BSM and **rare** H(125) decays

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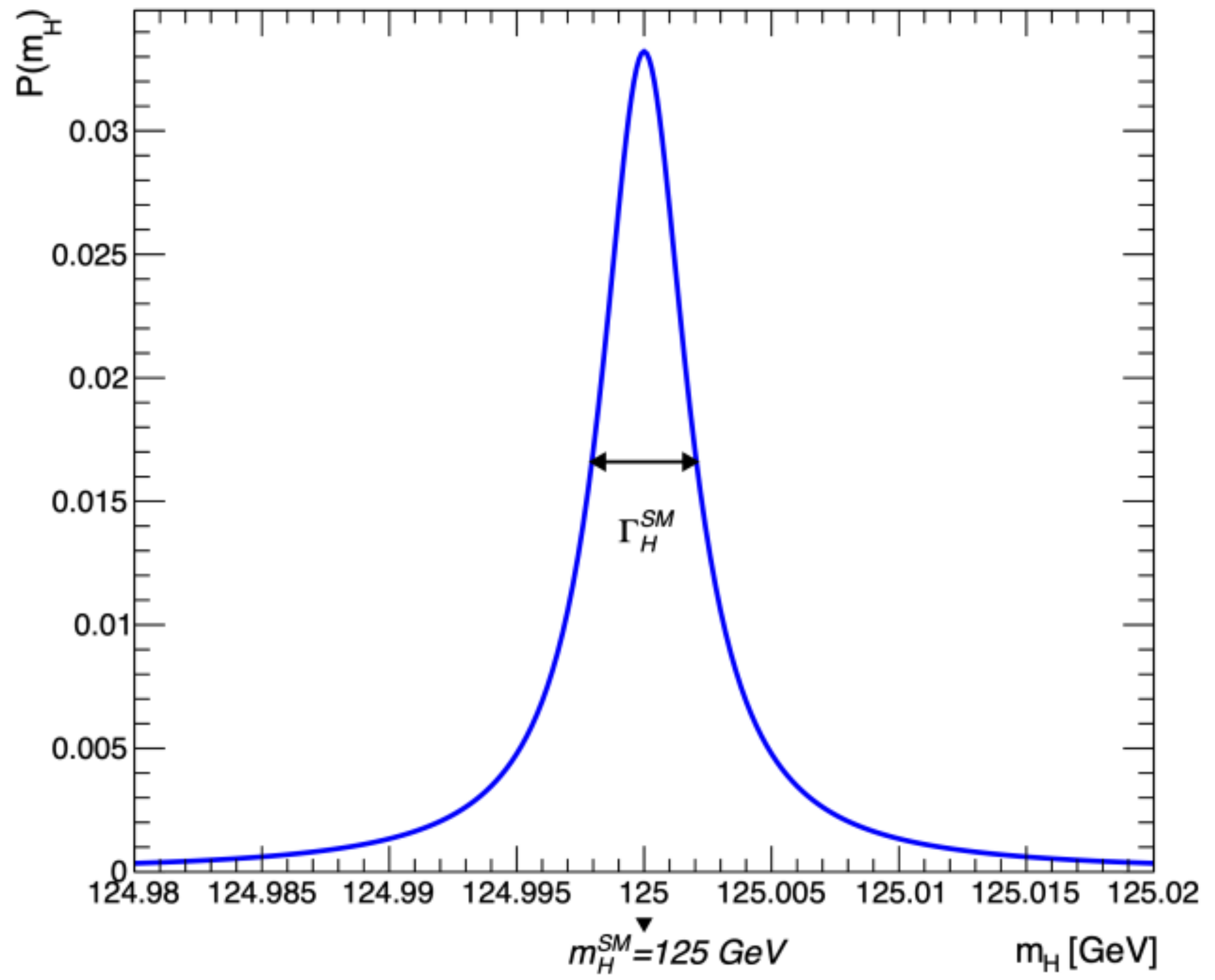
23-25 September, Orsay, Paris
Higgs Hunting 2024

University of Pittsburgh

ATLAS EXPERIMENT

Introduction

- **Rare but (maybe) not that rare:**
  - The Higgs width predicted by the SM is extremely small (w.r.t. the experimental resolution).
    - Most recent measurement of total width: $\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV [j.physletb.2023.138223].
    - Model-dependent measurement, hence the search for BSM in decays is very interesting

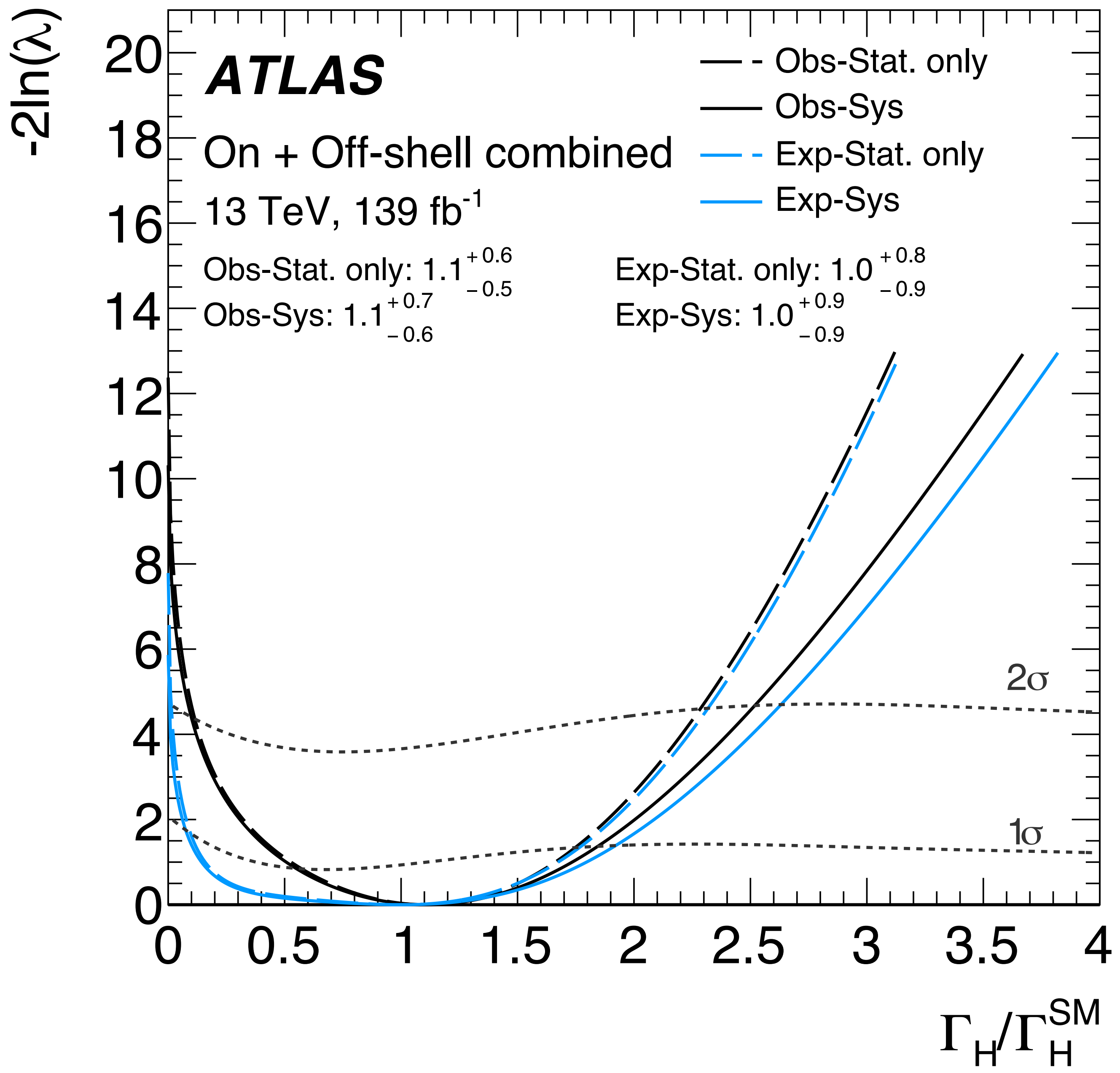


- This talk will cover the following recent results from ATLAS:
  - $H \to \omega/K^* + \gamma$ [10.1016/j.physletb.2023.138292]
  - $H \to D^*\gamma$ [10.1016/j.physletb.2024.138762]
  - $H \to Z\gamma$ [10.1103/PhysRevLett.132.021803]
  - $H \to b\bar{b}\tau^+\tau^-$ [arXiv:2407.01335]
  - $H \to Z + \gamma\gamma$ [10.1016/j.physletb.2024.138536]
  - $H \to e/\mu + \tau$ [10.1007/JHEP07(2023)166]

Allowed by the SM but with extremely small BR ($H \to \omega/K^* + \gamma$, $H \to D^*\gamma$, $H \to Z\gamma$)

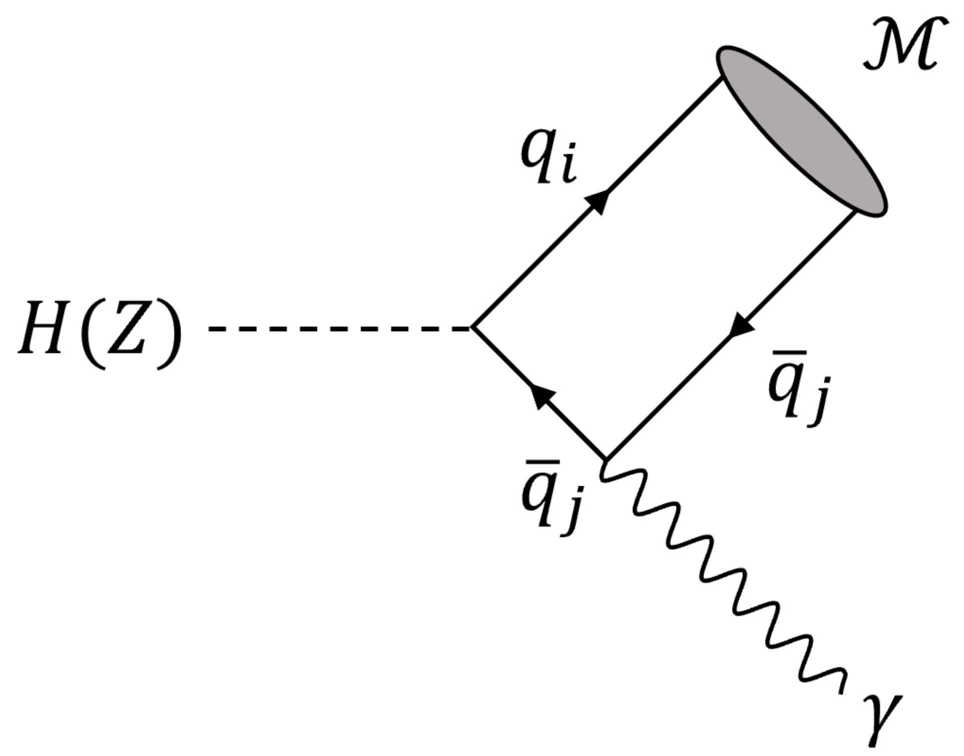
Preferred by models introducing BSM light pseudoscalar (2HDM+s) ($H \to b\bar{b}\tau^+\tau^-$, $H \to Z + \gamma\gamma$)

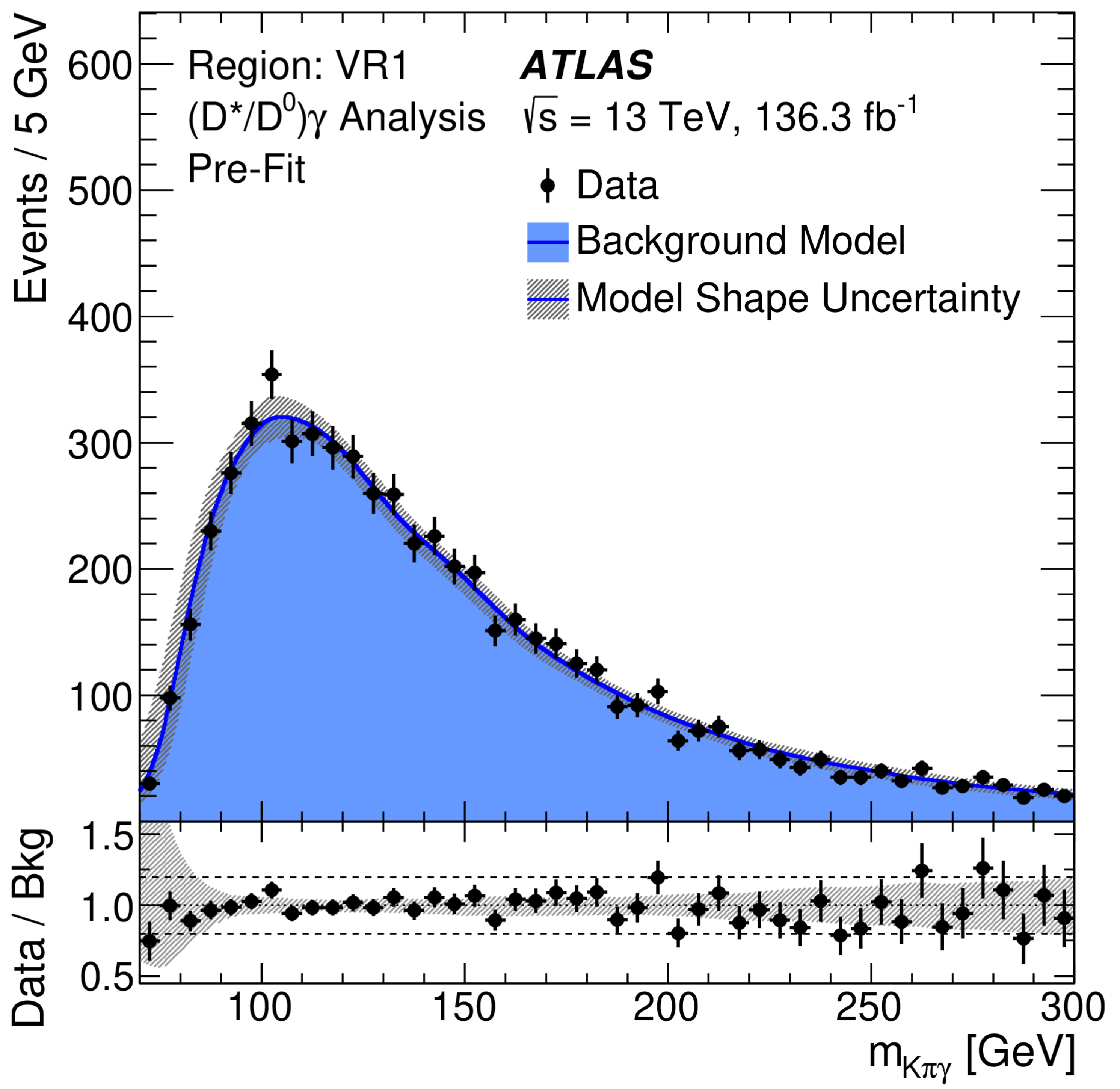
→ Search for Lepton-flavour-violating (LFV) ($H \to e/\mu + \tau$)



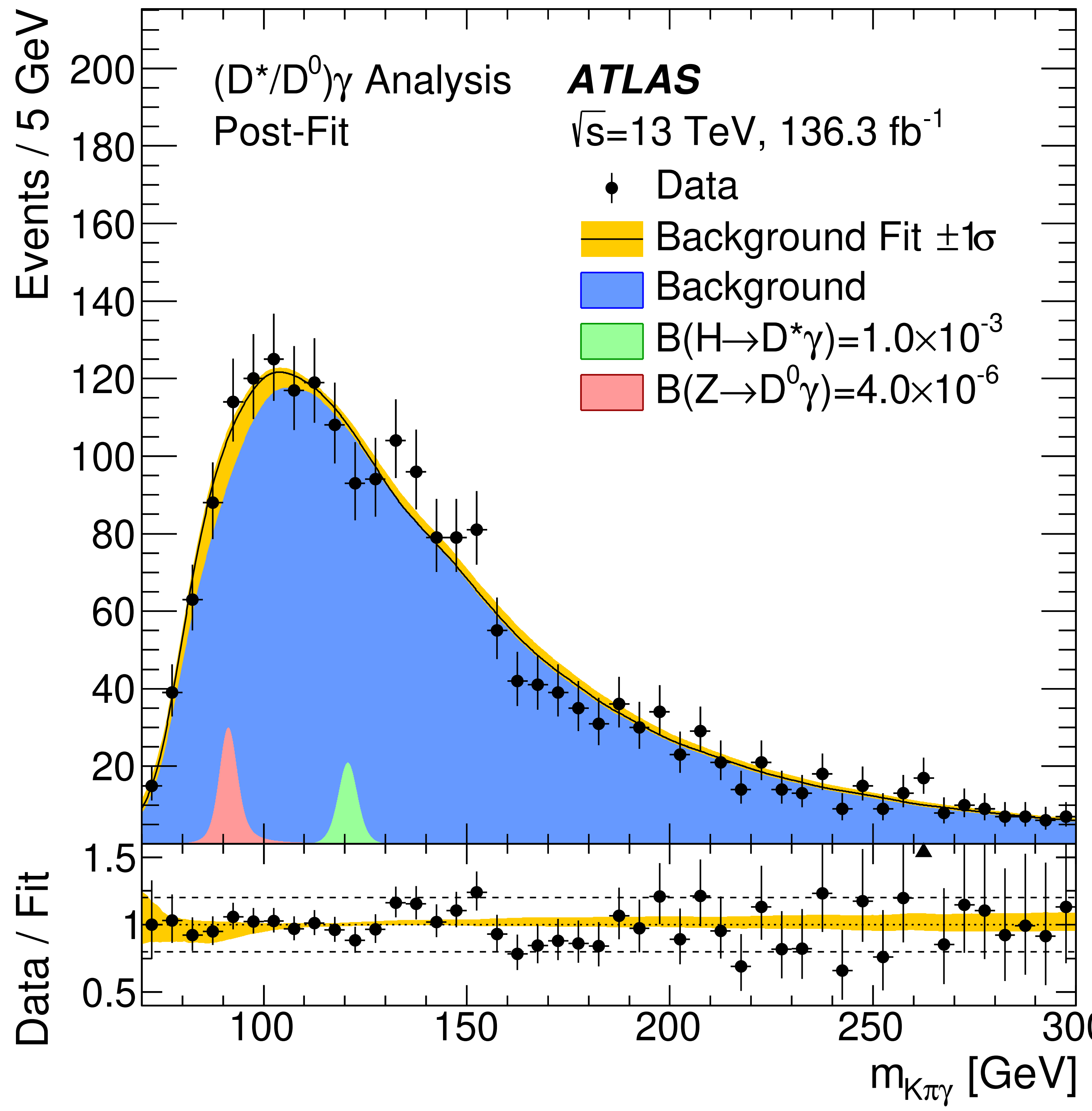
$H \to D^*\gamma$ overview

- Targeting for flavour violating couplings $H \to q\bar{q}'$, probes H_{uc} couplings
  - Forbidden at tree-level within the SM → any observation would imply new physics!
- Meson candidate reconstructed by the tracks.
  - Signal region (SR): di-track $p_T > 39$ GeV, with di-track isolation and γ isolation requirements.
- Background modelling:
  - Major background: mix of multi-jet and γ + jet events.
  - Using a non-parametric fully data-driven method, based on [JHEP 10 (2022) 001].
    - Derived the PDF from a dataset using a relaxed event selection.
    - 3 validation regions designed to test the background modelling.





$H \to D^*\gamma$ results



- Data is consistent with expected backgrounds - no significant deviations observed.
- This analysis also provides limits on LFV $Z \to D^0\gamma$ and $Z \to K_s\gamma$ process (share the similar signal & background signature).
- First limits on $H \to D^*\gamma$ and $Z \to K_s\gamma$ branching fractions at LHC!
- Limit on $Z \to D^0\gamma$ is an improvement on the LHCb results of 2×10^{-3} [10.1088/1674-1137/aceae9].

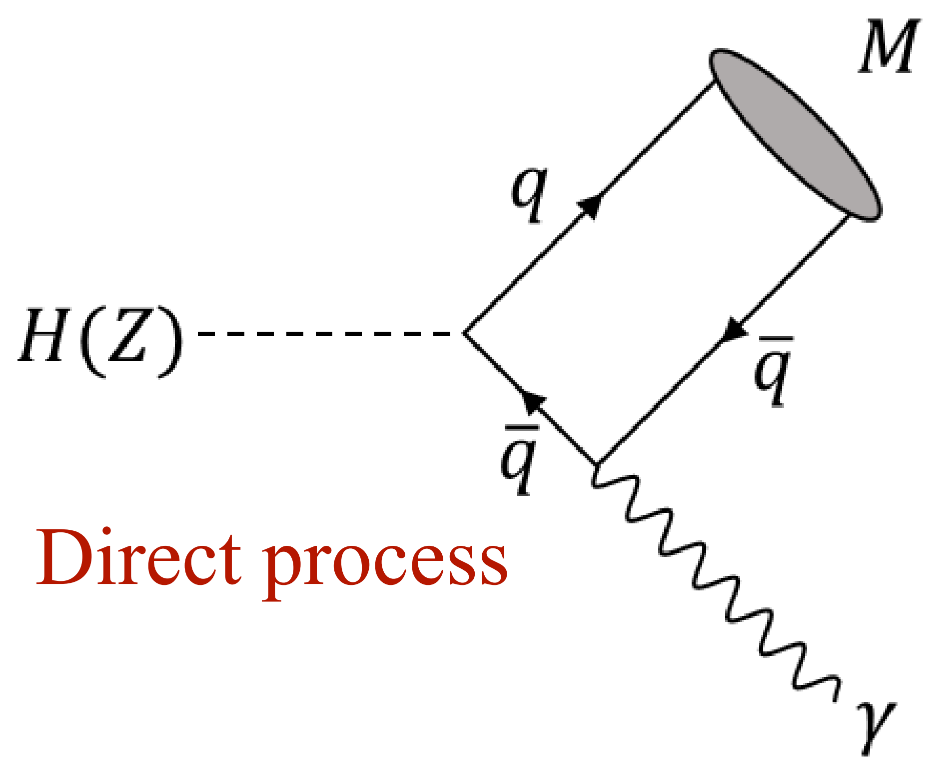
Assuming SM Higgs production

	95% CL upper limits			
	Branching Fraction		$\sigma \times \mathcal{B}$ [fb]	
Channel	Observed	Expected	Observed	Expected
$H \to D^*\gamma$	1.0×10^{-3}	$1.2^{+0.5}_{-0.3} \times 10^{-3}$	58	68^{+28}_{-19}
$Z \to D^0\gamma$	4.0×10^{-6}	$3.4^{+1.4}_{-1.0} \times 10^{-6}$	235	200^{+82}_{-56}
$Z \to K_s^0\gamma$	3.1×10^{-6}	$3.0^{+1.3}_{-0.8} \times 10^{-6}$	185	176^{+77}_{-49}

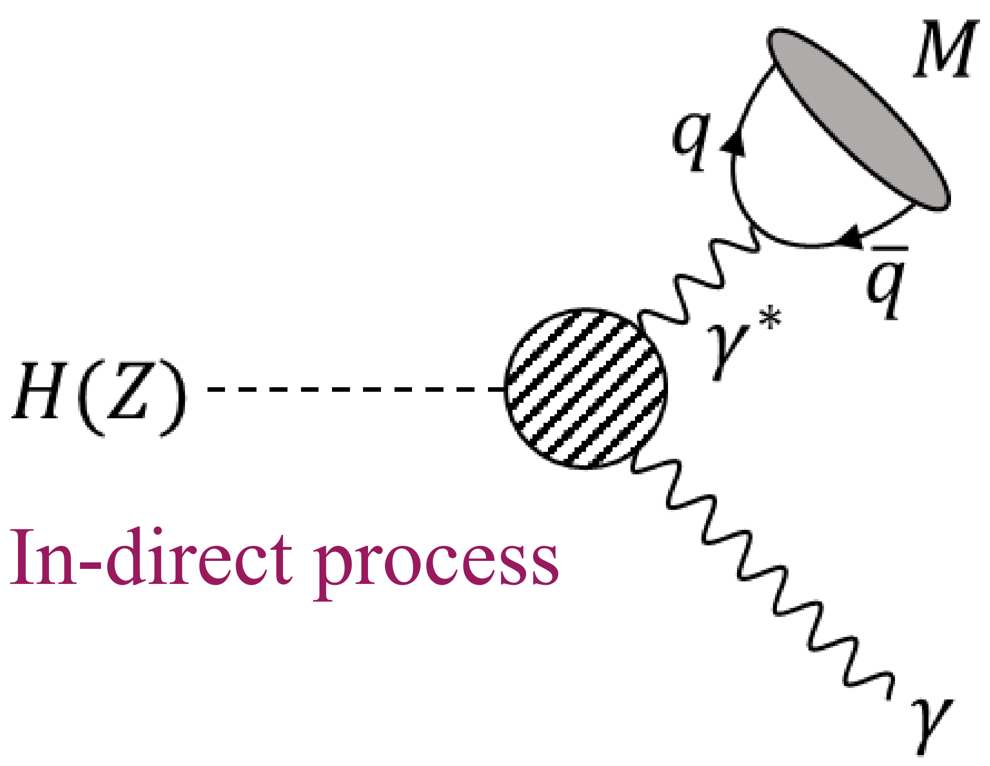
Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B} = 10^{-3}$	Z signal $\mathcal{B} = 10^{-6}$
$H \to D^*\gamma$	116–126	203 (214.8 ± 5.5)	25.4 ± 2.0	–
$Z \to D^0\gamma$	86–96	215 (206 ± 14)	–	10.3 ± 0.7
$Z \to K_s^0\gamma$	86–96	21 (19.5 ± 2.0)	–	4.2 ± 0.4

$H \to \omega/K^* + \gamma$ overview

- Motivation: to measure the Higgs to light and charm quark Yukawa couplings.
- **Challenge**: direct measuring Higgs coupling to light quarks is difficult.
  - Not only the small rates, but huge irreducible background from $H \to c\bar{c}$.



Direct process



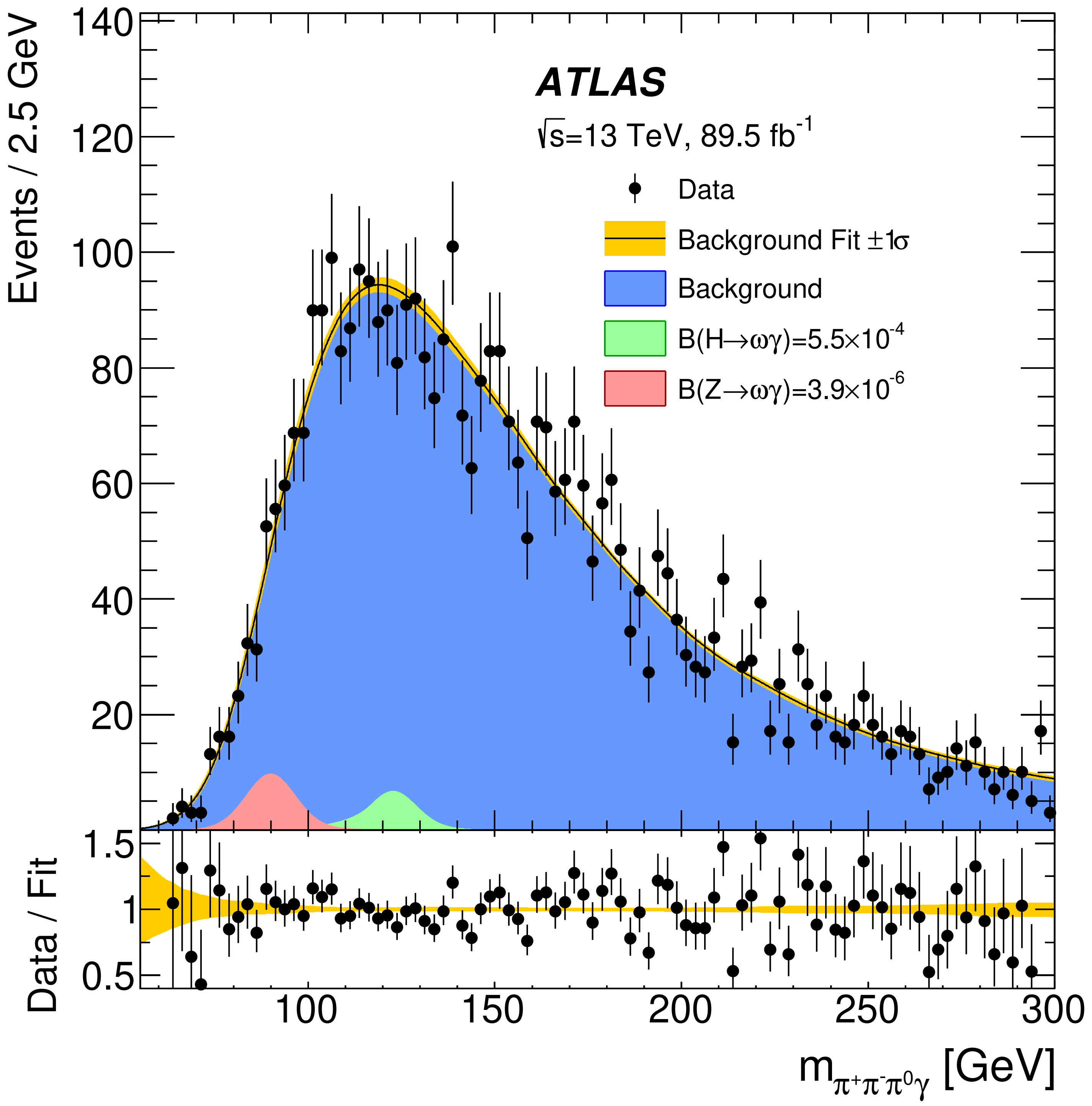
In-direct process

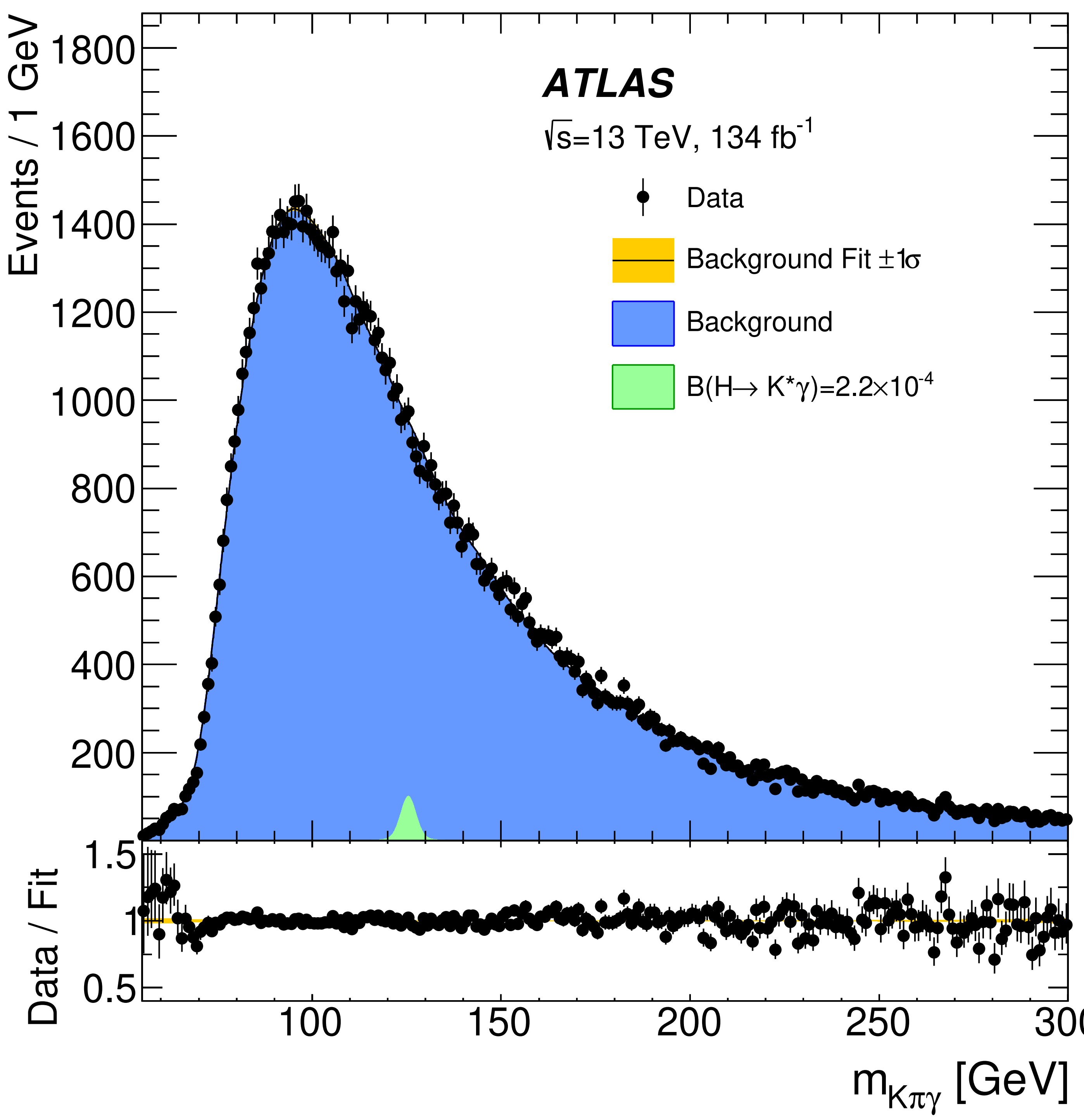
$\omega(782), \Gamma = 8.49 \pm 0.08$ MeV	$K^*(892), \Gamma = 50.8 \pm 0.6$ MeV
Quark component: $\frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d})$	Quark component: $d\bar{s}$
Most common decay mode: $\pi^+\pi^-\pi^0$ (98%)	Most common decay mode: $K^+\pi^-$ (~100%)
Meson signature: two charged tracks with an additional π^0.	Small SM rate induced by loop contributions. If observed, indicating flavour violating H decays.

- **Solution**: using exclusive decays of Higgs to a meson and a photon.
  - Include direct and indirect ($H \to \gamma\gamma^*$) processes.
  - Distinct final state: high p_T isolated photon recoiling agains high p_T meson.
- Major background: QCD production of γ+jet and multijet events.
  - Using a non-parametric fully data-driven method, based on [JHEP 10 (2022) 001].

$H \to \omega/K^* + \gamma$ results

- Invariant mass of objects is used as the final discriminant variable.
- The observed data is consistent with the SM prediction.
- Upper limits on the branching fraction of $H \to \omega\gamma$ and $H \to K^*\gamma$ are derived.
  - Also deriving the branching fraction of $Z \to K^*\gamma$, by replacing Higgs with Z signal samples.

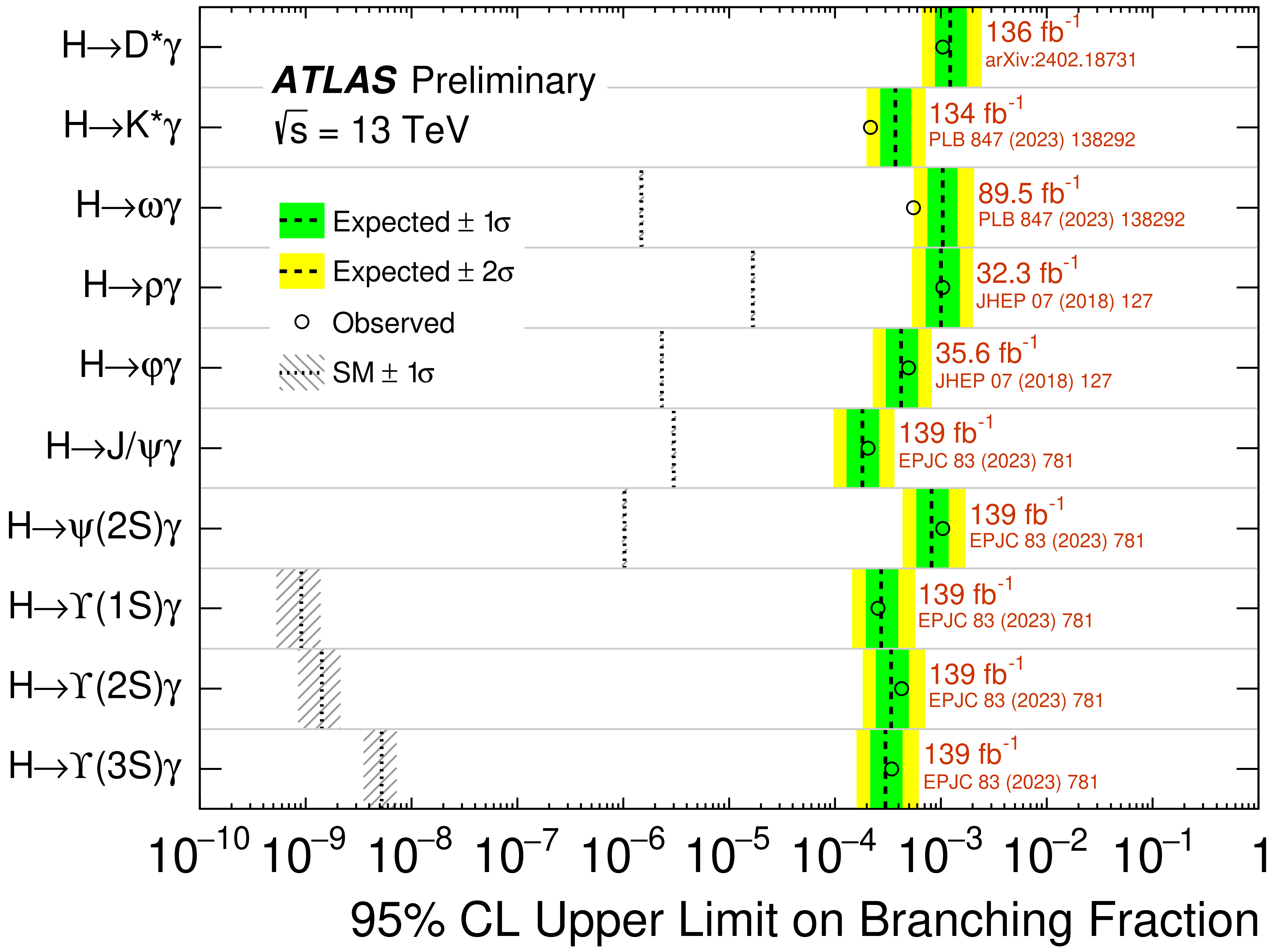


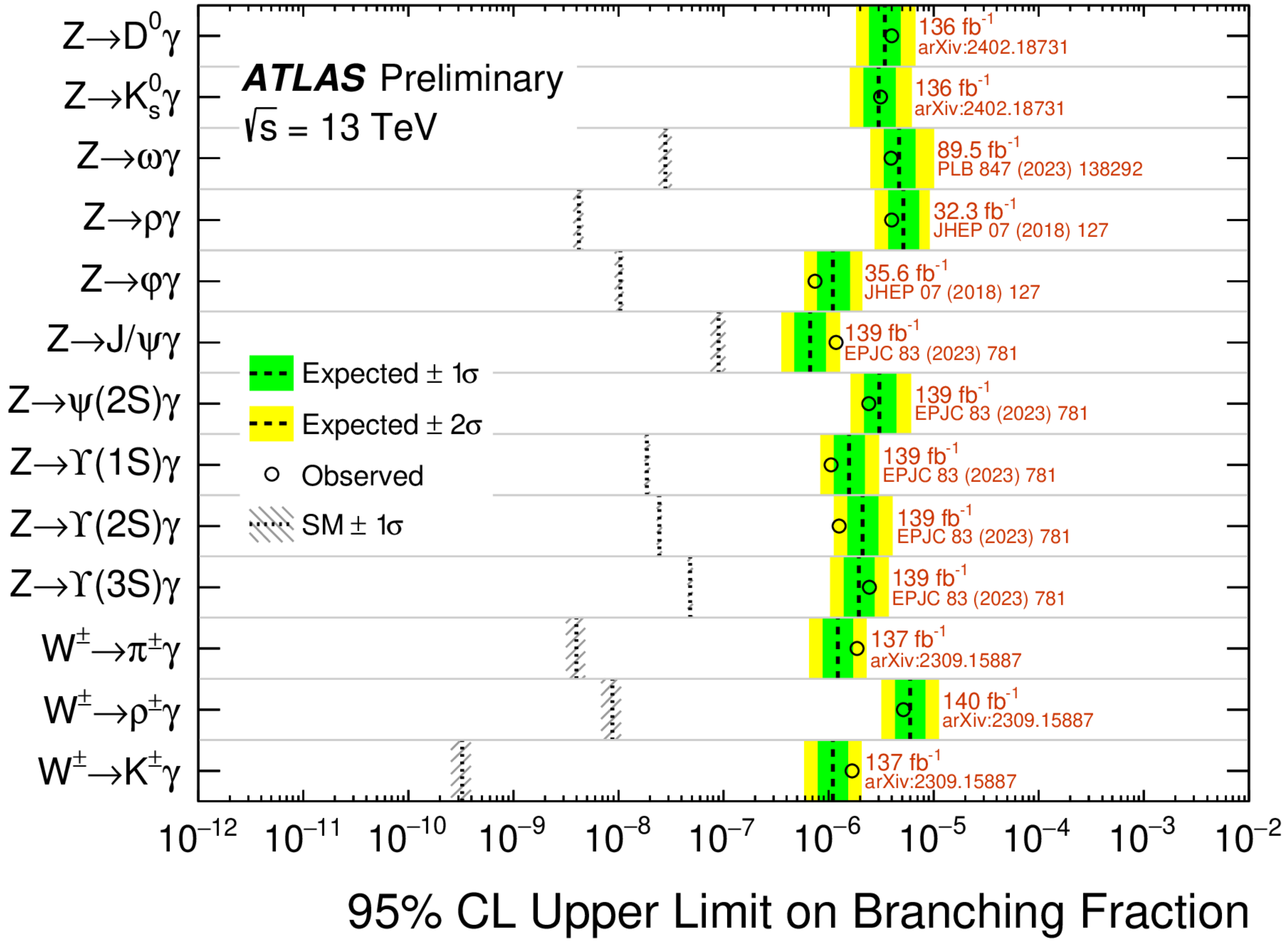


Channel	Mass range [GeV]	Observed (Expected) background	H signal $\mathcal{B} = 10^{-4}$	Z signal $\mathcal{B} = 10^{-6}$
$H \to \omega\gamma$	115–135	686 (730 ± 17)	9 ± 1	–
$Z \to \omega\gamma$	80–100	388 (386 ± 16)	–	18 ± 2
$H \to K^*\gamma$	120–130	9526 (9630 ± 50)	53 ± 4	–

Summary of $H \to \mathcal{M}\gamma$

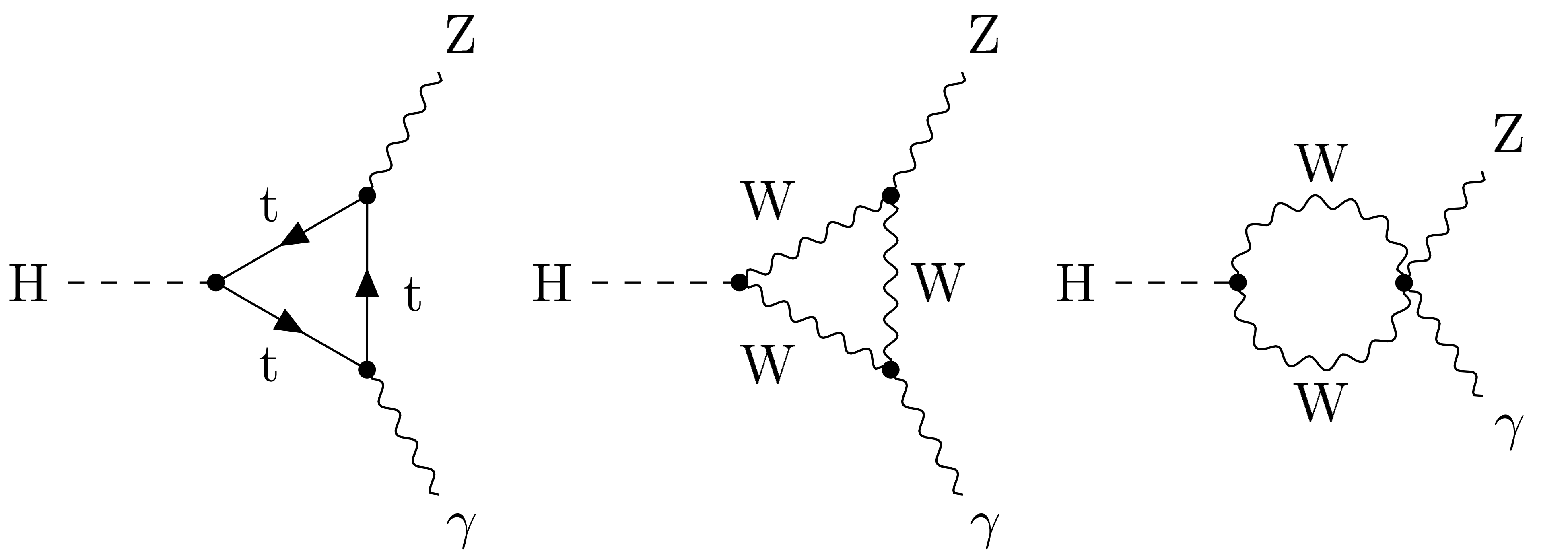
- Summary of 9 ATLAS Run 2 exclusive searches for $H \to \mathcal{M}\gamma$ [ATL-PHYS-PUB-2023-004].
  - These analyses also provide limits on $V \to \mathcal{M}\gamma$.

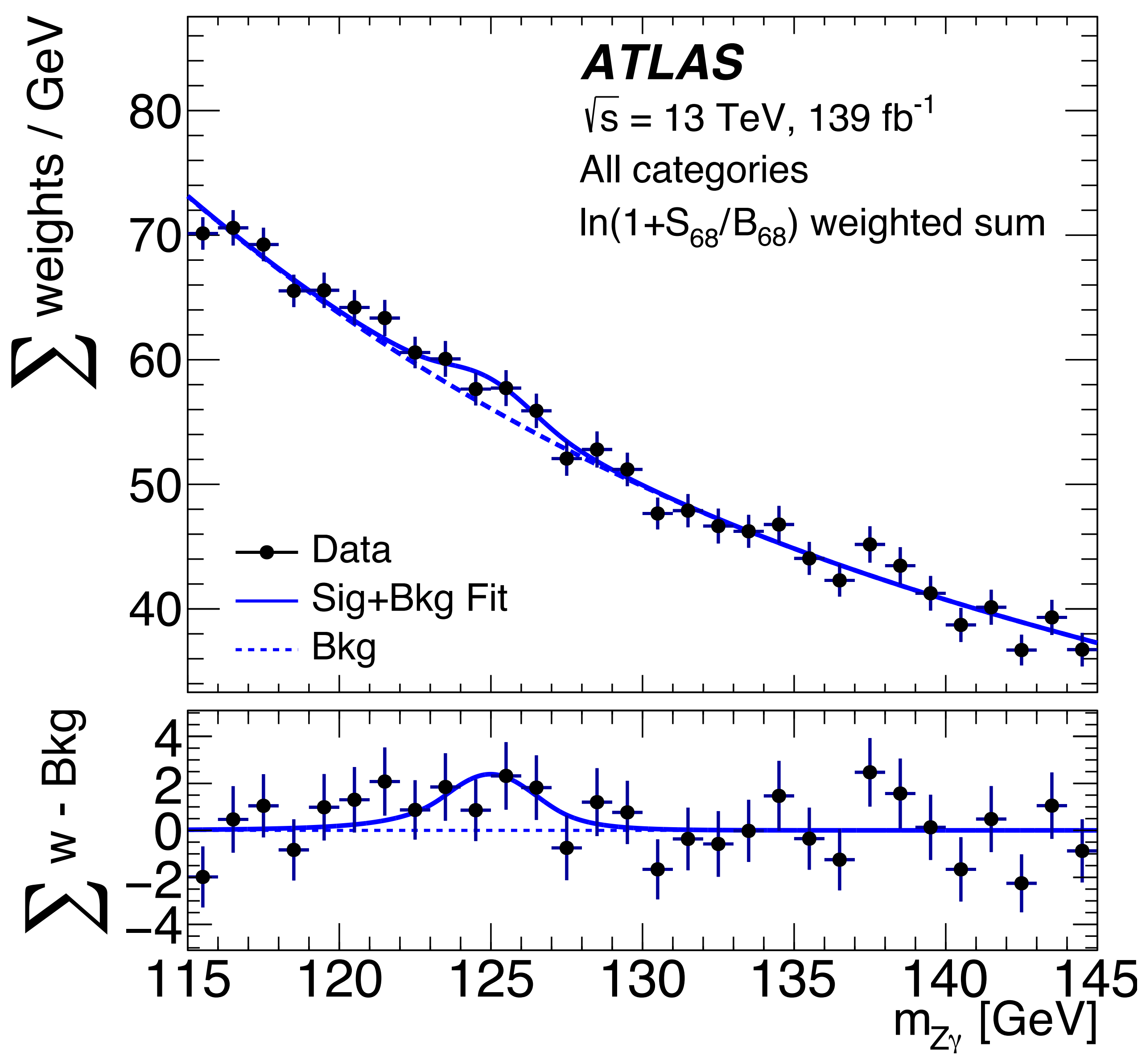


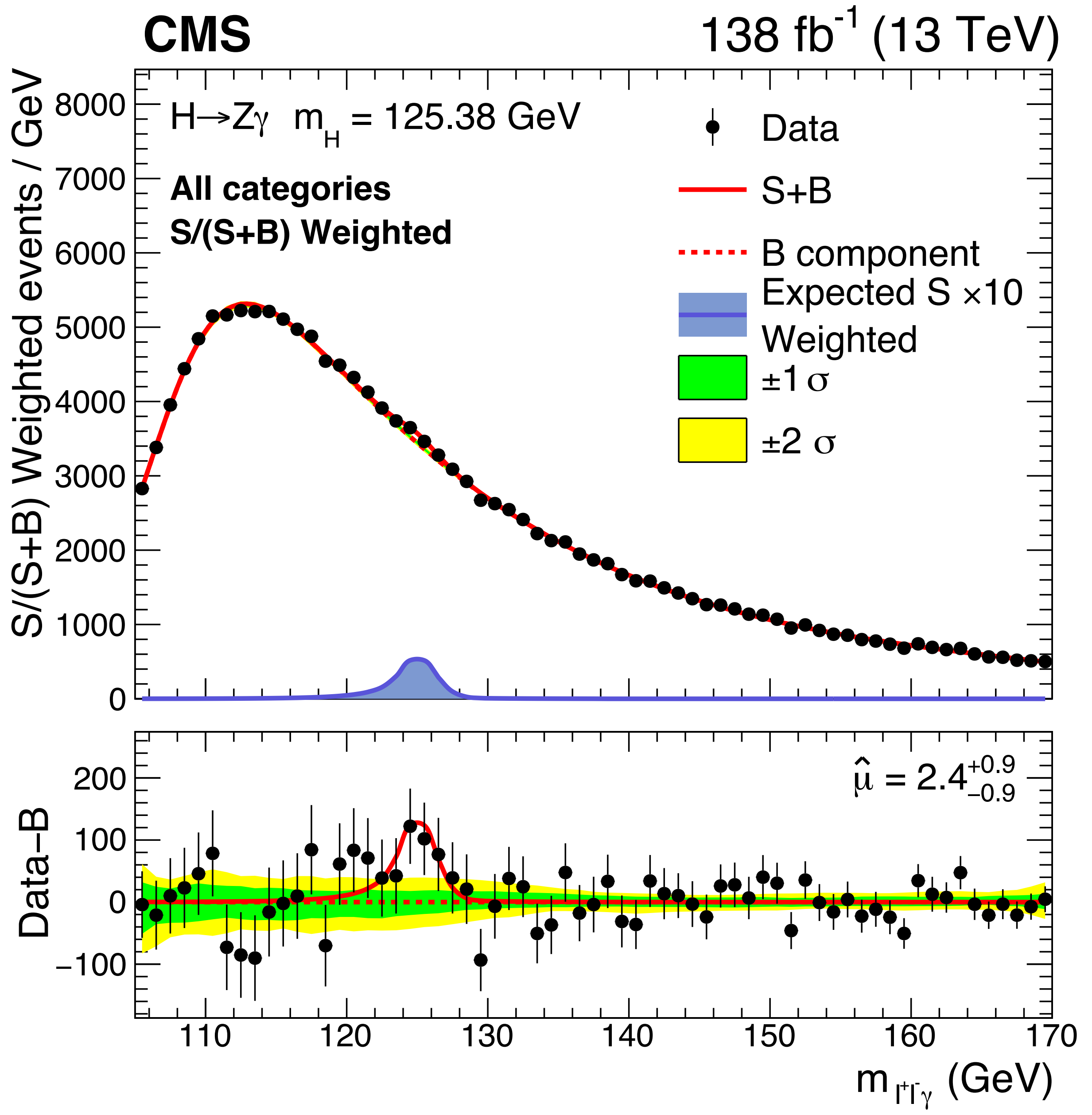


$H \to Z\gamma$ (ATLAS+CMS) overview

- Small branching ratio predicted by SM with loop processes.
  - Br($H \to Z\gamma$)=$(1.52 \pm 0.11) \times 10^{-3}$ at $m_H = 125.09$ GeV.
- ATLAS and CMS have found evidence for a mild excess but no observation yet.
  - ATLAS [Phys. Lett. B 809 (2020) 135754]: $\mu = 2.0^{+1.0}_{-0.9}$ with observed (expected) local significance $2.2(1.2)\sigma$.
  - CMS [JHEP 05 (2023) 233]: $\mu = 2.4^{+0.9}_{-0.9}$ with observed (expected) local significance $2.7(1.2)\sigma$.
- Dominant by statistical uncertainty. **Strong motivation for a combination!**
  - Both analyses use profiled likelihood fit.
  - Major difference: CMS analyses using a "discrete profiling method" to account for uncertainties in the background function. In the combination, the maximum likelihood is given by the "envelope". Both method gives consistent results.







$H \to Z\gamma$ (ATLAS+CMS) results

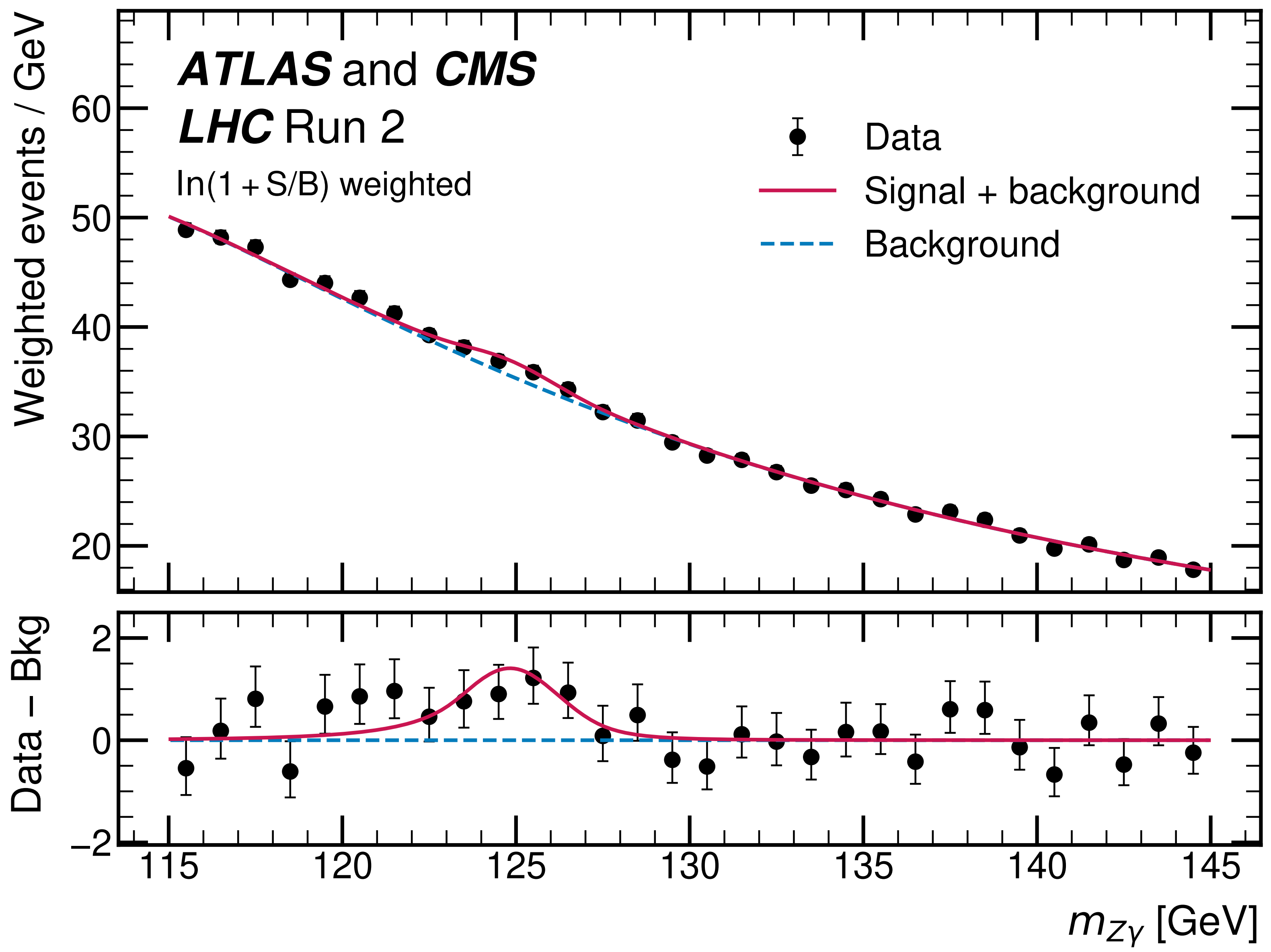
- Using full Run 2 dataset, 139 fb^{-1} from ATLAS and 138 fb^{-1} from CMS [10.1103/PhysRevLett.132.021803].

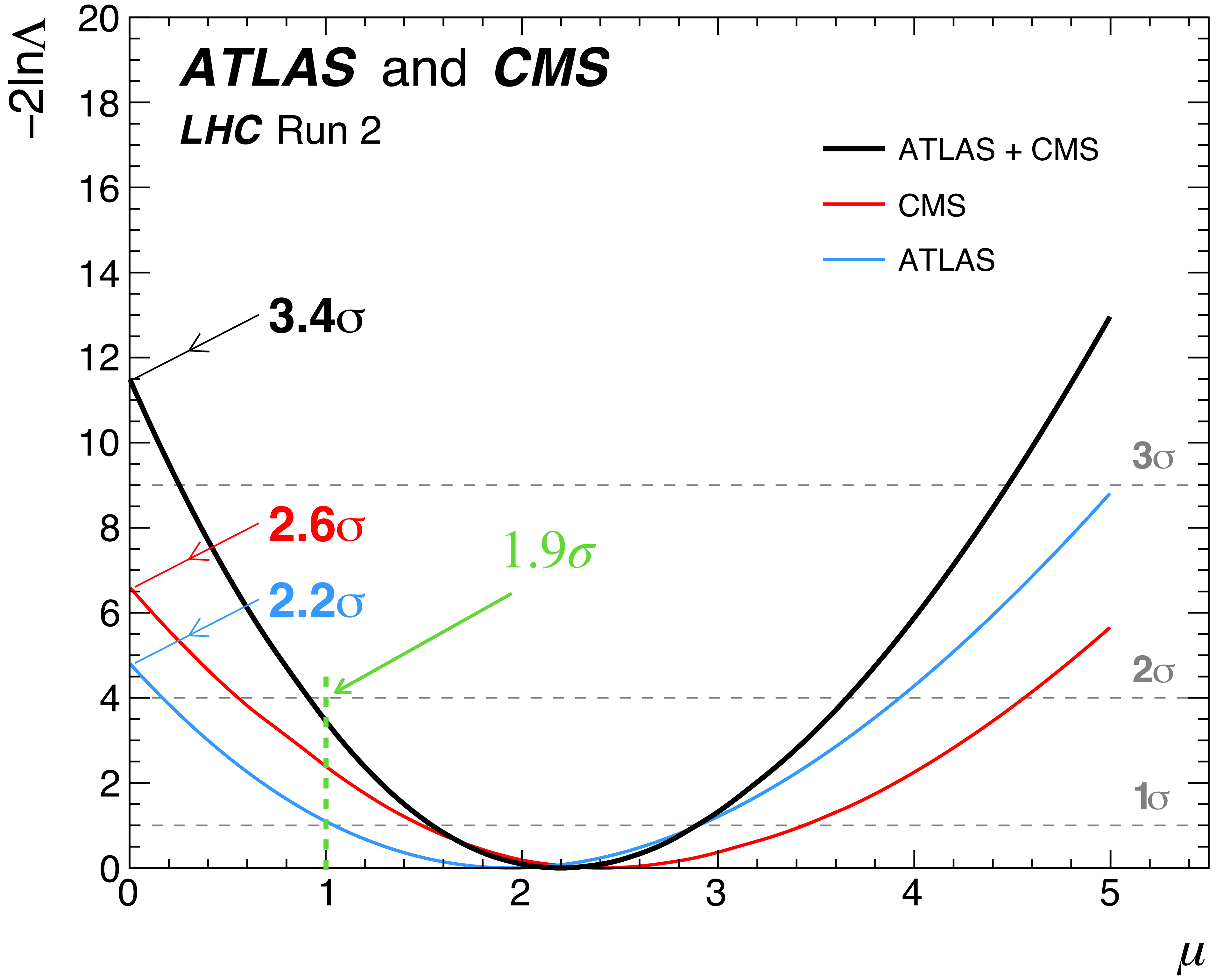
ATLAS only: 2.2σ

CMS only: 2.6σ

Combined: 3.4σ, 1.9σ deviated from SM prediction.

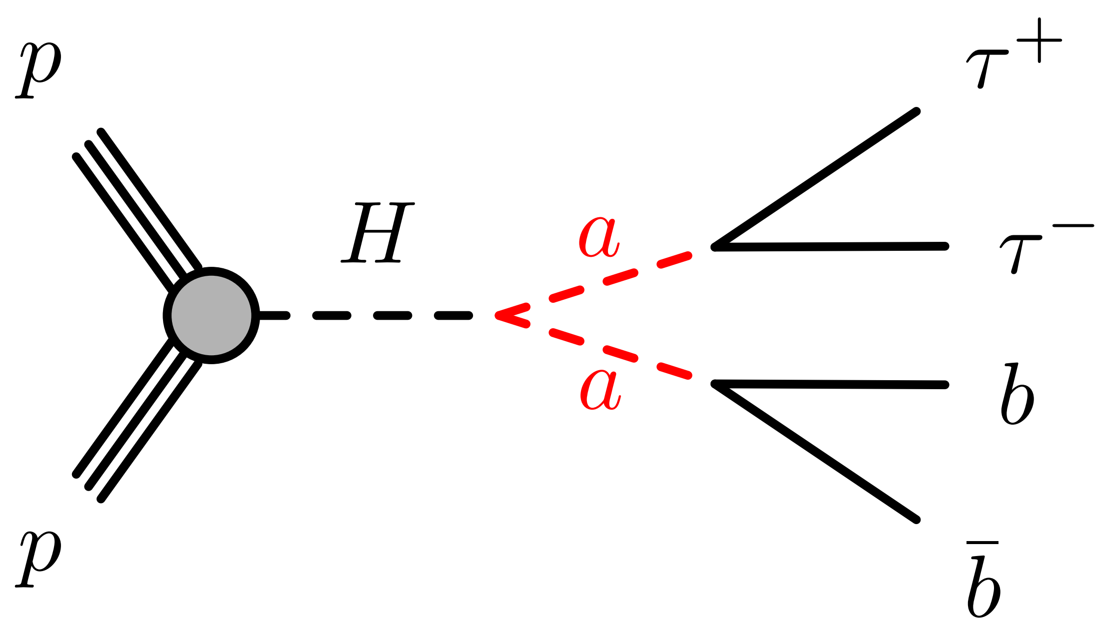
- Likelihood scan gives the best-fit signal strength at 2.2 ± 0.7 times the SM prediction.





$H \to b\bar{b}\tau\bar{\tau}$ overview

- Predicted by models with two Higgs doublets plus additional pseudo scalar (2HDM+s).
- Due to the Yukawa coupling, large branching fraction for m_a from 12 to 60 GeV for most 2HDM type models.
- Analysis strategy:
  - 3 channels: $e\mu$, $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$ (using lepton triggers, avoid SF lepton to reduce backgrounds).
  - 3 categories: 1 b-jet, 2 b-jet, 1 merged DeXTer B-jet [ATL-PHYS-PUB-2022-042].
- Major background: tops, Z+jets, fake leptons, fake τs.
  - Dedicated control region defined in each channel for each background: Top CR, Z CR, SS CR.
- Using parameterised NN scores as final discriminants to enhance sensitivity.

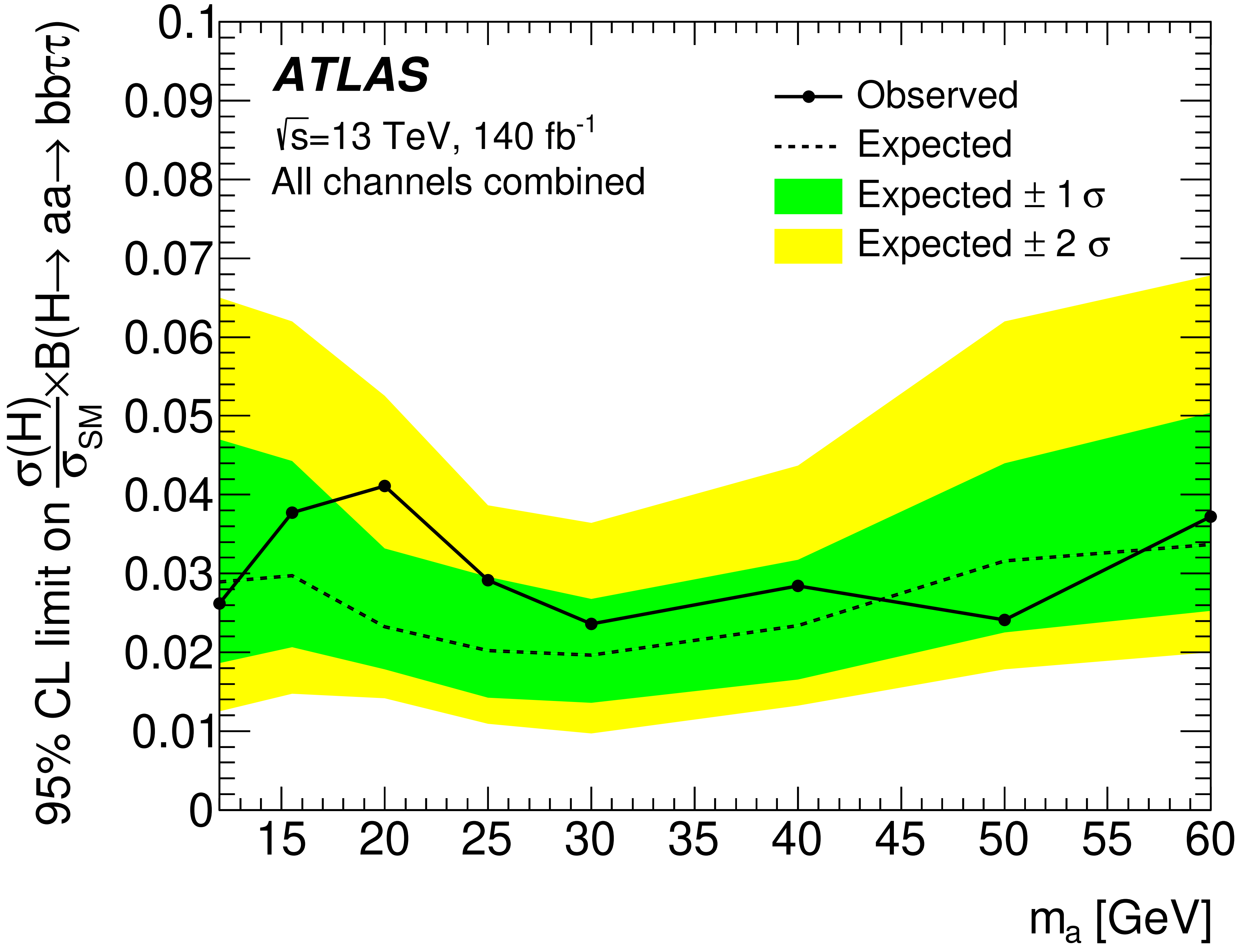


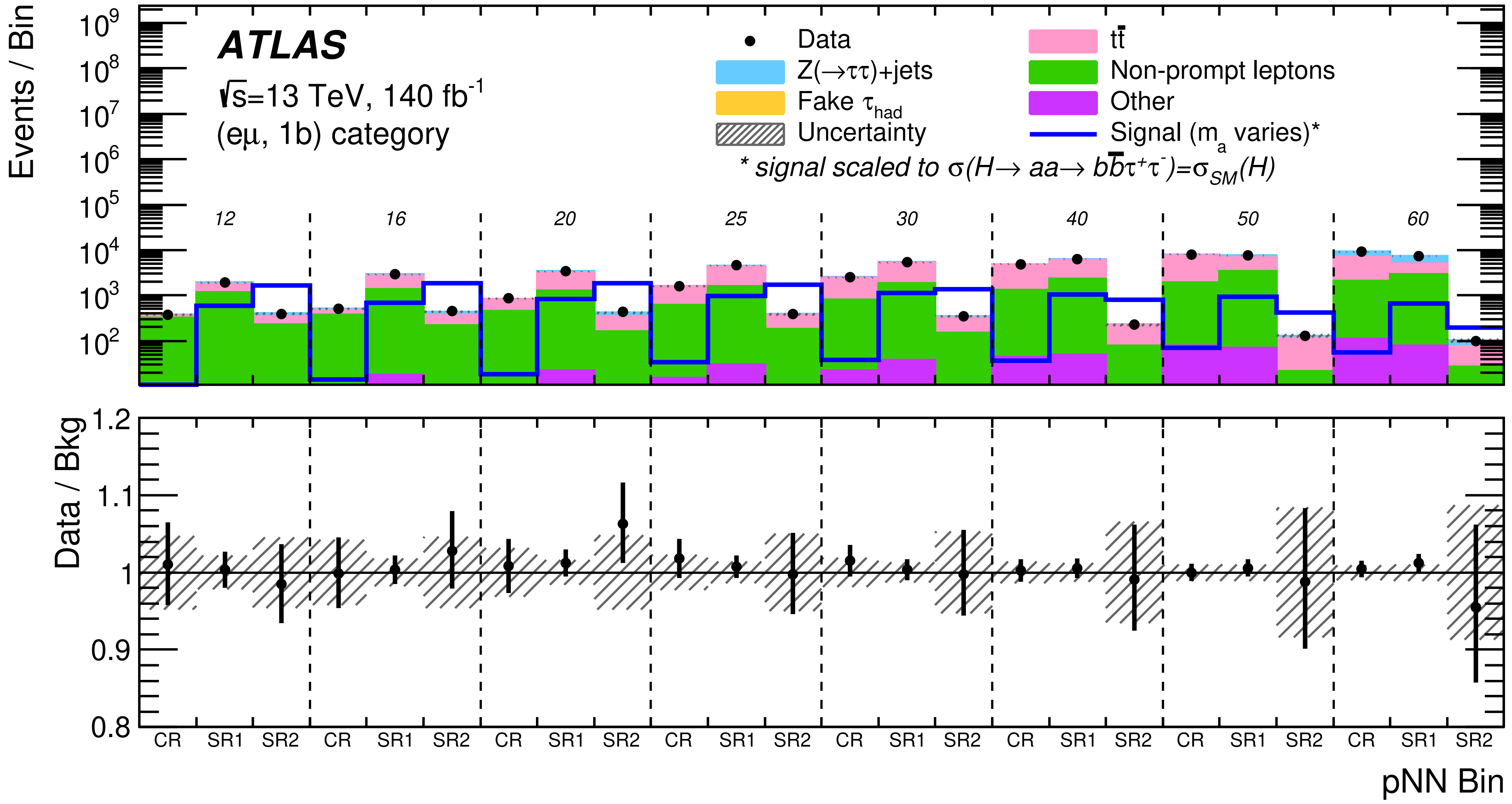
τ-lepton decays	$1B,0b$	$0B,1b$	$0B,2b$
$e\mu$	$(e\mu,1B)$	$(e\mu,1b)$	$(e\mu,2b)$
$\mu\tau_{\text{had}}$	$(\mu\tau_{\text{had}},1B)$	$(\mu\tau_{\text{had}},1b)$	$(\mu\tau_{\text{had}},2b)$
$e\tau_{\text{had}}$	$(e\tau_{\text{had}},1B)$	$(e\tau_{\text{had}},1b)$	$(e\tau_{\text{had}},2b)$

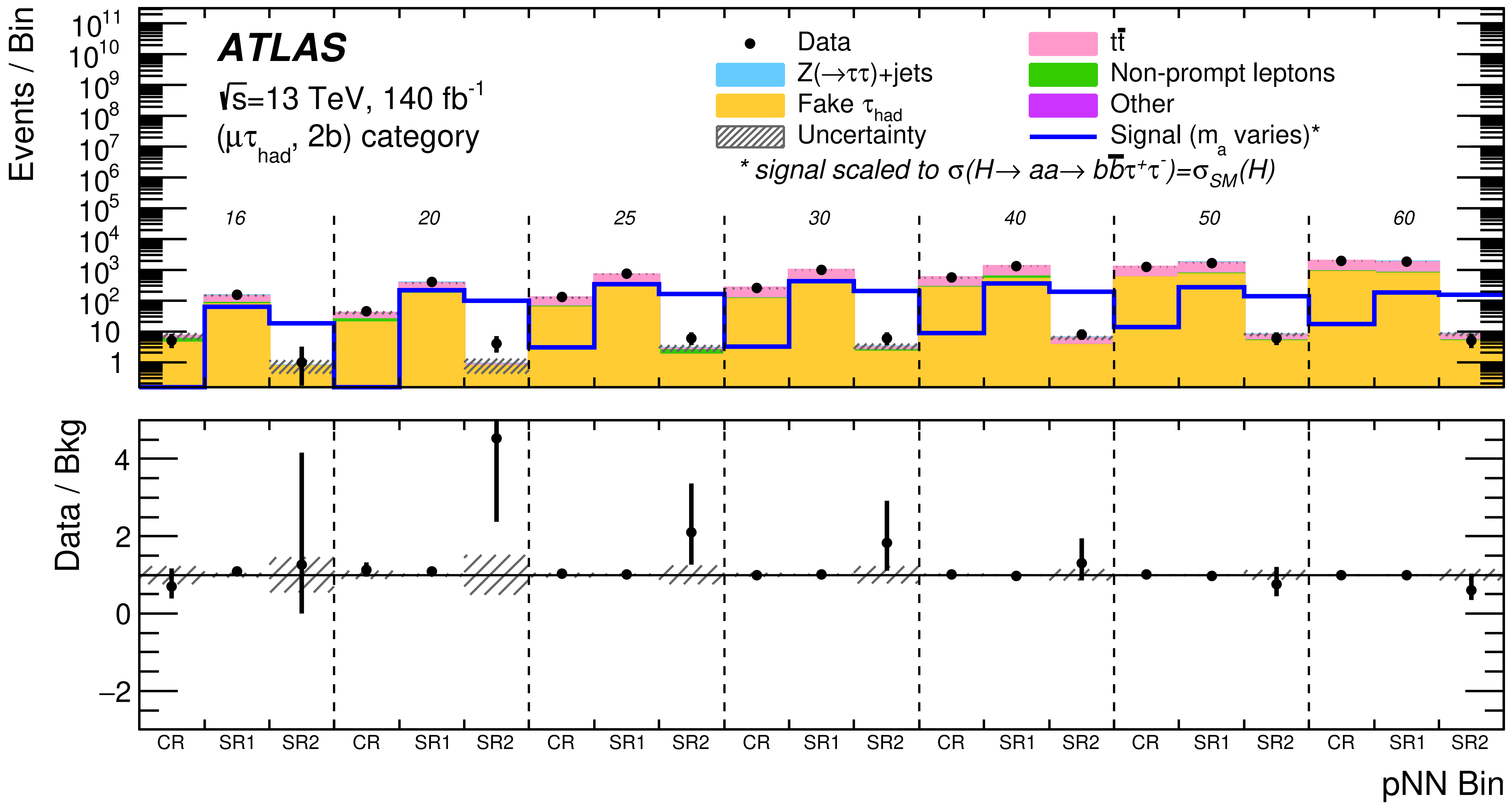
Heavy-flavor jets

$H \rightarrow b\bar{b}\tau\bar{\tau}$ results

- First limit setting on $H \rightarrow aa \rightarrow b\bar{b}\tau\bar{\tau}$ in ATLAS.
- No significant excess above the SM background expectation is observed.
  - Upper limits at 95% confidence level are set on $\mathrm{Br}(H \rightarrow aa \rightarrow b\bar{b}\tau\bar{\tau})$ of 2.2 to 3.9% for $12 < m_a < 60$ GeV.

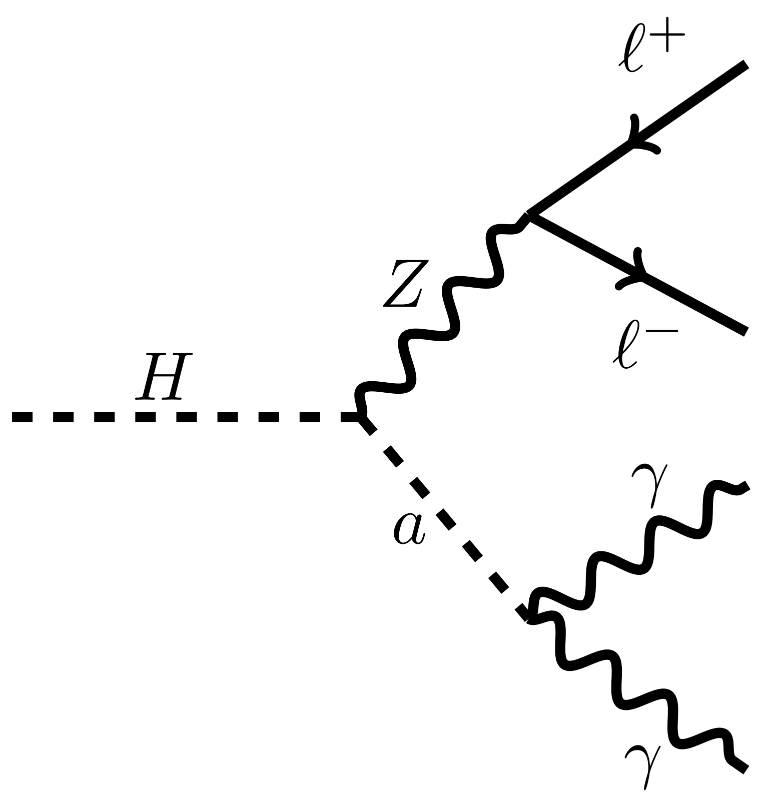


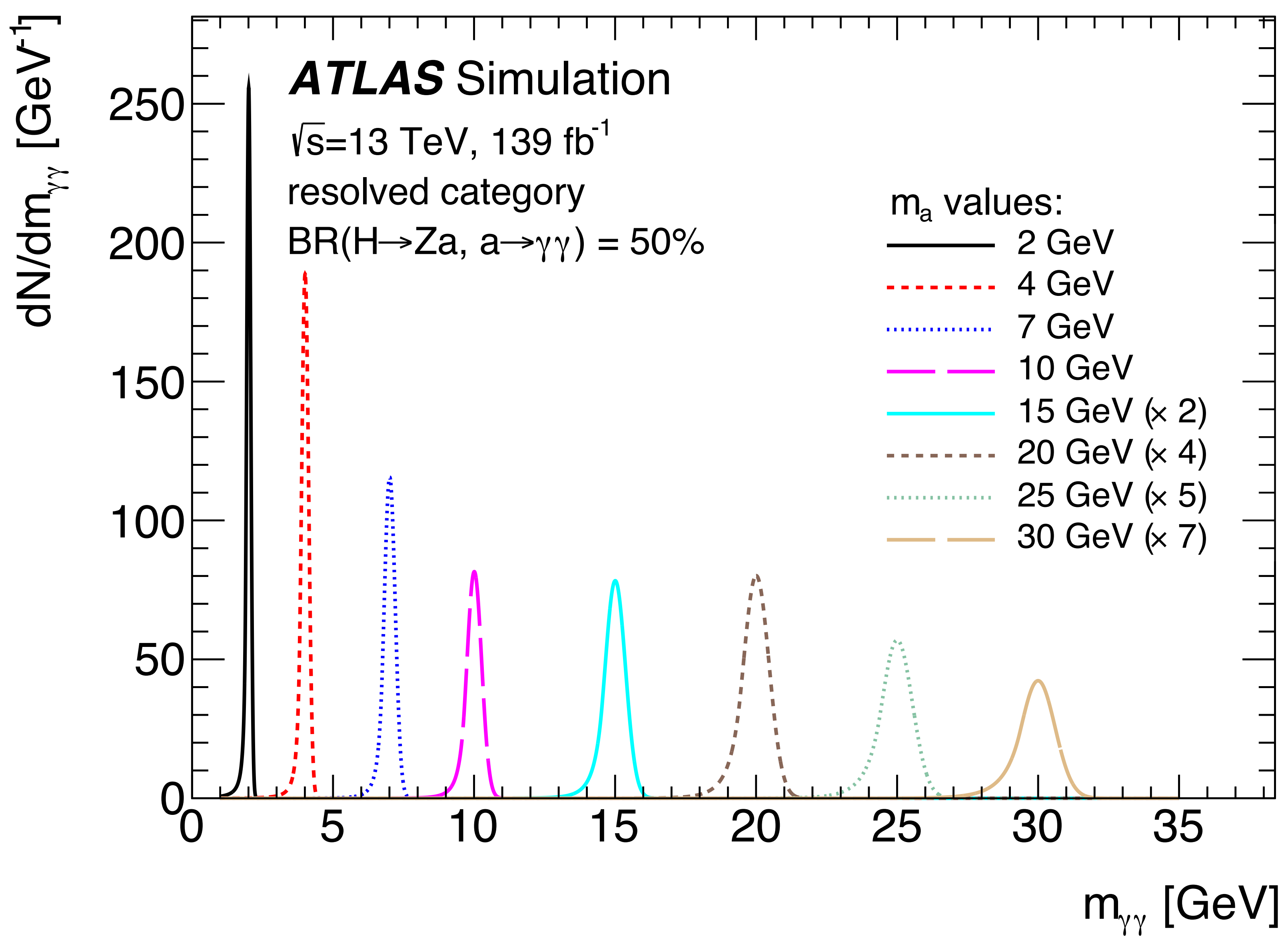




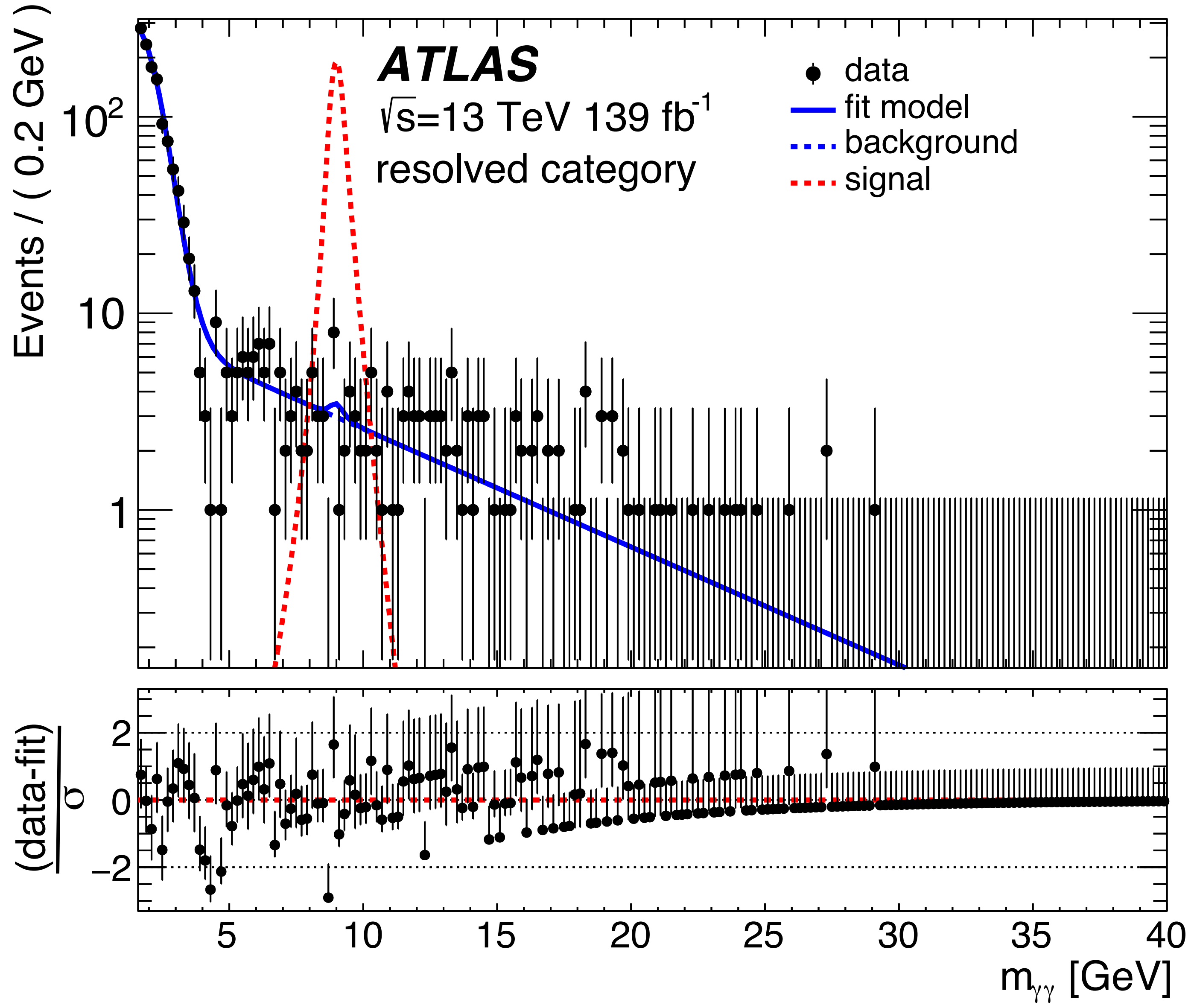
$H \to Z + \gamma\gamma$ overview

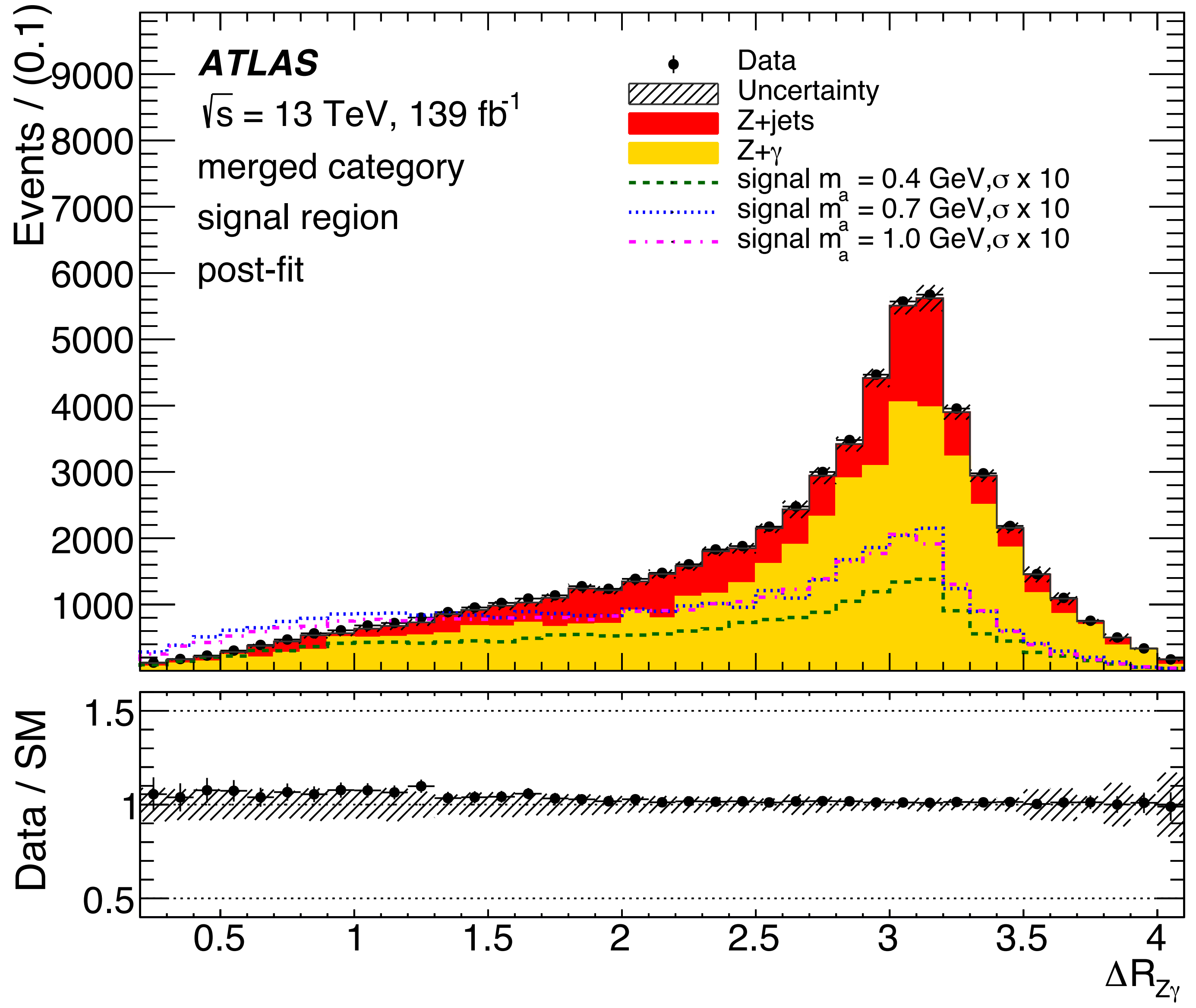
- Hidden sector search for pseudo-scalar portal (axions/ALPs) with photon couplings.
    - Targeting m_a from 0.1 GeV to 10 GeV.
    - Final states: Z with two collimated photons.
- Two categories designed for resolved and merged di-photon signatures.
    - Resolved category ($m_a > 2.5$ GeV): di-photon fully reconstructed with $\Delta R_{\gamma\gamma} < 1.5$ plus some topological requirements. SR with 110 GeV $< m_{ll\gamma\gamma} <$ 140 GeV, able to discriminate ALP mass.
    - Merged category ($m_a < 2.5$ GeV): only one photon reconstructed with $p_T > 20$ GeV and track isolation (no calo isolation required). SR with 110 GeV $< m_{ll\gamma} <$ 130 GeV, cannot discriminate ALP mass with single photon. Using $\Delta R(Z\gamma)$ as the final discriminant.
- Major background: $Z\gamma$ and Z+jets. MC template used for merged category and data-driven used for resolved category.

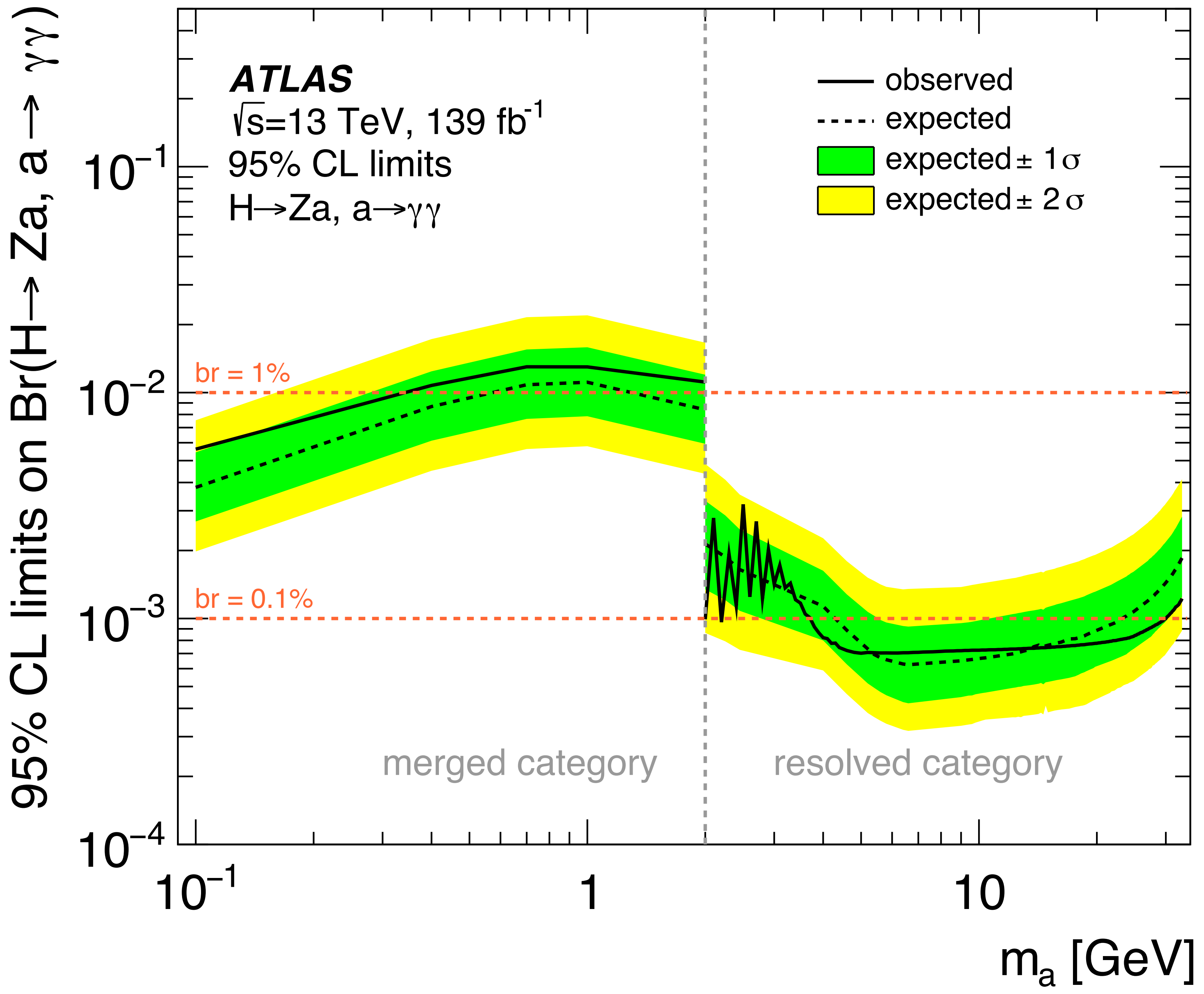




$H \to Z + \gamma\gamma$ results



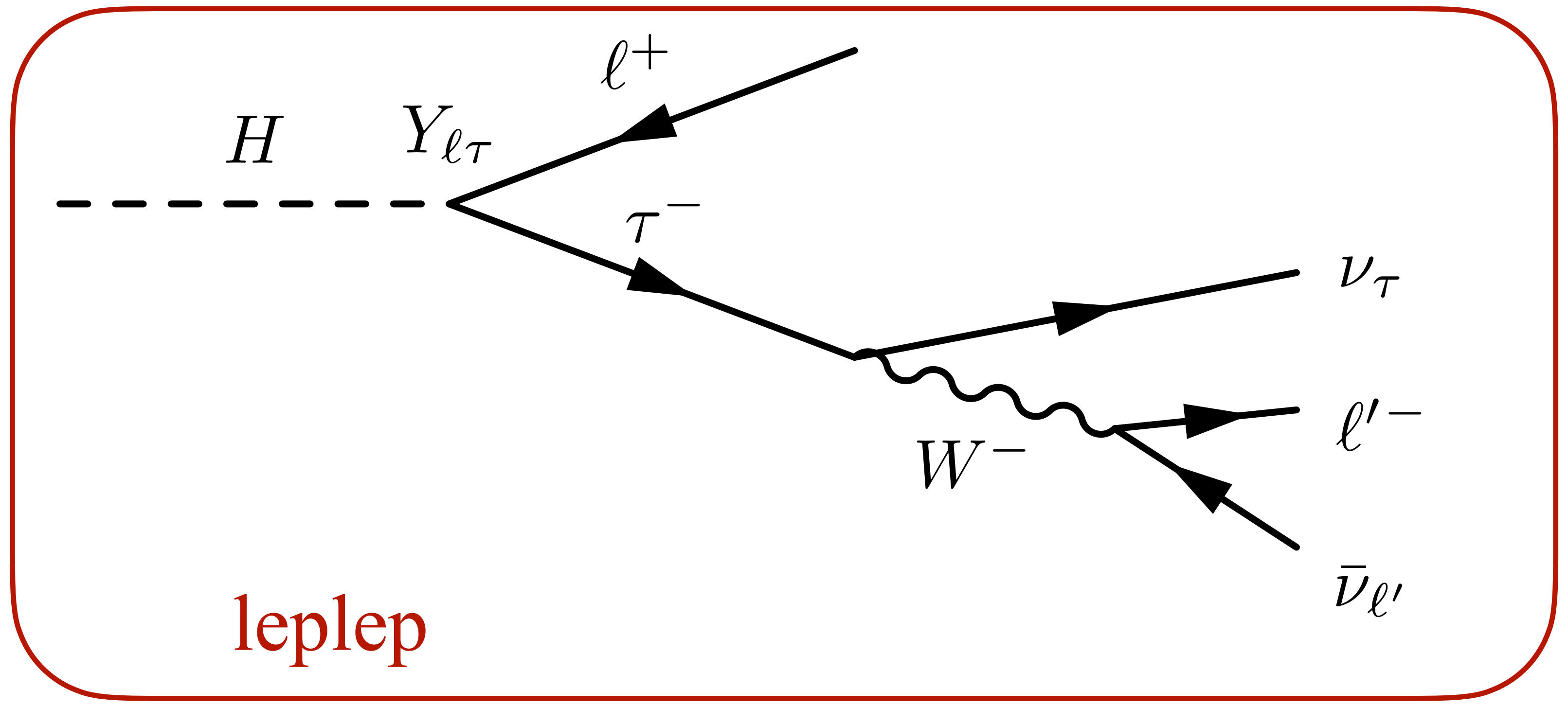


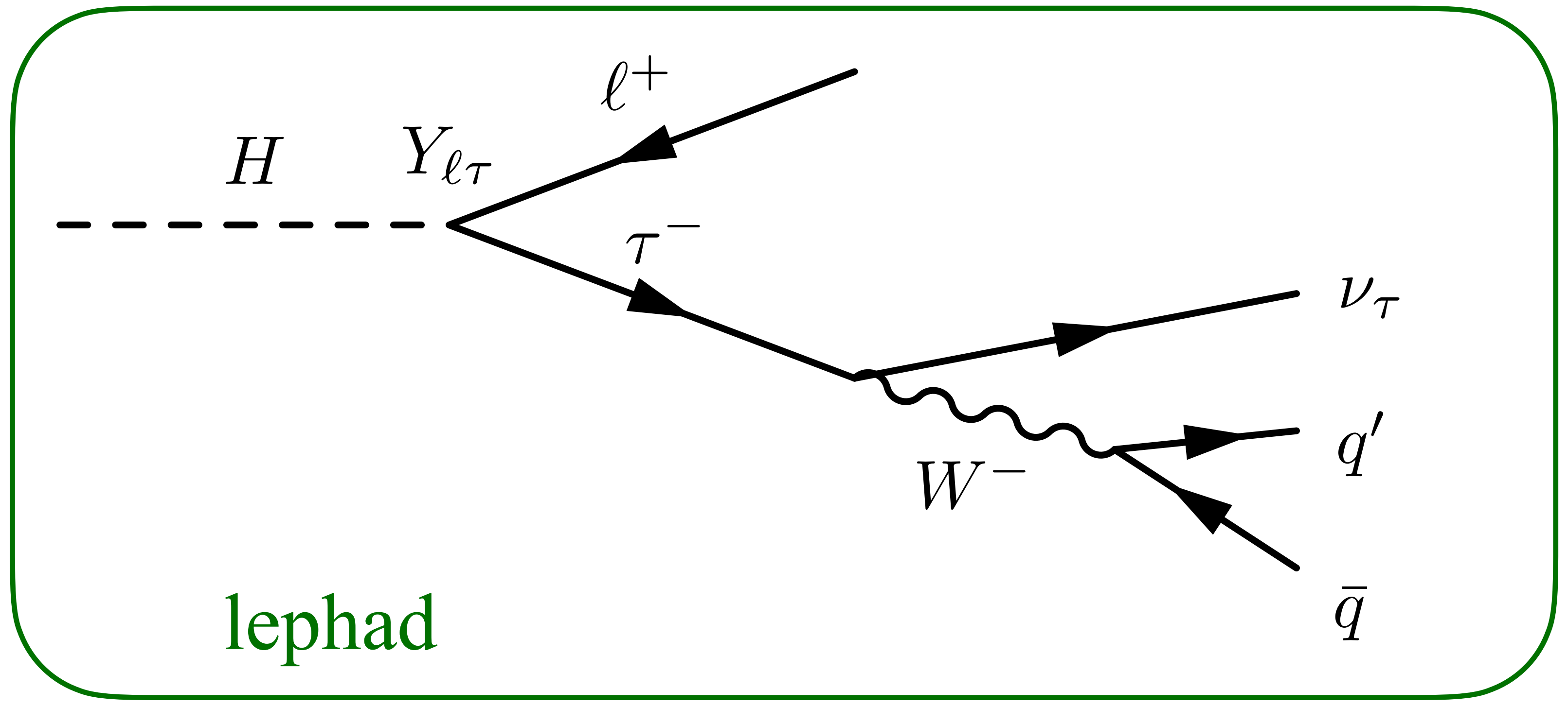


- First ATLAS search for $H \to Za$ with ALP decaying to $\gamma\gamma$.
- No significant excess observed.
  - Excludes the range of branching ratios of the Higgs boson decay to $Za(\gamma\gamma)$ from 0.08% to 2%.
  - Results could be further interpreted with ALP effective couplings to photons $|C_{\gamma\gamma}|/\Lambda$.

$H \to e/\mu + \tau$ overview

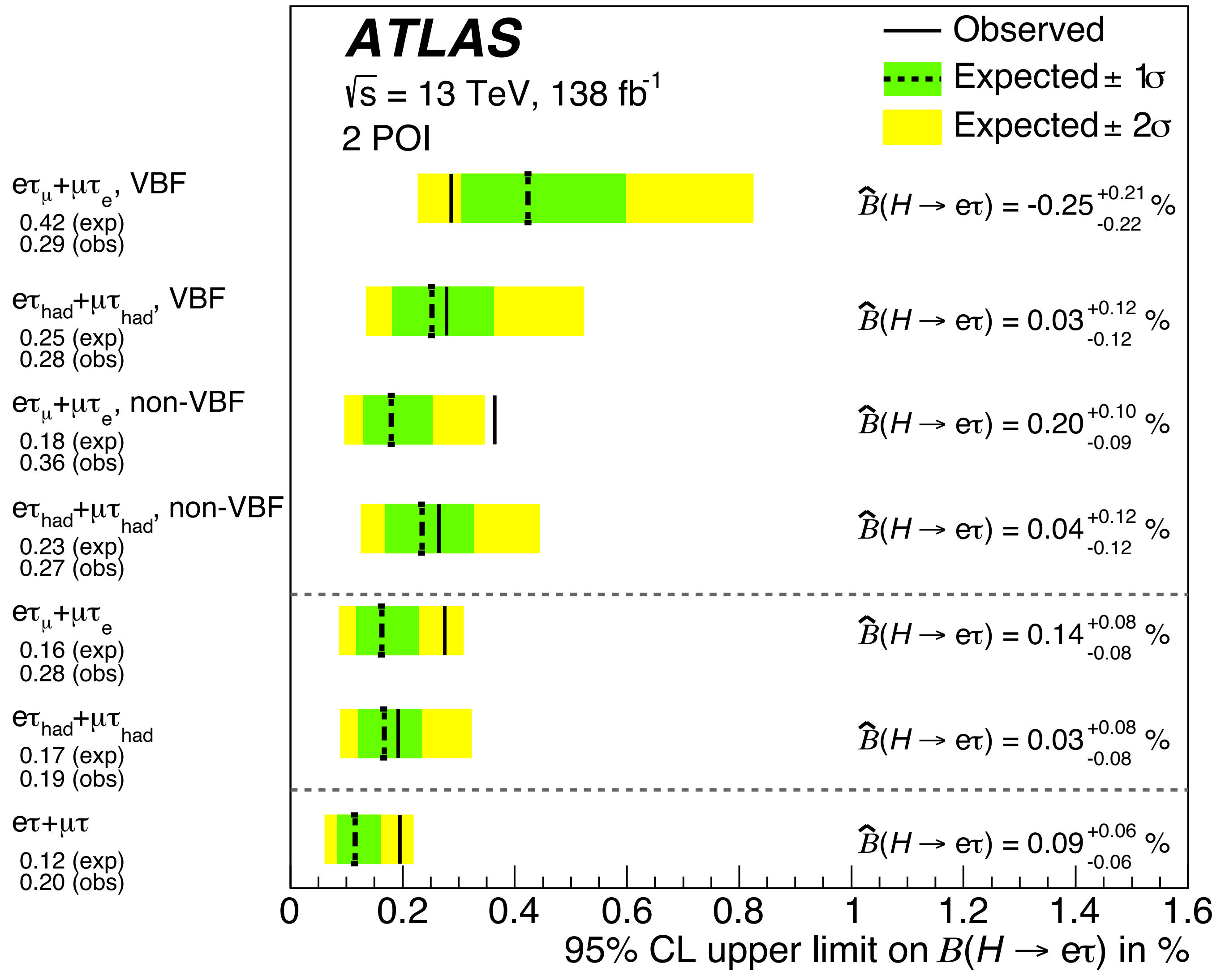
- Higgs produced via ggF VBF and VH.
  - Loose preselection and further categorisation into VBF and non-VBF regions.
- Leplep channel: $e\tau_\mu$ and $\mu\tau_e$.
  - Two different analysis based on background estimation methods.
    - Symmetry based: fake background data-driven, other background estimated via data-driven symmetry method [PhysRevD.90.015025].
    - MC template based: fake background data-driven, other background estimated with MC templates.
- Lephad channel: $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$.
  - Fake background data-driven, other background (mainly top and $Z \to \tau\tau$) estimated via MC templates.
- BDT and NN used to enhance sensitivity as final discriminants.

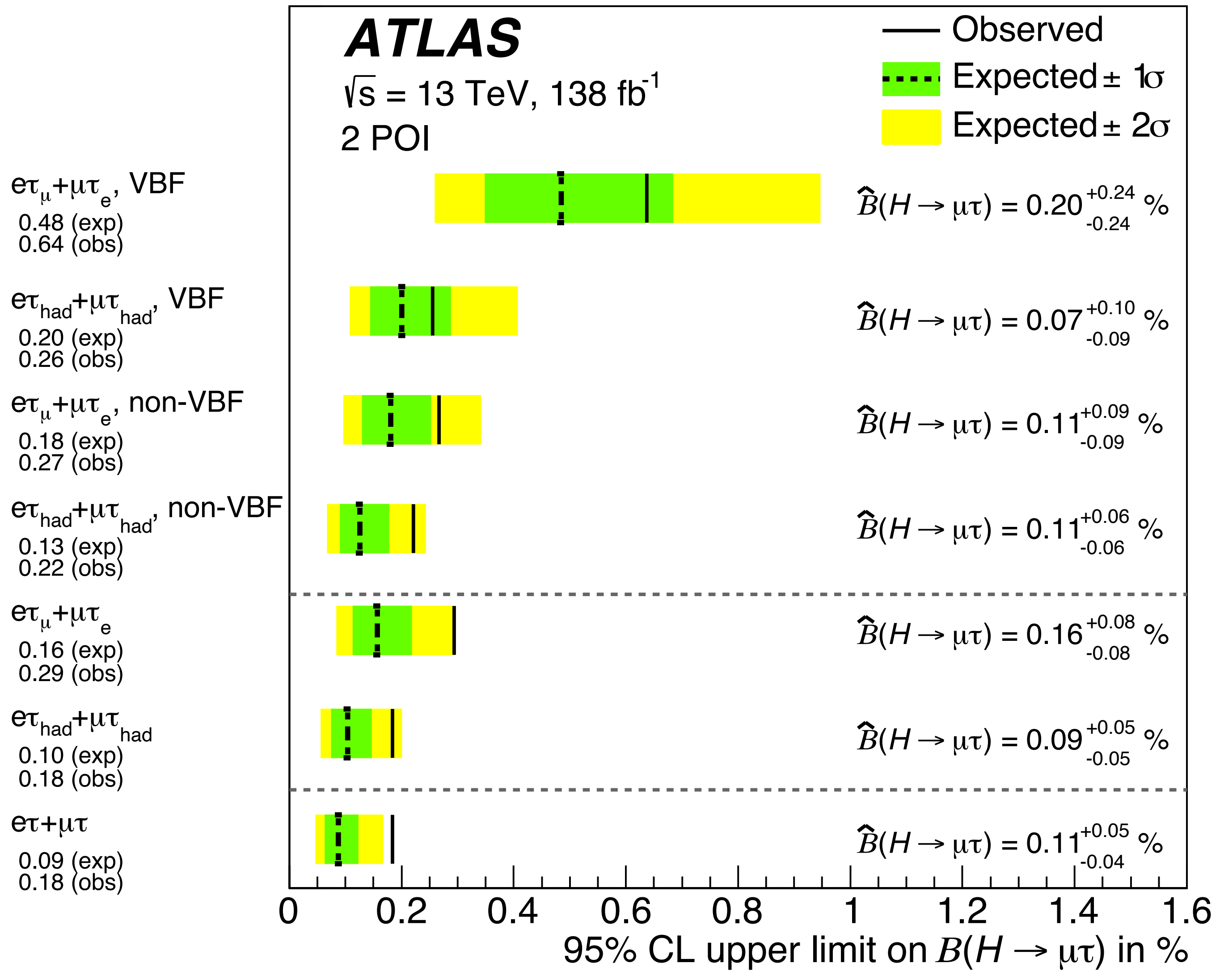


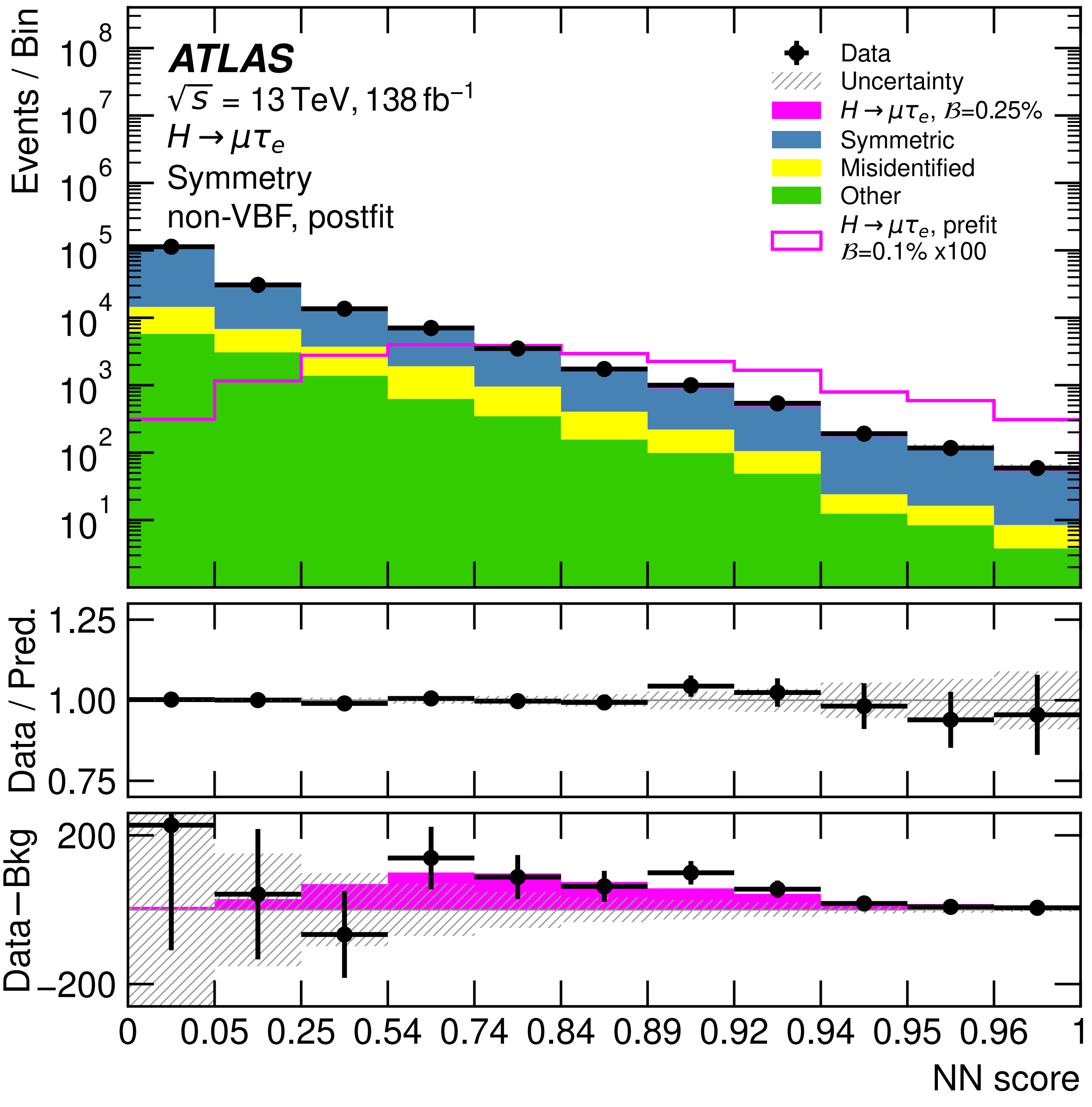


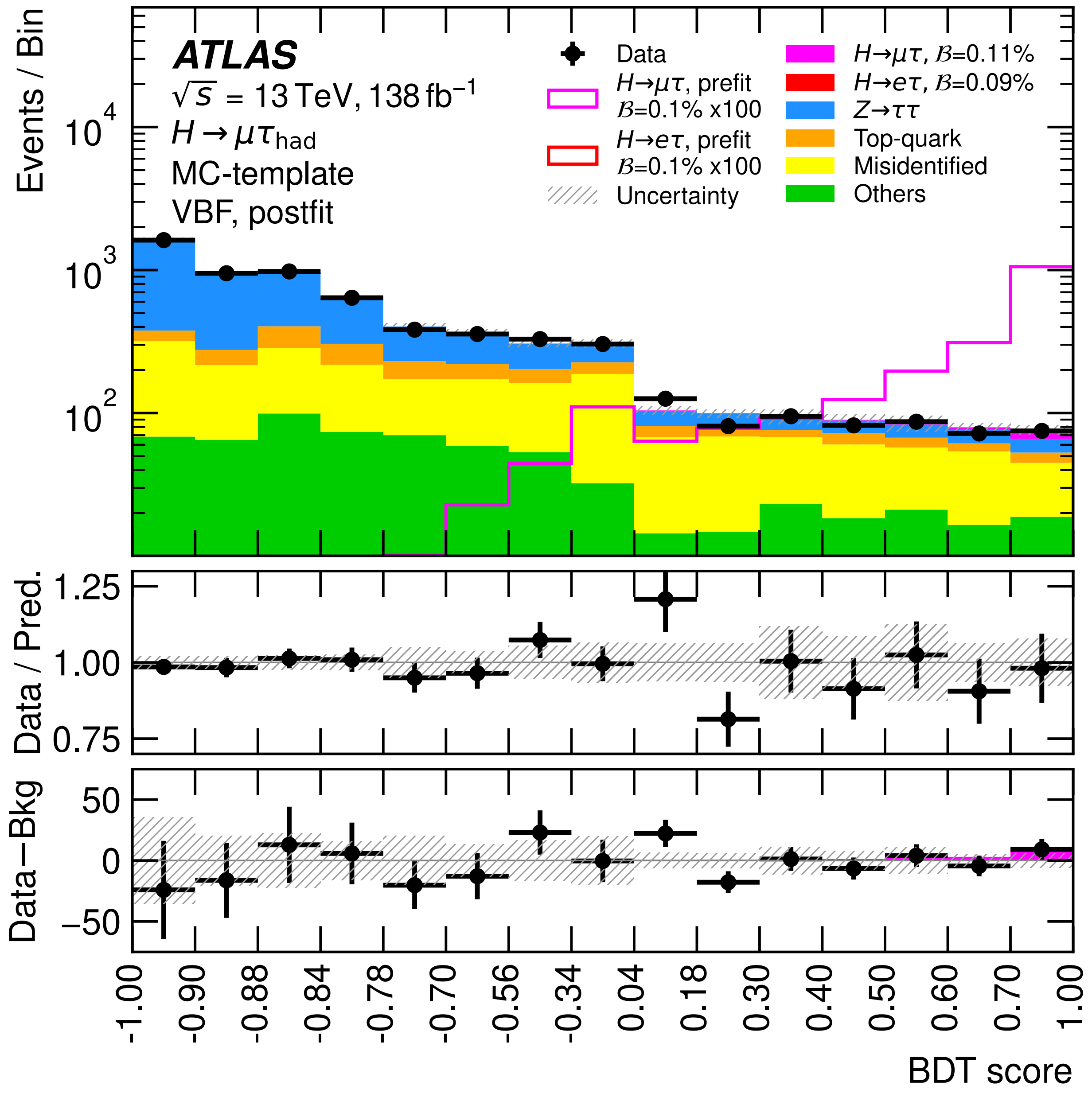
$H \rightarrow e/\mu + \tau$ results

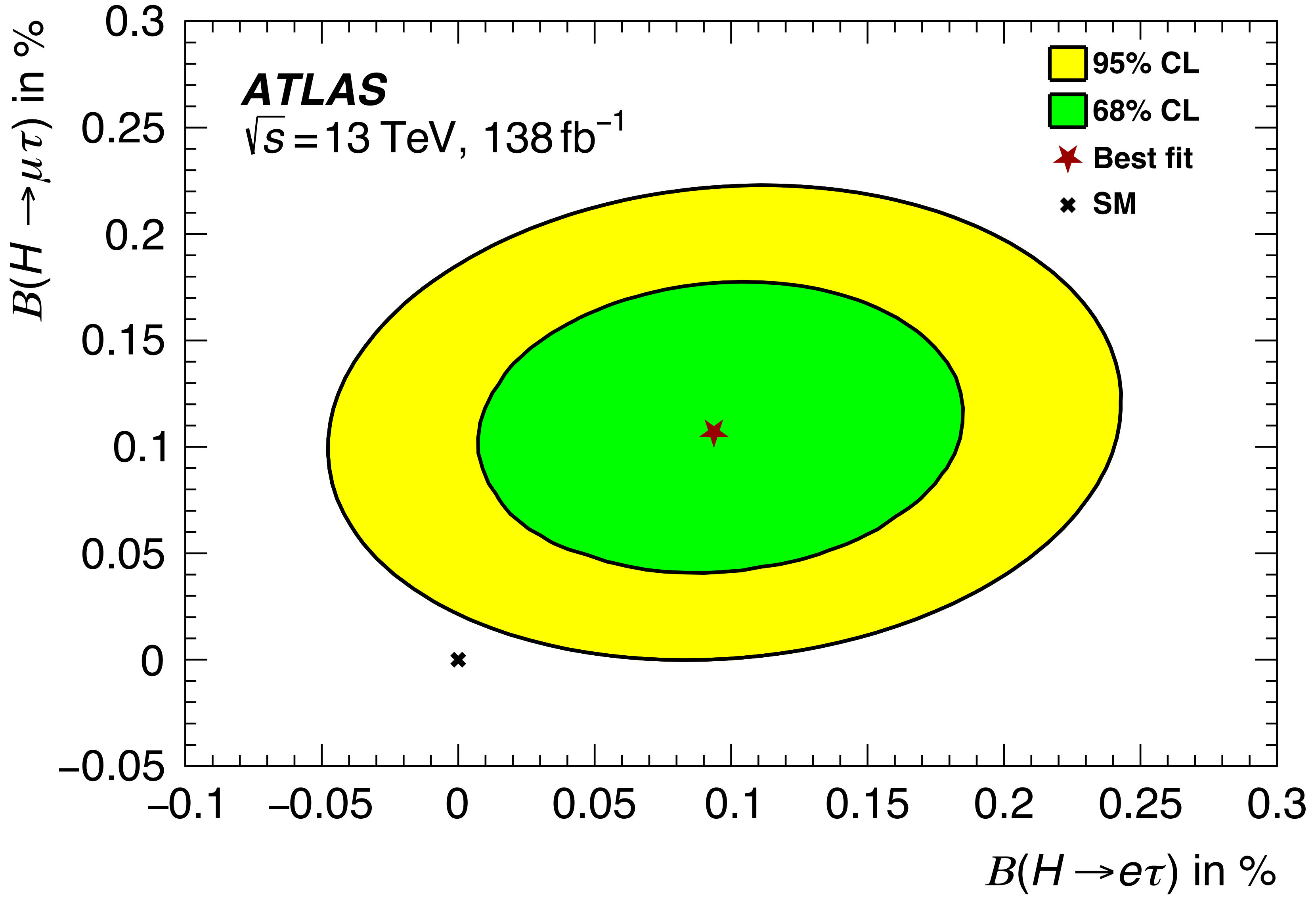
- Leplep and lephad channels combined to deliver the final limits.
  - Results on the branching ratios (MC template method) and on the branching ratio difference (Symmetry method) are obtained.
- About 1.6σ excess in $e\tau$ and 2.4σ in $\mu\tau$ in 2POI fit.



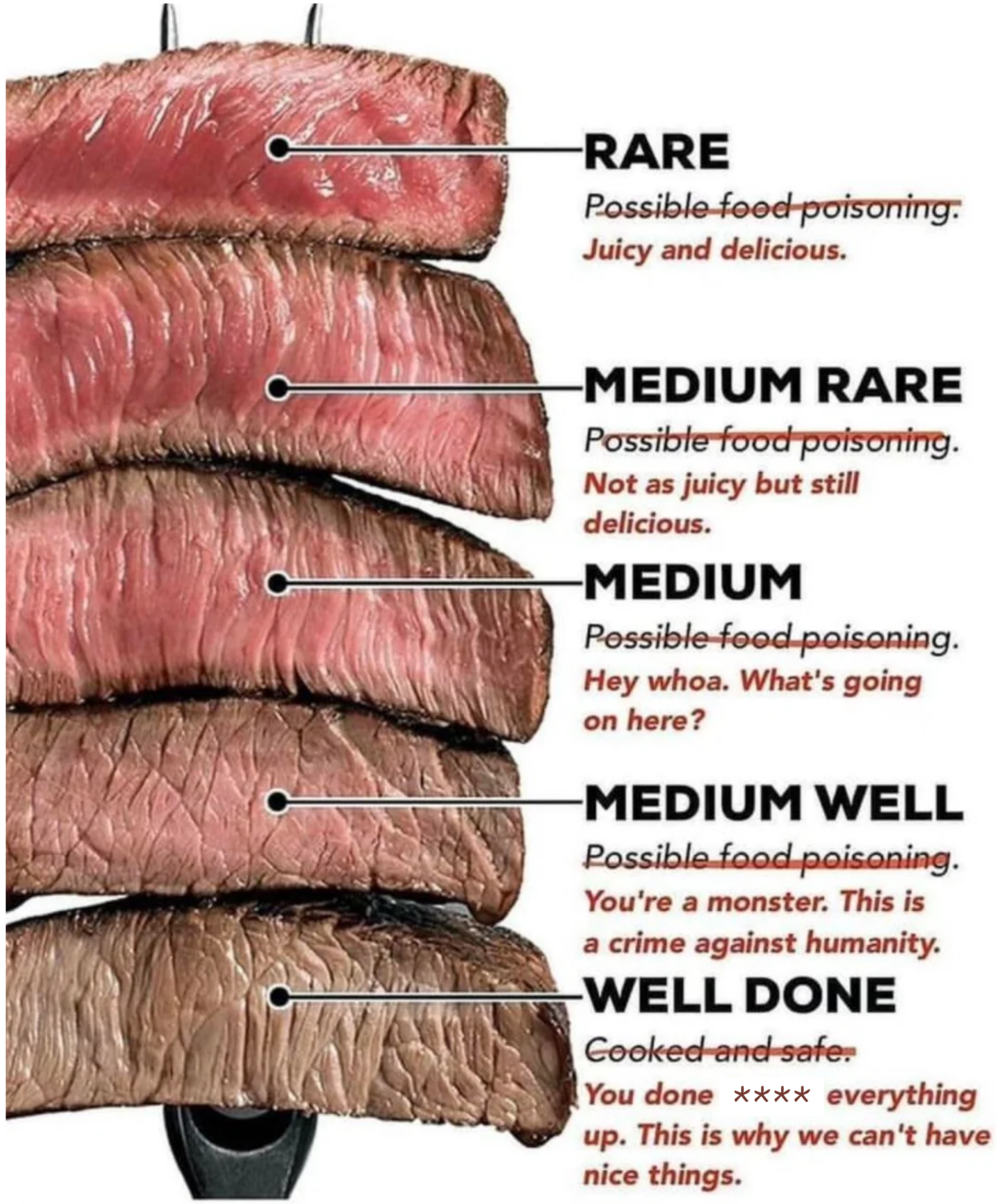








Summary

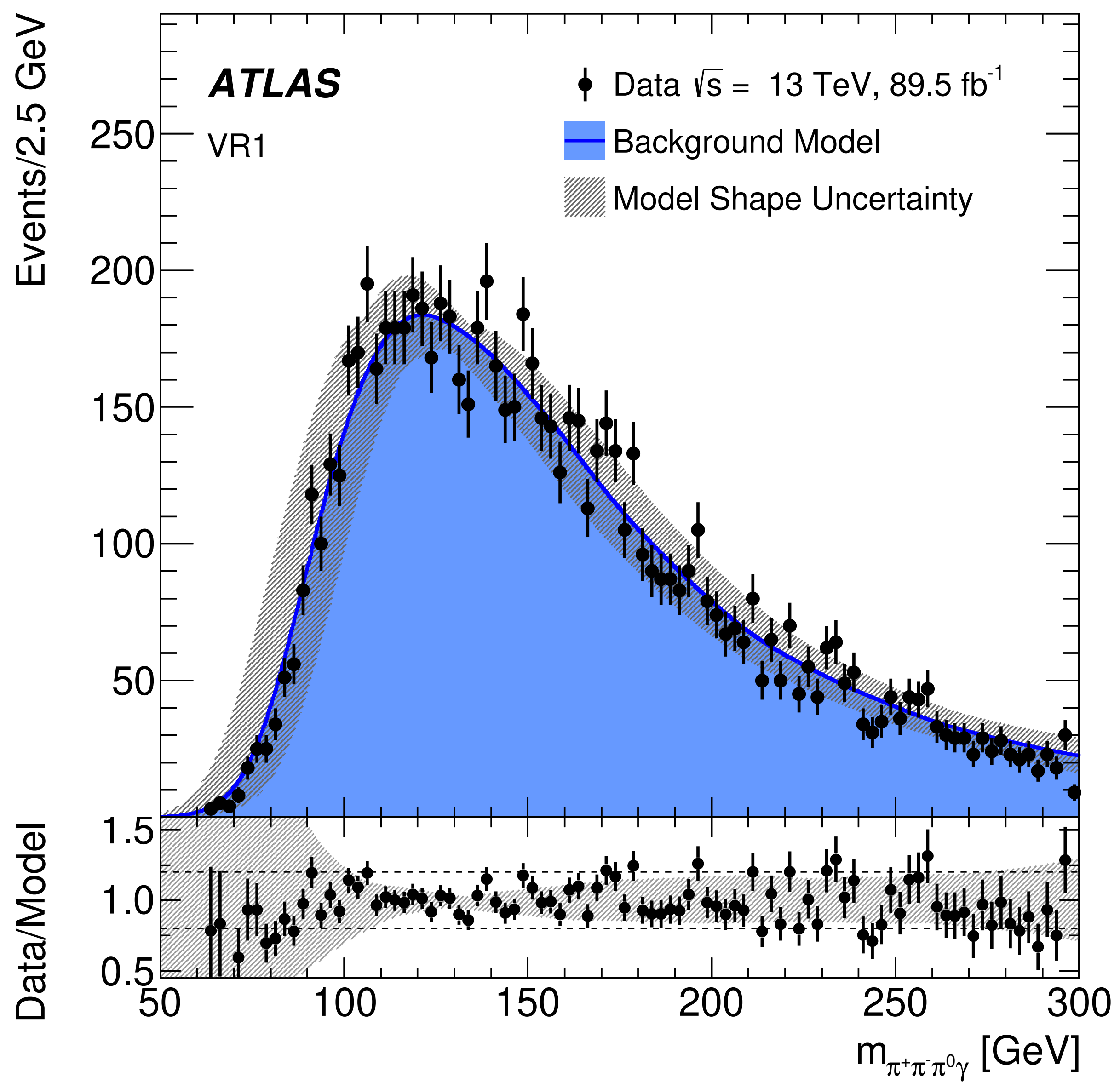


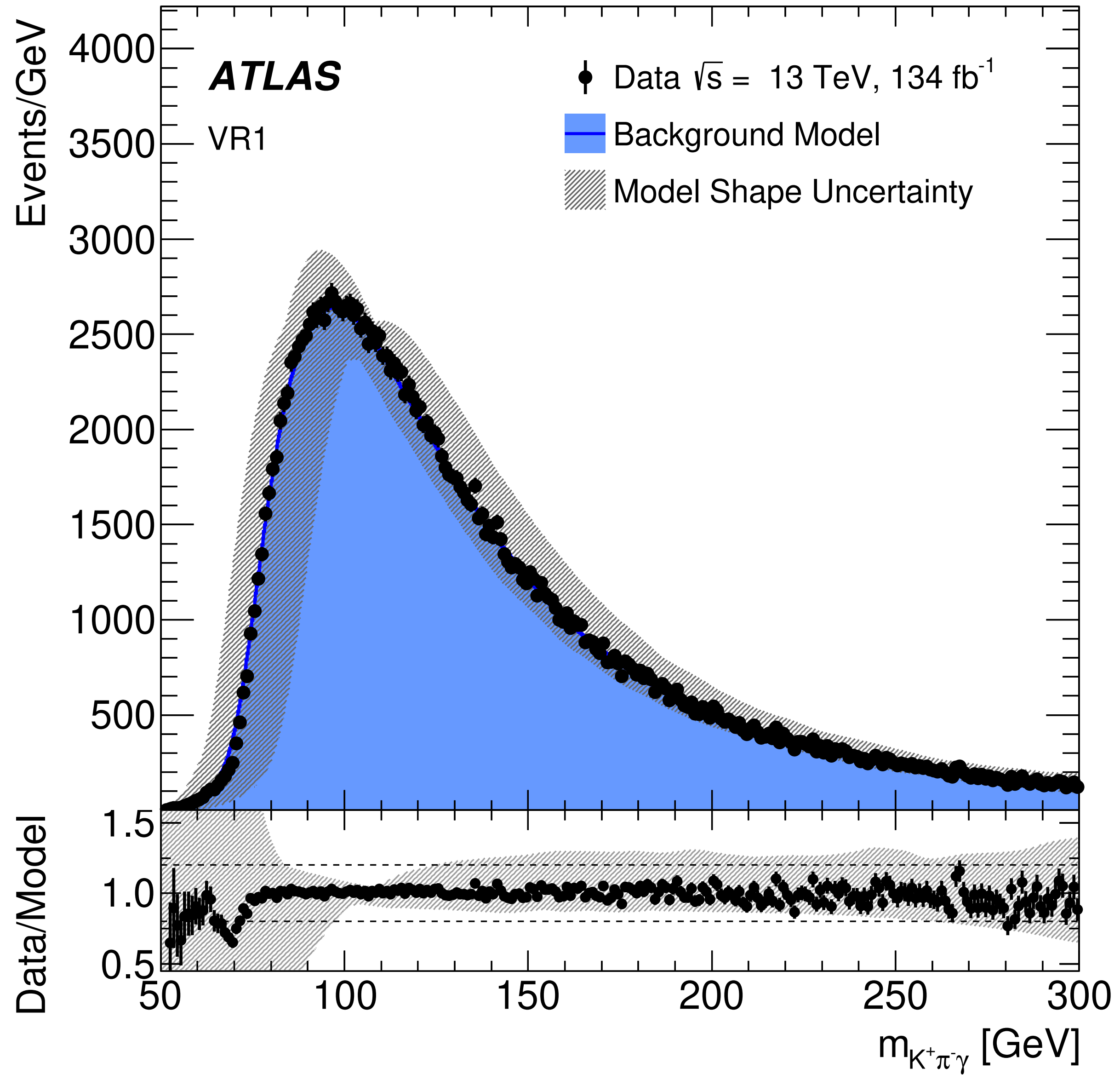
- Due to the nature of Yukawa coupling and the narrow width of H(125), strong motivation to search for its rare decay modes.
  - Any observation will bring evidence of new physics!
- Major background is fake (non-prompt) events, many novel data-driven methods are developed.
- ML algorithm heavily used for collimated object identifications and final discrimination.
- No clear evidence observed yet, but many limits are dominated by statistics.
  - Many efforts to use Run 3 data are taking place right now, and covering more phase space!

Backup slides

$H \to \omega/K^* + \gamma$ overview

- Trigger: based on a variation of standard τ triggered objects.
  - Similar signature with hadronic τ.
- Mesons reconstruction based on di-track objects. All tracks has $p_\pi^T > 15$ GeV and at least one track has $p_\pi^T > 20$ GeV.
  - $H \to \omega\gamma$: $279 < m_{\pi\pi} < 648$ MeV, $650 < m_\omega < 850$ MeV, best track pair compatible to 450 MeV selected (optimised with toy MC).
  - $H \to K^*\gamma$: $791 < m_{K^*} < 991$ MeV, best track pair compatible to $m(K^*)$ selected.
- Major background: QCD production of γ+jet and multijet events.
  - Using a non-parametric fully data-driven method, based on [JHEP 10 (2022) 001].
    - Derived the PDF from a dataset using a loose event selection, smoothed with Gaussian Kernel Density Estimation.
    - Model variables: $p_T(\mathscr{M})$, $p_T(\gamma)$, DiTrack isolation, $\Delta\eta$, $\Delta\phi$, γ isolation (calo and track), $\eta(\mathscr{M})$, $\phi(\mathscr{M})$, $m(\mathscr{M})$.
  - Dedicated validation regions designed to test the background modelling.





$H \to Z + \gamma\gamma$ results