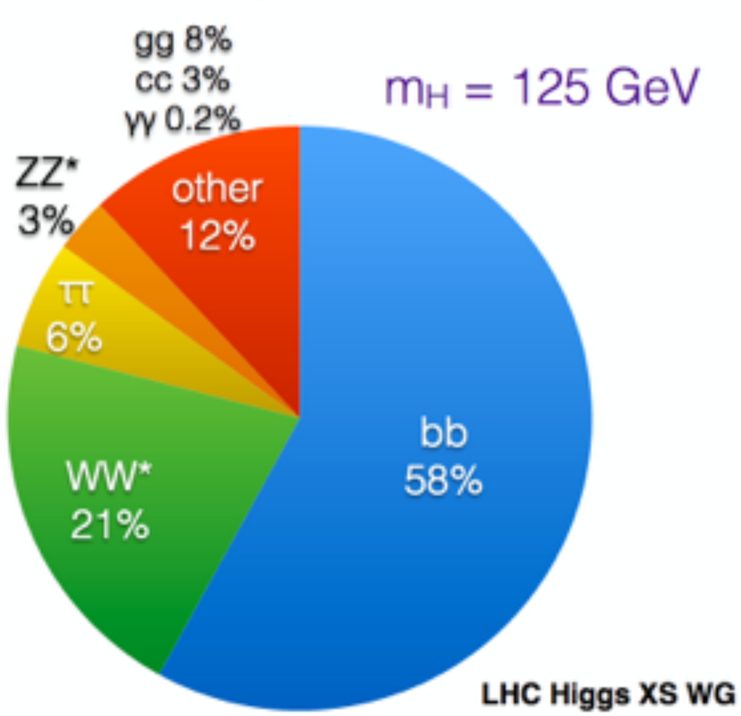
25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April 2017 - Birmingham

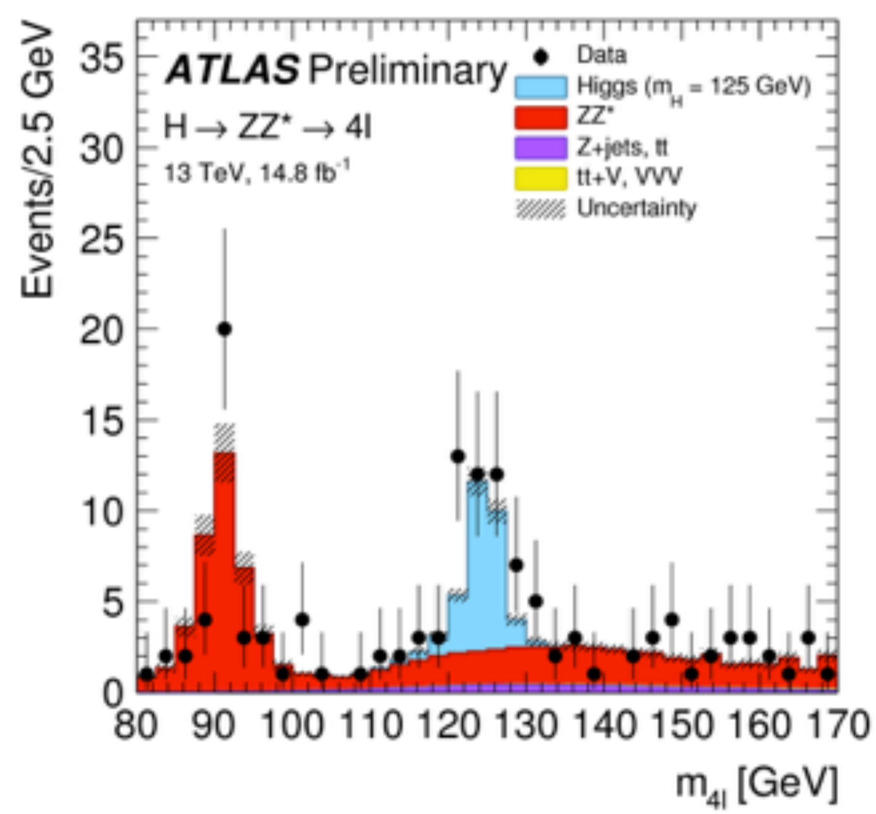
Search for non-standard and rare decays of the Higgs boson with the ATLAS detector

Roger Caminal Armadans - University of Illinois at Urbana-Champaign
On behalf of the ATLAS collaboration

SM Higgs boson decays

- The Higgs boson has been observed as a resonance in several decay channels.
- Other channels are predicted to exist by the SM, some of them with very small branching fraction.
  - An excess on these channels would be an indication of new physics.
- Furthermore, many BSM theories predict additional decays:
  - Higgs portal models of Dark Matter
  - Models with an extended Higgs sector e.g. 2HDM+S like the NMSSM.
  - Neutral naturalness





Overview of Higgs BSM searches

Searches for **deviations from the SM in measurements of Higgs boson properties**

- Spin
- CP
- Couplings ←

Direct searches for BSM phenomena

Additional Higgs-like scalars

- Neutral or charged
- Decays to SM particles or to Higgs bosons

BSM Higgs decays and couplings

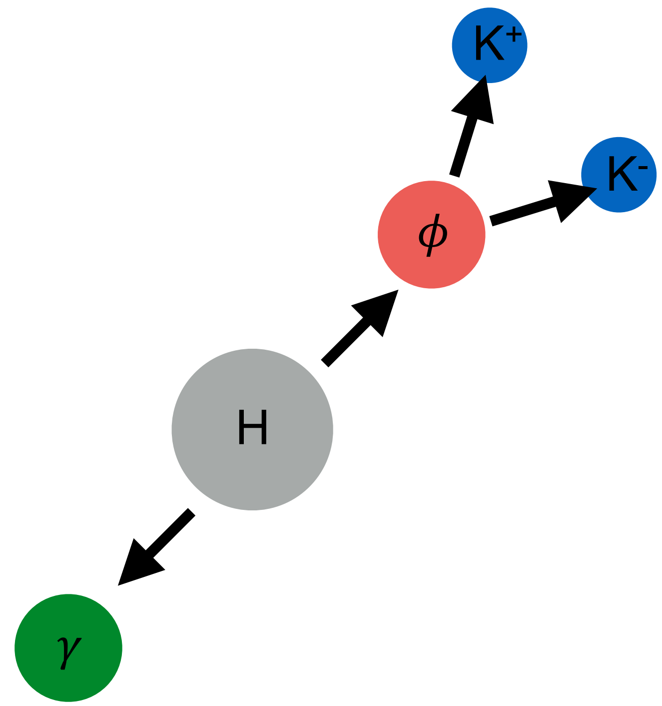
- New light resonances ←
- Flavor violating couplings ←
- …

Disclaimer: this is not an extensive list of analyses.

This talk will focus only on the latest ATLAS results on searches for some of these non-standard and rare decays.

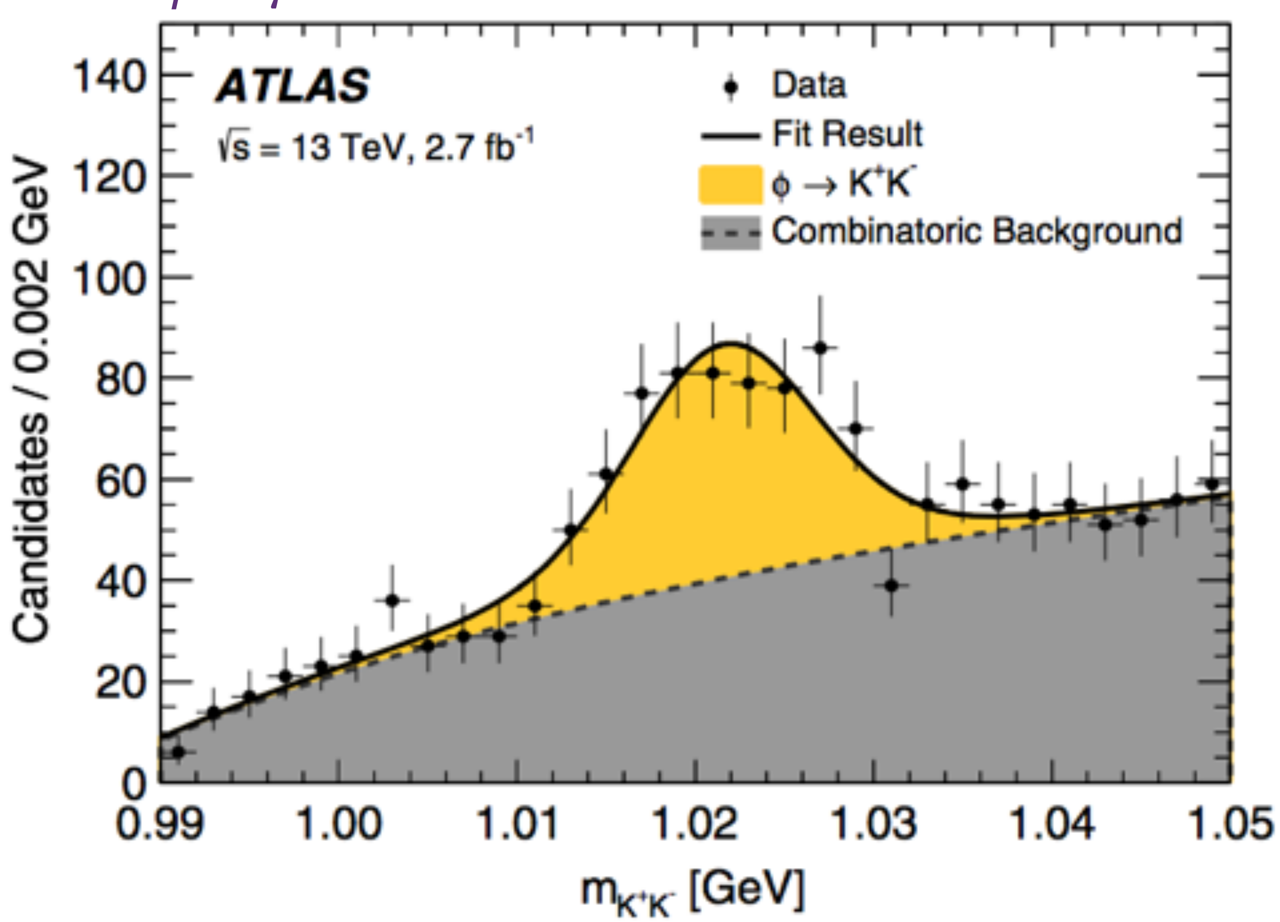
Higgs boson decaying to $\phi\,\gamma$

Phys. Rev. Lett. 117, 111802
arXiv:1607.03400



- Possibility to access strange-quark Yukawa coupling, unconstrained by existing measurements.
- Very small branching fraction predicted by SM, BR~10^{-6}.
  - Larger values would be a clear indication of new physics.

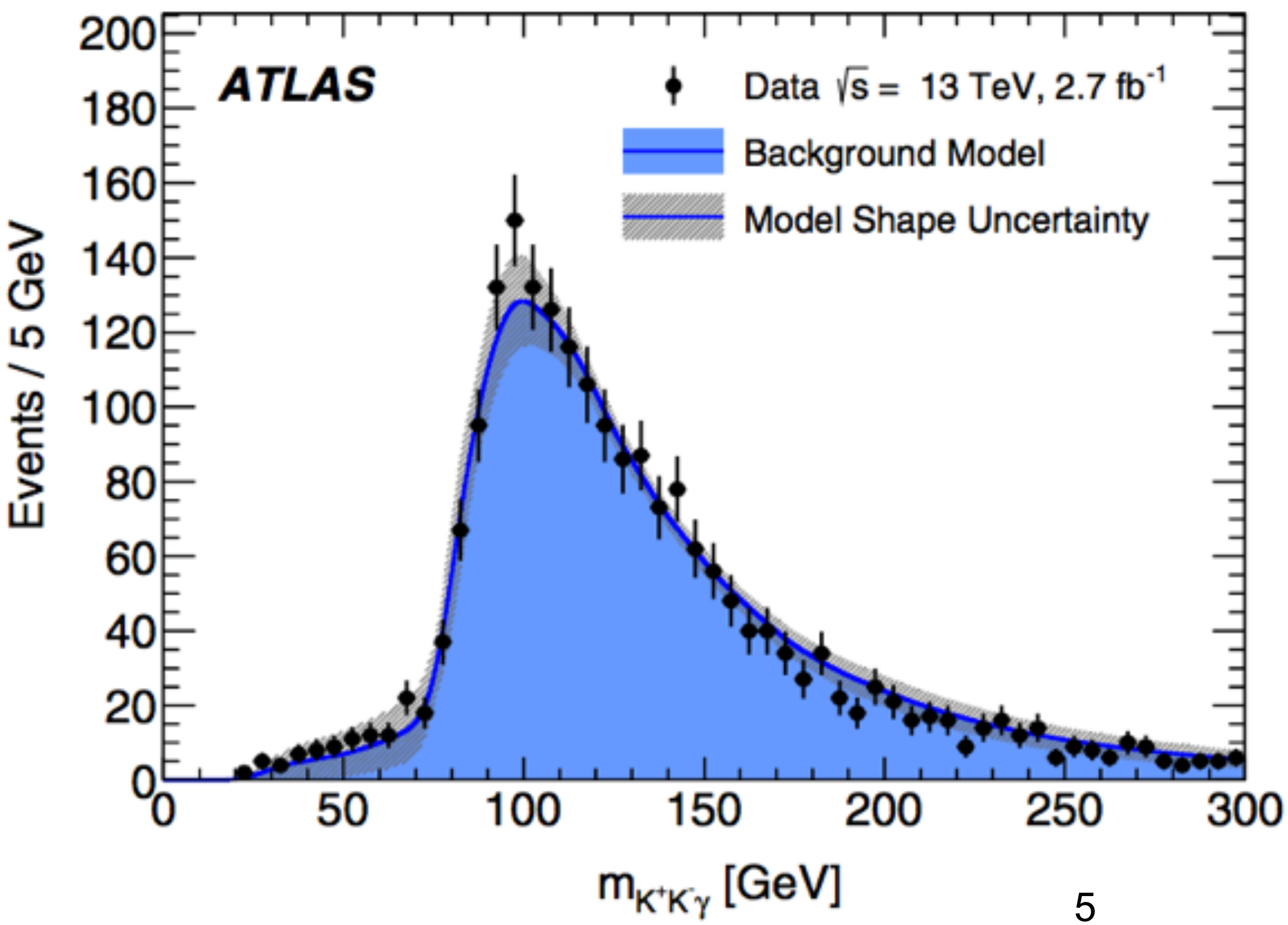
$\phi + \gamma$ candidates in ATLAS



- Select events with:
  - At least two opposite charge tracks from the PV with a very small opening angle.
  - ϕ meson reconstructed based on the mass of the two tracks.
  - Photons reconstructed from clusters of energy in the LAr calorimeter.
  - Isolation and (K^+K^-, γ) pairs to be separated.

Higgs boson decaying to $\phi\ \gamma$

- Main background from inclusive multi-jet or photon+jet, where $\phi \rightarrow K^+K^-$ candidate from tracks associated to a jet.
  - Estimated in region similar to SR with isolation and some kinematic conditions relaxed.



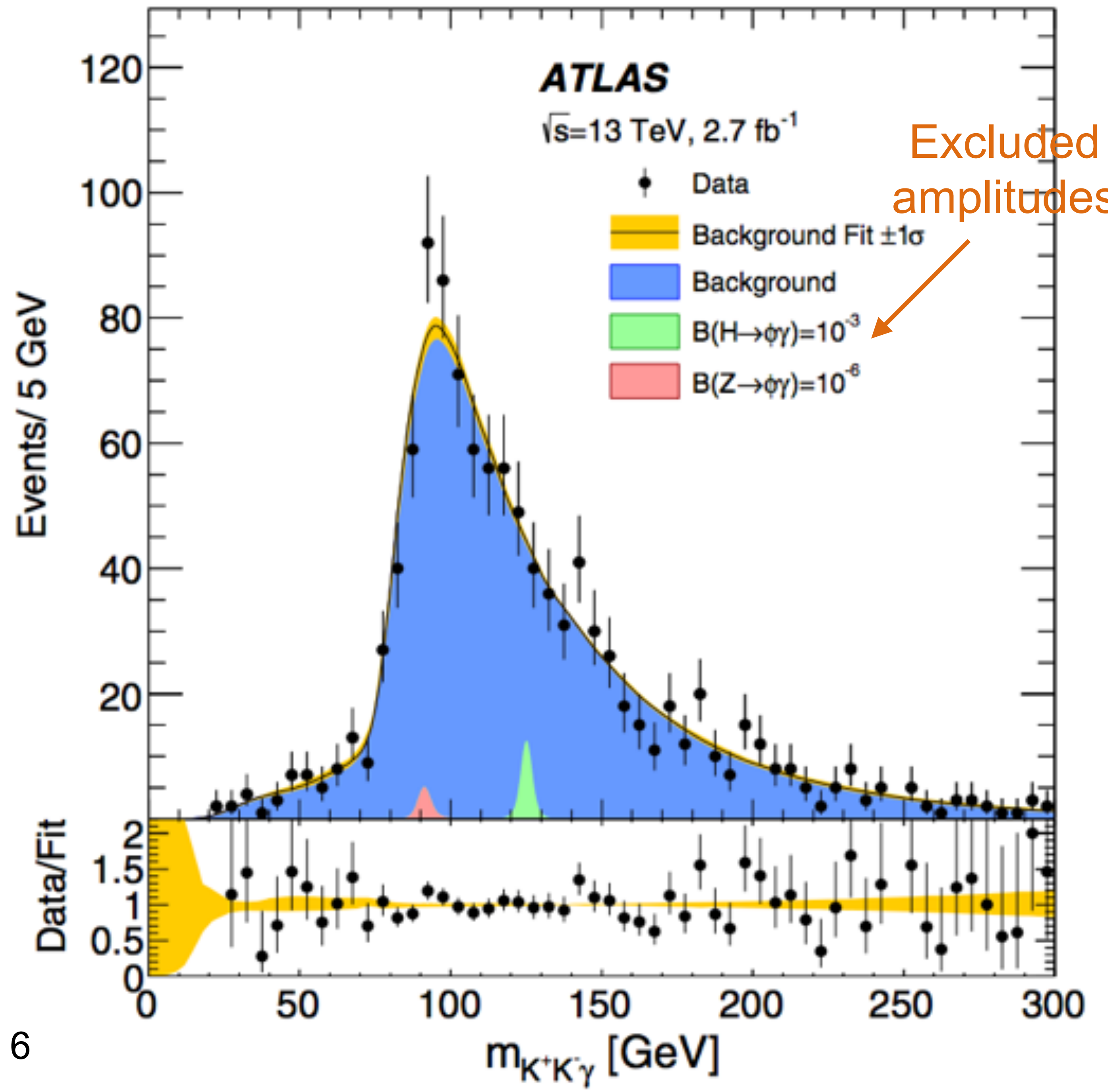
- Other background sources (e.g. $Z \rightarrow \ell\ell\gamma$) studied and found to be negligible.
- Two different regions: H search and Z search.

Higgs boson decaying to $\phi\ \gamma$

- No significant excess of events has been found above the background.
- Set upper limits on the branching fractions for the Higgs (and the Z) boson decays to $\phi\gamma$

SM prediction:
BR(H→ $\phi\gamma$) = (2.31 ± 0.11) × 10^{-6}
BR(Z→ $\phi\gamma$) = (1.17 ± 0.08) × 10^{-8}

Branching fraction limit (95% C.L.)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)[10^{-3}]$	$1.5^{+0.7}_{-0.4}$	1.4
$\mathcal{B}(Z \to \phi\gamma)[10^{-6}]$	$4.4^{+2.0}_{-1.2}$	8.3

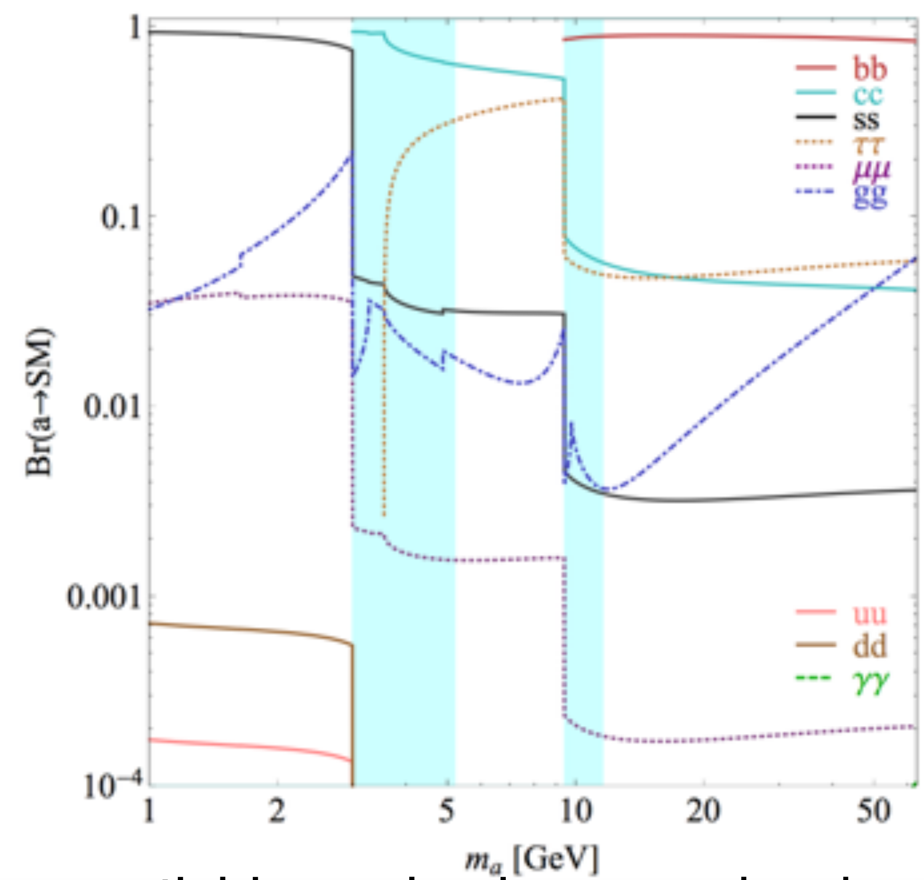


- Provides a baseline for a potential measurement at a future high-luminosity LHC

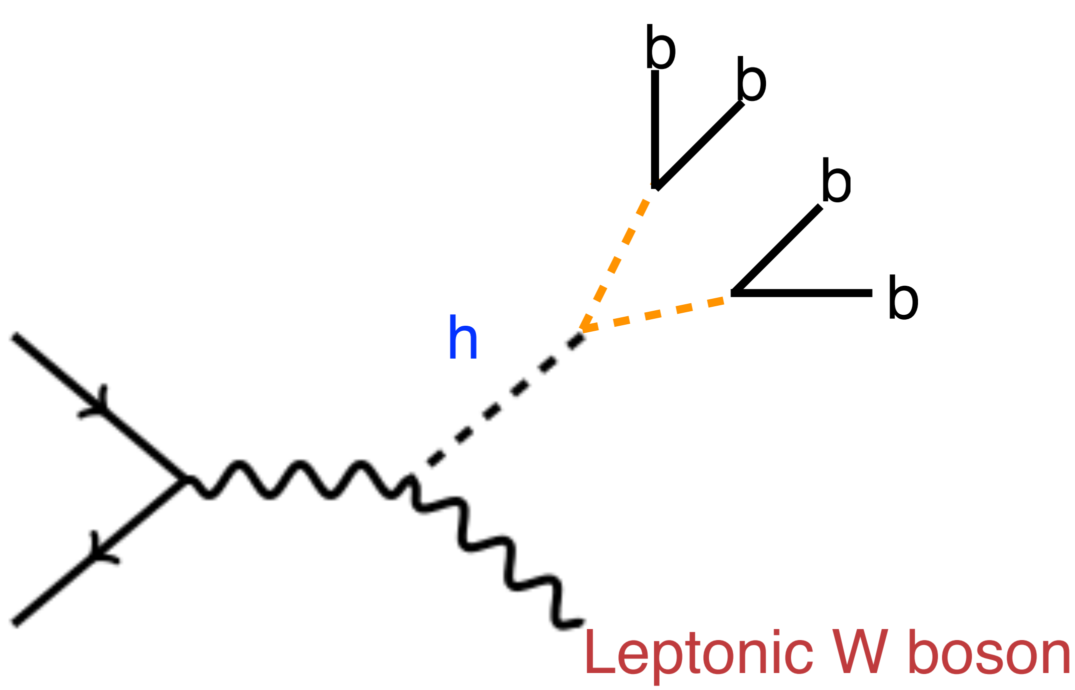
Eur. Phys. J. C 76 (2016) 605
arXiv:1606.08391

New light resonances: H→a a

- Higgs decaying to light spin-0 particles.
  - Many different models predicting different branching fractions.
    - In many of them, $a \to b\bar{b}$ is the preferred decay when $m_a > 2m_b$.
- This talk focusses on the latest result with 13 TeV data:
  - Decay $a \to b\bar{b}$.



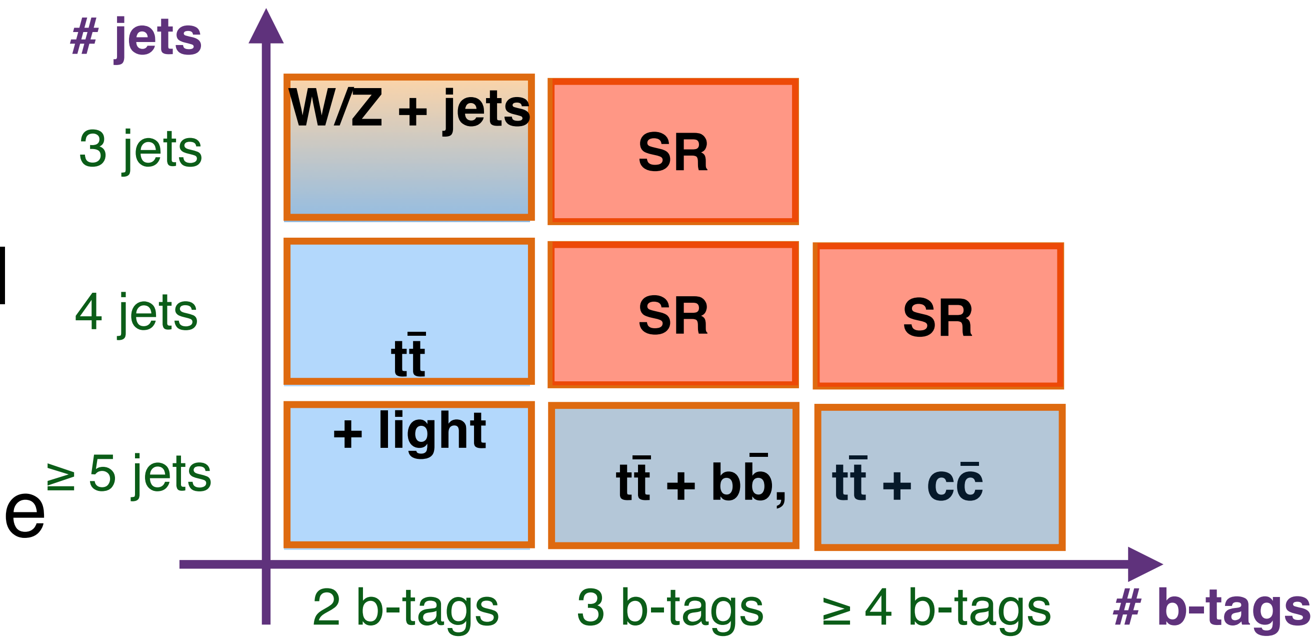
exotichiggs.physics.sunysb.edu



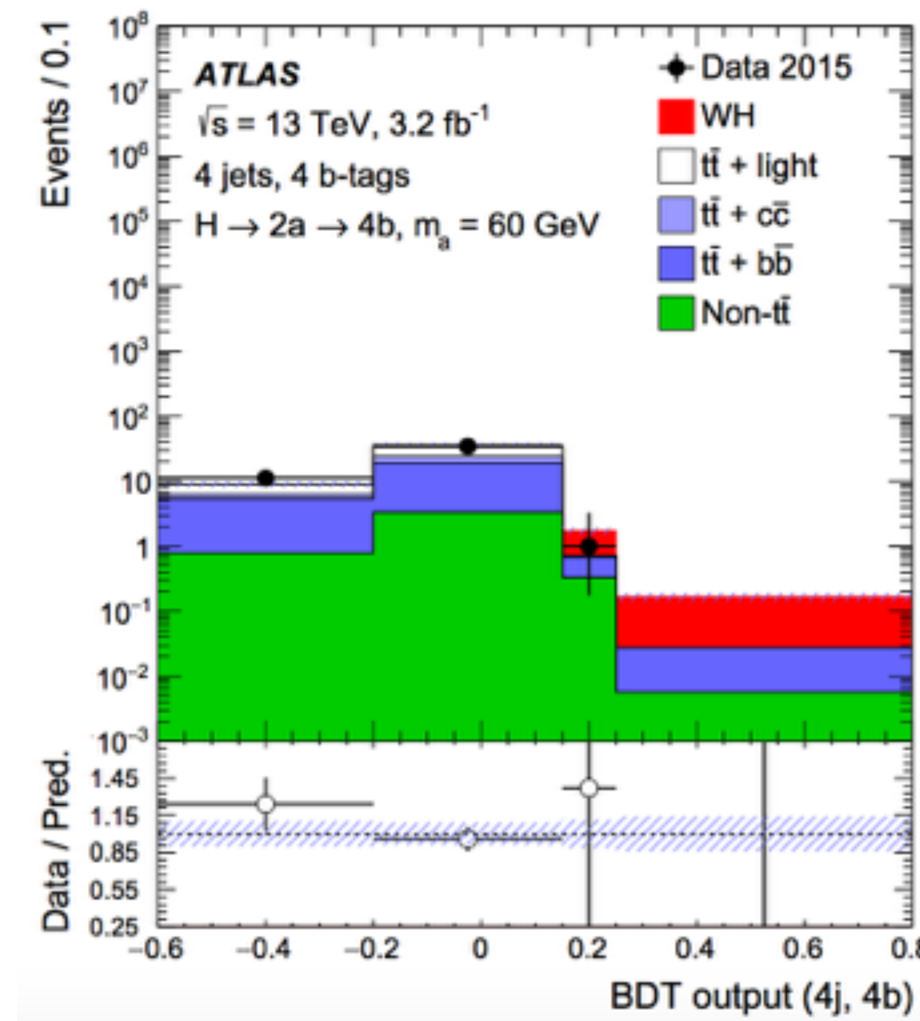
- Higgs production in association to a W boson, decaying leptonically.

New light resonances: H→a a

- Profile likelihood fit of the background predictions to data simultaneously in control and signal regions based on N_{jets} and $N_{b\text{-}jets}$
  - Use control regions to estimate the main background processes.
  - Profile systematic uncertainties.

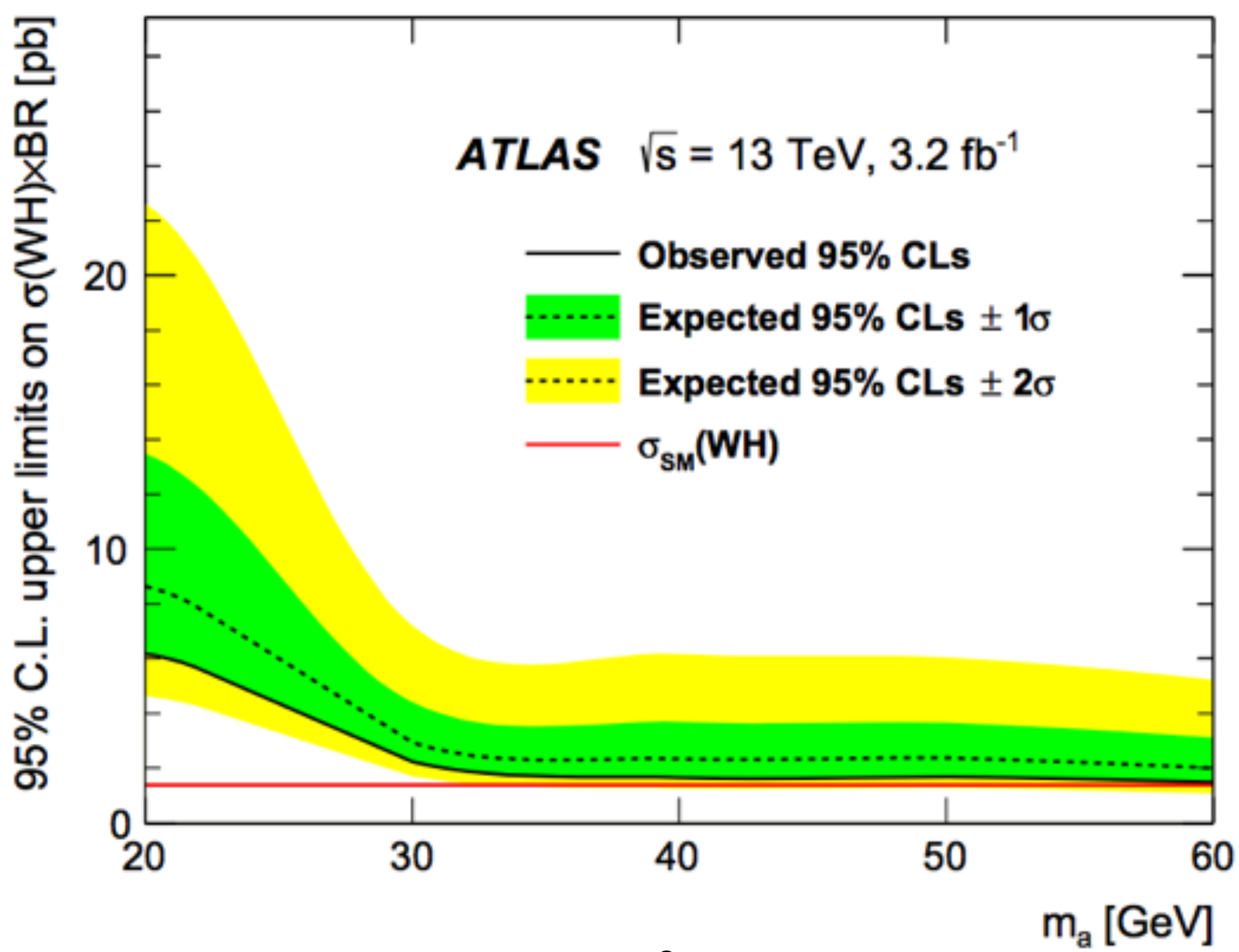


- Variables included in the fit
  - Control regions: scalar sum of jets p_T
  - Signal regions: combine kinematic variables into a BDT discriminant to distinguish signal and background → improves sensitivity of the search



New light resonances: H→a a

- Limit on the $\sigma(WH) \times \mathrm{BR}(H \to aa) \times \mathrm{BR}(a \to b\bar{b})^2$ measurement is ~100% BR.
- Main uncertainty is statistics.
  - Sensitivity is very likely to improve with more data.

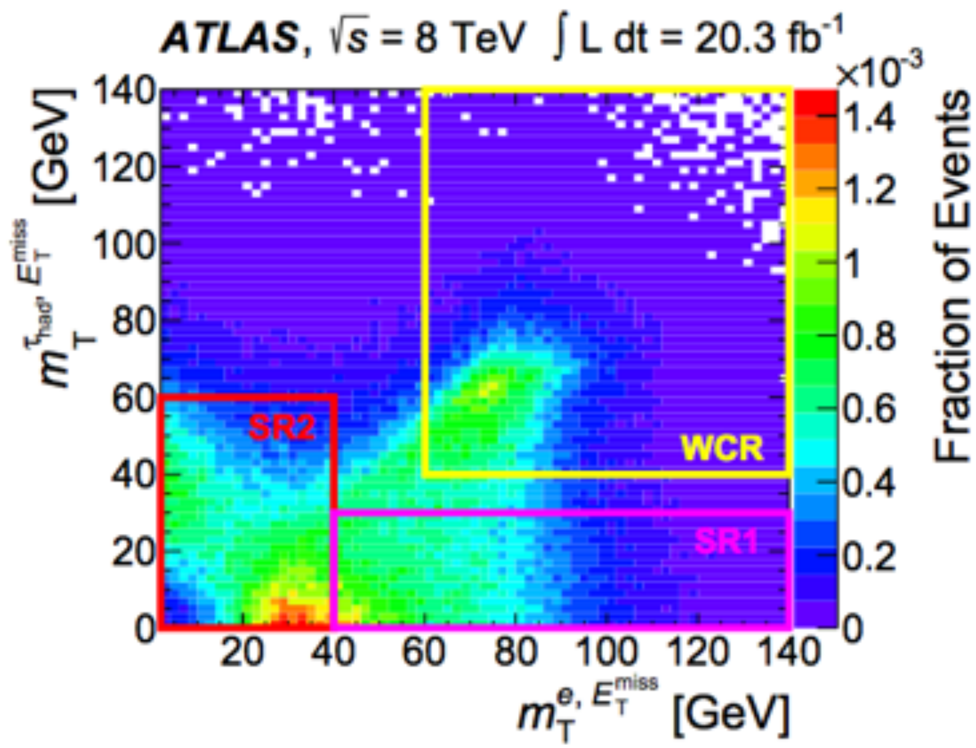


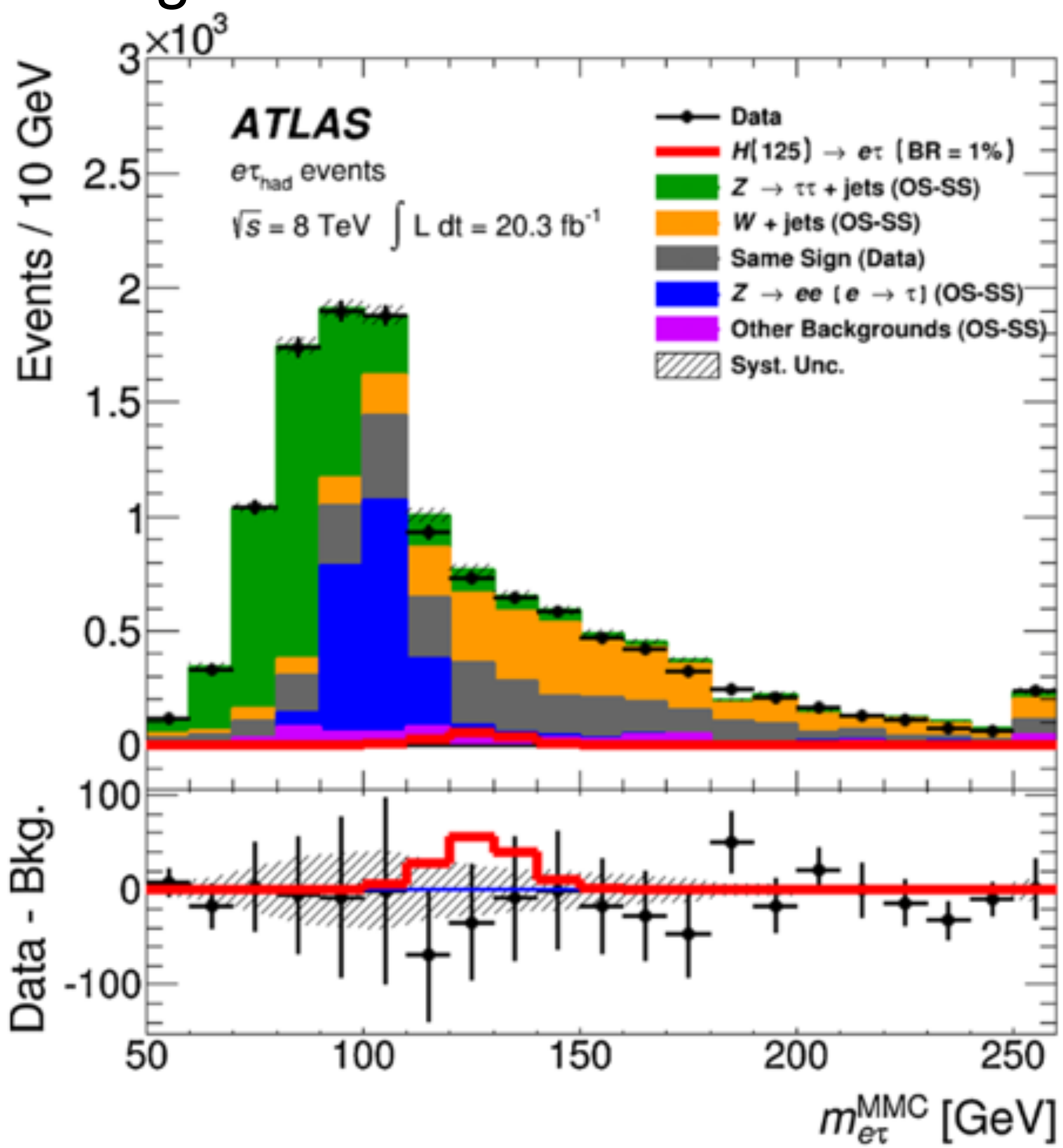
SM cross section for pp→WH: 1.373 pb

Flavor violating couplings

Eur. Phys. J. C 77 (2017) 70
arXiv:1604.07730

- Search for a Higgs boson decaying into $e\tau_{had}$, $e\tau_{lep}$ or $\mu\tau_{lep}$.
- The $e\tau_{had}$ channel requires events with exactly one energetic electron and one opposite-charge τ.





- Data-driven background estimation using SS leptons and dedicated validation regions
- Search for the LFV signal by fitting $m^{MMC}_{e\tau}$.
  - Computed from the observed e, τ and E_T^{miss} (from τ decays) aiming to reconstruct the Higgs mass.

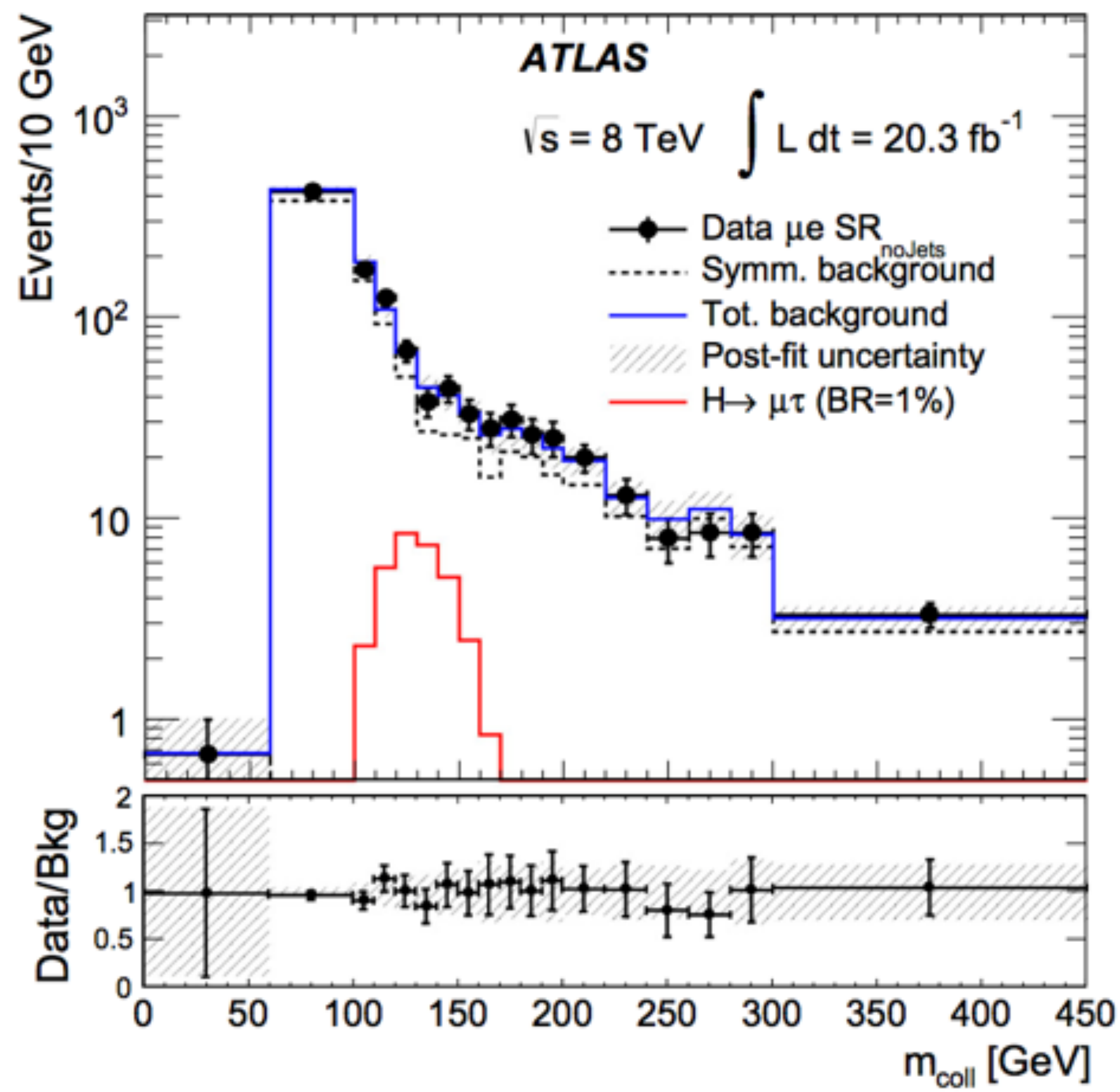
Flavor violating couplings

- The $e\tau_{lep}/\mu\tau_{lep}$ channel requires events with exactly two opposite sign leptons, one electron and one muon.

  - Background estimation uses the property that the kinematic distributions of prompt electrons and muons are approximately the same

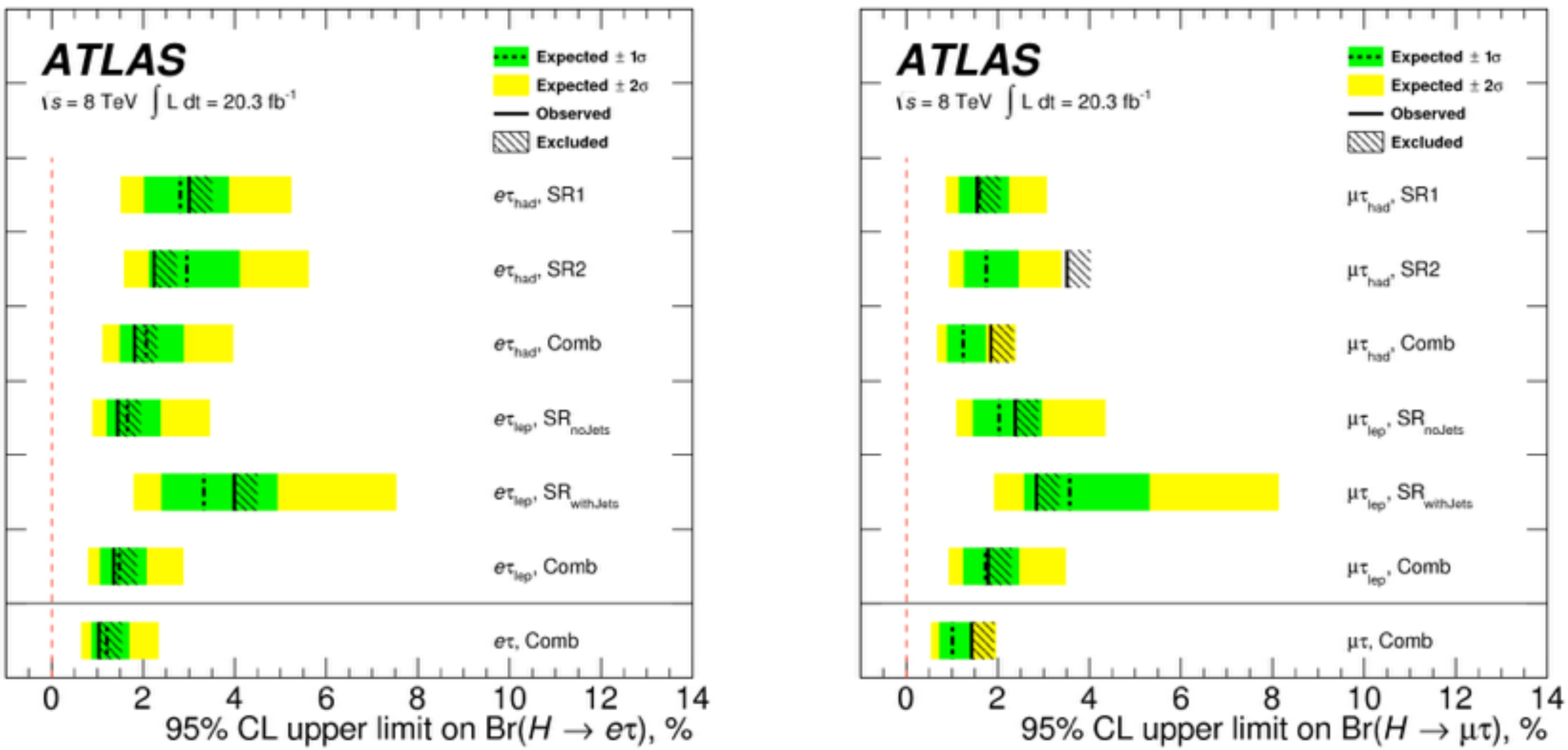
  - Final discriminant based on m_{coll}:

$$m_{\text{coll}} = \sqrt{2p_{\text{T}}^{\ell_1}(p_{\text{T}}^{\ell_2} + E_{\text{T}}^{\text{miss}})(\cosh\Delta\eta - \cos\Delta\phi)}.$$



Flavor violating couplings

- Upper limits on branching ratio for $H \to e\tau$ and $H \to \mu\tau$ decays are computed.
  - Combine $e\tau_{had}$, $\mu\tau_{had}$ [arXiv:1508.03372], $e\tau_{lep}$ and $\mu\tau_{lep}$ channels.



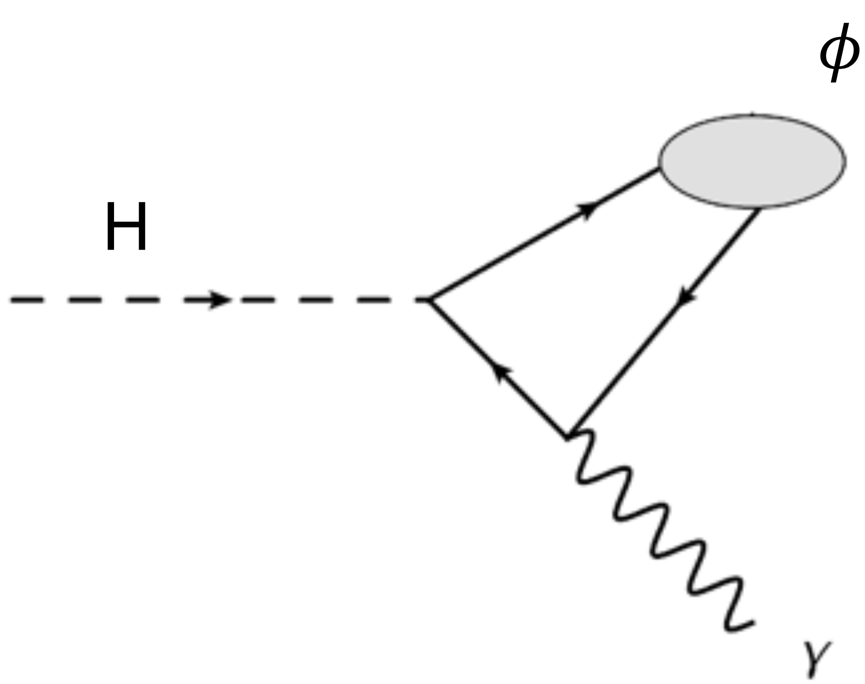
Conclusions

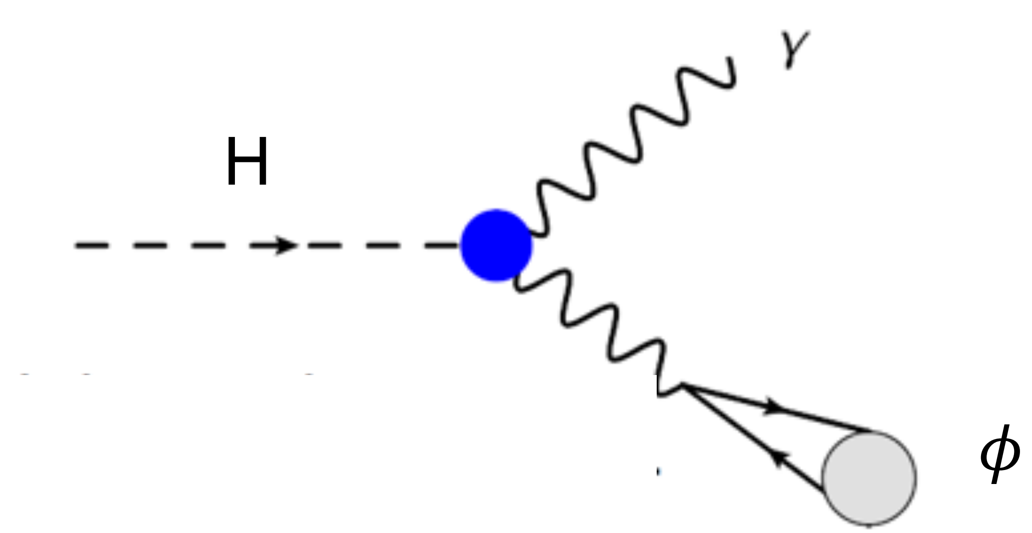
- Three searches for non-standard and rare decays of the Higgs boson with the ATLAS detector have been presented.
- Limits on different models have been extended or set for the first time.
- No significant deviations from the Standard Model have been found.
- Increase of sensitivity of the analyses expected when more data is analyzed.

Backup slides

Higgs boson decaying to $\phi\ \gamma$ - processes

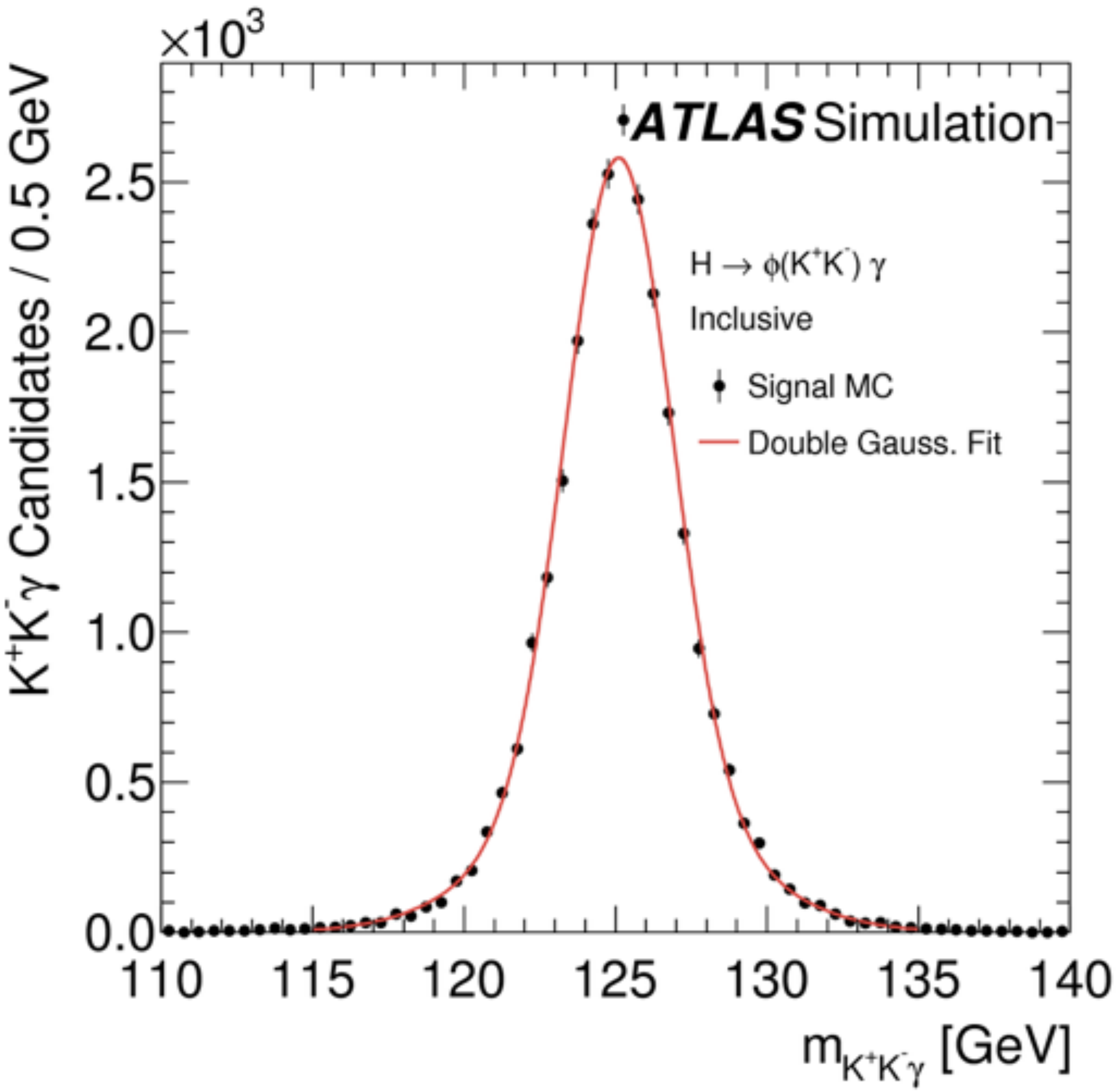
- Different production mechanisms:
  - Direct production: sensitive to Hss coupling, is small.
  - Indirect production: interferes quantum-mechanically with direct production, is larger.
- Interference gives unique information on the phase of the Hss coupling.





Higgs boson decaying to $\phi\ \gamma$ - signal modeling

- Signal MC Higgs mass peak fitted with a double gaussian function.



Higgs boson decaying to $\phi\ \gamma$ - background model

- Dominated by di-jet production and γ+jet production (ϕ reconstructed within a jet).
  - Cannot be modeled with MC due to complicated mixture of contributing processes.
  - Data-driven event mixing approach
- Define a region with loose (kinematics and isolation) $\phi\gamma \rightarrow K^+K^-\gamma$ events.
  - Signal negligible with respect to large background
- Parametrize set of variables (i.e. $K^+K^-\gamma$ mass, γ isolation…) and keep track of the correlations.
- Build a "toy" event by picking randomly a value for each of these variables, starting from $m_{di\text{-}track}$ and considering correlations.
- Normalization:
  - Before unblinding: normalize to data in loose region.
  - After unblinding: free fit parameter.

Higgs boson decaying to $\phi\ \gamma$ - systematic unc.

- Theoretical systematic uncertainties:
  - PDFs, α_s and scales of the signal MC sample for the different production modes.
- Experimental systematic uncertainties:
  - Photon scale/reconstruction/identification/isolation
  - Trigger efficiency
  - Track reconstruction efficiency and isolation.
- Uncertainty on the inclusive background model:
  - Alternative shape generated by changing the parametrization of some of the variables used to buy the toy model.
  - The magnitude of the resulting changes in $m_{K+K-\gamma}$ distribution are constrained by the fit to the data.
  - An extra closure test is performed by re-deriving the background shape from simulated γ+jets events inputs, in place of data.

Higgs boson decaying to $\phi\ \gamma$ - yields

- Signal region yields

Observed (Expected) Background					Expected Signal	
Mass Range [GeV]					Z	H
All	81–101		120–130		$\mathcal{B}[10^{-6}]$	$\mathcal{B}[10^{-3}]$
1065	288	(266 ± 9)	89	(87 ± 3)	6.7 ± 0.7	13.5 ± 1.5

Higgs boson decaying to $\phi\ \gamma$ - Limits

- Systematic uncertainties on identification, scale and resolution of photons, track reconstruction efficiency, and on the shape of the background templates, considered.
- Un-binned maximum-likelihood fit to the $m_{KK\gamma}$ distribution.
- Set upper limits on the branching fractions for the Higgs (and the Z) boson decays to $\phi\gamma$
  - No significant excess of events has been found above the background.

Branching fraction limit (95% C.L.)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)[10^{-3}]$	$1.5^{+0.7}_{-0.4}$	1.4
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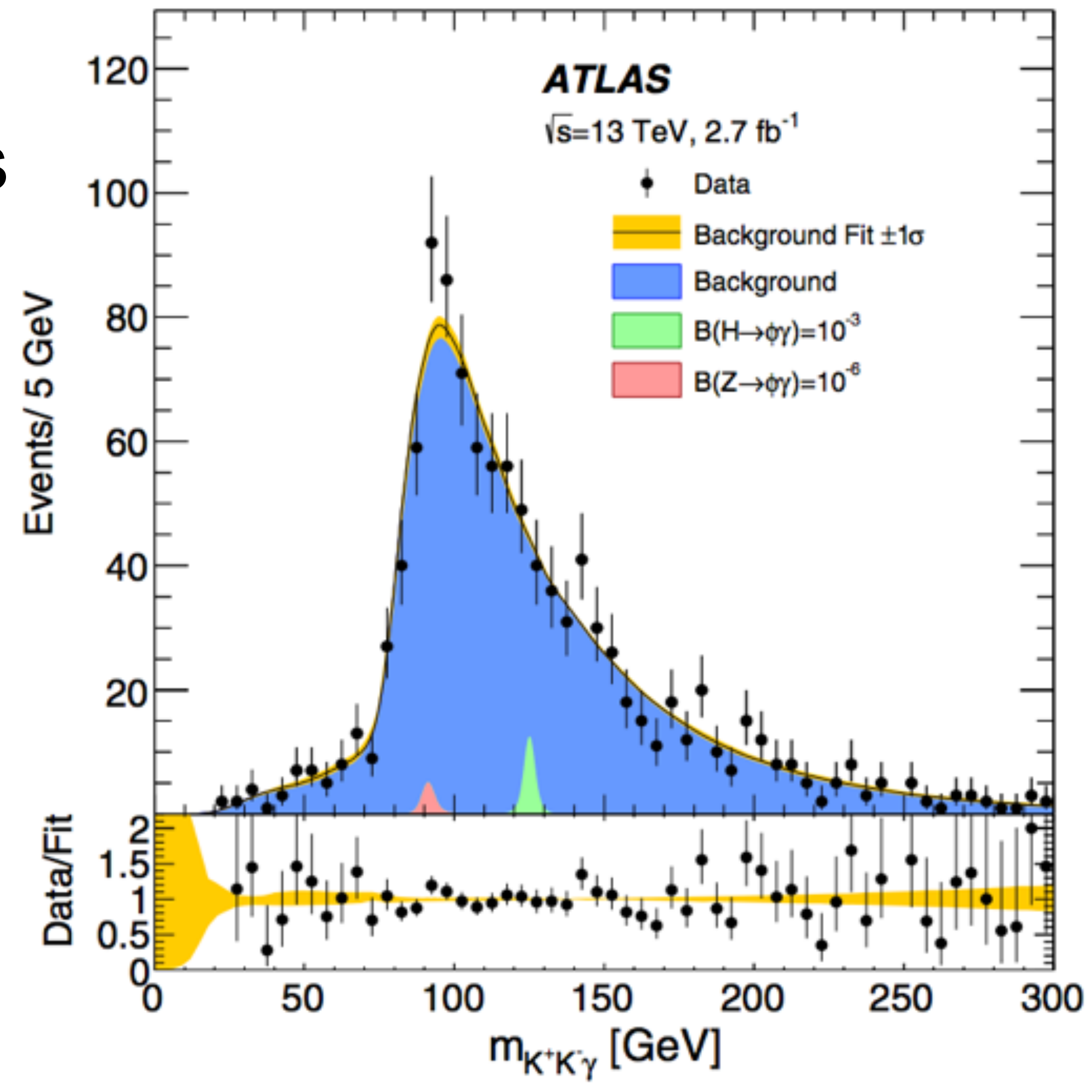
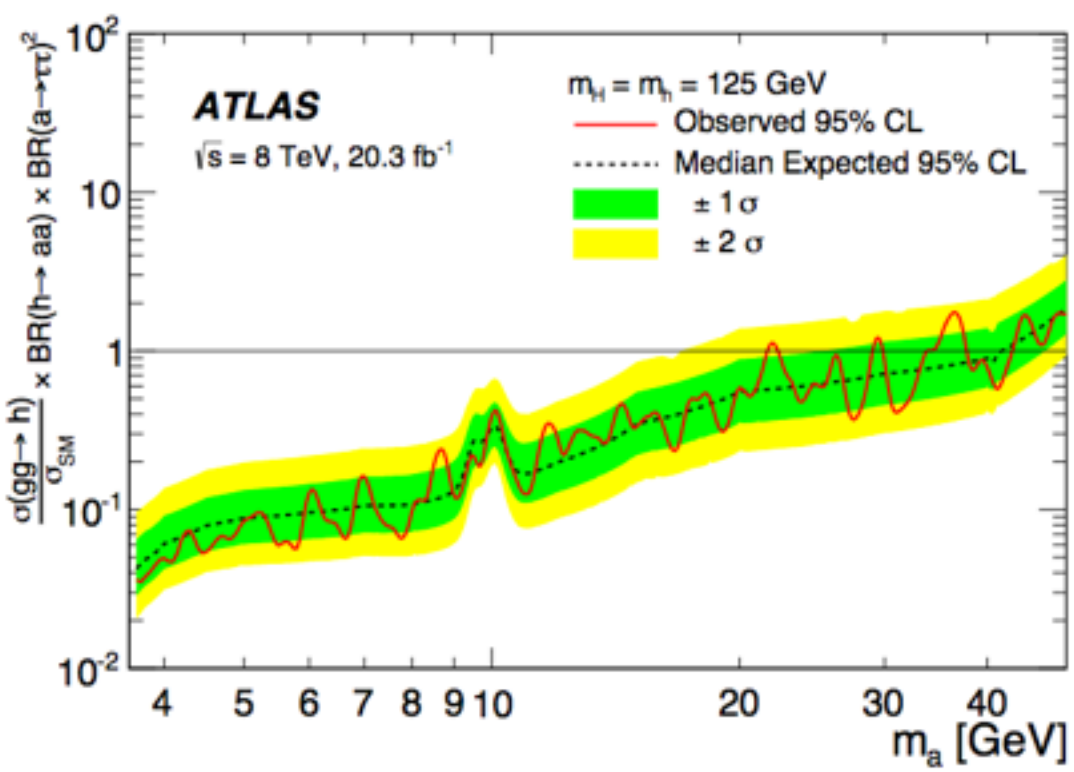
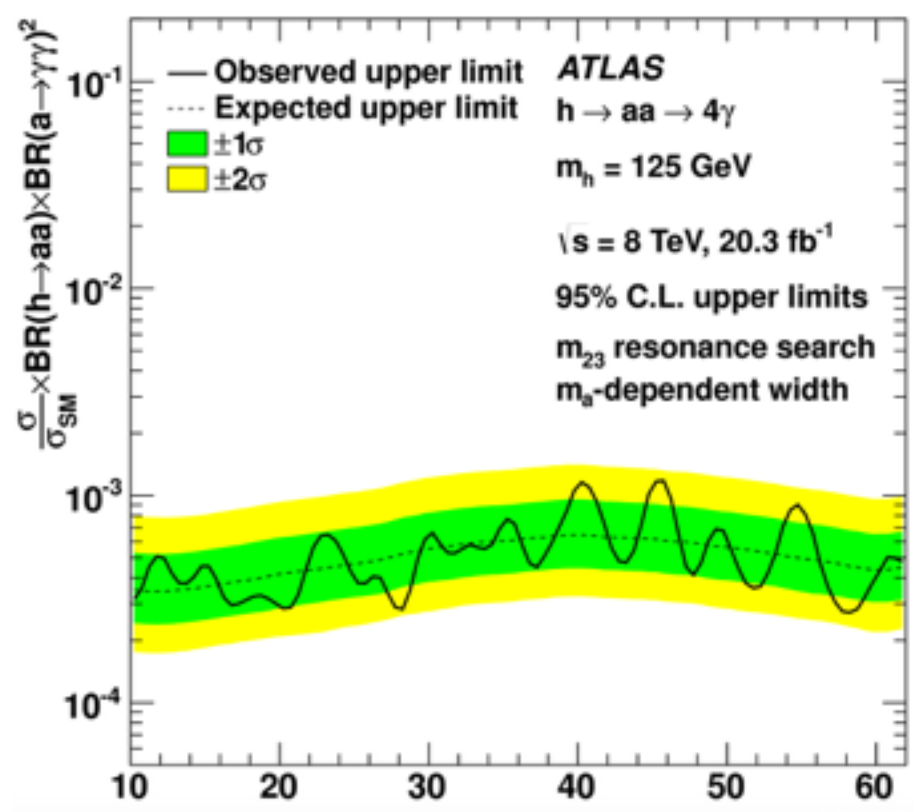


New light resonances: H→a a

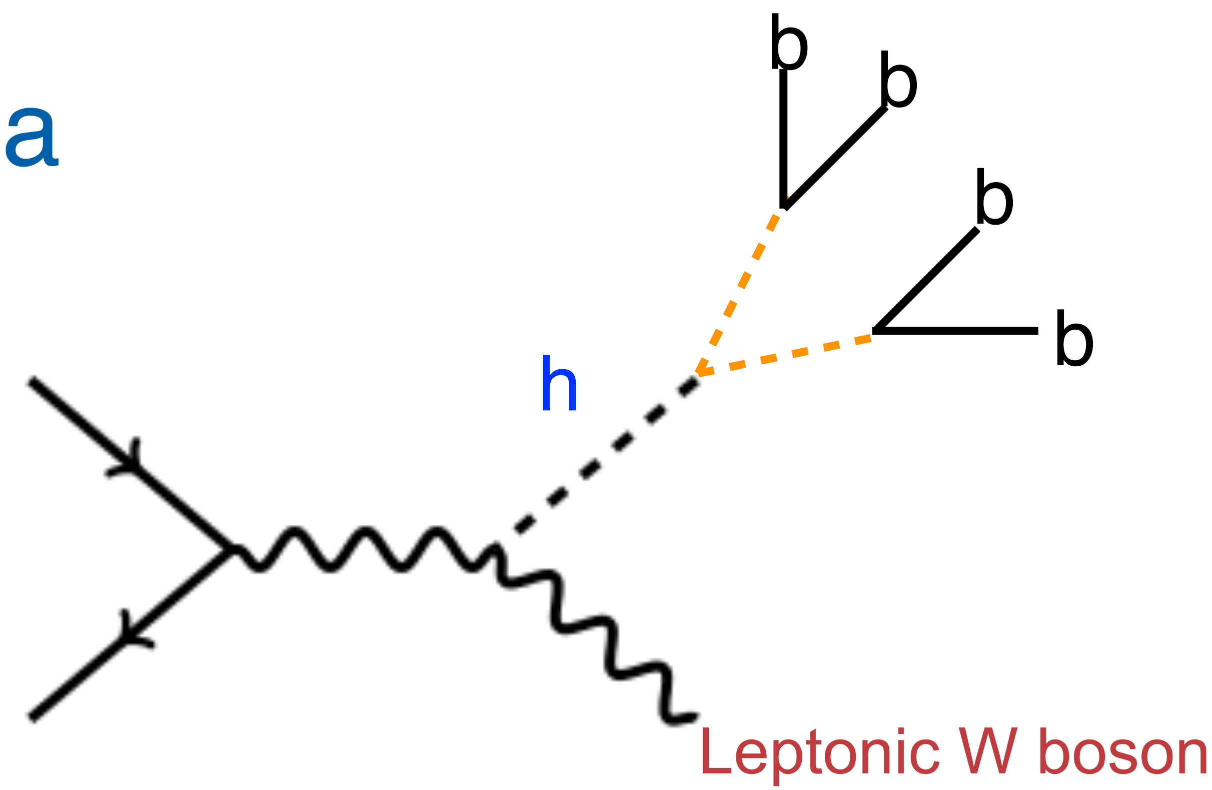
- Several analyses have been performed in the past by ATLAS, targeting different decays
  - H→a a→μμ $\tau\tau$
    - Phys.Rev. D92 (2015) no.5, 052002 [arXiv:1509.05051]
  - H→a a→$\gamma\gamma$ $\gamma\gamma$
    - Eur. Phys. J. C 76(4) , 1-26 (2016) [arXiv:1505.01609]
  - H→Z_D Z_D→$\ell\ell$ $\ell\ell$, H→Z Z_D→$\ell\ell$ $\ell\ell$
    - arXiv:1505.07645, arXiv:1505.07645
  - …



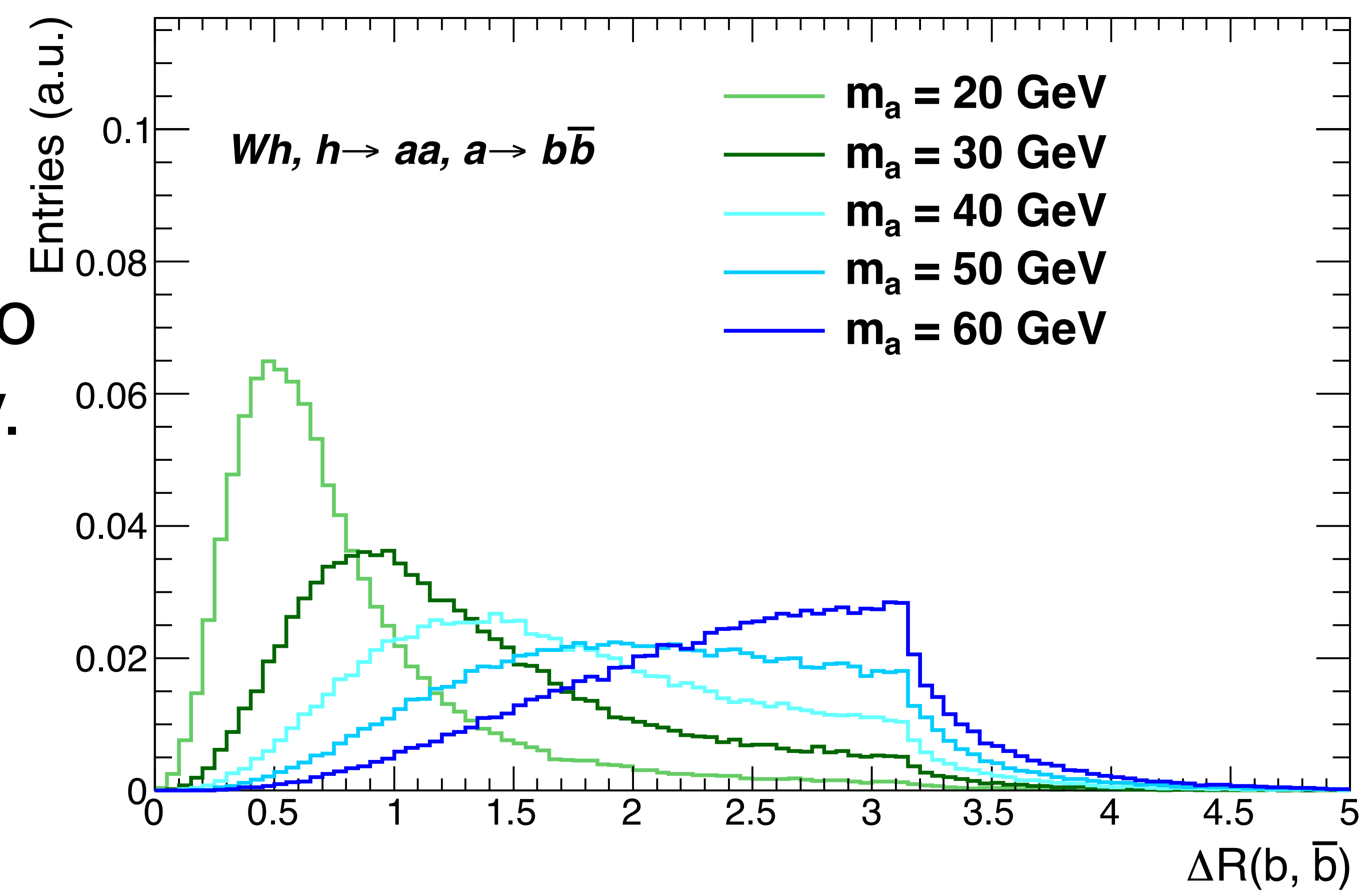


New light resonances: $H \rightarrow a\ a$

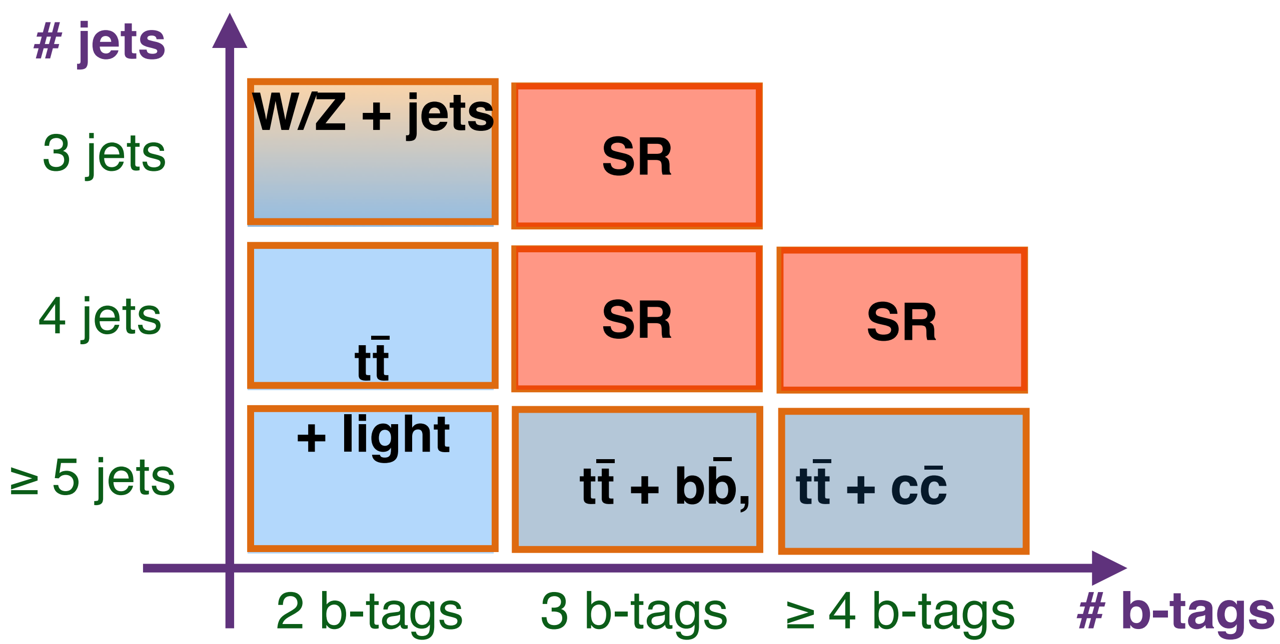
- Higgs production in association to a W boson, decaying leptonically.
  - Signature: at least 1 lepton, E_T^{miss} and multiple low p_T b-jets.
- Kinematics largely dependent (
  the mass of the spin-0.

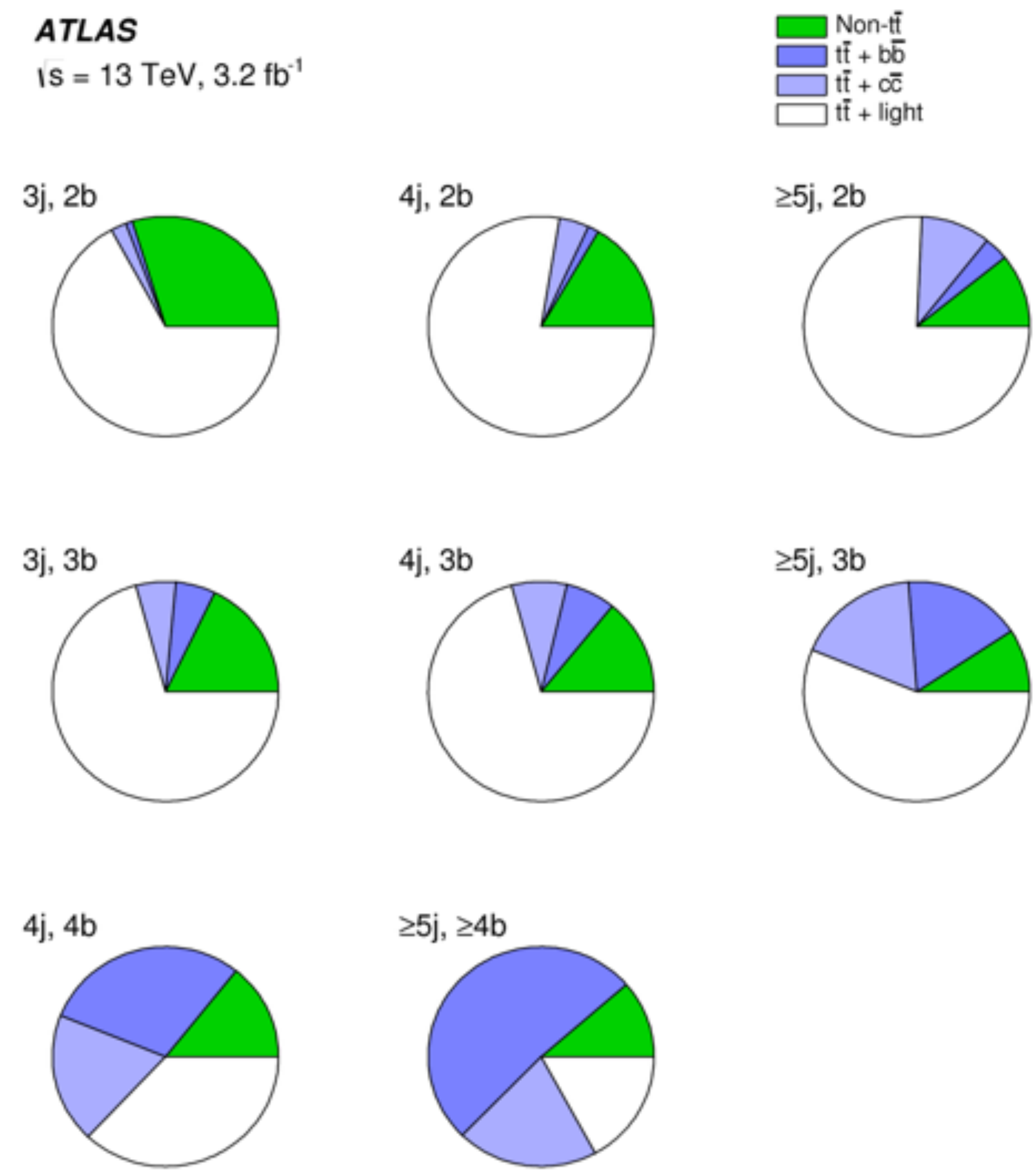


- Higgs production in association to a W boson, decaying leptonically.
  - Signature: at least 1 lepton, E_T^{miss} and multiple low p_T b-jets.
- Kinematics largely dependent on the mass of the spin-0.



New light resonances: H→a a - regions composition

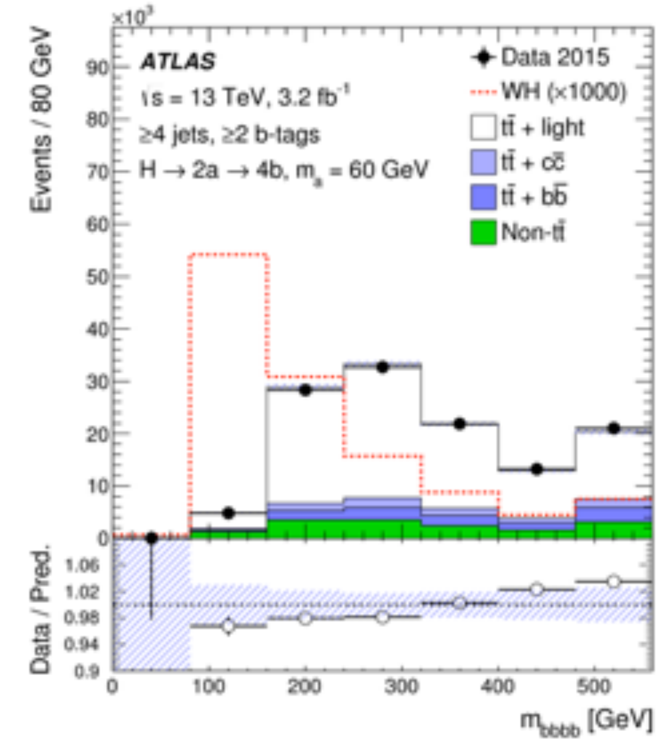


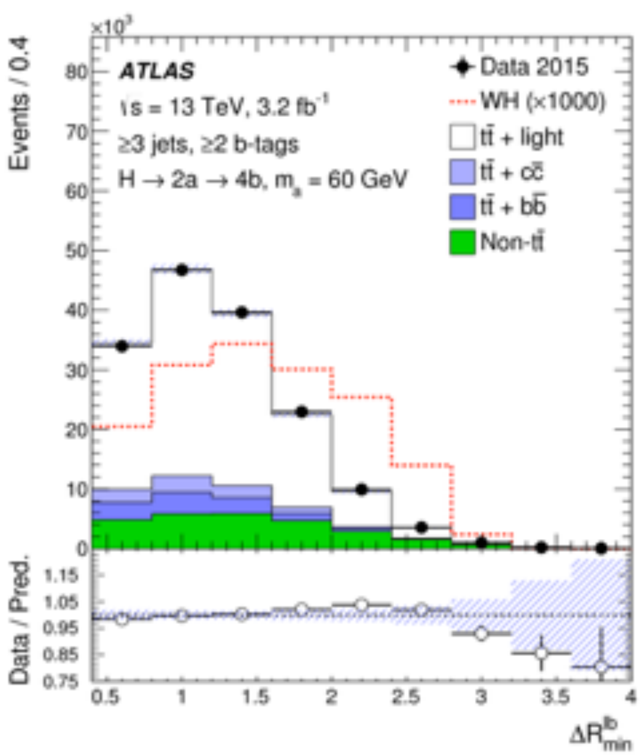


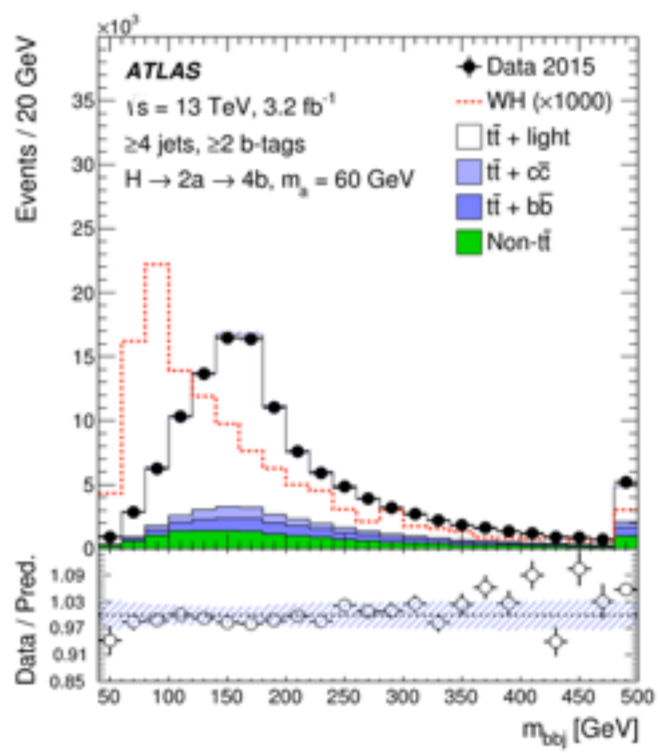
New light resonances: H→a a - BDTs

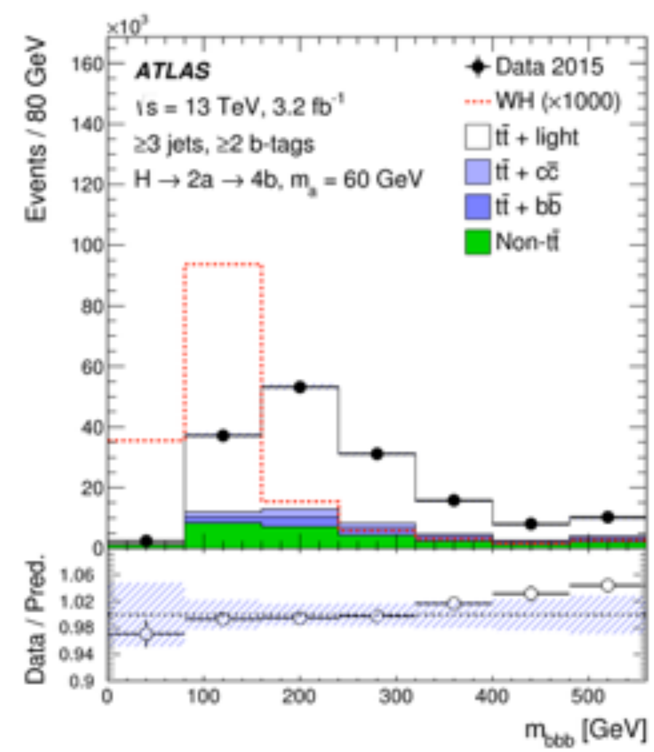
- Boosted Decision Tree trained in each signal region

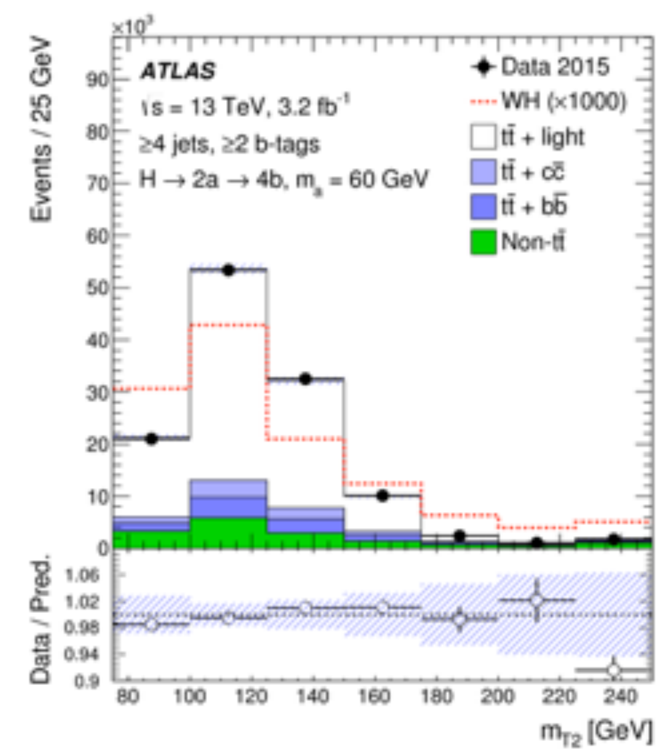
Region	m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\text{min}}$	H_{T}	p^{W}_{T}	$\Delta R^{bb}_{\text{av}}$	$\Delta R^{\ell b}_{\text{min}}$	m_{bbj}	m_{T2}
Signal									
(3j, 3b)	✓			✓	✓	✓	✓		
(4j, 3b)	✓			✓	✓	✓		✓	
(4j, 4b)		✓	✓	✓		✓			✓
Control				✓					







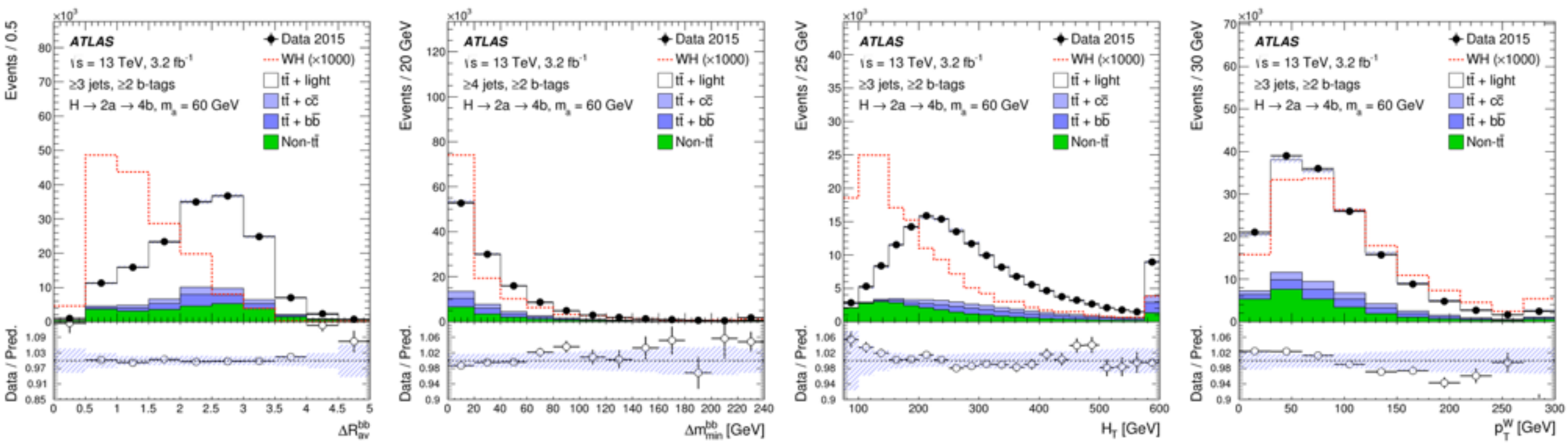




New light resonances: H→a a - BDTs

- Boosted Decision Tree trained in each signal region

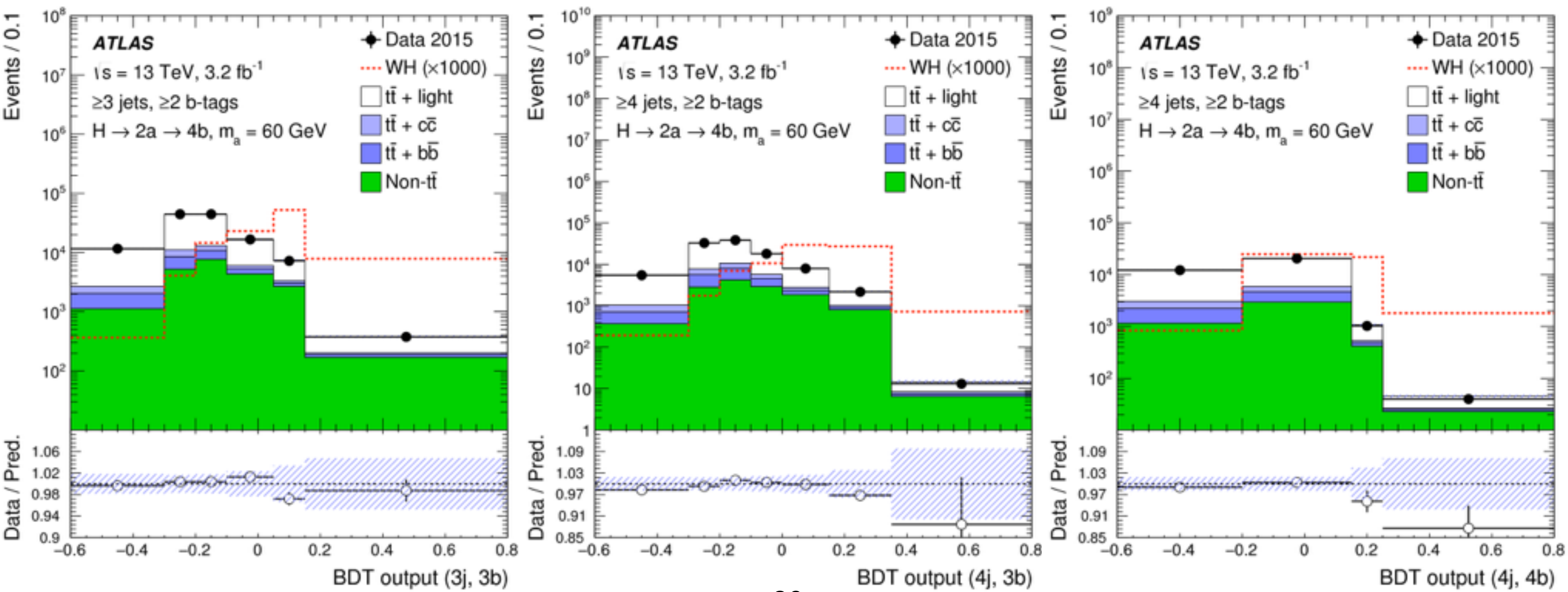
Region	m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\text{min}}$	H_{T}	p^{W}_{T}	$\Delta R^{bb}_{\text{av}}$	$\Delta R^{\ell b}_{\text{min}}$	m_{bbj}	m_{T2}
Signal									
(3j, 3b)	✓			✓	✓	✓	✓		
(4j, 3b)	✓			✓	✓	✓		✓	
(4j, 4b)		✓	✓	✓		✓			✓
Control				✓					



New light resonances: H→a a - BDTs

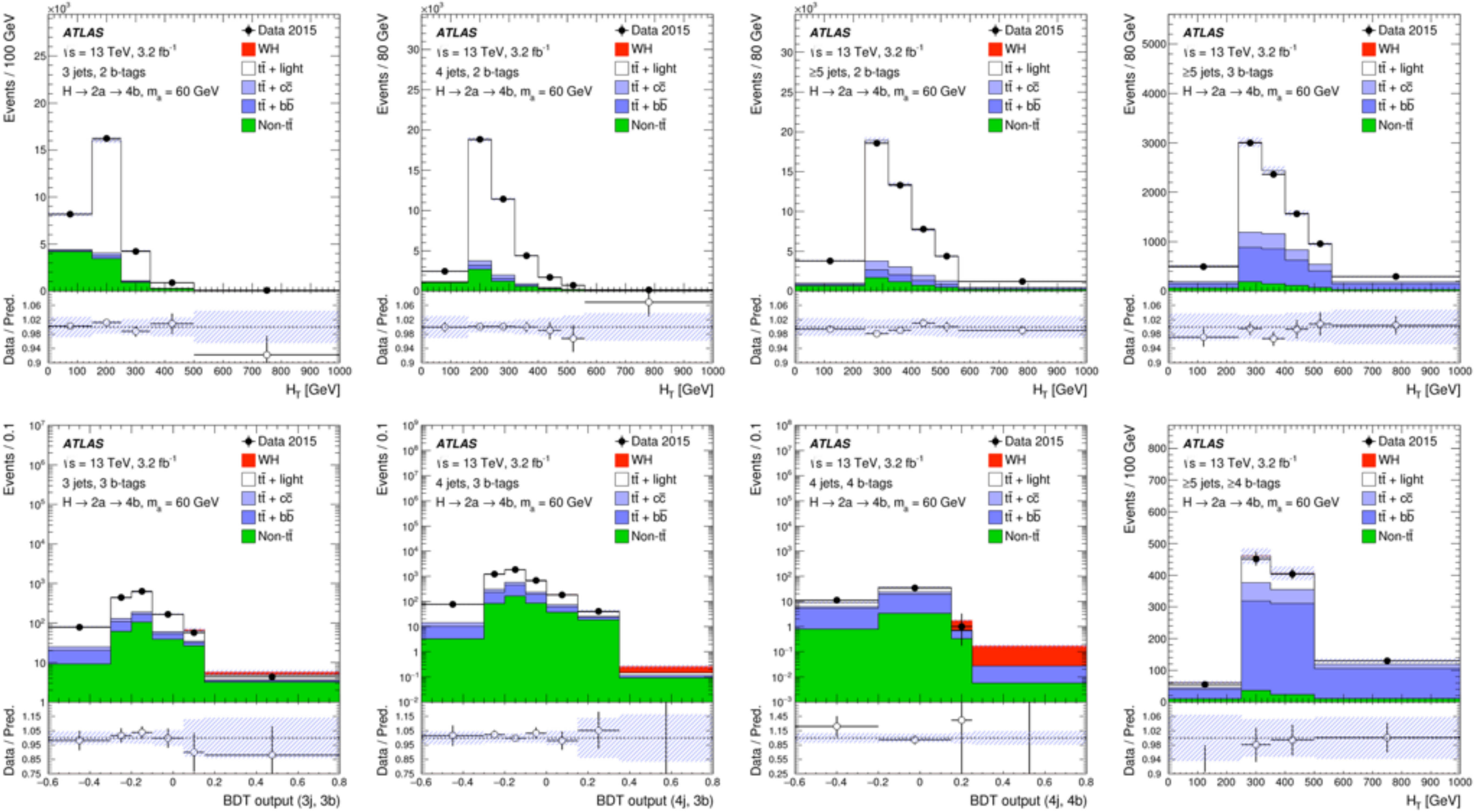
- Boosted Decision Tree trained in each signal region

Region	m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\mathrm{min}}$	H_{T}	p_{T}^{W}	$\Delta R^{bb}_{\mathrm{av}}$	$\Delta R^{\ell b}_{\mathrm{min}}$	m_{bbj}	m_{T2}
Signal									
(3j, 3b)	✓			✓	✓	✓	✓		
(4j, 3b)	✓			✓	✓	✓		✓	
(4j, 4b)		✓	✓	✓		✓			✓
Control				✓					



New light resonances: H→a a - Fit distributions

- Signal and control region variables entering the fit



New light resonances: H→a a - Systematic uncertainties

- Systematic uncertainties (4 jets, 4 b-tags) on the signal and main backgrounds.

Systematic uncertainty [%]	WH, $H \to 2a \to 4b$	$t\bar{t}$ + light	$t\bar{t} + c\bar{c}$	$t\bar{t} + b\bar{b}$
Luminosity	4	4	4	4
Lepton efficiencies	1	1	1	1
Jet efficiencies	6	4	4	4
Jet energy resolution	5	1	3	1
Jet energy scale	4	2	4	3
b-tagging efficiency	17	5	5	9
c-tagging efficiency	1	6	12	4
Light-jet-tagging efficiency	2	29	5	3
Theoretical cross sections	–	5	5	5
$t\bar{t}$: modelling	–	6	45	26
$t\bar{t}$+HF: normalisation	–	–	35	18
$t\bar{t}$+HF: modelling	–	–	–	5
Signal modelling	7	–	–	–
Total	21	31	54	21

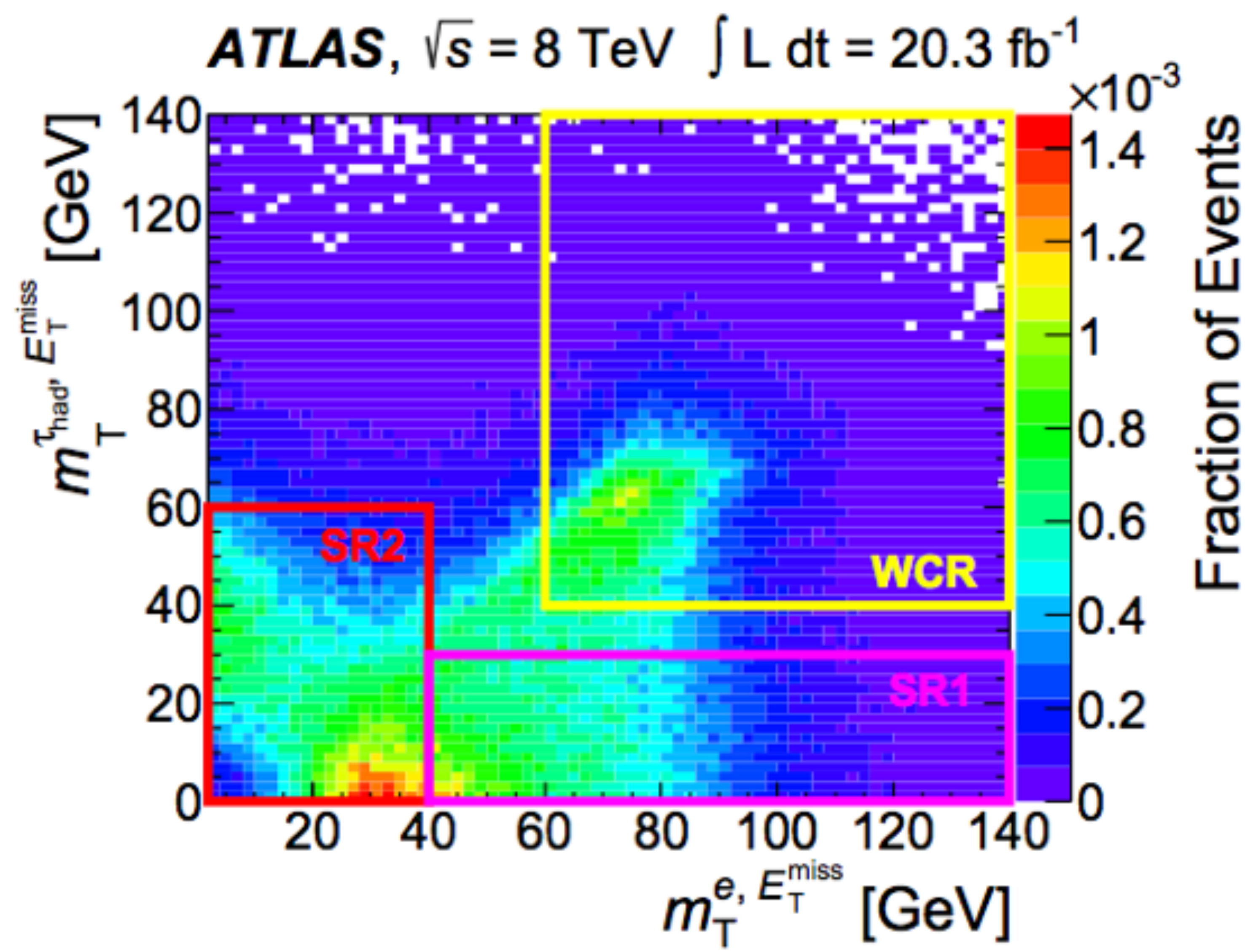
New light resonances: H→a a - Signal region yields

- Yields in the signal regions.

Process	(3j, 3b)	(4j, 3b)	(4j, 4b)
$t\bar{t}$ + light	1089 ± 76	2940 ± 180	53 ± 16
$t\bar{t} + c\bar{c}$	70 ± 28	280 ± 110	21 ± 11
$t\bar{t} + b\bar{b}$	172 ± 55	610 ± 160	74 ± 15
$t\bar{t} + \gamma/W/Z$	0.8 ± 0.1	4 ± 1	0.4 ± 0.1
W + jets	93 ± 31	129 ± 40	2 ± 1
Z + jets	18 ± 12	14 ± 10	–
Single-top-quark	135 ± 13	208 ± 17	8 ± 1
Multijet	48 ± 20	67 ± 28	4 ± 2
Dibosons	4 ± 1	9 ± 1	0.6 ± 0.4
$t\bar{t} + H$	0.7 ± 0.1	4 ± 1	0.8 ± 0.2
Total	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166
WH, $H \to 2a \to 4b$			
$m_a = 60\ GeV$	10 ± 2	9 ± 1	3 ± 1
$m_a = 40\ GeV$	11 ± 2	10 ± 2	2 ± 1
$m_a = 20\ GeV$	6 ± 1	5 ± 1	0.7 ± 0.2

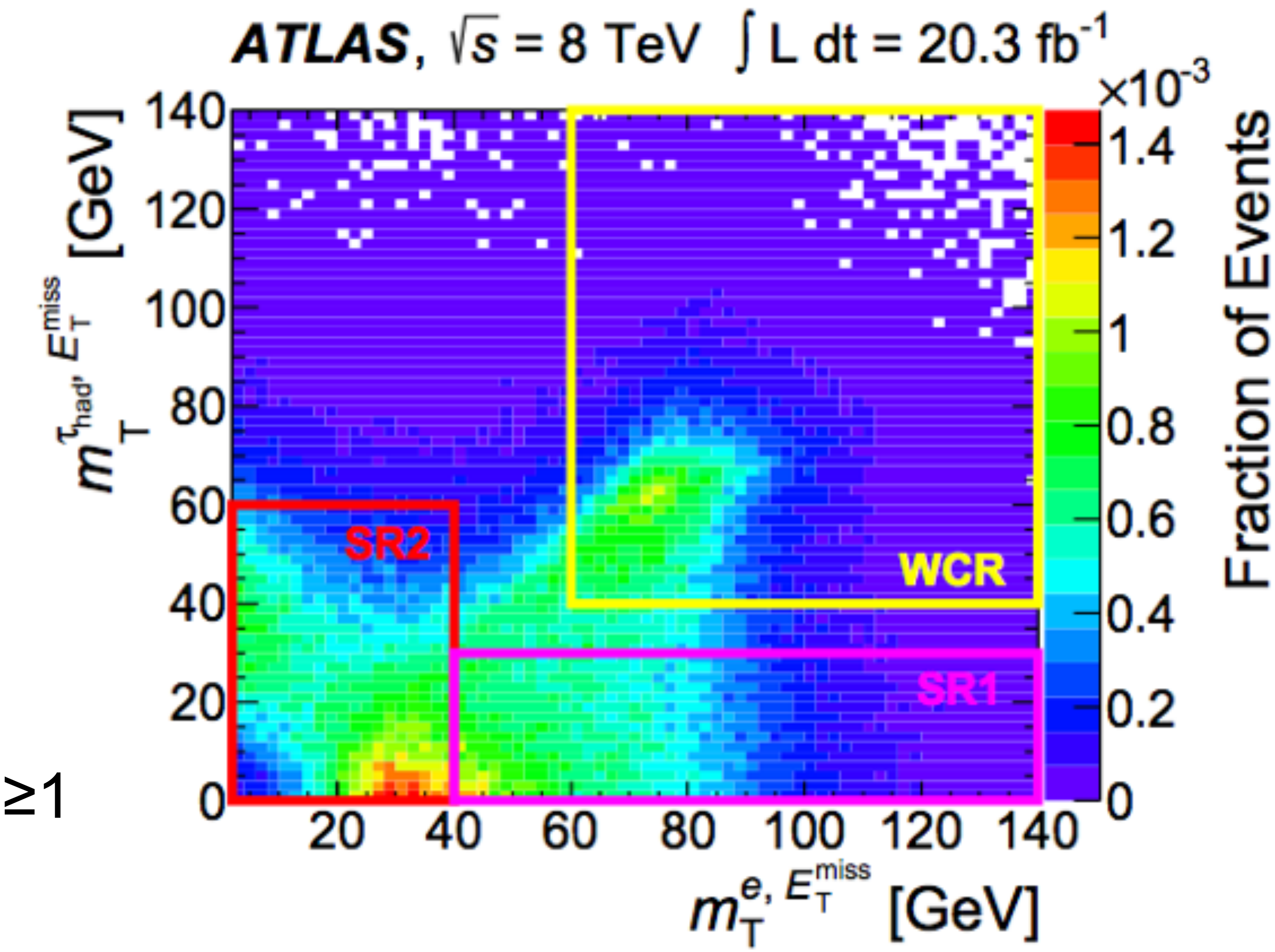
FV couplings: $H \rightarrow e\tau_{had}$ - Region definitions

- The $e\tau_{had}$ channel requires events with exactly one energetic electron and one opposite-charge τ.
- Irreducible background: $Z \rightarrow \tau\tau$, $t\bar{t}$, single-top, $VV \rightarrow e\tau + X$…
  - Very strong charge anticorrelation: $N_{OS} >> N_{SS}$
- Reducible background
  - τ_{had} from a jet
    - W+jets, multi-jet (e from semi-leptonic b-decays), dibosons, $t\bar{t}$ and single-top.
  - τ_{had} from either a jet or an electron
    - Z(ee)+jets
- Events with misidentified τ_{had} have:
  - Much softer $p_T(\tau_{had})$.
  - More separation between τ_{had} and E_T^{miss}.

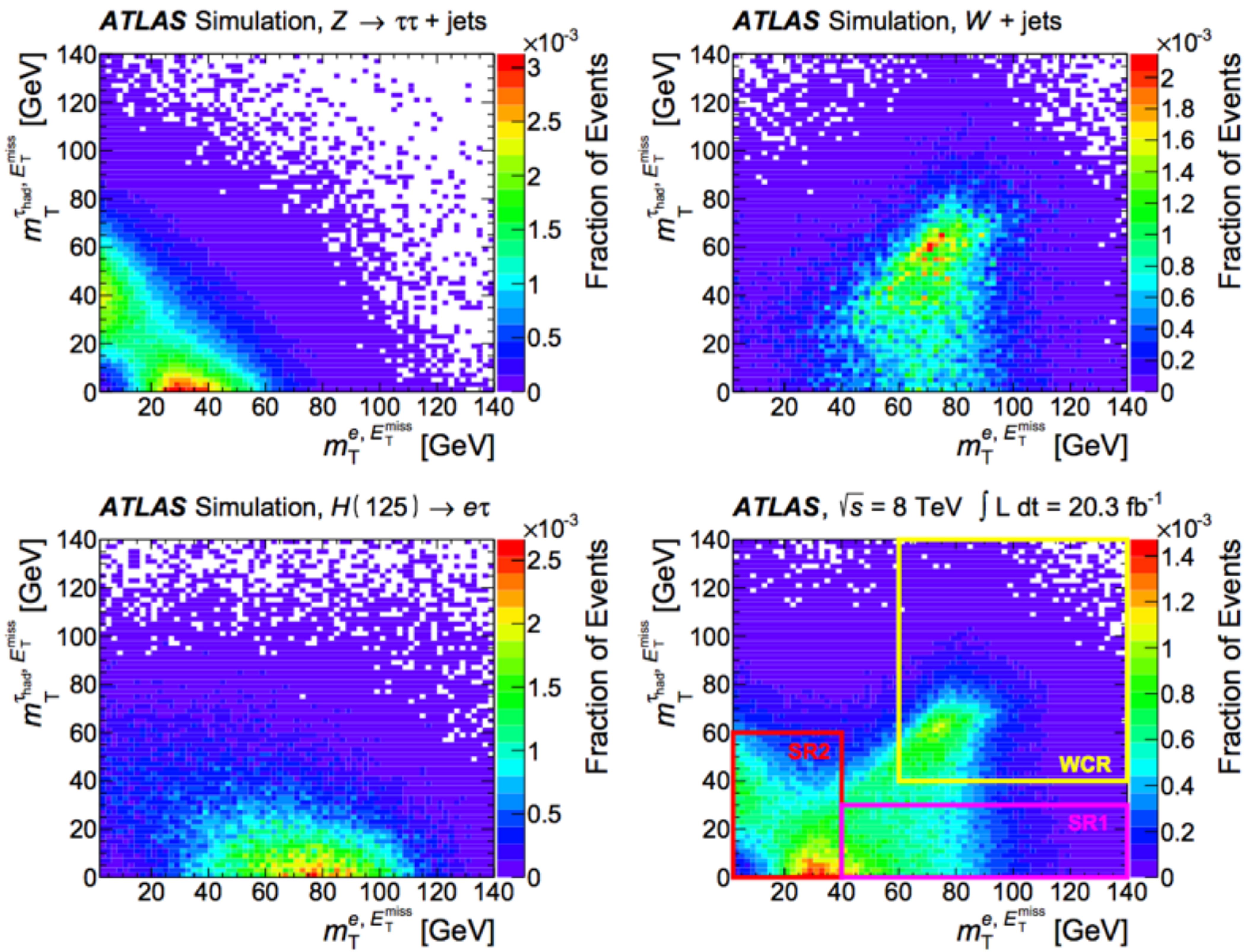


FV couplings: $H \rightarrow e\tau_{had}$ - Region definitions

- Baseline selection:
  - Exactly 1 electron and 1 τ_{had} with $E_T(e) > 26$ GeV, $p_T(\tau_{had}) > 45$ GeV
  - $|\eta(e) - \eta(\tau_{had})| < 2$ to reject W+jets and multi-jet.
- Two signal regions using transverse mass between (e, E_T^{miss}) and (τ_{had}, E_T^{miss})
  - OS electron and τ_{had}.
  - No requirement on jet multiplicity, exactly 0 b-tagged jets.
  - Both regions with similar sensitivity, but dominated by different backgrounds.
- W+jets is checked in WCR.
- $t\bar{t}$ is checked in TCR, with 2 jets, ≥1 b-tagged.



FV couplings: H→eτ$_{had}$ - Region definitions



FV couplings: $H \to e\tau_{had}$ - Background estimation

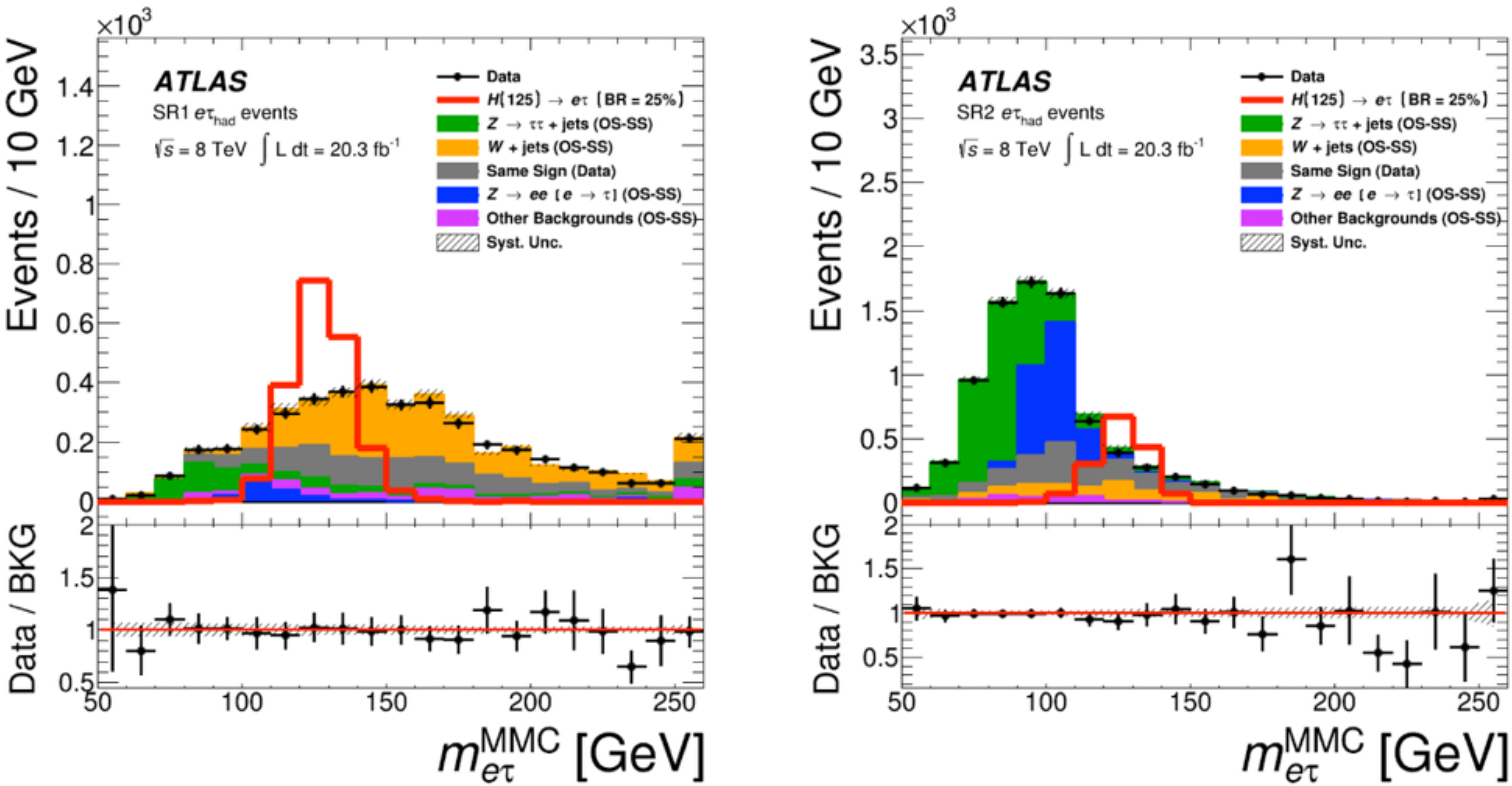
- Rely on the observation that shape of $m^{MMC}_{e\tau}$ is the same for OS and SS events.

$$N_{\rm OS}^{\rm bkg} = r_{\rm QCD} \cdot N_{\rm SS}^{\rm data} + \sum_{\text{bkg-}i} N_{\rm OS-SS}^{\text{bkg-}i}$$

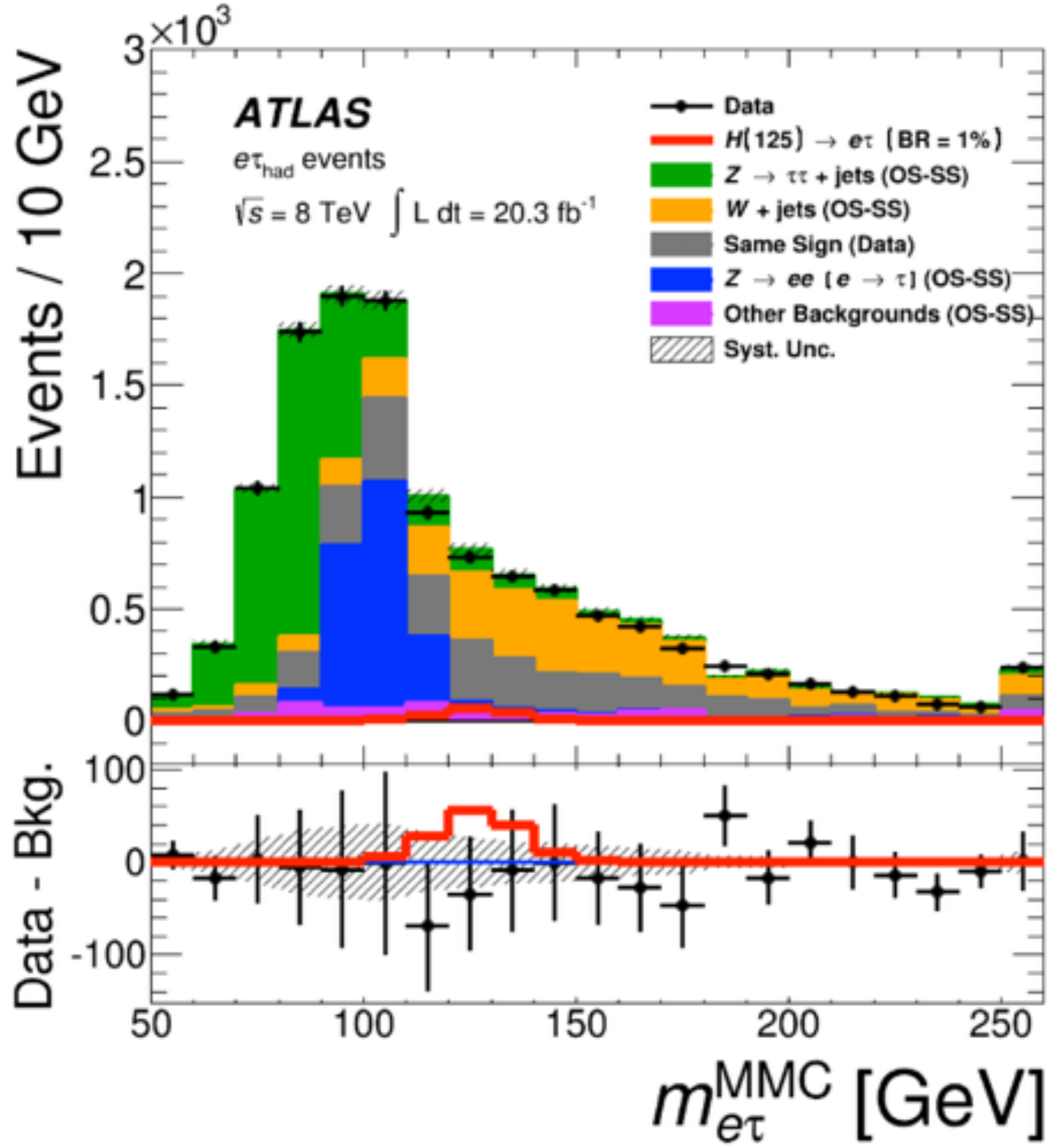
- $N_{\rm OS}^{\rm bkg}$: Total background events in SR1 or SR2
- $r_{\rm QCD}$: To account for potential differences in flavor composition $= N_{OS}^{\text{multi-jet}} / N_{SS}^{\text{multi-jet}}$
- $N_{\rm SS}^{\rm data}$: Data events in SR1 or SR2 requiring SS. Contains W+jets, multi-jets…
- $\sum N_{\rm OS-SS}^{\text{bkg-}i}$: Add-on terms for the different background components $= N_{OS}^{\text{bkg-i}} - r_{QCD} \times N_{SS}^{\text{bkg-i}}$

- $Z(\tau\tau)$+jets normalization is a free parameter in the final fit.
- Normalizations for bkg-i are extracted for SS and OS in the different control regions when possible.
  - W+jets and tt from WCR and TCR. W+jets has extra free normalization in the fit.
  - Z(ee)+jets has 2 components: $e \to \tau_{had}$, estimated from simulation with corrections from T&P studies.; and jet$\to\tau_{had}$, estimated in a region with 2 OS electrons.

FV couplings: H→$e\tau_{had}$ - Signal regions



FV couplings: H→eτ_{had} - Signal regions

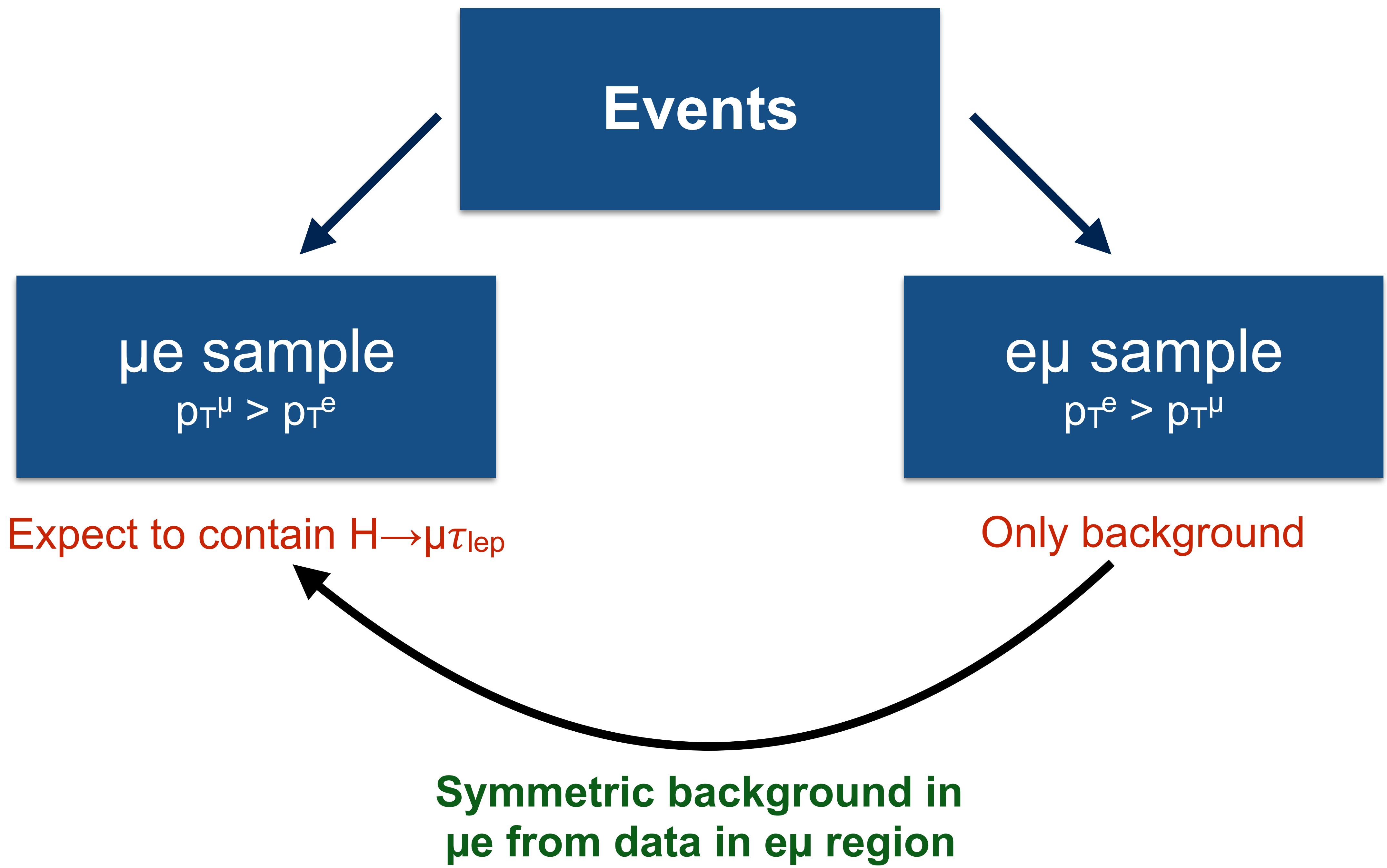


FV couplings: $H\rightarrow e\tau_{lep}$ and $H\rightarrow \mu\tau_{lep}$ - Background estimation

- Select events with one electron and one muon, opposite sign.
  - Two exclusive signal regions defined: with and without central jets.
  - Fit m_{coll} distribution (the more sophisticated m_{MMC} does not improve the results)
- Background estimation based on the following premises:
  - Kinematic distributions of prompt e and μ are approximately the same.
  - FV decays of the Higgs boson break this symmetry.

FV couplings: H→$e\tau_{lep}$ and H→$\mu\tau_{lep}$ - Background estimation

- Example case for H→$\mu\tau_{lep}$ signal (similar for H→$e\tau_{lep}$).



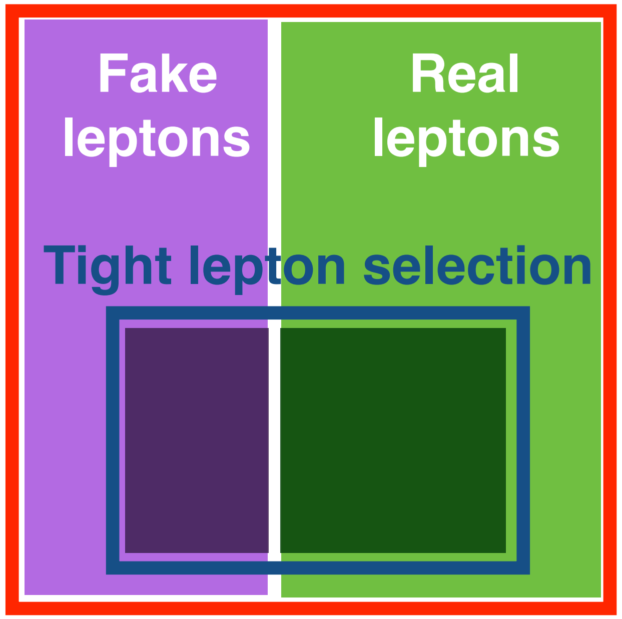
FV couplings: H→eτ_{lep} and H→$\mu\tau_{\mathrm{lep}}$ - Background estimation

- Some asymmetries in the SM background estimation need to be considered:
  - Events containing non-prompt leptons.
    - Leptons from mis-identified jets or hadronic decays within jets.
    - Electrons and muons effected differently because the origin of the non-prompt is different.
    - Estimated with matrix-method technique.
  - Electrons and muons have different reconstruction and trigger efficiencies.
    - Events in the eμ region corrected by the following factor when estimating the background in μe region:

$$\frac{\varepsilon^{\mu e}}{\varepsilon^{e\mu}} = \frac{\varepsilon^{\mu e}_{\mathrm{trig.}}\left(p_{\mathrm{T}}^{\ell_2}\right)\varepsilon^{\mu}_{\mathrm{reco.}}\left(p_{\mathrm{T}}^{\ell_1}\right)\varepsilon^{e}_{\mathrm{reco.}}\left(p_{\mathrm{T}}^{\ell_2}\right)}{\varepsilon^{e\mu}_{\mathrm{trig.}}\left(p_{\mathrm{T}}^{\ell_2}\right)\varepsilon^{e}_{\mathrm{reco.}}\left(p_{\mathrm{T}}^{\ell_1}\right)\varepsilon^{\mu}_{\mathrm{reco.}}\left(p_{\mathrm{T}}^{\ell_2}\right)}$$

FV couplings: H→eτ$_{lep}$ and H→μτ$_{lep}$ - Matrix method

- Given a "loose" and a "tight" lepton selection, the composition in terms of real and fake leptons is



$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}}$$

$$N^{\text{tight}} = N^{\text{tight}}_{\text{real}} + N^{\text{tight}}_{\text{fake}}$$

We want to estimate this!

- Since the "tight" is a subset of the "loose" sample, define fake (real) efficiency f (r) as:

$$f = \frac{N^{\text{tight}}_{\text{fake}}}{N^{\text{loose}}_{\text{fake}}}$$

$$r = \frac{N^{\text{tight}}_{\text{real}}}{N^{\text{loose}}_{\text{real}}}$$

$$N^{\text{loose}} = N^{\text{loose}}_{\text{real}} + N^{\text{loose}}_{\text{fake}}$$

$$N^{\text{tight}} = r \times N^{\text{loose}}_{\text{real}} + f \times N^{\text{loose}}_{\text{fake}}$$

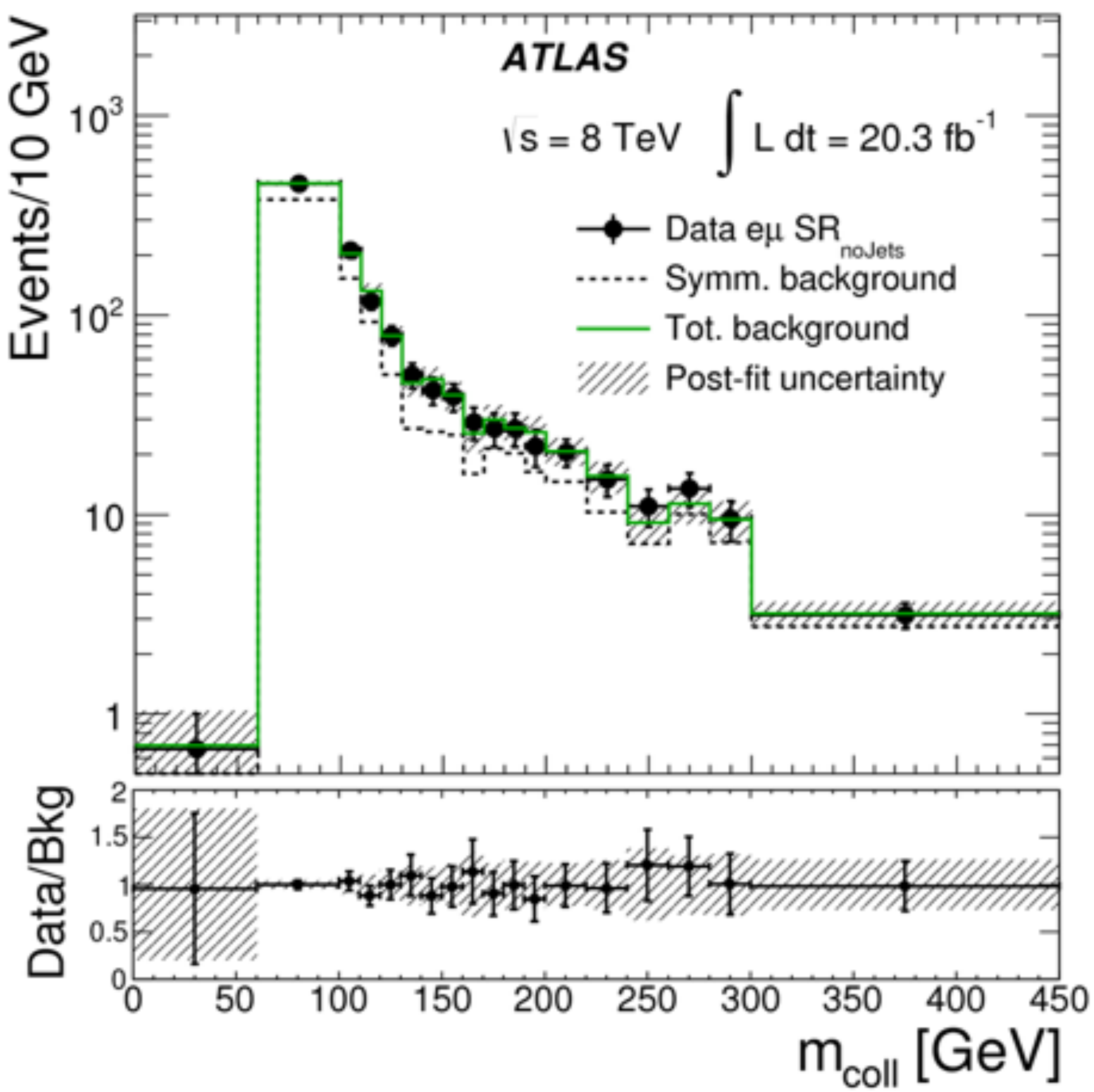
- So that one can solve the system of equations and get:

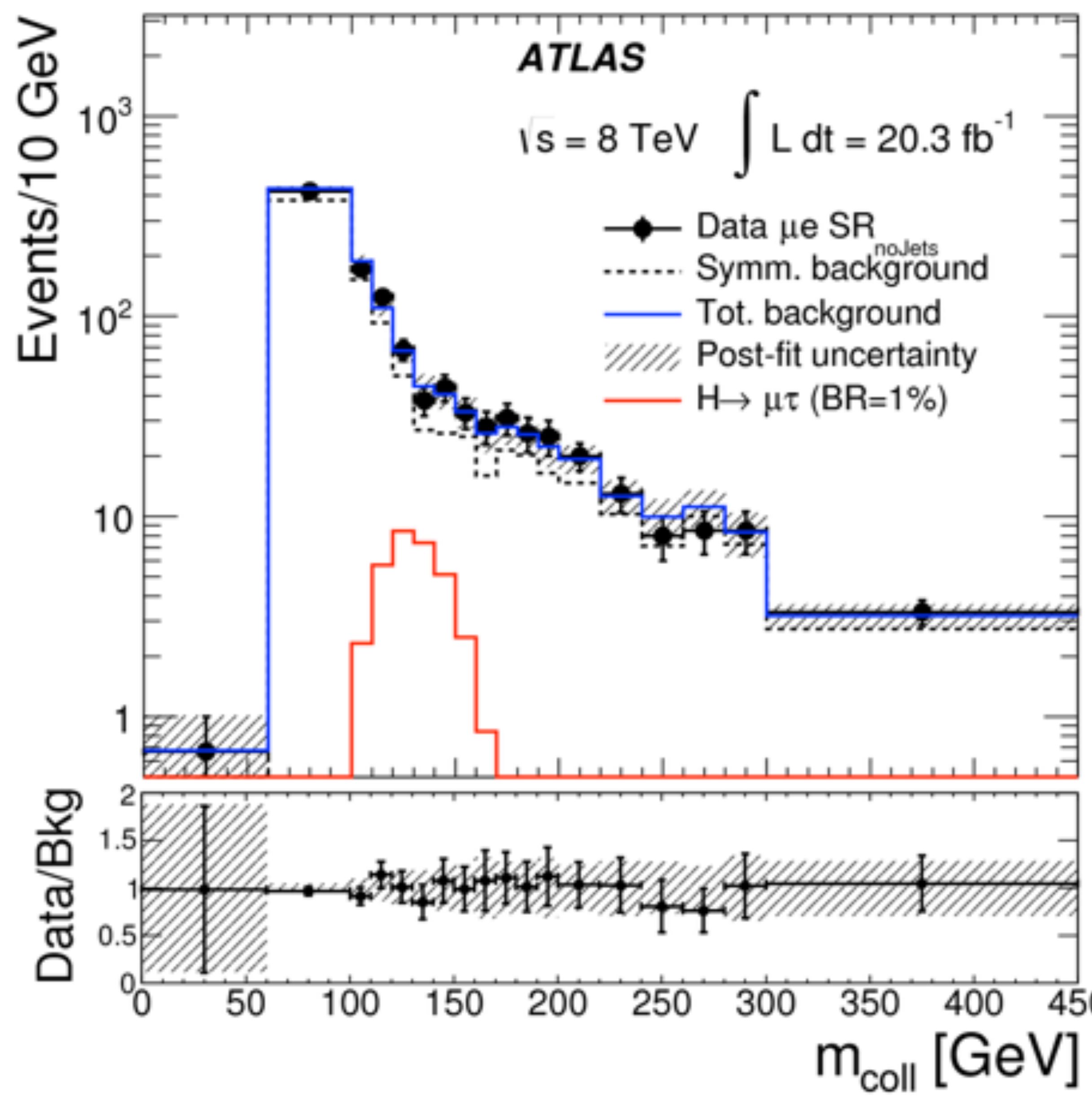
$$N^{\text{tight}}_{\text{fake}} = \frac{f}{r-f}(r \times N^{\text{loose}} - N^{\text{tight}})$$

$$w = \frac{f}{r-f}(r - \wp)$$

FV couplings: H→eτ_{lep} and H→$\mu\tau_{lep}$ - Signal regions

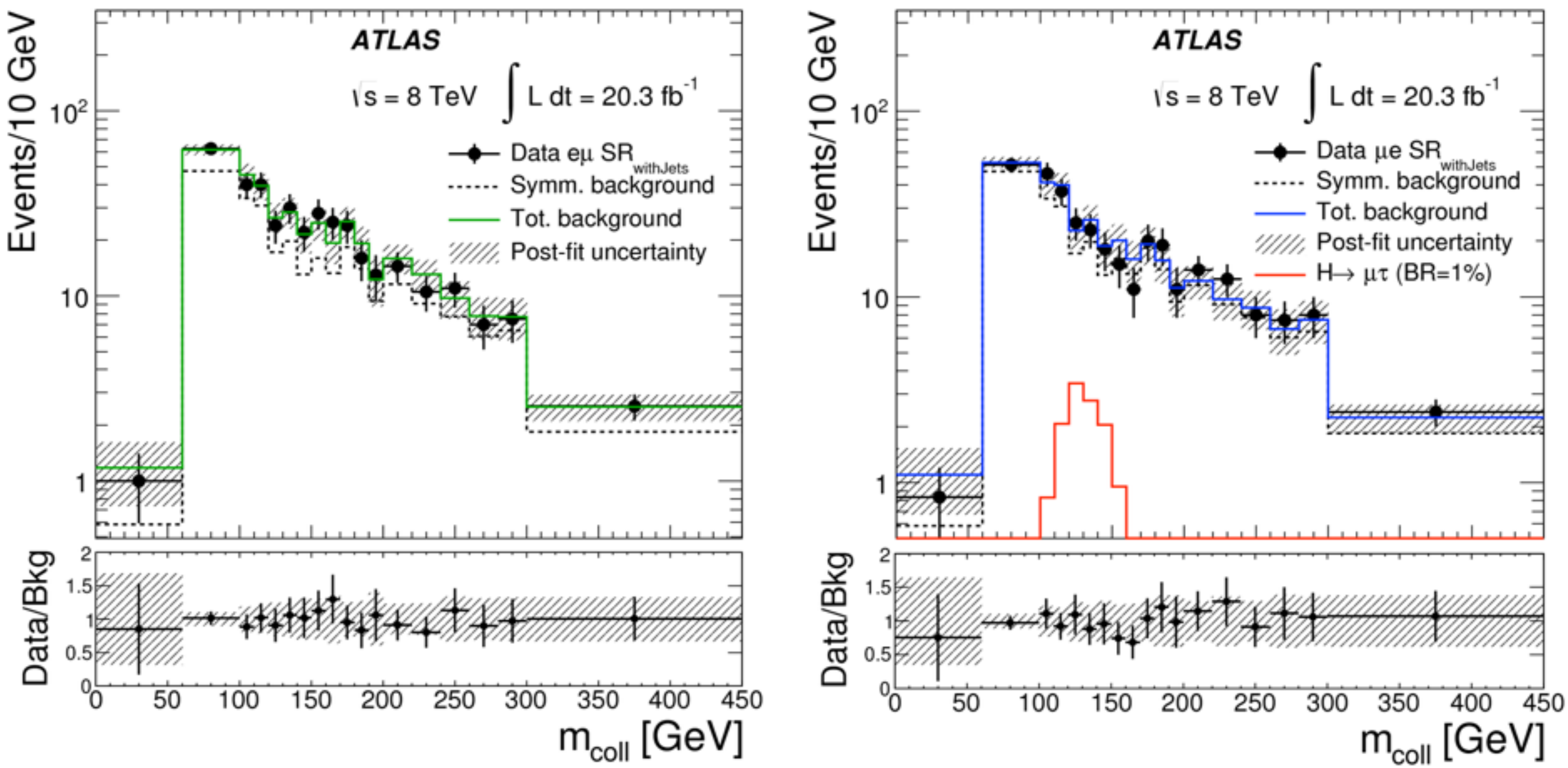
- Signal region with no central jets





FV couplings: $H \to e\tau_{lep}$ and $H \to \mu\tau_{lep}$ - Signal regions

- Signal region with central jets



FV couplings: combination

Channel	Category	Expected limit (%)	Observed limit (%)	Best fit Br (%)
$H \to e\tau_{had}$	SR1	$2.81^{+1.06}_{-0.79}$	3.0	$0.33^{+1.48}_{-1.59}$
	SR2	$2.95^{+1.16}_{-0.82}$	2.24	$-1.33^{+1.56}_{-1.80}$
	Combined	$2.07^{+0.82}_{-0.58}$	1.81	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{lep}$	SR_{noJets}	$1.66^{+0.72}_{-0.46}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$SR_{withJets}$	$3.33^{+1.60}_{-0.93}$	3.99	$0.74^{+1.59}_{-1.62}$
	Combined	$1.48^{+0.60}_{-0.42}$	1.36	$-0.26^{+0.79}_{-0.82}$
$H \to e\tau$	Combined	$1.21^{+0.49}_{-0.34}$	1.04	$-0.34^{+0.64}_{-0.66}$
$H \to \mu\tau_{had}$	SR1	$1.60^{+0.64}_{-0.45}$	1.55	$-0.07^{+0.81}_{-0.86}$
	SR2	$1.75^{+0.71}_{-0.49}$	3.51	$1.94^{+0.92}_{-0.89}$
	Combined	$1.24^{+0.50}_{-0.35}$	1.85	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{lep}$	SR_{noJets}	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$SR_{withJets}$	$3.57^{+1.74}_{-1.00}$	2.85	$-1.03^{+1.66}_{-1.82}$
	Combined	$1.73^{+0.74}_{-0.49}$	1.79	$0.03^{+0.88}_{-0.86}$
$H \to \mu\tau$	Combined	$1.01^{+0.40}_{-0.29}$	1.43	$0.53^{+0.51}_{-0.51}$