

Search for rare and exotic decays of the Higgs boson in ATLAS

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on behalf of the ATLAS collaboration



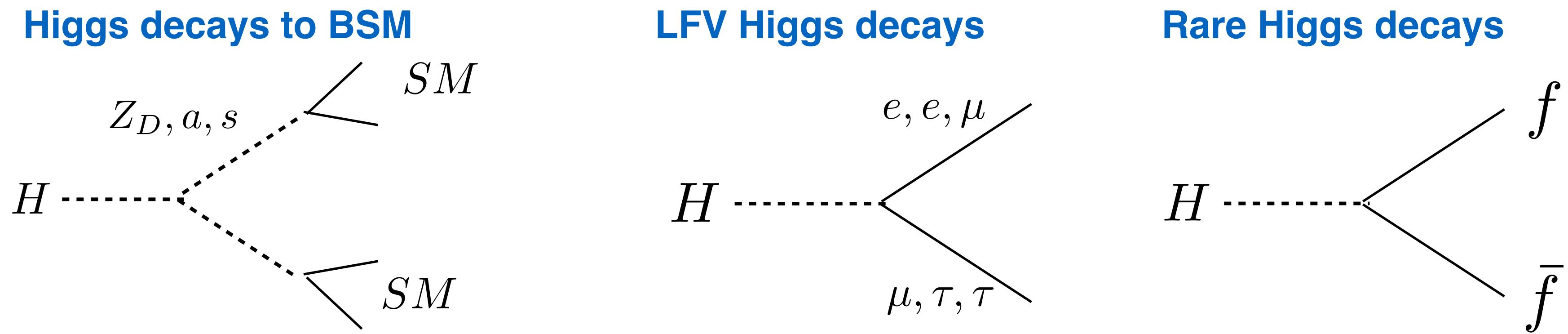
Higgs as a portal to BSM physics

Strong motivation for new physics, Higgs provides a great opportunity

- New physics could couple to the SM only through the Higgs boson, or have too small couplings to be directly produced
- Higgs width is extremely small, additional widths can lead to substantial BR

Exotic decays of $H(125)$ as a signature for BSM physics

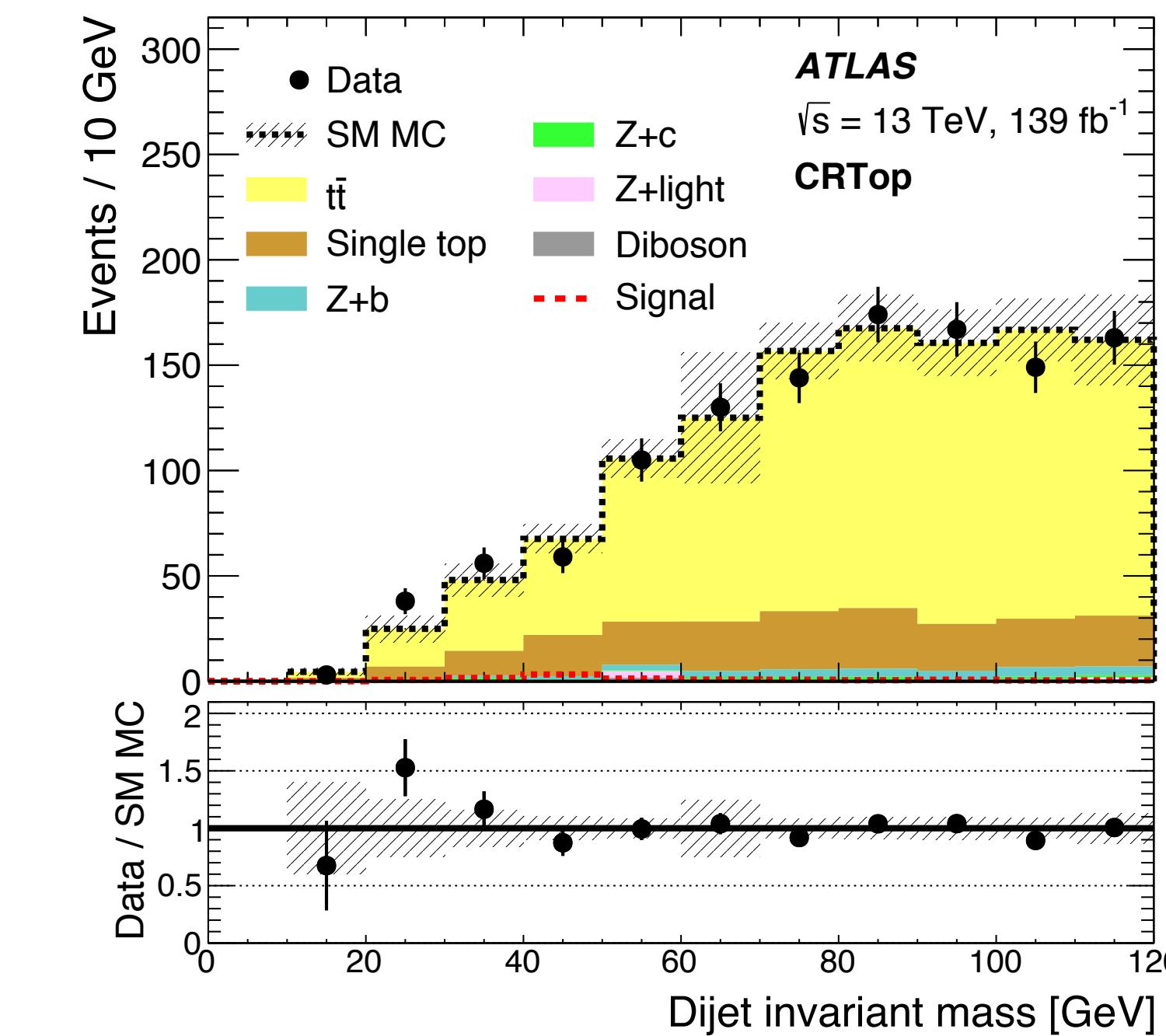
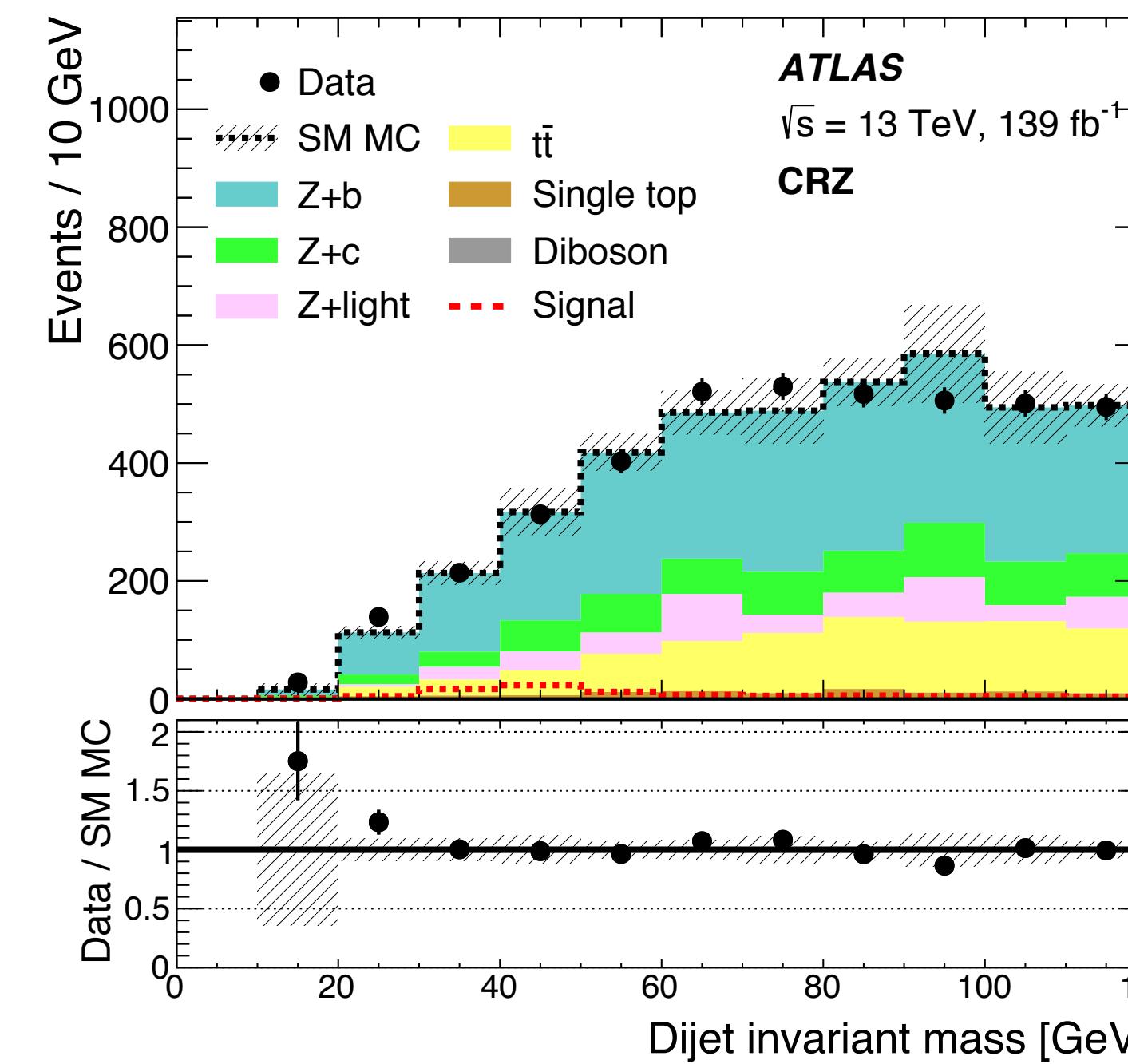
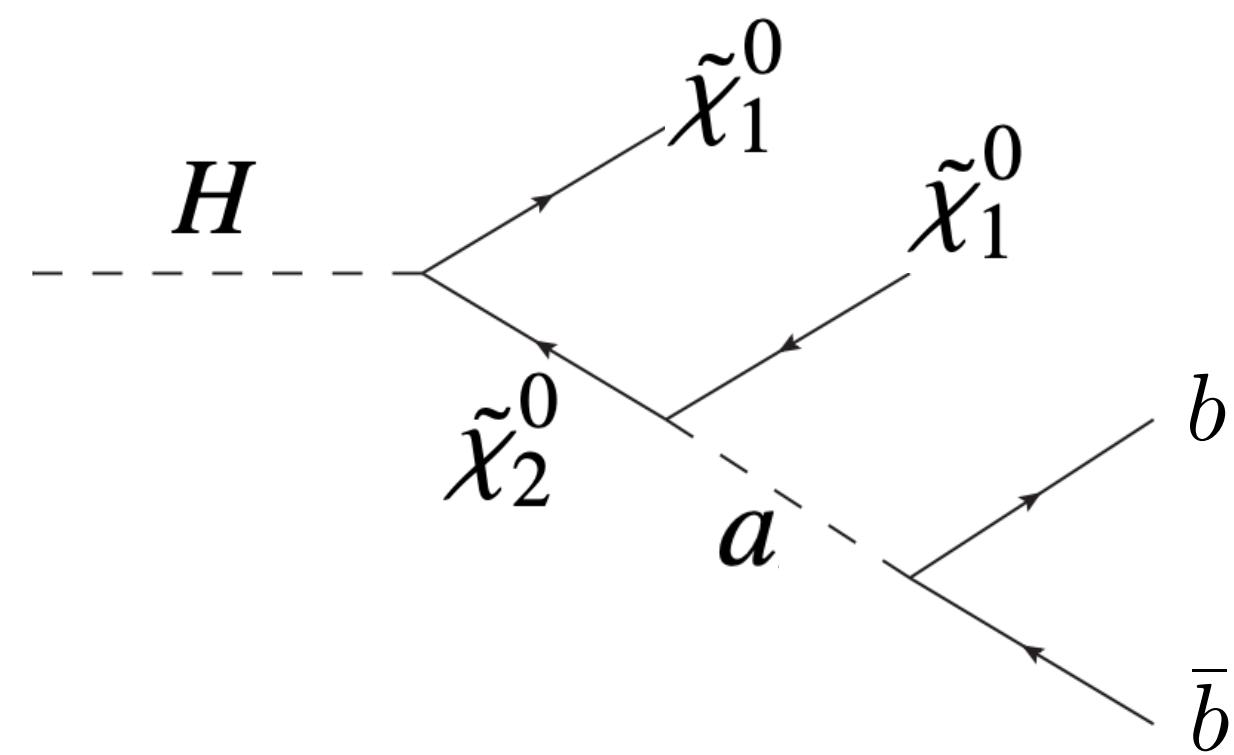
- Current constraints from fits to SM Higgs couplings ([ATLAS-CONF-2021-053](#))
 - $\text{BR}(H \rightarrow \text{invisible}) < 9\%$
 - $\text{BR}(H \rightarrow \text{undetected}) < 16\%$



BSM decays: $H \rightarrow bb + MET$

Analysis targets ZH production with the decay $H \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_1^0 \rightarrow a \tilde{\chi}_1^0 \tilde{\chi}_1^0$ motivated by NMSSM models

- Final state is $Z(l\bar{l})+bb+MET$, with low-mass resonant m_{jj} as the main analysis variable
- Dijet mass templates for main backgrounds ($Z+HF$ and $t\bar{t}$) taken from CRs
- MC correction for the extrapolation of the shape ($Z+HF$ only) and normalization to the SR



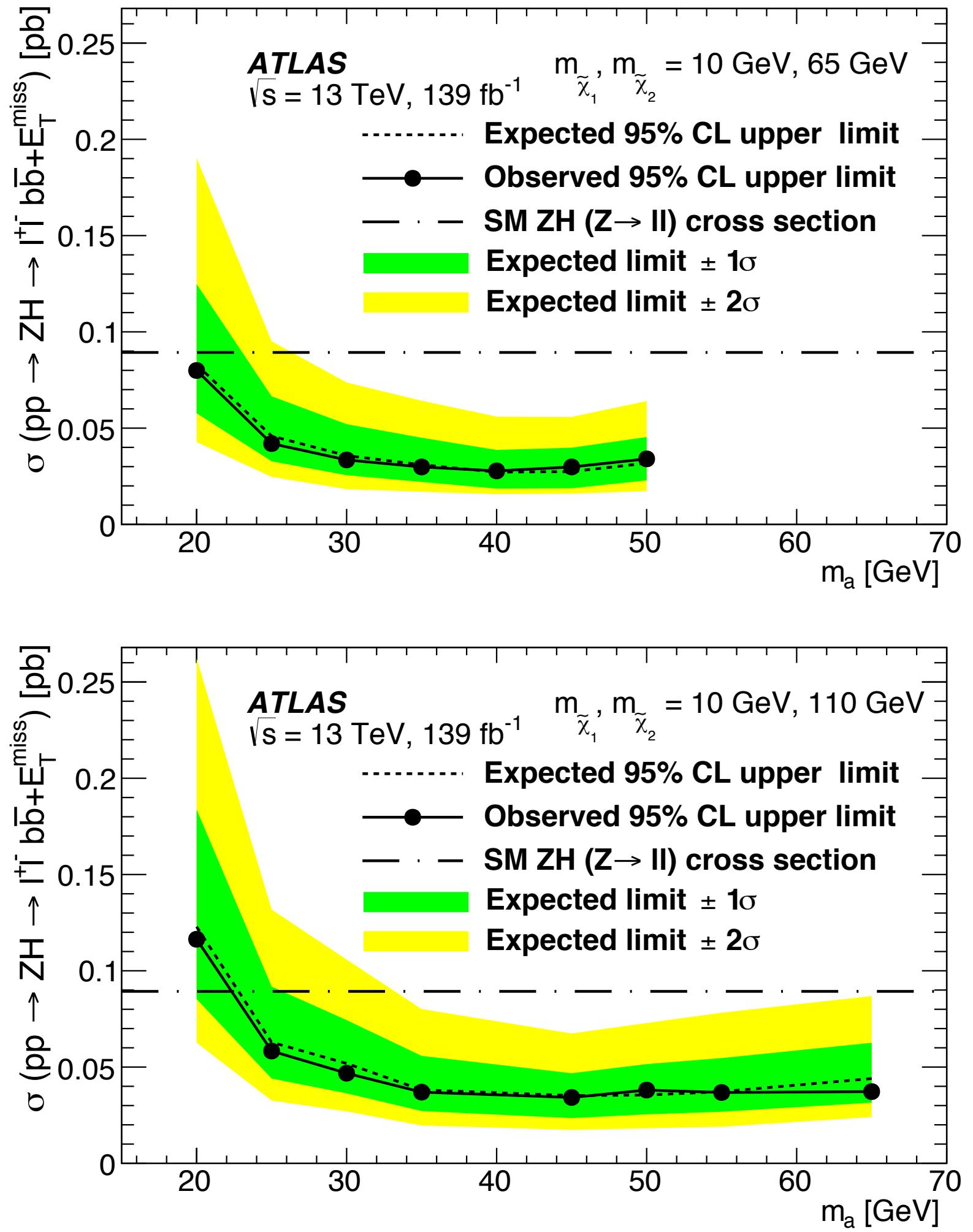
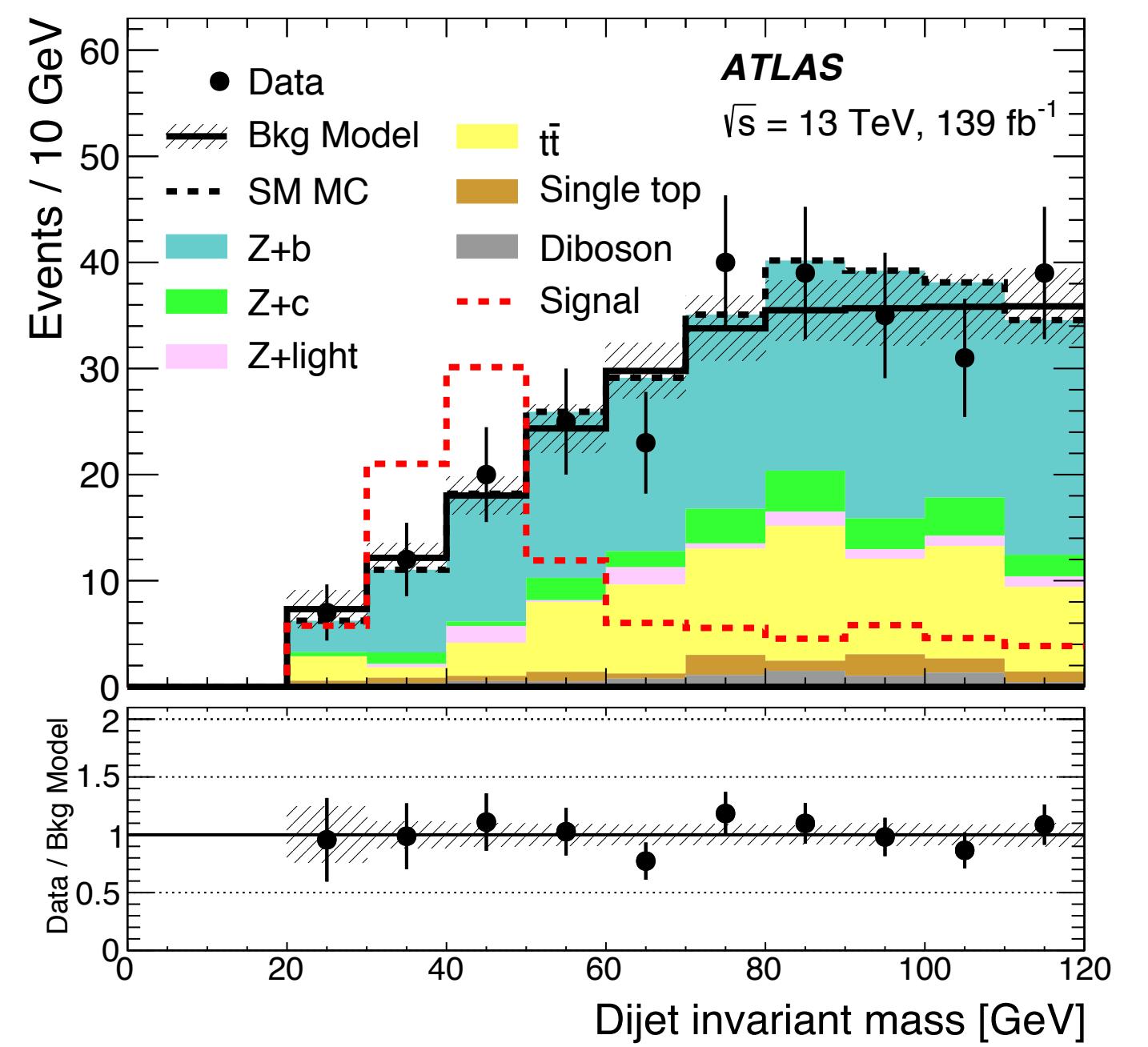
BSM decays: $H \rightarrow b\bar{b} + \text{MET}$

Reduced sensitivity to systematic uncertainties from simulation as MC is mainly used to predict ratios between CRs and SR

- Total background uncertainty < 10% over most of the dijet mass range

No excess, set cross-section limits as a function of m_a for different choices of $m_{\tilde{\chi}_1}, m_{\tilde{\chi}_2}$

- First direct LHC limits on this decay



BR of BSM particles assumed to be 100%

BSM decays: $H \rightarrow XX/ZX \rightarrow 4\ell$

Search for exotic decays of the Higgs boson into four leptons through intermediate scalars or vector bosons, motivated by dark-sector models

Three selections tailored to different kinematic ranges

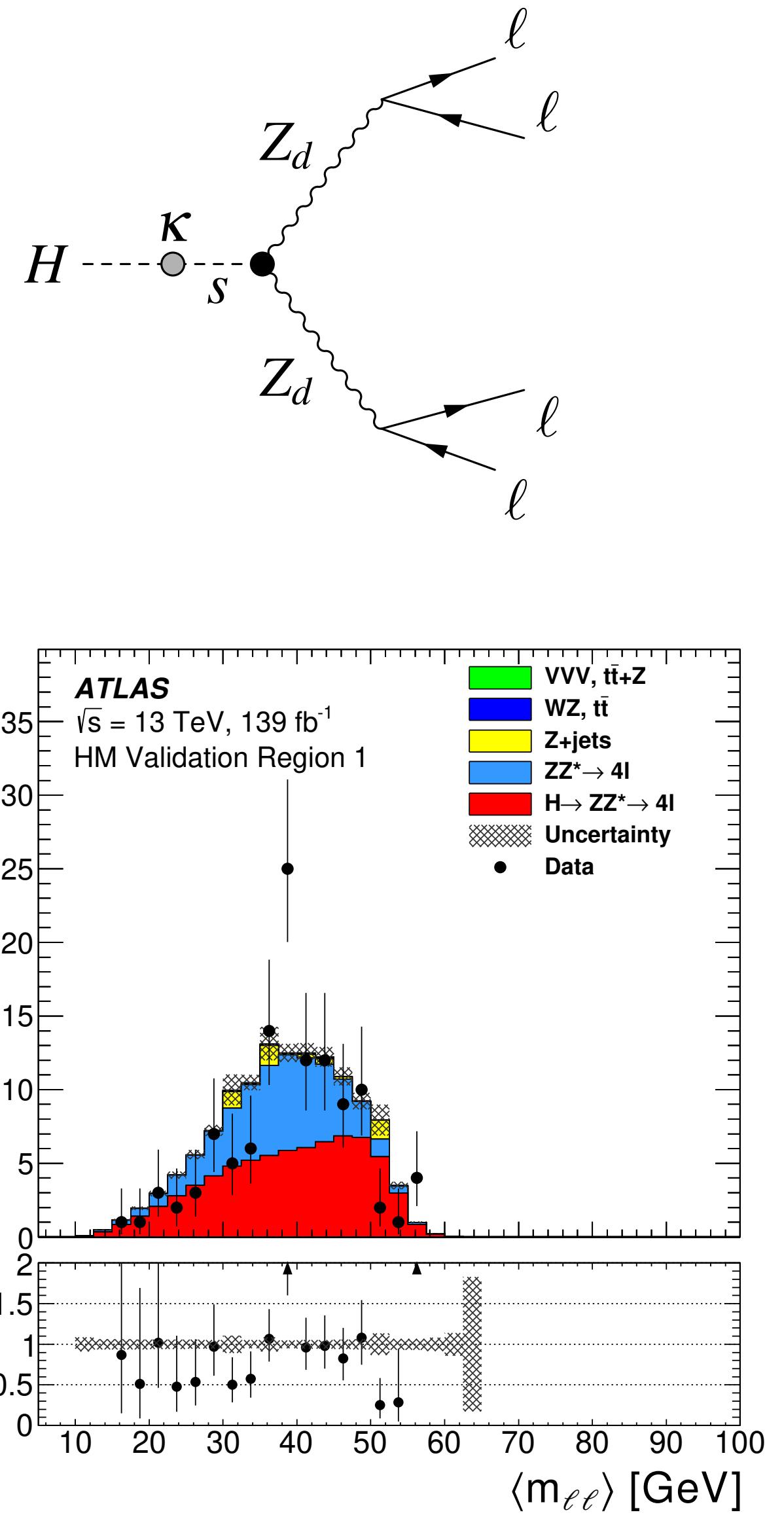
- High-mass (HM): $H \rightarrow XX \rightarrow 4\ell$ ($15 \text{ GeV} < m_X < 60 \text{ GeV}$), search in $\langle m_{\ell\ell} \rangle$
- Low-mass (LM): $H \rightarrow XX \rightarrow 4\mu$ ($1 \text{ GeV} < m_X < 15 \text{ GeV}$), search in $\langle m_{\mu\mu} \rangle$
- Single Z boson (ZX): $H \rightarrow ZX \rightarrow 4\ell$ ($15 \text{ GeV} < m_X < 55 \text{ GeV}$), search in m_{34}

Main backgrounds are estimated from simulation

- HM and ZX: $H \rightarrow 4\ell$ (~70%), diboson $\rightarrow 4\ell$ (~25%)
- LM: ZZ^* and muons from heavy-flavour jets decays (~30%)

Multiple validation regions defined inverting one or more of the selection cuts

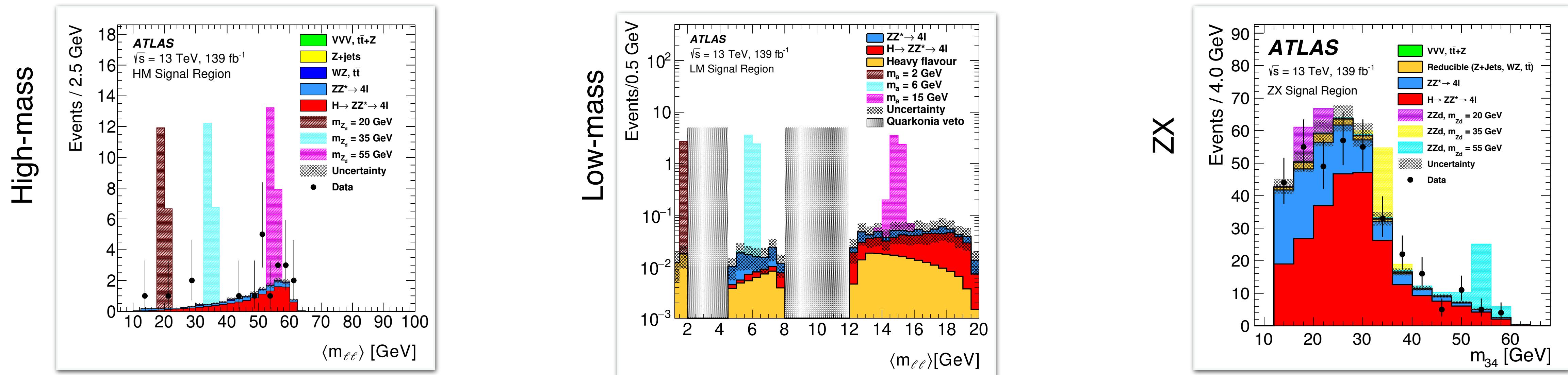
- Very good agreement across all validation regions



BSM decays: $H \rightarrow XX/ZX \rightarrow 4\ell$

No significant excess observed, largest deviation in HM $\langle m_{\ell\ell} \rangle \approx 28$ GeV, with local significance of 2.5σ

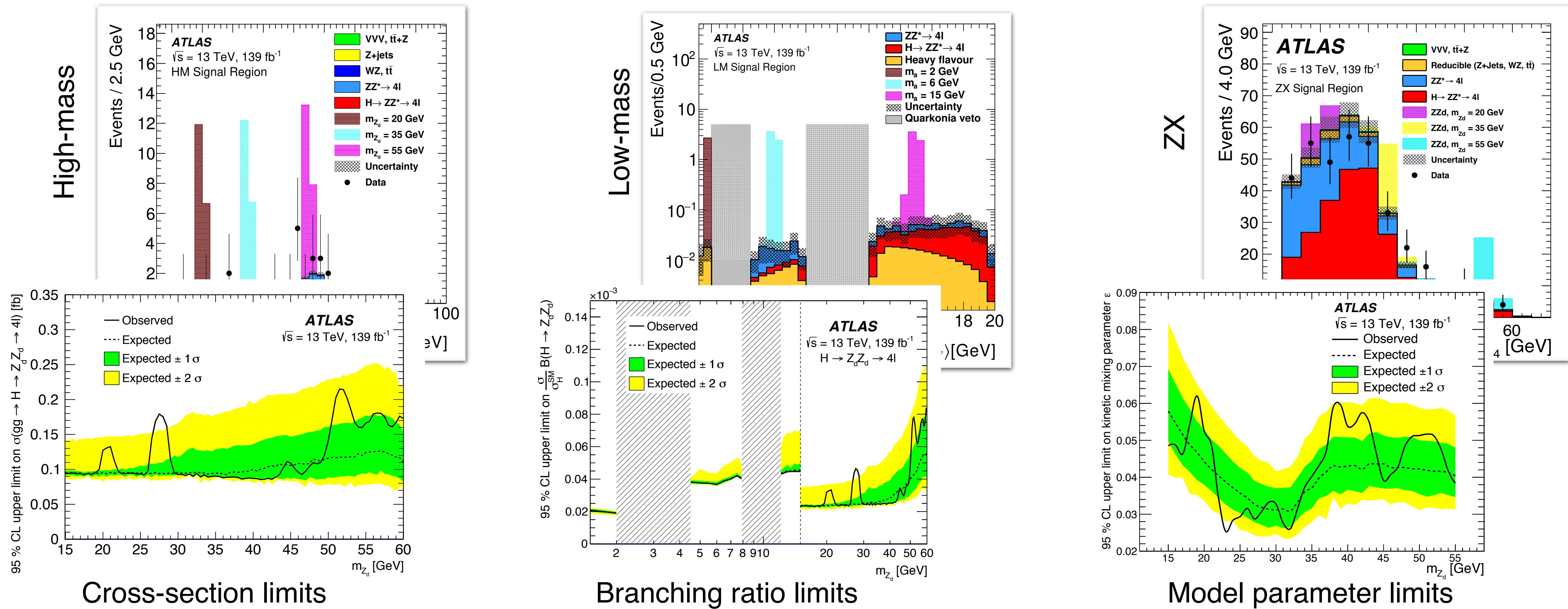
- Set limits on allowed signal cross-section, fiducial cross-section, Higgs branching ratios, and/or model parameters



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- Set limits on allowed signal cross-section, fiducial cross-section, Higgs branching ratios, and/or model parameters



BSM decays: $H \rightarrow aa \rightarrow 2\mu 2b$

Search for Higgs decays via intermediate pseudo-scalars to a final state with two b-jets and two muon

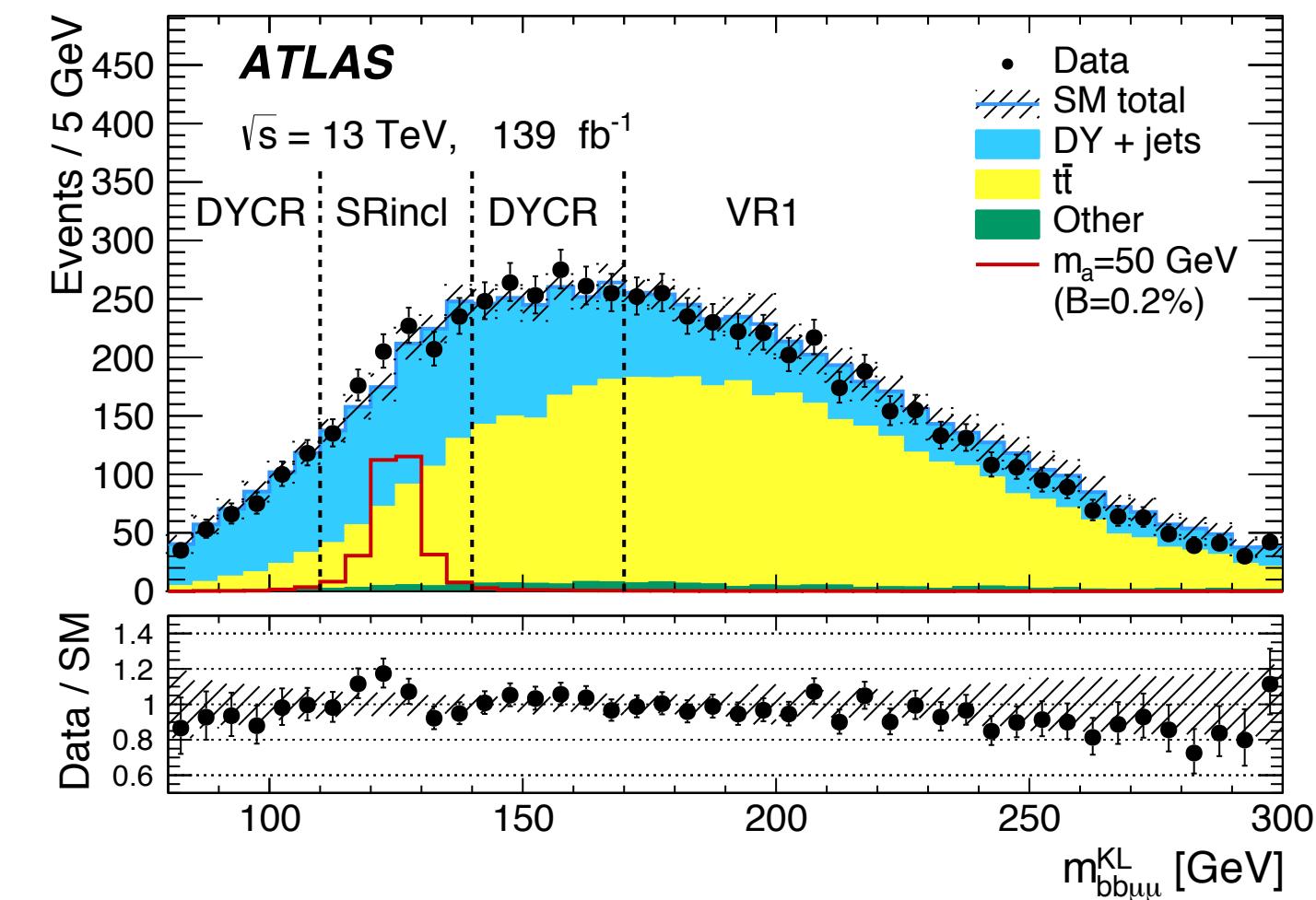
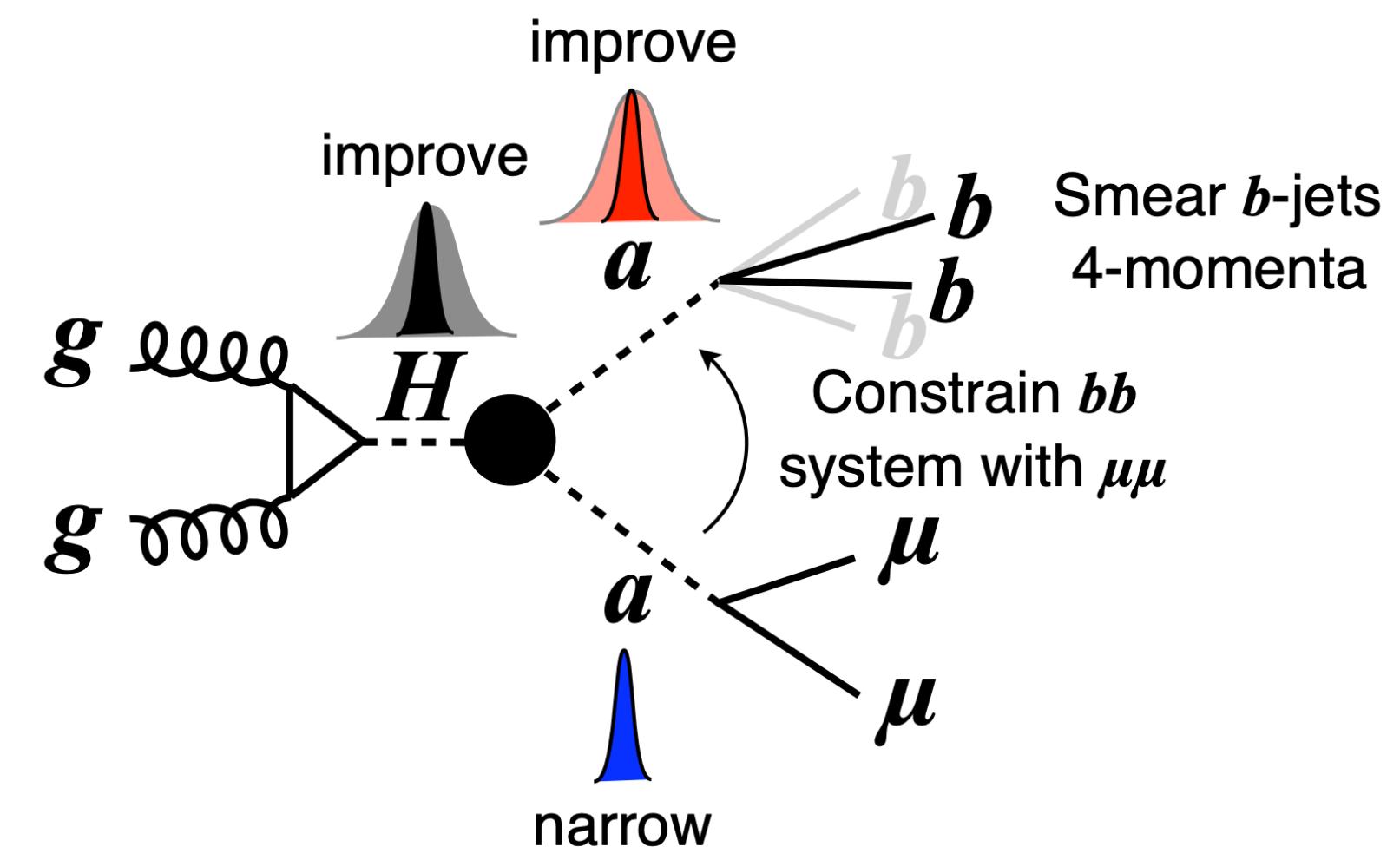
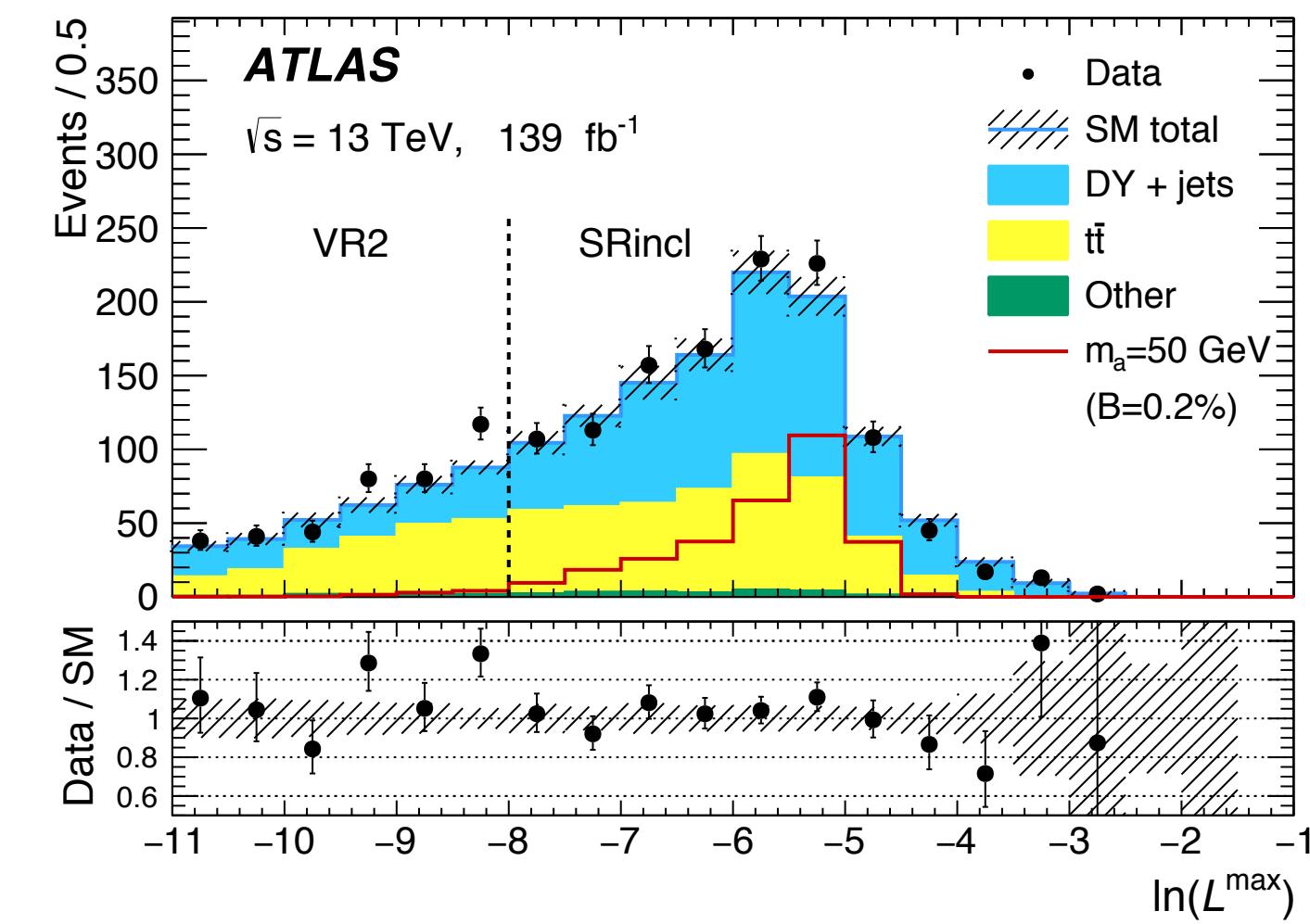
- Good balance between large $\text{BR}(a \rightarrow bb)$ and clean signature from $a \rightarrow \mu\mu$

Exploit the great resolution of $m_{\mu\mu}$ to improve m_{bb} via a kinematic likelihood fit

- Shift the b-jet energies within the resolution to maximize the likelihood
- Cut on the kinematic likelihood fit score (L^{\max}) to select $m_{\mu\mu} \sim m_{bb}$ events

Selection:

- $\ln(L^{\max}) > -8$
- $110 < m_{\mu\mu bb} < 140 \text{ GeV}$
- $E_T^{\text{miss}} < 60 \text{ GeV}$



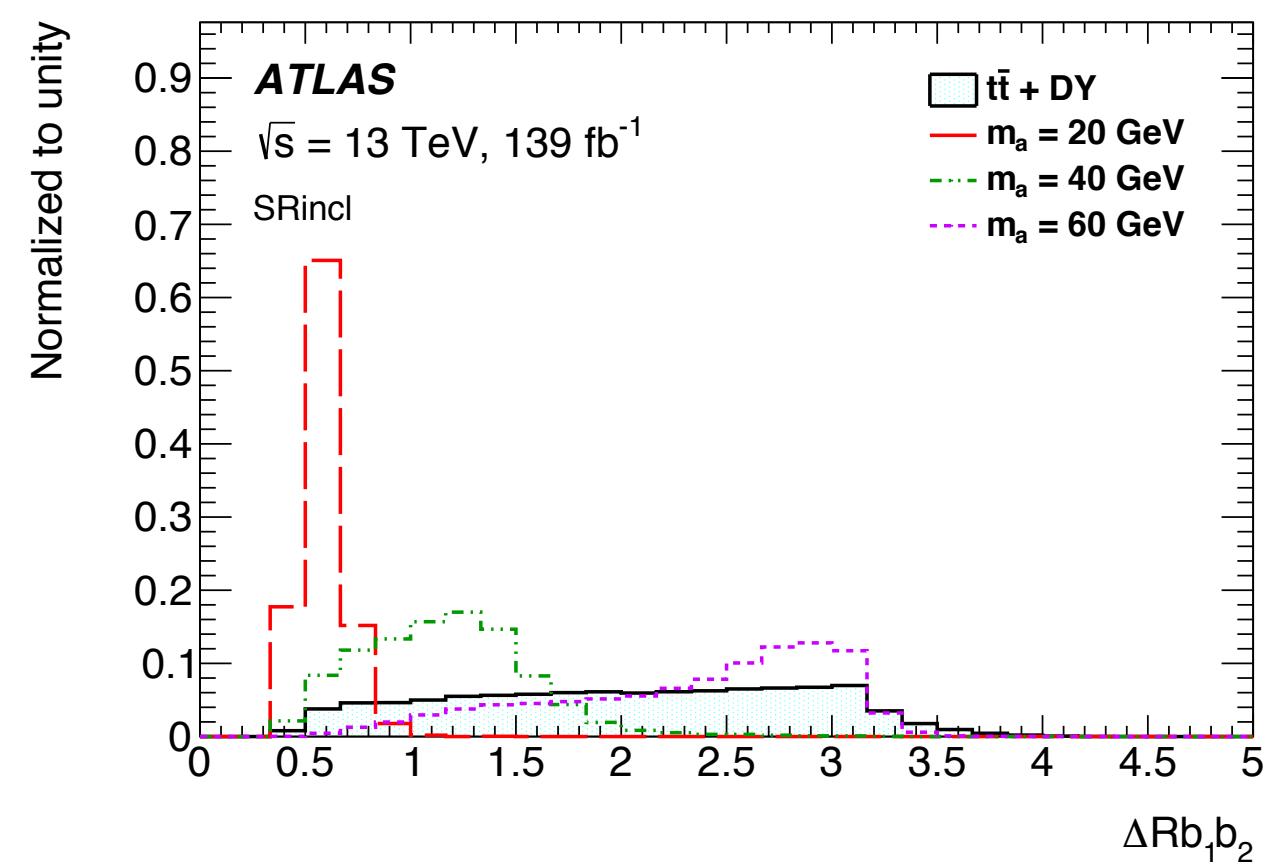
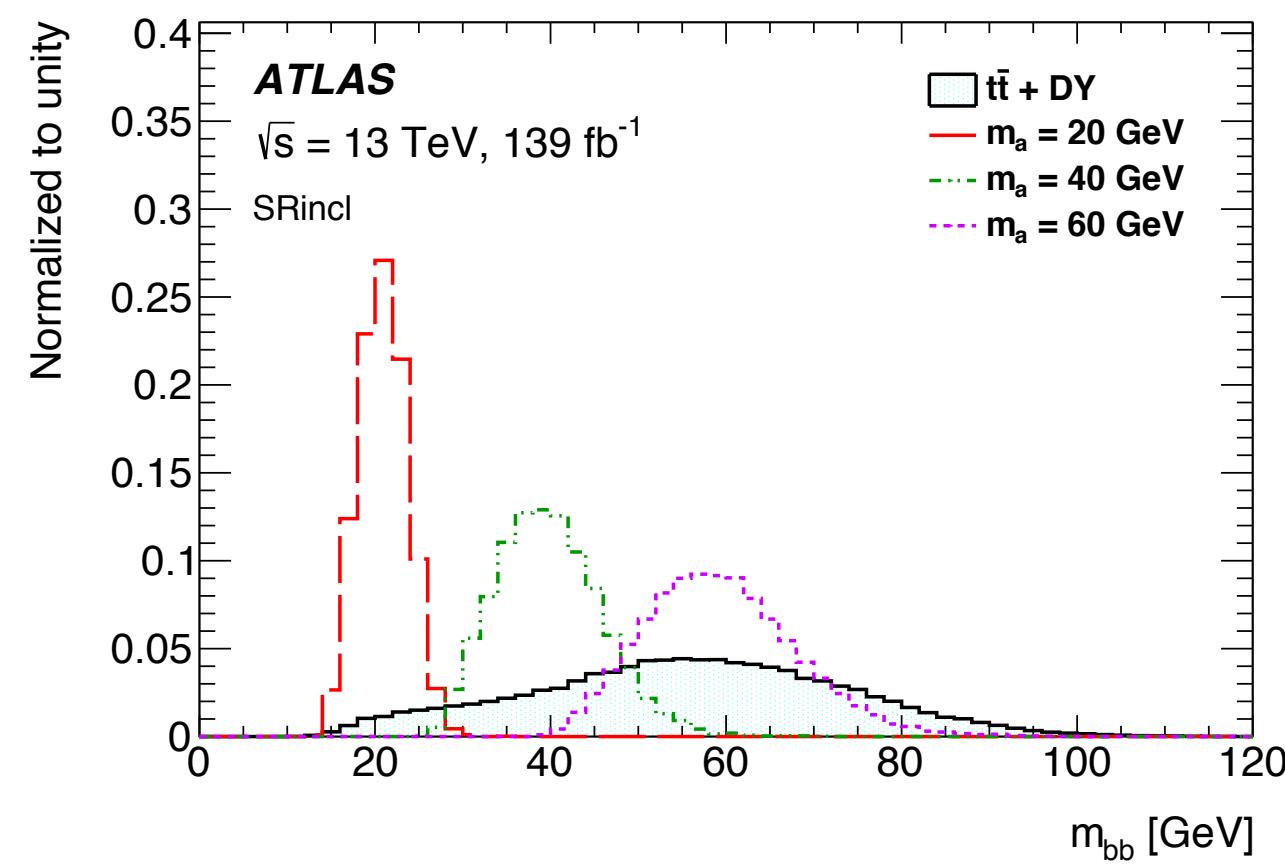
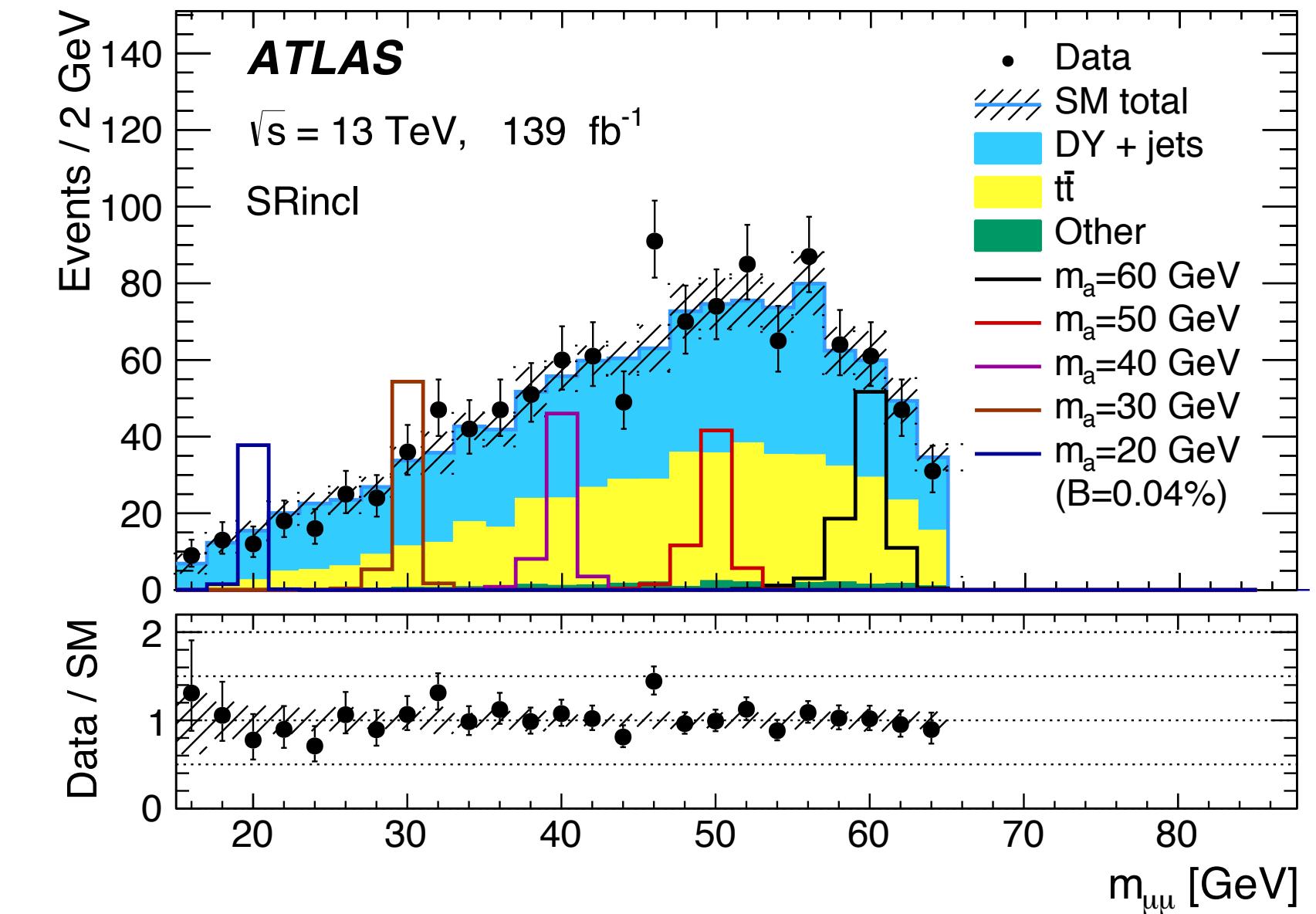
BSM decays: $H \rightarrow aa \rightarrow 2\mu 2b$

Narrow resonance searched for in the $m_{\mu\mu}$ spectrum in the range $16 \text{ GeV} < m_{\mu\mu} < 62 \text{ GeV}$, in bins defined as $(m_a \pm X) \text{ GeV}$:

- $X=1 \text{ GeV}$ for $m_a \leq 45 \text{ GeV}$
- $X=1.5 \text{ GeV}$ for $m_a > 45 \text{ GeV}$

Train BDTs to separate the signal from the DY and ttbar backgrounds

- 12 BDTs trained in 8 GeV wide $m_{\mu\mu}$ windows, to exploit m_a kinematic dependence

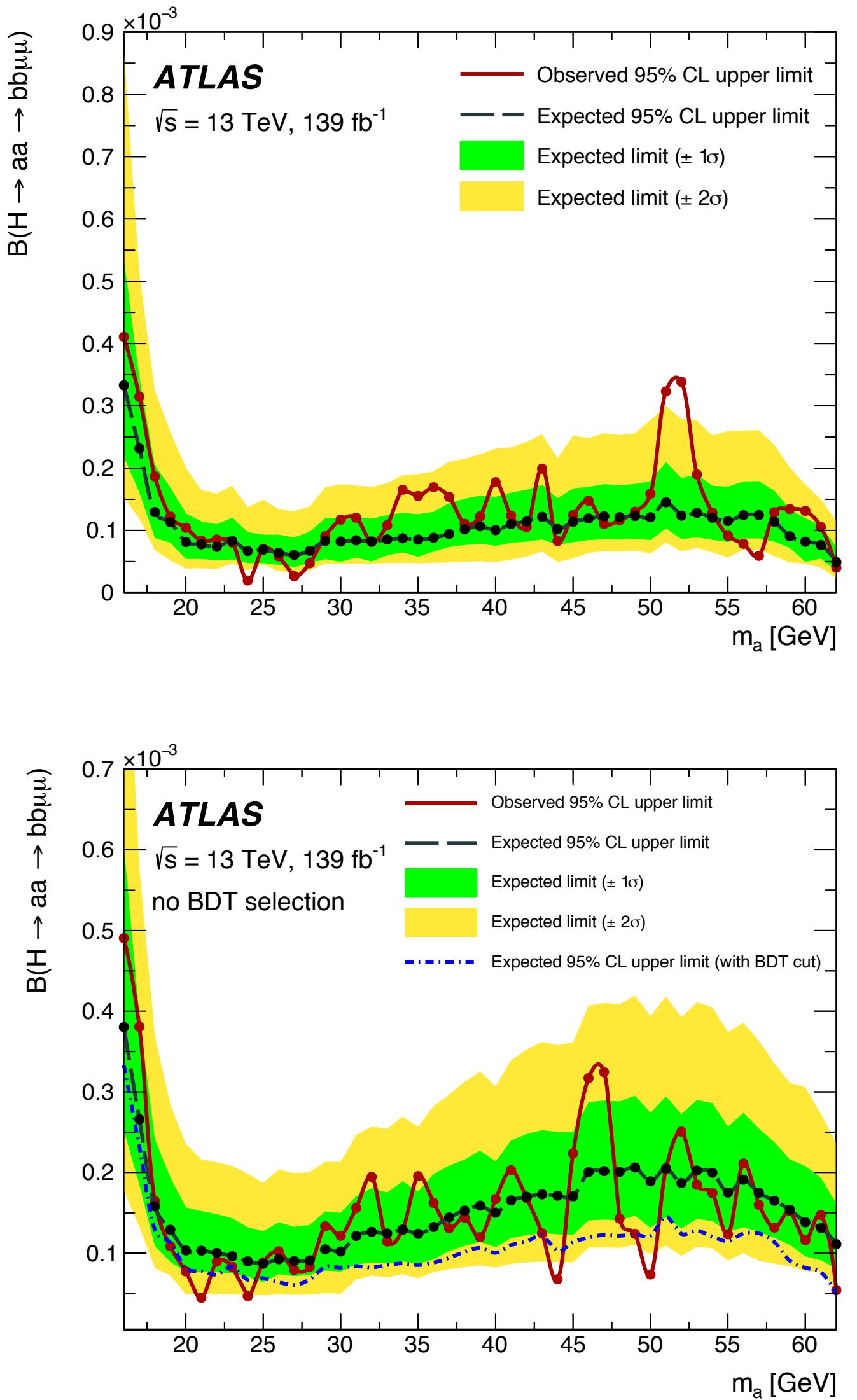
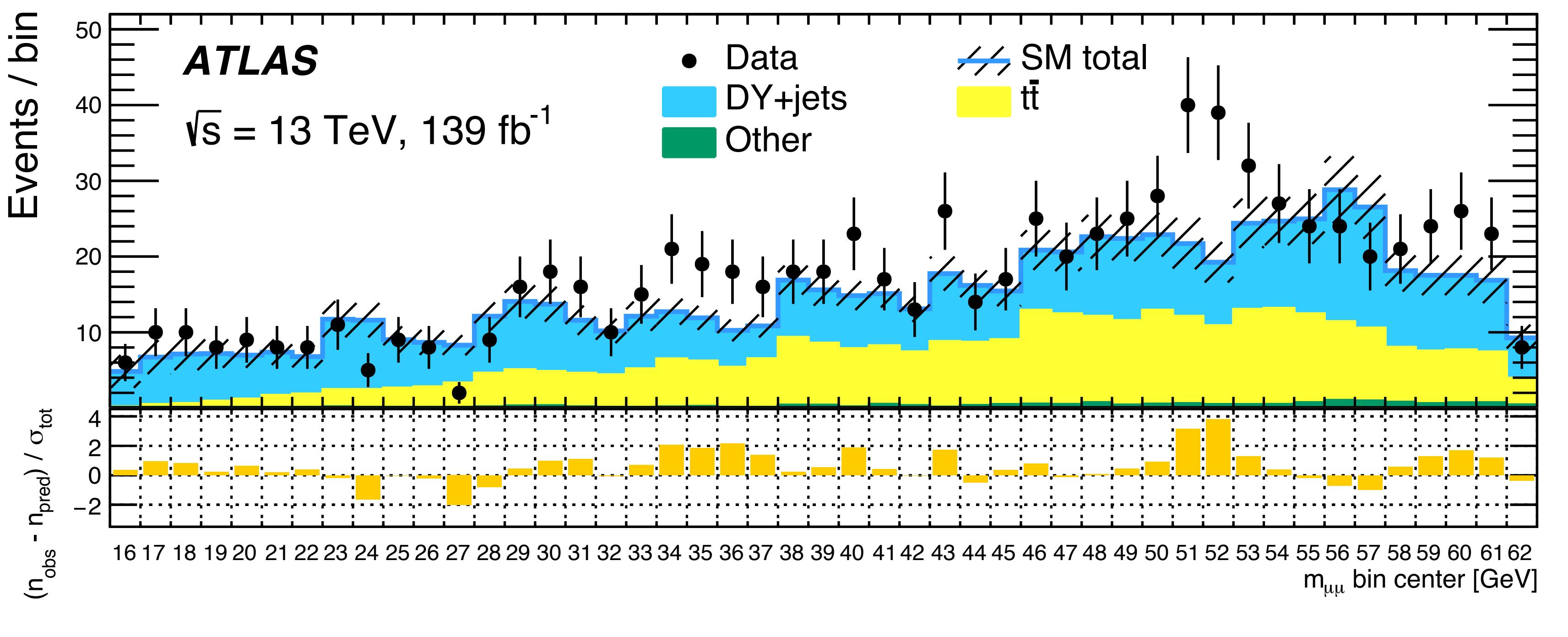


BSM decays: $H \rightarrow aa \rightarrow 2\mu 2b$

Excess of 3.3σ (1.7σ) local (global) observed at $m_a=52$ GeV

- Results also provided without the BDT cut, no significant excess

Around 40% improvement in excluded BR from the BDT selection



LFV decays: $H \rightarrow e\mu$

Search for the lepton-flavour-violating decay $H \rightarrow e\mu$ (and $H \rightarrow ee$)

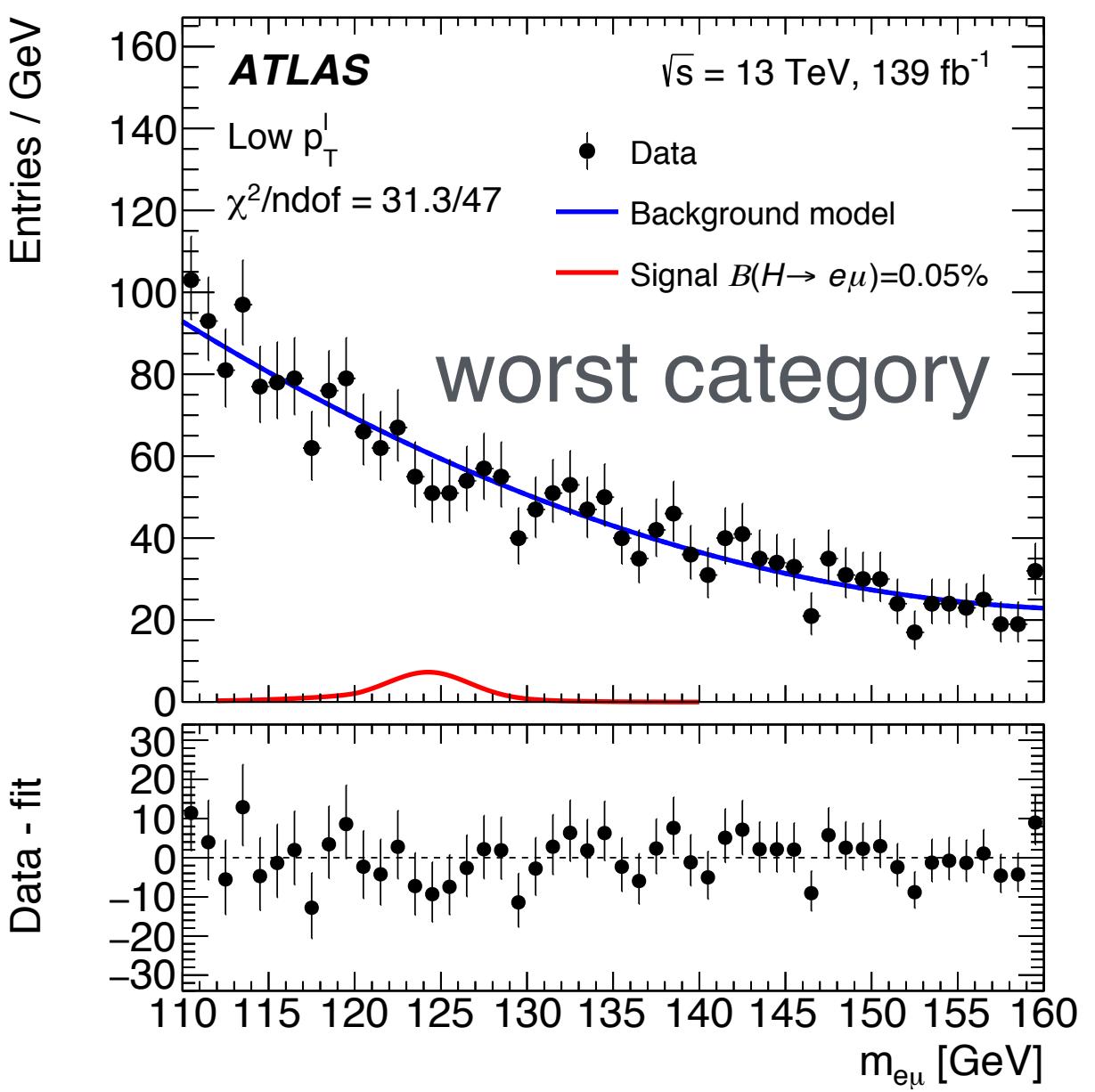
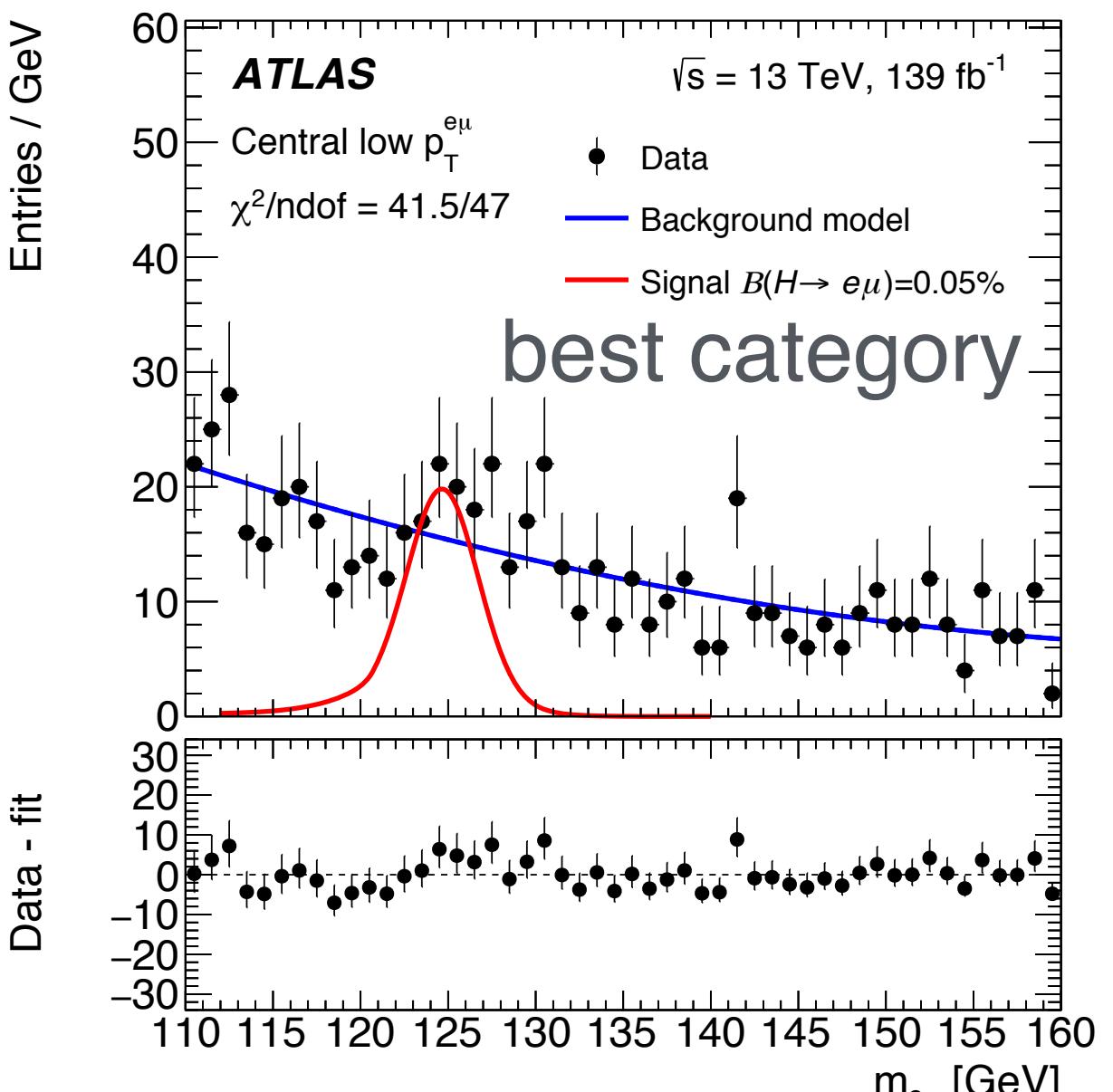
- Renewed interest in LFV in light of the recent flavour anomalies

Events are split into eight categories with different S/B ratios

- low p_T lepton, VBF, and central/non-central \times [low,mid,high] $p_T(\text{II})$

Signal and backgrounds are determined with analytic functions

- signal: crystal ball + gaussian, parameters fitted from simulation
- background: Bernstein polynomial of second degree, constrained by the sidebands



LFV decays: $H \rightarrow e\mu$

No significant excess, the observed (expected) upper limit on the branching fraction is found to be:

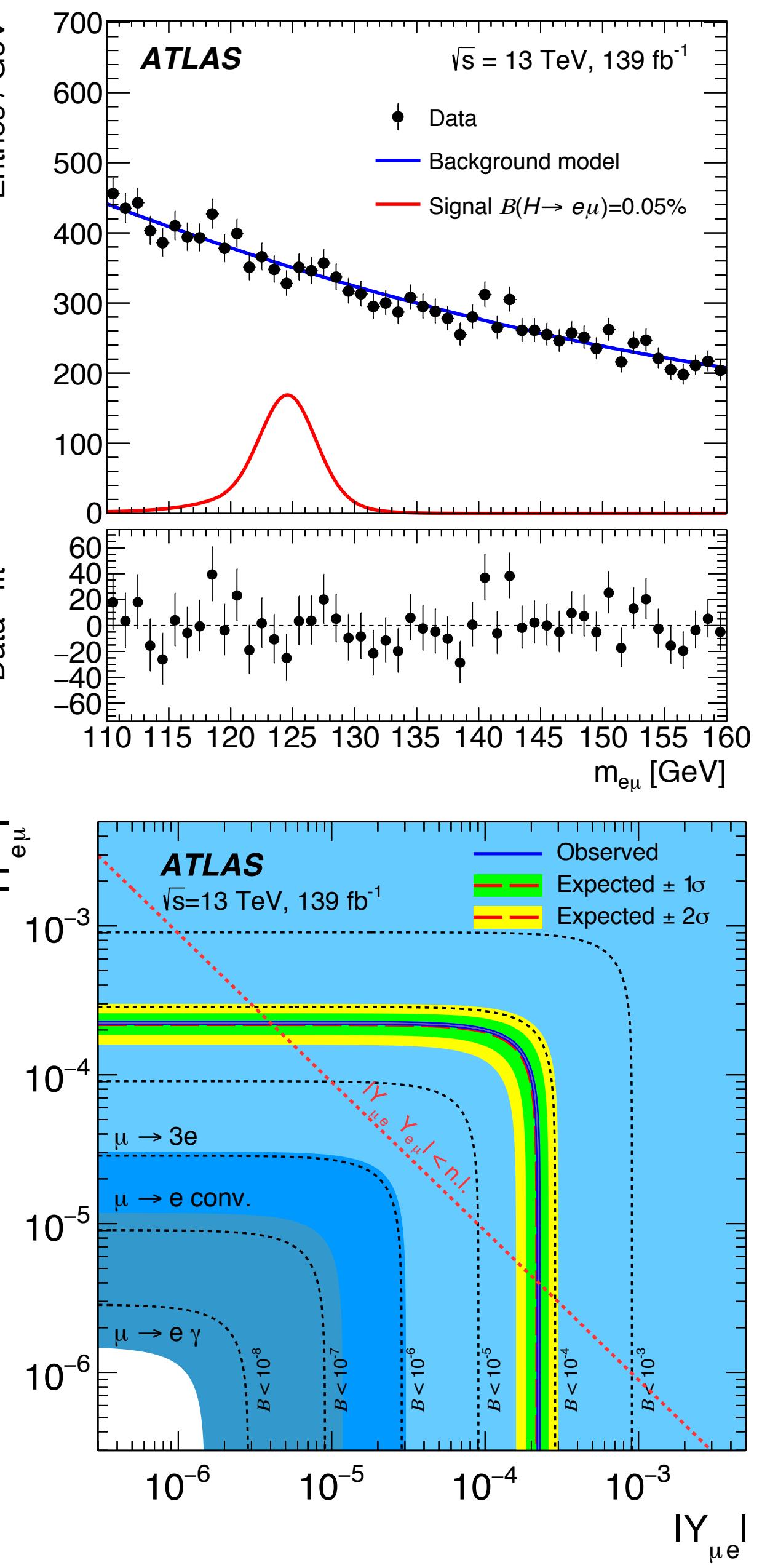
- $\text{BR}(H \rightarrow e\mu) < 6.2 \times 10^{-5} (5.9 \times 10^{-5})$
- First ATLAS result on this decay

Limits on the branching ratio can be translated into constraints on the flavour violating Yukawa couplings $Y_{e\mu}$ and $Y_{\mu e}$:

- $|Y_{e\mu}|^2 + |Y_{\mu e}|^2 = 8\pi\Gamma_H^{\text{SM}}/m_H \cdot B(H \rightarrow e\mu)/(1 - B(H \rightarrow e\mu))$
- Indirect constraints from muon decays are stronger but assume SM values for the Y_{ee} and $Y_{\mu\mu}$ Yukawa couplings

Also searches for $H \rightarrow e\tau/\mu\tau$ with 36 fb^{-1} ([paper](#)):

- $\text{BR}(H \rightarrow e\tau) < 0.47\%$
- $\text{BR}(H \rightarrow \mu\tau) < 0.28\%$



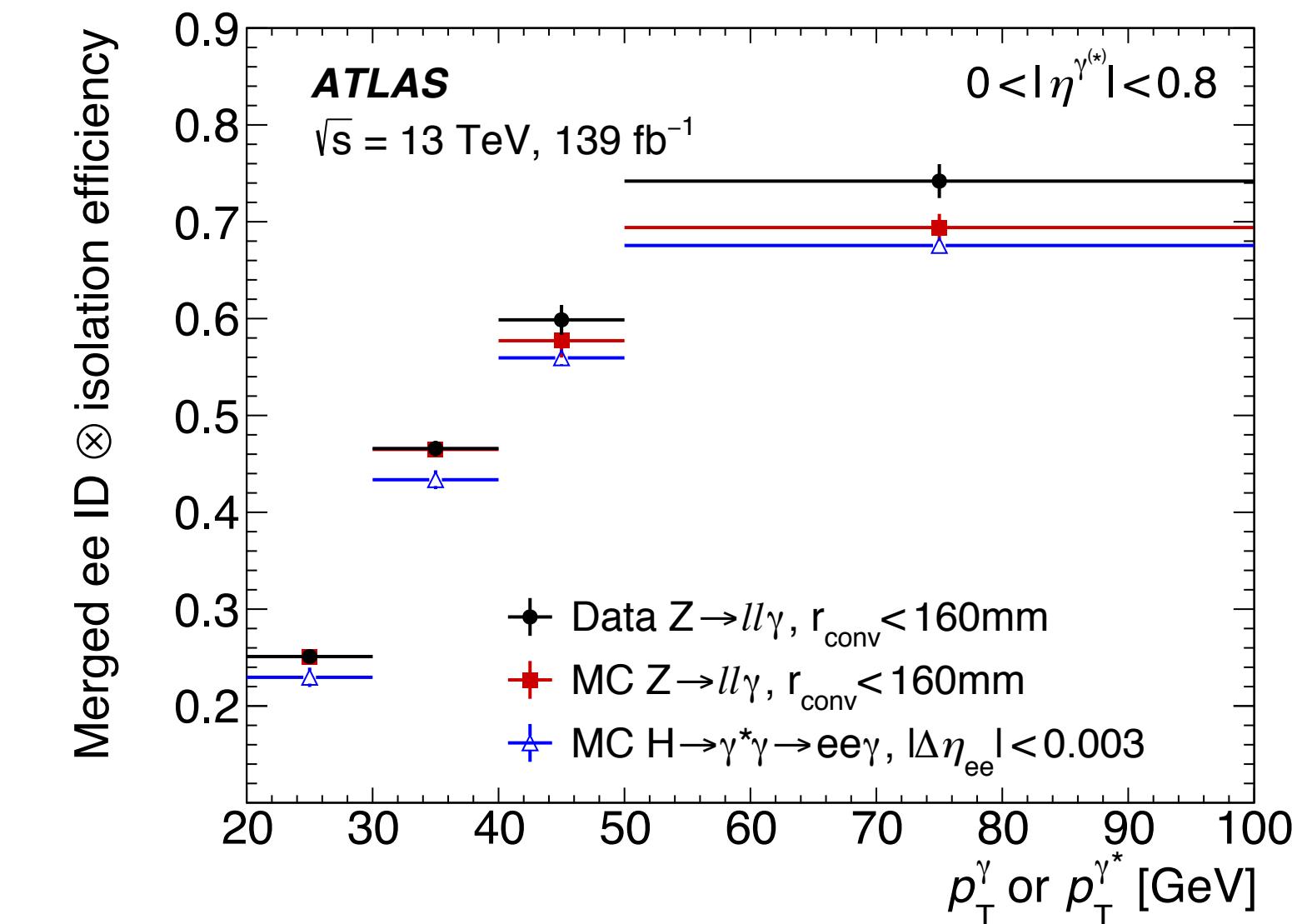
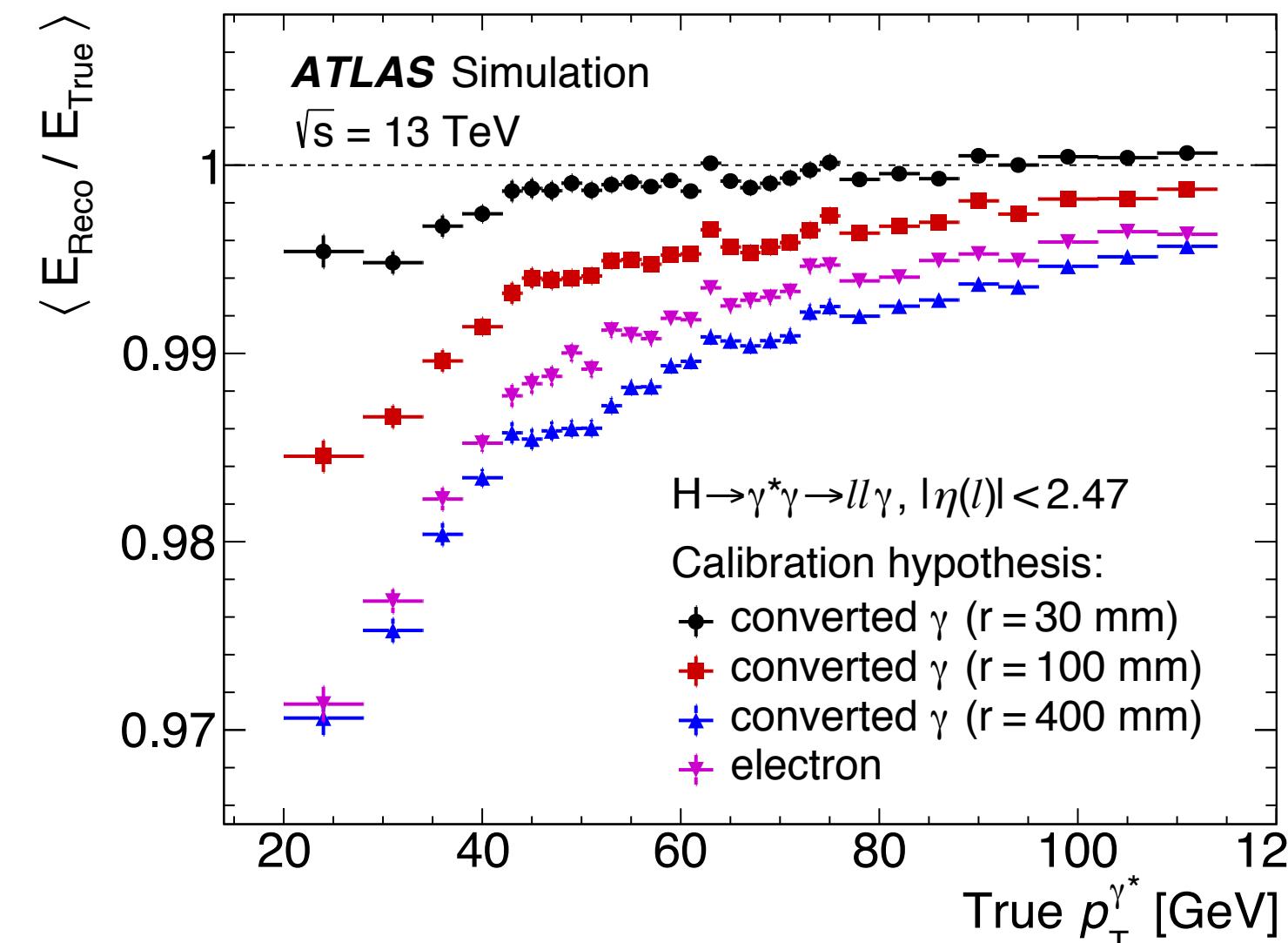
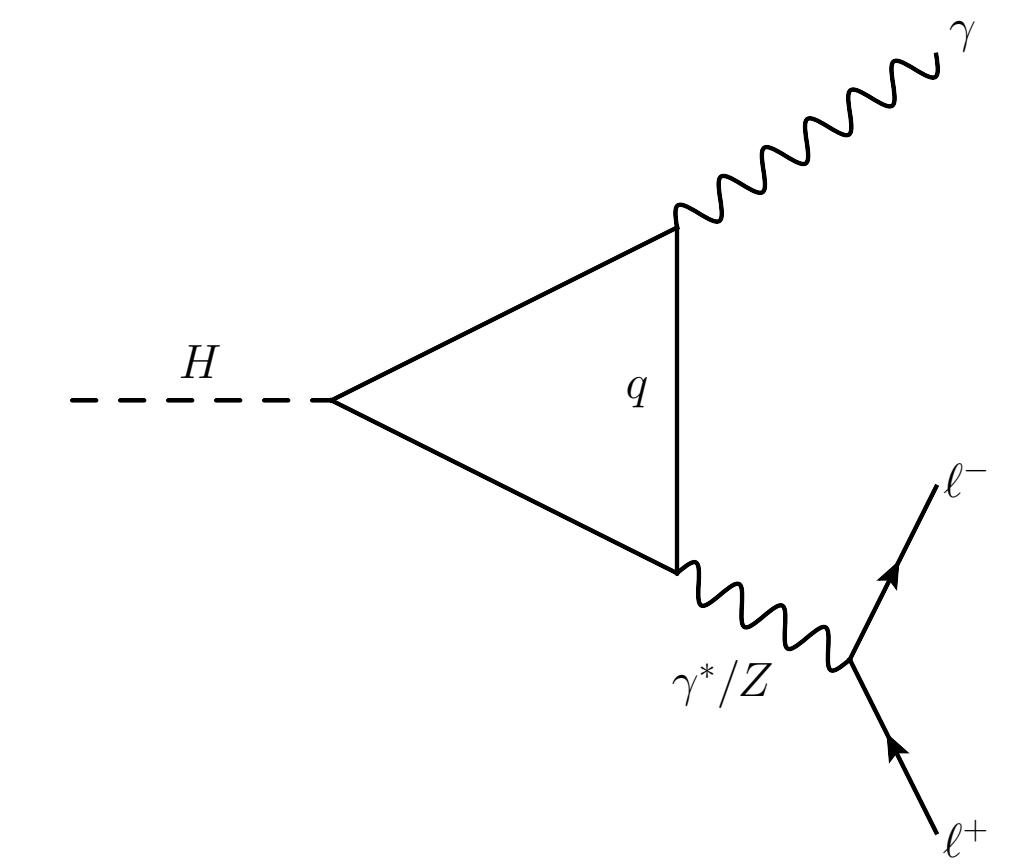
Rare decays: $H \rightarrow \ell\ell\gamma$

Search for $H \rightarrow \ell\ell\gamma$ with dilepton mass < 30 GeV

- Boosted e^+e^- pairs produce overlapping showers in the electromagnetic calorimeter
- Dedicated reconstruction to recover merged electrons with one cluster and two tracks
- Dedicated trigger to recover inefficiency

Events are split into nine categories with different S/B ratios

- $[\mu\mu, ee \text{ resolved}, ee \text{ merged}] \times [\text{VBF enriched}, \text{high } p_{Tt}, \text{low } p_{Tt}]$

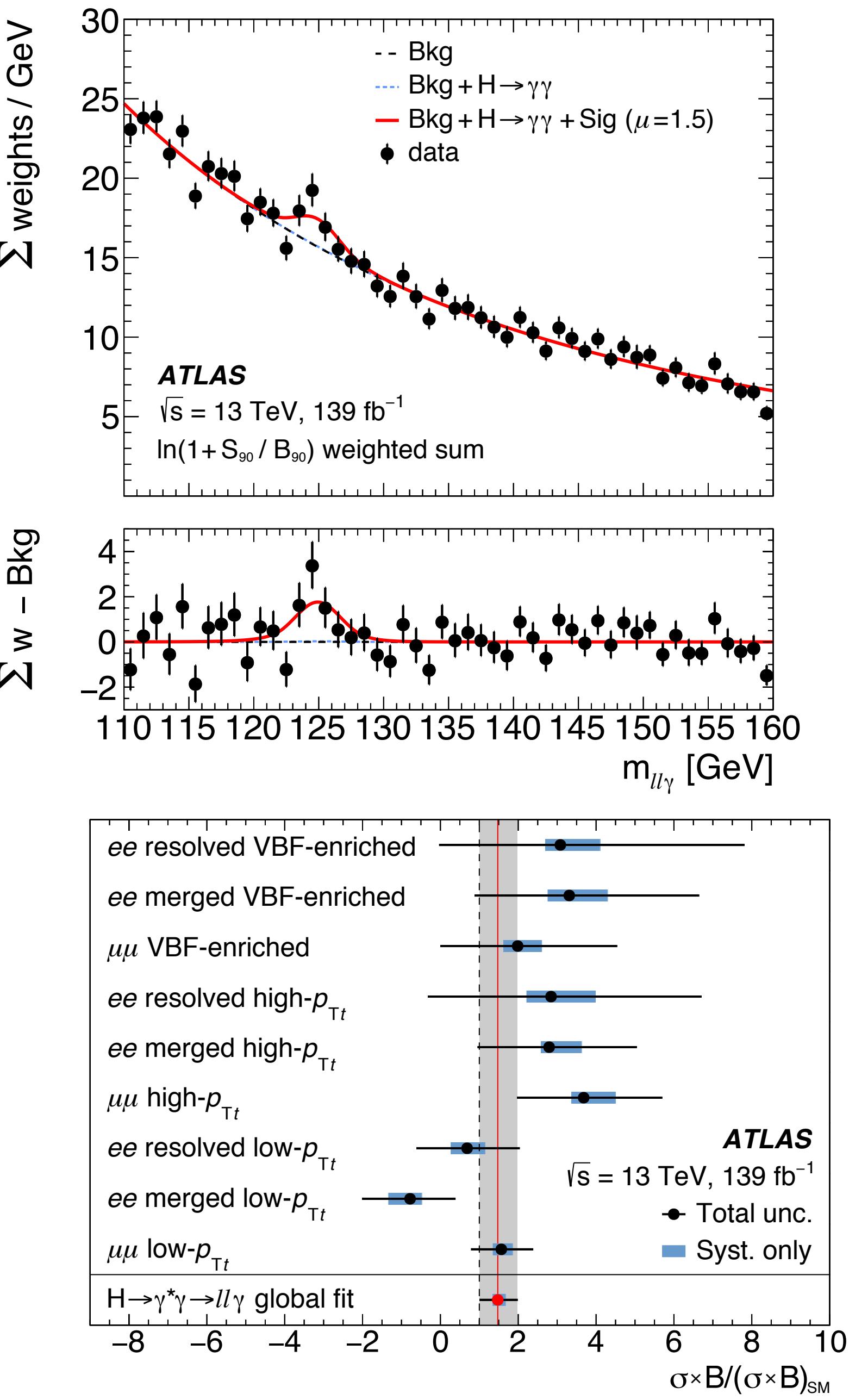


p_{Tt} strongly correlated to transverse momentum of $\ell\ell\gamma$ system. See backup

Rare decays: $H \rightarrow \ell\ell\gamma$

Unbinned likelihood fit to the 9 categories

- Best-fit value of the signal-strength parameter is
 $\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5$ (stat.) $+0.2 -0.1$ (syst.)
- The observed (expected) significance over the background-only hypothesis for a Higgs boson with a mass of 125.09 GeV is 3.2σ (2.1σ)
- **First evidence for decay to low mass $\ell\ell$ +photon**
- The Higgs boson production cross-section times the $H \rightarrow \ell\ell\gamma$ branching ratio for $m_{\ell\ell} < 30$ GeV is in agreement with the SM prediction:
 $\sigma = 8.7 \pm 2.7$ (stat.) $+0.7 -0.6$ (syst.) fb



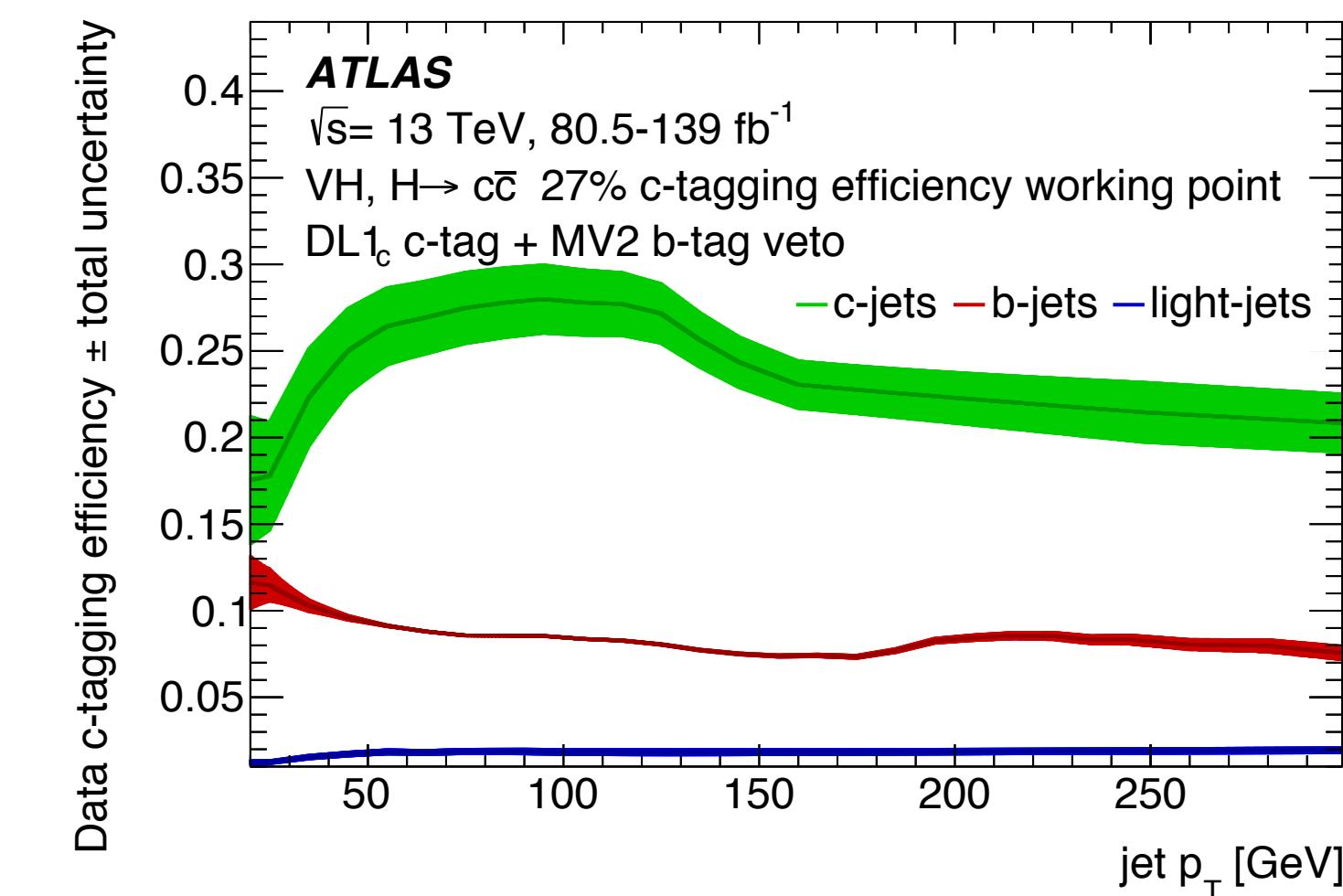
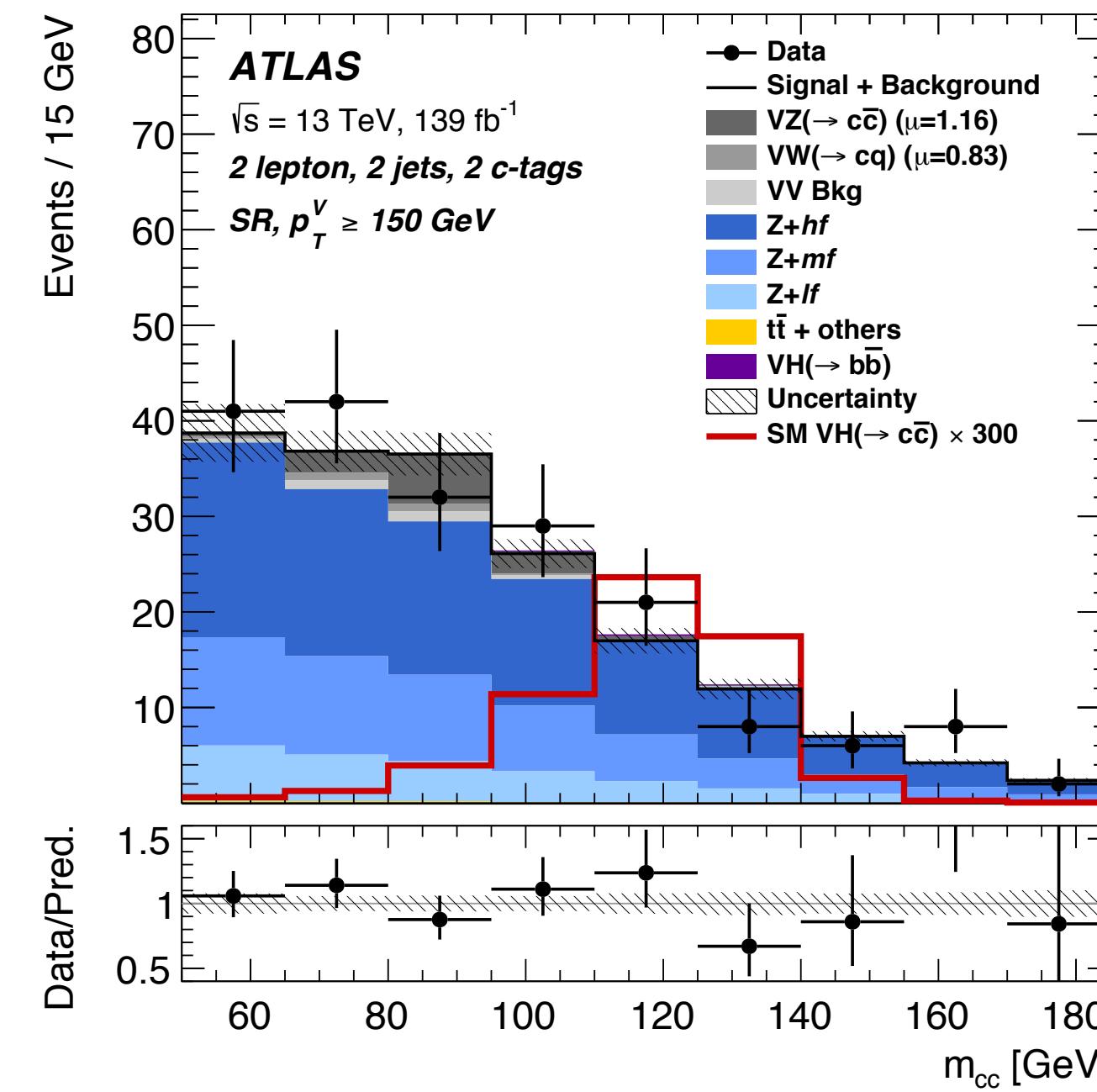
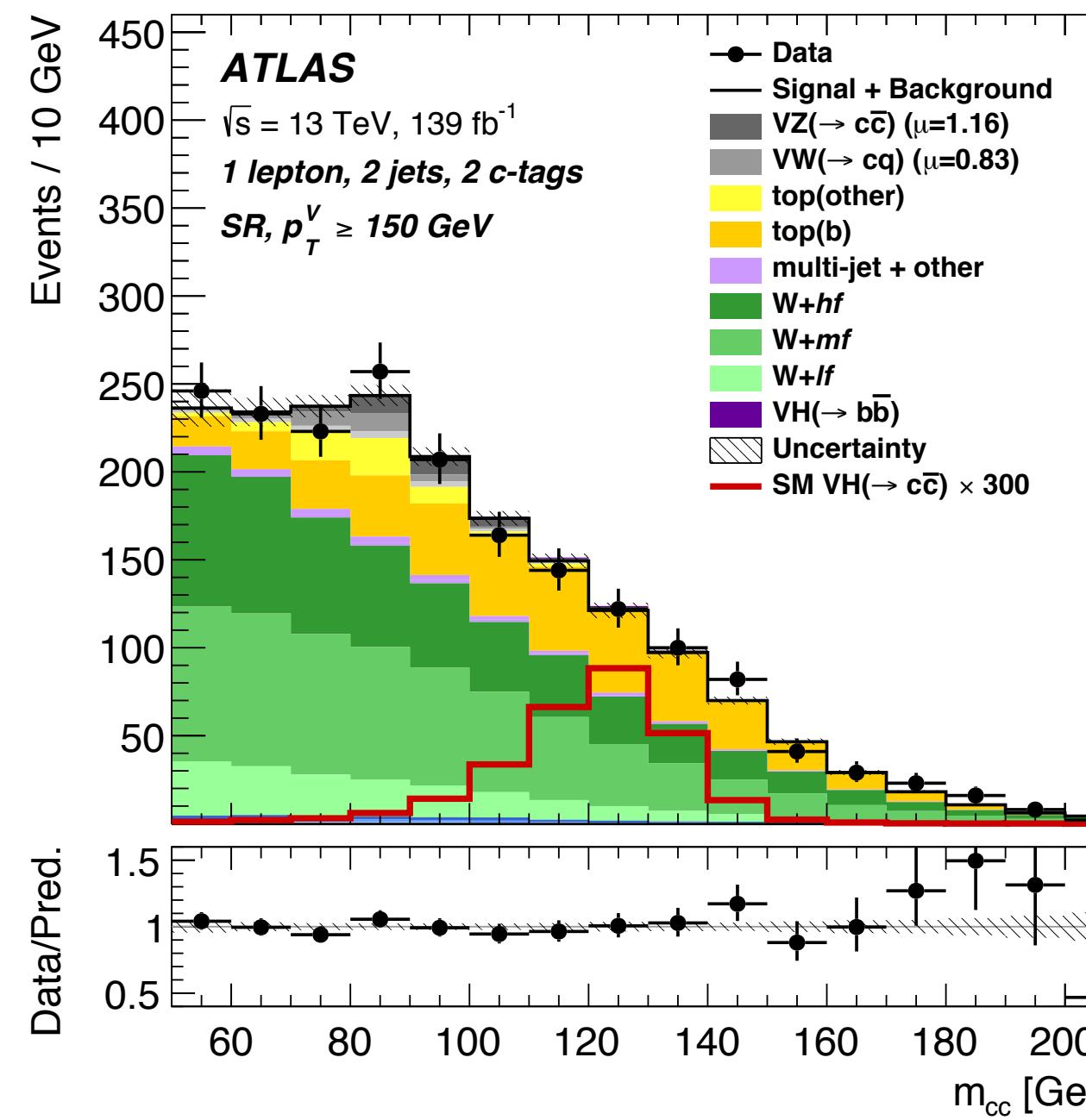
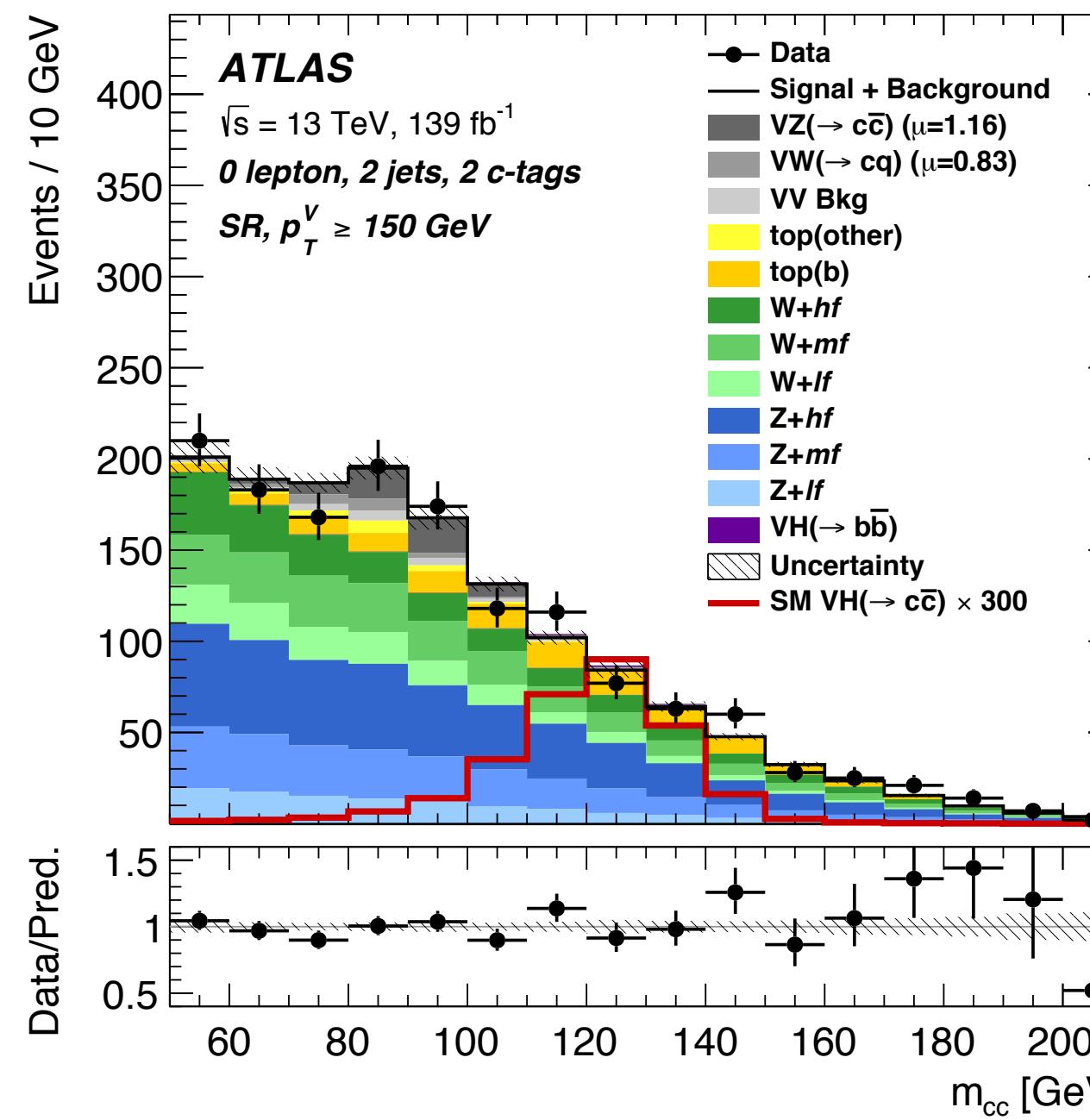
Rare decays: $H \rightarrow cc$

Extremely difficult final state with small BR ($\sim 3\%$)

- Exploit VH production to trigger and suppress QCD background, use 0/1/2-lepton categories

Crucial dependence on c-jet identification, which is experimentally challenging

- Customised jet tagger configuration with an average efficiency of 27% to tag c-jets, and b- and light-jet misidentification rates of 8% and 1.6%, respectively.



Rare decays: $H \rightarrow cc$

Events split into 16 categories:

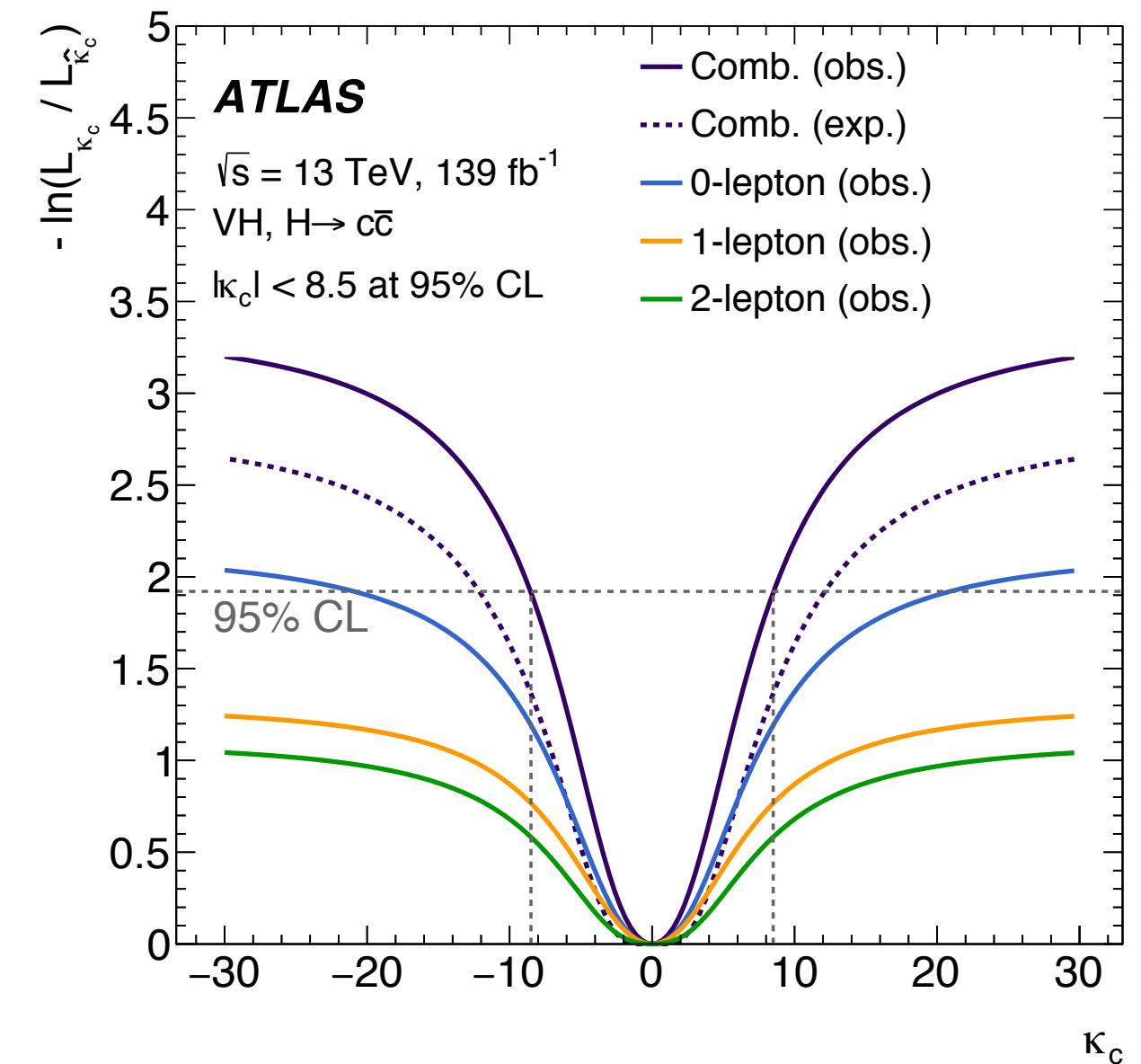
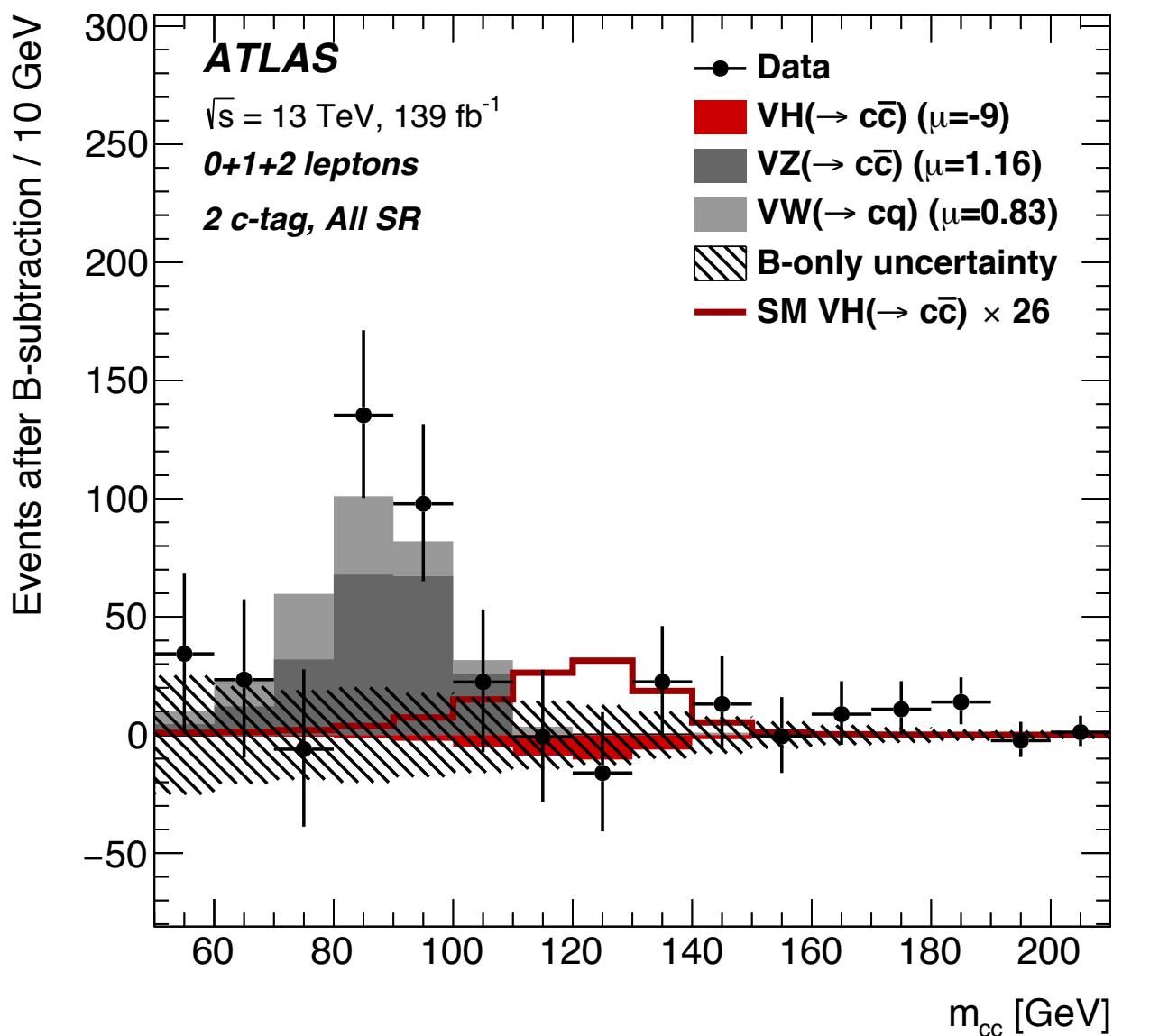
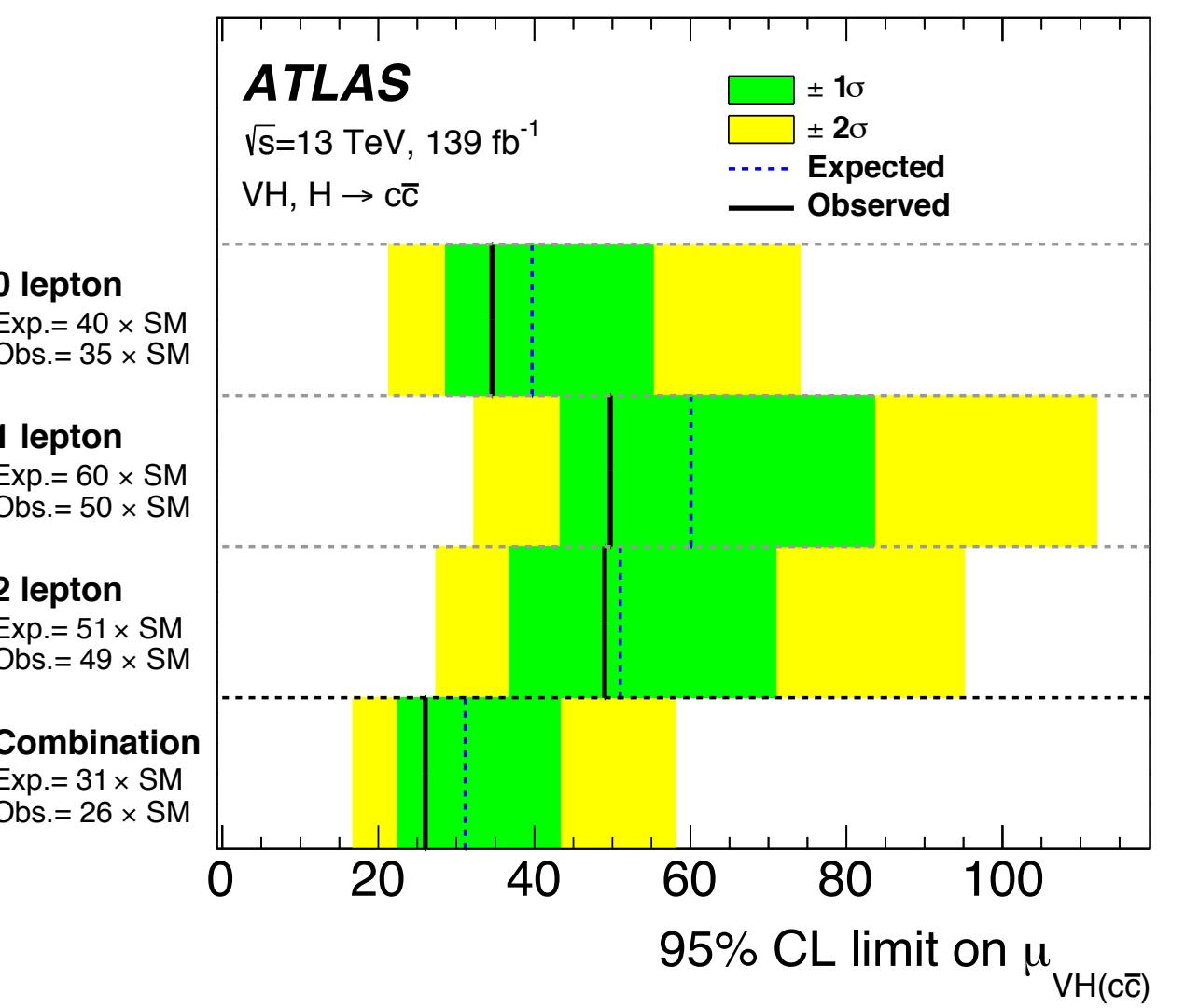
- [0, 1, 2 low- $p_T V$, 2 high- $p_T V$] leptons \times [1, 2] c-jets \times [2, 3] jets
- 28 additional control regions defined to improve $V+jets$ and $t\bar{t}$ modeling

Likelihood fit to the m_{cc} variable in all categories

- Simultaneous extraction of the $VZ(cc)$, $VW(cq)$ backgrounds, and the $VH(cc)$ signal
- Upper limit on the signal strength of $\mu < 26$ (31^{+12}_{-8}) observed (expected)

The $VH(cc)$ signal strength is reparameterised within the kappa framework to the Higgs-charm coupling modifier κ_c

- Constrain $|\kappa_c| < 8.5$ (12.4 expected)



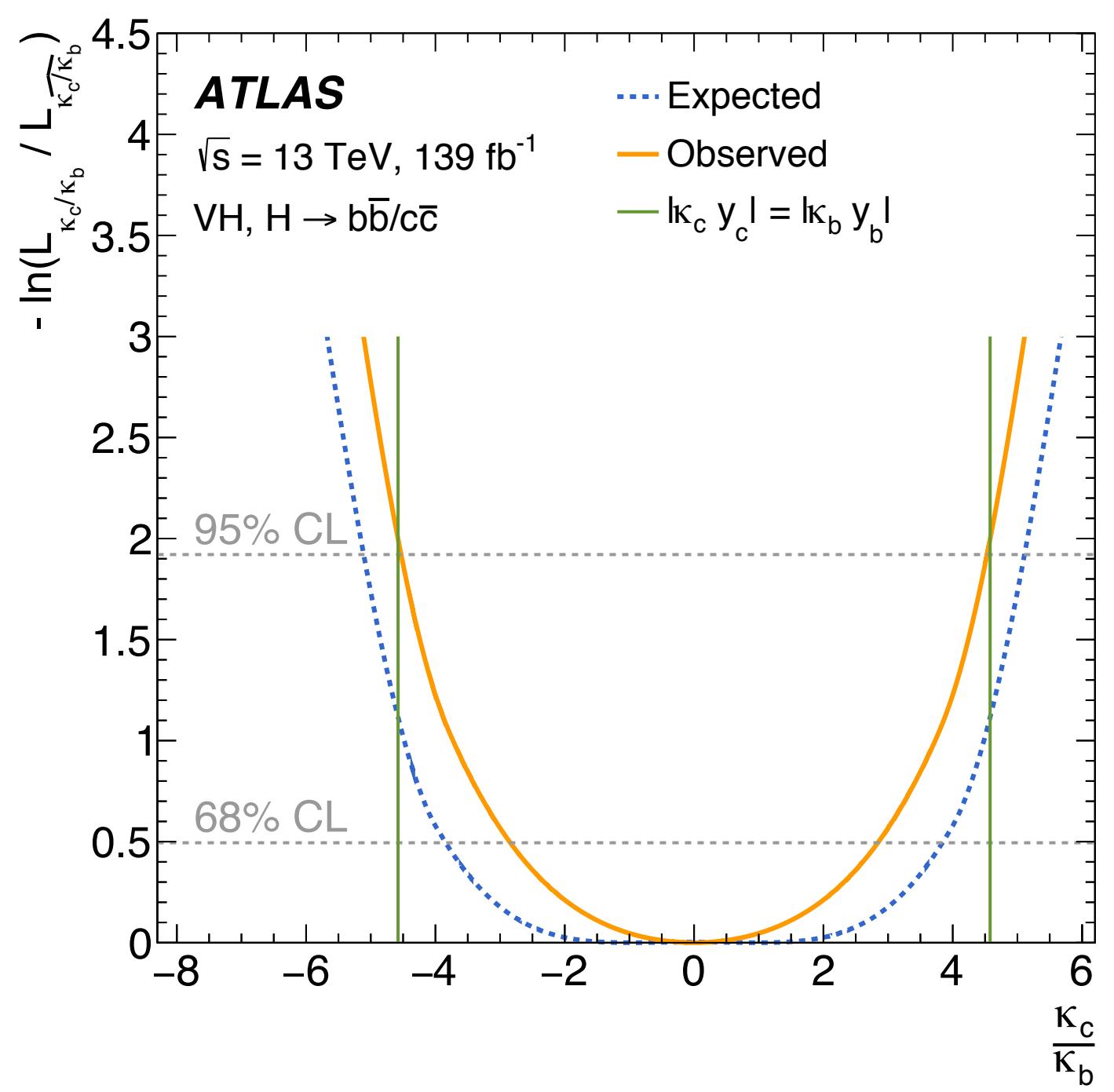
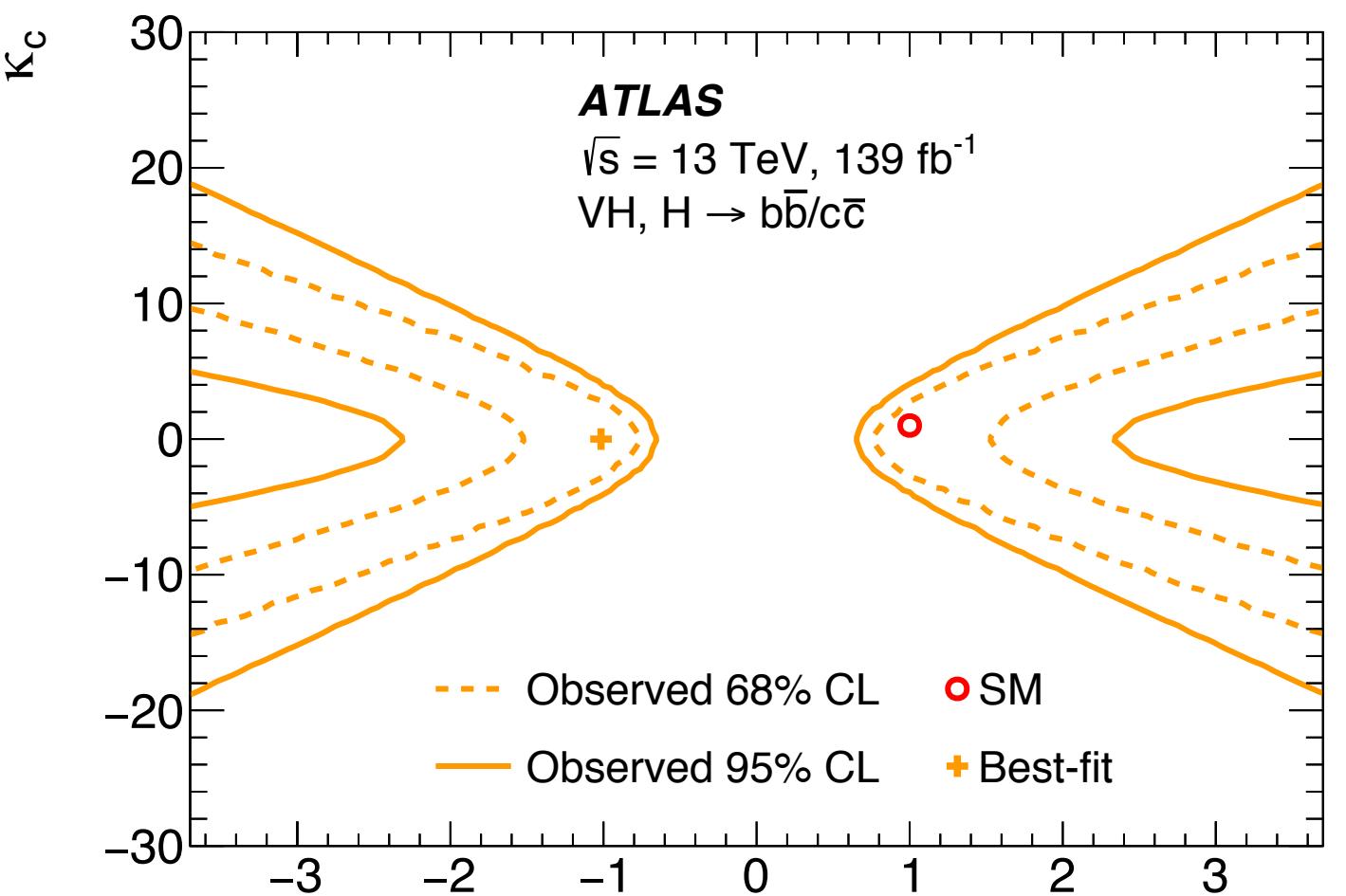
Rare decays: $H \rightarrow cc$

Analysis is combined with the VH(bb) measurement

- Designed to be orthogonal via b-jet vetoes

Extraction of coupling modifiers in the kappa framework

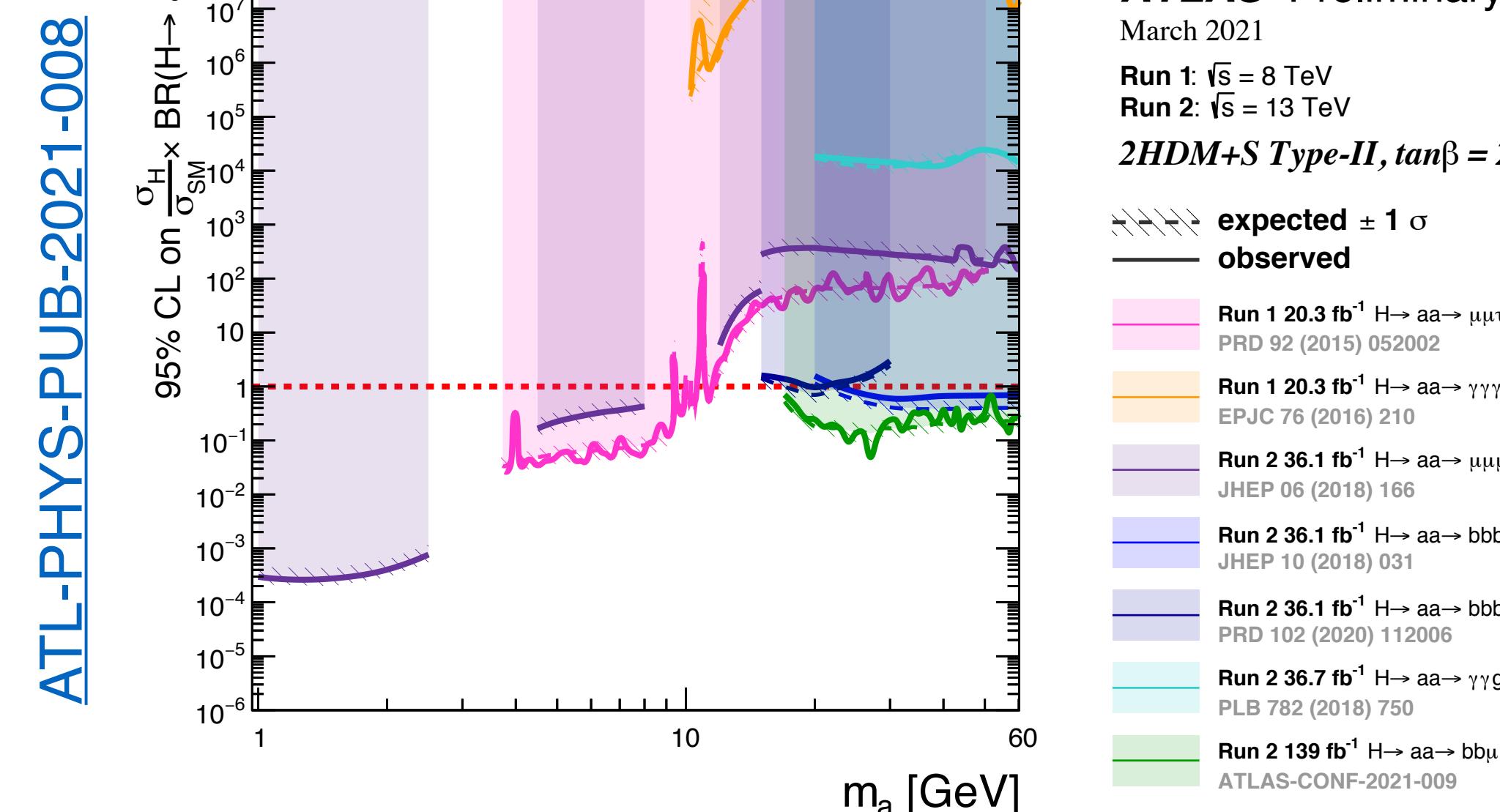
- Weak constraints in the 2-dimensional coupling plane
- Increases in one coupling can be compensated with an increase in the other, leading to similar BRs
- Constraint can be derived on the ratio $|k_b/k_c|$ without any assumptions about the width of the Higgs boson:
- **$|k_b/k_c| < 4.5$ (5.1 expected) which is smaller than $m_b/m_c = 4.578$**



Conclusions

Extensive program of searches in ATLAS for BSM, LFV and rare Higgs decays

- Only covered some representative examples, please see backup for a more exhaustive list
- No significant excess but a few interesting deviations ($2\mu 2b$, 4ℓ)
- Analyses keep improving, we are getting access to small BRs, rare and challenging decays
- Run 3 will provide an even larger dataset with an upgraded detector
- Plenty of room for surprises: $\text{BR}(\text{H} \rightarrow \text{invisible}) < 0.09$ and $\text{BR}(\text{H} \rightarrow \text{undetected}) < 0.16$, stay tuned



Backup

List of analyses

- In bold analyses covered in this talk

BSM decays	
$H \rightarrow 2\mu 2b$	<u>139 fb-1</u>
$H \rightarrow XX/ZX \rightarrow 4l$	<u>139 fb-1</u>
$H \rightarrow bb + MET$	<u>139 fb-1</u>
$H \rightarrow Za \rightarrow lljj$	<u>139 fb-1</u>
$H \rightarrow \text{invisible}$	<u>139 fb-1</u>
$H \rightarrow bbbb \text{ resolved}$	<u>36 fb-1</u>
$H \rightarrow bbbb \text{ merged}$	<u>36 fb-1</u>
$H \rightarrow \gamma\gamma jj$	<u>36 fb-1</u>
LFV decays	
$H \rightarrow e\mu$	<u>139 fb-1</u>
$H \rightarrow e\tau/\mu\tau$	<u>36 fb-1</u>
Rare decays	
$H \rightarrow ll\gamma$	<u>139 fb-1</u>
$H \rightarrow cc$	<u>139 fb-1</u>
$H \rightarrow Z\gamma$	<u>139 fb-1</u>
$H \rightarrow \mu\mu$	<u>139 fb-1</u>
$H \rightarrow J/\psi + \text{photon}$	<u>36 fb-1</u>

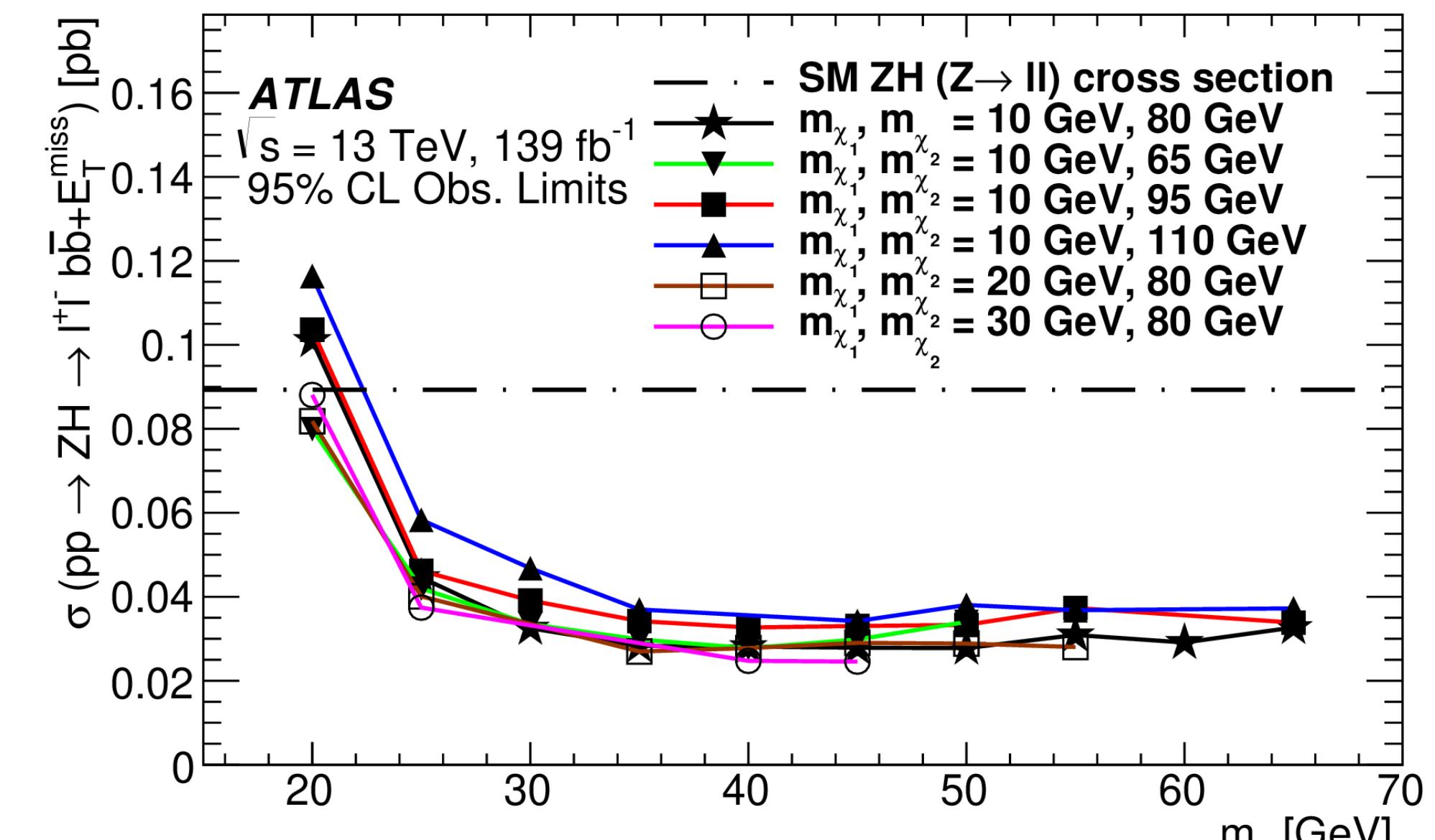
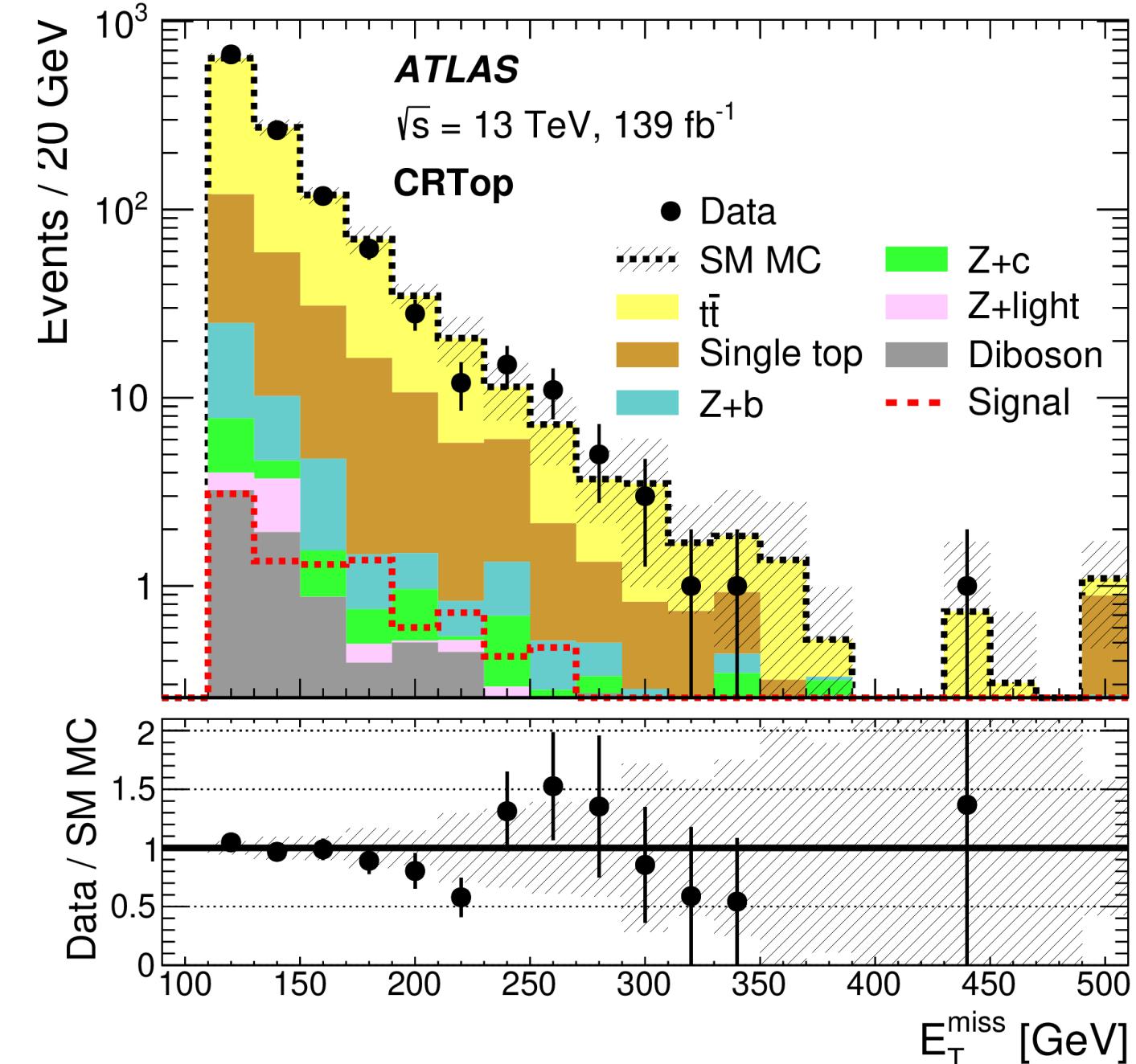
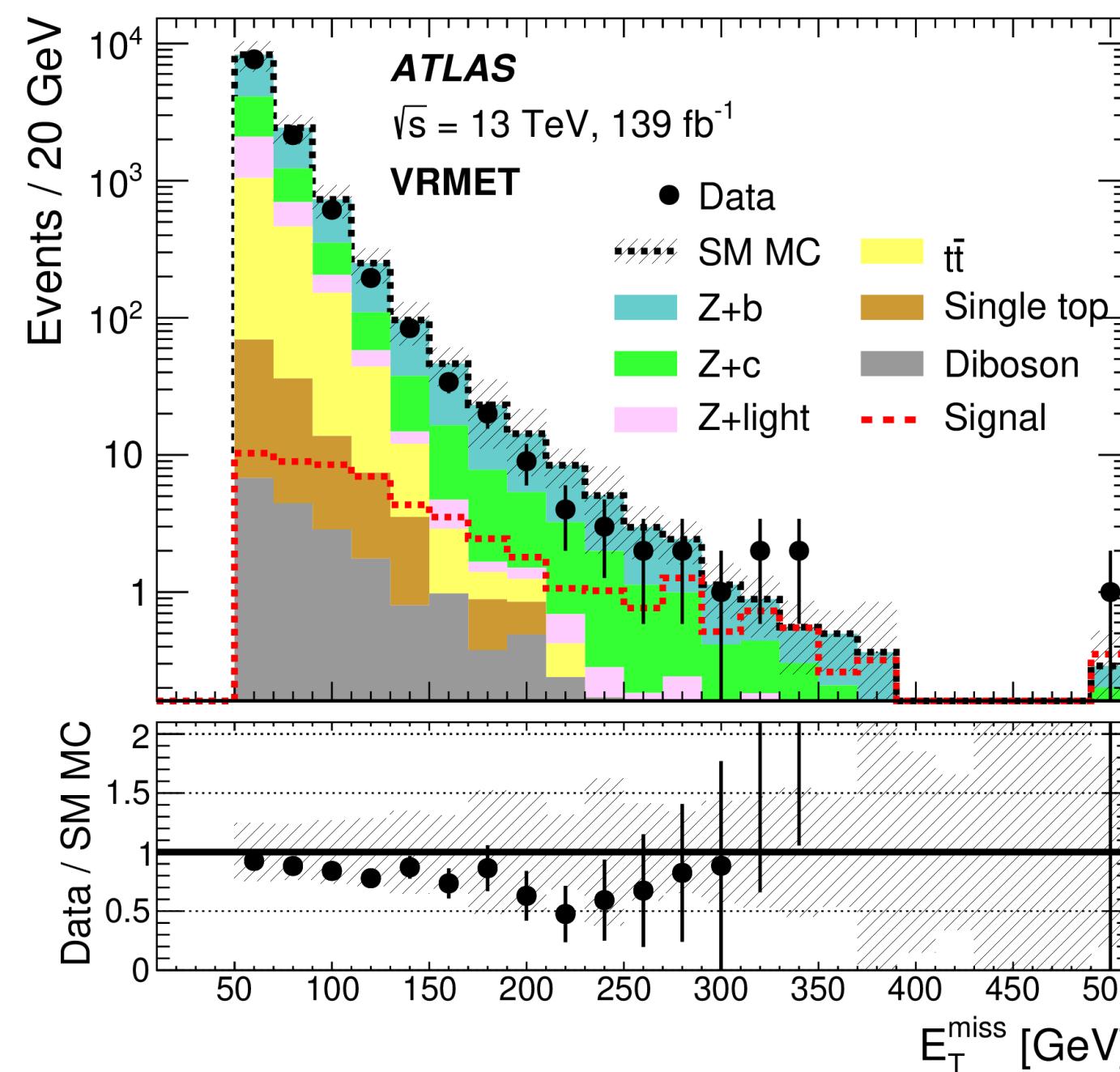
$p_{\text{T}t}$ definition in $H \rightarrow \ell\ell\gamma$

The $p_{\text{T}t}$ is defined as the component of the transverse momentum of the $\ell\ell\gamma$ system that is perpendicular to the difference of the three-momenta of the dilepton system and the photon candidate ($p_{\text{T}t} = |\vec{p}_{\text{T}}^{\ell\ell\gamma} \times \hat{t}|$, where $\hat{t} = (\vec{p}_{\text{T}}^{\ell\ell} - \vec{p}_{\text{T}}^{\gamma})/|\vec{p}_{\text{T}}^{\ell\ell} - \vec{p}_{\text{T}}^{\gamma}|$). This quantity is strongly correlated with the transverse momentum of the $\ell\ell\gamma$ system, but has better experimental resolution [89, 90].

- [89] <https://arxiv.org/abs/hep-ex/9710010>
- [90] <https://arxiv.org/abs/0807.4956>

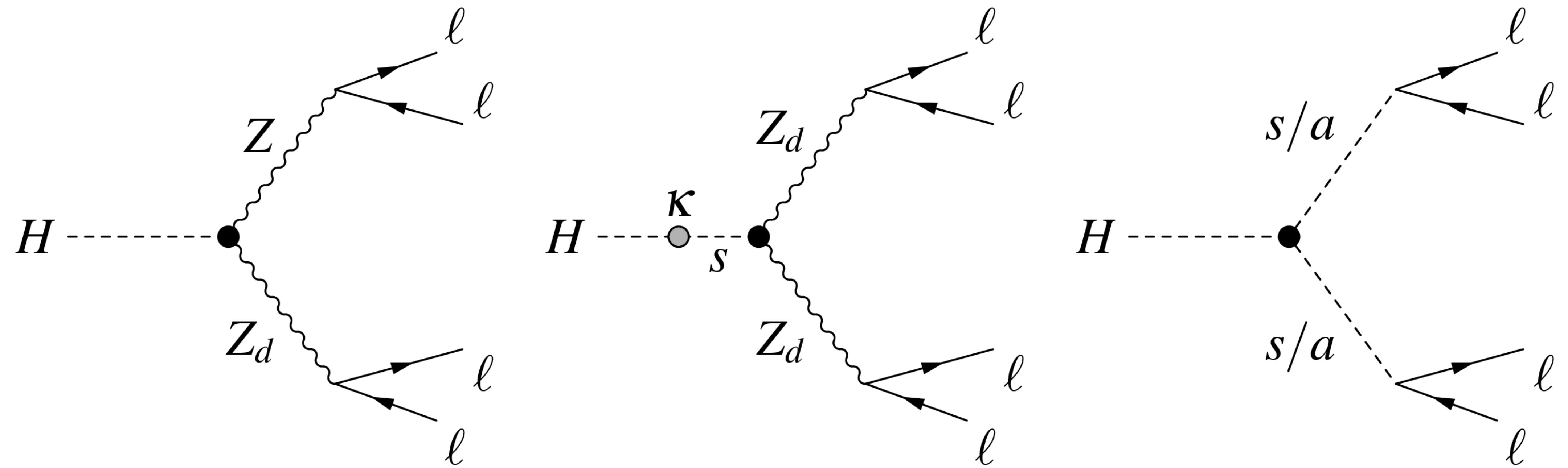
BSM decays: $H \rightarrow b\bar{b} + \text{MET}$

Top control region, validation region, and limits for all masses



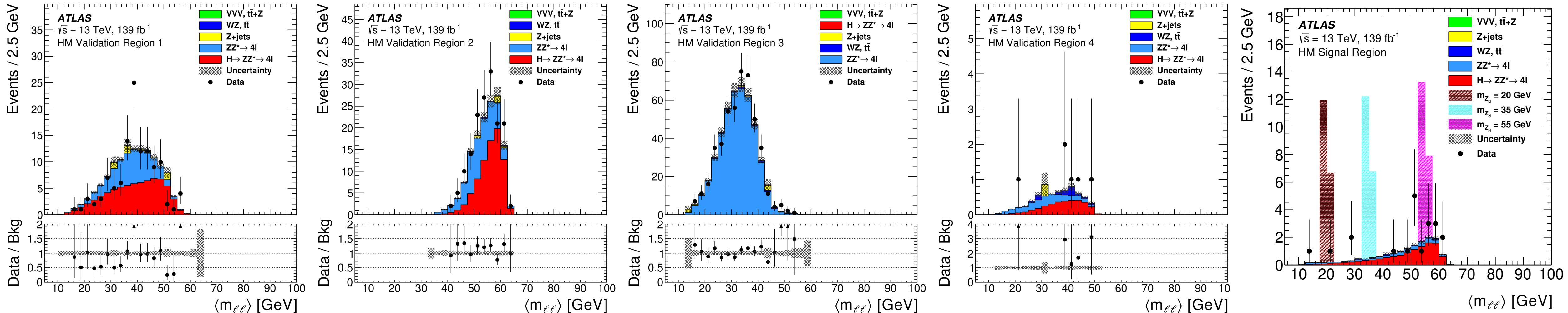
BSM decays: $H \rightarrow XX/ZX \rightarrow 4\ell$

Signal models

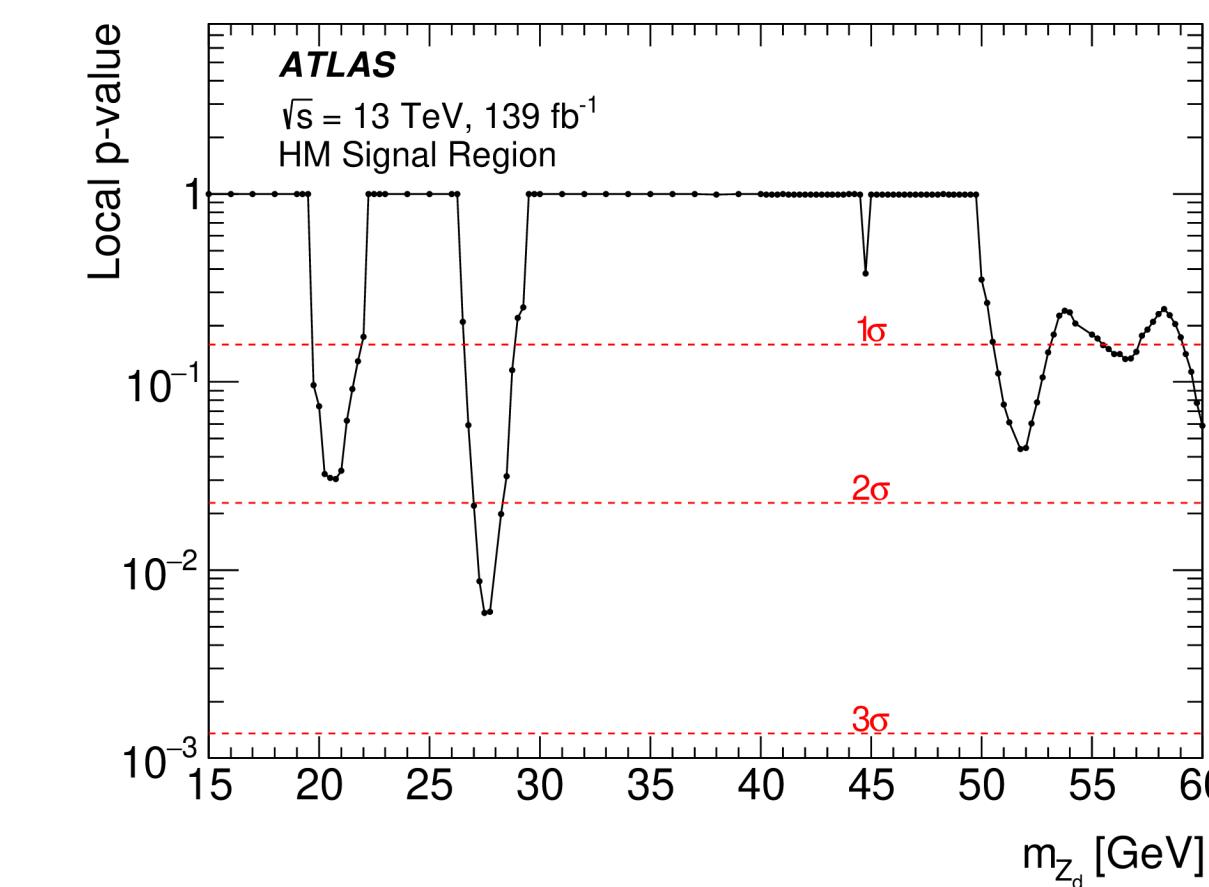
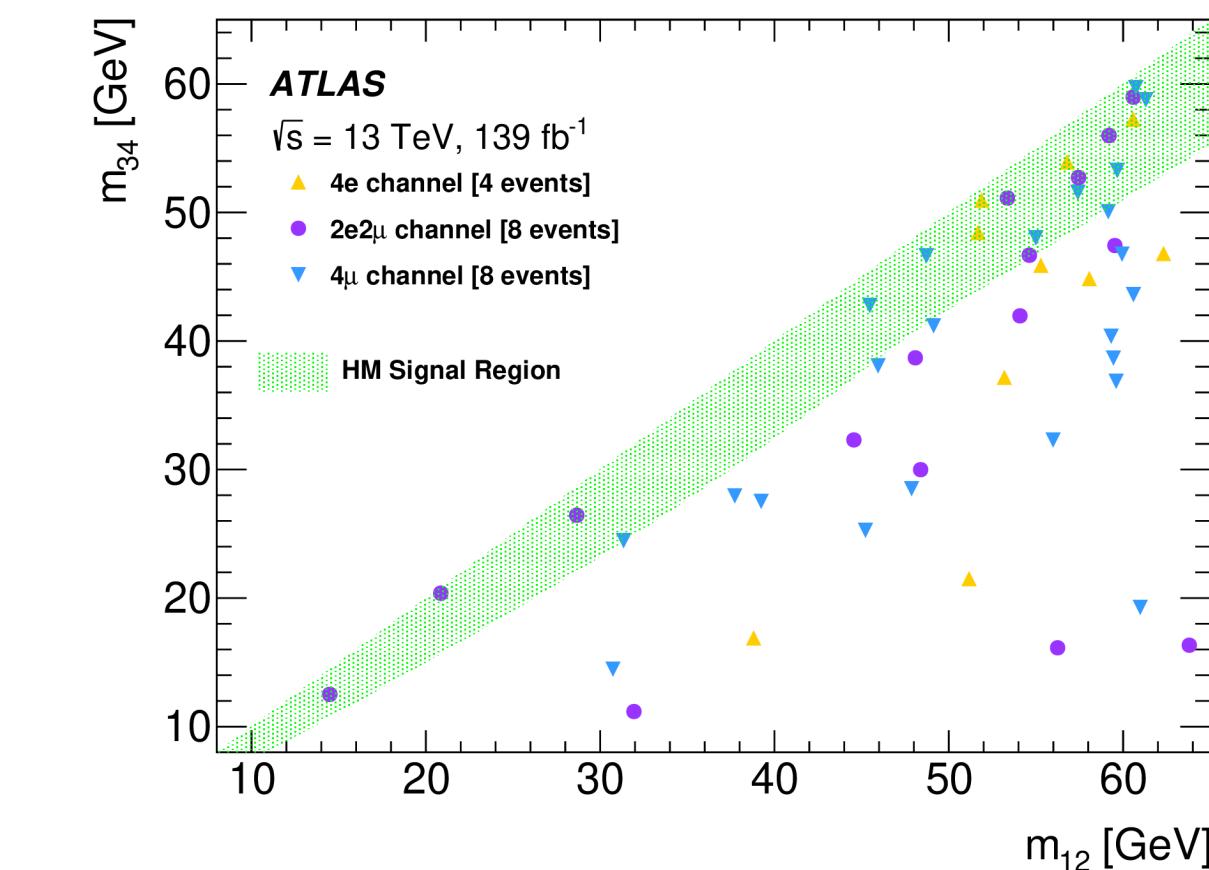
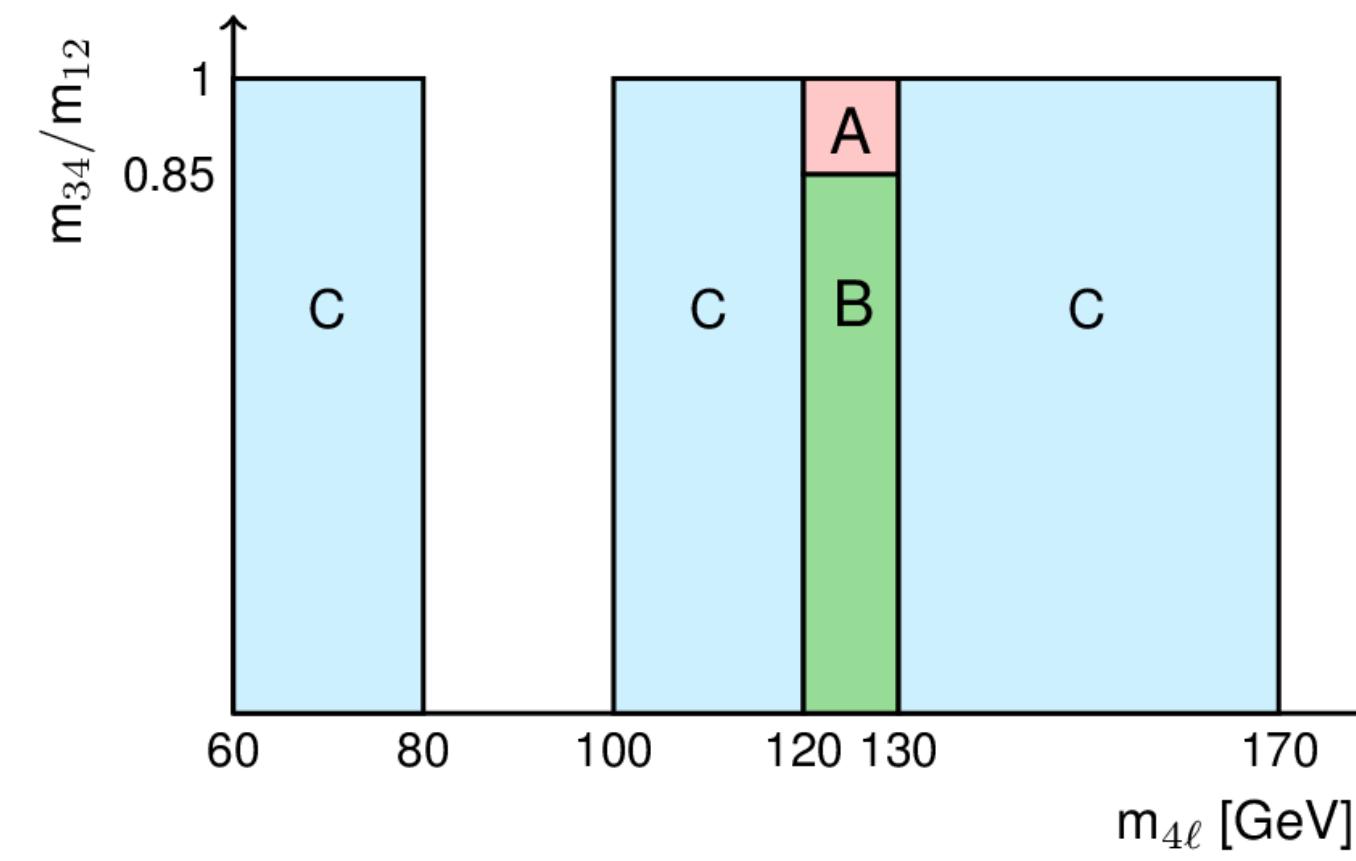


BSM decays: $H \rightarrow XX/ZX \rightarrow 4\ell$

High-mass regions

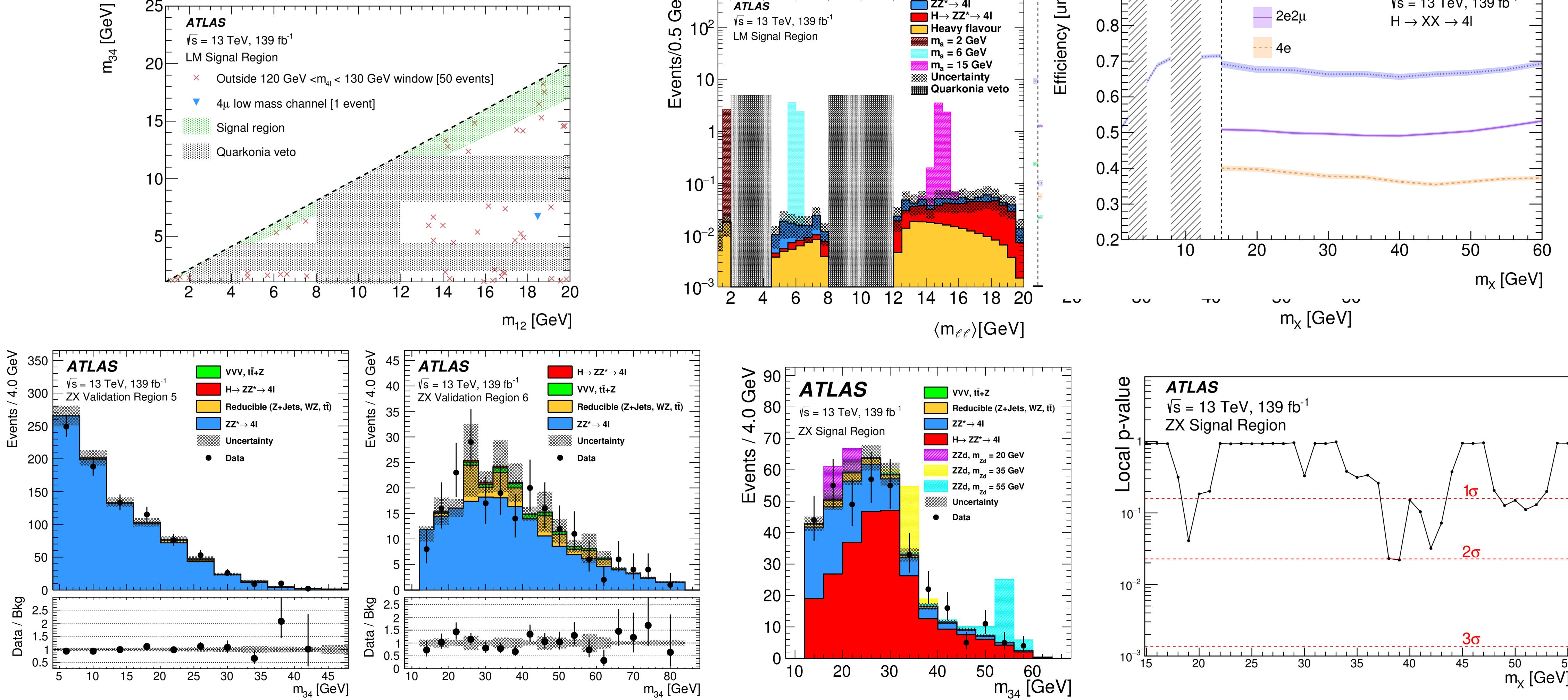


Standard selection



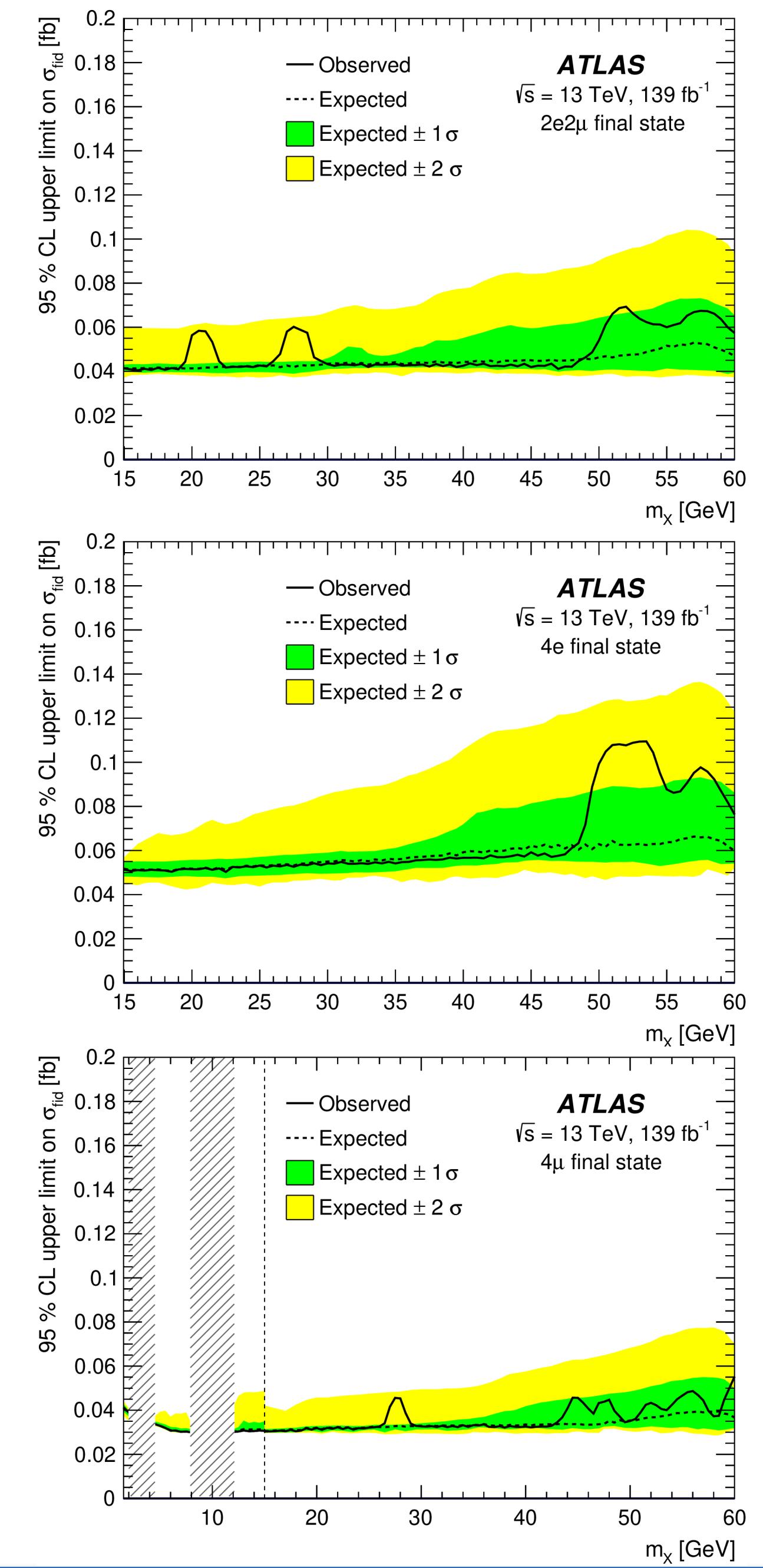
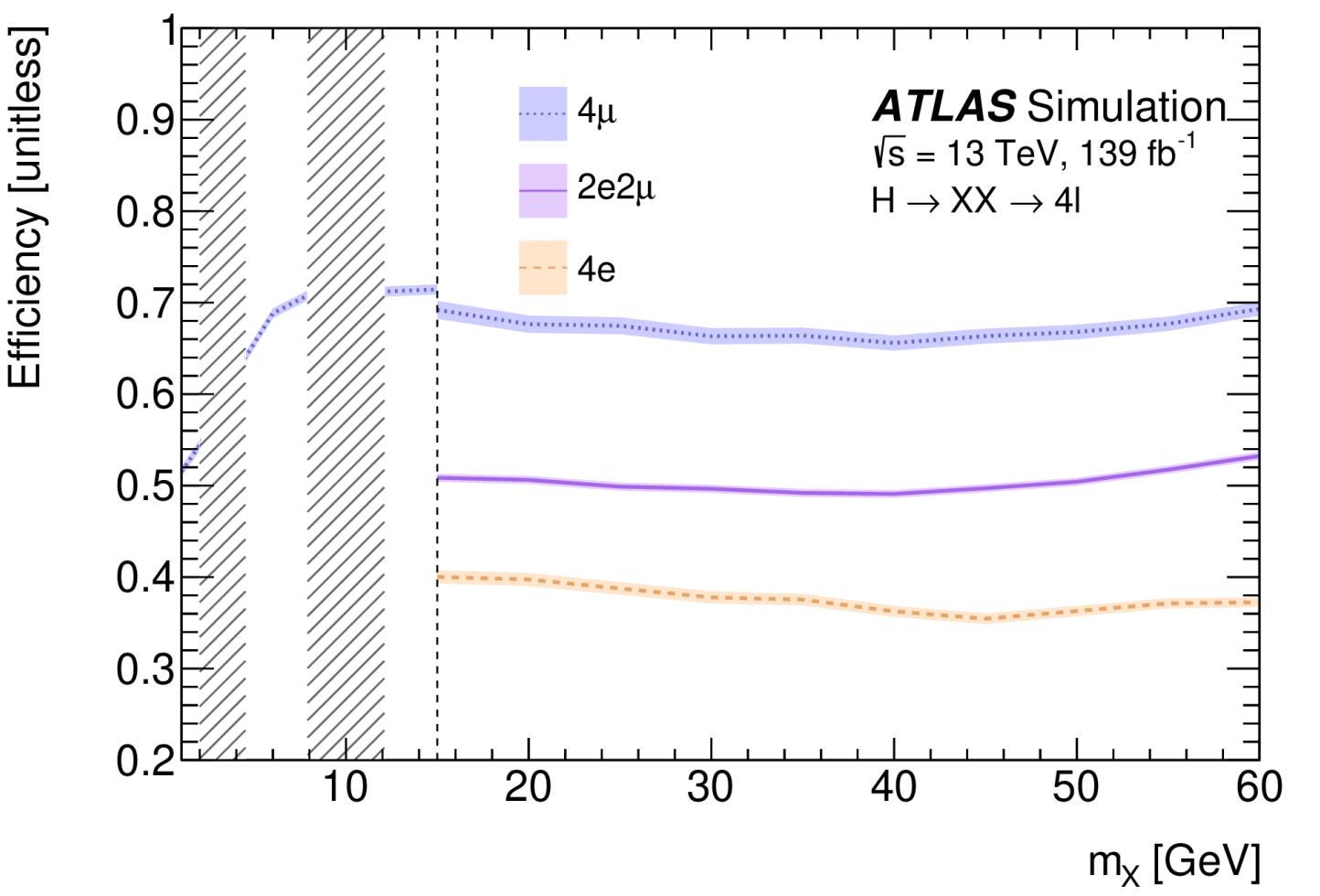
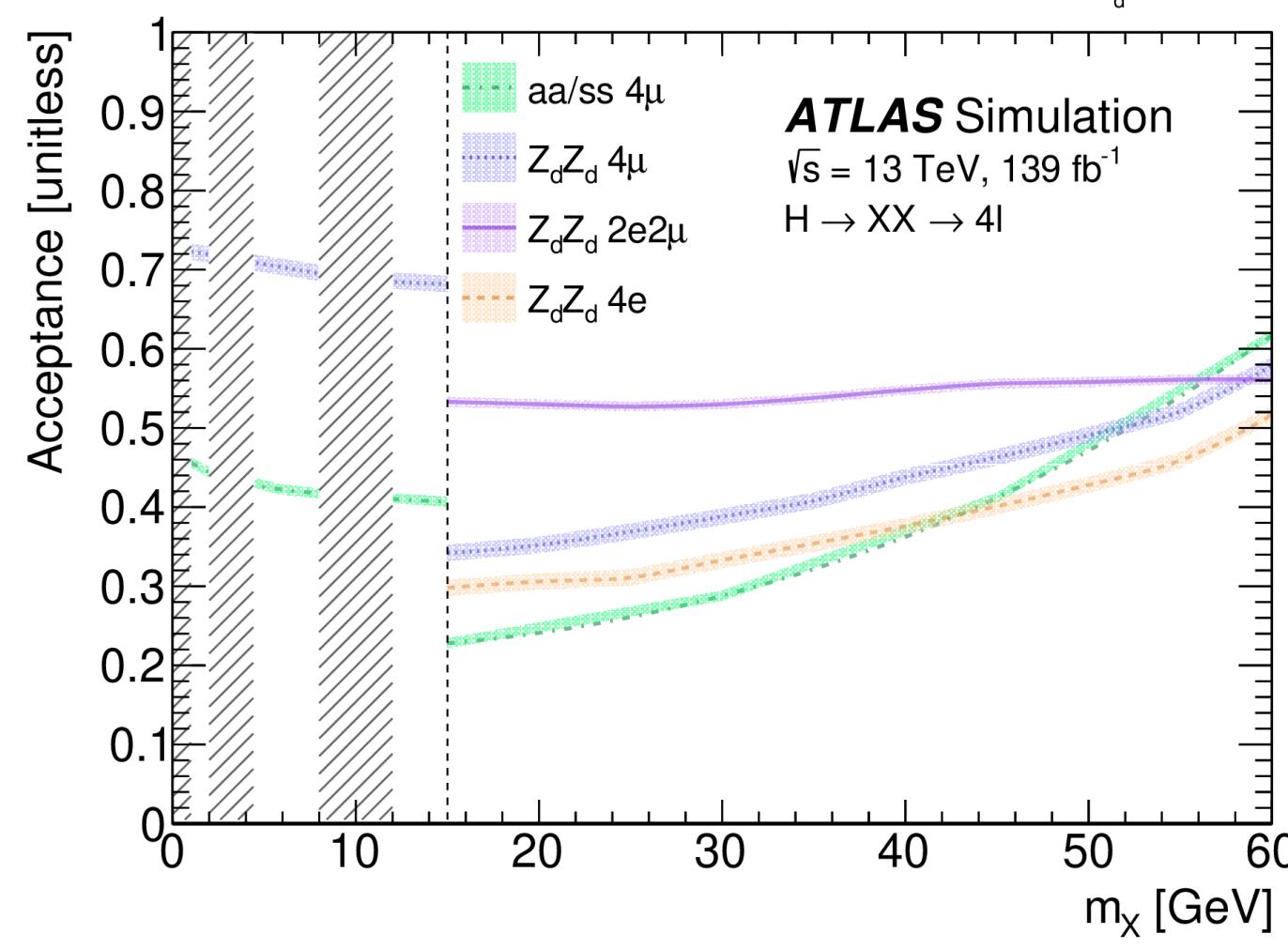
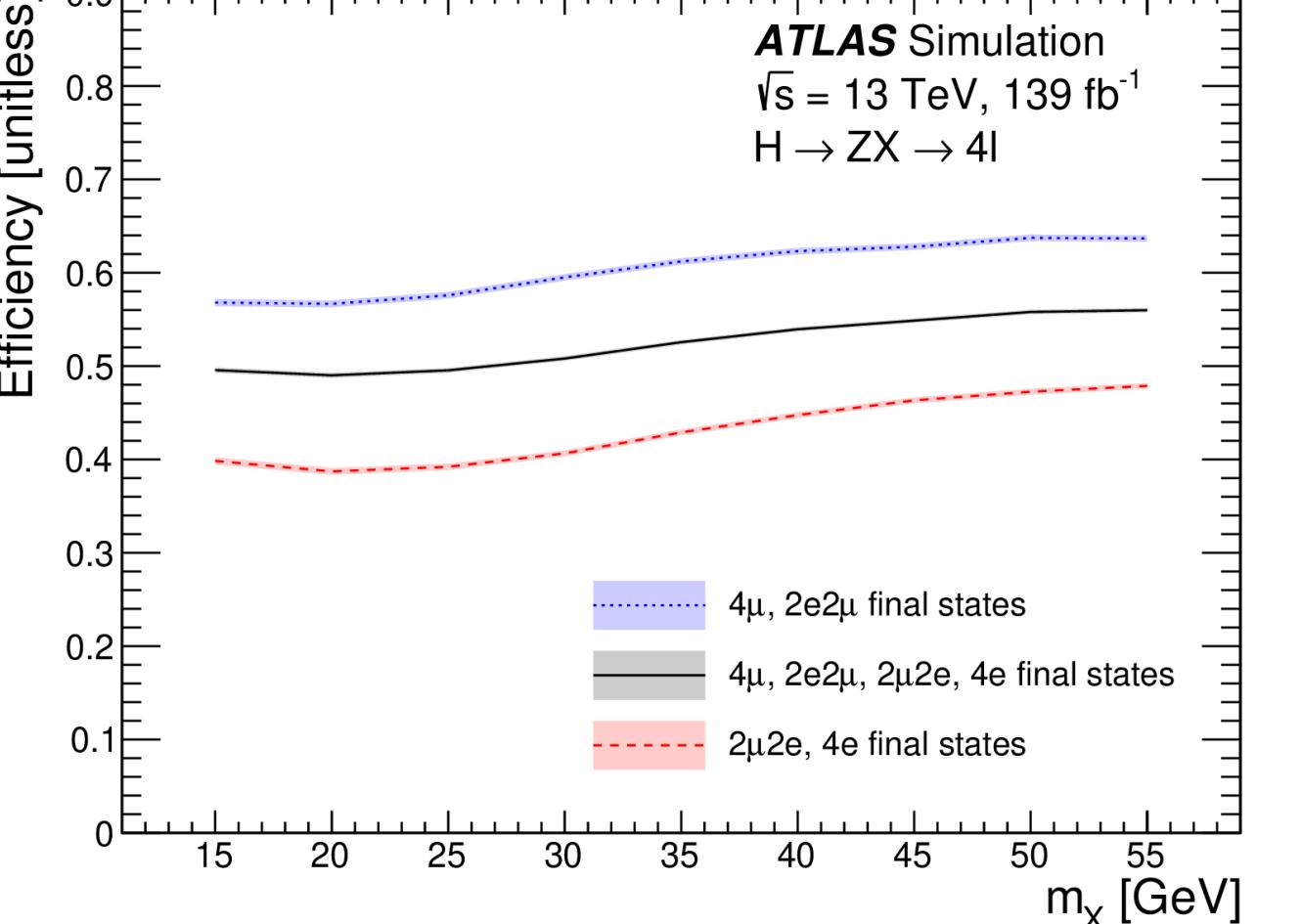
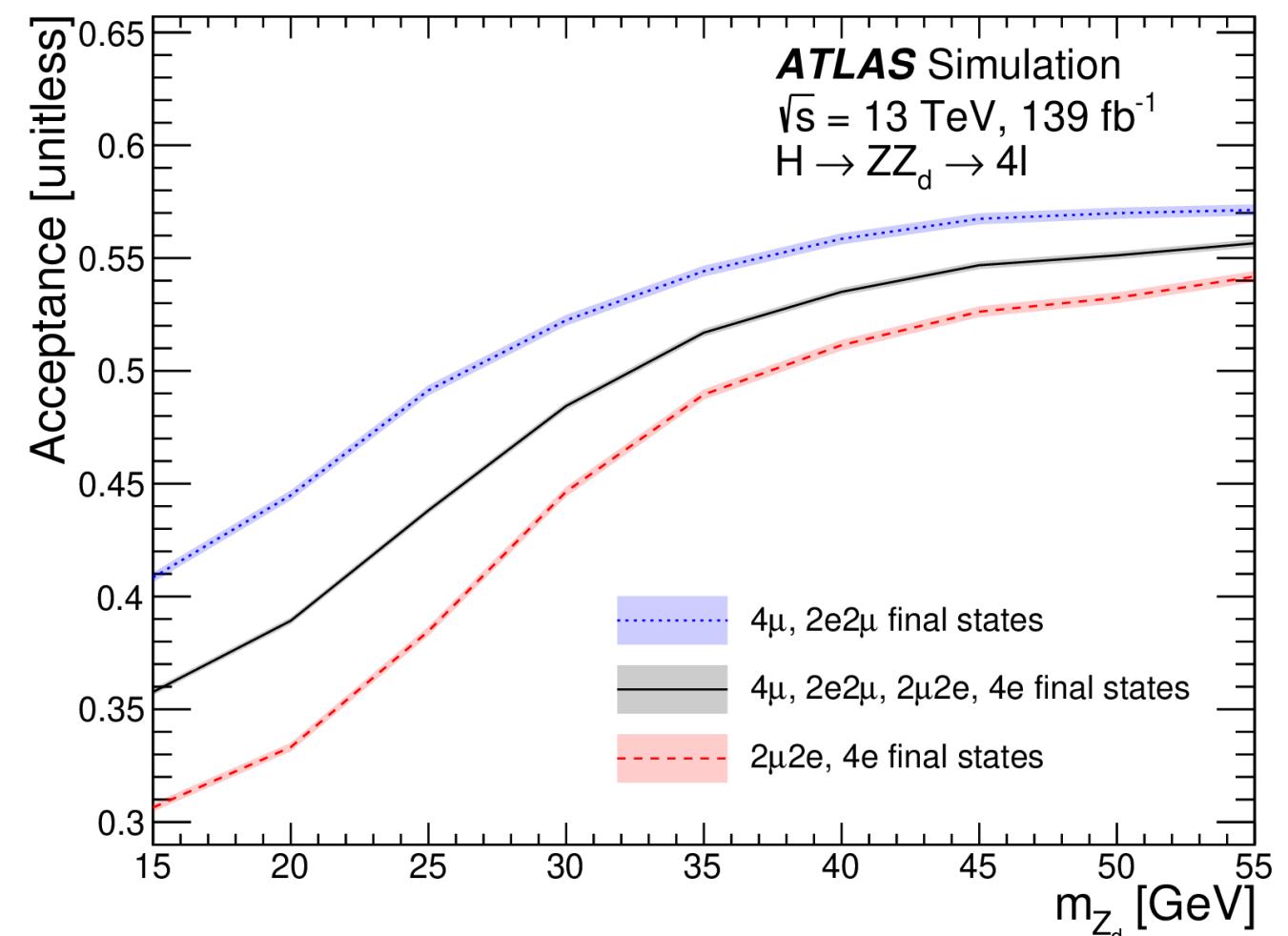
BSM decays: $H \rightarrow XX/ZX \rightarrow 4\ell$

Low-mass and ZX regions



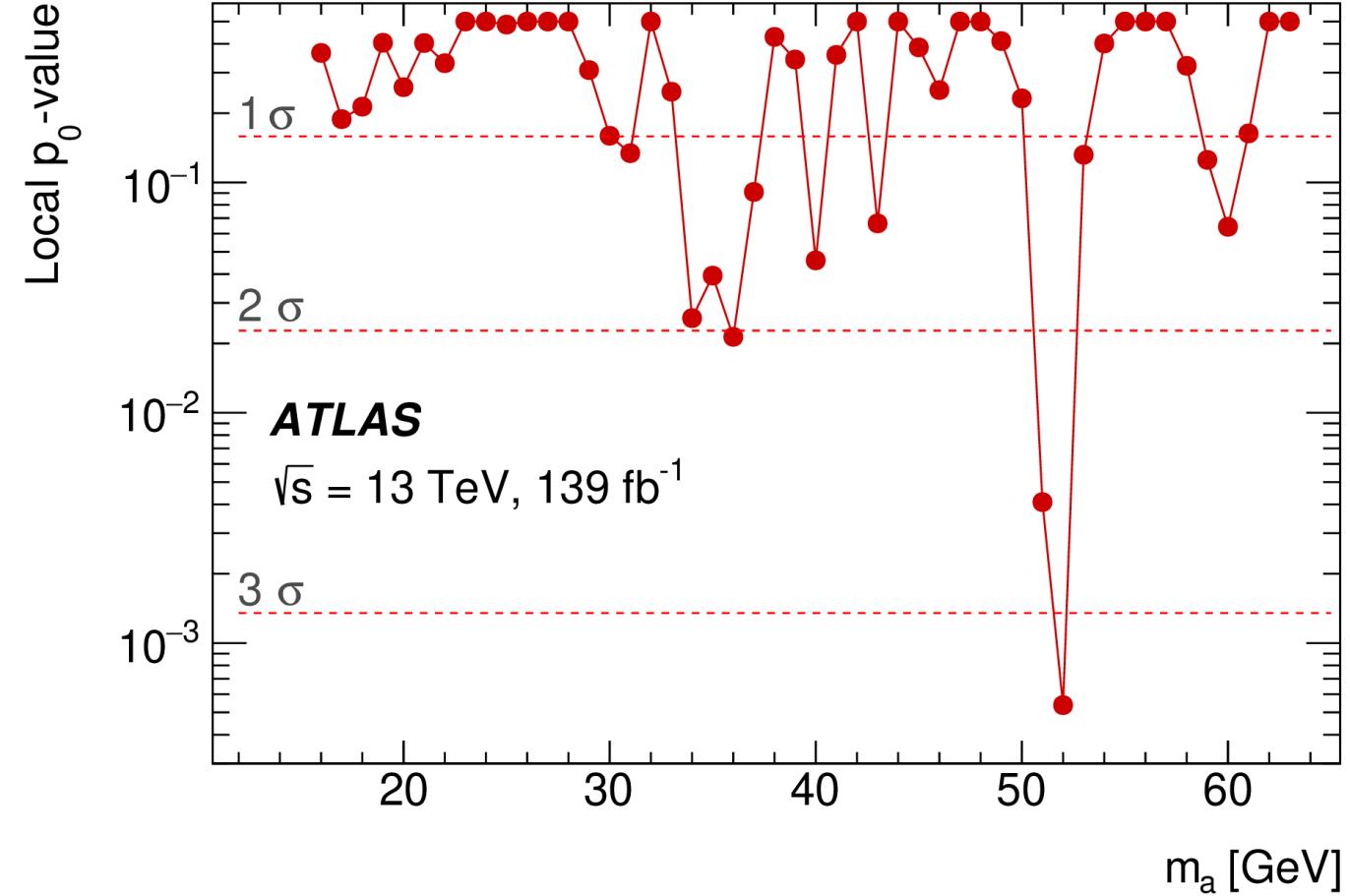
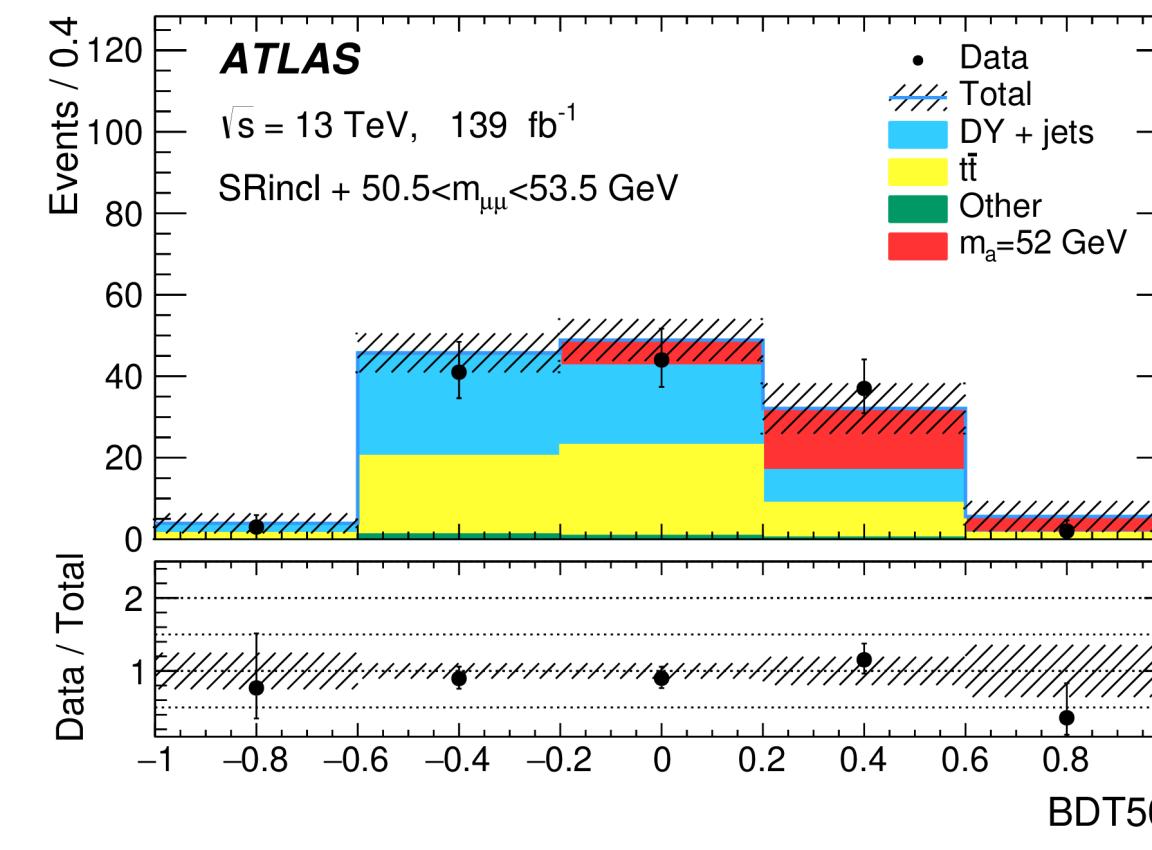
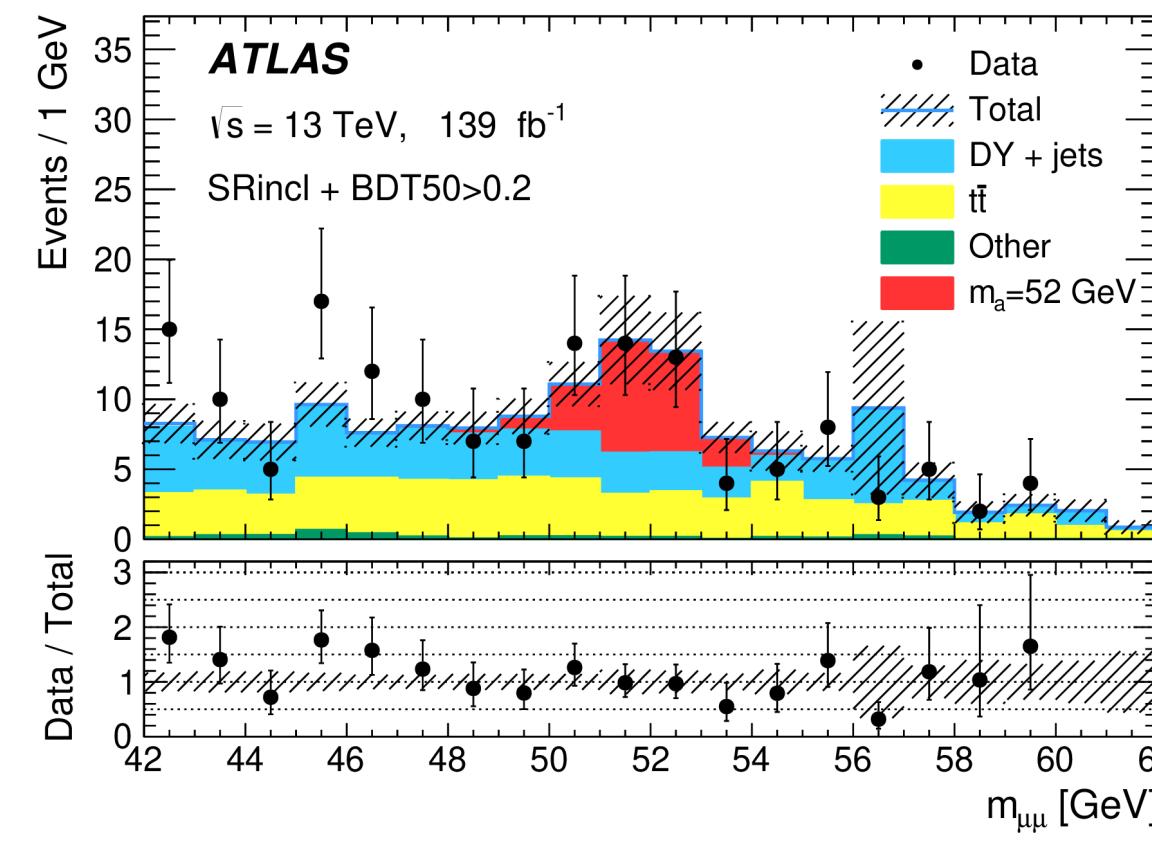
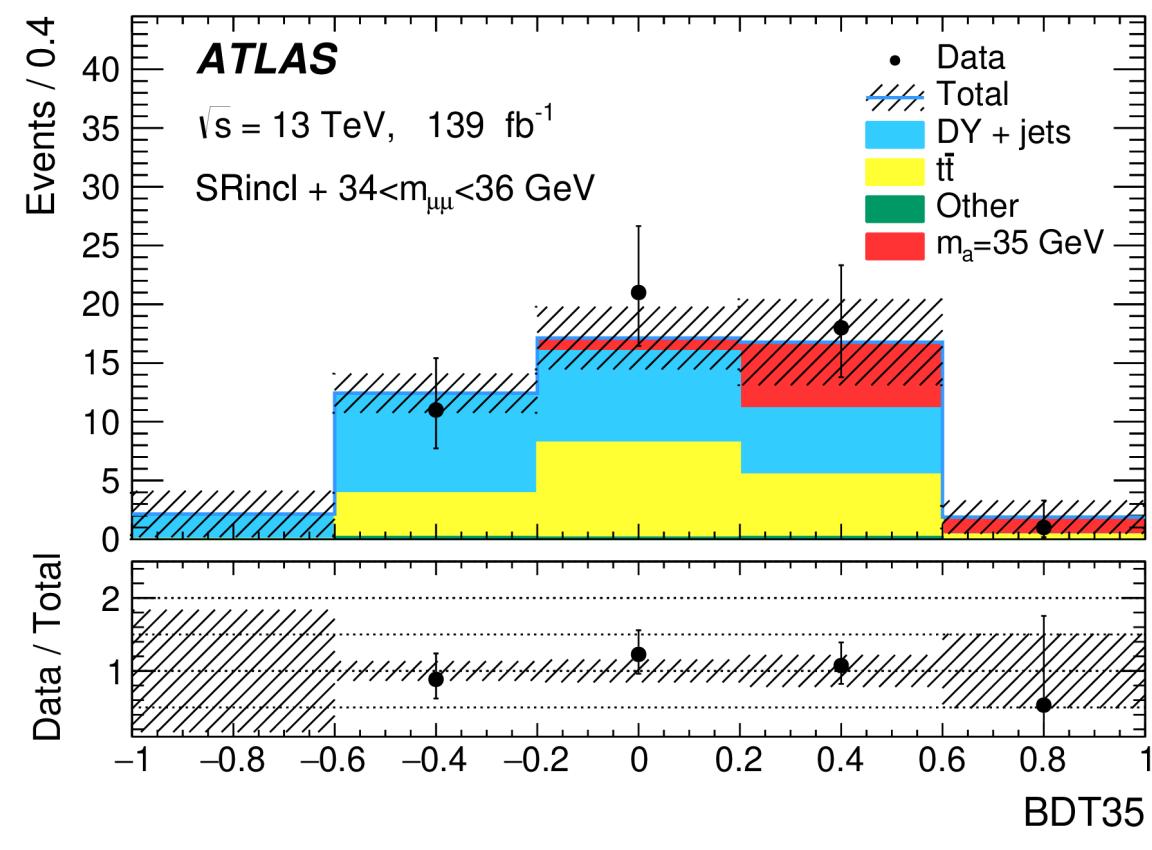
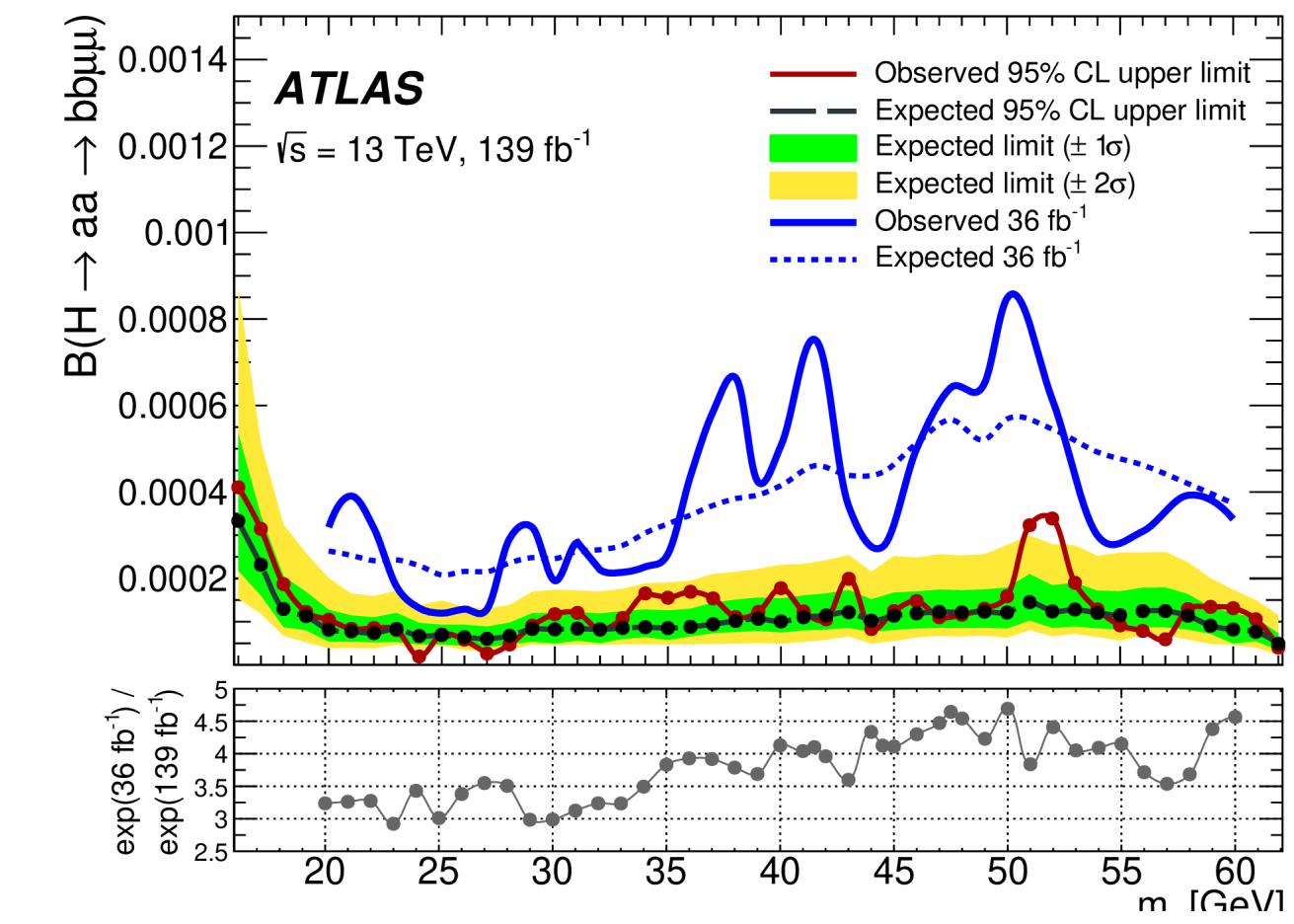
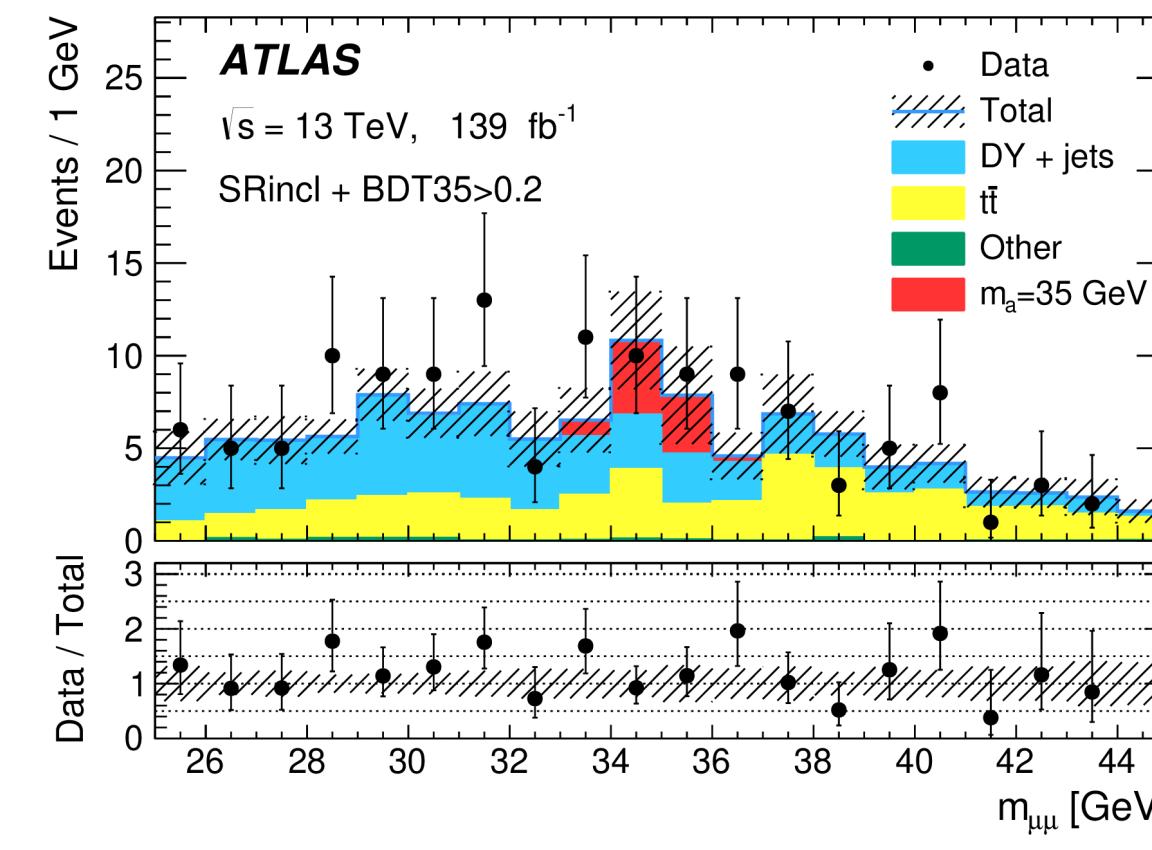
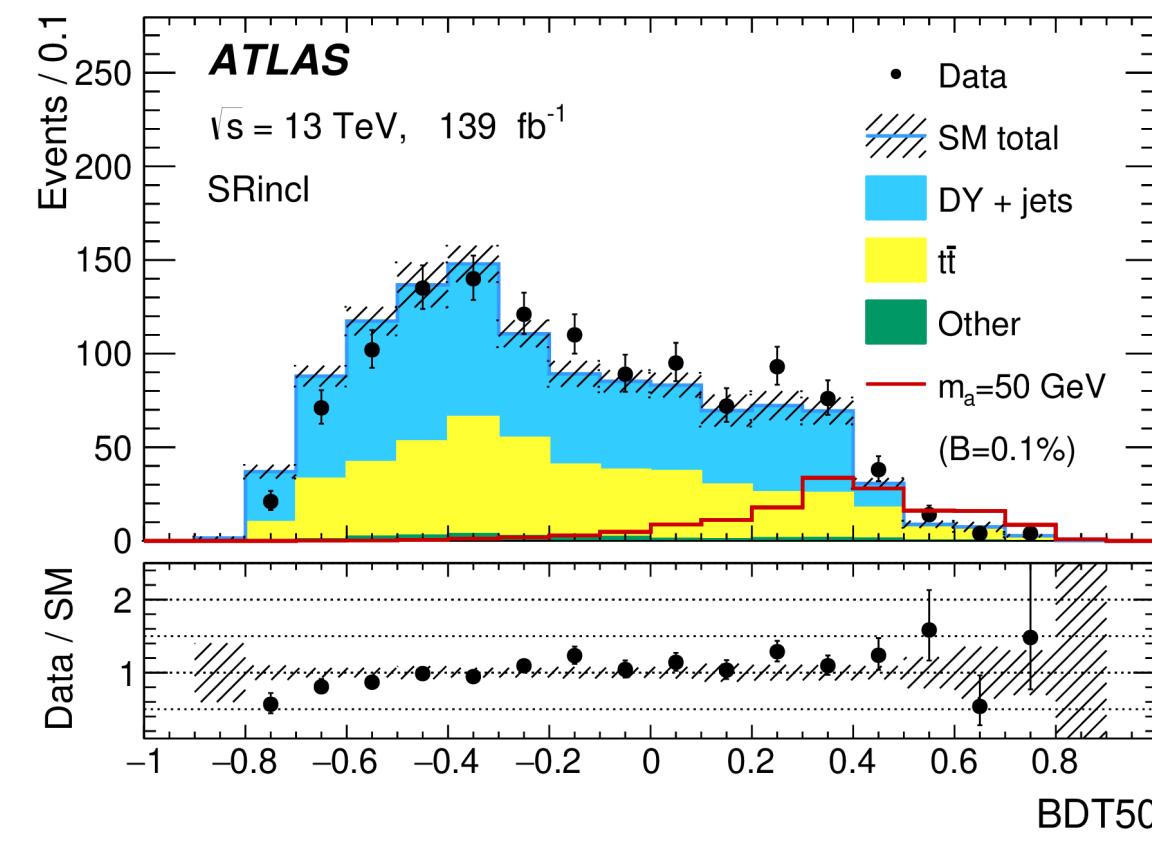
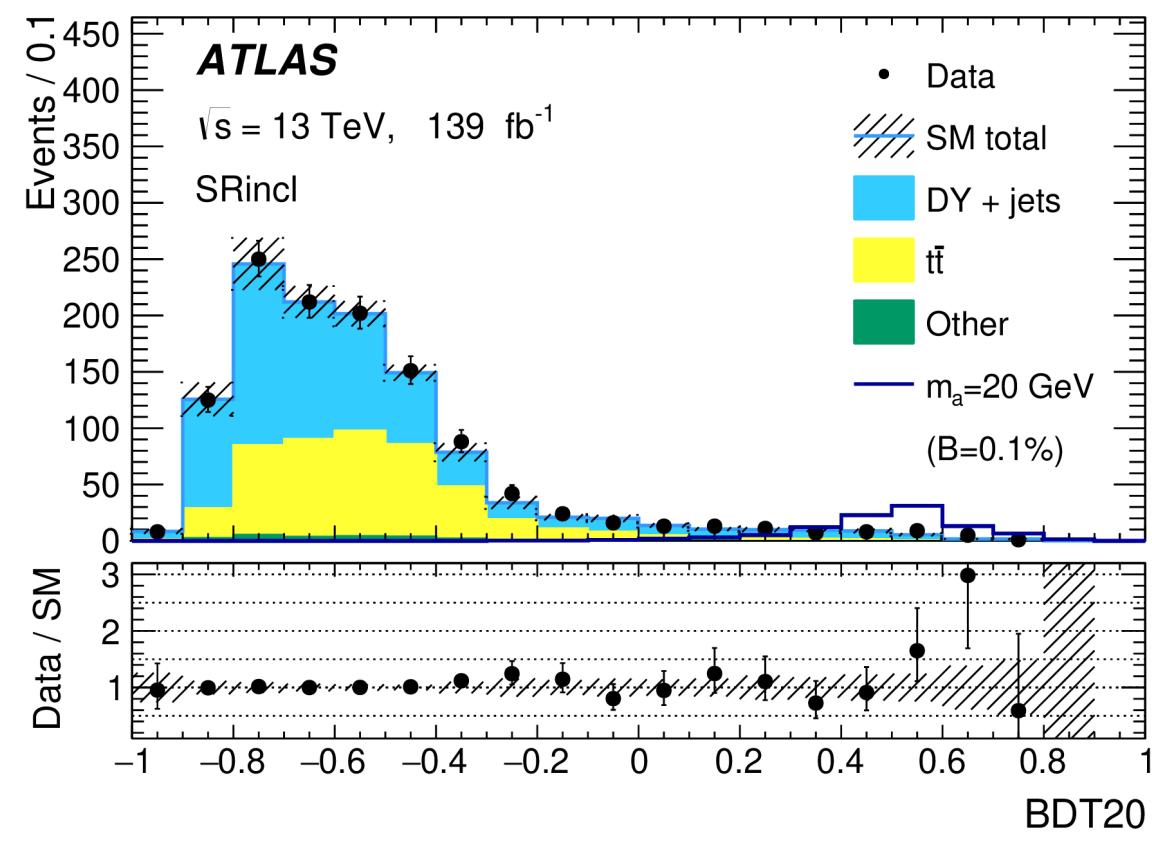
BSM decays: $H \rightarrow XX/ZX \rightarrow 4\ell$

Fiducial cross-section limits



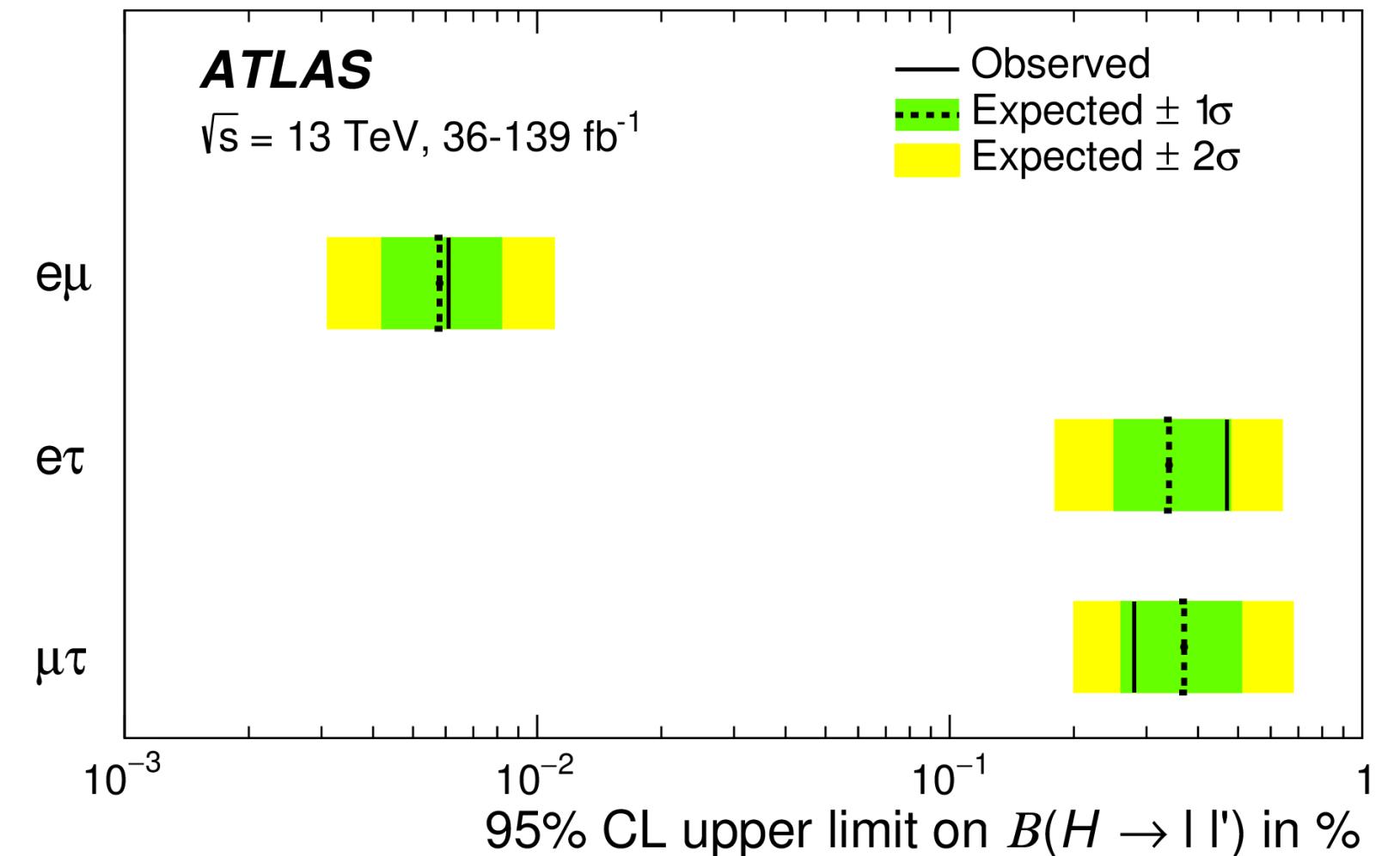
BSM decays: $H \rightarrow aa \rightarrow 2\mu 2b$

BDT, $m_{\mu\mu}$ distributions and limits

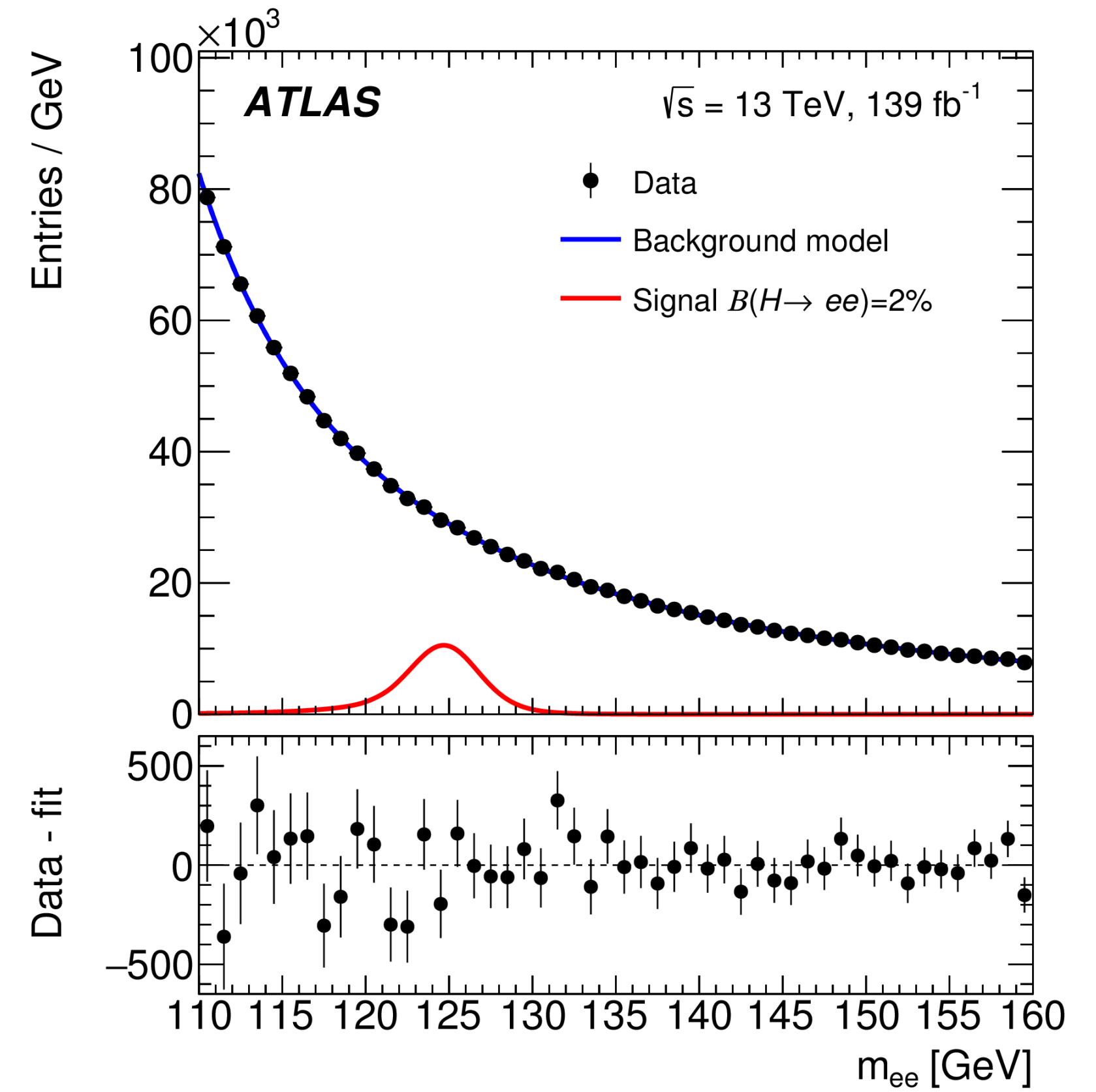


LFV decays: $H \rightarrow e\mu$

$H \rightarrow e\mu$ (left) and $H \rightarrow ee$ (right)



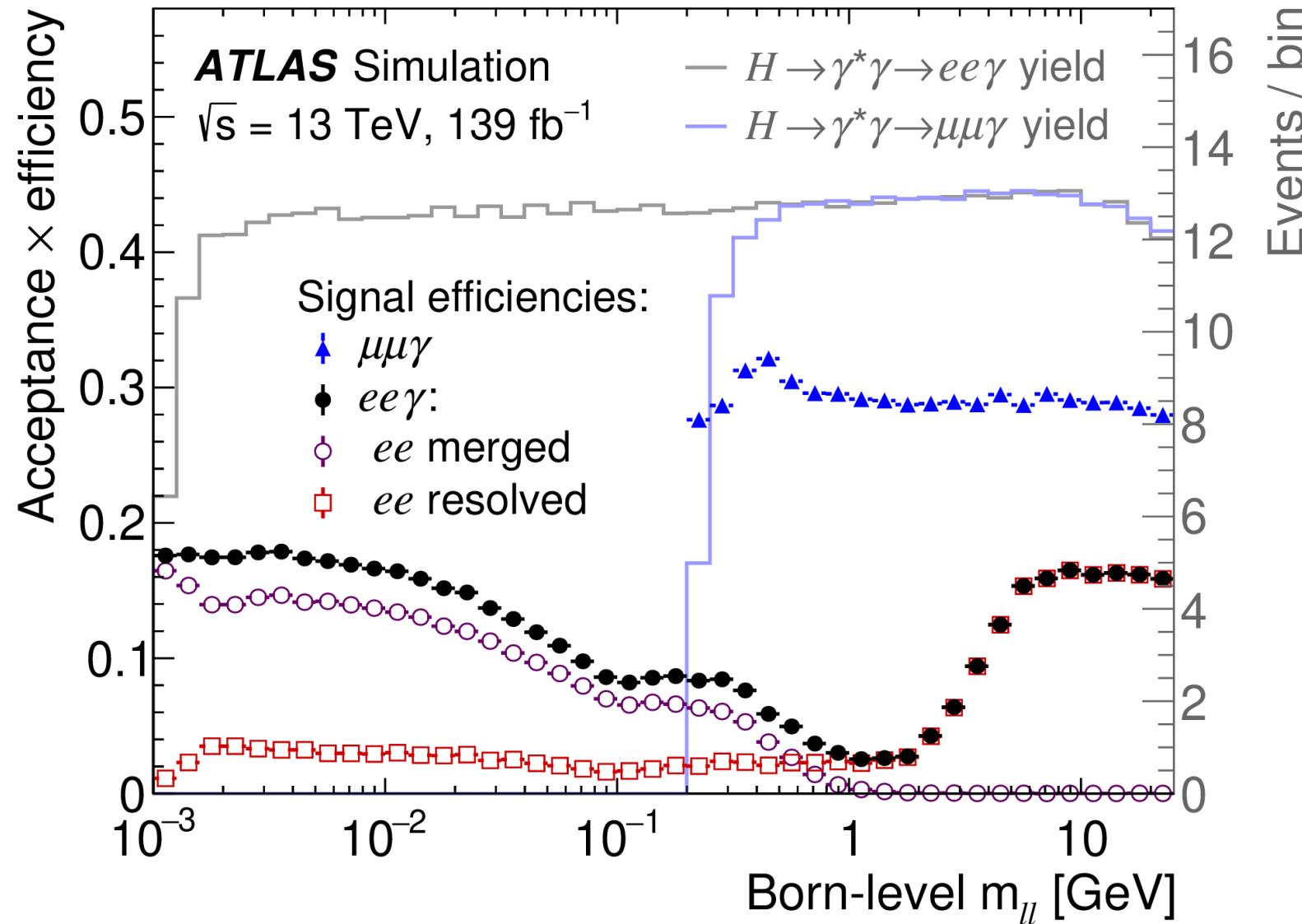
Category	S	B	S/B	Data
Central Low $p_T^{\ell\ell}$	210	150	1.35	171
Forward Low $p_T^{\ell\ell}$	400	560	0.72	532
Central Medium $p_T^{\ell\ell}$	250	290	0.86	277
Forward Medium $p_T^{\ell\ell}$	450	830	0.54	854
Central High $p_T^{\ell\ell}$	180	280	0.65	299
Forward High $p_T^{\ell\ell}$	300	700	0.43	707
VBF	83	100	0.82	102
Low p_T^ℓ	89	600	0.15	558



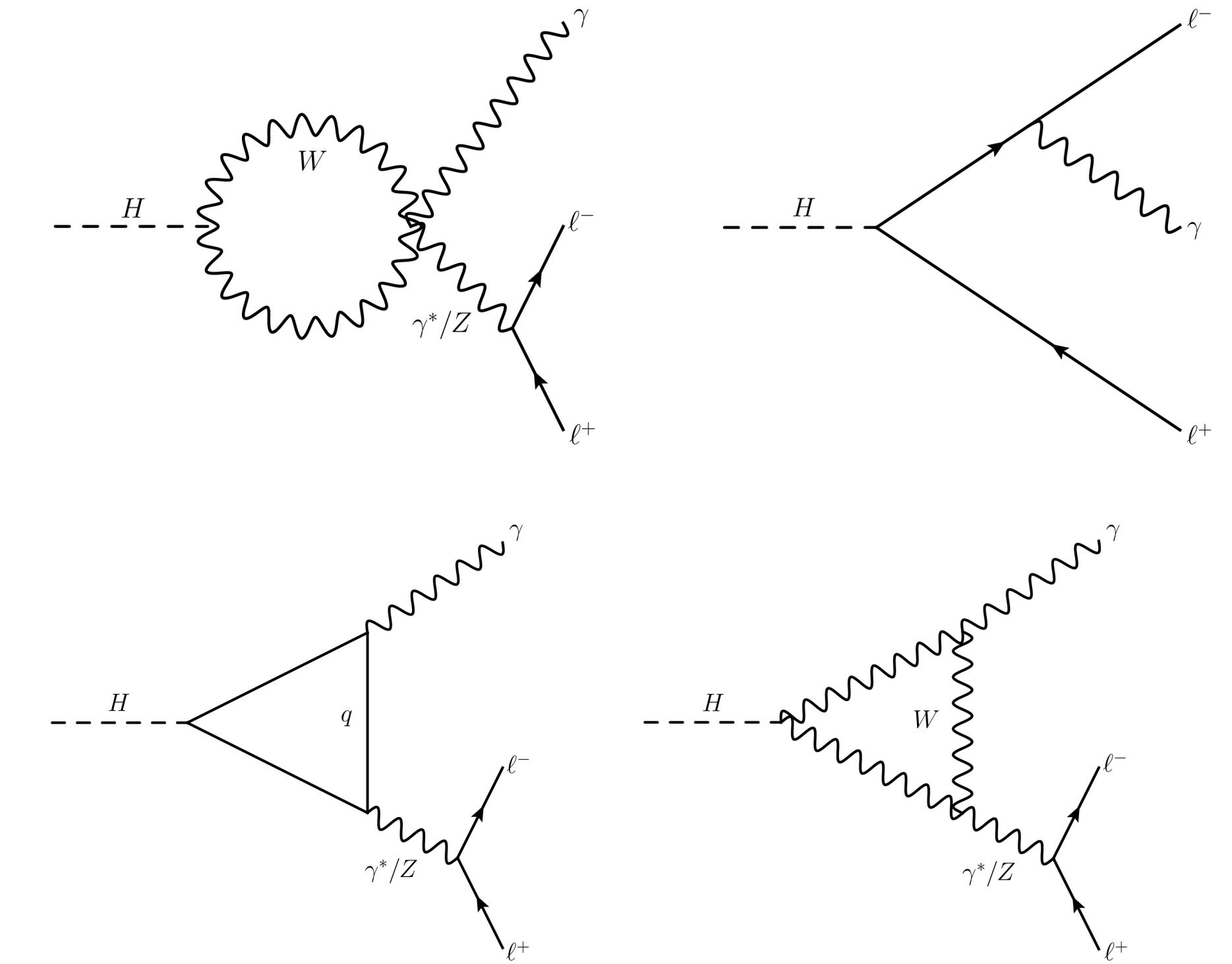
Category	S	B	S/B	Data
Central Low $p_T^{\ell\ell}$	230	39200	0.0057	39872
Forward Low $p_T^{\ell\ell}$	390	98500	0.0039	100844
Central Medium $p_T^{\ell\ell}$	420	30700	0.014	31182
Forward Medium $p_T^{\ell\ell}$	710	74900	0.0095	76477
Central High $p_T^{\ell\ell}$	380	13400	0.028	13625
Forward High $p_T^{\ell\ell}$	590	29900	0.020	30164
VBF	120	2530	0.049	2561

Rare decays: $H \rightarrow \ell\ell\gamma$

Signal efficiencies, uncertainties, and signal diagrams



Uncertainty source	μ	$\sigma \times \mathcal{B}$
Spurious Signal		6.1
$\mathcal{B}(H \rightarrow \ell\ell\gamma)$	5.8	-
QCD scale	4.7	1.1
$\ell, \gamma, \text{jets}$		4.0
PDF	2.3	0.9
Luminosity		1.7
Pile-up		1.7
Minor prod. modes		0.8
$H \rightarrow \gamma\gamma$ background		0.7
Parton Shower		0.3
Total systematic	11	7.9
Statistical	31	
Total	33	32



Rare decays: $H \rightarrow cc$

2-dimensional signal strength fit,
top CR, background composition

