Searches for exotic decays of the Higgs boson and additional scalar particles in ATLAS

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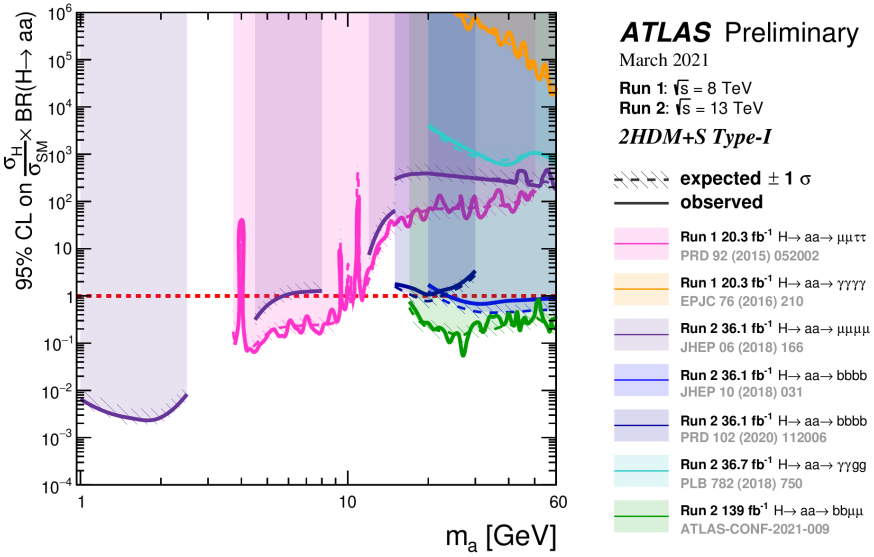
TeVPA 2021, 29th October 2021



BERKELEY LAB

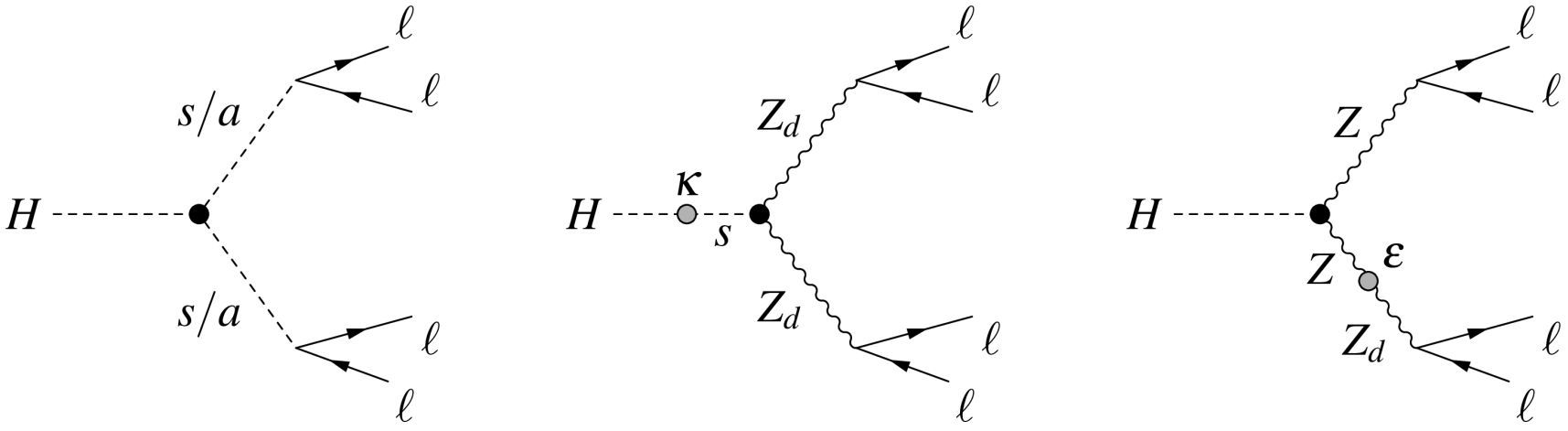
ATLAS EXPERIMENT

Introduction

- The discovery of a Higgs boson with a mass of about 125 GeV **completed** the particle content of the Standard Model (SM) ✓
- Many observations are **yet to be explained**, and extensions to the SM might address these shortcomings
  - Naturalness
  - Dark matter, perhaps via a Higgs portal
  - Baryon asymmetry
  - Diffuse gamma-ray excess from the galactic center
  - $g-2$ anomaly
- Many such models introduce additional Higgs-like bosons $\rightarrow$ unique window for the discovery of beyond the SM (BSM) physics
- ATLAS Higgs boson measurements set **21%** upper limit at 95% CL on Higgs boson decays to undetected final states
- Small $\Gamma^{\text{SM}}_{h_{125}} \rightarrow$ possible **large BSM branching fractions** $(\mathcal{B})$ ✓
- Searches are presented for BSM Higgs bosons and BSM 125 GeV Higgs boson decays, many using 139 fb^{-1} of 13 TeV pp collision data

$H \to XX/ZX \to 4\ell$ Searches – Overview (1/2)

ATLAS-CONF-2021-034



- **Target signal**: new spin-0 or spin-1 bosons X
  - Possibly a CP-odd (CP-even) Higgs boson a (s), or a dark photon Z_d
- **Searches**:
  - **Low-mass (LM)**: $H \to XX \to 4\mu$ ($1 < m_X < 15$ GeV)
  - **High-mass (HM)**: $H \to XX \to 4\ell$ ($15 < m_X < 60$ GeV), $\ell = e$ or μ
  - **Single Z boson (ZX)**: $H \to ZX \to 4\ell$ ($15 < m_X < 55$ GeV)
- **Triggers**: single- and di-lepton

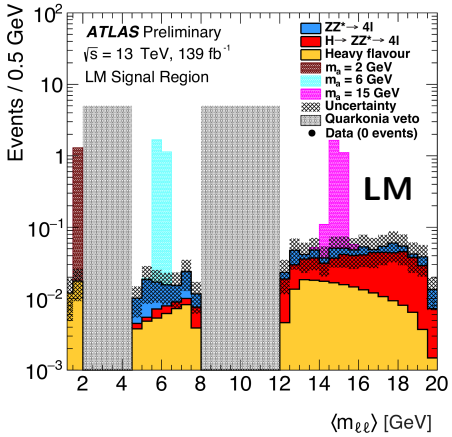
$H \to XX/ZX \to 4\ell$ Searches – Overview (2/2)

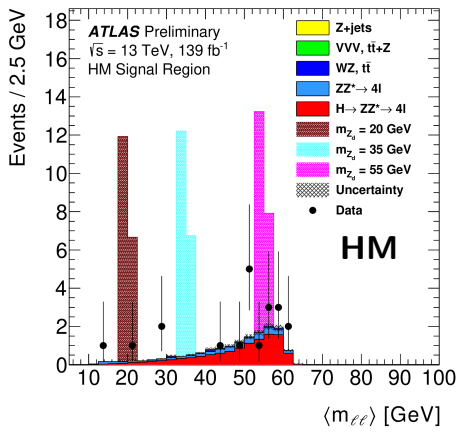
ATLAS-CONF-2021-034

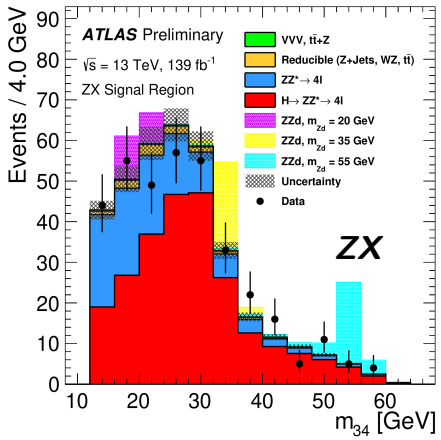
- **Selection overview**: quadruplets of same-flavour opposite-sign di-lepton pairs, with minimum p_{T} cuts, and H, X and Z mass-compatibility requirements where relevant
  - m_{12} and m_{34} defined as invariant masses of di-leptons, with $|m_{12} - m_Z| < |m_{34} - m_Z|$
- **Main backgrounds**: $H \to ZZ^* \to 4\ell$ and $ZZ^* \to 4\ell$
- **Modelling**: signal and main backgrounds modelled in Monte-Carlo simulation (MC), with data-driven $H \to ZZ^*$ normalisation for ZX search
- **Final discriminants**: $\boldsymbol{(m_{12} + m_{34})/2}$ for LM and HM searches, and $\boldsymbol{m_{34}}$ for ZX search
- **Main uncertainties**: data statistics in signal regions (SRs)

$H \to XX/ZX \to 4\ell$ Searches – Results

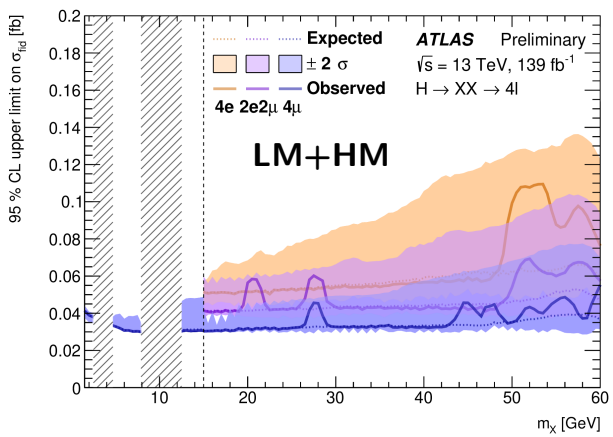
ATLAS-CONF-2021-034

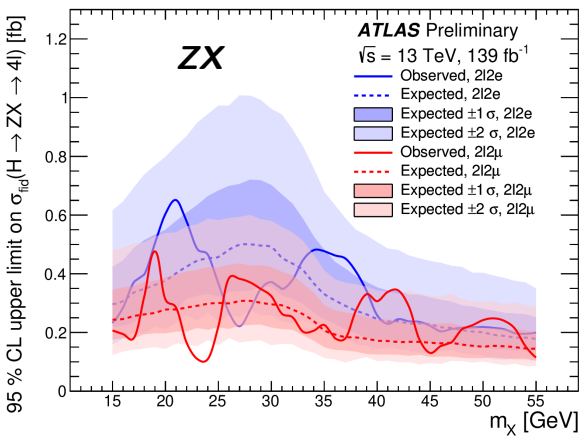






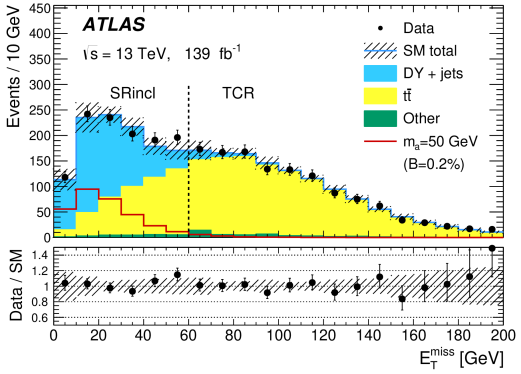
- Largest excess: HM search, $m_{Z_d} = 28$ GeV, **2.5 σ** local significance
- Model independent CL_S upper limits at 95% CL set on fiducial cross sections
- Model dependent upper limits also calculated (backup)

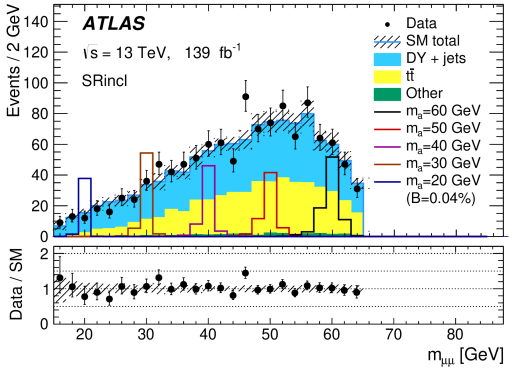


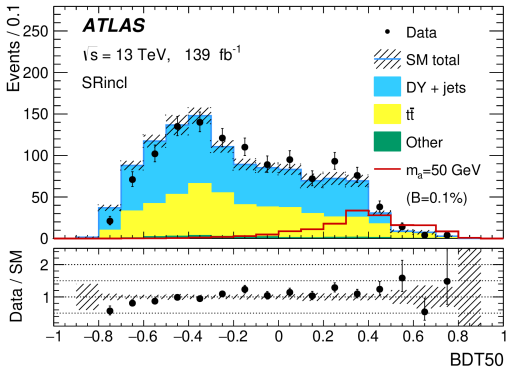


HDBS-2021-03

- **Target signal**: a with $16 < m_a < 62$ GeV
- **Triggers**: single- and di-muon
- **Selection overview**: two opposite-sign muons, two b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}} < 60$ GeV, and boosted decision tree (BDT)
- **Main backgrounds**: $t\bar{t}$ and DY + jets
- **Categorisation**: SR, and two control regions (CRs), one for each main background
- **Modelling**: signal and $t\bar{t}$ shape from MC, DY + jets shape from a 0-b region in data with N_{jet}- and BDT-based corrections from MC, main backgrounds normalised using data
- **Final discriminant**: BDT and $m_{\mu\mu}$
- **Main uncertainties**: data statistics



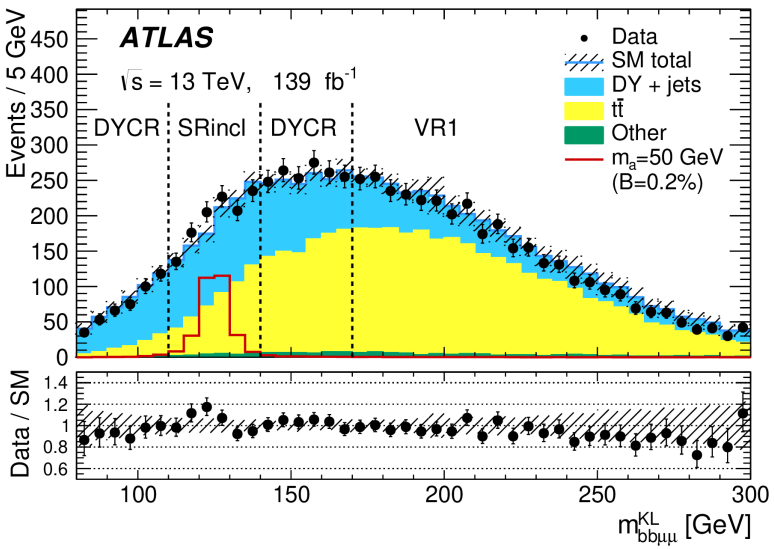


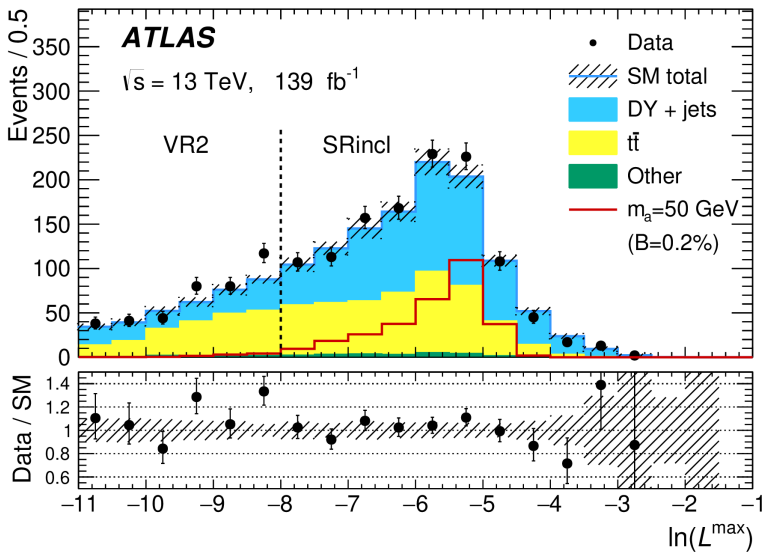


$H \to aa \to bb\mu\mu$ Search – Kinematic Likelihood-Fit

HDBS-2021-03

- Kinematic likelihood fit corrects the jet energies by exploiting the compatible invariant masses of the $a \to \mu\mu$ and $a \to bb$ systems $\to$ better four-body mass resolution and background rejection ✓
- $110 < m^{\mathrm{KL}}_{bb\mu\mu} < 140$ GeV
- $\ln(L^{\max}) > -8$

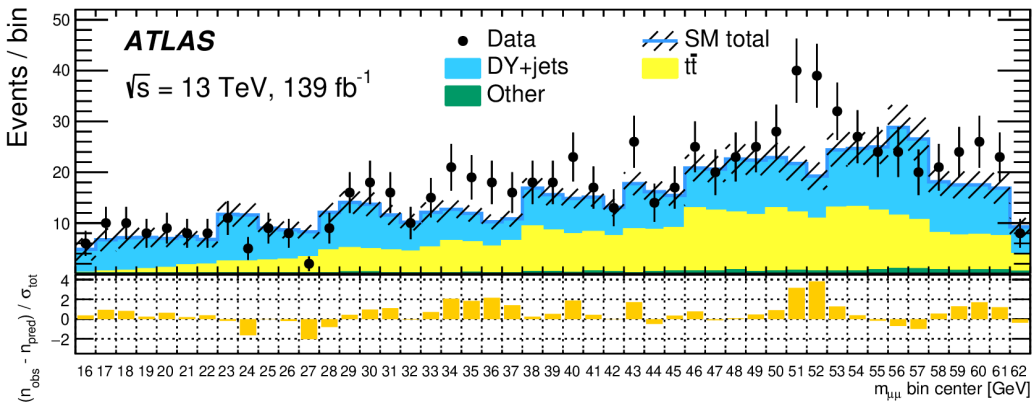


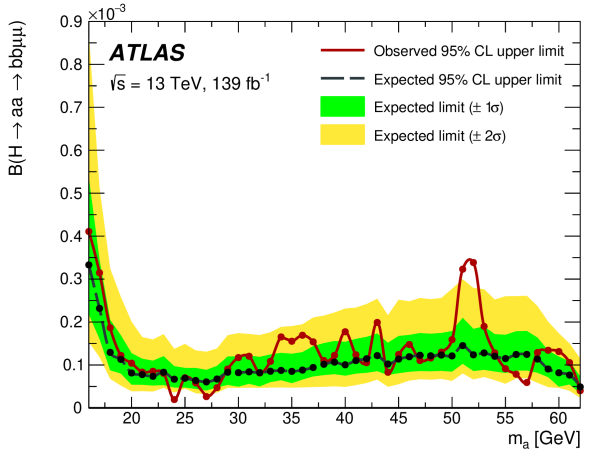


$H \to aa \to bb\mu\mu$ Search – Results

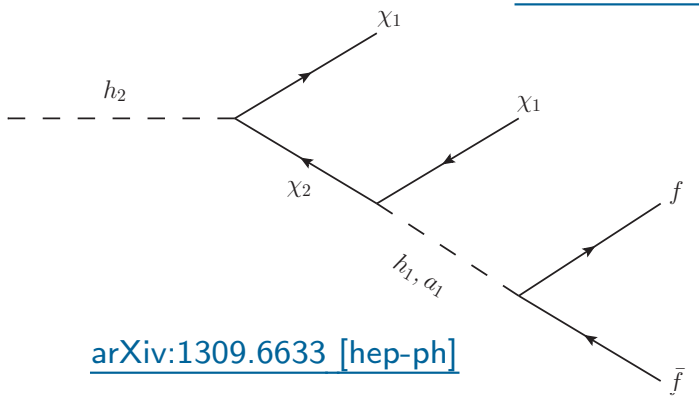
HDBS-2021-03

- Largest excess observed at $m_a = 52$ GeV and corresponds to a local (global) significance of 3.3 σ (**1.7 σ**)
- Binned likelihood fit to event yield in $m_{\mu\mu}$ bin in SR and in $t\bar{t}$ CR, and to $m_{\mu\mu}$ distribution in DY + jets CR used to set CL_S upper limits at 95% CL on $\mathcal{B}(H \to aa \to bb\mu\mu)$
- Limits improved by a factor of **2–5** over the full $m_{\mu\mu}$ range compared to previous ATLAS search ✓





HDBS-2018-07

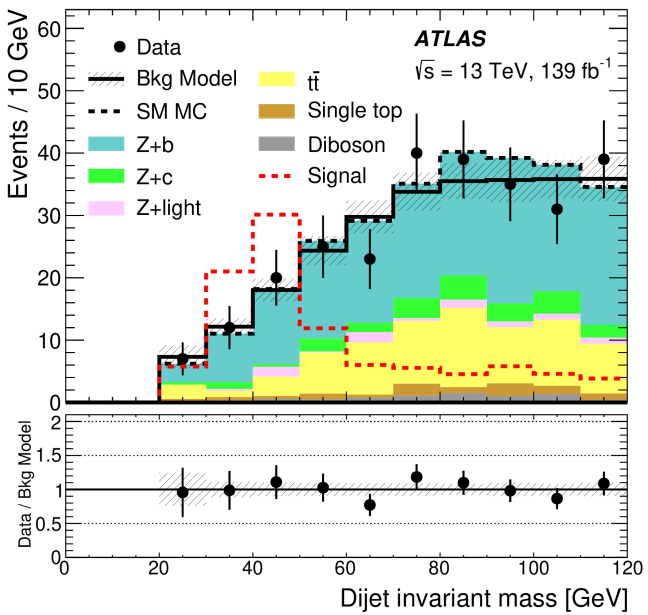


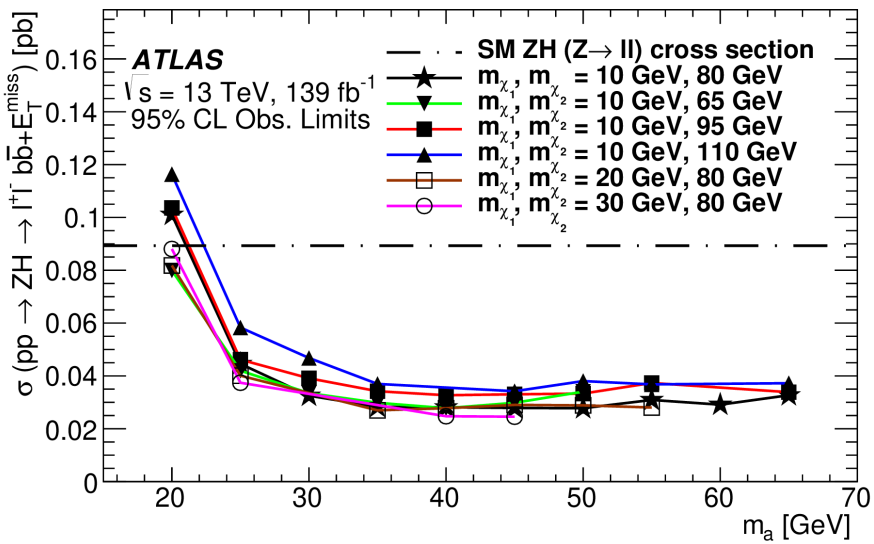
arXiv:1309.6633 [hep-ph]

- **Target signal**: $Z(\ell\ell)H$ production, and cascade decay through neutralinos $\tilde{\chi}_{1/2}^0$ and a, e.g. from Supersymmetry
- **Triggers**: single electron or muon
- **Selection overview**: di-lepton system compatible with Z, ≥ 2 jets with ≥ 1 b-tag, $E_{\text{T}}^{\text{miss}} > 100$ GeV, $0.8 < (p_{\text{T}}^{\text{jj}} + E_{\text{T}}^{miss})/p_{\text{T}}^{\ell\ell} < 1.2$
- **Main backgrounds**: $Z + \text{HF}$ and $t\bar{t}$
- **Categorisation**: SR, and CRs for $Z + \text{HF}$ and $t\bar{t}$ backgrounds
- **Modelling**: Signal modelled using MC, and $Z + \text{HF}$ and $t\bar{t}$ estimates from data CRs with MC-based corrections for SR/CR normalisations and to $Z + \text{HF}$ shape
- **Final discriminant**: m_{jj}, of two highest p_{T} jets, with ≥ 1 b-tag
- **Main uncertainties**: data statistics, background normalisation

HDBS-2018-07

- Binned likelihood fit to m_{jj} distribution used to set CL_S upper limits at 95% CL on $\mathcal{B}(H \to \tilde{\chi}_1^0\tilde{\chi}_2^0 \to a\tilde{\chi}_1^0\tilde{\chi}_1^0 \to bb\tilde{\chi}_1^0\tilde{\chi}_1^0)$ for a three-dimensional scan of the $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and a masses
- **First direct LHC limits** on this exotic Higgs boson decay ✓

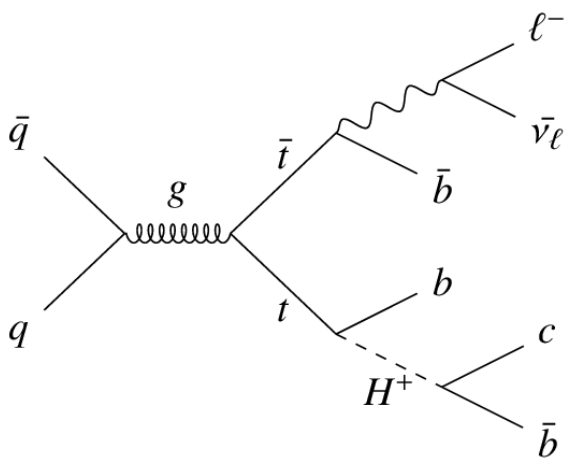


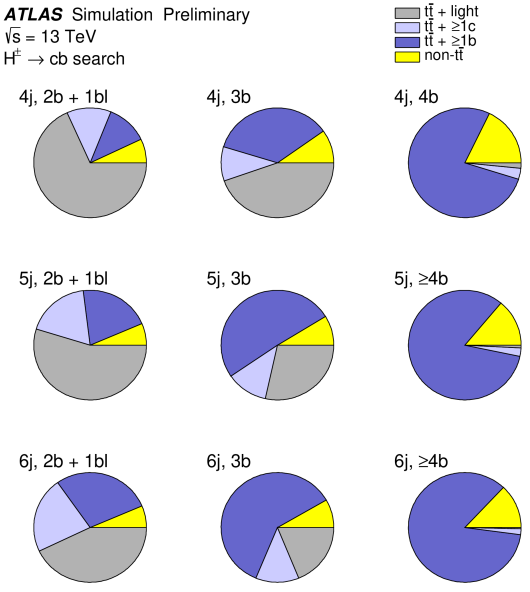


$tt \to tH^{\pm}b$, $H^{\pm} \to cb$ Search – Overview

ATLAS-CONF-2021-037

- **Target signal**: $H^{\pm}$ with $60 < m_{H^{\pm}} < 160$ GeV
- **First search of its kind** by ATLAS ✓
- **Triggers**: single-electron or single-muon
- **Selection overview**: 1 electron or muon, ≥ 4 jets with ≥ 2 b-tag
- **Main background**: $t\bar{t} + \text{HF}$
- **Categorisation**: 9 N_{jet} and $N_{b\text{-tag}}$ categories
- **Modelling**: MC used, with data-driven correction for $t\bar{t}$ background
- **Final discriminant**: **neural network** (NN), parameterised in $m_{H^{\pm}}$
- **Main uncertainties**: c-tagging calibration, light-jet mis-tagging rate, $t\bar{t}$ NLO generator, and $t\bar{t} + \text{HF}$ normalisation

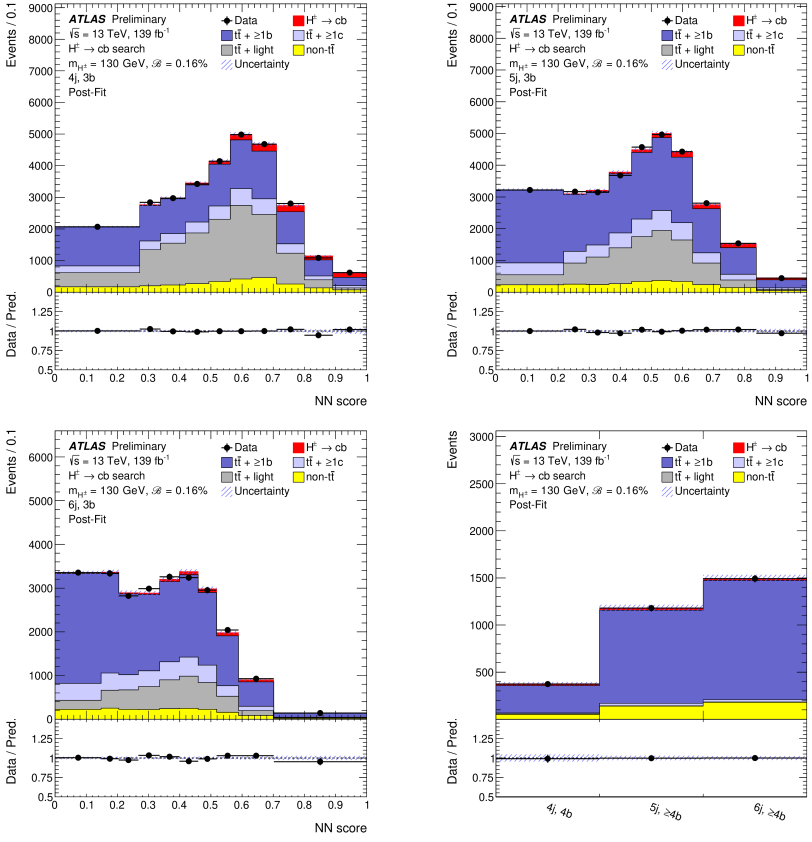


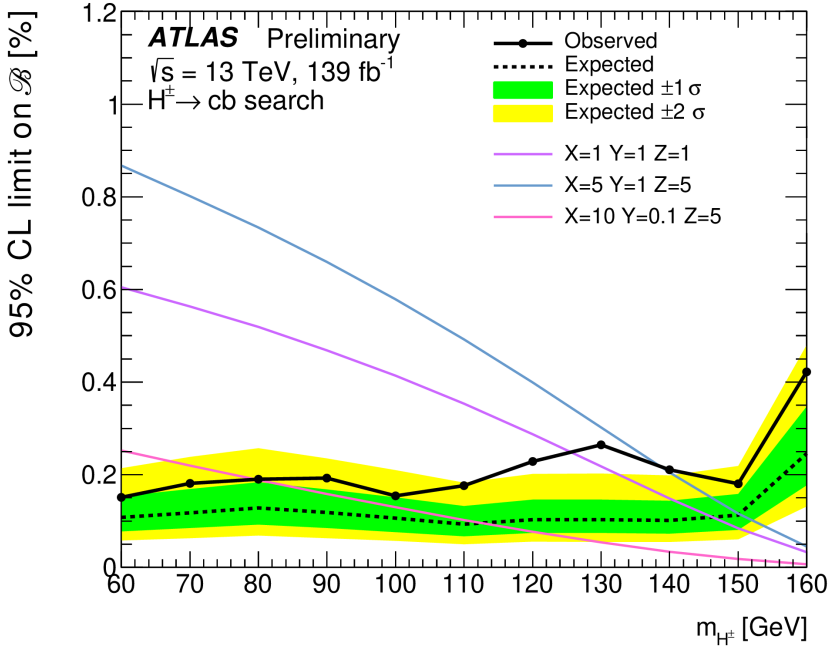


$tt \to tH^{\pm}b$, $H^{\pm} \to cb$ Search – Results

ATLAS-CONF-2021-037

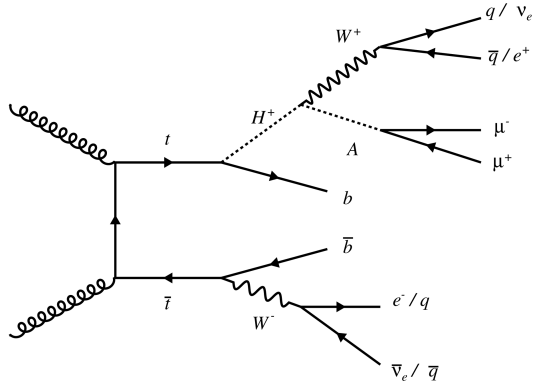
- Largest local (global) excess of 3 σ (**1.6 σ**) seen at $m_{H^{\pm}} = 130$ GeV
- Binned likelihood fit to NN output or yield after NN cut in 6 event categories used to set CL_S upper limits at 95% CL

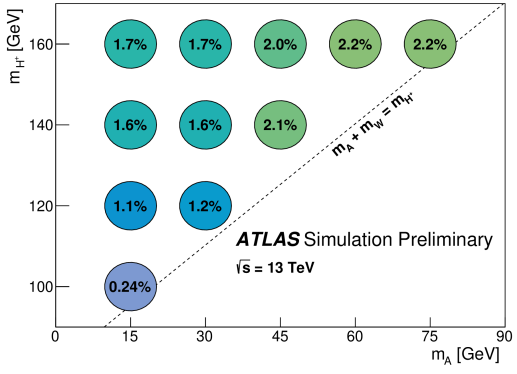




ATLAS-CONF-2021-047

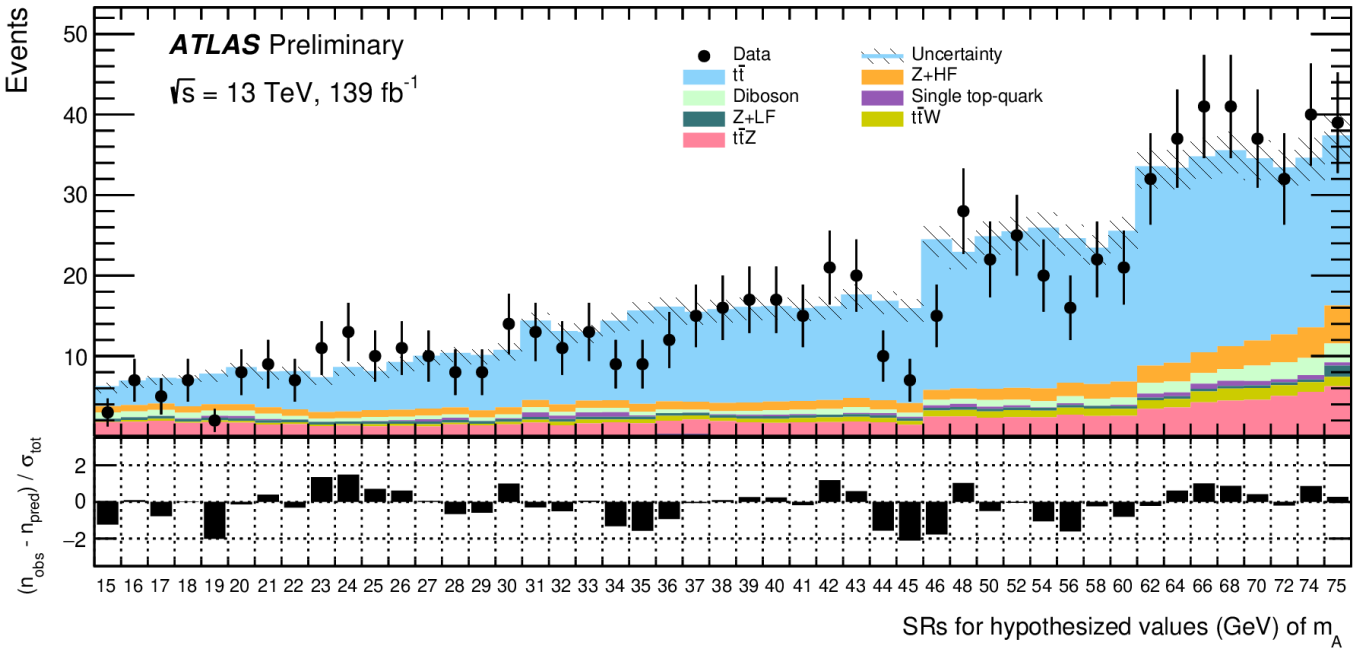
- **Target signal**: $H^{\pm}$ with $60 < m_{H^{\pm}} < 160$ GeV and A with $15 < m_A < 75$ GeV
- Bosonic decay modes of $H^{\pm}$ were recently described as "forgotten channels" ✓
- **First search of its kind** by ATLAS ✓
- **Triggers**: single- and di-muon
- **Selection overview**: 1 electron, 2 opposite-sign muons, ≥ 3 jets with ≥ 1 b-tag
  - $p_{\mathrm{T}}(\mu^{\mathrm{SS}})/p_{\mathrm{T}}(\mu^{\mathrm{OS}}) > 0.2$
  - No explicit $H^{\pm}$ reconstruction
- **Main background**: $t\bar{t}$
- **Categorisation**: SR, and 3 CRs for $t\bar{t}$, $Z + \mathrm{HF}$, $t\bar{t}Z$
- **Modelling**: MC used, with background normalisations determined in data CRs





ATLAS-CONF-2021-047

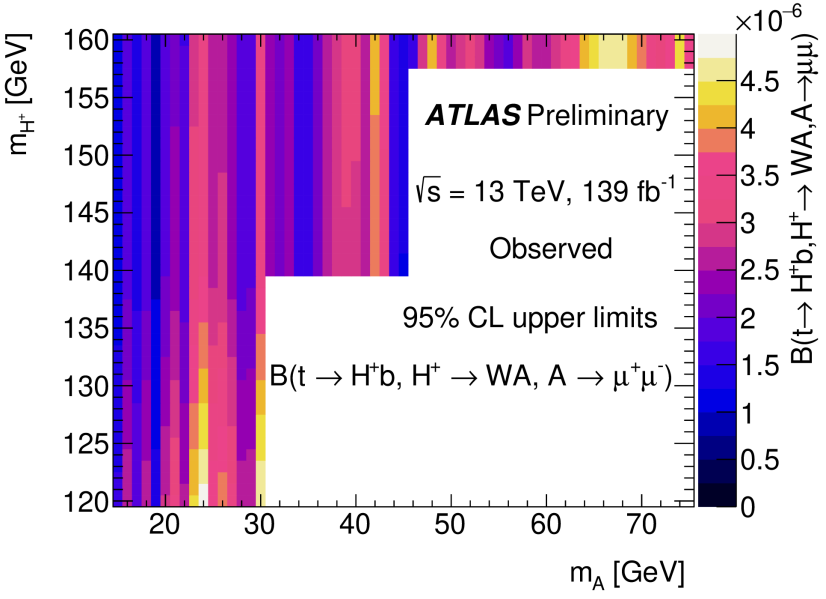
- **Final discriminant**: $m_{\mu\mu}$
- **Main uncertainties**: data statistics, $t\bar{t}$ and $t\bar{t}Z$ normalisations, $t\bar{t}$ hard-scatter and parton shower modelling, MC statistics
- No significant excess observed, with largest excess being 1.24 σ

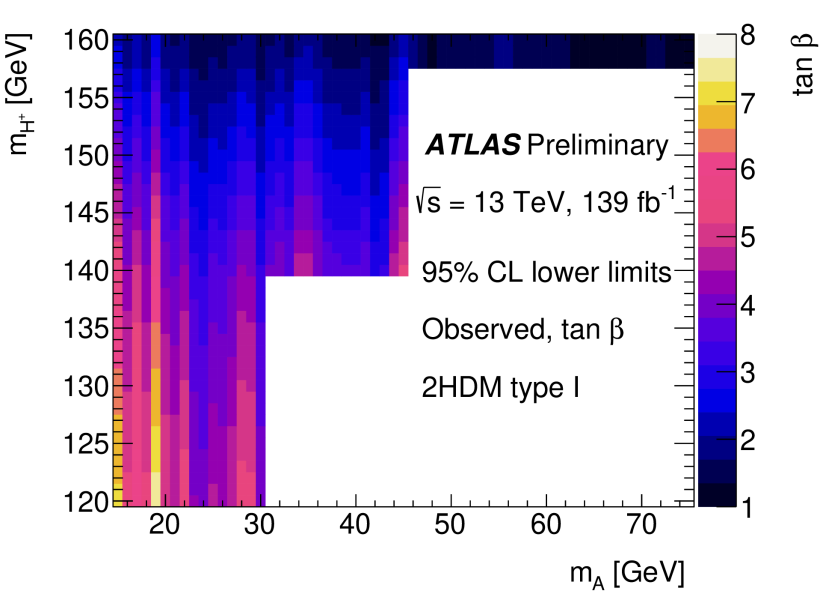


$tt \to tH^{\pm}b$, $H^{\pm} \to WA$, $A \to \mu\mu$ Search – Limits

ATLAS-CONF-2021-047

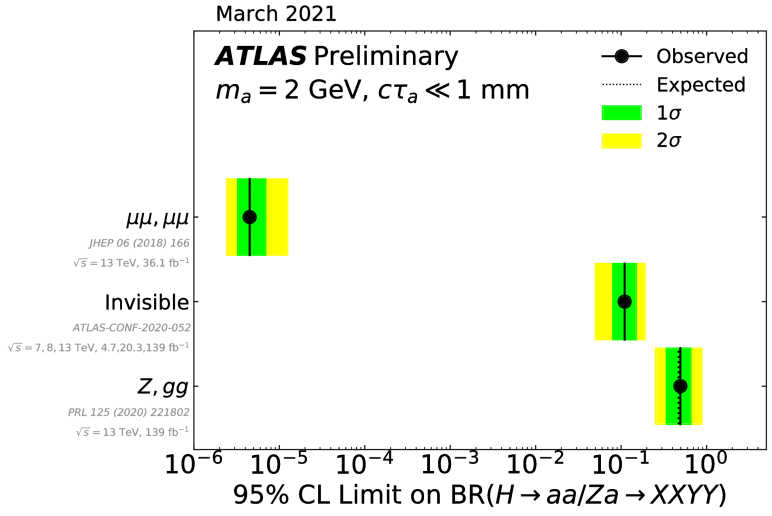
- Likelihood fit to event yield in single $m_{\mu\mu}$ bins used to set CL_S upper limits at 95% CL on $\mathcal{B}(t \to bH\pm) \times \mathcal{B}(H^{\pm} \to W^{\pm}A) \times \mathcal{B}(A \to \mu\mu)$
- **First lower limits on tan β** in the $m_{H^{\pm}}$, m_A space of the type-I 2HDM set using 2HDMC, under scenarios for m_H and m_{12}^2 ✓

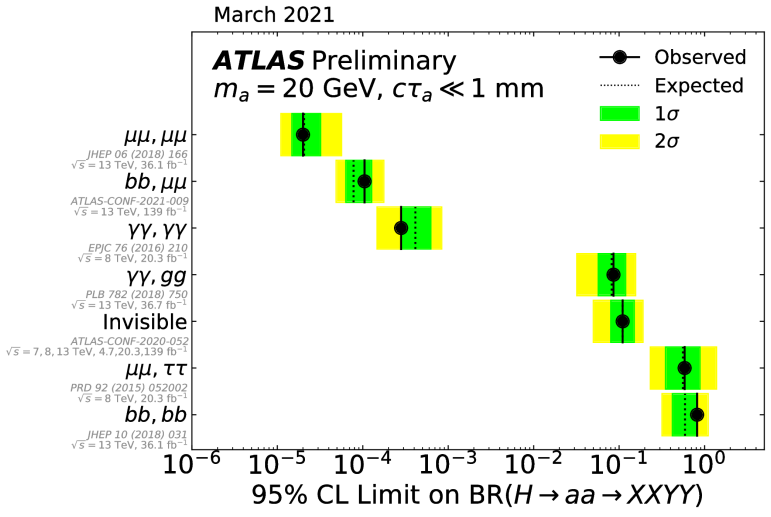


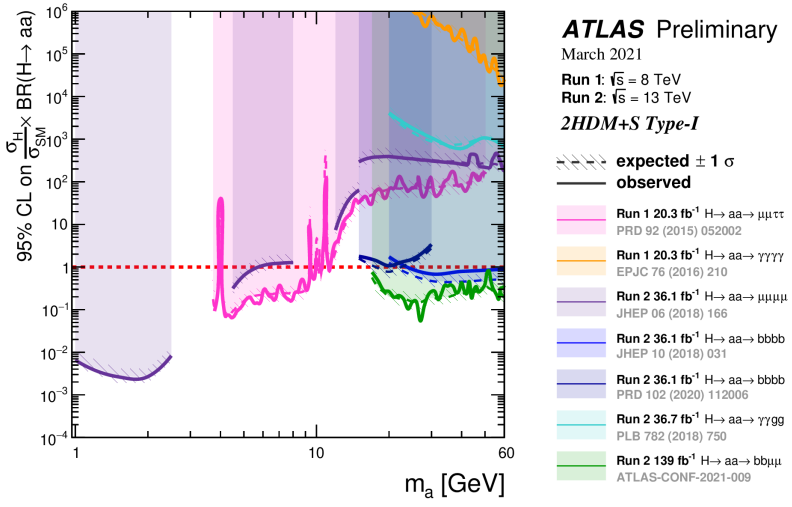


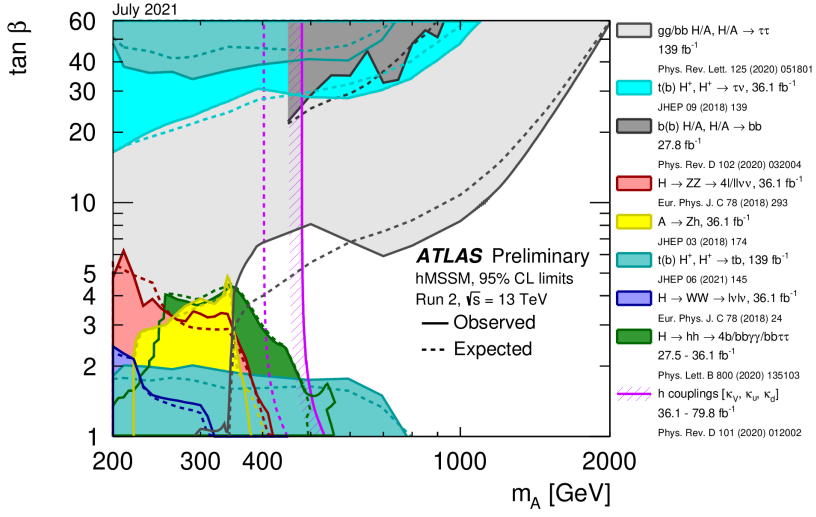
Summary Plots

ATL-PHYS-PUB-2021-008 and ATL-PHYS-PUB-2021-030









Incomplete list of additional ATLAS BSM Higgs sector searches

Channel	Luminosity	Result
$H^0 \to \gamma\gamma$	139 fb^{-1}	Mass-dependent limits
$tbH^{\pm}, H^{\pm} \to tb$	139 fb^{-1}	Limits in range 0.036–3.6 pb
$H^{-}H^{++} \to W^{-}ZW^{+}W^{+}$	139 fb^{-1}	Limits up to 230 GeV
$H^{--}H^{++} \to W^{-}W^{-}W^{+}W^{+}$	139 fb^{-1}	Limits up to 350 GeV
$A \to ZH^0 \to \ell\ell(bb/WW)$	139 fb^{-1}	Limits in range 6.2–380/23–8900 fb
$H^0 \to ZZ \to \ell\ell(\ell\ell/\nu\nu)$	139 fb^{-1}	Limits in range 1.9–87 fb for spin-0 H^0 in NWA
$H \to aa \to bbbb$	36 fb^{-1}	Limits as stringent as 0.71 pb
$H \to Za \to \ell\ell\mathrm{j}$	139 fb^{-1}	Limits in range 17–340 pb
$H^0 \to \tau\tau$	139 fb^{-1}	MSSM tan β-dependent limits

H^0 is a heavy BSM Higgs boson

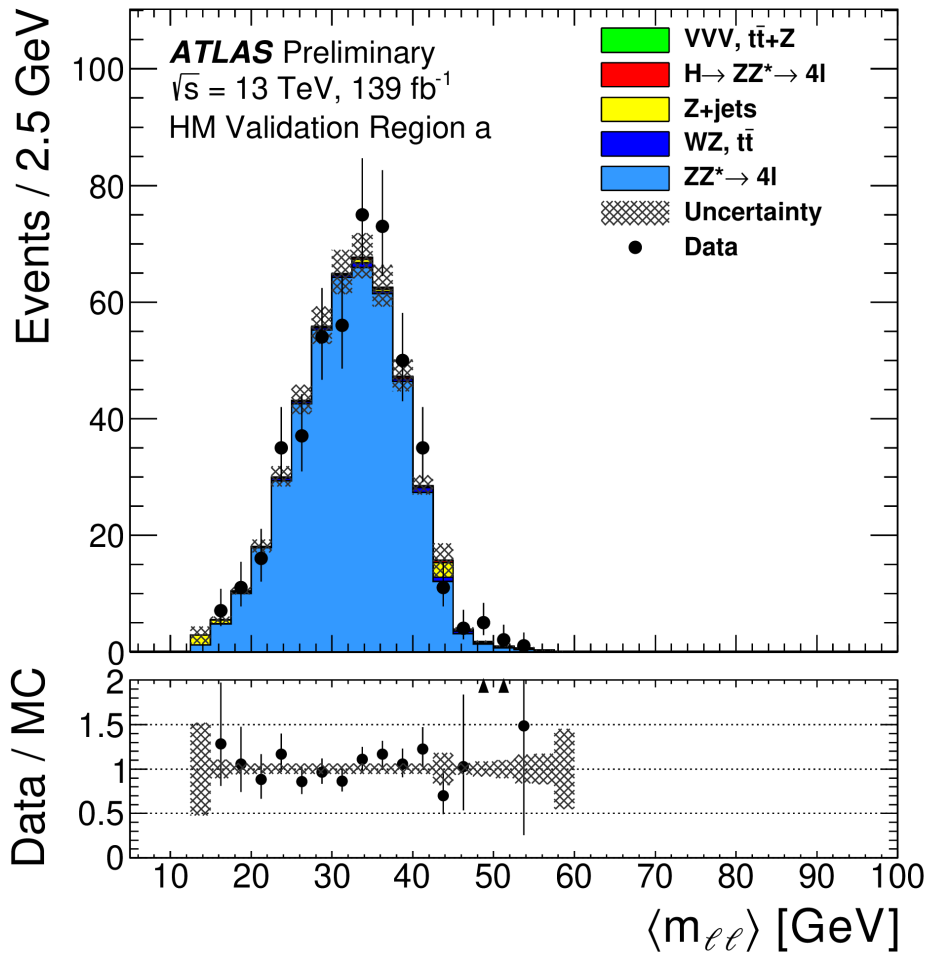
H is the observed 125 GeV Higgs boson

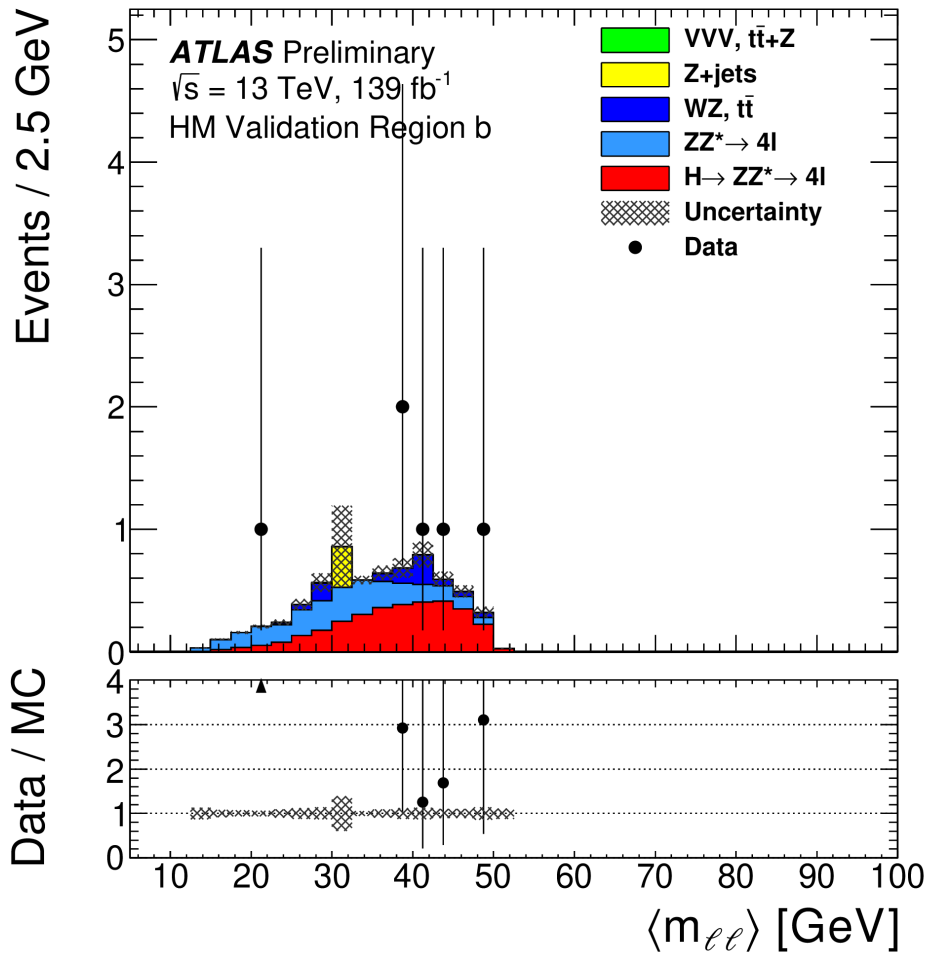
Limits are $\mathrm{CL_S}$ upper limits at 95% CL

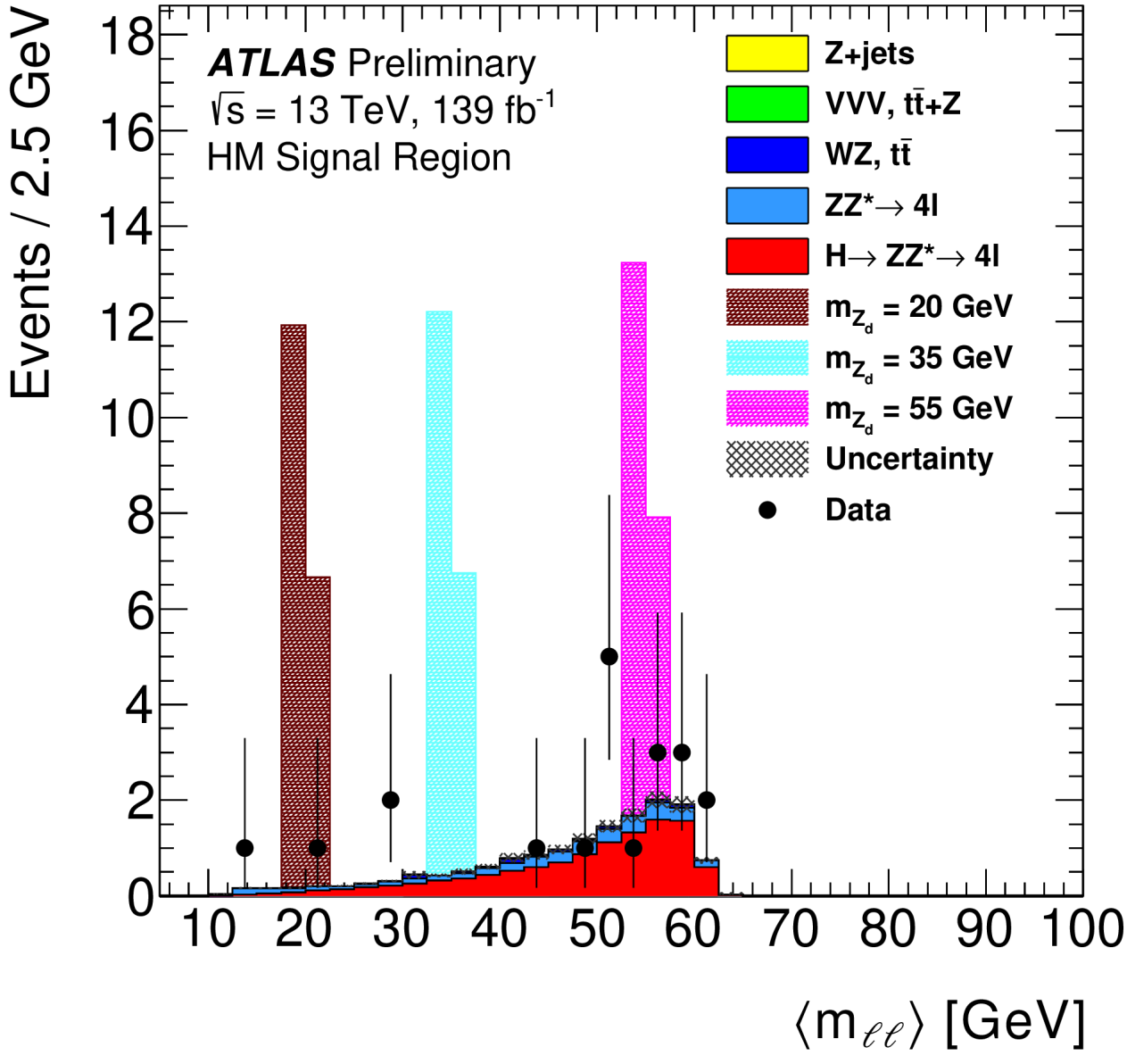
Backup Slides

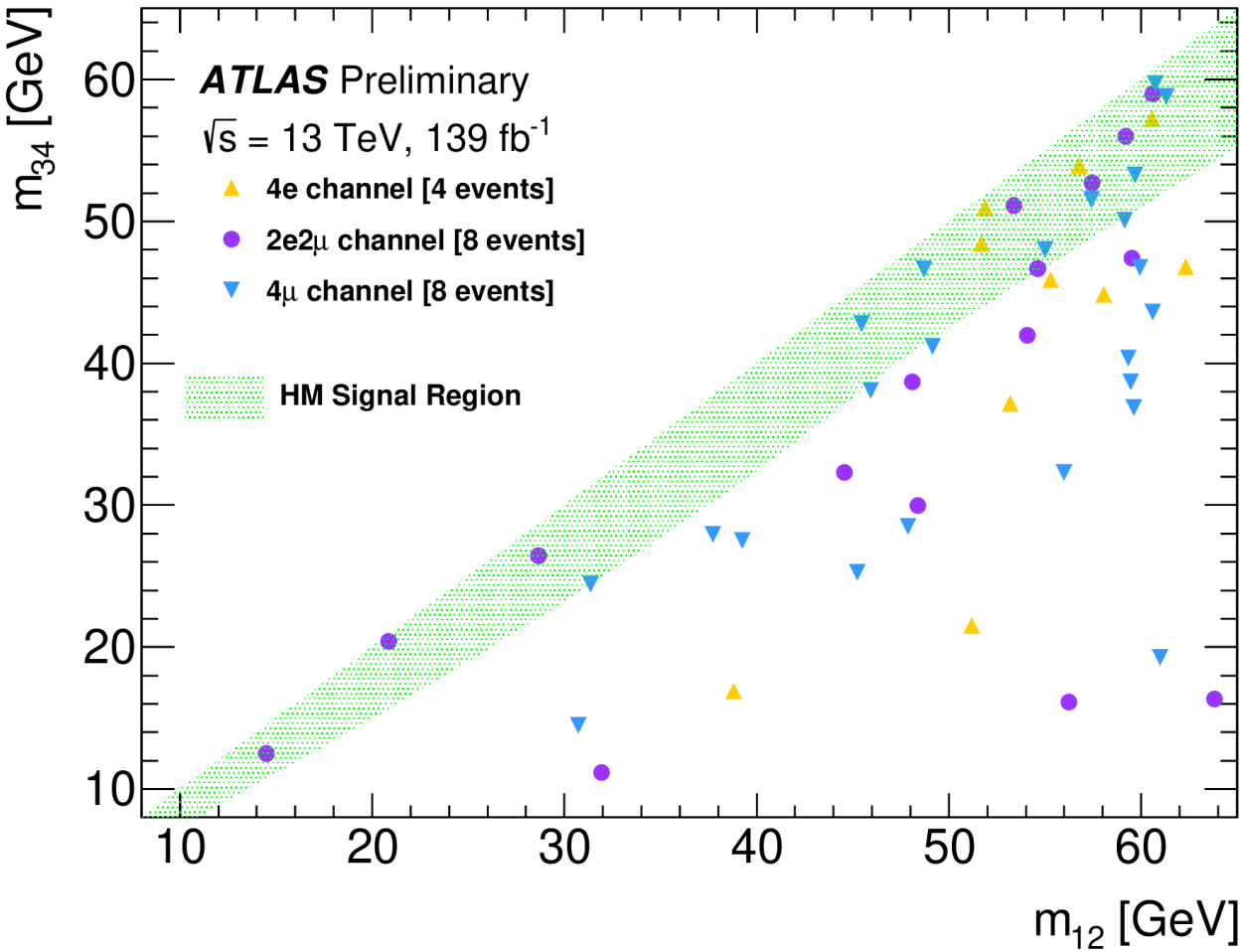
- Searches in this talk have limits set at the 95% confidence level (CL) using the CL_S procedure
- The test statistic used is based on the profile likelihood ratio
- Asymptotic formulae are often used

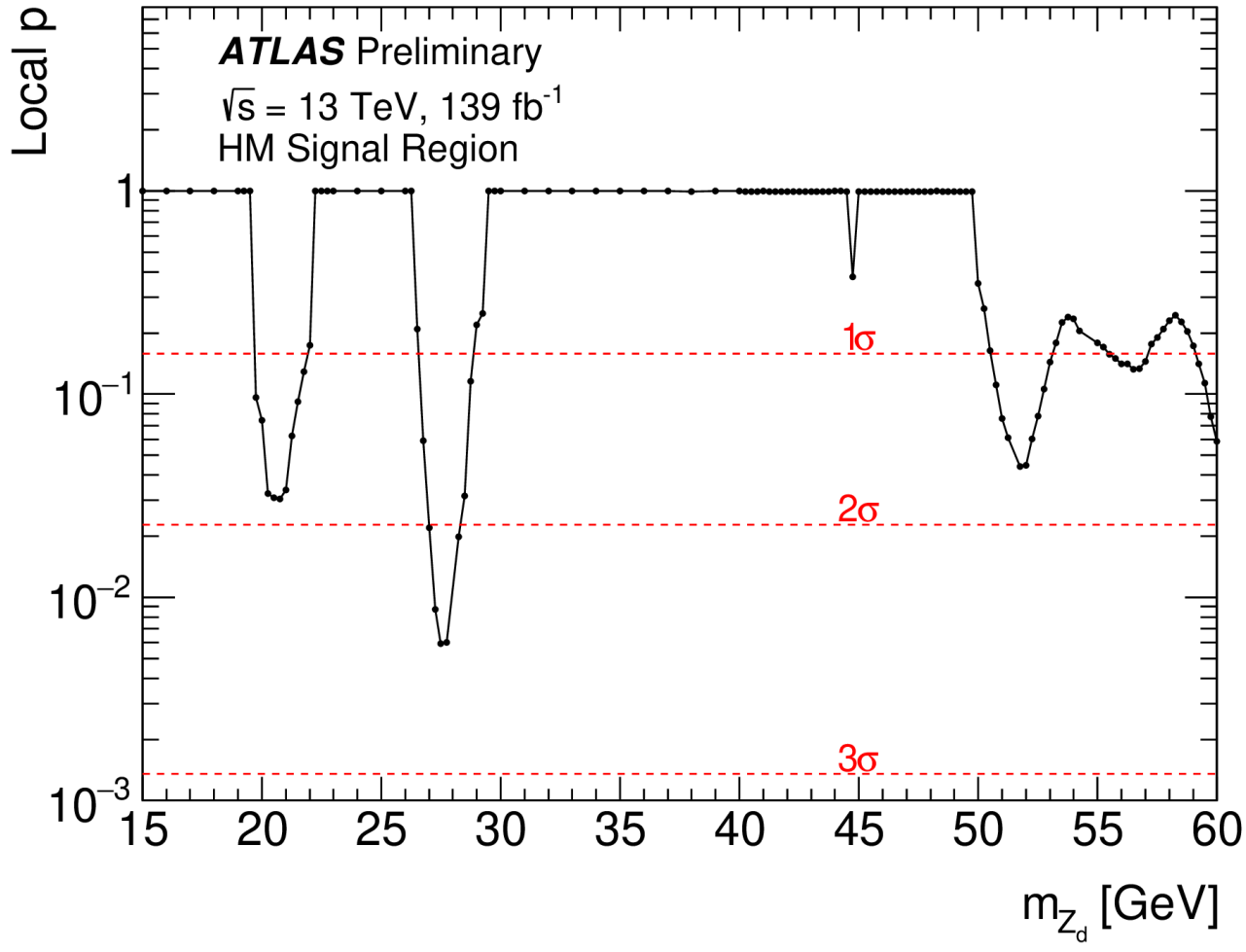
$H \to XX/ZX \to 4\ell$ Searches

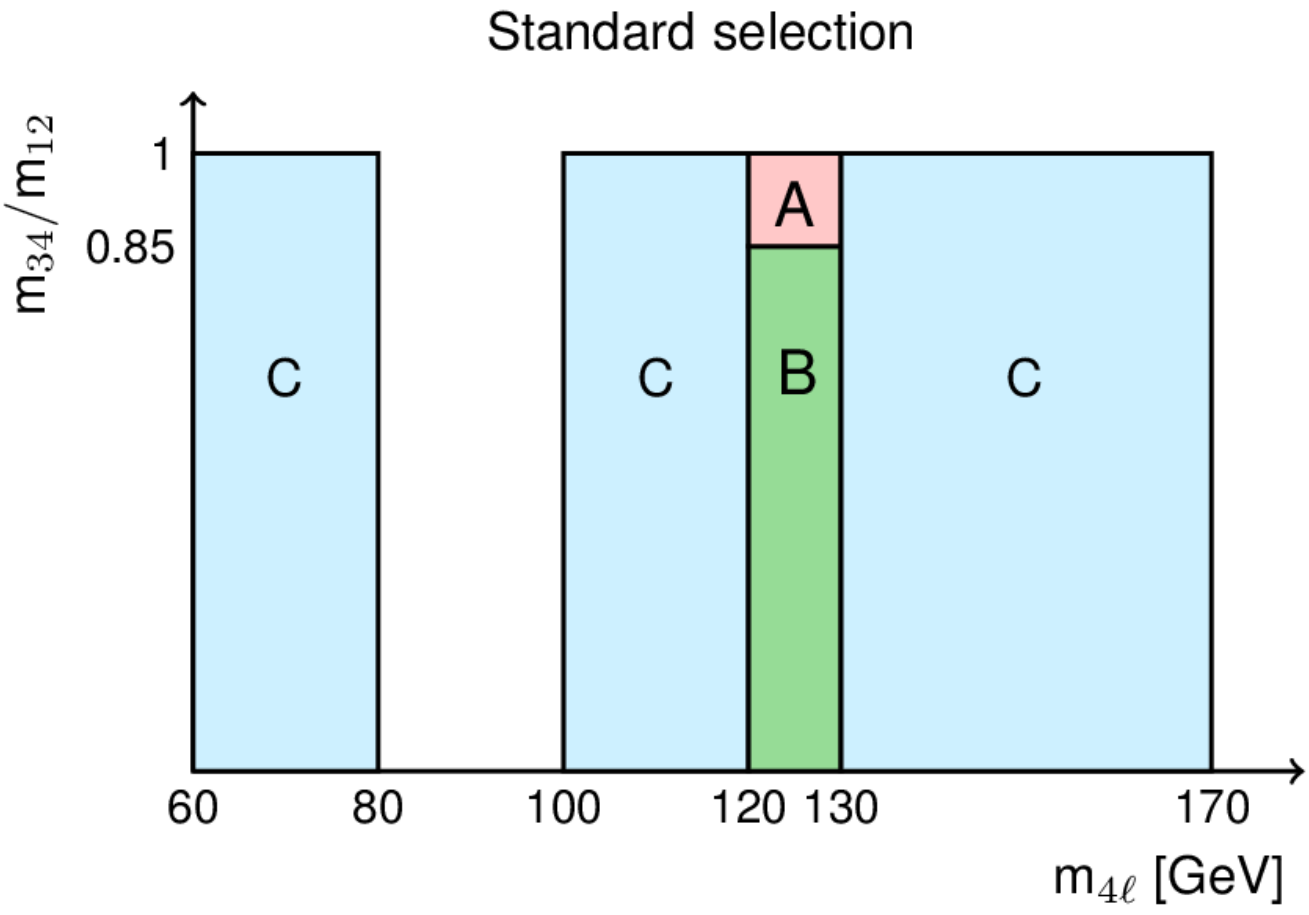

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
HM Validation Region a
VVV, tt̄+Z
H→ ZZ*→ 4l
Z+jets
WZ, tt̄
ZZ*→ 4l
Uncertainty
Data
Events / 2.5 GeV
Data / MC
⟨mℓℓ⟩ [GeV]

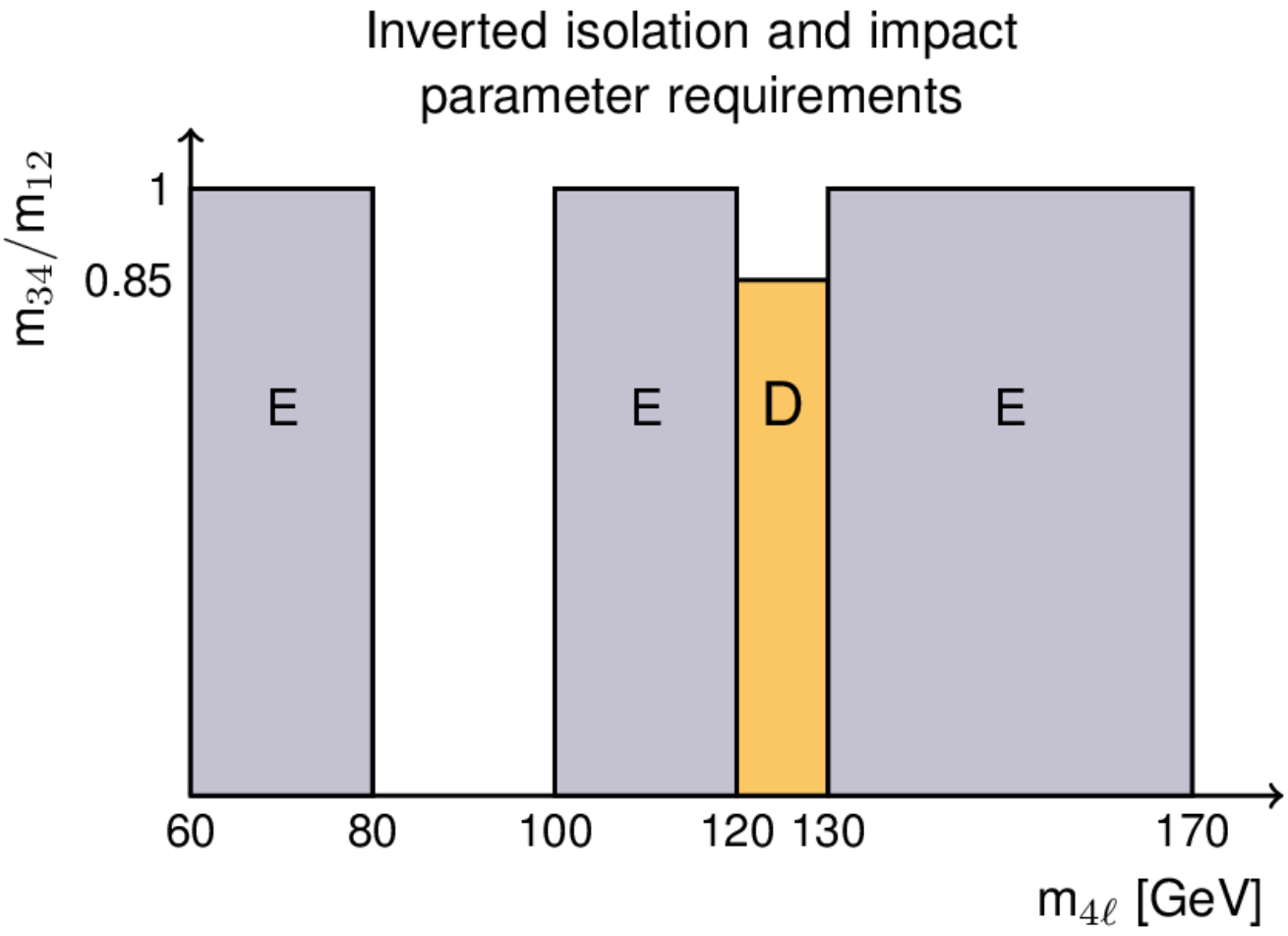

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
HM Validation Region b
VVV, tt̄+Z
Z+jets
WZ, tt̄
ZZ*→ 4l
H→ ZZ*→ 4l
Uncertainty
Data
Events / 2.5 GeV
Data / MC
⟨mℓℓ⟩ [GeV]

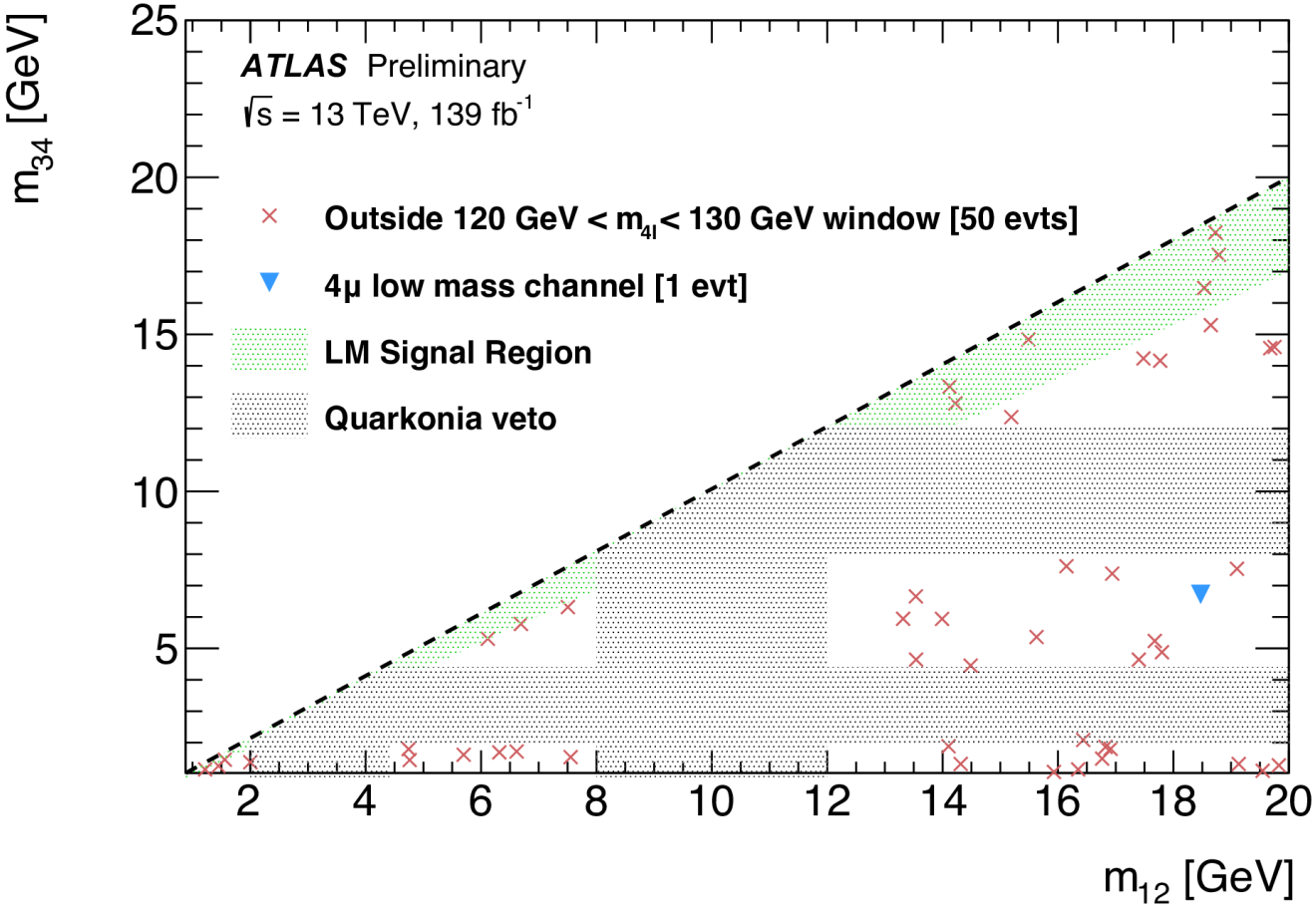

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
HM Signal Region
Z+jets
VVV, tt̄+Z
WZ, tt̄
ZZ*→ 4l
H→ ZZ*→ 4l
mZd = 20 GeV
mZd = 35 GeV
mZd = 55 GeV
Uncertainty
Data
Events / 2.5 GeV
⟨mℓℓ⟩ [GeV]
0
2
4
6
8
10
12
14
16
18
10
20
30
40
50
60
70
80
90
100

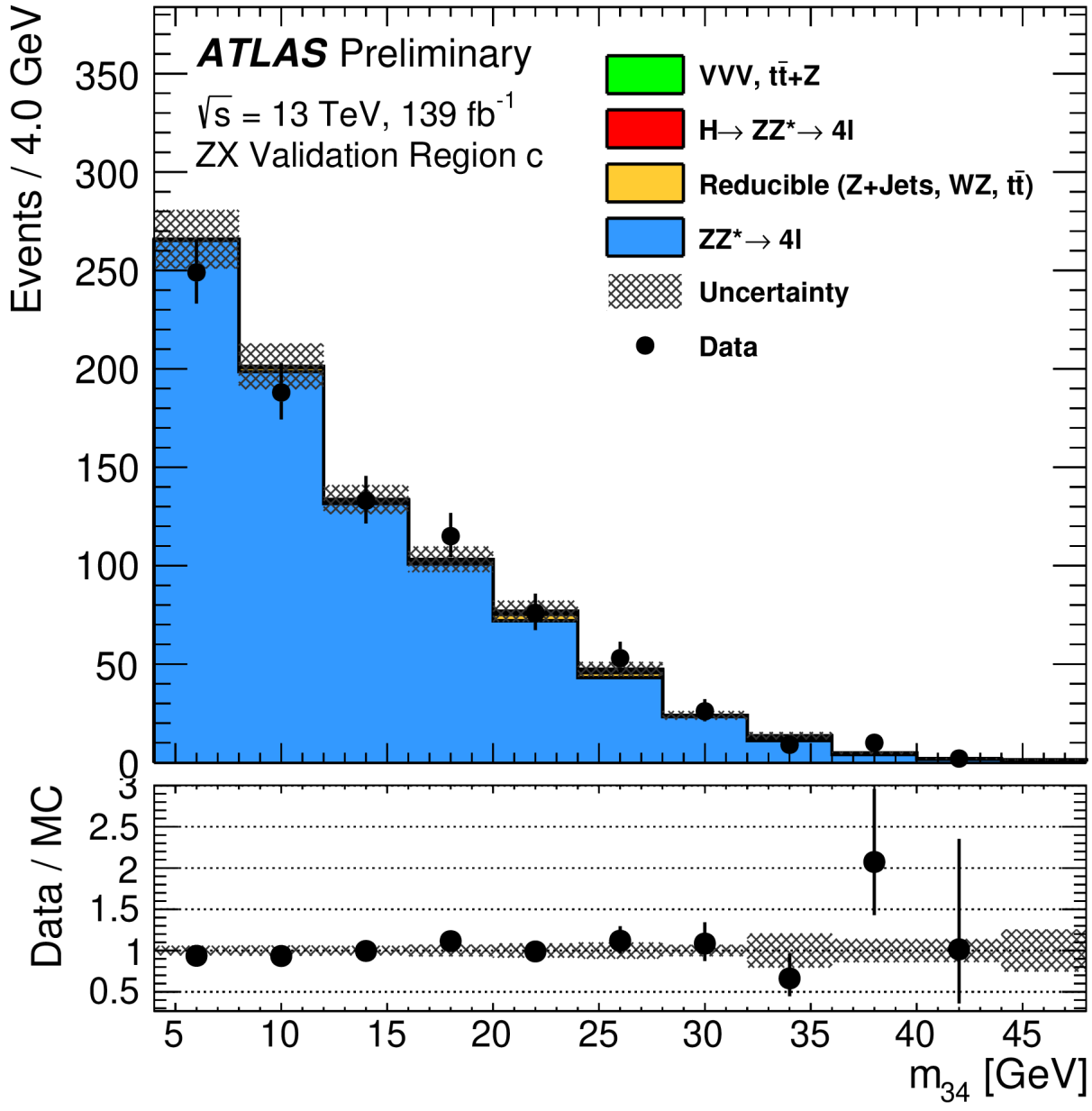

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
4e channel [4 events]
2e2μ channel [8 events]
4μ channel [8 events]
HM Signal Region
m34 [GeV]
m12 [GeV]
10
20
30
40
50
60

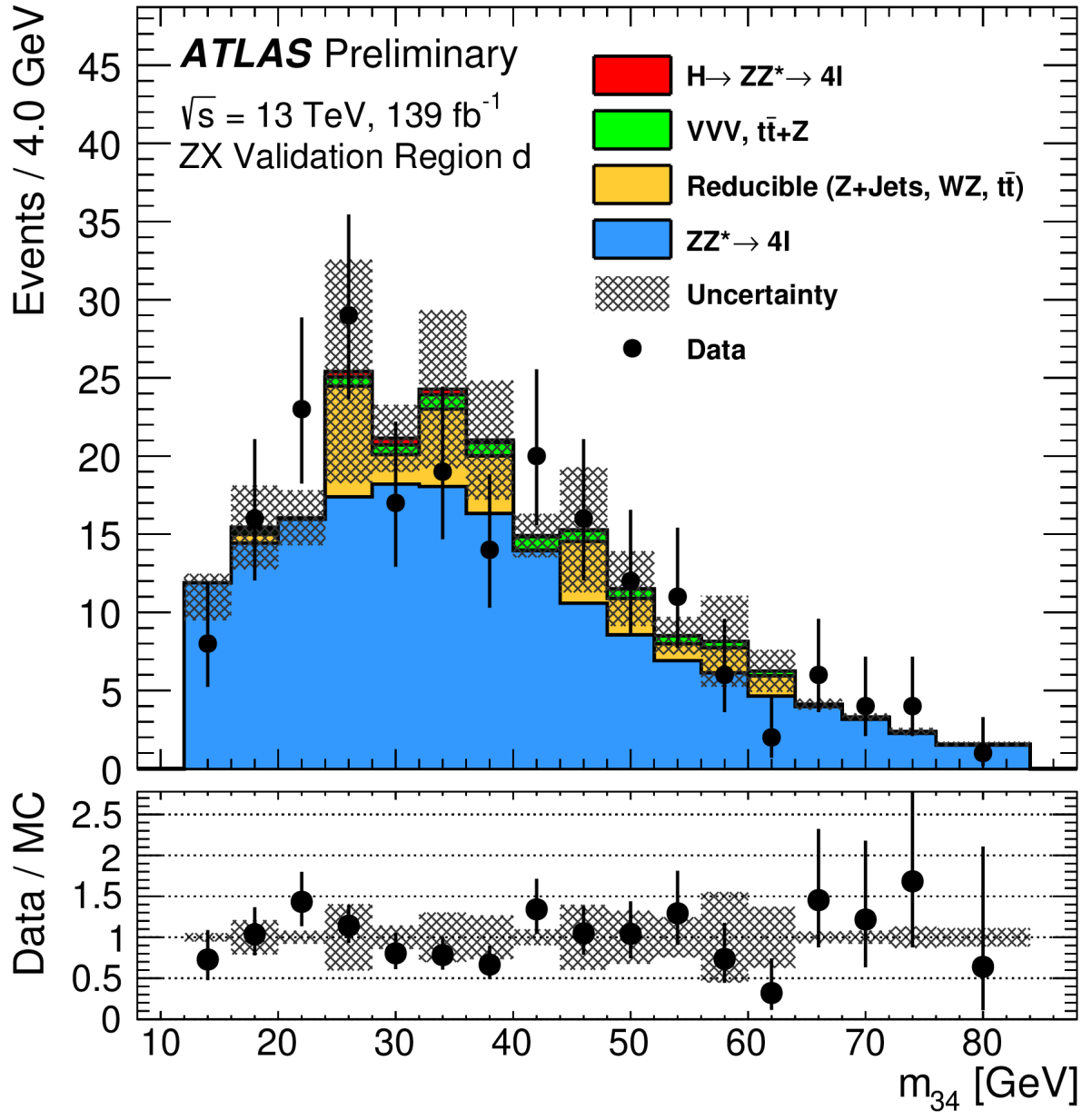

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
HM Signal Region
Local p
1
10−1
10−2
10−3
1σ
2σ
3σ
15
20
25
30
35
40
45
50
55
60
mZd [GeV]

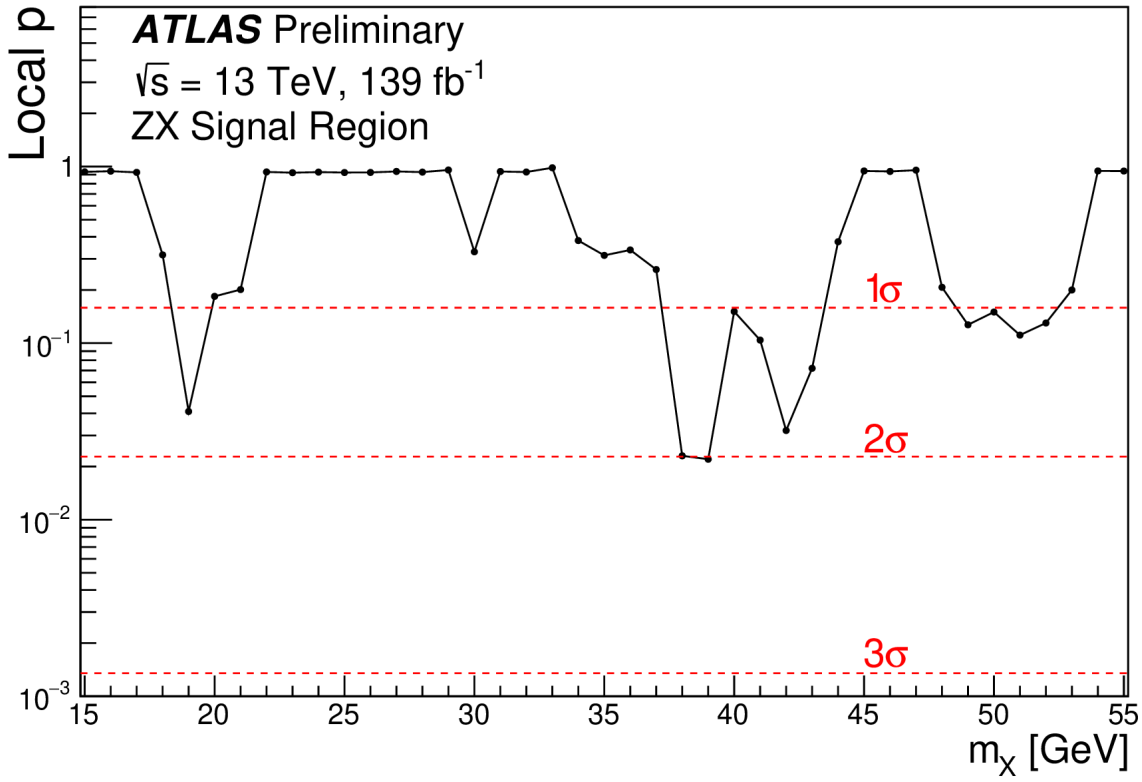

Standard selection
m_{34}/m_{12}
1
0.85
A
B
C
C
C
60
80
100
120
130
170
$m_{4\ell}$ [GeV]

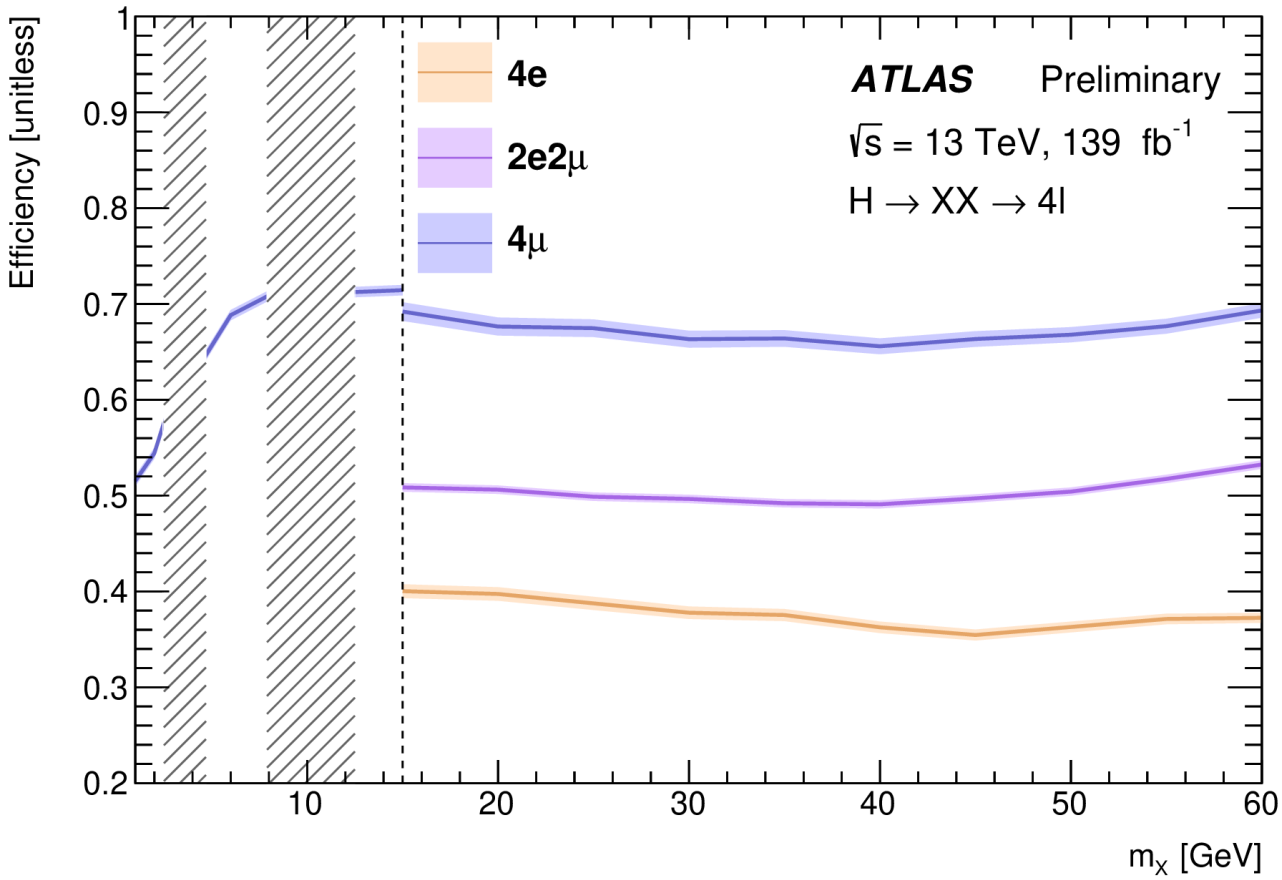

Inverted isolation and impact parameter requirements
m_{34}/m_{12}
1
0.85
E
E
D
E
60
80
100
120
130
170
$m_{4\ell}$ [GeV]

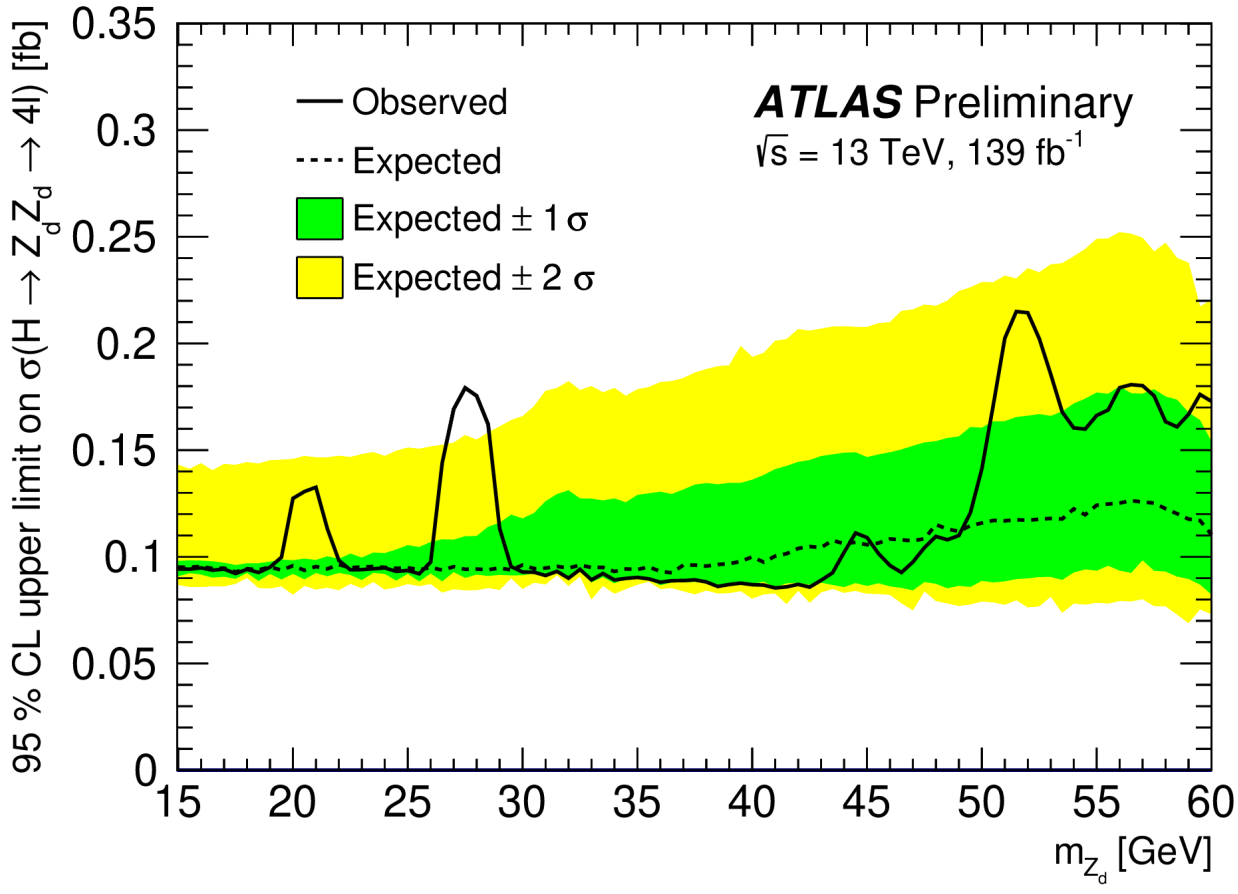

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Outside 120 GeV < m4l < 130 GeV window [50 evts]
4μ low mass channel [1 evt]
LM Signal Region
Quarkonia veto
m34 [GeV]
m12 [GeV]
25
20
15
10
5
2
4
6
8
10
12
14
16
18
20

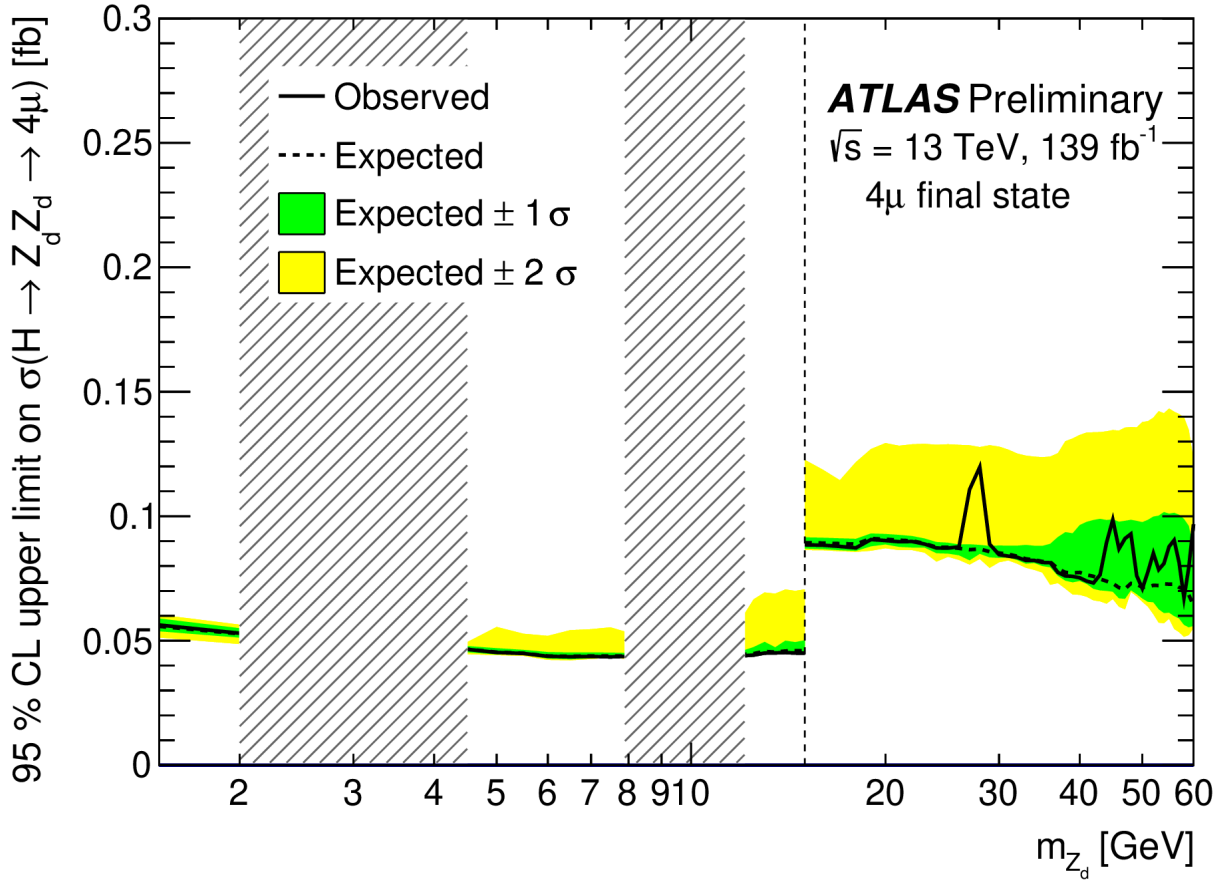

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
ZX Validation Region c
VVV, tt̄+Z
H→ ZZ*→ 4l
Reducible (Z+Jets, WZ, tt̄)
ZZ*→ 4l
Uncertainty
Data
Events / 4.0 GeV
Data / MC
m34 [GeV]

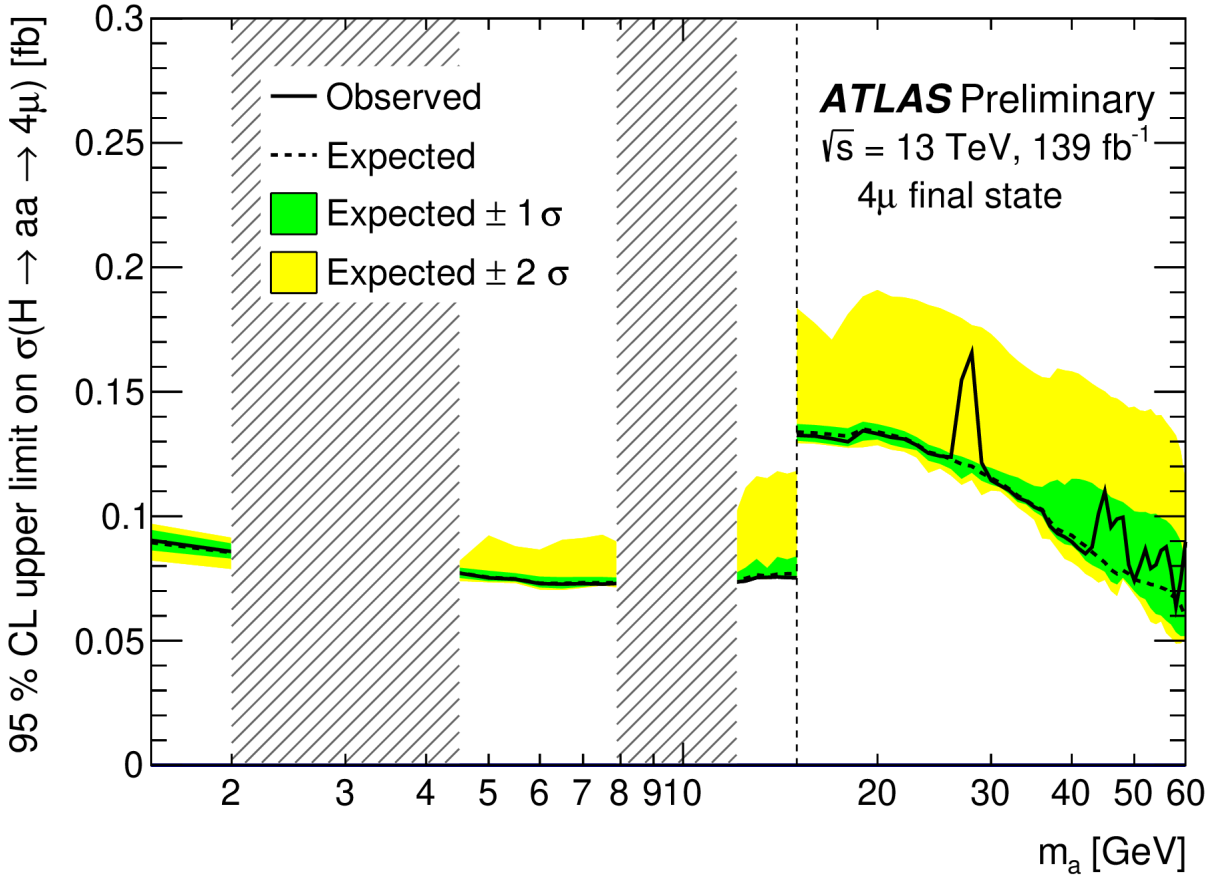

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
ZX Validation Region d
H→ ZZ*→ 4l
VVV, tt̄+Z
Reducible (Z+Jets, WZ, tt̄)
ZZ*→ 4l
Uncertainty
Data
Events / 4.0 GeV
Data / MC
m34 [GeV]

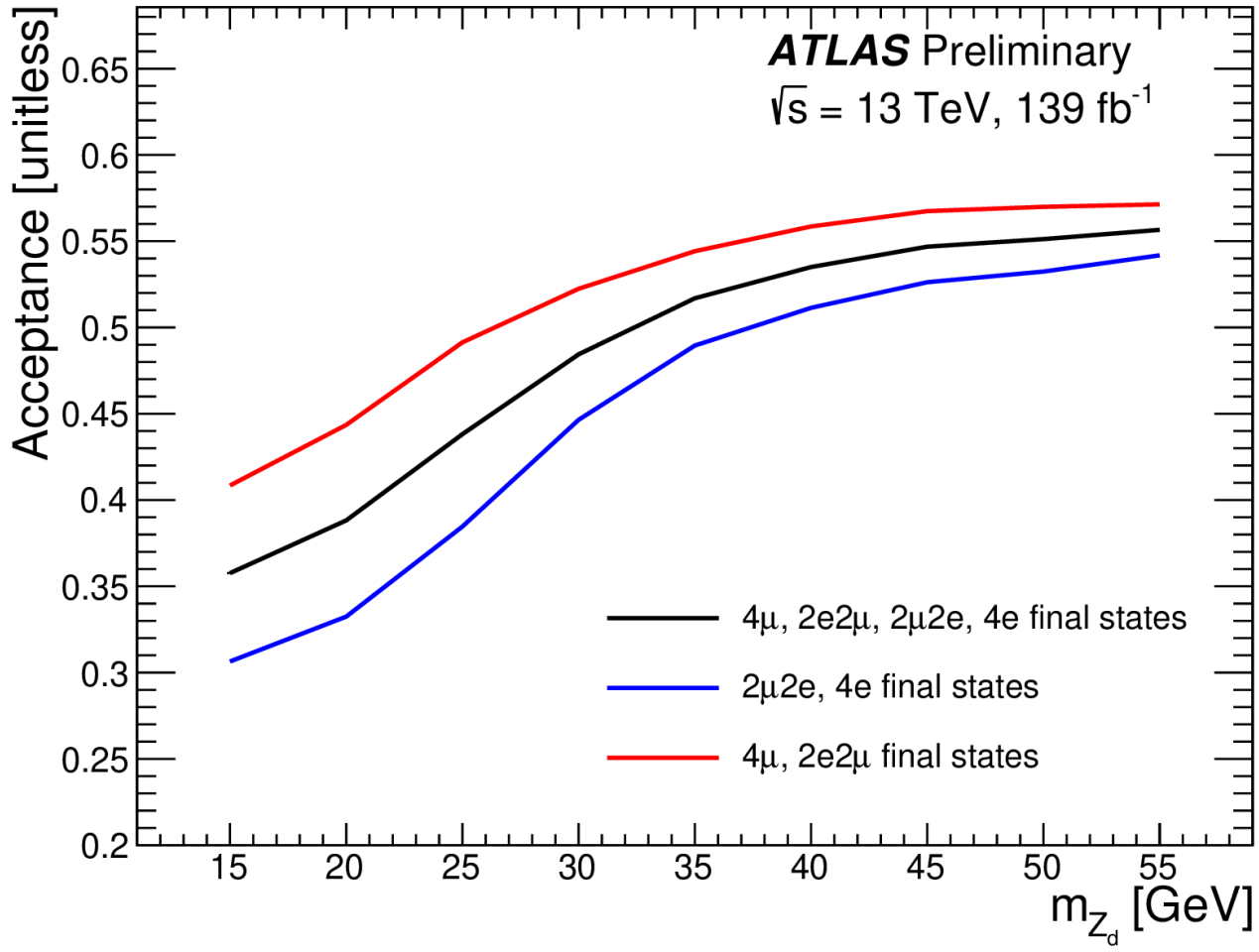

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
ZX Signal Region
Local p
1
10−1
10−2
10−3
1σ
2σ
3σ
15
20
25
30
35
40
45
50
55
mX [GeV]

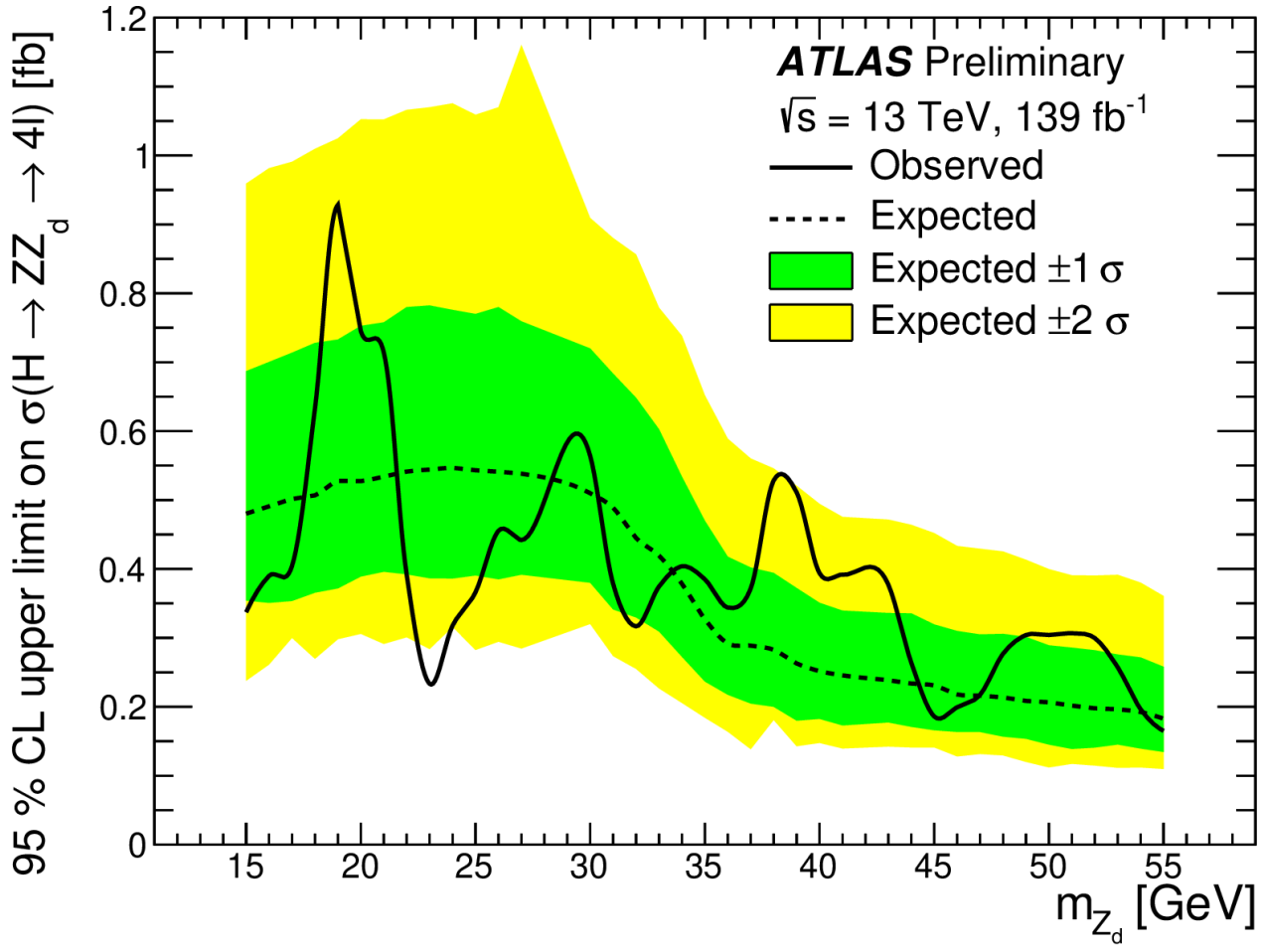

Efficiency [unitless]
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10
20
30
40
50
60
m_X [GeV]
4e
2e2μ
4μ
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
H → XX → 4l

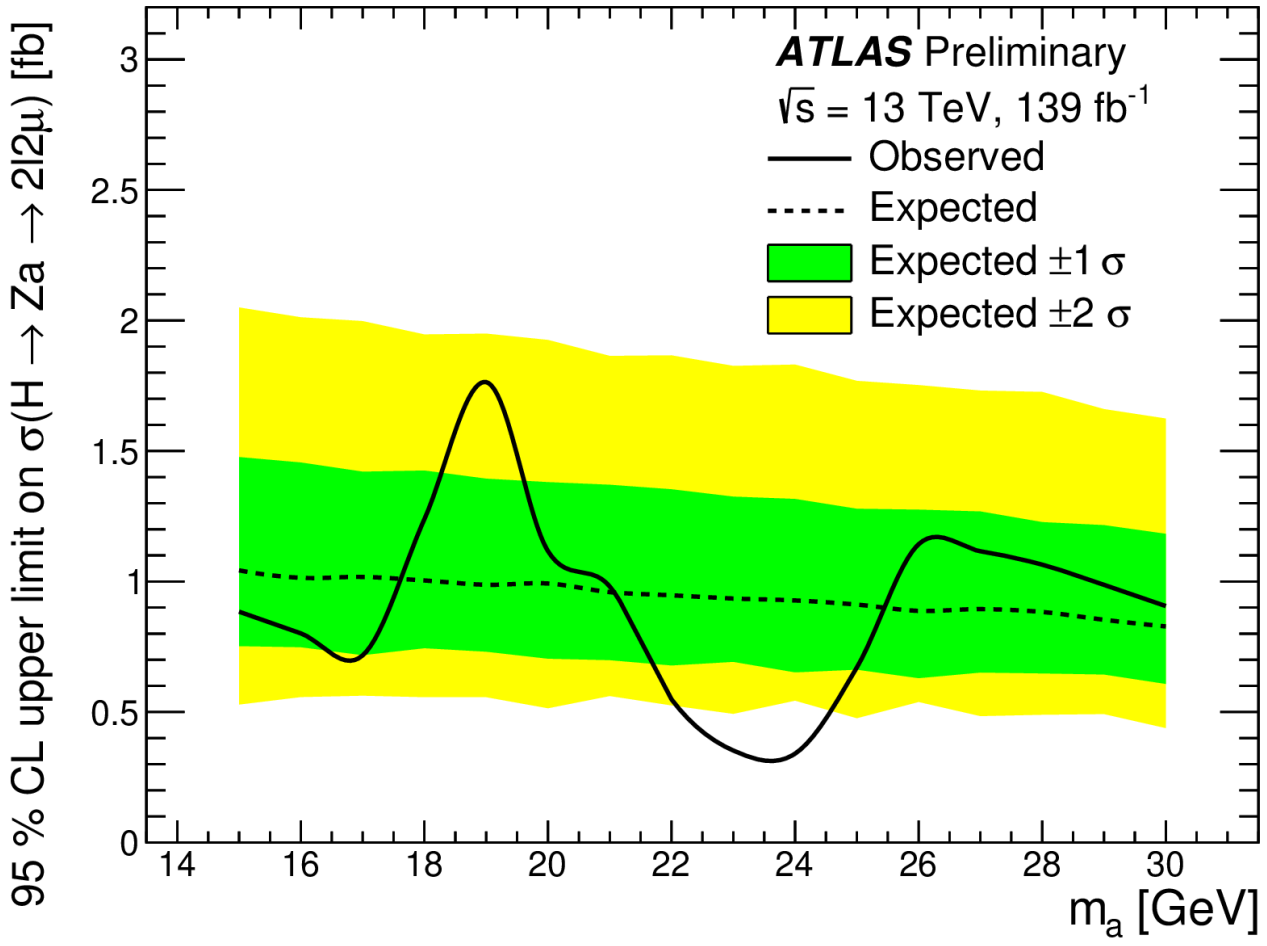

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
95 % CL upper limit on σ(H → Z dZ d → 4l) [fb]
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
15
20
25
30
35
40
45
50
55
60
m Z d [GeV]

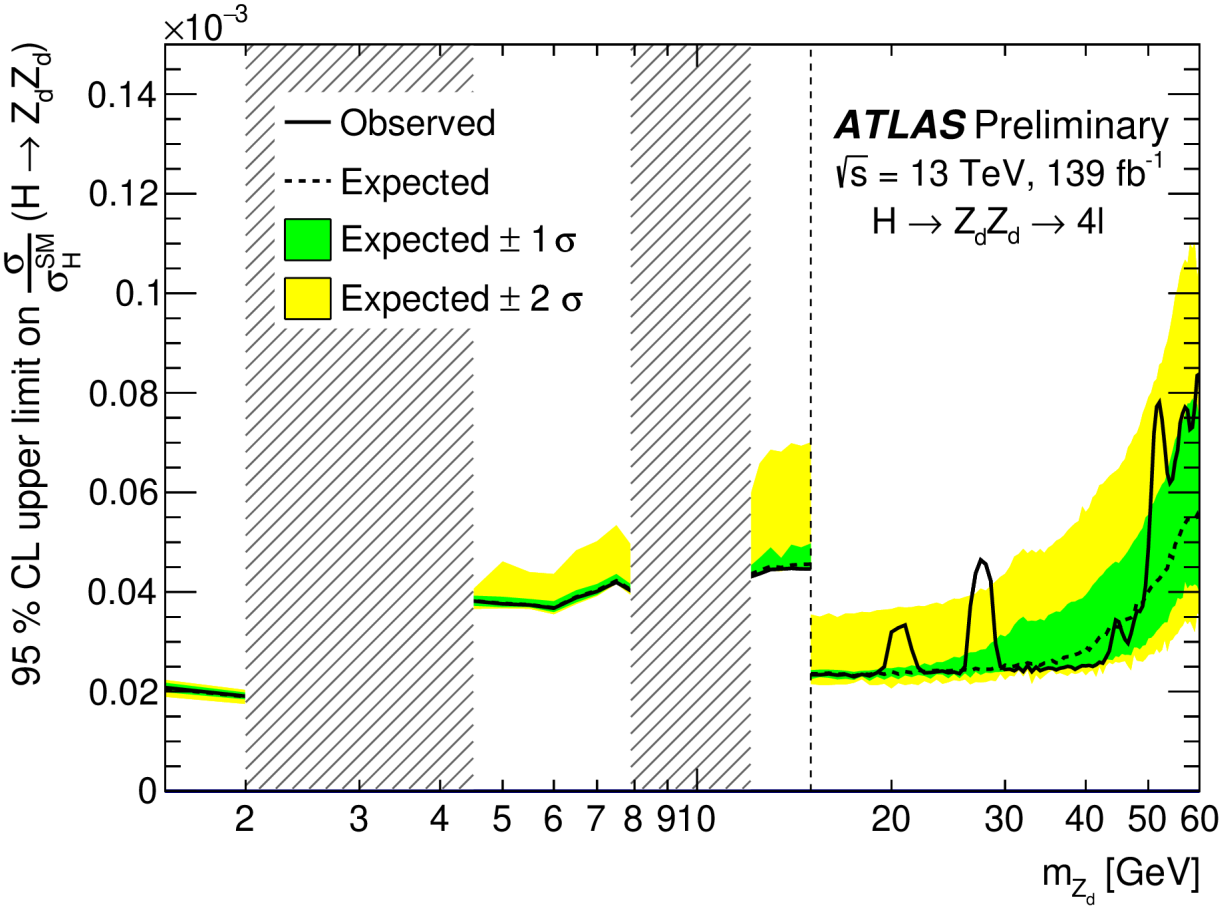

95 % CL upper limit on σ(H → Z_d Z_d → 4μ) [fb]
0.3
0.25
0.2
0.15
0.1
0.05
0
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
ATLAS Preliminary
√s = 13 TeV, 139 fb^-1
4μ final state
2
3
4
5
6
7
8
9
10
20
30
40
50
60
m_Zd [GeV]

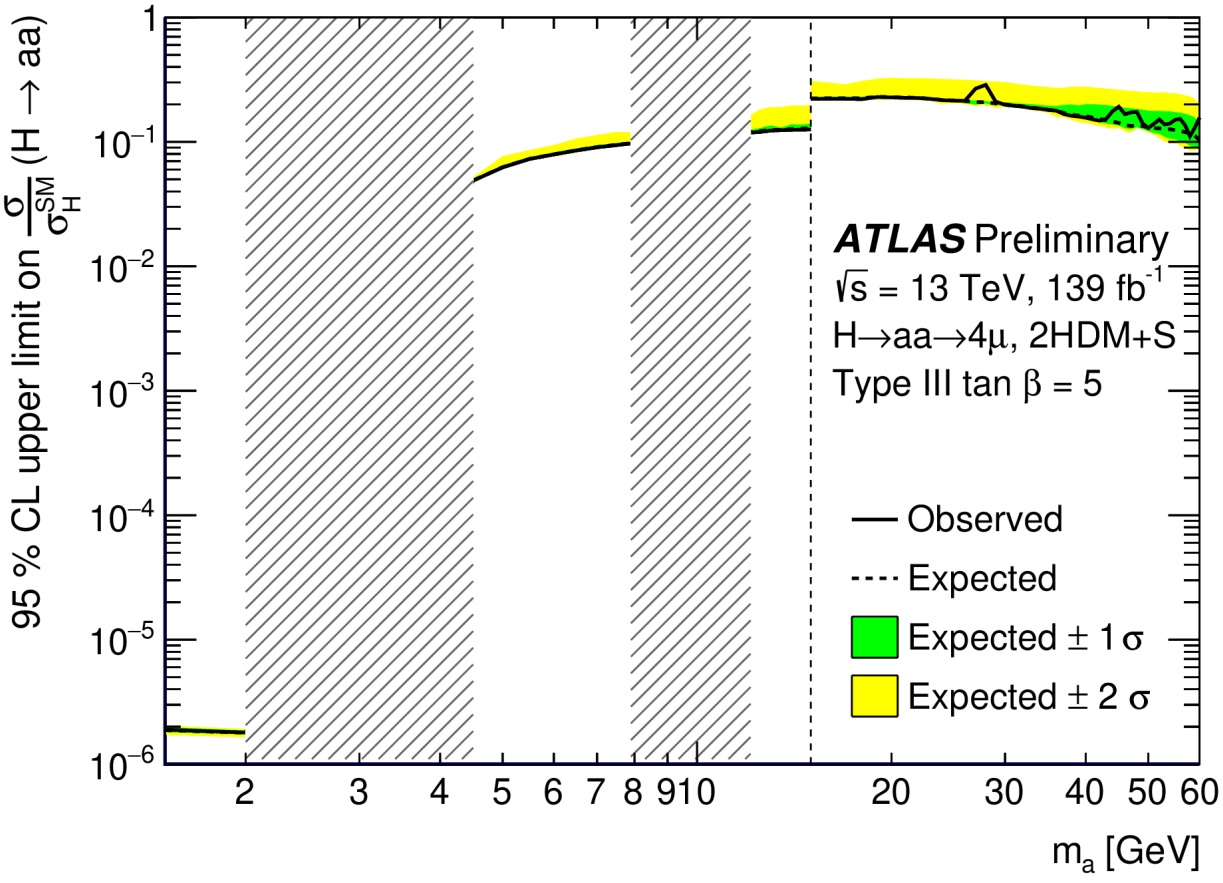

95 % CL upper limit on σ(H → aa → 4μ) [fb]
0.3
0.25
0.2
0.15
0.1
0.05
0
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
ATLAS Preliminary
√s = 13 TeV, 139 fb-1
4μ final state
2
3
4
5
6
7
8
9
10
20
30
40
50
60
ma [GeV]

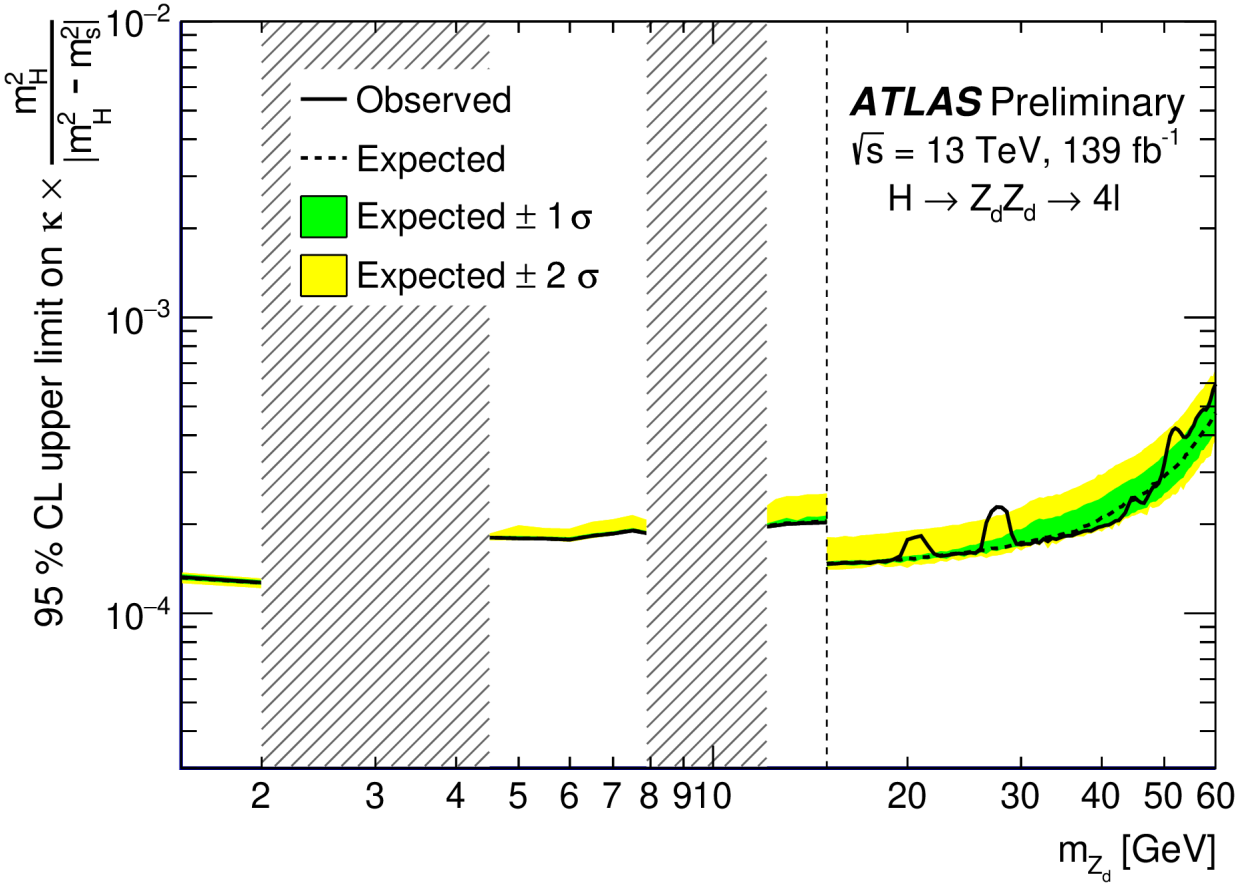

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Acceptance [unitless]
0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
15
20
25
30
35
40
45
50
55
mZd [GeV]
4μ, 2e2μ, 2μ2e, 4e final states
2μ2e, 4e final states
4μ, 2e2μ final states

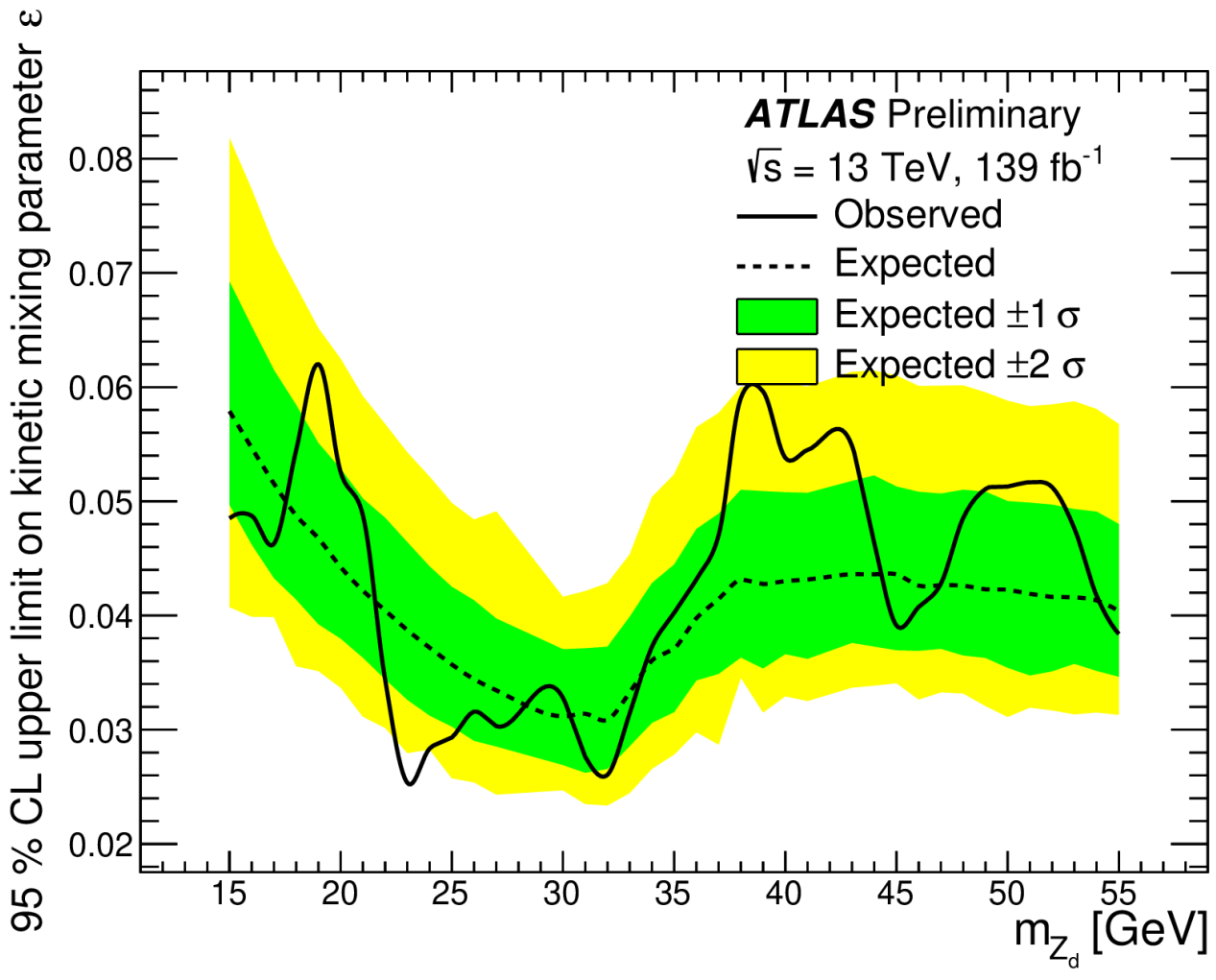

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Observed
Expected
Expected ±1 σ
Expected ±2 σ
95 % CL upper limit on σ(H → ZZd → 4l) [fb]
mZd [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
15
20
25
30
35
40
45
50
55

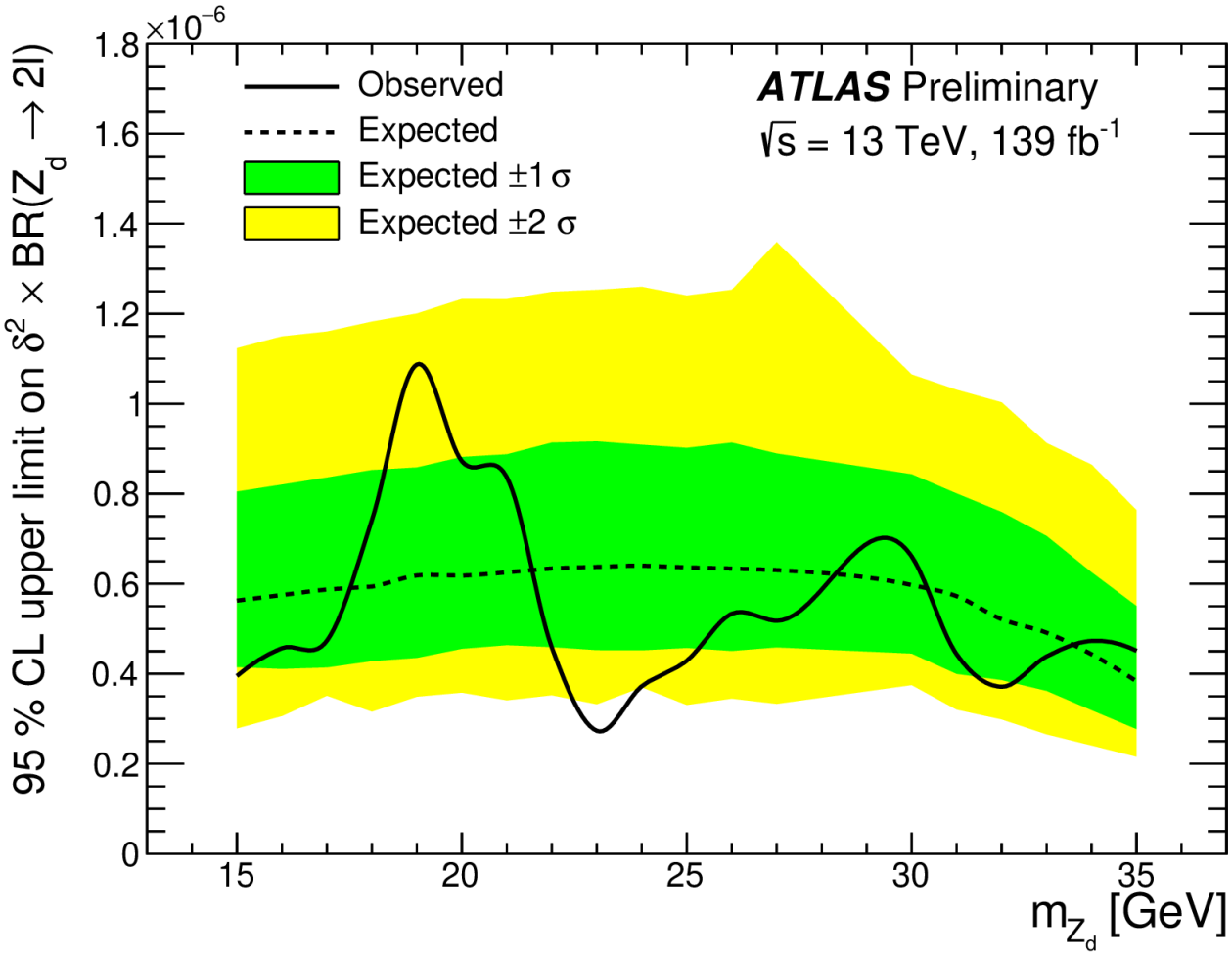

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Observed
Expected
Expected ±1 σ
Expected ±2 σ
95 % CL upper limit on σ(H → Za → 2l2μ) [fb]
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
14
16
18
20
22
24
26
28
30


×10⁻³
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
95 % CL upper limit on σ/σ_H^SM (H → Z_dZ_d)
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
H → Z_dZ_d → 4l
2
3
4
5
6
7
8
9
10
20
30
40
50
60
m_Z_d [GeV]


95 % CL upper limit on $\frac{\sigma}{\sigma_H^{SM}}(H \to aa)$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
2
3
4
5
6
7
8
9
10
20
30
40
50
60
m_a [GeV]
ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 139 fb^{-1}
H→aa→4μ, 2HDM+S
Type III tan β = 5
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ


95 % CL upper limit on κ × m²H / |m²H - m²s|
10⁻²
10⁻³
10⁻⁴
Observed
Expected
Expected ± 1 σ
Expected ± 2 σ
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
H → ZdZd → 4l
2
3
4
5
6
7
8
9
10
20
30
40
50
60
mZd [GeV]


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Observed
Expected
Expected ±1 σ
Expected ±2 σ
95 % CL upper limit on kinetic mixing parameter ε
0.08
0.07
0.06
0.05
0.04
0.03
0.02
15
20
25
30
35
40
45
50
55
mZd [GeV]


×10⁻⁶
95 % CL upper limit on δ² × BR(Z_d → 2l)
Observed
Expected
Expected ±1 σ
Expected ±2 σ
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
m_Z_d [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
15
20
25
30
35

Process	ME generator	ME PDF	PS/UE/HF model	UE tune
$H \to Z_d Z_d$ / $Z Z_d$	MadGraph5_aMC@NLO	NNPDF2.3lo	Pythia/EvtGen	A14
$H \to aa$	Powheg Box	PDF4LHC15 NNLO	Pythia/EvtGen	AZNLO
ggF	Powheg Box	PDF4LHC15 NNLO	Pythia/EvtGen	AZNLO
VBF	Powheg Box	CT10 NLO	Pythia/EvtGen	AZNLO
VH	Pythia	NNPDF2.3lo	Pythia/EvtGen	A14
$ggZH$	Powheg Box	NNPDF3.0nlo	Pythia/EvtGen	AZNLO
$b\bar{b}H$	MadGraph5_aMC@NLO	NNPDF2.3lo	Pythia/EvtGen	A14
$t\bar{t}H$	Powheg Box	NNPDF2.3lo	Pythia/EvtGen	A14
ZZ	Sherpa	NNPDF3.0nnlo	Sherpa	Sherpa default
VVV	Sherpa	NNPDF3.0nnlo	Sherpa	Sherpa default
$t\bar{t}Z$	Sherpa	NNPDF3.0nnlo	Sherpa	Sherpa default
Z + jets	Sherpa	NNPDF3.0nnlo	Sherpa	Sherpa default
$t\bar{t}$	Powheg Box	NNPDF3.0nlo	Pythia/EvtGen	A14
WZ	Powheg Box	CT10 NLO	Pythia/EvtGen	A14

		Single Z (ZX) analysis $H \to ZX \to 4\ell$ ($\ell = e, \mu$)	High-mass (HM) analysis $H \to XX \to 4\ell$ ($\ell = e, \mu$)	Low-mass (LM) analysis $H \to XX \to 4\mu$
Mass range		$15\,\text{GeV} < m_X < 55\,\text{GeV}$	$15\,\text{GeV} < m_X < 60\,\text{GeV}$	$1\,\text{GeV} < m_X < 15\,\text{GeV}$
Baseline electrons		$p_\text{T} > 7\,\text{GeV}$ and $\lvert\eta\rvert < 2.47$ Loose identification with an IBL hit $\lvert z_0 \sin\theta\rvert < 0.5\,\text{mm}$		—
Baseline muons		$p_\text{T} > 5\,\text{GeV}$ (15 GeV if calo-tagged) and $\lvert\eta\rvert < 2.7$ Loose identification $\lvert z_0 \sin\theta\rvert < 0.5\,\text{mm}$ and $d_0 < 1\,\text{mm}$ (except for standalone muons)		
Quadruplet selection		Require at least one quadruplet consisting of two pairs of same-flavour opposite-sign leptons Three leading-p_T leptons satisfying $p_\text{T} > 20\,\text{GeV}, 15\,\text{GeV}, 10\,\text{GeV}$ Number of calorimeter-tagged muons plus number of standalone muons not greater than 1 At least one lepton in the quadruplet responsible for firing at least one trigger For di-lepton triggers, all leptons of the trigger must match leptons in the quadruplet Define pairs m_{12} and m_{34} such that $\lvert m_{12} - m_Z\rvert < \lvert m_{34} - m_Z\rvert$		
		$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$ $12\,\text{GeV} < m_{34} < 115\,\text{GeV}$ $m_{14,32} > 5\,\text{GeV}$ ($4e/4\mu$)	—	
		$\Delta R(\ell, \ell') > 0.10$ (0.20) for same-flavour (different-flavour) leptons in the quadruplet		—
Quadruplet ranking		In order 4μ, $2e2\mu$, $2\mu2e$, $4e$ Smallest $\lvert m_Z - m_{12}\rvert$ Smallest $\lvert m_Z - m_{34}\rvert$	Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34}\rvert$	
Event selection	Isolation & impact parameter	Track and calorimeter isolation Excluding tracks/clusters from other leptons in the quadruplet $d_0/\sigma_{d_0} < 5$ for electrons and $d_0/\sigma_{d_0} < 3$ for muons		
	$m_{4\ell}$	$115\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$		$120\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$
	Z-veto	—	$10\,\text{GeV} < m_{12,34} < 64\,\text{GeV}$ For $4e$ and 4μ channels: $5\,\text{GeV} < m_{14,23} < 75\,\text{GeV}$	—
	Heavy-flavour veto	—	Reject event if $m_{12,34,14,23}$ in: $(m_{J/\Psi} - 0.25\,\text{GeV})$ to $(m_{\Psi(2S)} + 0.30\,\text{GeV})$, or $(m_{\Upsilon(1S)} - 0.70\,\text{GeV})$ to $(m_{\Upsilon(3S)} + 0.75\,\text{GeV})$	
	Signal region	—	$m_{34}/m_{12} > 0.85 - 0.1125 f(m_{12})$	$1.2\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$ $m_{34}/m_{12} > 0.85$ Reject event if $m_{12,34}$ in: 2 GeV to 4.4 GeV, or 8 GeV to 12 GeV

Table 1: Summary of event selection requirements for the ZX, HM, and LM analyses. The quarkonia masses are taken to be $m_{J/\Psi} = 3.096$ GeV, $m_{\Psi(2S)} = 3.686$ GeV, $m_{\Upsilon(1S)} = 9.461$ GeV, and $m_{\Upsilon(3S)} = 10.355$ GeV . See text for other definitions.

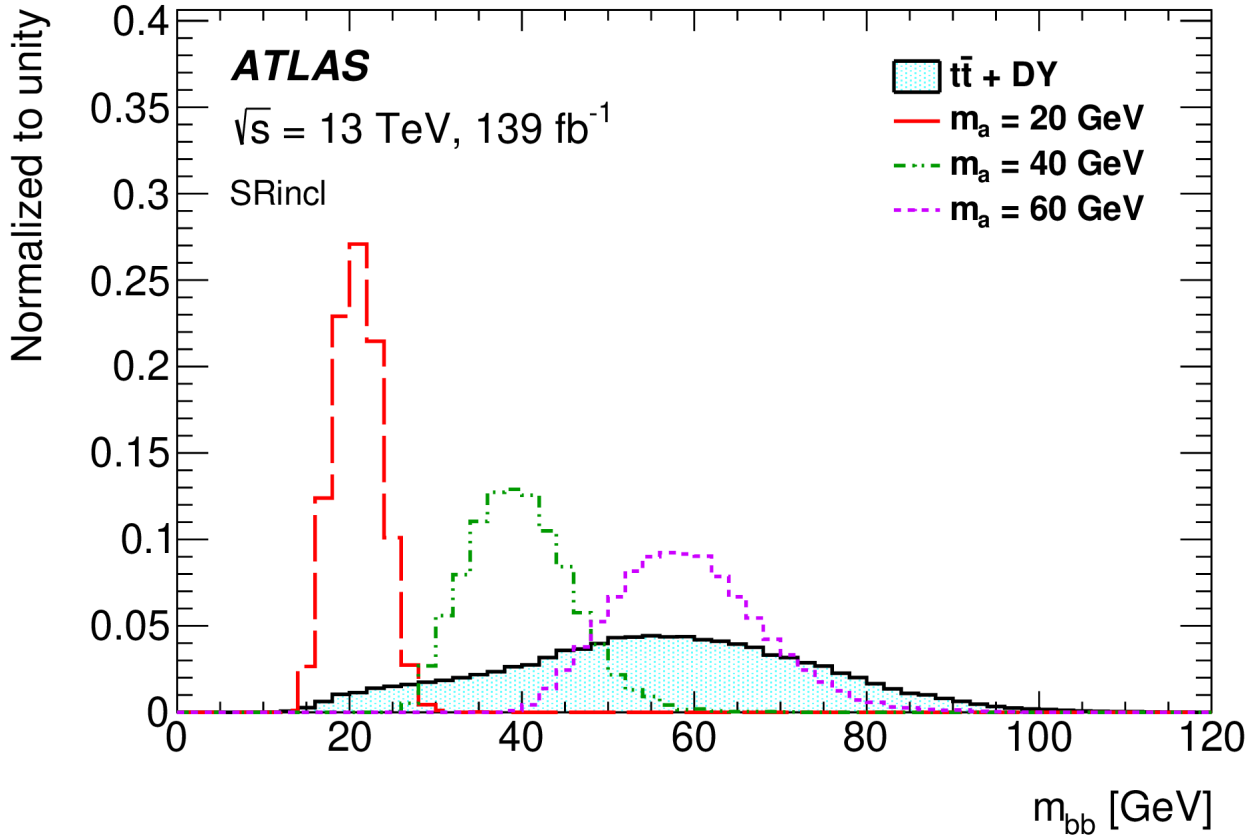
Process	Yield (±stat. ± syst.)
$H \to ZZ^* \to 4\ell$	$11.12 \pm 0.05 \pm 1.02$
$ZZ^* \to 4\ell$	$3.38 \pm 0.05 \pm 0.25$
$t\bar{t}$	$0.47 \pm 0.13 \pm 0.09$
Z + jets	$0.43 \pm 0.39^{+0.17}_{-0.01}$
$Z + t\bar{t} \to 4\ell$	$0.09 \pm 0.02 \pm 0.02$
WZ	$0.05 \pm 0.03^{+0.05}_{-0.00}$
VVV/VBS	Negligible
Heavy flavour	Negligible
Total	$15.6 \pm 0.4 \pm 1.2$
Data	20

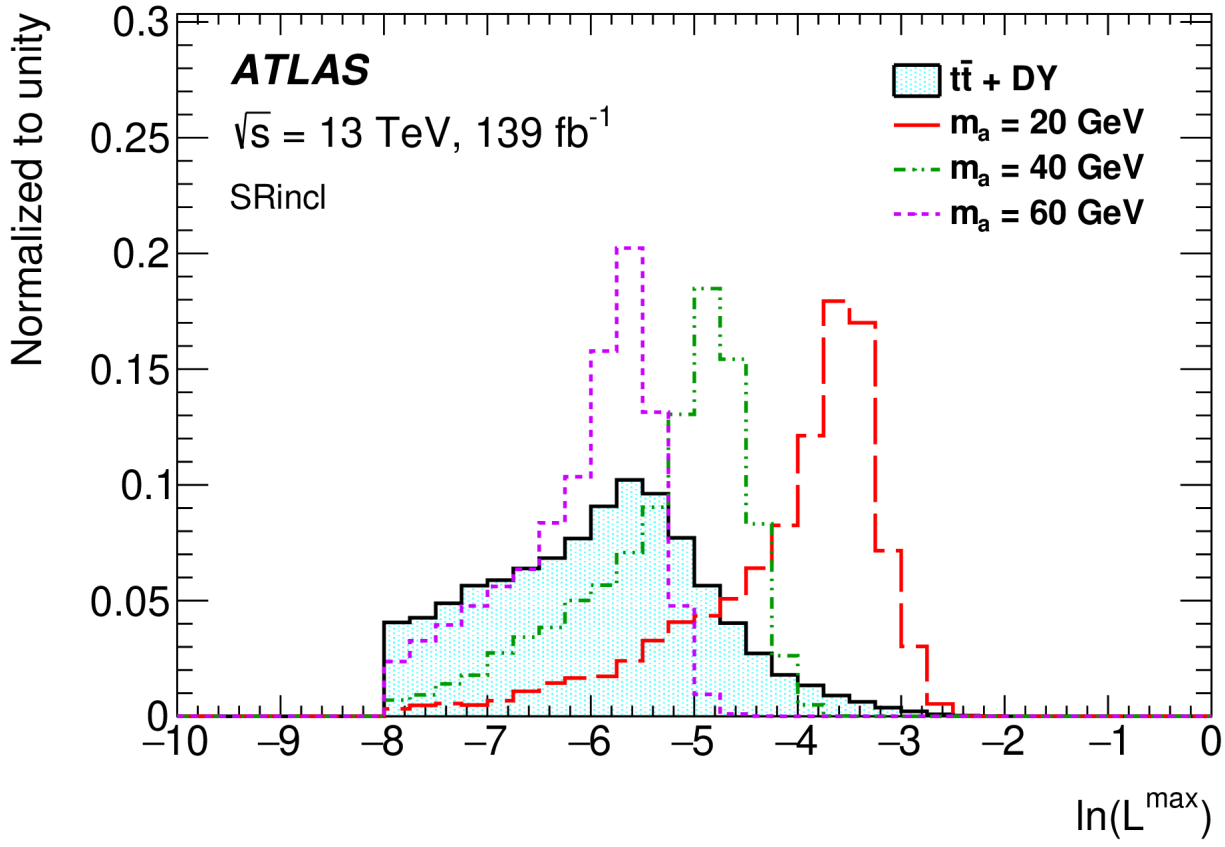
Process	Yield (±stat. ± syst.)
$H \to ZZ^* \to 4\mu$	$0.41 \pm 0.01 \pm 0.03$
$ZZ^* \to 4\mu$	$0.22 \pm 0.04 \pm 0.04$
VVV/VBS	Negligible
Heavy flavour	$0.26 \pm 0.09 \pm 0.10$
Total	$0.89 \pm 0.10 \pm 0.11$
Data	0

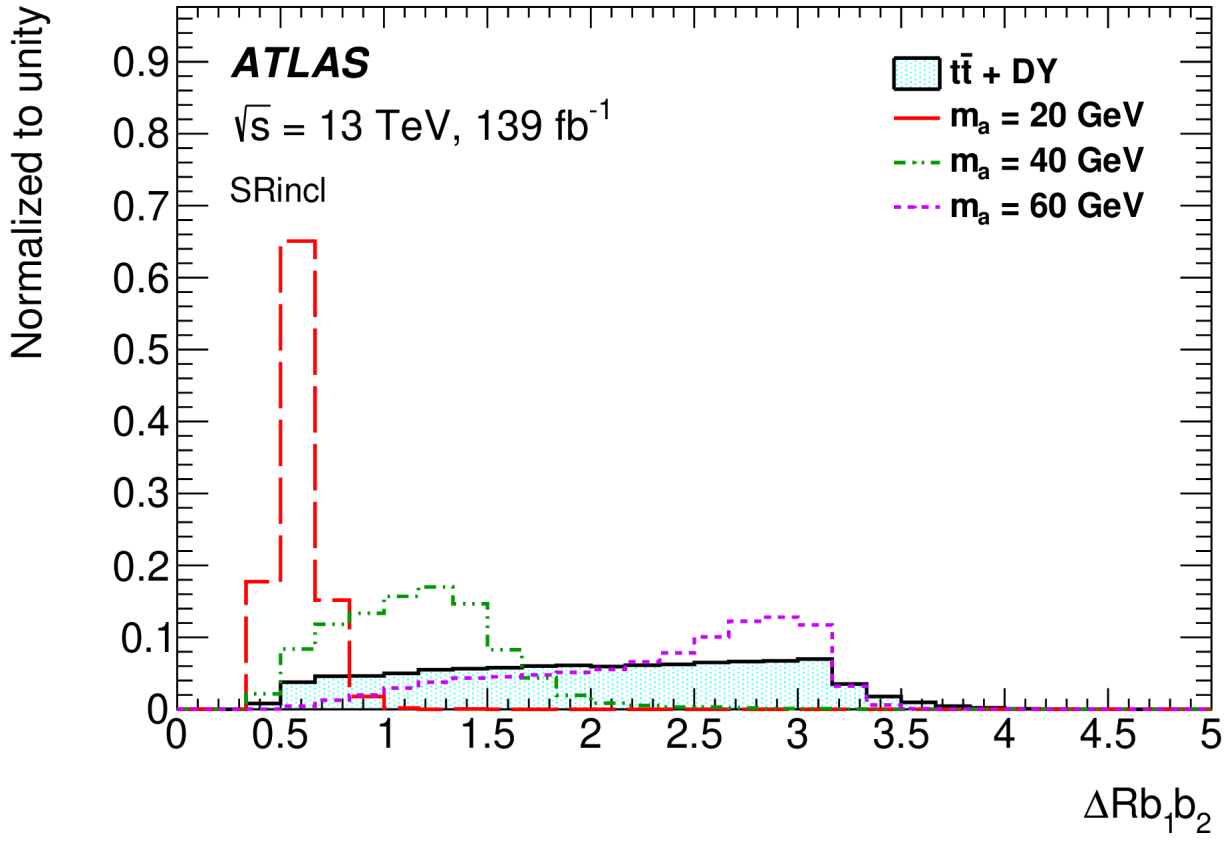
Process	Yield (±stat. ± syst.)		
	$2\ell 2\mu$	$2\ell 2e$	Total
$H \to ZZ^* \to 4\ell$	$127.9 \pm 0.1 \pm 3.6$	$76.1 \pm 0.1 \pm 10.2$	$204.0 \pm 0.2 \pm 12.4$
$ZZ^* \to 4\ell$	$70.2 \pm 0.2 \pm 1.9$	$33.0 \pm 0.2 \pm 3.6$	$103.3 \pm 0.3 \pm 4.6$
Reducible	$4.9 \pm 0.1 \pm 0.3$	$5.8 \pm 0.3 \pm 0.6$	$10.7 \pm 0.3 \pm 1.0$
$VVV, t\bar{t} + Z$	$1.1 \pm 0.1 \pm 0.04$	$0.7 \pm 0.1 \pm 0.1$	$1.8 \pm 0.1 \pm 0.1$
Total	$204.1 \pm 0.3 \pm 5.5$	$115.6 \pm 0.5 \pm 13.8$	$319.7 \pm 0.5 \pm 17.0$
Data	237	119	356

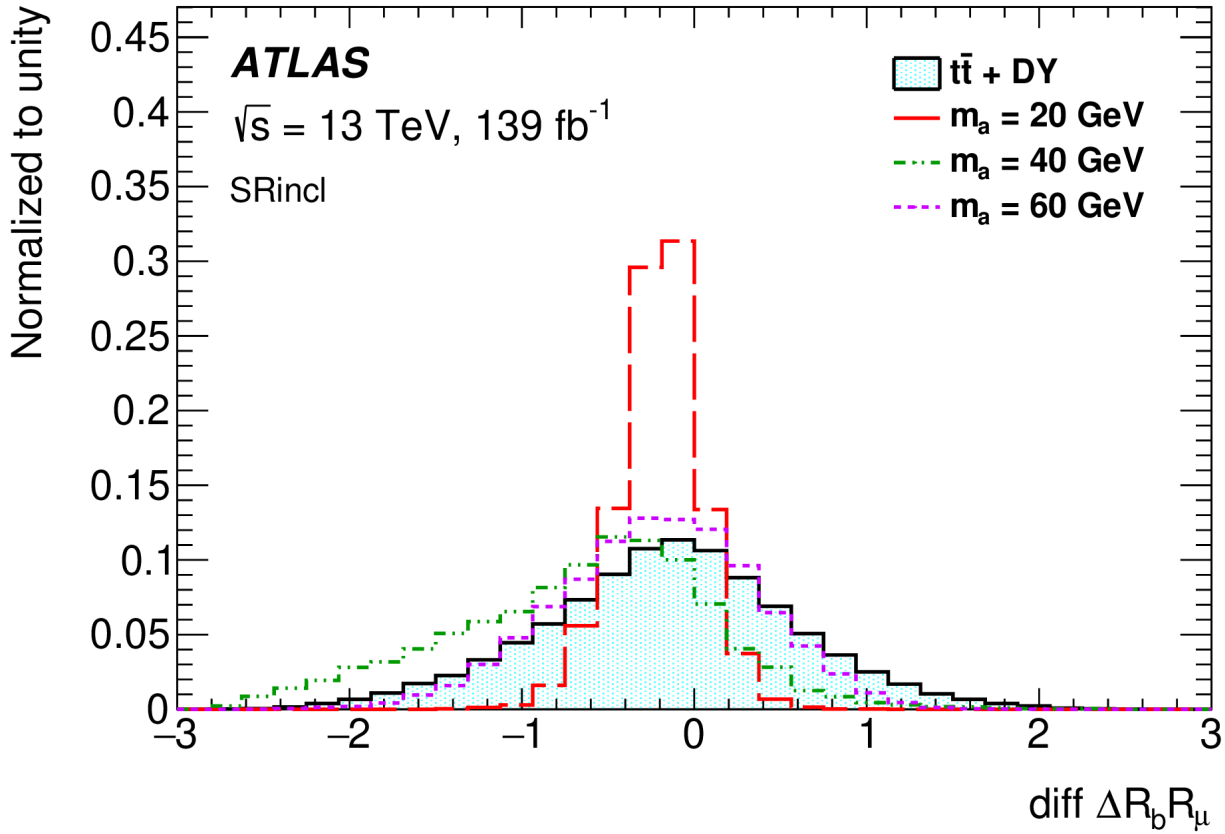
	Single Z (ZX) analysis $H \to XZ \to 4\ell$ ($\ell = e, \mu$)	High-mass (HM) analysis $H \to XX \to 4\ell$ ($\ell = e, \mu$)	Low-mass (LM) analysis $H \to XX \to 4\mu$
Mass range	$15\,\text{GeV} < m_X < 55\,\text{GeV}$	$15\,\text{GeV} < m_X < 60\,\text{GeV}$	$1\,\text{GeV} < m_X < 15\,\text{GeV}$
Electrons	$p_\text{T} > 7\,\text{GeV}$ $\quad$ $\lvert\eta\rvert < 2.5$		
Muons	$p_\text{T} > 5\,\text{GeV}$ $\quad$ $\lvert\eta\rvert < 2.7$		
Quadruplet	Three leading-p_T leptons satisfying $p_\text{T} > 20\,\text{GeV}, 15\,\text{GeV}, 10\,\text{GeV}$		
	$\Delta R > 0.10\,(0.20)$ between same-flavour (different-flavour) leptons		—
	—	$m_{34}/m_{12} > 0.85 - 0.1125 f(m_{12})$	$m_{34}/m_{12} > 0.85$
	$50\,\text{GeV} < m_{12} < 106\,\text{GeV}$ $12\,\text{GeV} < m_{34} < 115\,\text{GeV}$ $m_{14,23} > 5\,\text{GeV}$ ($4e/4\mu$)	$10\,\text{GeV} < m_{12,34} < 64\,\text{GeV}$ For $4e$ and 4μ channels: $5\,\text{GeV} < m_{14,23} < 75\,\text{GeV}$	$1.2\,\text{GeV} < m_{12,34} < 20\,\text{GeV}$
	—	Reject event if $m_{12,34,14,23}$ in either: $(m_{J/\psi} - 0.25\,\text{GeV})$ to $(m_{\psi(2S)} + 0.30\,\text{GeV})$, or $(m_{\Upsilon(1S)} - 0.70\,\text{GeV})$ to $(m_{\Upsilon(3S)} + 0.75\,\text{GeV})$	
	—	—	Reject event if $m_{12,34}$ in either 2 GeV to 4.4 GeV, or 8 GeV to 12 GeV
	$115\,\text{GeV} < m_{4\ell} < 130\,\text{GeV}$	—	—

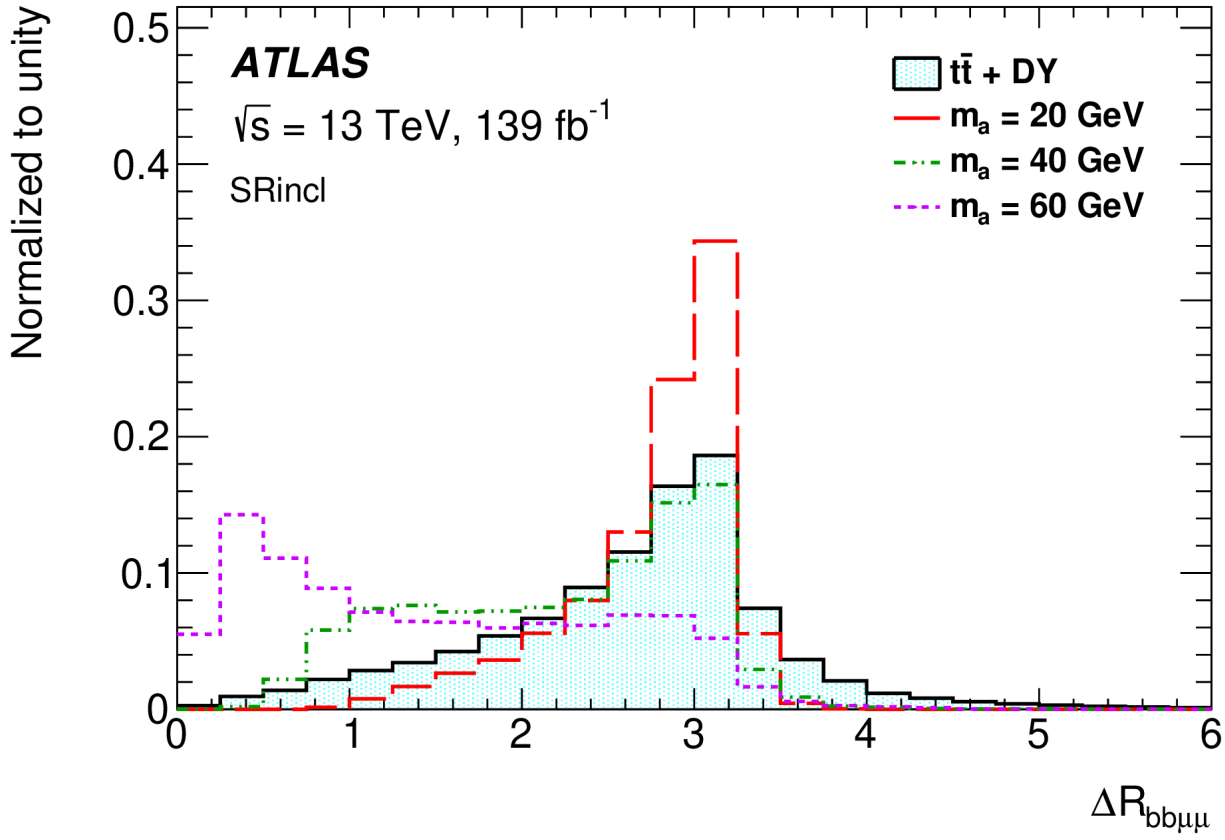
$H \to aa \to bb\mu\mu$ Search

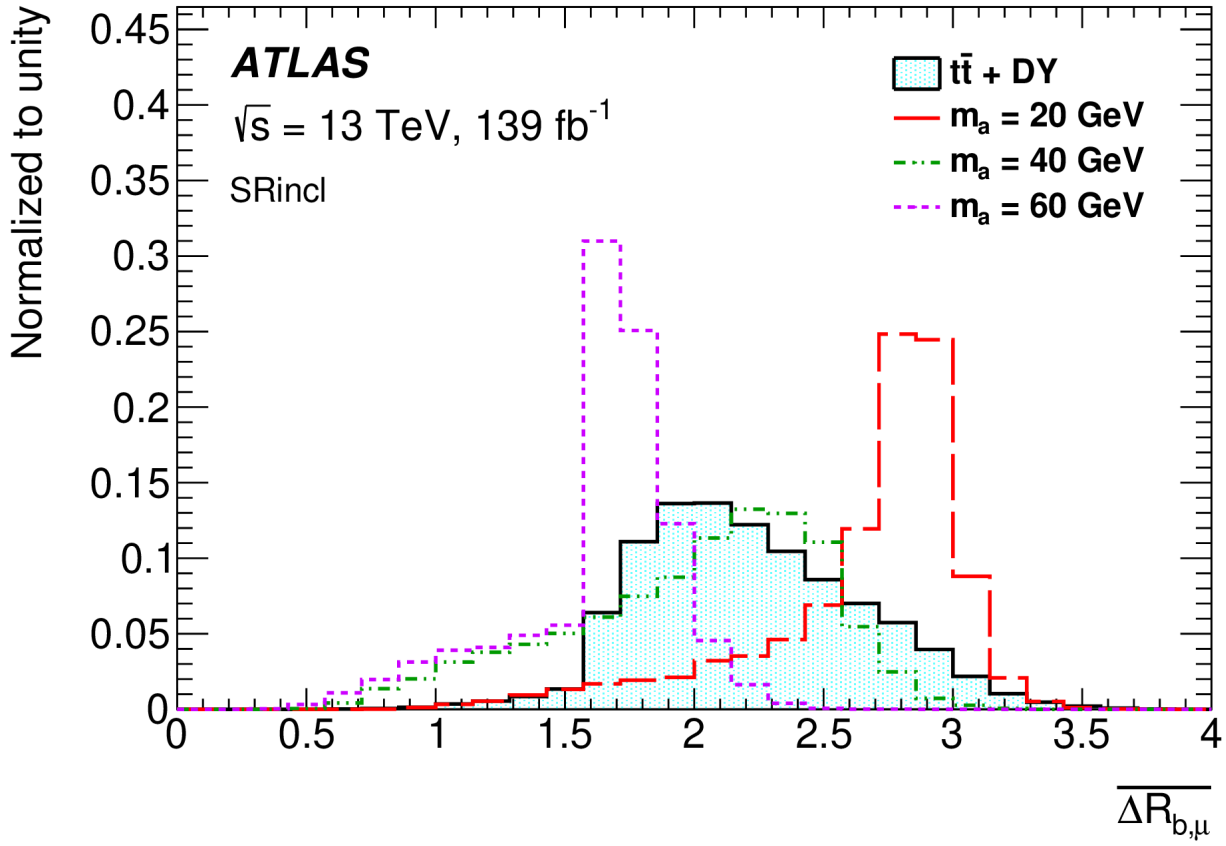

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
mbb [GeV]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0
20
40
60
80
100
120

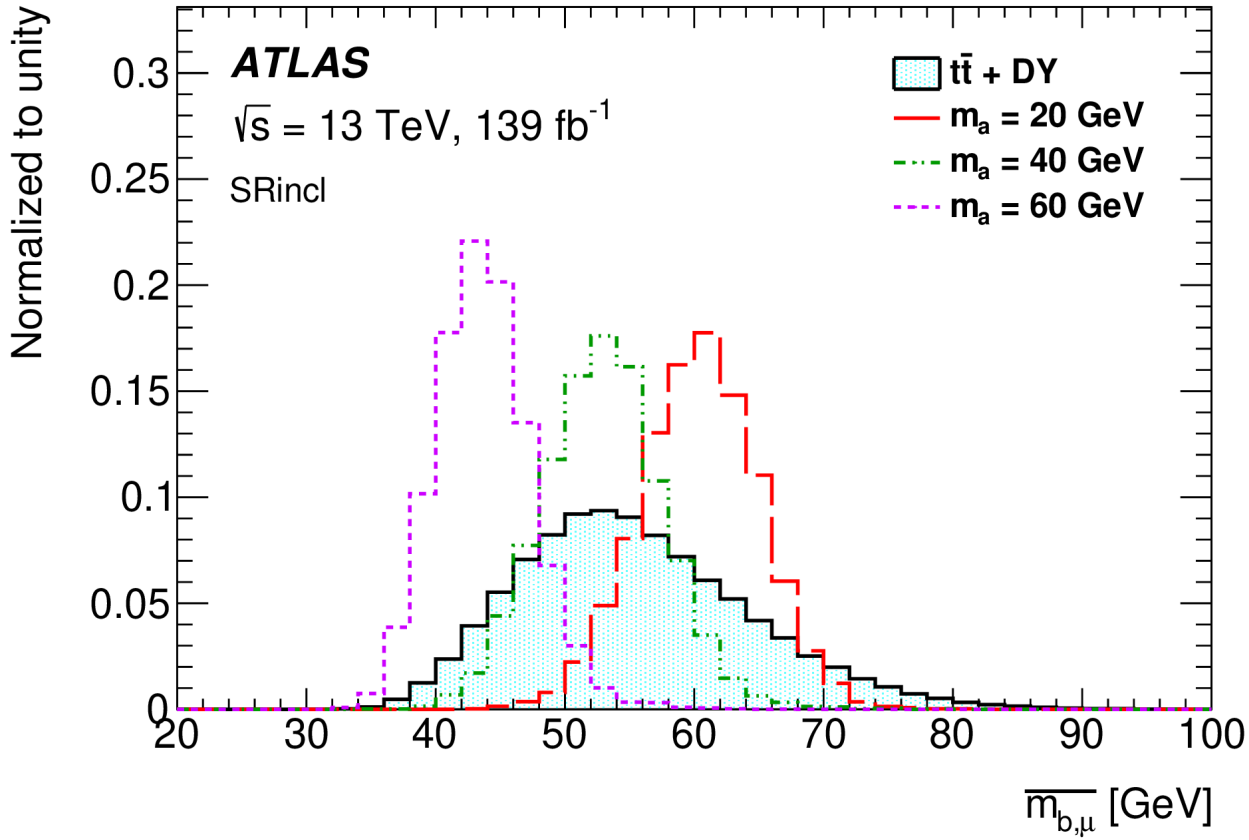

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
0.3
0.25
0.2
0.15
0.1
0.05
0
−10
−9
−8
−7
−6
−5
−4
−3
−2
−1
0
ln(Lmax)

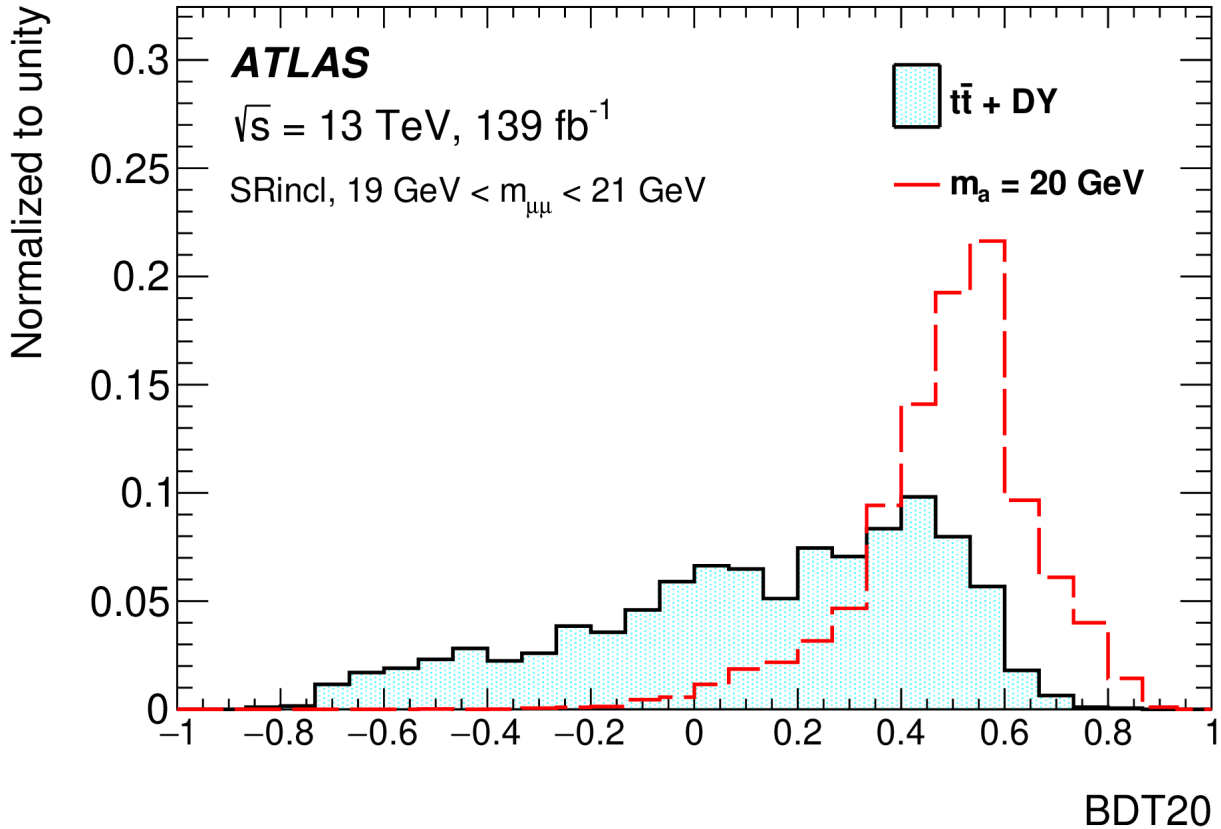

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
ΔRb1b2

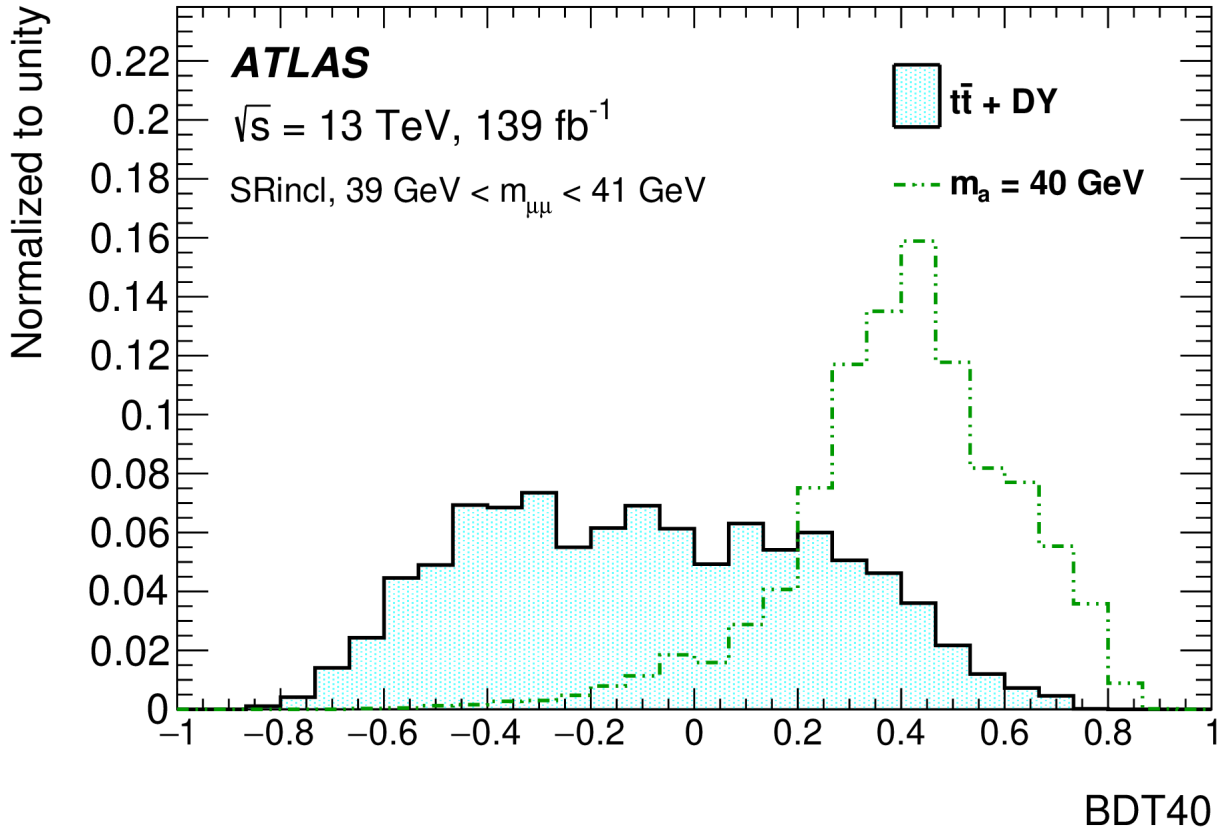

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−3
−2
−1
0
1
2
3
diff ΔRbRμ

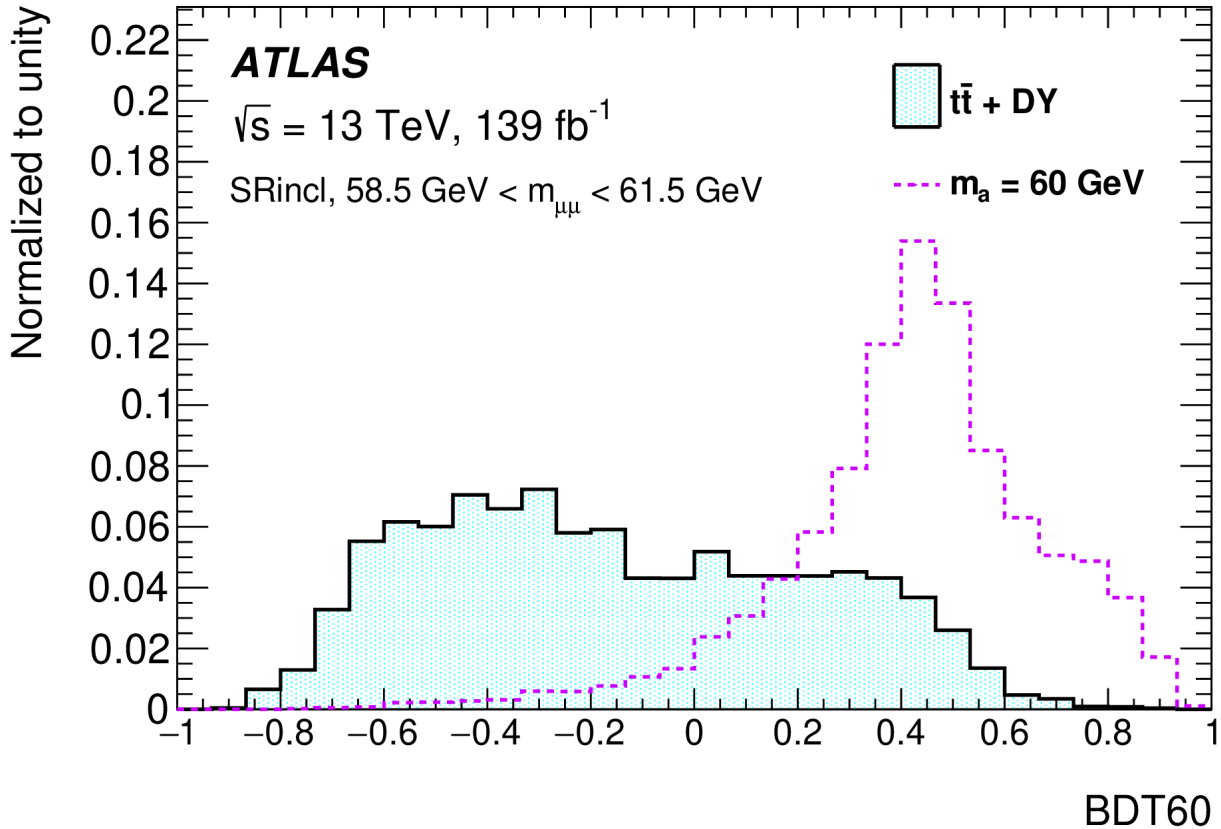

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
0.5
0.4
0.3
0.2
0.1
0
0
1
2
3
4
5
6
ΔRbbμμ

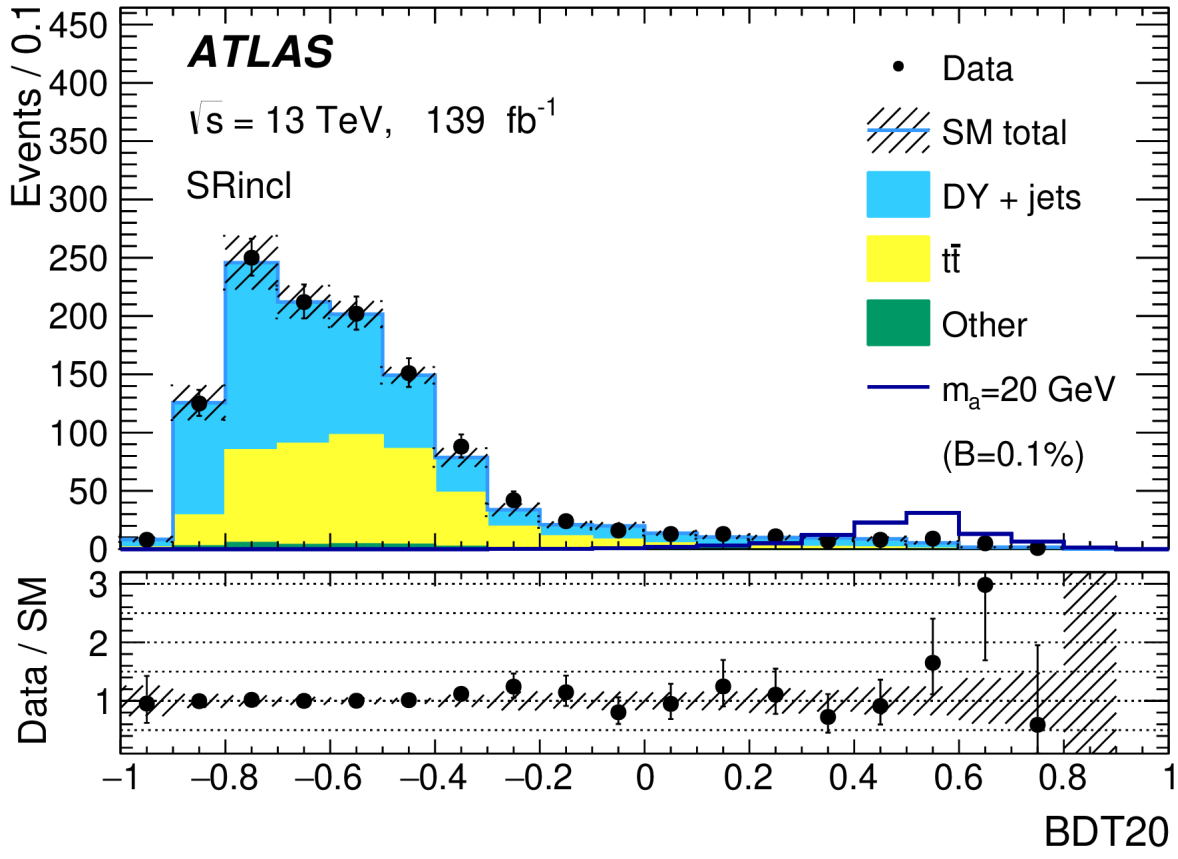

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
0.5
1
1.5
2
2.5
3
3.5
4
ΔRb,μ

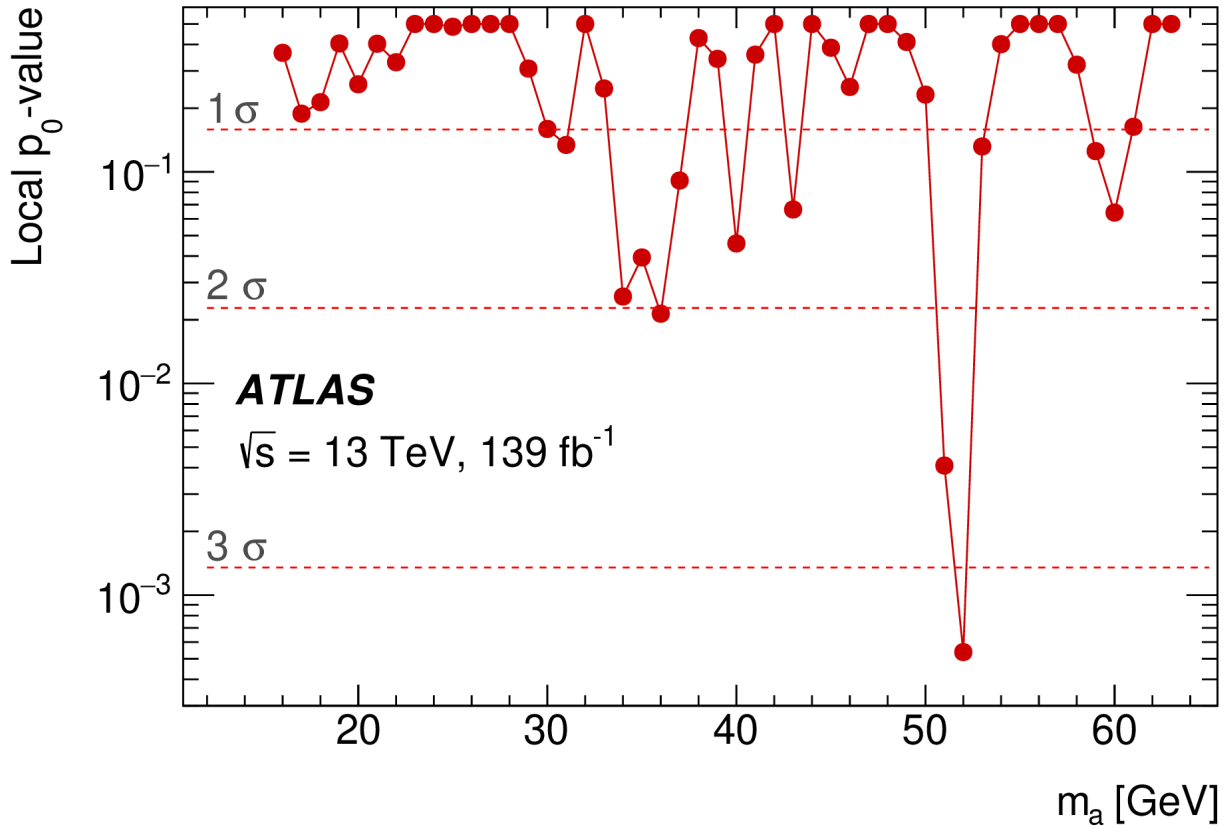

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
tt̄ + DY
ma = 20 GeV
ma = 40 GeV
ma = 60 GeV
Normalized to unity
0.3
0.25
0.2
0.15
0.1
0.05
0
20
30
40
50
60
70
80
90
100
m̄b,μ [GeV]

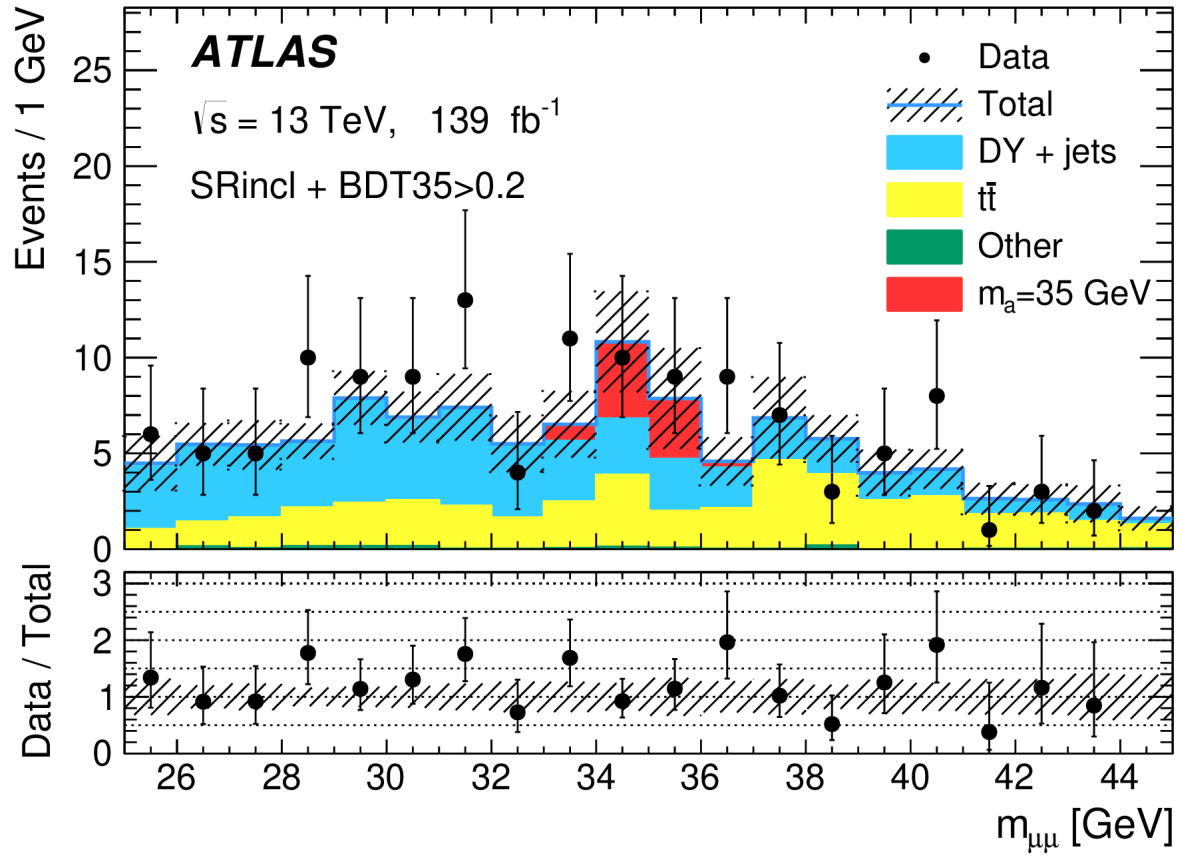

ATLAS
√s = 13 TeV, 139 fb-1
SRincl, 19 GeV < mμμ < 21 GeV
tt̄ + DY
ma = 20 GeV
Normalized to unity
0.3
0.25
0.2
0.15
0.1
0.05
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
BDT20

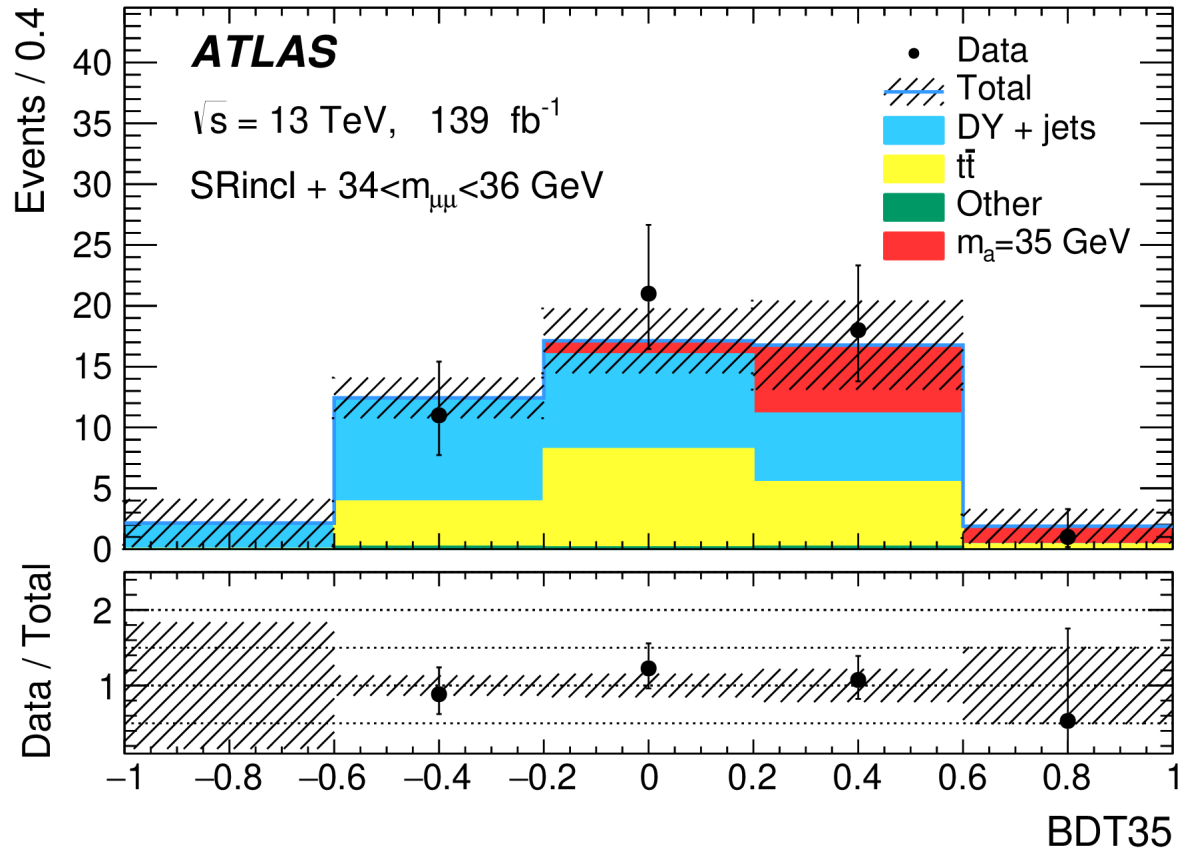

ATLAS
√s = 13 TeV, 139 fb-1
SRincl, 39 GeV < mμμ < 41 GeV
tt̄ + DY
ma = 40 GeV
Normalized to unity
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
BDT40

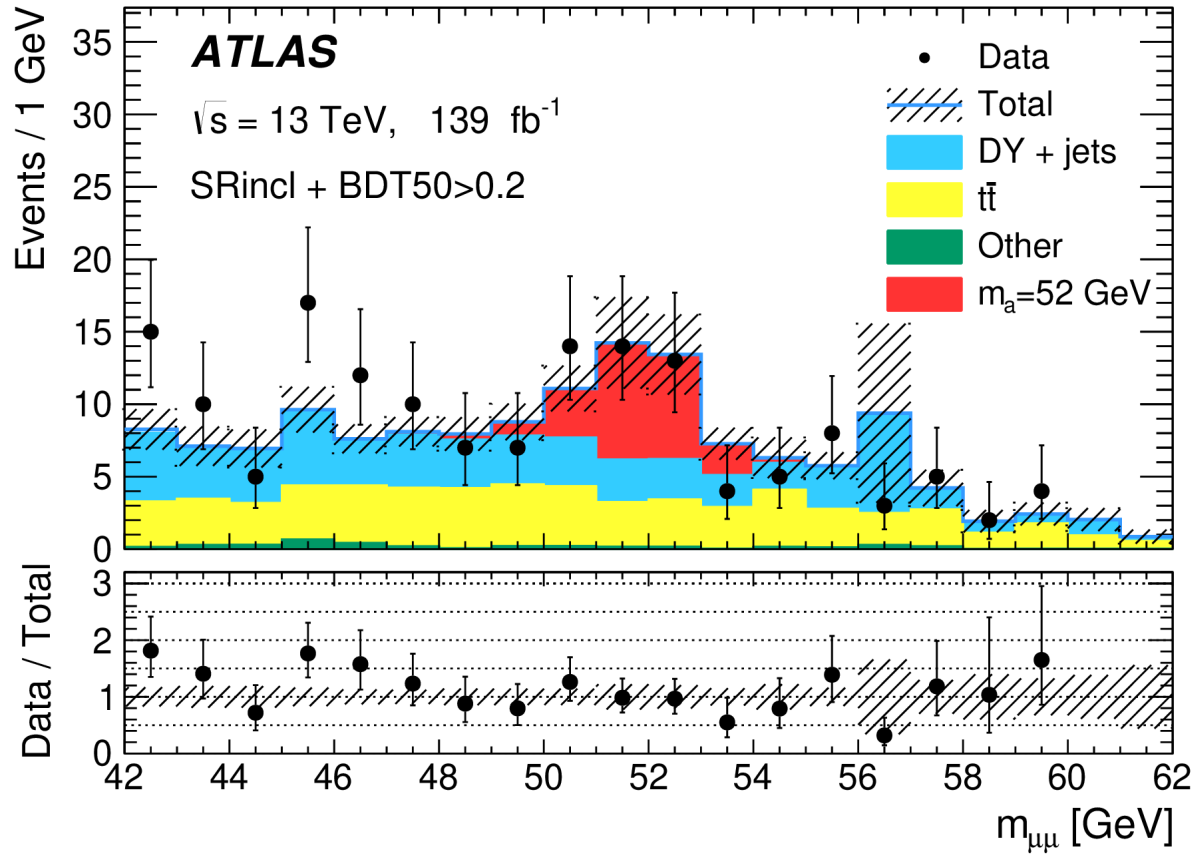

ATLAS
√s = 13 TeV, 139 fb-1
SRincl, 58.5 GeV < mμμ < 61.5 GeV
tt̄ + DY
ma = 60 GeV
Normalized to unity
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
BDT60

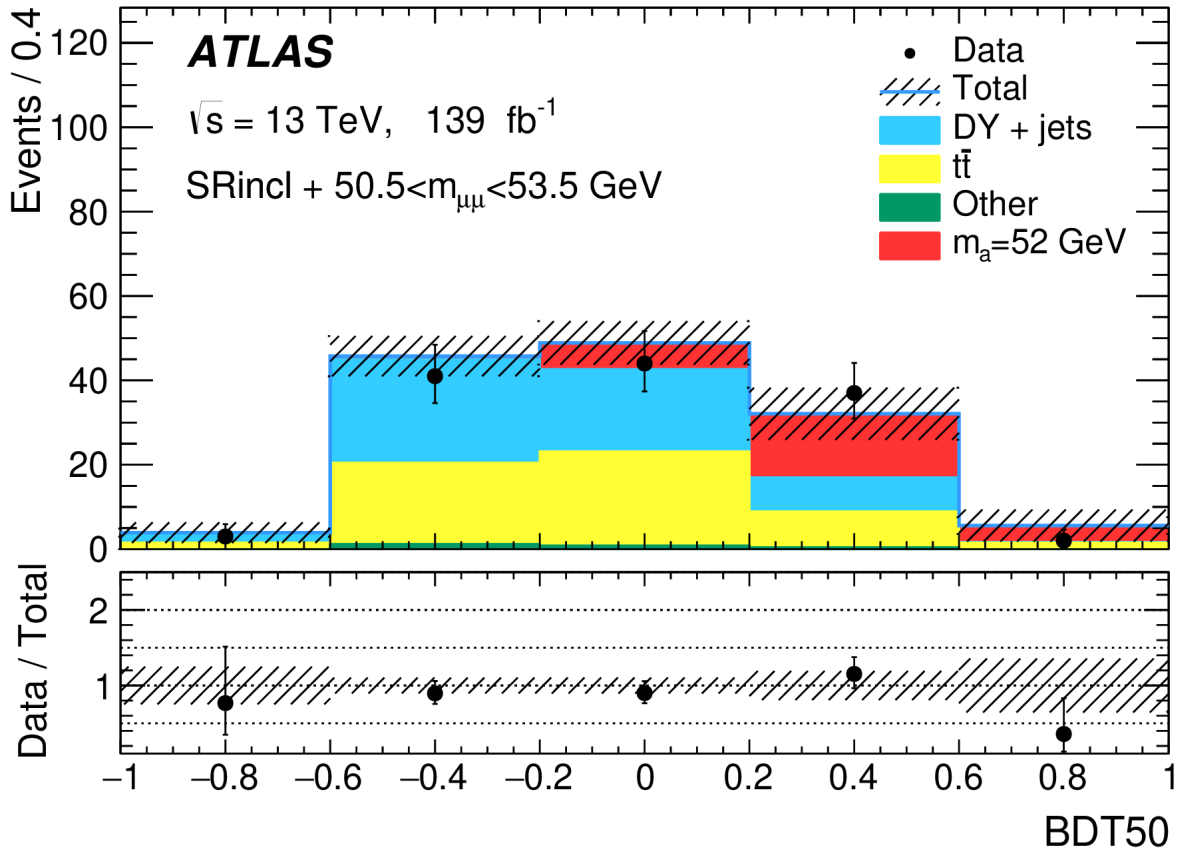

ATLAS
√s = 13 TeV, 139 fb-1
SRincl
Data
SM total
DY + jets
tt̄
Other
ma=20 GeV
(B=0.1%)
Events / 0.1
Data / SM
BDT20

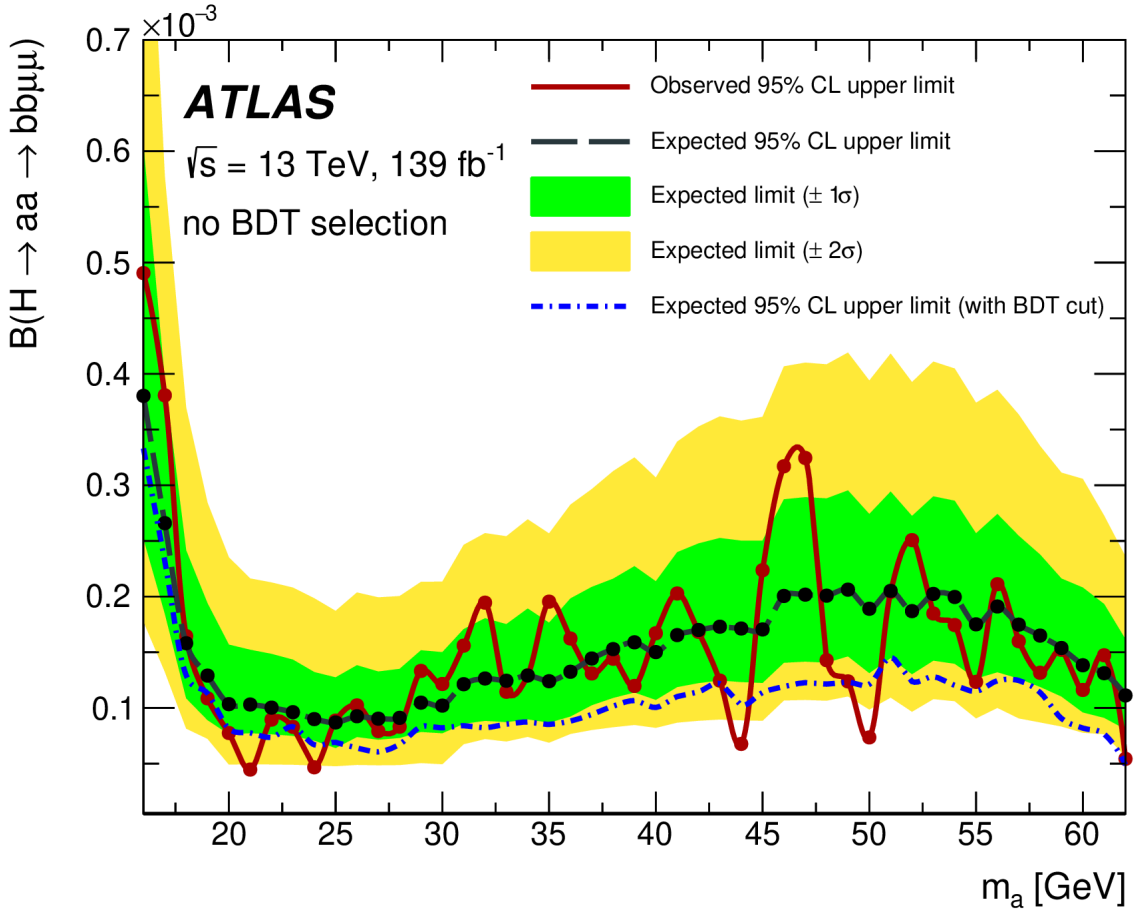

Local p_0-value
10^{-1}
10^{-2}
10^{-3}
1 σ
2 σ
3 σ
ATLAS
√s = 13 TeV, 139 fb^{-1}
20
30
40
50
60
m_a [GeV]

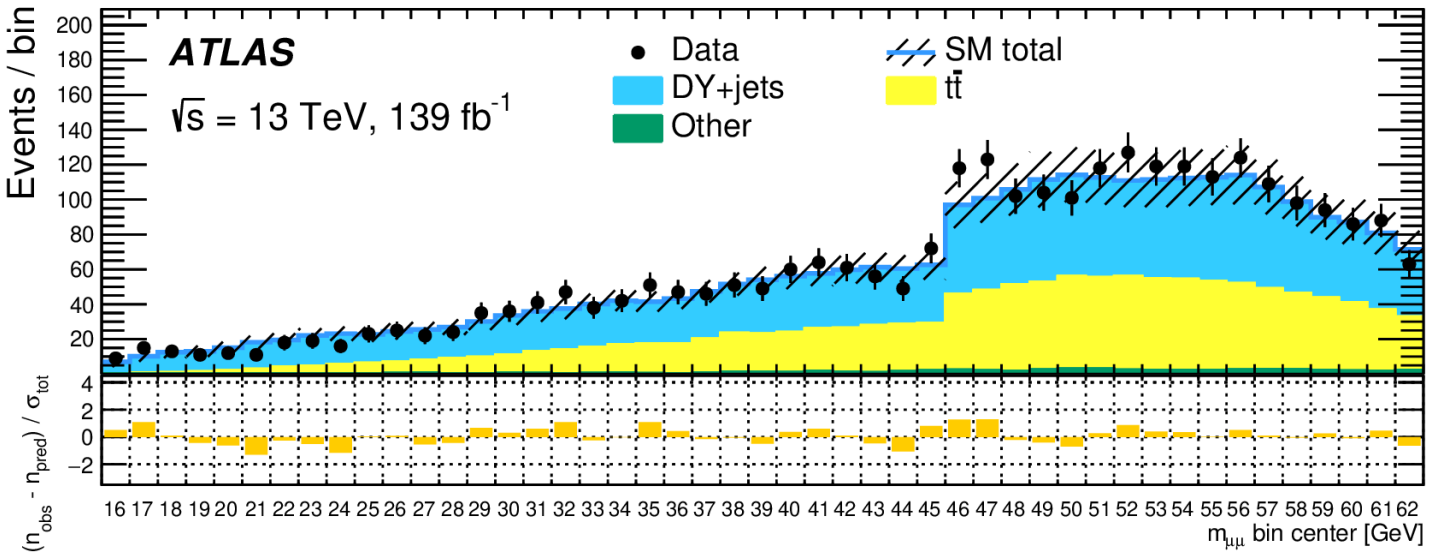

ATLAS
√s = 13 TeV, 139 fb-1
SRincl + BDT35>0.2
Data
Total
DY + jets
tt̄
Other
ma=35 GeV
Events / 1 GeV
Data / Total
mμμ [GeV]

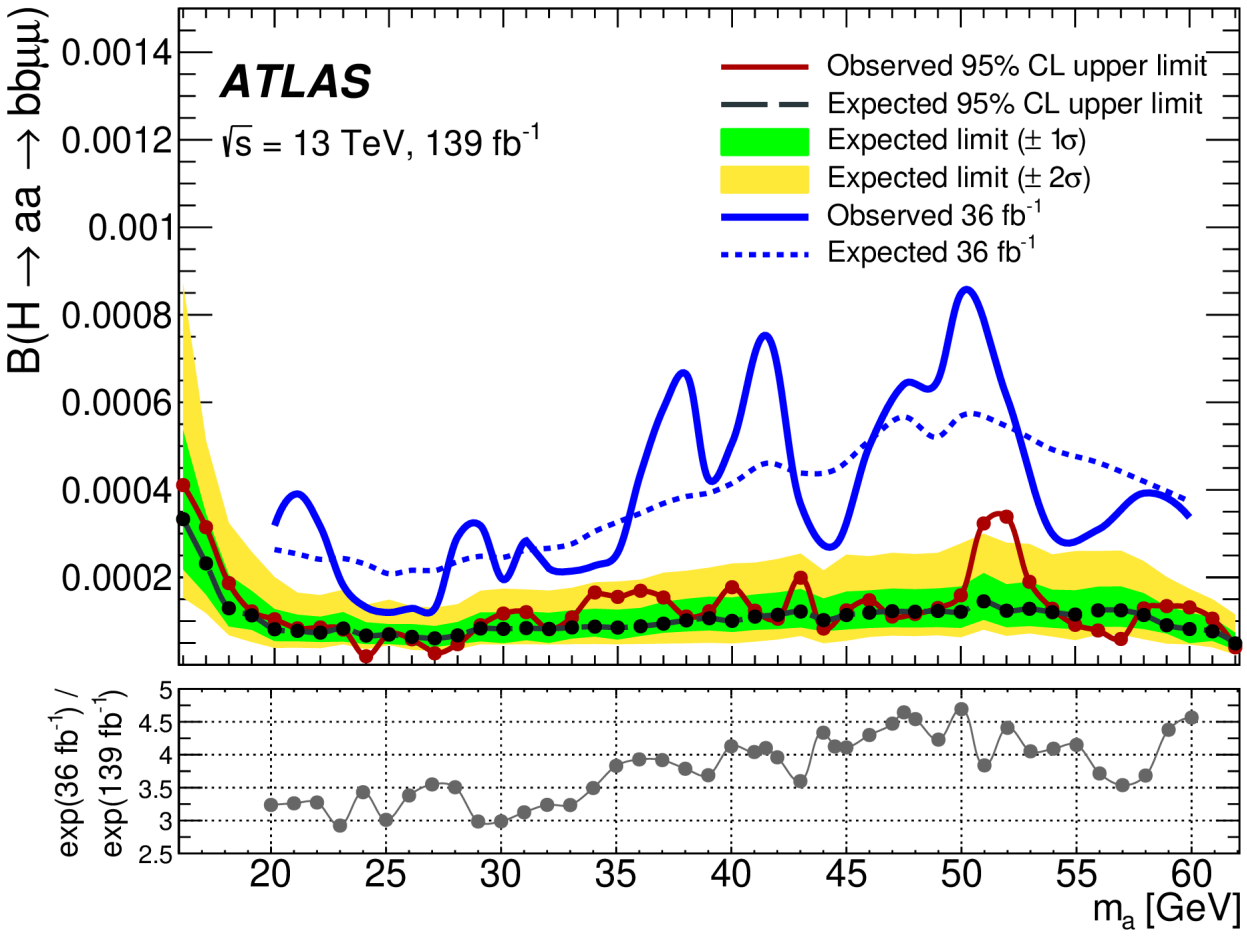

ATLAS
√s = 13 TeV, 139 fb-1
SRincl + 34<mμμ<36 GeV
Data
Total
DY + jets
tt̄
Other
ma=35 GeV
Events / 0.4
Data / Total
BDT35

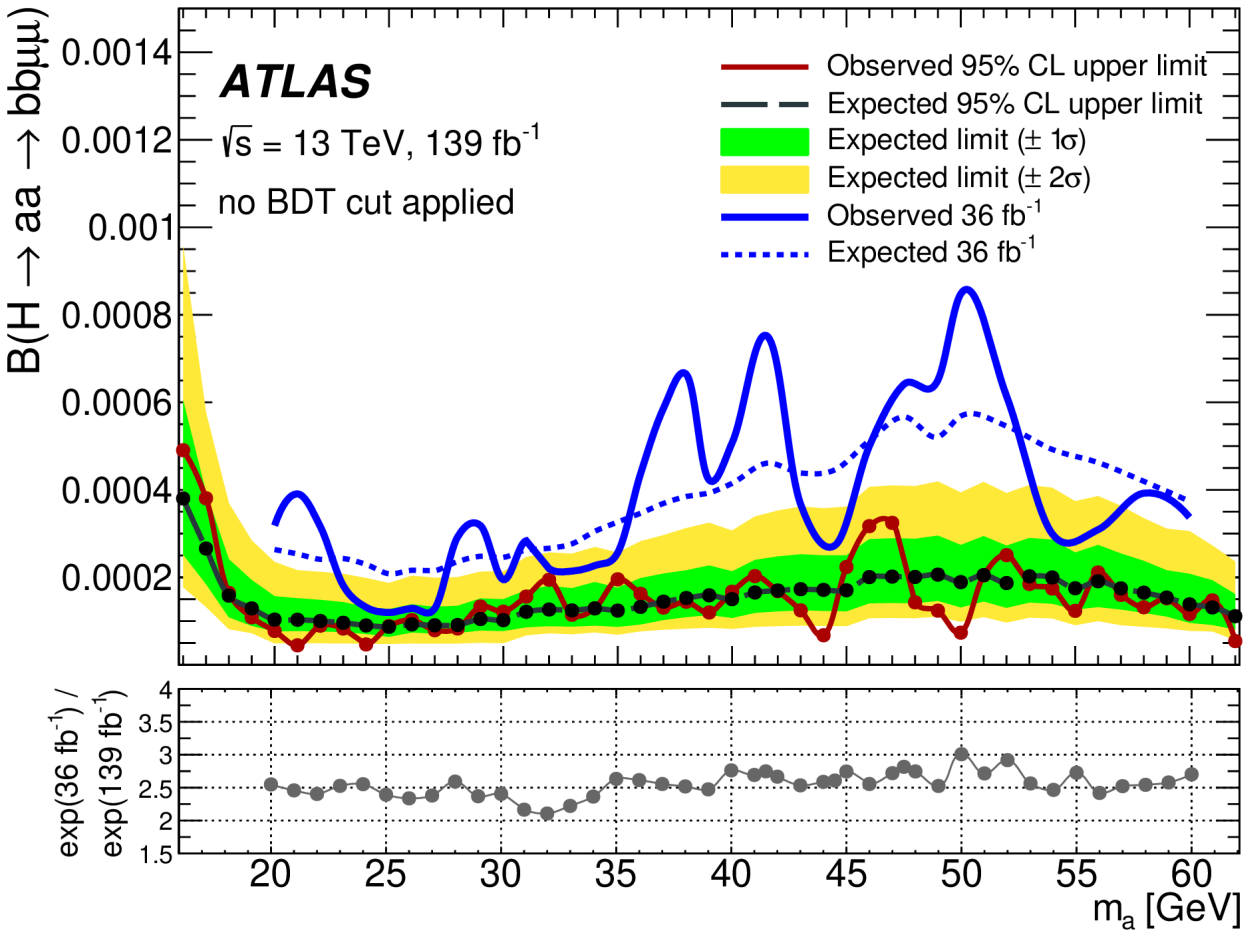

ATLAS
√s = 13 TeV, 139 fb-1
SRincl + BDT50>0.2
Data
Total
DY + jets
tt̄
Other
ma=52 GeV
Events / 1 GeV
Data / Total
mμμ [GeV]

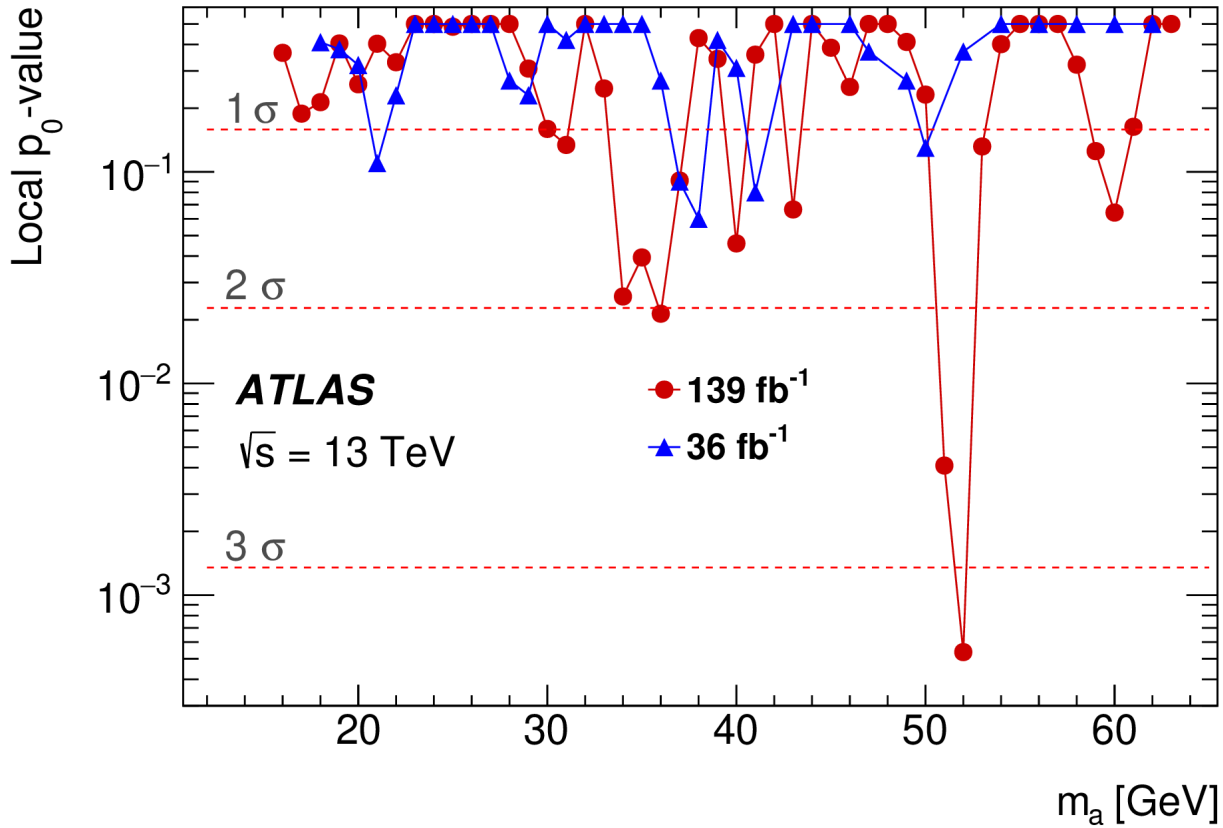

ATLAS
√s = 13 TeV, 139 fb-1
SRincl + 50.5<mμμ<53.5 GeV
Data
Total
DY + jets
tt̄
Other
ma=52 GeV
Events / 0.4
Data / Total
BDT50

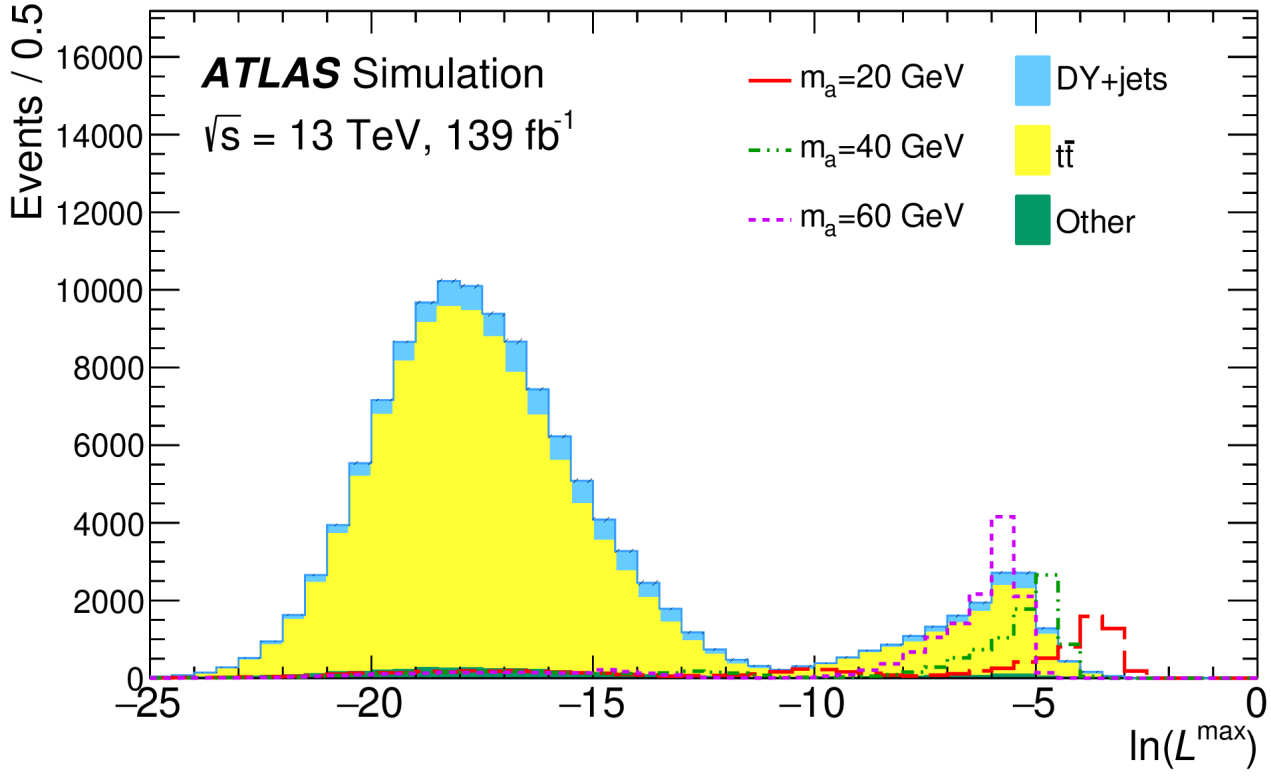

ATLAS
√s = 13 TeV, 139 fb-1
no BDT selection
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
Expected 95% CL upper limit (with BDT cut)
B(H → aa → bbμμ)
×10−3
0.7
0.6
0.5
0.4
0.3
0.2
0.1
20
25
30
35
40
45
50
55
60
ma [GeV]

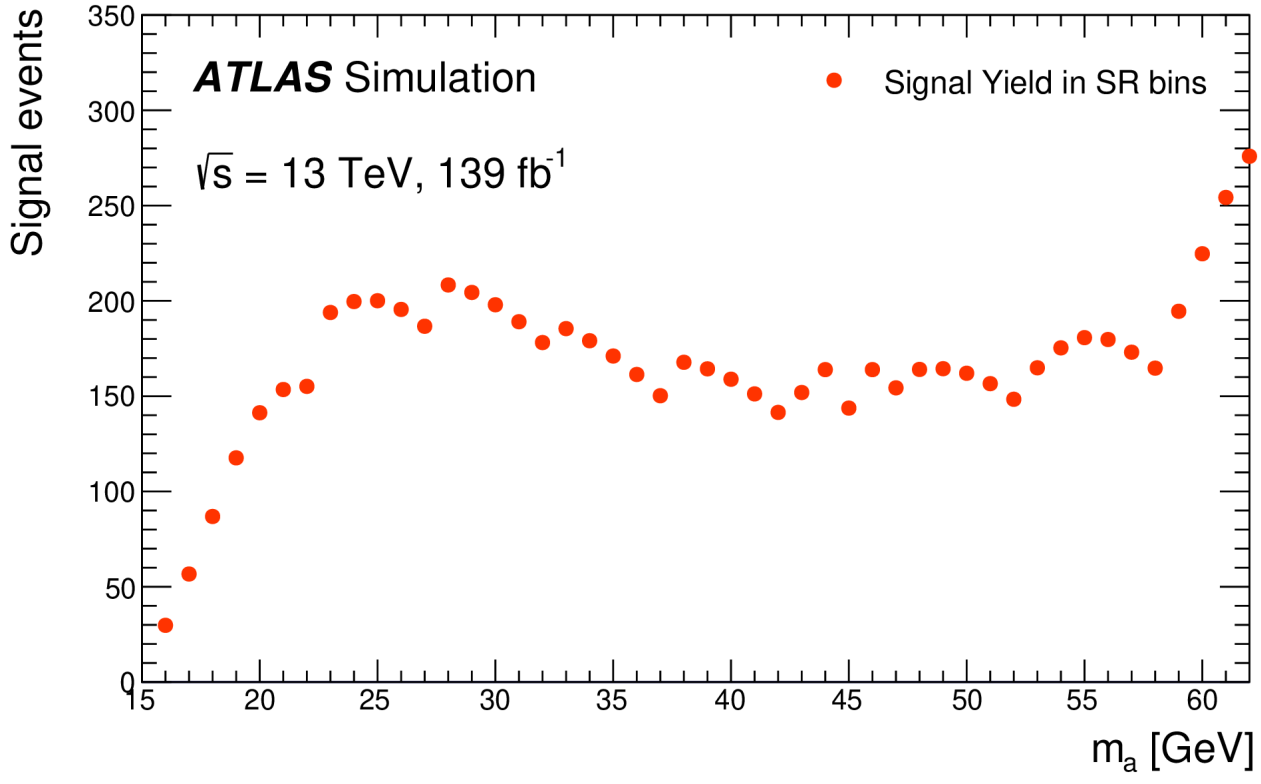

ATLAS
√s = 13 TeV, 139 fb-1
Data
DY+jets
Other
SM total
tt̄
Events / bin
(nobs - npred) / σtot
mμμ bin center [GeV]


ATLAS
√s = 13 TeV, 139 fb-1
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
Observed 36 fb-1
Expected 36 fb-1
B(H → aa → bbμμ)
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
exp(36 fb-1) / exp(139 fb-1)
5
4.5
4
3.5
3
2.5
20
25
30
35
40
45
50
55
60
ma [GeV]


ATLAS
√s = 13 TeV, 139 fb-1
no BDT cut applied
Observed 95% CL upper limit
Expected 95% CL upper limit
Expected limit (± 1σ)
Expected limit (± 2σ)
Observed 36 fb-1
Expected 36 fb-1
B(H → aa → bbμμ)
0.0014
0.0012
0.001
0.0008
0.0006
0.0004
0.0002
exp(36 fb-1) / exp(139 fb-1)
4
3.5
3
2.5
2
1.5
20
25
30
35
40
45
50
55
60
ma [GeV]


Local p_0-value
10^{-1}
10^{-2}
10^{-3}
1 σ
2 σ
3 σ
ATLAS
√s = 13 TeV
139 fb-1
36 fb-1
20
30
40
50
60
m_a [GeV]


ATLAS Simulation
√s = 13 TeV, 139 fb-1
ma=20 GeV
ma=40 GeV
ma=60 GeV
DY+jets
tt̄
Other
Events / 0.5
16000
14000
12000
10000
8000
6000
4000
2000
0
–25
–20
–15
–10
–5
0
ln(L max)


ATLAS Simulation
Signal Yield in SR bins
√s = 13 TeV, 139 fb-1
Signal events
350
300
250
200
150
100
50
0
15
20
25
30
35
40
45
50
55
60
ma [GeV]

	TCR	DYCR	SRincl	VR1	VR2
$m_{\mu\mu}$ [GeV]	[15, 65]				
$m_{bb\mu\mu}^{\mathrm{KL}}$ [GeV]	[110, 140]	[80, 110] or [140, 170]	[110, 140]	[170, 300]	[110, 140]
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 60	< 60			
$\ln(L^{\mathrm{max}})$	> -8				$[-11, -8]$
SR bins	SRincl & BDT$m_a > 0.2$ 2-GeV-wide (3-GeV-wide) $m_{\mu\mu}$ bins for $m_a \leq 45$ GeV ($m_a > 45$ GeV)				

Category	Source	Total background [%]	Signal [%]
DY	BDTm_a selection	7–14	–
	normalization	5–10	–
	$m_{\mu\mu}$ shape	1–8	–
	kinematics	0.3–6	–
	background subtraction	0.6–3	–
$t\bar{t}$	hadronization/PS	0.3–4	–
	hard-scatter generation	0.2–3	–
	normalization	0.2–3	–
Overall MC	Sample statistics	8–40	1–2
Jets	b-tagging	0.03–0.7	9–10
	Jet-energy resolution	1–3	6–7
	Jet-energy scale	1–3	4–5
Signal	FSR	–	5
	PS	–	4
	VH contribution	–	3.5
	MPI	–	3
	QCD scale	–	3
	ISR	–	3
	ggF cross-section		
	- missing higher-order QCD	–	5
	- PDF & α_S	–	3

$m_{\mu\mu}$ bin [GeV]	[15–17]	[24–26]	[34–36]	[44–46]	[50.5–53.5]	[60.5–63.5]
Observed events	6	9	19	17	39	8
Total background	4.8 ± 2.2	9.0 ± 1.8	11.9 ± 1.6	15.5 ± 2.0	19.3 ± 2.7	9.3 ± 1.7
DY	4.6 ± 2.1	6.4 ± 1.5	5.7 ± 1.1	6.4 ± 1.5	8.3 ± 2.1	5.3 ± 1.4
$t\bar{t}$	0.2 ± 0.1	2.6 ± 0.8	6.0 ± 1.1	8.5 ± 1.4	10.4 ± 2.4	3.5 ± 0.9
Other	0.03 ± 0.01	0.03 ± 0.00	0.24 ± 0.12	0.50 ± 0.40	0.50 ± 0.12	0.45 ± 0.19

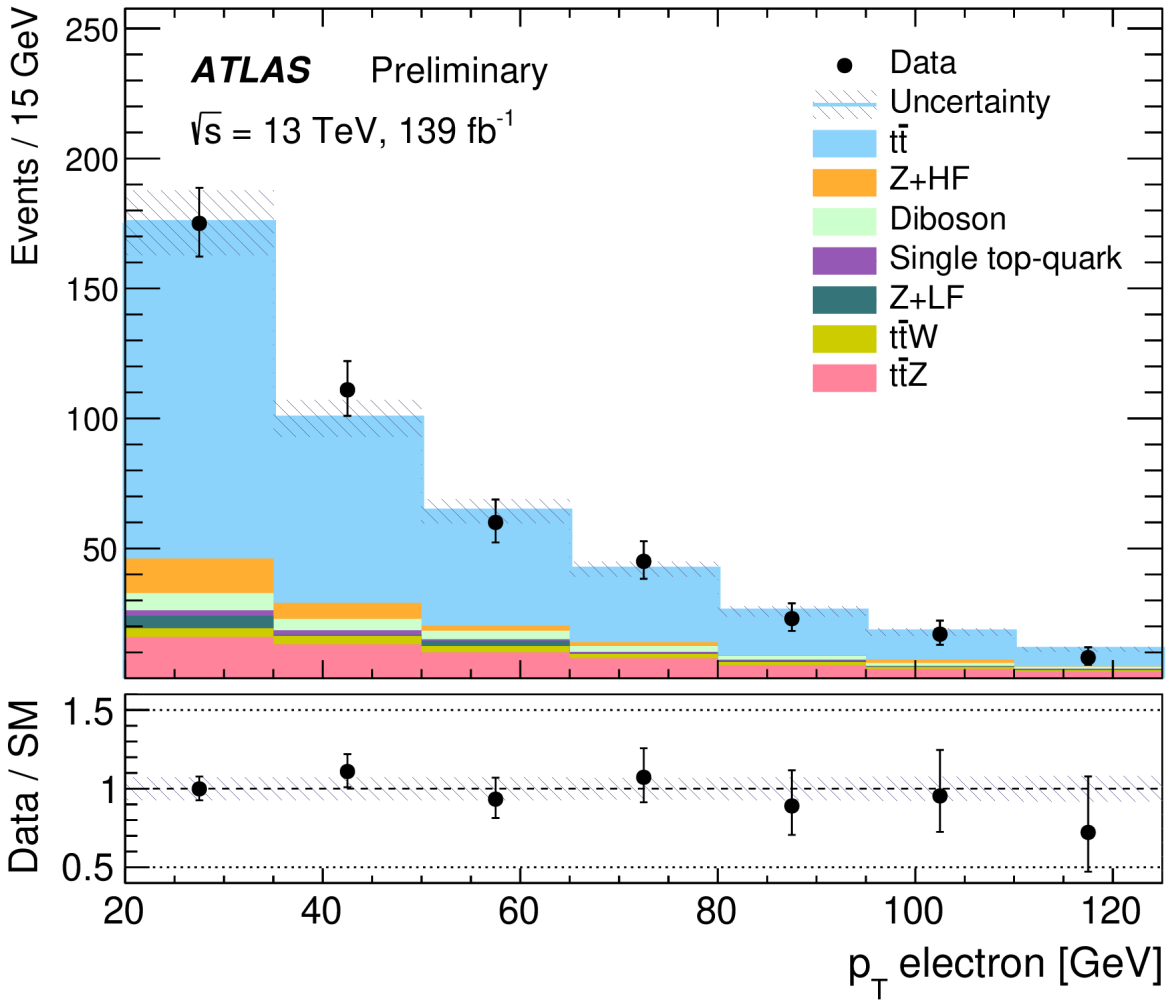
	$m_a = 16$ GeV				$m_a = 20$ GeV			
	ggF		VBF		ggF		VBF	
	Events	Rel. eff.	Events	Rel. eff.	Events	Rel. eff.	Events	Rel. eff.
Total ($\mathcal{L} \times \sigma \times \mathcal{B}$)	10804.5		841.1		10804.5		841.1	
Exactly 2 muons	4110.8		347.9		4142.5		362.1	
Trigger	3657.7	0.89	309.3	0.89	3679.7	0.89	322.0	0.89
15 GeV $< m_{\mu\mu} <$ 65 GeV	3510.6	0.96	296.4	0.96	3662.2	1	320.4	1
OS muons	3508.5	1	296.2	1	3658.7	1	320.2	1
$\geqslant$ 2 jets	1924.1	0.55	208.4	0.7	2190.4	0.6	231.0	0.72
Exactly 2 b-jets	123.8	0.064	13.4	0.064	270.9	0.12	22.6	0.10
$E_{\mathrm{T}}^{\mathrm{miss}} <$ 60 GeV	111.7	0.9	11.5	0.86	258.3	0.95	20.6	0.91
$\ln(L^{\mathrm{max}})$>-8	34.6	0.31	1.7	0.15	160.9	0.62	9.1	0.44
110 GeV $< m_{bb\mu\mu}^{\mathrm{KL}} <$ 140 GeV	29.6	0.86	1.5	0.86	149.7	0.93	8.3	0.91
$m_{\mu\mu}$ window	29.1	0.98	1.4	0.98	143.1	0.96	8.0	0.97
BDT > 0.2	28.4	0.98	1.4	0.99	133.6	0.93	7.7	0.96

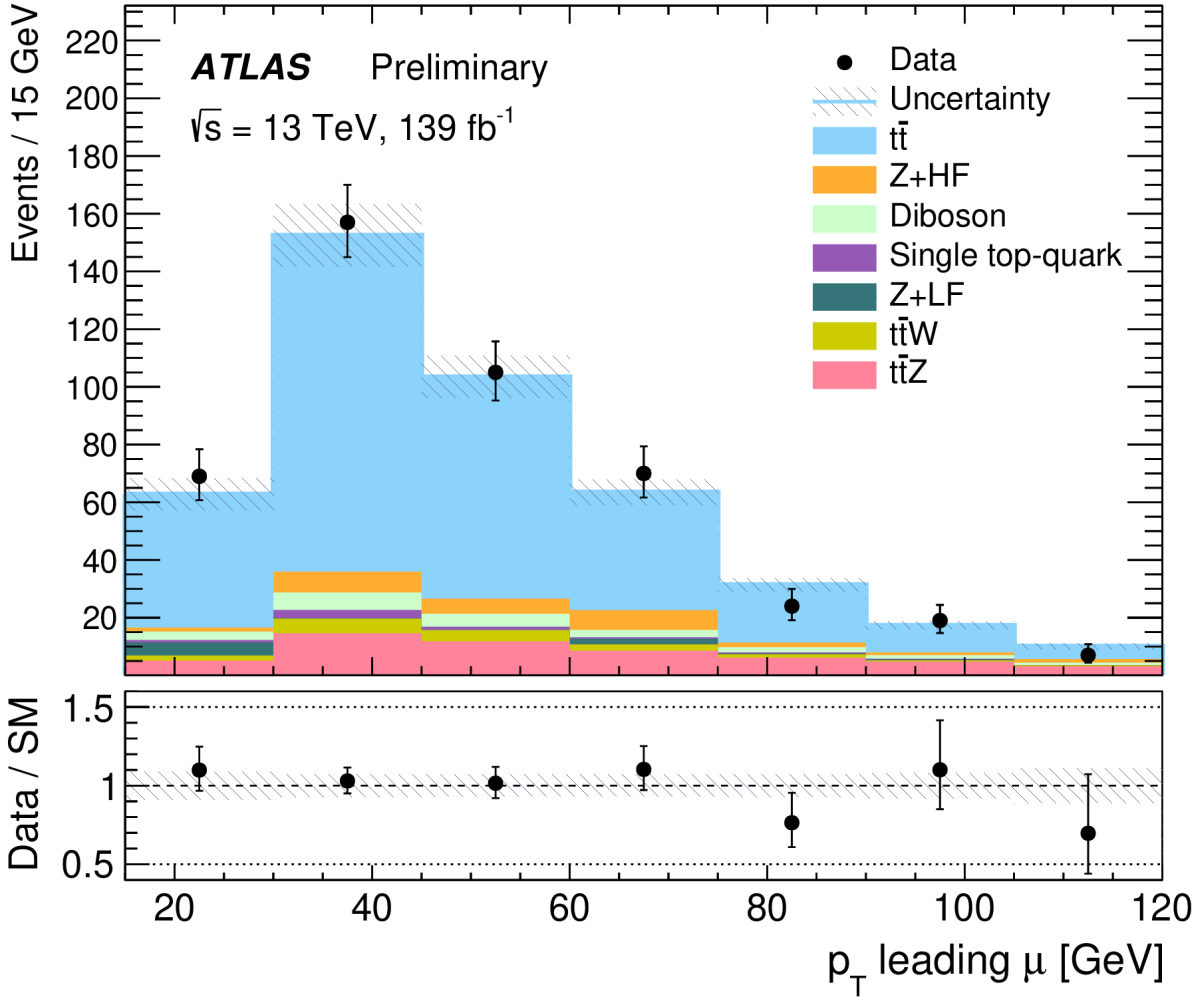
	$m_a = 30$ GeV				$m_a = 40$ GeV			
	ggF		VBF		ggF		VBF	
	Events	Rel. eff.	Events	Rel. eff.	Events	Rel. eff.	Events	Rel. eff.
Total ($\mathcal{L} \times \sigma \times \mathcal{B}$)	10804.5		841.1		10804.5		841.1	
Exactly 2 muons	4292.7		380.9		4409.2		390.1	
Trigger	3742.5	0.87	334.0	0.88	3906.3	0.89	350.2	0.9
15 GeV $< m_{\mu\mu} <$ 65 GeV	3739.1	1	333.6	1	3904.6	1	350.0	1
OS muons	3735.1	1	333.3	1	3900.4	1	349.7	1
$\geqslant$ 2 jets	2250.7	0.6	246.0	0.74	2309.8	0.59	261.3	0.75
Exactly 2 b-jets	331.6	0.15	37.4	0.15	314.5	0.14	41.0	0.16
$E_{\mathrm{T}}^{\mathrm{miss}} <$ 60 GeV	319.7	0.96	35.1	0.94	300.7	0.96	38.7	0.94
$\ln(L^{\mathrm{max}})$>-8	238.2	0.75	23.4	0.67	221.9	0.74	27.3	0.71
110 GeV $< m_{bb\mu\mu}^{\mathrm{KL}} <$ 140 GeV	225.3	0.95	22.3	0.95	208.8	0.94	25.9	0.95
$m_{\mu\mu}$ window	197.8	0.88	19.5	0.87	164.0	0.79	20.1	0.77
BDT > 0.2	179.3	0.91	18.7	0.96	140.2	0.85	18.7	0.93

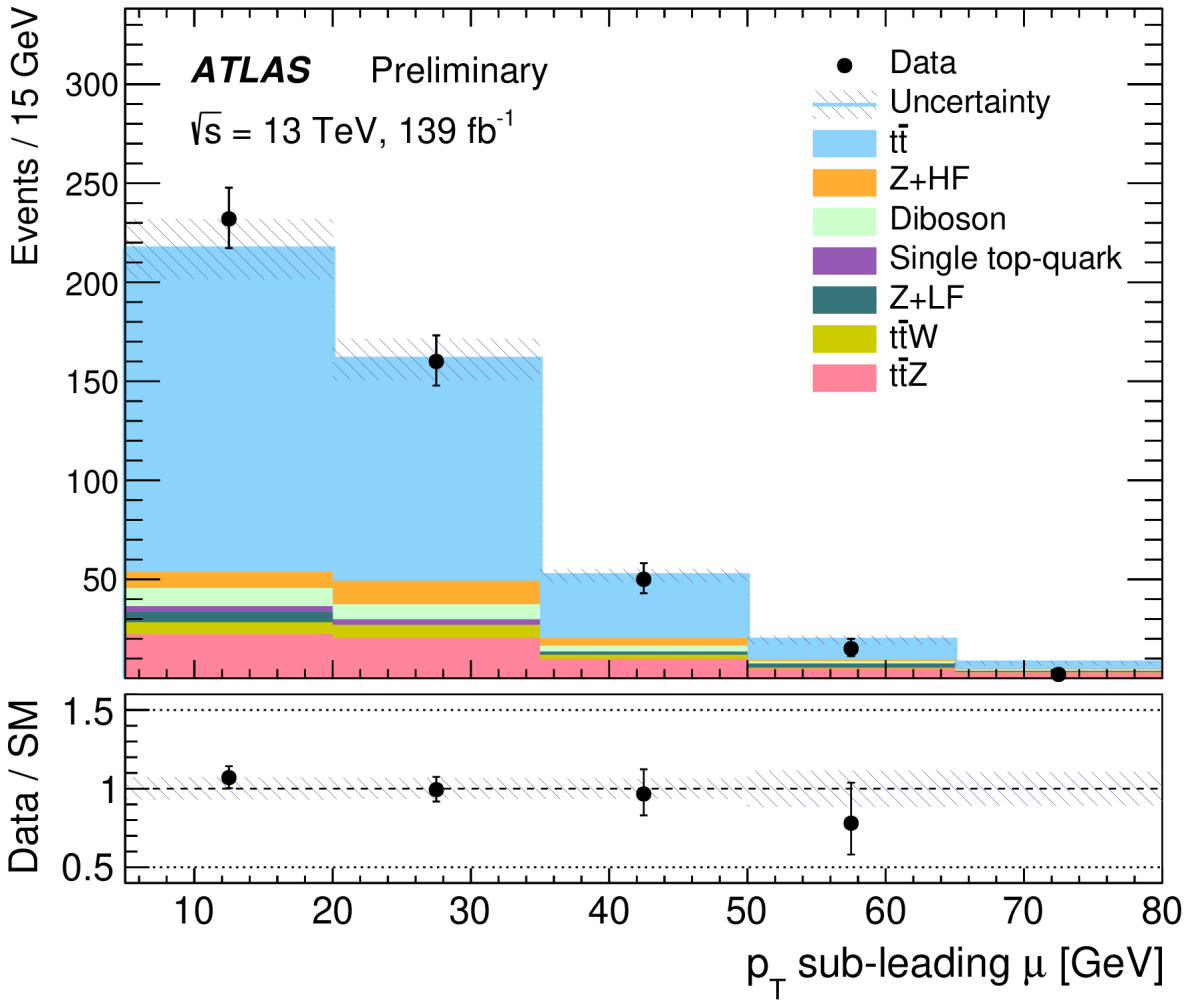
	$m_a = 50$ GeV				$m_a = 60$ GeV			
	ggF		VBF		ggF		VBF	
	Events	Rel. eff.	Events	Rel. eff.	Events	Rel. eff.	Events	Rel. eff.
Total ($\mathcal{L} \times \sigma \times \mathcal{B}$)	10804.5		841.1		10804.5		841.1	
Exactly 2 muons	4463.0		392.7		4428.8		395.3	
Trigger	3952.2	0.89	357.8	0.91	3903.0	0.88	362.8	0.92
15 GeV $< m_{\mu\mu} <$ 65 GeV	3950.5	1	357.7	1	3898.2	1	362.4	1
OS muons	3946.0	1	357.3	1	3894.9	1	362.1	1
$\geqslant$ 2 jets	2369.8	0.6	268.5	0.75	2512.4	0.65	278.0	0.77
Exactly 2 b-jets	318.1	0.13	41.5	0.15	422.3	0.17	46.1	0.17
$E_{\mathrm{T}}^{\mathrm{miss}} <$ 60 GeV	304.9	0.96	38.9	0.94	406.5	0.96	43.4	0.94
$\ln(L^{\mathrm{max}})$>-8	230.9	0.76	27.3	0.7	329.8	0.81	31.7	0.73
110 GeV $< m_{bb\mu\mu}^{\mathrm{KL}} <$ 140 GeV	218.4	0.95	25.8	0.95	314.7	0.95	30.2	0.95
$m_{\mu\mu}$ window	183.1	0.84	21.7	0.84	242.5	0.77	22.7	0.75
BDT > 0.2	142.6	0.78	19.4	0.89	204.0	0.84	20.7	0.91

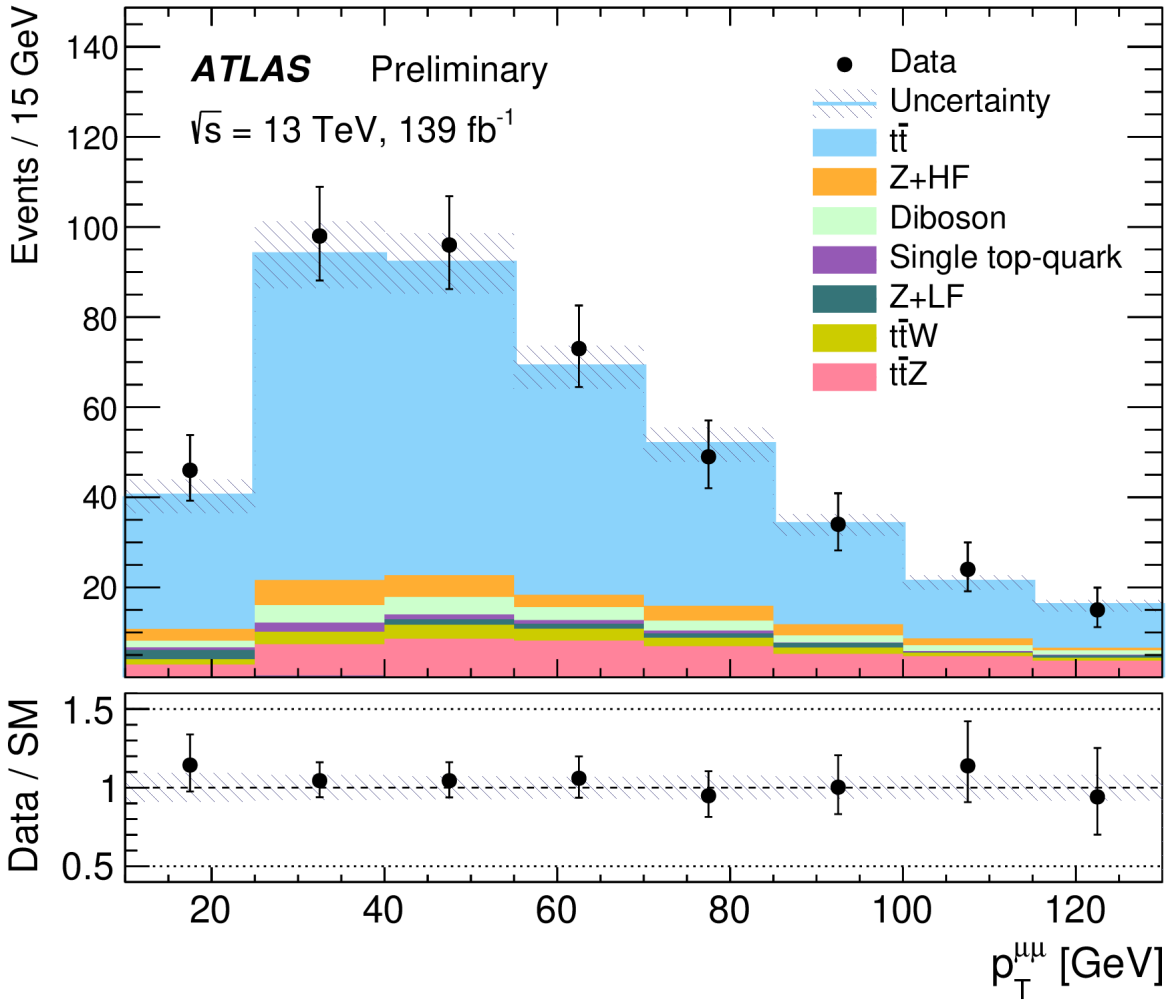
$tt \rightarrow tH^{\pm}b$, $H^{\pm} \rightarrow WA$, $A \rightarrow \mu\mu$ Search

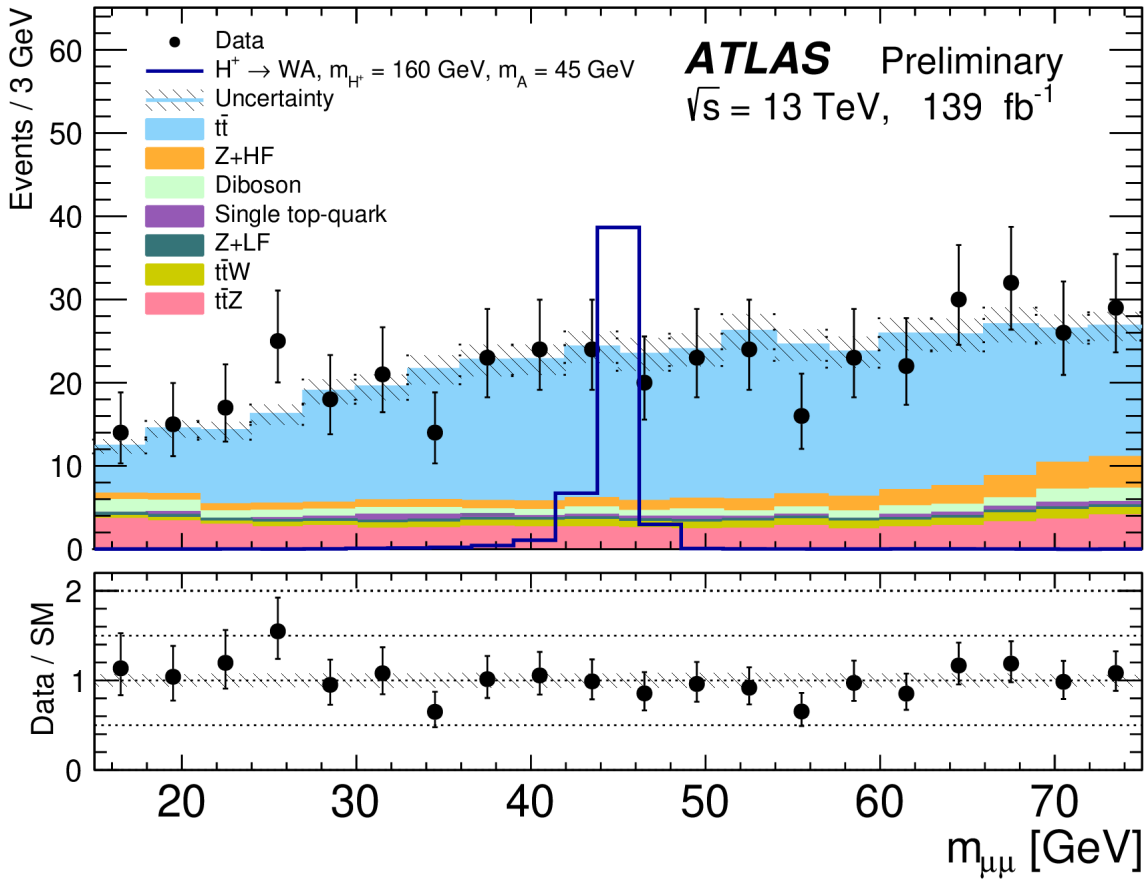
- $t\bar{t}$ **CR**: same-sign muons
- Z **+ HF CR**: $78 < m_{\mu\mu} < 102$ GeV, electron $p_{\mathrm{T}} < 20$ GeV
- $t\bar{t}Z$ **CR**: $78 < m_{\mu\mu} < 102$ GeV, electron $p_{\mathrm{T}} > 20$ GeV
- **VR**: no requirements on sign of muons, $30 < m_{e\mu} < 110$ GeV for the electron and leading muon

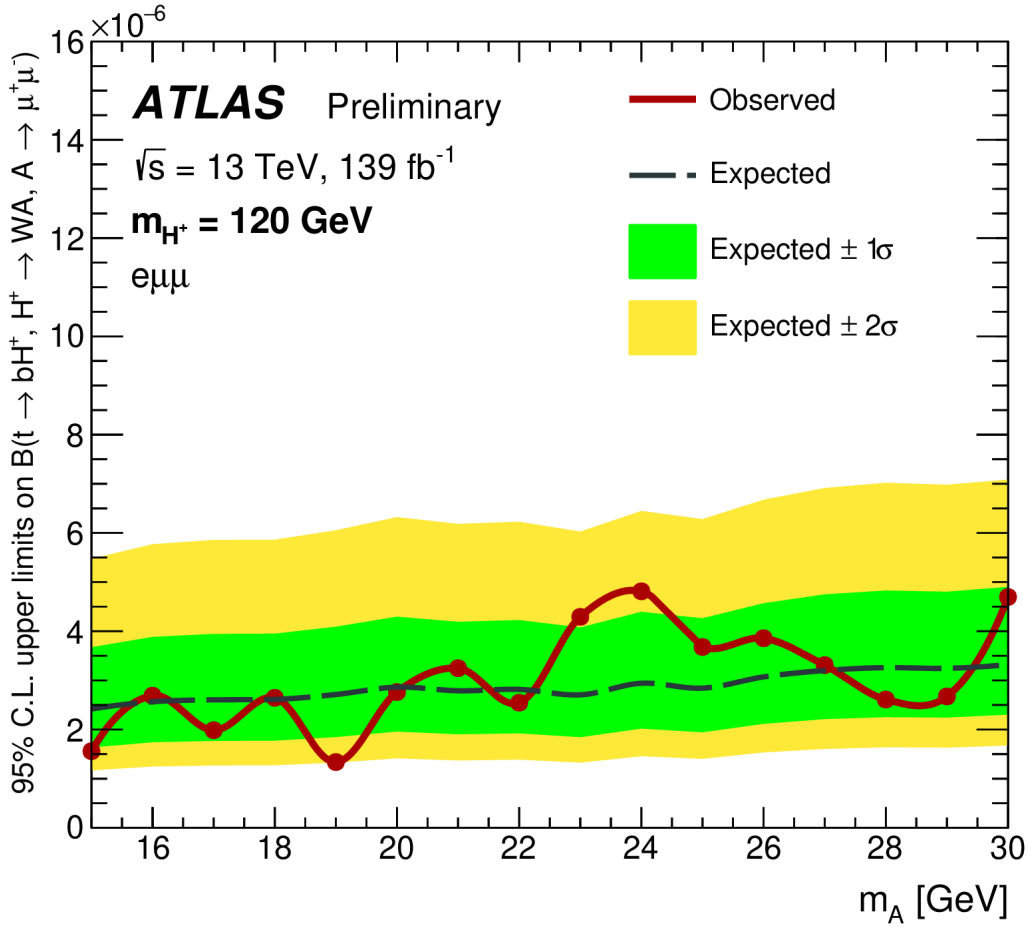

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Data
Uncertainty
tt̄
Z+HF
Diboson
Single top-quark
Z+LF
tt̄W
tt̄Z
Events / 15 GeV
Data / SM
pT electron [GeV]

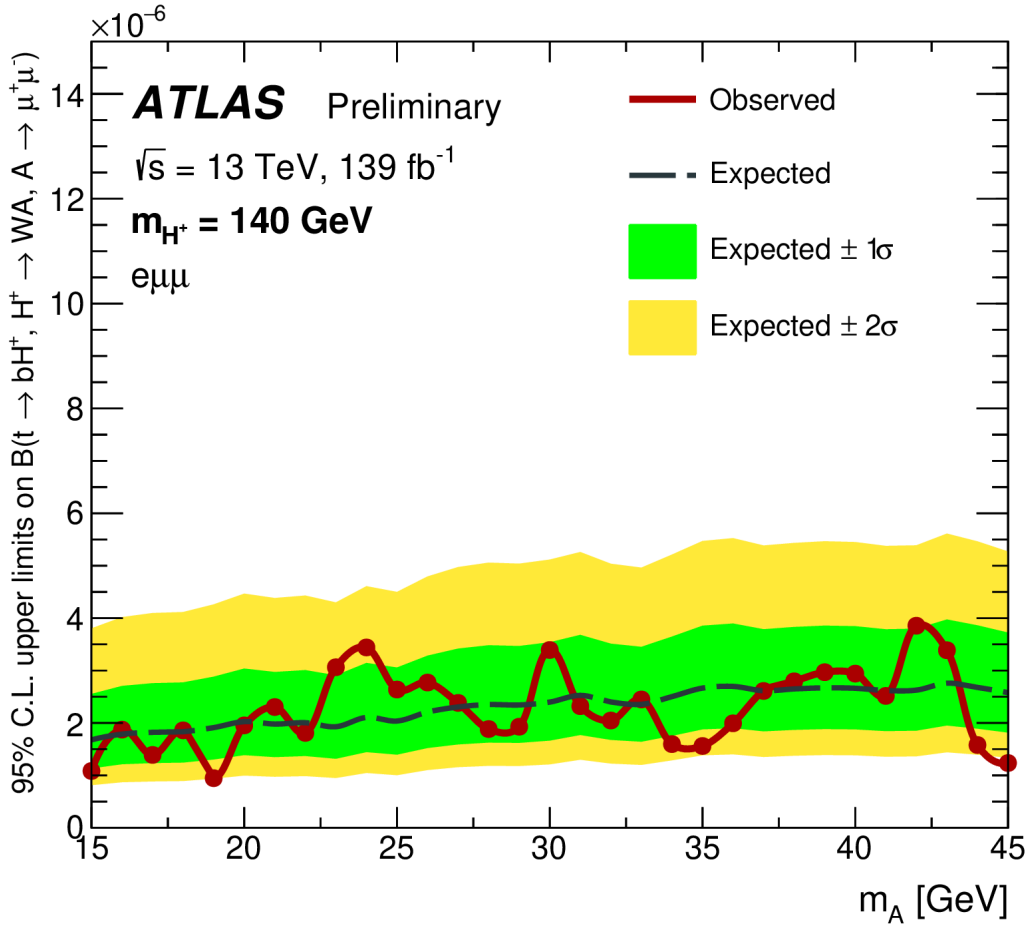

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Data
Uncertainty
tt̄
Z+HF
Diboson
Single top-quark
Z+LF
ttW
ttZ
Events / 15 GeV
Data / SM
pT leading μ [GeV]

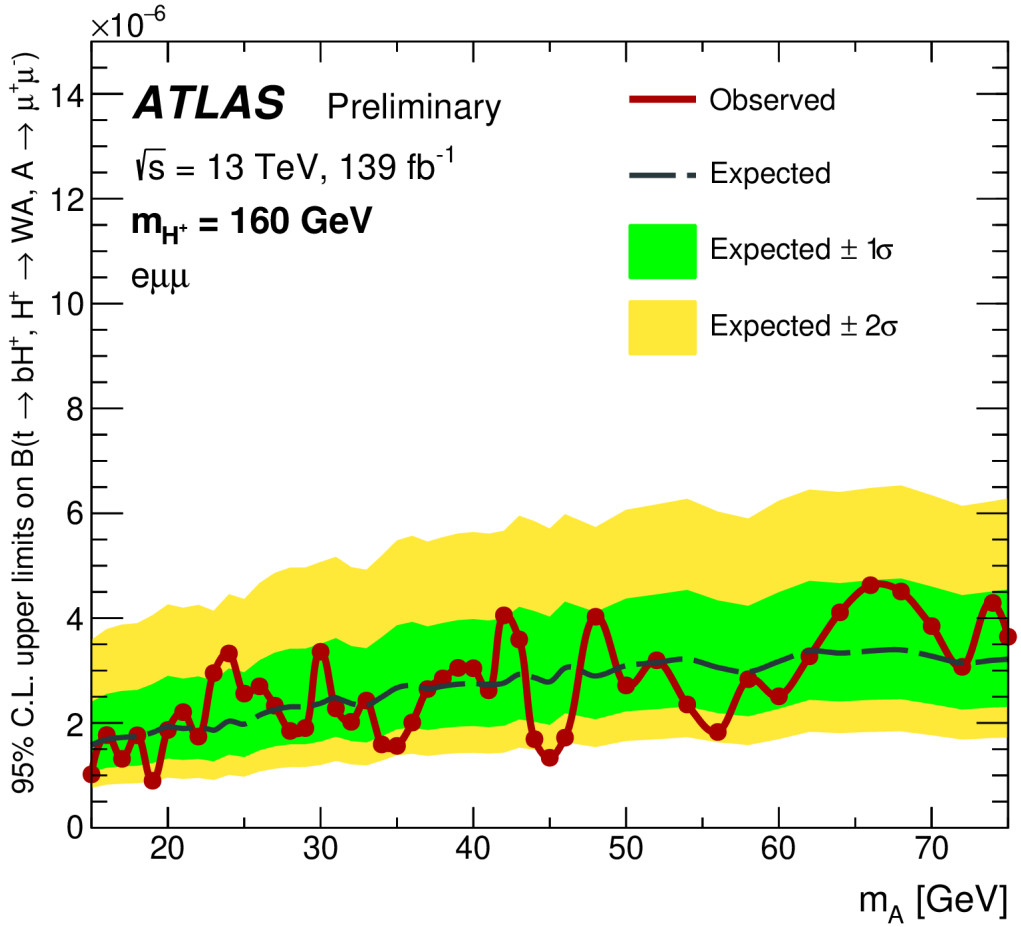

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Data
Uncertainty
tt̄
Z+HF
Diboson
Single top-quark
Z+LF
ttW
ttZ
Events / 15 GeV
300
250
200
150
100
50
Data / SM
1.5
1
0.5
10
20
30
40
50
60
70
80
pT sub-leading μ [GeV]

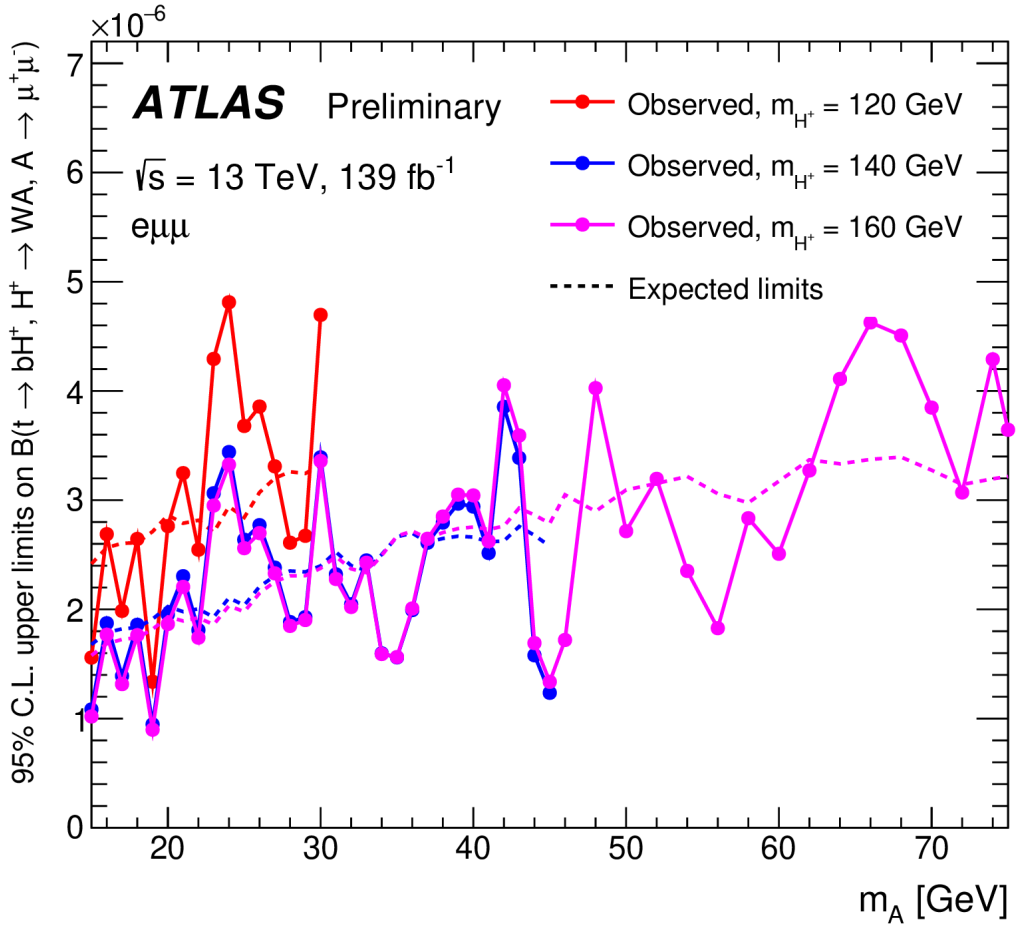

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Data
Uncertainty
tt̄
Z+HF
Diboson
Single top-quark
Z+LF
ttW
ttZ
Events / 15 GeV
Data / SM
p_T^μμ [GeV]

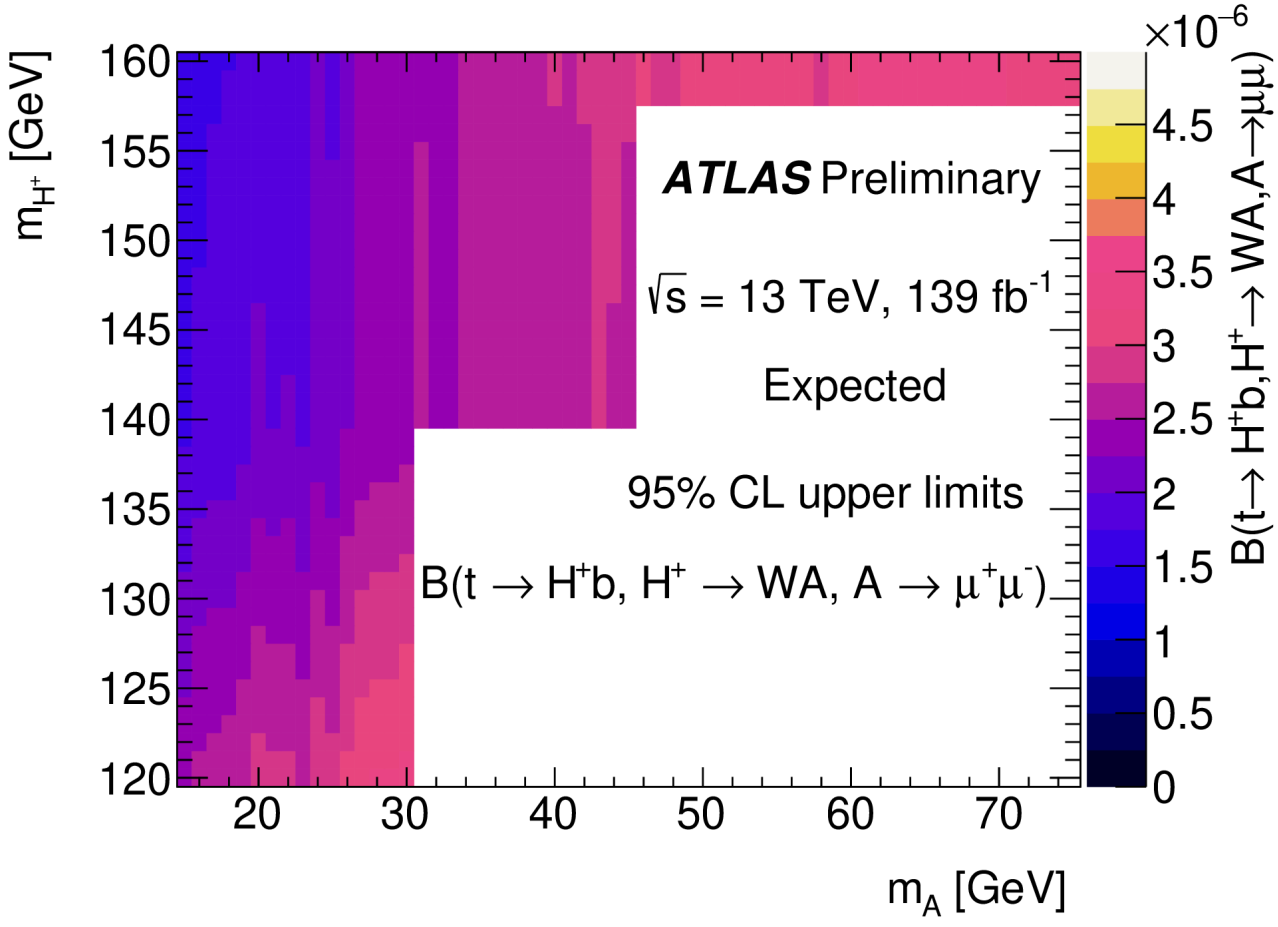

Data
H+ → WA, mH+ = 160 GeV, mA = 45 GeV
Uncertainty
tt̄
Z+HF
Diboson
Single top-quark
Z+LF
tt̄W
tt̄Z
ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Events / 3 GeV
Data / SM
mμμ [GeV]

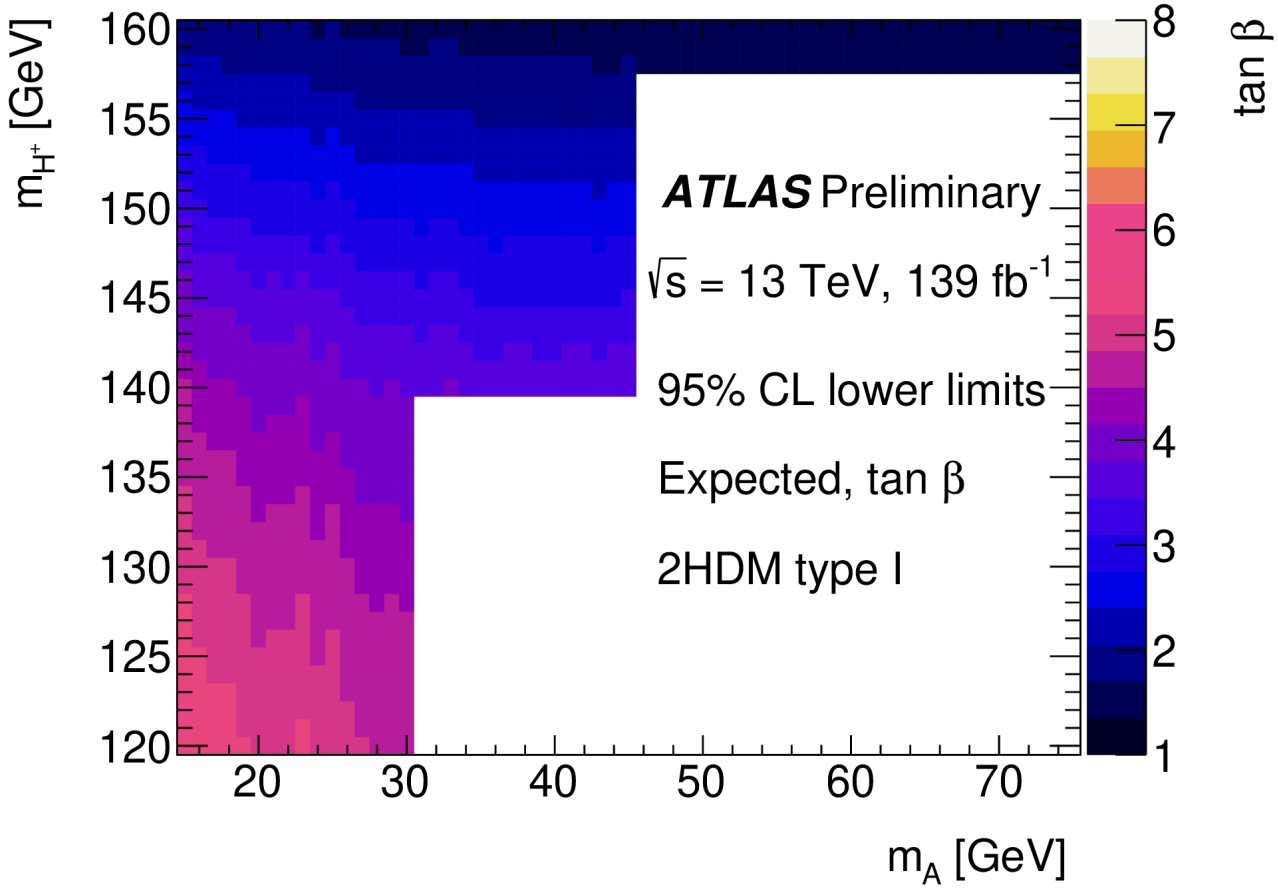

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
mH+ = 120 GeV
eμμ
Observed
Expected
Expected ± 1σ
Expected ± 2σ
95% C.L. upper limits on B(t → bH+, H+ → WA, A → μ+μ-)
×10−6
mA [GeV]
0
2
4
6
8
10
12
14
16
16
18
20
22
24
26
28
30


×10⁻⁶
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
m_H⁺ = 140 GeV
eμμ
Observed
Expected
Expected ± 1σ
Expected ± 2σ
95% C.L. upper limits on B(t → bH⁺, H⁺ → WA, A → μ⁺μ⁻)
m_A [GeV]
0
2
4
6
8
10
12
14
15
20
25
30
35
40
45


×10⁻⁶
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
m_H⁺ = 160 GeV
eμμ
Observed
Expected
Expected ± 1σ
Expected ± 2σ
95% C.L. upper limits on B(t → bH⁺, H⁺ → WA, A → μ⁺μ⁻)
m_A [GeV]
0
2
4
6
8
10
12
14
20
30
40
50
60
70


×10⁻⁶
ATLAS Preliminary
√s = 13 TeV, 139 fb⁻¹
eμμ
Observed, m_H+ = 120 GeV
Observed, m_H+ = 140 GeV
Observed, m_H+ = 160 GeV
Expected limits
95% C.L. upper limits on B(t → bH+, H+ → WA, A → μ+μ-)
m_A [GeV]
0
1
2
3
4
5
6
7
20
30
40
50
60
70


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Expected
95% CL upper limits
B(t → H+b, H+ → WA, A → μ+μ-)
mH+ [GeV]
mA [GeV]
B(t→ H+b,H+→ WA,A→μμ)
×10−6
160
155
150
145
140
135
130
125
120
20
30
40
50
60
70
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
95% CL lower limits
Expected, tan β
2HDM type I
m_H+ [GeV]
m_A [GeV]
tan β
160
155
150
145
140
135
130
125
120
20
30
40
50
60
70
8
7
6
5
4
3
2
1

	Event selection	
Trigger	single muon	di-muon
Muons	$p_{\mathrm{T}}^{\mathrm{leading}} > 27$ GeV, $p_{\mathrm{T}}^{\mathrm{subleading}} > 5$ GeV	$p_{\mathrm{T}}^{\mathrm{leading}} > 15$ GeV, $p_{\mathrm{T}}^{\mathrm{subleading}} > 15$ GeV
	exactly 2, opposite sign $12 < m_{\mu\mu}$ [GeV] < 77 $p_{\mathrm{T}}(\mu^{\mathrm{SS}})/p_{\mathrm{T}}(\mu^{\mathrm{OS}}) > 0.2$	
Electrons	exactly 1, $p_{\mathrm{T}} > 20$ GeV	
Jets	≥ 3, $p_{\mathrm{T}} > 20$ GeV ≥ 1 b-tagged jet	

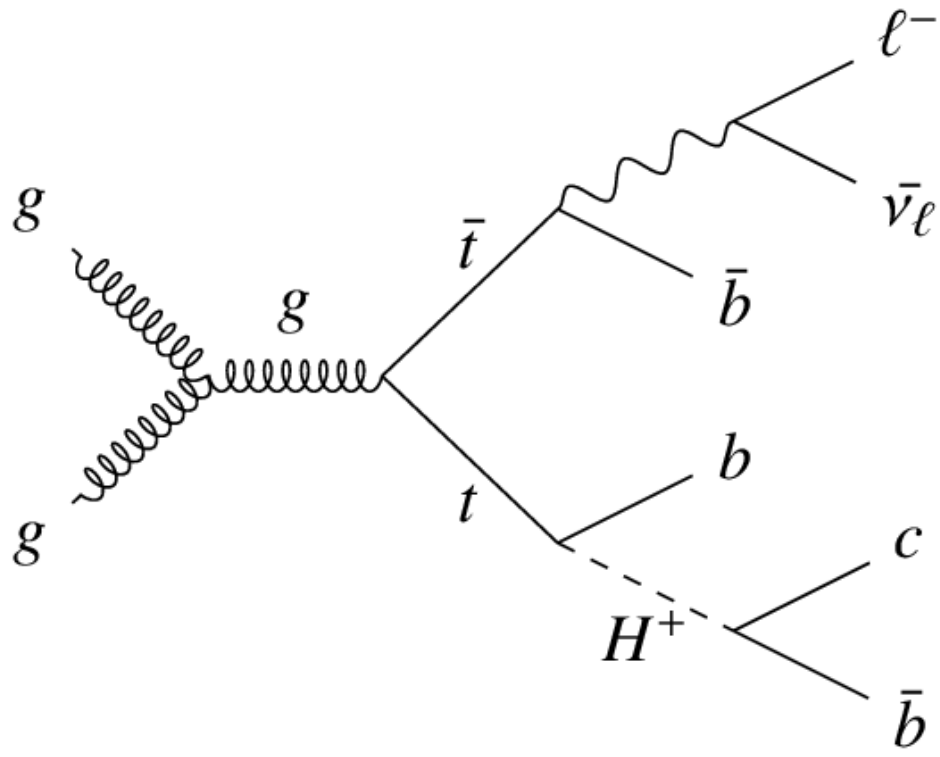
Source	Total background [%]	Signal [%]
$t\bar{t}$: hadronization/parton-shower	9–17	–
$t\bar{t}$: hard-scatter generation	7–13	–
$t\bar{t}$: ISR/FSR	1–4	–
$t\bar{t}$: normalization	4–7	–
ttZ: normalization	3–8	–
Diboson: cross-section	2-7	–
MC statistics	4–7	2
Jet energy resolution	3–6	
Signal: PDF & α_{S}	–	4
Signal: QCD scale	–	3.5
Signal: mass	–	3

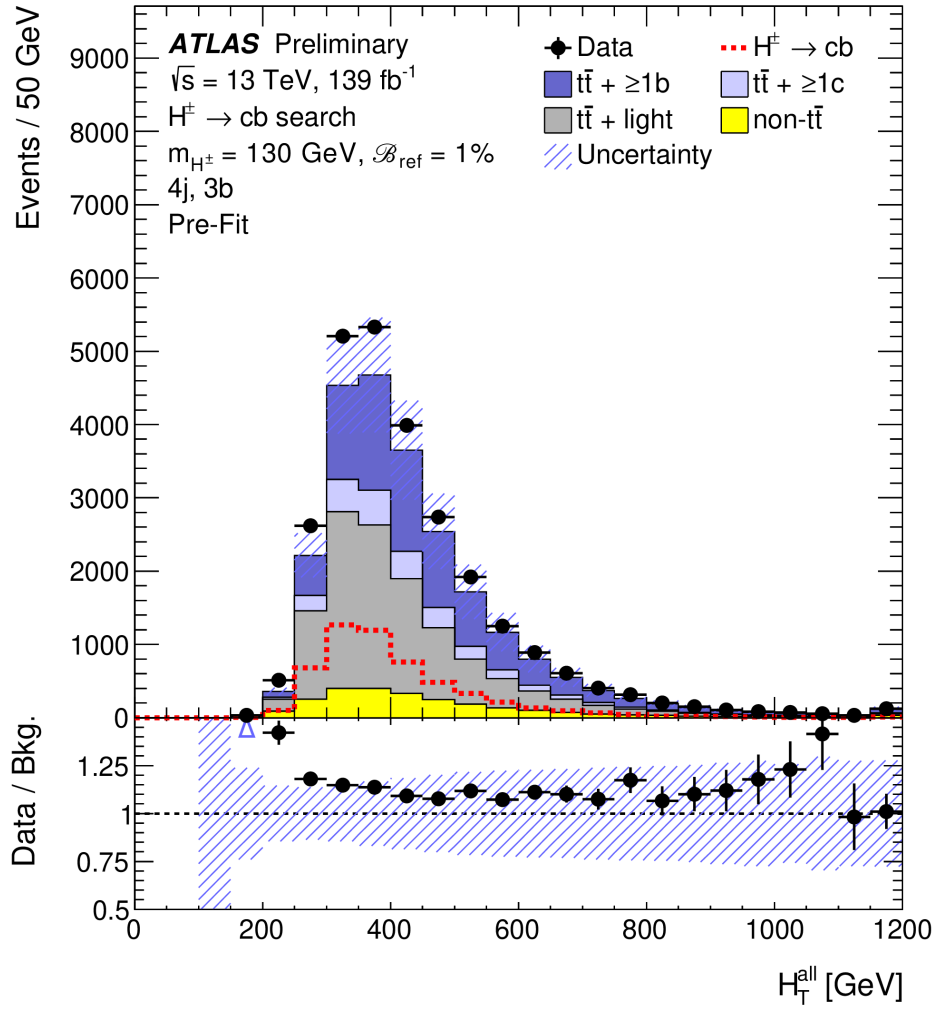
Regions		CRZ	CR$t\bar{t}$	CR$t\bar{t}Z$	VR	SRInclusive
Observed events		803	190	635	529	465
Fitted background events	Total	803 ±28	190 ±14	635 ±25	541 ±43	470 ±37
	$t\bar{t}$	136 ±21	170 ±14	97 ±19	388 ±46	320 ±39
	Z+HF	491 ±49	0.72 ± 0.16	43 ± 8	18 ± 6	29 ± 6
	Z+LF	84 ±29	0.41 ± 0.14	12 ± 4	2.82 ± 0.98	13 ± 4
	$t\bar{t}Z$	52 ±14	6.40 ± 1.64	327 ±83	76 ±19	64 ±16
	Diboson	34 ±17	0.58 ± 0.29	147 ±73	32 ±16	22 ±11
	W+jets	0.01 ± 0.01	0.40 ± 0.39	0 ± 0	0.08 ± 0.07	0.49 ± 0.48
	Single top	4.13 ± 0.29	4.38 ± 0.23	2.39 ± 0.12	9.00 ± 0.46	6.17 ± 0.33
	$t\bar{t}W$	1.06 ± 0.15	7.43 ± 0.97	6.42 ± 0.83	14 ± 2	16 ± 2
Pre-Fit background events	Total	762 ±93	181 ± 9	505 ±76	497 ±31	433 ±23
	$t\bar{t}$	131 ±15	163 ± 9	93 ±14	373 ±22	308 ±18
	Z+ HF	475 ±79	0.69 ± 0.08	42 ± 6	18 ± 7	28 ± 3
	Z+ LF	84 ±30	0.41 ± 0.14	12 ± 4	2.82 ± 0.99	13 ± 4
	$t\bar{t}Z$	32 ± 2	3.97 ± 0.12	202 ± 3	47 ± 1	40 ± 1
	Diboson	34 ±17	0.58 ± 0.29	147 ±74	32 ±16	23 ±11
	W+jets	0.01 ± 0.01	0.40 ± 0.40	0 ± 0	0.08 ± 0.07	0.49 ± 0.49
	Single top	4.13 ± 0.29	4.38 ± 0.23	2.39 ± 0.12	9.00 ± 0.47	6.17 ± 0.33
	$t\bar{t}W$	1.06 ± 0.15	7.43 ± 0.97	6.42 ± 0.84	14 ± 2	16 ± 2

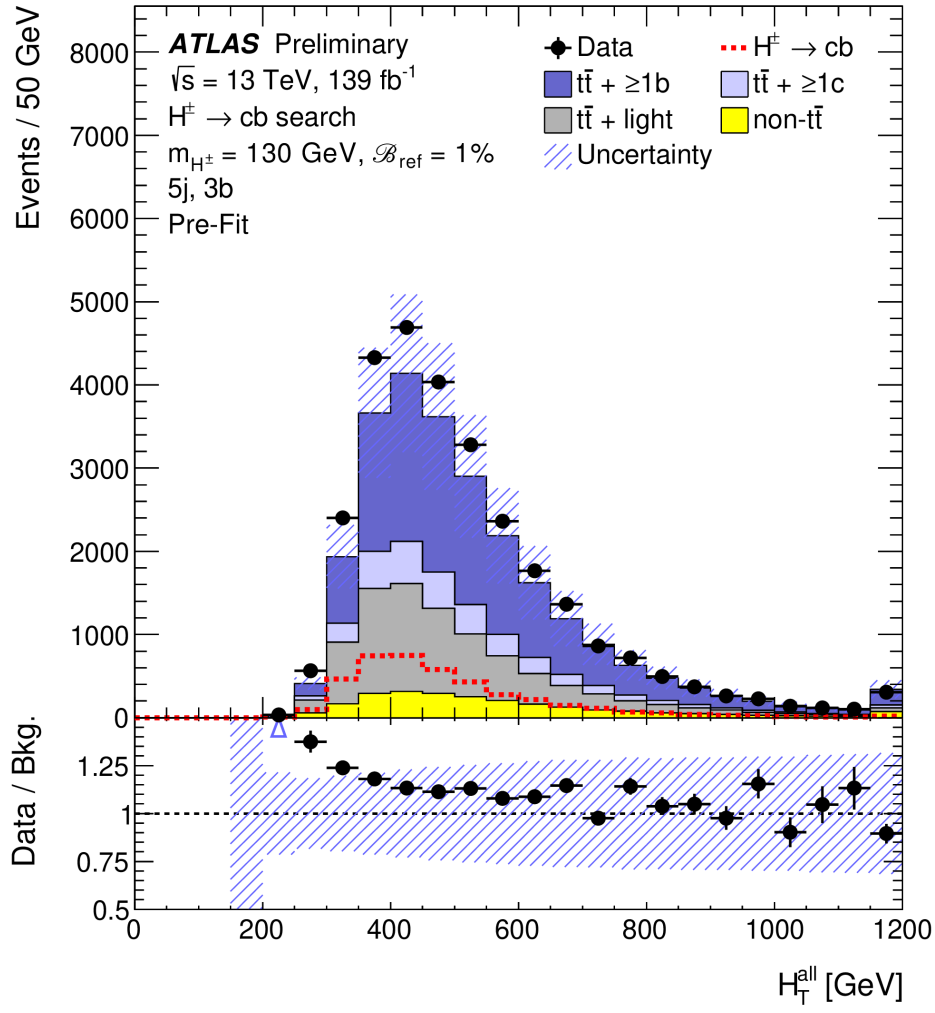
Masses, GeV		Upper limits on $\mathcal{B}$ ($\times 10^{-6}$), 95% CL						Lower limits on $\tan\beta$, 95% CL	
m_{H^+}	m_A	observed	-2 σ	-1 σ	expected	+1 σ	+2 σ	observed	expected
100	15	6.85	5.11	7.17	9.96	12.61	18.53	4.37	3.63
120	15	1.55	1.16	1.62	2.40	3.65	5.45	7.03	5.69
120	30	4.69	1.67	2.30	3.32	4.89	7.08	3.99	4.80
140	15	1.08	0.80	1.12	1.67	2.54	3.79	5.62	4.54
140	30	3.39	1.21	1.66	2.40	3.54	5.11	3.13	3.77
140	45	1.24	1.34	1.82	2.58	3.72	5.27	5.31	3.72
160	15	1.01	0.75	1.06	1.57	2.39	3.57	2.40	1.93
160	30	3.35	1.20	1.65	2.37	3.50	5.06	1.35	1.55
160	45	1.34	1.45	1.97	2.79	4.02	5.70	2.12	1.47
160	60	2.51	1.69	2.27	3.17	4.49	6.24	1.55	1.41
160	75	3.64	1.72	2.31	3.21	4.54	6.28	1.30	1.37

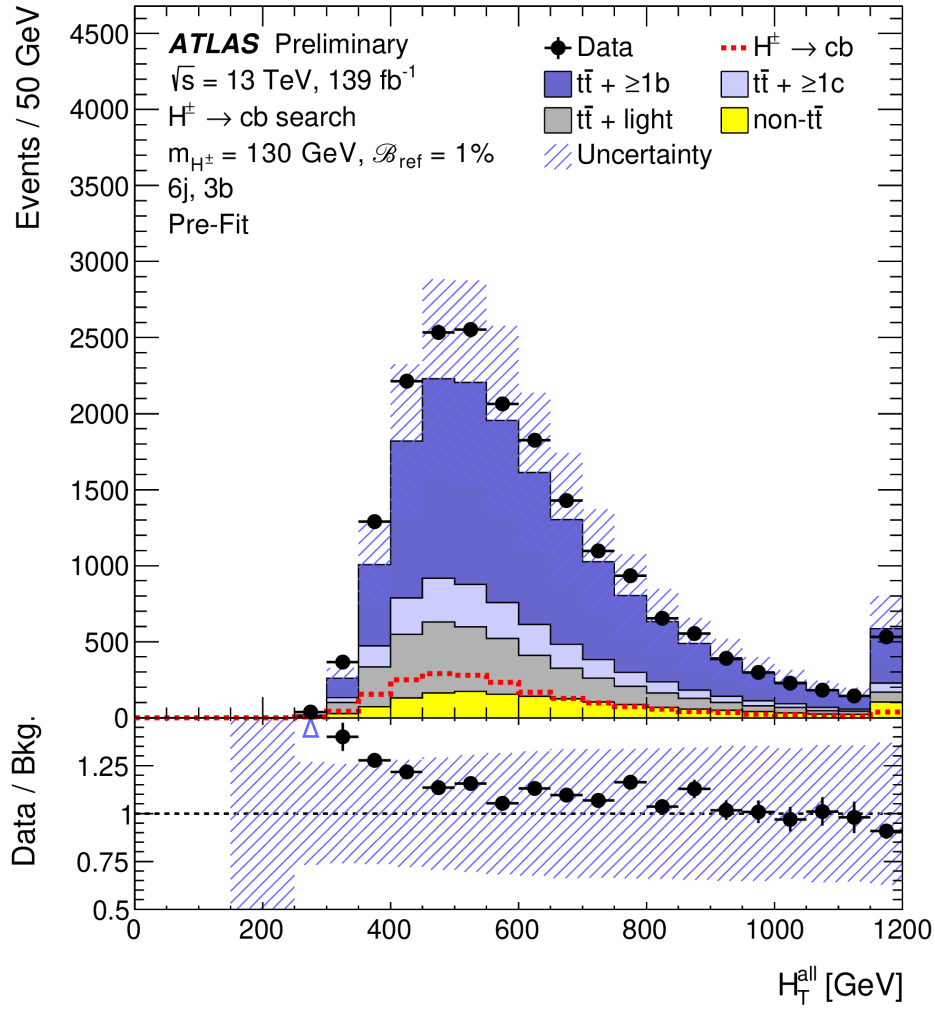
	H160a15		H160a45		H160a75		H140a15		H120a15		H120a30	
	events	eff., %	events	eff., %	events	eff., %	events	eff., %	events	eff., %	events	eff., %
$\mathcal{L} \times \sigma \times \mathcal{B}$	222.1	100	224.4	100	220.1	100	222.9	100	222.1	100	216.4	100
$\mathcal{L} \times \sigma \times \mathcal{B} \times \epsilon_{gen}$	135.5	61.0	141.4	63.0	140.9	64.0	138.2	62.0	142.1	64.0	145.0	67.0
= 2 muons	55.8	25.1	62.3	27.7	68.8	31.2	51.1	22.9	43.6	19.6	50.3	23.2
muon p_{T} selection	45.0	20.3	54.0	24.1	63.2	28.7	37.8	17.0	27.6	12.4	30.6	14.2
≥ 3 jets, 20 GeV	36.7	16.5	44.4	19.8	52.0	23.6	32.6	14.6	24.1	10.9	27.0	12.5
≥1 b-jet	26.9	12.1	32.5	14.5	38.5	17.5	26.6	12.0	20.7	9.3	23.1	10.7
OS muons	24.2	10.9	29.9	13.3	36.1	16.4	23.3	10.4	16.7	7.5	19.1	8.8
=1 electron	5.3	2.4	6.8	3.0	8.2	3.7	4.9	2.2	3.4	1.5	4.1	1.9
electron p_T > 20 GeV	4.6	2.1	5.9	2.6	7.2	3.3	4.2	1.9	3.0	1.4	3.5	1.6
mass window	4.2	1.9	4.8	2.1	5.2	2.4	3.8	1.7	2.6	1.2	2.9	1.3
$\frac{p_{\mathrm{T}}(\mu^{SS})}{p_{\mathrm{T}}(\mu^{OS})} > 0.2$	3.8	1.7	4.4	2.0	4.9	2.2	3.5	1.6	2.4	1.1	2.6	1.2

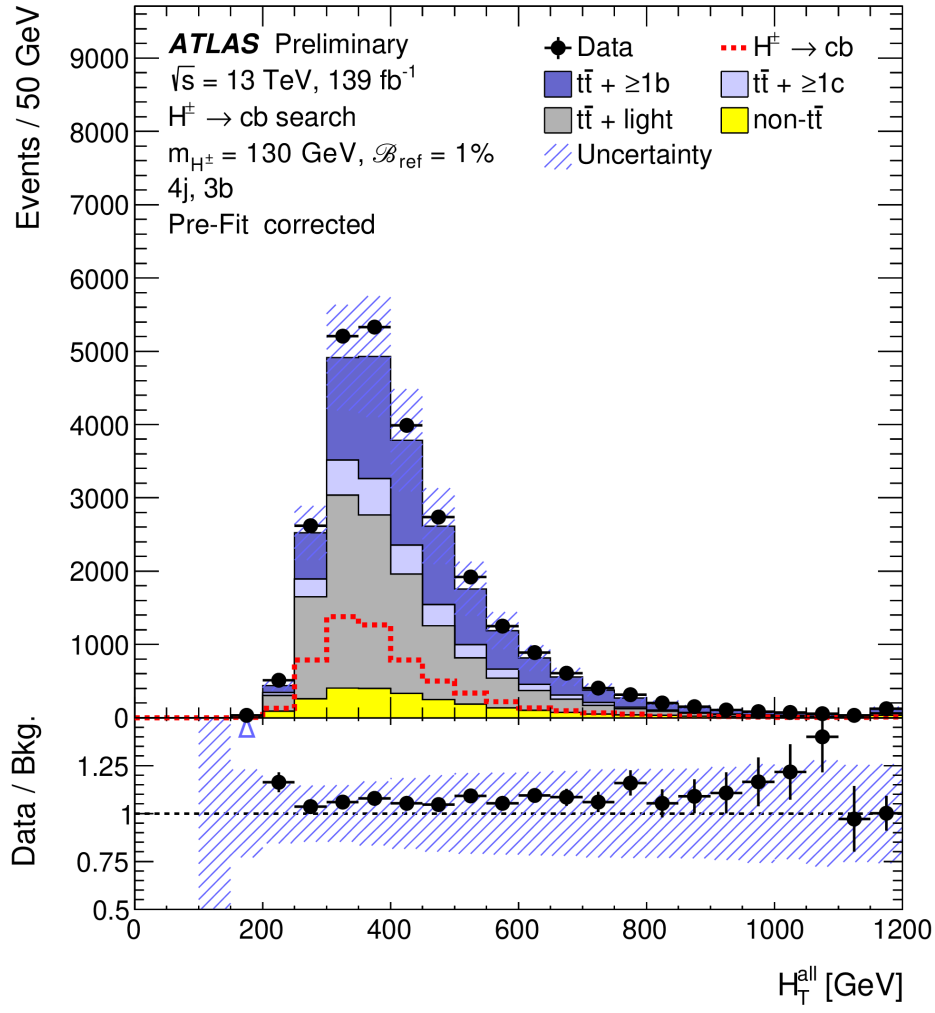
$tt \rightarrow tH^{\pm}b,\ H^{\pm} \rightarrow cb$ Search

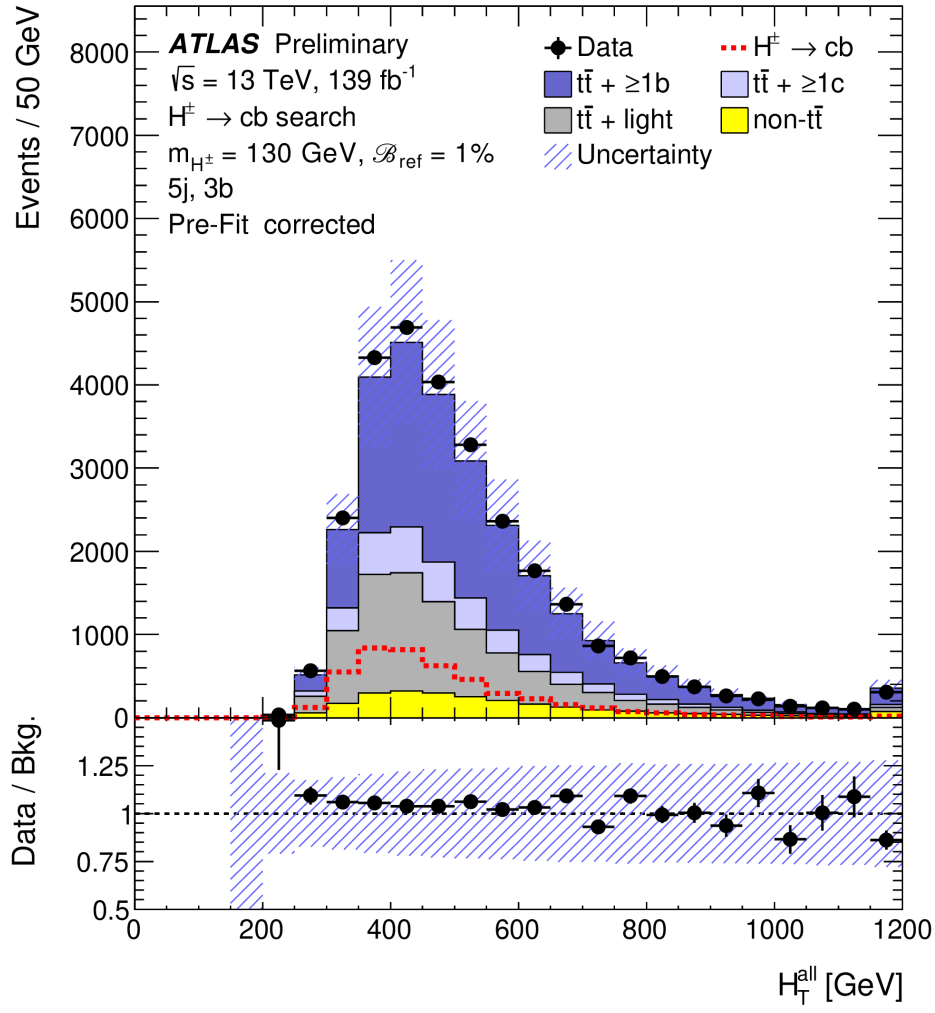

ℓ^-
$\bar{\nu}_\ell$
g
$\bar{t}$
$\bar{b}$
g
b
t
g
c
H^+
$\bar{b}$

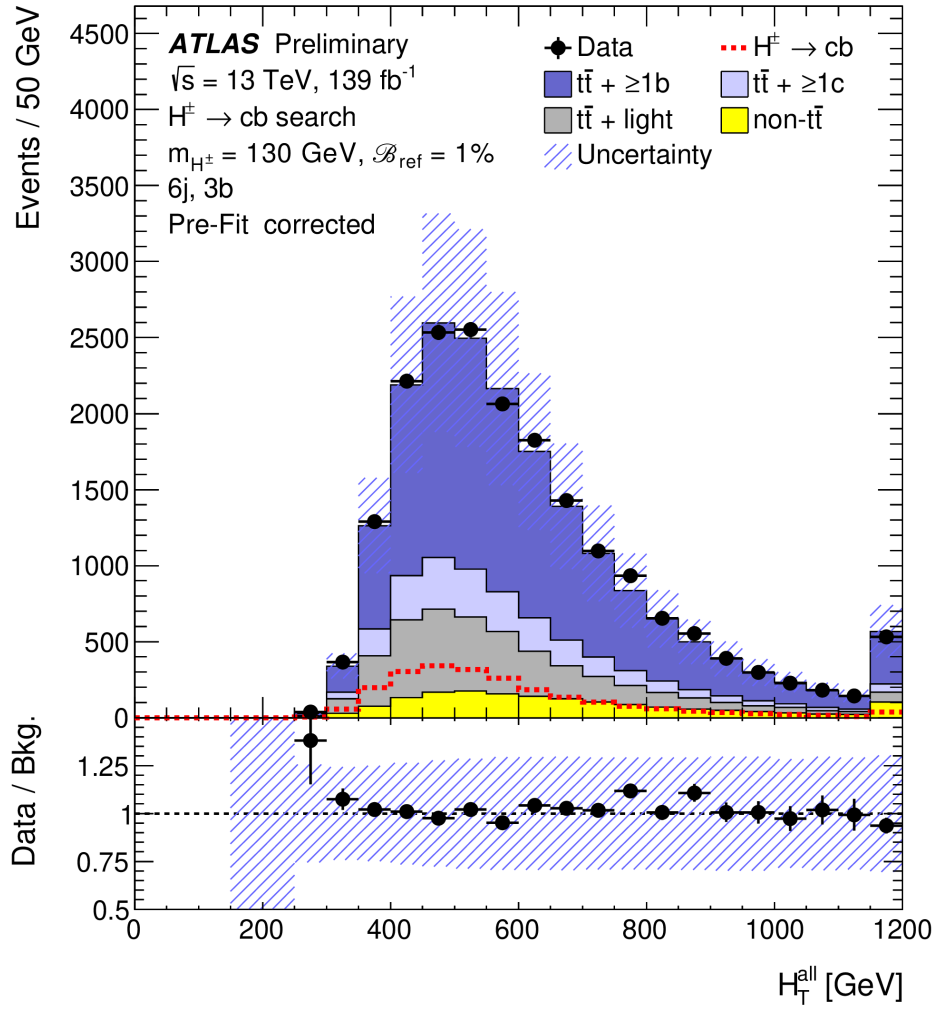

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
4j, 3b
Pre-Fit
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 50 GeV
Data / Bkg.
HTall [GeV]

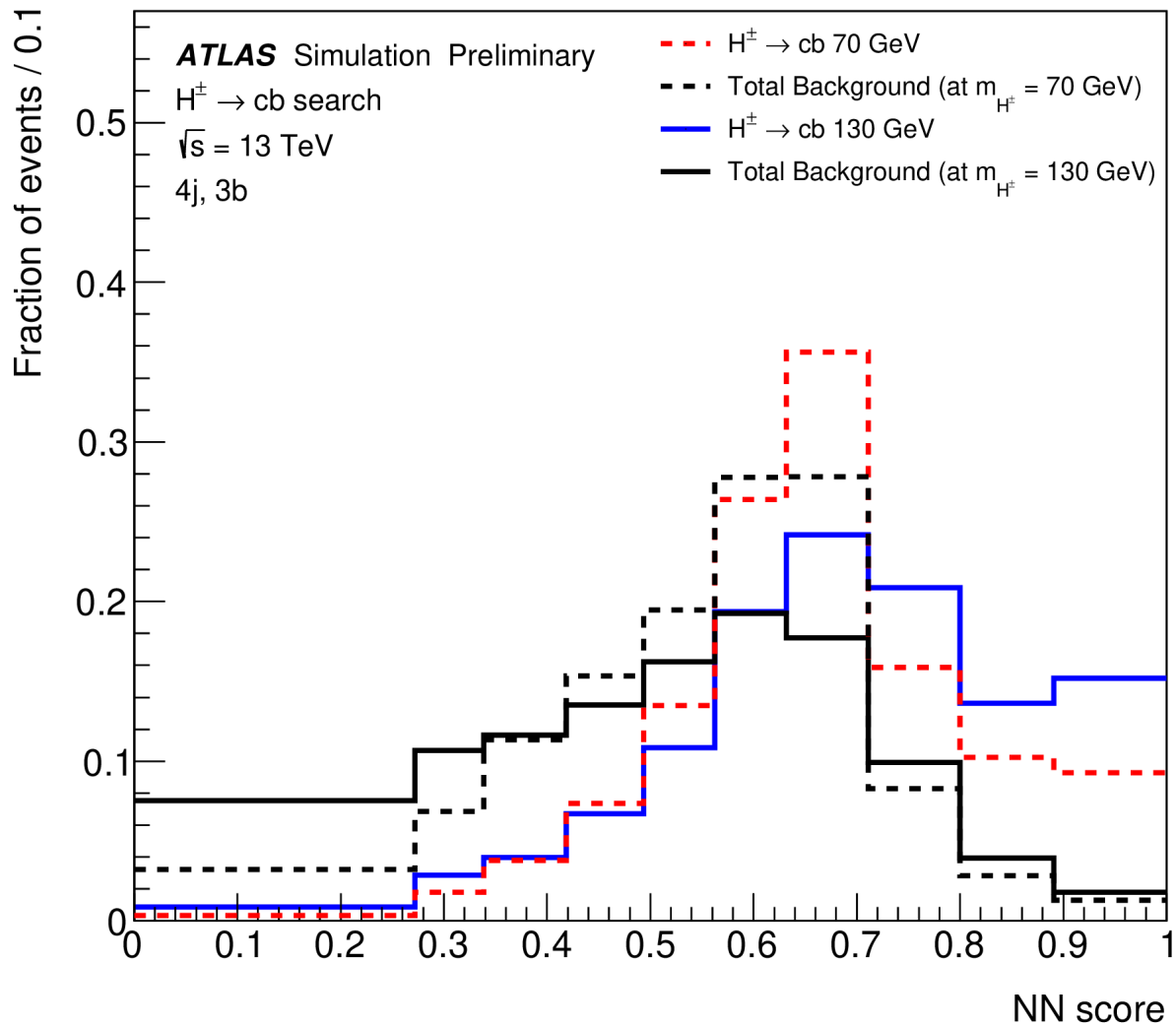

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
5j, 3b
Pre-Fit
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 50 GeV
Data / Bkg.
HTall [GeV]

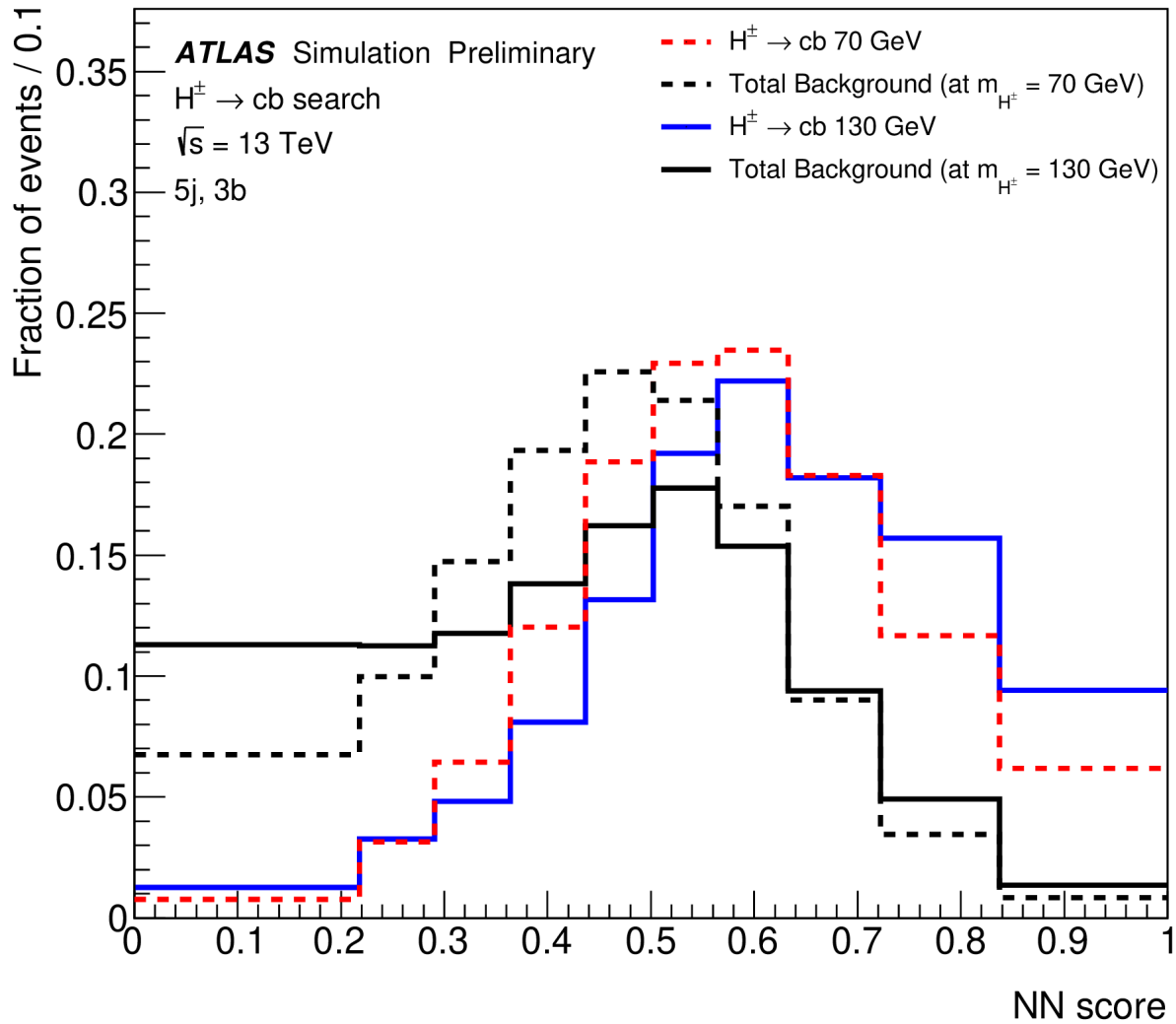

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
6j, 3b
Pre-Fit
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 50 GeV
Data / Bkg.
HTall [GeV]

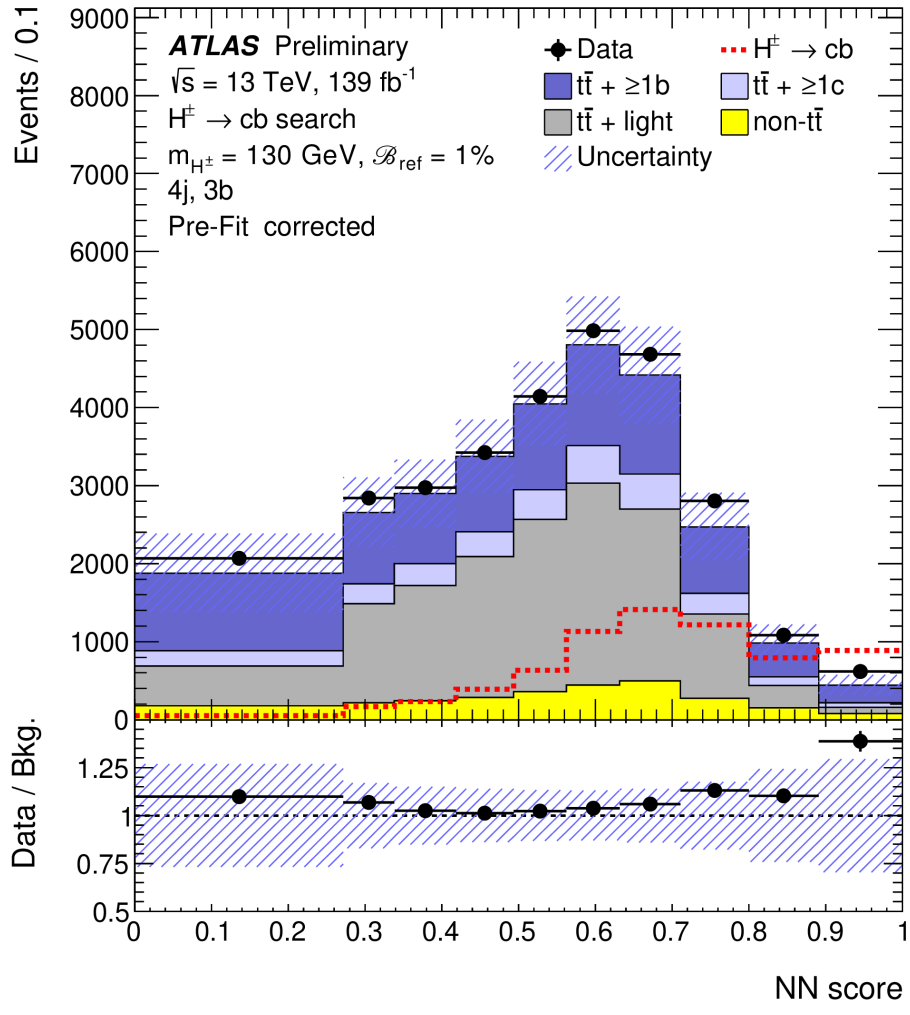

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
4j, 3b
Pre-Fit corrected
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 50 GeV
Data / Bkg.
HTall [GeV]

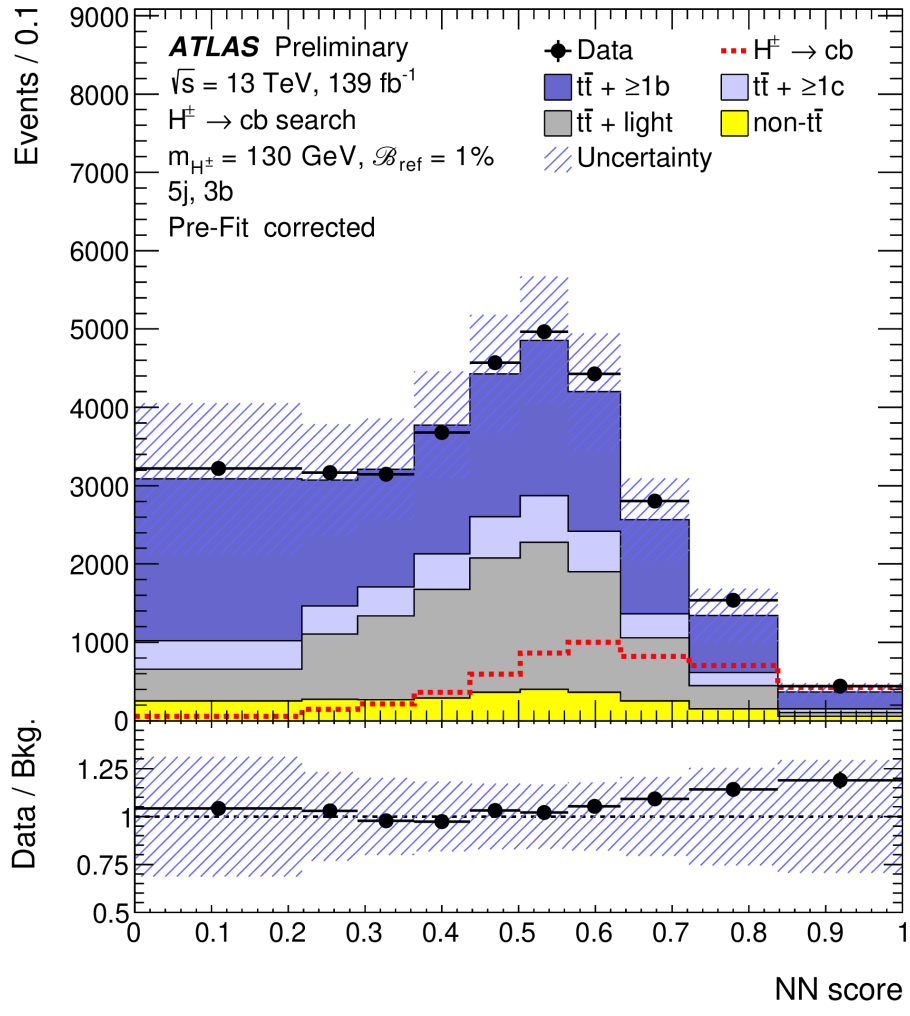

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
5j, 3b
Pre-Fit corrected
Data
H± → cb
tt̄ + ≥1b
tt̄ + ≥1c
tt̄ + light
non-tt̄
Uncertainty
Events / 50 GeV
Data / Bkg.
HTall [GeV]

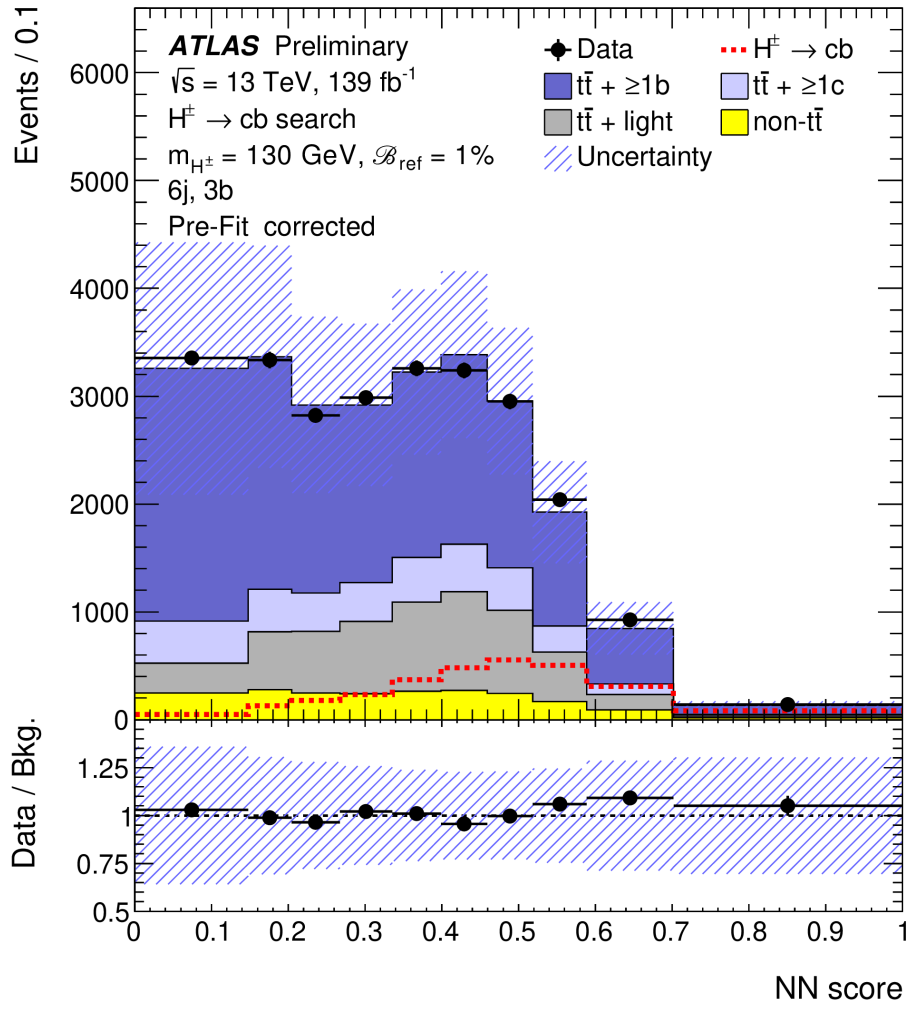

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
6j, 3b
Pre-Fit corrected
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 50 GeV
Data / Bkg.
HTall [GeV]

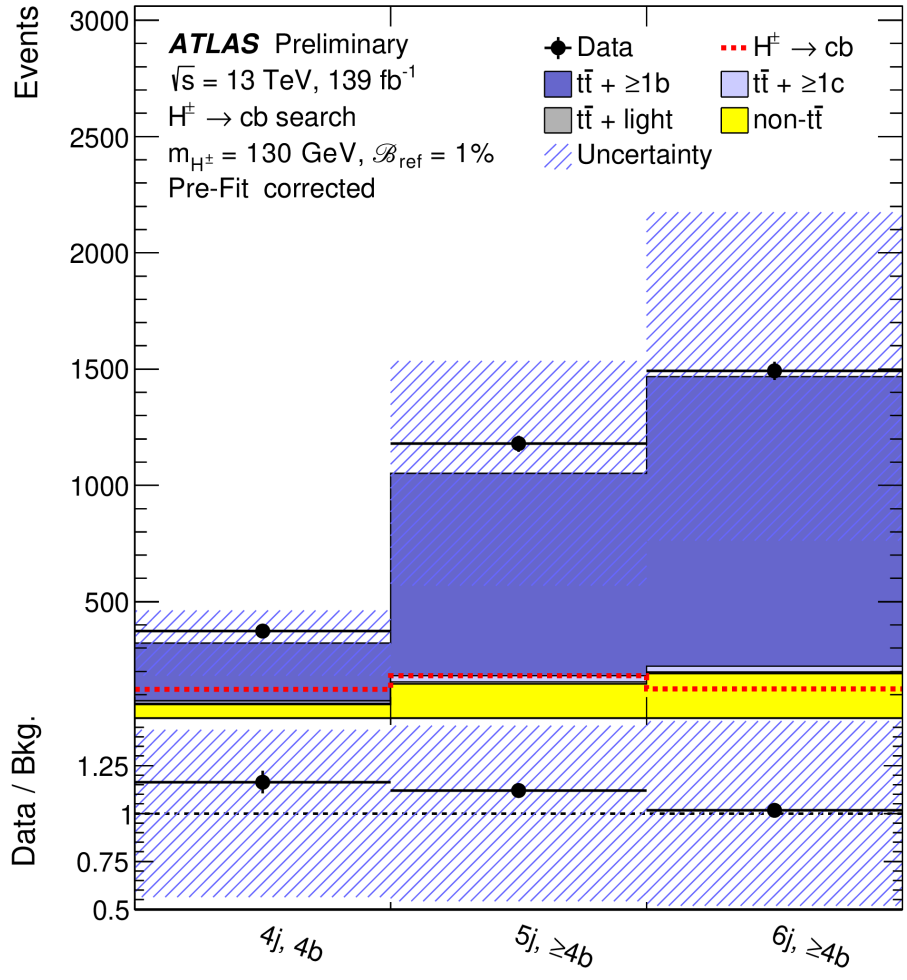

ATLAS Simulation Preliminary
H± → cb search
√s = 13 TeV
4j, 3b
H± → cb 70 GeV
Total Background (at m H± = 70 GeV)
H± → cb 130 GeV
Total Background (at m H± = 130 GeV)
Fraction of events / 0.1
NN score
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1


ATLAS Simulation Preliminary
H± → cb search
√s = 13 TeV
5j, 3b
H± → cb 70 GeV
Total Background (at m H± = 70 GeV)
H± → cb 130 GeV
Total Background (at m H± = 130 GeV)
Fraction of events / 0.1
NN score
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

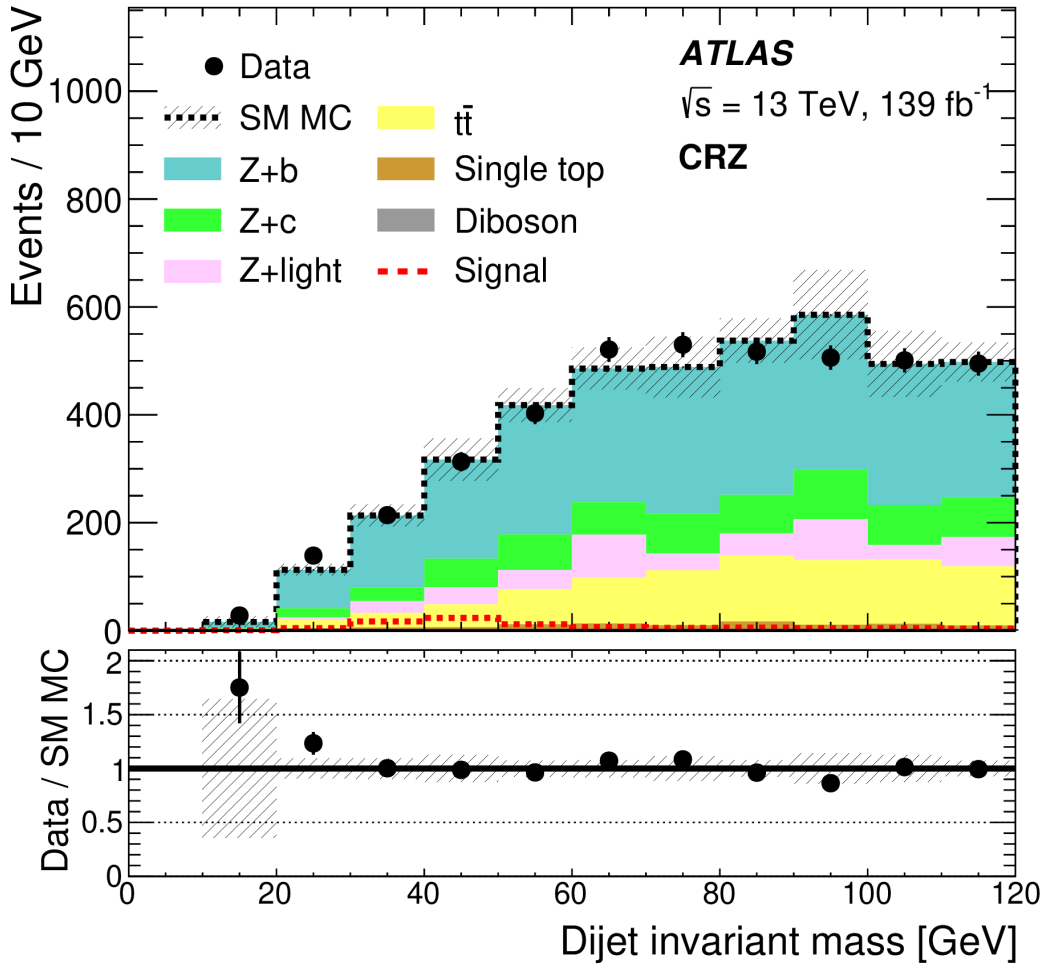

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
4j, 3b
Pre-Fit corrected
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 0.1
Data / Bkg.
NN score

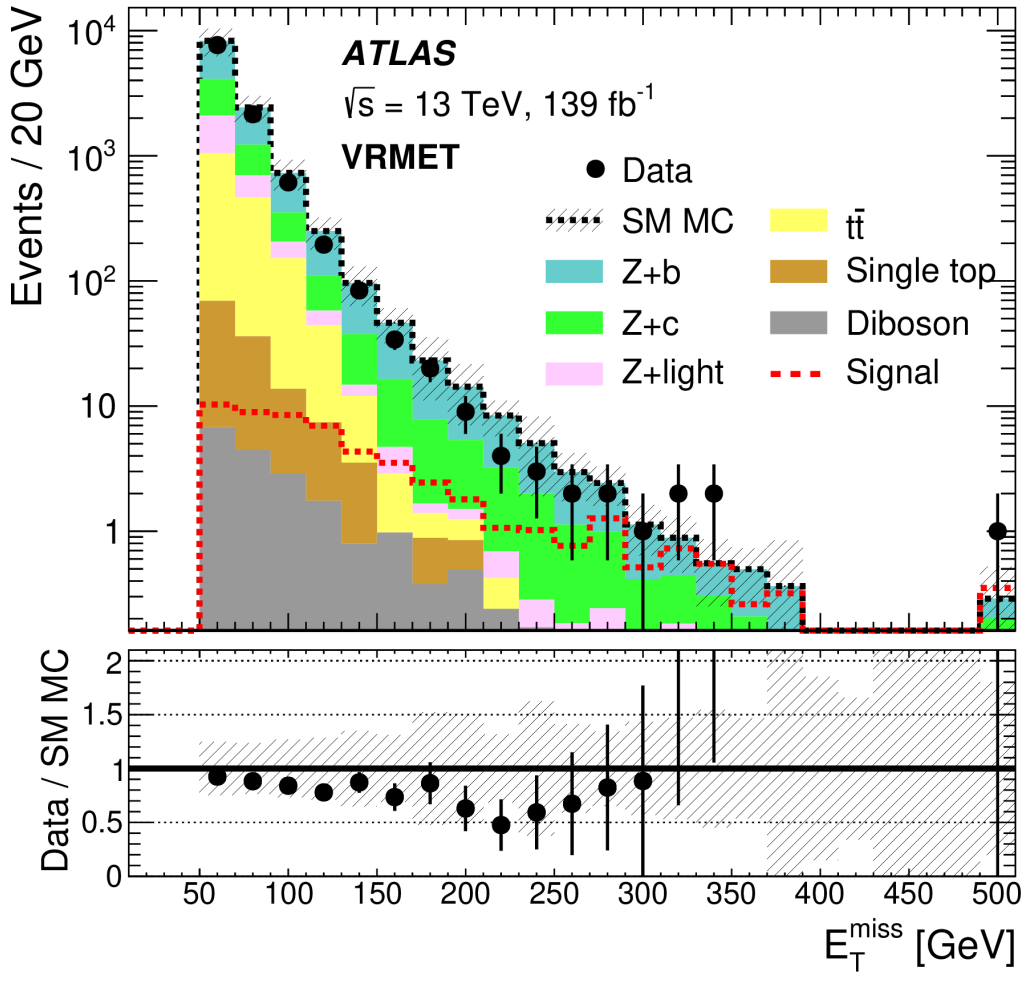

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
5j, 3b
Pre-Fit corrected
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 0.1
Data / Bkg.
NN score

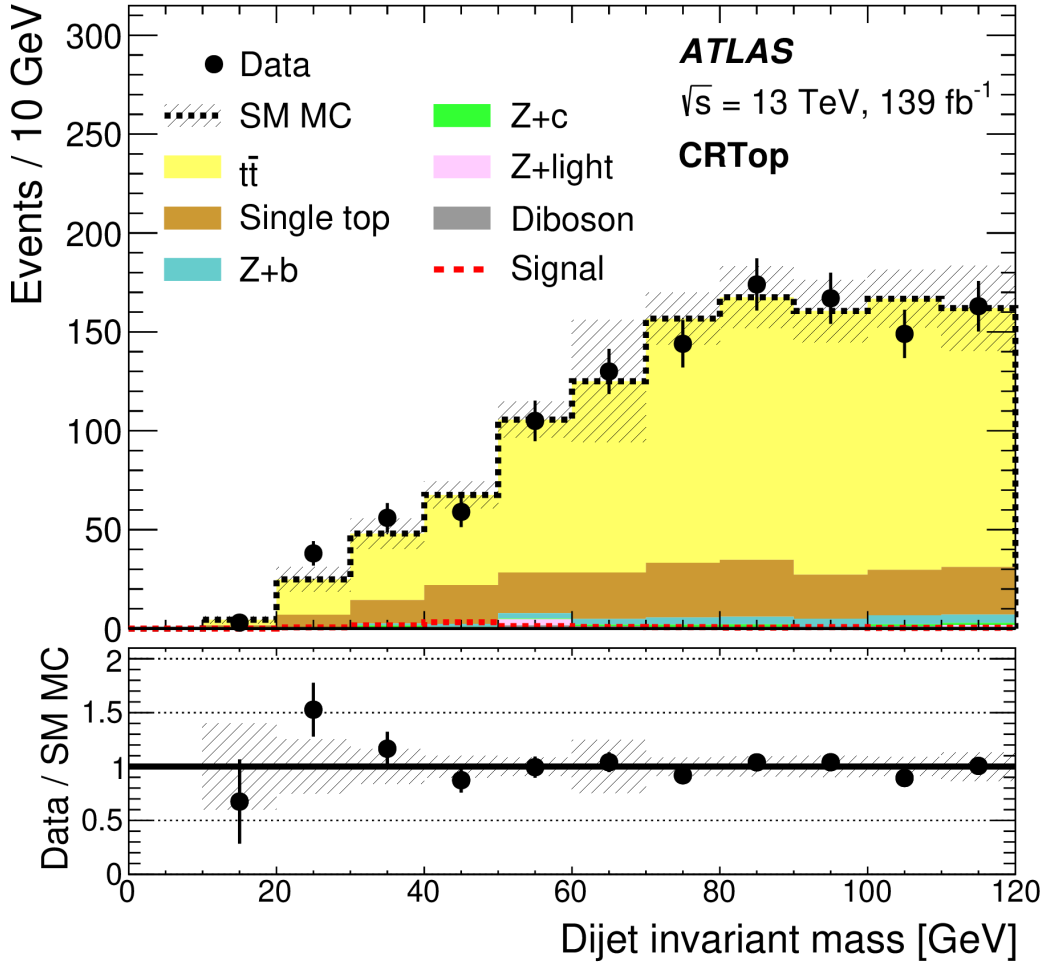

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
6j, 3b
Pre-Fit corrected
Data
tt̄ + ≥1b
tt̄ + light
Uncertainty
H± → cb
tt̄ + ≥1c
non-tt̄
Events / 0.1
Data / Bkg.
NN score

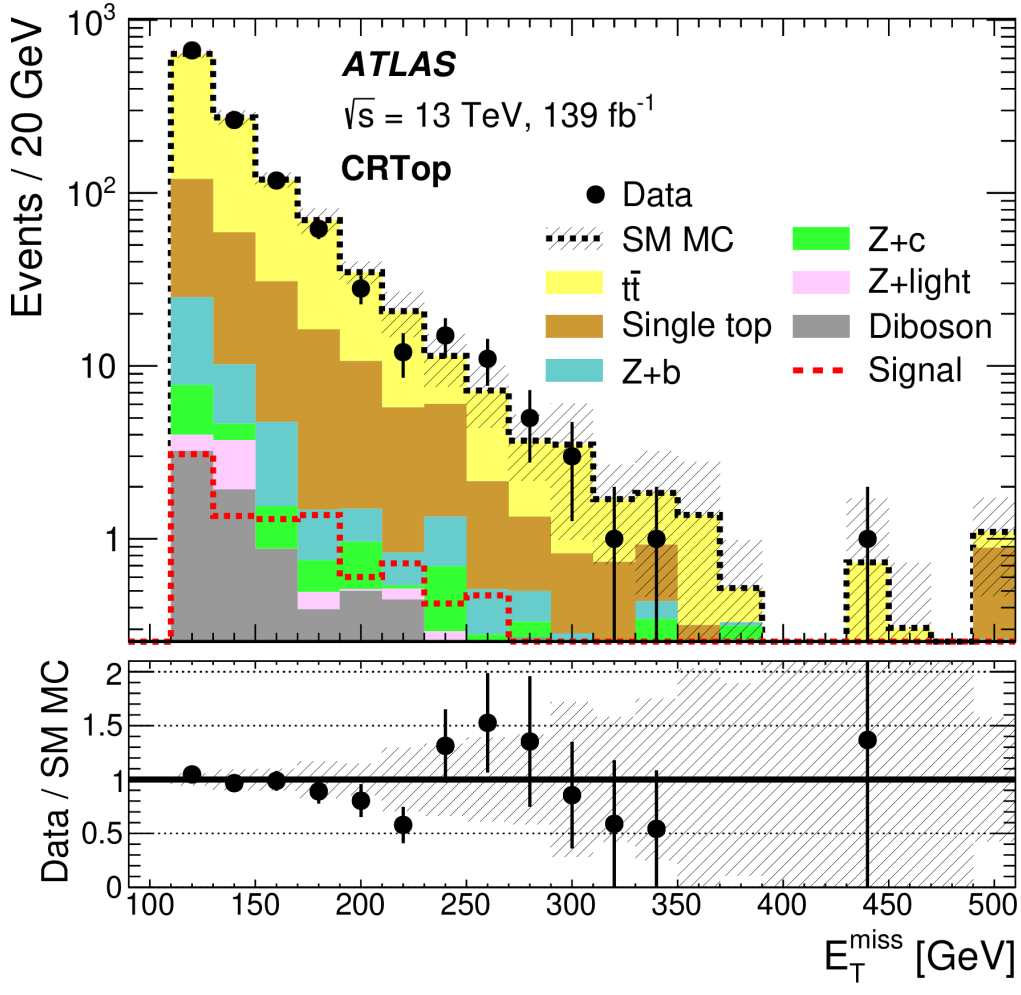

ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H± → cb search
mH± = 130 GeV, ℬref = 1%
Pre-Fit corrected
Data
H± → cb
tt̄ + ≥1b
tt̄ + ≥1c
tt̄ + light
non-tt̄
Uncertainty
Events
Data / Bkg.
3000
2500
2000
1500
1000
500
1.25
1
0.75
0.5
4j, 4b
5j, ≥4b
6j, ≥4b

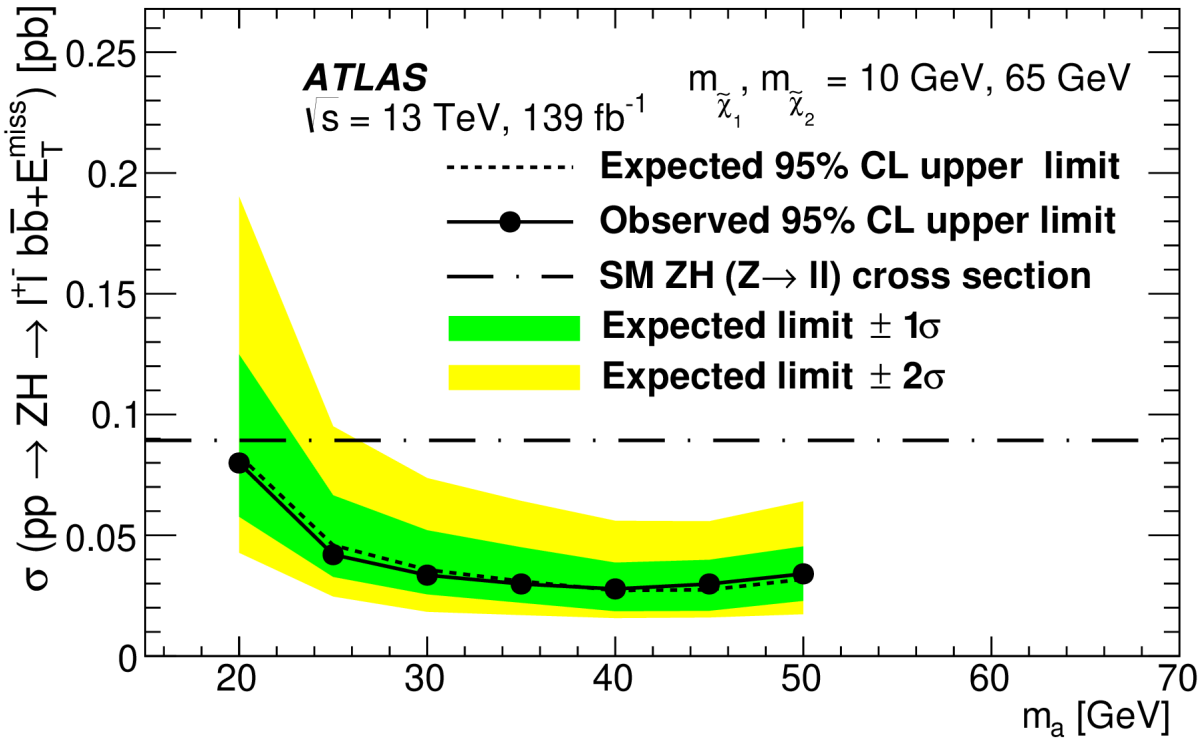
$$H \to \tilde{\chi}_1^0 \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 a \to$$
$$bb + \textbf{MET Search}$$

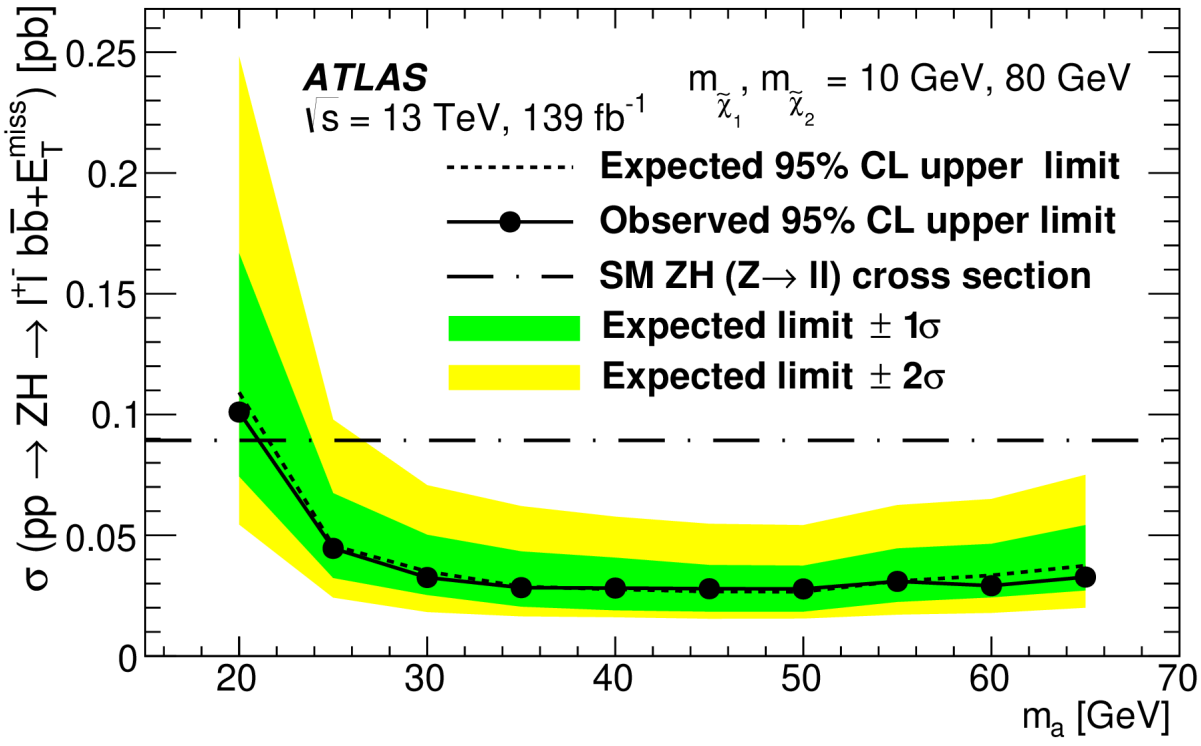

ATLAS
√s = 13 TeV, 139 fb-1
CRZ
Data
SM MC
Z+b
Z+c
Z+light
tt̄
Single top
Diboson
Signal
Events / 10 GeV
Data / SM MC
Dijet invariant mass [GeV]

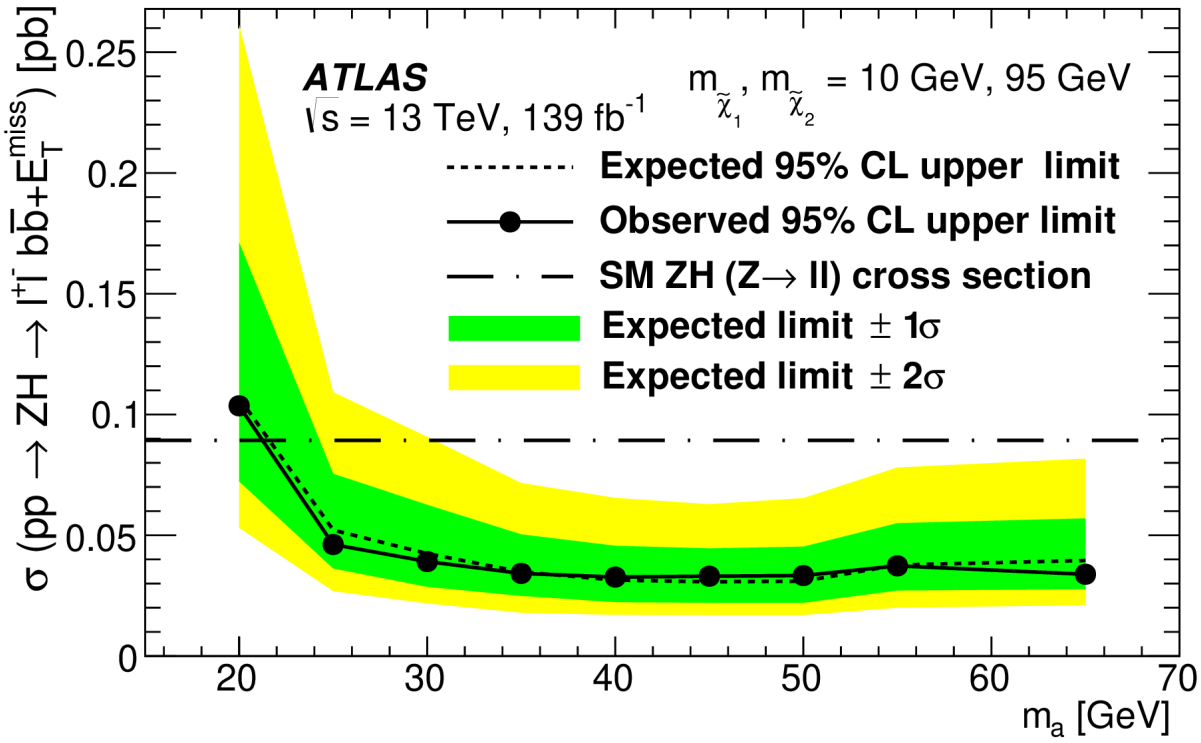

ATLAS
√s = 13 TeV, 139 fb-1
VRMET
Data
SM MC
Z+b
Z+c
Z+light
tt̄
Single top
Diboson
Signal
Events / 20 GeV
Data / SM MC
E_T^miss [GeV]

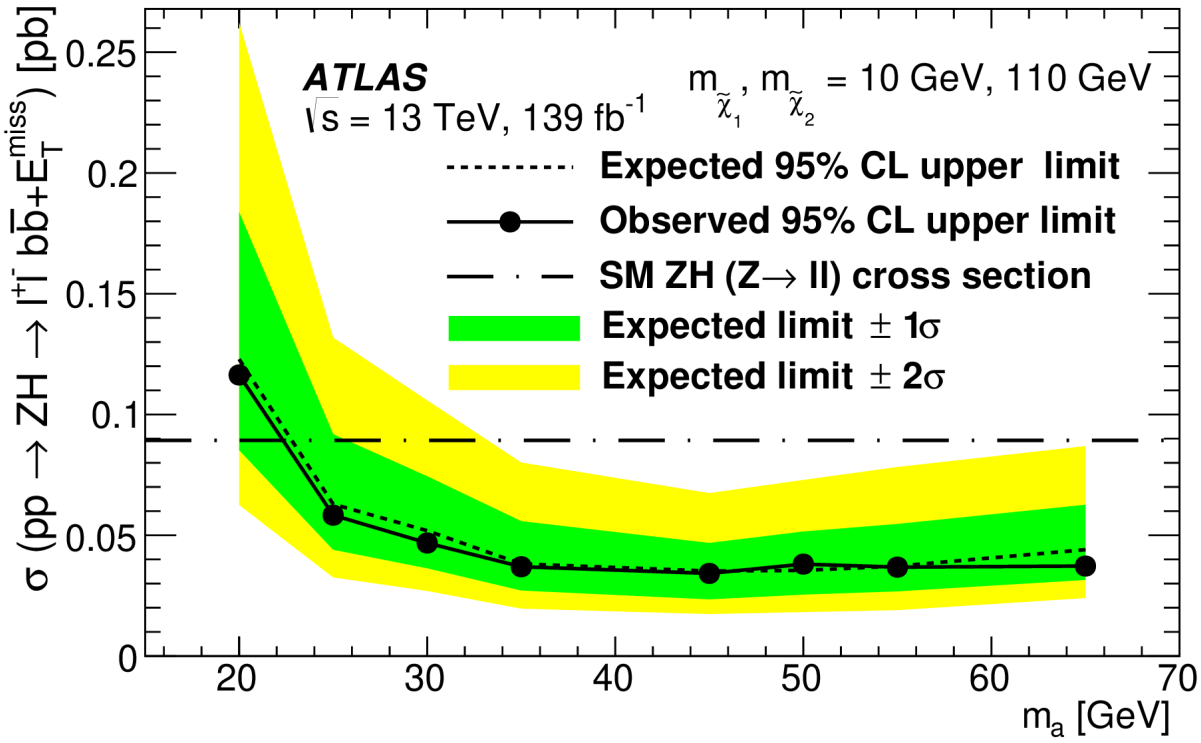

ATLAS
√s = 13 TeV, 139 fb-1
CRTop
Data
SM MC
tt̄
Single top
Z+b
Z+c
Z+light
Diboson
Signal
Events / 10 GeV
Data / SM MC
Dijet invariant mass [GeV]
0
50
100
150
200
250
300
0.5
1
1.5
2
0
20
40
60
80
100
120

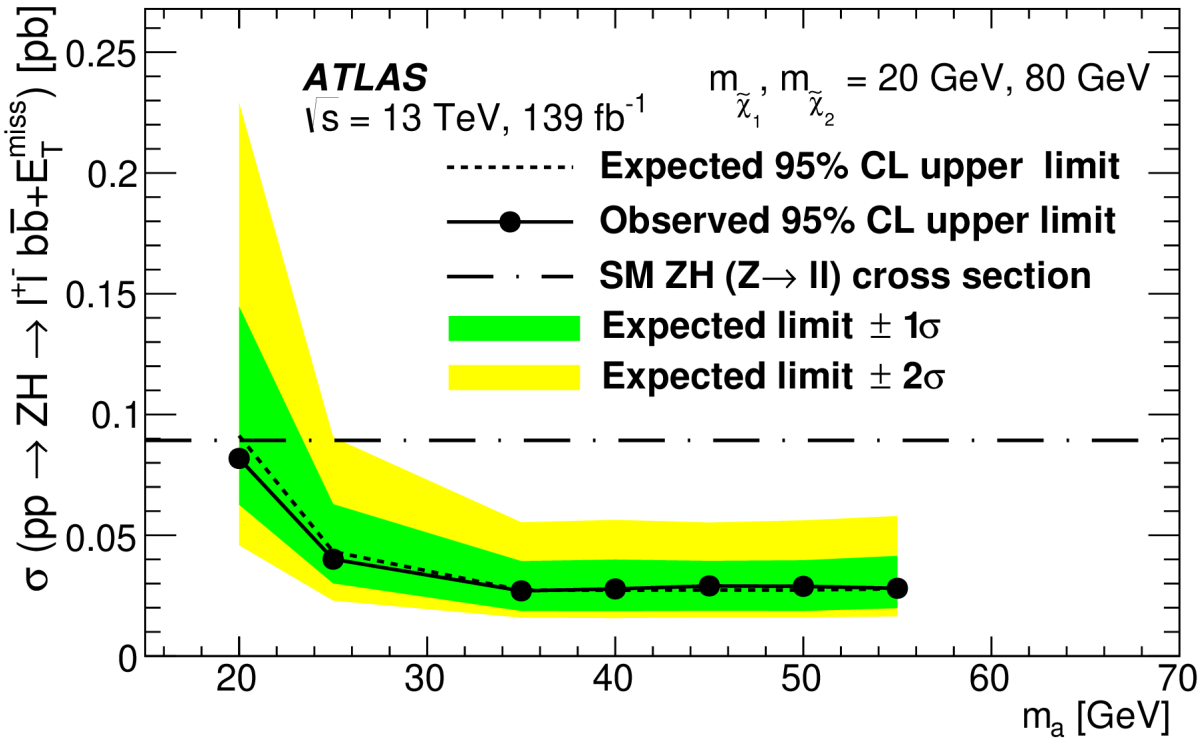

ATLAS
√s = 13 TeV, 139 fb-1
CRTop
Data
SM MC
tt̄
Single top
Z+b
Z+c
Z+light
Diboson
Signal
Events / 20 GeV
Data / SM MC
E_T^miss [GeV]

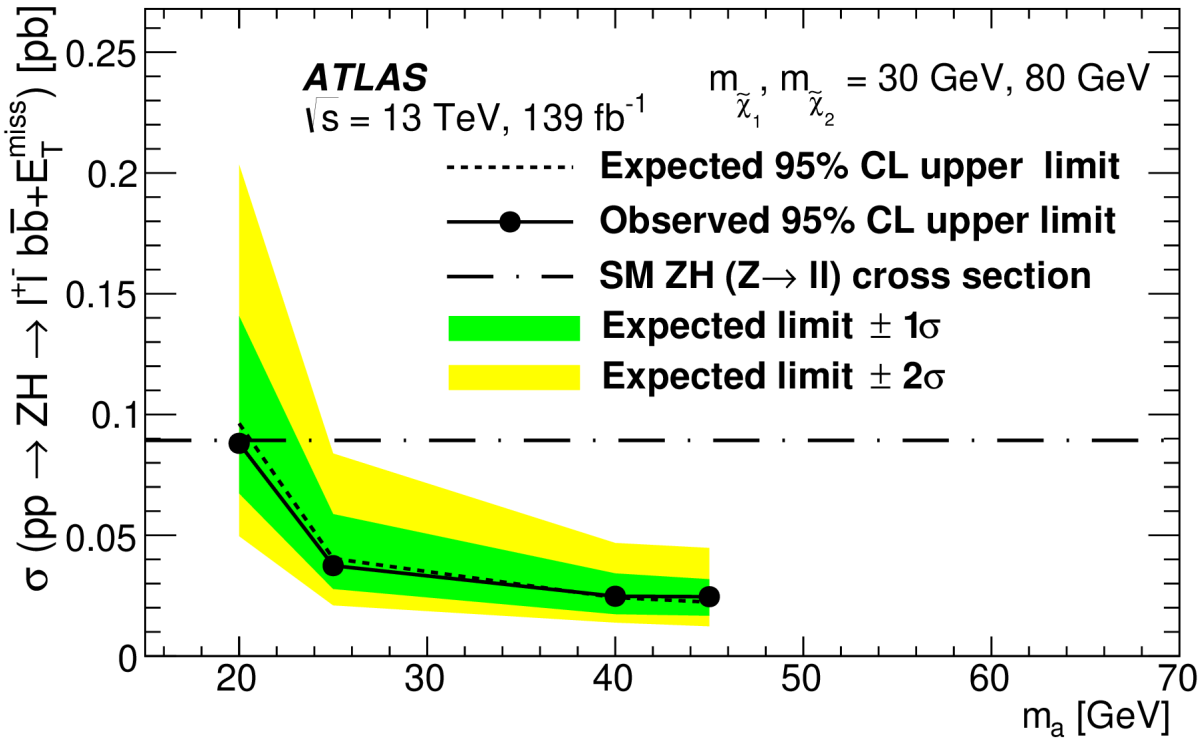

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 65 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
SM ZH (Z→ ll) cross section
Expected limit ± 1σ
Expected limit ± 2σ
σ (pp → ZH → l+l- bb̄+E_T^miss) [pb]
0
0.05
0.1
0.15
0.2
0.25
20
30
40
50
60
70
m_a [GeV]

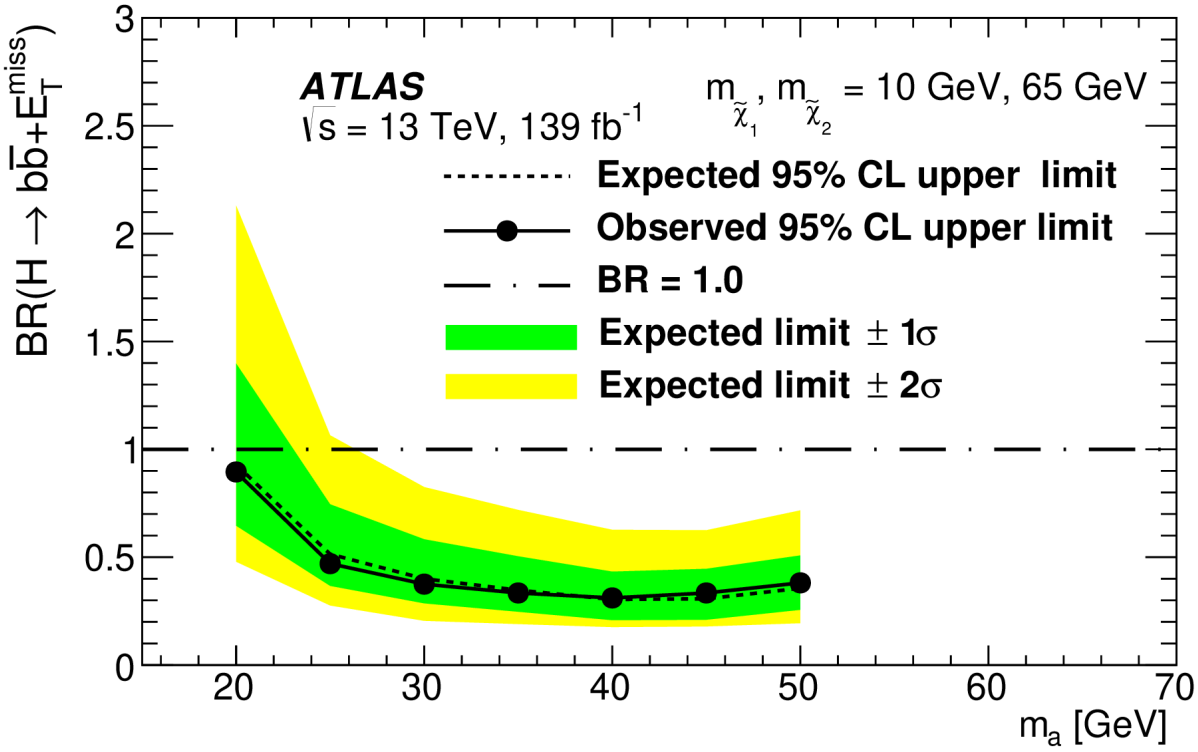

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 80 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
SM ZH (Z→ ll) cross section
Expected limit ± 1σ
Expected limit ± 2σ
σ (pp → ZH → l+l- bb̄+E_T^miss) [pb]
0.25
0.2
0.15
0.1
0.05
0
20
30
40
50
60
70
m_a [GeV]

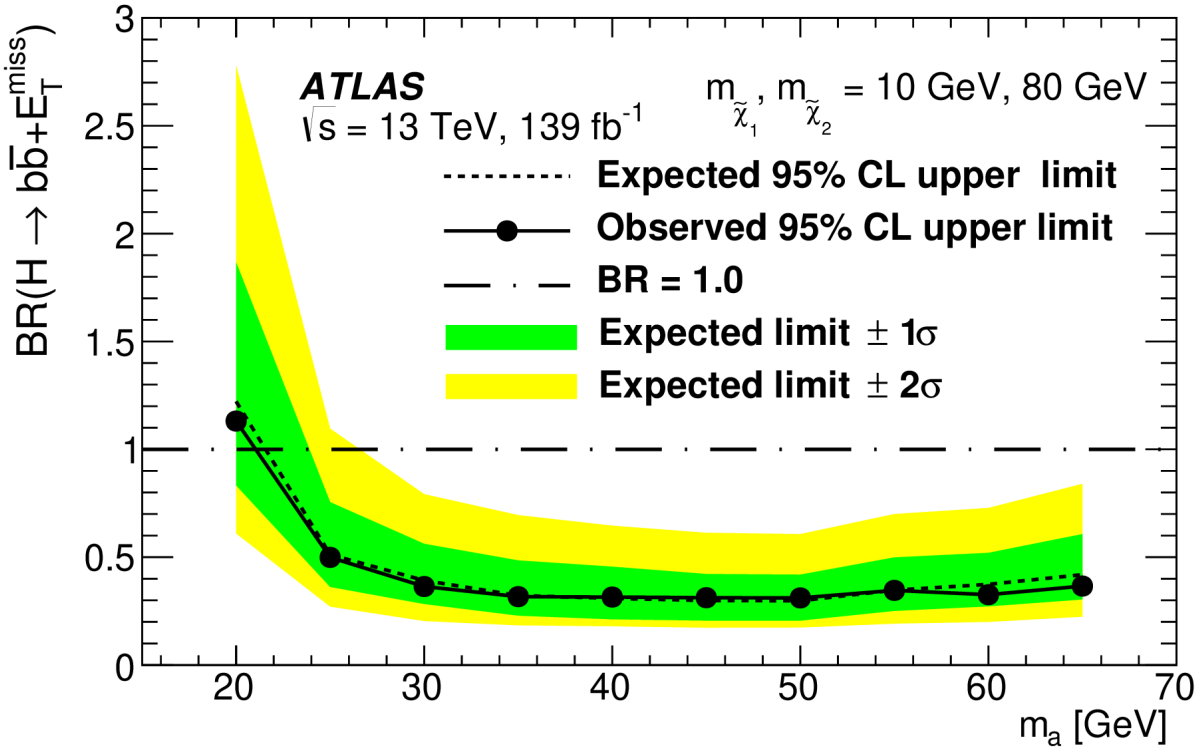

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 95 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
SM ZH (Z→ ll) cross section
Expected limit ± 1σ
Expected limit ± 2σ
σ (pp → ZH → l+l- bb̄+E_T^miss) [pb]
0
0.05
0.1
0.15
0.2
0.25
20
30
40
50
60
70
m_a [GeV]

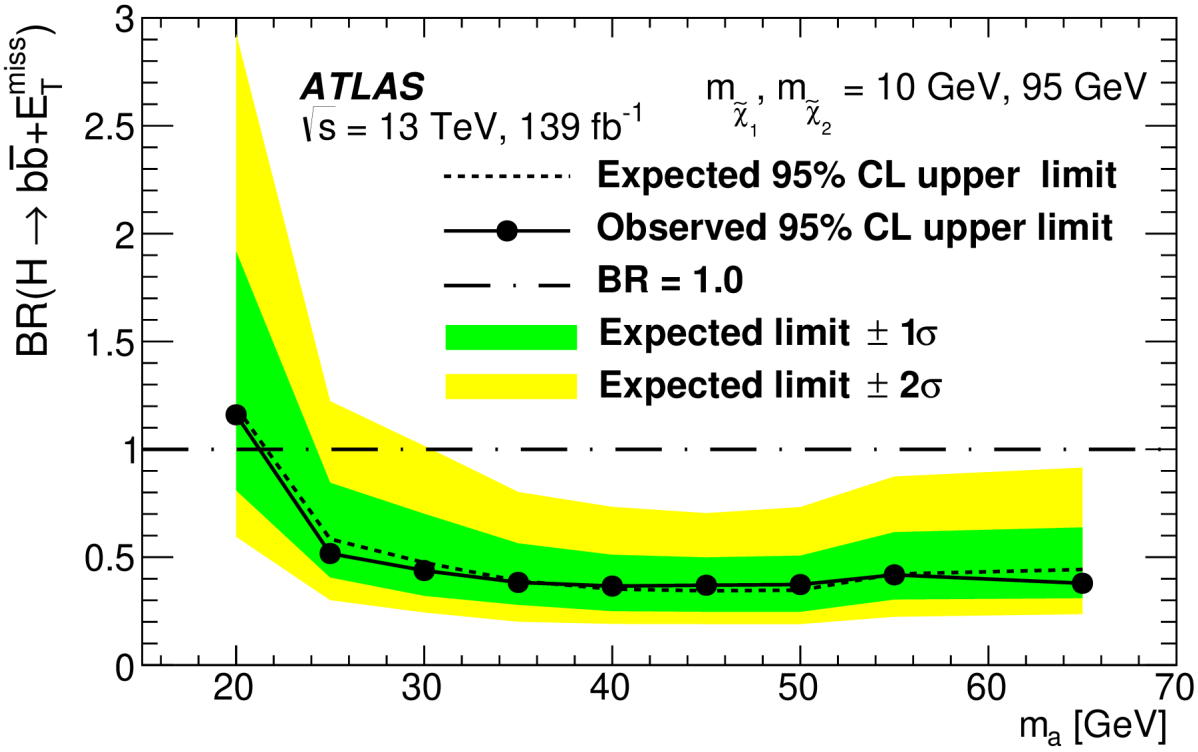

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 110 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
SM ZH (Z→ ll) cross section
Expected limit ± 1σ
Expected limit ± 2σ
σ (pp → ZH → l+l- bb̄+E_T^miss) [pb]
0
0.05
0.1
0.15
0.2
0.25
20
30
40
50
60
70
m_a [GeV]

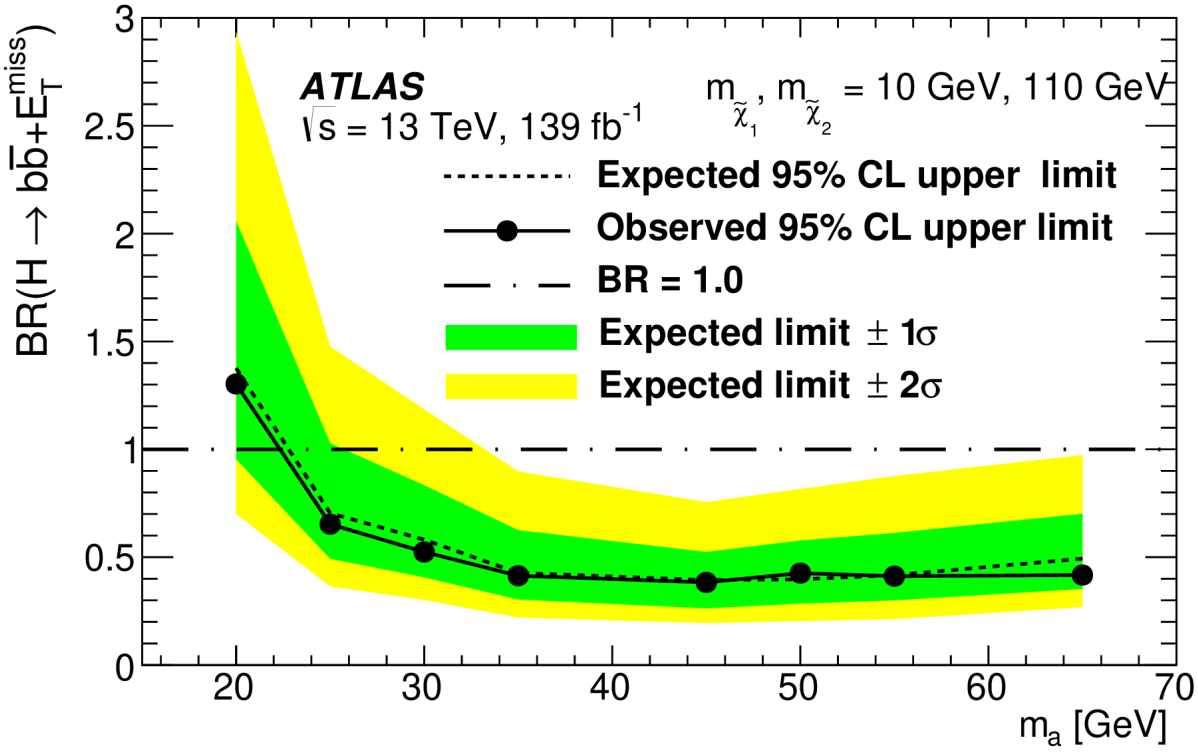

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 20 GeV, 80 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
SM ZH (Z→ ll) cross section
Expected limit ± 1σ
Expected limit ± 2σ
σ (pp → ZH → l+l- bb̄+E_T^miss) [pb]
0.25
0.2
0.15
0.1
0.05
0
20
30
40
50
60
70
m_a [GeV]

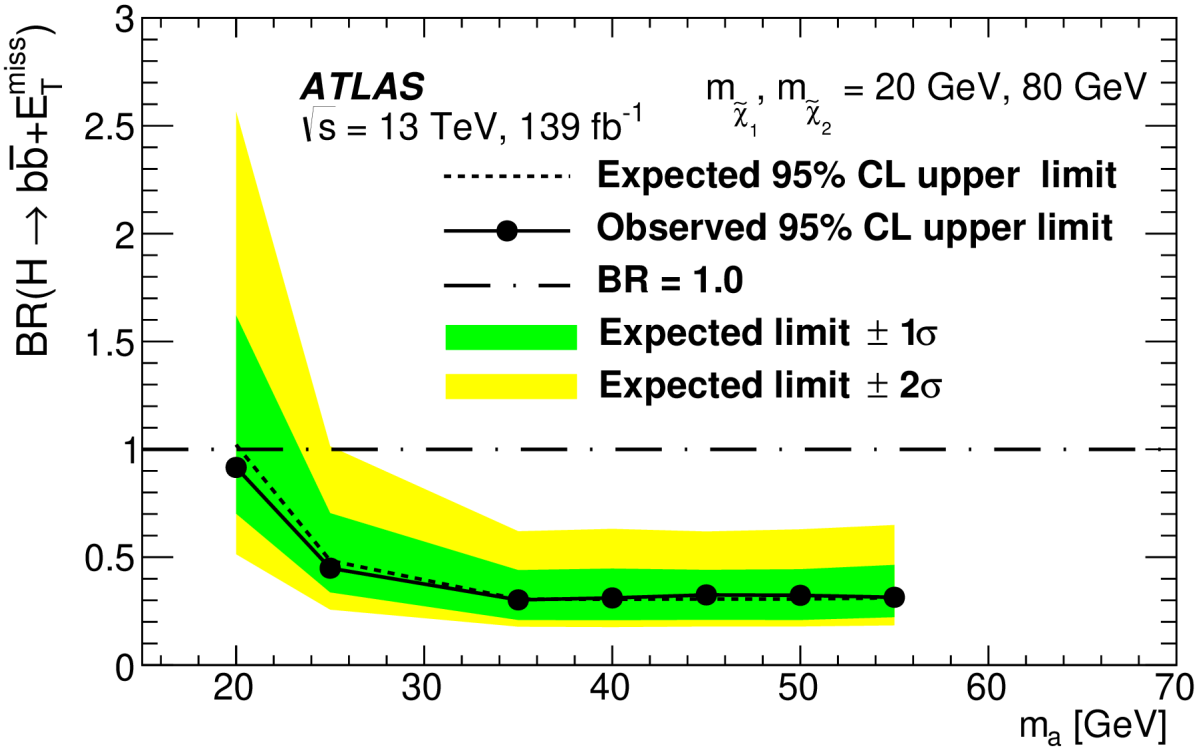

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 30 GeV, 80 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
SM ZH (Z→ ll) cross section
Expected limit ± 1σ
Expected limit ± 2σ
σ (pp → ZH → l+l- bb̄+E_T^miss) [pb]
m_a [GeV]
0
0.05
0.1
0.15
0.2
0.25
20
30
40
50
60
70

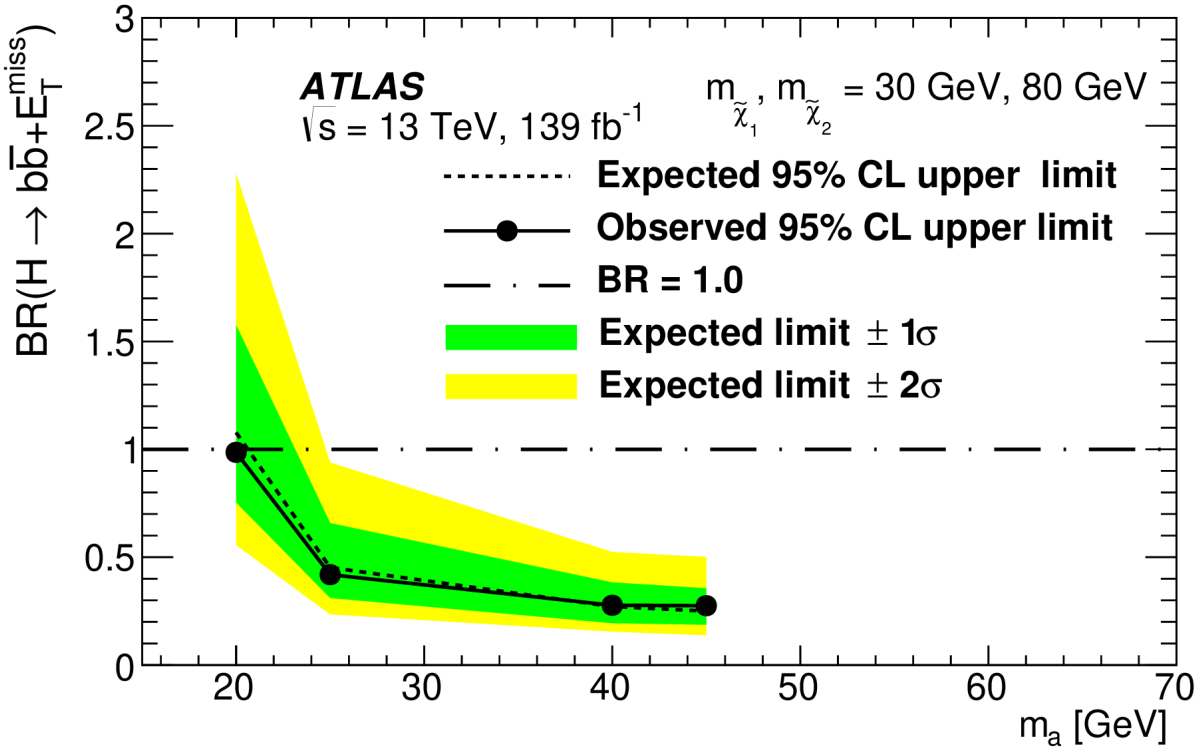

ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 65 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
BR = 1.0
Expected limit ± 1σ
Expected limit ± 2σ
BR(H → bb̄+E_T^miss)
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
20
30
40
50
60
70


ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 80 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
BR = 1.0
Expected limit ± 1σ
Expected limit ± 2σ
BR(H → bb̄+E_T^miss)
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
20
30
40
50
60
70


ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 95 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
BR = 1.0
Expected limit ± 1σ
Expected limit ± 2σ
BR(H → bb̄+E_T^miss)
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
20
30
40
50
60
70


ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 10 GeV, 110 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
BR = 1.0
Expected limit ± 1σ
Expected limit ± 2σ
BR(H → bb̄+E_T^miss)
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
20
30
40
50
60
70


ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 20 GeV, 80 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
BR = 1.0
Expected limit ± 1σ
Expected limit ± 2σ
BR(H → bb̄+E_T^miss)
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
20
30
40
50
60
70


ATLAS
√s = 13 TeV, 139 fb-1
m χ̃1 , m χ̃2 = 30 GeV, 80 GeV
Expected 95% CL upper limit
Observed 95% CL upper limit
BR = 1.0
Expected limit ± 1σ
Expected limit ± 2σ
BR(H → bb̄+E_T^miss)
m_a [GeV]
0
0.5
1
1.5
2
2.5
3
20
30
40
50
60
70

Process	Generator	Parton shower	PDF	Tune	Normalization
Nominal samples					
$t\bar{t}$	POWHEG BOX v2 [39,40,41,42,43]	PYTHIA 8.230 [44]	NNPDF3.0nlo [45]	A14 [46], NNPDF2.3lo [47]	NNLO+NNLL [48,49,50,51,52,53,54]
Z + jets	SHERPA 2.2.1 [55]	SHERPA 56,57,58,59	NNPDF3.0nnlo [45]	SHERPA	NNLO [60]
Single-top (Wt)	POWHEG BOX v2 [61]	PYTHIA 8.230	NNPDF3.0nlo	A14, NNPDF2.3lo	NLO+NNLL [62]
Diboson	SHERPA 2.2.1–2.2.2	SHERPA	NNPDF3.0nnlo	SHERPA	NLO
NMSSM signal	POWHEG BOX v2	PYTHIA 8.210	CTEQ6L1 [63]	AZNLO [64]	NNLO(QCD) + NLO(EWK) [65]
Alternative samples					
$t\bar{t}$	POWHEG BOX v2	HERWIG7 [66,67]	NNPDF3.0nlo	A14, NNPDF2.3lo	NNLO+NNLL
$t\bar{t}$	MADGRAPH5_aMC@NLO 2.6.0 [68]	PYTHIA 8.230	NNPDF3.0nlo	A14, NNPDF2.3lo	NNLO+NNLL
Z + jets	MADGRAPH5_aMC@NLO 2.2.2	PYTHIA 8.186 [69]	NNPDF3.0nnlo	A14, NNPDF2.3lo	NNLO

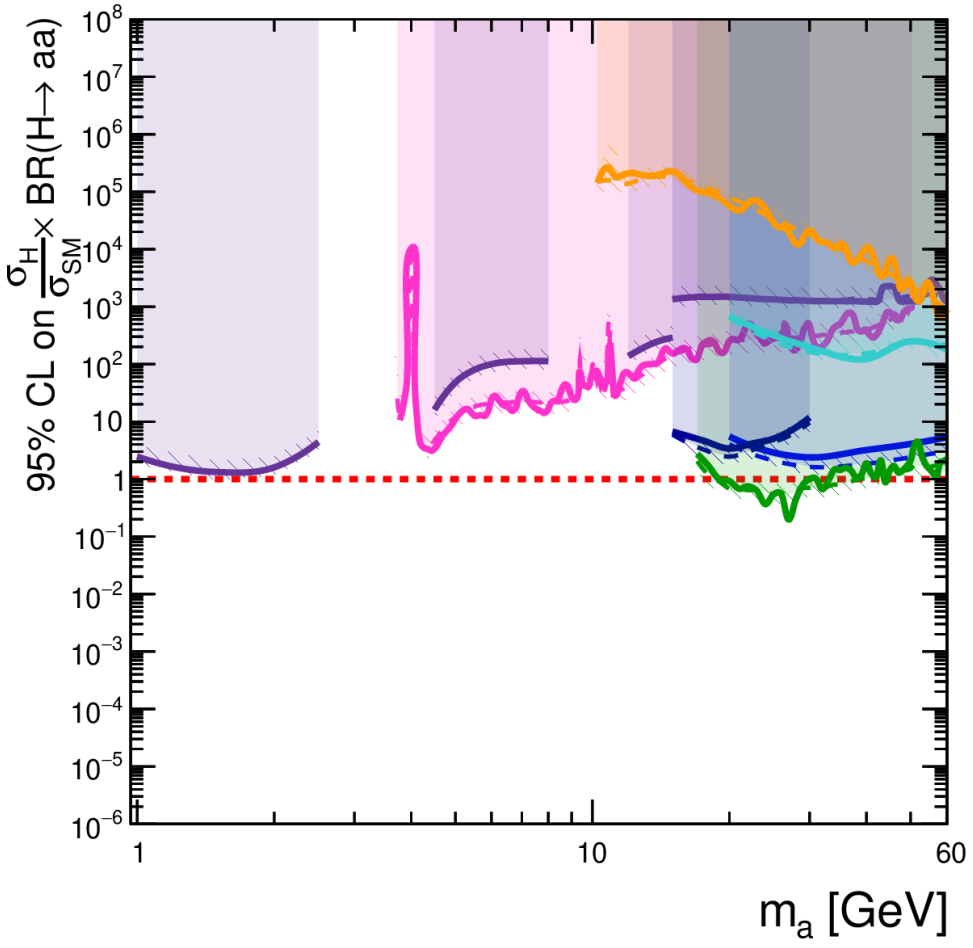
	SR	CRZ	CRTop	VRMET
Number of leptons			2	
Number of jets			≥ 2	
Number of b-tagged jets			≥ 1	
Dilepton p_{T} [GeV]			> 40	
p_{T} fraction			[0.8, 1.2]	
Dilepton mass [GeV]	[81, 101]	[81, 101]	[50, 81] or > 101	[81, 101]
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 100	[60, 100]	> 100	> 50
Dijet mass [GeV]	[20, 120]	[20, 120]	[20, 120]	> 150

Requirement	Events passed (unweighted)	Events passed (weighted)
Initial number of events	240000	-
Skimming selection	111725	-
Preselection	52762	2779.0
Two opposite-sign same-flavour leptons	52309	2755.3
$m_{\ell\ell} \in [81, 101]\ GeV$	47340	2494.0
$p_{\mathrm{T}}^{\ell\ell} > 40$ GeV	39469	2078.5
≥ 2 jets with $p_{\mathrm{T}} > 20$ GeV	20641	1084.7
≥ 1 b-tagged jet	15387	800.5
$E_{\mathrm{T}}^{\mathrm{miss}} > 100\ GeV$	4445	231.6
p_{T} fraction $\in [0.8, 1.2]$	2921	151.9
$m_{jj} \in [20, 120]\ GeV$	2084	108.4

$m_a, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$ [GeV]	Acceptance × Efficiency	Acceptance	Efficiency
20,10,65	0.00485 ± 0.00015	0.00692 ± 0.00017	0.701 ± 0.012
25,10,65	0.00562 ± 0.00016	0.00942 ± 0.00020	0.597 ± 0.011
30,10,65	0.00668 ± 0.00017	0.01082 ± 0.00022	0.618 ± 0.010
35,10,65	0.00722 ± 0.00018	0.01201 ± 0.00023	0.601 ± 0.009
40,10,65	0.00805 ± 0.00019	0.01267 ± 0.00023	0.635 ± 0.009
45,10,65	0.00882 ± 0.00019	0.01349 ± 0.00024	0.654 ± 0.009
50,10,65	0.00823 ± 0.00019	0.01243 ± 0.00023	0.662 ± 0.009
20,10,80	0.00409 ± 0.00013	0.00615 ± 0.00016	0.665 ± 0.013
25,10,80	0.00540 ± 0.00015	0.00832 ± 0.00019	0.649 ± 0.011
30,10,80	0.00653 ± 0.00017	0.01058 ± 0.00021	0.618 ± 0.010
35,10,80	0.00736 ± 0.00018	0.01185 ± 0.00022	0.622 ± 0.009
40,10,80	0.00833 ± 0.00019	0.01311 ± 0.00024	0.636 ± 0.009
45,10,80	0.00863 ± 0.00019	0.01318 ± 0.00024	0.654 ± 0.009
50,10,80	0.00920 ± 0.00020	0.01422 ± 0.00025	0.647 ± 0.008
55,10,80	0.00877 ± 0.00019	0.01395 ± 0.00024	0.629 ± 0.009
60,10,80	0.00892 ± 0.00020	0.01329 ± 0.00024	0.671 ± 0.009
65,10,80	0.00813 ± 0.00019	0.01219 ± 0.00023	0.666 ± 0.009
20,10,95	0.00387 ± 0.00013	0.00559 ± 0.00016	0.692 ± 0.013
25,10,95	0.00480 ± 0.00015	0.00736 ± 0.00018	0.652 ± 0.012
30,10,95	0.00568 ± 0.00016	0.00875 ± 0.00019	0.649 ± 0.011
35,10,95	0.00631 ± 0.00017	0.01023 ± 0.00021	0.617 ± 0.010
40,10,95	0.00730 ± 0.00018	0.01152 ± 0.00022	0.634 ± 0.009
45,10,95	0.00783 ± 0.00018	0.01241 ± 0.00023	0.631 ± 0.009
50,10,95	0.00817 ± 0.00019	0.01263 ± 0.00023	0.647 ± 0.009
55,10,95	0.00803 ± 0.00020	0.01227 ± 0.00024	0.655 ± 0.010
65,10,95	0.00820 ± 0.00019	0.01215 ± 0.00023	0.675 ± 0.009

$m_a, m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}$ [GeV]	Acceptance × Efficiency	Acceptance	Efficiency
20,10,110	0.00352 ± 0.00013	0.00482 ± 0.00015	0.730 ± 0.01368
25,10,110	0.00419 ± 0.00014	0.00649 ± 0.00017	0.645 ± 0.01265
30,10,110	0.00508 ± 0.00015	0.00790 ± 0.00018	0.643 ± 0.01143
35,10,110	0.00567 ± 0.00016	0.00898 ± 0.00020	0.631 ± 0.01077
45,10,110	0.00723 ± 0.00018	0.01153 ± 0.00022	0.627 ± 0.00949
50,10,110	0.00698 ± 0.00017	0.01149 ± 0.00022	0.608 ± 0.00960
55,10,110	0.00733 ± 0.00018	0.01176 ± 0.00022	0.623 ± 0.00942
65,10,110	0.00758 ± 0.00018	0.01135 ± 0.00022	0.668 ± 0.00931
20,20,80	0.00462 ± 0.00014	0.00656 ± 0.00017	0.703 ± 0.01199
25,20,80	0.00559 ± 0.00016	0.00877 ± 0.00019	0.637 ± 0.01087
35,20,80	0.00778 ± 0.00018	0.01235 ± 0.00023	0.630 ± 0.00915
40,20,80	0.00873 ± 0.00019	0.01398 ± 0.00024	0.624 ± 0.00861
45,20,80	0.00915 ± 0.00016	0.01462 ± 0.00019	0.626 ± 0.00655
50,20,80	0.00939 ± 0.00020	0.01475 ± 0.00025	0.637 ± 0.00831
55,20,80	0.00953 ± 0.00020	0.01429 ± 0.00025	0.667 ± 0.00828
20,30,80	0.00474 ± 0.00014	0.00705 ± 0.00017	0.672 ± 0.01188
25,30,80	0.00593 ± 0.00016	0.00933 ± 0.00020	0.635 ± 0.01054
40,30,80	0.00973 ± 0.00020	0.01532 ± 0.00025	0.635 ± 0.00816
45,30,80	0.01092 ± 0.00022	0.01722 ± 0.00027	0.634 ± 0.00769

Summary Plots: Exotic Higgs Boson Decays



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV

2HDM+S Type-II, tanβ = 0.5

expected ± 1 σ

observed

Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002

Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210

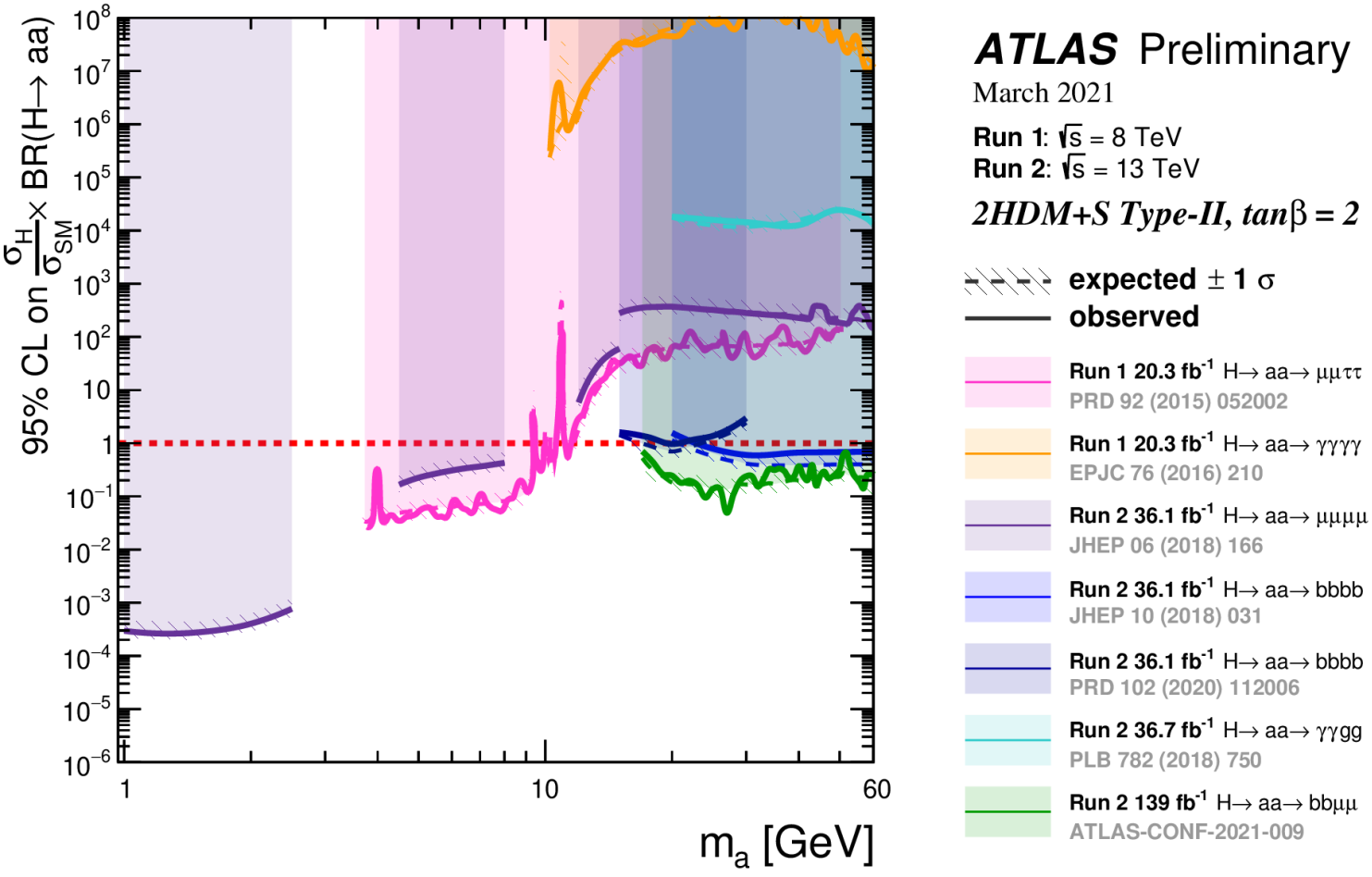
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166

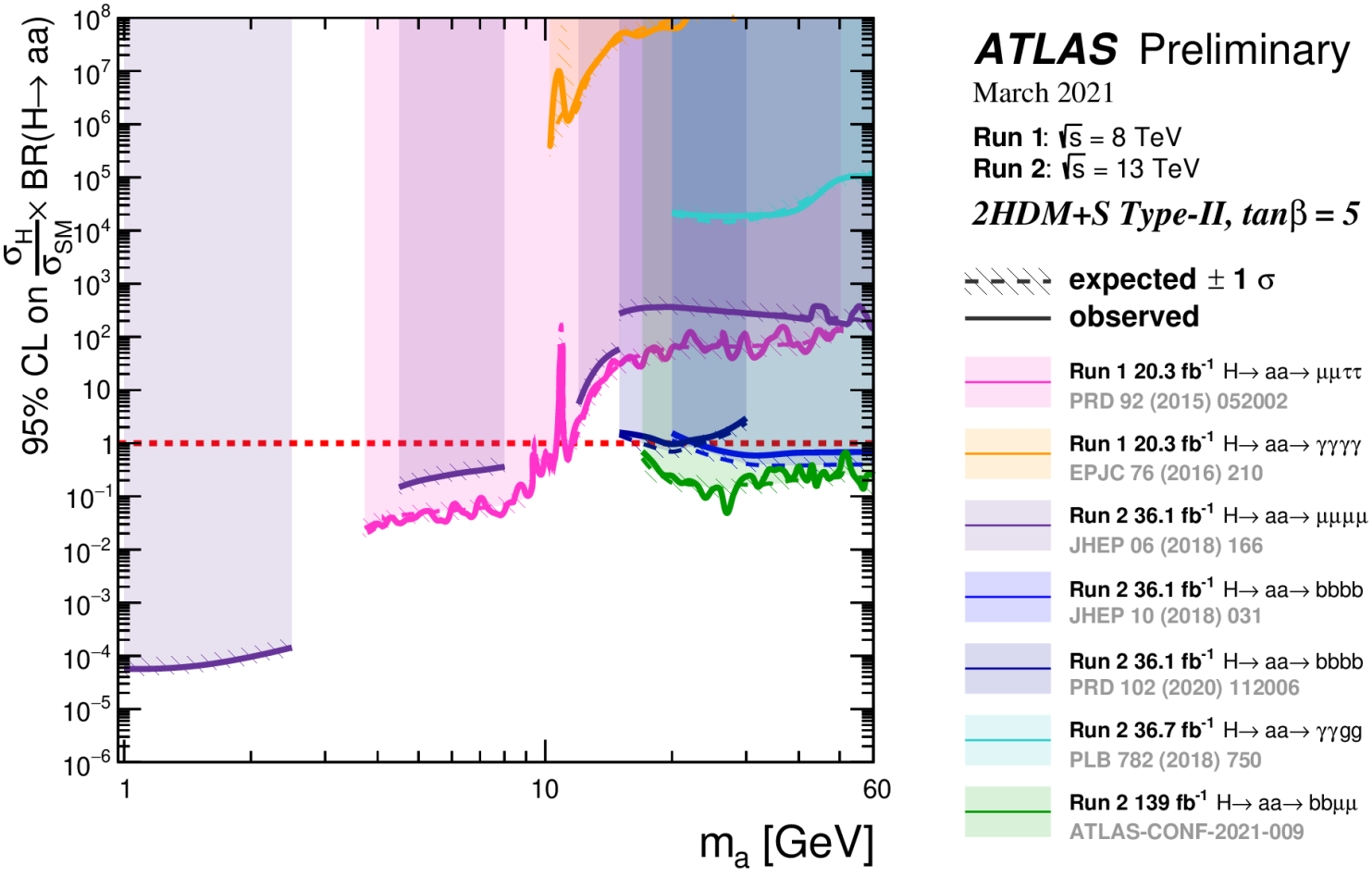
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031

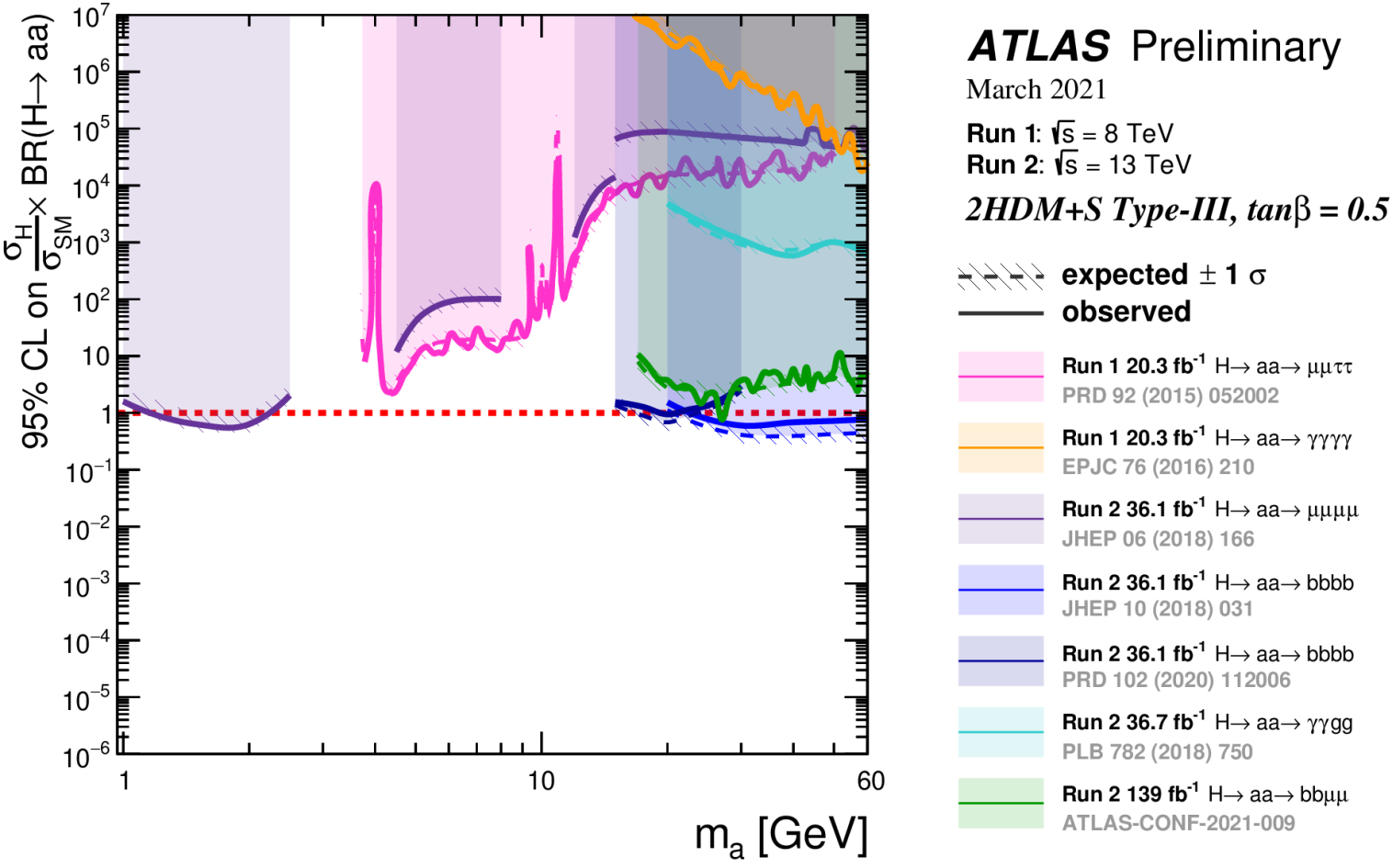
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006

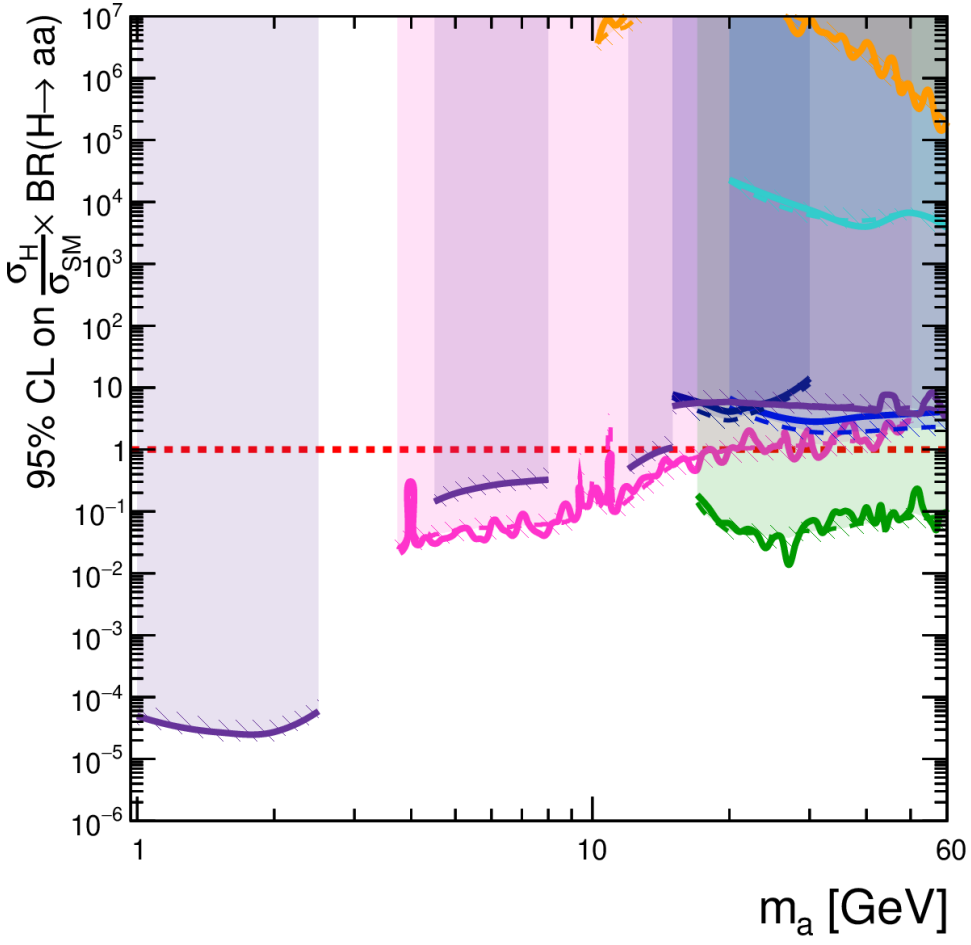
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750

Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009


95% CL on $\frac{\sigma_H}{\sigma_{SM}} \times$ BR(H→ aa)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
60
m_a [GeV]
ATLAS Preliminary
March 2021
Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV
2HDM+S Type-II, tanβ = 2
expected ± 1 σ
observed
Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002
Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750
Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009


95% CL on $\frac{\sigma_H}{\sigma_{SM}} \times$ BR(H→ aa)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1
10
60
m_a [GeV]
ATLAS Preliminary
March 2021
Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV
2HDM+S Type-II, tanβ = 5
expected ± 1 σ
observed
Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002
Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750
Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009


ATLAS Preliminary
March 2021
Run 1: √s = 8 TeV
Run 2: √s = 13 TeV
2HDM+S Type-III, tanβ = 0.5
expected ± 1 σ
observed
Run 1 20.3 fb-1 H→ aa→ μμττ
PRD 92 (2015) 052002
Run 1 20.3 fb-1 H→ aa→ γγγγ
EPJC 76 (2016) 210
Run 2 36.1 fb-1 H→ aa→ μμμμ
JHEP 06 (2018) 166
Run 2 36.1 fb-1 H→ aa→ bbbb
JHEP 10 (2018) 031
Run 2 36.1 fb-1 H→ aa→ bbbb
PRD 102 (2020) 112006
Run 2 36.7 fb-1 H→ aa→ γγgg
PLB 782 (2018) 750
Run 2 139 fb-1 H→ aa→ bbμμ
ATLAS-CONF-2021-009
95% CL on σH/σSM × BR(H→ aa)
ma [GeV]
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
1
10
60



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV

***2HDM+S Type-III, tan*β = 2**

expected ± 1 σ

observed

Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002

Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210

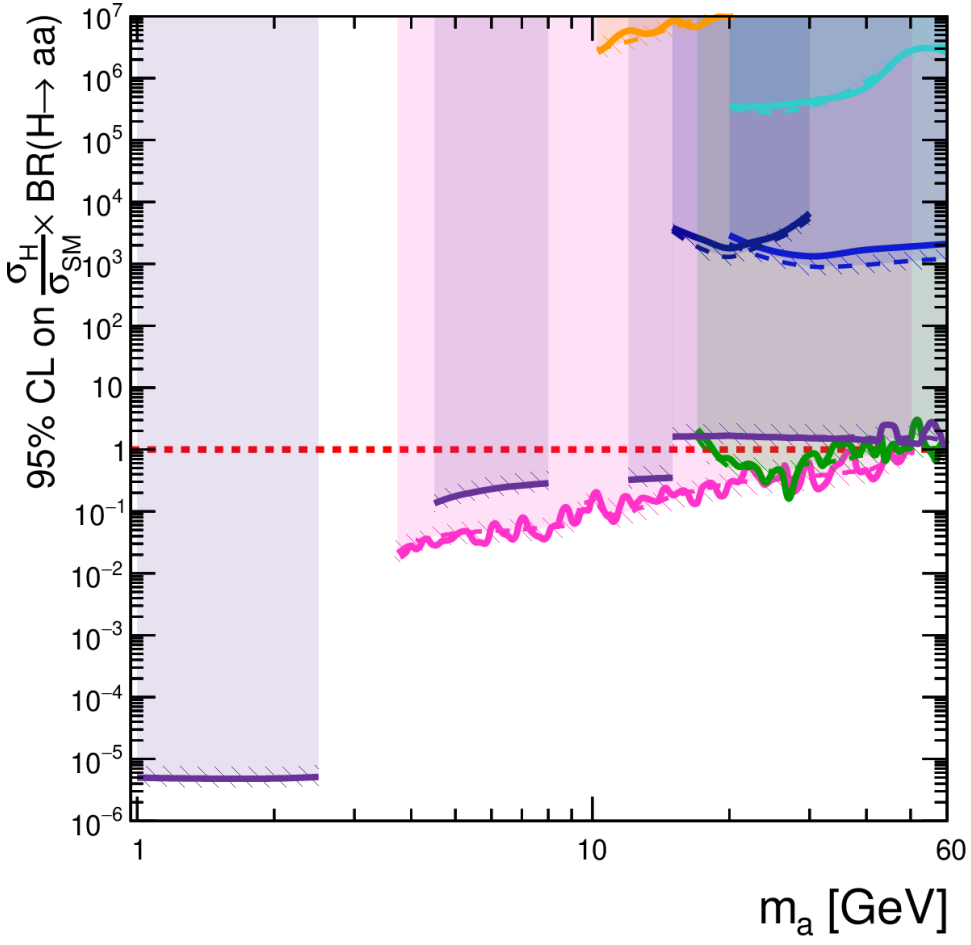
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166

Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031

Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006

Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750

Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s}$ = 8 TeV

Run 2: $\sqrt{s}$ = 13 TeV

2HDM+S Type-III, tanβ = 5

expected ± 1 σ

observed

Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002

Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210

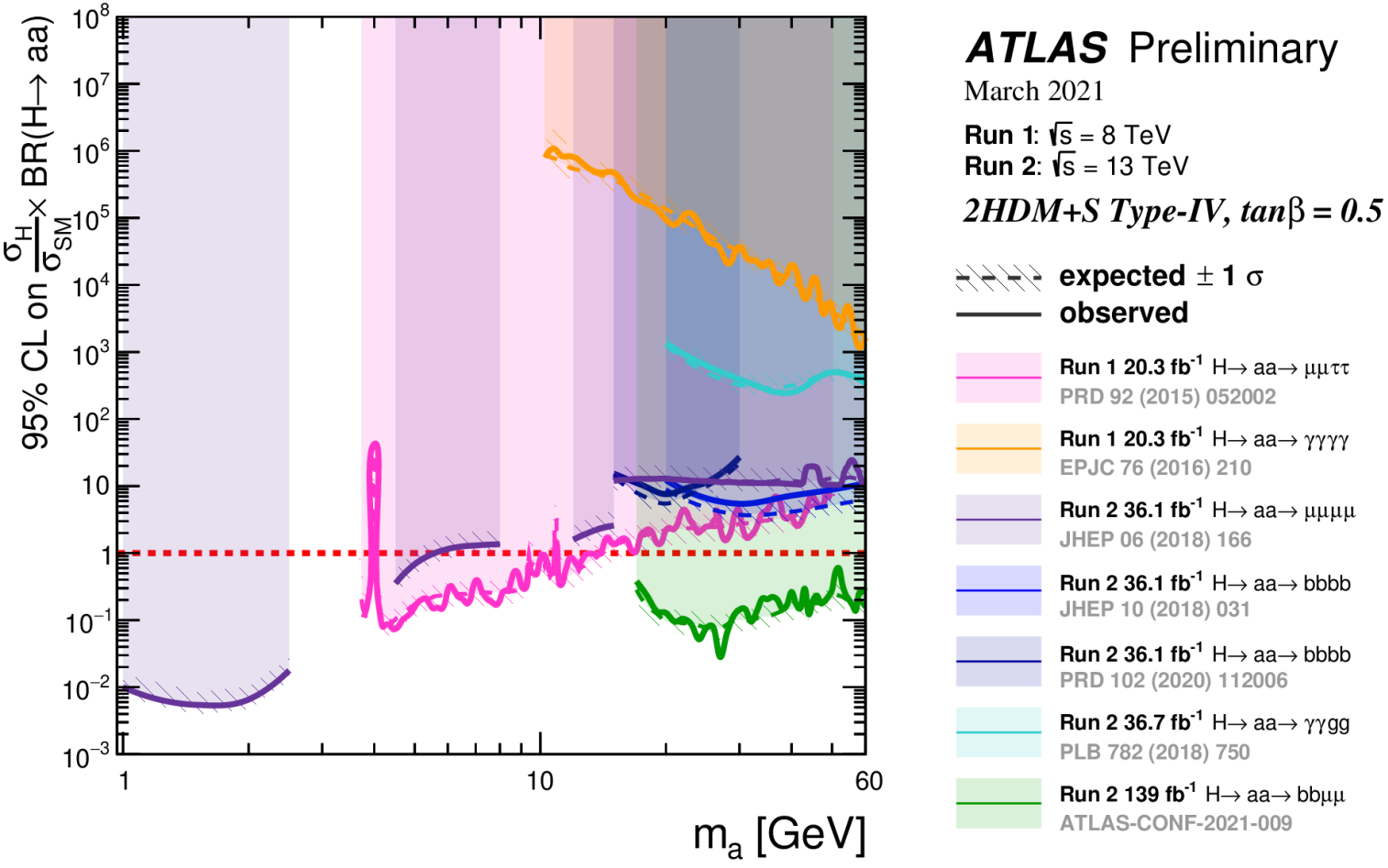
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166

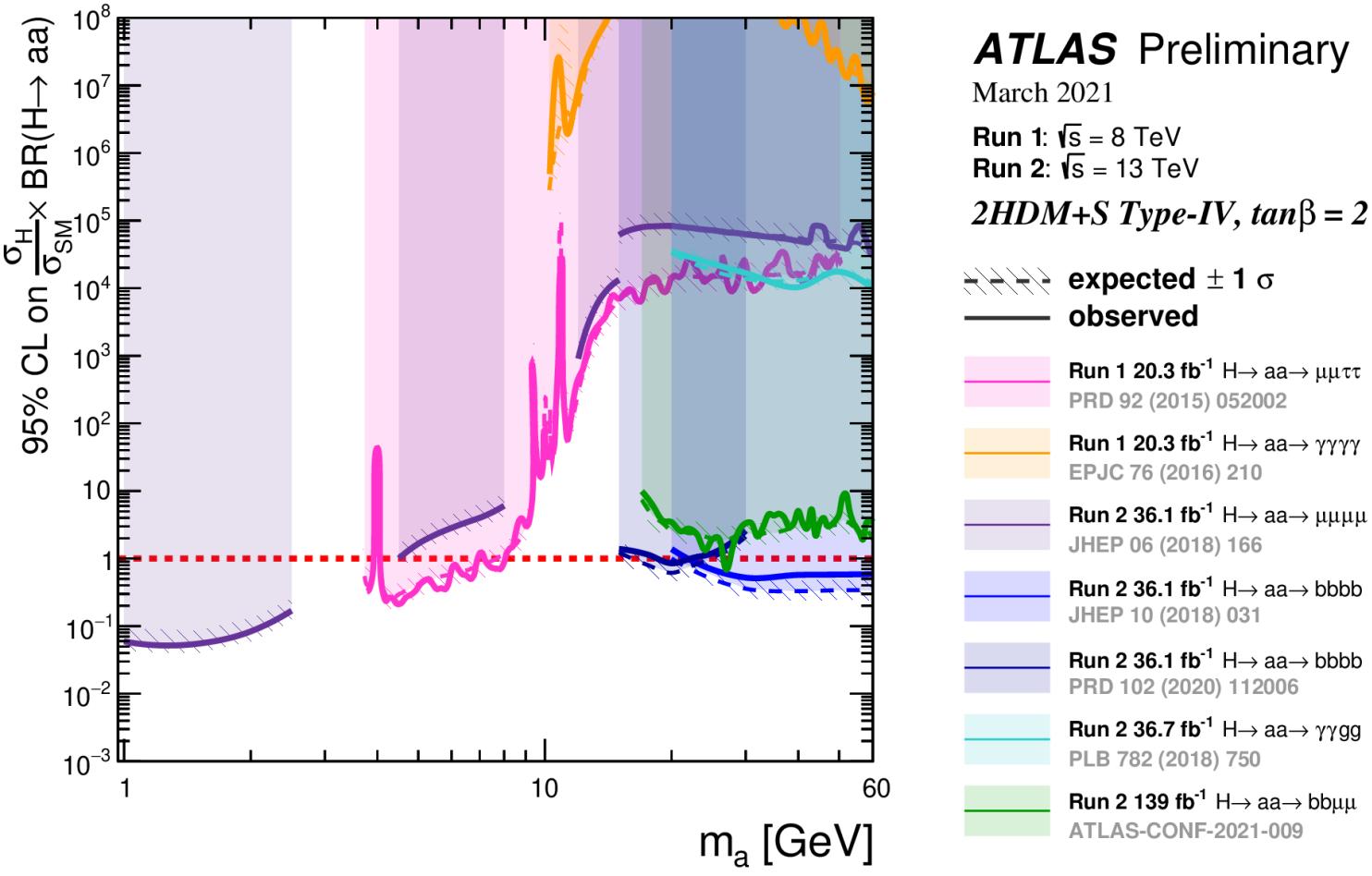
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031

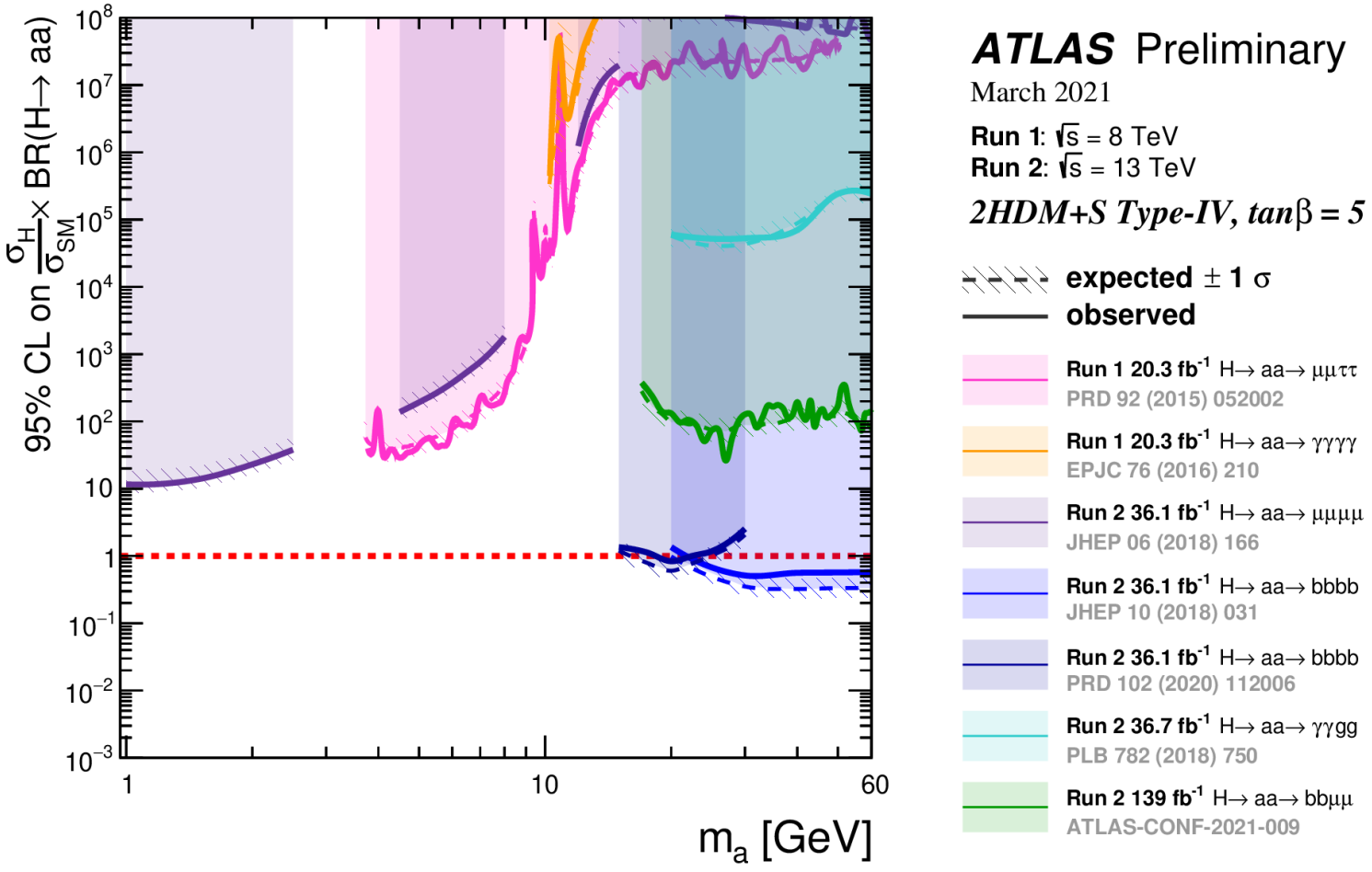
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006

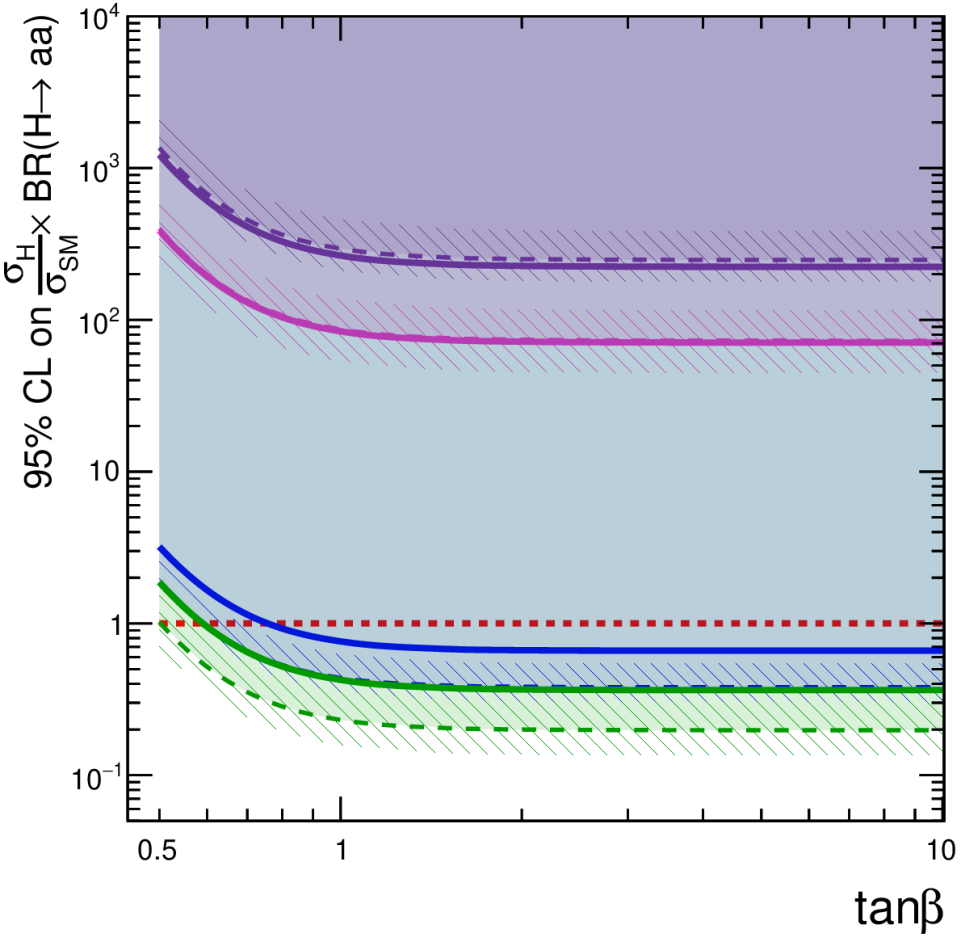
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750

Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009


95% CL on $\frac{\sigma_H}{\sigma_{SM}} \times$ BR(H→ aa)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
10
60
m_a [GeV]
ATLAS Preliminary
March 2021
Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV
2HDM+S Type-IV, tanβ = 0.5
expected ± 1 σ
observed
Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002
Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750
Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009


95% CL on $\frac{\sigma_H}{\sigma_{SM}} \times$ BR(H→ aa)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
10
60
m_a [GeV]
ATLAS Preliminary
March 2021
Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV
2HDM+S Type-IV, tanβ = 2
expected ± 1 σ
observed
Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002
Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750
Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009


95% CL on $\frac{\sigma_H}{\sigma_{SM}} \times$ BR(H→ aa)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
1
10
60
m_a [GeV]
ATLAS Preliminary
March 2021
Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV
2HDM+S Type-IV, tanβ = 5
expected ± 1 σ
observed
Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002
Run 1 20.3 fb^{-1} H→ aa→ γγγγ
EPJC 76 (2016) 210
Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031
Run 2 36.1 fb^{-1} H→ aa→ bbbb
PRD 102 (2020) 112006
Run 2 36.7 fb^{-1} H→ aa→ γγgg
PLB 782 (2018) 750
Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV

2HDM+S Type-II, m_a = 40 GeV

expected ± 1 σ

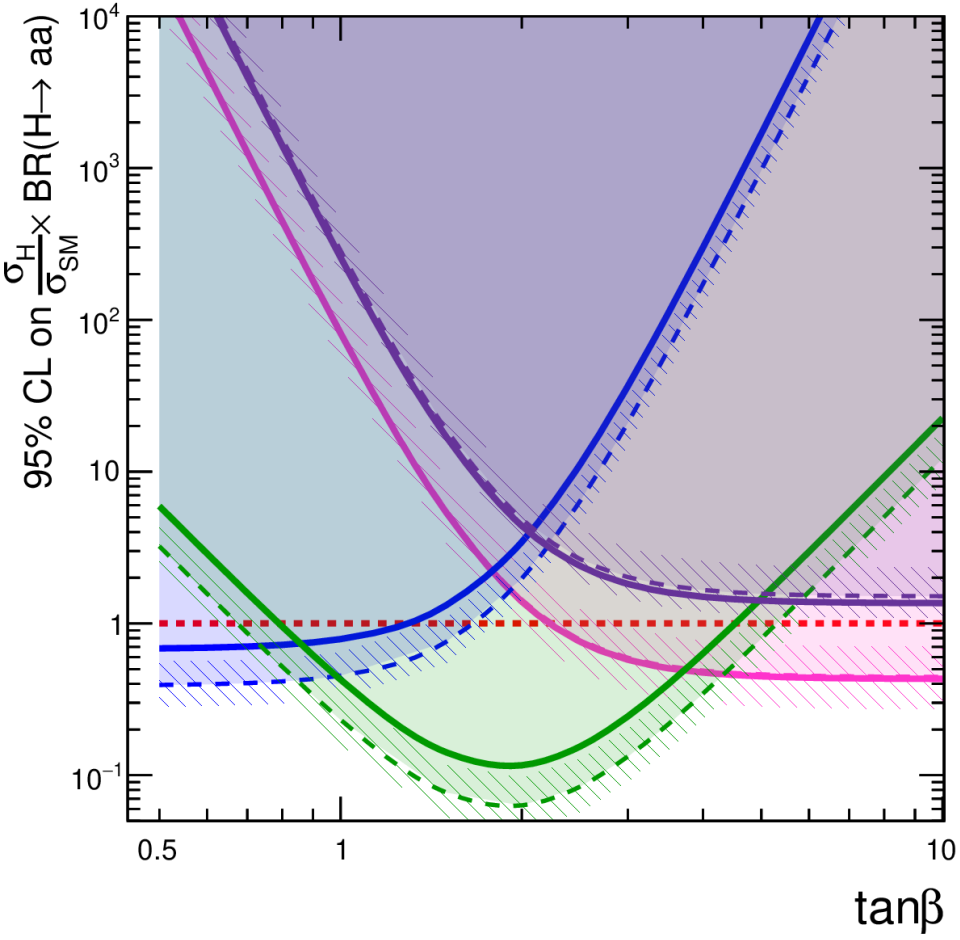
observed

Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002

Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031

Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009

Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV

2HDM+S Type-III, m_a = 40 GeV

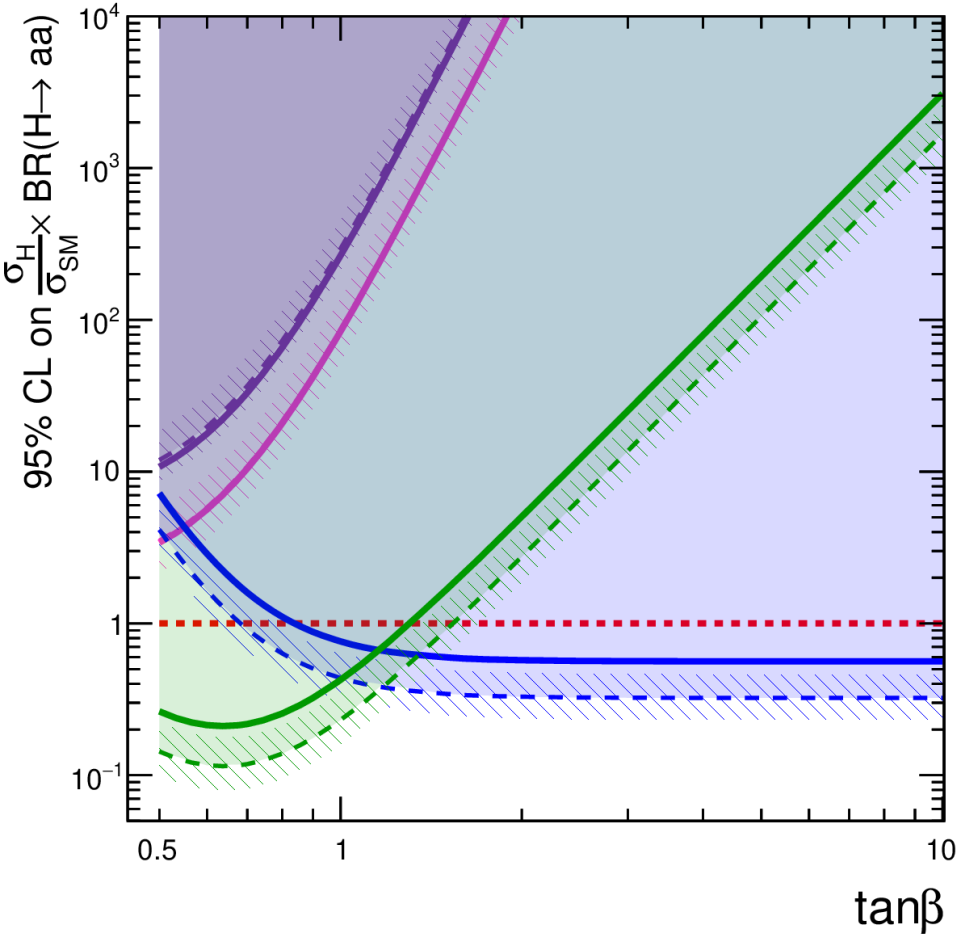
expected ± 1 σ
observed

Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002

Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031

Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009

Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166



ATLAS Preliminary

March 2021

Run 1: $\sqrt{s}$ = 8 TeV
Run 2: $\sqrt{s}$ = 13 TeV

2HDM+S Type-IV, m_a = 40 GeV

expected ± 1 σ

observed

Run 1 20.3 fb^{-1} H→ aa→ μμττ
PRD 92 (2015) 052002

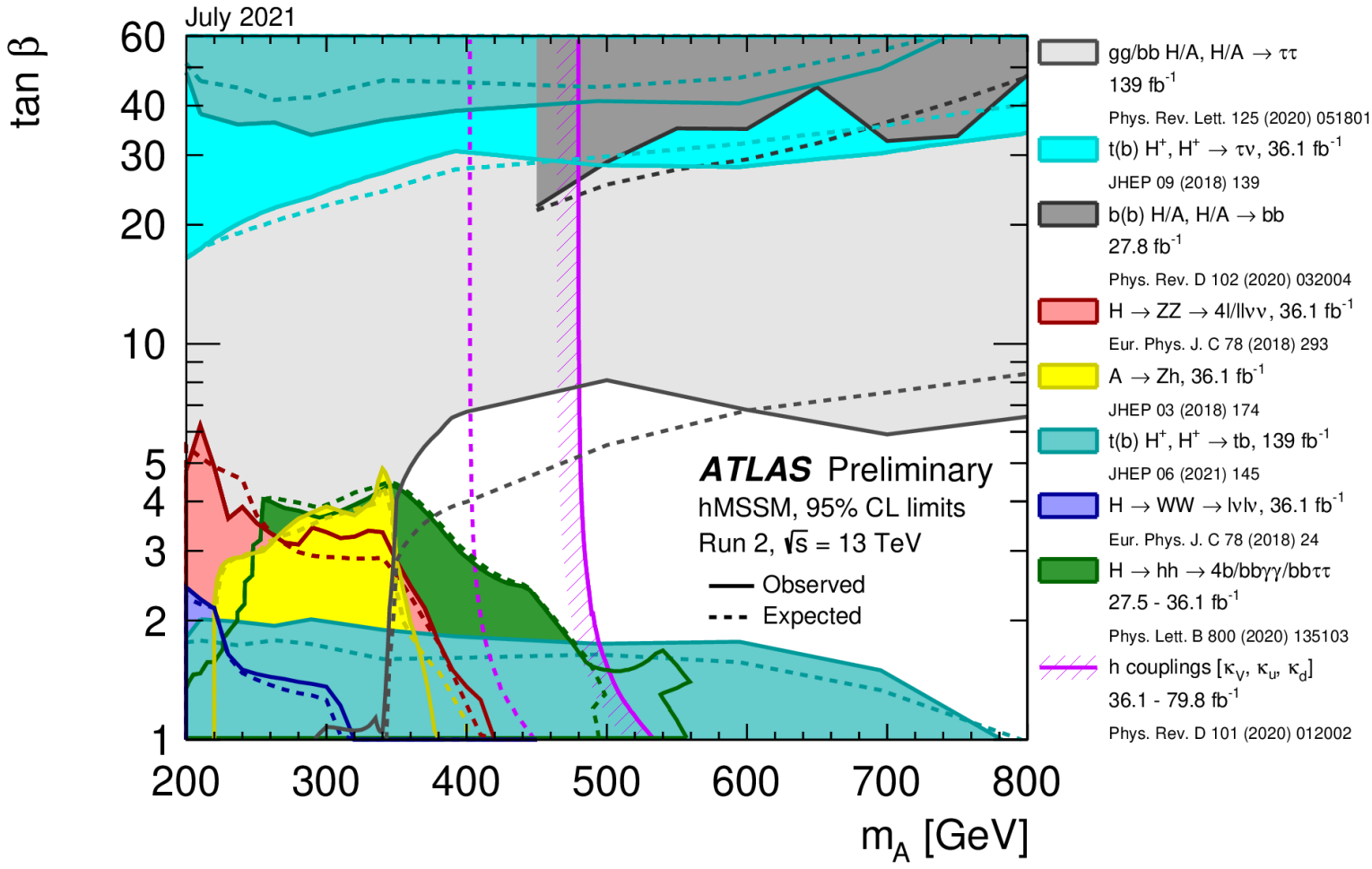
Run 2 36.1 fb^{-1} H→ aa→ bbbb
JHEP 10 (2018) 031

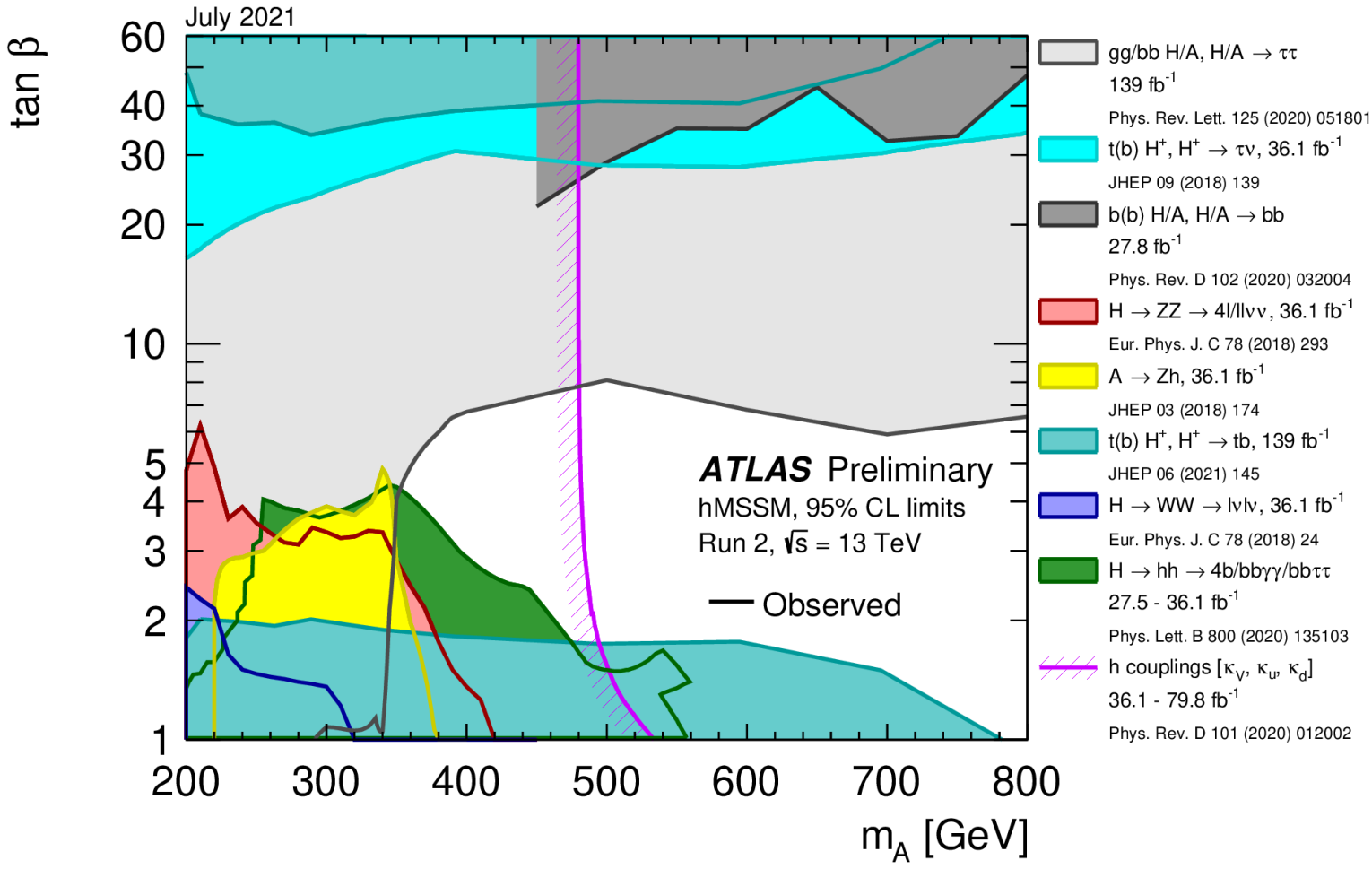
Run 2 139 fb^{-1} H→ aa→ bbμμ
ATLAS-CONF-2021-009

Run 2 36.1 fb^{-1} H→ aa→ μμμμ
JHEP 06 (2018) 166

		X																	
		$e^{\pm}$	$\mu^{\pm}$	$\tau^{\pm}$	Z	W	γ	q/g	c	b	Inv.	ϕ,ρ	$J/\psi,\Upsilon$	$\ell^{\pm}\ell^{\mp}$	$\tau^{\pm}\tau^{\mp}$	$q\bar{q}/ggg$	$\gamma\gamma$	$b\bar{b}$	Other
Y	$e^{\mp}$	[10]	[10]	[11]															
	$\mu^{\mp}$		[12]	[11]															
	$\tau^{\mp}$			SM															
	Z/Z^*				SM		[13]				–	–	[2]	[6]	–	[2]	–	–	–
	W/W^*					SM													–
	γ						SM				[14]	[15]	[16]	[17]	–	–	–	–	–
	q/g							–	–	–									
	c								[18]										
	b									SM									
	Inv.										[19]			–	–	–	–	–	–
	ϕ,ρ											–	–						
	$J/\psi,\Upsilon$												–						
	$\ell^{\pm}\ell^{\mp}$													[6]	[9]	–	–	[1]	–
	$\tau^{\pm}\tau^{\mp}$														–	–	–	–	–
	$q\bar{q}/ggg$															–	[5]	–	–
	$\gamma\gamma$																[8]	–	–
	$b\bar{b}$																	[3, 4]	–
	Other																		Many LLP

Summary Plots: hMSSM Interpretations


July 2021
tan β
60
40
30
20
10
5
4
3
2
1
200
300
400
500
600
700
800
m_A [GeV]
ATLAS Preliminary
hMSSM, 95% CL limits
Run 2, √s = 13 TeV
Observed
Expected
gg/bb H/A, H/A → ττ
139 fb-1
Phys. Rev. Lett. 125 (2020) 051801
t(b) H+, H+ → τν, 36.1 fb-1
JHEP 09 (2018) 139
b(b) H/A, H/A → bb
27.8 fb-1
Phys. Rev. D 102 (2020) 032004
H → ZZ → 4l/llνν, 36.1 fb-1
Eur. Phys. J. C 78 (2018) 293
A → Zh, 36.1 fb-1
JHEP 03 (2018) 174
t(b) H+, H+ → tb, 139 fb-1
JHEP 06 (2021) 145
H → WW → lνlν, 36.1 fb-1
Eur. Phys. J. C 78 (2018) 24
H → hh → 4b/bbγγ/bbττ
27.5 - 36.1 fb-1
Phys. Lett. B 800 (2020) 135103
h couplings [κV, κu, κd]
36.1 - 79.8 fb-1
Phys. Rev. D 101 (2020) 012002


July 2021
tan β
60
40
30
20
10
5
4
3
2
1
200
300
400
500
600
700
800
m_A [GeV]
ATLAS Preliminary
hMSSM, 95% CL limits
Run 2, √s = 13 TeV
Observed
gg/bb H/A, H/A → ττ
139 fb-1
Phys. Rev. Lett. 125 (2020) 051801
t(b) H+, H+ → τν, 36.1 fb-1
JHEP 09 (2018) 139
b(b) H/A, H/A → bb
27.8 fb-1
Phys. Rev. D 102 (2020) 032004
H → ZZ → 4l/llνν, 36.1 fb-1
Eur. Phys. J. C 78 (2018) 293
A → Zh, 36.1 fb-1
JHEP 03 (2018) 174
t(b) H+, H+ → tb, 139 fb-1
JHEP 06 (2021) 145
H → WW → lνlν, 36.1 fb-1
Eur. Phys. J. C 78 (2018) 24
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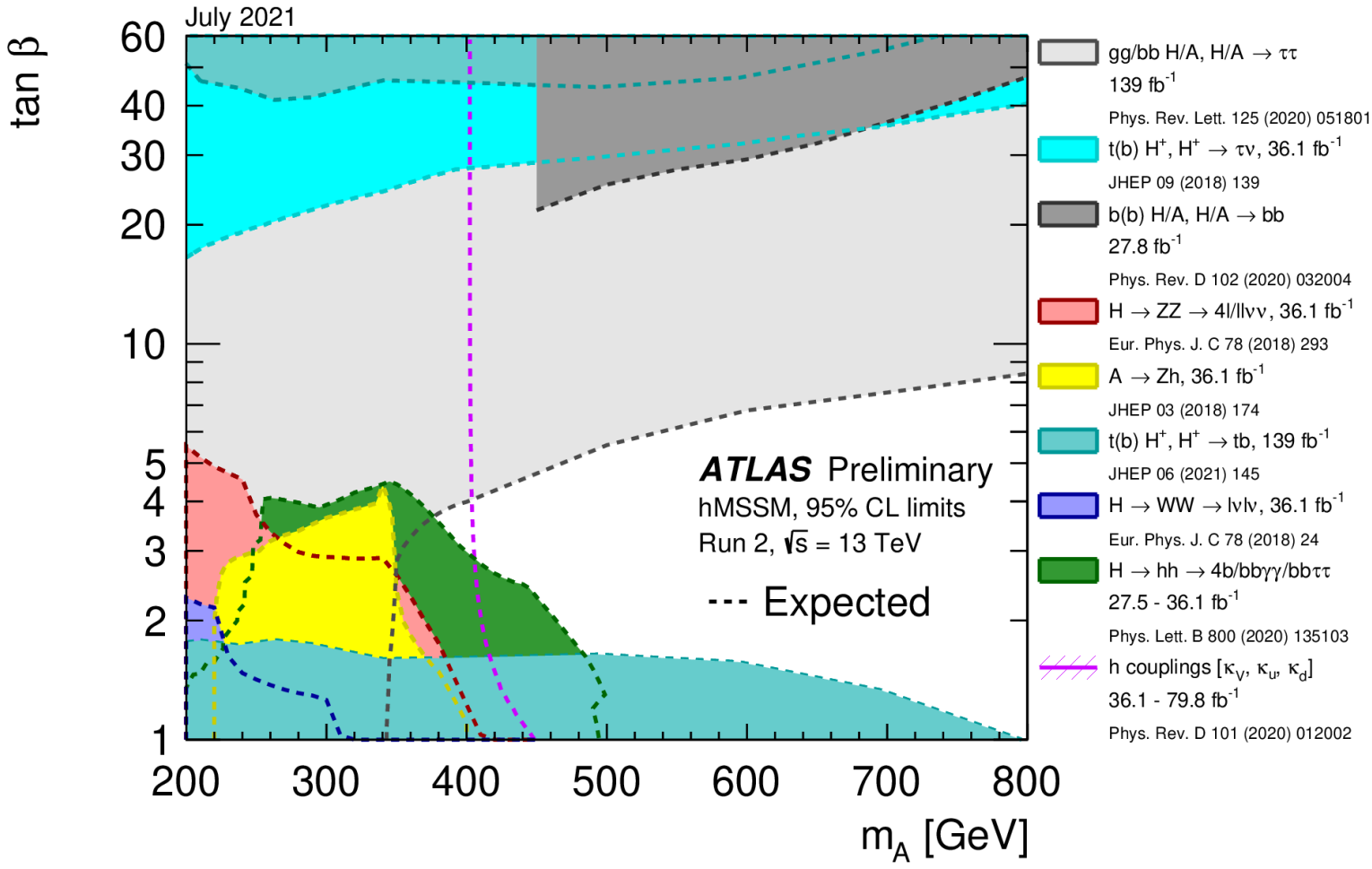
27.5 - 36.1 fb-1
Phys. Lett. B 800 (2020) 135103
h couplings [κV, κu, κd]
36.1 - 79.8 fb-1
Phys. Rev. D 101 (2020) 012002


July 2021
tan β
60
40
30
20
10
5
4
3
2
1
200
300
400
500
600
700
800
m_A [GeV]
ATLAS Preliminary
hMSSM, 95% CL limits
Run 2, √s = 13 TeV
--- Expected
gg/bb H/A, H/A → ττ
139 fb-1
Phys. Rev. Lett. 125 (2020) 051801
t(b) H+, H+ → τν, 36.1 fb-1
JHEP 09 (2018) 139
b(b) H/A, H/A → bb
27.8 fb-1
Phys. Rev. D 102 (2020) 032004
H → ZZ → 4l/llνν, 36.1 fb-1
Eur. Phys. J. C 78 (2018) 293
A → Zh, 36.1 fb-1
JHEP 03 (2018) 174
t(b) H+, H+ → tb, 139 fb-1
JHEP 06 (2021) 145
H → WW → lνlν, 36.1 fb-1
Eur. Phys. J. C 78 (2018) 24
H → hh → 4b/bbγγ/bbττ
27.5 - 36.1 fb-1
Phys. Lett. B 800 (2020) 135103
h couplings [κV, κu, κd]
36.1 - 79.8 fb-1
Phys. Rev. D 101 (2020) 012002