Searches for Non-Standard Model Higgs Bosons

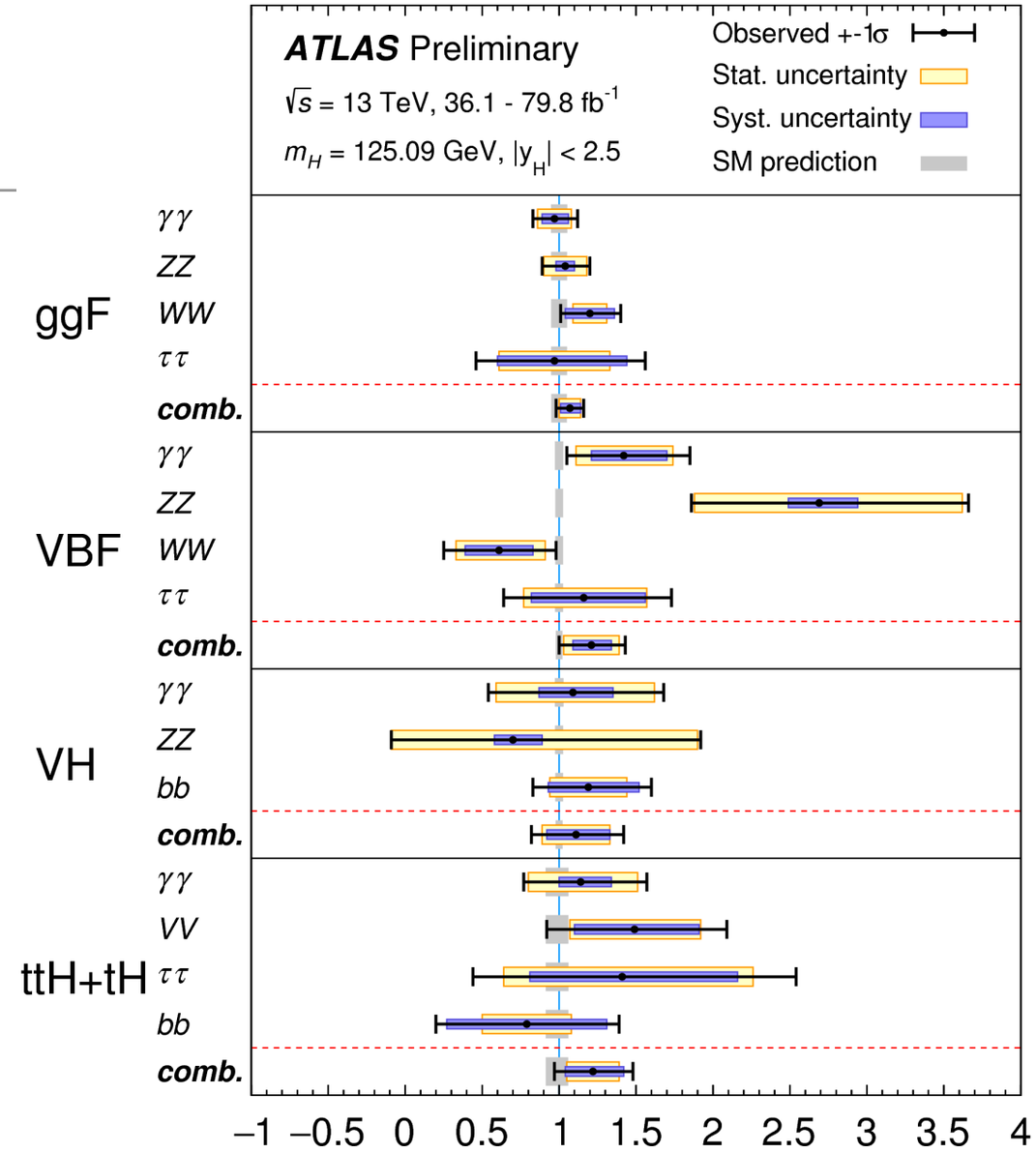
Syed Haider Abidi
on behalf of the ATLAS collaboration
Sep 13th, 2018

Physics
UNIVERSITY OF TORONTO

Introduction

- Discovery of a scalar particle @ ~ 125 GeV ‘completed’ the SM
  - Further probing of this scalar particle → very much SM-like

- However, this doesn’t rule out BSM scenarios

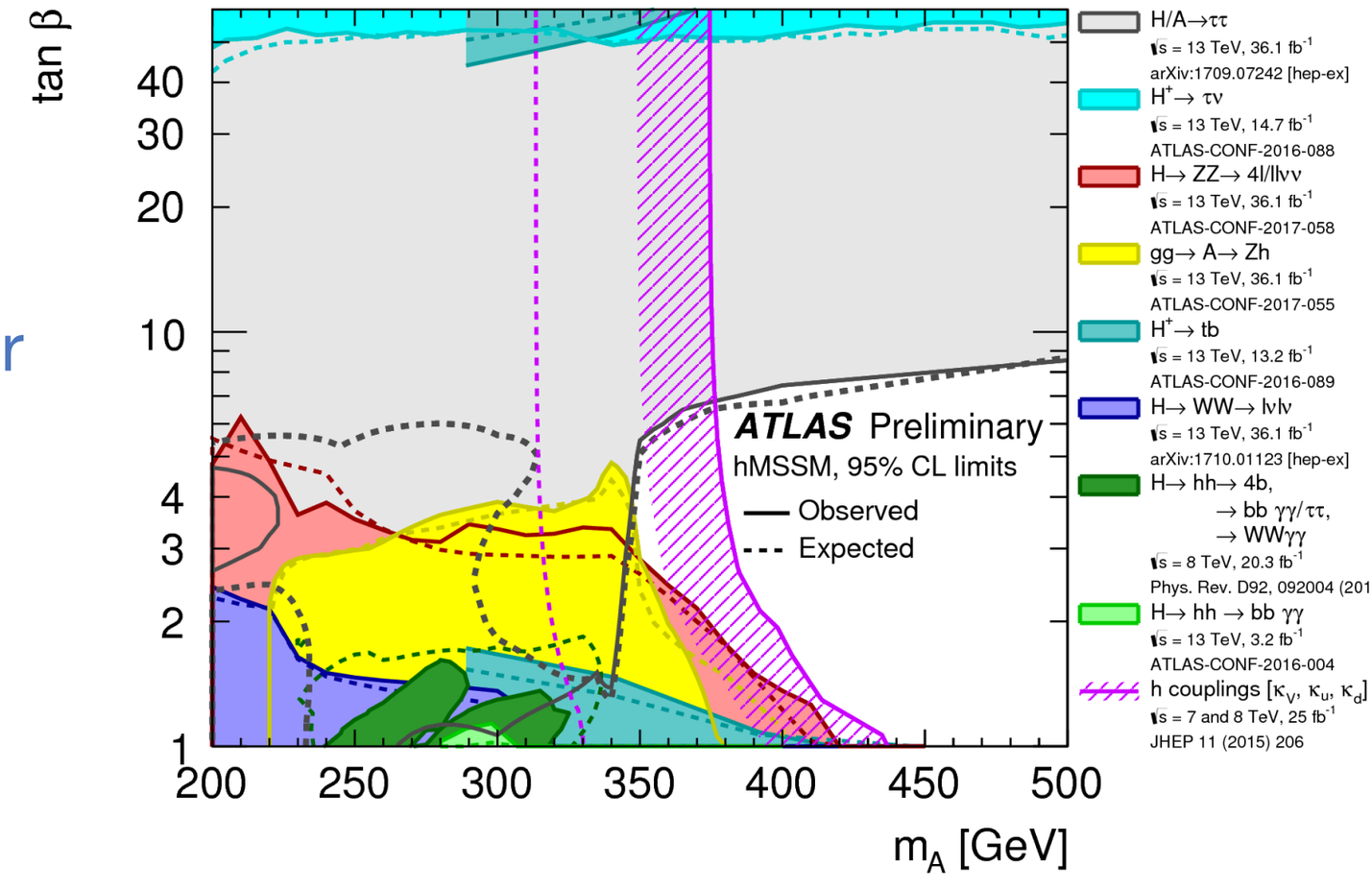


- Different strategies:
  - **Indirect** - probe for small deviations in properties (CP, couplings,…) of SM particles
  - **Direct through decay** - SM particles decaying into BSM particles
  - Direct through production - Explicitly look for BSM particles produced at the LHC decaying into SM particles
    - Focus of this talk

BSM Scenarios

- **2HDM model** - 2 Higgs doublet in the Lagrangian
  - 5 bosons: h, H, A & $H^{\pm}$
  - Several types based on coupling - Type-II ~ MSSM SUSY
  - 2 parameters at tree level: **tanβ** and M_A
  - Rich decay phenomenology
- **Higgs triplet model** (HTM)
  - Includes additional $H^{\pm\pm}$

- A curated list of results to cover the different decays



Heavy Neutral Higgs Boson

- Dominant production at LHC:
  - gluon-gluon fusion (ggF)
  - b-associated fusion (bbH)

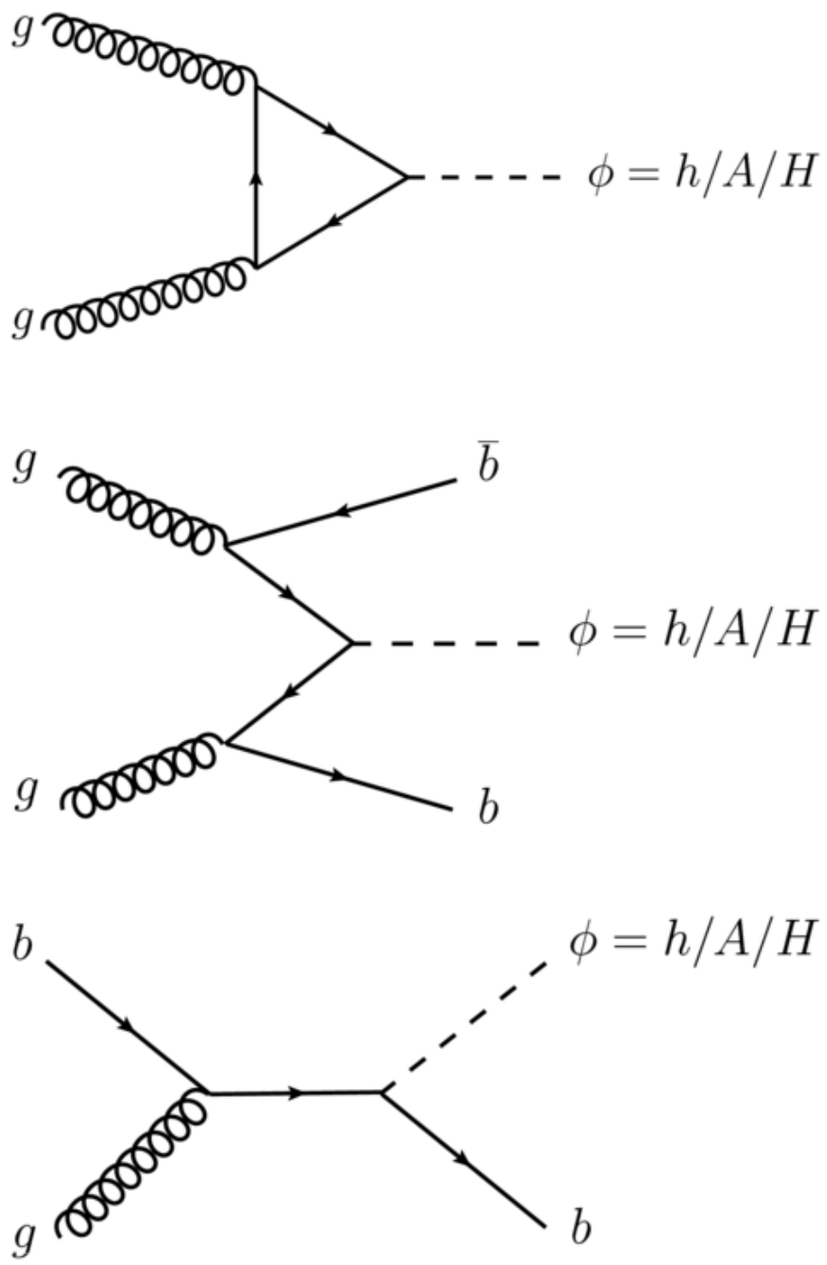
- For Type-II, coupling to down-type fermions enhanced at large tanβ
  - $\phi \to \tau\bar{\tau}$ has large branching ratio

- For low tanβ and $M_\phi \geq 2M_{Top}$, $\phi \to t\bar{t}$ decay is accessible

Latest ATLAS results

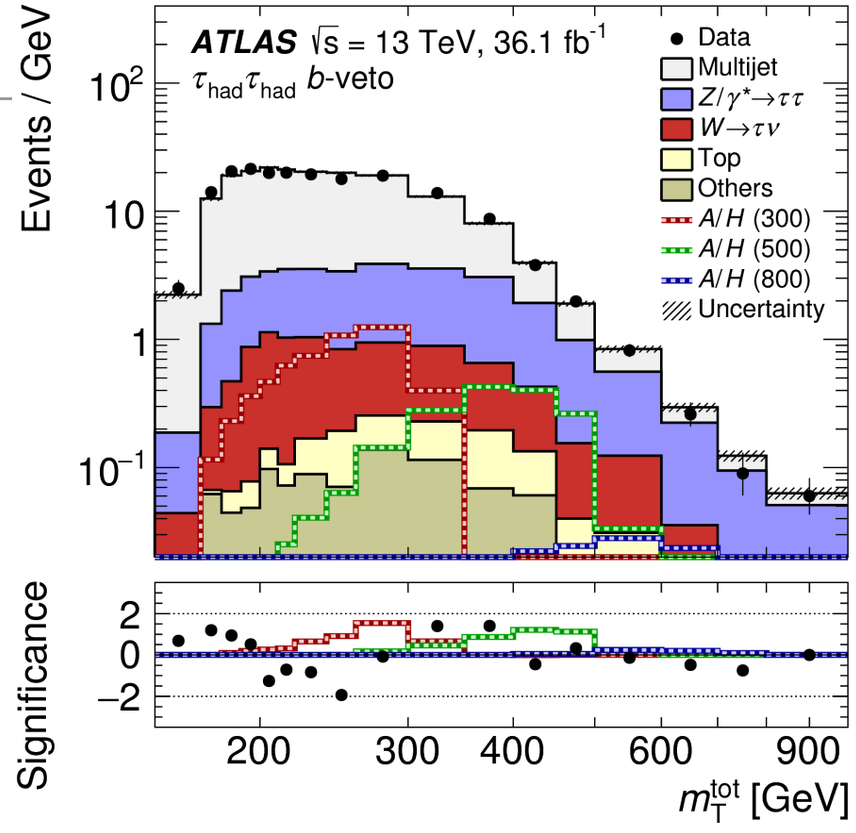
Search BSM A/H/Z→ττ	HIGG-2016-12	13 TeV, 36/fb
A/H→tt with interference	EXOT-2016-04	8 TeV, 20/fb

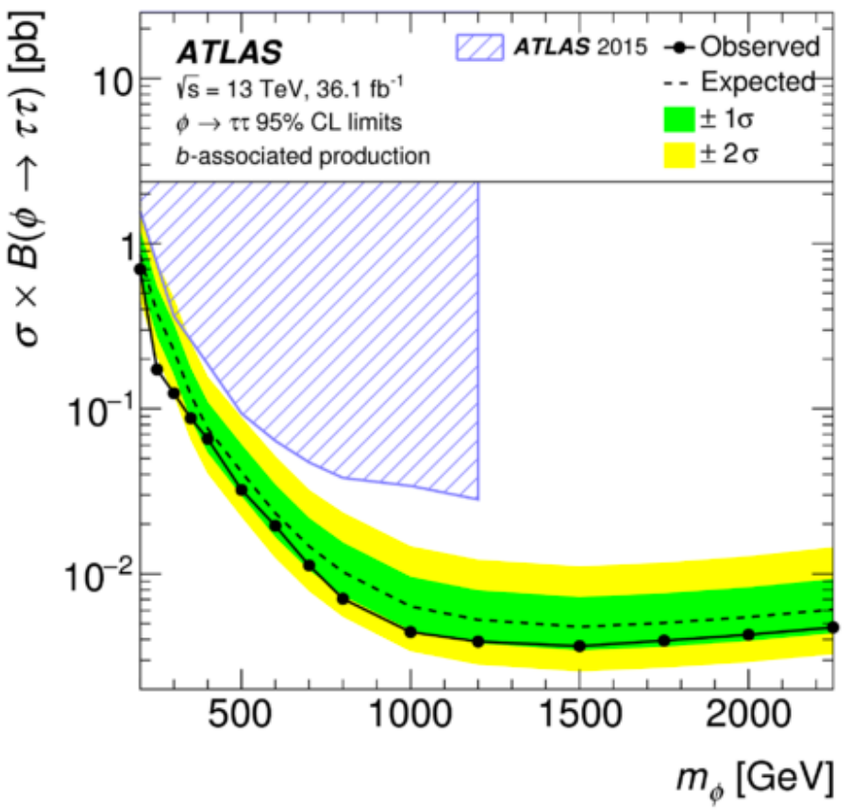
Heavy Higgs production @ LHC



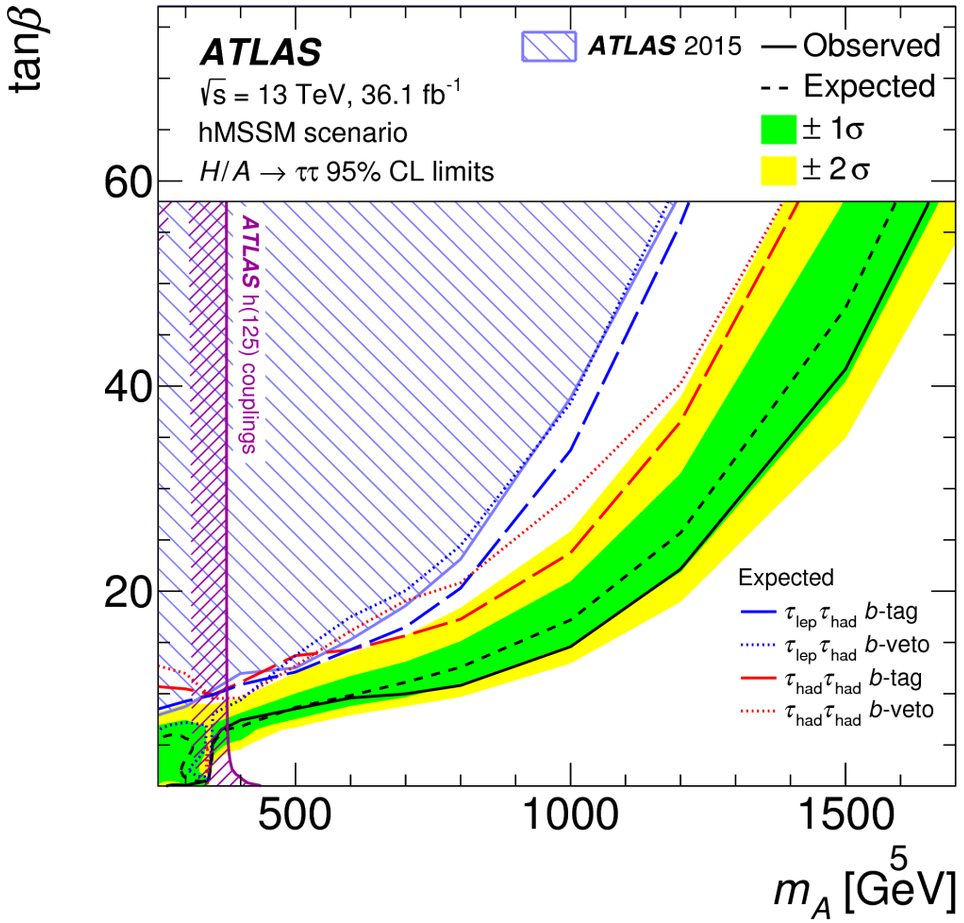
A/H→ττ

- Two decay modes - $\tau_{Lep}\tau_{Had}$ & $\tau_{Had}\tau_{Had}$
  - For $M_{A/H} < 0.6$ TeV, $\tau_{Lep}\tau_{Had}$ dominates
  - $\tau_{Had}\tau_{Had}$ is sensitive for higher mass range
- Target production mode - b-tag and b-veto regions
- Large background from jet→τ conversion
- **Model independent** limit on ggF and bbH XS
- Exclusion at the 95% CL for hMSSM scenarios:
  tanβ > 1.0 for M_A = 0.25 TeV
  tanβ > 42 for M_A = 1.5 TeV



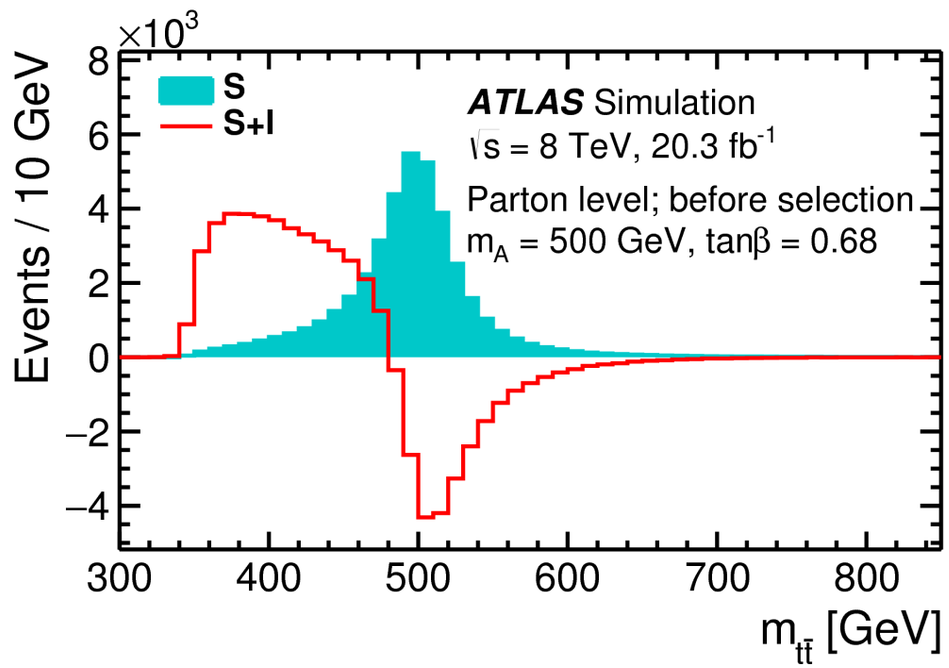


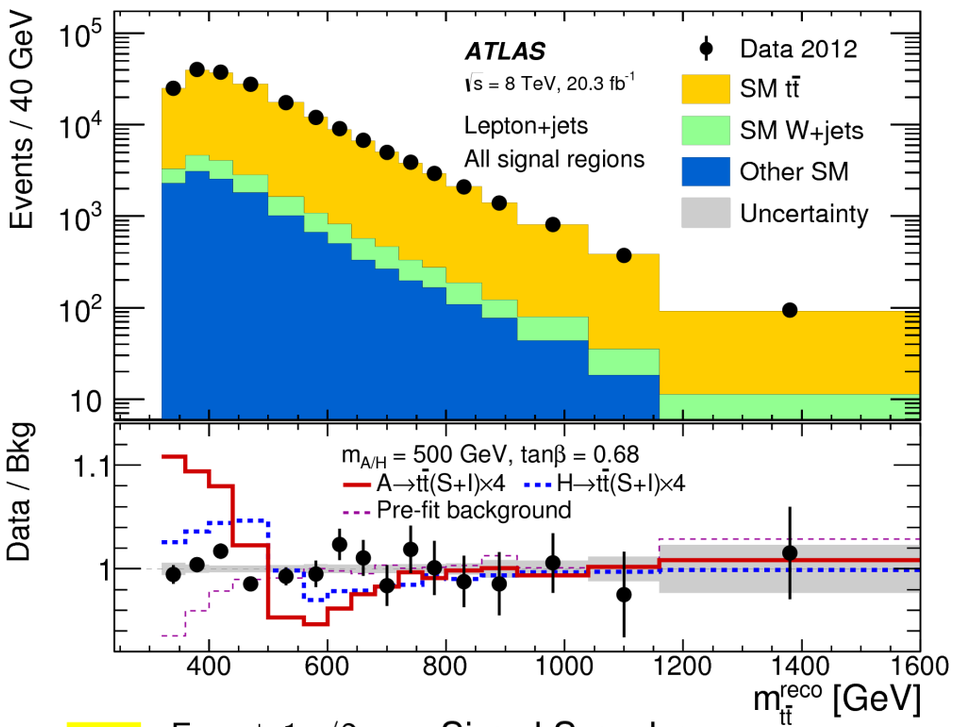
+ ggF limits
& MSSM

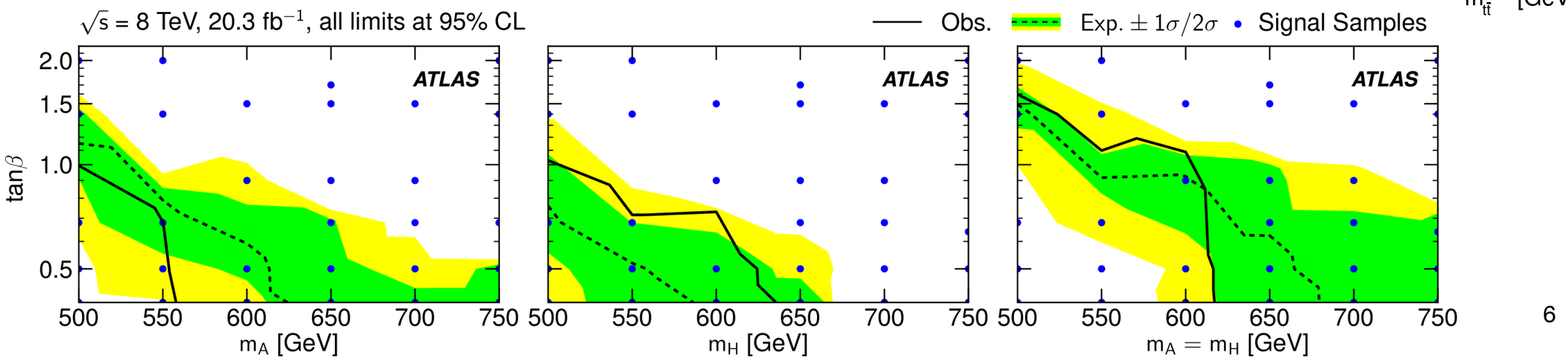


A/H→tt

- Significant interference: A/H→**tt** and gg→**tt**
  - Modification of resonance to peak-dip structure
- Resolved kinematics, with **lepton+jet** final state
  - Sensitivity up to $M_{A/H}$ ~ 800 GeV
  - 6 categories - lep flavour and tagged
    - M_{tt}^{reco} as the discriminating variable
- **Exclusion** at the 95% CL for Type-II 2HDM:
  $\tan\beta < 0.69$ for $M_A = 550$ GeV
  $\tan\beta < 0.72$ for $M_H = 550$ GeV







Heavy Neutral Higgs Boson

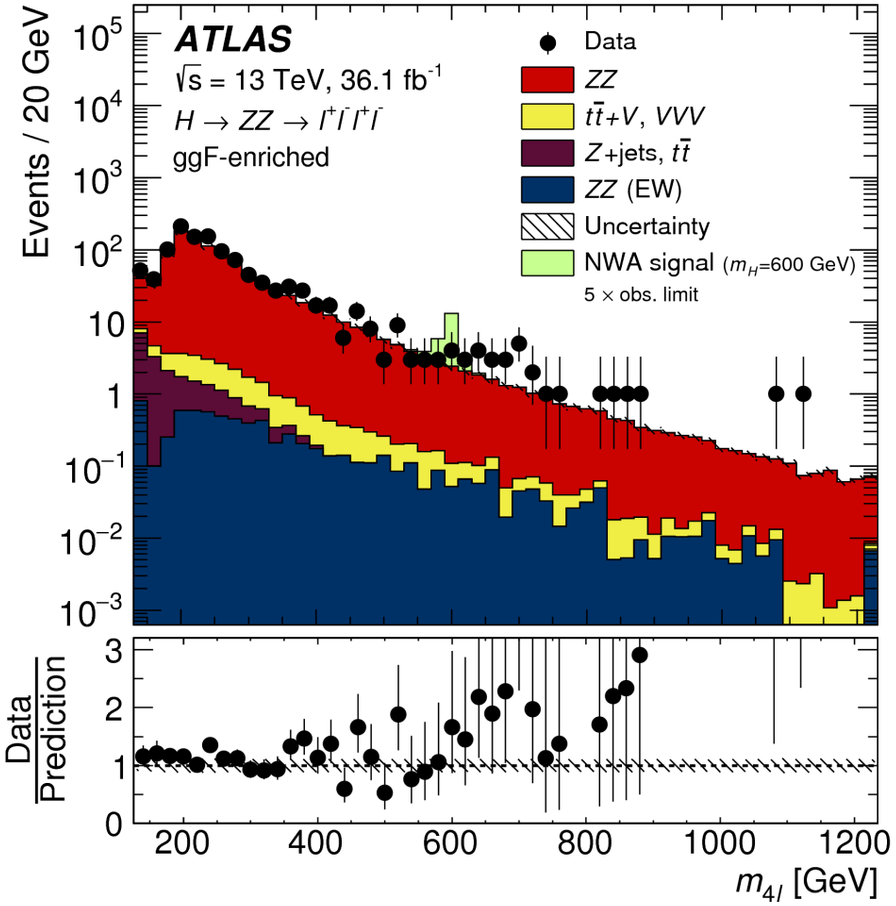
- In BSM scenarios, heavy Higgs decay to vector boson possible
  - Mixing of the h & H particle states
  - Coupling parameterized typically as **cos(β-α)**

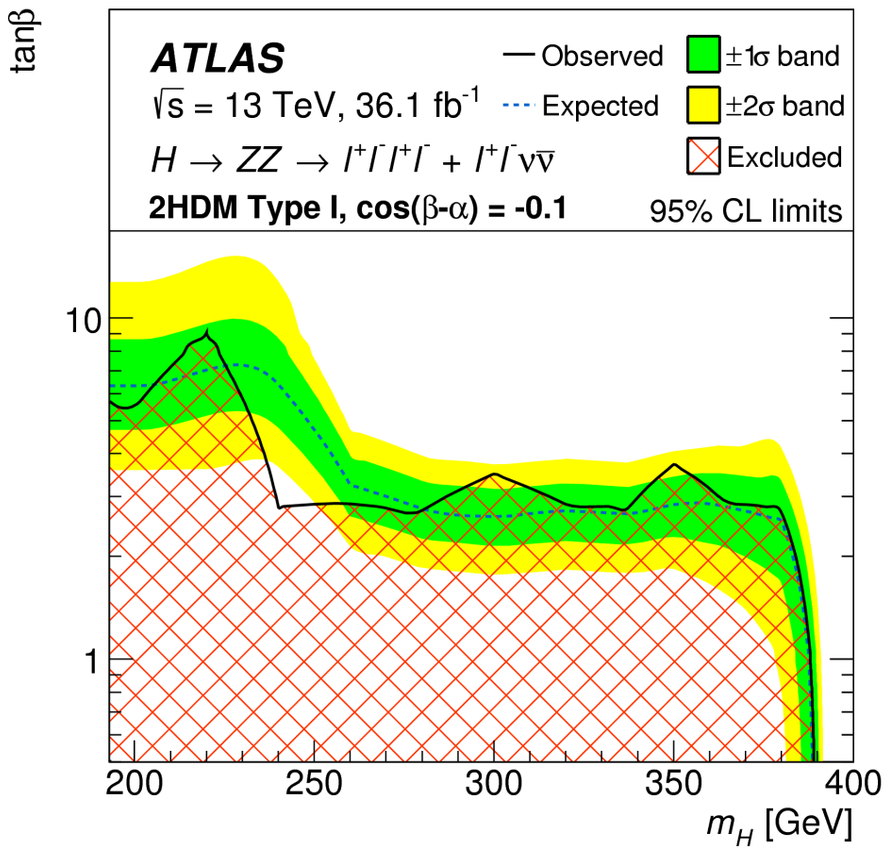
Latest ATLAS results

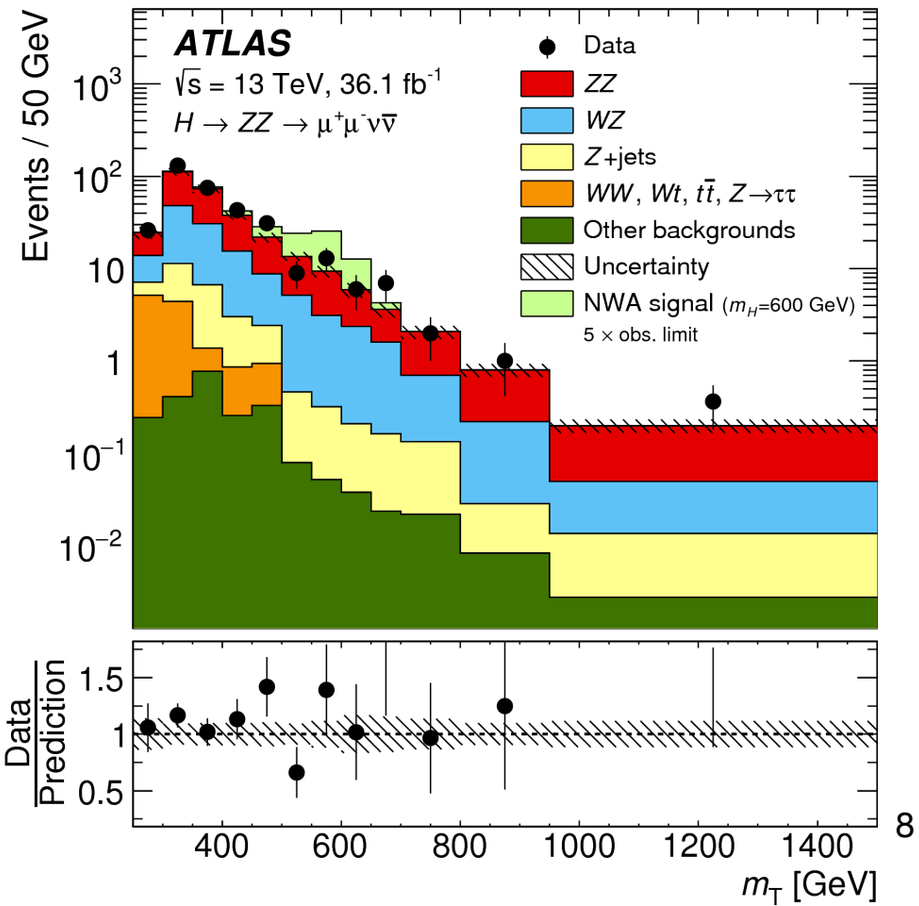
H→ZZ→4l,2l2ν	HIGG-2016-19	13 TeV, 36/fb
H→WW→eνμν	HIGG-2016-31	
A→ZH→llbb & A→Vh→ll'bb	EXOT-2016-34 & EXOT-2016-10	
New **Combination of VV/VH final states**	EXOT-2017-31	

H→ZZ→4l,2l2ν

- Events with opposite flavour same sign lepton pair(s)
  - 4l: Fully reconstruct the decay kinematics - m_{4l} as observable
  - 2l2ν: Reconstruct the leading Z - m_T as observable
- Split into VBF- and ggF-like SR
  - Gain in sensitivity by splitting in lepton flavour
- Interference between h-H and Bkg taken into account for large width
- Small excess at M_H ~ 700 GeV in 4l
- Global significance at 1.3σ

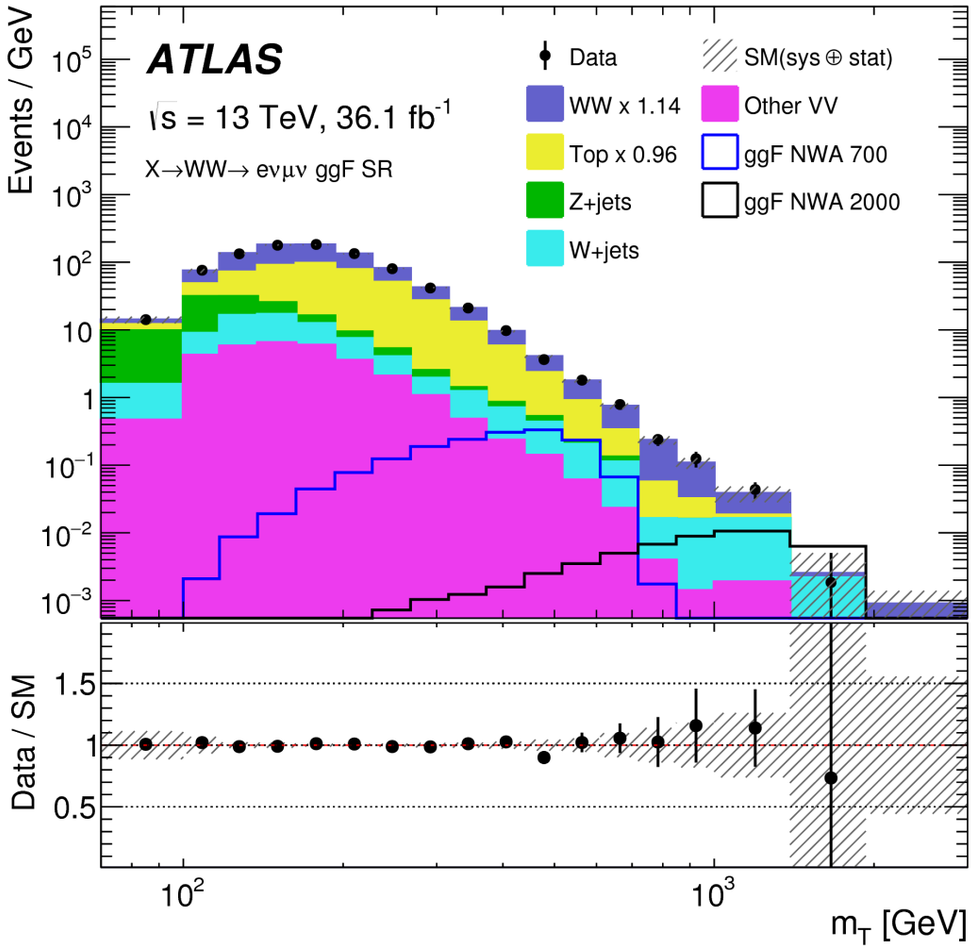


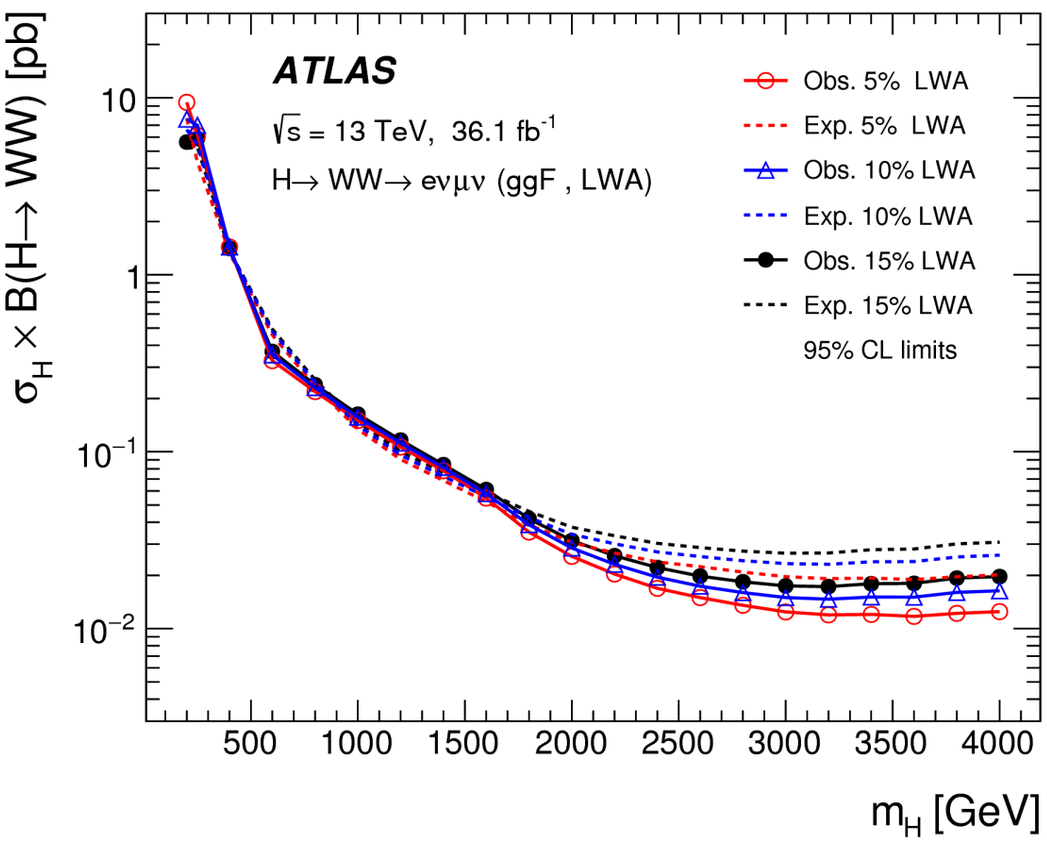


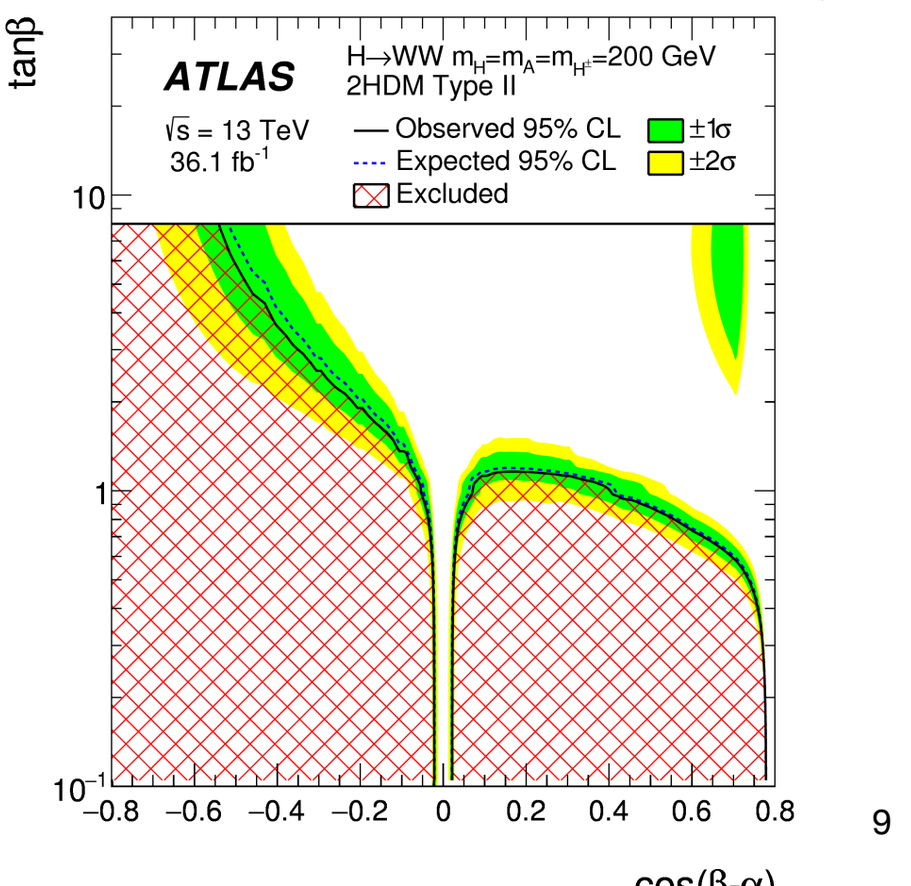


H→WW→eνμν

- Events with opposite flavour **lepton pair with missing energy**
  - Reduce Z+jets background
- 3 Signal region:
  - 2 VBF-Like (N_{jets} =1 or N_{jets} ≥2)
  - 1 ggF-like (inclusive in N_{jets})
- Multiple interpretation of the results
  - Large width - interference with background

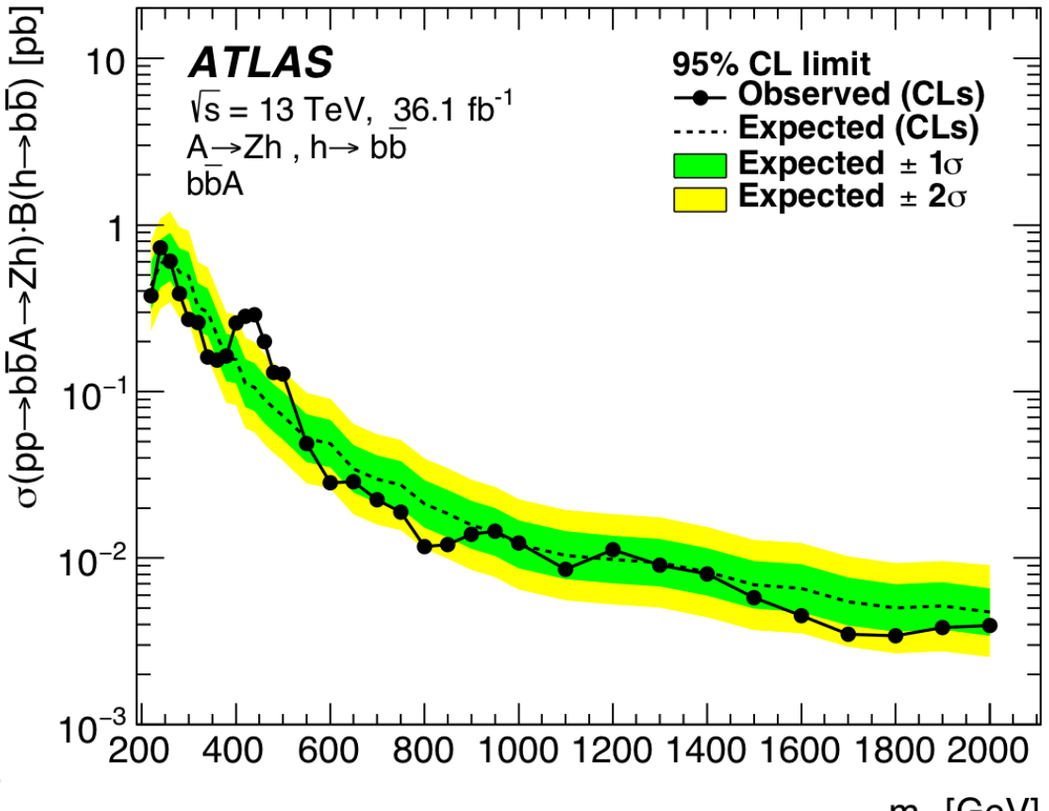


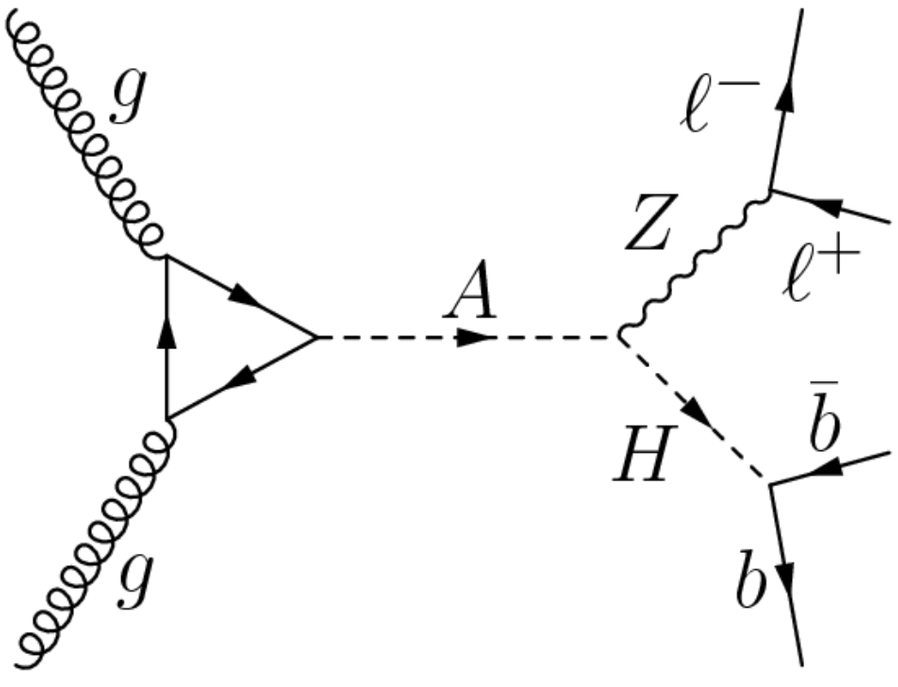


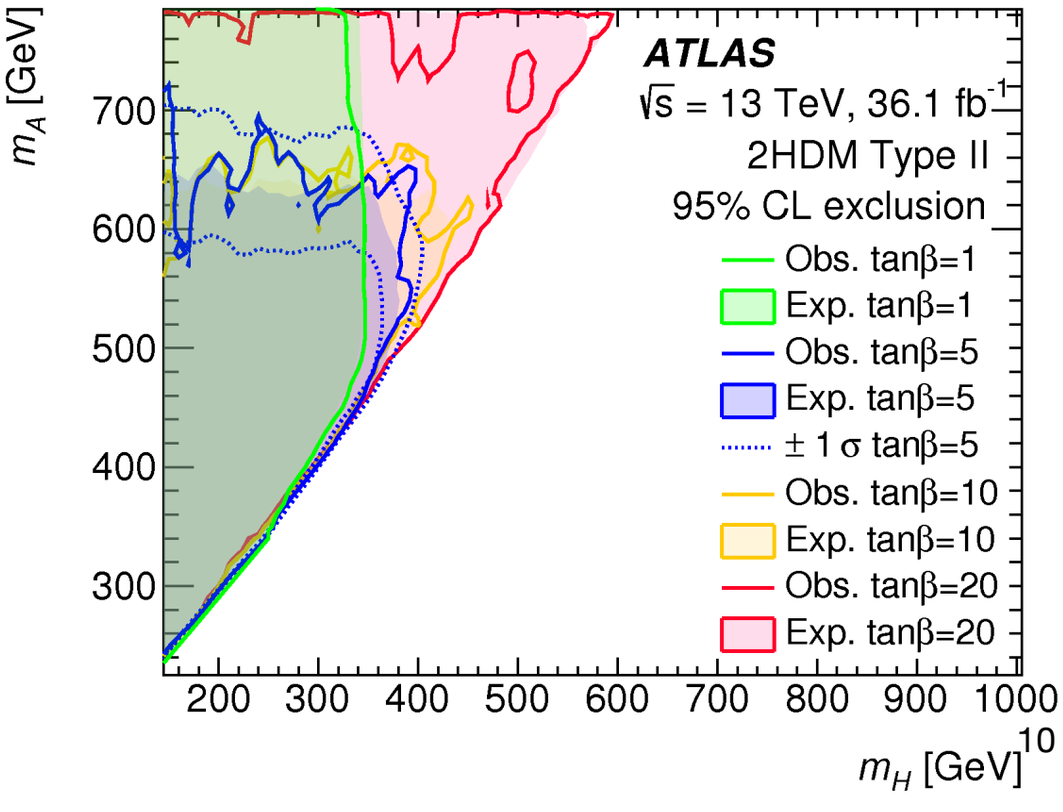


A→ZH→llbb, A→Vh→ll'bb

- Search for a heavy CP-odd scalar
- **Isolated leptons or ν and ≥ 2 b-tagged jets**
- ZH: search for heavy CP-odd and even scalar
- Vh: all lepton vector boson decay
  - Impacts of large width take into account
- Results interpreted in various models
  - **Mild excess** at M_A = 440 GeV for A→Vh
  - Arises from 3+ b-tag region in the 2-lepton channel. Local (global) significance: 3.6 (2.4)σ

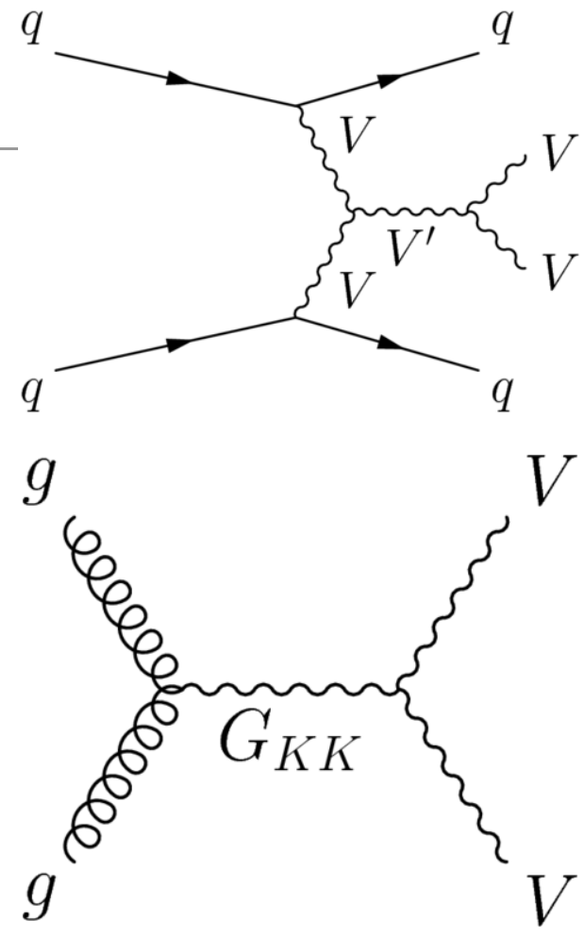


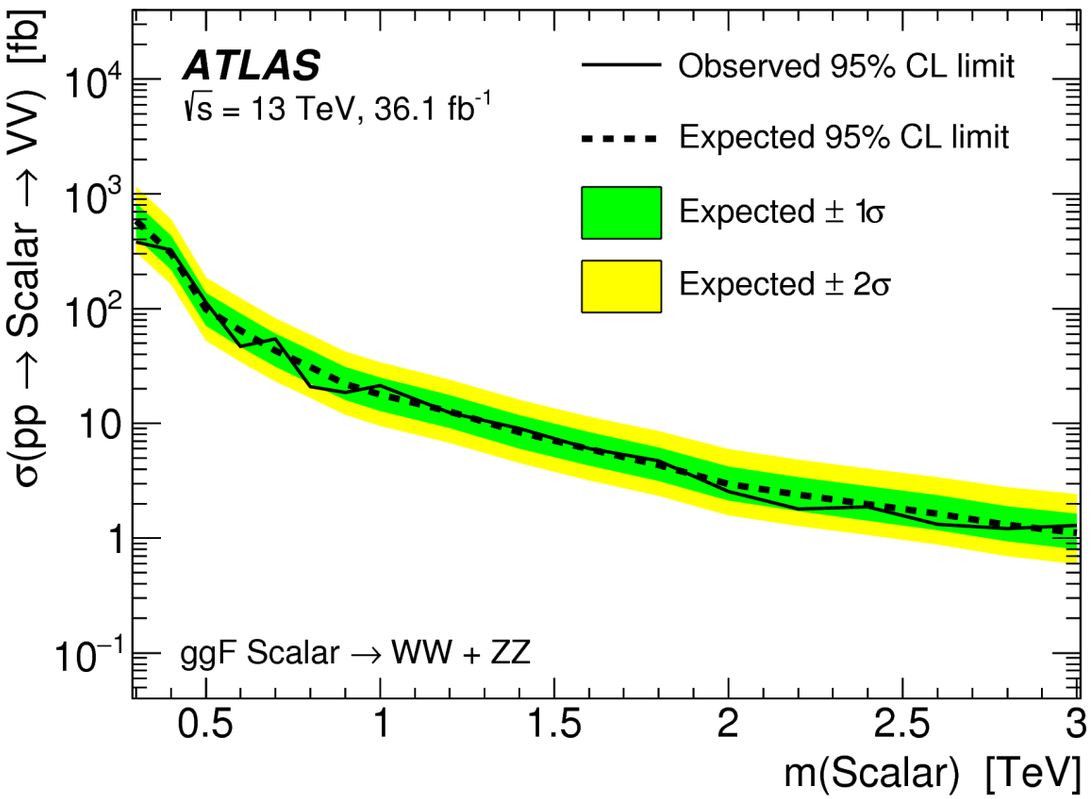


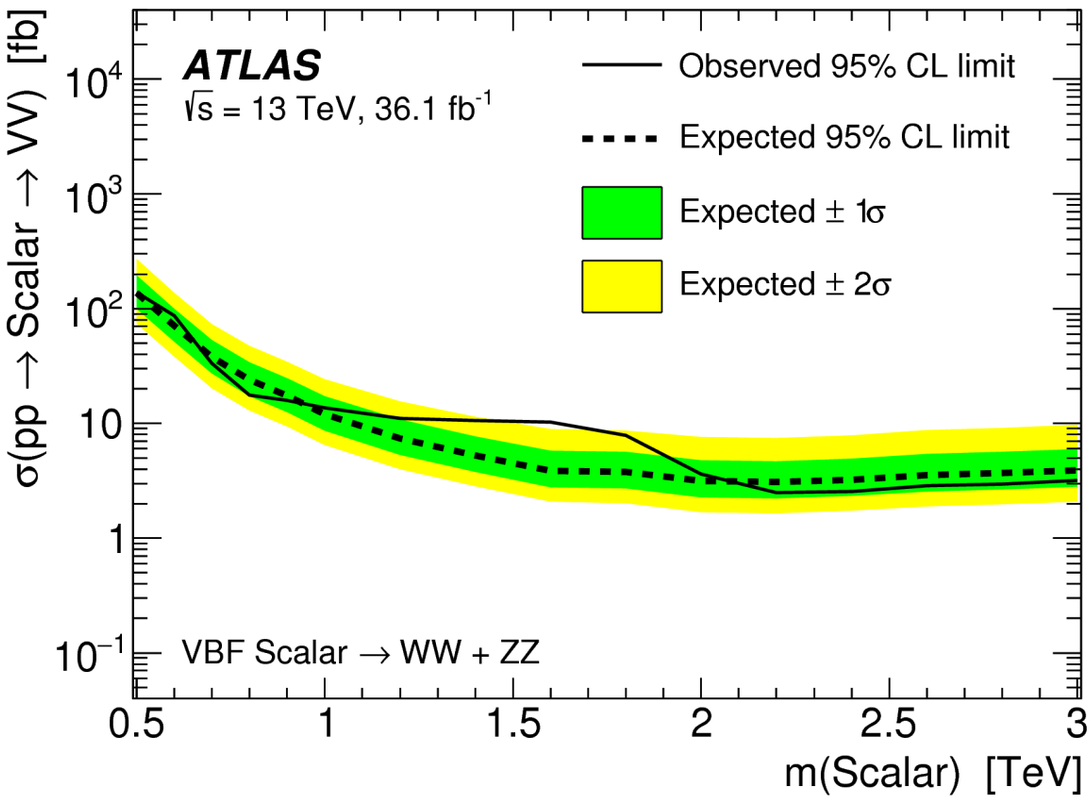


Combination of VV/VH final states

- A **global** heavy resonance search - combination of ATLAS results
  - Final states: *qqqq, vvqq, lvqq, llqq, lvlv, llvv, lvll, llll, qqbb, vvbb, lvbb, and llbb*
  - **Correlation** of experimental and theoretical systematics
- General results parameterized as a function of quark, lepton and boson couplings
- For scalar resonance, exclusion limits at 95% CL
  - ggF: 380 - 1.3 fb for $M_H \in$ [0.3 - 3.0 TeV]
  - VBF: 140 - 3.2 fb for $M_H \in$ [0.5 - 3.0 TeV]



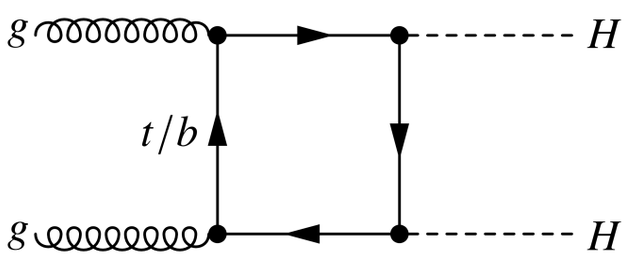


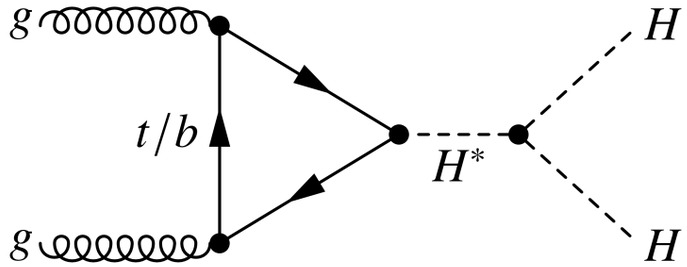


Di-Higgs Search

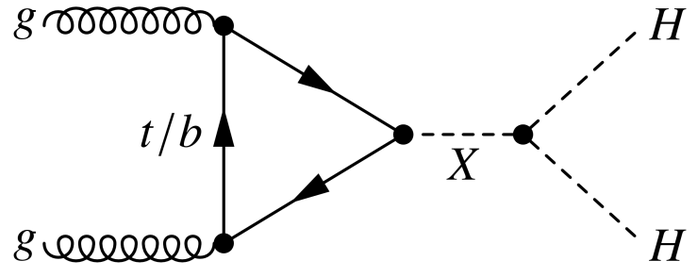
- Low mass Higgs boson offers **another portal** to probe for BSM physics
- Search for heavy scalar decaying into two 125 GeV Higgs boson
  - Many decay modes - balance between background and expected events

SM





BSM



Latest ATLAS results

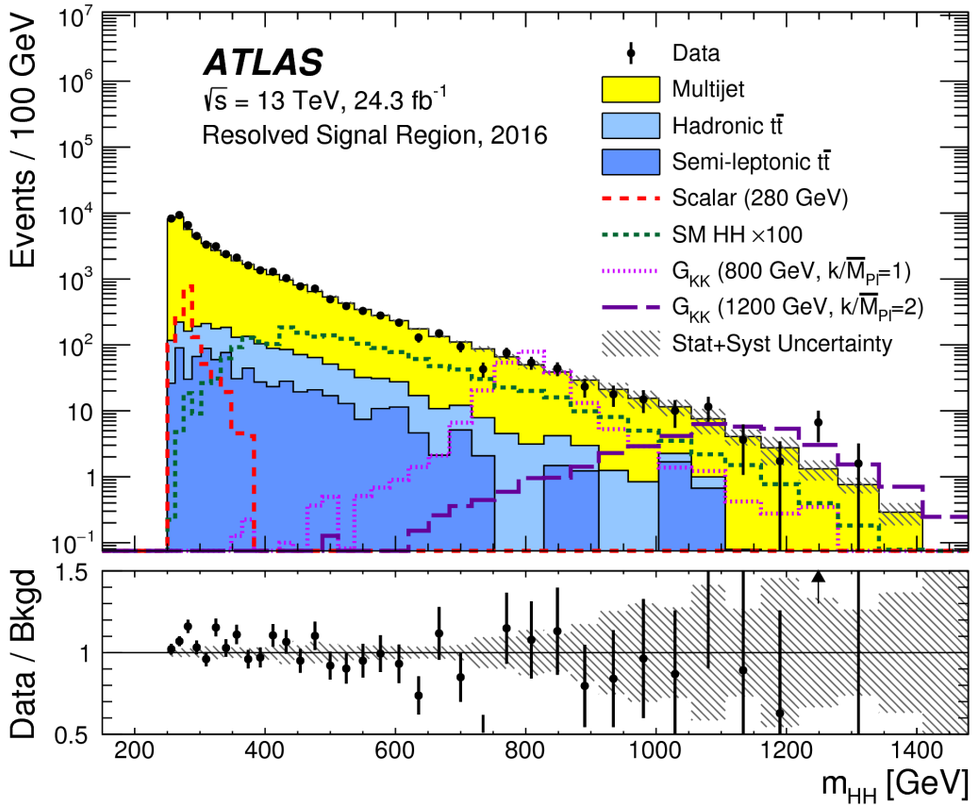
	H→hh→bbbb	EXOT-2016-31	13 TeV, 27.5-36/fb
	H→hh→bbγγ	HIGG-2016-15	
New	H→hh→bbττ	HIGG-2016-16	
New	HH combination	ATLAS-CONF-2018-043	

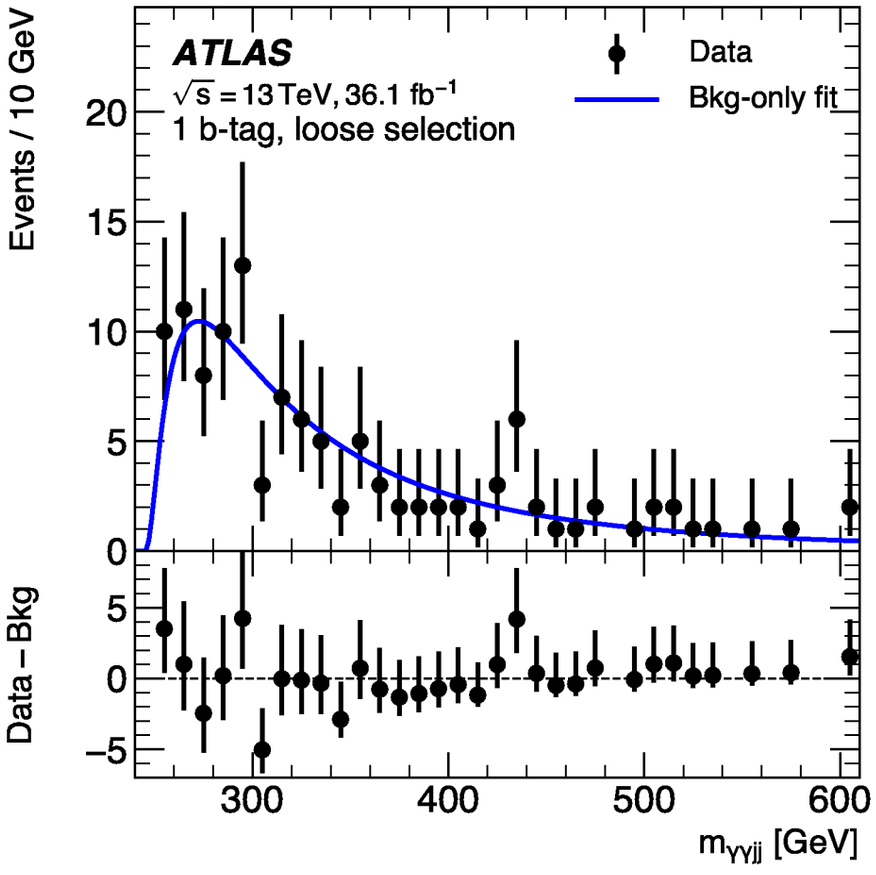
DiHiggs BR

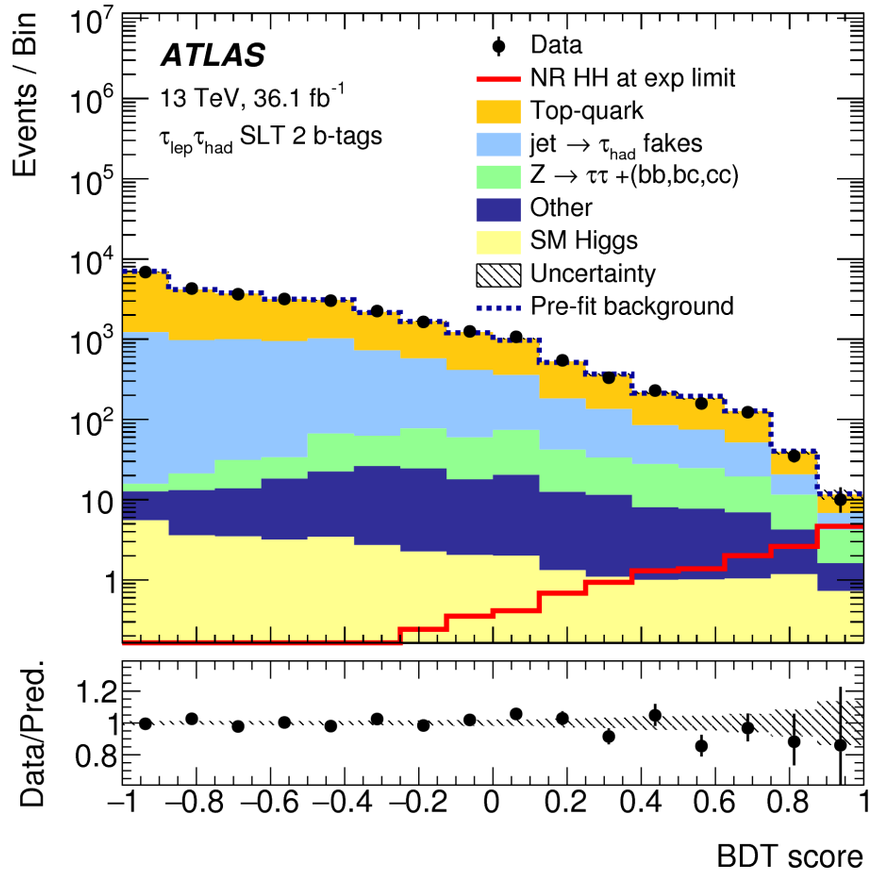
	bb	WW	ττ	ZZ	γγ
bb	33%				
WW	25%	4.6%			
ττ	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
γγ	0.26%	0.10%	0.029%	0.013%	0.0053%

H→hh→bbbb/bbγγ/bbττ

- **bbbb**: **Largest** branching ratio but large background
  - Resolved and boosted topology targeted separately to **extend** sensitivity
- **bbγγ**: **Profit** from narrow peak in yy distribution
  - **Improvement** in resolution by constraining M_{jj} $=M_{\gamma\gamma}$
- **bbττ**: **Target** decay modes - $\tau_{Lep}\tau_{Had}$ & $\tau_{Had}\tau_{Had}$
  - **BDT** to separate signal from di-top, Z→ττ and multi jet background

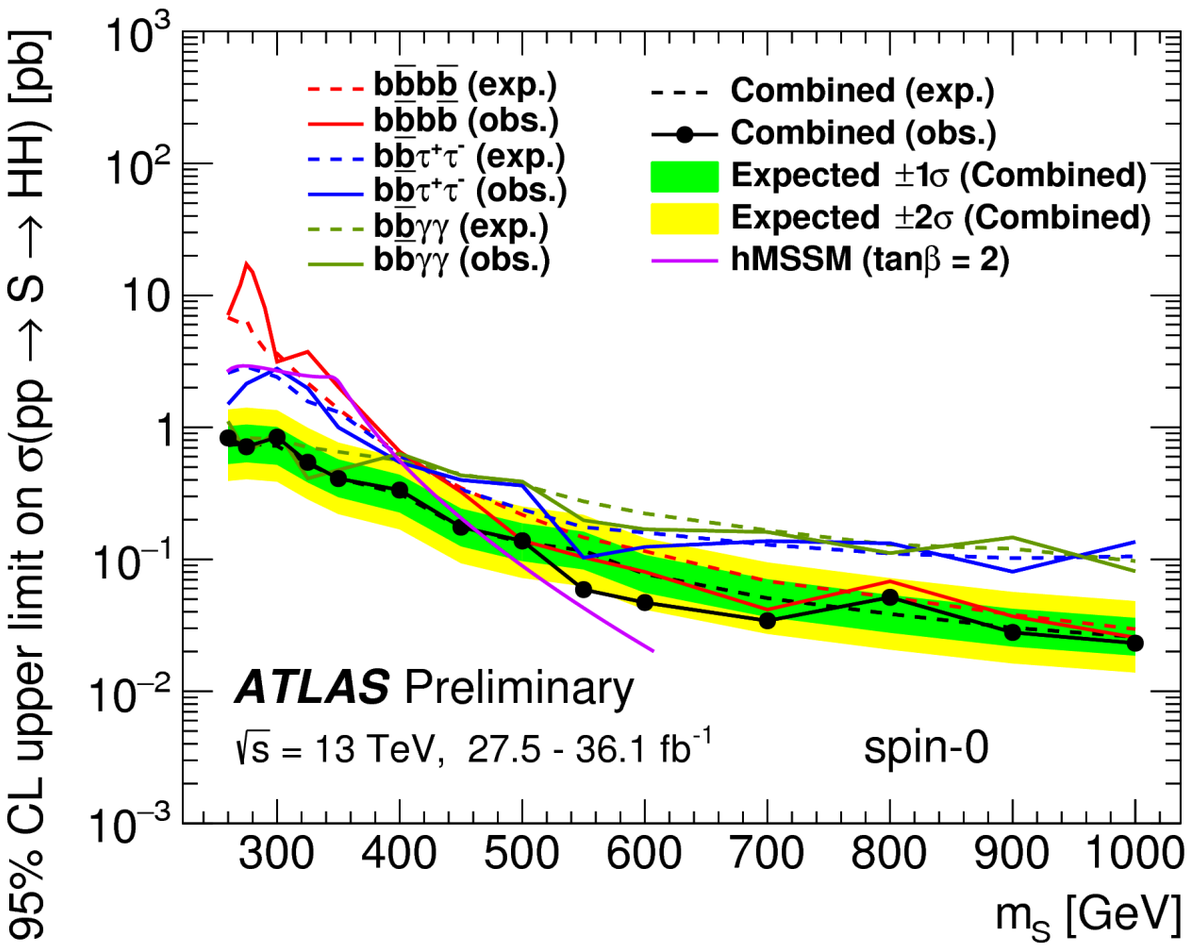


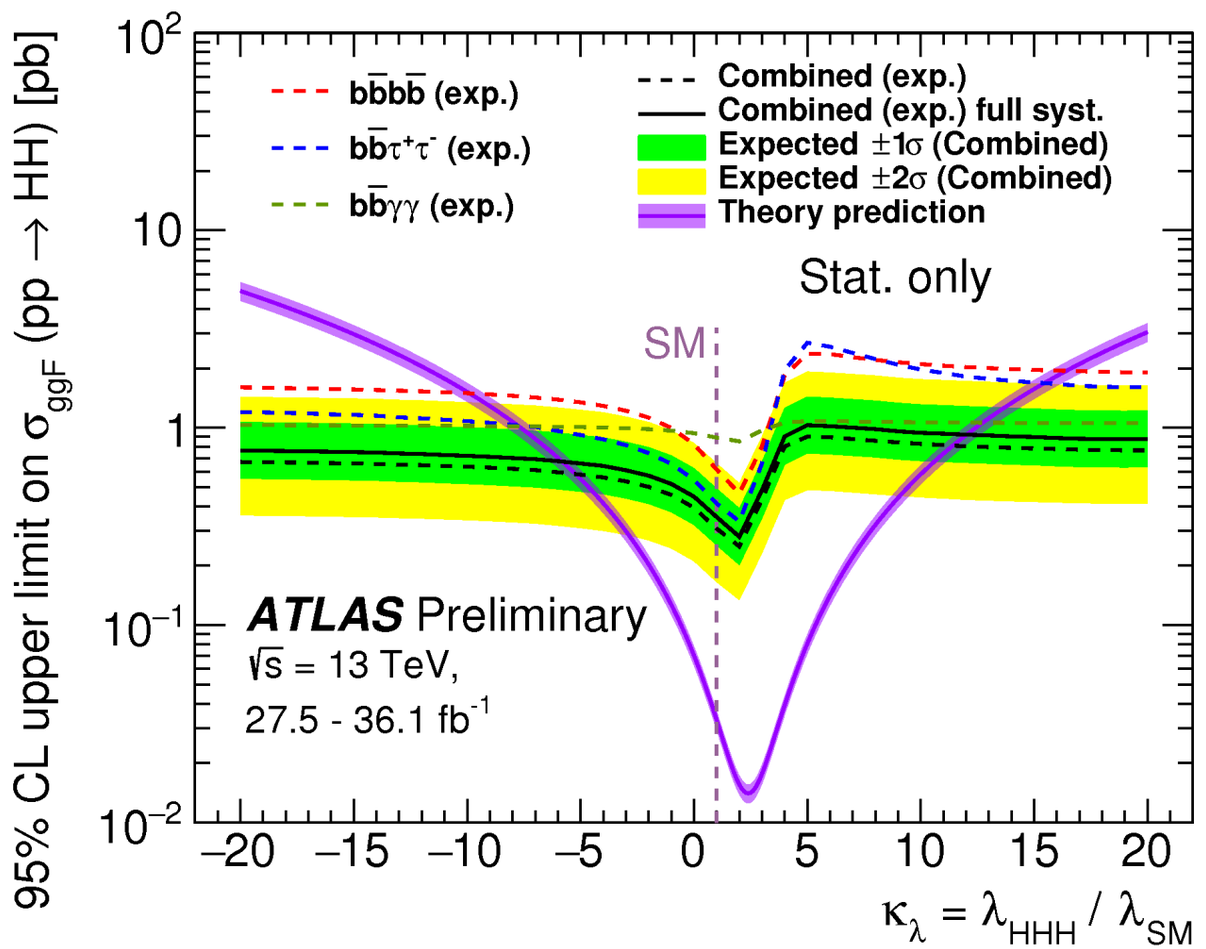




Combination - Di-Higgs Search

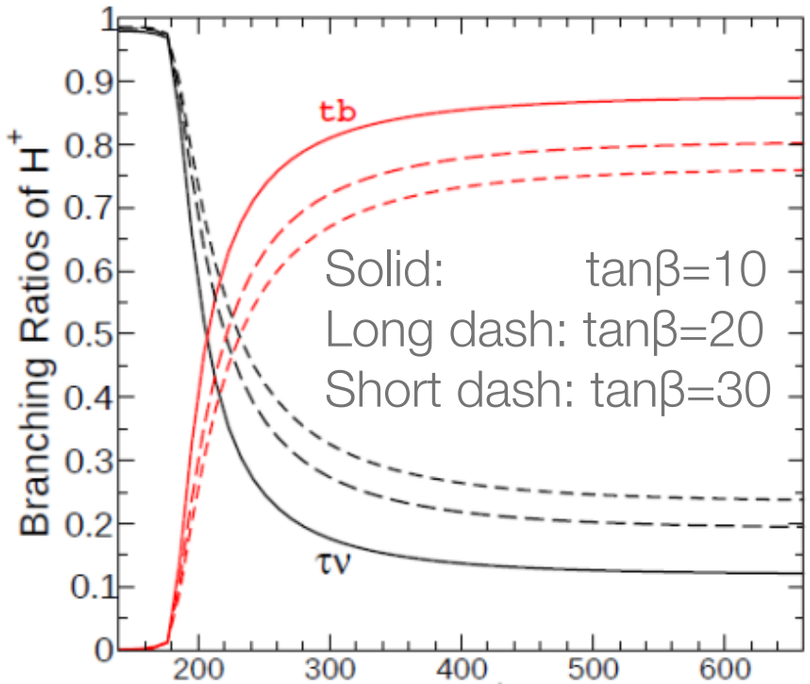
- **Combination** of the bbbb, bbγγ and bbττ channels
  - **Correlation** of experimental and theoretical systematics
- Stringent limits on SM production @ < 6.7SM
  - Limits on non-resonant production
- Exclusion limit on heavy spin-0 particles





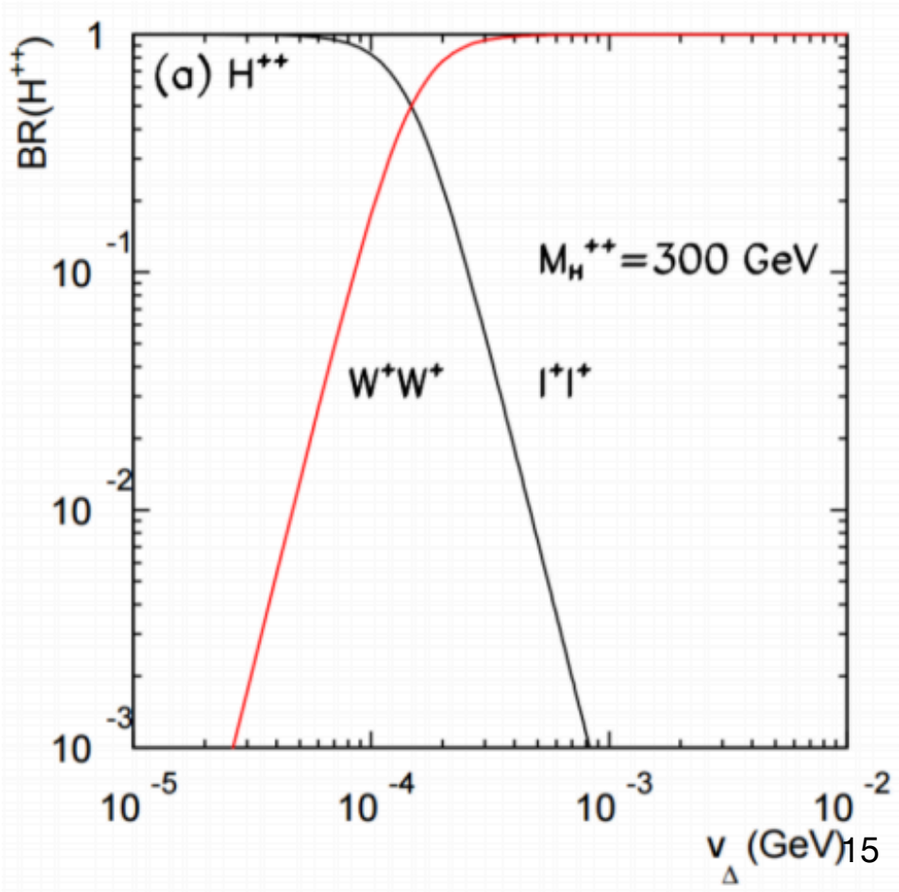
Charged Higgs

- Extension to SM predict **charged scalar** particles
  - Further extensions include **doubly charged Higgs** ($H^{\pm\pm}$)
- In many models such as **MSSM,** $H^{\pm}$ predominantly decays to **tb** or **τν** final states
  - Top associated production at the LHC
- $H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$ probes high triplet vacuum expectation values



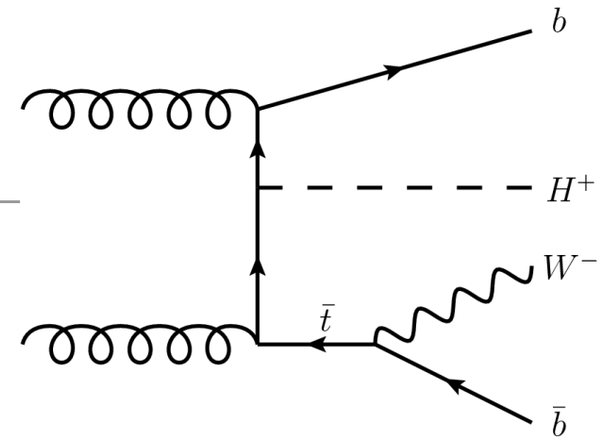
Latest ATLAS results

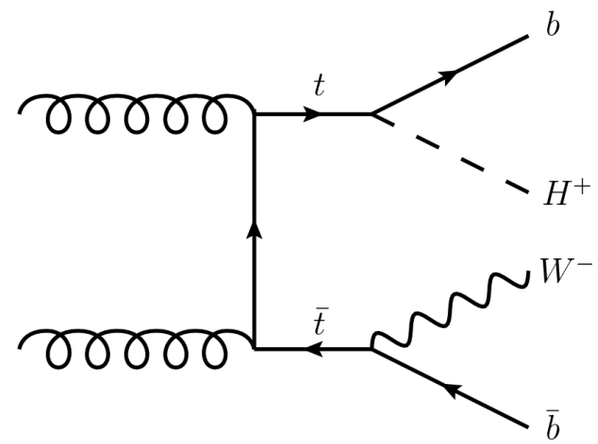
	$H^{\pm} \rightarrow \tau\nu$	HIGG-2016-11	13 TeV, 36/fb
New	$H^{\pm} \rightarrow tb$	HIGG-2017-04	
New	$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$	HIGG-2016-09	

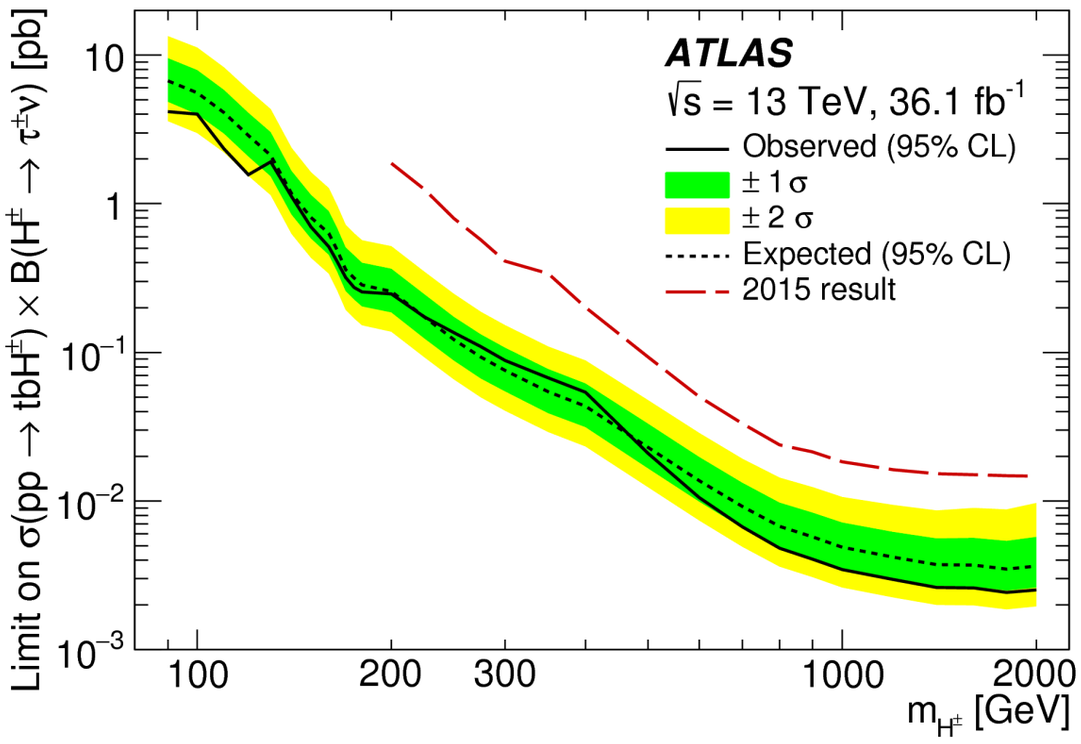


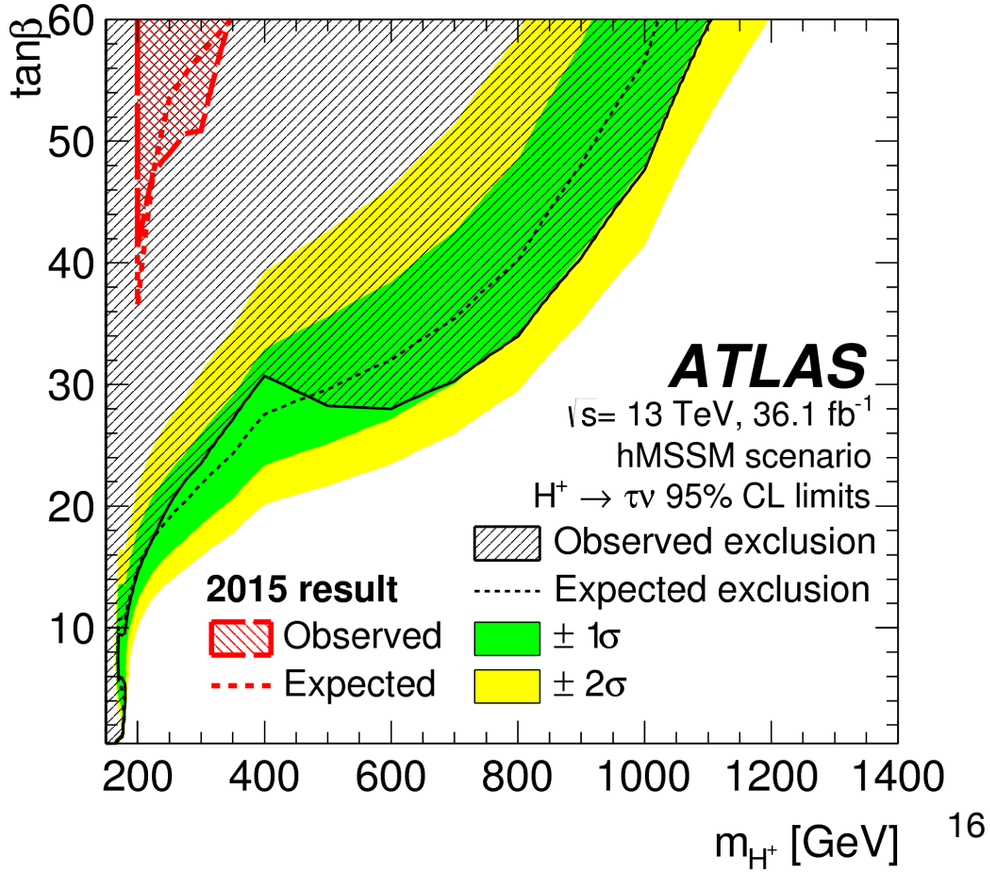
$H^{\pm} \rightarrow \tau\nu$

- Targets top associated production mode
  - **All-hadronic** and **leptonic** W decay
  - Only τ_{Had} considered
- Interference in production at M_{H^+} ~160-180 GeV
  - First time this region is probed!
- BDT observable trained in 5 mass bins with similar kinematic
  - 1- and 3- prong τ polarization used to reduce background
- All tan β values are excluded for $M_{H^+} < 160$ GeV. M_{H^+} ~1.1 TeV is excluded at tanβ = 60 at 95%CLs for hMSSM scenario



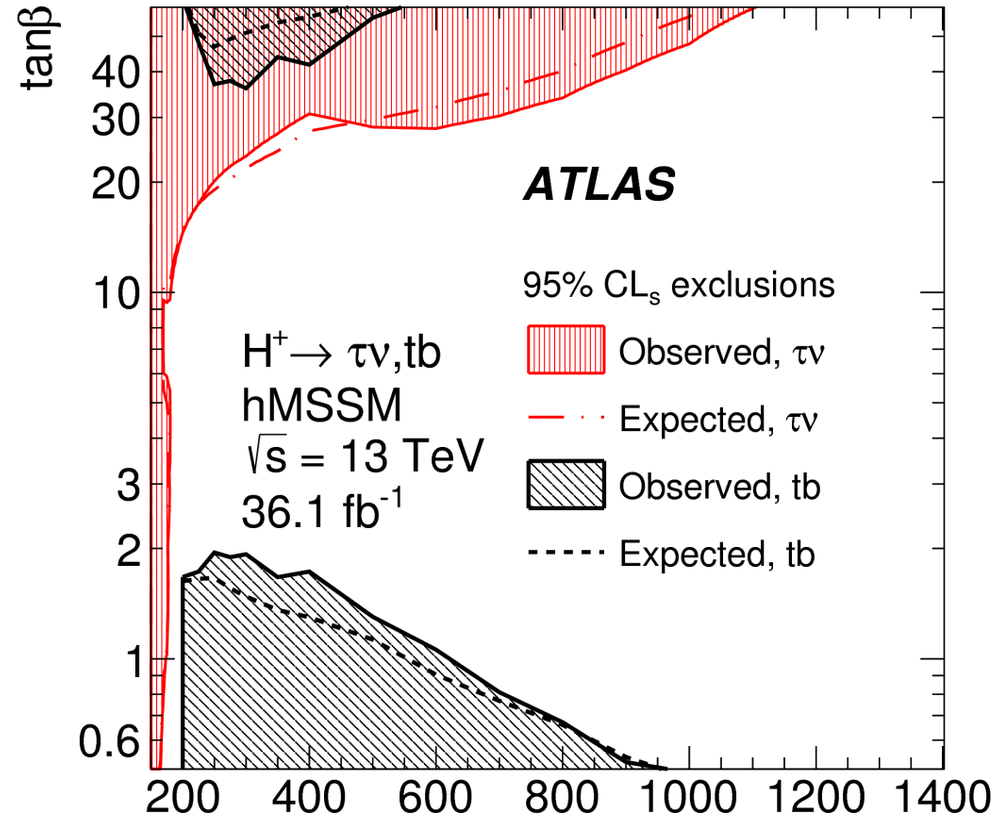


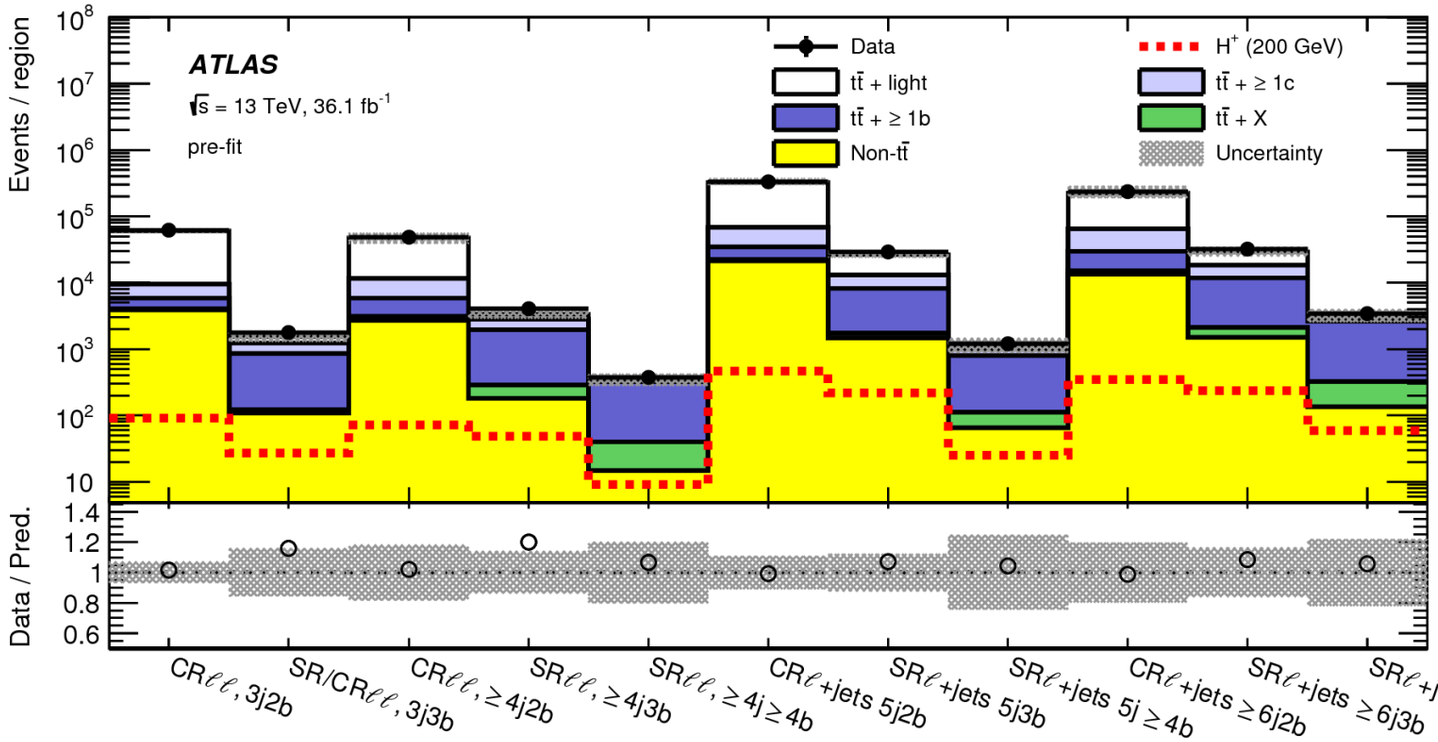


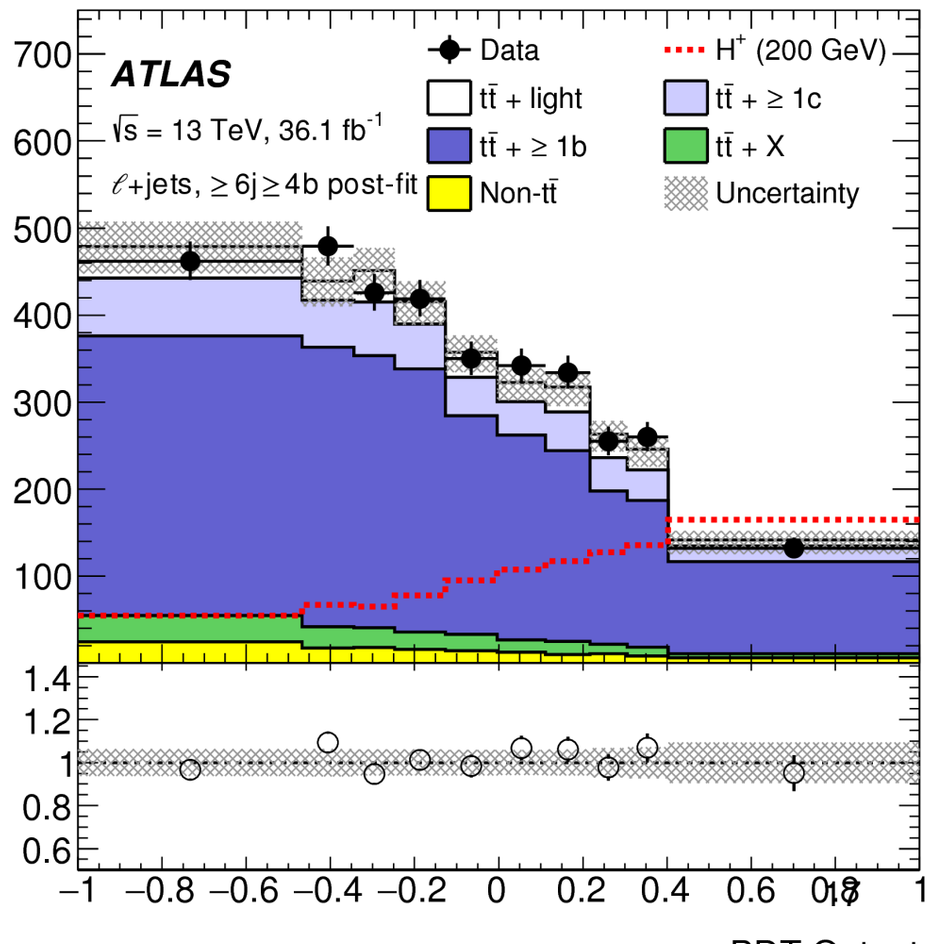


$H^{\pm} \rightarrow tb$

- Complementary to the τν - sensitivity for low tanβ
- Top associated production:
  - All leptonic or semi-lepton decay of Ws
- Multiple categories based on number of jets and b-tagged jets
  - BDT observable in each category
- Exclusion limits at 95% CL for hMSSM scenario:
  - $\tan\beta \in [0.5\text{-}1.95]$ for $M_H \in [200 - 965\ \text{GeV}]$

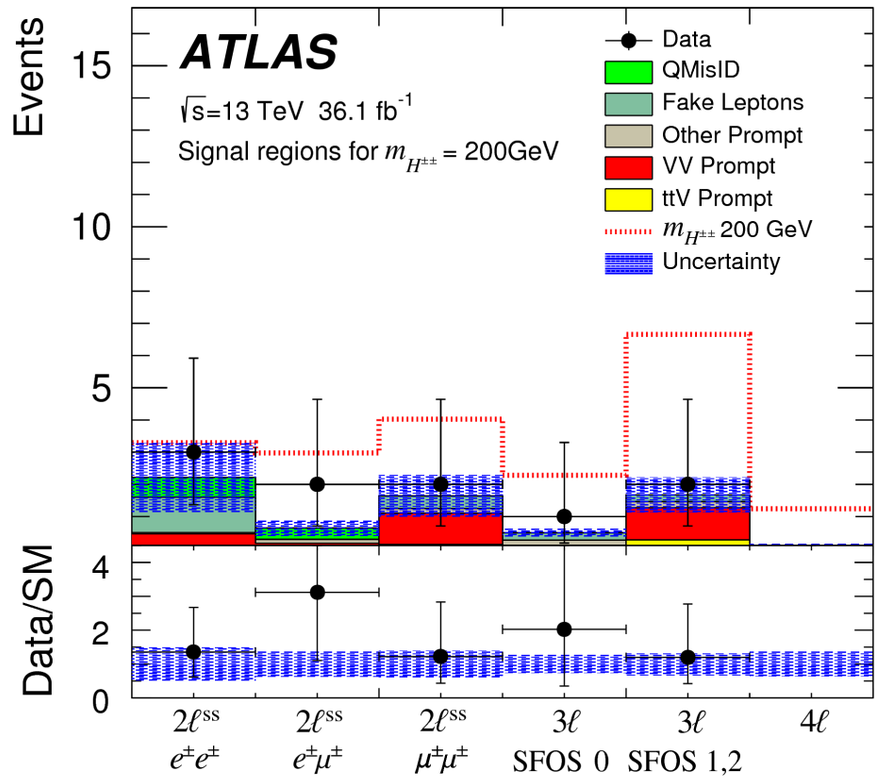


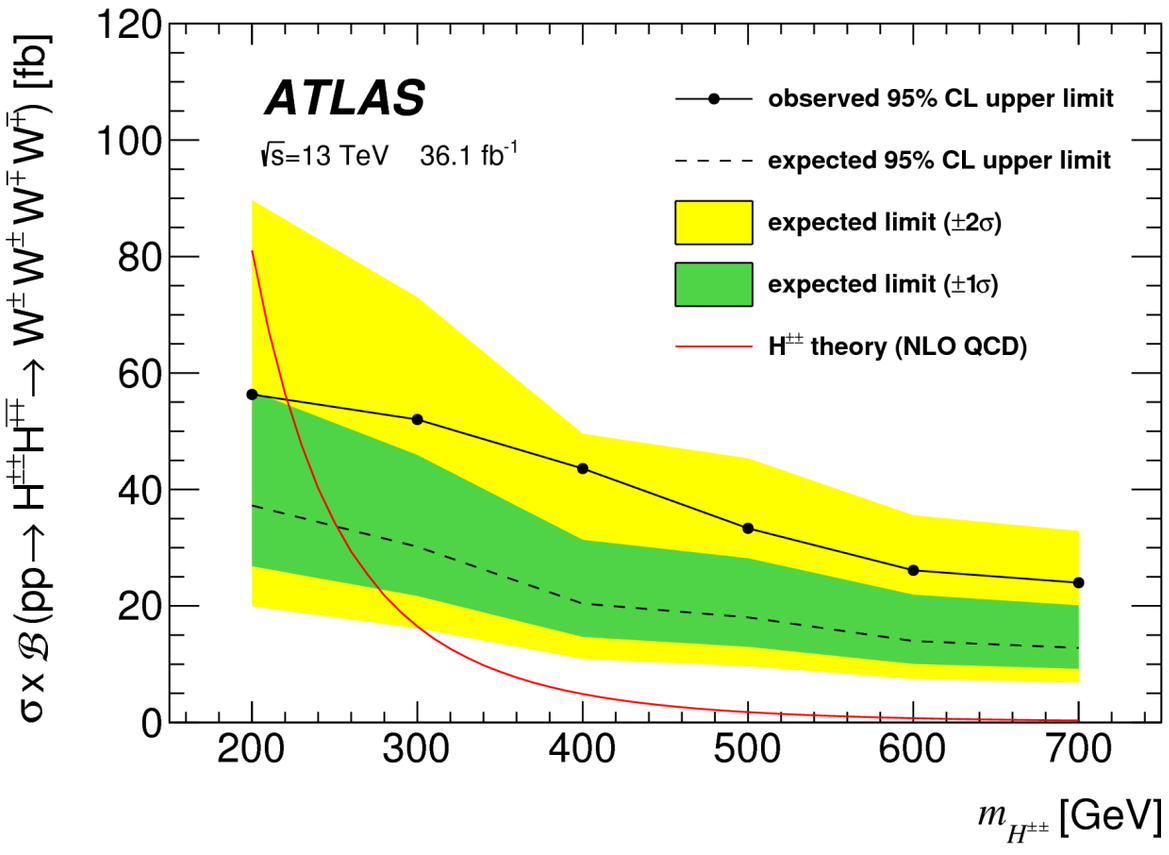


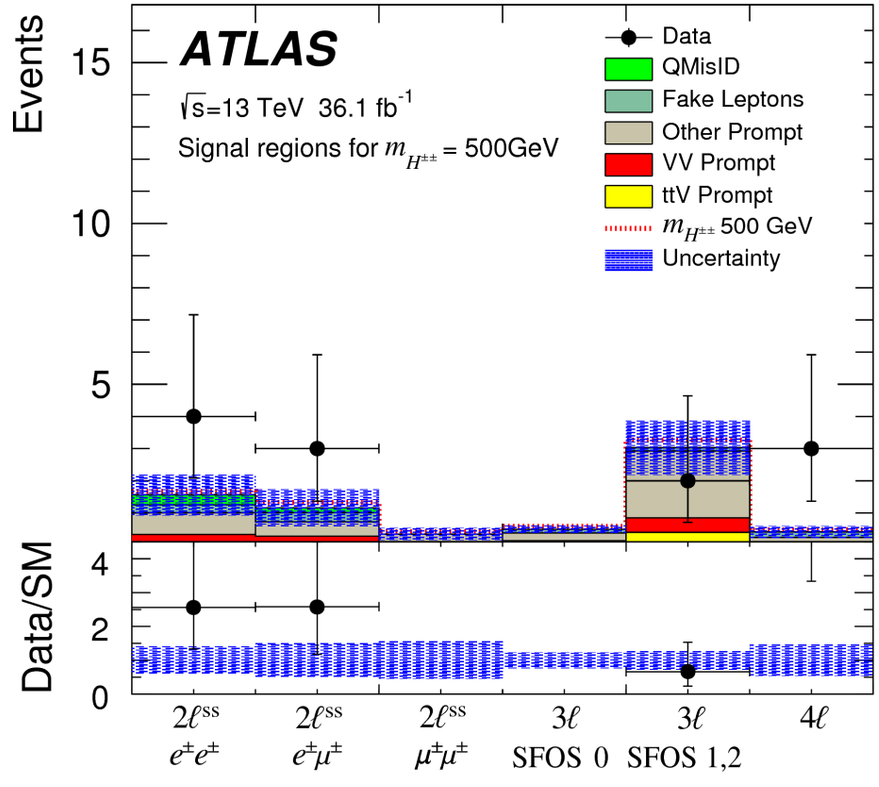


$H^{\pm\pm} \rightarrow W^{\pm}W^{\pm}$

- First search probing in this decay mode
- Pair production - 4 **W's** in the final state
  - **2 same sign-, 3- and 4-lepton + jet final state**
  - b-jet veto to reduce di-top background
- **Cut optimization** on 8 discriminating variables
  - Function of the probed mass
- **Counting** experiment in 6 categories
- $M_{H^{++}} < 220$ GeV **excluded at 95% CL** for triplet vacuum expectation value of 0.1 GeV



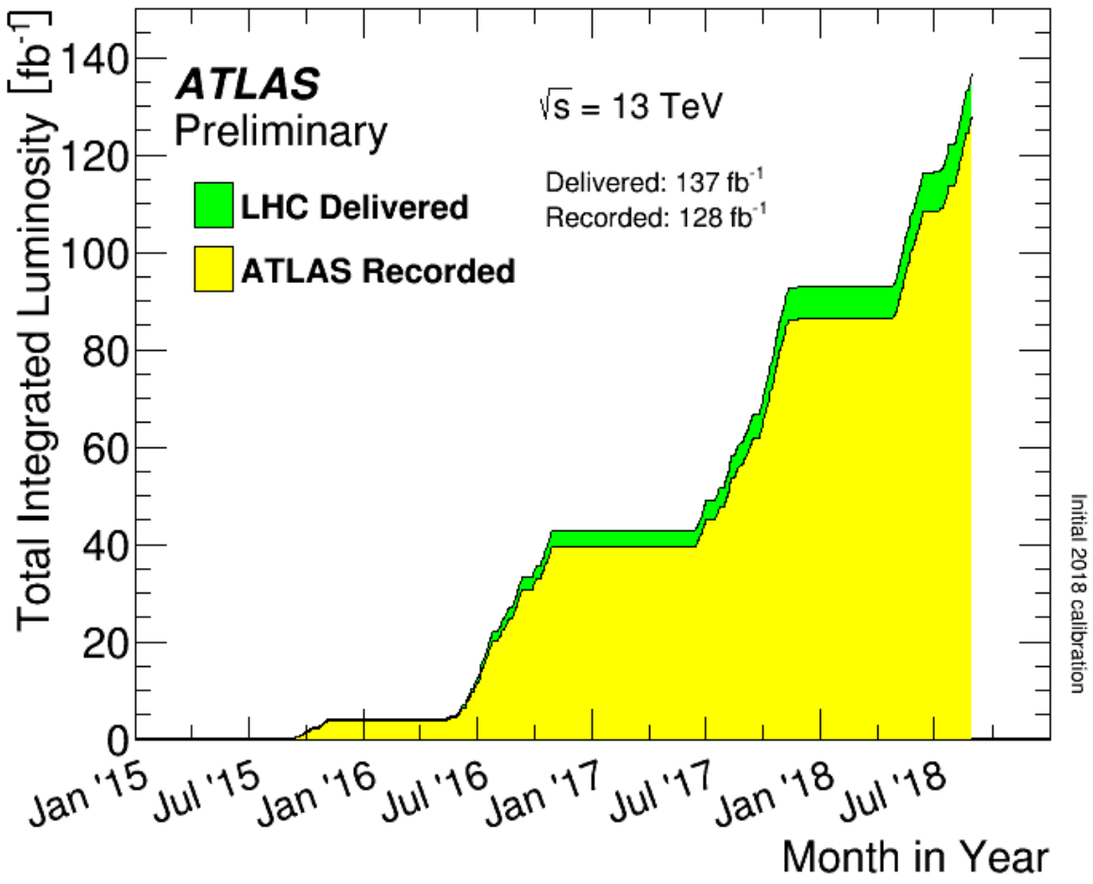




Conclusions

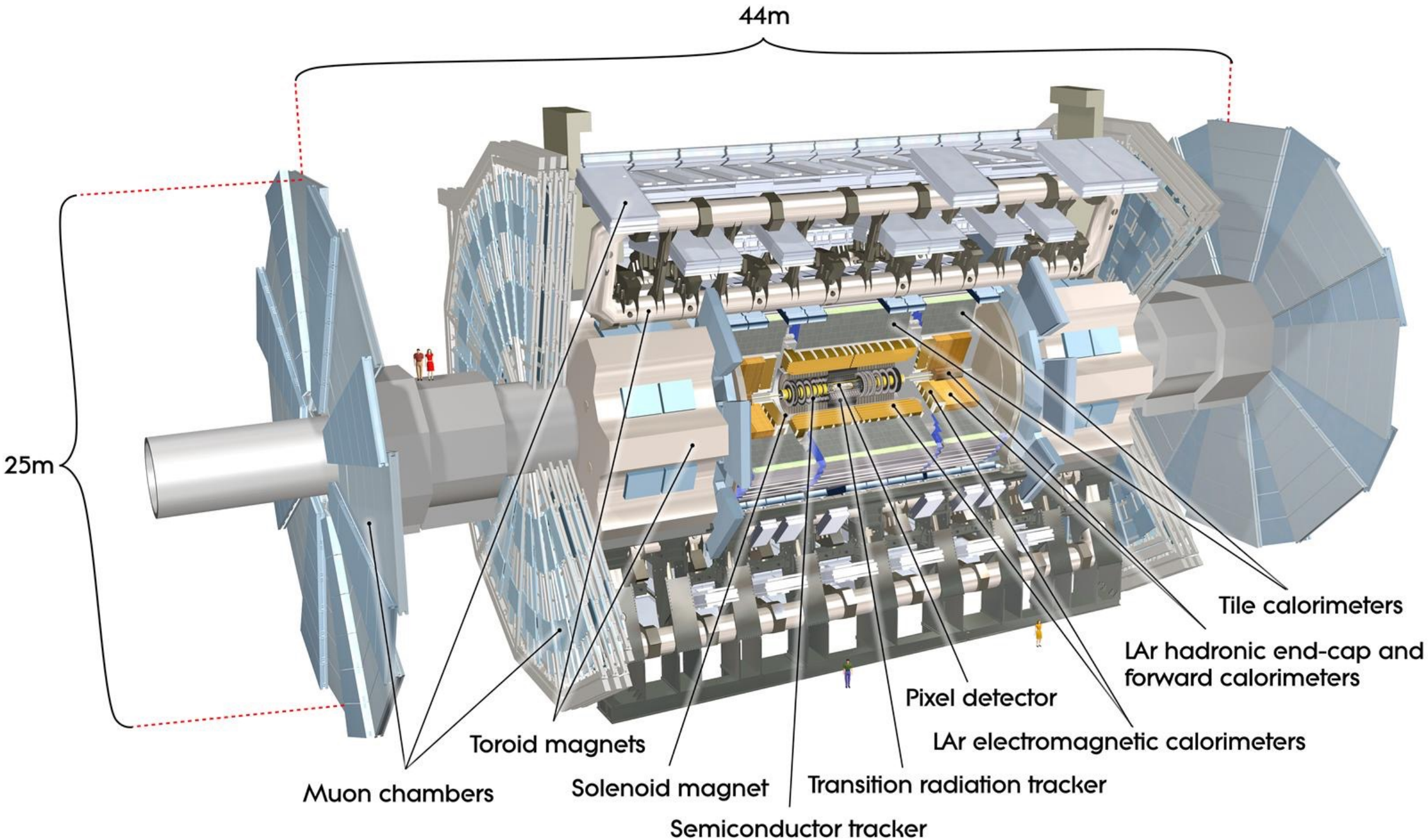
- ATLAS is **highly active** in searching for BSM physics in the Higgs sector
  - A small subset of results shown
  - **Full list of results** at https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- Global summary: **No significant excess** over SM has been found so far
  - **Exclusion limits** set for different BSM scenarios

- Larger dataset being collected ~ 150/fb
  - Gearing up to explore new phase space!

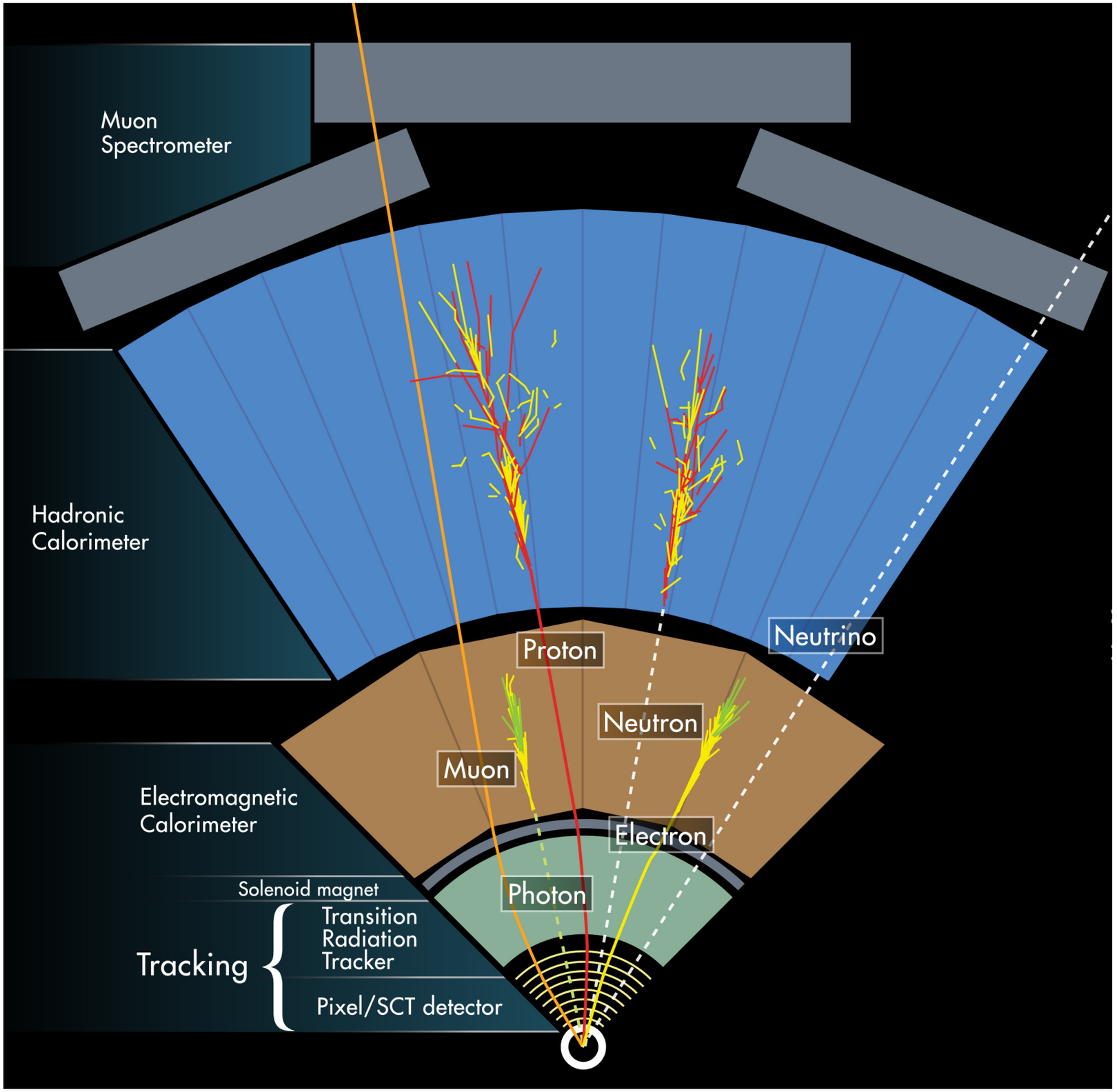


Backup

ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and
forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker

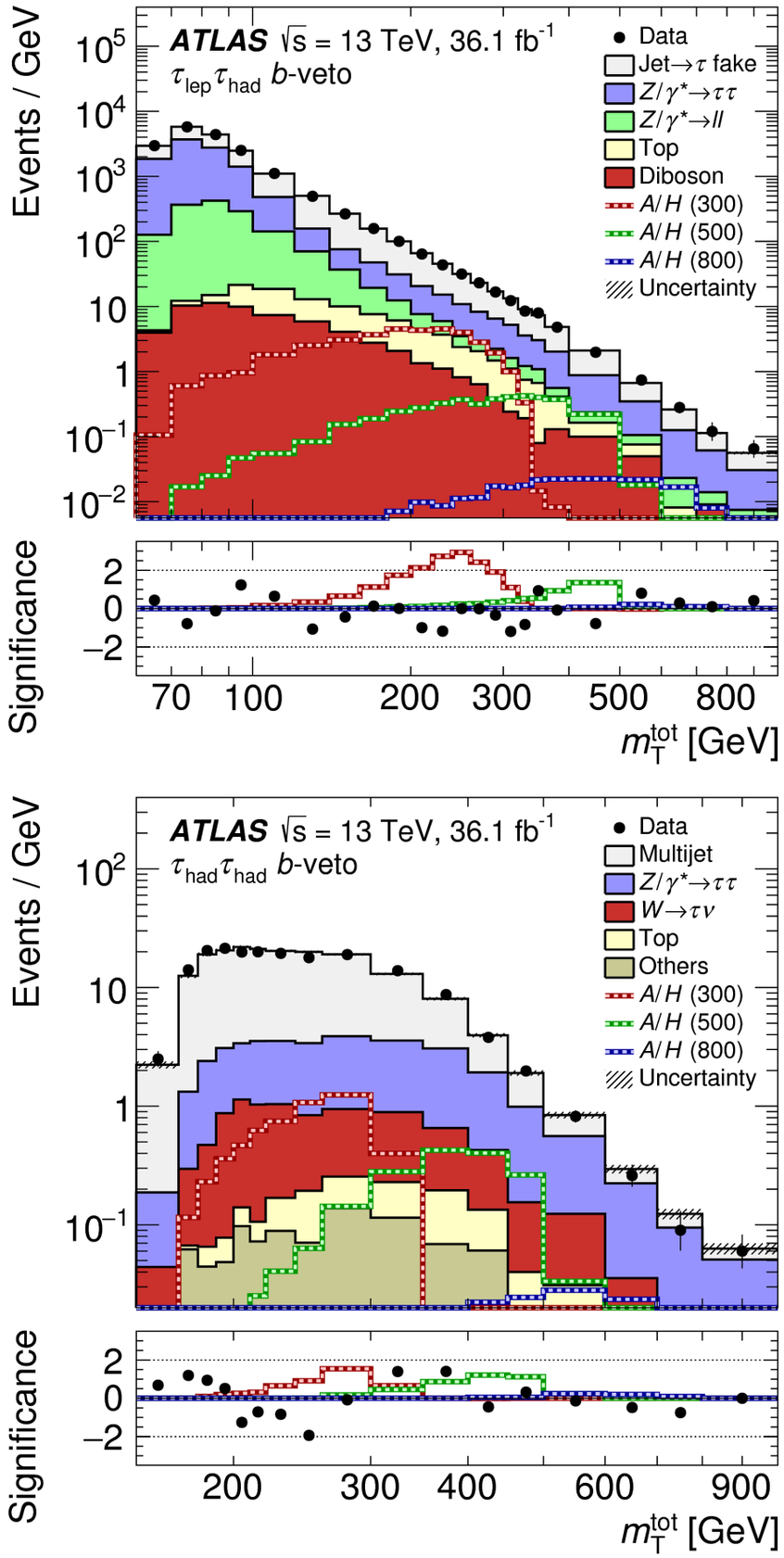
Layer of the detector

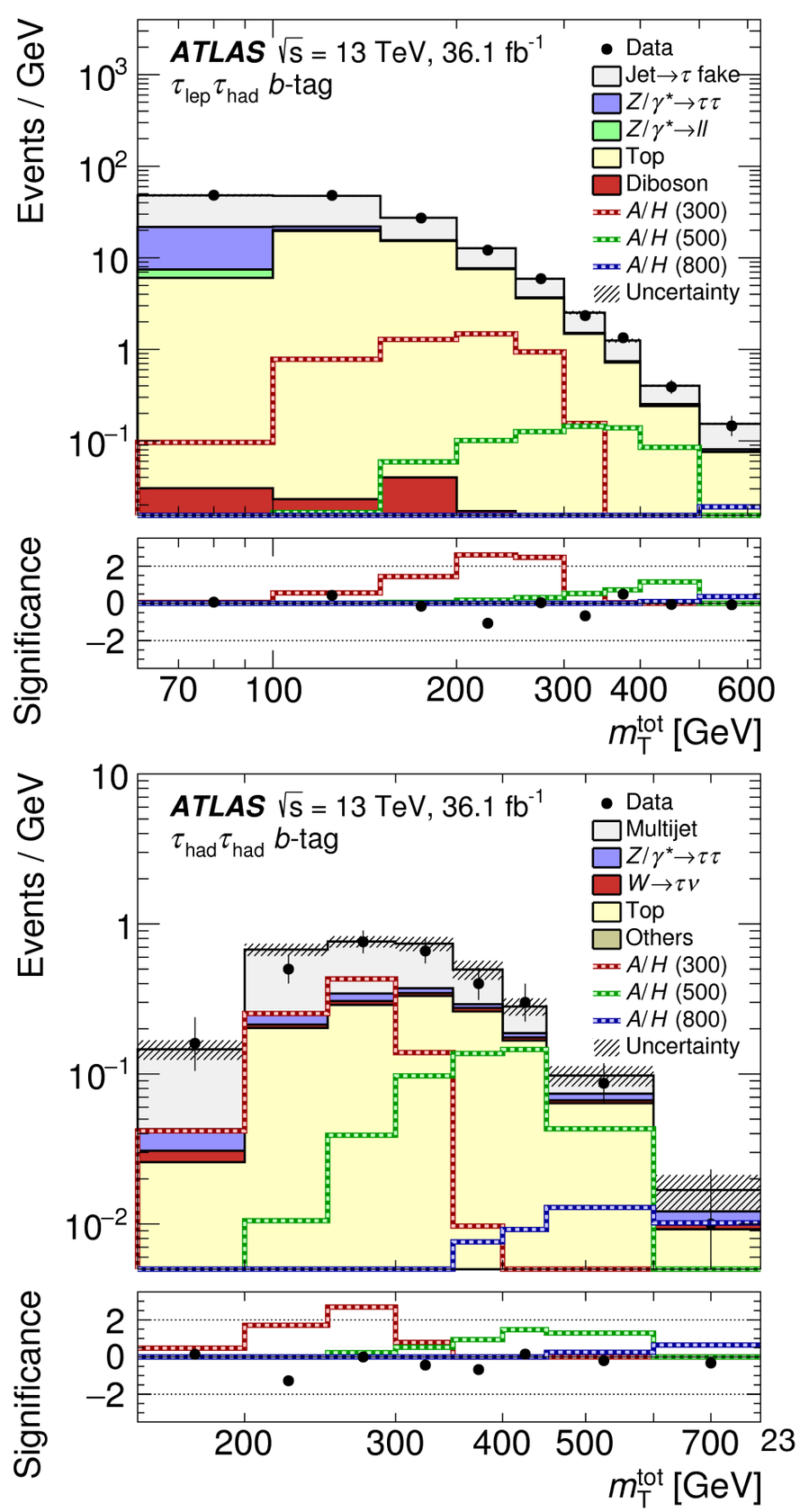


A/H→ττ

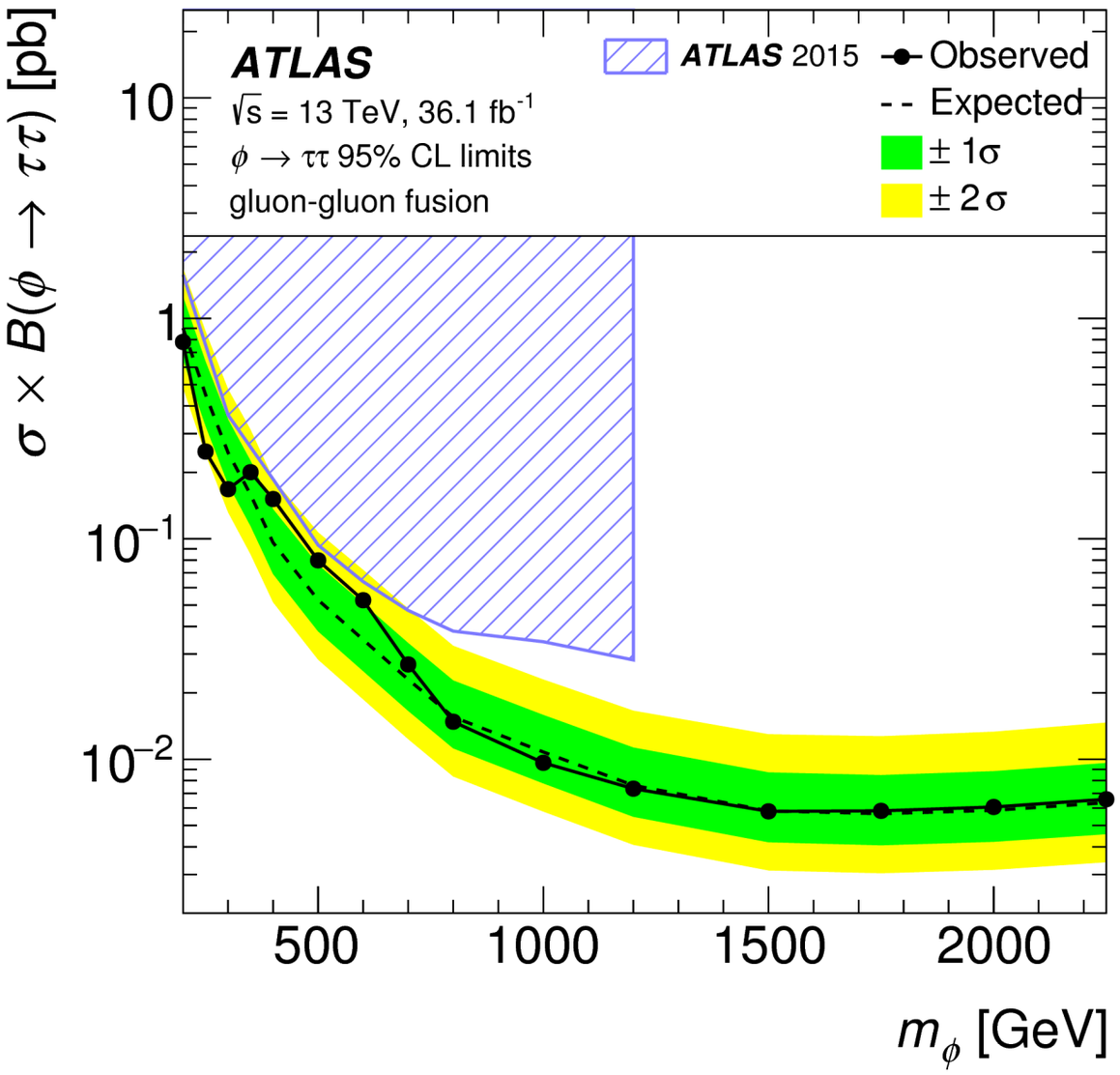
Observable $m_{\mathrm{T}}^{\mathrm{tot}} \equiv \sqrt{(p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{p}_{\mathrm{T}}^{\tau_1} + \mathbf{p}_{\mathrm{T}}^{\tau_2} + \mathbf{E}_{\mathrm{T}}^{\mathrm{miss}})^2}$

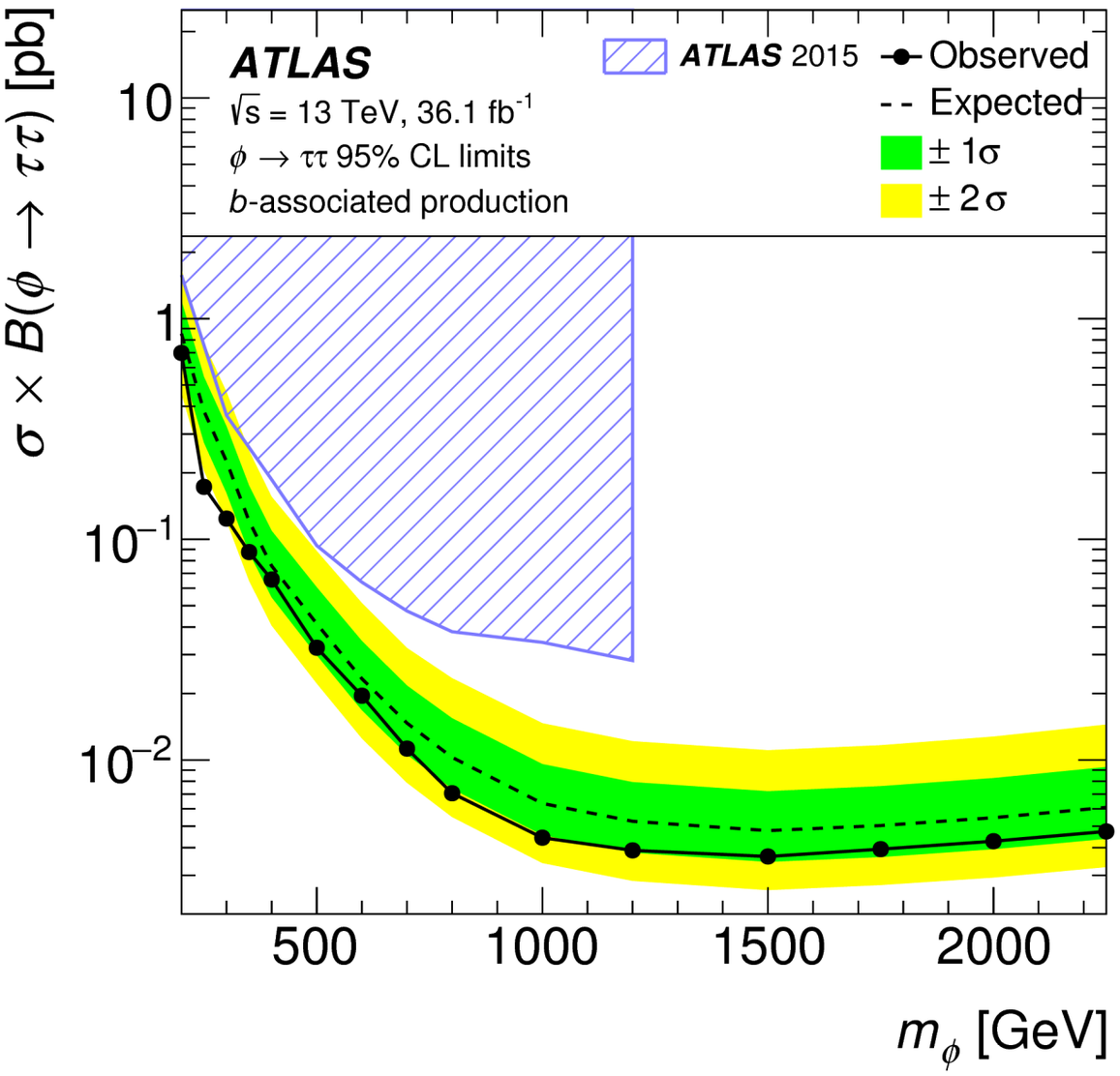
Observed distribution



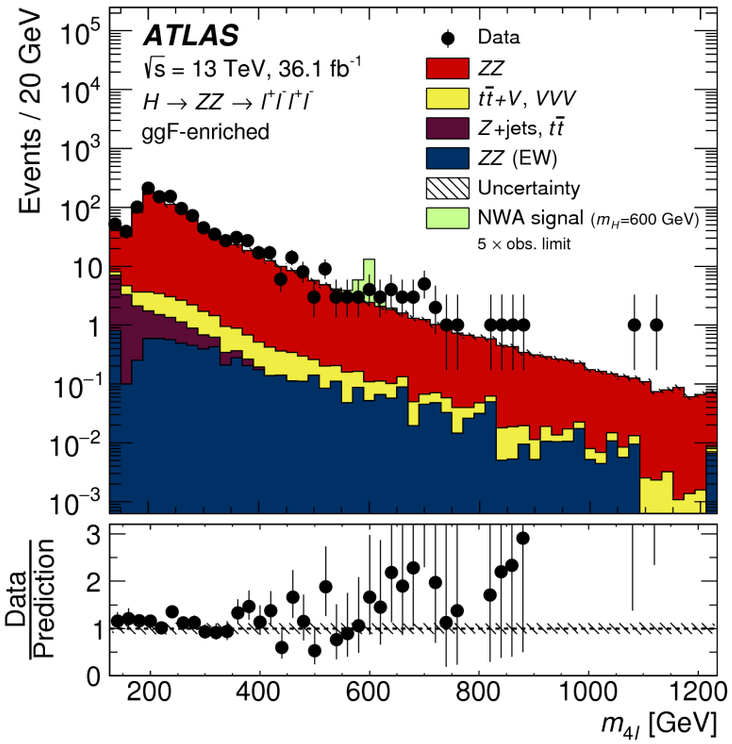


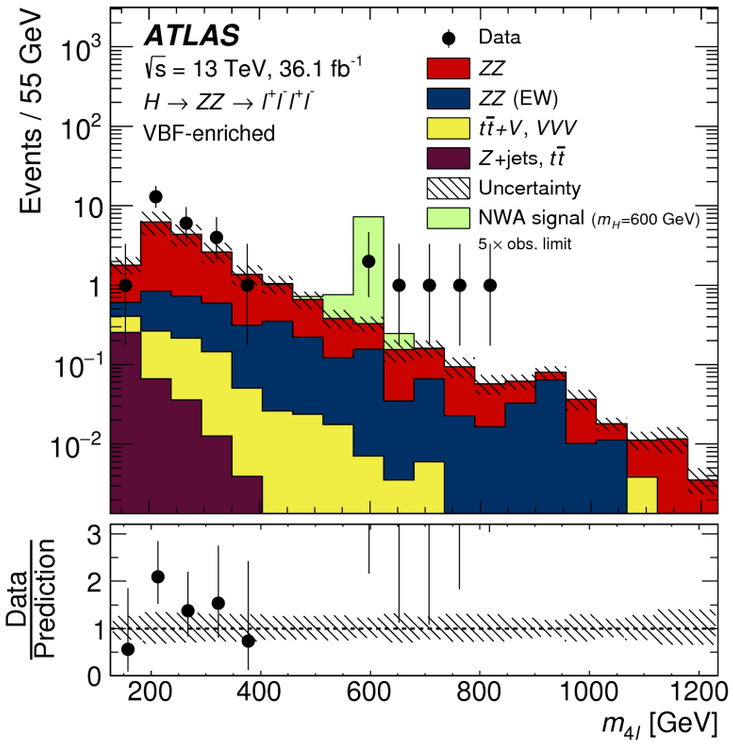
A/H→ττ

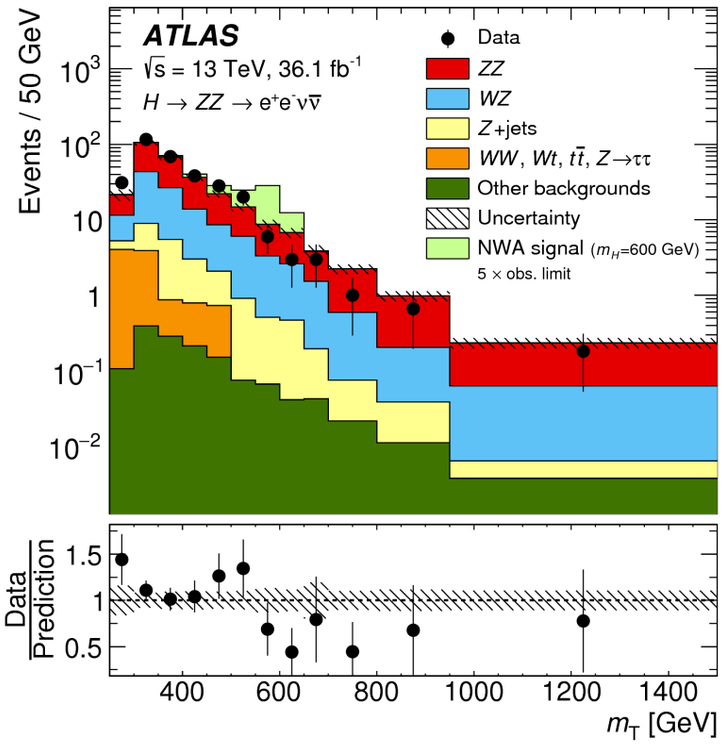

ATLAS
√s = 13 TeV, 36.1 fb-1
φ → ττ 95% CL limits
gluon-gluon fusion
ATLAS 2015
Observed
Expected
± 1σ
± 2σ
σ × B(φ → ττ) [pb]
10
1
10−1
10−2
500
1000
1500
2000
mφ [GeV]

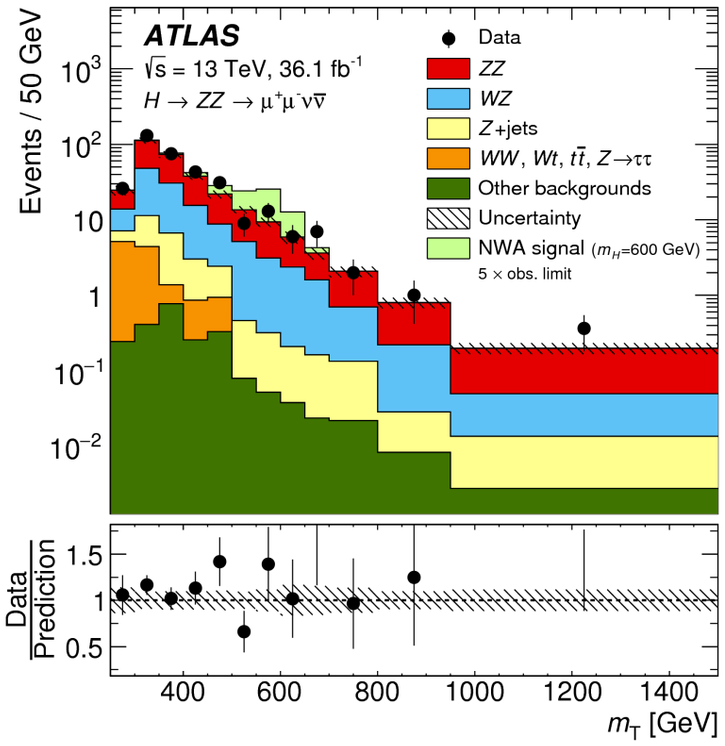

ATLAS
√s = 13 TeV, 36.1 fb-1
φ → ττ 95% CL limits
b-associated production
ATLAS 2015
Observed
Expected
± 1σ
± 2σ
σ × B(φ → ττ) [pb]
10
1
10−1
10−2
500
1000
1500
2000
mφ [GeV]

H→ZZ→4l,2l2ν

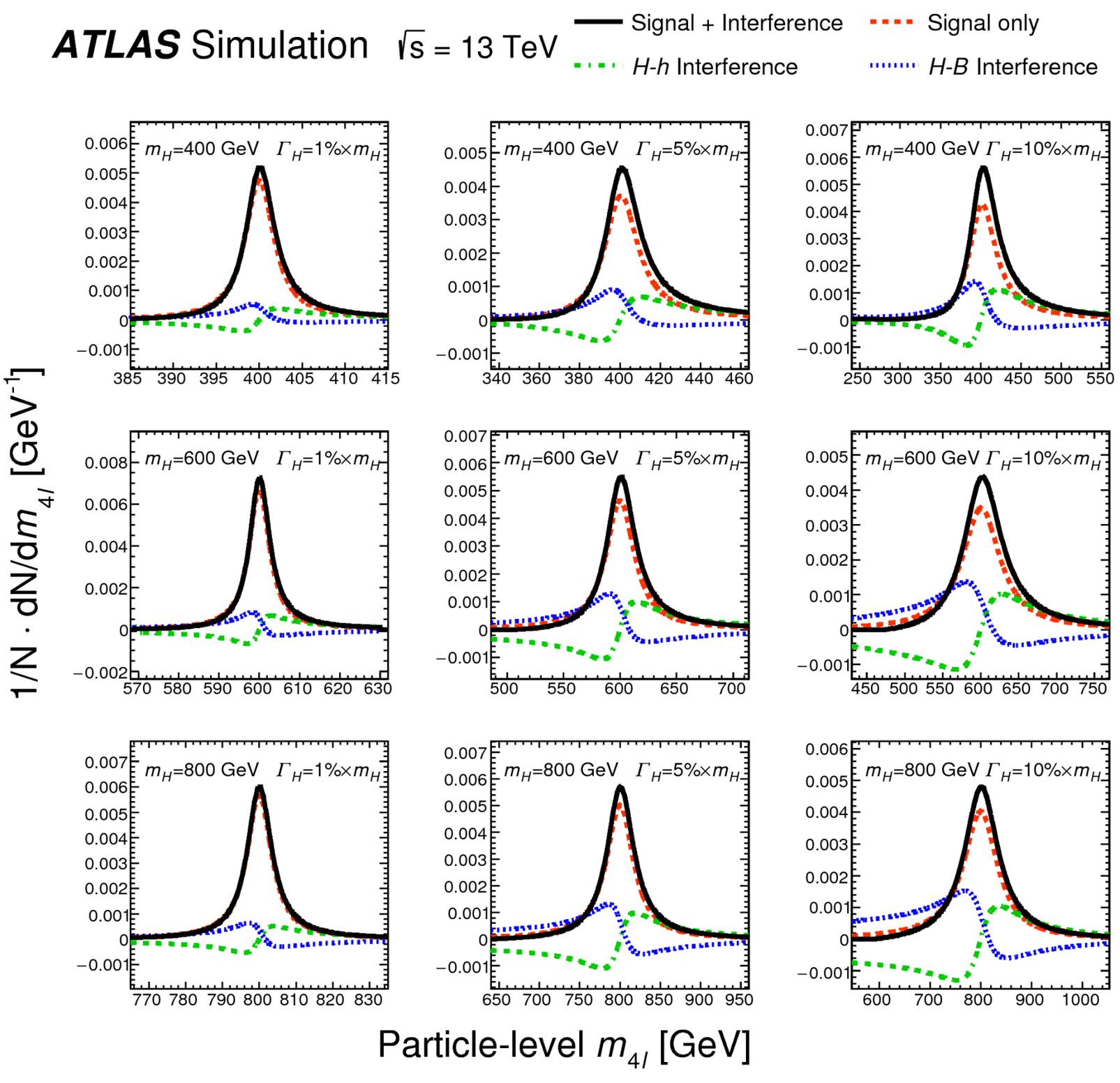

ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → l+l-l+l-
ggF-enriched
Data
ZZ
tt̄+V, VVV
Z+jets, tt̄
ZZ (EW)
Uncertainty
NWA signal (mH=600 GeV)
5 × obs. limit
Events / 20 GeV
Data / Prediction
m4l [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → l+l-l+l-
VBF-enriched
Data
ZZ
ZZ (EW)
tt̄+V, VVV
Z+jets, tt̄
Uncertainty
NWA signal (mH=600 GeV)
5 × obs. limit
Events / 55 GeV
Data / Prediction
m4l [GeV]

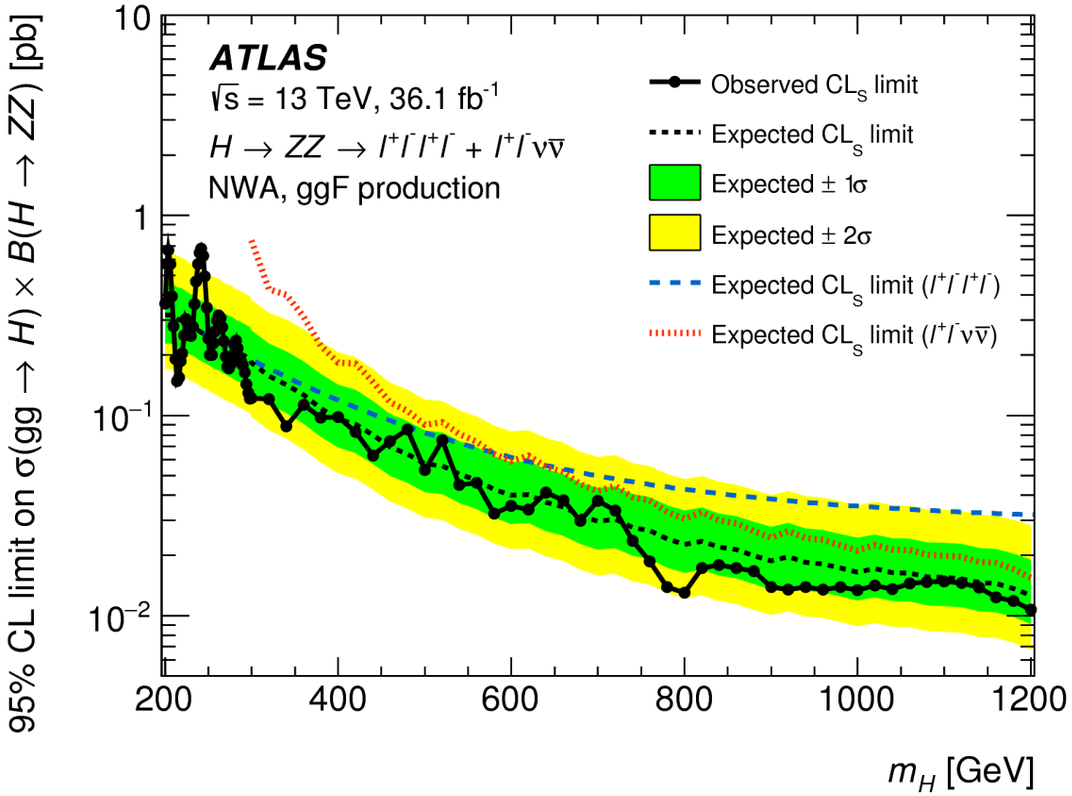

ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → e+e-νν̄
Data
ZZ
WZ
Z+jets
WW, Wt, tt̄, Z→ττ
Other backgrounds
Uncertainty
NWA signal (mH=600 GeV)
5 × obs. limit
Events / 50 GeV
Data / Prediction
mT [GeV]

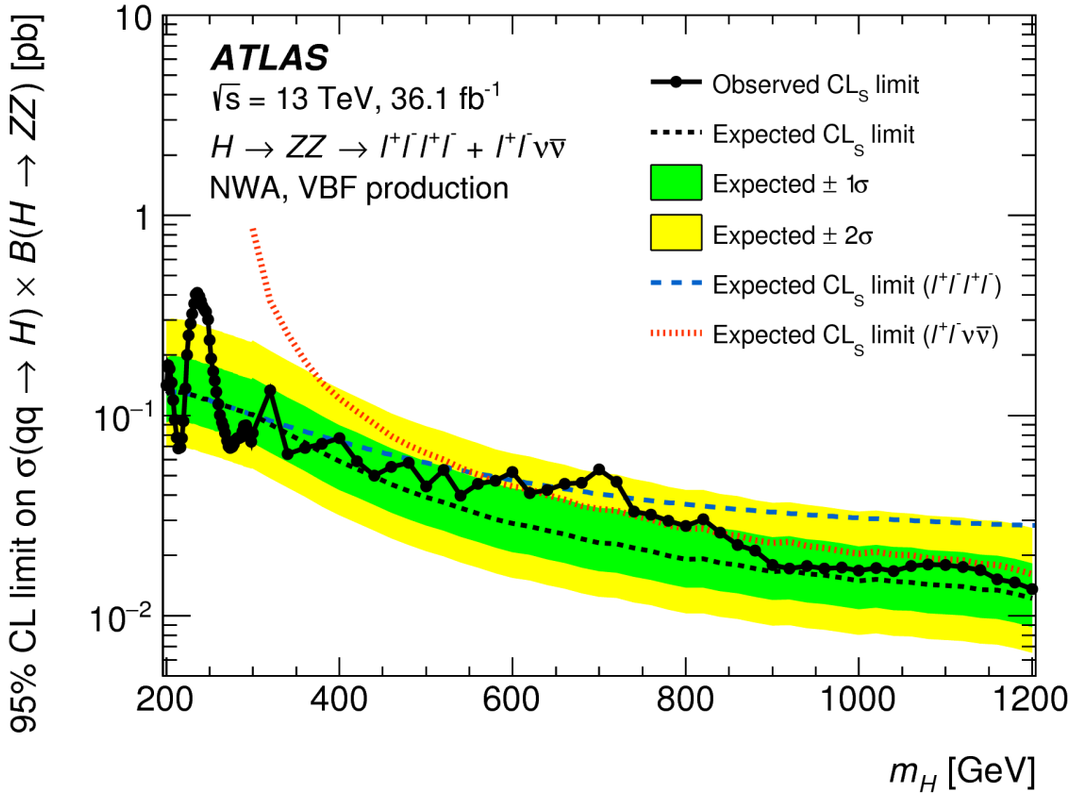

ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → μ+μ-νν̄
Data
ZZ
WZ
Z+jets
WW, Wt, tt̄, Z→ττ
Other backgrounds
Uncertainty
NWA signal (mH=600 GeV)
5 × obs. limit
Events / 50 GeV
Data / Prediction
mT [GeV]

H→ZZ→4l,2l2ν

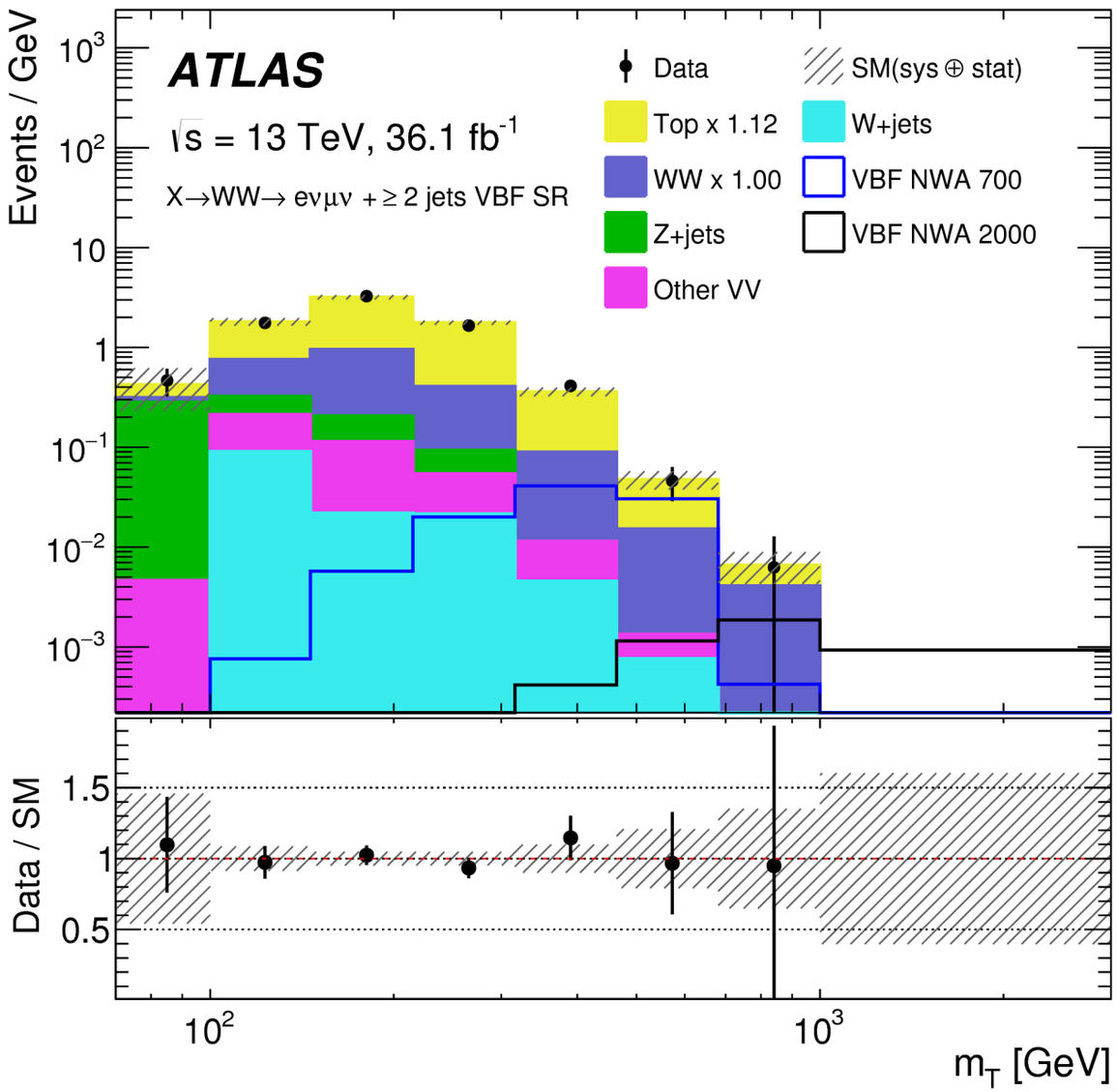

ATLAS Simulation √s = 13 TeV
Signal + Interference
Signal only
H-h Interference
H-B Interference
m_H=400 GeV Γ_H=1%×m_H
m_H=400 GeV Γ_H=5%×m_H
m_H=400 GeV Γ_H=10%×m_H
m_H=600 GeV Γ_H=1%×m_H
m_H=600 GeV Γ_H=5%×m_H
m_H=600 GeV Γ_H=10%×m_H
m_H=800 GeV Γ_H=1%×m_H
m_H=800 GeV Γ_H=5%×m_H
m_H=800 GeV Γ_H=10%×m_H
1/N · dN/dm_4l [GeV^-1]
Particle-level m_4l [GeV]

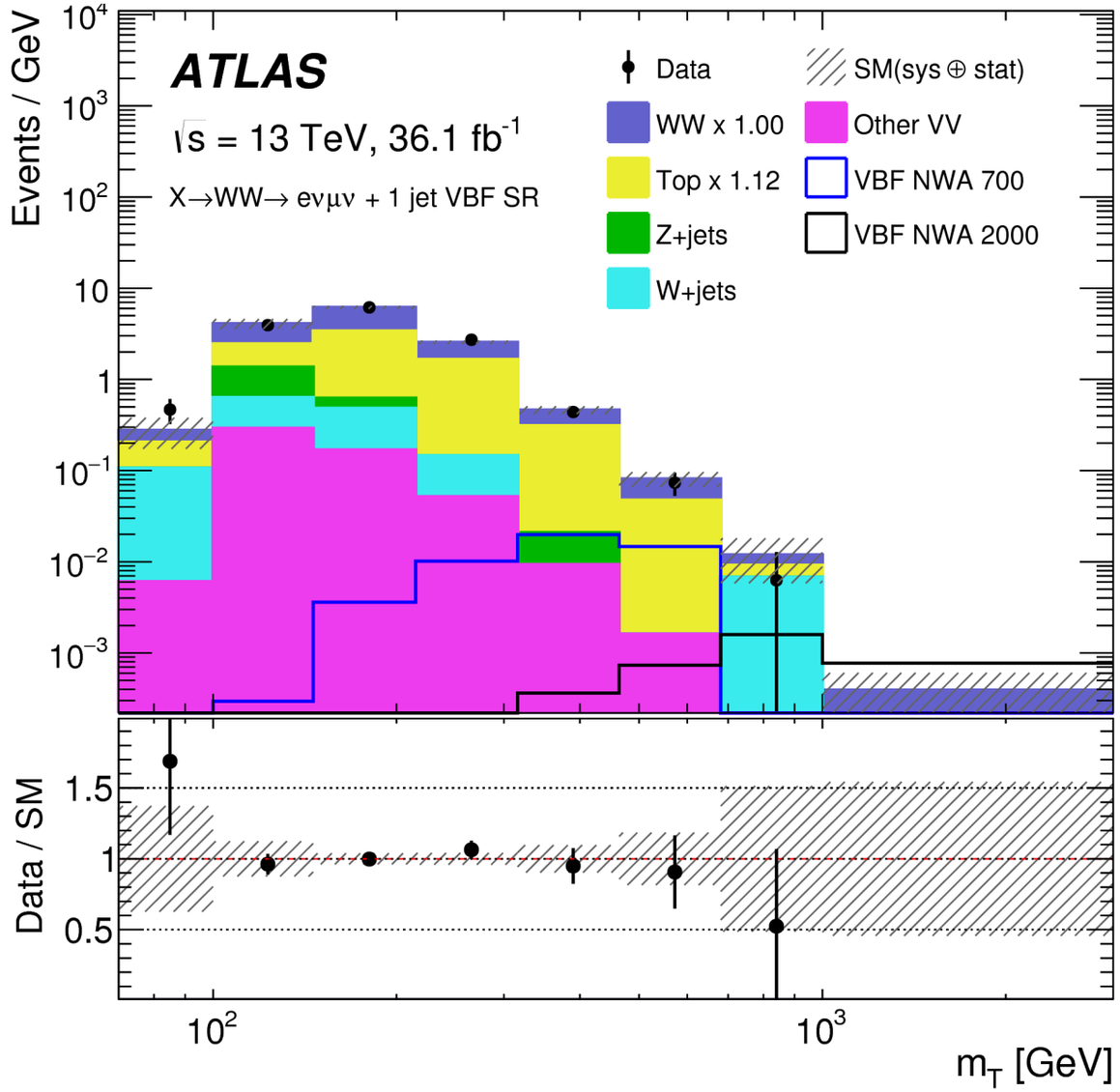
H→ZZ→4l,2l2ν


ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → l+l-l+l- + l+l-νν̄
NWA, ggF production
Observed CLs limit
Expected CLs limit
Expected ± 1σ
Expected ± 2σ
Expected CLs limit (l+l-l+l-)
Expected CLs limit (l+l-νν̄)
95% CL limit on σ(gg → H) × B(H → ZZ) [pb]
mH [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
H → ZZ → l+l-l+l- + l+l-νν̄
NWA, VBF production
Observed CLs limit
Expected CLs limit
Expected ± 1σ
Expected ± 2σ
Expected CLs limit (l+l-l+l-)
Expected CLs limit (l+l-νν̄)
95% CL limit on σ(qq → H) × B(H → ZZ) [pb]
mH [GeV]

H→WW→eνμν





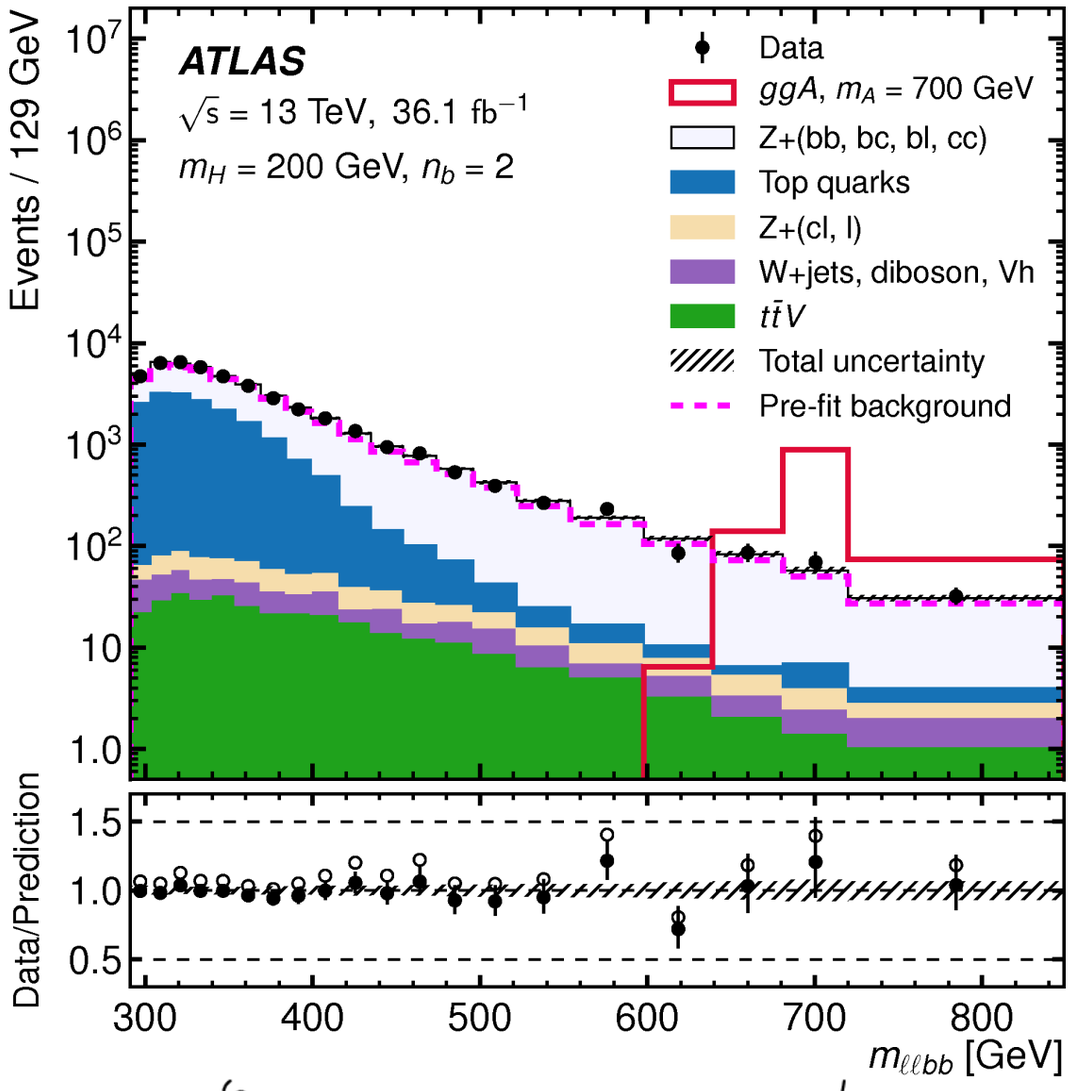
$$m_{\mathrm{T}} = \sqrt{\left(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left|\mathbf{p}_{\mathrm{T}}^{\ell\ell} + \boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2},$$

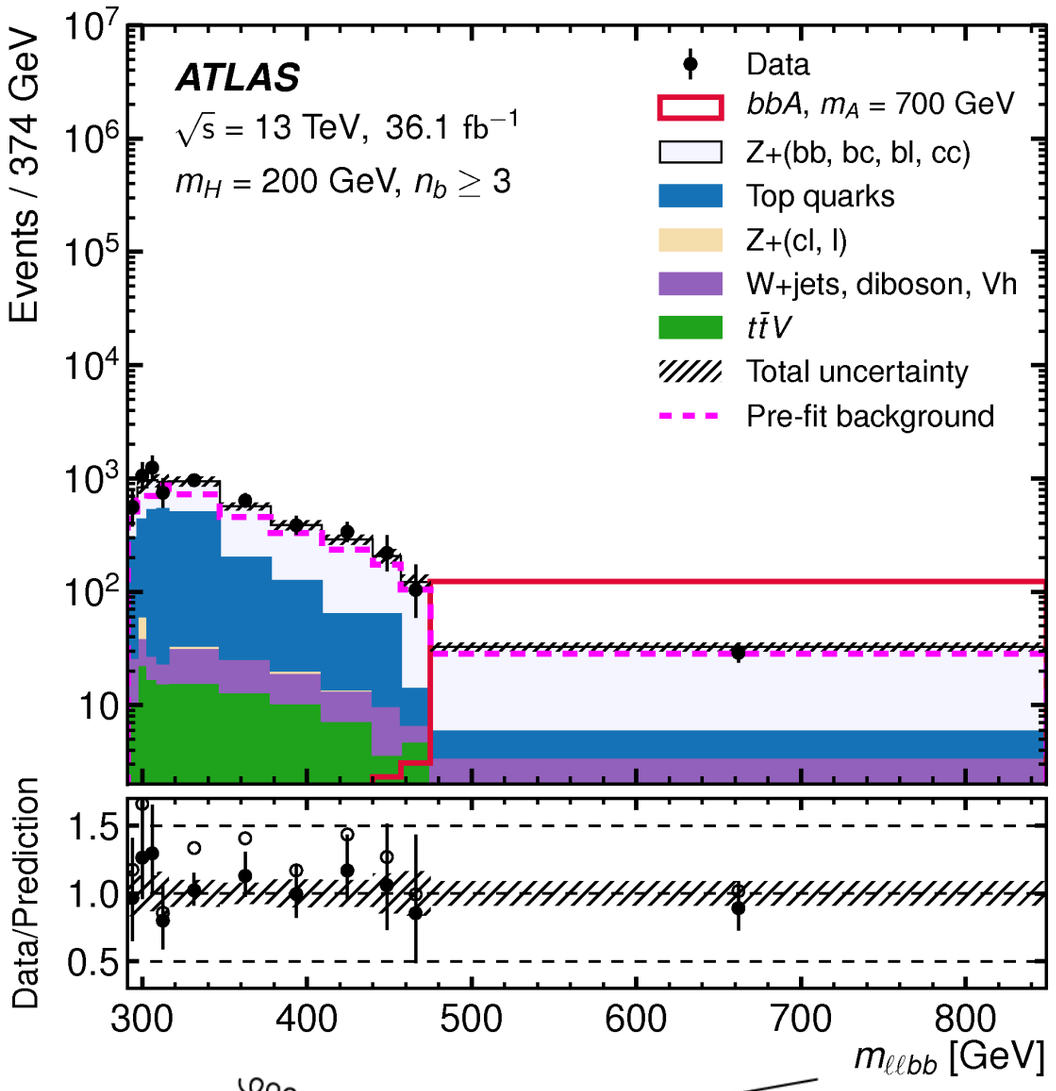
where

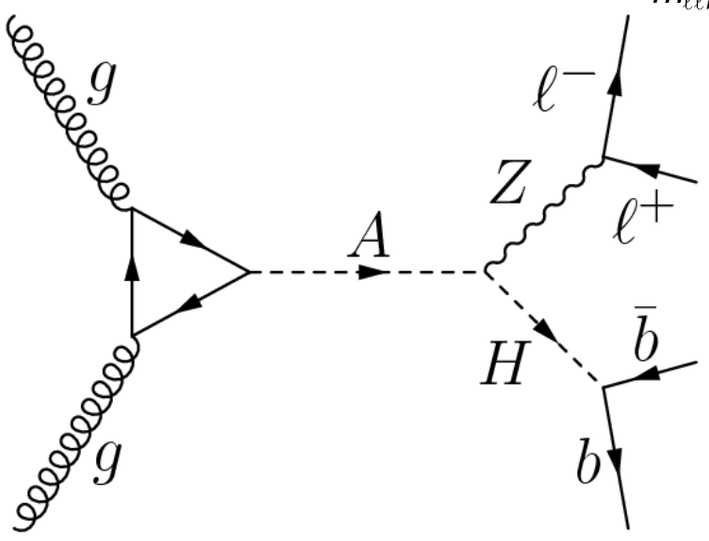
$$E_{\mathrm{T}}^{\ell\ell} = \sqrt{\left|\mathbf{p}_{\mathrm{T}}^{\ell\ell}\right|^2 + m_{\ell\ell}^2},$$

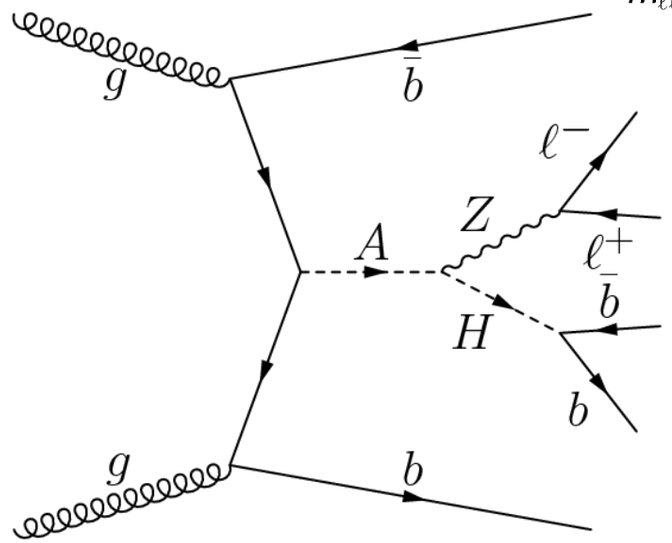
and $\mathbf{p}_{\mathrm{T}}^{\ell\ell}$ is the transverse momentum vector of the leading and subleading leptons.

A→ZH→llbb

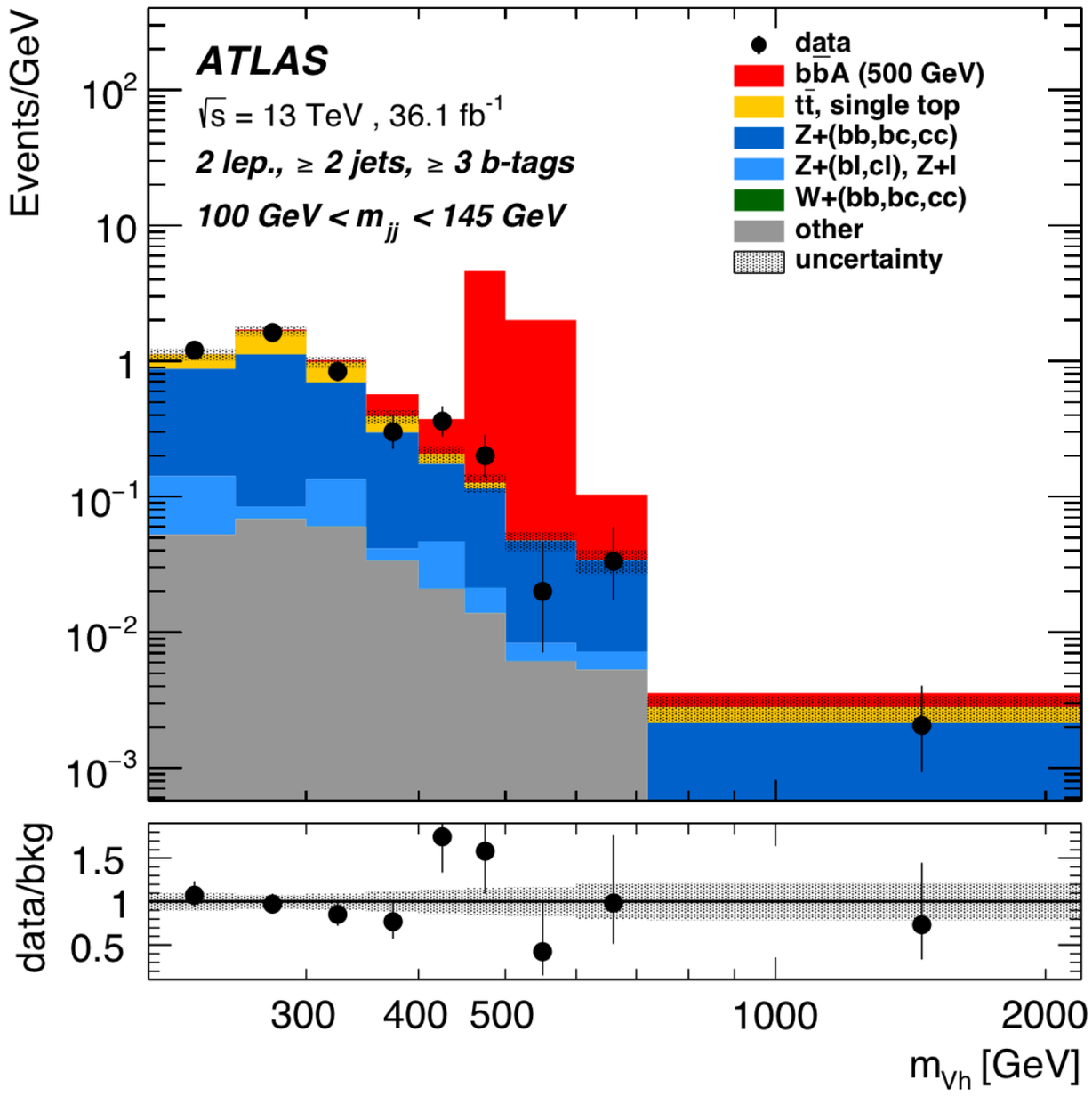

ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
m_H = 200 GeV, n_b = 2
Data
ggA, m_A = 700 GeV
Z+(bb, bc, bl, cc)
Top quarks
Z+(cl, l)
W+jets, diboson, Vh
$t\bar{t}V$
Total uncertainty
Pre-fit background
Events / 129 GeV
Data/Prediction
$m_{\ell\ell bb}$ [GeV]


ATLAS
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
m_H = 200 GeV, $n_b \geq 3$
Data
bbA, m_A = 700 GeV
Z+(bb, bc, bl, cc)
Top quarks
Z+(cl, l)
W+jets, diboson, Vh
$t\bar{t}V$
Total uncertainty
Pre-fit background
Events / 374 GeV
Data/Prediction
$m_{\ell\ell bb}$ [GeV]


g
g
A
Z
H
ℓ^-
ℓ^+
$\bar{b}$
b

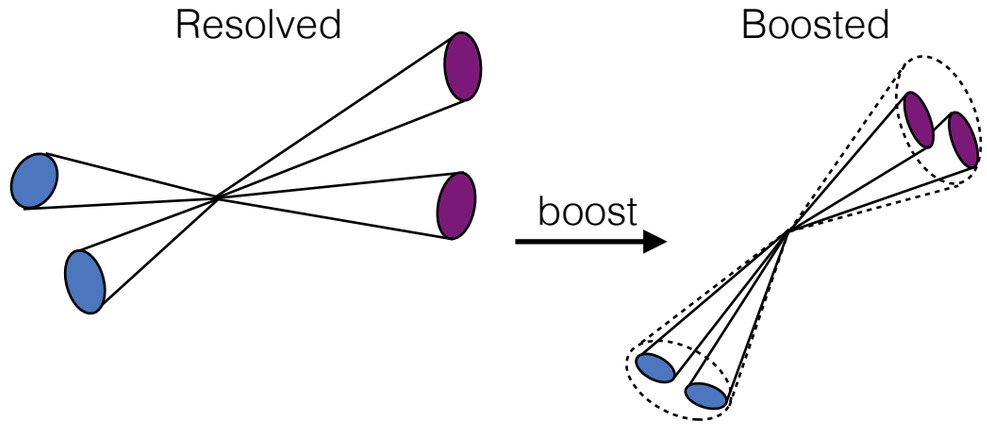

g
g
$\bar{b}$
A
Z
H
ℓ^-
ℓ^+
$\bar{b}$
b
b

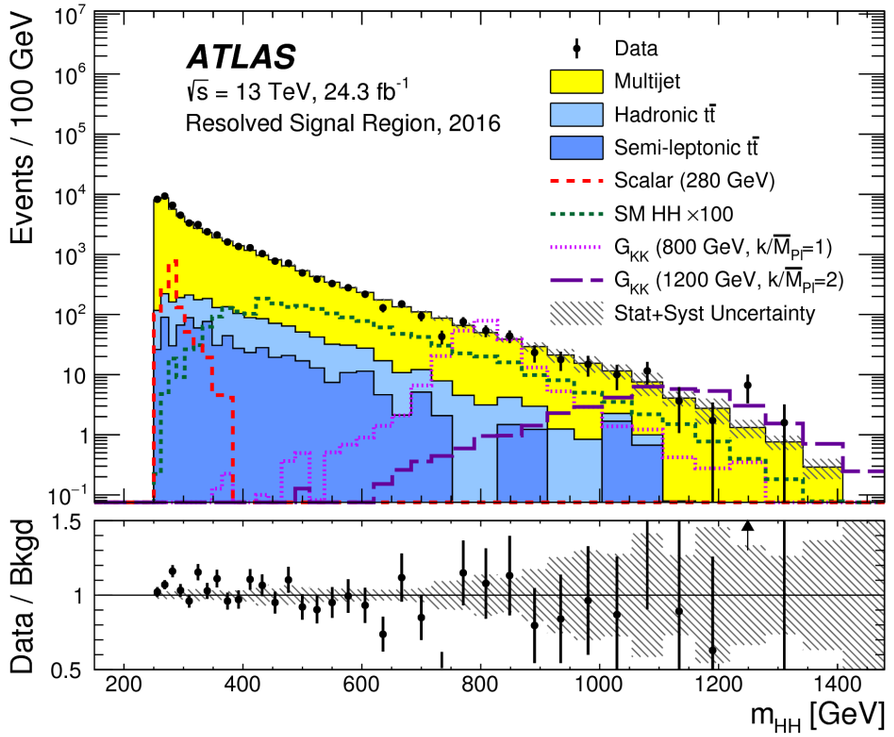
A→Vh→ll'bb

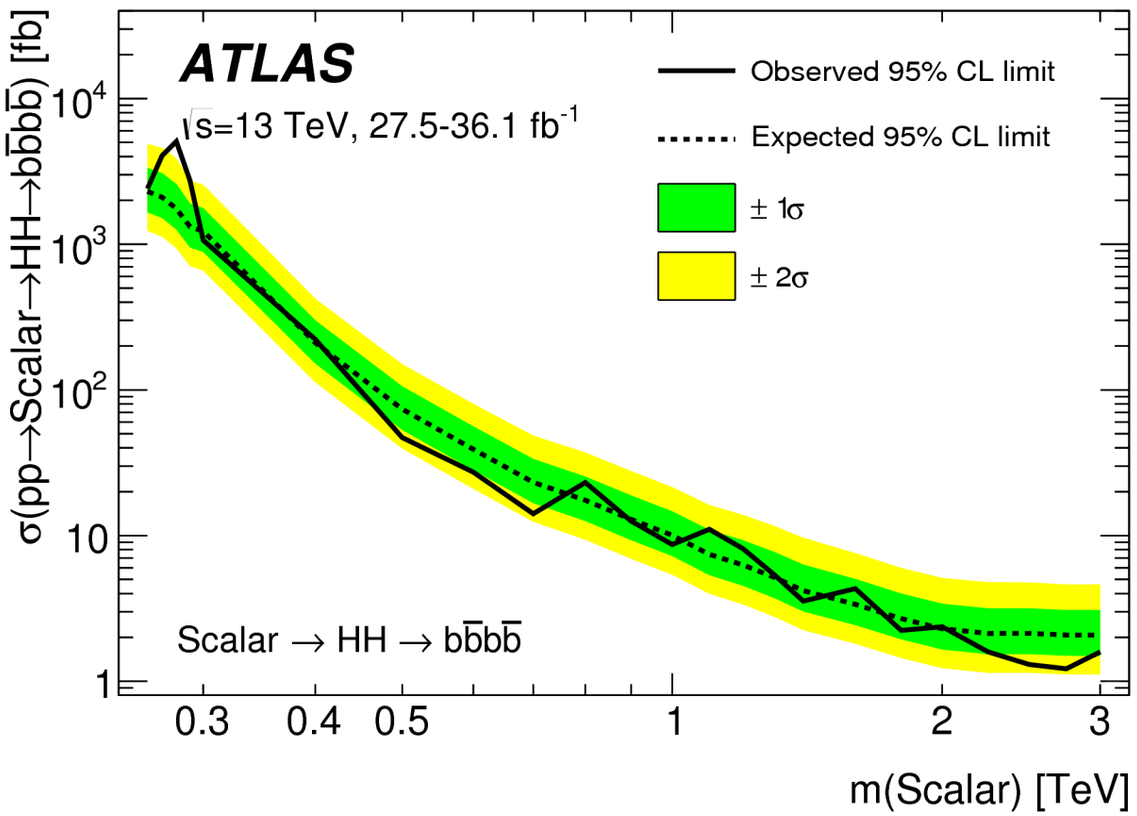

ATLAS
√s = 13 TeV , 36.1 fb-1
2 lep., ≥ 2 jets, ≥ 3 b-tags
100 GeV < mjj < 145 GeV
data
bb̄A (500 GeV)
tt̄, single top
Z+(bb,bc,cc)
Z+(bl,cl), Z+l
W+(bb,bc,cc)
other
uncertainty
Events/GeV
data/bkg
mVh [GeV]

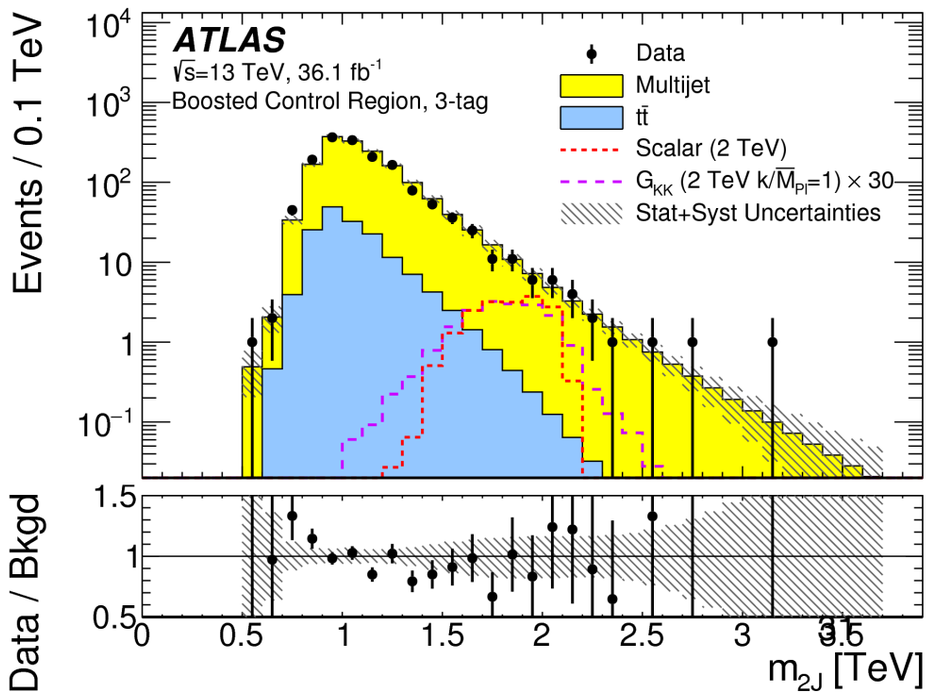
H→hh→bbbb

- Largest branching ratio but large backgrounds
- **Resolved**: four R=0.4 b-tagged jets, with $M_{2j} \sim M_h$
  - Sensitivity up-to **1.2 TeV**
- **Boosted**: two R=1.0 jets with $M_J \sim M_h$ and 2-4 b-tag sub-jets
  - Sensitivity up-to **3 TeV**
- $M4_j$ jet pT cut to reduce background
- Veto events with 3 jet topology consistent with top decay
- Final discriminant - invariant mass of the 4(2) jet system



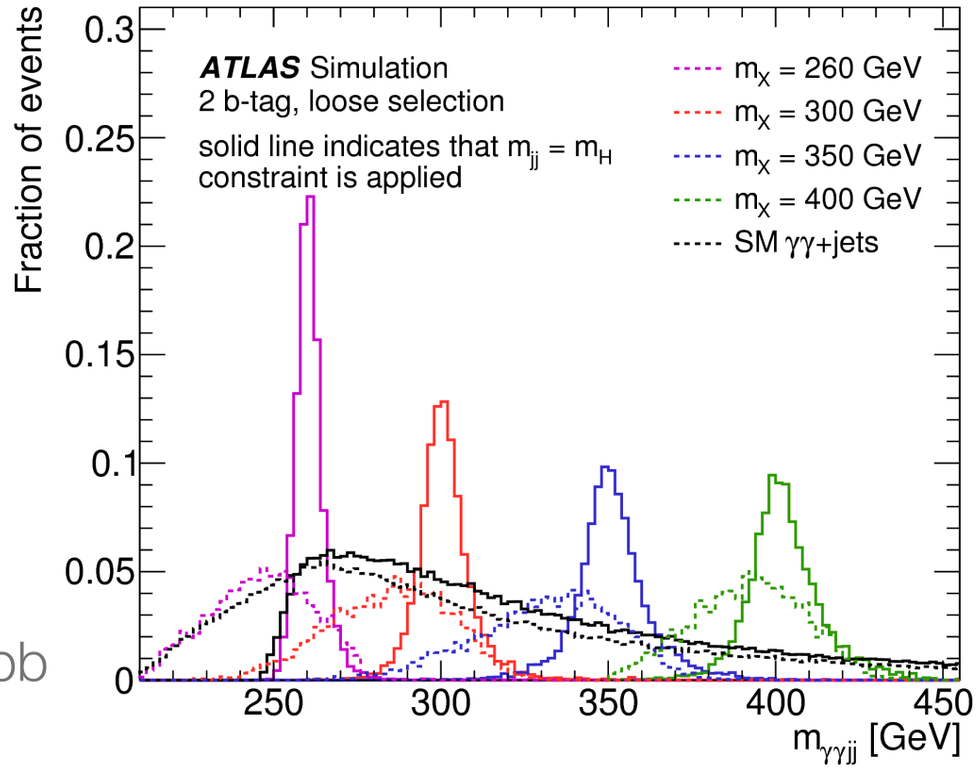


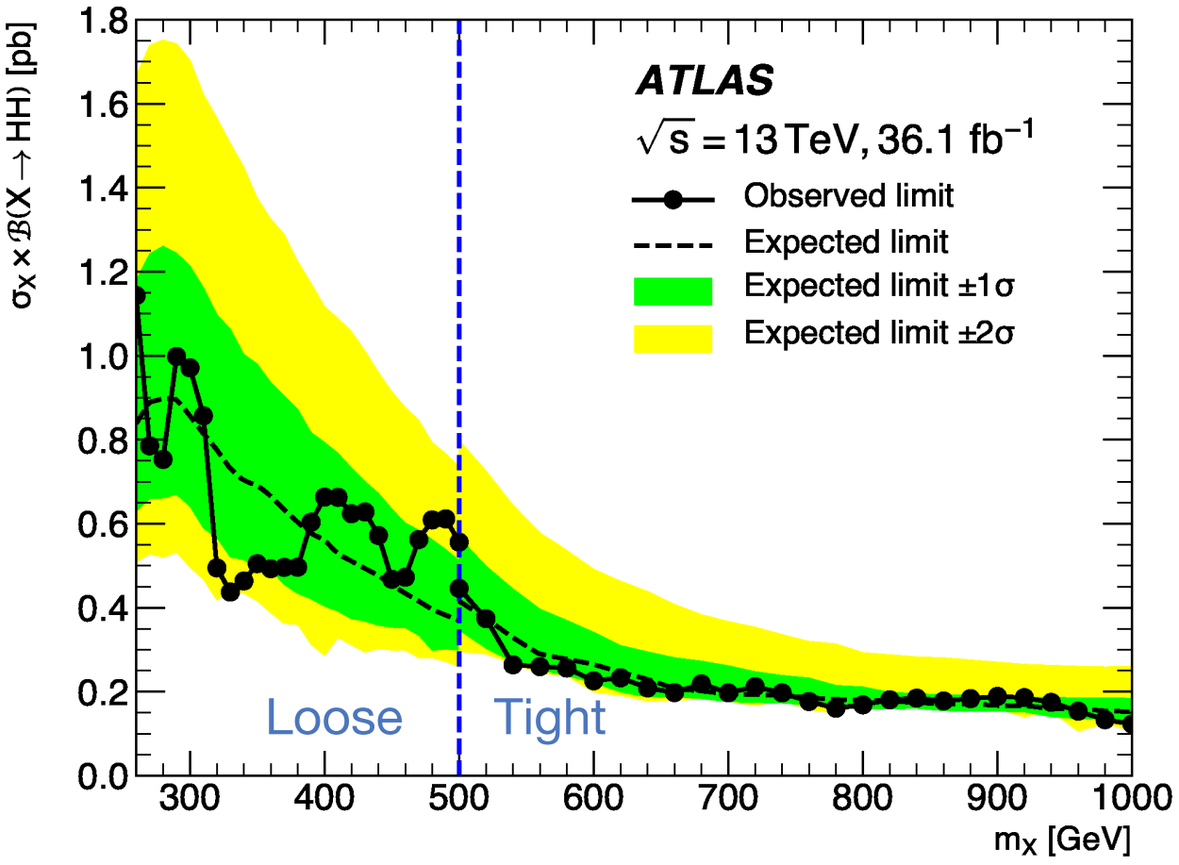


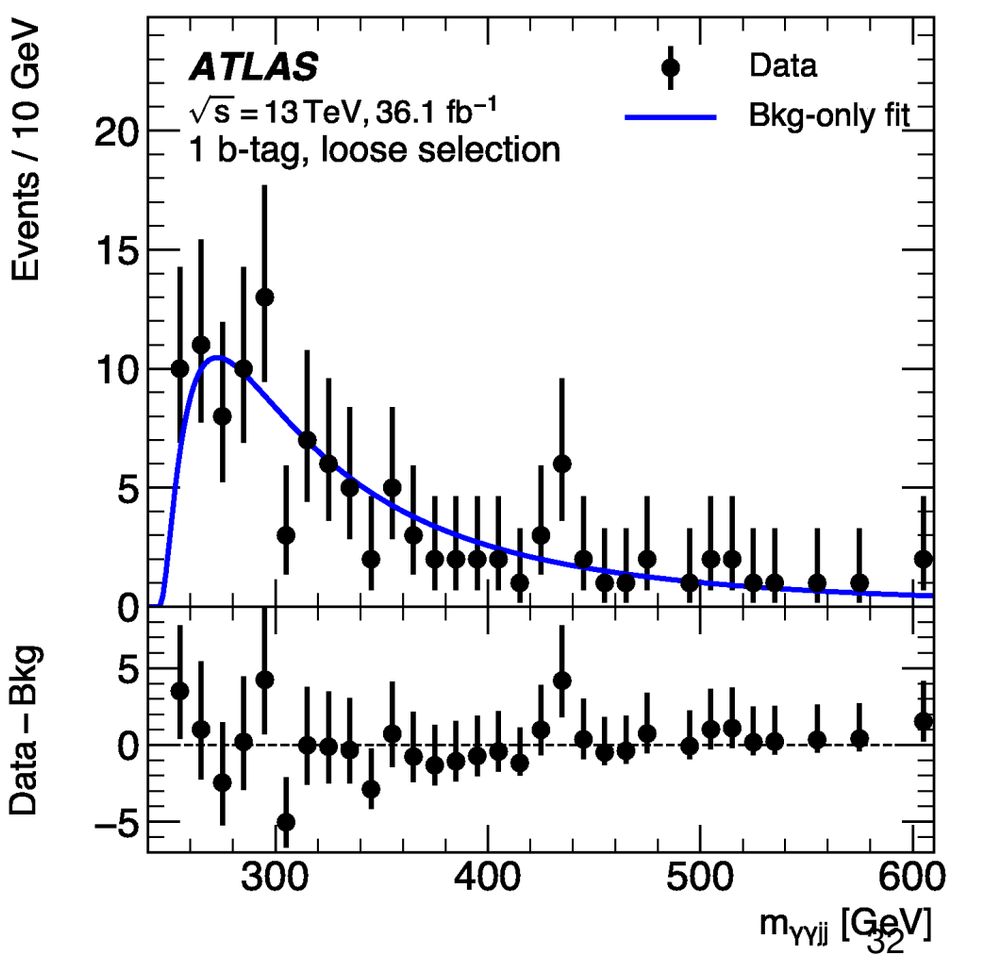


H→hh→bbγγ

- Smaller background due to presence of isolated photons
  - **Narrow peak** in the $M_{\gamma\gamma}$ spectrum with **1 or 2 b-tagged** jets
- 'Loose' ('Tight') selection for low(high) resonance SR
  - Higher jet pT cuts and Smaller $M_{\gamma\gamma}$ / M_{jj} window
- Veto >2 b-tagged jets event to ensure orthogonality with bbbb
- 60% improvement in resolution by constraining $M_{jj} = M_{\gamma\gamma}$
- Parameterized fit to $M_{\gamma\gamma jj}$ distribution
- For scalar resonance, exclusion limits at 95% CL
  - 1.1 - 0.12 pb for $M_H \in$ [0.26 - 1.0 TeV]







H→hh→bbττ

- Two decay modes - $\tau_{Lep}\tau_{Had}$ & $\tau_{Had}\tau_{Had}$
  - Further split, for **semileptonic** decay based on triggers
- BDT trained to separate signal from di-top, Z→ττ and multi jet background
  - Trained for each signal mass point
  - Includes nearby mass points to allow to interpolation
- Mass range 305 GeV < M_X < 402 GeV excluded at 95% CL for tanβ = 2 for hMSSM scenario