Search for $X \rightarrow SH$ in VV$\tau\tau$ final state with the ATLAS detector

Babar Ali (Czech Technical University in Prague, IEAP)
On behalf of the ATLAS Collaboration

LHCHWG
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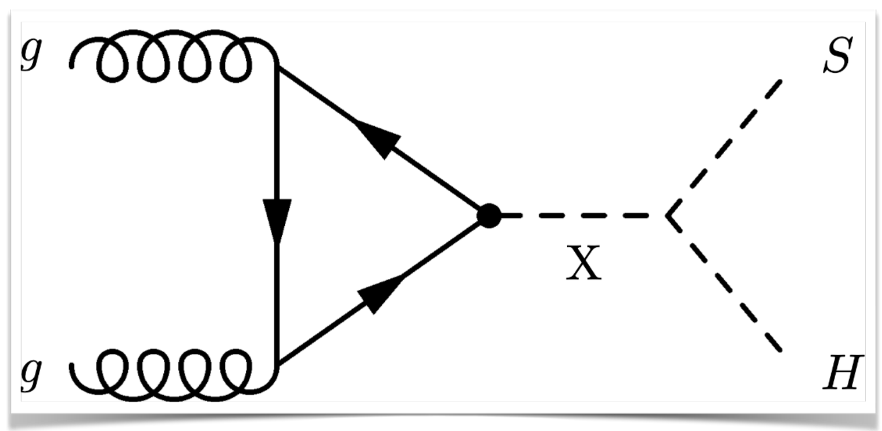
ggF $X \to SH$ production

- DiHiggs production is rare in the Standard Model (SM) $\sigma^{HH}_{\text{ggF}} \approx 31^{+6.7\%}_{-23.2\%}$ fb@$\sqrt{s} = 13$ TeV
- Physics beyond the Standard Model (BSM) can enhance the HH production with additional scalar particles
- BSM scenarios tested include 2HDM, 2HDM+S, MSSM, NMSSM et. al.
- The models hypothesize the existence of a new scalar singlet S
  - $X \to SH, SS$, where X is heavy CP-even scalar boson



Fresh

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- Signature based search in mass range $500 < m_X < 1500$ GeV and $200 < m_S < 500$
  - $S \to VV$ decays assumed to have the same relative coupling as a SM-Higgs
  - $H \to \tau\tau$, where τ-leptons decay hadronically
- First of its kind using 140 fb^{-1} data & competitive with $VVbb, VV\gamma\gamma, bb\tau\tau, bbbb$ in high mass

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Phys. Rev. D92 (2015) 092004

Event selection

- Based on $S \to VV$ decay, three final states are selected

$S \to WW \to 1\ell + 2\tau$

Exactly one light lepton

Two hadronic taus with opposite-sign

At least two jets

$S \to WW \to 2\ell + 2\tau$

Exactly two light leptons with opposite-sign

Two hadronic taus with opposite-sign

$|m_{\ell\ell} - m_Z| > 10$ GeV

$m_{\ell\ell} > 12$ GeV

$S \to ZZ \to 2\ell + 2\tau$

Exactly two light leptons with opposite-sign

Two hadronic taus with opposite-sign

$|m_{\ell\ell} - m_Z| < 10$ GeV

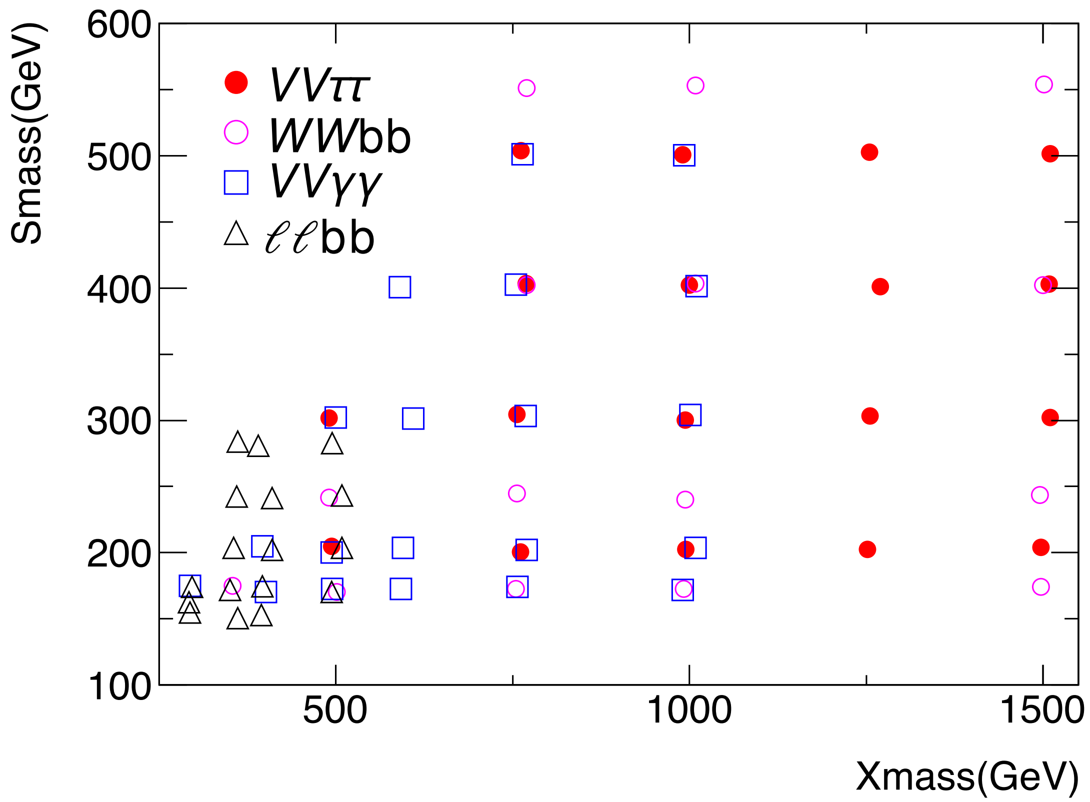
$m_{\ell\ell} > 12$ GeV

In all three channels:

- Require 0 b-tagged jets
- Light leptons $p_T > 10$ GeV and τ_{had} $p_T > 20$ GeV
- $\Delta R(\tau_0, \tau_1) \leq 2$
- Trigger on single lepton or dilepton triggers (only single lepton trigger in $S \to WW \to 1\ell + 2\tau$)

Monte Carlo simulation

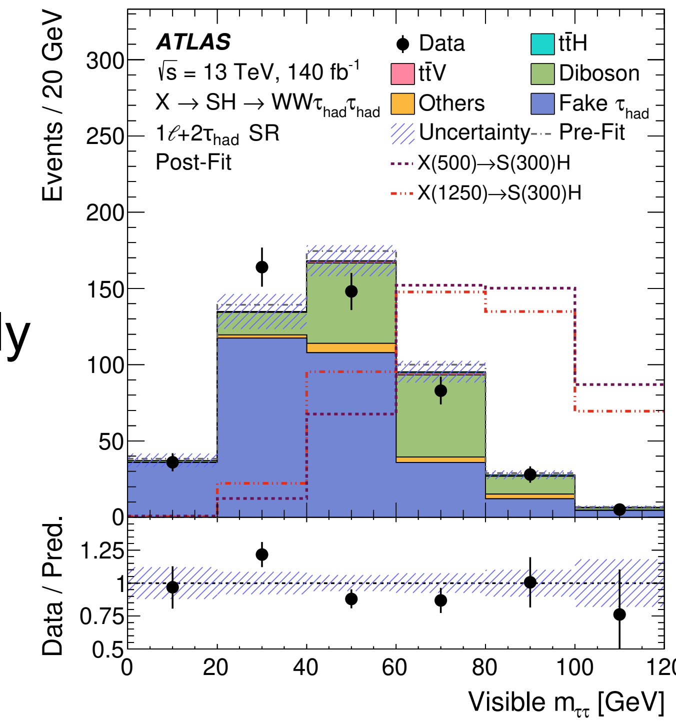
- Signal events are generated in generic 2HDM+S model
  - Kinematic parameters are model-independent
  - Results can be interpreted in other BSM models
  - Leading-order accuracy with Pythia-8 generator
- Heavy scalar X constrained to decay only into S and H
  - S decays to WW or ZZ bosons,
  - H decays to a pair of τ_{had} leptons
  - Fully and semi-leptonic decays of WW
  - Only two-lepton final state in ZZ decays

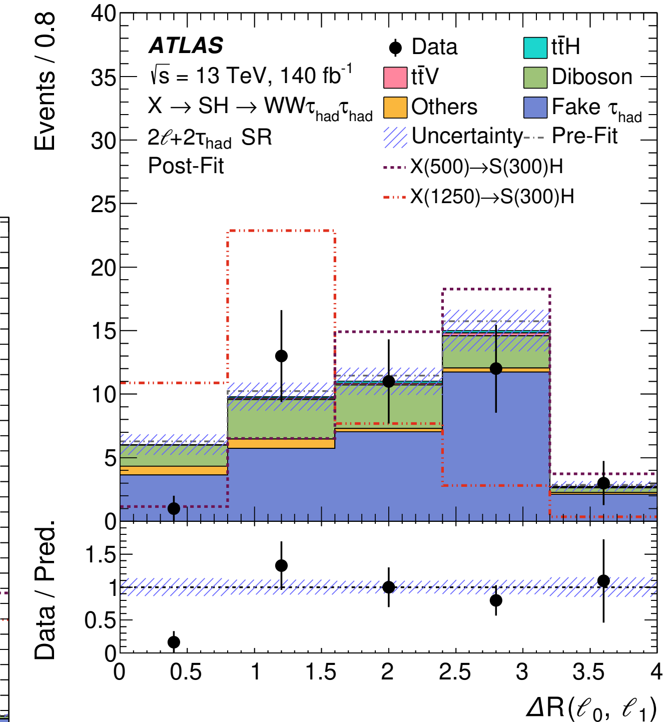


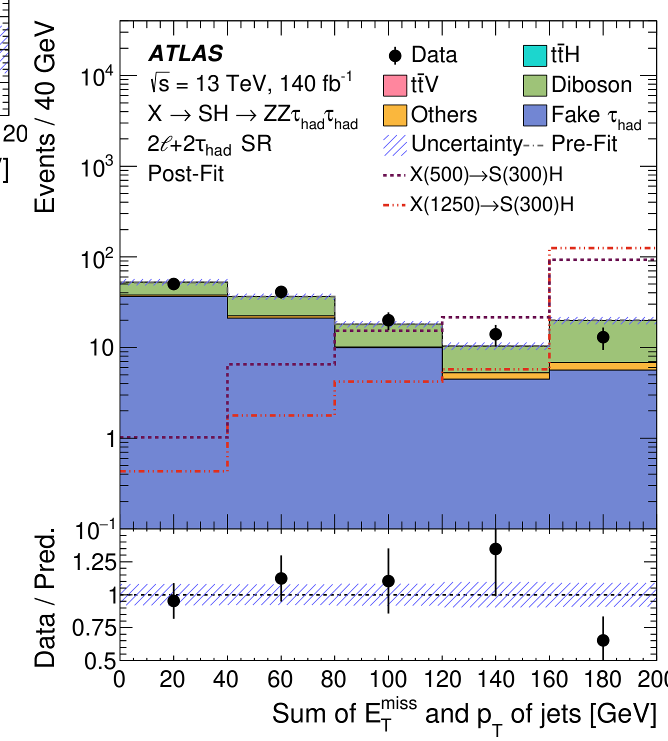
- Eighteen mass points are considered
- SM non-resonant ggF HH production to study the theory systematics

Multivariate discriminant

- Boosted Decision Trees (BDT) are employed to separate the signal from all the backgrounds
- Parameterised BDT method is used to simplify the training procedure
  - Parametrisation in m_X for given m_S
  - Generated m_X mass as an input parameter
  - m_X values of background events are randomly assigned to match signal
- BDT training is performed separately in three channels with four m_S mass points (12 different BDTs trained)







Variable	Definition	WW $1\ell2\tau_{\rm had}$	WW $2\ell2\tau_{\rm had}$	ZZ $2\ell2\tau_{\rm had}$
$m_{\rm X,\ truth}$	generated mass of generated X particle	×	×	×
$\Delta R(\tau\tau, \ell_0)$	angular distance between the leading lepton and the $\tau\tau$ system	×	×	×
$\min(\Delta R(\tau\tau, {\rm j}))$	minimum angular distance between a jet and the $\tau\tau$ system	×	-	-
$\Delta R(\ell, \ell)$	angular distance between two leptons	-	×	×
$\Delta\phi(\tau\tau, E_T^{\rm miss})$	azimuthal angle between the $\tau\tau$ system and $E_T^{\rm miss}$	×	×	×
$E_T^{\rm miss} + \Sigma p_{\rm T}({\rm jets})$	sum of $E_T^{\rm miss}$ momentum and $p_{\rm T}$ of jets	-	-	×
$p_{{\rm T}\tau 0}$	leading tau-lepton $p_{\rm T}$	×	×	×
$m_{\tau\tau}$	visible invariant mass of the $\tau\tau$ system	×	×	×
$m_{\ell\ell}$	invariant mass of the dilepton system	-	×	-
$\min(\Delta R(\ell, {\rm j}))$	minimum angular distance between a jet and the lepton	×	-	-
$\min(\Delta R({\rm j}, {\rm j}))$	minimum angular distance between two jets	×	-	-
$p_{{\rm T}\tau 1}$	subleading τ-lepton $p_{\rm T}$	×	×	×
$m_{\rm T}^W$	transverse mass calculated from the lepton(s) and $E_T^{\rm miss}$ in the event	×	×	×
dilep_type	dilepton type: one of $\mu\mu$, $e\mu$, μe, ee	-	×	-

Background modelling

$S \rightarrow WW \rightarrow 1\ell/2\ell + 2\tau$

Fake τ_{had} from V+jets process: ~67% estimated using data-driven fake factor (FF) method

Diboson ~27%, $t\bar{t}V$, $t\bar{t}H$: estimated from MC simulation

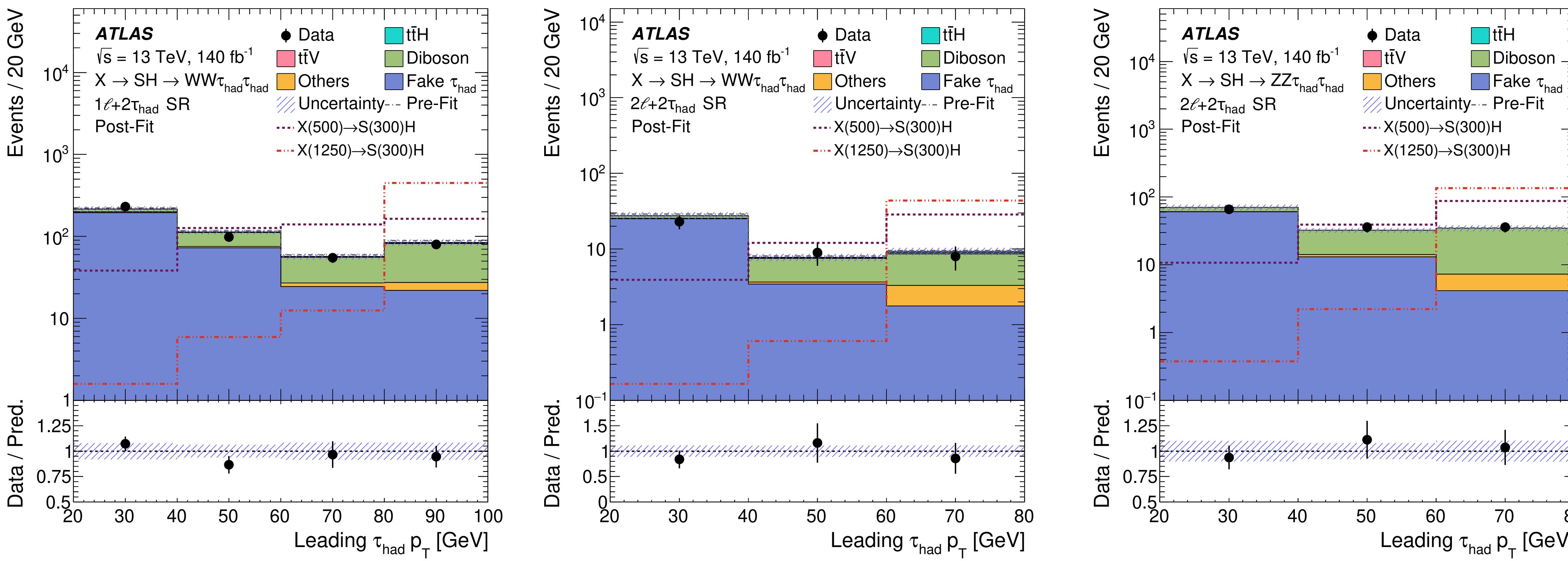
Others (light lepton, b- or c- jets misidentified as fake τ_{had}) from MC

$S \rightarrow ZZ \rightarrow 2\ell + 2\tau$

Fake τ_{had} from V+jets process: 56% estimated using FF method

Diboson 40%, $t\bar{t}V$, $t\bar{t}H$: estimated from MC simulation

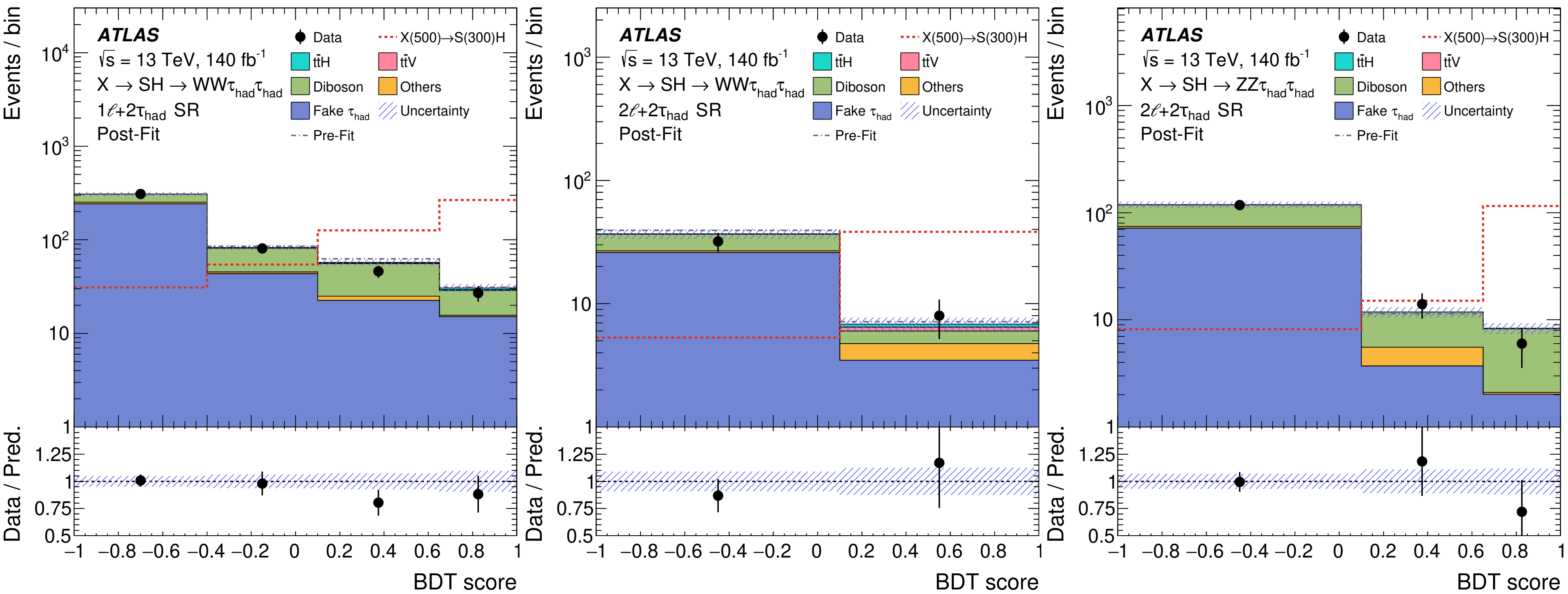
Others (light lepton, b- or c- jets misidentified as fake τ_{had}) from MC



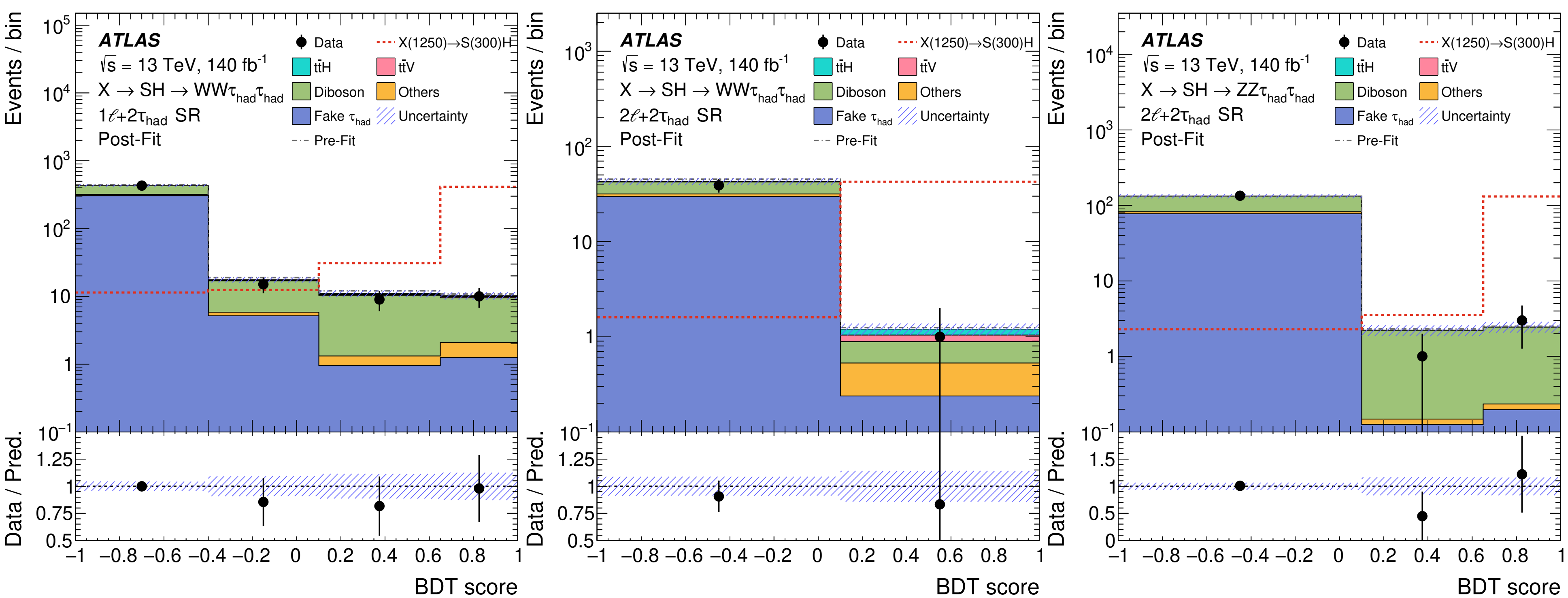
- Fake τ_{had} background is validated in a dedicated region (two same-sign τ_{had})
- Leading source of systematic uncertainty from real τ_{had} subtraction ($^{+7.5}_{-12}$ %)

BDT output

$m_X = 500,\ m_S = 300$ GeV



$m_X = 1250,\ m_S = 300$ GeV



- A likelihood fit is performed on each BDT output and for each mass point in three channels
- No excess of events is observed
- Set 95% CL upper limits
- Dominant systematic uncertainties include tau-lepton fakes, diboson modelling, τ_{had} identification efficiency, light lepton identification and trigger efficiencies

Limits on $X \to SH$

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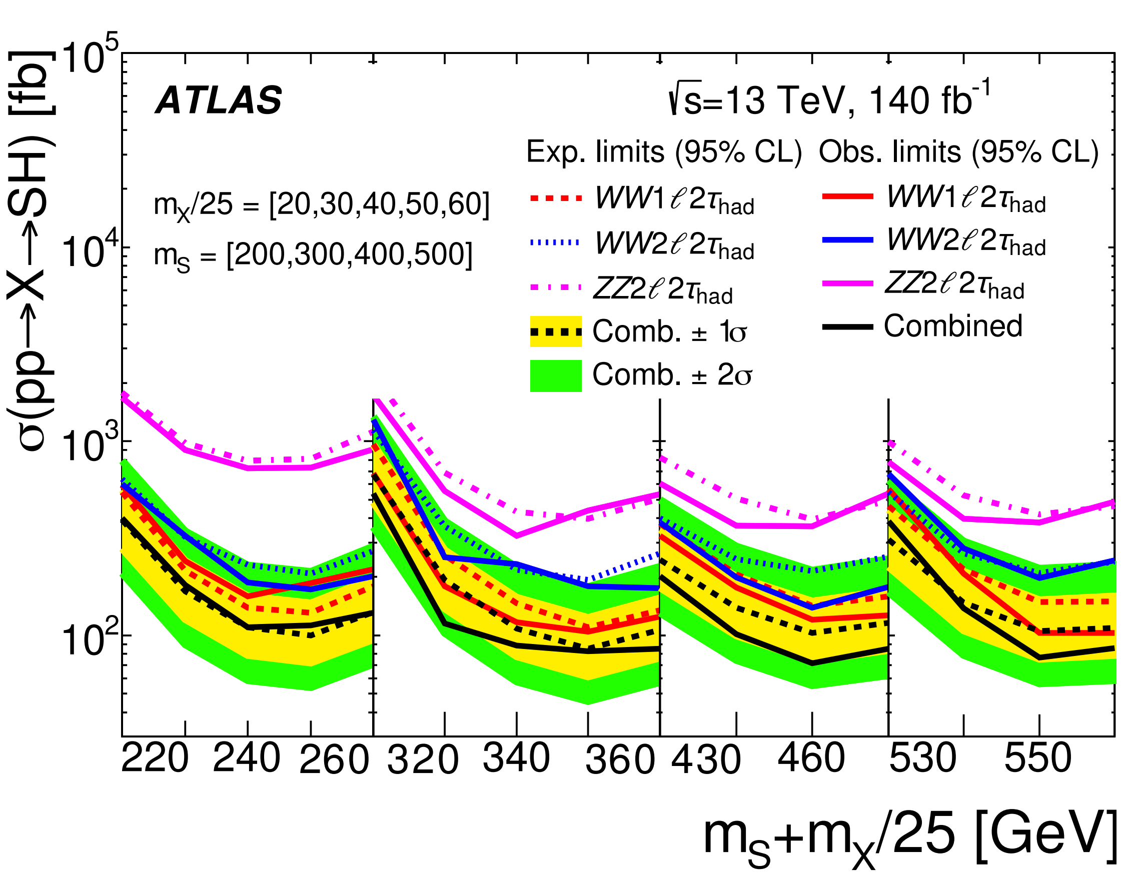
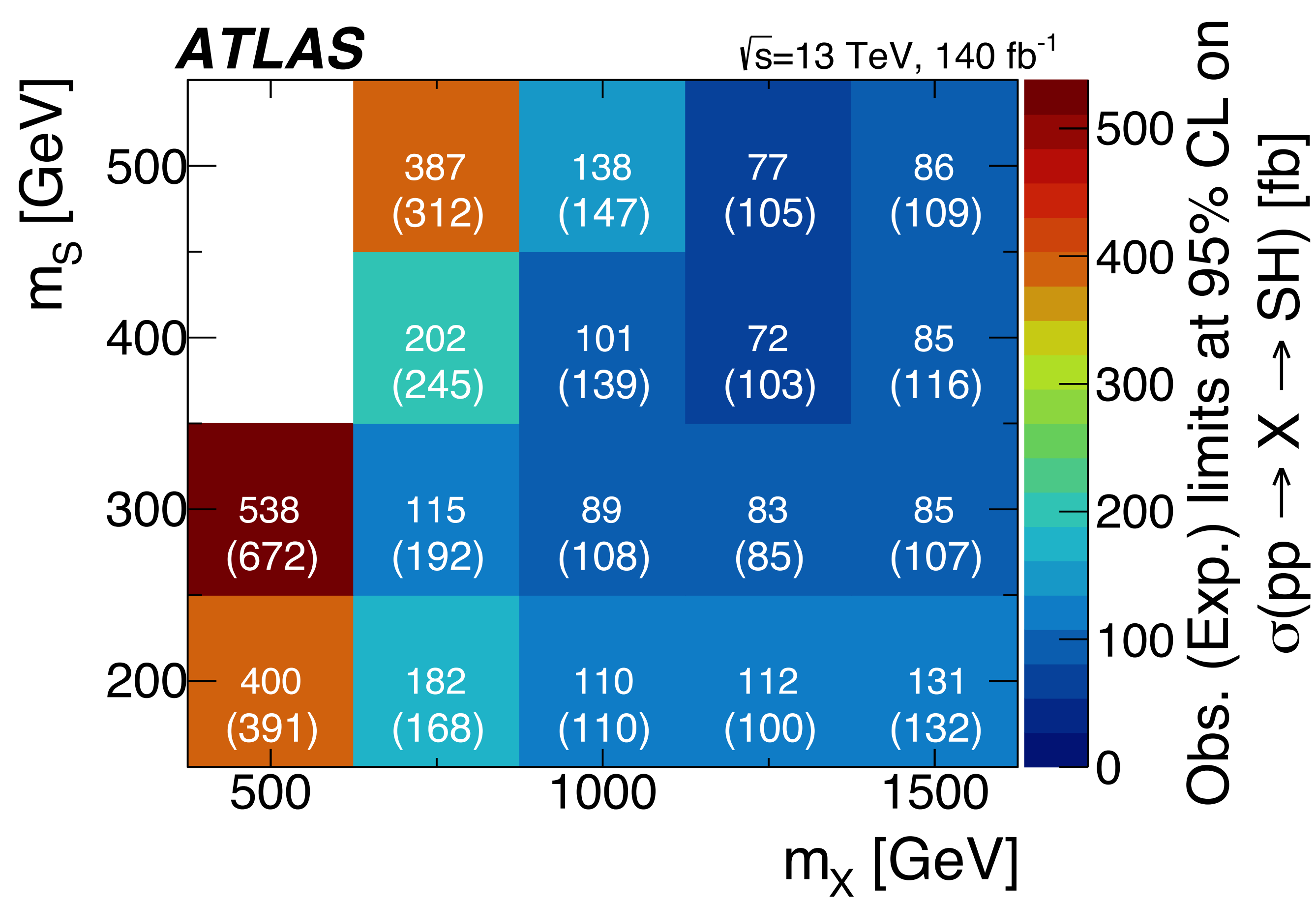
- Observed and expected limits on $\sigma(X \to SH)$ for all three channels combined
- Combined limit is dominated by $WW1\ell 2\tau$ channel and improved $26\% - 53\ \%$ by other channels
- Impact of total systematic uncertainty is between 2% and 14%
- Best expected limit is 85 fb for $m_X = 1250,\ m_S = 300$ GeV





$72 < \sigma(pp \to X \to SH) < 542\ fb$

Limit comparison with NMSSM scans

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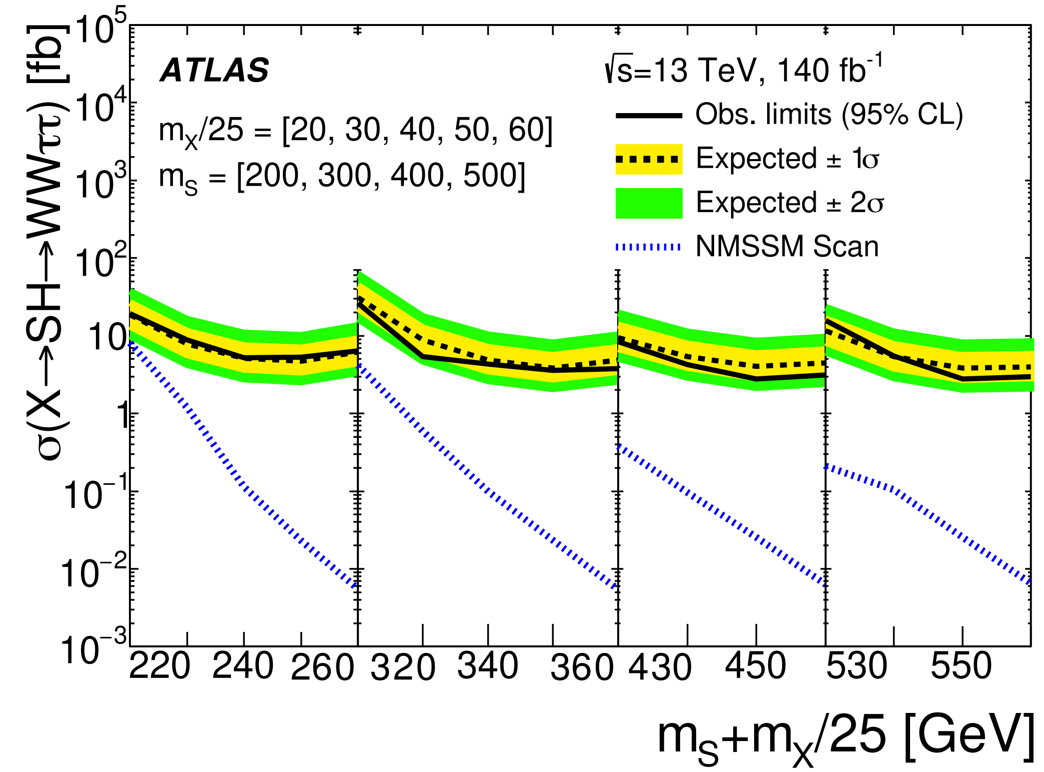
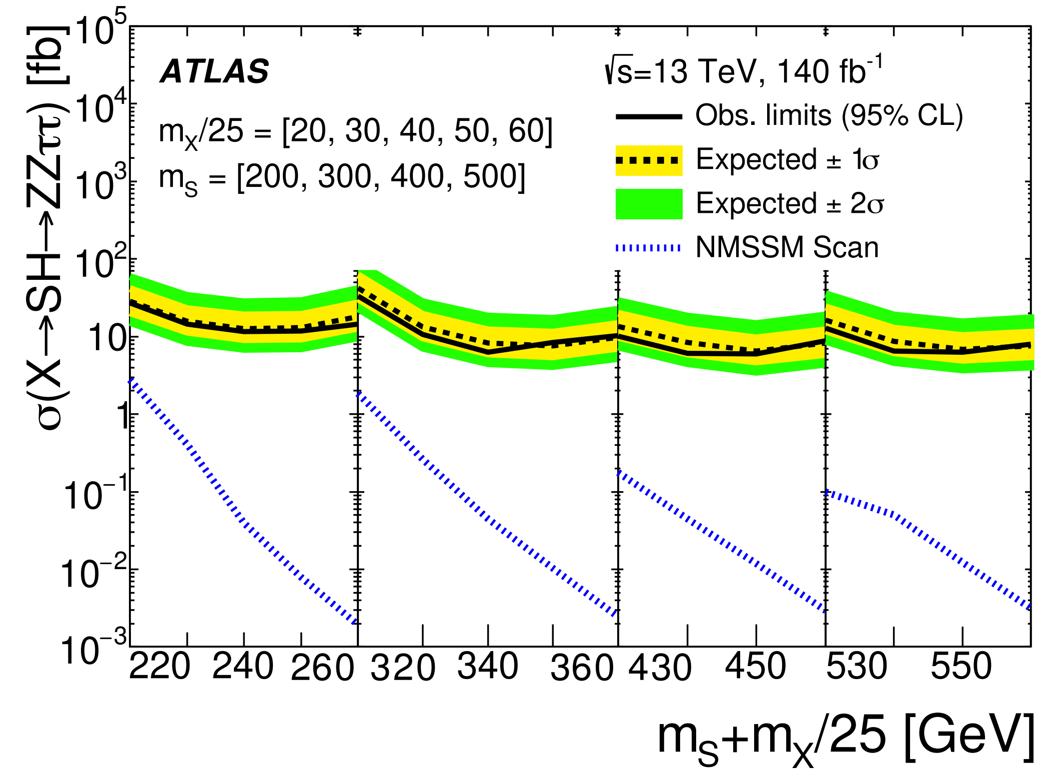
- Limits on $\sigma(X \to SH \to WW\tau\tau)$ from combination of $WW1\ell 2\tau$ and $WW2\ell 2\tau$ channels, and $\sigma(X \to SH \to ZZ\tau\tau)$

- Maximum possible values allowed for cross-section of $(X \to SH \to WW\tau\tau)$ and $(X \to SH \to ZZ\tau\tau)$ processes in the NMSSM parameter space

- Parameter scan using NMSSMTOOLS by the NMSSM group of LHCHXSWG3
  - Measurements of Higgs boson properties
  - Searches for supersymmetry
  - B-meson physics
  - Searches for dark matter

- Observed limits approach the allowed cross-sections in the low$-m_X$ and low$-m_S$ part of the NMSSM parameter space





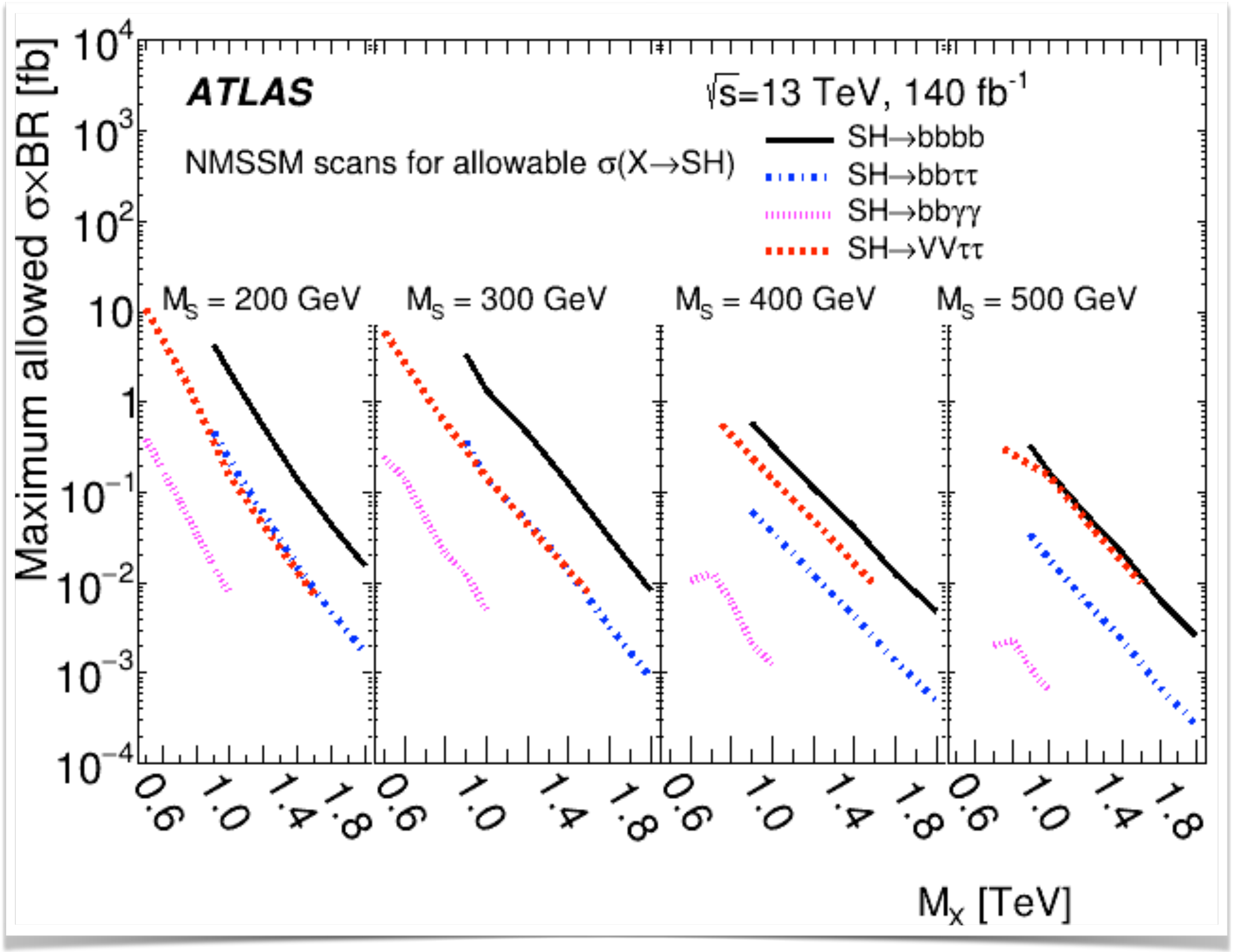
NMSSM scans for $\sigma(X \rightarrow SH) \times \mathrm{BR}$

- Maximum allowed $\sigma(X \rightarrow SH) \times \mathrm{BR}$

- Parameter scan using NMSSMTOOLS by the NMSSM group of LHCHXSWG3
  - Measurements of Higgs boson properties
  - Searches for supersymmetry
  - B-meson physics
  - Searches for dark matter

- NMSSM scan for $VV\tau\tau$ is compatible with other scans using $X \rightarrow SH \rightarrow bbbb$, $bb\tau\tau$ and $bb\gamma\gamma$ final states

- Still room for $VV\tau\tau$ to set constraints on BSM models



Summary

- Search for $X \to SH \to VV\tau\tau$ using 140 fb^{-1} proton-proton data
- Explored X mass ranges from 500 to 1500 GeV, with S mass in the range from 200 to 400 GeV
- No excess of events was observed beyond the SM expectation
- Observed limit on $\sigma(X \to SH)$ is between $72 - 542$ fb for SM-like $S \to VV$ decay
- Dominant by $SH \to WW\ 1\ell + 2\tau$ channel
- NMSSSM scans: observed limits approach the allowed cross-section at low mass points
- Improvements in low mass regions including Run-3 data will provide further constraints

Backup

2D Limits on $X \rightarrow SH \rightarrow VV\tau\tau$

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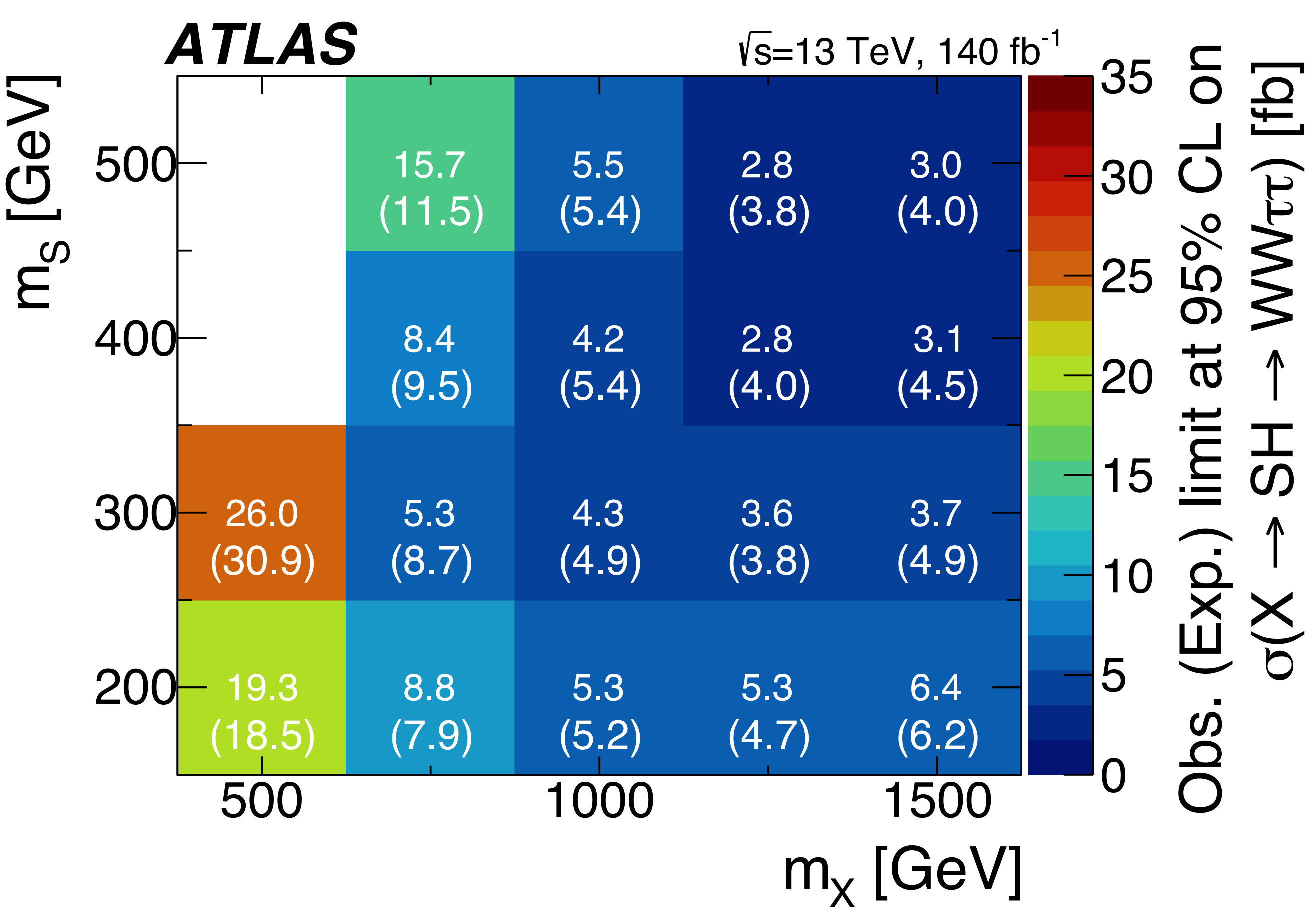
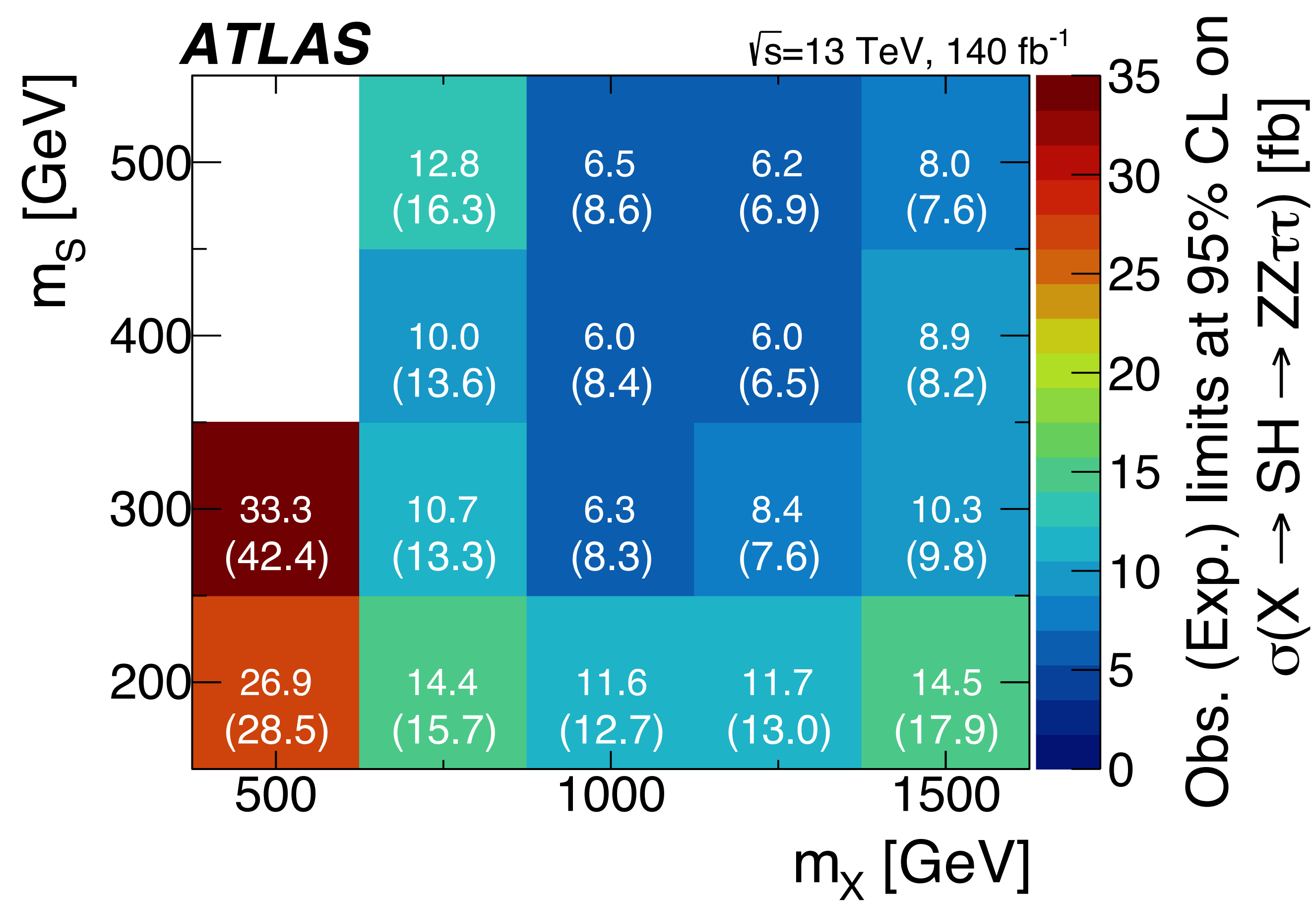
- Observed and expected 2D limits on $\sigma(X \rightarrow SH \rightarrow WW\tau\tau)$ from combination of $WW1\ell 2\tau$ and $WW2\ell 2\tau$ channels, and for $\sigma(X \rightarrow SH \rightarrow ZZ\tau\tau)$

- Each mass point limit is compared to the limits obtained using the BDTs trained for the (lower or upper) neighbouring mass values and found to be consistent within 15%
  - Interpolating the limits between mass points is unnecessary



$3 < \sigma(pp \rightarrow X \rightarrow SH \rightarrow WW\tau\tau) < 26\ fb$



$6 < \sigma(pp \rightarrow X \rightarrow SH \rightarrow ZZ\tau\tau) < 33\ fb$

Limit numbers $X \to SH \to VV\tau\tau$

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- Observed and expected limits on $\sigma(X \to SH \to VV\tau\tau)$

m_X	m_S	Combined $\sigma(pp \to X \to SH)$ [fb]		$\sigma(pp \to X \to WW\tau\tau)$ [fb]		$\sigma(pp \to X \to ZZ\tau\tau)$ [fb]	
(GeV)	(GeV)	Observed	Expected	Observed	Expected	Observed	Expected
500	200	400	391^{+170}_{-110}	19	18^{+8}_{-5}	27	28^{+13}_{-8}
750	200	182	168^{+74}_{-47}	8.8	$8^{+3.5}_{-2}$	14	16^{+7}_{-4}
1000	200	110	110^{+49}_{-31}	5.3	5^{+2}_{-1}	12	13^{+6}_{-4}
1250	200	112	100^{+46}_{-28}	5.4	5^{+2}_{-1}	12	13^{+6}_{-4}
1500	200	131	132^{+62}_{-37}	6.4	6^{+3}_{-2}	14	18^{+9}_{-5}
500	300	538	672^{+290}_{-190}	26	31^{+13}_{-9}	33	42^{+19}_{-12}
750	300	115	192^{+83}_{-54}	5.3	9^{+4}_{-2}	11	13^{+6}_{-4}
1000	300	88.6	108^{+48}_{-30}	4.3	5^{+2}_{-1}	6.3	8^{+4}_{-2}
1250	300	82.6	85^{+38}_{-24}	3.6	4^{+2}_{-1}	8.4	8^{+4}_{-2}
1500	300	85.4	107^{+49}_{-30}	3.7	5^{+2}_{-1}	10	10^{+5}_{-3}
750	400	202	245^{+107}_{-68}	8.4	10^{+4}_{-3}	10	14^{+6}_{-4}
1000	400	101	139^{+62}_{-39}	4.2	$5^{+2}_{-1.5}$	6	8^{+4}_{-2}
1250	400	71.7	103^{+46}_{-29}	2.8	4^{+2}_{-1}	6	6.5^{+3}_{-2}
1500	400	85.1	116^{+53}_{-32}	3.1	4.5^{+2}_{-1}	8.9	8^{+4}_{-2}
750	500	387	312^{+135}_{-87}	16	11^{+5}_{-3}	13	$16^{+8}_{-4.5}$
1000	500	138	147^{+65}_{-41}	5.5	$5^{+2}_{-1.5}$	6.5	9^{+4}_{-2}
1250	500	77	105^{+47}_{-29}	2.8	4^{+2}_{-1}	6.2	7^{+3}_{-2}
1500	500	85.9	109^{+50}_{-31}	3	4^{+2}_{-1}	8	8^{+4}_{-2}

Event yields

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- Event yields in all three channels

Process	$WW1\ell2\tau_{\text{had}}$	$WW2\ell2\tau_{\text{had}}$	$ZZ2\ell2\tau_{\text{had}}$
$\text{t}\bar{\text{t}}\text{H}$	2.6 ± 0.3	0.50 ± 0.06	0.035 ± 0.004
$\text{t}\bar{\text{t}}\text{V}$	3.4 ± 0.4	0.58 ± 0.07	0.10 ± 0.02
Others	15.6 ± 3.0	2.1 ± 0.4	4.7 ± 0.8
Diboson	135.1 ± 15.5	11.1 ± 1.3	55.0 ± 6.1
Fake τ_{had}	312.4 ± 21.5	30.1 ± 3.7	77.8 ± 9.0
Total background	468.6 ± 19.3	44.0 ± 3.9	138.0 ± 9.1
Data	464	40	138