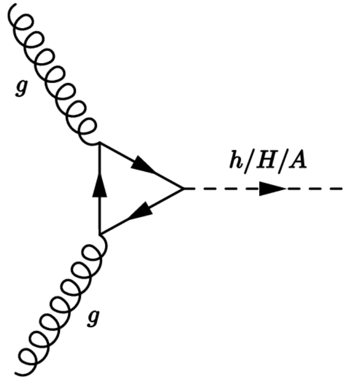
MSSM $\mathrm{H}/A \rightarrow \tau\tau$ in ATLAS

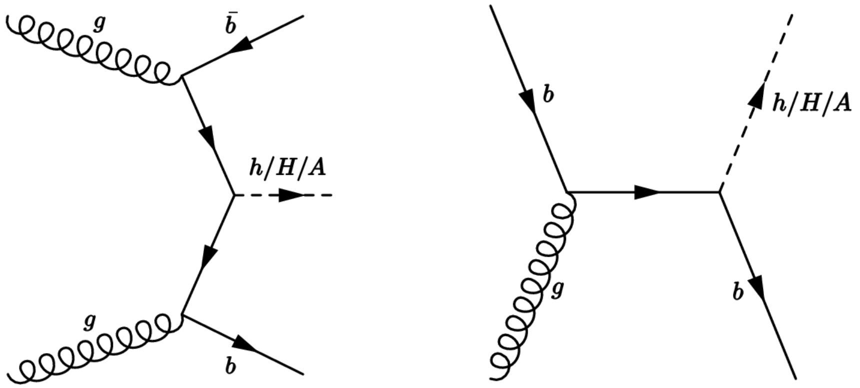
Pedro Sales de Bruin on behalf of the ATLAS collaboration

$H/A \to \tau\tau$ – overview

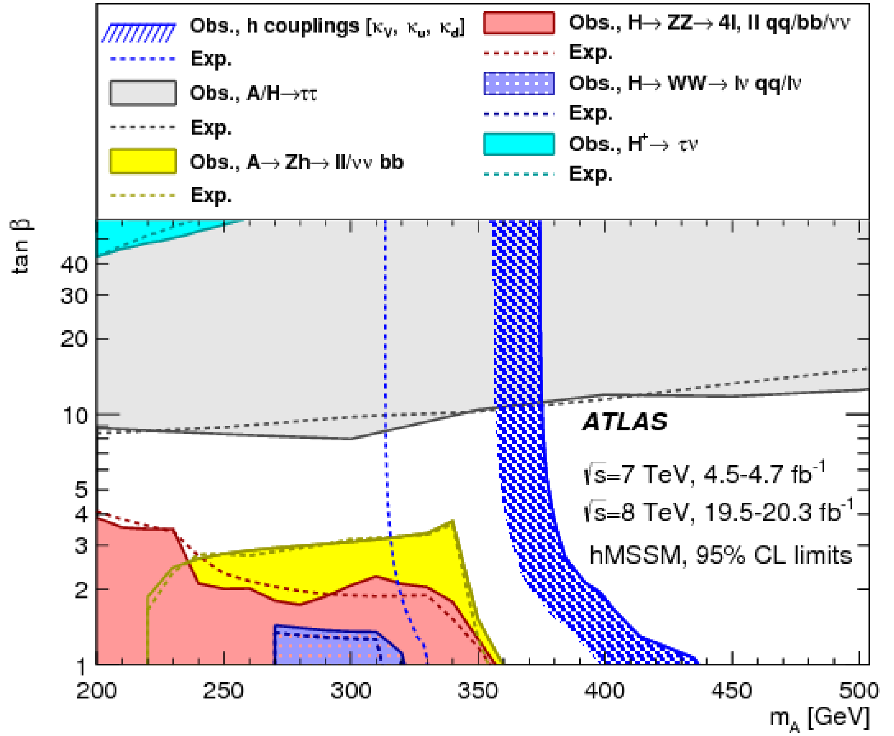
- The $H/A \to \tau\tau$ channel is the most powerful channel to search for MSSM Higgs bosons at high $\tan\beta$
- Will show latest search using 13.3 fb^{-1} of 13 TeV Run-2 data (ATLAS-CONF-2016-085)
- The analysis is split into $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels
- Each channel is sub-divided into b-veto and b-tagged categories. Additional high-E_T^{miss} category for $\tau_{lep}\tau_{had}$ channel



gluon-fusion



b-associated production



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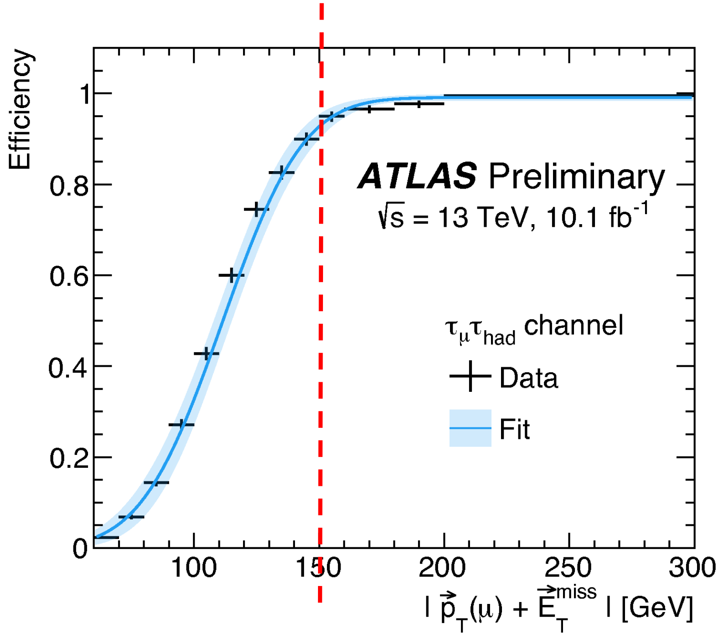
$\tau_{lep}\tau_{had}$ selection

Events triggered by E_T^{miss} OR Single Lepton Triggers passing preselection

- $E_T^{miss}(+\vec{p}_T(\mu)) > 150$ GeV → E_T^{miss} triggers → Common selection → high E_T^{miss}
- $E_T^{miss}(+\vec{p}_T(\mu)) < 150$ GeV → single lepton triggers → Common selection → b-veto / b-tag

$\epsilon_b = 77\%$



Common Selection

- τ pT > 25 GeV passing medium TauID
- Lepton pT > 30 GeV passing medium quality criteria
- $\Delta\phi(l, \tau_{vis}) > 2.4$
- $m_T(l, E_T^{miss}) < 40$ GeV,

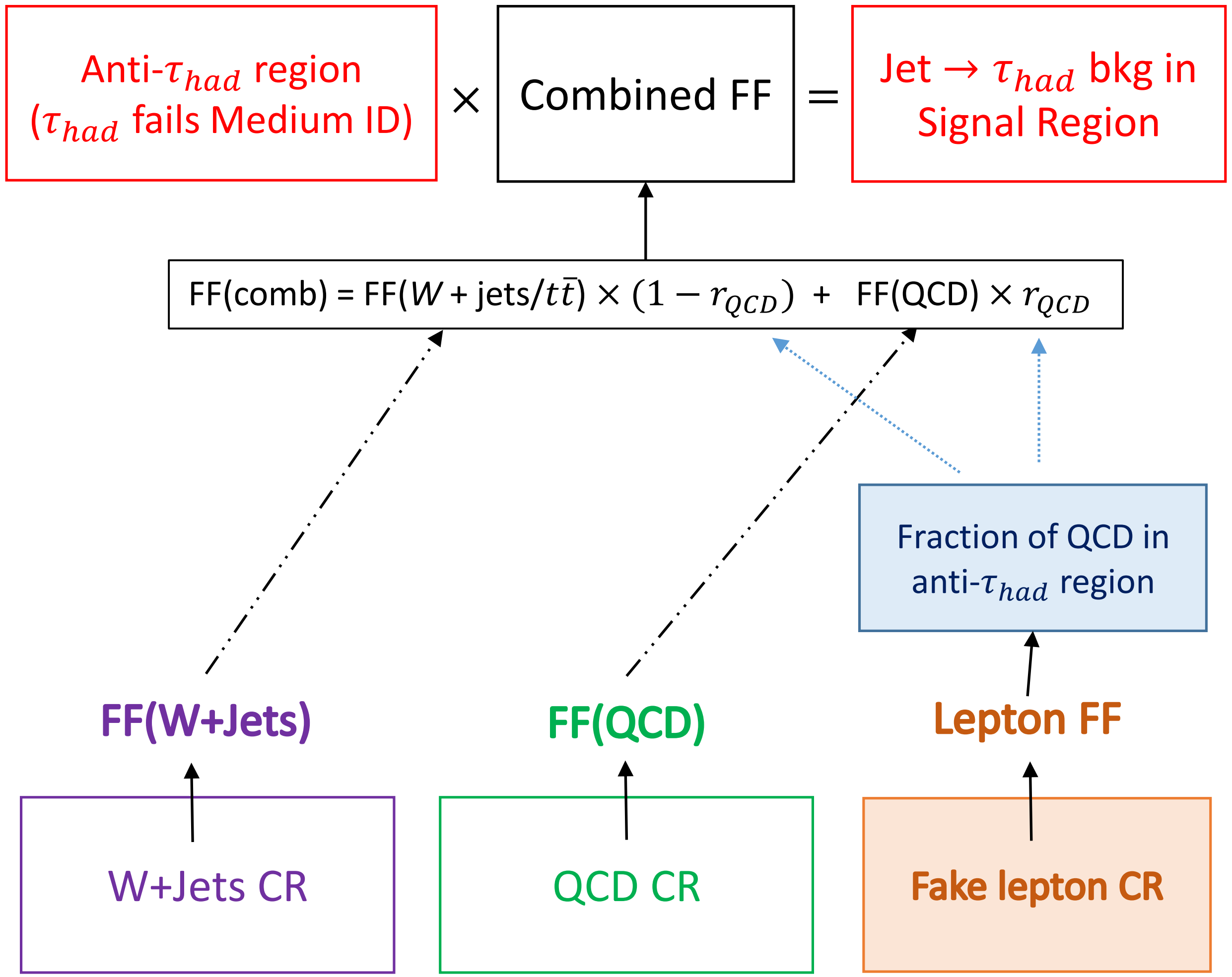
where $m_T(l, E_T^{miss}) \equiv \sqrt{2p_{T,l}E_T^{miss}\left(1 - \cos\left(\Delta\phi(l, E_T^{miss})\right)\right)}$

- For $e\tau_{had}$ channel, an additional veto of events with $m_{\tau\tau}^{vis}$ near the Z mass

$\tau_{lep}\tau_{had}$ backgrounds overview

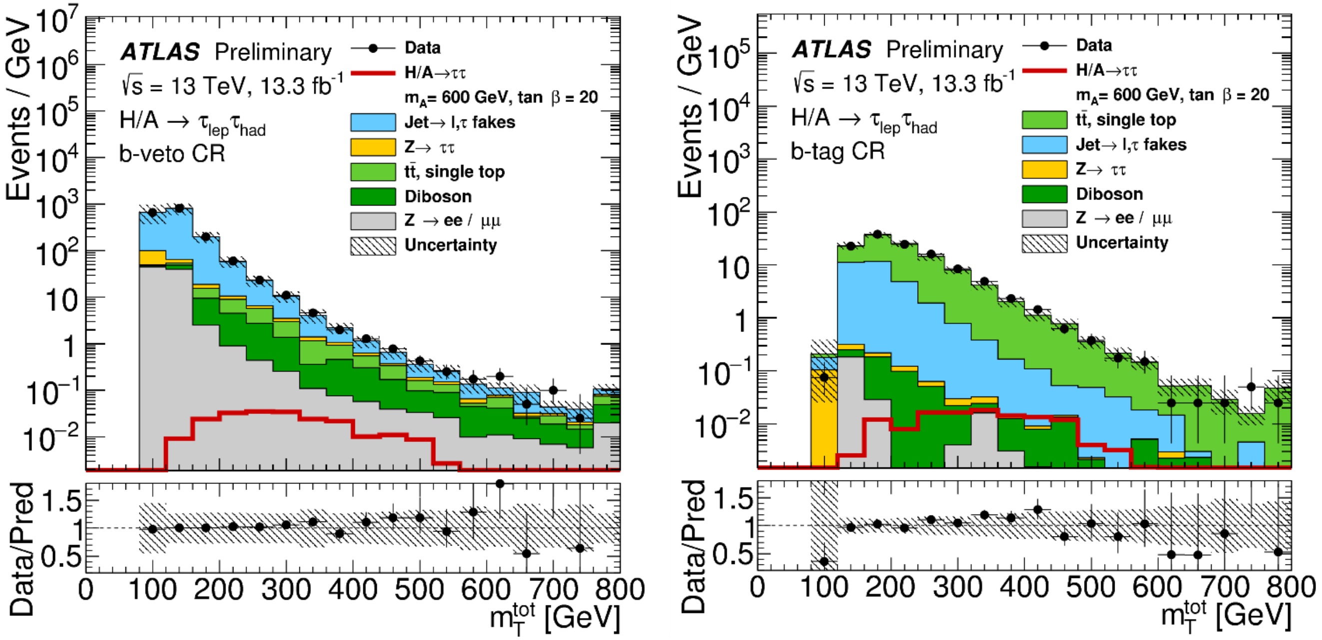
- Events with truth-matched leptons, taus and lepton faking τ_{had} taken from simulation. Mostly from $\boldsymbol{Z} \to \ell\ell$ and $\boldsymbol{Z} \to \boldsymbol{\tau\tau}$. Scale factors in $e \to \tau_{had}$ events
- Background with jets faking taus estimated with a data-driven method
- Fake-τ_{had} background is mostly **W+Jets** (where the lepton is true), or **multi-jet** (where both lepton and tau are faked by QCD jets). Top background also important for b-tag region
- Fake factors (**FF**) computed as ratio of pass/fail Medium TauID and applied in anti-tau control region (**CR**)
- Fraction of QCD in anti-tau region (**r_{QCD}**) computed using fake factors from a fake lepton control region

Fake background treatment



$\tau_{lep}\tau_{had}$ control regions

- W+jets/top CR definition is identical to signal region but with an inverted transverse mass cut:
  - $e\tau_{had}$: $m_T(l, E_T^{miss}) > 70$ GeV
  - $\mu\tau_{had}$: $m_T(l, E_T^{miss}) > 60$ GeV
- For the FF(W+jets/$t\bar{t}$), no significant differences observed between *b*-veto/*b*-tag or between *W*+jets and Top, so single set of FF is used
- The FF(QCD) are computed in a control region where the lepton is anti-isolated
- The r_{QCD} is obtained using lepton fake factors derived in a fake lepton control region with no loose τ_{had} and leptons without isolation requirement. They are defined as the pass/fail ratio of the lepton isolation



ATLAS-CONF-2016-085

$\tau_{had}\tau_{had}$ selection

- Single tau trigger with threshold 80 GeV (125 GeV for later run periods)
- 2 OS τ_{had} with $p_{T,\tau_1} > 110$ (140) GeV and $p_{T,\tau_2} > 55$ (65) GeV
- No light leptons
- Leading tau passes medium ID. Subleading tau passes loose ID
- $\Delta\phi\left(\tau_{had,1}^{vis}, \tau_{had,2}^{vis}\right) > 2.7$
- b-tag ($N_{bjets} > 0$) and b-veto ($N_{bjets} = 0$) categories; $\epsilon_b = 70\%$

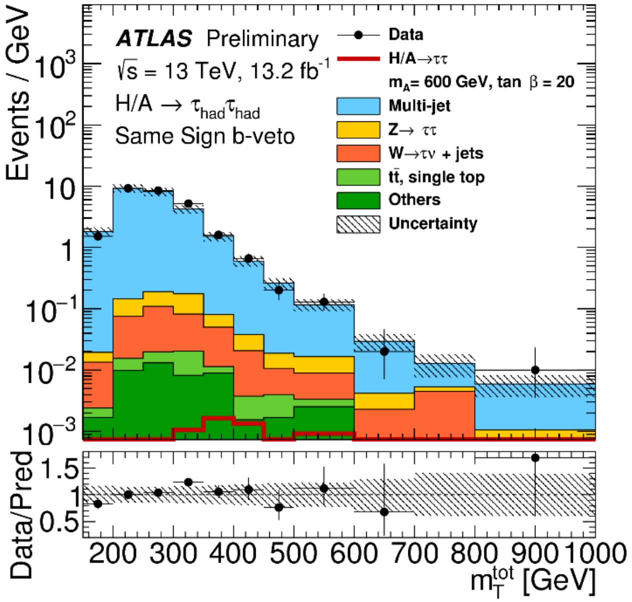
$\tau_{had}\tau_{had}$ backgrounds

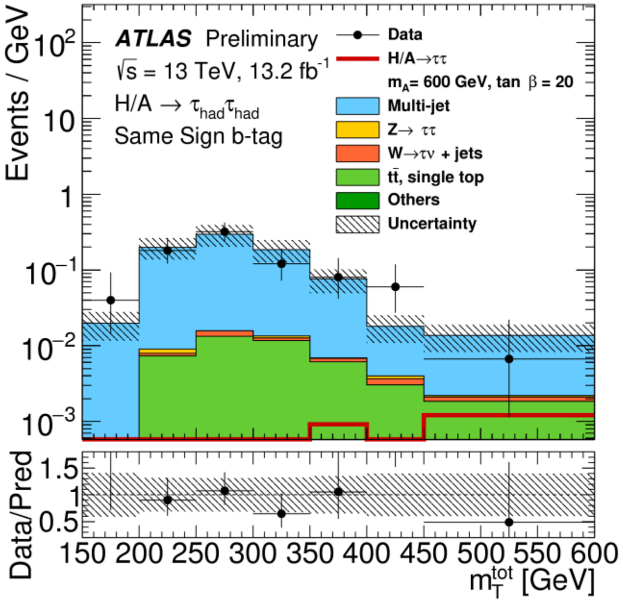
- QCD background estimated with data-driven fake factors. All other backgrounds estimated from simulation
- QCD fake factors are defined as pass/fail TauID ratio of subleading tau. Parameterized in tau pT and N_{tracks}, and done separately for b-tag/b-veto. Computed in QCD control region obtained by inverting TauID requirement of leading tau. Uses jet triggers and no charge requirement for improved statistics

- MC events with fake taus weighted with data-driven fake rates computed in $W \to \mu\nu$ + jets and top control regions and applied to all MC events with fake taus
- Definitions of fake rate control regions are:

  Single muon trigger, $p_T(\mu) > 55$ GeV, $p_T(\tau_{had}) > 50$ GeV, $\Delta\phi(\mu,\tau) > 2.4$, $m_T(\mu, E_T^{miss}) > 40$ GeV

  - b-veto: $\Sigma_{l=\mu,\tau} \cos\left(\Delta\phi\left(l, E_T^{miss}\right)\right) < 0$, $N_{bjet} = 0$
  - b-tag: $N_{bjet} > 0$





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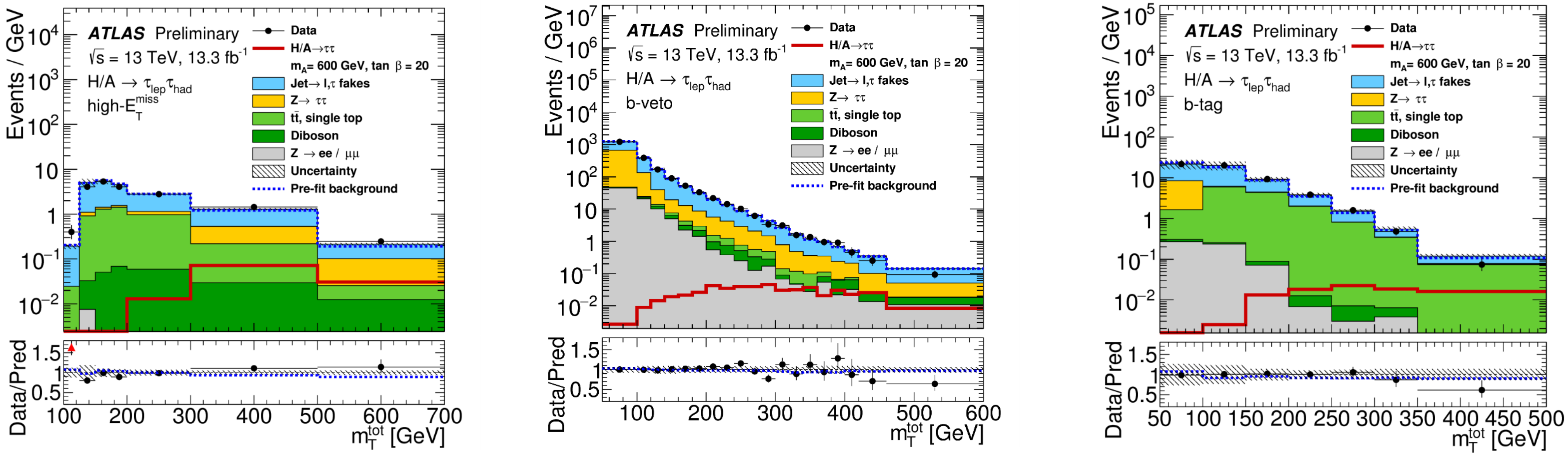
$\tau_{lep}\tau_{had}$ results

- $m_T^{tot} = \sqrt{\left(m_T(l, E_T^{miss})\right)^2 + \left(m_T(\tau_{had}, E_T^{miss})\right)^2 + \left(m_T(l, \tau_{had})\right)^2}$
- Good agreement between prediction and observed data



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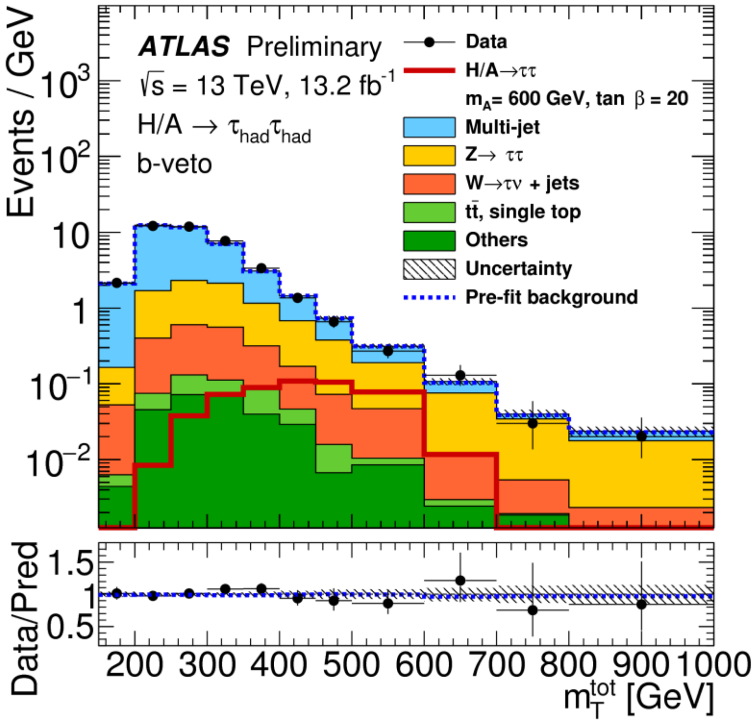
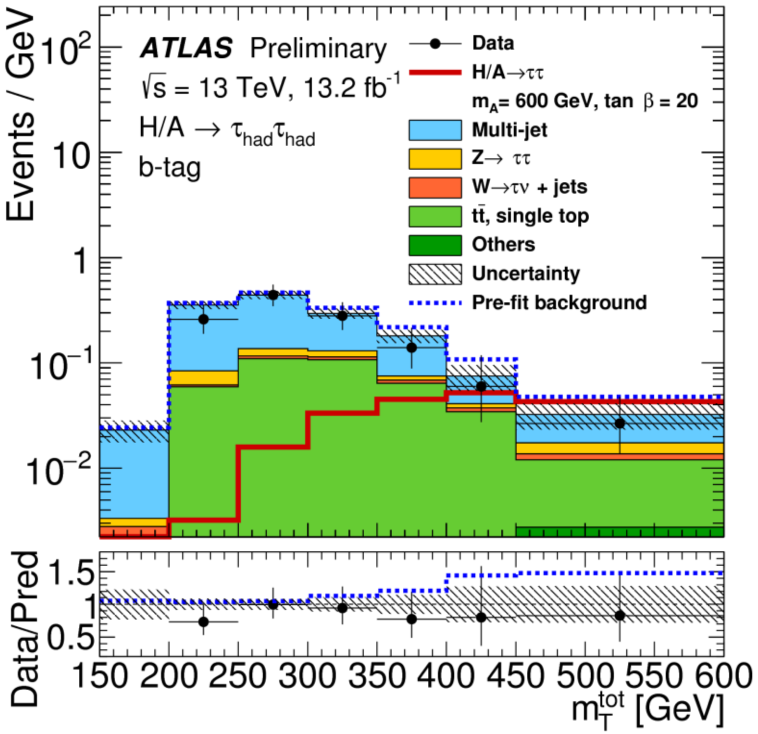
$\tau_{had}\tau_{had}$ results

- $m_T^{tot} = \sqrt{\left(m_T\left(\tau_{had,1}, E_T^{miss}\right)\right)^2 + \left(m_T\left(\tau_{had,2}, E_T^{miss}\right)\right)^2 + \left(m_T\left(\tau_{had,1}, \tau_{had,2}\right)\right)^2}$
- Good agreement between prediction and observed data





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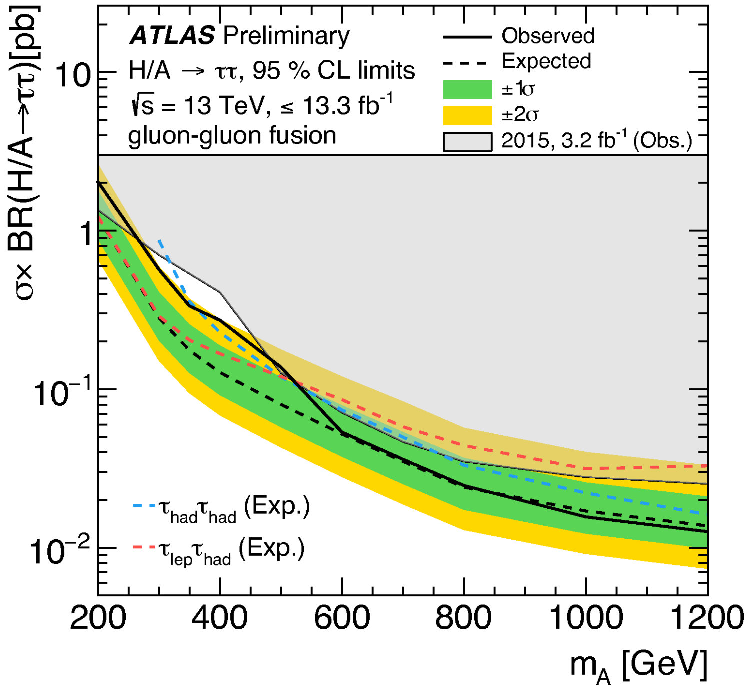
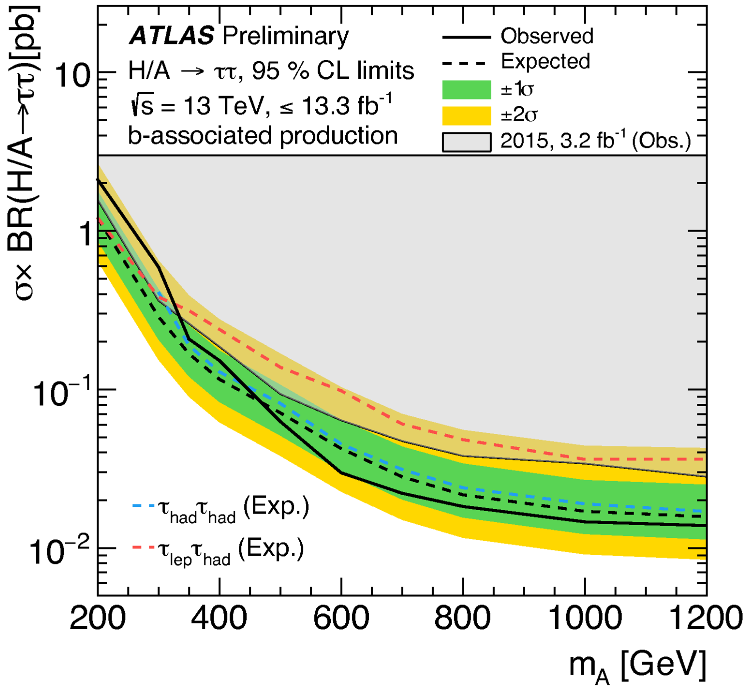
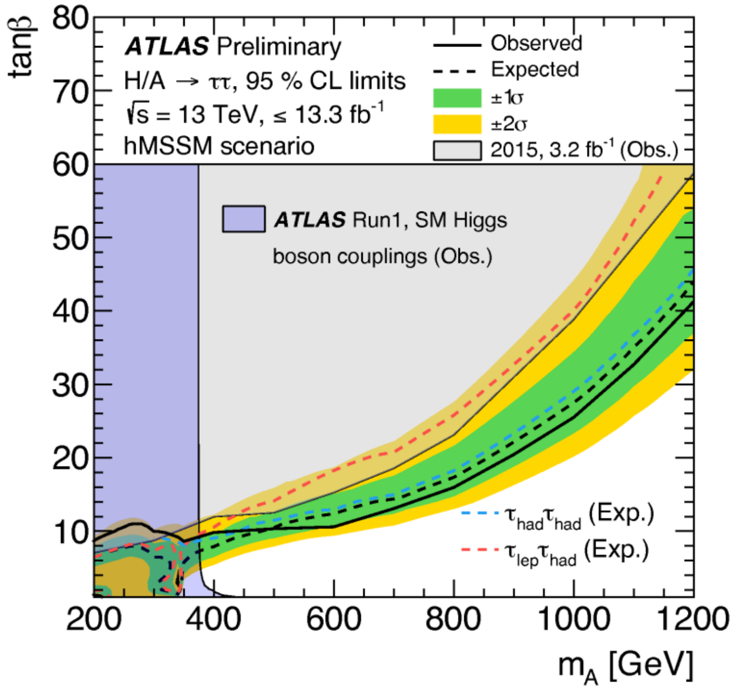
Limits

- Derived 95% CL upper limits on cross section X BR for gluon-fusion and *b*-associated production. Exclusions range from ~2.0 pb to 13 fb depending on m_A and production mode
- Noticeable increase of parameter space exclusion at high mass compared to 3.2 fb^{-1} Run-2 result (shown in grey)







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hMSSM = scenario with some parameters fixed from experiment (e.g. $m_h = 125$ GeV)

Conclusion

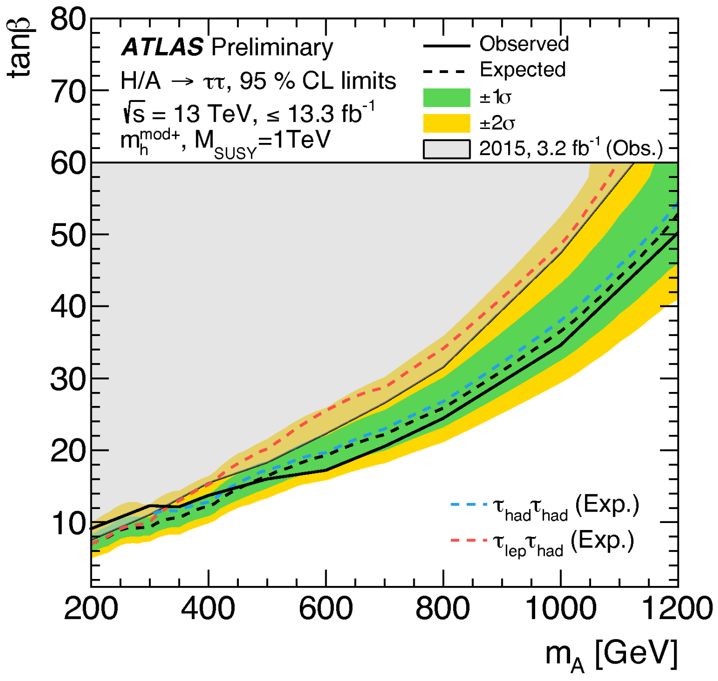
- The latest status of the search for heavy neutral MSSM Higgs bosons decaying to $\tau\tau$ using 13.3/fb of 13 TeV Run-2 data has been shown.
- No significant excess is observed, signal production upper limits are set and results are interpreted for a variety of MSSM benchmark scenarios.
- Exciting prospects for even stronger results as more data is gathered!

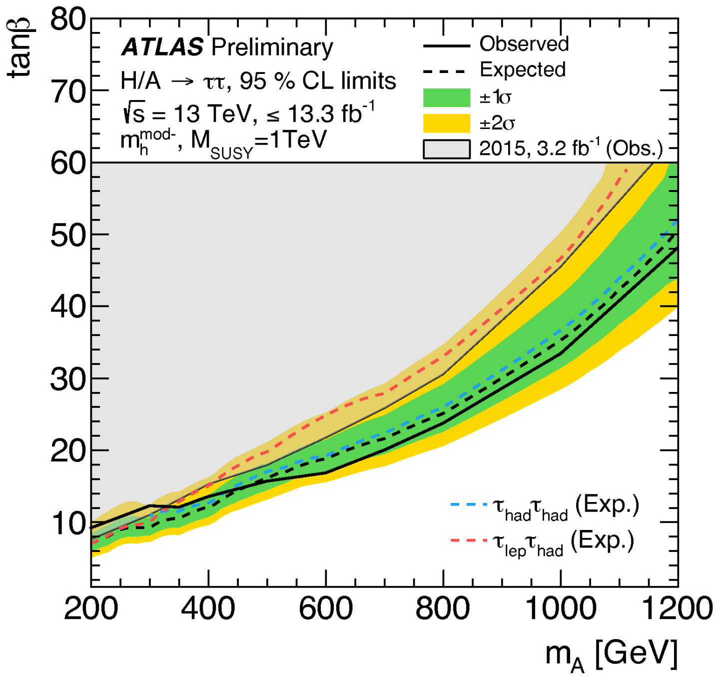
Thanks!

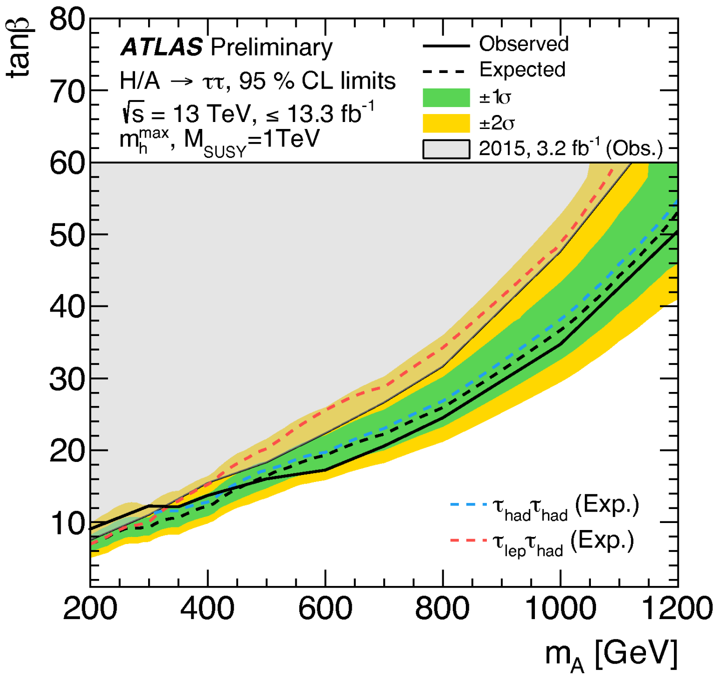
BACKUP

MSSM exclusion – more benchmarks

- Results were interpreted also for m_h^{max}, $m_h^{mod\pm}$ benchmark scenarios







m_h^{max} = scenario with maximal stop mixing, gives maximal light h mass for fixed $\tan\beta$, m_A
m_h^{mod} = modified m_h^{max}, X_t/M_S reduced to give $m_h = 125$ GeV for larger region of parameter space. Two scenarios according to sign of X_t/M_S term

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Selection Summary

$\tau_{\rm lep}\tau_{\rm had}$ signal region	$\Delta\phi(\tau_{\text{had-vis}},\ell) > 2.4$, $m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) < 40~GeV$, Veto $80 < m_{e,\tau} < 110~GeV$ for $\tau_e\tau_{\rm had}$,
high-$E_{\rm T}^{\rm miss}$ category:	$E_{\rm T}^{\rm miss}$ ($\lvert\vec{p_{\rm T}}(\mu) + \vec{E}_{\rm T}^{\rm miss}\rvert$)$> 150~GeV$ for $\tau_e\tau_{\rm had}$ ($\tau_\mu\tau_{\rm had}$),
b-tag/b-veto categories:	fail high-$E_{\rm T}^{\rm miss}$ category requirements, $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
b-veto/$t\bar{t}$ fake-factor control region	$m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) > 70$ (60) GeV for $\tau_e\tau_{\rm had}$ ($\tau_\mu\tau_{\rm had}$), $N_{b\text{-tag}} = 0$ different $\tau_{\text{had-vis}}$ identification for the anti-$\tau_{\rm had}$ region
b-tag control region	$N_{b\text{-tag}} \geq 1$, $m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) > 100~GeV$
Multi-jet fake-factor control region	invert e,μ isolation requirement, $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto and high-$E_{\rm T}^{\rm miss}$ categories) different $\tau_{\text{had-vis}}$ identification for the anti-$\tau_{\rm had}$ multi-jet control region
Multi-jet control region for $r_{\rm MJ}$ estimation	$m_{\rm T}(\ell, E_{\rm T}^{\rm miss}) < 30$ GeV, no e,μ isolation requirement, no $\tau_{\text{had-vis}}$ passing loose identification, $N_{\rm jet} \geq 1$ and $N_{b\text{-tag}} = 0$ (b-veto category), $N_{\rm jet} \geq 2$ and $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{\rm jet} \geq 1$, $N_{b\text{-tag}} = 0$ and $E_{\rm T}^{\rm miss}$ ($\lvert\vec{p_{\rm T}}(\mu) + \vec{E}_{\rm T}^{\rm miss}\rvert$)$> 150~GeV$ for $\tau_e\tau_{\rm had}$ ($\tau_\mu\tau_{\rm had}$) (high-$E_{\rm T}^{\rm miss}$ category)

$\tau_{\rm had}\tau_{\rm had}$ signal region	$\Delta\phi(\tau_{\text{had-vis},1},\tau_{\text{had-vis},2}) > 2.7$, $N_{b\text{-tag}} \geq 1$ and $p_{\rm T} > 65~GeV$ for the sub-leading $\tau_{\text{had-vis}}$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
Multi-jet fake-factor control region	pass single-jet trigger, leading $\tau_{\text{had-vis}}$ with $p_{\rm T} > 100~GeV$ that fails medium identification, no charge requirements and for leading $\tau_{\text{had-vis}}$ $n_{\rm tracks} \leq 7$ (b-tag category), $n_{\rm tracks} = 1,3$ (b-veto category), $\frac{p_{\rm T}^{\tau_{\text{had-vis},2}}}{p_{\rm T}^{\tau_{\text{had-vis},1}}} > 0.3$
Fake rate control region	pass single-muon trigger, isolated muon with $p_{\rm T} > 55~GeV$, $\tau_{\text{had-vis}}$ with $p_{\rm T} > 50~GeV$, $\Delta\phi(\mu,\tau_{\text{had-vis}}) > 2.4$, $m_{\rm T}(\mu, E_{\rm T}^{\rm miss}) > 40~GeV$ %$\sum_{L=\mu,\tau}\cos\Delta\phi(L, E_{\rm T}^{\rm miss}) < 0$ (for b-veto category only) $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
Same-sign validation region	The two $\tau_{\text{had-vis}}$ objects are required to have the same electric charge

Event Yields

$\tau_e\tau_{\rm had}$ channel	b-tag category			b-veto category			high-$E_T^{\rm miss}$ category		
$Z \to \tau\tau$+jets	150	±	40	14200	±	900	13	±	2
Jet $\to \ell, \tau_{\text{had-vis}}$ fakes	770	±	260	20000	±	3900	72	±	9
$Z \to \ell\ell$+jets	20	±	4	1370	±	180	-	±	-
$t\bar{t}$ and single top quark	370	±	30	90	±	14	29	±	3
Diboson	3.0	±	0.6	141	±	13	2.6	±	0.6
Total prediction	1320	±	270	35800	±	4000	117	±	11
Data	1304			35841			123		
$m_A = 600GeV, \tan\beta = 20$ ($m_h^{\rm mod+}$)									
ggH	0.019	±	0.007	1.02	±	0.17	0.32	±	0.06
bbH	4.5	±	0.9	7.2	±	1.5	3.9	±	0.9

$\tau_\mu\tau_{\rm had}$ channel	b-tag category			b-veto category			high-$E_T^{\rm miss}$ category		
$Z \to \tau\tau$+jets	210	±	50	19800	±	1100	91	±	11
Jet $\to \ell, \tau_{\text{had-vis}}$ fakes	960	±	340	18800	±	1900	540	±	60
$Z \to \ell\ell$+jets	10	±	3	1700	±	130	0.22	±	0.08
$t\bar{t}$ and single top quark	350	±	30	85	±	13	187	±	17
Diboson	1.3	±	0.5	190	±	16	14.9	±	2.0
Total prediction	1530	±	350	40600	±	2100	830	±	70
Data	1539			40556			839		
$m_A = 600GeV, \tan\beta = 20$ ($m_h^{\rm mod+}$)									
ggH	0.010	±	0.004	0.4	±	0.06	1.3	±	0.2
bbH	1.6	±	0.4	3.0	±	0.7	16	±	3

$\tau_{\rm had}\tau_{\rm had}$ channel	b-tag category			b-veto category		
$Z \to \tau\tau$+jets	4.0	±	0.9	340	±	40
Multi-jet	47	±	4	1500	±	60
$W \to \tau\nu$ + jets	1.50	±	0.21	91	±	9
$t\bar{t}$ and single top quark	20	±	6	10	±	6
Others	0.51	±	0.21	14.8	±	2.0
Total prediction	73	±	6	1980	±	40
Data	63			2006		
$m_A = 600GeV, \tan\beta = 20$ ($m_h^{\rm mod+}$)						
ggH	0.042	±	0.014	3.2	±	0.7
bbH	14	±	4	27	±	8

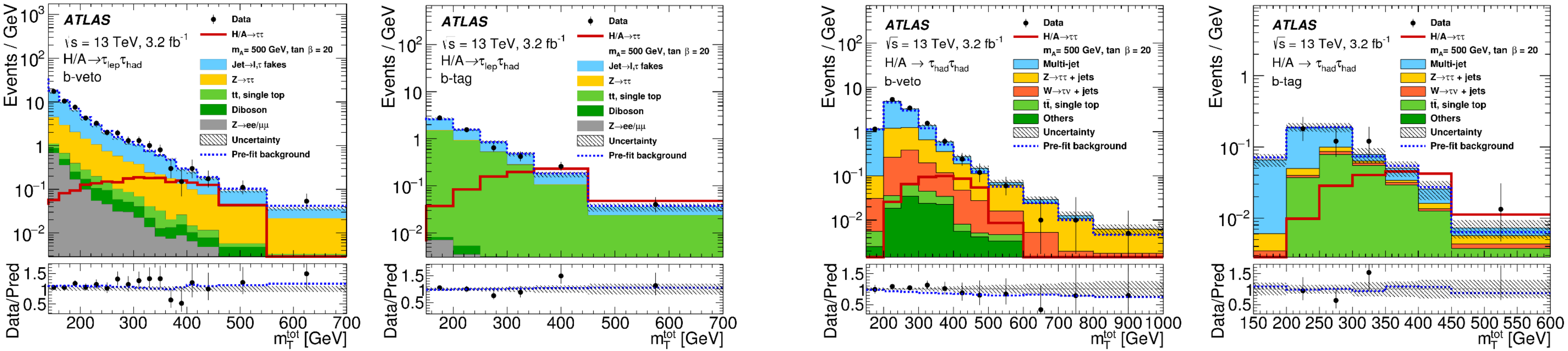
Systematic Uncertainties

Shown as fractional impact on total signal strength with $m_A = 600$ GeV, $\tan\beta = 20$

Source of uncertainty	F_- (%)	F_+ (%)
$t\bar{t}$ background parton shower model	-21	$+39$
$\tau_{\text{had-vis}}$ energy scale, detector modelling	-10	$+12$
r_{MJ} estimation b-veto region ($\tau_\mu\tau_{\text{had}}$)	$-\ 5$	$+\ 6$
r_{MJ} estimation b-veto region ($\tau_e\tau_{\text{had}}$)	$-\ 2.3$	$+\ 3.0$
bbH signal cross-section uncertainty	$-\ 3.8$	$+\ 1.6$
Multi-jet background ($\tau_{\text{had}}\tau_{\text{had}}$)	$-\ 2.2$	$+\ 2.6$
Jet-to-$\tau_{\text{had-vis}}$ fake rate b-veto region ($\tau_{\text{lep}}\tau_{\text{had}}$)	$-\ 1.3$	$+\ 2.9$
$\tau_{\text{had-vis}}$ energy scale, in-situ calibration	$-\ 1.4$	$+\ 1.1$
r_{MJ} estimation high-$E_{\text{T}}^{\text{miss}}$ region ($\tau_\mu\tau_{\text{had}}$)	$-\ 1.4$	$+\ 1.0$
τ trigger (2016)	$-\ 0.5$	$+\ 1.3$
Statistics (data and simulation)	-48	$+25$

$H/A \to \tau\tau$: 3.2/fb results

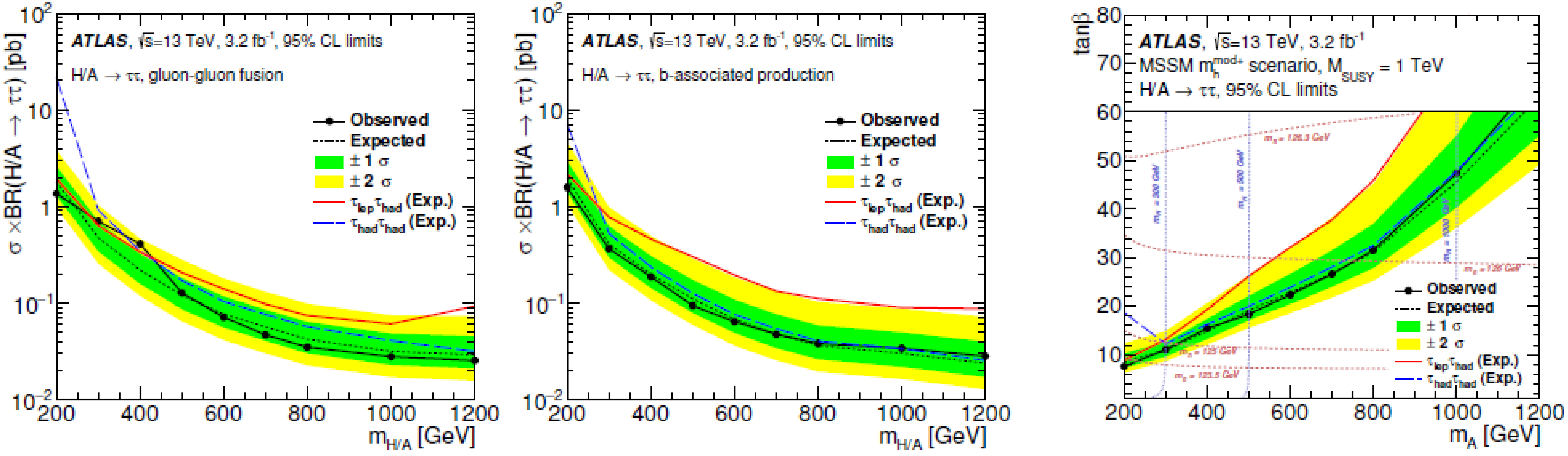
- Good agreement between prediction and observed data



arXiv:1608.00890v2 (submitted to EPJC)

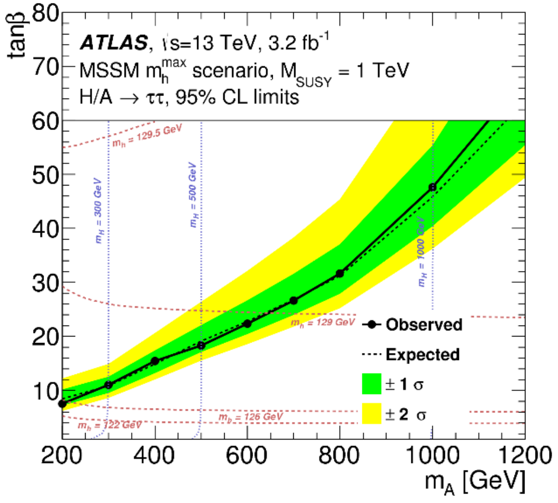
$H/A \to \tau\tau$: results

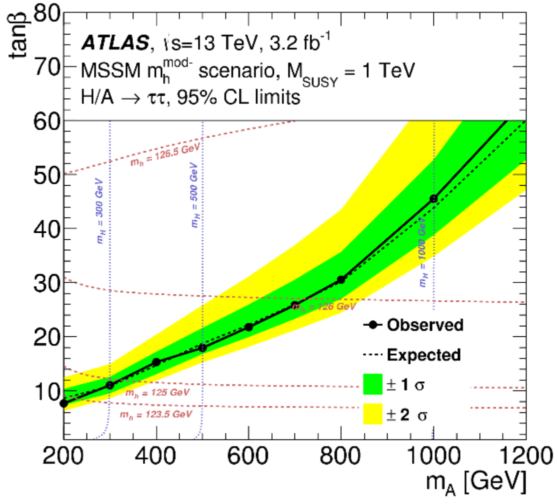
- The results were interpreted in several MSSM benchmark scenarios

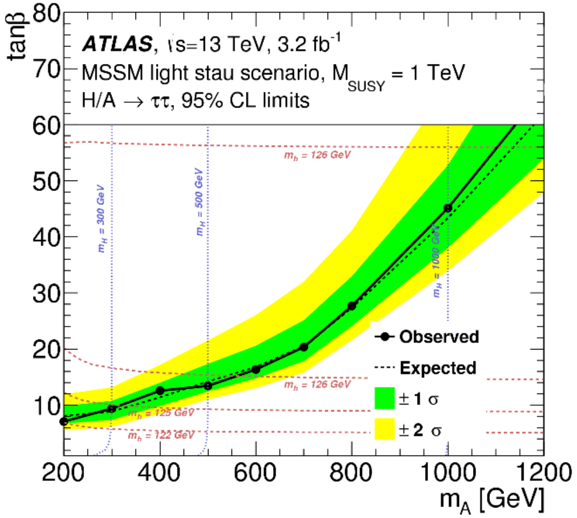


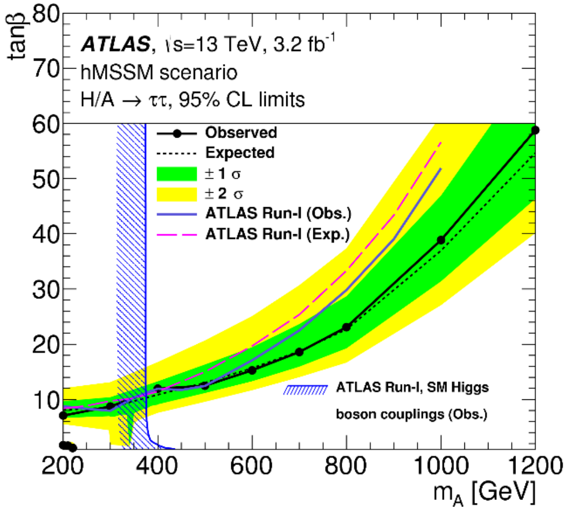
arXiv:1608.00890v2 **(submitted to EPJC)**

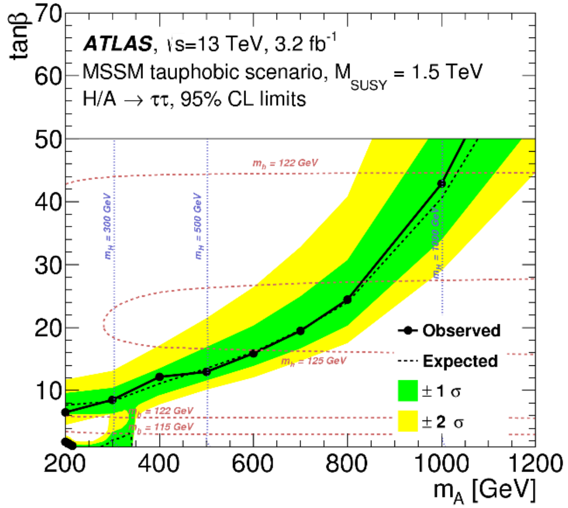
$H/A \rightarrow \tau\tau$ – more benchmarks

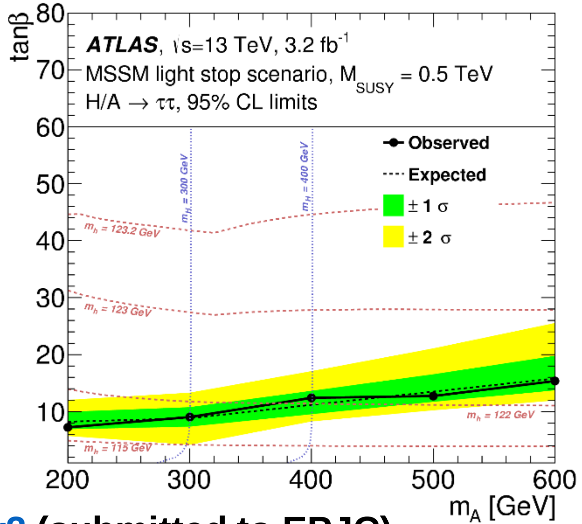












arXiv:1608.00890v2 (submitted to EPJC)

$\tau_{lep}\tau_{had}$ backgrounds: e fakes

- The ehad channel also has a significant background of $Z \rightarrow ee$ events
- An additional problem is that there is a strong mismodelling in the forward region associated with this background
- The problem is solved by 3 measures:
  - Vetoing events with $\eta_{\tau_{had}} > 2.3$
  - Vetoing ehad events with $80(90) < m^{vis}_{\tau_{lep}\tau_{had}} < 110(100)$ GeV for 1p (3p), the so-called *Z*-mass control region
  - Using $e \rightarrow \tau_{had}$ scale factors computed in the *Z*-mass control region

$\tau_{lep}\tau_{had}$ backgrounds: multi-jet fraction (r_{QCD})

- To quantify the fraction of QCD and W+jets, lepton fake factors are computed in a fake lepton control region (CR)
- The selection for this CR is:
  - Single lepton trigger and exactly one lepton, no isolation required because the fake factors are the ratio of pass/fail isolation
  - No loose τ_{had}
  - $N_{jet} \geq 1, N_{b-tag} = 0$ (b-veto); $N_{jet} \geq 2, N_{b-tag} = 1$ (b-tag); $N_{jet} \geq 1, N_{b-tag} = 0, E_T^{miss} > 150$ GeV (high MET);
  - $m_T\left(l, E_T^{miss}\right) < 30$ GeV
- Parameterized as a function of lepton η, they are defined as the pass/fail ratio of the isolation criteria of the lepton
- FF are applied to an anti-isolated anti-τ region to estimate the dijet background fraction in the isolated anti-τ region
- The r_{QCD} is then defined as:

$$r_{QCD} = \frac{QCD}{data\ - true\ MC}$$

- r_{QCD} is parameterized as a function of tau p_T