Searches for Beyond Standard Model Higgs bosons in *pp* collisions at $\sqrt{s}$ = 8 and 13 TeV with the ATLAS detector

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Final Exam

Outline

Theory and Apparatus

- Standard Model
- Beyond Standard Models
- LHC and ATLAS
- Working with tau leptons

→

$A \rightarrow Zh \rightarrow ll\tau_{lep}\tau_{had}$

- Overview
- Selection
- Backgrounds
- Results

→

MSSM $H/A \rightarrow \tau\tau$

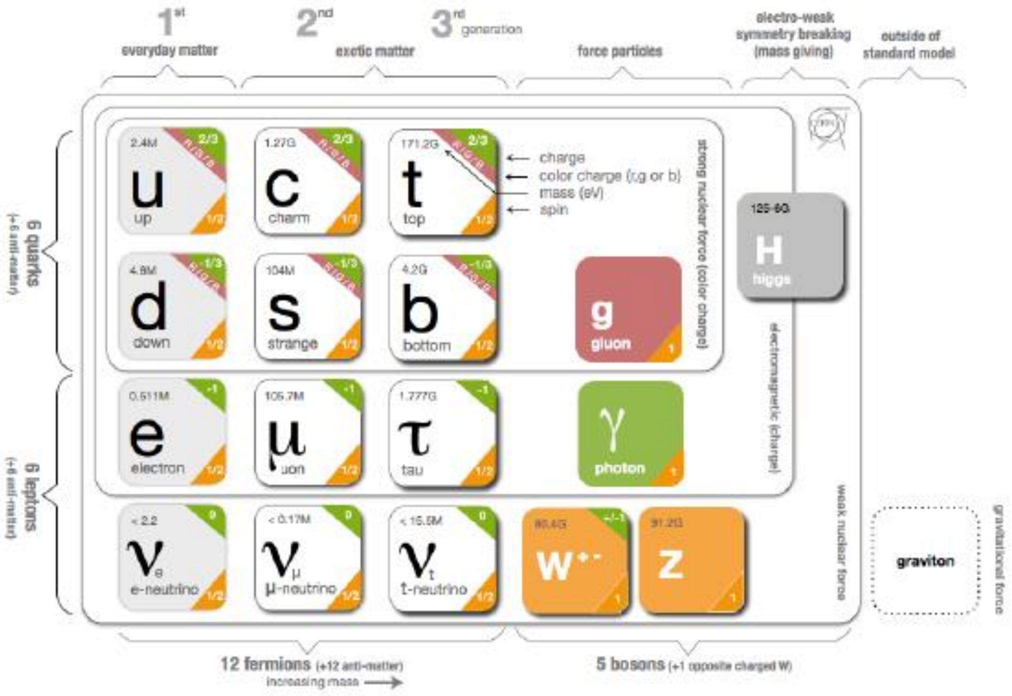
- Overview
- Selection
- Backgrounds
- Results

↓

Conclusion

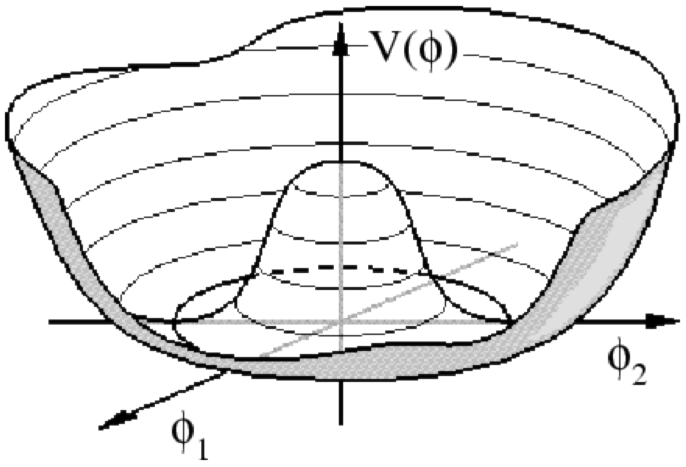
The Standard Model

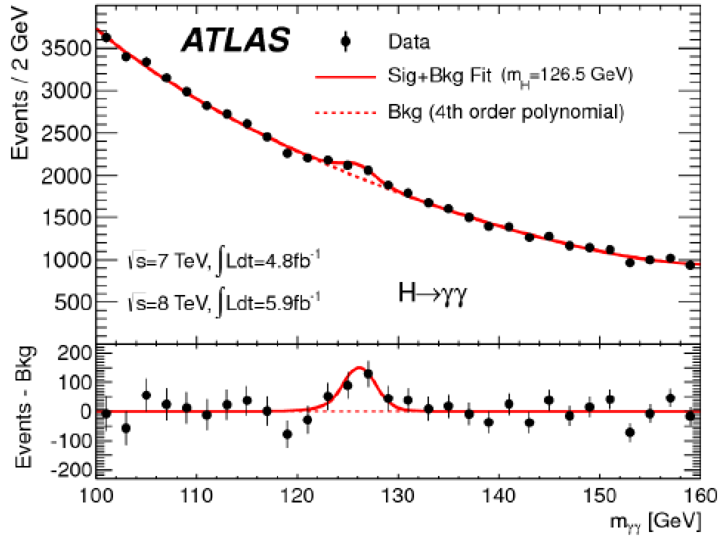
- The most complete theory of fundamental particles and their interactions
- Higgs boson recently discovered, completes the SM particle content
- Particles are divided into bosons and fermions.
- Bosons (γ, g, $W^{\pm}$, Z and h) are the force mediators
- Fermions make up visible matter and are divided into quarks and leptons



The Higgs field

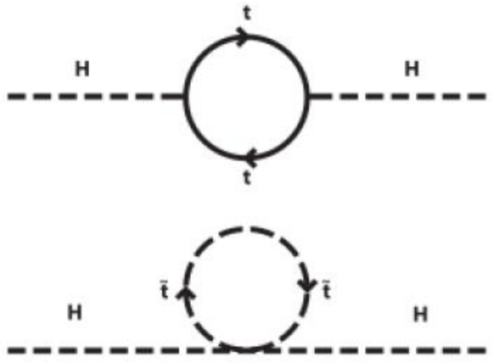
- The electroweak symmetry is broken by the non-zero vacuum expectation value of the Higgs field
- The Higgs field is responsible for giving the masses to the gauge bosons and fermions
- A particle compatible with the SM Higgs was discovered in 2012 at 125 GeV



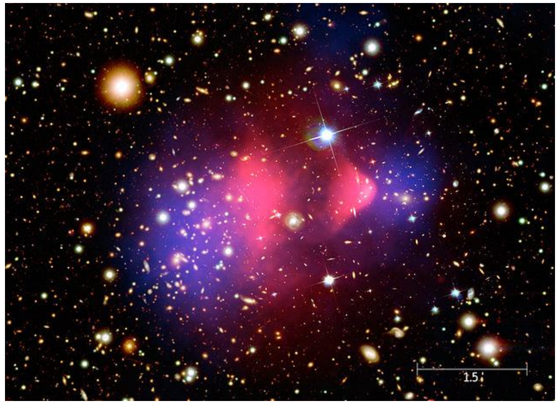


Beyond Standard Models

- We know the standard model of particle physics, while very successful, cannot be the full picture:
  - Naturalness problem
  - CP-violation
  - Dark matter / dark energy
  - Gravity

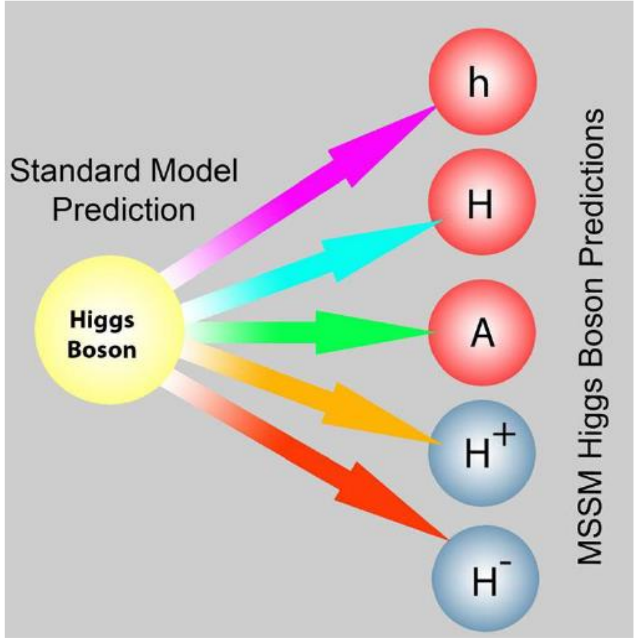


- It is then necessary to go Beyond the Standard Model to seek solutions to these problems.
- There is a very large number of BSM theories that solve the SM shortcomings in different ways.
- This talk will focus on extensions to the Higgs sector, in particular through 2-Higgs-Doublet Models (2HDM) and its particular case, the MSSM.



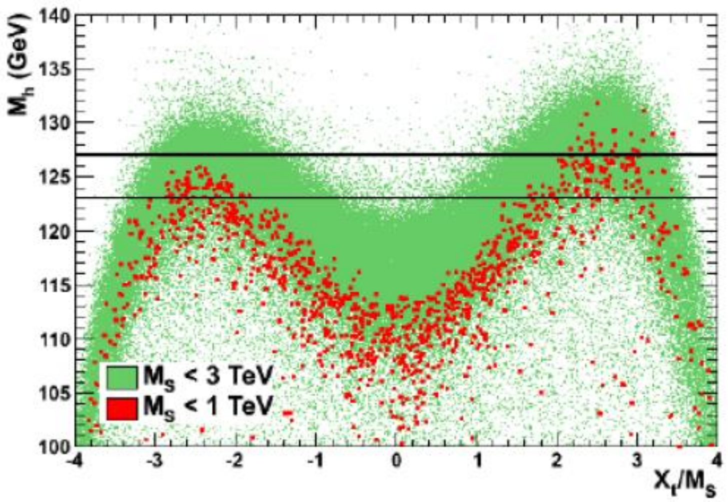
2HDM

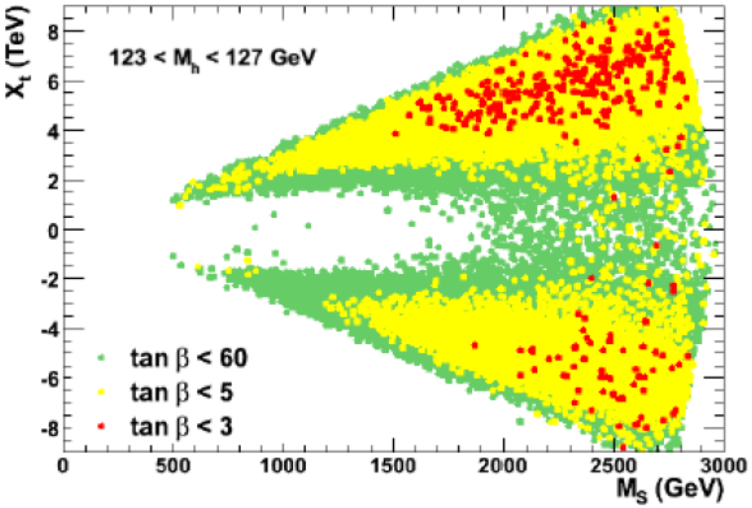
- A simple extension to the Standard Model Higgs sector is the addition of a second Higgs doublet. This (large) class of models is collectively called 2 Higgs Doublet Models or 2HDM
- With the added doublet, the Higgs sector is now composed of 5 Higgs bosons: h (in most models the 125 GeV Higgs), H, A, H^+ and H^-
- 2HDMs are a very broad class of models. Will focus on two types of 2HDM:
  - Type-I: all quarks and charged leptons couple to only one Higgs doublet
  - Type-II: up-type quarks couple to ϕ_1 and down-type quarks and charged leptons couple to ϕ_2



MSSM

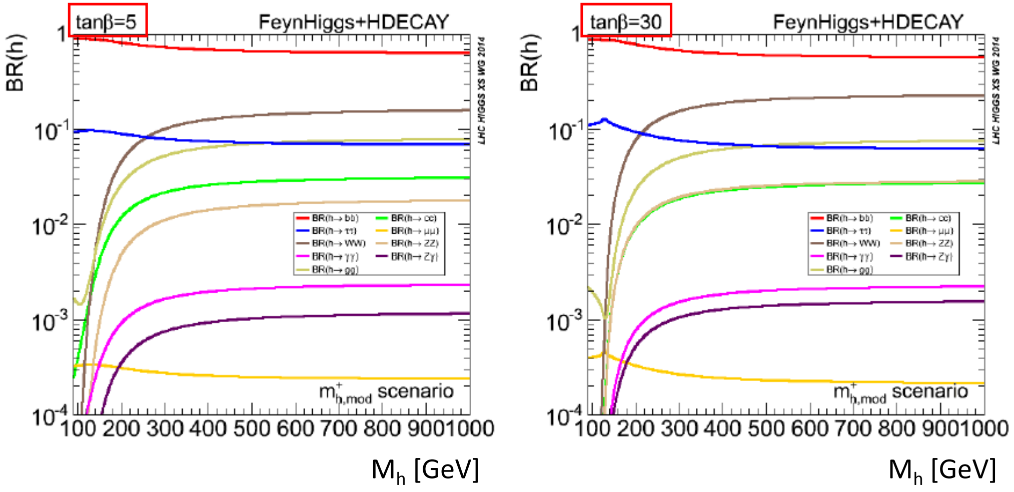
- The Minimal Supersymmetric Standard Model (MSSM) is a minimal realization of supersymmetry that is particular case of type-II 2HDM.
- SUSY doubles the particle content of the SM.
- A motivation for SUSY is that it can solve the naturalness problem. In SUSY, the one-loop corrections to the Higgs mass cancel with the corrections from the interactions of the Higgs with the fermionic superpartners.
- MSSM models are still compatible with the 125 GeV Higgs discovery.

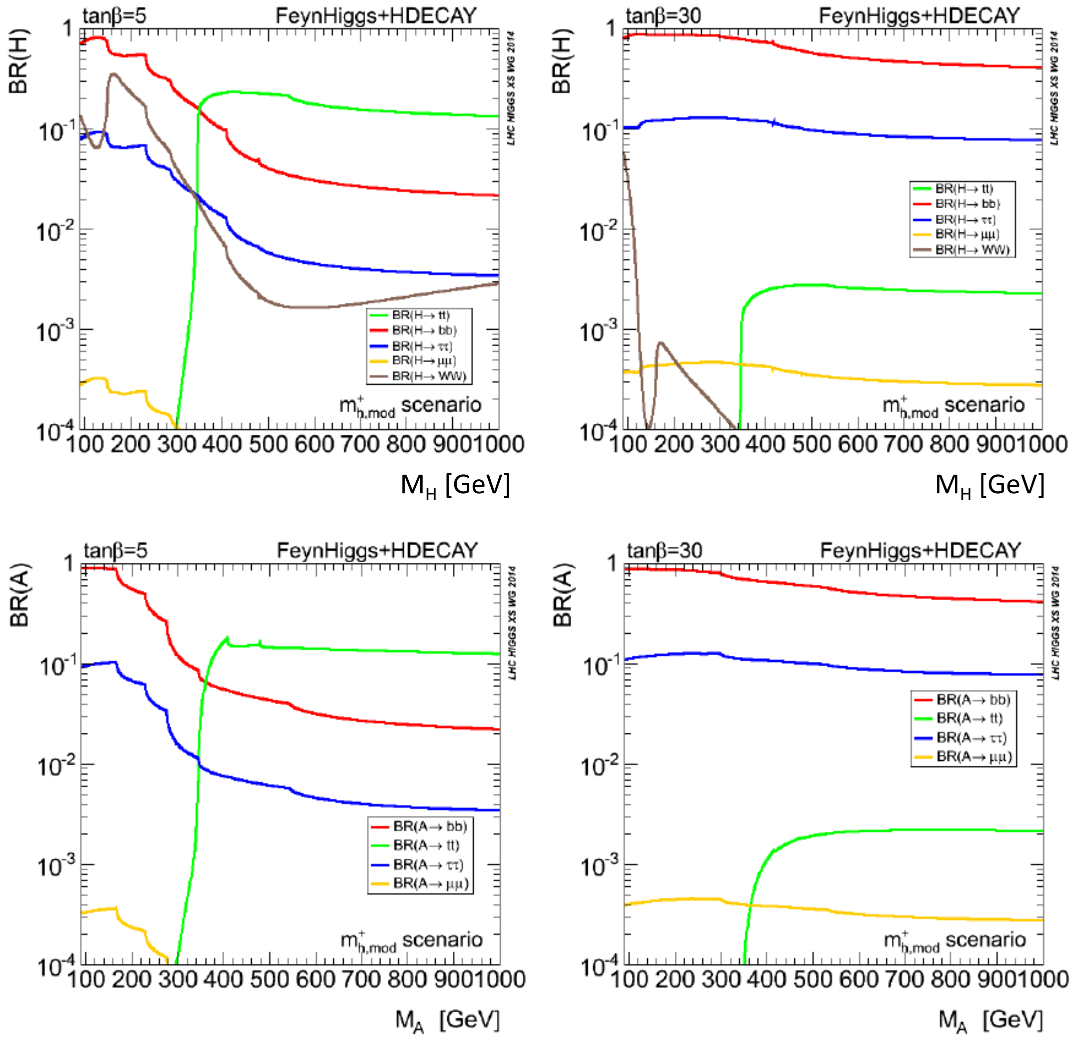




From Arbey (2012) *et al.*

MSSM branching ratios

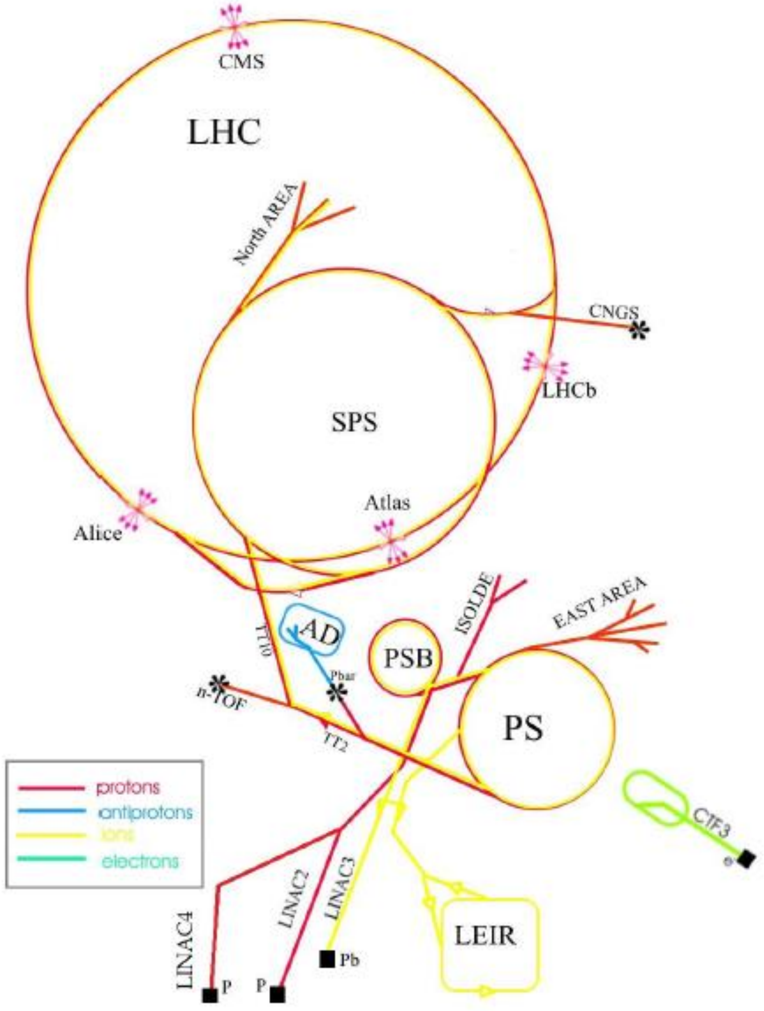




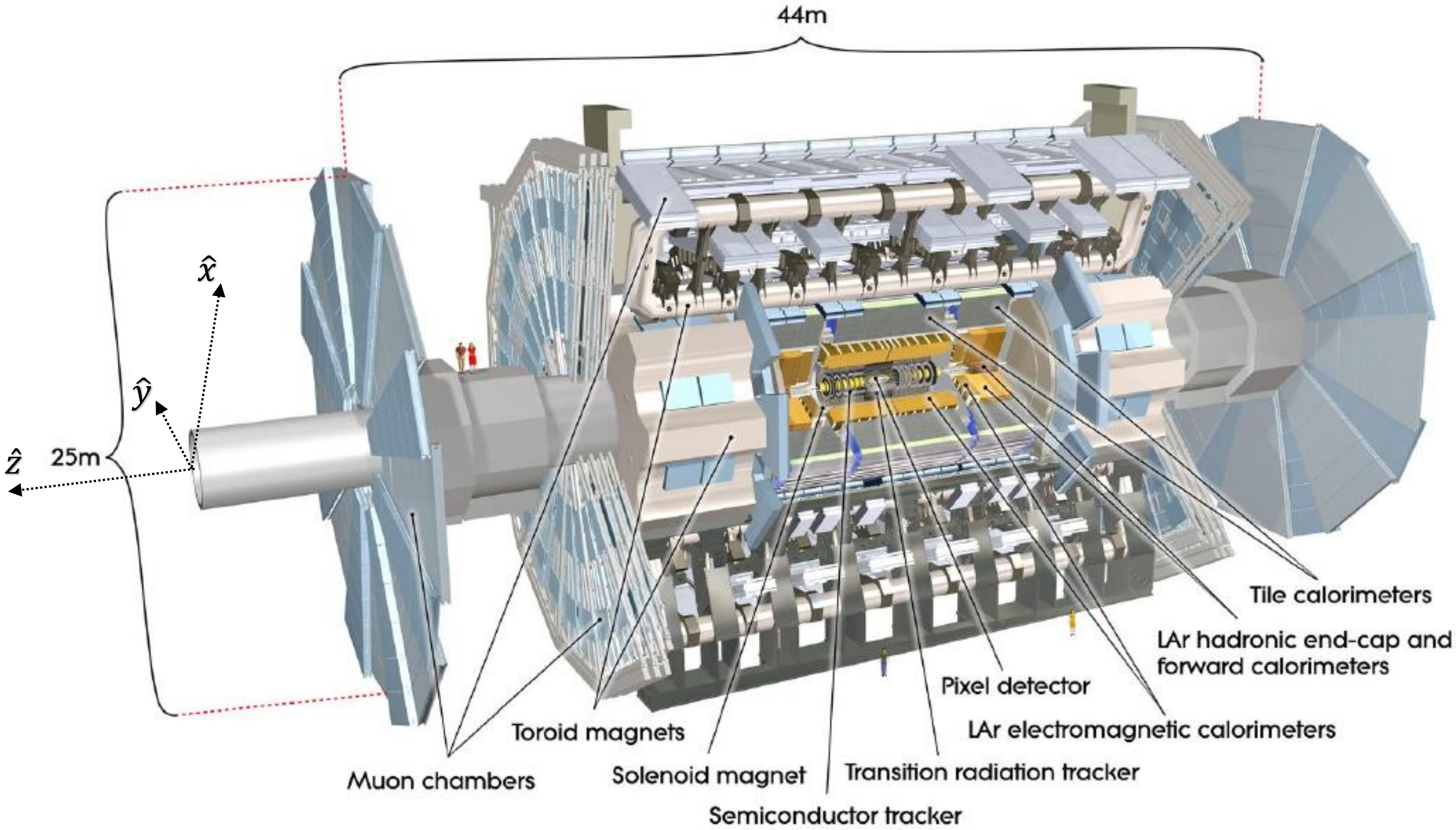
BR plots from LHCHXWG

The Large Hadron Collider (LHC)

- Located at CERN near Geneva, Switzerland, the LHC is an underground proton-proton (and heavy ion) collider with 27 km of circumference
- Currently colliding hadrons at center-of-mass (c.o.m.) energy of 13 TeV
- Houses 4 major experiments: ATLAS, CMS, LHCb, Alice
- Has been operational since 2010. The data-taking period of 2010-2013 is referred to as Run-1, with collisions at c.o.m. energies of 8 TeV (with a shorter 7 TeV period initially)
- After Run 1, the LHC underwent a planned shutdown for hardware upgrades, and resumed in 2015 (Run 2) with collisions at 13 TeV.



A Toroidal LHC Apparatus (ATLAS)

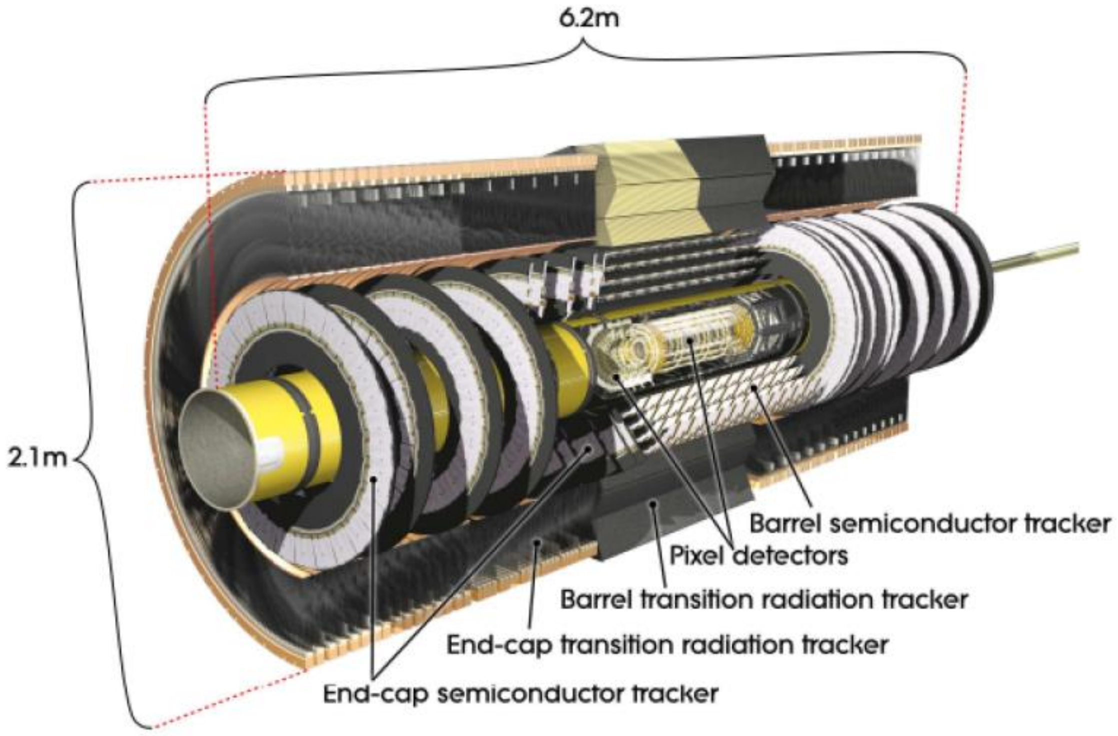


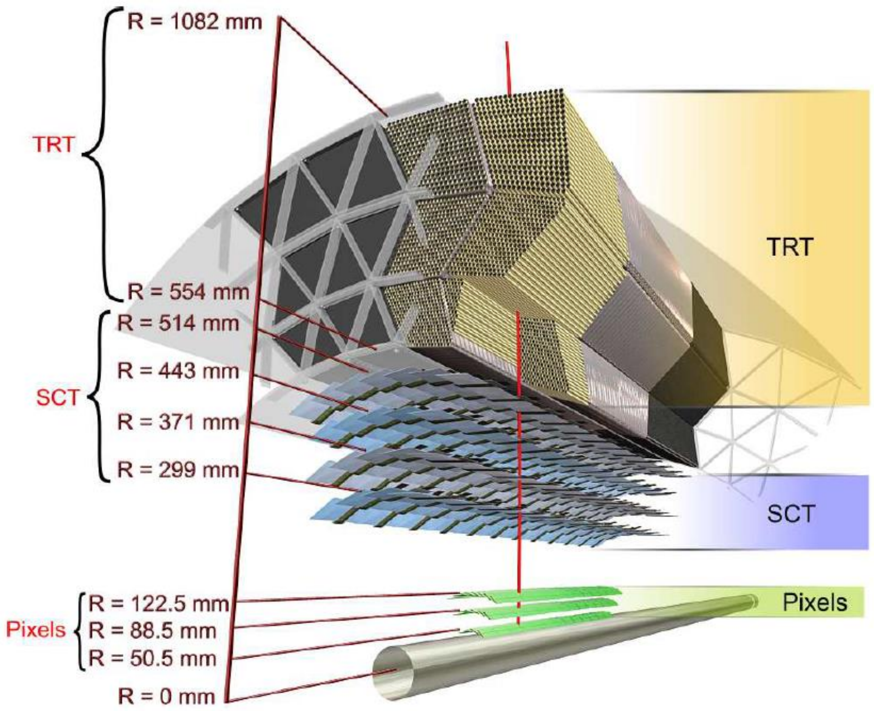
$$y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

$\eta \equiv -\ln \tan \frac{\theta}{2}$, where θ is the azimuthal angle

The Inner Detector

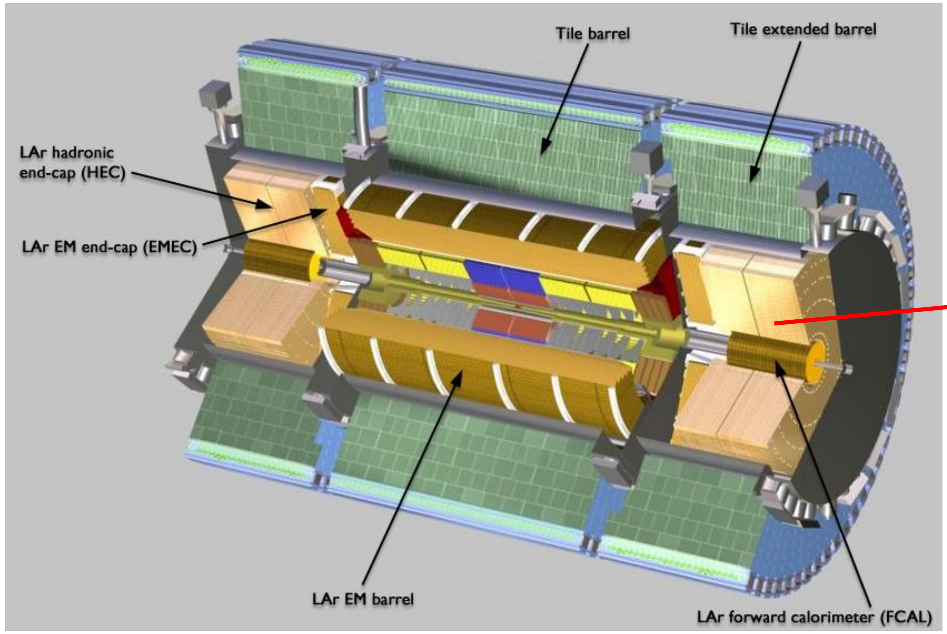
- Consists of IBL, Pixel, SCT and TRT
- Fine resolution and has a 2 Tesla magnetic field that allows it to measure charged particles tracks and their momentum

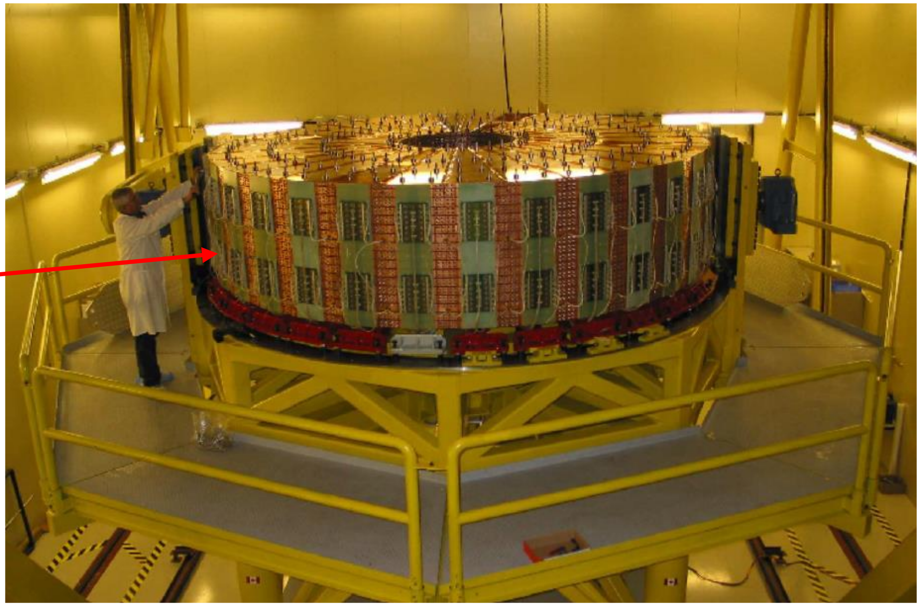




The Calorimeters

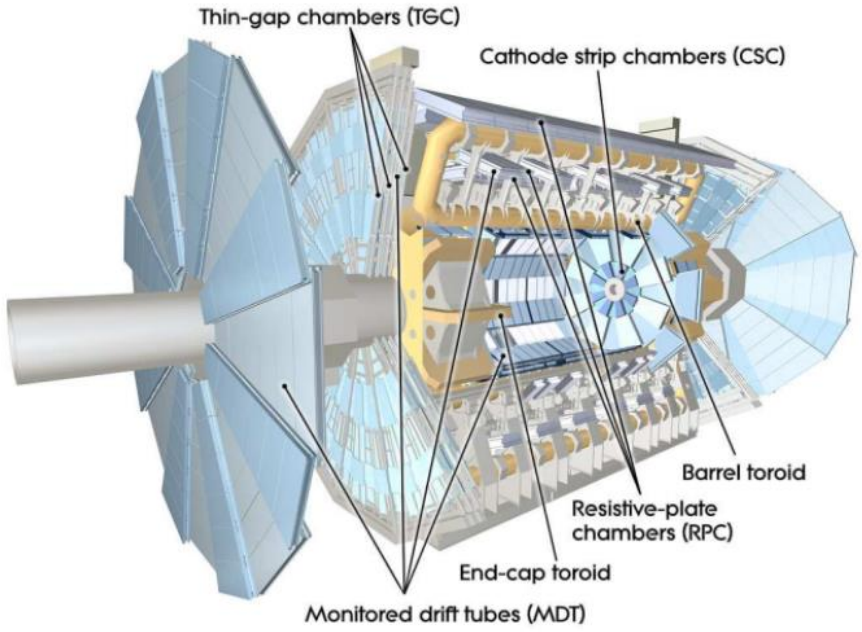
- ATLAS has two calorimeter systems: the EM calorimeter and the hadronic calorimeter
- The EM calorimeter is a lead-liquid Argon detector well suited for reconstructing electrons and photons
- The hadronic calorimeter is subdivided into a Tile, Hadronic end-cap (HEC), and Forward (FCal) calorimeters. It measures the energy deposits of hadronic showers.





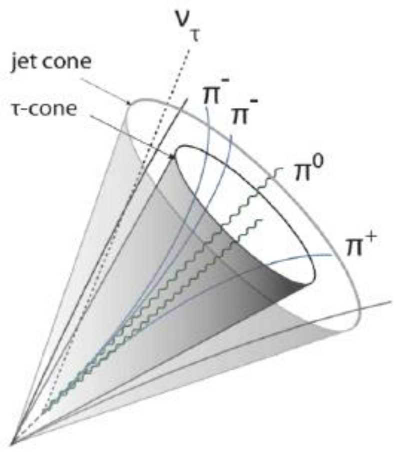
The Muon Spectrometer

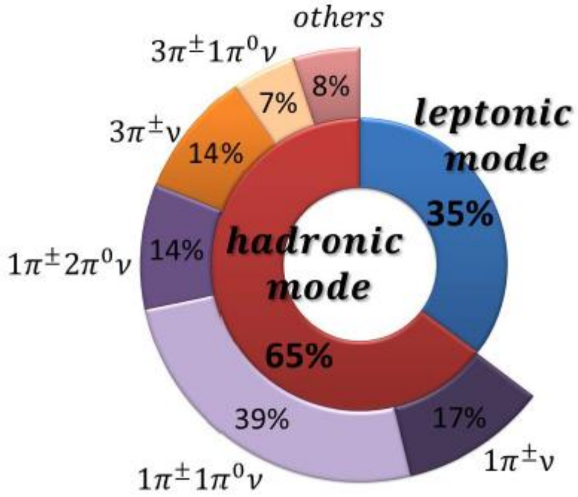
- Immersed in a magnetic field from the toroid magnet, the muon spectrometer measures the momentum and position of muons
- The magnetic field is not uniform, and has a bending power varying between 2 and 8 Tm
- Has 4 subdetector systems: the MDT, RPC, CSC and TGC
- The MDT and CSC provide precise position measurements. The TGC and RPC help with this measurement and provide the infrastructure for the ATLAS muon triggers.



Taus

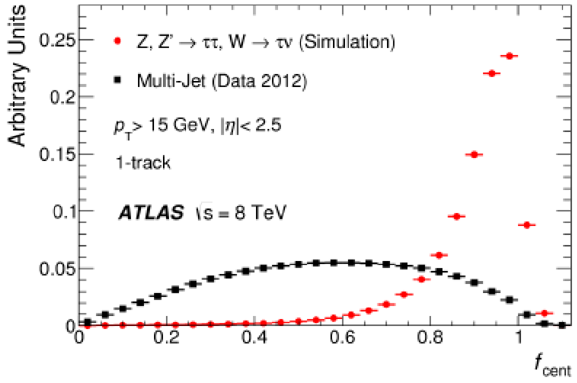
- The heavy Higgs particles decay mostly to taus or $b\bar{b}$, especially at high $\tan\beta$. However, the heavy backgrounds in the latter make the tau channel more appealing.
- Taus are referred to as leptonic when they decay to light leptons (e, μ), or hadronic when they decay to pions.
- Hadronic taus are further classified as 1-prong (1p) or 3-prong (3p) depending on the number of charged pions in the decay
- Hadronic taus look like narrow jets, making jets the biggest source of fake taus.
- Reconstructing parent particle mass for final states with taus can be challenging due to neutrinos in decay

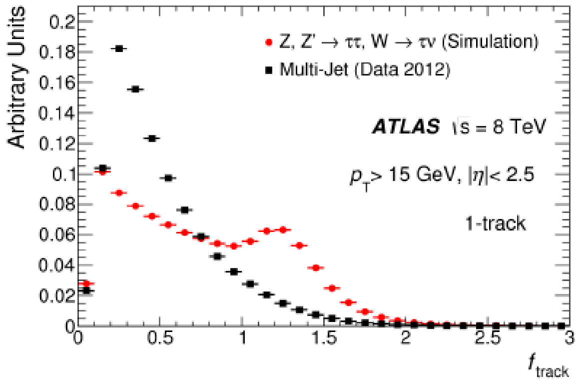


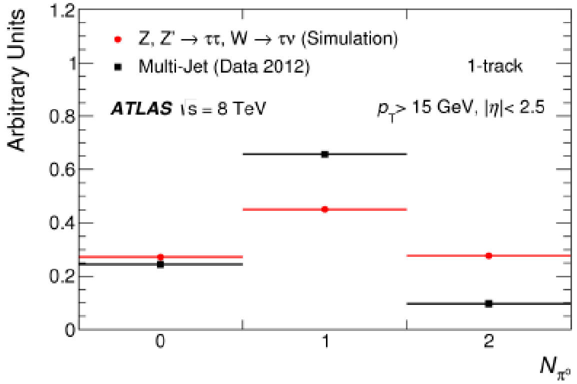


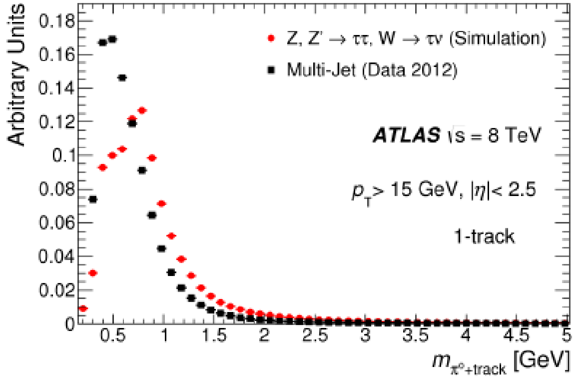
TauID – Boosted Decision Tree

- The discrimination between taus and jets in ATLAS is achieved through a boosted decision tree (BDT), a type of multivariate classifier, called the TauID.
- Uses 8 – 9 input variables where the kinematic differences between true and fake hadronic tau objects are most evident
- Trained separately for 1-track and 3-track hadronic taus.
- Uses tau objects from simulated $Z \rightarrow \tau\tau$ events and multijet background obtained from data.



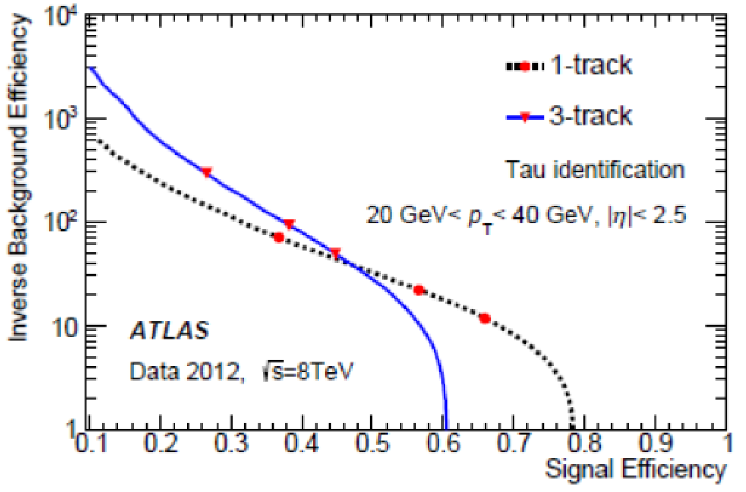


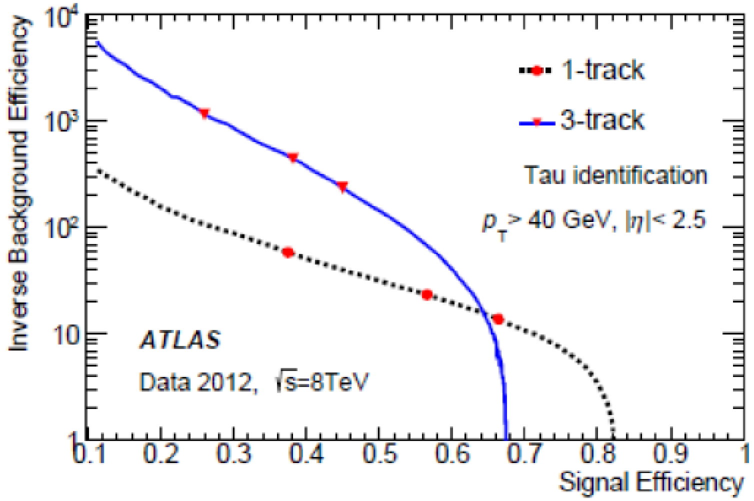


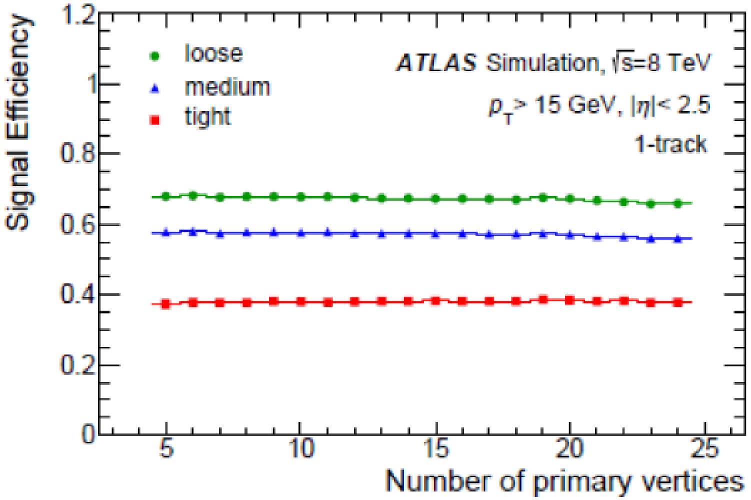


TauID – result

- The new ID included for the first time π^0 information, and thus performed significantly better than the previous iteration. Working points were also tuned, flat efficiency in p_T and robust versus pileup.
- Three efficiency points are defined (*tuned*), Loose, Medium and Tight, which have progressively lower signal selection efficiencies. These efficiencies are roughly 65% (70%), 55% (60%) and 35% (40%) for 1p (3p), respectively.
- ***Identification and energy calibration of hadronically decaying tau leptons with the ATLAS experiment in pp collisions at √s=8 TeV***. Eur.Phys.J. C75 (2015) no.7, 303

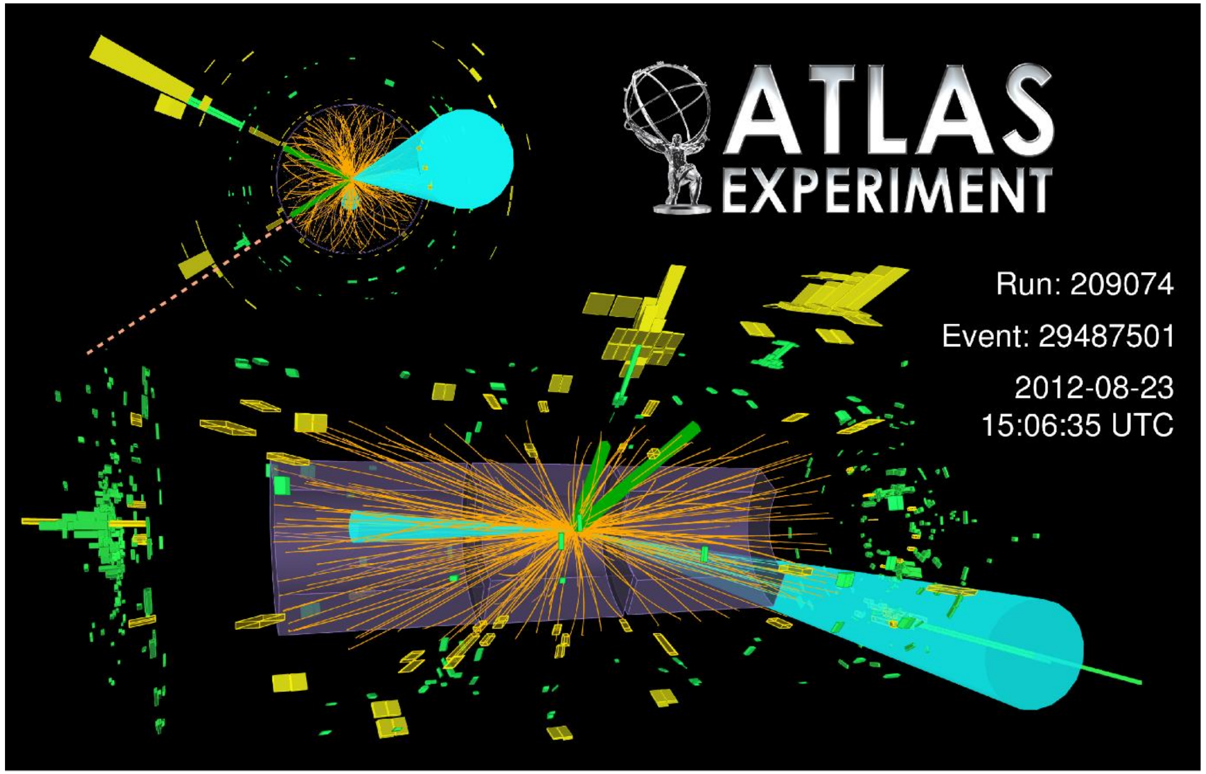


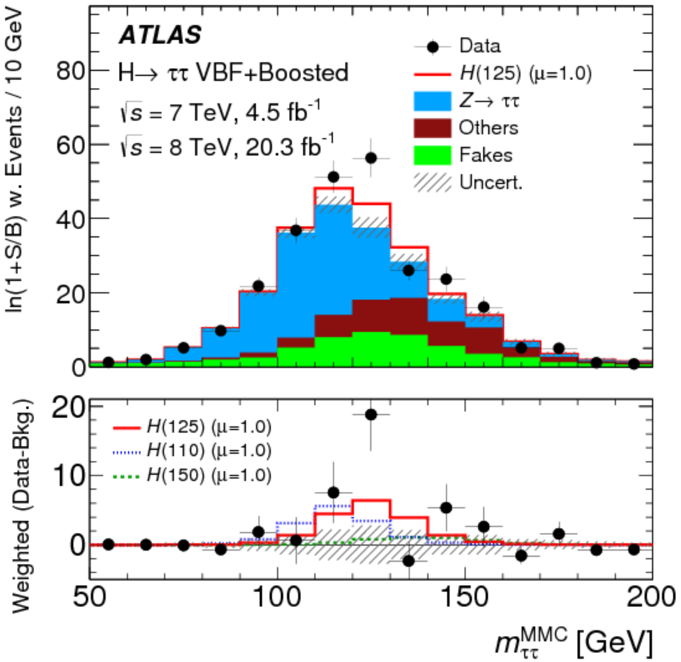




Run-I evidence of $H \rightarrow \tau\tau$!

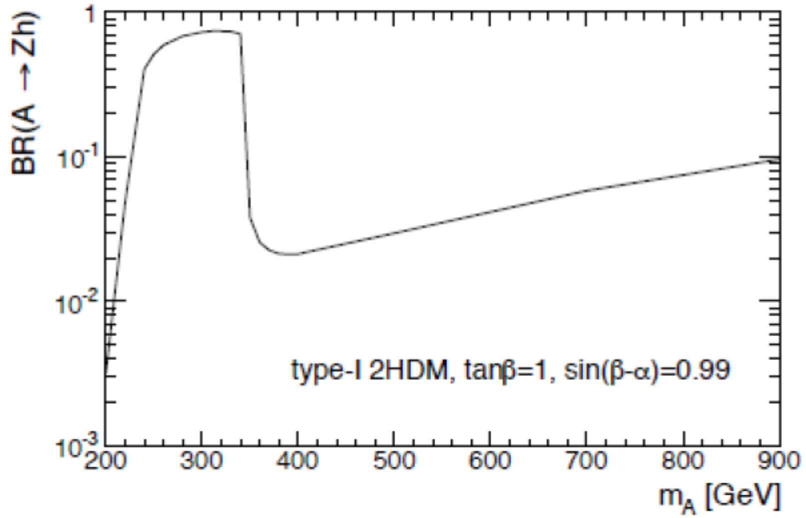
- This TauID was used in the Run-I Standard Model $h \rightarrow \tau\tau$ analysis and most Run I tau-related ATLAS analysis
- ***Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector*** (JHEP 1504 (2015) 117)





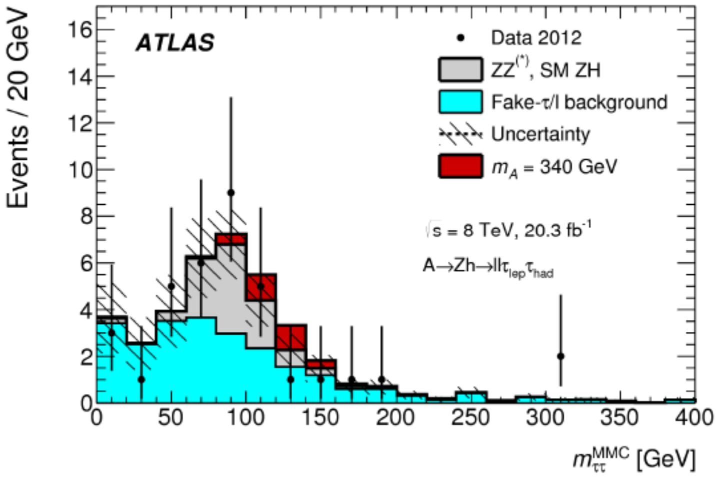
$A \rightarrow Zh \rightarrow \tau_{lep}\tau_{had}$ – overview

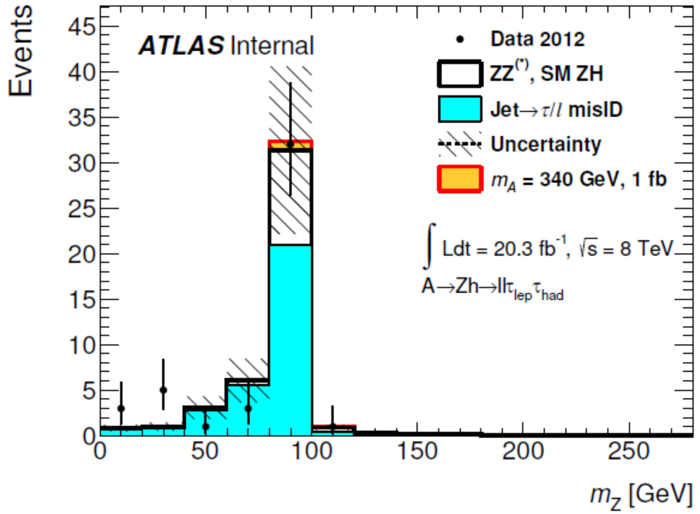
- This channel is relevant in 2 Higgs doublet models (2HDM)
- Branching ratio to Zh dominates for m_A below $t\bar{t}$ threshold
- Uses 20.3 fb^{-1} of 8 TeV Run 1 data.
- ***Search for a CP-odd Higgs boson decaying to Zh in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*** (Physics Letters B 744 (2015) 163-183)



$A \rightarrow Zh \rightarrow ll\tau_{lep}\tau_{had}$ – selection

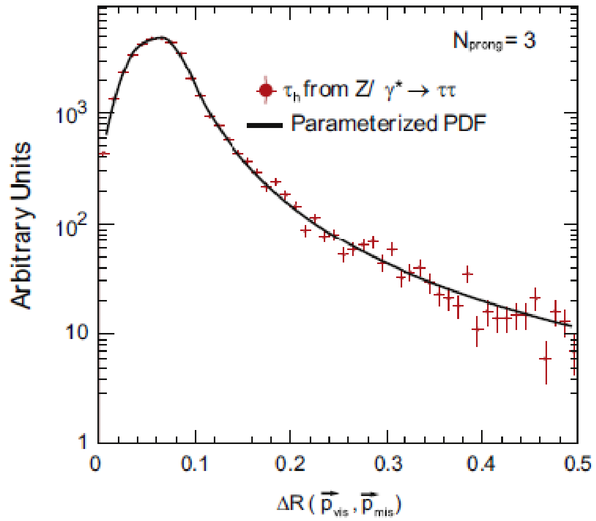
- Single Lepton (e, μ) Triggers
- Two same-flavor, opposite sign (OS), isolated leptons
- $80 < M_{ll} < 100$ GeV
- Exactly 1 additional e or μ
- Exactly 1 τ_{had} passing medium TauID
- τ_{had} and light lepton are OS
- $75 < M_{\tau\tau}^{MMC} < 175$ GeV





Mass reconstruction

- Since the tau decays contain neutrinos, missing energy complicates di-tau mass reconstruction, therefore the Missing Mass Calculator is used to reconstruct $m_{\tau\tau}$
- The MMC solves the kinematic equations of the di-tau by applying a probability based scan of possible solutions.



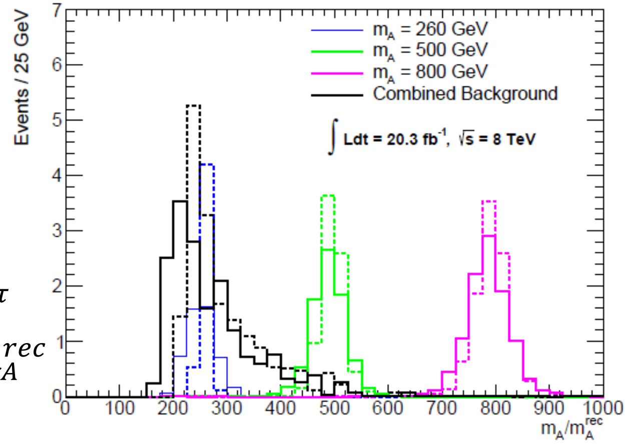
$$E_{T,x}^{miss} = p_1^{miss}\sin\theta_1^{miss}\cos\phi_1^{miss} + \mathrm{p}_2^{miss}\sin\theta_2^{miss}\cos\phi_2^{miss}$$
$$E_{T,y}^{miss} = p_1^{miss}\sin\theta_1^{miss}\sin\phi_1^{miss} + \mathrm{p}_2^{miss}\sin\theta_2^{miss}\sin\phi_2^{miss}$$
$$M_{\tau_1}^2 = \left(m_1^{miss}\right)^2 + \left(m_1^{vis}\right)^2 + 2\sqrt{\left(p_1^{vis}\right)^2 + \left(m_1^{vis}\right)^2}\sqrt{\left(p_1^{miss}\right)^2 + \left(m_1^{miss}\right)^2} - 2p_1^{vis}p_1^{miss}\cos\Delta\theta_{\nu m_1}$$
$$M_{\tau_2}^2 = \left(m_2^{miss}\right)^2 + \left(m_2^{vis}\right)^2 + 2\sqrt{\left(p_2^{vis}\right)^2 + \left(m_2^{vis}\right)^2}\sqrt{\left(p_2^{miss}\right)^2 + \left(m_2^{miss}\right)^2} - 2p_2^{vis}p_2^{miss}\cos\Delta\theta_{\nu m_2}$$

- Discriminant variable is the 4-object invariant mass, re-scaled using the known Z, *h* SM values:

$$m_A^{rec} = m_{ll\tau\tau} - (m_{ll} - m_Z^0) - (m_{\tau\tau}^{MMC} - m_H^0)$$

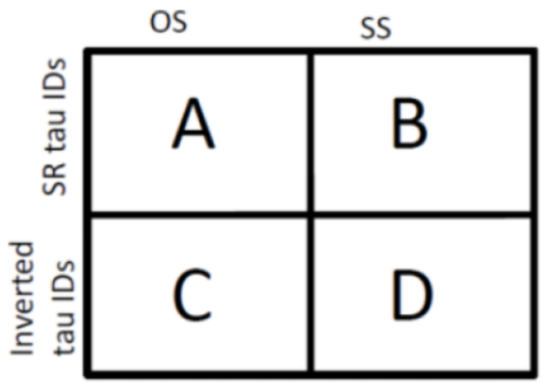
Solid line: $m_{ll\tau\tau}$

Dashed line: m_A^{rec}

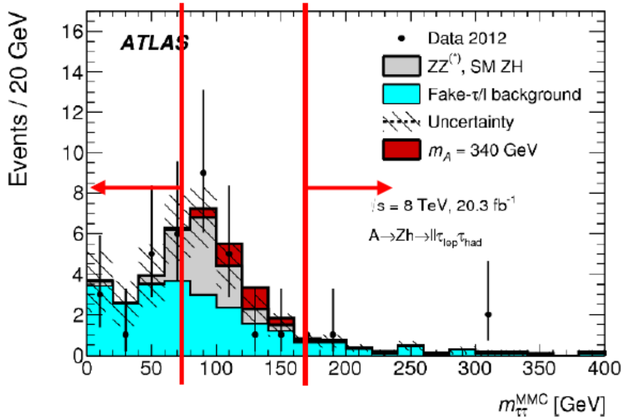


$A \rightarrow Zh \rightarrow ll\tau_{lep}\tau_{had}$ – background estimation I

- Main backgrounds to the analysis were Z+jets (reducible) and diboson (irreducible).
- Irreducible backgrounds were taken from simulation
- Our initial plan was to use an SS/OS/TauID ABCD method. However, the limited statistics due to the selection in the final state made this difficult
- In the end, we successfully estimated the reducible backgrounds (i.e. jets faking taus) using the following template method:
    - Use entire B+C+D control region (template region) to model background shape in A
    - Scale template shape with normalization factor **from Higgs mass sidebands** (outside 75-175 GeV).

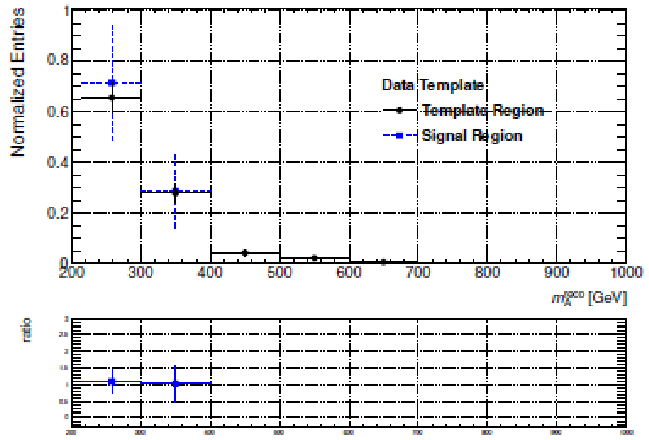


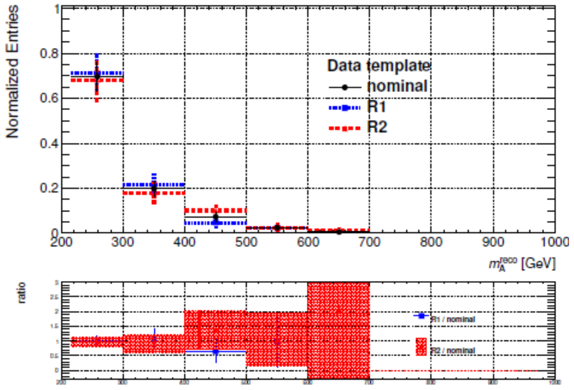
$$f_{scale} = \frac{A_{h-side}}{(B+C+D)_h - side}$$

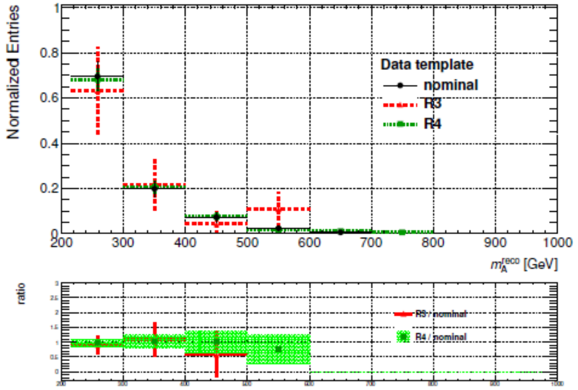


$A \to Zh \to ll\tau_{lep}\tau_{had}$ – background estimation II

- Template region's shape is similar to that in region A (comparison in *h*-sidebands)
- I also investigated alternative control regions both to use as cross-checks and to measure the systematic error or our fake background prediction
- The dominant systematic errors of our fake prediction came mostly from the normalization factor statistical uncertainty and the template systematics
- The final systematic error of the fake prediction ended up as the largest source of systematic error for the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$
- For $\tau_{lep}\tau_{had}$, $N_{fakes} = 9.4 \pm 3.5$







R1 = only SS; R2 = only OS; R3 = Loose ID taus; R4 = Loose lepton; R5 = both tau and lepton are loose

$A \rightarrow Zh \rightarrow ll\tau_{lep}\tau_{had}$ – systematics

- The dominant systematic is the normalization of the data-driven background.
- Pile-up and tau identification uncertainties are the most important uncertainties in the simulated signal

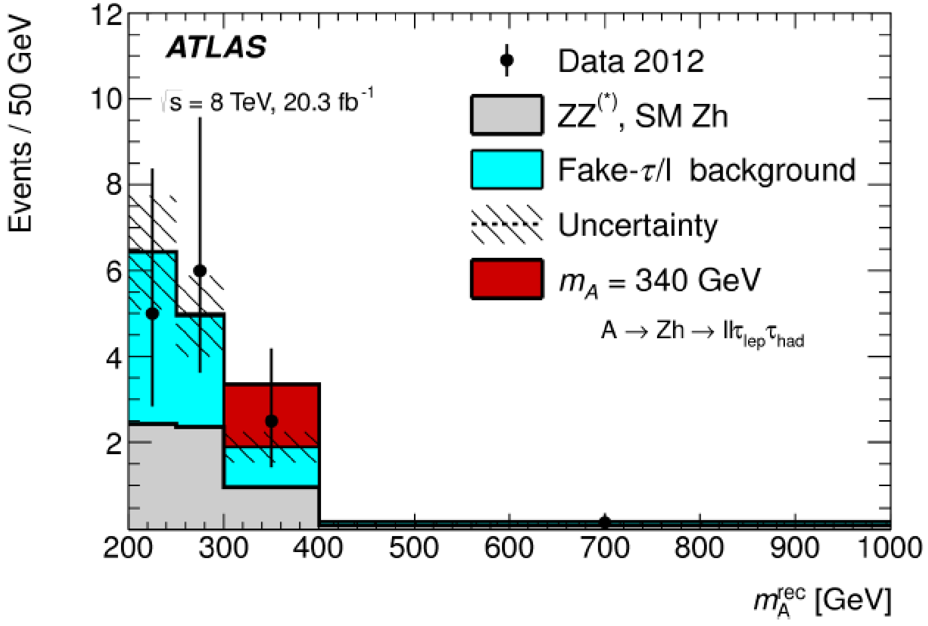
$\tau_{lep}\tau_{had}$ channel systematics

Sample	Systematic	Uncertainty (%)
MC background	SM h tautau BR	0.60
MC background	luminosity	2.80
MC background	tau ID	0.40
MC background	PDF gg	0.50
MC background	pdf Higgs qq	0.40
MC background	PDF qq	3.30
MC background	QCD scale gg	1.70
MC background	QCD scale qq	3.30
MC background	QCD scale Vh	0.30
Total (for Background)		5.79
Fake background	Data driven norm.	37.70
Signal	electron efficiency	1.40
Signal	electron energy scale	0.50
Signal	ATLAS ggAZh Acc ISR	0.50
Signal	ATLAS ggAZh Acc PDF	2.30
Signal	ATLAS ggAZh Acc Scale	0.20
Signal	JER	0.30
Signal	JES	0.60
Signal	luminosity	2.80
Signal	muon trigger	0.50
Signal	muon efficiency	1.10
Signal	muon scale	0.20
Signal	pile-up	4.30
Signal	tau ID	3.30
Signal	tau energy scale	0.80
Total (for Signal)		6.90

$A \rightarrow Zh \rightarrow ll\tau_{lep}\tau_{had}$ – results I

- Very good agreement between prediction and observed data

Sample	Full selection truth-matched $ll\tau$	Full selection Other
Z+jets	0.0	1.10 ± 0.66
WW	0.0	0.0
ZZ	6.97 ± 0.17	0.30 ± 0.03
WZ	0.0	2.15 ± 0.32
Triboson	0.08 ± 0.01	0.0
Top	0.0	0.0
Top+Z	0.02 ± 0.01	0.07 ± 0.02
SM Zh	0.85 ± 0.02	0.02 ± 0.00
$gg \rightarrow A \rightarrow Zh$ lephad		
m_A = 260 GeV	0.478 ± 0.031	0.009 ± 0.001
m_A = 400 GeV	0.662 ± 0.043	0.015 ± 0.001
	Total event number	
truth-matched $ll\tau$	7.9 ± 0.17	
fakes (normalized template)	9.4 ± 3.5	
Total background estimate	17.4 ± 3.5	
Data	18	



Statistical interpretation

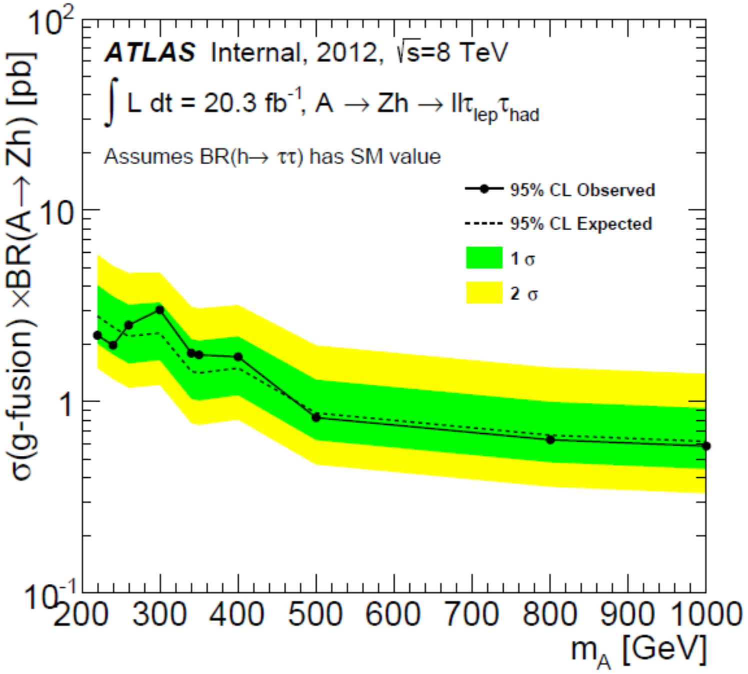
- The parameter of interest of both searches is the signal strength, μ, given by the ratio of the fitted signal production cross section times branching ratio to its counterpart model-predicted value
- The fitted value is obtained my maximizing a binned likelihood (or minimizing $-2\ln\mathcal{L}$), given by

$$\mathcal{L}(\mu,\theta) = \prod_{j=bins,channels} \mathcal{F}_P\left(N_j \middle| \mu \cdot s_j(\theta) + b_j(\theta)\right) \prod_{\theta_i} \mathcal{F}_G(\theta_i|0,1)$$

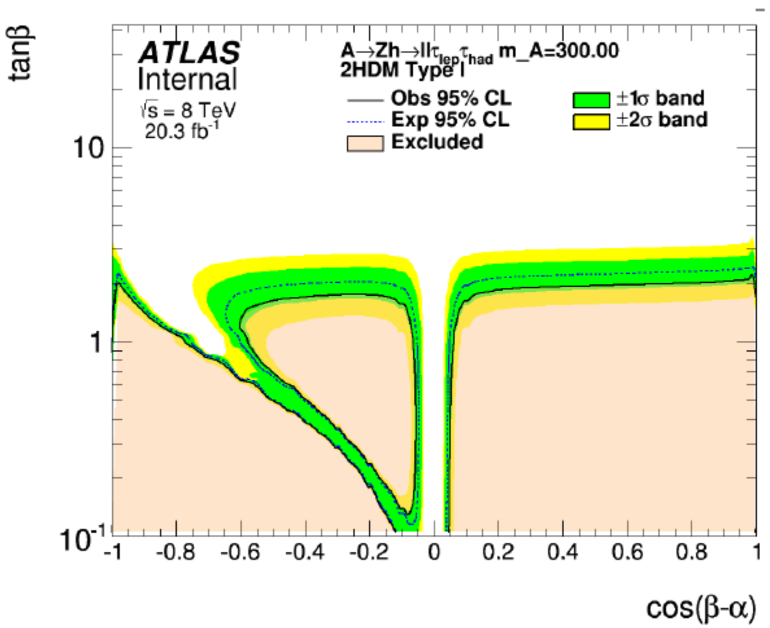
- Production upper limits are set at 95% confidence-level with the modified frequentist approach (CL_S)
- With upper limits in hand, a scan of the relevant parameter space is performed. Points in the parameter space where the model predicts a production rate above the upper limit are excluded.

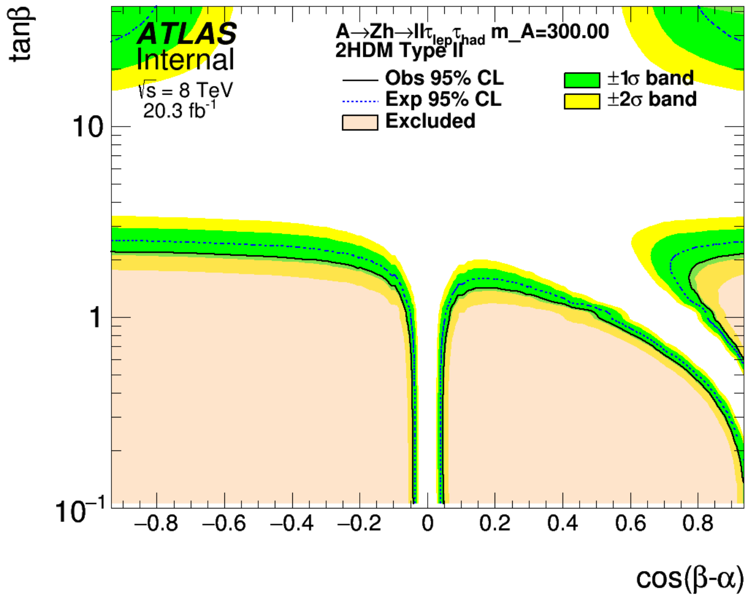
$\mathcal{F}_P$ = Poisson distribution
s_j (b_j) = expected signal (background) events in bin j
θ = nuisance parameters

$A \to Zh \to ll\tau_{lep}\tau_{had}$ – results II



95% CL_S upper limit on $gg \to A$ production





Exclusions in the 2HDM Type I and Type II planes obtained using only the result from the $\tau_{lep}\tau_{had}$ channel

$$\tan\beta = \frac{v_2}{v_1}$$

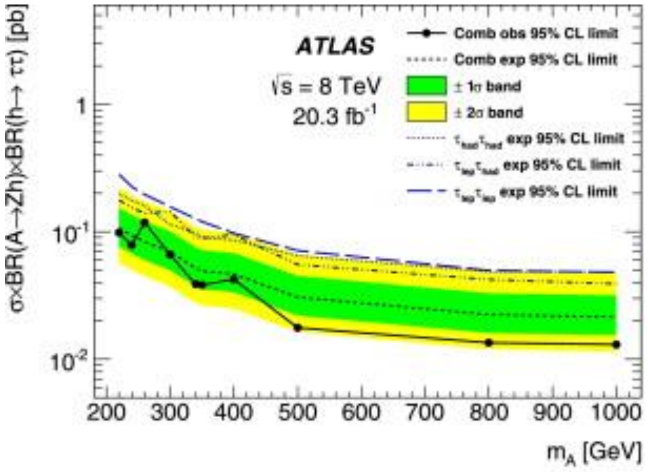
α = mixing angle of CP-even Higgses

$A \to Zh$ – results II

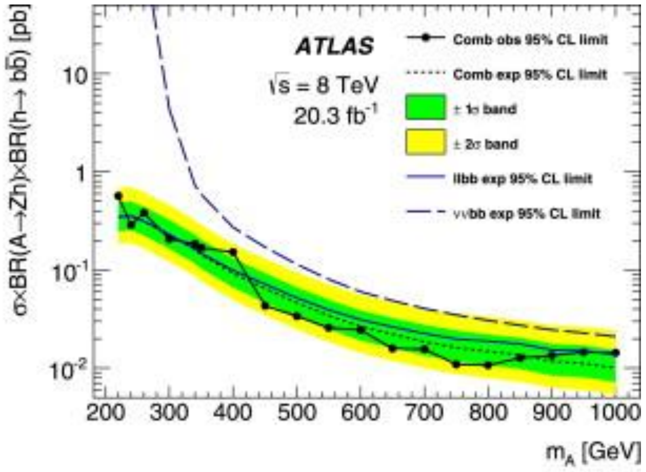
- The A → Zh → $ll\tau_{lep}\tau_{had}$ search was published as part of a larger study that included the $ll\tau_{lep}\tau_{lep}$, $ll\tau_{had}\tau_{had}$, $llbb$ and $\nu\nu bb$ channels.

The number of predicted and observed events for the $\ell\ell\tau\tau$ channels.

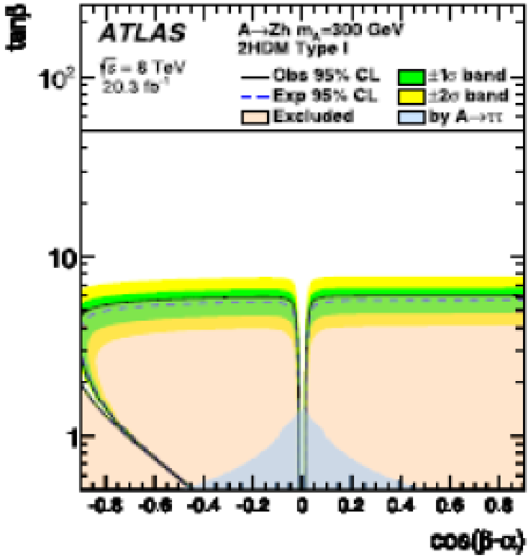
	Expected background	Data
$\ell\ell\tau_{had}\tau_{had}$	28 ± 6	29
$\ell\ell\tau_{lep}\tau_{had}$	17 ± 4	18
$\ell\ell\tau_{lep}\tau_{lep}$ (SF)	9.5 ± 0.6	10
$\ell\ell\tau_{lep}\tau_{lep}$ (DF)	7.2 ± 0.7	7

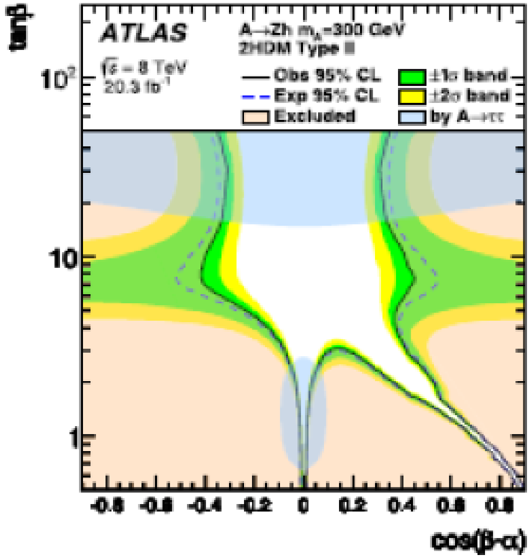


(a) $A \to Zh$, $h \to \tau\tau$

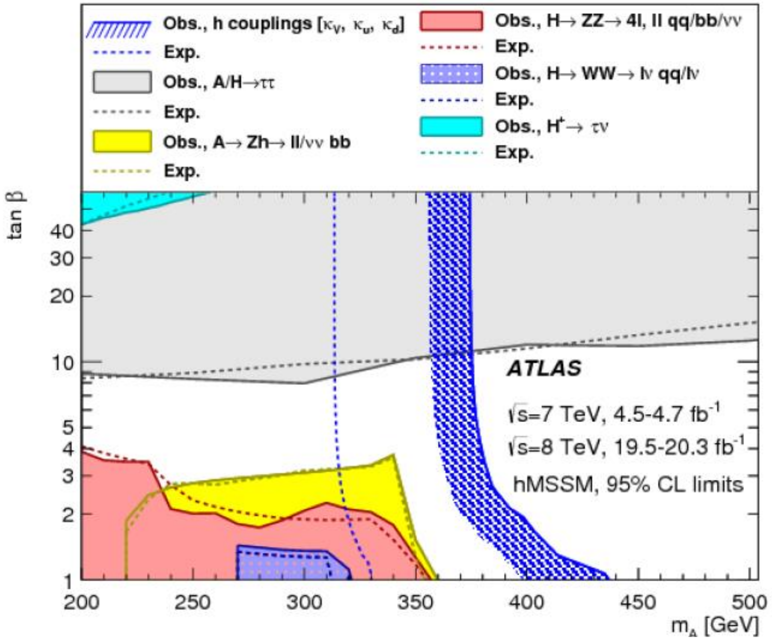


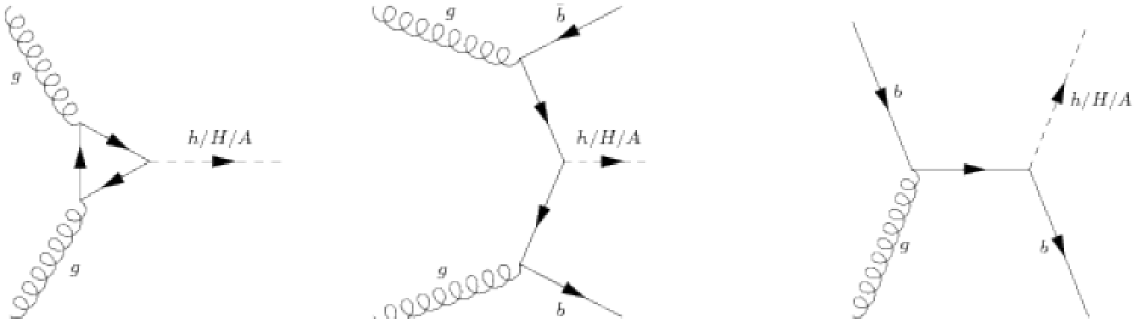
(b) $A \to Zh$, $h \to bb$





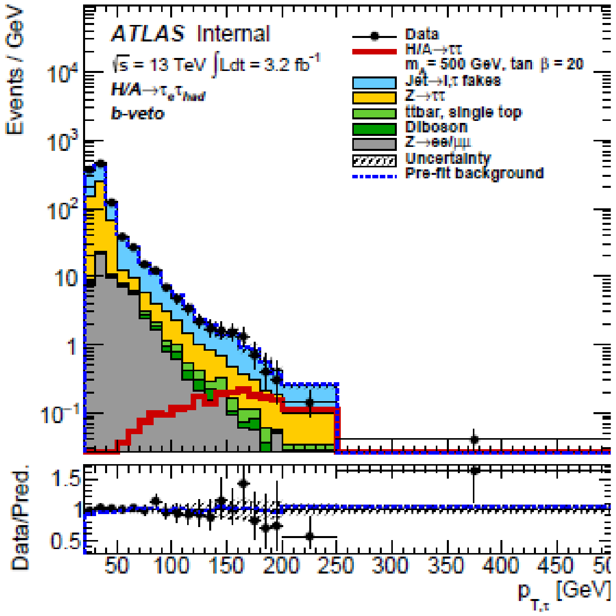
- The $H/A \to \tau\tau$ channel is the most powerful channel to search for neutral MSSM Higgs
- The complete analysis is split into $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels
- Each channel is sub-divided into b-veto and b-tagged categories
- My thesis details my work for the b-veto category of the $\tau_{lep}\tau_{had}$ channel
- Submitted to the arXiv 2 days ago! http://arxiv.org/abs/1608.00890

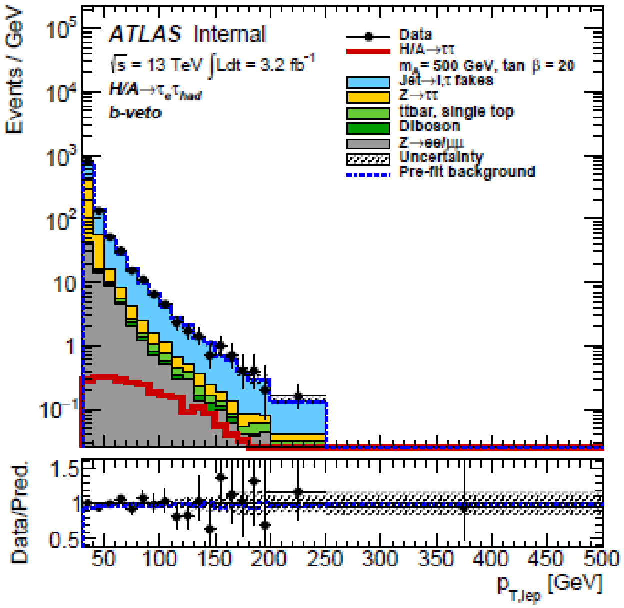




$H/A \rightarrow \tau_{lep}\tau_{had}$ – Selection

- Single lepton triggers
- τ pT > 25 GeV passing medium TauID
- Medium quality lepton pT > 30 GeV
- $\Delta\phi(l, \tau_{vis}) > 2.4$
- $m_T\left(l, E_T^{miss}\right) < 40$ GeV,
- where $m_T\left(l, E_T^{miss}\right) \equiv \sqrt{2p_{T,l}E_T^{miss}\left(1 - \cos\left(\Delta\phi\left(l, E_T^{miss}\right)\right)\right)}$
- For $e\tau_{had}$ channel, an additional veto of events with $m_{\tau\tau}^{vis}$ near the Z mass
- Veto of b-tagged jets

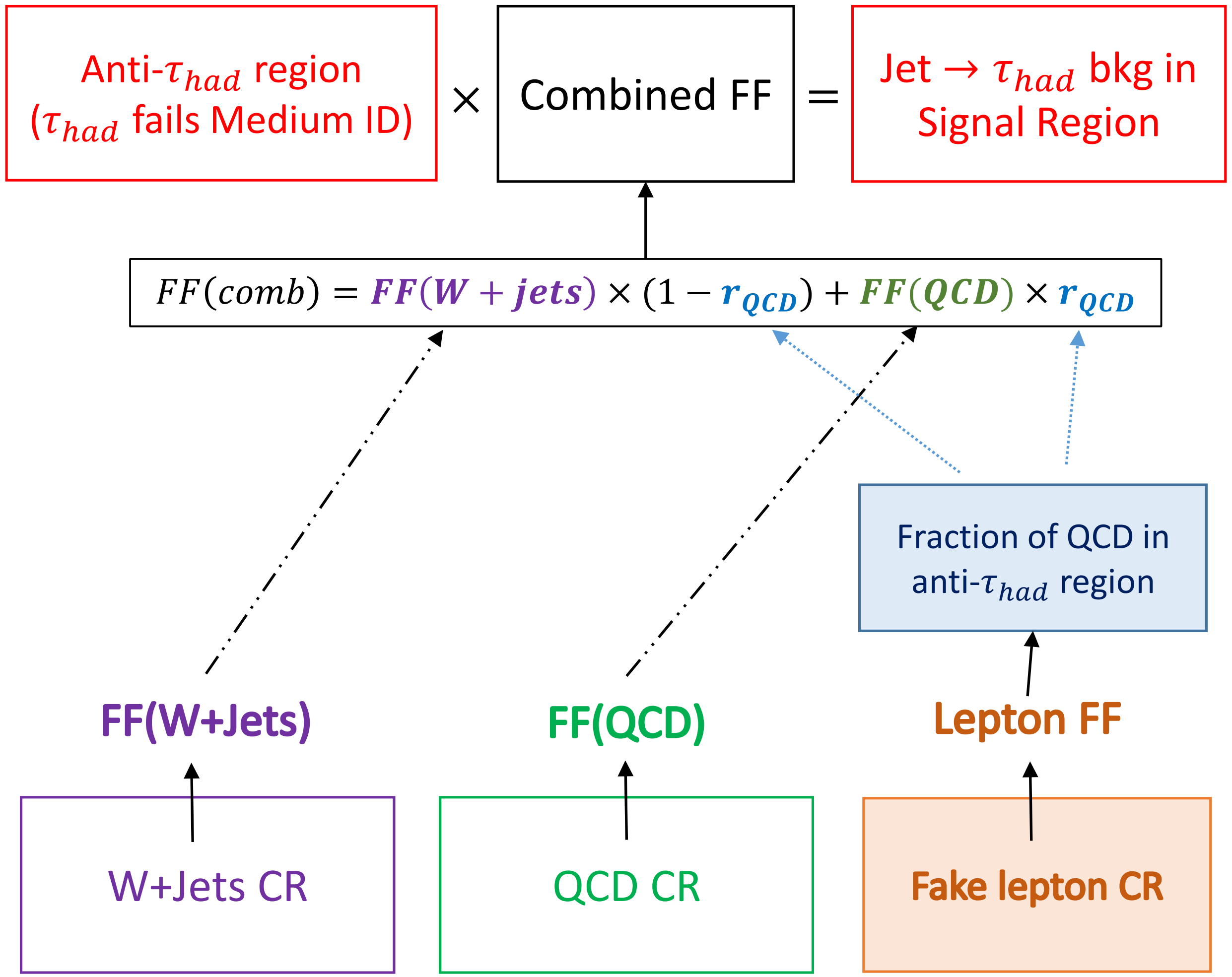




$\tau_{lep}\tau_{had}$ backgrounds: overview

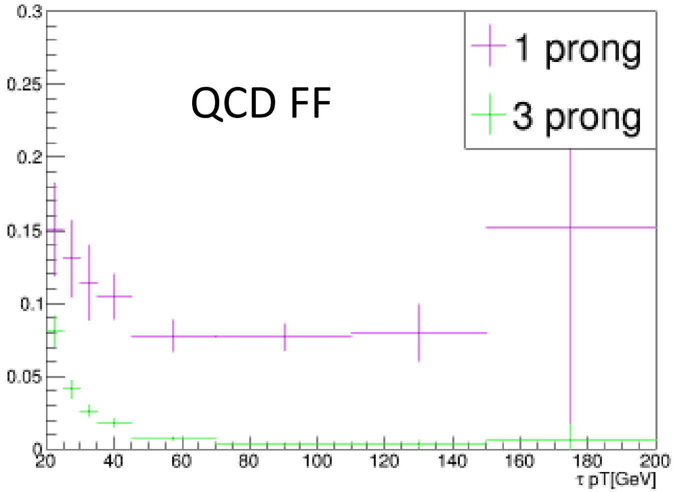
- Events with truth-matched leptons, taus and lepton faking τ_{had} taken from simulation. Mostly from $Z \rightarrow \ell\ell$ and $Z \rightarrow \tau\tau$. Scale factors in $e \rightarrow \tau_{had}$ events.
- Background with jets faking taus estimated with a data-driven method
- Fake-τ_{had} background is mostly **W+Jets** (where the lepton is true), or **multi-jet** (where both lepton and tau are faked by QCD jets)
- 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

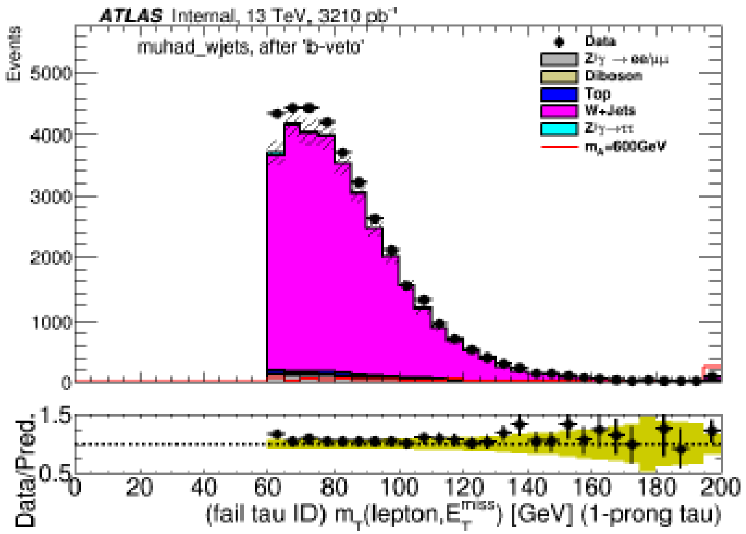
Fake background treatment

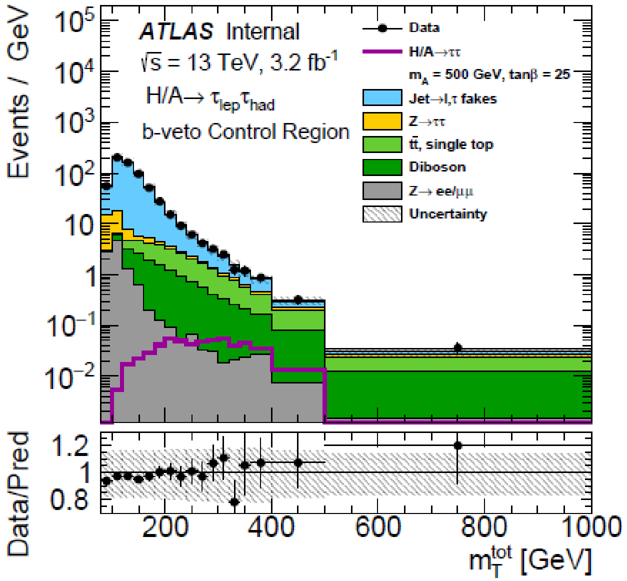


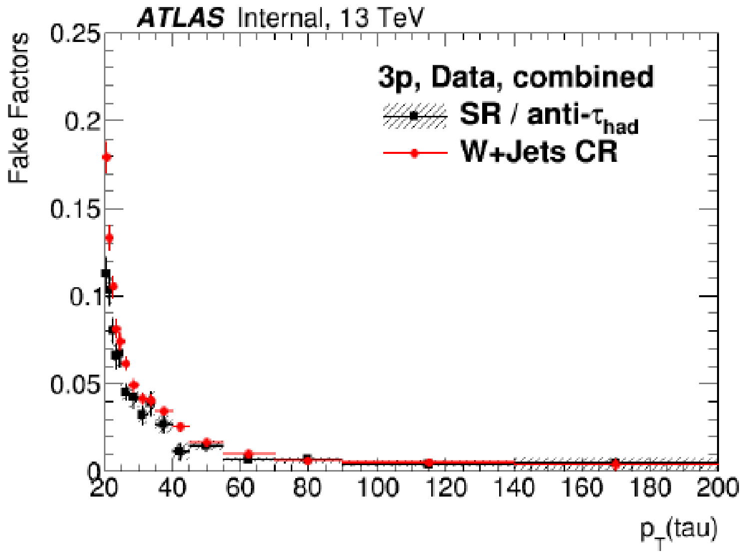
$\tau_{lep}\tau_{had}$ backgrounds: FF(W+jets) & FF(QCD)

- The fake factors are calculated as a function of tau momentum, and separately for 1p and 3p
- W+jets CR definition is identical to signal region but with an inverted transverse mass cut:
  - $e\tau_{had}: 70 < m_T(l, E_T^{miss})$
  - $\mu\tau_{had}: 60 < m_T(l, E_T^{miss})$
- The FF(QCD) are computed in the control region where the lepton is anti-isolated





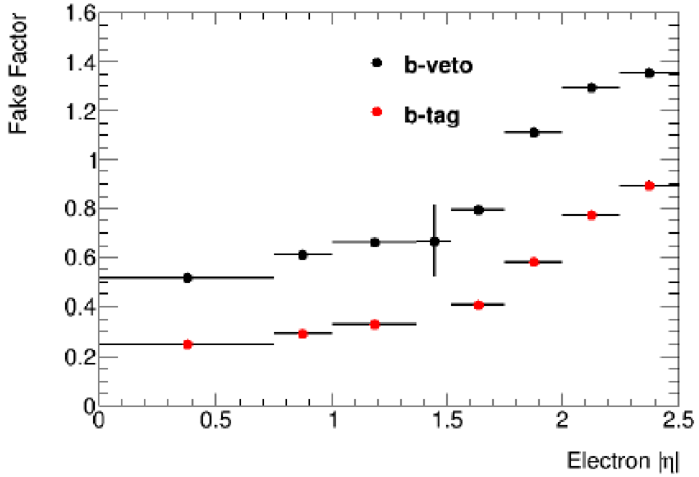


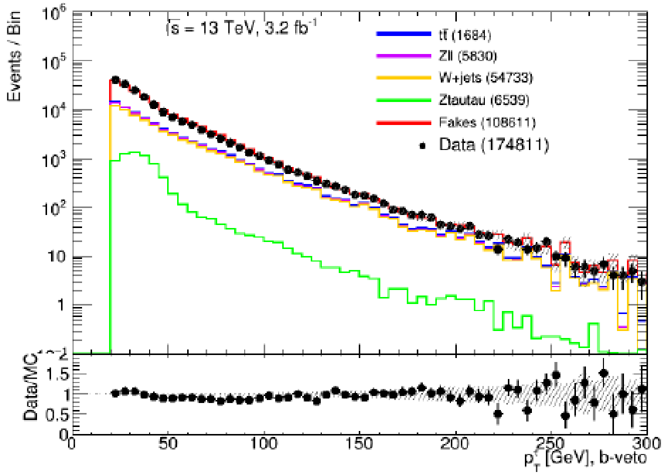


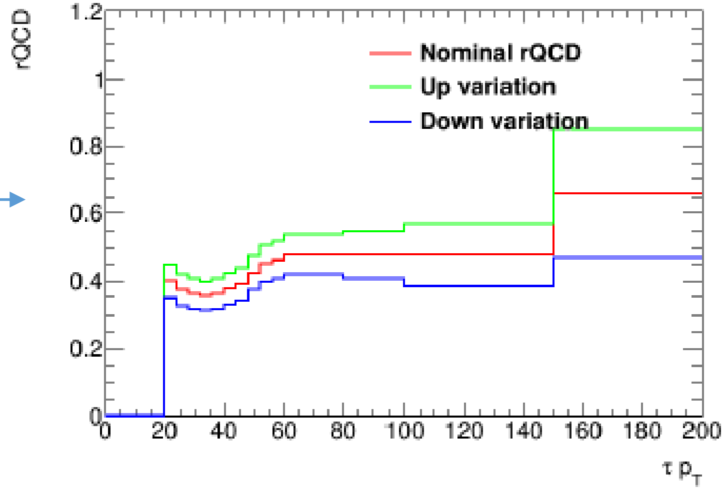
$\tau_{lep}\tau_{had}$ backgrounds: multi-jet fraction (r_{QCD})

- 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} but at least one jet
  - $m_T(l, E_T^{miss}) < 30$ GeV
- Parameterized as a function of lepton η
- FF are applied to an anti-isolated anti-τ (fail TauID) region to estimate the dijet background fraction in the isolated anti-τ region

$$FF(comb) = FF(W + jets) \times (1 - r_{QCD}) + FF(QCD) \times r_{QCD}$$





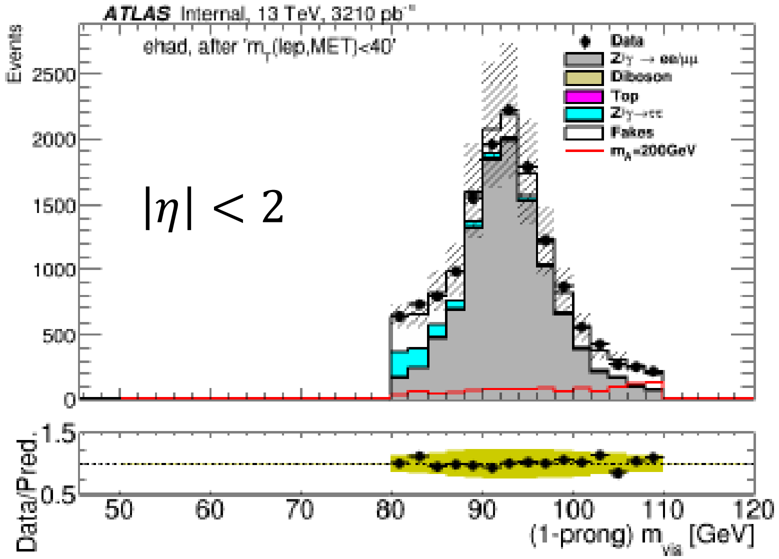


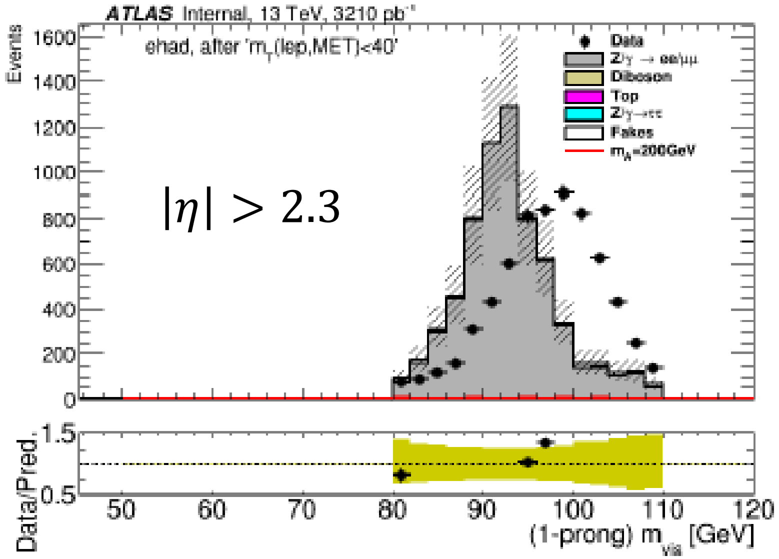
Systematic Uncertainties of fake background

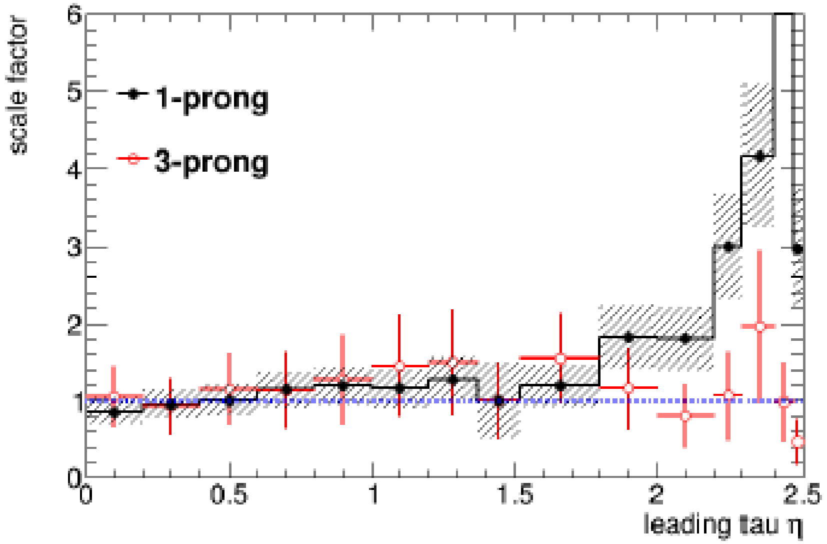
- Data-driven background prediction has a number of systematic uncertainties:
  - Extrapolation from W+Jets CR to signal region (20%). Counterpart uncertainty is negligible for multi-jet FF
  - Contamination of CR with other backgrounds (<3% for W+Jets, <13% for QCD)
  - Uncertainties in the subtraction of truth-matched simulated events in data (10%)
  - Uncertainty in jet composition in anti-τ_{had} region, estimated by varying the BDT score threshold (5%)
  - Lepton fake factor uncertainty estimated by varying m_T cut (4%)
  - Statistical uncertainty

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

- The ehad channel also has a significant background of $Z \to ee$ 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 $80 < m^{vis}_{\tau_{lep}\tau_{had}} < 110$ GeV for 1p (3p), the so-called *Z*-mass control region
  - Using $e \to \tau_{had}$ scale factors computed in the *Z*-mass control region







Systematic Uncertainties of simulated samples

- Dominant uncertainties are TauID and TES.

Electron channel, backgrounds, b-veto				
Systematic	$Z \to \ell\ell$	Top	$Z \to \tau\tau$	Diboson
Muon	0.00	0.11	0.00	0.06
Electron	1.99	1.48	1.27	1.43
Tau reco/ID	0.03	10.43	10.81	10.09
Tau e-scale	0.00	5.75	2.22	5.21
Jet	2.58	5.23	2.51	1.79
MET	1.35	1.13	0.67	0.89
b-tagging	0.02	6.53	0.03	0.01
Pile-up	1.91	3.13	3.30	2.88

Electron channel, signal, gluon fusion, b-veto category						
Systematic	ggH200	ggH300	ggH400	ggH500	ggH800	ggH1000
Electron	0.94	1.22	0.99	1.14	1.51	1.74
Tau reco/ID	11.32	9.05	7.84	7.43	7.99	8.66
Tau e-scale	8.55	5.43	5.07	4.27	4.27	3.27
Jet	2.75	3.21	1.87	2.07	1.95	2.07
MET	1.22	1.23	0.51	0.61	0.51	1.09
b-tagging	0.02	0.05	0.03	0.03	0.04	0.04
Pile-up	2.17	5.61	1.42	3.71	0.78	5.10
Electron channel, signal, b-associated production, b-veto category						
Systematic	bbH200	bbH300	bbH400	bbH500	bbH800	bbH1000
Muon	0.04	0.04	0.04	0.06	0.04	0.03
Electron	1.37	1.13	1.30	1.47	1.85	2.01
Tau reco/ID	11.39	8.90	8.10	7.36	7.96	8.60
Tau e-scale	5.62	5.17	4.42	3.70	4.04	0.93
Jet	3.13	2.15	2.06	2.28	1.86	2.26
MET	1.90	0.50	0.40	0.57	0.60	0.48
AF2	3.69	2.48	2.35	2.22	2.19	2.17
b-tagging	1.64	1.83	1.81	1.79	1.82	1.73
Pile-up	1.22	3.31	1.99	0.66	1.86	0.90

Systematic Uncertainties of simulated samples

- Dominant uncertainties are TauID and TES.

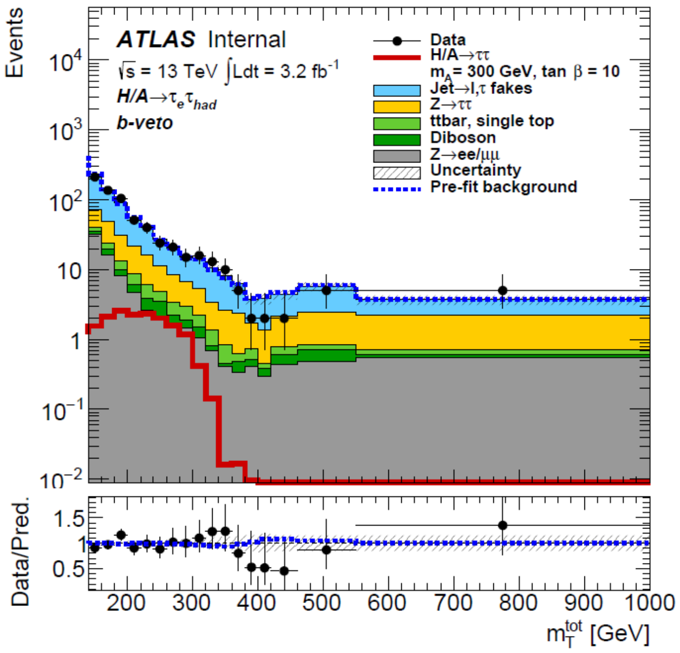
Muon channel, backgrounds, b-veto				
Systematic	$Z \to \ell\ell$	Top	$Z \to \tau\tau$	Diboson
Muon	0.96	2.42	1.25	1.83
Electron	0.00	0.00	0.01	0.11
Tau reco/ID	0.00	10.84	11.06	10.71
Tau e-scale	0.00	5.53	4.51	5.88
Jet	3.17	5.00	2.97	3.76
MET	3.23	0.57	0.86	1.20
b-tagging	0.07	6.26	0.03	0.01
Pile-up	0.96	2.98	2.43	2.24

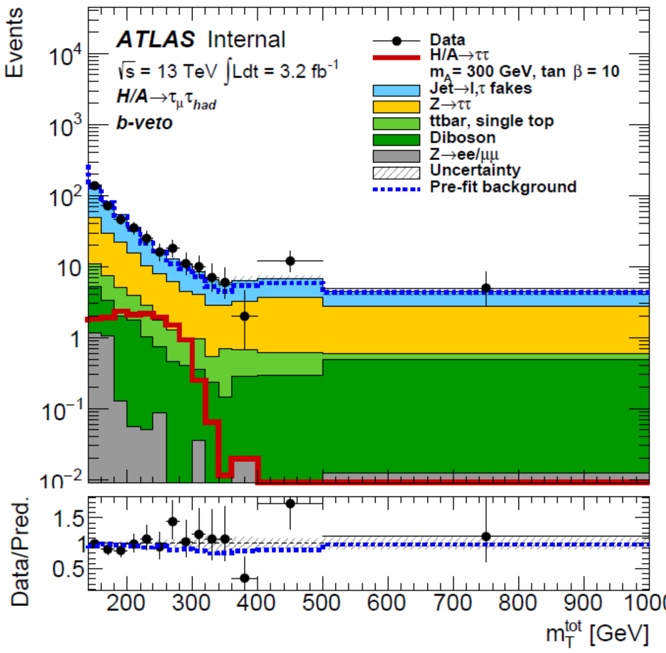
Muon channel, signal, gluon fusion, b-veto category						
Systematic	ggH200	ggH300	ggH400	ggH500	ggH800	ggH1000
Muon	1.84	2.31	2.70	2.83	3.13	3.32
Electron	0.00	0.00	0.00	0.00	0.00	0.00
Tau reco/ID	12.00	9.38	8.12	7.58	7.96	8.67
Tau e-scale	2.73	3.58	4.25	4.11	4.15	3.55
Jet	2.22	2.71	2.43	2.13	2.59	2.31
MET	0.56	0.60	1.06	0.55	0.57	0.58
b-tagging	0.03	0.05	0.04	0.04	0.06	0.05
Pile-up	0.88	1.69	0.63	1.33	3.40	3.96

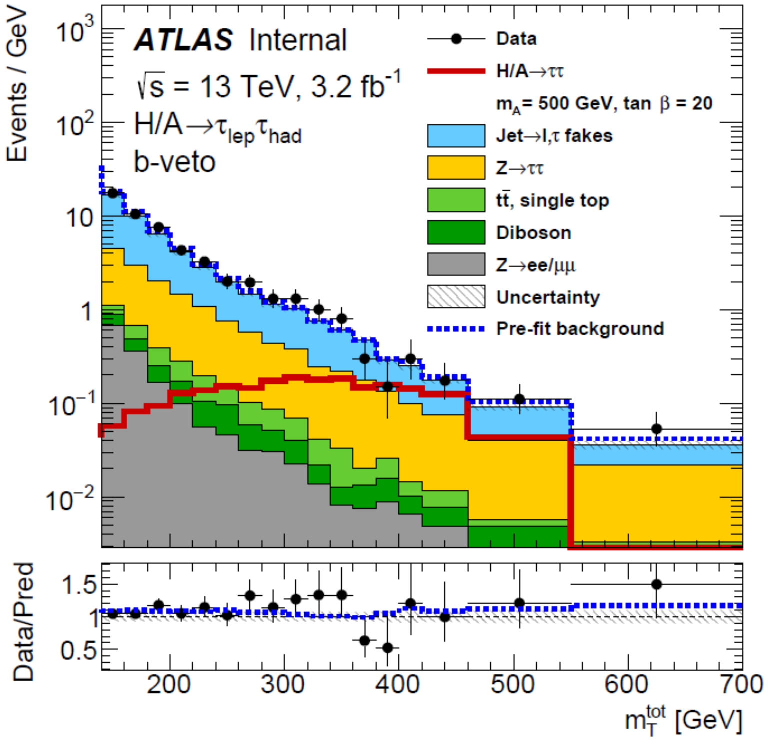
Muon channel, signal, b-associated production, b-veto category						
Systematic	bbH200	bbH300	bbH400	bbH500	bbH800	bbH1000
Muon	1.79	2.46	2.71	2.99	3.23	3.38
Electron	0.06	0.09	0.05	0.02	0.04	0.03
Tau reco/ID	11.85	9.20	8.28	7.43	7.86	8.49
Tau e-scale	3.22	4.07	4.22	4.40	5.01	2.71
Jet	4.06	2.41	2.59	3.37	2.29	2.93
MET	0.78	1.12	0.56	0.46	0.65	0.57
AF2	2.91	2.57	2.49	2.43	2.22	2.20
b-tagging	1.50	1.73	1.76	1.81	1.96	1.84
Pile-up	0.81	2.25	0.26	2.62	4.16	2.52

$H/A \rightarrow \tau_{lep}\tau_{had}$ – results I

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

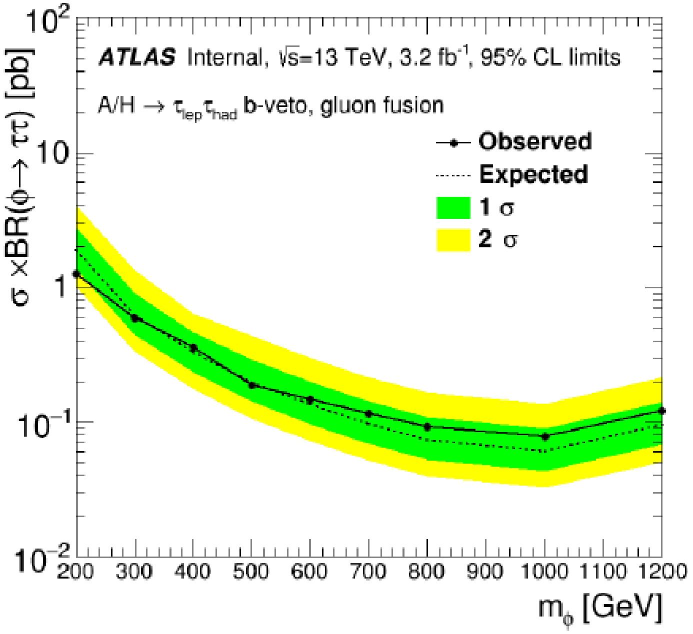


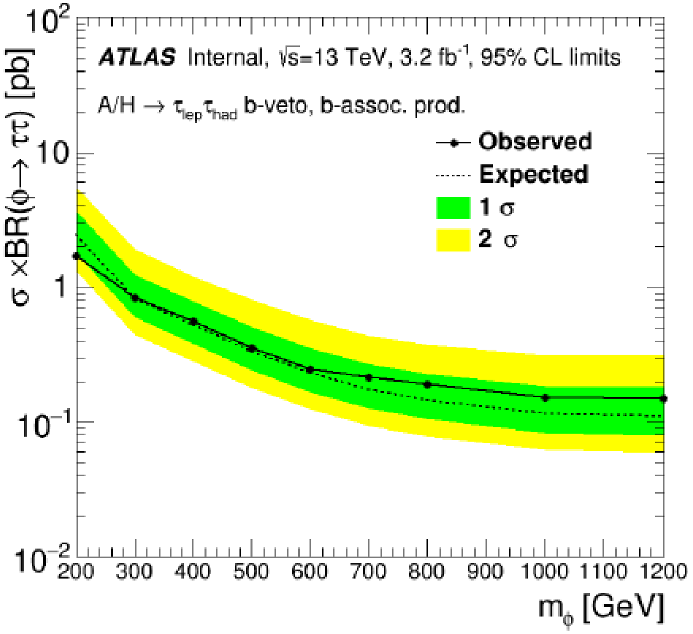


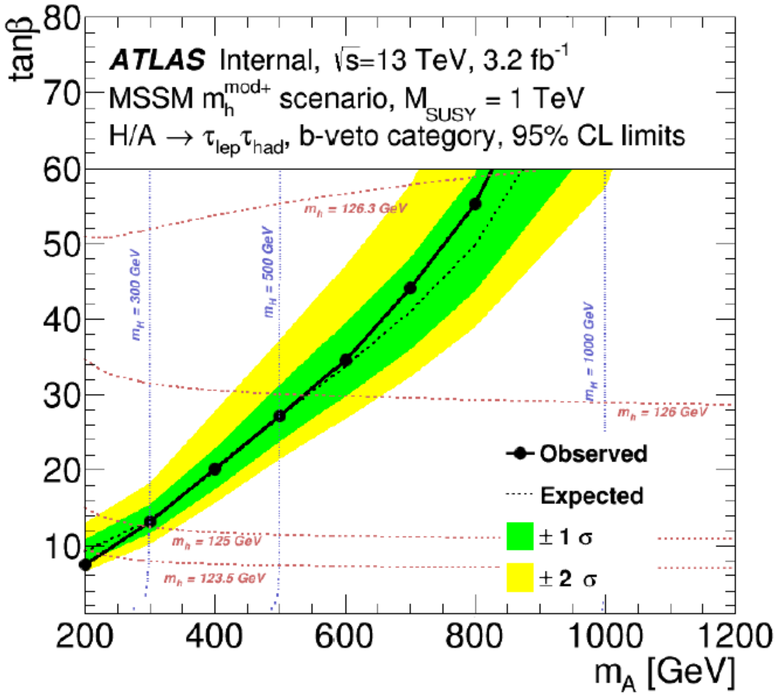


$H/A \rightarrow \tau_{lep}\tau_{had}$ – results II

- No excess found so upper limits set on σ X BR set



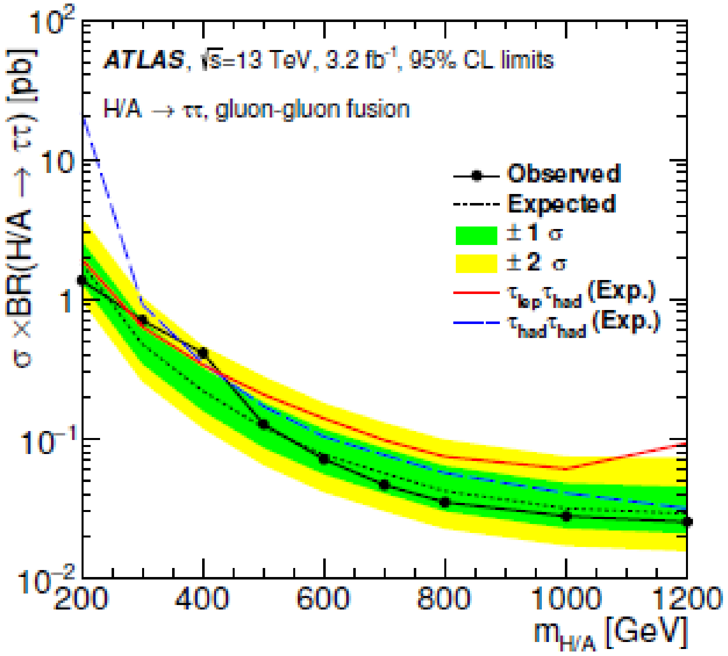


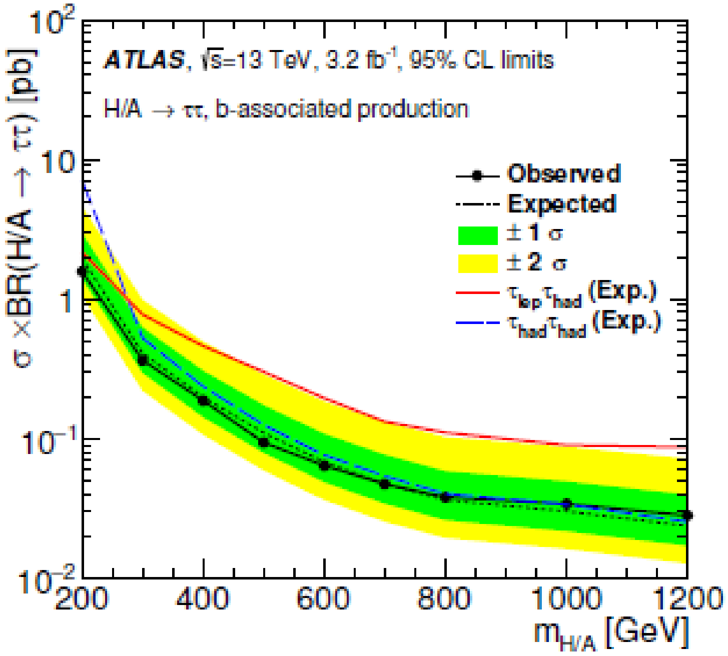


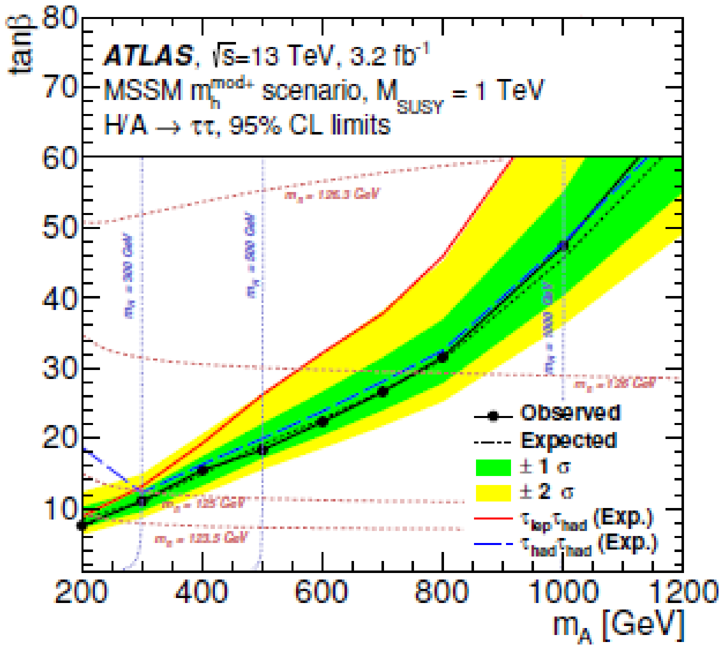
m_h^{mod+} = benchmark where stop mixing is chosen that gives m_h = 125 GeV

$H/A \to \tau\tau$ – combined results

- The soon to be published result includes both the $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ search channels, along with their respective b-tag categories.







Summary

- I've shown here a summary of my PhD work, focusing on the Run-II MSSM $\mathrm{H}/A \rightarrow \tau_{lep}\tau_{had}$ search and run-I $A \rightarrow Zh \rightarrow ll\tau_{lep}\tau_{had}$ search
- Results were interpreted for several MSSM or 2HDM benchmark scenarios, with strong exclusion of available parameter space

Thanks to

- Anna Goussiou, for the support and guidance of the last 6 years
- Nikos Rompotis, for invaluable advice through the years
- To my supervisory committee: Gordon Watts, Henry Lubatti, Ann Nelson, Jason Detwiler, Shih-Chieh Hsu and Julianne Dalcanton. Special thanks to my reading committee, Anna, Shih-Chieh and Ann.
- The deadline for thesis submission is August 19th. Therefore, please let me know as soon as possible (August 10th) if you have additional comments.

Timeline

- Thanks to the reading committee for the fast turnaround time with the thesis draft. I plan to address all comments in the next few days. I have already implemented most of the comments made up to now
- The deadline for thesis submission is August 19^{th}, but I would like to finalize and submit within a week's time to avoid complications.

THESIS COMMENTS AND CHANGES

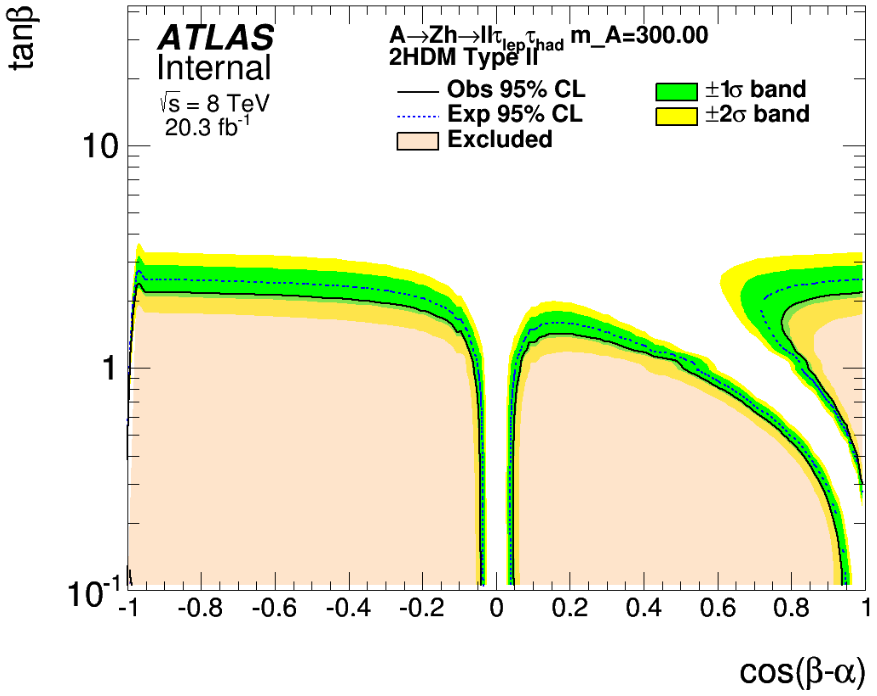
Thesis changes since initial circulation

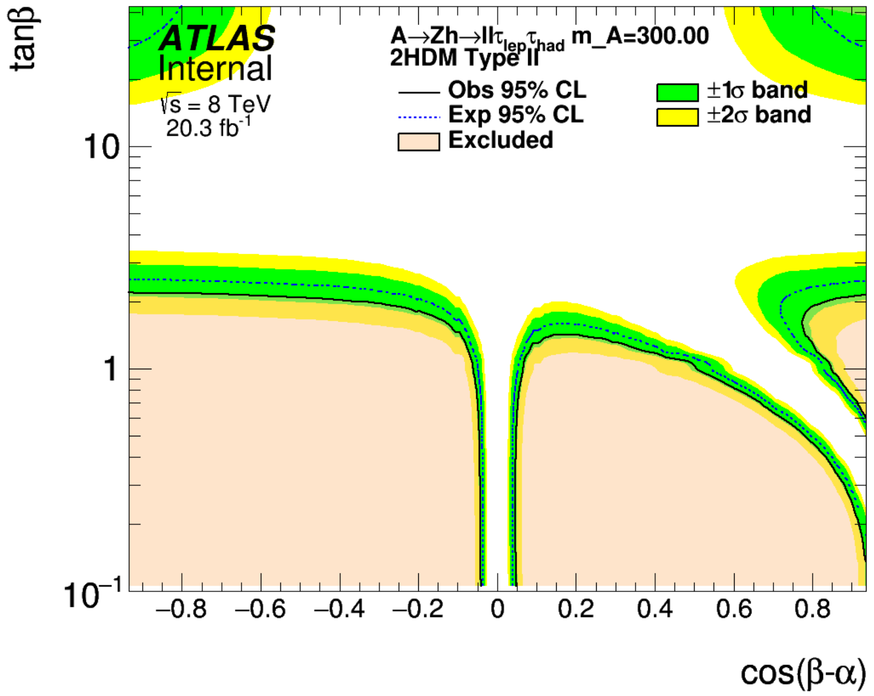
Minor or Cosmetic

- Typos, figure positioning to improve flow, removed subfigure letter label of figures with only 1 plot, improved figure and table sizes.
- Fixed some bibliography typos and style issues. Also fixed out-of-order citations due to referencing in table captions.
- Restructured some sentences but kept meaning unchanged. Improved caption of a few figures.
- Edited Figure 2.7 to have correct x-axis titles (source is incorrect and has m_A for all cases).
- Dphi correction plots replaced with prettier plots.
- A few equations were off by a minus sign. Also typos in equations.

Thesis changes since initial circulation

- Added *b*-associated production to the interpretation of type-II 2HDM.





This production mode is only relevant at high tan beta in type II 2HDM, and is ignored in the type-I plot.

Thesis Draft Comments

- Ann: “(2.21) this result is cutoff procedure dependent. a naive cutoff would give a result 3 times bigger (the 3 from color). But you can get any answer with a different cutoff procedure. The cutoff dependence vanishes after renormalization. A more sophisticated argument is that the cutoff dependence indicates the expected order of magnitude of the parameter--this is basically dimensional analysis.”

- Response: Adjusted the sentence to emphasize the dependence on the cutoff, instead of presenting the correction with an equation

> Higgs coupling to heavy fermions are so great. For example, the one-loop diagrams from the interaction of the Higgs with fermions will give a correction that goes quadratically with the scale of new physics. If this scale were to be the Planck scale, then the corrections would be $\Delta m_h^2 \sim 10^{38}$ GeV, more than 30 orders of magnitute higher than the physical Higgs mass. This is fixed only by the *unnatural*, fine-tuned solution where the bare mass of the

Thesis Draft Comments

- Ann: “eq. (2.22) This is not the most general 2HDM, as there could be terms such as H_1 H_1^dagger H_1 H_2^dagger. It is the most general where the dim 4 terms respect an H_1-> -H_1 symmetry. This symmetry can be imposed to ensure that only one type of Higgs couples to each charge of fermion, preventing flavor changing neutral currents. The term H_1 H_2^dagger softly breaks the symmetry but because the breaking is soft it will not induce renormalization of the unwanted Yukawa terms.”

- Response: The paragraph has been restructured to mention FCNC in 2HDMs (originally mentioned in line 189).

“A general 2HDM scalar sector contains 14 parameters, but for a phenomenologically minded model we can simplify it by requiring it to be CP-conserving and that CP is not spontaneously broken. **Another important note on 2HDMs is that, in general, their Yukawa terms allow for flavor-changing neutral currents (FCNC) at tree-level which would not be compatible with experimental observation. However, the FCNC can be naturally suppressed by imposing discrete symmetries to the lagrangian that remove quartic terms with an odd number of either doublet.** With those restrictions in mind, the most general 2HDM potential…”

The paragraph in line 189 has also modified (FCNC in 2HDMs was originally mentioned here when talking about 2HDM types):
“The discrete symmetries of the 2HDM lagrangian in Equation 2.22 cause the fermions to couple to the Higgs doublets in specific ways and the different 2HDMs are categorized accordingly. In type-I 2HDMs…”

Thesis changes since initial circulation

Text updates

- Added flipped and lepton-specific 2HDM description
- Expanded statistics appendix to better describe limit setting
- Will clarify fake factor method of MSSM a bit.

BACKUP

2HDM - details

- Two ways of getting a SM-like Higgs:
  - All Higgses are heavy apart from h, so they can be integrated out and the SM is an EFT with $h \sim h_{SM}$. This is called the ***decoupling limit***
  - If the mixing between the CP-even *h* and *H* is zero, the little *h* aligns with the SM Higgs. Effectively, this corresponds to the limit $\sin(\beta - \alpha) \to 1$

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2.$$

$$h = \rho_1 \sin\alpha - \rho_2 \cos\alpha$$
$$H = -\rho_1 \cos\alpha - \rho_2 \sin\alpha$$
$$A = \eta_1 \sin\beta - \eta_2 \cos\beta$$

Model	u_R^i	d_R^i	e_R^i
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2

Higgs Sector Extensions

Other ways to extend Higgs sector:

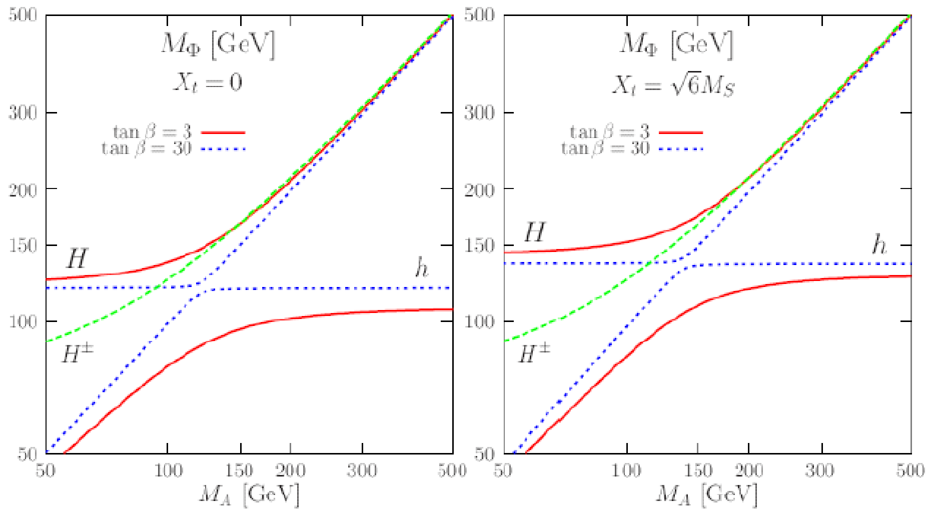
- Add just an electroweak singlet: gives 2 CP-even Higgses, h and H
- Add a doublet + singlet (e.g. NMSSM): 5 Higgses + 2 light Higgses, a_1 and a_2
- Add a triplet: gives doubly-charged Higgs H^{++}
- Higgs-portal: DM, Hidden Valley

Interesting properties

- In the limit $\sin(\beta - \alpha) \to 1$, the light Higgs couplings approach the SM values and the other Higgses are pushed to higher masses
- At tree level, the MSSM depends only on two parameters, usually taken to be the ratio of the vev's of the two doublets $\tan\beta$. For example, at LO:

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}\right]$$



From Djouadi (2008) *et al.*

	type-I	type-II
y_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
y_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
y_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
y_h^{VV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
y_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
y_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
y_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
y_H^{VV}	$\cos(\alpha-\beta)$	$\cos(\alpha-\beta)$
y_A^u	$\cot\beta$	$\cot\beta$
y_A^d	$-\cot\beta$	$\tan\beta$
y_A^ℓ	$-\cot\beta$	$\tan\beta$
y_A^{VV}	0	0

pMSSM

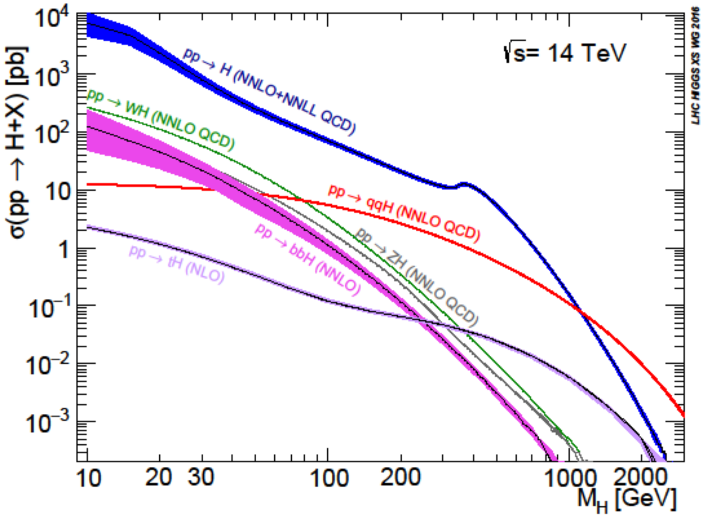
- Full unconstrained MSSM has 105 parameters
- pMSSM has 22, due to following constraints:
  - No new source of CP violation
  - No FCNC
  - First and second generation universality

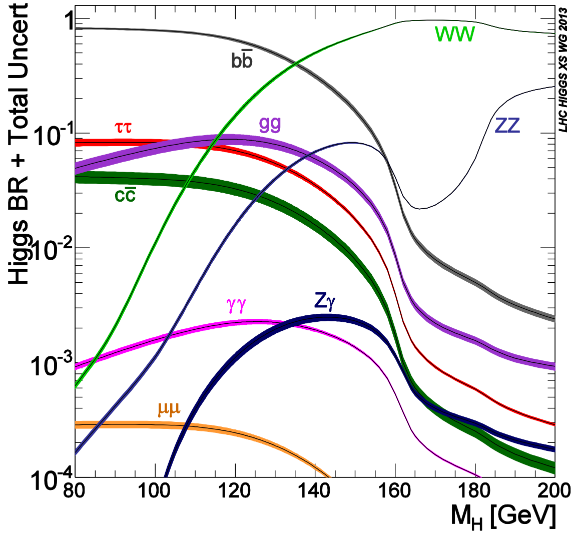
Stop mixing $X_t \equiv A_t - \mu \cot \beta$

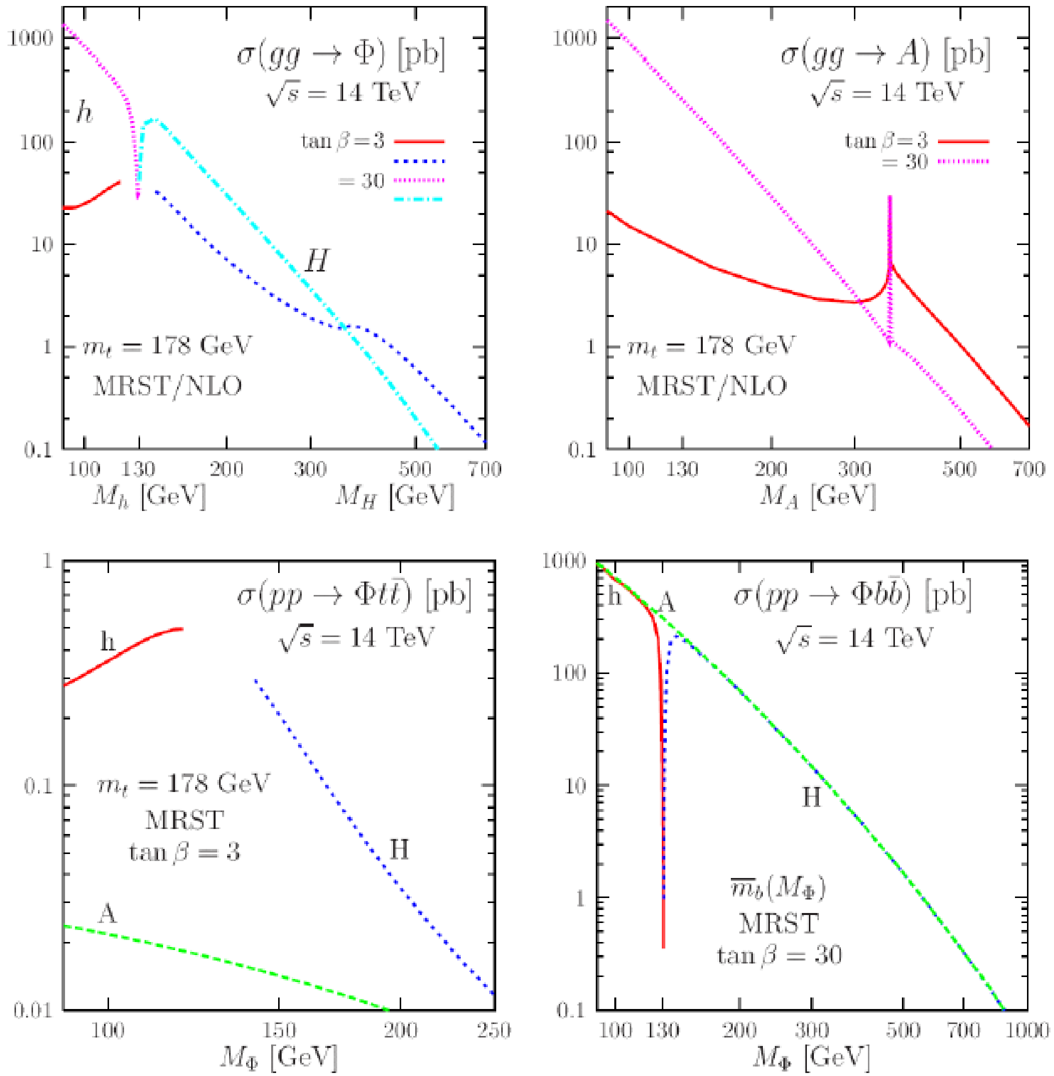
- $\tan(\beta)$: which is the ratio of the two Higgs doublet vev's;
- m_{H_1} and m_{H_2}: the Higgs mass parameters;
- M_1, M_2, M_3: the bino, wino and gluino mass parameters;
- $m_{\tilde{q}}$, $m_{\tilde{u}_R}$, $m_{\tilde{d}_R}$, $m_{\tilde{l}}$, $m_{\tilde{e}_R}$: the mass parameters for the first two generations of squarks and sleptons;
- A_u, A_d, A_e: the trilinear couplings of the first two generations of squarks and sleptons;
- $m_{\tilde{Q}}$, $m_{\tilde{t}_R}$, $m_{\tilde{b}_R}$, $m_{\tilde{L}}$, $m_{\tilde{\tau}_R}$: the mass parameters of the third generation;
- A_t, A_b, A_τ: the trilinear couplings of the third generation;

Higgs production rates

From Djouadi (2008) *et al.*







Standard model values

Data-driven background estimation methods

- Used for:
  - objects or kinematic regions where simulation is known not to do well.
  - multi-jet background estimation

- Here I describe two methods often used in ATLAS.

ABCD method

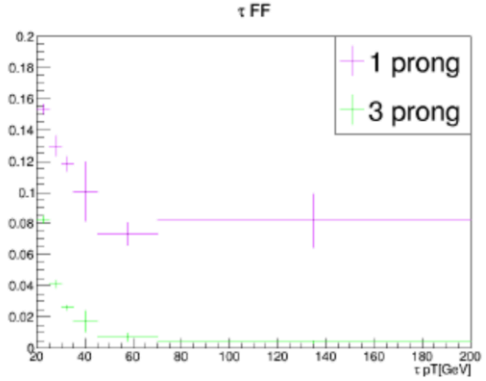
- Invert two cuts in signal region (A) to create 3 control regions
- Prediction in signal region (A) is made by scaling a background shape in a control region (B) with a normalization factor computed from ratio of yields in C and D

	Pass X	Fail X
Pass Y	Signal Region (A) ↑	C ↑
Fail Y	B (background shape)	D

Scale factor = N_C/N_D

Fake Factor method

- Compute a prediction by weighing events in a control region with a fake factor
- Fake factor defined as $FF(x) = \frac{N_{pass}(x_i)}{N_{fail}(x_i)}$
- Answers the question "how often will this fake object be found misclassified in my signal region?"
- Can be binned in N-dimensions, and with variables other than your discriminant variable (e.g. pT).

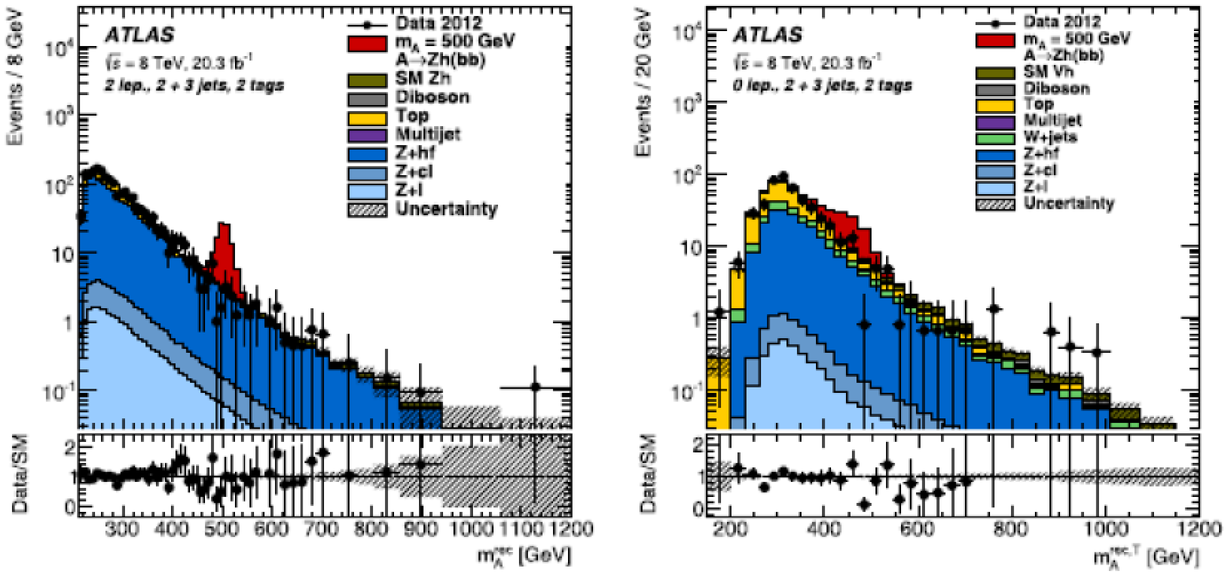


AZh->llbb - overview

- Give brief overview

Table 2
Predicted and observed number of events for the $\ell\ell bb$ and $\nu\nu bb$ final states shown after the profile likelihood fit to the data.

	$(\ell\ell bb)$	$\nu\nu bb$
Z + jets	1443 ± 60	225 ± 11
W + jets	–	55 ± 8
Top	317 ± 28	203 ± 15
Diboson	30 ± 5	10.8 ± 1.6
SM Zh, Wh	31.7 ± 1.8	22.5 ± 1.2
Multi-jet	20 ± 16	3.2 ± 3.1
Total background	1843 ± 34	521 ± 12
Data	1857	511



(a) $\ell\ell bb$ (b) $\nu\nu bb$

$H/A \rightarrow \tau_{lep}\tau_{had}$ event preselection

- LepHad triggers: e24_lhmedium_L1EM20VH(L1EM18VH), e60_lhmedium, e120_lhloose; mu20_iloose_L1MU15 and mu50
- HadHad trigger: HLT_tau80_medium1_tracktwo_L1TAU60

- Overlap removal cone of 0.2 in order muons > electrons > leading tau > jets. Cone of 0.4 used for jets overlapping with e or mu (chosen after looking at $\Delta R(jet, \ell)$).

- Exclude crack electrons, max eta of 2.47 (2.5) for electrons (muons). Gradient isolation working point

- pT of objects used in overlap removal: 15 GeV for electrons, 7 GeV for muons.

$H/A \to \tau_e \tau_{had}$ – Cutflow

Cut: Backgrounds	Top			$Z \to \tau\tau$+jets		
	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)
pre-selection	3316.2 ± 11.2	27.7	2.8	7102.3 ± 54.5	0.9	0.0
$\Delta\phi(\tau,\ell) > 2.4$	1354.4 ± 7.1	22.0	2.6	5516.2 ± 47.8	0.7	0.0
$m_T(\ell, E_T^{miss}$	221.0 ± 2.9	33.4	3.2	4286.2 ± 42.2	0.7	0.0
b-veto	51.9 ± 1.4	36.1	2.0	4216.5 ± 41.7	0.7	0.0

Cut: Backgrounds	W+jets			Diboson		
	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)
pre-selection	12258.0 ± 146.4	99.4	0.0	524.4 ± 5.6	22.0	3.6
$\Delta\phi(\tau,\ell) > 2.4$	6340.7 ± 105.5	99.3	0.0	261.1 ± 3.6	15.8	3.9
$m_T(\ell, E_T^{miss}$	1142.8 ± 44.8	99.5	0.0	53.3 ± 1.8	20.3	8.5
b-veto	1116.3 ± 44.0	100.0	0.0	51.2 ± 1.7	19.1	8.6

Cut: Backgrounds	$Z \to \ell\ell$+jets		
	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)
pre-selection	1796 ± 29	30.9	69.0
$\Delta\phi(\tau,\ell) > 2.4$	1377 ± 26	21.2	78.7
$m_T(\ell, E_T^{miss}$	920 ± 21	17.7	82.3
b-veto	907 ± 21	17.6	82.4

$H/A \to \tau_\mu \tau_{had}$ – Cutflow

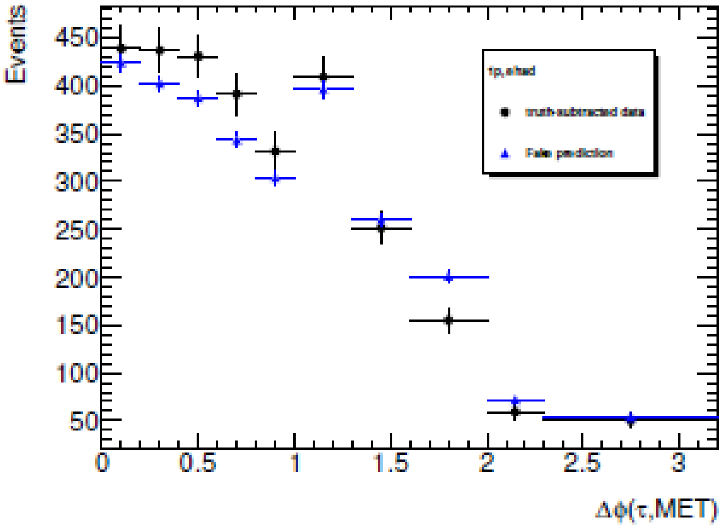
Cut: Backgrounds	Top			$Z \to \tau\tau$+jets		
	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)
pre-selection	3914.7 ± 11.7	28.6	2.6	8599.8 ± 58.5	0.9	0.0
$\Delta\phi(\tau,\ell) > 2.4$	1559.5 ± 7.4	24.2	2.4	6859.5 ± 52.1	0.7	0.0
$m_T(\ell, E_T^{miss}$	258.9 ± 3.0	34.4	3.0	5145.7 ± 45.2	0.8	0.0
b-veto	61.3 ± 1.4	39.3	2.6	5072.5 ± 44.7	0.7	0.0

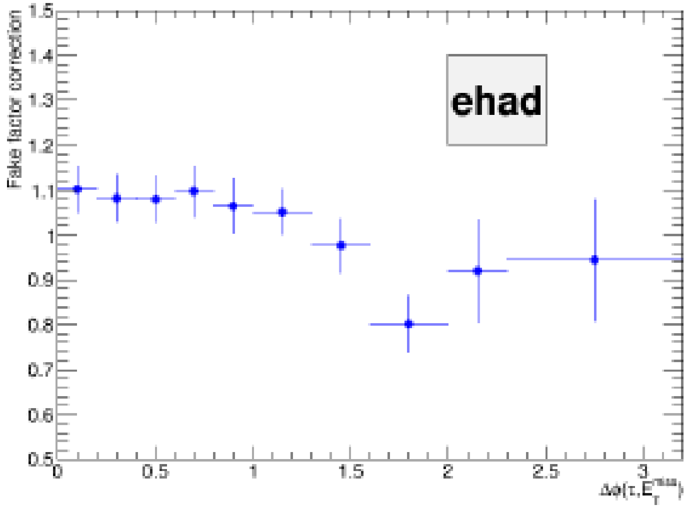
Cut: Backgrounds	W+jets			Diboson		
	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)
pre-selection	17590 ± 190	99.6	0.0	615.9 ± 5.7	24.1	3.6
$\Delta\phi(\tau,\ell) > 2.4$	9937 ± 140	99.5	0.0	314.0 ± 3.9	19.7	3.8
$m_T(\ell, E_T^{miss}$	1538 ± 55	99.5	0.0	61.9 ± 1.8	18.0	7.0
b-veto	1504 ± 54	99.5	0.0	60.1 ± 1.8	17.5	7.0

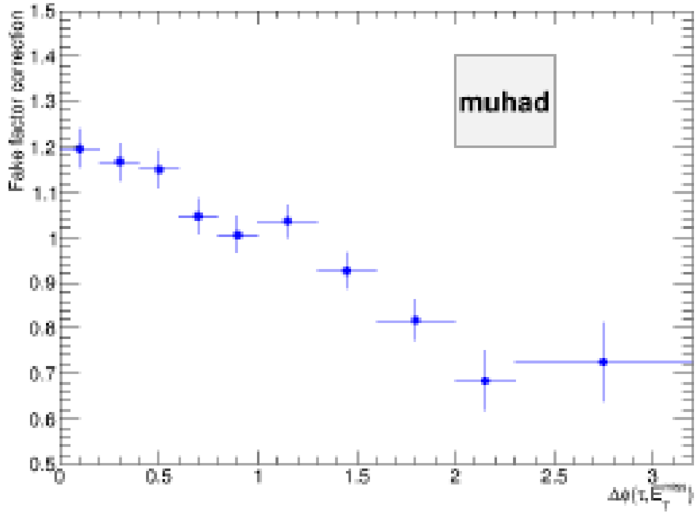
Cut: Backgrounds	$Z \to \ell\ell$+jets		
	Events	jet $\to \tau_{had}$ (%)	$e \to \tau_{had}$ (%)
pre-selection	2465 ± 32	19.6	80.4
$\Delta\phi(\tau,\ell) > 2.4$	2050 ± 29	13.6	86.3
$m_T(\ell, E_T^{miss}$	931 ± 19	8.7	91.3
b-veto	920 ± 19	8.8	91.2

MSSM – $\Delta\phi$ correction of FF

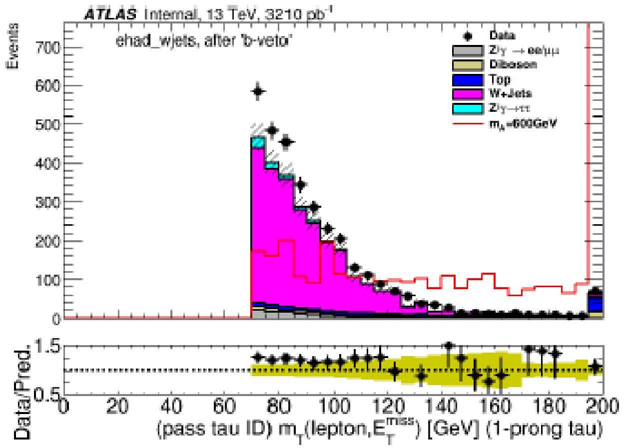
- An additional dependence on the missing energy was found for the fake rate. A scale factor is derived in the respective control regions parameterized in $\Delta\phi(l, E_T^{miss})$ for QCD and $\Delta\phi(\tau_{had}, E_T^{miss})$ for W+Jets.



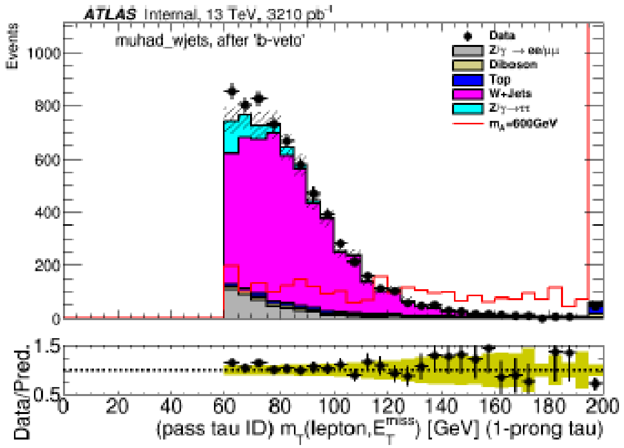




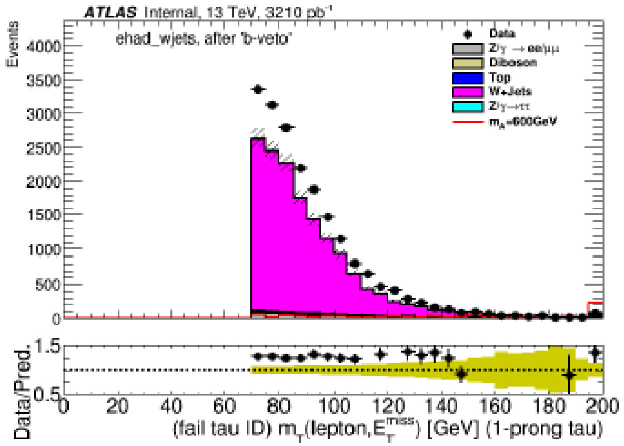
MSSM – W+jets CR plots

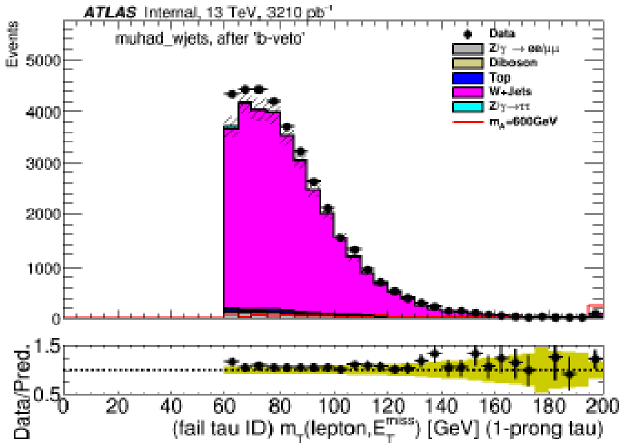


(a)

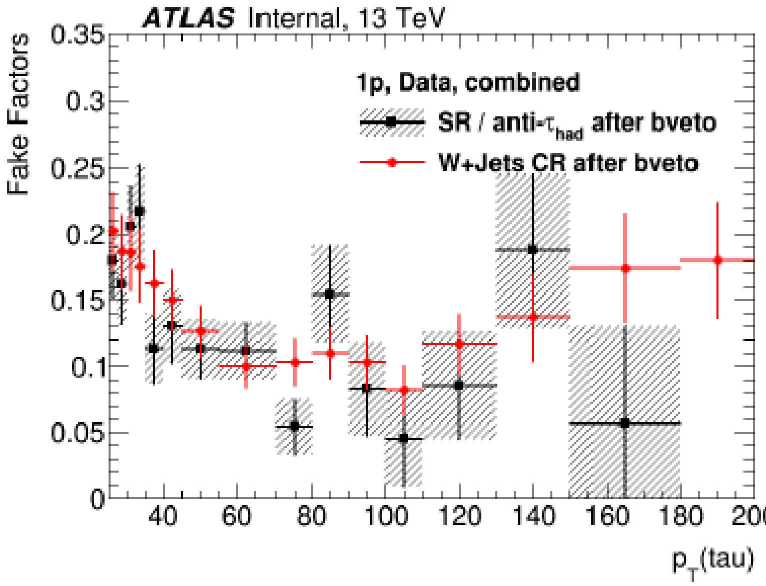


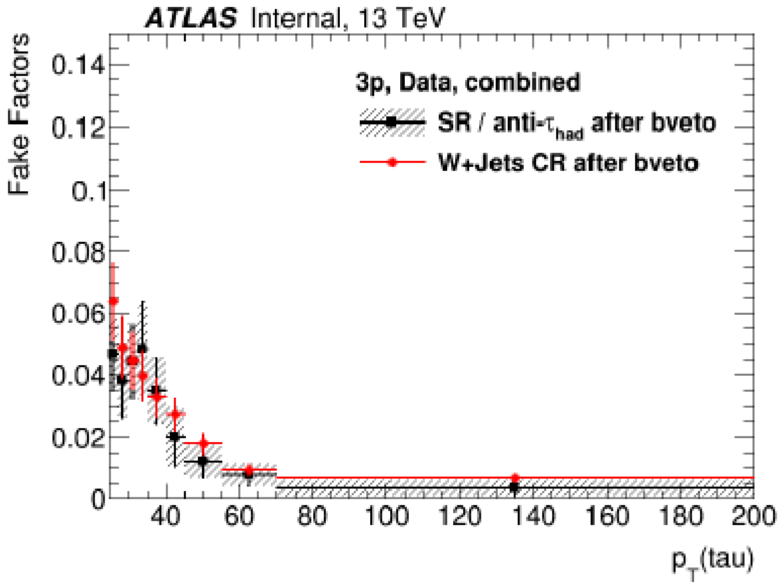
(b)

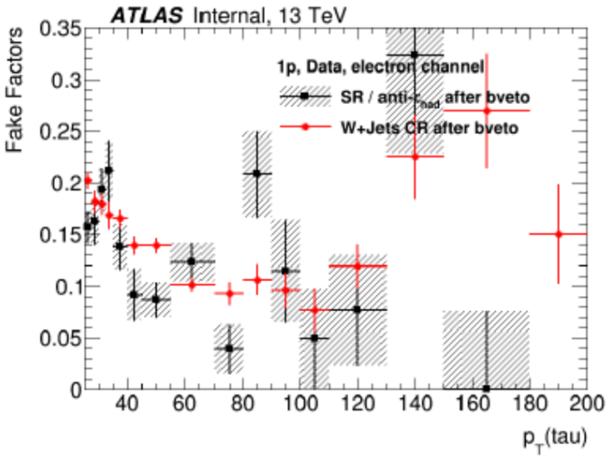


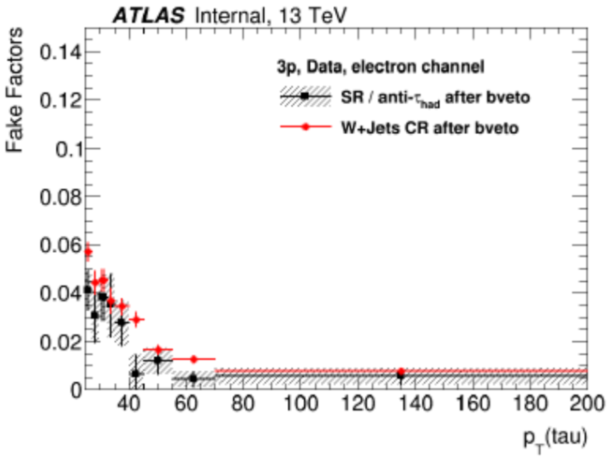


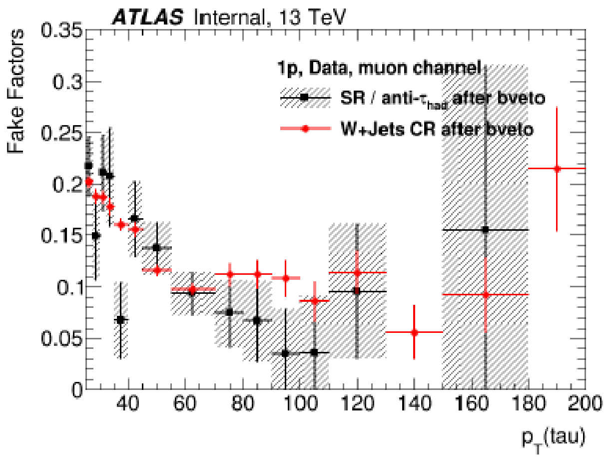
MSSM – all W+Jets FF

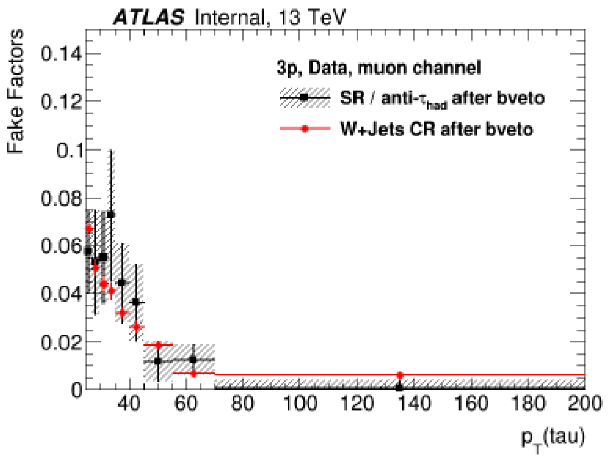




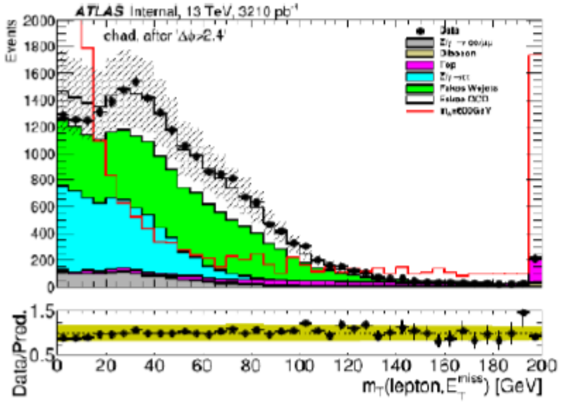


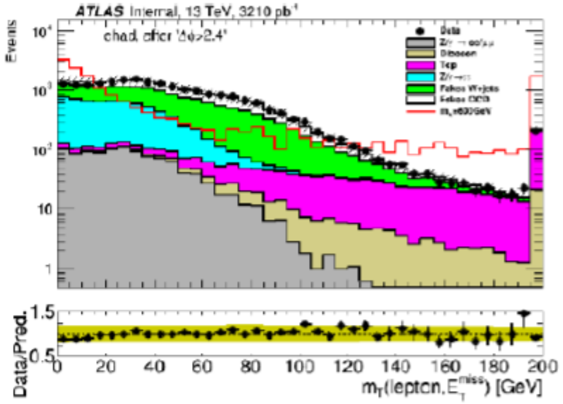


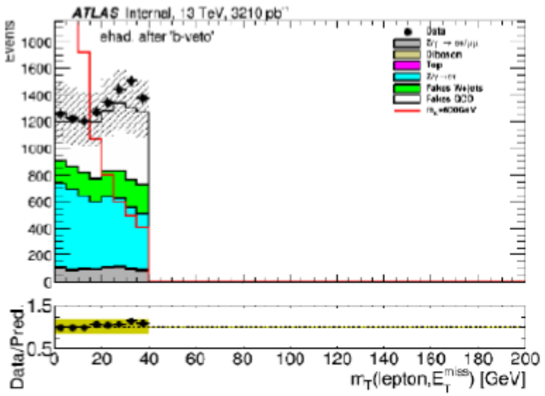


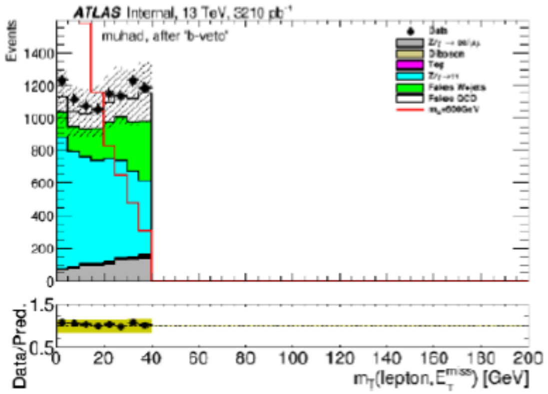


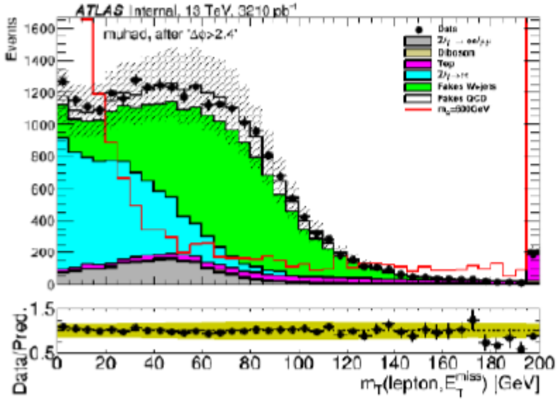
MSSM – Fake Composition

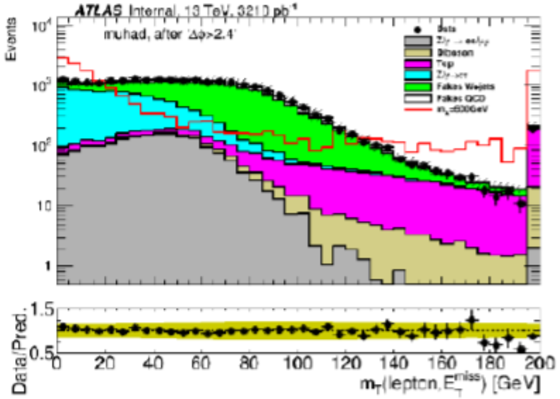




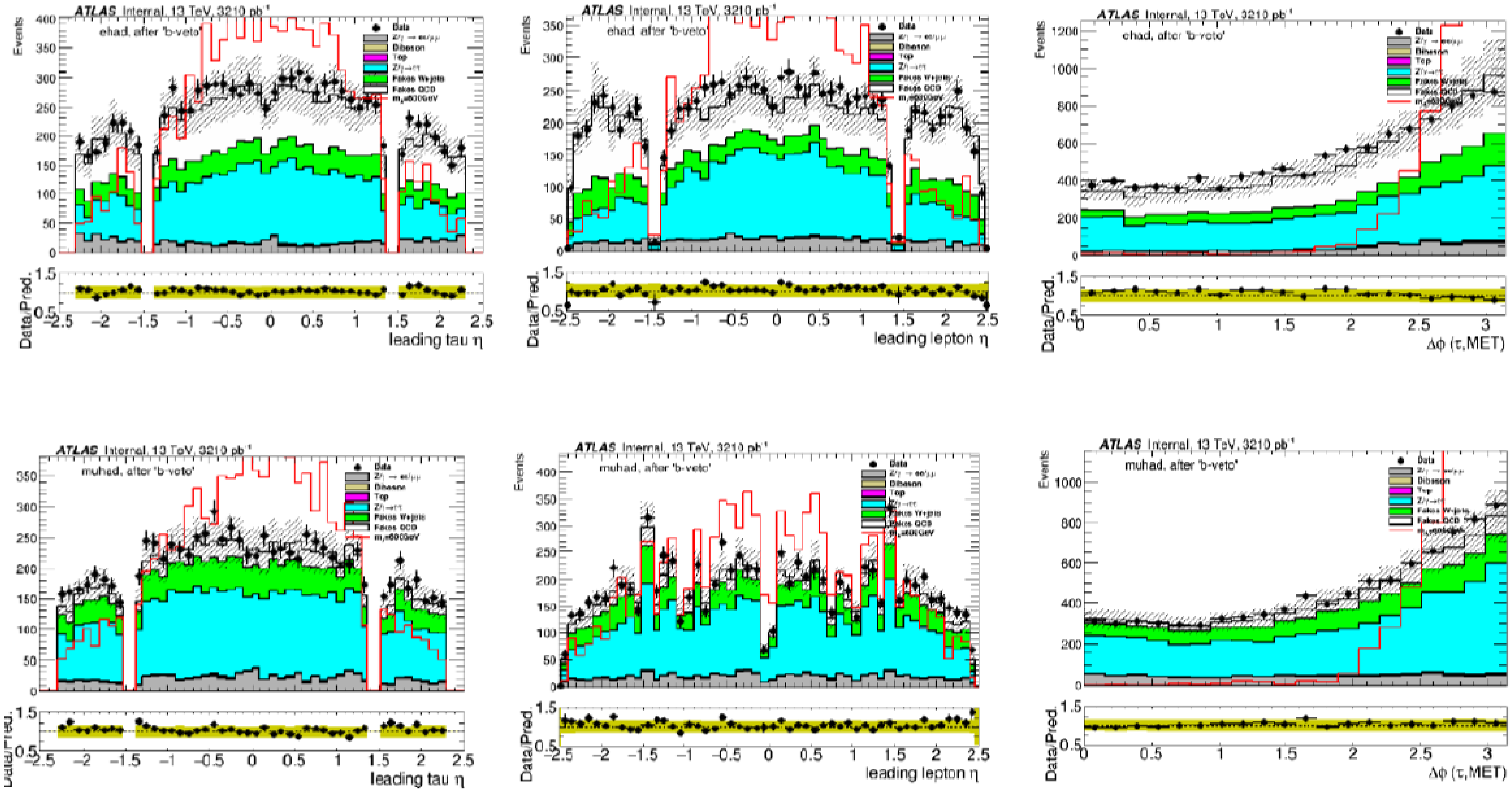






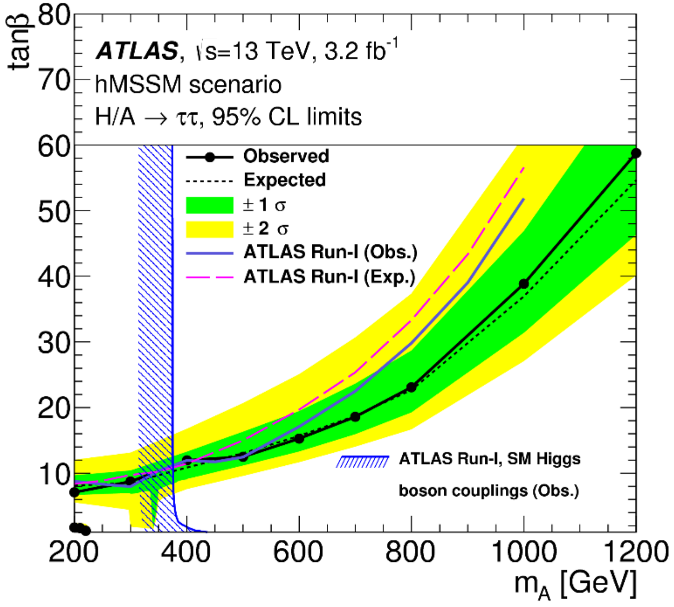


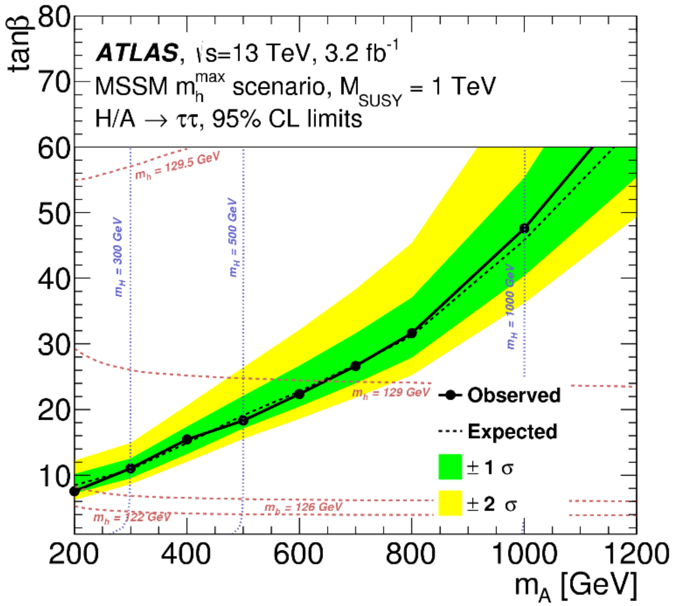
MSSM – Fake Composition

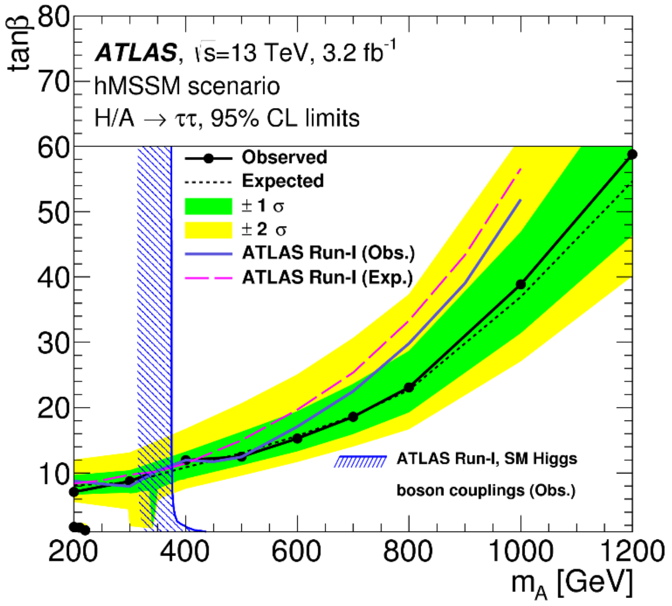


Other MSSM scenarios

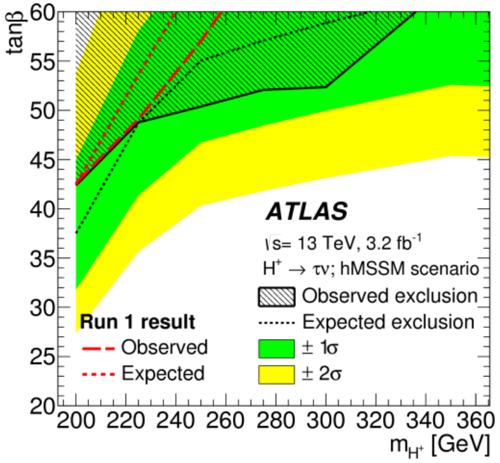
hMSSM: fix m_h=125, other Run 1 constraints

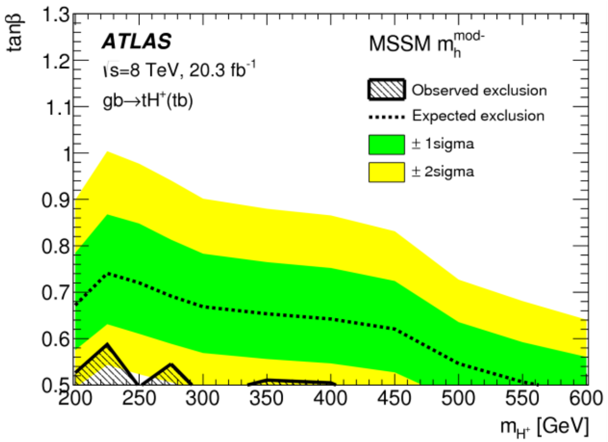






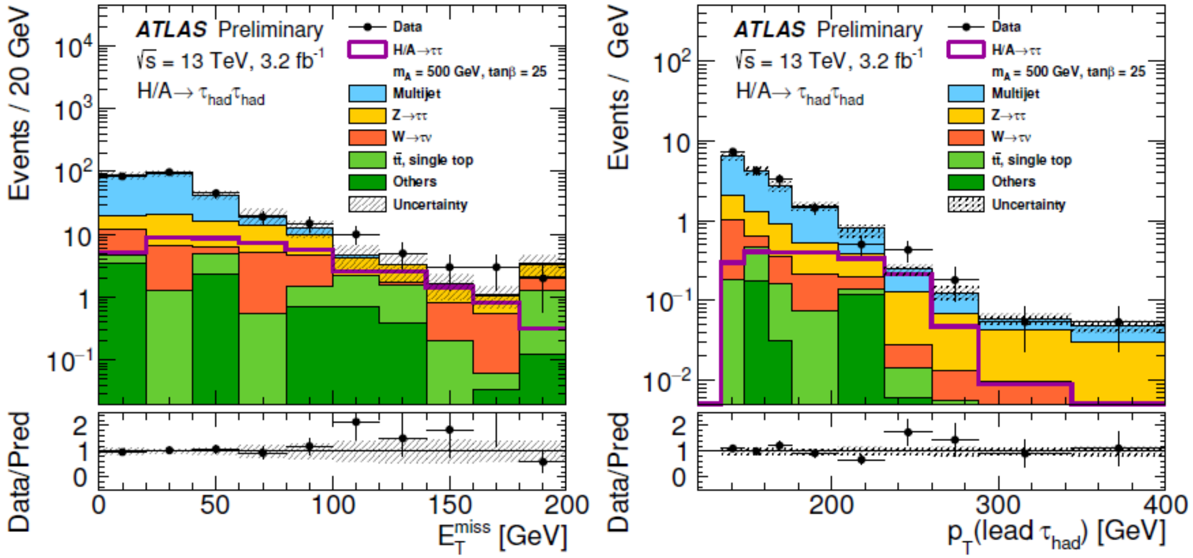
Exclusions from charged higgs:





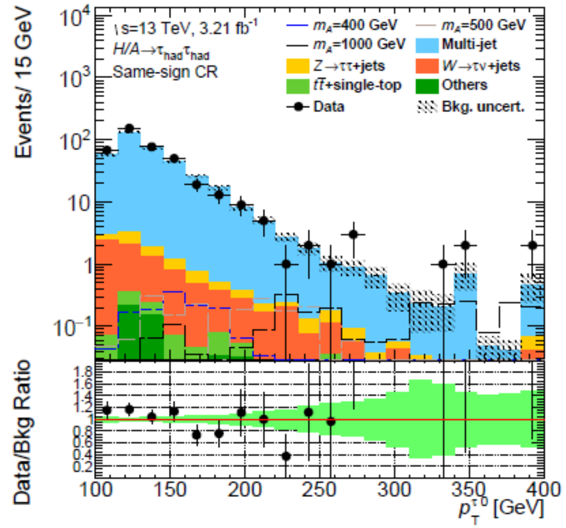
$H/A \rightarrow \tau_{had}\tau_{had}$ – Selection

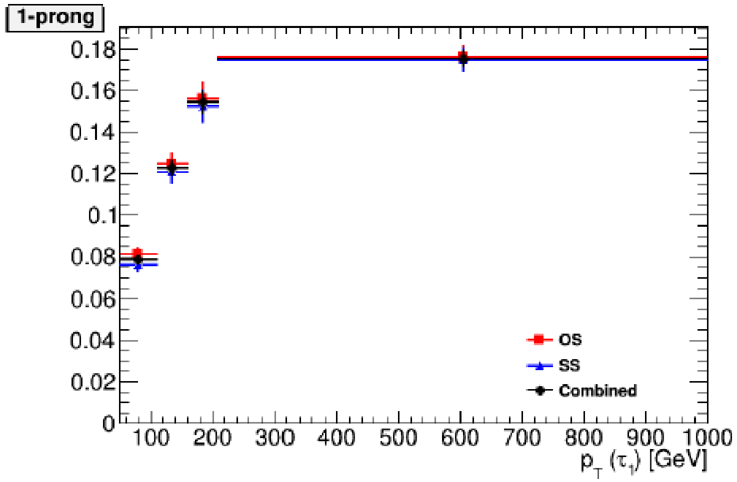
- Di-tau trigger (80 and 60 GeV taus)
- 2 OS τ_{had} with $p_{T,\tau_1} > 110$ GeV and $p_{T,\tau_2} > 55$ GeV.
- No light leptons
- Leading tau passes medium ID. Subleading tau passes loose ID.
- $\Delta\phi(\tau^{vis}_{had,1}, \tau^{vis}_{had,2}) > 2.7$

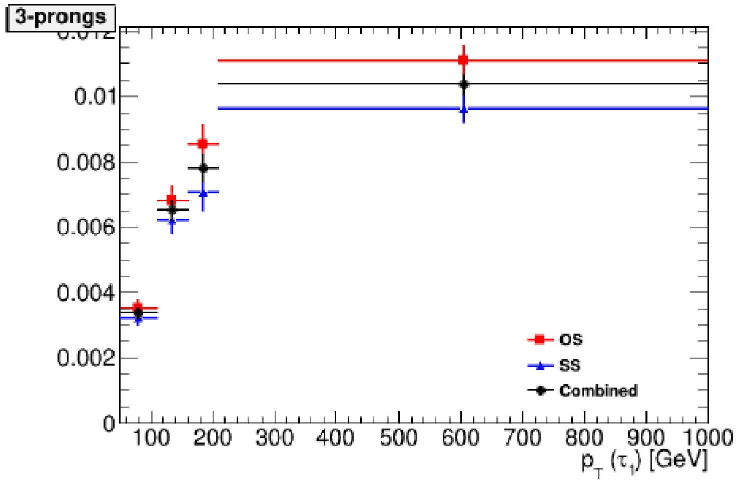


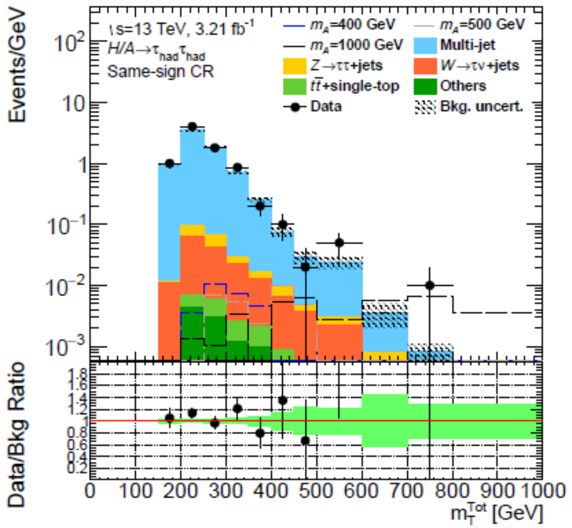
$\tau_{had}\tau_{had}$: multi-jet background

- Multi-jet production obtained using jet triggers, and a tag and probe logic to the two fake-tau system. Uses OS and SS taus to boost statistics
- Fake factors parameterized in tau pT and number of tracks are derived from di-jets events in data. These FF are then applied to data events where the leading tau passes identification but the subleading doesn't.





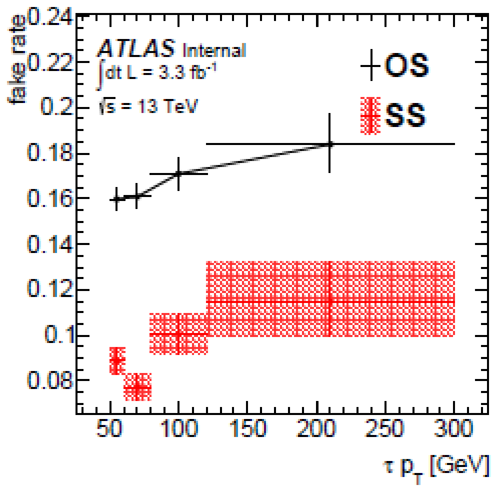


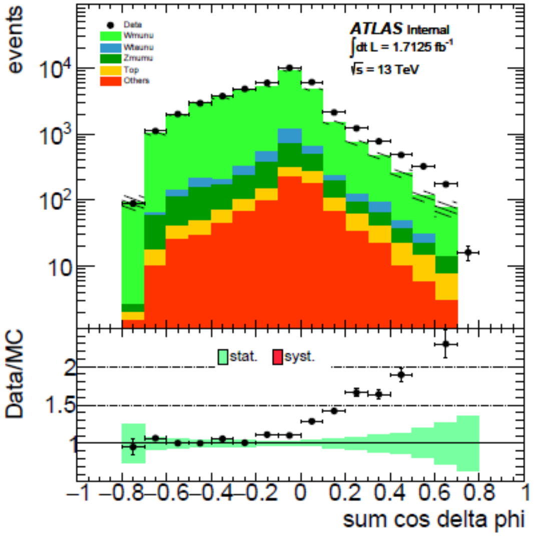


$\tau_{had}\tau_{had}$: MC background with fake taus

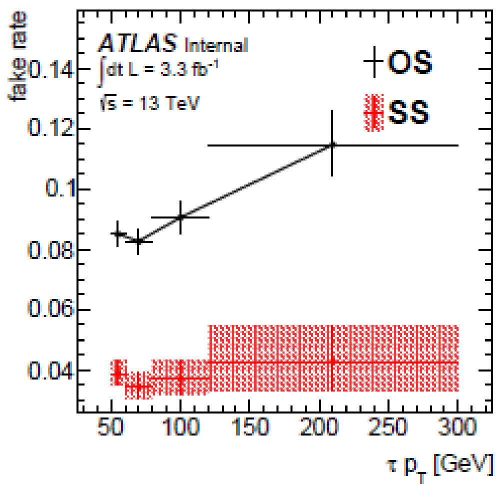
- Data driven fake rates computed in a $W \rightarrow \mu\nu$ + jets control region and applied to all MC events with fake taus
- Isolation requirement and $\Sigma_{l=\mu,\tau} \cos\left(\Delta\phi\left(l, E_T^{miss}\right)\right) < 0$ to suppress multi-jet background
- Fake factors are computed for Medium and Loose TauID working points and applied to leading and subleading taus, respectively
- Additional pT-based correction applied to W+Jets MC in order to achieve good data/MC modelling

Loose ID, 1p

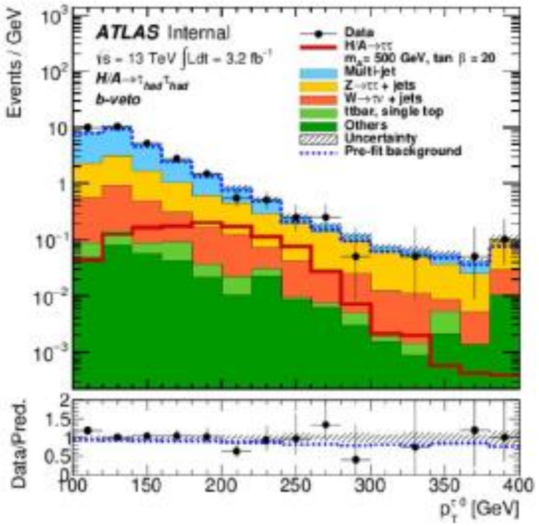


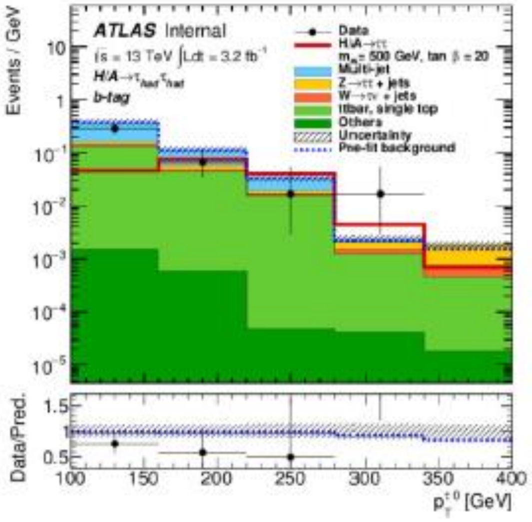


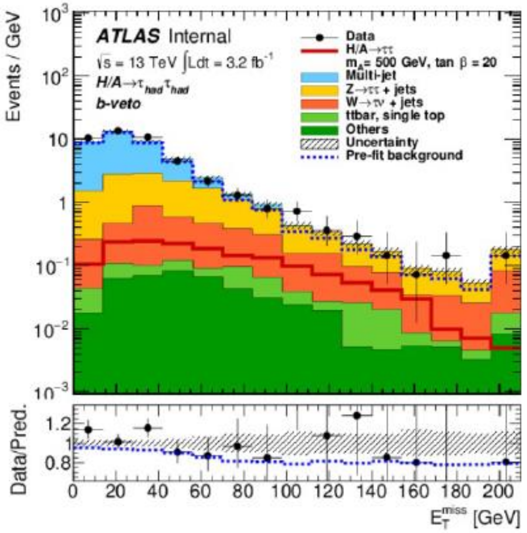
Medium ID, 1p

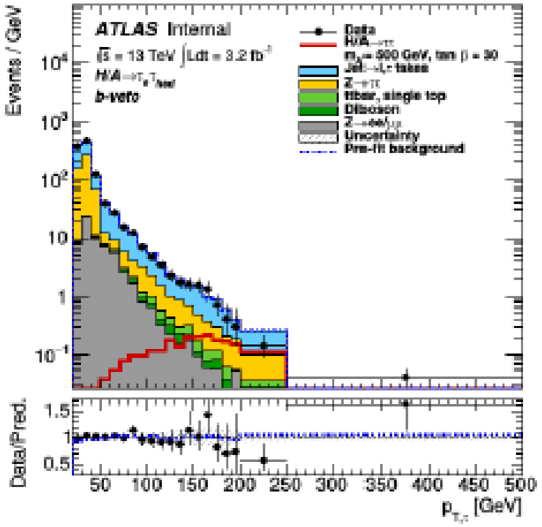


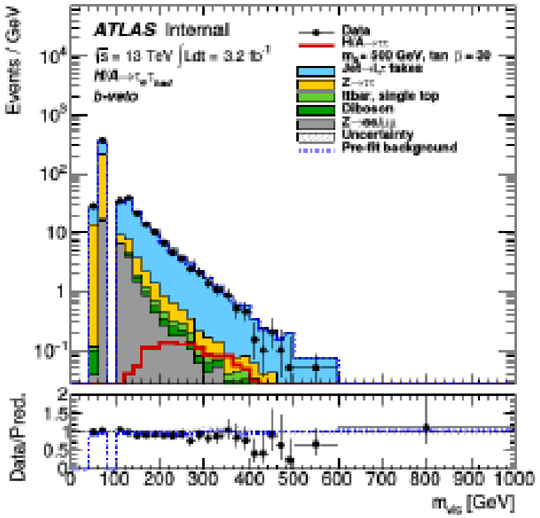
Kinematic variable distributions

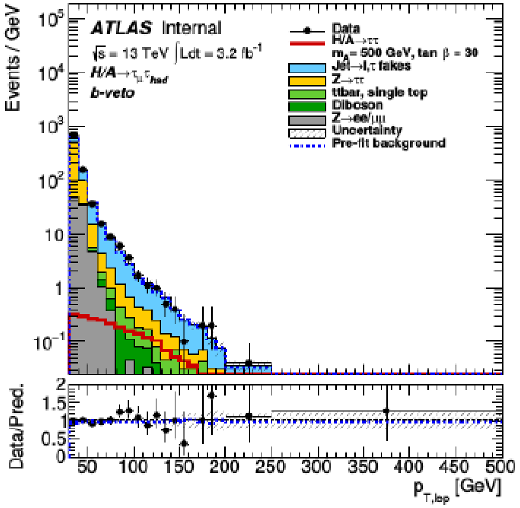




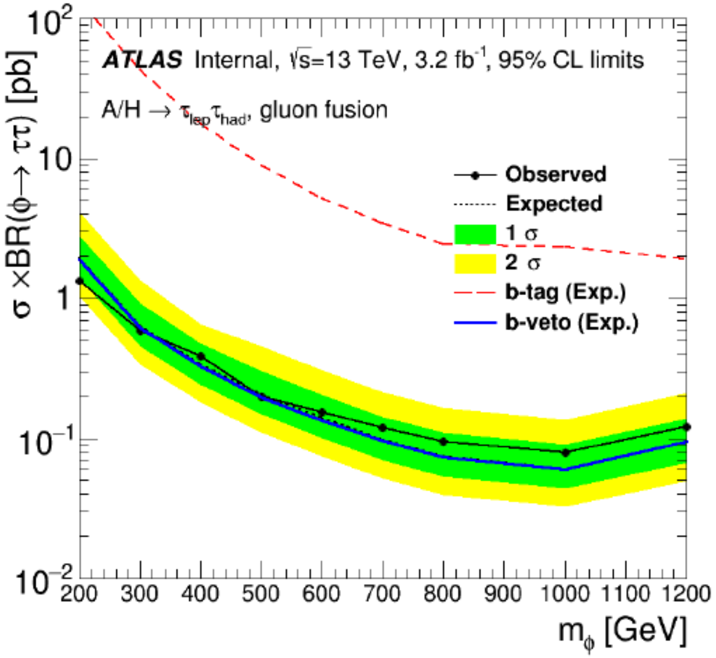


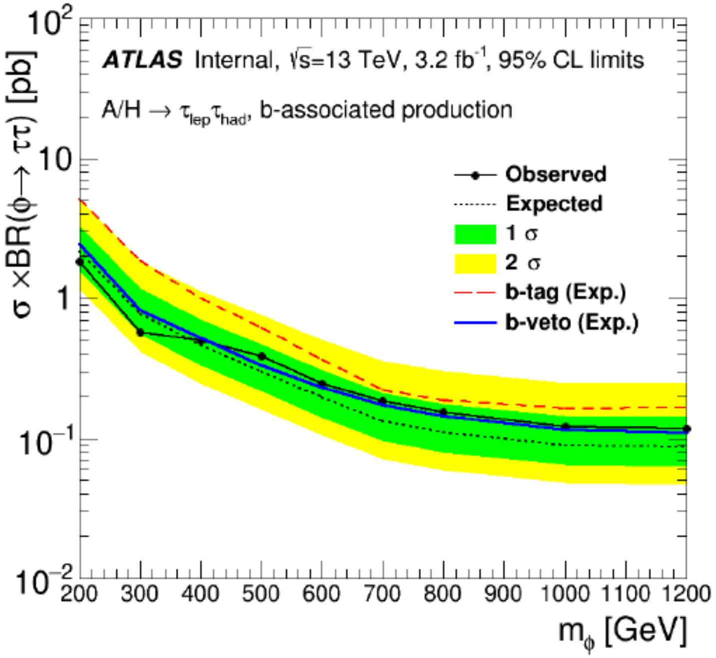






$H/A \rightarrow \tau\tau$ – b-veto / b-tag comparison





CONF NOTE

- A preliminary version of the analysis was made public as a CONF NOTE at the end of last year (ATLAS-CONF-2015-061)
- Early result did note include flavor-tagging. Current analysis also has improved selection and background estimation, and
- Results were presented as upper limits on σ X BR, and interpreted for various benchmark scenarios
- We achieved better exclusion than Run-I for high mass range