

$p_T(\mu) = 18 \text{ GeV}$   
 $p_T^{\text{vis}}(\tau_h) = 26 \text{ GeV}$   
 $m_{\text{vis}}(\mu, \tau_h) = 47 \text{ GeV}$   
 $m_T(\mu, E_T^{\text{miss}}) = 8 \text{ GeV}$   
 $E_T^{\text{miss}} = 7 \text{ GeV}$

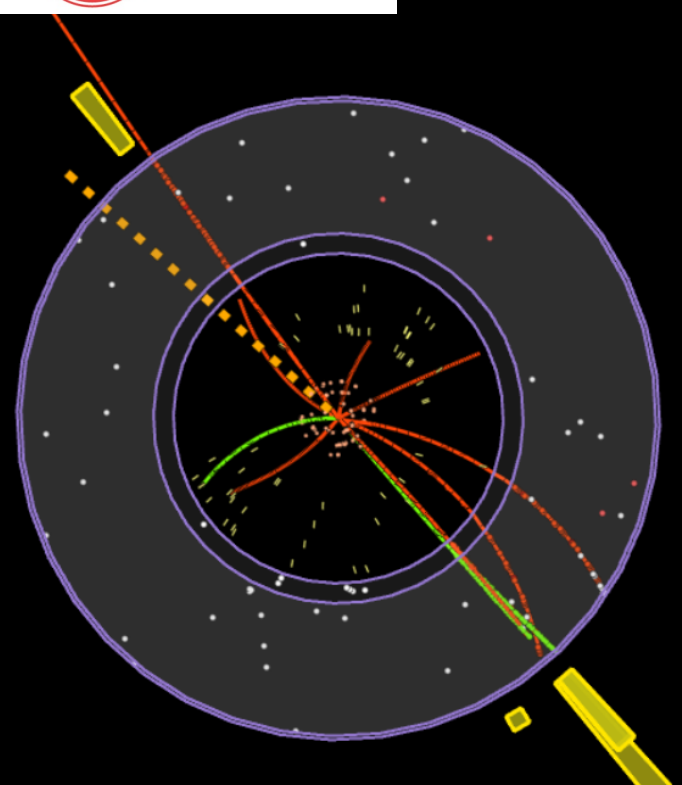
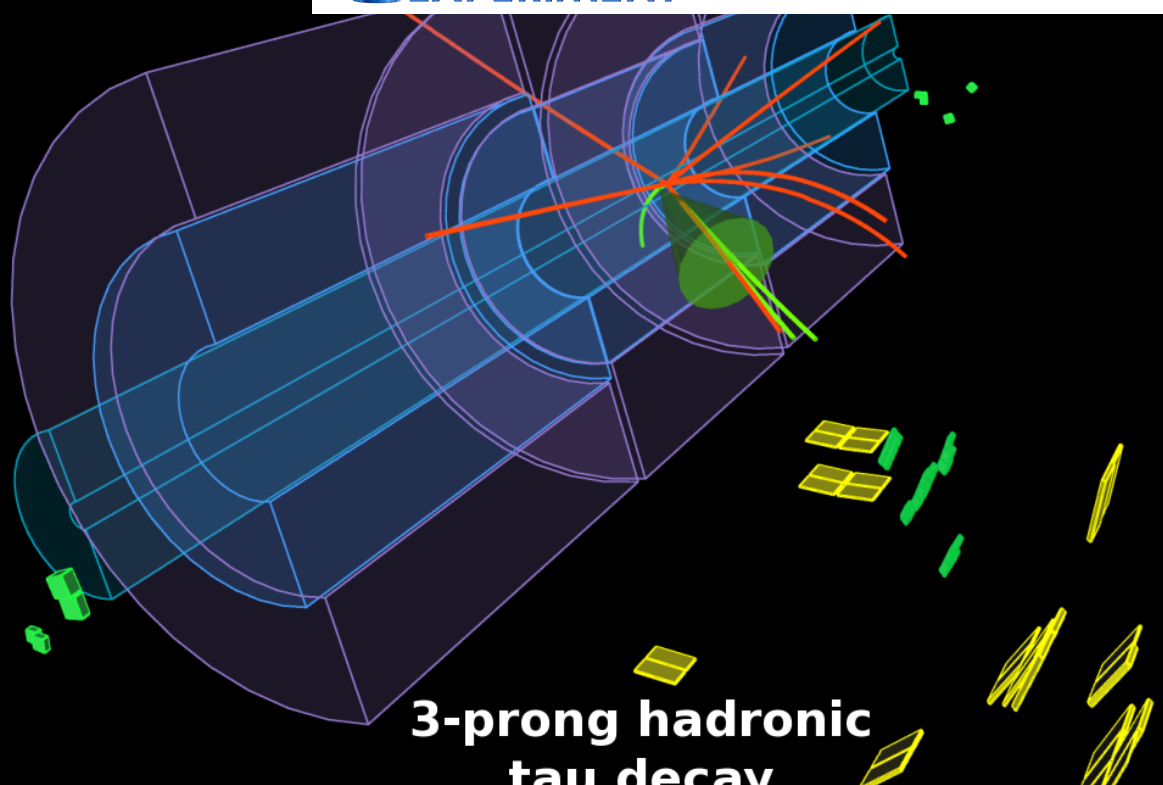
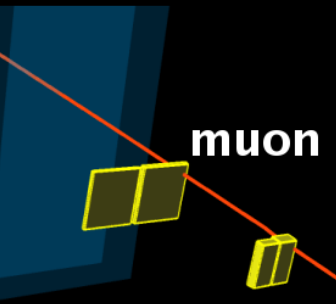
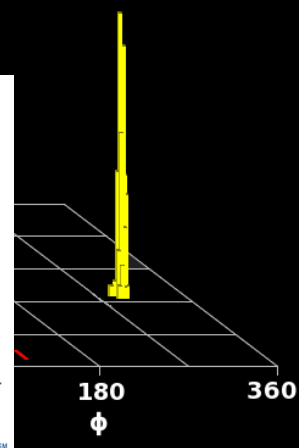
# ATLAS EXPERIMENT

2 GeV

## Search for Higgs bosons decaying into tau leptons with ATLAS



Aidan Randle-Conde  
Southern Methodist University



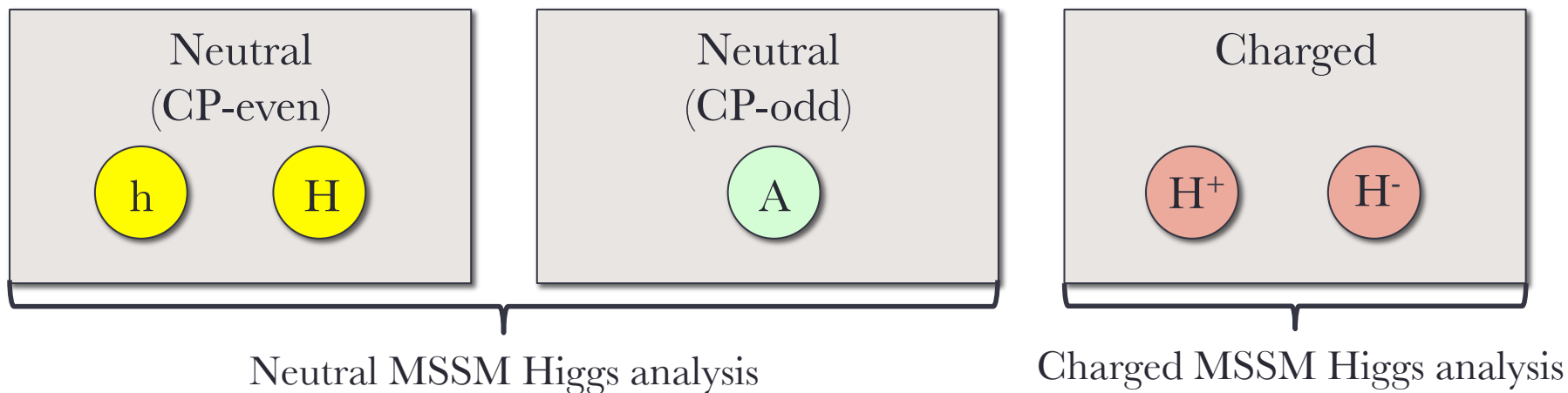
# Introduction

- The Higgs sector
- The ATLAS detector
- The ATLAS experiment
- Background estimations
- Likelihood analysis
- Neutral MSSM  $H \rightarrow \tau\tau$  analysis
- Charged MSSM  $H^\pm \rightarrow \tau\nu$  analysis
- Conclusion
  
- Backup



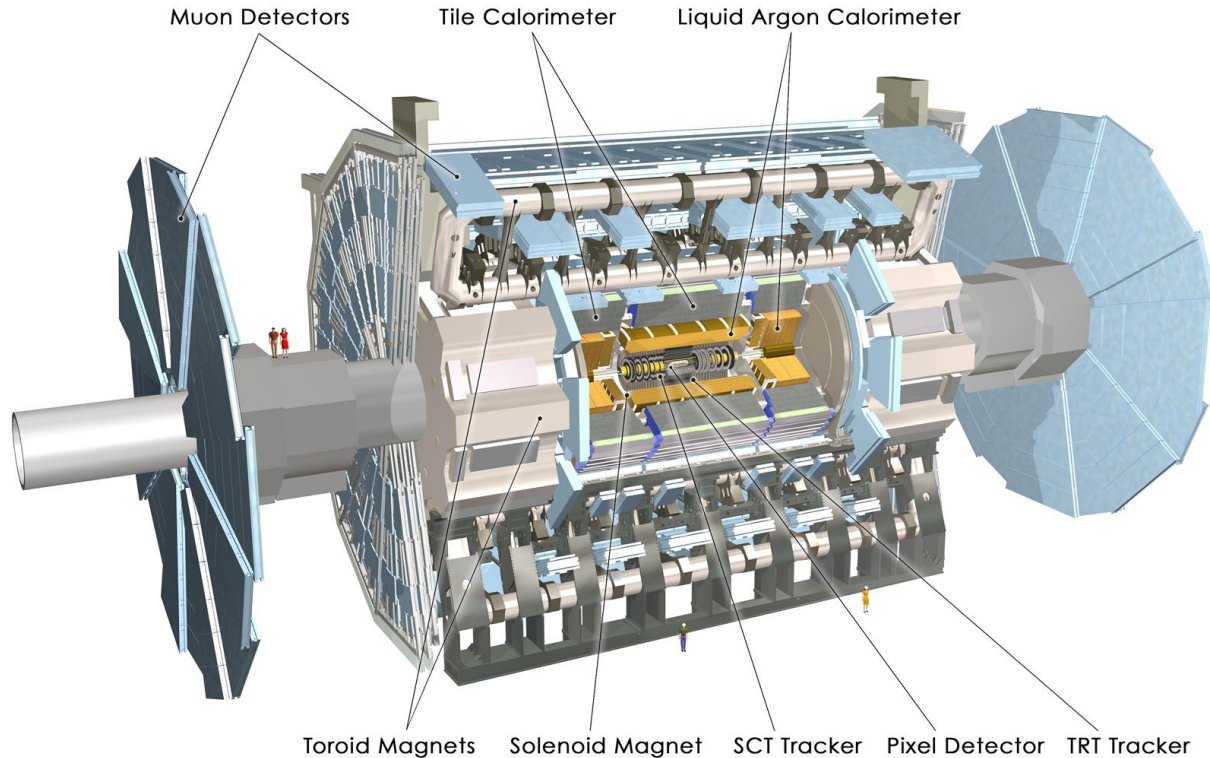
# Higgs sector

- Many Higgs scenarios beyond the standard model (SM) include several Higgs bosons:
  - two CP even neutral  $h, H$  bosons (including the SM Higgs boson)
  - one CP odd neutral  $A$  boson
  - two charged  $H^\pm$  bosons
- A popular model is the minimal supersymmetric (MSSM) extension to the SM
- Simplest scenario has two main parameters:
  - the mass of the  $A$  boson,  $m_A$  and ratio of vacuum expectation values,  $\tan\beta$
- Decays of additional Higgs bosons to massive gauge bosons generally suppressed by a factor of  $\cos^2(\beta-\alpha)$ 
  - Decays to  $\tau\tau$  favored



(Throughout this talk I use  $H$  for all Higgs bosons)

# The ATLAS detector

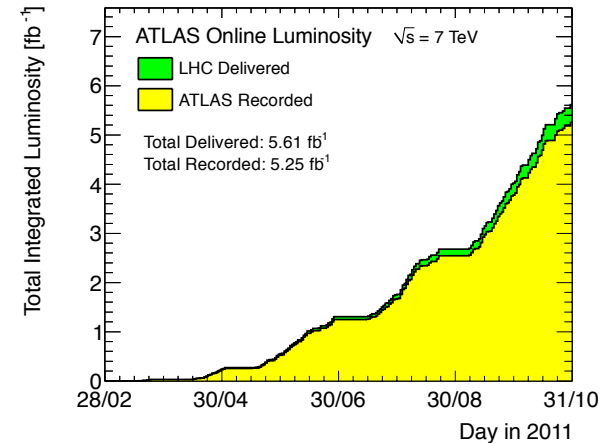


Conserving momentum in the transverse plane gives the missing transverse energy,  $E_T^{\text{miss}}$

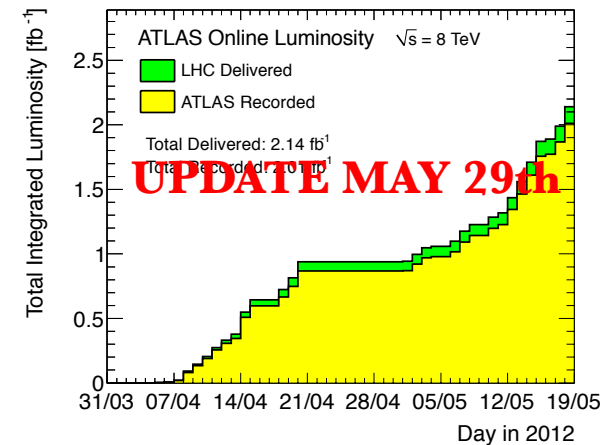
Coverage for electron reconstruction in region  $|\eta| < 2.37$  excluding  $1.37 < |\eta| < 1.52$

$$\eta = -\ln(\tan(\theta / 2))$$

## These analyses:

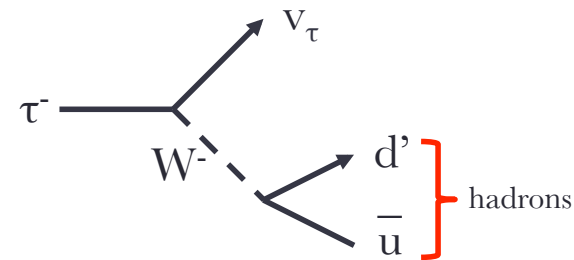
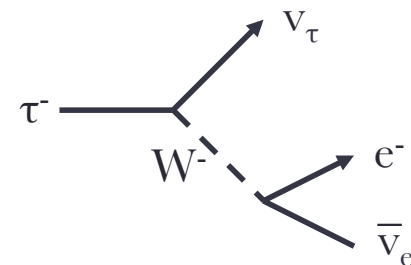


## Great start for 2012:



# Working with $\tau$ leptons

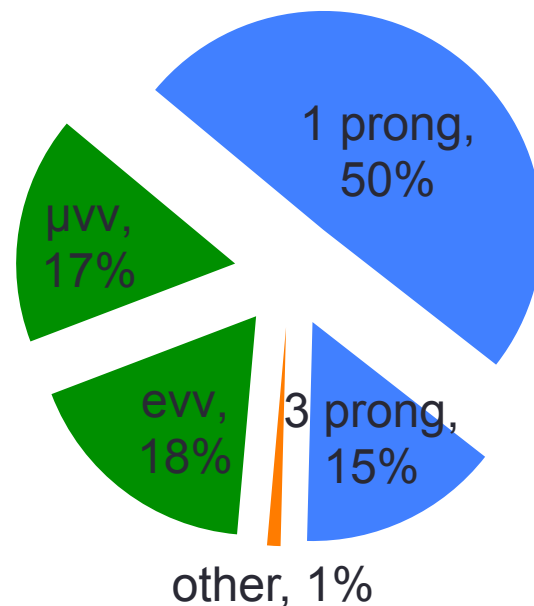
- $\tau$  leptons present several challenges for analyses:
  - Large number of neutrinos in the final state
  - Leptonic and hadronic decays must be treated separately
    - Hadronic decays include “1 prong” ( $\nu\pi^\pm+n\pi^0$ ), “3 prong” ( $\nu 3\pi^\pm+n\pi^0$ ) and “other” (mostly  $\nu K+X$ )



## Leptonic decays

Use existing algorithms for light lepton identification:

- Well defined control samples
- Well understood energy scales
- Clean signatures



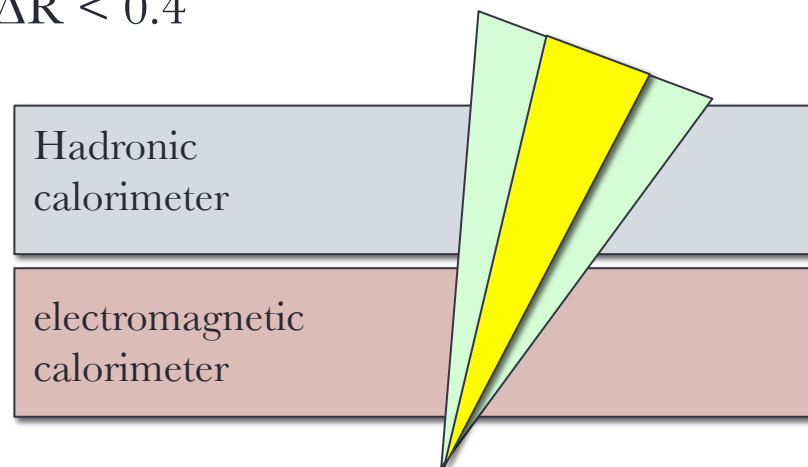
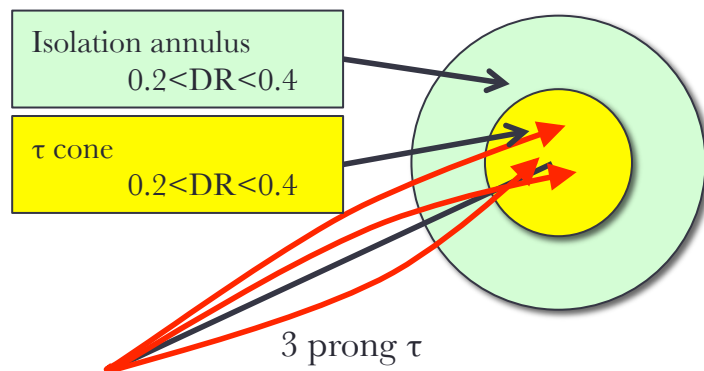
## Hadronic decays

Use algorithms specific to  $\tau$  leptons:

- Final states manifest as jet-like objects
- Some separation of 1 and 3 prong decays

# $\tau$ leptons identification

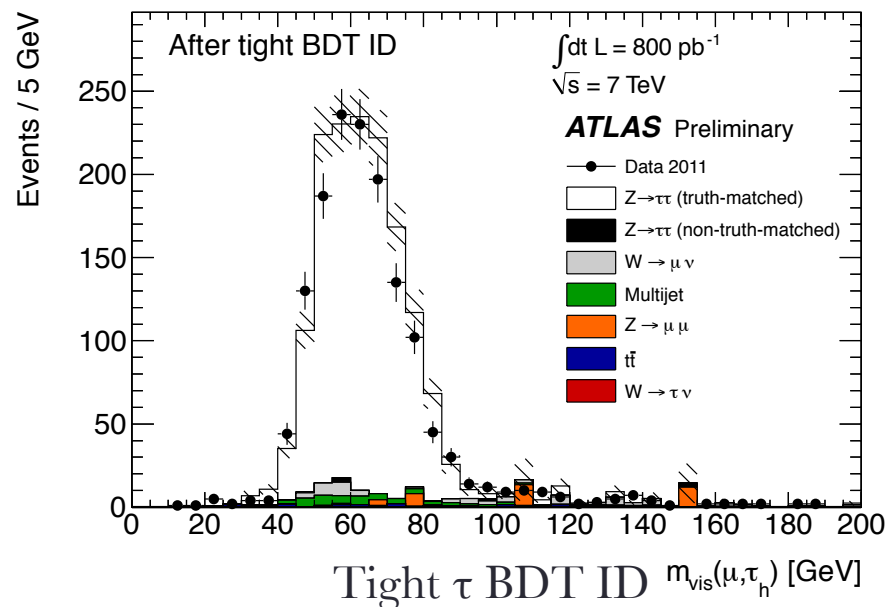
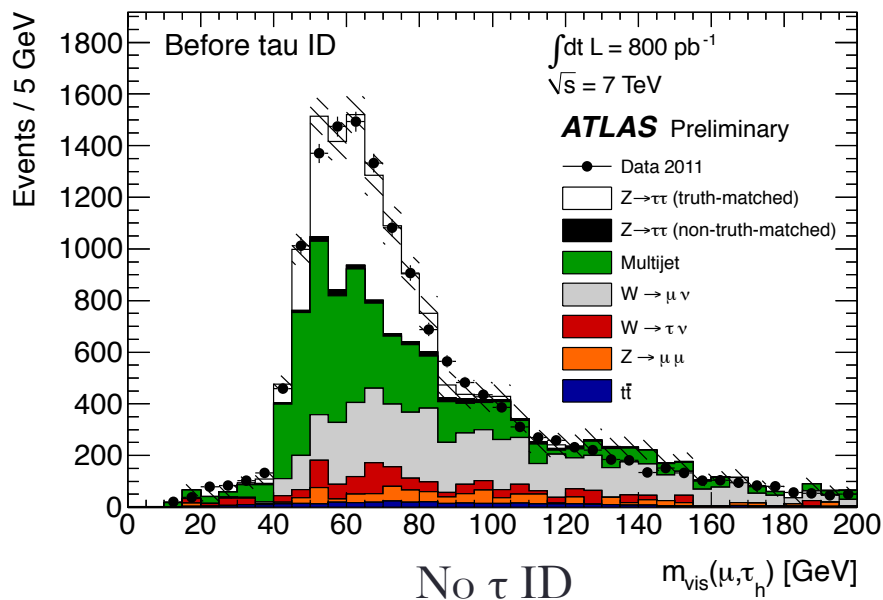
- Start with a list of jet candidates to seed the algorithm
  - Identify tracks within a cone of  $\Delta R < 0.2$ , where  $\Delta R^2 = (\Delta\eta)^2 + (\Delta\Phi)^2$ 
    - Use information from the tracking system and calorimeter systems
  - Require an isolation annulus of  $0.2 < \Delta R < 0.4$



- Classifiers include simple selection (“cuts”), boosted decision trees and likelihood selectors
- Use data driven control samples and MC
- Rejection of QCD multi-jets and electrons

# $\tau$ leptons identification performance

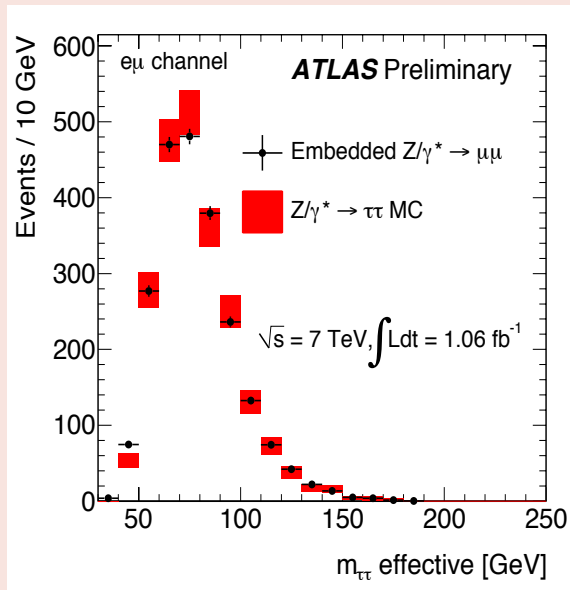
- There are three levels of discrimination for each classifier: loose, medium, and tight
- Plotting invariant visible mass of  $\mu\tau_{\text{hadronic}}$  from  $Z \rightarrow \tau(\mu\nu)\tau(\nu + \text{hadrons})$  candidates shows excellent performance:



# Background estimations

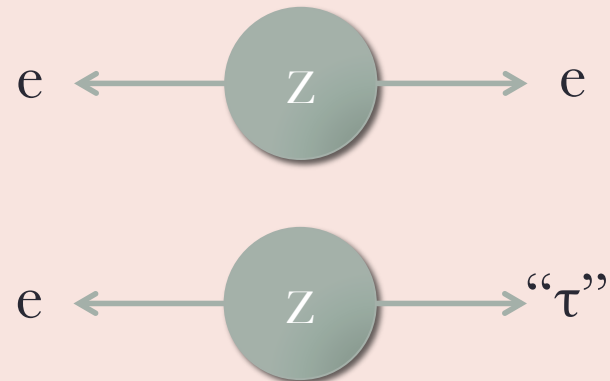
## Embedding

- Take very pure  $Z \rightarrow \mu\mu / W \rightarrow \mu\nu$  samples in data
- Replace  $\mu$  with  $\tau$  taken from Monte Carlo (MC) samples
- Apply selection criteria
- Generally smaller uncertainties



## Tag and probe

- Take very pure  $Z \rightarrow ll / W \rightarrow l\nu$  samples in data
- Tag one side of the decay with a lepton/neutrino
- Apply selection to the other side
- Estimate fake rate





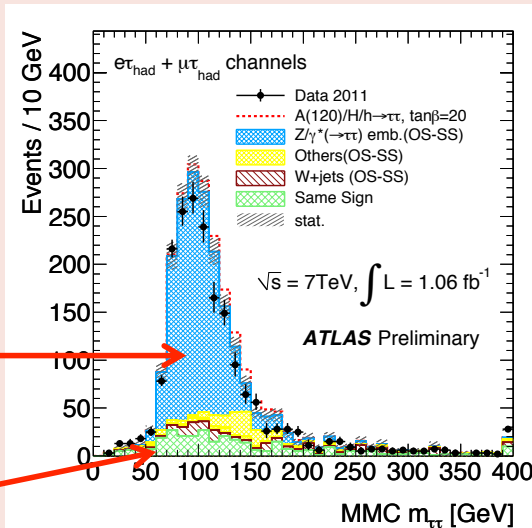
# Background estimations

## Opposite/same sign

- Define the opposite sign (OS) sample and same sign (SS) sample according to the charges of the  $\tau$  pair
- Estimate differences between OS and SS samples using MC
- Add these differences to the SS sample in data to estimate the size of the OS sample in data.

OS-SS  
peaking

SS smooth



## ABCD method

- Use two uncorrelated variables (eg isolation, OS vs SS) to define four regions A, B, C, D

A	B
C	D

- Estimate background in region A using the relation:

$$n_A = \frac{n_C}{n_D} n_B$$

# Neutral MSSM Higgs analysis

$$\int L dt = 1.06 \text{ fb}^{-1}$$

Neutral  
(CP-even)



Neutral  
(CP-odd)



Charged

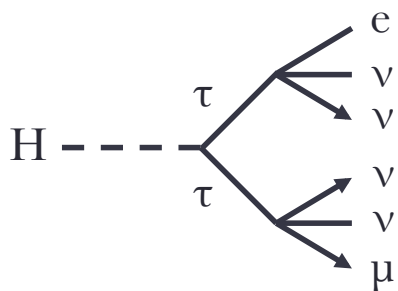


Neutral MSSM Higgs analysis

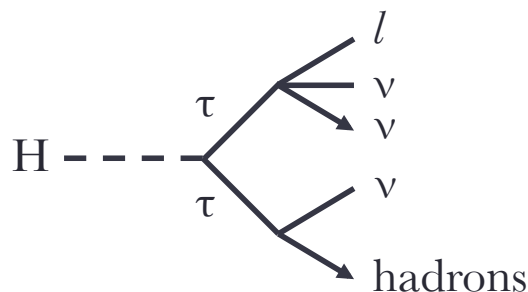
# MSSM neutral $H \rightarrow \tau\tau$ analysis

- The following final states of the  $\tau\tau$  system are considered:

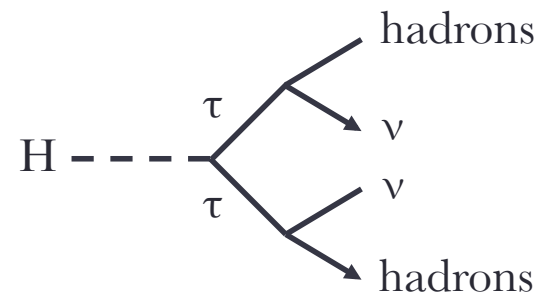
$$\tau\tau \rightarrow e\mu 4\nu$$



$$\tau\tau \rightarrow l\tau_{\text{had}} 3\nu \quad (l=e,\mu)$$



$$\tau\tau \rightarrow \tau_{\text{had}}\tau_{\text{had}} \nu\nu$$

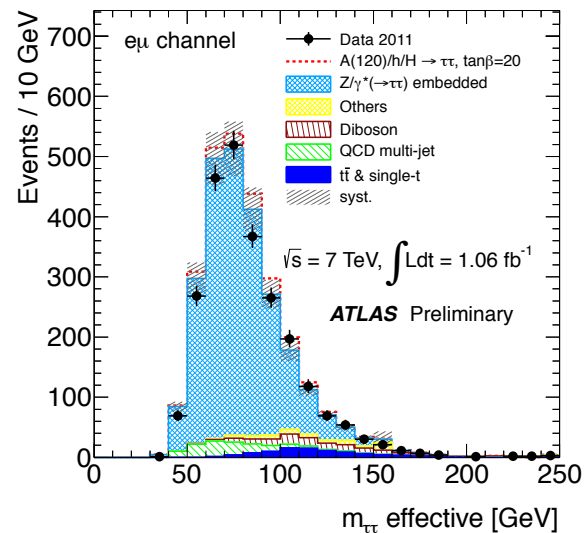


Electrons	Muons	$\tau_{\text{had}}$
$E_T > 15 \text{ GeV}$	$p_T > 15 \text{ GeV}c^{-1}$	$p_T > 20 \text{ GeV}c^{-1}$
Single electron trigger ( $E_T > 20 \text{ GeV}$ )	Single muon trigger ( $p_T > 18 \text{ GeV}c^{-1}$ )	Double hadronic $\tau$ trigger ( $p_T > 29 \text{ GeV}c^{-1}, 20 \text{ GeV}c^{-1}$ )

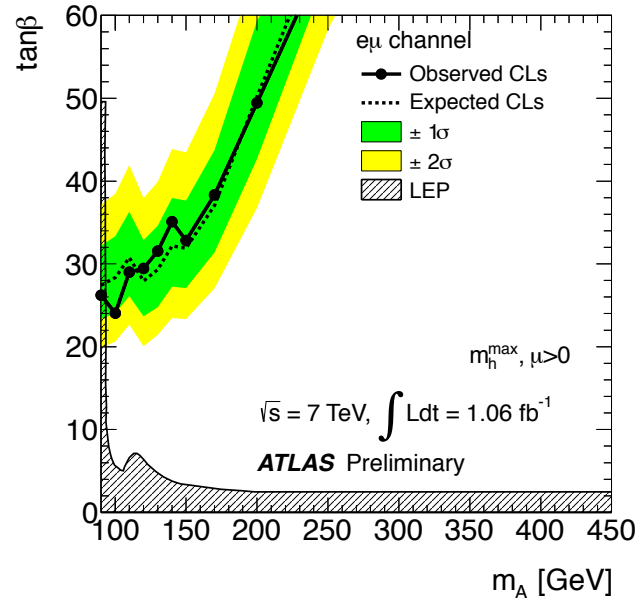
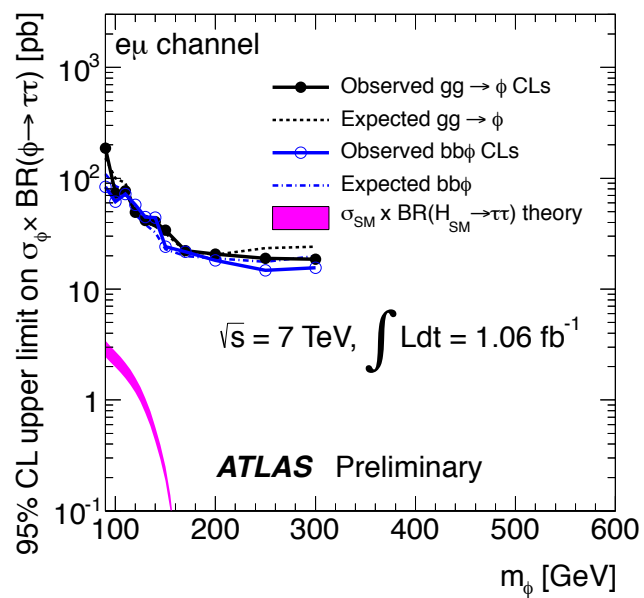
# MSSM neutral $H \rightarrow \tau\tau$ ( $e\mu$ )

- Signal and background components are obtained with a profile likelihood ratio to the effective mass,  $m_{\tau\tau}^{\text{eff}}$ :

$$\left(m_{\tau\tau}^{\text{eff}}\right)^2 = \left(p_{\tau^+} + p_{\tau^-} + p_T^{\text{miss}}\right)^2 \leftarrow 4\text{-vectors}$$

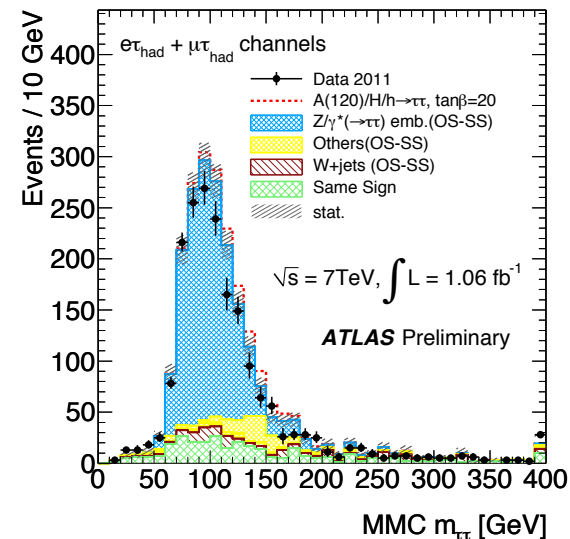


Source	Systematic uncertainty
Production cross section	14%
Object selection	6%

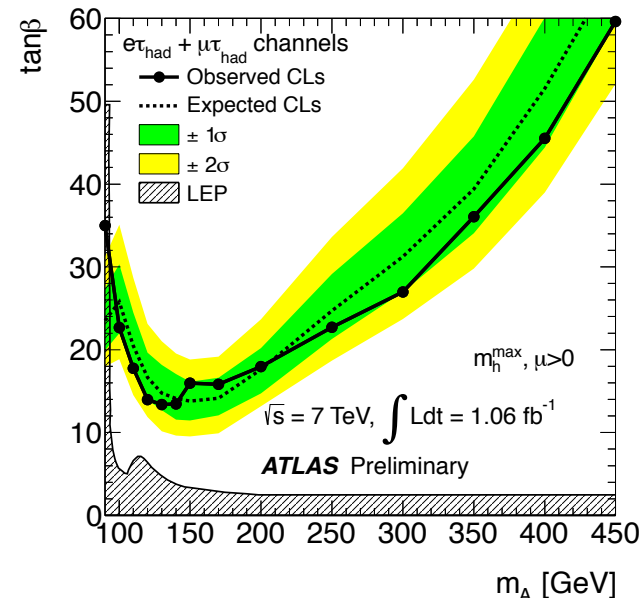
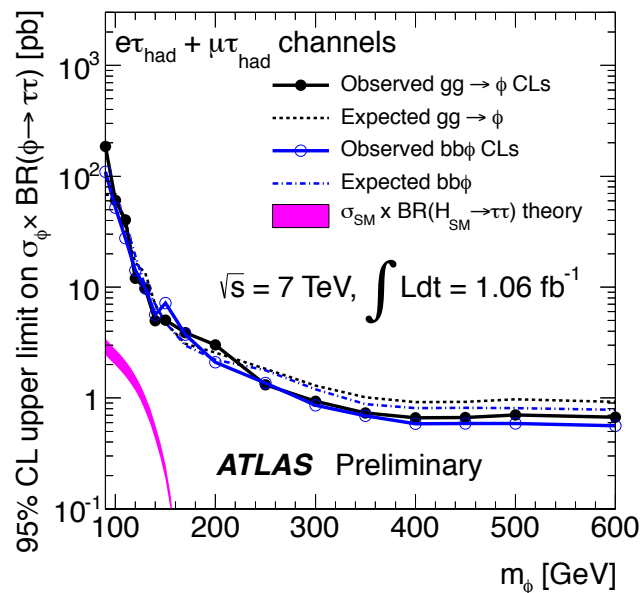


# MSSM neutral $H \rightarrow \tau\tau$ ( $l\tau_{had}$ )

- Signal and background components are obtained with a profile likelihood ratio to the missing mass calculated (MMC) spectrum
  - More sophisticated than co-linear method
  - Use of kinematic constraints
  - Details in the backup slides

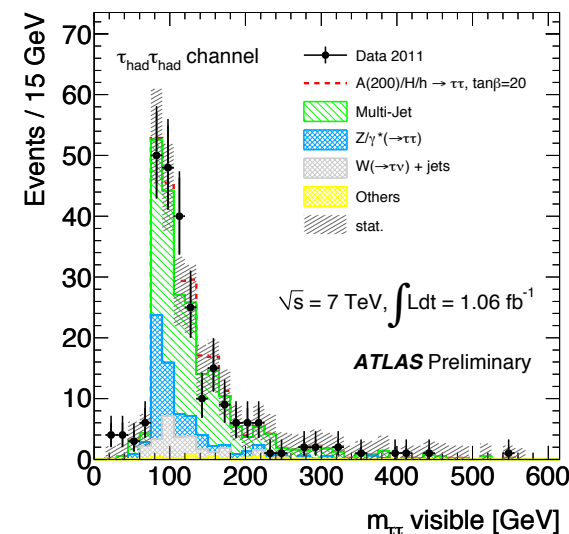


Source	Systematic uncertainty
Production cross section	16%
Energy scale and resolution	12%

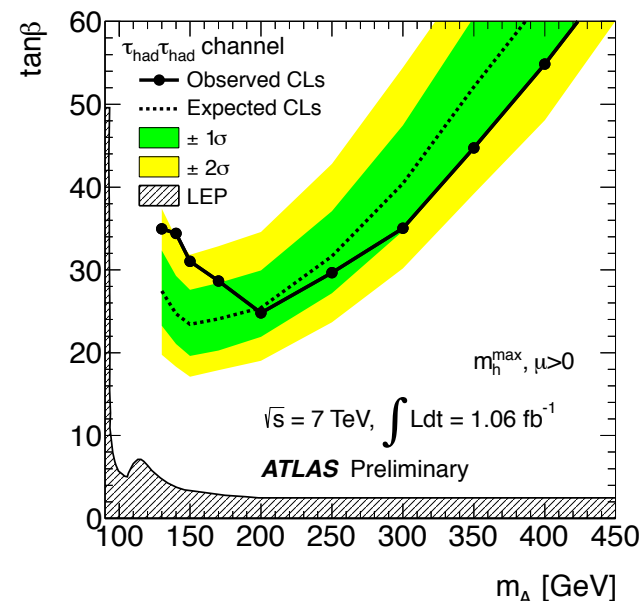
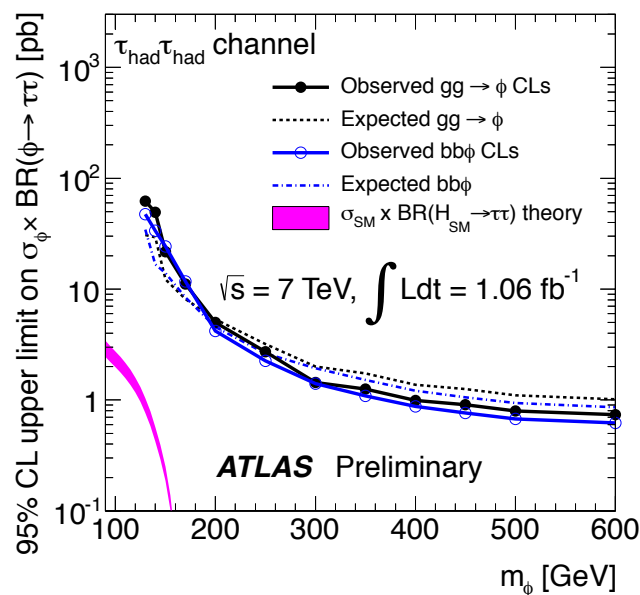


# MSSM neutral $H \rightarrow \tau\tau$ ( $\tau_{had}\tau_{had}$ )

- Signal and background components are obtained with a profile likelihood ratio to the visible mass

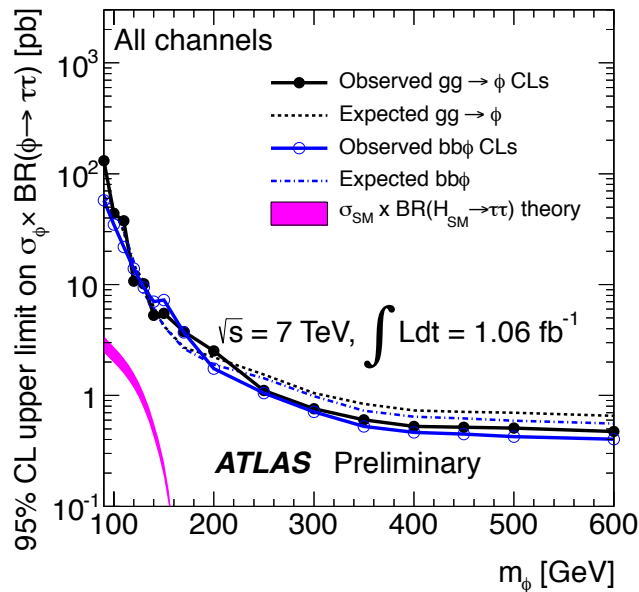
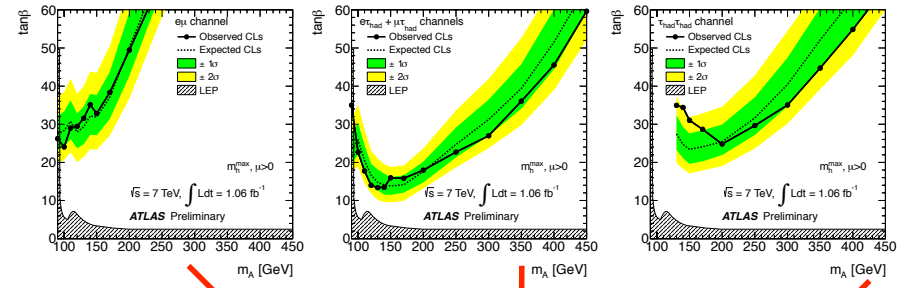
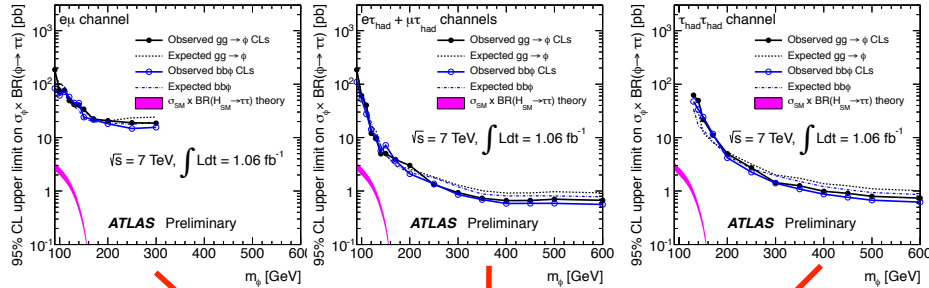


Source	Systematic uncertainty
Energy scale and resolution	50%
Production cross section	16%

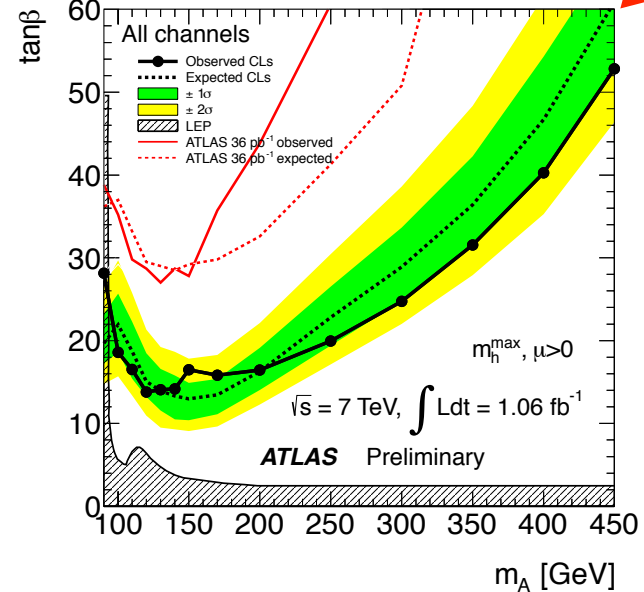


# MSSM neutral $H \rightarrow \tau\tau$ (combination)

- The results are combined to extract more stringent exclusions:



Note  $e\mu$  and  $\tau_{had}\tau_{had}$  analyses sensitive to different ranges of  $m_H$



# Charged MSSM Higgs analysis

$$\int L dt = 4.6 \text{ fb}^{-1}$$

Neutral  
(CP-even)

h

H

Neutral  
(CP-odd)

A

Charged

H<sup>+</sup>

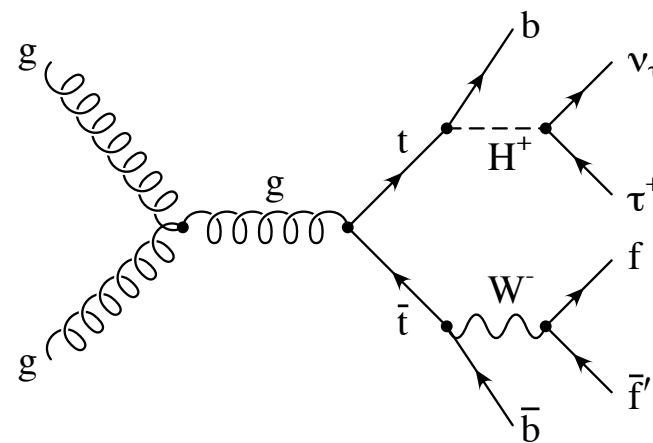
H<sup>-</sup>

Charged MSSM Higgs analysis



# Charged MSSM $H^\pm \rightarrow \tau\nu$

- Many non-minimal Higgs scenarios include:
  - Higgs triplets models
  - Two Higgs doublets models
- These models include a charged Higgs boson
- Discovery of a charged Higgs boson would be unambiguous evidence of physics beyond the standard model
- For  $\tan\beta > 3$  the dominant decay of the charged Higgs would be  $H \rightarrow \tau\nu$
- Dominant production mechanism is via  $gg$  fusion  $t\bar{t}$  production:
- This analysis only considers  $m_H < 150 \text{ GeV}c^{-2}$



# Charged MSSM $H^\pm \rightarrow \tau \nu$

- Three modes considered:

## lepton+jets

- W decays hadronically
- $\tau$  decays leptonically
- At least 4 jets (=2 b-tagged)

$$t\bar{t} \rightarrow b\bar{b}(q'\bar{q})(\tau_{lep}\nu)$$

## $\tau$ +lepton

- W decays leptonically
- $\tau$  decays hadronically
- At least 2 jets (>0 b-tagged)

$$t\bar{t} \rightarrow b\bar{b}(l\nu)(\tau_{had}\nu)$$

## $\tau$ +jets

- W decays hadronically
- $\tau$  decays hadronically
- At least 4 jets (>0 b-tagged)

$$t\bar{t} \rightarrow b\bar{b}(q'\bar{q})(\tau_{had}\nu)$$

- The following object selections and triggers are applied:

Electrons	Muons	$\tau_{had}$
$E_T > 20 \text{ GeV}$	$p_T > 15 \text{ GeV}c^{-1}$	$p_T > 20 \text{ GeV}c^{-1}$
Single electron trigger ( $E_T > 20-22 \text{ GeV}$ )	Single muon trigger ( $p_T > 18 \text{ GeV}c^{-1}$ )	Single hadronic $\tau$ + $E_T^{miss}$ trigger ( $p_T^{\tau} > 35 \text{ GeV}c^{-1}$ , $E_T^{miss} > 29 \text{ GeV}c^{-1}$ )

# Charged MSSM $H^\pm \rightarrow \tau\nu$ (lepton+jets)

- Signal region defined by  $m_T^W < 60 \text{ GeV} c^{-2}$  and  $\cos\theta_l^* < -0.6$  where:

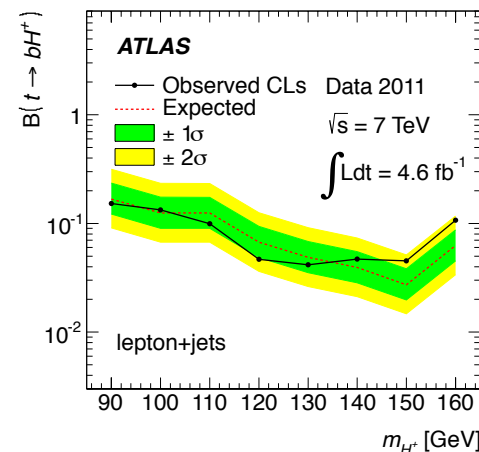
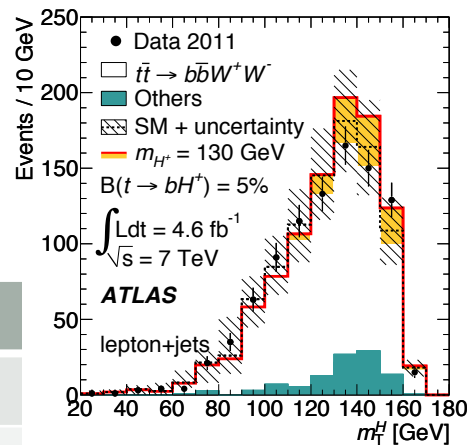
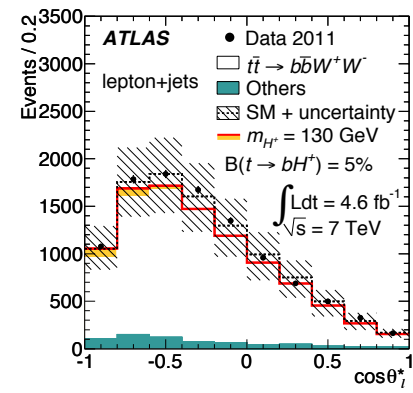
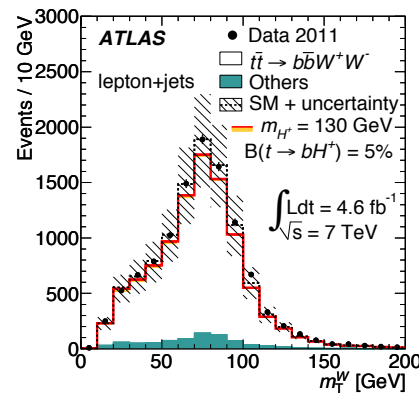
$$m_T^W = \sqrt{2p_T^l E_T^{\text{miss}} (1 - \cos\phi_{l,\text{miss}})}$$

$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{top}^2 - m_W^2} \cong \frac{4p^b \cdot p^l}{m_{top}^2 - m_W^2} - 1$$

assume b-jet and lepton come from the same top quark

- Signal and background components are obtained with a profile likelihood ratio to the transverse mass,  $m_T^H$ :

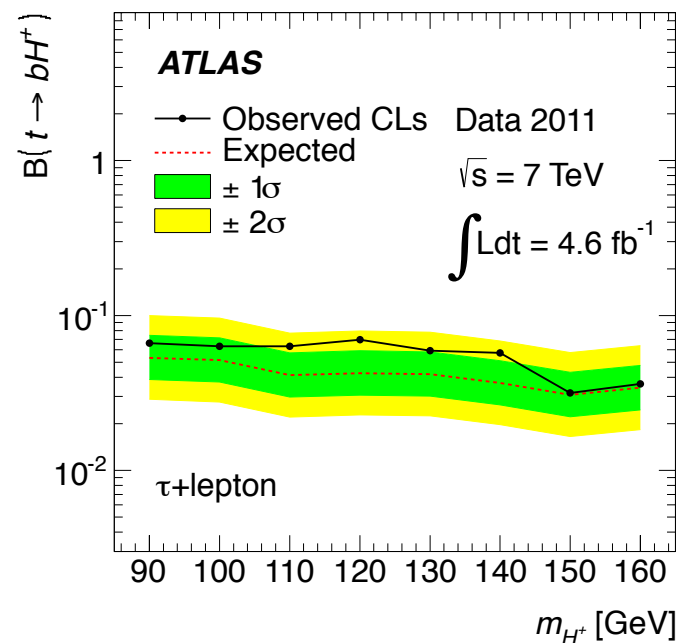
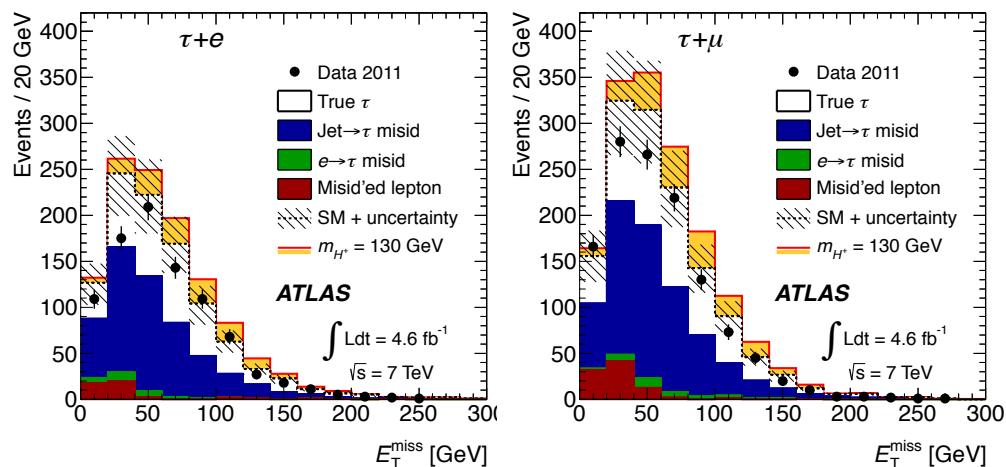
$$(m_T^H)^2 = \left( \sqrt{m_{top}^2 + \left( \vec{p}_T^l + \vec{p}_T^b + \vec{p}_T^{\text{miss}} \right)^2} - p_T^b \right)^2 - \left( \vec{p}_T^l + \vec{p}_T^{\text{miss}} \right)^2$$



	Systematic uncertainty
tt background (Jet energy scale)	14%
tt background (Jet energy resolution)	6%

# Charged MSSM $H^\pm \rightarrow \tau\nu$ ( $\tau$ +lepton)

- Signal and background components are obtained with a profile likelihood ratio to the missing transverse energy
- $\tau$  fake rates estimated with tag and probe method (electrons) and a control sample in data (jets)

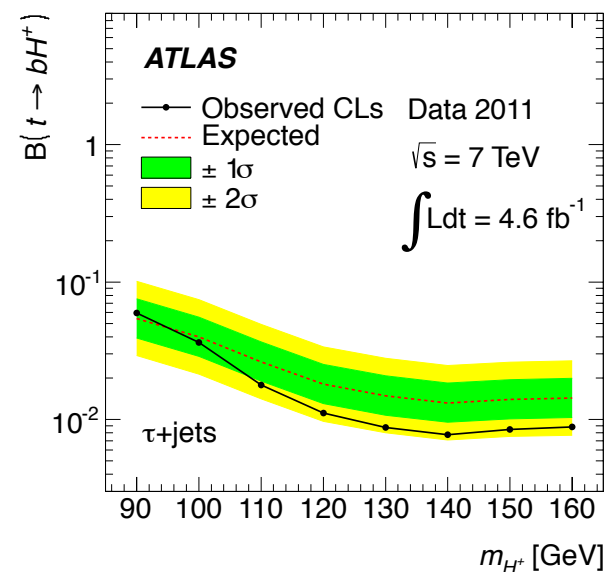
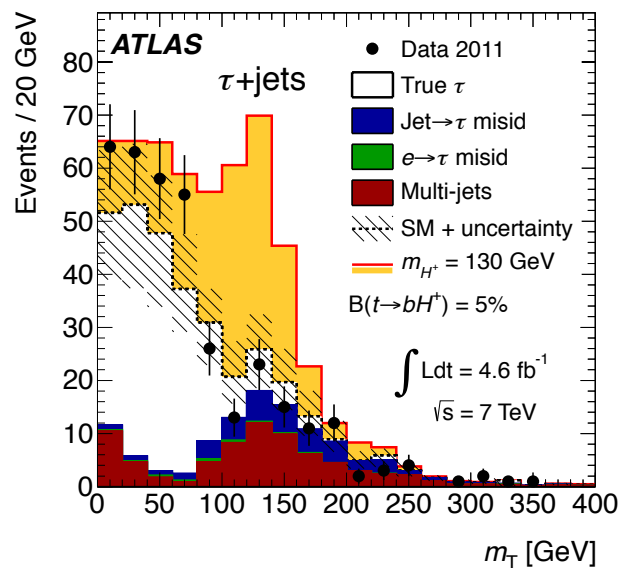


	Systematic uncertainty
Signal efficiency	13%
Fake jet $\rightarrow$ $\tau$ (Jet composition)	8%

# Charged MSSM $H^\pm \rightarrow \tau\nu$ ( $\tau$ +jets)

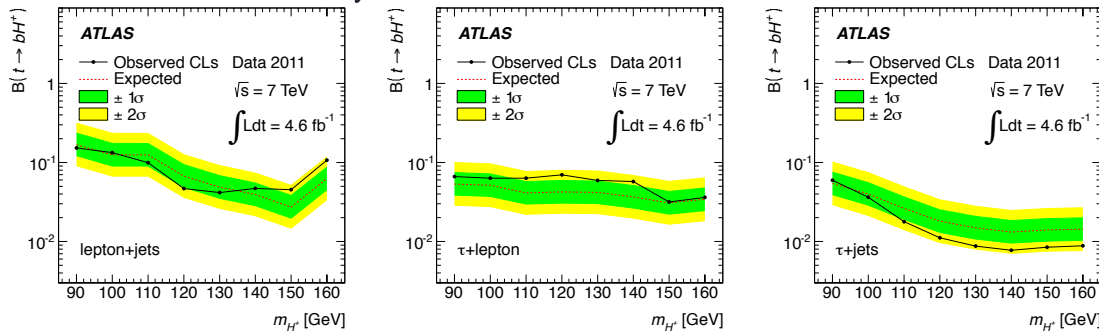
- Signal and background components are obtained with a profile likelihood ratio to the transverse mass of the charged Higgs candidate
- Fake rates estimated with control region in data (QCD multi-jets), embedding (real  $\tau$ ), and tag and probe (fake  $\tau$ )

	Systematic uncertainty
Signal efficiency	25%
QCD multi jet estimation	14%

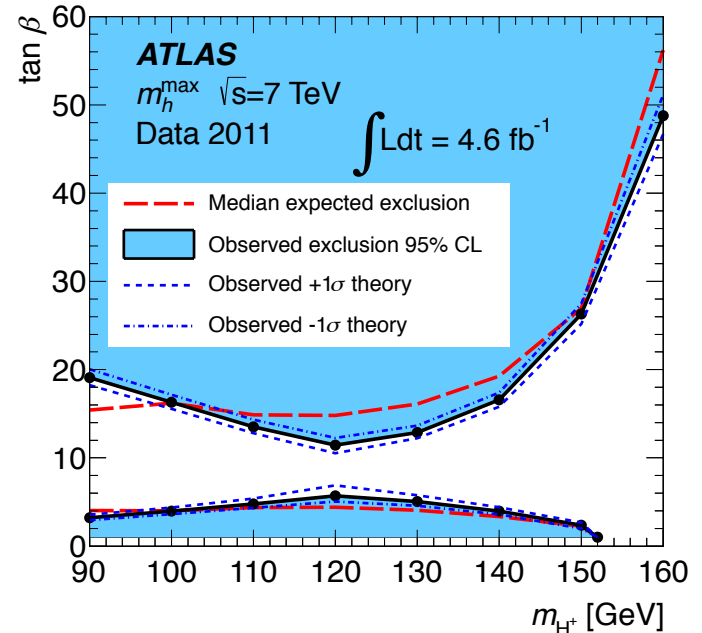
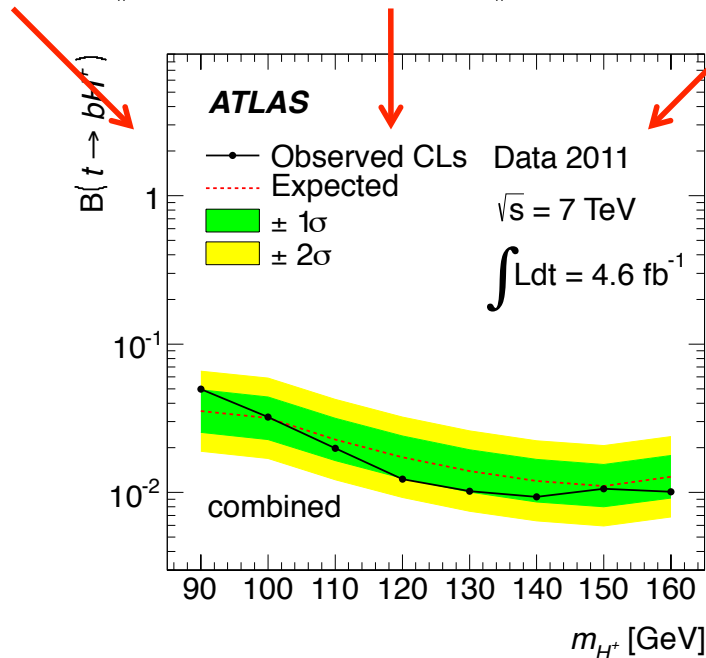


# Charged MSSM $H^\pm \rightarrow \tau\nu$ (combination)

- Combining the results shows the  $t$ +jets mode dominates sensitivity:



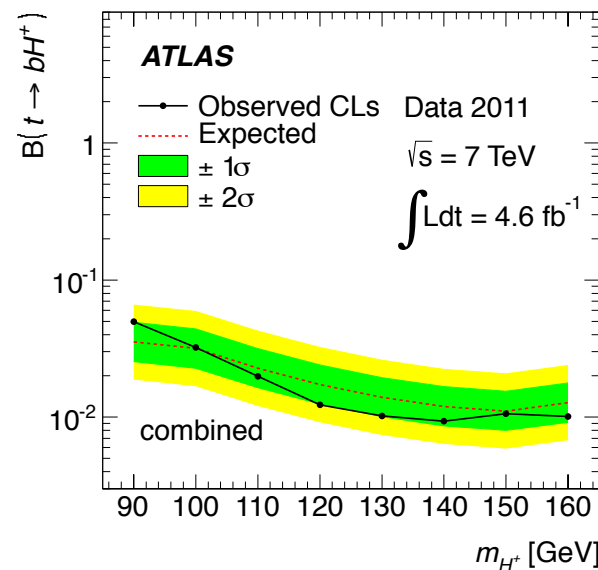
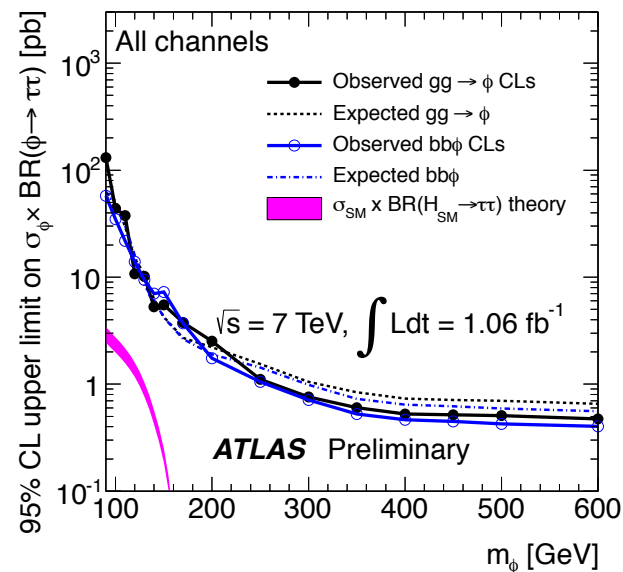
- Exclusion in the  $\tan\beta$  vs  $m_H$  plane:



# Conclusion

- ATLAS has produced state of the art, competitive results for a wide range of Higgs searches with tau leptons
  - Excellent performance of  $\tau$  reconstruction
  - Limits will continue to improve with 2012 data
- Limit on cross section  $\sigma(H \rightarrow \tau\tau)$  for neutral MSSM Higgs boson from 0.5-100pb
- Limit on branching fraction  $B(t \rightarrow bH^\pm)$  for charged MSSM Higgs boson from 1-5%
- Interpreted as exclusion on  $\tan\beta$  vs  $m_H$  planes

Many thanks to colleagues in ATLAS and to the LHC for its excellent performance!



# Backup

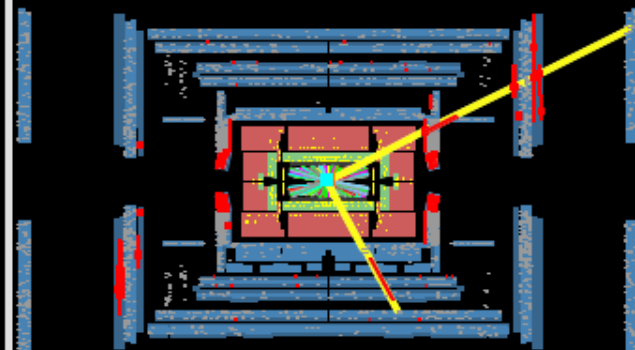
- Standard model Higgs analysis
- The ATLAS experiment
- Detailed  $\tau$  lepton identification
- Likelihood analysis
- MMC method
- Vertex jet fraction
- Detailed systematic uncertainties



# ATLAS EXPERIMENT

Run Number: 201289, Event Number: 24151616

Date: 2012-04-15 16:52:58 CEST





# Standard Model Higgs analysis

$$\int L dt = 4.7 \text{ fb}^{-1}$$

Neutral  
(CP-even)



Neutral  
(CP-odd)



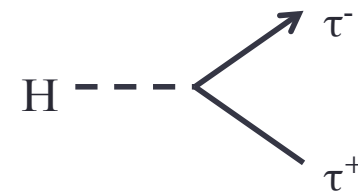
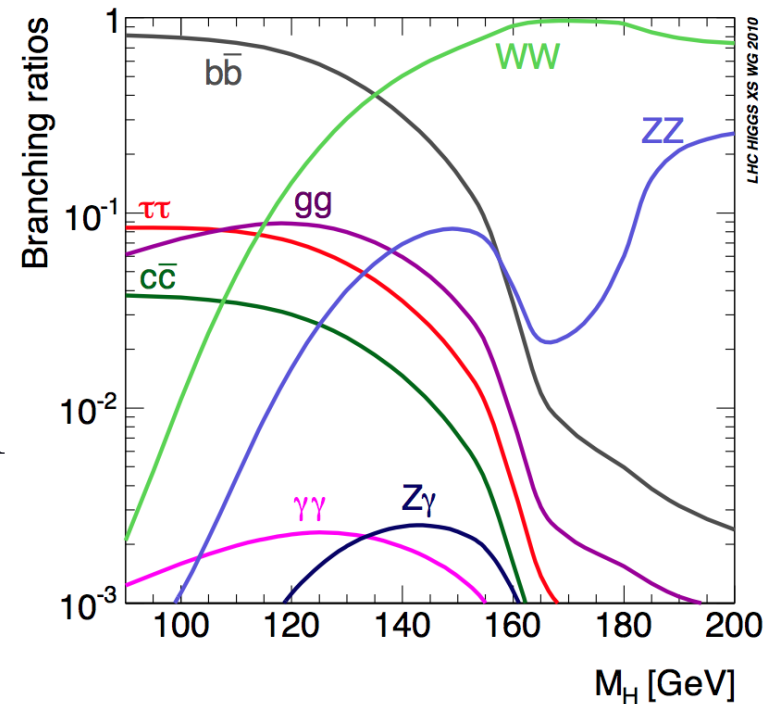
Charged



  
SM Higgs  
analysis

# Standard Model $H \rightarrow \tau\tau$

- The decay  $H \rightarrow \tau\tau$  is an important mode for the standard model Higgs search
- Sensitive in low mass searches ( $100\text{-}150\text{GeV}c^{-2}$ )
- Observation confirms spin-0 or spin-1 nature of a new particle
  - Combine with  $H \rightarrow \gamma\gamma$  to demonstrate the existence of a massive scalar boson
- The decay is a tree level process
  - $\sim 8\%$  branching fraction
  - Relatively clean signal compared to  $bb$



# Standard Model $H \rightarrow \tau\tau$

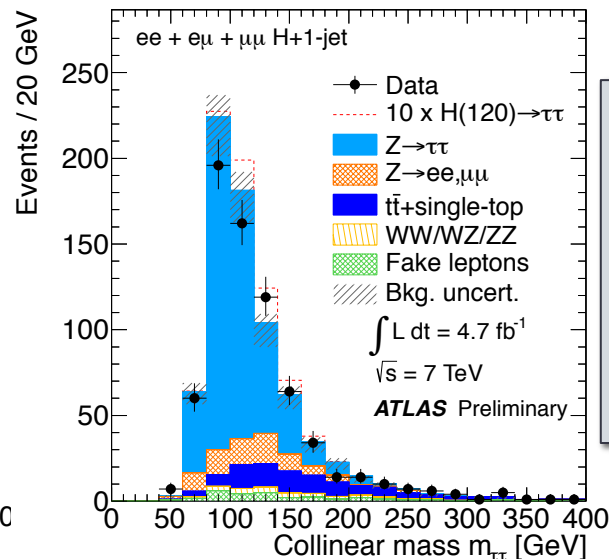
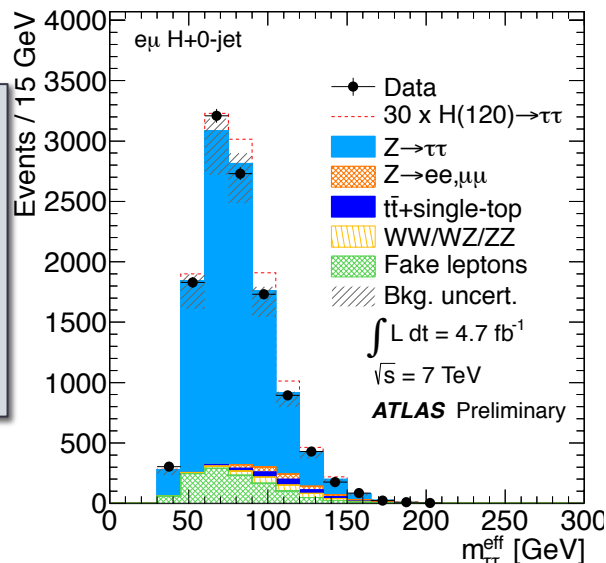
- All final states of the  $\tau\tau$  system are considered:
  - $\tau\tau \rightarrow ll4\nu$  ( $l=e,\mu$ )
  - $\tau\tau \rightarrow l\tau_{\text{had}}3\nu$  ( $l=e,\mu$ )
  - $\tau\tau \rightarrow \tau_{\text{had}}\tau_{\text{had}}\nu\nu$
- The following object selections and triggers are applied:

Electrons	Muons	$\tau_{\text{had}}$
$E_T > 15\text{GeV}$	$p_T > 15\text{GeV}c^{-1}$	$p_T > 20\text{GeV}c^{-1}$
Single electron trigger ( $E_T > 20\text{GeV}$ )	Single muon trigger ( $p_T > 18\text{GeV}c^{-1}$ )	Double hadronic $\tau$ trigger ( $p_T > 29\text{GeV}c^{-1}, 20\text{GeV}c^{-1}$ )

# Standard Model $H \rightarrow \tau\tau$ ( $ll4\nu$ )

## H+0-jets

- Only em mode to suppress Z background
- $\Delta\Phi(e\mu) > 2.5$

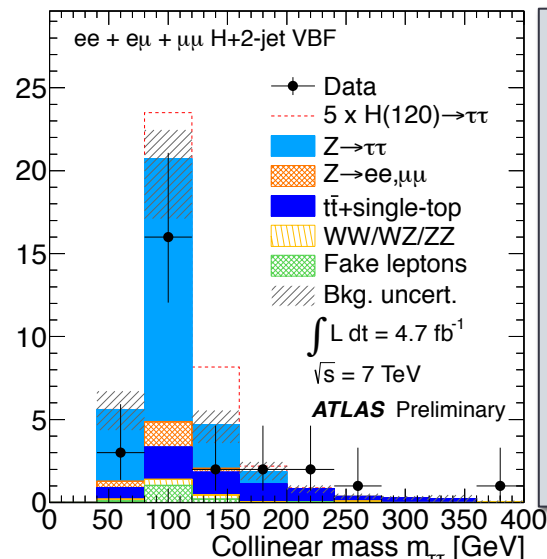
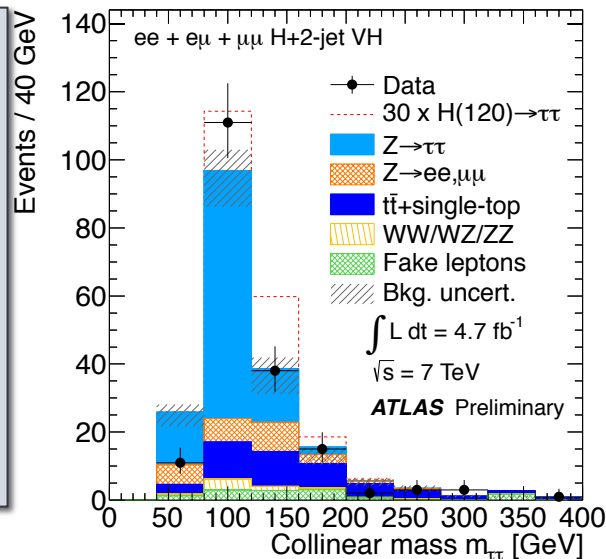


## H+1-jet

- 1 jet with  $E_T > 40\text{GeV}$
- $E_{T\text{miss}} > 40\text{GeV}$  for  $ee/\mu\mu$
- $E_{T\text{miss}} > 20\text{GeV}$  for  $e\mu$

## H+2-jet VH

- $> 0$  jets with  $E_T > 40, 25\text{GeV}$
- $E_{T\text{miss}} > 40\text{GeV}$  for  $ee/\mu\mu$
- $E_{T\text{miss}} > 20\text{GeV}$  for  $e\mu$
- $50 < m(jj) < 120\text{GeV}c^{-2}$



## H+2-jets VBF

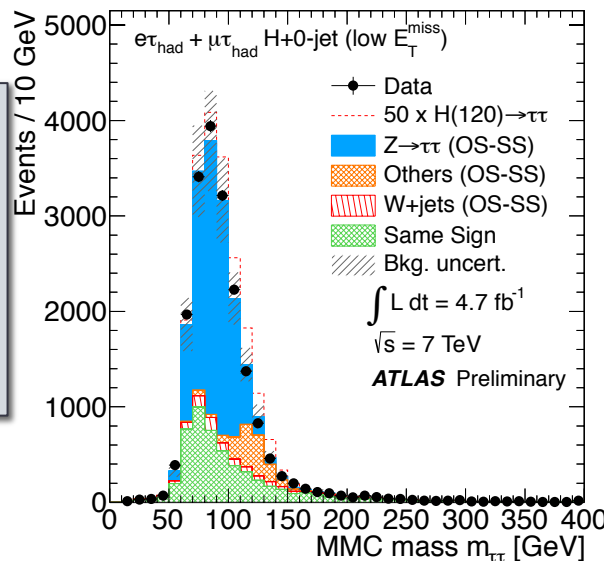
- Two jets with  $E_T > 40, 25\text{GeV}$
- $E_{T\text{miss}} > 40\text{GeV}$  for  $ee/\mu\mu$
- $E_{T\text{miss}} > 20\text{GeV}$  for  $e\mu$
- $\Delta\eta(jj) > 3$
- $m(jj) > 350\text{GeV}c^{-2}$

# Standard Model $H \rightarrow \tau\tau$ ( $l\tau_{\text{had}}3\nu$ )

## H+0-jets

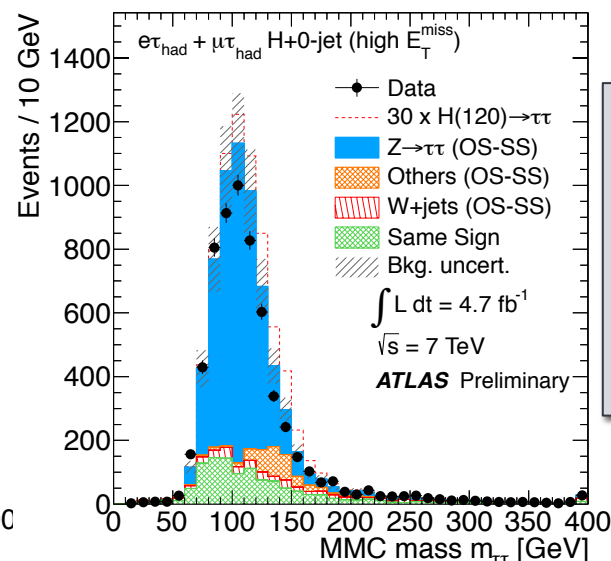
Low  $E_T^{\text{miss}}$

- No jets with  $E_T > 25\text{GeV}$
- $E_T^{\text{miss}} < 20\text{GeV}$



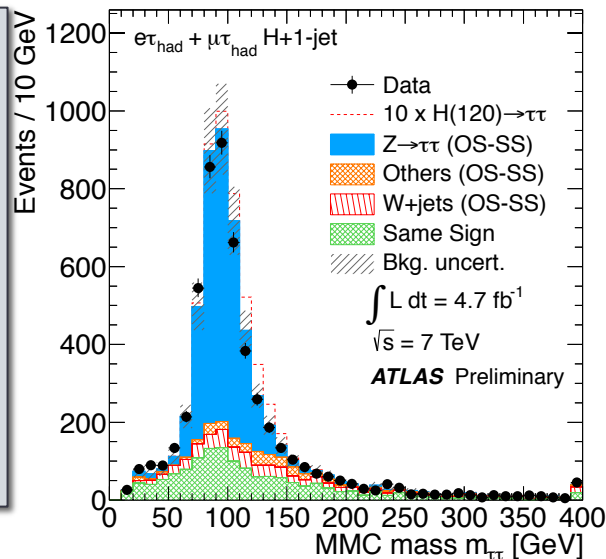
## H+0-jets High $E_T^{\text{miss}}$

- No jets with  $E_T > 25\text{GeV}$
- $E_T^{\text{miss}} > 20\text{GeV}$



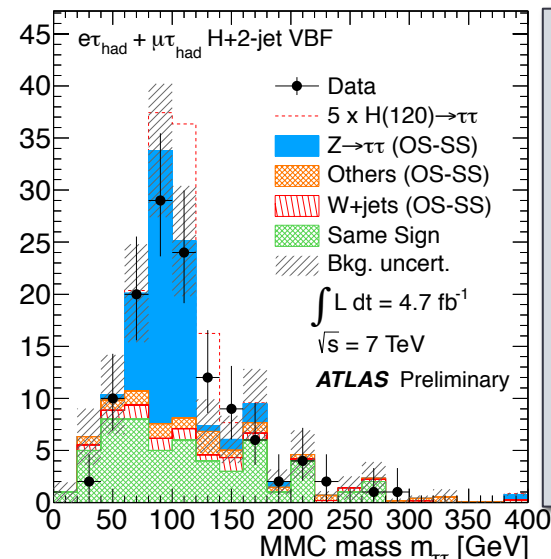
## H+1-jet

- $> 0$  jets with  $E_T > 25\text{GeV}$
- $E_T^{\text{miss}} > 20\text{GeV}$
- Event fails VBF selection
- Separation of  $e$  and  $\mu$  modes



## H+2-jets VBF

- At least two jets with  $E_T > 25\text{GeV}$
- $E_T^{\text{miss}} > 20\text{GeV}$
- $\eta(j1) \cdot \eta(j2) < 0$
- $\Delta\eta(jj) > 3$
- $m(jj) > 300\text{GeV}c^{-2}$
- $l$  and  $\tau_{\text{had}}$  between jets in  $\eta$

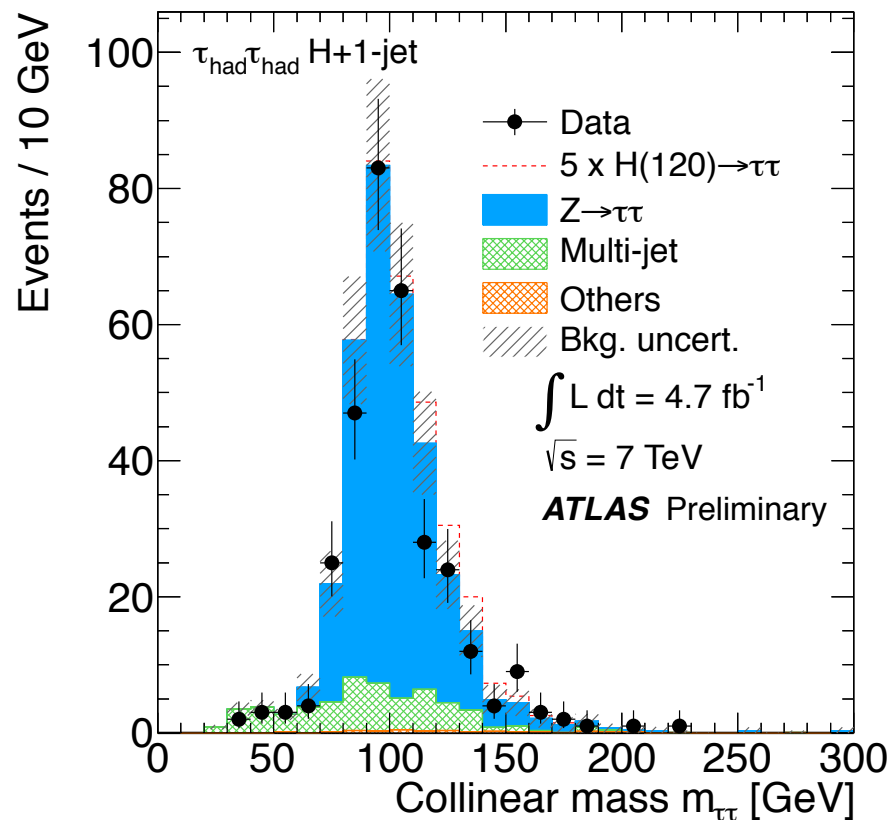


# Standard Model $H \rightarrow \tau\tau$ ( $\tau_{\text{had}}\tau_{\text{had}}2\nu$ )

- Only one category
  - H+1-jet
- Background estimation:
  - $Z \rightarrow \tau\tau$  estimate comes from data driven methods
  - QCD multi jet background estimate comes from:
    - SS sample in data
    - two dimensional track fitting multiplicity in data

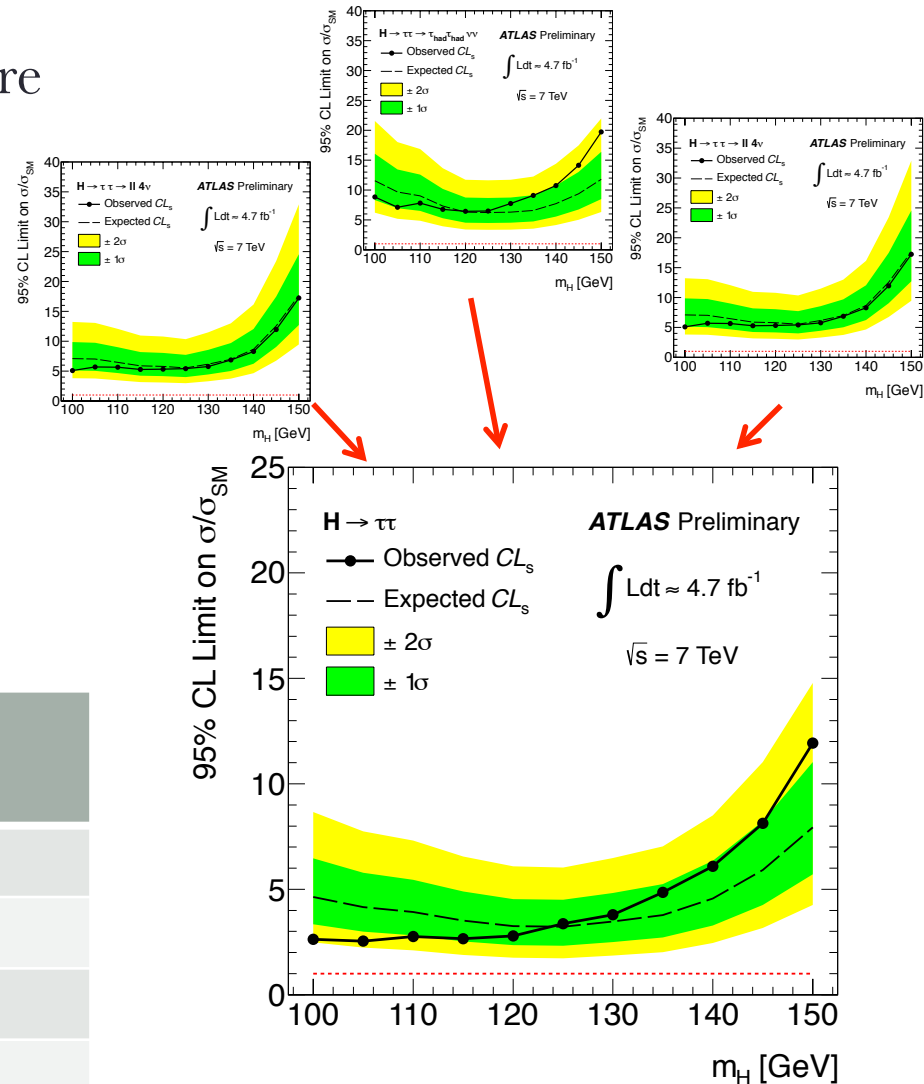
## H+1-jet

- At least 1 jet with  $E_T > 40 \text{ GeV}$
- $E_T^{\text{miss}} > 20 \text{ GeV}$
- $\Delta R(\tau\tau) < 2.2$
- $m(\tau\tau) > 225 \text{ GeV}c^{-2}$



# Standard Model $H \rightarrow \tau\tau$ results

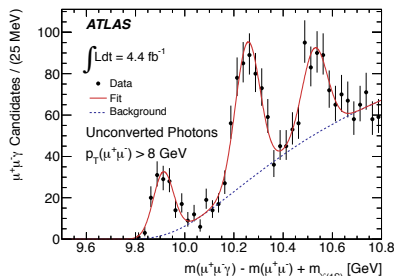
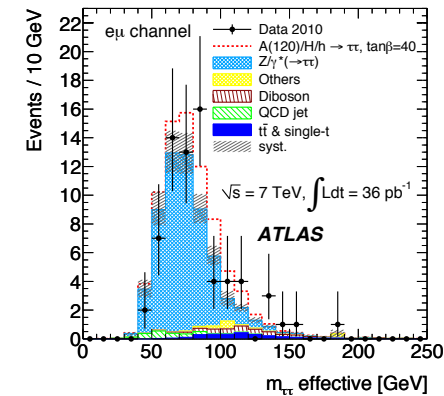
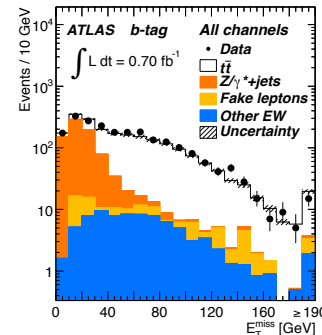
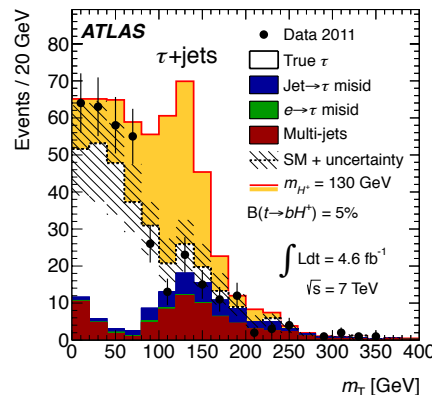
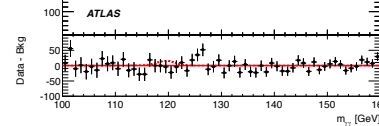
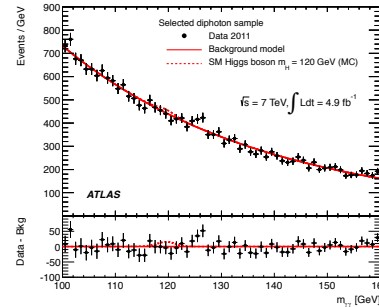
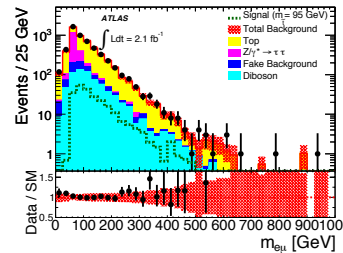
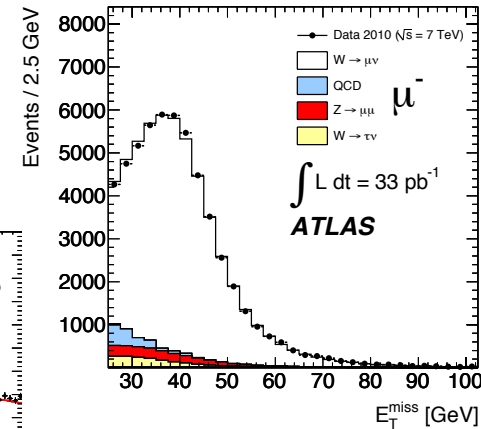
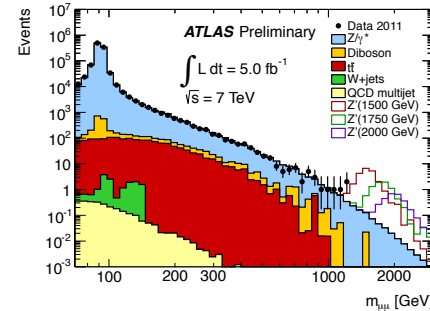
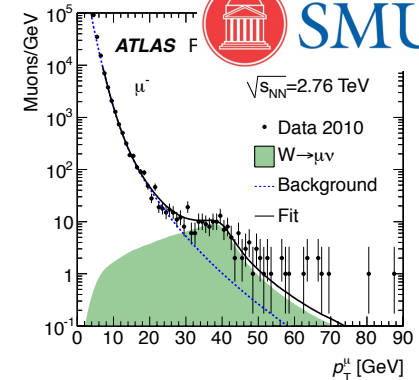
- Over the range  $100\text{GeV}c^{-2} < m_H < 150\text{GeV}c^{-2}$  there is no observation of an excess
- Combined expected limits range from 3.2-7.9 times the SM
- Similar sensitivity in all modes
- Most significant deviation ( $150\text{GeV}c^{-2}$ ) is less than  $2\sigma$
- Stay tuned for updates as luminosity and energy increase!



Source	Systematic uncertainty
QCD scale	8-25%
Jet production cross section	24% per jet
Jet energy scale	up to 12%
Fake leptons/ $\tau_{had}$	6-40%

# The ATLAS experiment

- ATLAS is a general purpose experiment
- Wide range of analyses:
  - Standard Model physics
  - Standard Model Higgs
  - Beyond Standard Model Higgs
  - Exotica ( $Z'$ ,  $W'$ ...)
  - Top physics
  - Heavy ions
  - B physics
  - SUSY





# $\tau$ leptons identification classifiers

- Use simple selection (cut) based, likelihood, and boosted decision tree (BDT) classifiers to reject fakes.
- Jets (arising from quarks and gluons) and electrons treated are separately:

	Jet rejection	Electron rejection
Monte Carlo (MC) samples	pythia $W \rightarrow \tau\nu$ , $Z \rightarrow \tau\tau$ , $Z' \rightarrow \tau\tau$	pythia $Z \rightarrow \tau\tau$ , $Z \rightarrow ee$ for BDT
Data samples	QCD background from dijet events	$Z \rightarrow ee$ for cut based Tag and probe $Z \rightarrow ee$
Classifiers	<ul style="list-style-type: none"> <li>• Cut based (care taken to reduce pileup dependence)</li> <li>• Likelihood</li> <li>• BDT</li> </ul>	<ul style="list-style-type: none"> <li>• Cut based</li> <li>• BDT</li> </ul>
1 prong / 3 prong	Separate classifiers for 1 prong and 3 prong decays	Important primarily for 1 prong decays

# Likelihood analysis

- For a spectrum with  $N$  bins with probability functions  $\theta$ , hypothesize  $s$  signal events and  $f_b$  background events
- Likelihood takes the following form where  $f_b$  depends on  $\theta$ :

$$L(\mu, \theta) = \prod_{i=1}^N \frac{(\mu s_i + \theta f_{bi})^{n_i}}{n_i!} e^{-(\mu s_i + \theta f_{bi})}$$

- $\mu$  represents the strength of signal process
  - ( $\mu=0$  for background only,  $\mu=1$  for expected signal)

Most likely  $\theta$  for given  $\mu$

- Take the ratio  $\lambda$  to test for a given  $\mu$ :  $\lambda(\mu) = L\left(\mu, \hat{\theta}_\mu\right) \div L\left(\hat{\mu}, \hat{\theta}\right)$

- Combining multiple channels gives  $\lambda(\mu) = \prod_i L_i\left(\mu_i, \hat{\theta}_{\mu i}\right) \div \prod_i L_i\left(\hat{\mu}_i, \hat{\theta}_i\right)$

- Minimize  $t = -2\ln\lambda(\mu)$  to find value of  $\mu$  most compatible with data
  - Take look elsewhere effect into account

# MMC method

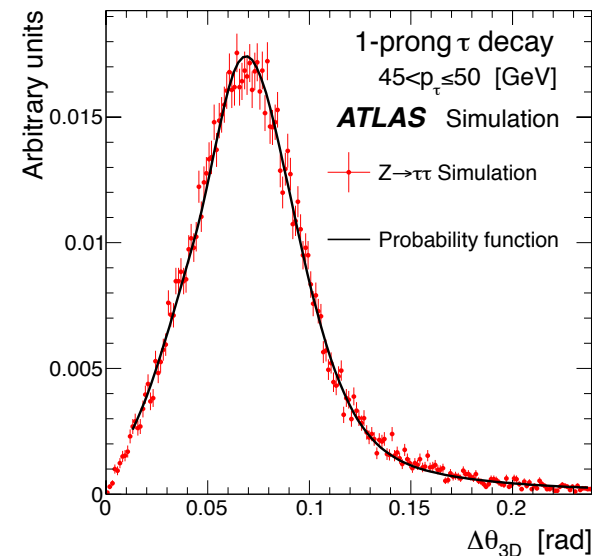
- Find the best transverse momenta for invisible particles by solving four equations:

$$E_x^{miss} = \sum_{i=1,2} p_{miss1}^i \sin \theta_{miss}^i \cos \phi_{miss}^i p_{miss}^i$$

$$E_y^{miss} = \sum_{i=1,2} p_{miss1}^i \sin \theta_{miss}^i \sin \phi_{miss}^i p_{miss}^i$$

$$i = 1, 2 : m_\tau^2 = (m_{miss}^i)^2 + (m_{vis}^i)^2 + 2\sqrt{\left(\left(p_{vis}^i\right)^2 + \left(m_{vis}^i\right)^2\right)\left(\left(p_{miss}^i\right)^2 + \left(m_{miss}^i\right)^2\right)} - 2p_{vis}^i p_{miss}^i \cos \Delta\theta_{vm_i}$$

- There are more unknown quantities than constraints, so scan the  $\Delta\Phi_1$ - $\Delta\Phi_2$  plane (where  $\Delta\Phi_i = \Phi_{\tau_i}^{invisible} - \Phi_{\tau_i}^{visible}$ )
- Weight candidates by probability density function obtained from simulation
- Choose most probable values of  $\Delta\Phi_i$



# Jet vertex fraction

- Jet vertex fraction (JVF) of a jet measures the probability that a jet is associated with a given primary vertex:
  - JVF uses track information with primary vertices and combining these with calorimeter jets
  - JVF safe as the average number of simultaneous uncorrelated soft collisions (pileup) increases

# Neutral MSSM $H \rightarrow \tau\tau$ detailed selection

- The following final states of the  $\tau\tau$  system are considered:
  - $\tau\tau \rightarrow e\mu 4\nu$
  - $\tau\tau \rightarrow l\tau_{\text{had}} 3\nu$  ( $l=e,\mu$ )
  - $\tau\tau \rightarrow \tau_{\text{had}}\tau_{\text{had}}\nu\nu$

## Electrons

- Transverse energy ( $E_T$ )  $> 15 \text{ GeV}$
- $|\eta| < 2.47$  excluding  $1.37 < |\eta| < 1.52$
- $E_{\text{iso}}$  in cone  $\Delta R < 0.2$  less than 8% of  $E_T(e)$
- $p_{\text{iso}}$  in cone  $\Delta R < 0.4$  less than 6% of  $p_T(e)$

## $\tau_{\text{hadronic}}$

- $p_T > 20 \text{ GeVc}^{-1}$
- $|\eta| < 2.5$
- 1 prong or 3 prong (each prong  $p_T > 1 \text{ GeVc}^{-1}$ ) with charge of  $\pm 1$

## Muons

- Transverse momentum ( $p_T$ )  $> 15 \text{ GeVc}^{-1}$
- $|\eta| < 2.5$
- $E_{\text{iso}}$  in cone  $\Delta R < 0.2$  less than 4% of  $p_T(\mu)$
- $p_{\text{iso}}$  in cone  $\Delta R < 0.4$  less than 6% of  $p_T(\mu)$
- z distance from primary vertex  $< 1 \text{ cm}$

# Charged MSSM $H^\pm \rightarrow \tau \nu$ detailed selection

- Three modes considered:

## lepton+jets

- W decays hadronically
- $\tau$  decays leptonically

$$t\bar{t} \rightarrow b\bar{b}(q'\bar{q})(\tau_{lep}\nu)$$

## $\tau$ +lepton

- W decays leptonically
- $\tau$  decays hadronically

$$t\bar{t} \rightarrow b\bar{b}(l\nu)(\tau_{had}\nu)$$

## $\tau$ +jets

- W decays hadronically
- $\tau$  decays hadronically

$$t\bar{t} \rightarrow b\bar{b}(q'\bar{q})(\tau_{had}\nu)$$

- The following object selections are applied:

## Electrons

- $E_T > 20 \text{ GeV}$
- $|\eta| < 2.47$ , excluding  $1.37 < |\eta| < 1.52$
- $\eta$  and  $E_T$  dependent isolation requirement

## Muons

- $p_T > 15 \text{ GeV}c^{-1}$
- $|\eta| < 2.5$
- $E_{iso}$  in cone  $\Delta R < 0.2$  less than  $4 \text{ GeV}$
- $p_{iso}$  in cone  $\Delta R < 0.4$  less than  $2.5 \text{ GeV}c^{-1}$

## $\tau_{hadronic}$

- $p_T > 20 \text{ GeV}c^{-1}$
- $|\eta| < 2.3$
- 1 prong or 3 prong (each prong  $p_T > 1 \text{ GeV}c^{-1}$ ) with charge of  $\pm 1$

## Jets

- b-jet tagging algorithms used to identify b-jets
- $|\eta| < 2.4$
- Jets matched to primary vertex (JVF)

# MSSM $H \rightarrow \tau\tau$ full systematic uncertainties I (e $\mu$ mode)

- Uncertainties are expressed as a fraction of the yield per background sample

Source	W+jets	Diboson	top	$Z \rightarrow ll$	$Z \rightarrow \tau\tau$	signal
Inclusive cross section	-	7%	10%	5%	5%	14%
Detector acceptance	-	4%	3%	2%	5%	5%
e efficiency	-	4%	4%	4%	4%	4%
$\mu$ efficiency	-	2%	2%	2%	2%	2%
$\tau$ efficiency and fake rate	-	-	-	-	-	-
Energy scale and resolution	-	2%	6%	1%	1%	1%
Luminosity	-	3.7%	3.7%	3.7%	3.7%	3.7%
Total	-	10%	13%	8%	9%	16%

# MSSM $H \rightarrow \tau\tau$ full systematic uncertainties II ( $l\tau_{\text{had}}$ mode)

- Uncertainties are expressed as a fraction of the yield per background sample

Source	W+jets	Diboson	top	$Z \rightarrow ll$	$Z \rightarrow \tau\tau$	signal
Inclusive cross section	-	7%	10%	5%	5%	14%
Detector acceptance	-	2%	2%	14%	14%	7%
e efficiency	-	3.1%	3.6%	3.1%	3.0%	3.6%
$\mu$ efficiency	-	1.2%	1.1%	1.3%	1.8%	1.0%
$\tau$ efficiency and fake rate	-	9.1%	9.1%	48%	9.1%	9.1%
Energy scale and resolution	-	+19% -9%	+5% -4%	+39% -25%	11%	+30% -23%
Luminosity	-	3.7%	3.7%	3.7%	3.7%	3.7%
Total	-	+23% -16%	15%	+64% -56%	21%	+35% -30%



# MSSM $H \rightarrow \tau\tau$ full systematic uncertainties III ( $\tau_{\text{had}}\tau_{\text{had}}$ mode)

- Uncertainties are expressed as a fraction of the yield per background sample

Source	W+jets	Diboson	top	$Z \rightarrow ll$	$Z \rightarrow \tau\tau$	signal
Inclusive cross section	5%	7%	10%	-	5%	16%
Detector acceptance	20%	7%	9%	-	14%	9%
e efficiency	0.8%	0.5%	0.3%	-	0.5%	0.1%
$\mu$ efficiency	0.3%	0.4%	0.0%	-	0.4%	0.1%
$\tau$ efficiency and fake rate	21%	15	13%	-	15%	15%
Energy scale and resolution	+34% -21%	+26% -12%	12%	-	+63% -23%	+9% -8%
Luminosity	3.7%	3.7%	3.7%	-	3.7%	3.7%
Total	+45% -36%	+32% -22%	23%	-	+67% -31%	+26% -25%

# $H^\pm \rightarrow \tau\nu$ full systematic uncertainties I (lepton+jets mode)

Source	Uncertainty
control region	6%
Z mass window	4%
jet energy scale	16%
jet resolution	7%
sample composition	31%

# $H^\pm \rightarrow \tau \nu$ full systematic uncertainties II ( $\tau$ +lepton mode)

Source	Uncertainty
statistics in control region	2%
jet composition	11%
object-related systematic uncertainties	23% normalization + 3% shape
$\tau$ +lepton $e \rightarrow \tau$ misidentification probability	20%
lepton misidentification study: choice of control region	4%
lepton misidentification study: Z mass window	5%
lepton misidentification study: jet energy scale	14%
lepton misidentification study: jet resolution	4%
lepton misidentification study: sample composition	39%

# $H^\pm \rightarrow \tau\nu$ full systematic uncertainties III ( $\tau$ +jets mode)

Source	Uncertainty
embedding parameters	6% normalization + 3% shape
muon isolation	7% normalization + 2% shape
parameters in normalization	16%
$\tau$ identification	5%
$\tau$ energy scale	6% normalization + 1% shape
jet $\rightarrow\tau$ misidentification study: statistics in control region	2%
jet $\rightarrow\tau$ misidentification study: jet composition	12%
jet $\rightarrow\tau$ misidentification study: purity in control region	6% normalization + 1% shape
jet $\rightarrow\tau$ misidentification study: object related systematic uncertainties	21% normalization + 2% shape
$e\rightarrow\tau$ misidentification probability	22%
multi jet fit related uncertainties	32%
multi jet $E_T^{\text{miss}}$ shape in control region	16%

# $H^\pm \rightarrow \tau\nu$ full systematic uncertainties IV (generator uncertainties)

Source	Uncertainty
lepton+jets generator and parton shower (bbW <sup>-</sup> H <sup>+</sup> signal region)	10%
lepton+jets generator and parton shower (bbW <sup>+</sup> H <sup>-</sup> signal region)	8%
lepton+jets generator and parton shower (bbW <sup>-</sup> H <sup>+</sup> control region)	7%
lepton+jets generator and parton shower (bbW <sup>+</sup> H <sup>-</sup> control region)	6%
lepton+jets initial and final state radiation (signal region)	8%
lepton+jets initial and final state radiation (control region)	13%
$\tau$ +lepton generator and parton shower (bbW <sup>-</sup> H <sup>+</sup> )	2%
$\tau$ +lepton generator and parton shower (bbW <sup>+</sup> H <sup>-</sup> )	5%
$\tau$ +lepton initial and final state radiation	13%
$\tau$ +jets generator and parton shower (bbW <sup>-</sup> H <sup>+</sup> )	5%
$\tau$ +jets generator and parton shower (bbW <sup>+</sup> H <sup>-</sup> )	5%
$\tau$ +jets initial and final state radiation	19%

# SM $H \rightarrow \tau\tau$ full systematic uncertainties

Source	Uncertainty
QCD scale	8-25%
Vector boson production cross section	4-5%
Jet production cross section	24% per jet
QCD production cross section (including top)	3-6%
Parton distribution function	8%
Luminosity	3.9%
Trigger efficiencies	1-2%
Jet energy scale	up to 12%
$\tau$ energy scale	2-5%
Fake leptons/ $\tau_{\text{had}}$	6-40%

# References

- ATLAS Collaboration
  - <http://www.atlas.ch>
- Search for neutral MSSM Higgs bosons decaying to  $\tau^+\tau^-$  pairs in proton-proton collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector
  - <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-132/>
- Search for charged Higgs bosons decaying via  $H^\pm \rightarrow t\bar{u}$  in top quark pair events using pp collision data at  $\sqrt{s} = 7$  TeV with the ATLAS detector
  - <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HIGG-2012-09/>
- Search for the Standard Model Higgs boson in the  $H \rightarrow \tau\tau$  decay mode with  $4.7 \text{ fb}^{-1}$  of ATLAS data at  $\sqrt{s} = 7$  TeV
  - <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2012-014/>
- Performance of the Reconstruction and Identification of Hadronic Tau Decays with ATLAS
  - <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2011-152/>
- Asymptotic formulae for likelihood-based tests of new physics
  - <http://arxiv.org/abs/1007.1727>
- Further reading for MSSM scenarios:
  - H. P. Nilles, Phys. Rep. 110 (1984) 1. (available at [http://ccdb5fs.kek.jp/cgi-bin/img\\_index?8303226](http://ccdb5fs.kek.jp/cgi-bin/img_index?8303226))
  - H. E. Haber and G. L. Kane, Phys. Rep. 117 (1985) 75. (available at <http://www.sciencedirect.com/science/article/pii/0370157385900511>)