Higgs$\rightarrow\tau^+\tau^-$

ATLAS results, and considerations on the way forwards

Considerations by P. Rosendahl T. Burgess and B. Stugu

(Presented by B. Stugu)

Geilo Dec. 18th. 2012

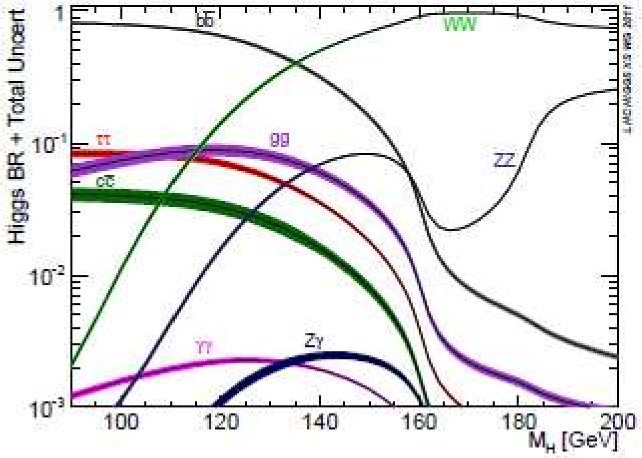
Higgs→$\tau^+\tau^-$

$$\tau^+ \rightarrow l^+ \nu\bar{\nu}$$

$$\tau^+ \rightarrow \pi^+\bar{\nu}$$

$$\tau^+ \rightarrow \rho^+\bar{\nu} \rightarrow \pi^+\pi^0\ \nu$$

$\tau^+ \rightarrow n\pi\bar{\nu}$ (*one or three charged pions)*

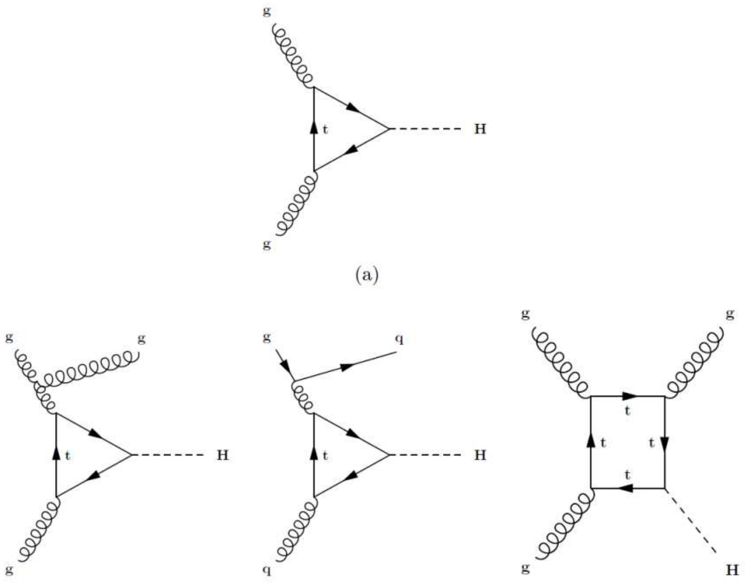


Signatures:
-*two leptons* and missing Et
-*lepton,narrow jet* and missing Et
-*two narrow jets* and missing Et
-Mass resolution is poor due to escaping energy
-Mvis: the visible mass is a broad distribution around half the boson mass

Higgs production at the LHC

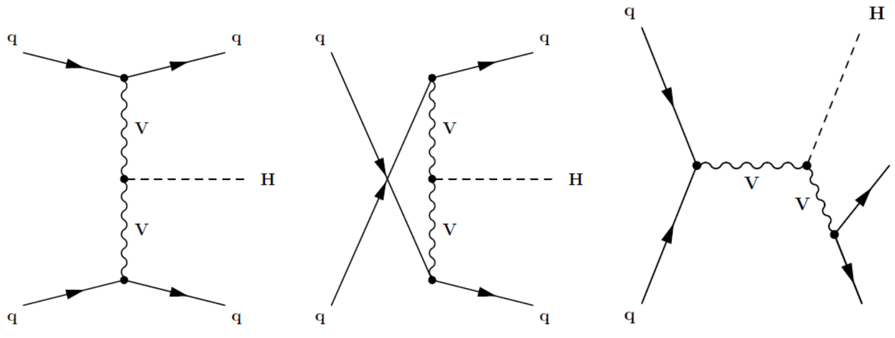
gluon-gluon fusion (ggF)
Small pT of the higgs
Dominating cross-section

Vector Boson Fusion (VBF)
Large pt
Just 10% total cross-section
Can use one or two additional jets to tag



(a) (b) (c) (d)

’VBF’ ’Boosted’



(a) (b) (c)

Figure 2.4: Feynman diagrams for Higgs production through weak interactions.

Candidate event for a Higgs boson produced by vector boson fusion

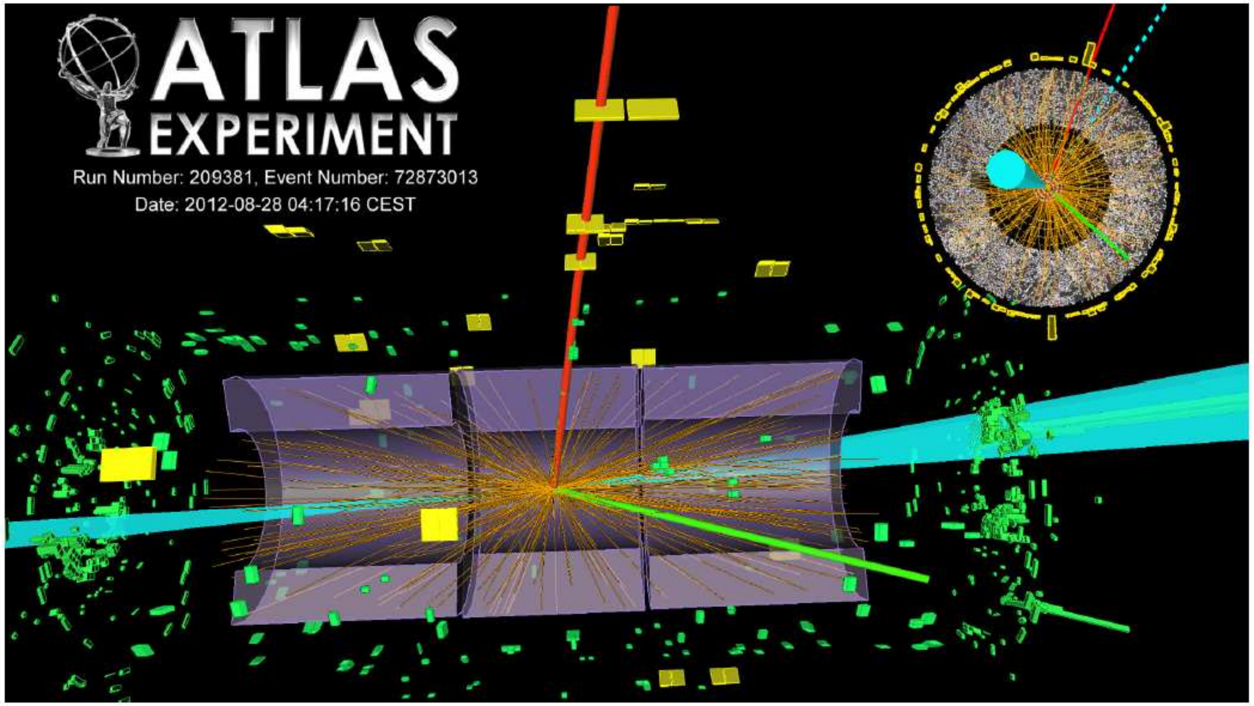


Figure 22: Display of an event selected by the $H \to \tau_{\text{lep}}\tau_{\text{lep}}$ analysis in the VBF category, where one τ decays to an electron and the other to a muon. The electron is indicated by a green track and the muon indicated by a red track. The dashed line represents the direction of the $E_{\text{T}}^{\text{miss}}$ vector, and there are two VBF jets marked with turquoise cones. The muon p_{T} is 20 GeV, the electron p_{T} is 17 GeV, $E_{\text{T}}^{\text{miss}} = 43$ GeV, $m_{jj} = 1610$ GeV and $m_{MMC} = 126$ GeV.

Main backgrounds

$Z \rightarrow \tau^+ \tau^-$

Irreducible,but differences in
-mass
-spin (J=1 while H has J=0)
-production kinematics

QCD-jets: HUGE, can be reduced

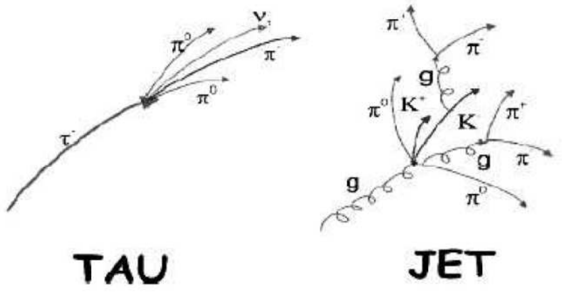
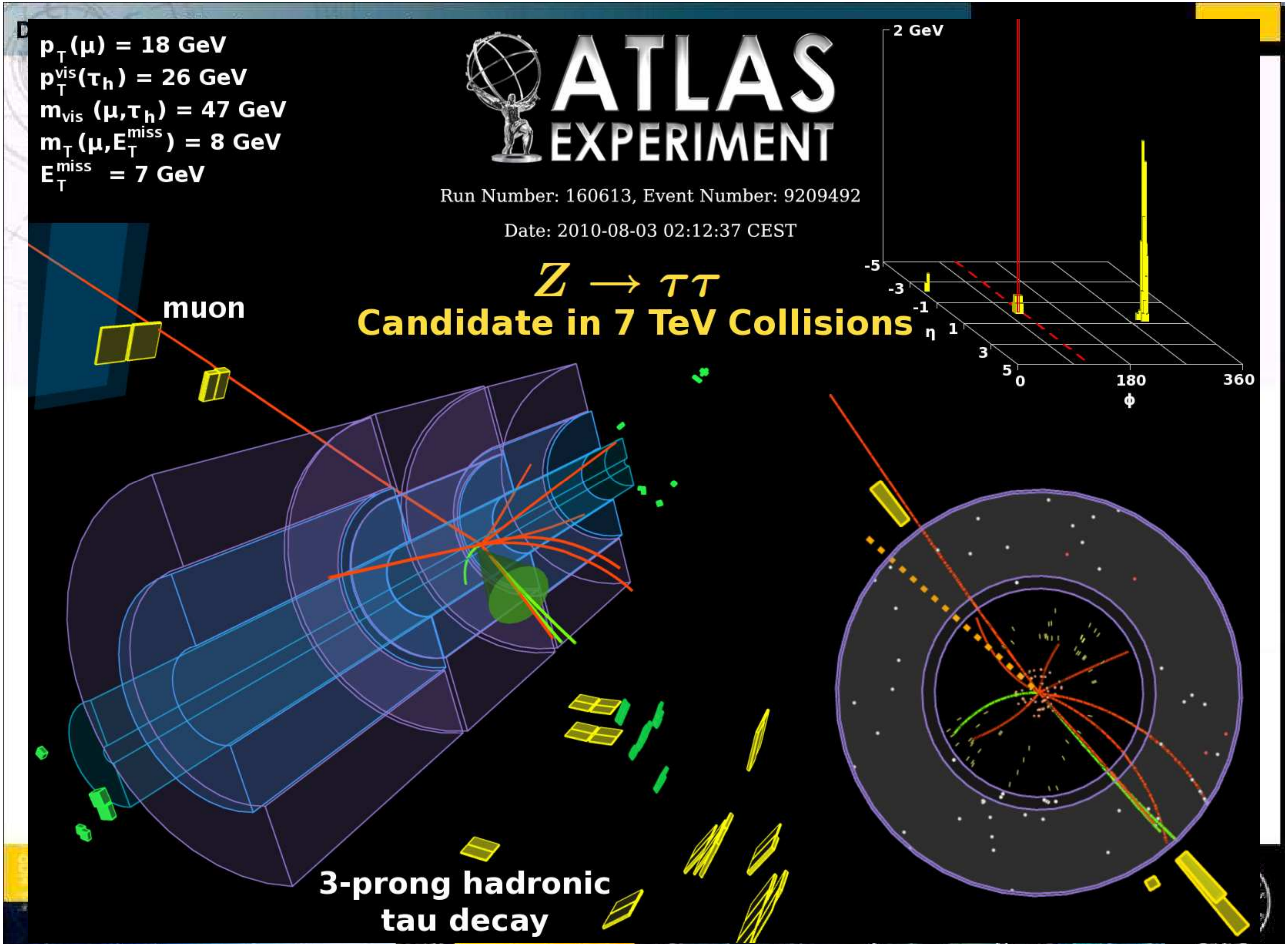


Figure 3.9: Tau signature vs jet signature

From A. Aasvold
MSc thesis UiB

$Z \rightarrow \tau\tau$ Candidate in 7 TeV Collisions



$p_T(\mu)$ = 18 GeV

$p_T^{vis}(\tau_h)$ = 26 GeV

$m_{vis}(\mu,\tau_h)$ = 47 GeV

$m_T(\mu,E_T^{miss})$ = 8 GeV

E_T^{miss} = 7 GeV

ATLAS EXPERIMENT

Run Number: 160613, Event Number: 9209492

Date: 2010-08-03 02:12:37 CEST

Identification of τ leptons decaying to one or several hadrons ('jets')

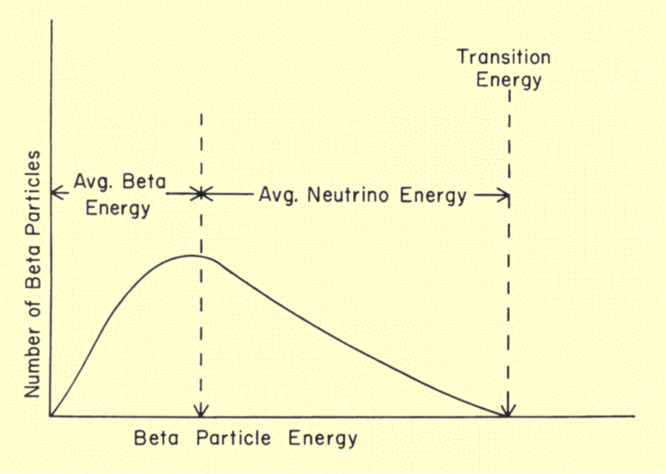
- Charged multiplicity of jet is low (1 or 3)
- Neutral energy from one or several π^0 is close to the charged track
- displaced impact parameter w.r.t. production vertex.

ATLAS Analysis strategy

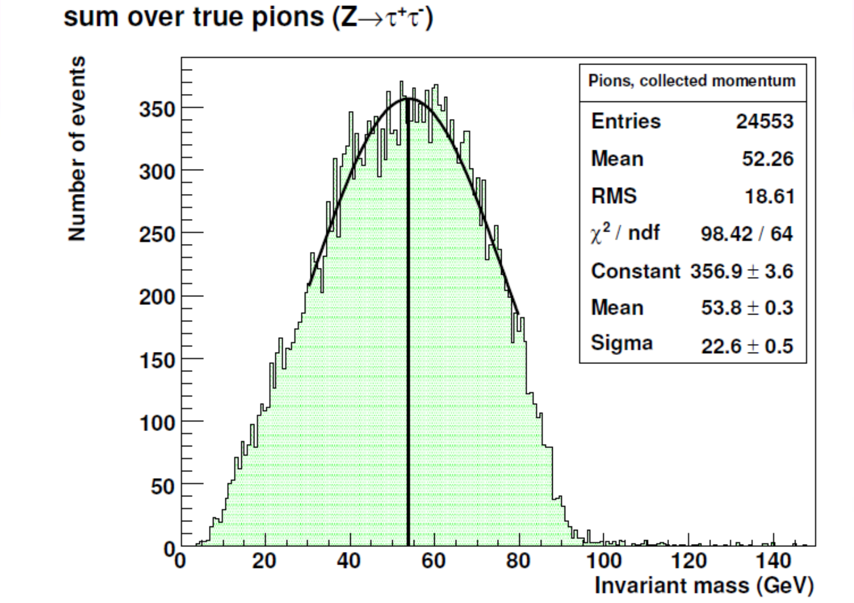
- Divide according to final state of the two τs
  - Lepton-lepton (14.4%)
    - Clean final state, in particular *eμ + missing energy*
  - Lepton-hadron (52.9%)
  - Hadron-hadron (38.5%)
    - Largest background, but a little less missing energy
- Subdivide according to production mode
  - boosted, with one jet
  - VBF
- Combine results in the end

ABOUT MASS RECONSTRUCTION

Less than half the mass and of the decaying boson is visible

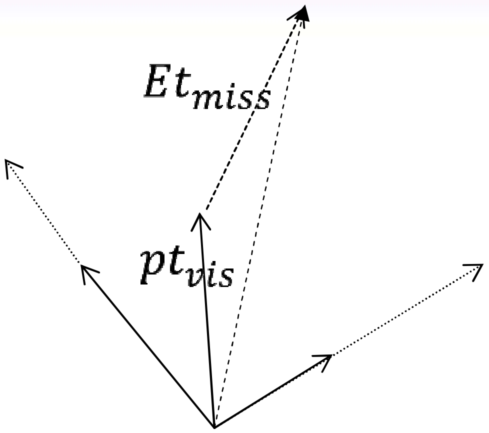


Energy spectrum in beta decay
(from Wikipedia)



Generator level visible mass
(Msc thesis of Alette Aasvold)

Approximate reconstruction of boson mass is possible if one assumes that escaping neutrinos are collinear with the visible part of the tau decay *Collinear approximation*.



Problem when there is no transverse boost of the boson

Current ATLAS analysis aims at selecting 'VBF' events, with a large transverse boost.

MMC (Missing mass calculator)

- Uses all the measurements, and adds in known distributions of the neutrino energies to form a most probable estimate of the boson mass.

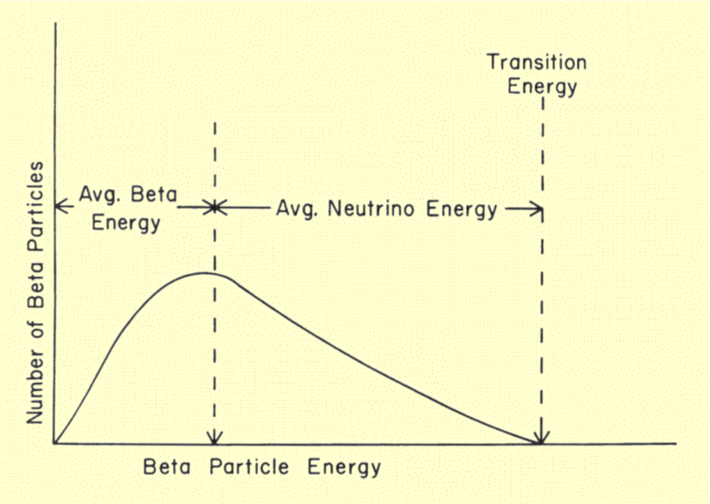


Illustration: β decay (from wikipedia)

Gets the mass right and shows improved mass resolution (maybe 20% narrower relative width)

Involved tuning procedures

Example of event selection

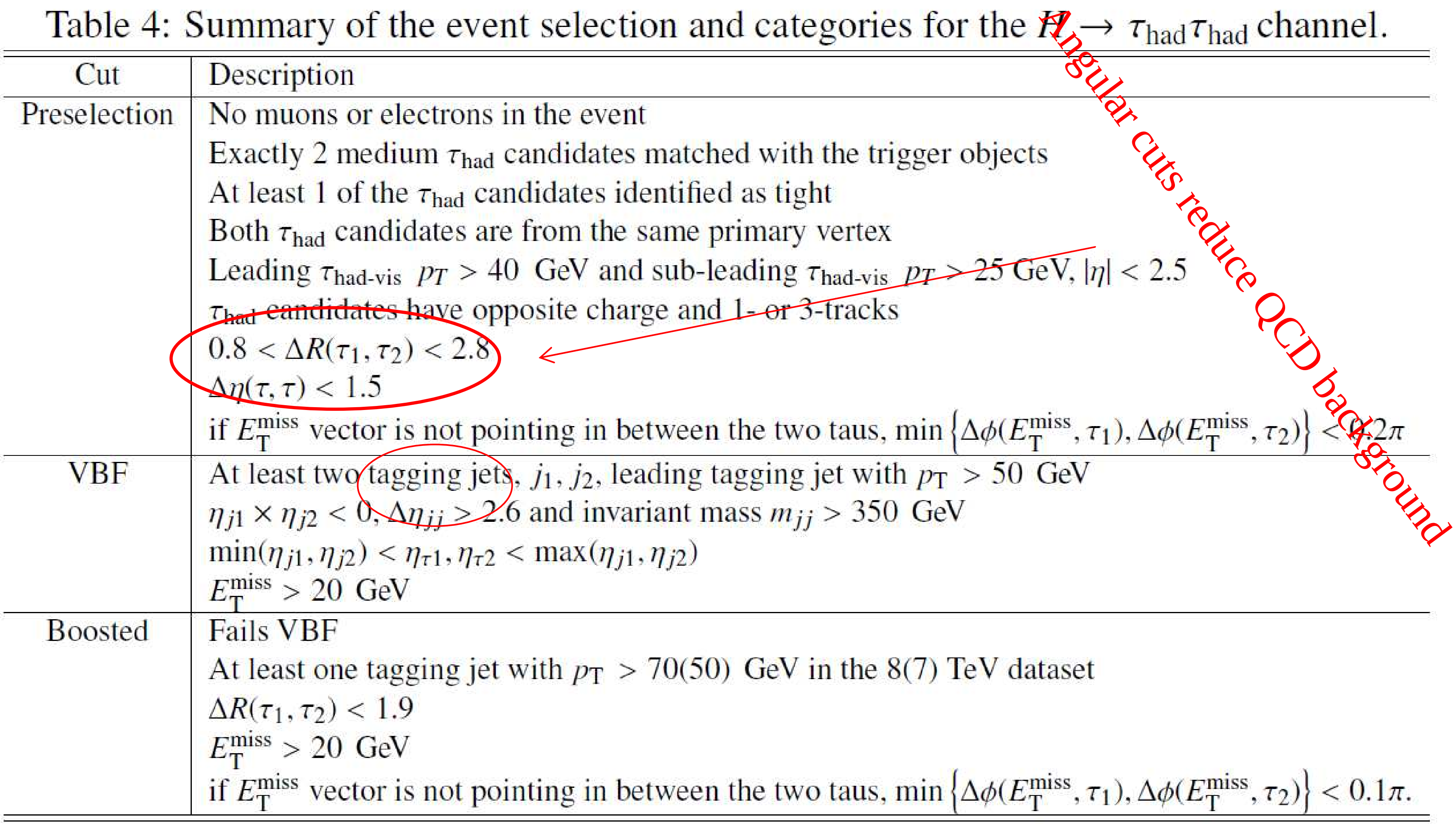
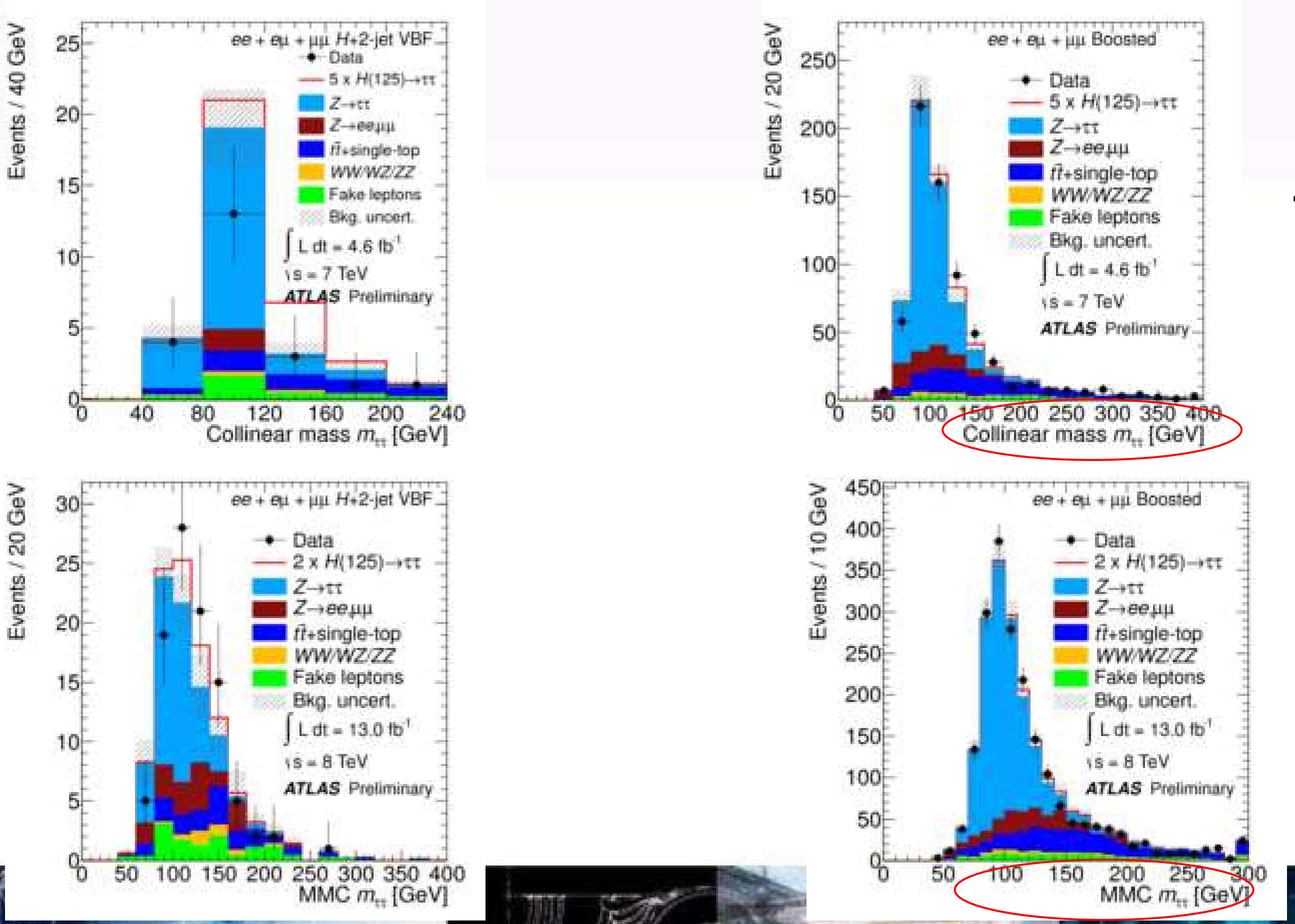


Table 4: Summary of the event selection and categories for the $H \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel.

Cut	Description
Preselection	No muons or electrons in the event
	Exactly 2 medium τ_{had} candidates matched with the trigger objects
	At least 1 of the τ_{had} candidates identified as tight
	Both τ_{had} candidates are from the same primary vertex
	Leading $\tau_{\text{had-vis}}$ $p_T > 40$ GeV and sub-leading $\tau_{\text{had-vis}}$ $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
	τ_{had} candidates have opposite charge and 1- or 3-tracks
	$0.8 < \Delta R(\tau_1, \tau_2) < 2.8$
	$\Delta\eta(\tau, \tau) < 1.5$
	if $E_{\mathrm{T}}^{\mathrm{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1), \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2)\right\} < 0.2\pi$
VBF	At least two tagging jets, j_1, j_2, leading tagging jet with $p_{\mathrm{T}} > 50$ GeV
	$\eta_{j1} \times \eta_{j2} < 0$, $\Delta\eta_{jj} > 2.6$ and invariant mass $m_{jj} > 350$ GeV
	$\min(\eta_{j1}, \eta_{j2}) < \eta_{\tau1}, \eta_{\tau2} < \max(\eta_{j1}, \eta_{j2})$
	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
Boosted	Fails VBF
	At least one tagging jet with $p_{\mathrm{T}} > 70(50)$ GeV in the 8(7) TeV dataset
	$\Delta R(\tau_1, \tau_2) < 1.9$
	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV
	if $E_{\mathrm{T}}^{\mathrm{miss}}$ vector is not pointing in between the two taus, $\min\left\{\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1), \Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2)\right\} < 0.1\pi$.

Angular cuts reduce QCD background

Example of final mass plots to analyse
a) lep-lep final state

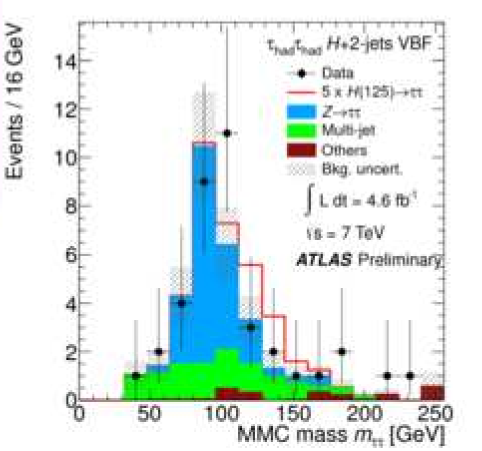


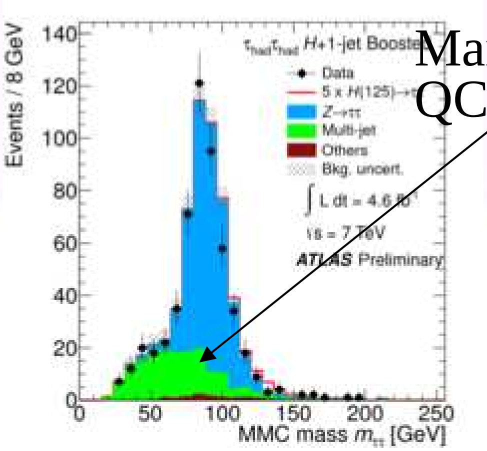
2011 analysis

2012 analysis

Mass plots in had-had final state

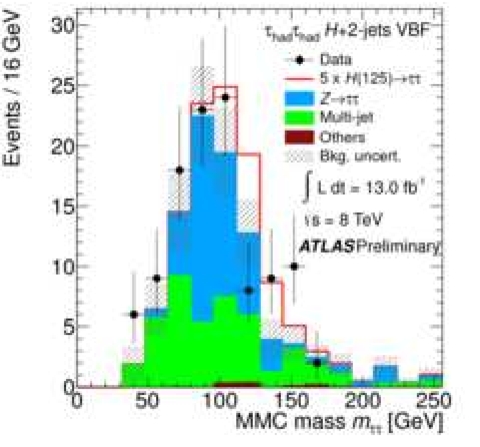
2011

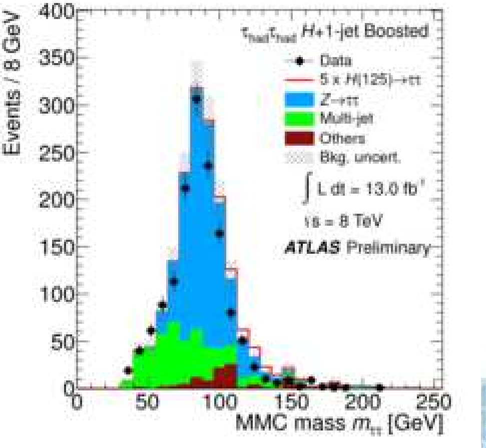




Manageable QCD background

2012





Example of event yield and backgrounds

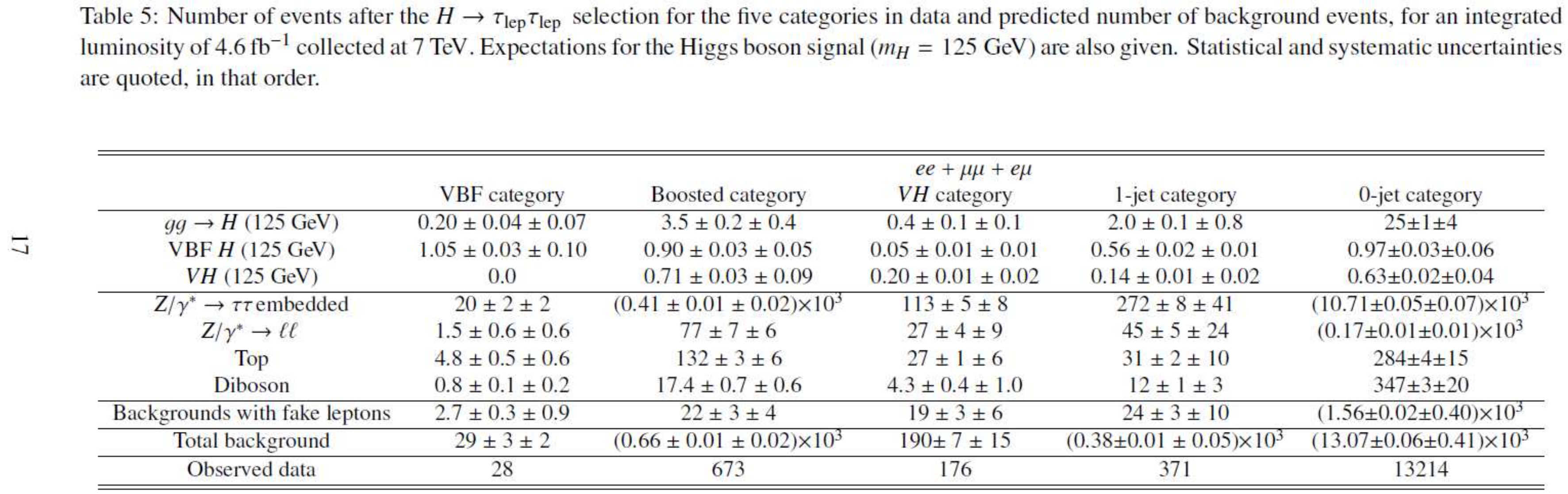
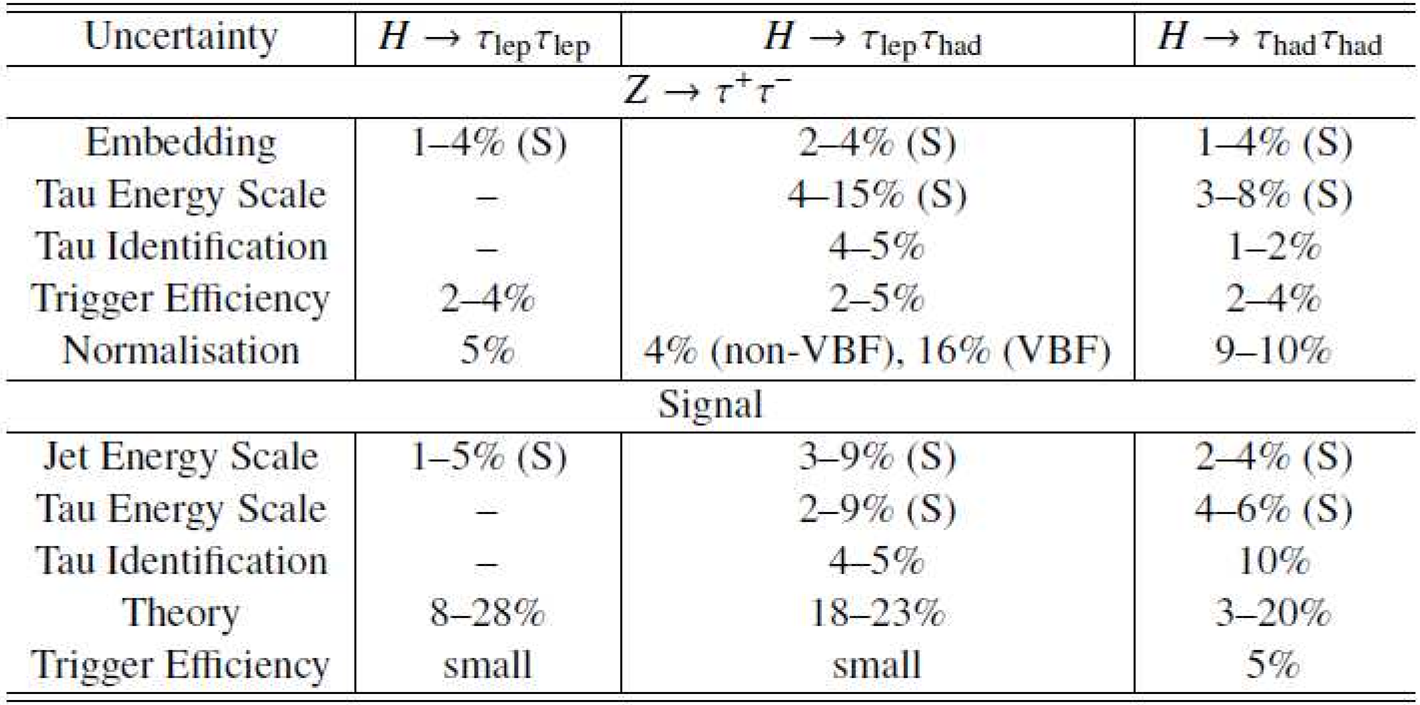


Table 5: Number of events after the $H \rightarrow \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$ selection for the five categories in data and predicted number of background events, for an integrated luminosity of 4.6 fb^{-1} collected at 7 TeV. Expectations for the Higgs boson signal (m_H = 125 GeV) are also given. Statistical and systematic uncertainties are quoted, in that order.

	VBF category	Boosted category	$ee+\mu\mu+e\mu$ VH category	1-jet category	0-jet category
$gg \rightarrow H$ (125 GeV)	0.20 ± 0.04 ± 0.07	3.5 ± 0.2 ± 0.4	0.4 ± 0.1 ± 0.1	2.0 ± 0.1 ± 0.8	25±1±4
VBF H (125 GeV)	1.05 ± 0.03 ± 0.10	0.90 ± 0.03 ± 0.05	0.05 ± 0.01 ± 0.01	0.56 ± 0.02 ± 0.01	0.97±0.03±0.06
VH (125 GeV)	0.0	0.71 ± 0.03 ± 0.09	0.20 ± 0.01 ± 0.02	0.14 ± 0.01 ± 0.02	0.63±0.02±0.04
$Z/\gamma^* \rightarrow \tau\tau$ embedded	20 ± 2 ± 2	(0.41 ± 0.01 ± 0.02)$\times10^3$	113 ± 5 ± 8	272 ± 8 ± 41	(10.71±0.05±0.07)$\times10^3$
$Z/\gamma^* \rightarrow \ell\ell$	1.5 ± 0.6 ± 0.6	77 ± 7 ± 6	27 ± 4 ± 9	45 ± 5 ± 24	(0.17±0.01±0.01)$\times10^3$
Top	4.8 ± 0.5 ± 0.6	132 ± 3 ± 6	27 ± 1 ± 6	31 ± 2 ± 10	284±4±15
Diboson	0.8 ± 0.1 ± 0.2	17.4 ± 0.7 ± 0.6	4.3 ± 0.4 ± 1.0	12 ± 1 ± 3	347±3±20
Backgrounds with fake leptons	2.7 ± 0.3 ± 0.9	22 ± 3 ± 4	19 ± 3 ± 6	24 ± 3 ± 10	(1.56±0.02±0.40)$\times10^3$
Total background	29 ± 3 ± 2	(0.66 ± 0.01 ± 0.02)$\times10^3$	190± 7 ± 15	(0.38±0.01 ± 0.05)$\times10^3$	(13.07±0.06±0.41)$\times10^3$
Observed data	28	673	176	371	13214

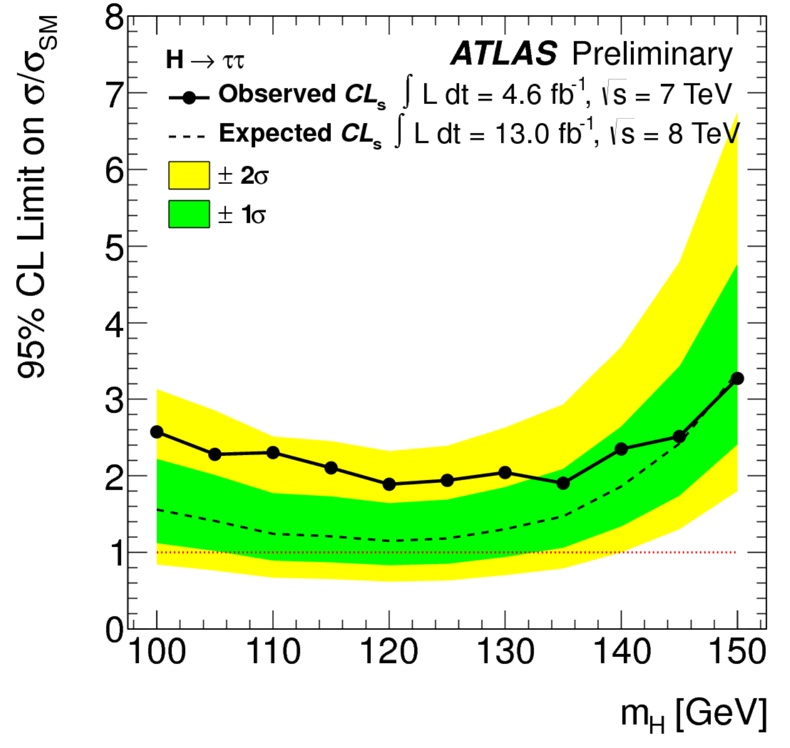
Combined number of Higgs->tautau decays in the samples is expected to be around **230** if the Higgs mass is 125 GeV

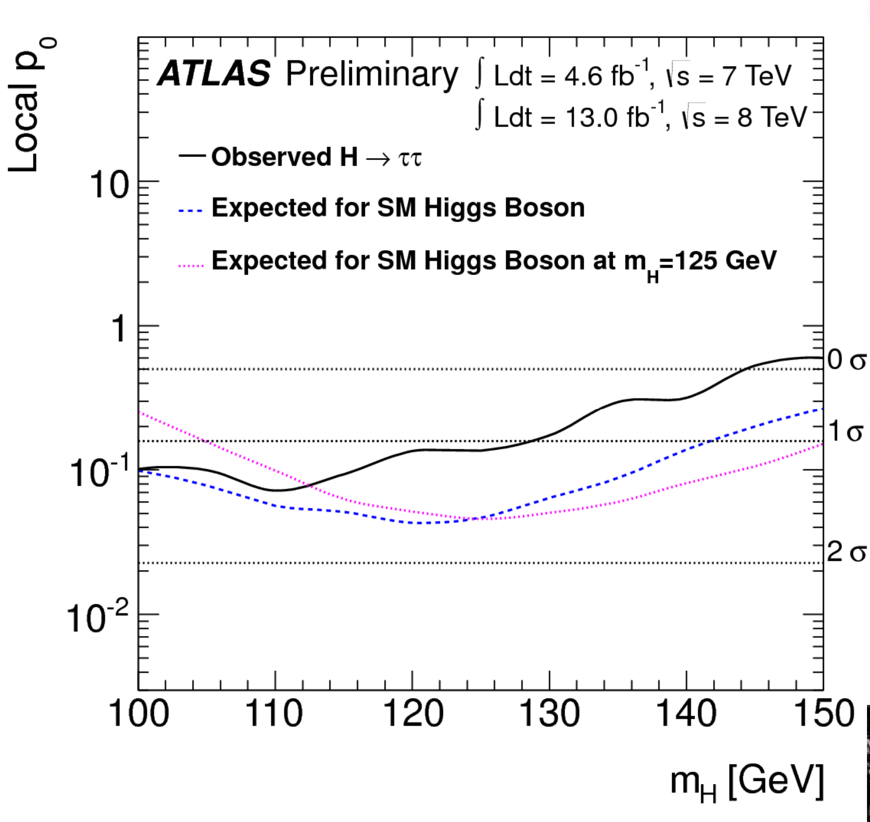
Systematics



Uncertainty	$H \rightarrow \tau_{\mathrm{lep}}\tau_{\mathrm{lep}}$	$H \rightarrow \tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	$H \rightarrow \tau_{\mathrm{had}}\tau_{\mathrm{had}}$
$Z \rightarrow \tau^+\tau^-$			
Embedding	1–4% (S)	2–4% (S)	1–4% (S)
Tau Energy Scale	–	4–15% (S)	3–8% (S)
Tau Identification	–	4–5%	1–2%
Trigger Efficiency	2–4%	2–5%	2–4%
Normalisation	5%	4% (non-VBF), 16% (VBF)	9–10%
Signal			
Jet Energy Scale	1–5% (S)	3–9% (S)	2–4% (S)
Tau Energy Scale	–	2–9% (S)	4–6% (S)
Tau Identification	–	4–5%	10%
Theory	8–28%	18–23%	3–20%
Trigger Efficiency	small	small	5%

Result on limits (p₀ is probability for background only)

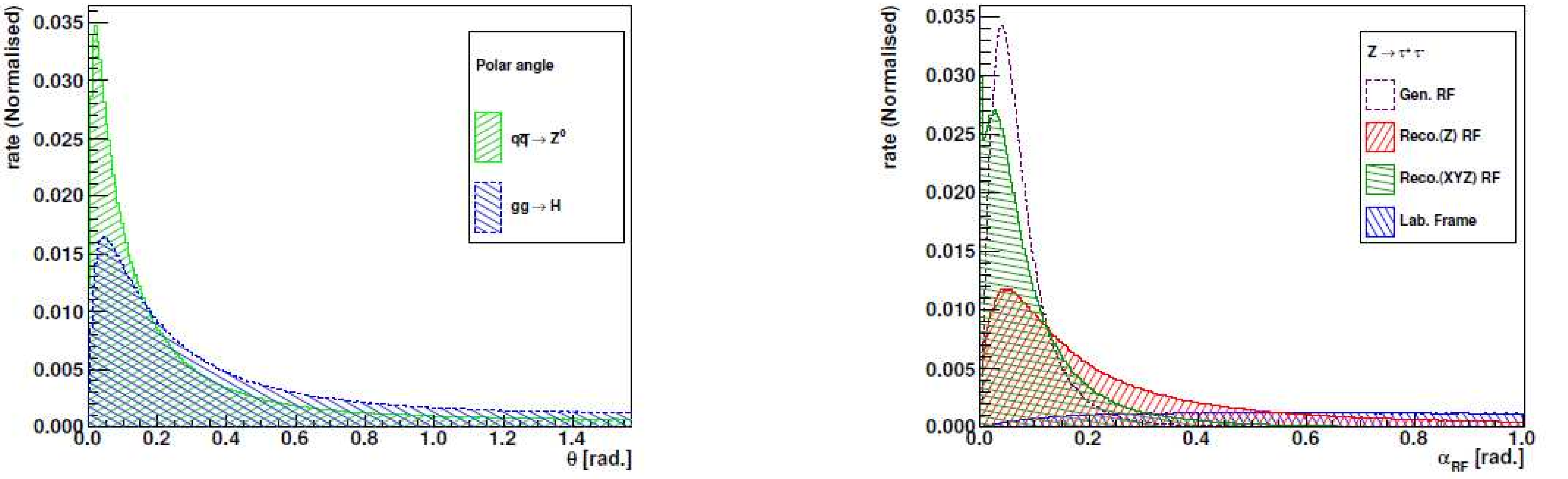




Can we still improve the analysis?

- Include more of the ggf events?
- Improved ‘final’ plot? (MMC mass for the moment)
- Improved identification of the hadronic taus?
- Improved understanding of shape and normalisation of background?

Higgs production by gluon-gluon fusion is mostly forwards

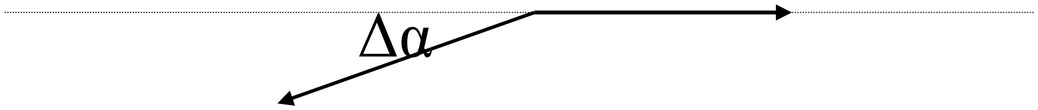


a) Polar angle, θ, of the Z^0 and 114 GeV/c^2 H osons. Typically the bosons are produced at mall angles close to the beam axis.

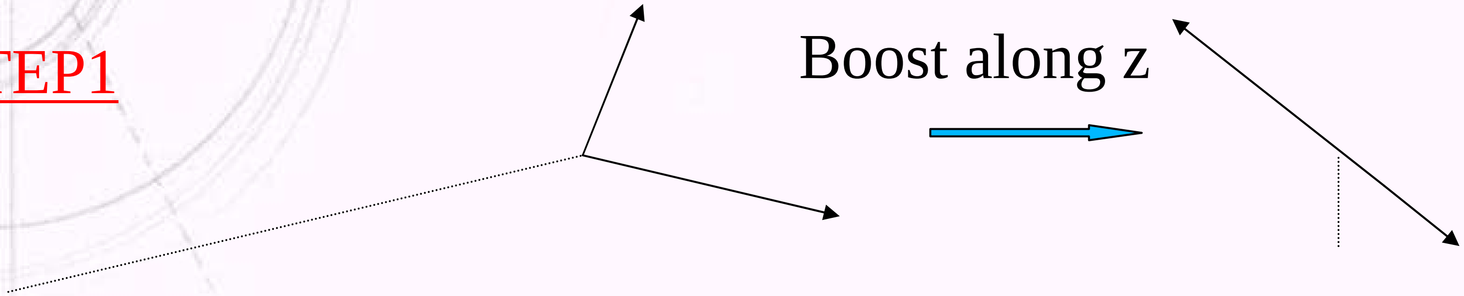
(b) Acollinearity, α, for $Z^0 \to \tau^+\tau^-$ in the gene ated and reconstructed RFs and in the laborato frame of the Z^0.

Figure 1. Angular distributions for simulated heavy boson decays.

- In Z/H system, the tau decay products are nearly *collinear*.
- *Acollinearity*, *Δα*, of just a few degrees.
- We propose to find the boost of the system that minimises the acollinearity (using simple and quick iterative minimisation method)



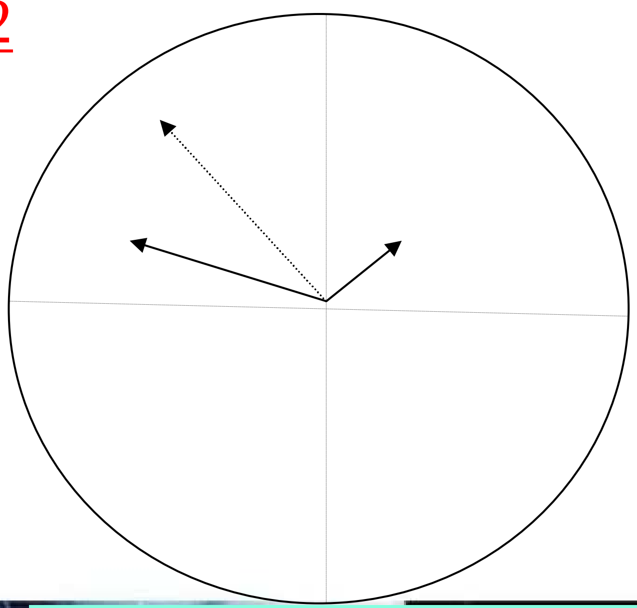
STEP1



Boost along z

…until longitudinal tau momenta are back to back

STEP2



Boost transversally along (x,y)

$x = (p^{\tau 1} + p^{\tau 2} + E_{tmiss})_x$

$y = (p^{\tau 1} + p^{\tau 2} + E_{tmiss})_y$

until the two transverse tau momenta are back to back

Not necessarily use STEP2 if E_{tmiss} is small or delta(phi) is close to π

Illustration of minimisation procedure, and quality of β reconstruction

From JHEP01(2012)043
(Rosendahl,Burgess,Stugu)

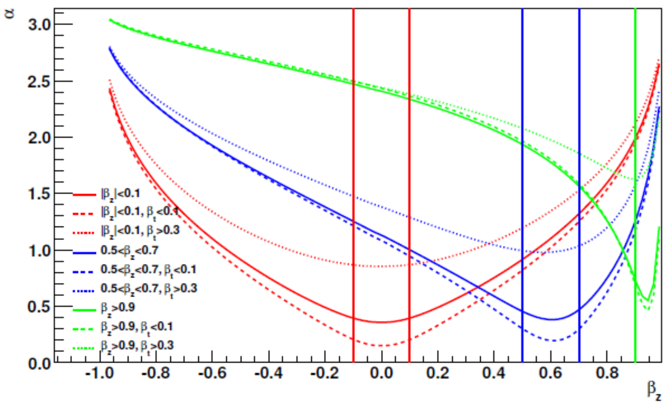
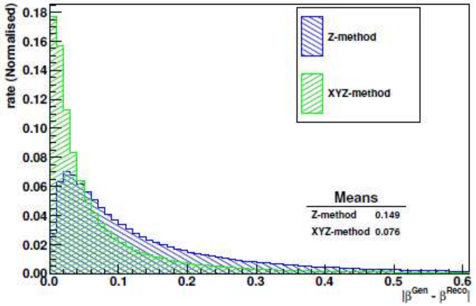
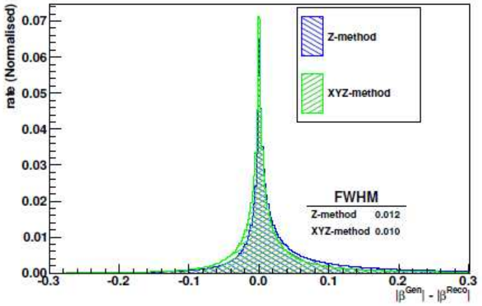


Figure 2. Average acollinearity as a function of attempted longitudinal boost for various ranges of true boost.



(a) Vectorial difference between the generated and reconstructed RF.

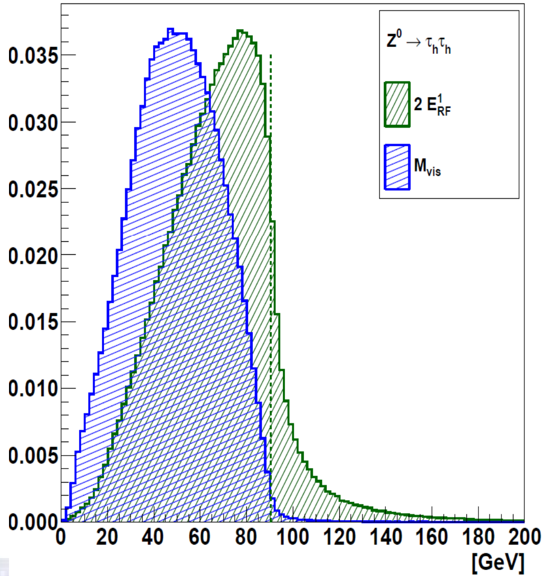


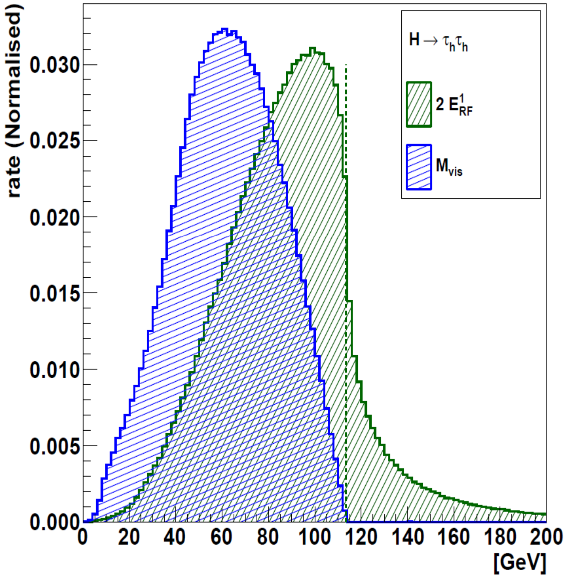
(b) Difference in magnitude between the generated and reconstructed β.

A new mass estimator: Use 2 x leading tau energy in CM to get accumulation at endpoint (2E1*) (corresponding to the mass).

Generator level illustration

Z->hadhad (left)
Higgs115GeV ggF (right)





Sensitivity to helicity correlations improves when going to the boson rest frame.

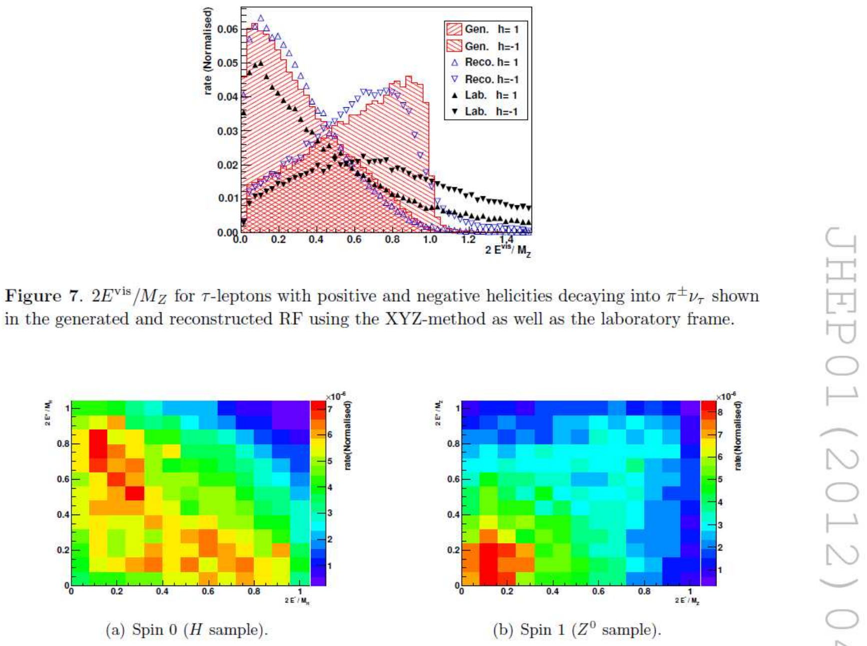


Figure 7. $2E^{\mathrm{vis}}/M_Z$ for τ-leptons with positive and negative helicities decaying into $\pi^\pm\nu_\tau$ shown in the generated and reconstructed RF using the XYZ-method as well as the laboratory frame.

(a) Spin 0 (H sample).

(b) Spin 1 (Z^0 sample).

Figure 8. Energy correlations in the reconstructed RF using the XYZ-method of a $\tau^+\tau^-$ pair with both τ-leptons decaying to $h^\pm\nu_\tau$. To avoid effects coming from the mass differences all energies are scaled with the mass of the decaying boson.

JHEP01(2012)043

$$H/Z \to \tau^+\tau^- \to \pi^+\bar{\nu}\,\pi^-\nu$$

Spin0/Spin1 likelihood ratios.

Gain in sensitivity, *S*, by going to approximate rest fame
Separation of log likelihoods is

$$n_\sigma = S\sqrt{N_{events}}$$

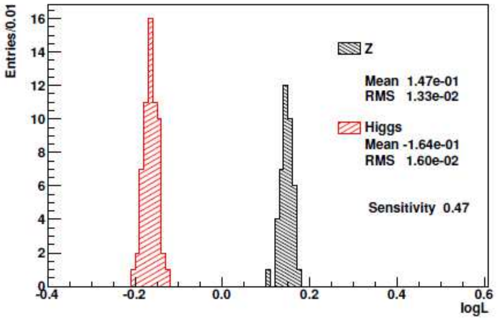


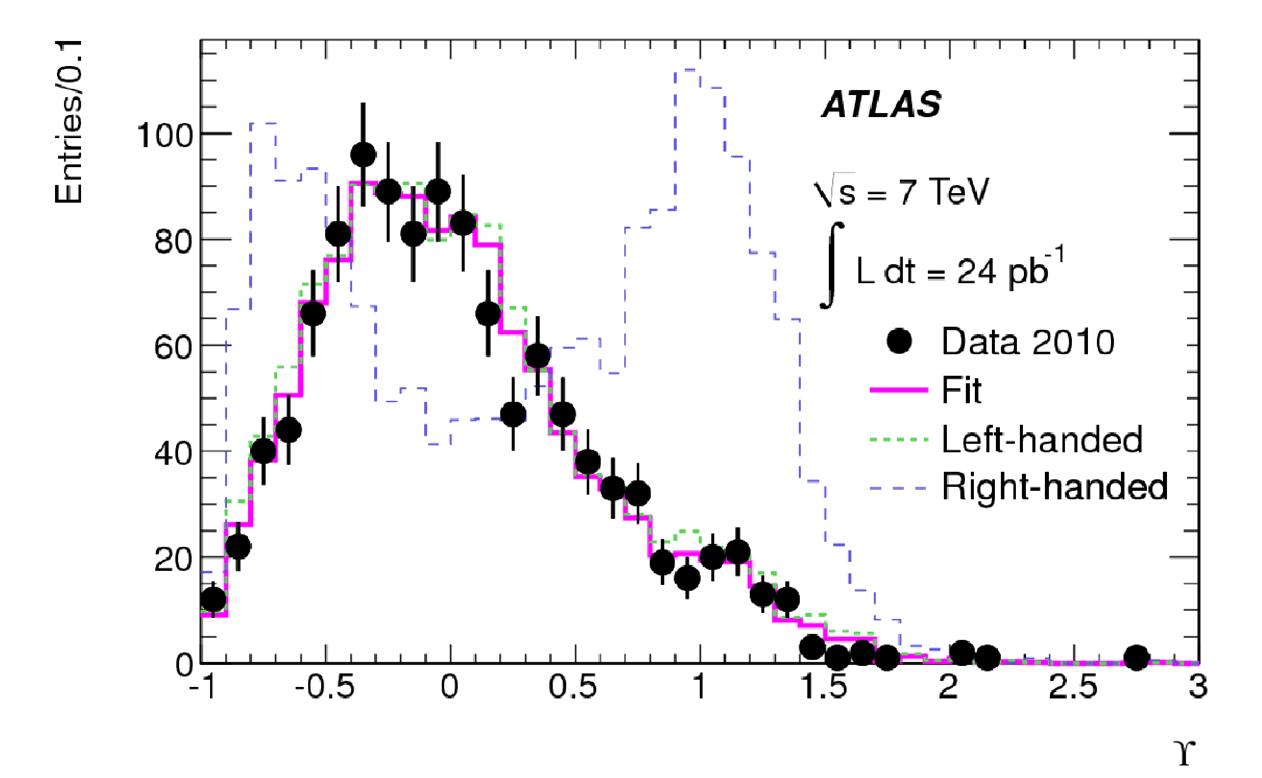
Figure 9. Log likelihood plot for energy-energy correlations in the reconstructed RF using the XYZ-method when both τ-leptons decays into $h^\pm\,\nu_\tau$.

τ decay mode		Sensitivity			
τ_1	τ_2	Reco.RF(Z)	Reco.RF(XYZ)	Lab.	True RF
$\ell^\pm\,\nu_\tau\,\overline{\nu}_\ell$	$\ell^\pm\,\nu_\tau\,\overline{\nu}_\ell$	0.13	0.09	0.06	0.08
$\ell^\pm\,\nu_\tau\,\overline{\nu}_\ell$	$h^\pm\,\nu_\tau$	0.17	0.13	0.06	0.15
$\ell^\pm\,\nu_\tau\,\overline{\nu}_\ell$	$h^\pm\,\nu_\tau\;nh^0$	0.15	0.07	0.05	0.13
$h^\pm\,\nu_\tau$	$h^\pm\,\nu_\tau$	0.42	0.47	0.23	0.51
$h^\pm\,\nu_\tau$	$h^\pm\,\nu_\tau\;nh^0$	0.21	0.15	0.10	0.18
$h^\pm\,\nu_\tau\;nh^0$	$h^\pm\,\nu_\tau\;nh^0$	0.19	0.13	0.09	0.18

Table 2. Sensitivity to spin of the boson for different decay modes of the two τ-leptons shown in the true and reconstructed RFs as well as in the laboratory frame.

Polarisation of $W^+ \rightarrow \tau^+\nu \rightarrow \rho^+\nu \rightarrow \pi^+\pi^0\nu$ has already been measured in ATLAS by use of

$$\Upsilon = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}$$



$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1.06 \pm 0.04 \pm^{0.04}_{0.07}$$

Conclusions

- Latest ATLAS published exclusion limits are not sensitive enough for discovery of the Standard Model Higgs in the tau-tau final state.
- Improvements are feasible, but not easy
  - More data
  - Better understanding of background shapes
  - Explicit inclusion of spin variables (maybe some two-dimensional spinn likelihood vs mass plot?)
- 2013 should be an exciting year, even without new data!