

# Search for the neutral MSSM Higgs bosons in the $H \rightarrow \mu^+ \mu^-$ and $H \rightarrow \tau^+ \tau^-$ decay modes with the ATLAS detector at the LHC

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On behalf of the ATLAS Collaboration



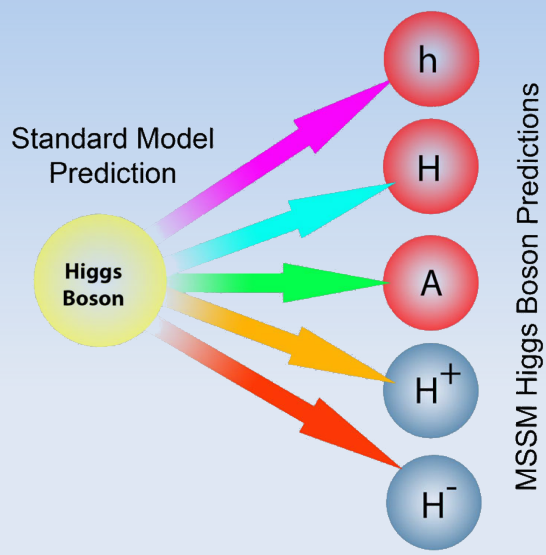
ICHEP2012

Melbourne Convention and Exhibition Centre  
4<sup>th</sup> - 12<sup>th</sup> July 2012



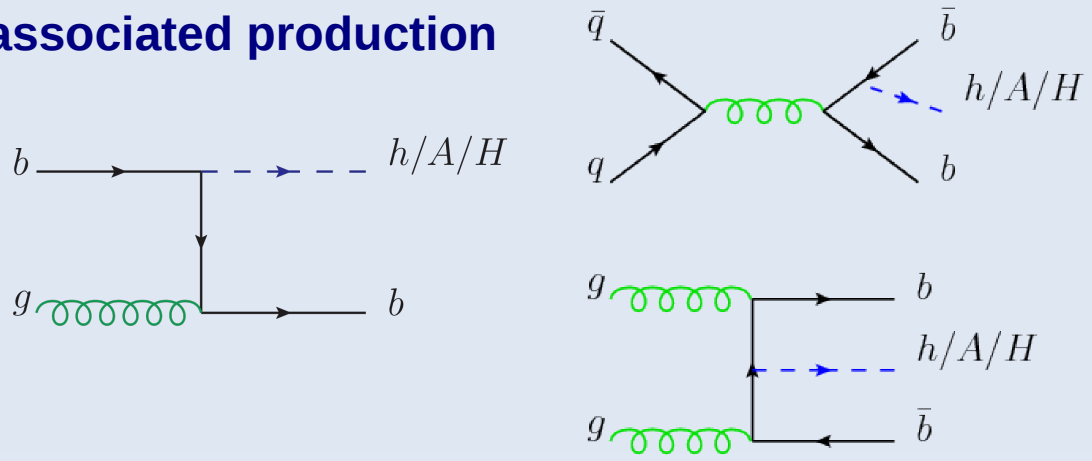
Bundesministerium  
für Bildung  
und Forschung

# The Higgs bosons in the MSSM

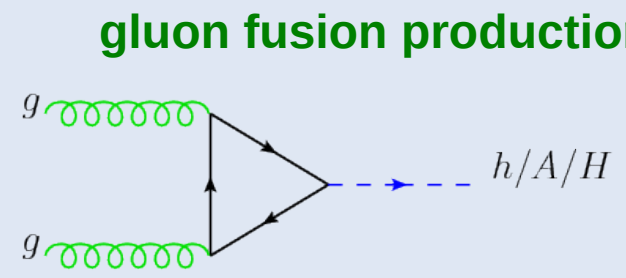


- Two free parameters @ Born level:  
 $m_A, \tan \beta$
- Enhanced coupling to down-type fermions  
 $\Rightarrow$  Enhanced  $\text{BR}(A \rightarrow \tau^+ \tau^-)$   
 $\Rightarrow$  Main production processes shown below  
 $\sigma \sim (\tan \beta)^2$
- $\text{BR}(A \rightarrow \mu^+ \mu^-) \approx 0.04\%$ : Challenging, clean signature

## b-associated production

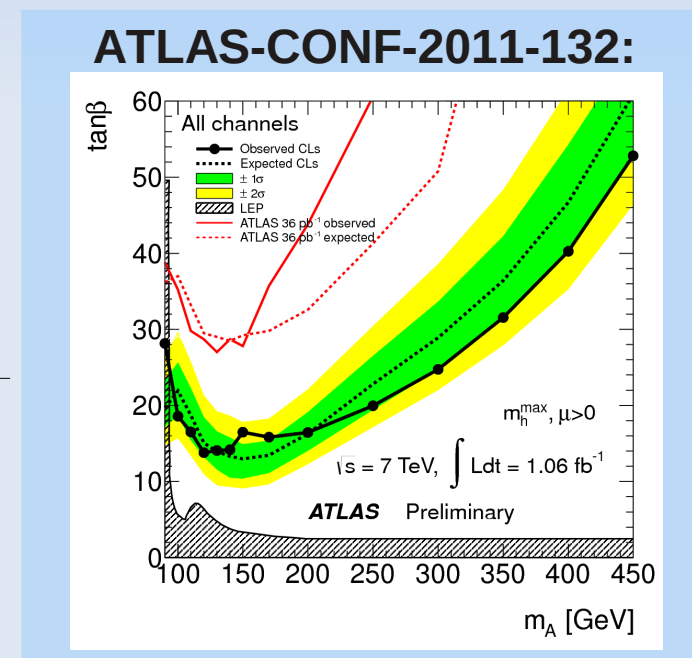
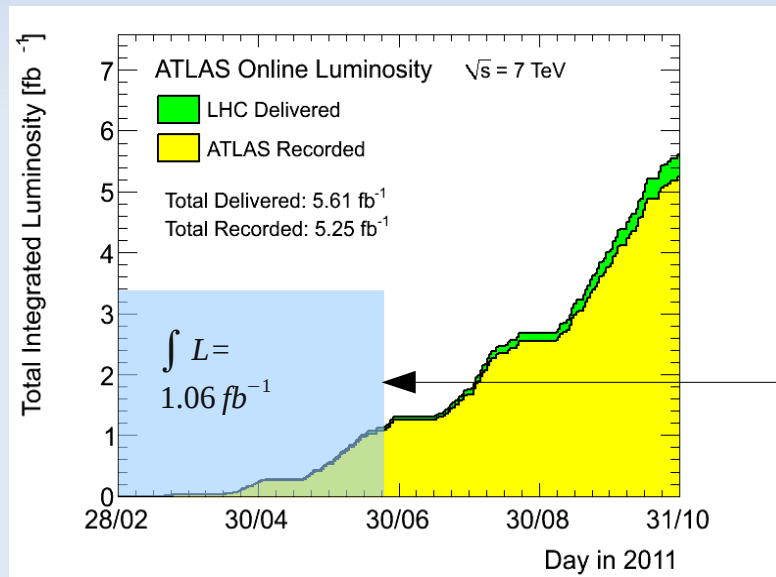


## gluon fusion production



# Previous results

- 2011, an exciting year:  
Excellent performance of the LHC and the ATLAS experiment
- Search for neutral Higgs boson in the MSSM at ATLAS up to now:



- This talk: Update using
  - The full data set of 2011:  $\int L = 4.7 - 4.8 \text{ fb}^{-1}$
  - The decay modes  $h/A/H \rightarrow \tau^+\tau^-$  and  $h/A/H \rightarrow \mu^+\mu^-$  (new)

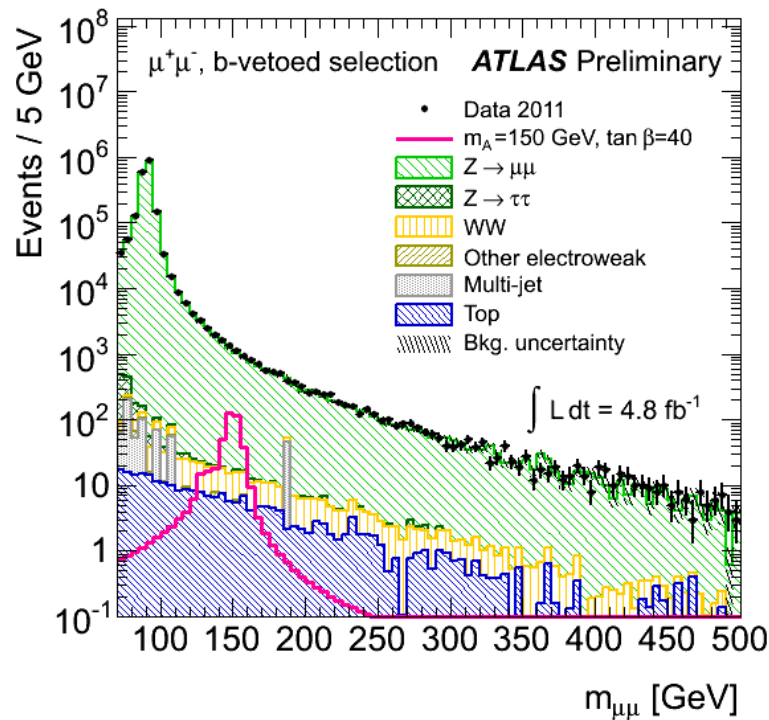
$$h/A/H \rightarrow \mu^+ \mu^-$$

# $h/A/H \rightarrow \mu^+ \mu^-$

## Topological event selection:

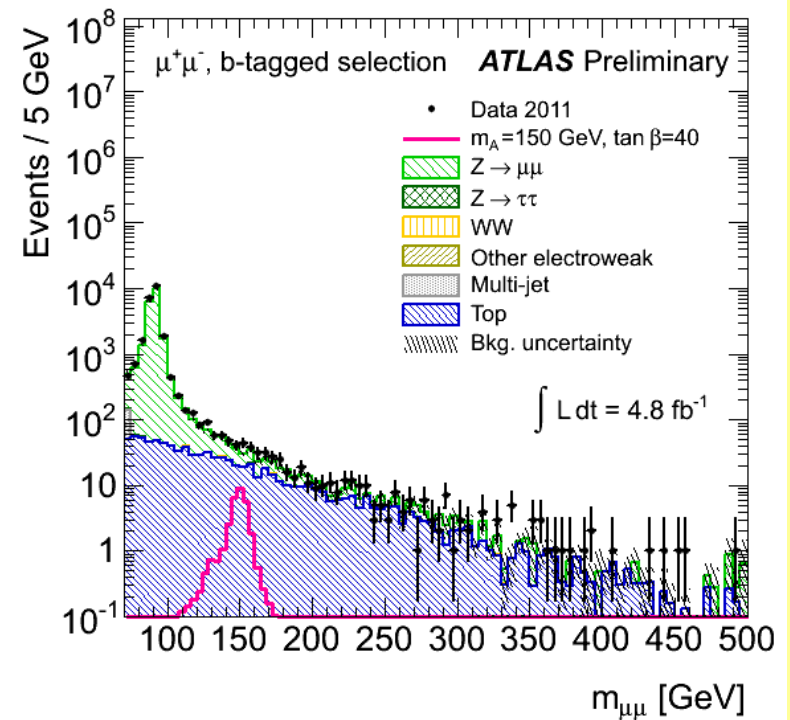
$$\begin{aligned}
 &2 \text{ isolated } \mu \\
 &p_T > 20, 15 \text{ GeV}, q_{\mu_1} \times q_{\mu_2} = -1 \\
 &m(\mu, \mu) > 70 \text{ GeV} \\
 &E_T^{\text{miss}} < 40 \text{ GeV}
 \end{aligned}$$

## b-vetoed selection:



## b-tagged selection:

$$1 b\text{-jet}, p_T > 20 \text{ GeV}$$



# h/A/H→ μ<sup>+</sup>μ<sup>-</sup>: Background Estimation

- Sideband fits to data outside signal windows for each (m<sub>A</sub>, tan β)

**Background model:**

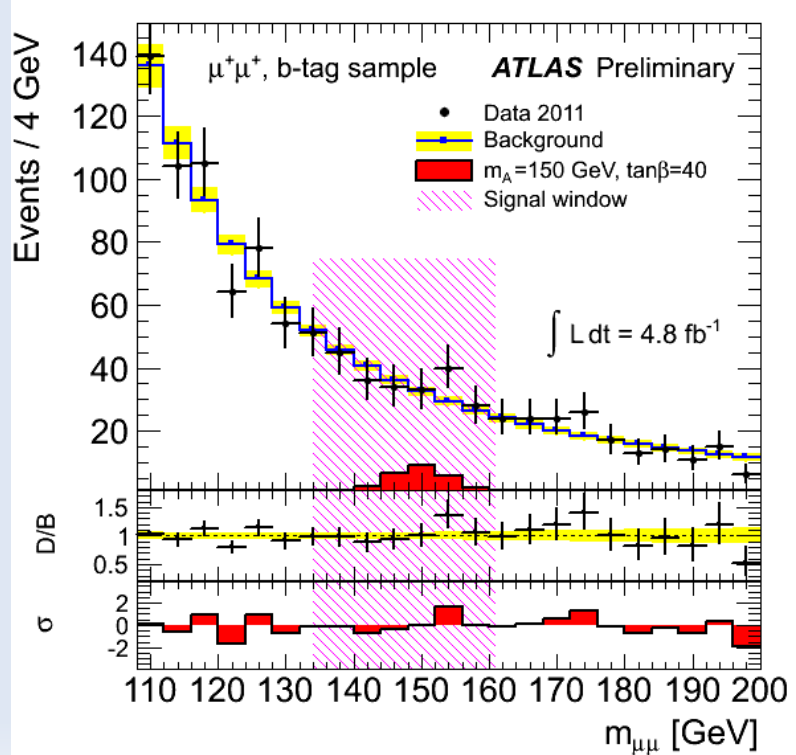
$$N_B \cdot \left[ \boxed{f_Z} \otimes \boxed{f_{Gauss}} \right]$$

$\uparrow$   $\uparrow$   
 $Z/\gamma^*$  curve Resolution

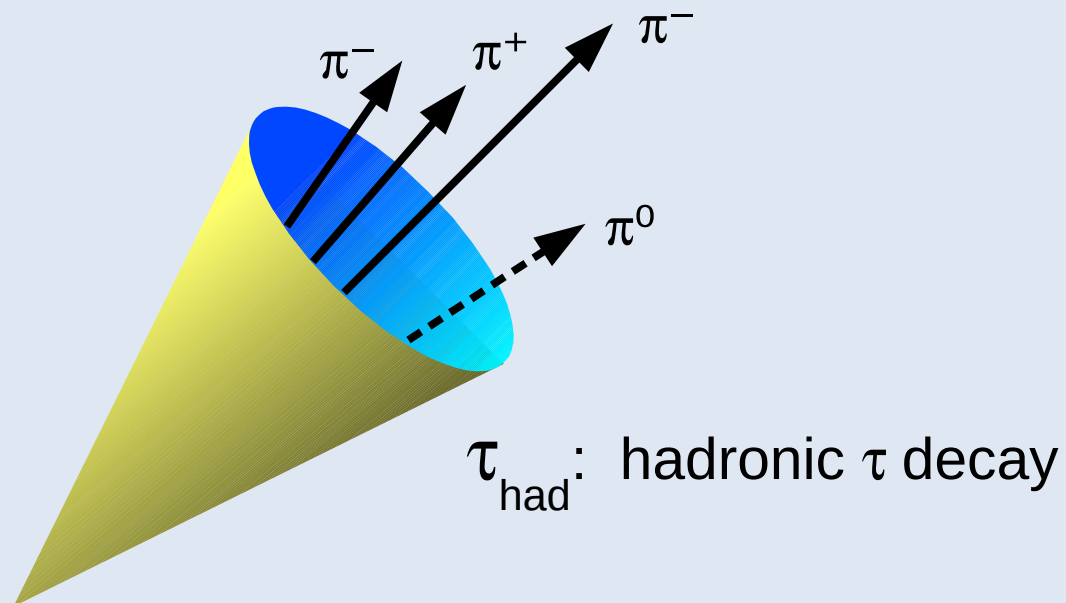
**Signal model:**

$$N_S \left[ \boxed{\frac{1}{[x^2 - M^2]^2 + M^2 \gamma^2}} \otimes \boxed{f_{Gauss}} + C \boxed{f_{Landau}} \right]$$

$\uparrow$   $\uparrow$   $\uparrow$   
Signal curve Resolution Left tail



$$\begin{aligned} h/A/H &\rightarrow \tau^+ \tau^- \rightarrow e\mu \, 4\nu \\ &\rightarrow e\tau_{\text{had}} \, 3\nu, \mu\tau_{\text{had}} \, 3\nu \\ &\rightarrow \tau_{\text{had}} \tau_{\text{had}} \, 2\nu \end{aligned}$$



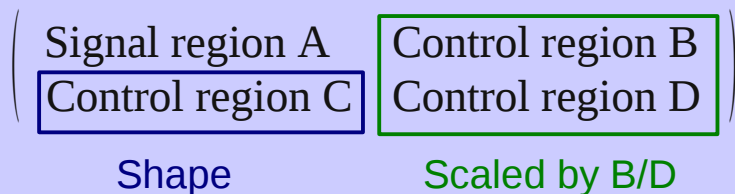
# h/A/H $\rightarrow \tau^+ \tau^-$ : Common techniques

## $Z/\gamma^* \rightarrow \tau^+ \tau^-$ embedding:

- Select  $Z/\gamma^* \rightarrow \mu^+ \mu^-$  data (high purity, Signal free)
- Replace muons by simulated  $\tau$ -leptons  
 $\rightarrow Z/\gamma^* \rightarrow \tau^+ \tau^-$  event

## Multi-jet background:

- From data via control regions

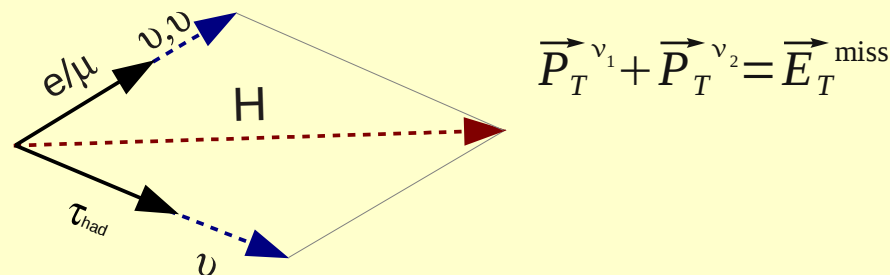


## Jets misidentified as $\tau_{\text{had}}$ :

- Difficult to describe in simulations  
 $\rightarrow$  Correction factors derived in control regions  
 $\rightarrow$  Misidentification rate measurements

## Mass reconstruction:

- **Visible mass:**  $m_{\tau\tau}^{\text{visible}} = \sqrt{(p_{\tau_1} + p_{\tau_2})^2}$
- **MMC Mass:** (Elagin et. al., NIM A654, 481)



- Scan  $\nu$  momenta wrt.  $E_T^{\text{miss}}$  resolution
- Calculate mass
- Weight with PDF



# $h/A/H \rightarrow \tau^+\tau^- \rightarrow e\mu 4\nu$

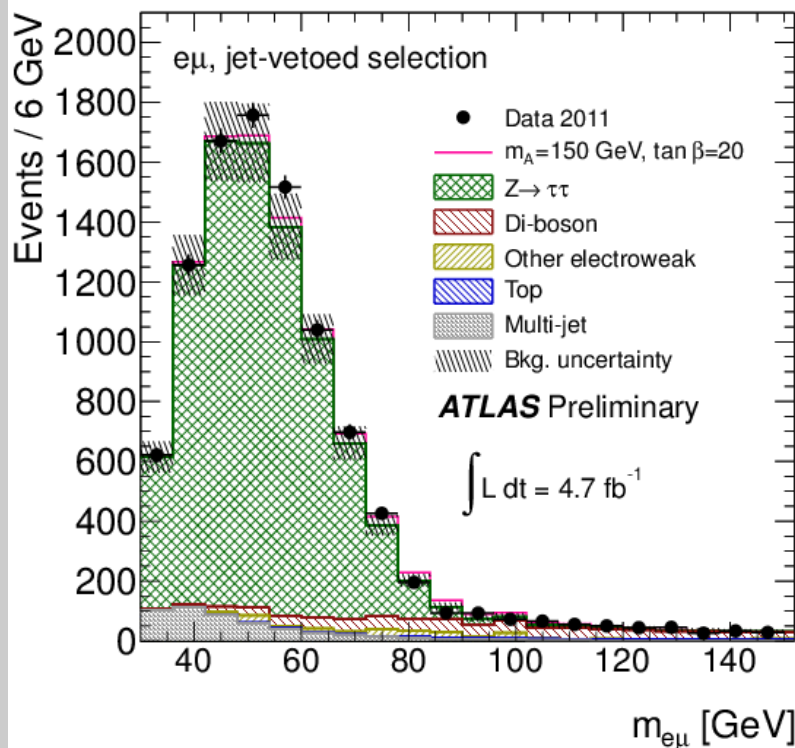
## Topological event selection:

1 isolated  $\mu$  & 1 isolated  $e$   
 $p_T^\mu > 10-20$  GeV,  $p_T^e > 15-24$  GeV  
 $q(e) \times q(\mu) = -1$   
 $m(e, \mu) > 30$  GeV  
 $\Delta\phi(e, \mu) > 2.0$

Trigger decision dependent

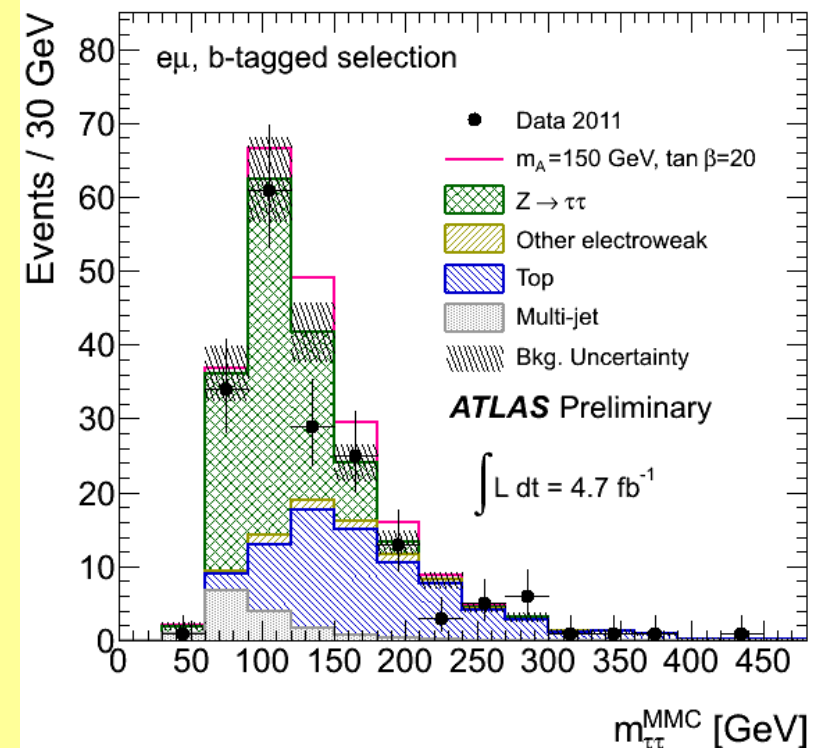
## Jet-vetoed selection:

No jets  
 $(p_T > 20$  GeV)



## b-tagged selection:

1  $b$ -jet ( $p_T > 20$  GeV)  
 No additional  $b$ -jet  
 $p_T^e + p_T^\mu + E_T^{\text{miss}} < 125$  GeV  
 $\cos\Delta\phi(\mu, E_T^{\text{miss}}) + \cos\Delta\phi(e, E_T^{\text{miss}}) > -0.2$   
 $\sum p_T^{\text{jets}} < 100$  GeV



# $h/A/H \rightarrow \tau^+\tau^- \rightarrow e\tau_{had} 3\nu, \mu\tau_{had} 3\nu$

## Topological event selection:

1 isolated  $\mu$ ,  $p_T > 20$  GeV

OR 1 isolated  $e$ ,  $p_T > 25$  GeV

1  $\tau_{had}$ ,  $p_T > 20$  GeV

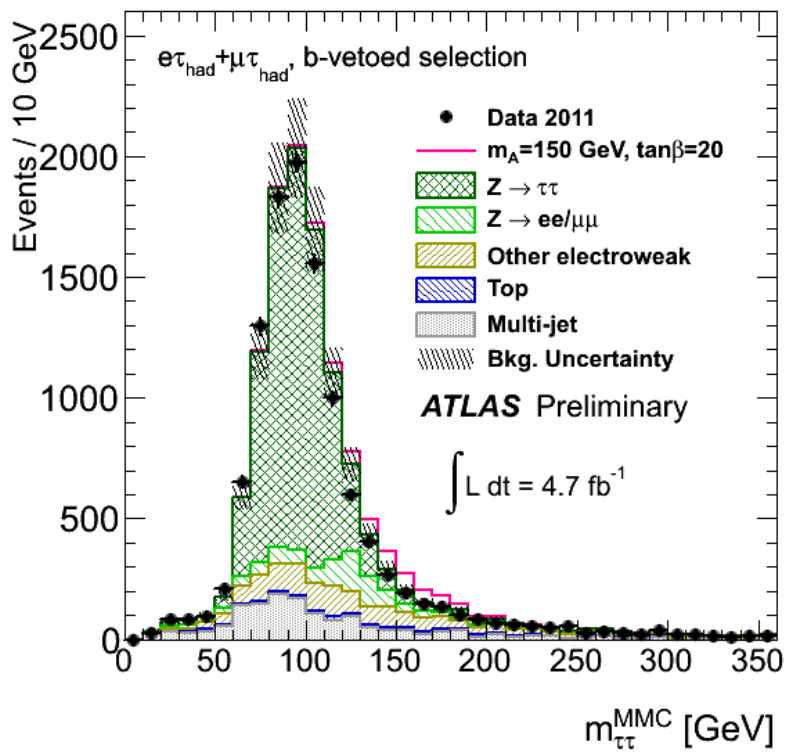
$q(e/\mu) \times q(\tau_{had}) = -1$

$$m_T = \sqrt{2 * p_T^{e/\mu} * E_T^{miss} (1 - \cos \Delta \phi)} < 30 \text{ GeV}$$

No additional  $e/\mu$

## b-vetoed selection:

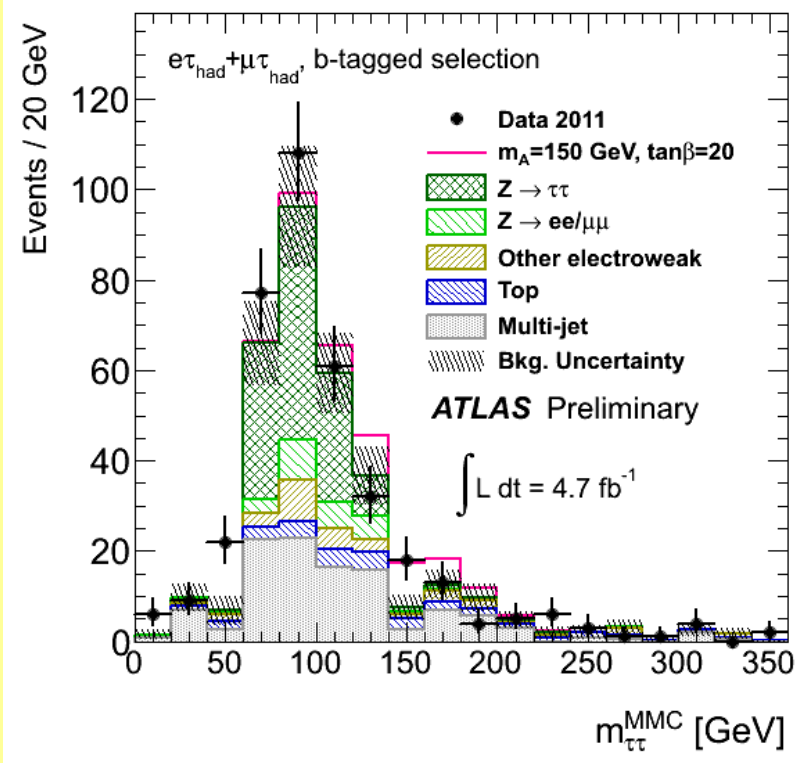
$$E_T^{miss} > 20 \text{ GeV}$$



## b-tagged selection:

1  $b$ -jet

$$20 \text{ GeV} < p_T^{b-jet} < 50 \text{ GeV}$$



$$h/A/H \rightarrow \tau^+ \tau^- \rightarrow \tau_{had} \tau_{had} 2\nu$$

**Topological event selection:**

$2 \tau_{had}$   
 $p_T > 45 \& 30 \text{ GeV}$   
 $e \& \mu \text{ Veto}$   
 $E_T^{miss} > 25 \text{ GeV}$

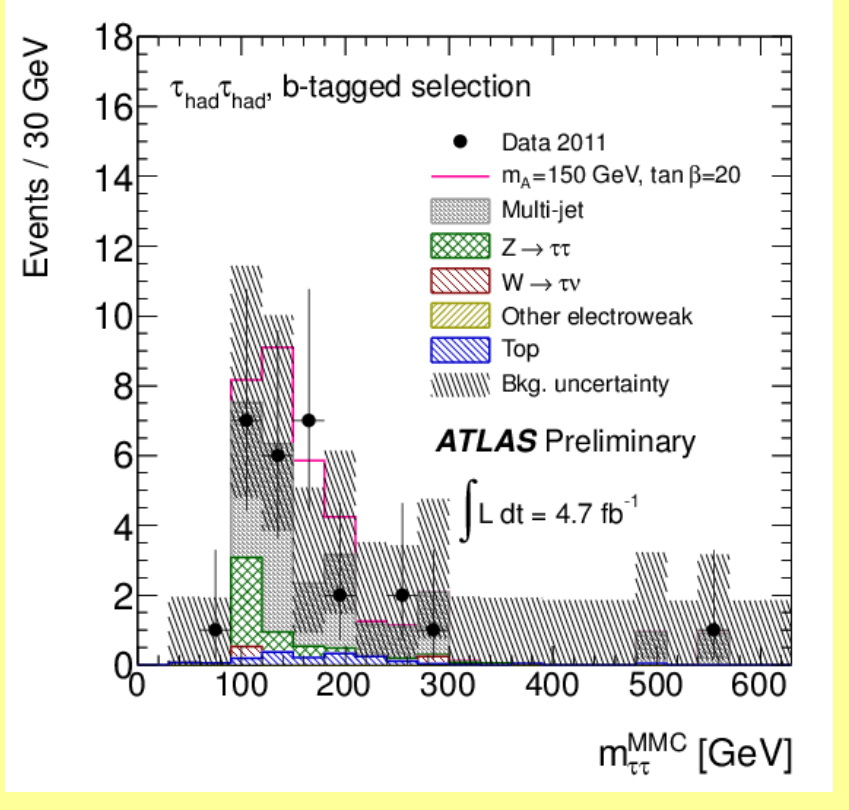
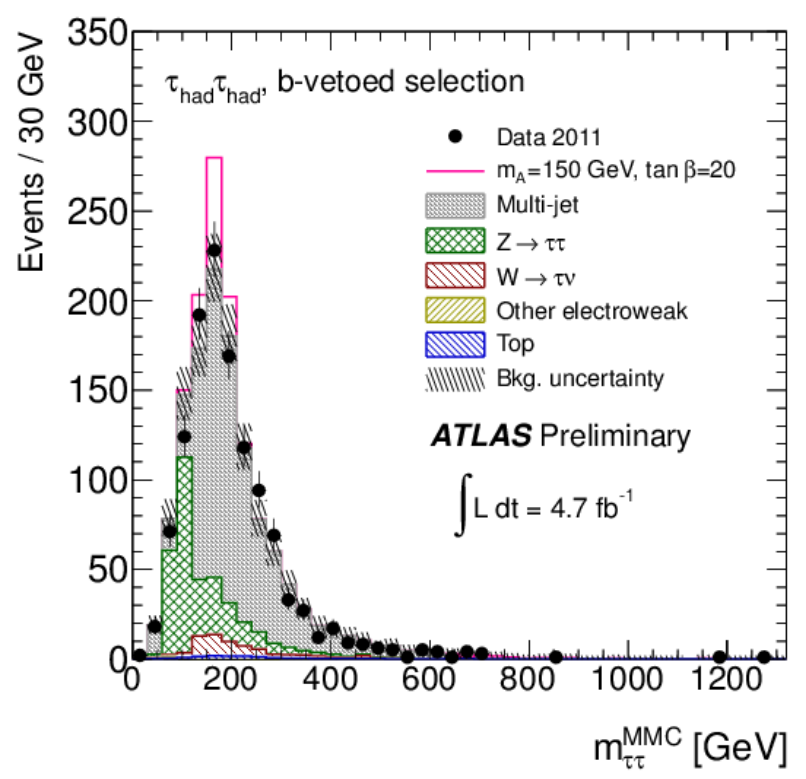


**b-tagged selection:**

$1 \text{ } b\text{-jet}$   
 $20 \text{ GeV} < p_T^{b\text{-jet}} < 50 \text{ GeV}$

**b-vetoed selection:**

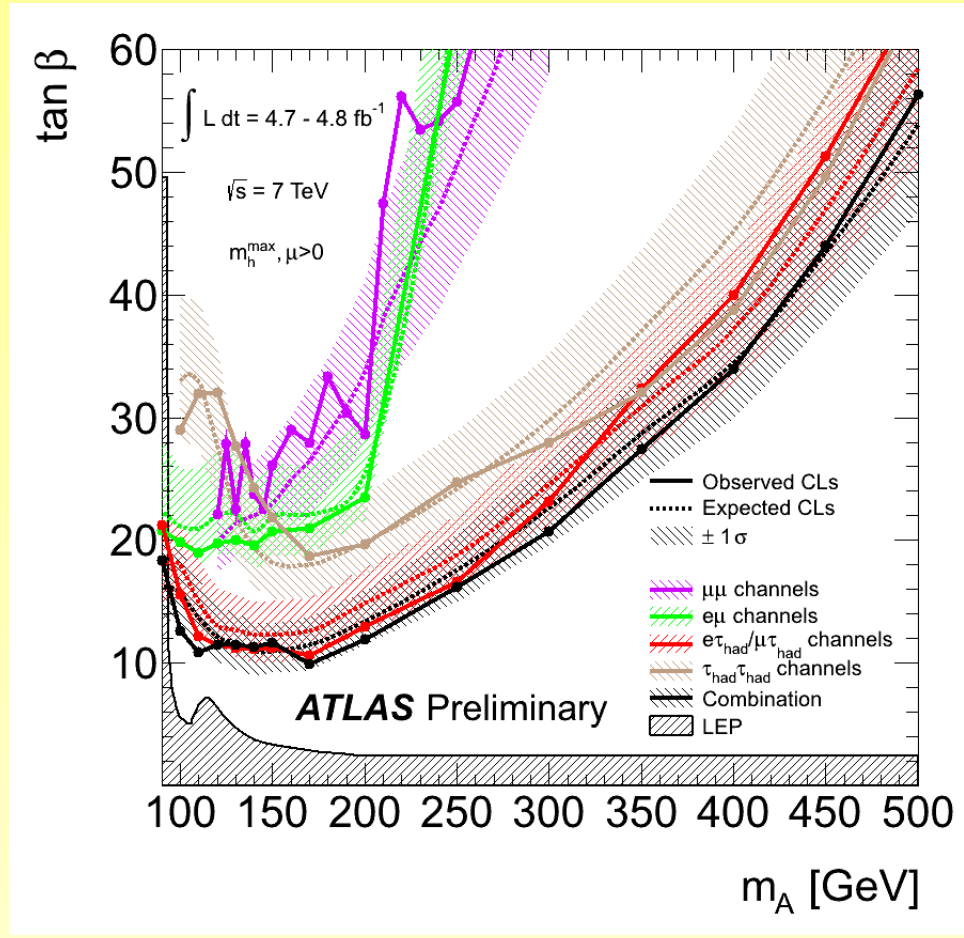
For the leading  $\tau_{had}$ :  
 $p_T > 60 \text{ GeV}$



# Results

No excess of events above the expected SM background  
has been observed in data  
95% Confidence Limit exclusion limits based on  $CL_s$

Limits in the  $m_A - \tan \beta$  plane



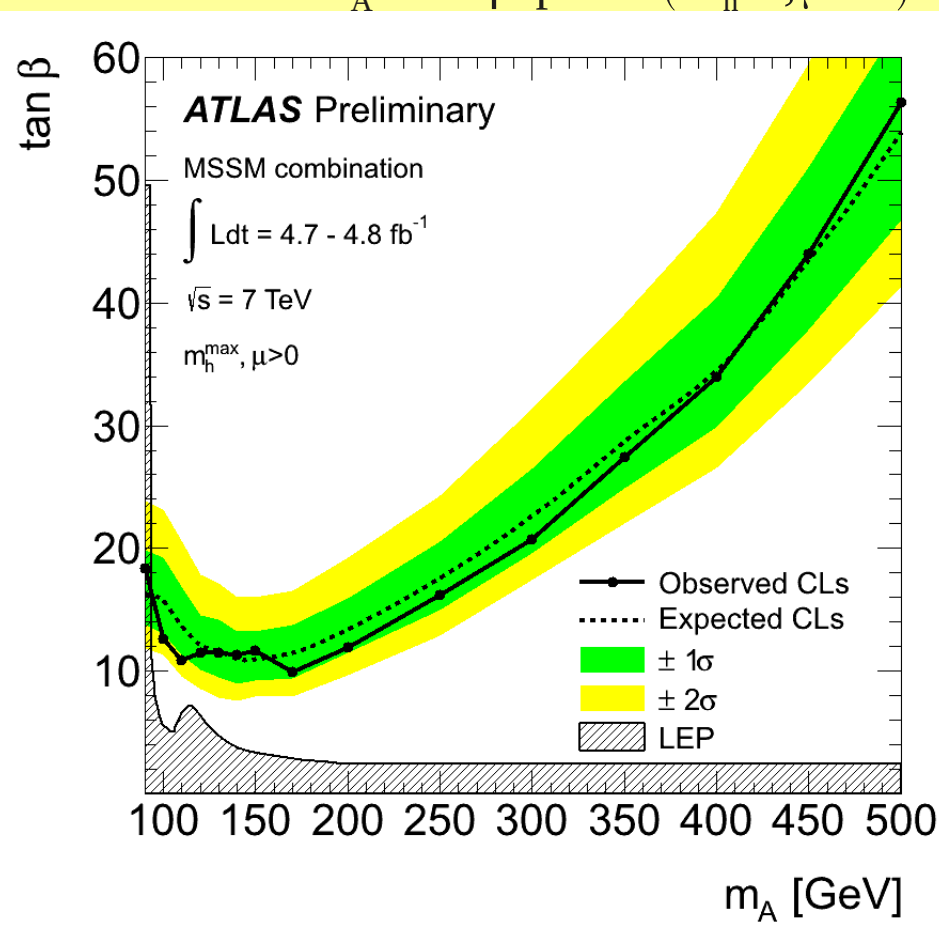
- $m_h^{\max}, \mu > 0$
- Fix parameters to obtain a maximum  $m_h$
- $\mu > 0$  favoured by  $(g-2)_\mu$  measurements

# Results

**No excess of events above the expected SM background  
has been observed in data**

95% Confidence Limit exclusion limits based on  $CL_s$

Limits in the  $m_A - \tan \beta$  plane ( $m_h^{\max}, \mu > 0$ )

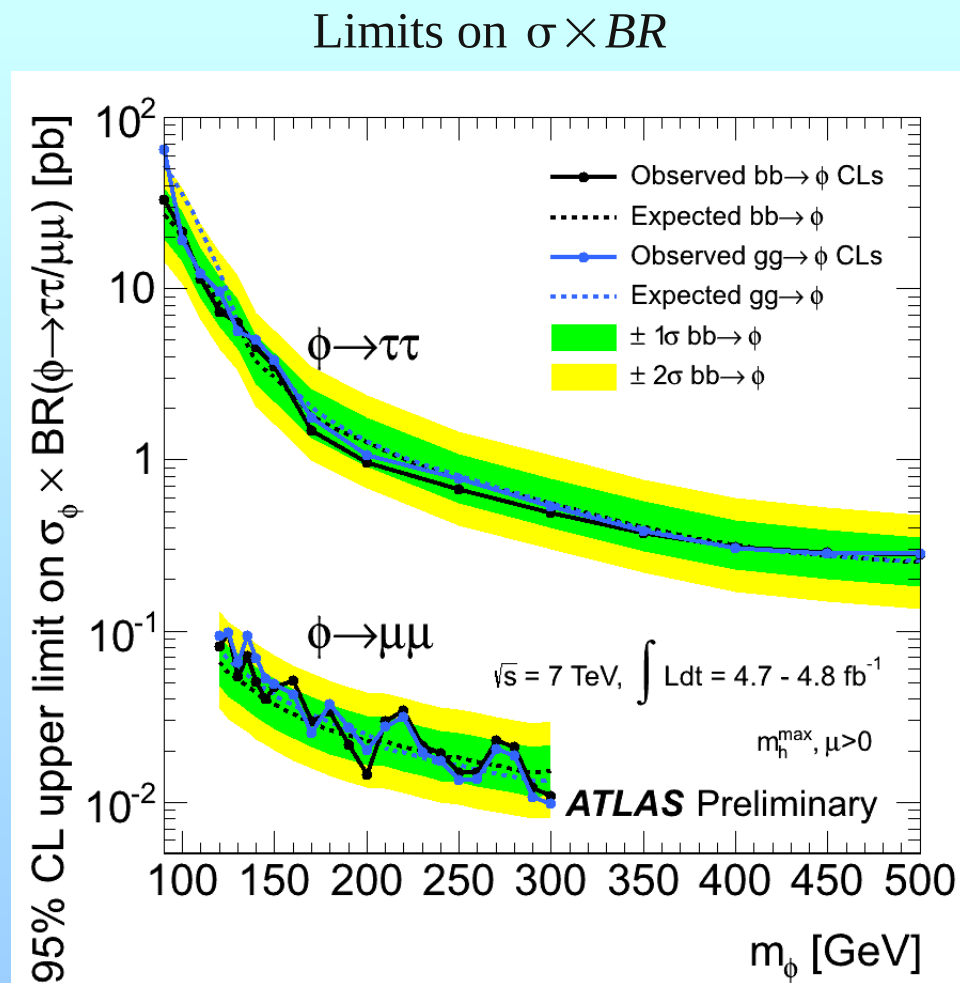




# Results

**No excess of events above the expected SM background  
has been observed in data**

95% Confidence Limit exclusion limits based on  $CL_s$



# Conclusion



- 2011: Great year of data taking for LHC & ATLAS  
→ Update on searches for neutral Higgs bosons in the MSSM ( $4.7\text{-}4.8\text{ fb}^{-1}$ ):

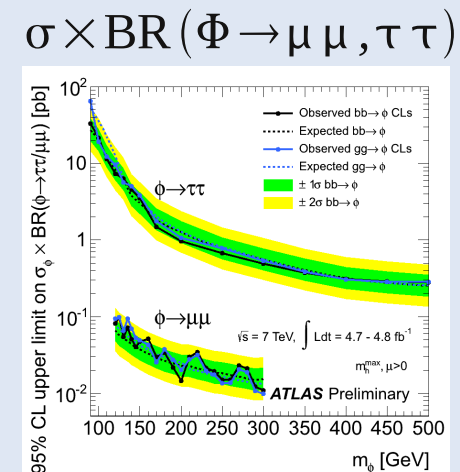
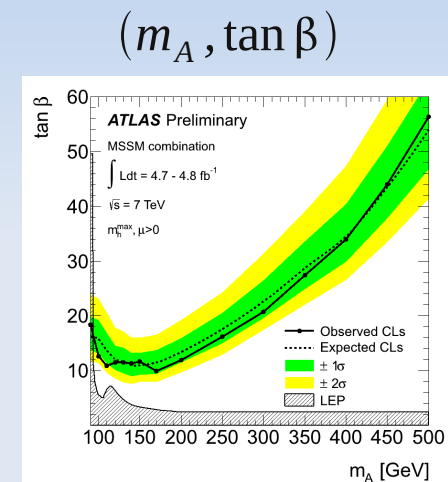
$$h/A/H \rightarrow \mu^+ \mu^-$$

**ATLAS-CONF-2012-094**

$$h/A/H \rightarrow \tau^+ \tau^- \rightarrow e\mu\ 4\nu, e\tau_{\text{had}}\ 3\nu, \mu\tau_{\text{had}}\ 3\nu, \tau_{\text{had}}\tau_{\text{had}}\ 2\nu$$

- Exploit two dominant Higgs bosons production mechanisms  
→ Dedicated event selections:
  - b-tagged: b-associated production
  - (b-) Jet vetoed: gluon fusion production
- No excess observed
- MSSM Higgs boson not yet excluded  
→ Very excited & look forward to analyze 2012 data

**Thank you for your attention !**

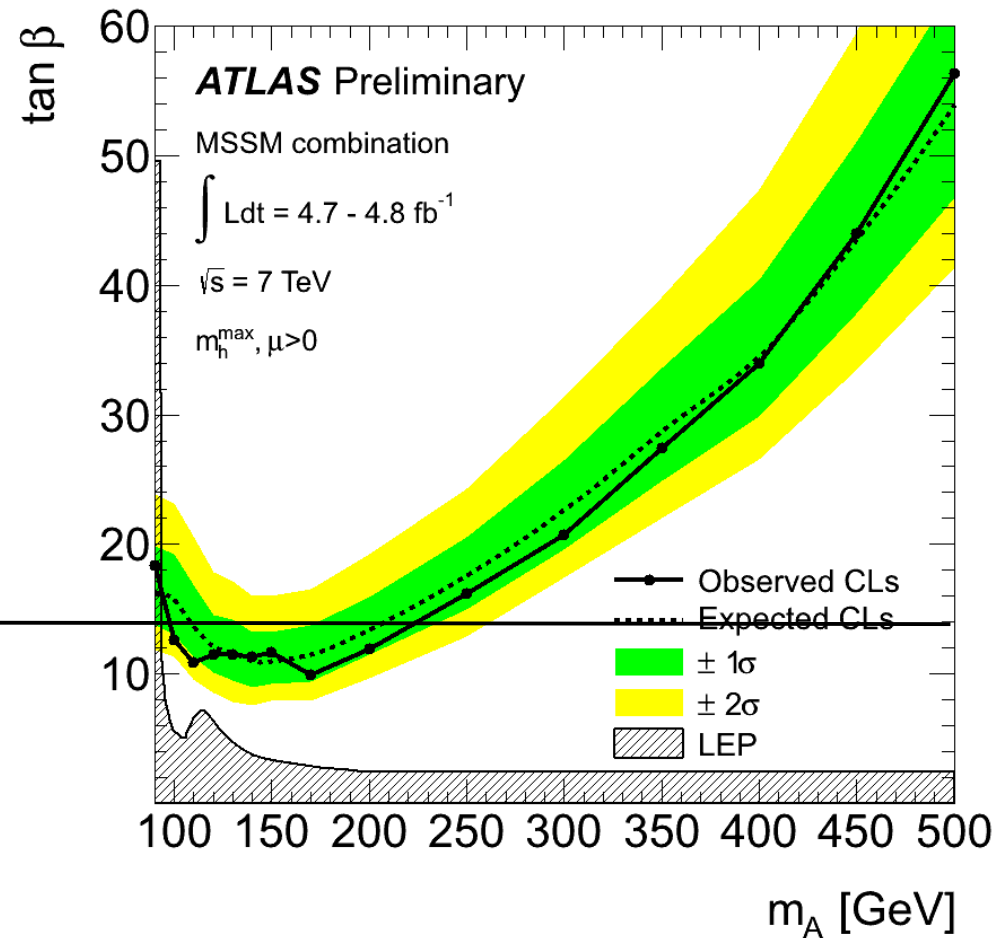
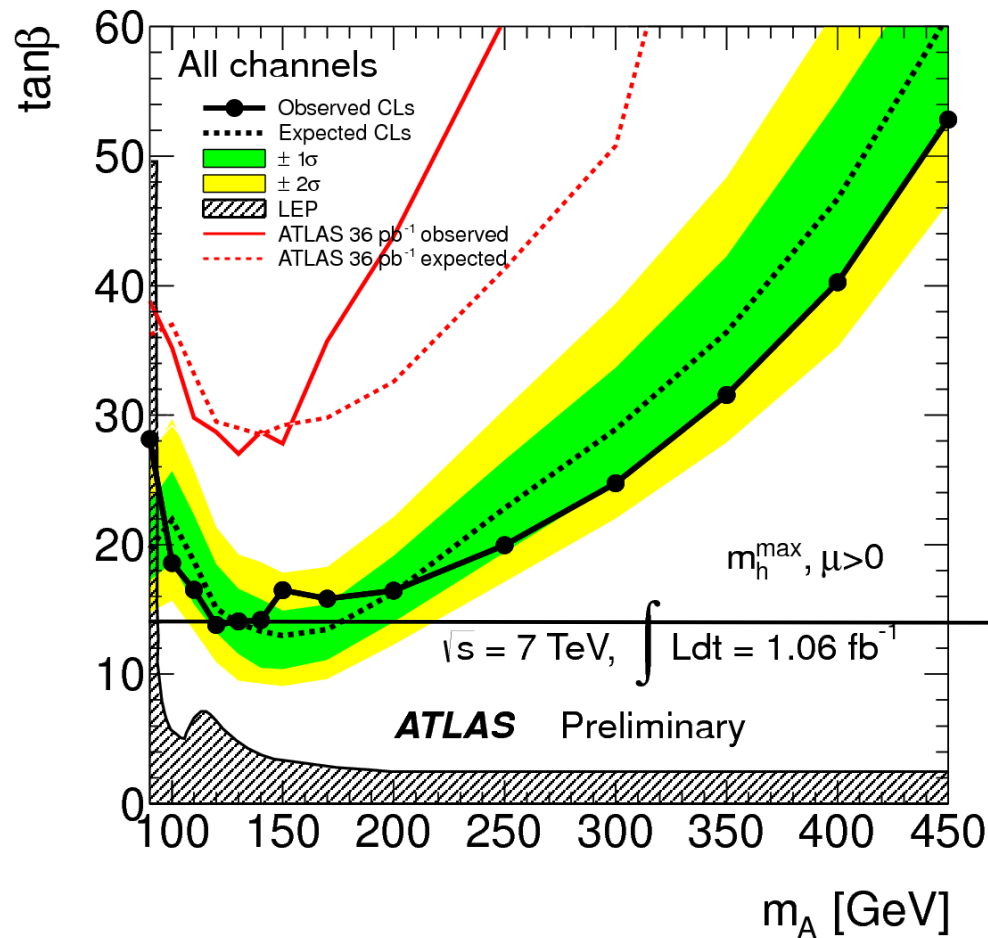


# Backup





# Comparison



## Note:

Statistical uncertainties on background predictions were only taken into account for the new exclusion limit, not for the old one !

# Coordinates & Objects definitions



## ATLAS coordinates:

$z$ : Beam axis

$\varphi$ : azimuthal angle

$\theta$ : Polar angle wrt.  $z$

$\eta = -\ln \tan \beta$

( $\eta = 2.5 \rightarrow \beta \approx 9^\circ$ )

Distances:  $\Delta R^2 = \Delta \varphi^2 + \Delta \eta^2$

## Electrons:

Calorimeter Cluster & Track

$E_T > 15 \text{ GeV} / c$

$\eta < 2.47$

Isolation:  $E_T^{\Delta R < 0.2} < 8 \%$

$p_T^{\Delta R < 0.4} < 6 \%$

## Muons:

Muon Spectrometer &

Inner Detector track

High Track Quality

$p_T > 10 \text{ GeV} / c$

$\eta < 2.5$

Isolation:  $E_T^{\Delta R < 0.2} < 4 \%$

$p_T^{\Delta R < 0.4} < 6 \%$

## $\tau_{had}$ :

1 or 3 tracks

$E_T > 20 \text{ GeV} / c$

$\eta < 2.5$

Tight collimation

ID : Multivariate  
technique (BDT)

## Jets:

$k_T$  Algorithm ( $\Delta R < 0.4$ )

$p_T > 20 \text{ GeV} / c$

$\eta < 2.5$

b-Jet Identification:

Multivariate technique (NN)

## $E_t^{miss}$ :

All calorimeter Clusters

Appropriate calibrations for jets /  $\tau_{had}$

$\mu$  Tracks

(Individually for isolated  
and non-isolated  $\mu$ )

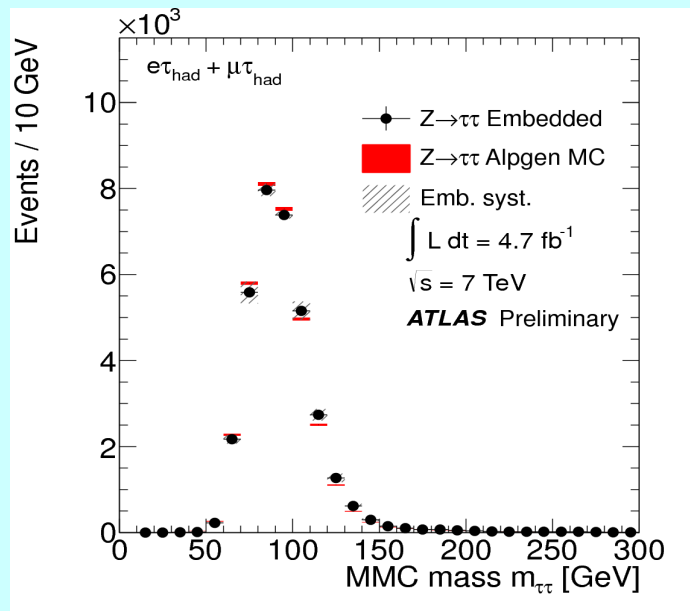
# h/A/H→τ<sup>+</sup>τ<sup>-</sup> : Common techniques

## Additional information



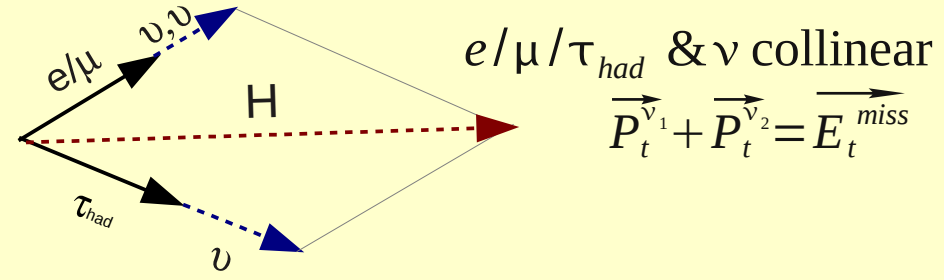
### Z/γ<sup>\*</sup>→τ<sup>+</sup>τ<sup>-</sup> Embedding:

- Select Z/γ<sup>\*</sup>→μ<sup>+</sup>μ<sup>-</sup> data  
(High purity, Signal free)
- Replace μ's by simulated τ's  
→ Z/γ<sup>\*</sup>→τ<sup>+</sup>τ<sup>-</sup> event



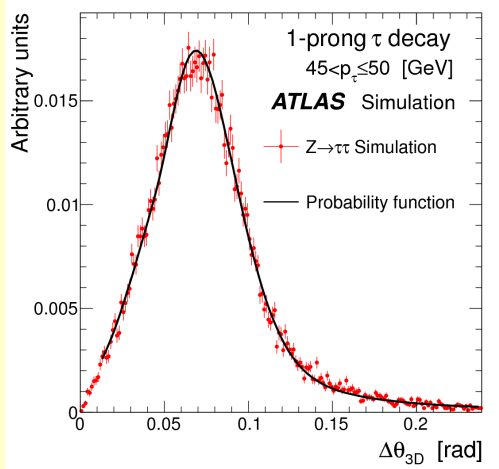
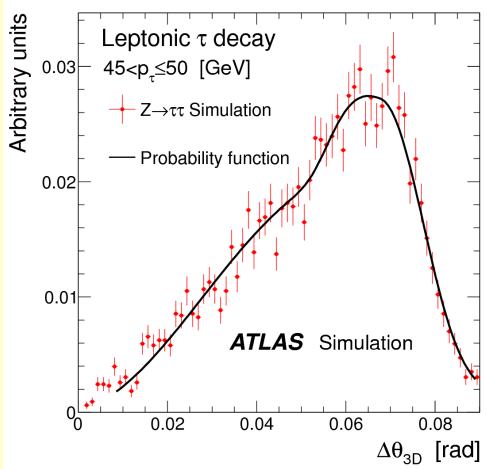
### Mass reconstruction (MMC):

- Collinear Approximation:



- MMC Mass: (Elagin et. al., NIM A654, 481)

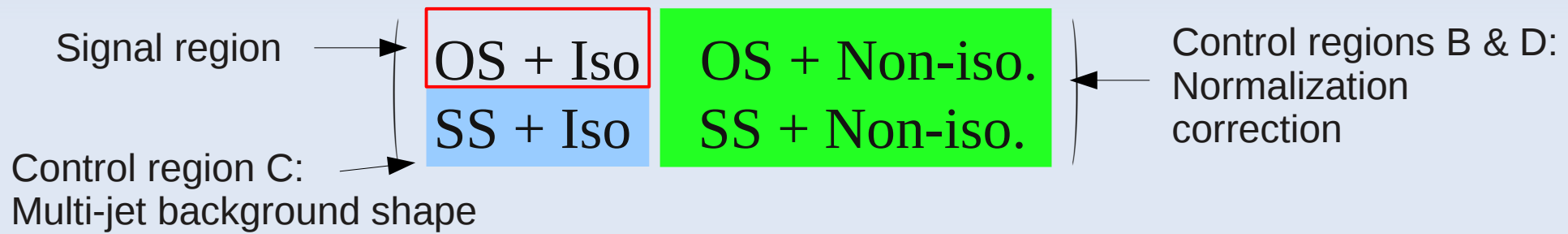
### PDF examples:



# Multi-jet background estimation



- Example:  $h/A/H \rightarrow \tau^+ \tau^- \rightarrow e \tau_{\text{had}} 3\nu, \mu \tau_{\text{had}} 3\nu$ :
  - $e/\mu$  Isolation: isolated (Iso.) / non-isolated (Non-iso.)
  - $q(\tau_{\text{had}}) \times q(e/\mu) = -1$  (OS) /  $+1$  (SS)

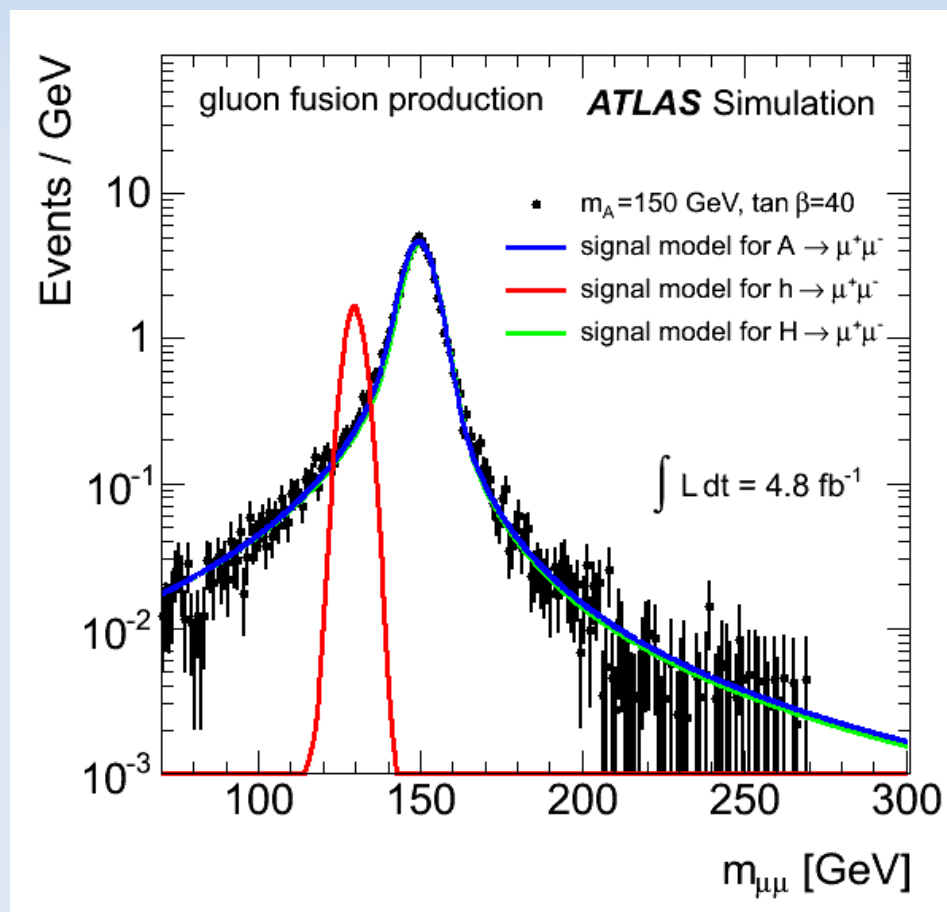
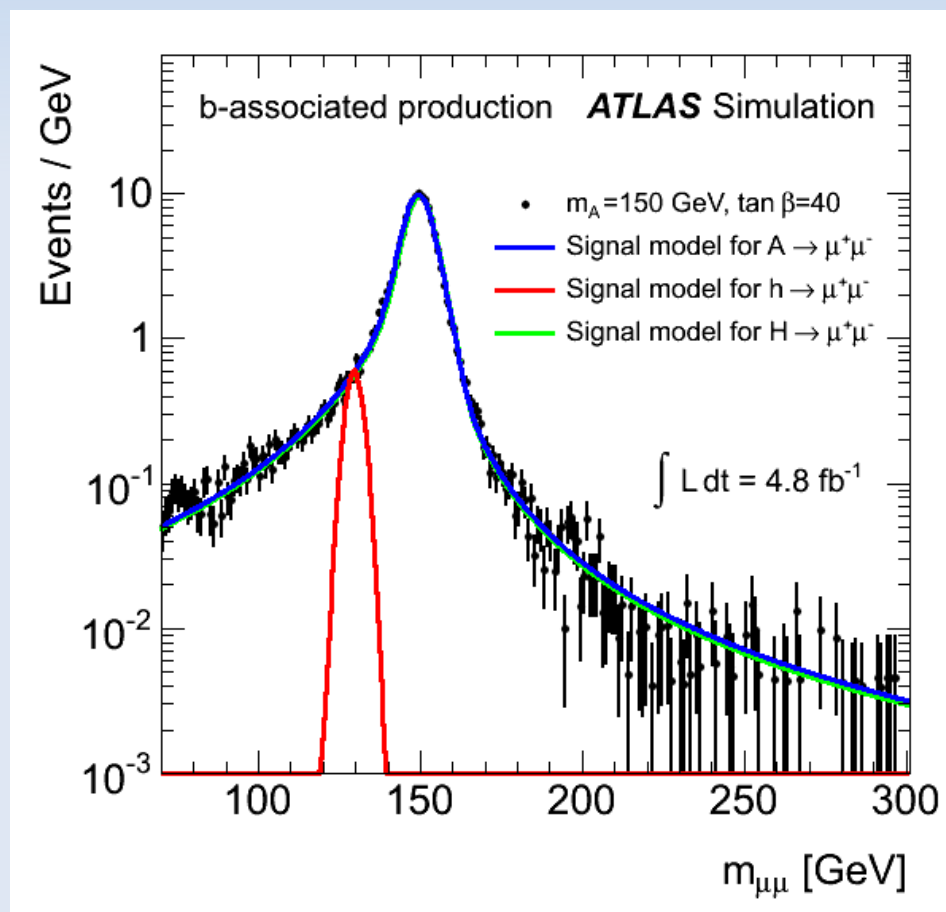


- Assume:
  - Variables not correlated for Multi-jet events
  - Mass shape not correlated to these variables

$$n_{\text{Multi-jet}}^{\text{Signal Region}} = n_{\text{Data}}^{\text{Control Region C}} \times \frac{n_{\text{Data}}^{\text{Control Region B}}}{n_{\text{Data}}^{\text{Control Region D}}}$$

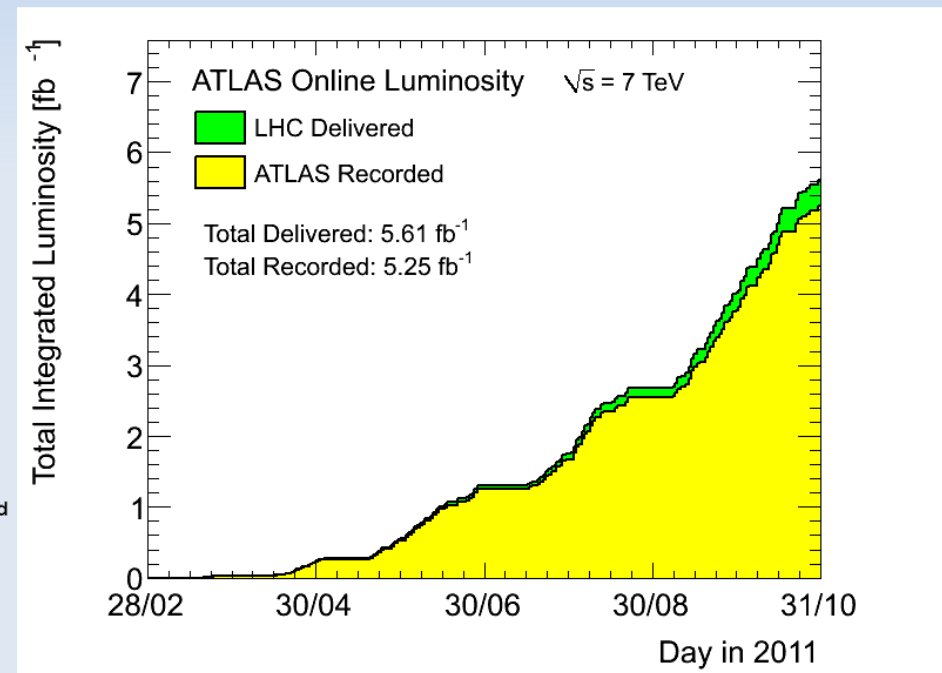
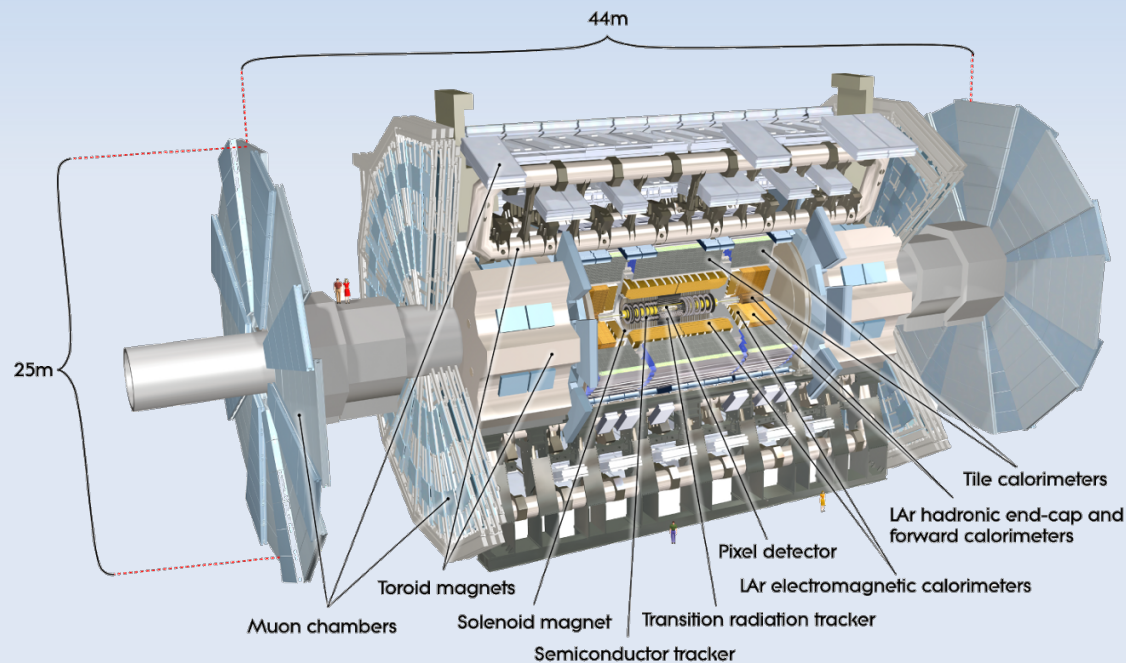
$$(h/A/H) \rightarrow \mu^+ \mu^-$$

Signal modeling:  
(All resonances (=h/A/H) taken into account)



# The ATLAS detector

- 2011, an exciting year:  
Great performance of the LHC & the ATLAS experiment



# Old results



- These next slides show the results for  $1.06 \text{ fb}^{-1}$ :  
ATLAS-CONF-2011-132

$h/A/H \rightarrow \mu^+ \mu^-$ :  
Unfortunately no public results, yet



$$h/A/H \rightarrow \tau^+ \tau^-$$

# 1.06 fb<sup>-1</sup>: h/A/H→τ<sup>+</sup>τ<sup>-</sup> : Common techniques



## Z→τ<sup>+</sup>τ<sup>-</sup> Embedding:

- Select Z→μ<sup>+</sup>μ<sup>-</sup> data (High purity, Signal free)
- Replace muons by simulated τ-leptons  
→ Z→τ<sup>+</sup>τ<sup>-</sup> event

## Multi-jet background:

- From data via side band extrapolation
- Signal region A  
Control region C  
Shape

Control region B  
Control region D  
Scaled by B/D

## Jets misidentified as τ<sub>had</sub>:

- Difficult to describe in simulations
  - Applies to Multi-jet and W+jets
- $n_{OS}^{Bkg} = n_{SS}^{Bkg} + n_{OS-SS}^W + n_{OS-SS}^Z + n_{OS-SS}^{other}$

↑   ↑   ↑   ↑

Data

Simulation,  
corrected to data

Embedding

Simulation

## Mass reconstruction:

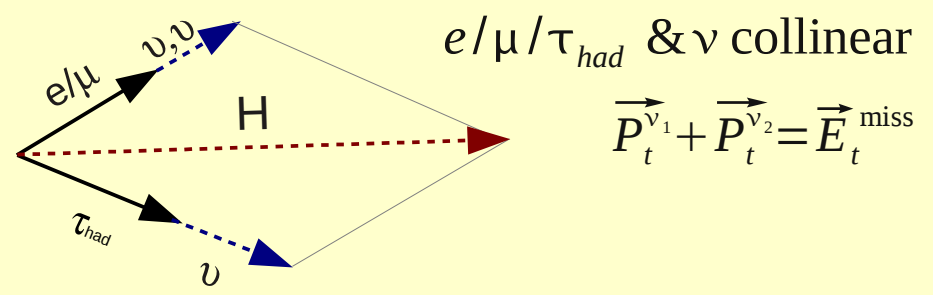
- Visible Mass:

$$m_{\tau\tau}^{visible} = \sqrt{(p_{\tau_1} + p_{\tau_2})^2}$$

- Effective Mass:

$$m_{\tau\tau}^{effective} = \sqrt{(p_{\tau_1} + p_{\tau_2} + p_T^{miss})^2}$$

- Collinear Approximation:



- MMC Mass: (Elagin et. al., arXiv:1012.4686)

Relaxed collinearity requirement:

- Scan ν momenta wrt.  $E_t^{miss}$  Resolution
- Weight with PDF

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## 1.06 fb<sup>-1</sup>: h/A/H → τ<sup>+</sup>τ<sup>-</sup> → eμ4ν

### Topological event selection:

1 isolated μ & 1 isolated e

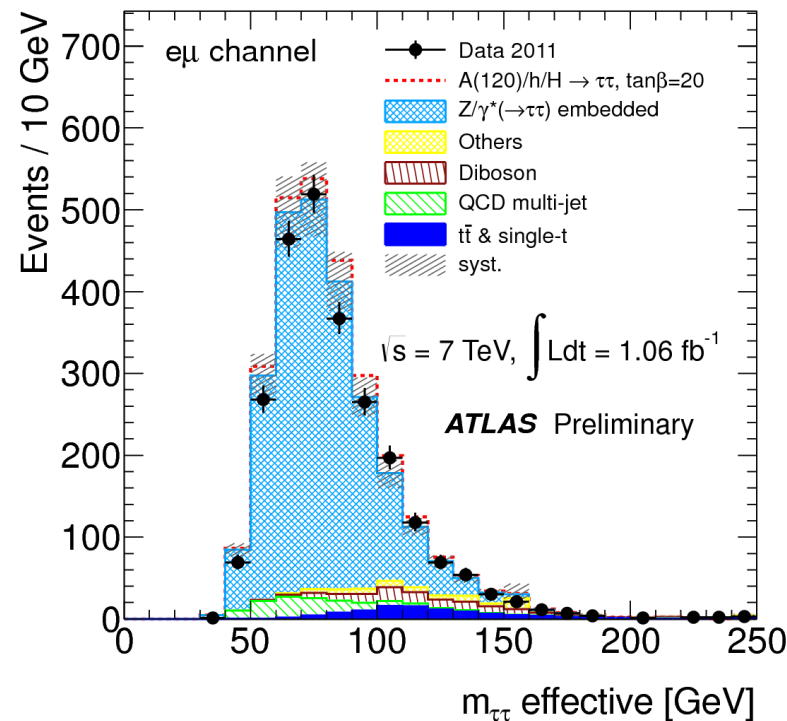
$$p_T^\mu > 10 - 20 \text{ GeV}, \quad p_T^e > 15 - 22 \text{ GeV}$$

$$q(e) \times q(\mu) = -1$$

$$p_T^\mu + p_T^e + E_T^{\text{miss}} < 120 \text{ GeV}$$

$$\Delta\phi(e, \mu) > 2.0$$

Trigger  
decision  
dependent



$$h/A/H \rightarrow \tau^+ \tau^- \rightarrow \mu \tau_{\text{had}} 2\nu, e \tau_{\text{had}} 2\nu$$

### Topological event selection:

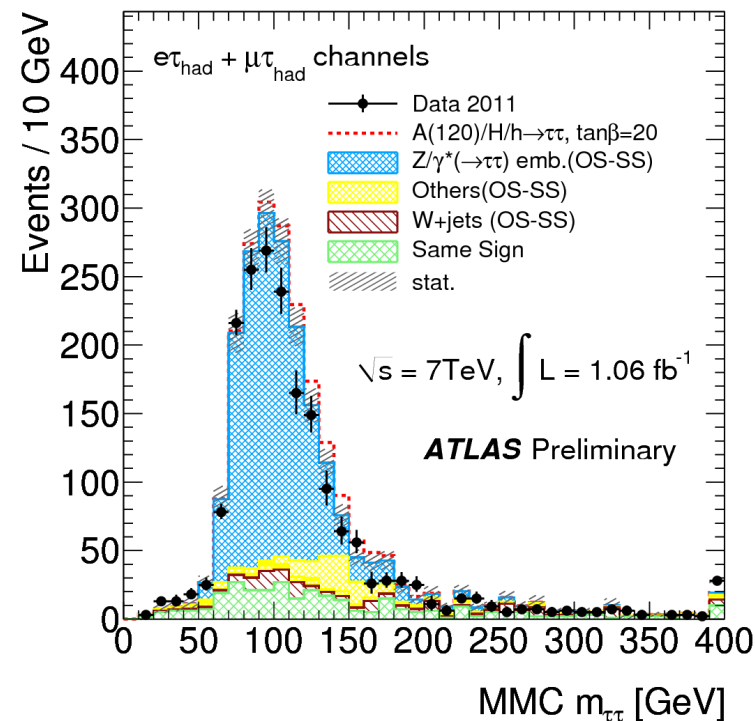
1 isolated  $\mu$  ( $p_T > 20$  GeV) or 1 isolated  $e$  ( $p_T > 25$  GeV)

No additional  $e/\mu$

1  $\tau_{\text{had}}$  ( $p_T > 20$  GeV)

$q(e/\mu) \times q(\tau_{\text{had}}) = -1$

$E_T^{\text{miss}} > 20$  GeV &  $m_T = \sqrt{2 \times p_T^{e/\mu} \times E_T^{\text{miss}} (1 - \cos \Delta \phi)} < 30$  GeV



# 1.06 fb<sup>-1</sup>: h/A/H → $\tau^+\tau^- \rightarrow \tau_{\text{had}}\tau_{\text{had}}2\nu$



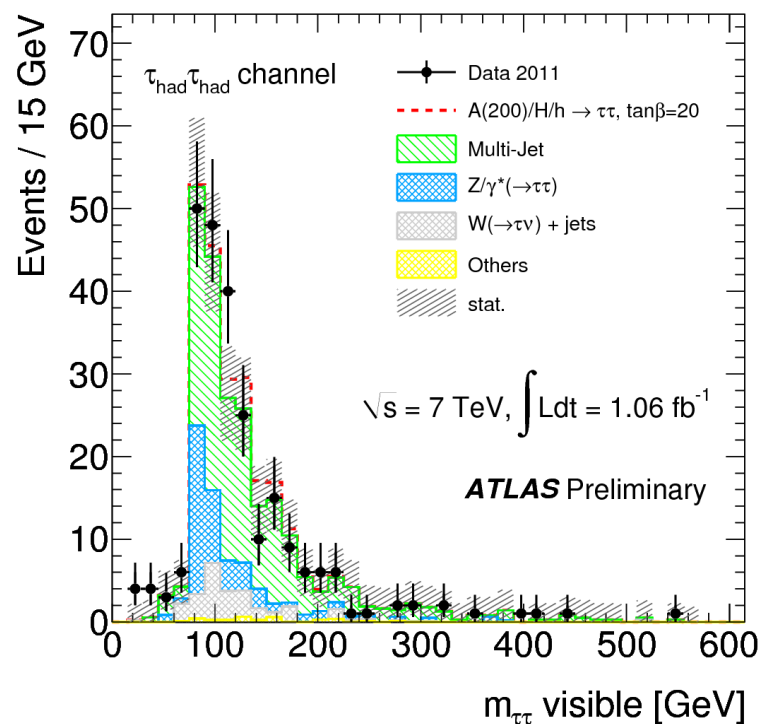
## Topological event selection:

$$2\tau_{\text{had}}$$

$$p_T > 45 \text{ \& } 30 \text{ GeV}$$

$$\text{e- \& } \mu\text{-Veto}$$

$$E_T^{\text{miss}} > 25 \text{ GeV}$$

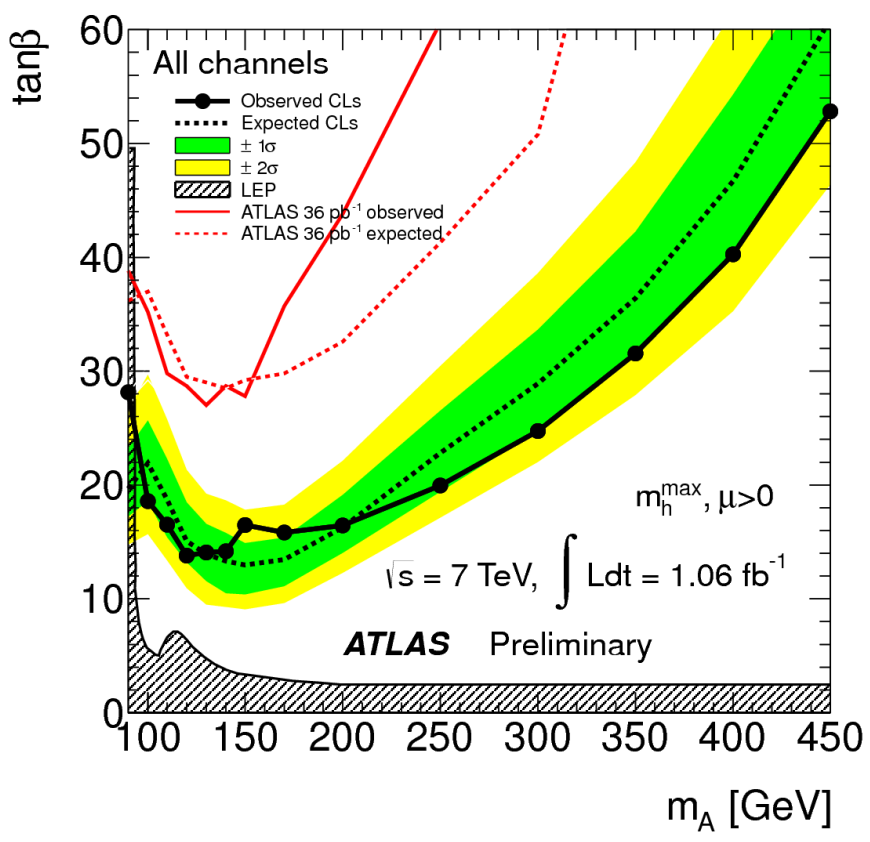


# Results: ATLAS-CONF-2011-132

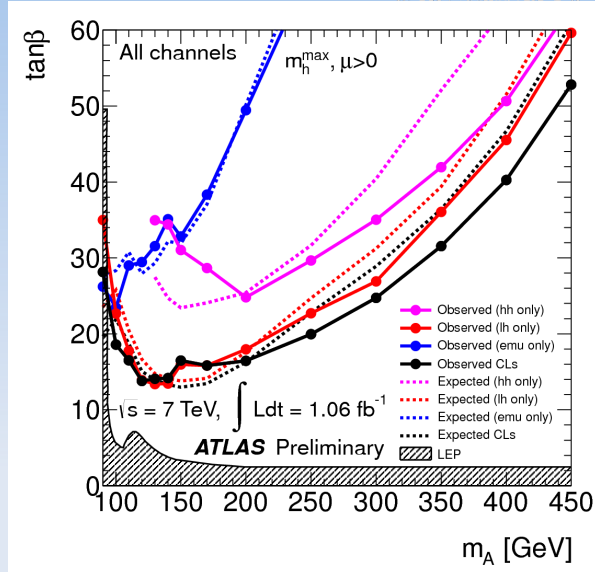


**No excess of events above the expected SM background has been observed in data**  
95% Confidence Limit exclusion limits based on  $CL_s$

Limits in  $(m_A, \tan \beta)$



Individual contributions



Limits on  $\sigma \times BR$

