

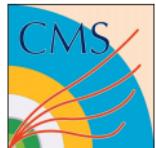
Non-SM Higgs searches at the LHC



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on behalf of the ATLAS and CMS Collaborations



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Outline

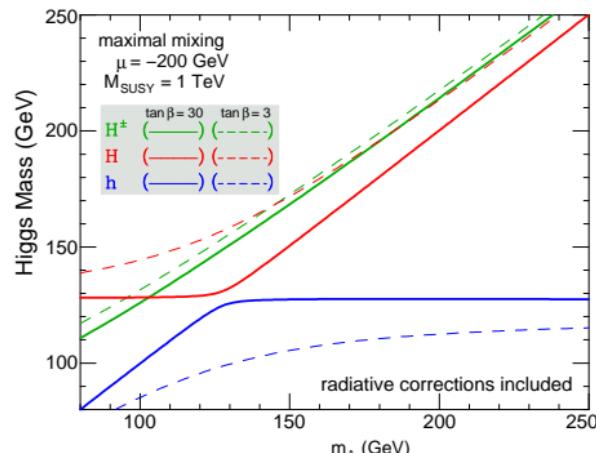
Most non-SM Higgs searches at the LHC are performed within MSSM.

- Several benchmark scenarios, selecting most interesting regions of parameter space.
(m_h^{\max} -scenario is used for most of the results presented here.)

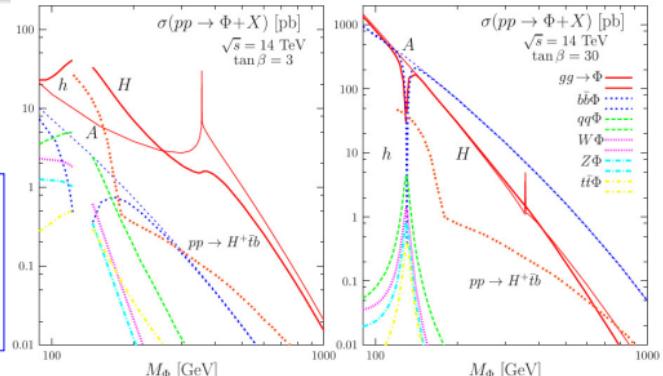
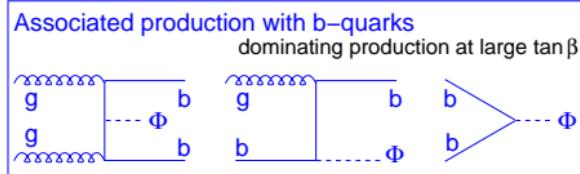
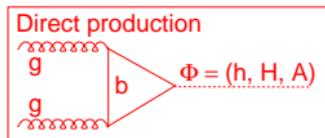
Scenario	M_{SUSY} (GeV)	X_t (GeV)	μ (GeV)	M_2 (GeV)	$M_{\tilde{g}}$ (GeV)	Upper bound on m_h (GeV)
m_h^{\max}	1000	2000	200	200	800	133
no mixing	2000	0	200	200	800	116
gluophobic	350	-750	300	300	500	119
small- α	800	-1100	2000	500	500	123

The Higgs sector of the MSSM

- Two Higgs doublets,
resulting in 5 physical Higgs bosons:
 h^0 , H^0 , A^0 and H^\pm .
- At the tree-level, the Higgs sector is determined by only two parameters:
(m_A , $\tan \beta = \frac{v_u}{v_d}$).
- In the m_h^{\max} -scenario, the lightest neutral Higgs is constrained by
 $m_h < 133$ GeV.
- Mass degeneration at large $\tan \beta$: $h^0 \& A^0$ ($m_A < 130$ GeV) or $H^0 \& A^0$ ($m_A > 130$ GeV).
 \Rightarrow observed signal is given by the sum of all degenerate states.



Dominant production modes:



Higgs boson decays:

- $\Phi \rightarrow \tau^+ \tau^-$

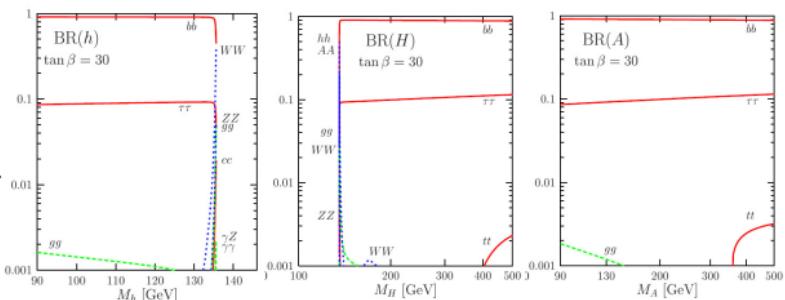
Large BR, clear final state.

- $\Phi \rightarrow \mu^+ \mu^-$

Very low branching fraction,
but excellent mass resolution.

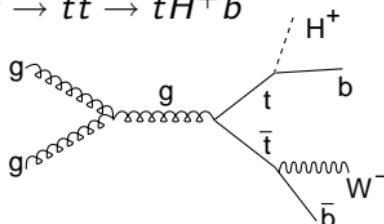
- $\Phi \rightarrow b\bar{b}$

Dominant decay, but
large QCD background.

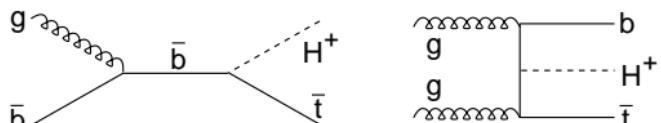


Dominant production modes, depend on the mass m_{H^\pm} :

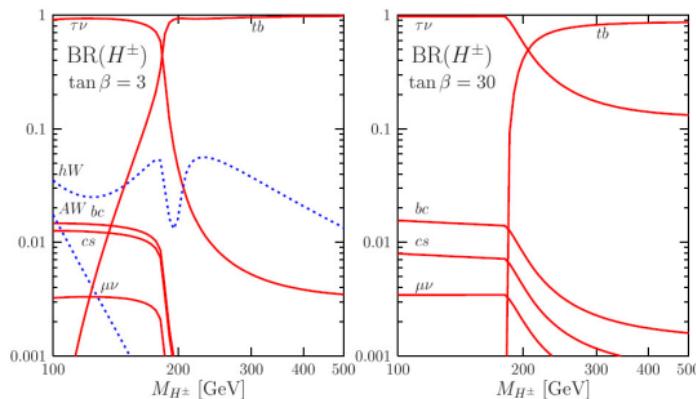
Light H^\pm ($m_{H^\pm} < m_{top}$):
 $gg \rightarrow t\bar{t} \rightarrow \bar{t}H^+ b$



Heavy H^\pm ($m_{H^\pm} > m_{top}$):
 $g\bar{b} \rightarrow \bar{t}H^+$ and $gg \rightarrow \bar{t}bH^+$



H^\pm decay modes:



Two dominant decays:

- For $m_{H^\pm} < m_{top}$:
 $H^\pm \rightarrow \tau^\pm \nu$
- For $m_{H^\pm} > m_{top}$:
 $H^\pm \rightarrow tb$ and $H^\pm \rightarrow \tau^\pm \nu$

Search for the neutral MSSM Higgs bosons:

- $h/H/A \rightarrow \tau^+\tau^- \rightarrow \ell\ell + 4\nu$ (ATLAS and CMS)
 $\rightarrow \ell\tau_{jet} + 3\nu$ (CMS; currently under study in ATLAS)
 $\rightarrow \tau_{jet}\tau_{jet} + 2\nu$ (CMS; currently under study in ATLAS)
- $h/H/A \rightarrow \mu^+\mu^-$ (ATLAS and CMS)

Search for the charged MSSM Higgs bosons:

- Light H^\pm :
 $tt \rightarrow (H^\pm b)(W^\mp b) \rightarrow (\tau\nu b)(\ell^\mp\nu b) \rightarrow (\tau_{jet}\nu\nu b)(\ell^\mp\nu b)$ (ATLAS and CMS)
 $tt \rightarrow (H^\pm b)(W^\mp b) \rightarrow (\tau\nu b)(qqb) \rightarrow (\tau_{jet}\nu\nu b)(qqb)$ (only ATLAS)
 $tt \rightarrow (H^\pm b)(W^\mp b) \rightarrow (\tau\nu b)(qqb) \rightarrow (\ell\nu\nu\nu b)(qqb)$ (only ATLAS)
- Heavy H^\pm :
 $gg, gb \rightarrow t[b]H^\pm \rightarrow (Wb)[b](\tau\nu) \rightarrow (bqq)[b](\tau_{jet}\nu\nu)$ (ATLAS and CMS)
 $gg, gb \rightarrow t[b]H^\pm \rightarrow (Wb)[b](tb) \rightarrow (b\ell\nu)[b](bqqb)$ (ATLAS and CMS)

Additional searches not presented in this talk:

$h \rightarrow bb$, $A/H \rightarrow \chi_2^0\chi_2^0$, non-MSSM models (Randall-Sundrum, Little Higgs), etc.

References:

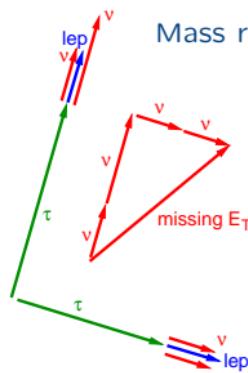
- CERN-LHCC-2006-021 ([CMS](#), J.Phys.G: Nucl.Part.Phys.34 995-1579)
- CERN-OPEN-2008-020 ([ATLAS](#), arXiv:0901.0512)

All presented results are obtained for the center of mass energy $\sqrt{s}=14$ TeV and an integrated luminosity of $1\text{-}30 \text{ fb}^{-1}$.

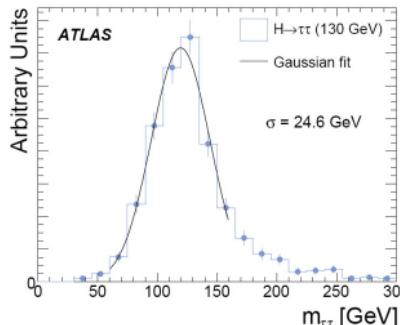
- Most recent theoretical calculations and Monte Carlo generators.
- Detailed detector simulation.
- Pile-up effects simulated for CMS ($L=2\times10^{33} \text{ cm}^{-2}\text{s}^{-1}$).
ATLAS results shown without the pile-up and cavern background.
These effects are currently under study by ATLAS,
and are shown/expected to be small at the luminosity $L=10^{33} \text{ cm}^{-1}\text{s}^{-1}$.
- Detailed consideration of systematic uncertainties in each channel.
- Methods for the background estimation from control data samples.

Main background processes: $Z/\gamma^*(+jets)$, $t\bar{t}$, $W+jets$, QCD multijets.

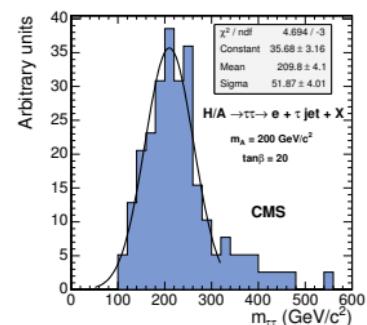
	$2\ell 4\nu$	$\ell\tau_{jet} 3\nu$	$2\tau_{jets} 2\nu$
Trigger	single- or di-lepton	single-lep or lepton + τ_{jet}	single- or di- τ_{jet}
Higgs decay	2 isolated leptons	1 isol. lepton + 1 τ_{jet}	2 τ_{jets}
b -tagging (against Z/γ^*)	CMS: = 1 b -jet. ATLAS: ≥ 1 b -jet. (Not exactly two b -jets, due to the soft p_T^b -spectrum for the signal.)		
Central jet veto (against $t\bar{t}$)	CMS: No additional jets in the central region (except b - and τ -jets). ATLAS: Not more than two jets (including the b -tagged jets).		
Transverse mass (against $W+jets$)	$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(p_T^\ell, E_T^{\text{miss}}))}$		
Higgs mass reconstruction	Collinear approximation: τ decay products emitted in τ -direction. No back-to-back decays, momentum fractions of ν -s should be positive.		



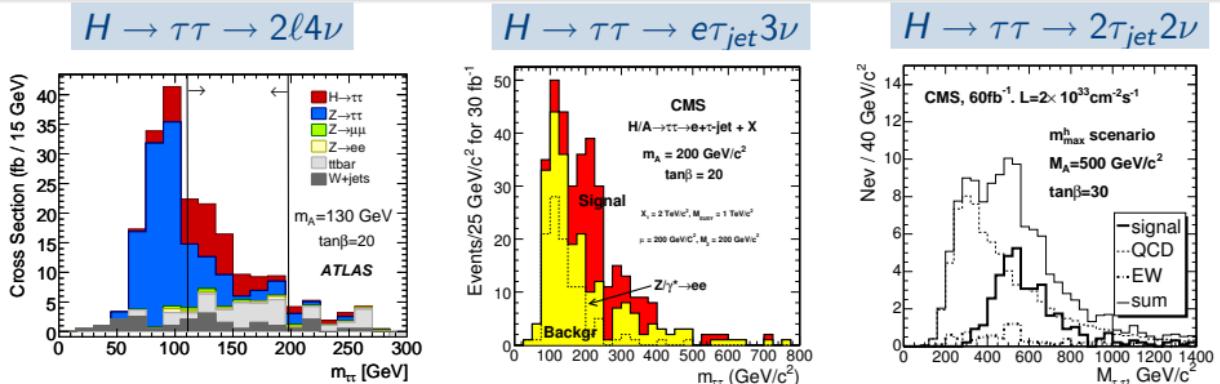
Mass resolution: $\sim 20\%$ in $H \rightarrow \tau\tau \rightarrow 2\ell 4\nu$



$\sim 25\%$ in $H \rightarrow \tau\tau \rightarrow e\tau_{jet} 3\nu$



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



Dominant systematic uncertainty: E_T^{miss} and jet energy scale,
additional uncertainty from fake τ_{jets} due to the tracker misalignment.

⇒ Background contributions need to be estimated from control data.

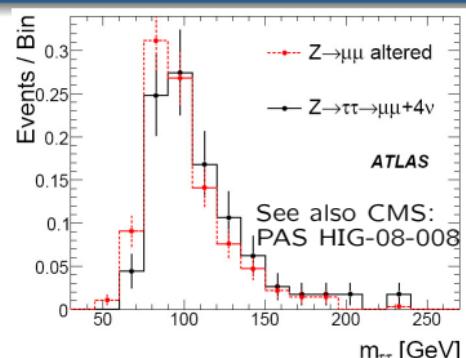
- $t\bar{t}$ (from MC) Uncertainty: 5-10%.
- $Z \rightarrow \tau\tau$ from $Z \rightarrow \mu\mu$ or $Z \rightarrow ee$ control data:

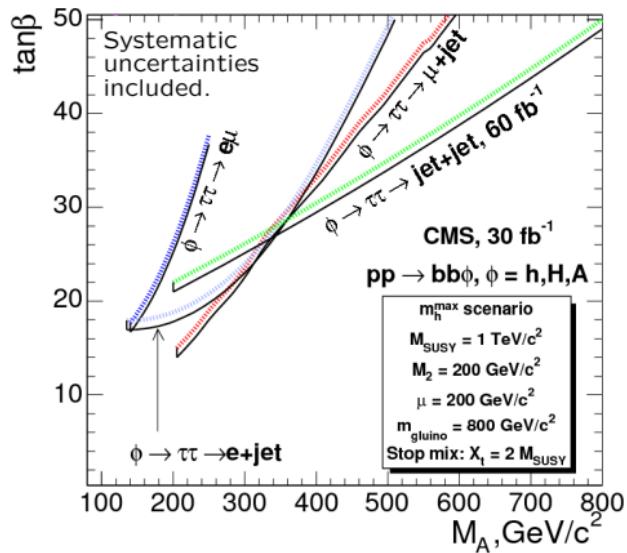
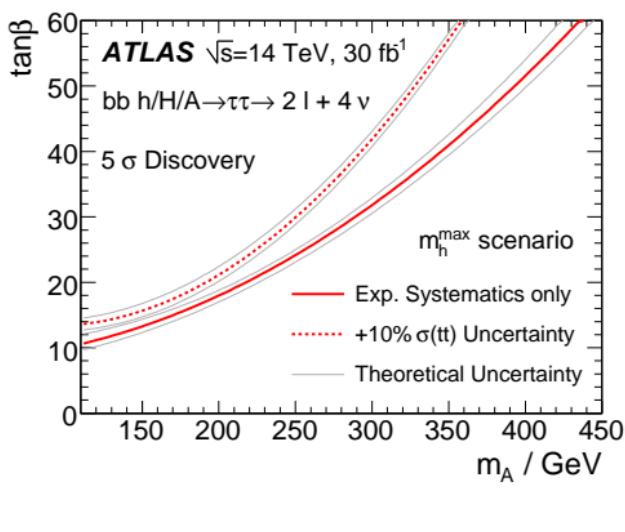
Shape: replacing the real e/μ by a simulated τ -decay.

$$\text{Normalization: } \left[\frac{(Z \rightarrow \ell\ell)_{\text{Data}}}{(Z \rightarrow \ell\ell)_{\text{MC}}} \right]_{\text{control}} = \left[\frac{(Z \rightarrow \tau\tau)_{\text{Data}}}{(Z \rightarrow \tau\tau)_{\text{MC}}} \right]_{\text{signal region}}$$

Expected systematic uncertainty: 3%.

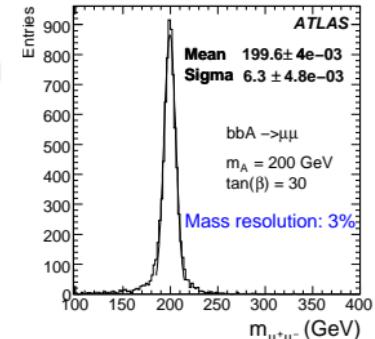
- QCD multijets from data:
Selecting same-sign τ -pairs (signal free sample).
Expected systematic uncertainty: 5-20%.





- Leptonic decay mode ($2\ell 4\nu$): mass region up to 450 GeV.
- Semi-leptonic decays ($\ell\tau_{\text{jet}} 3\nu$): intermediate masses, 200-500 GeV.
- Hadronic decay mode ($2\tau_{\text{jet}} 2\nu$): for high masses, above 400 GeV.

Wide region of the $(m_A, \tan \beta)$ -plane covered with $L = 30 \text{ fb}^{-1}$.



Motivation

- Branching ratio into $\mu\mu$ -pairs is about 300 times smaller than $\text{BR}(\Phi \rightarrow \tau\tau)$.
- However, muons provide for a very clean signature with an excellent mass resolution.
(3% for $m_{\mu\mu}$, compared to 20% for the $\tau\tau$ -channel.)

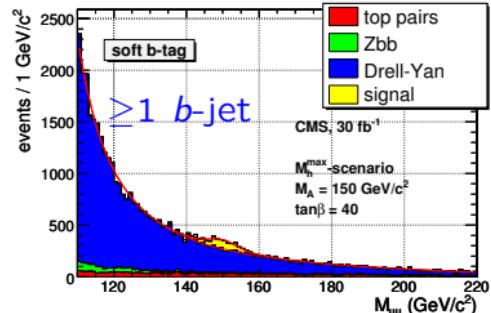
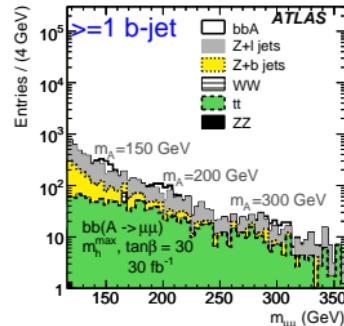
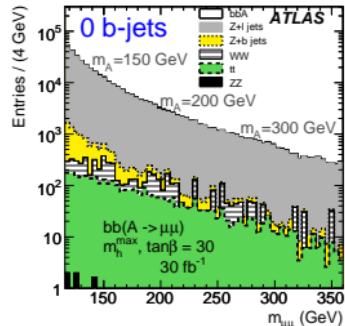
Event selection:

Main background processes: $Z/\gamma^*(+jets)$, $t\bar{t}$ (ZZ , WW negligible).

Trigger Higgs decay E_T^{miss} (against $t\bar{t}$)	single high- p_T muon, $p_T > 20$ GeV 2 isolated muons of opposite charge < 40 GeV	
b -tagging (against Z) Jet veto (against $t\bar{t}$)	0 b -jets (ATLAS only)	≥ 1 b -jet (CMS and ATLAS) $p_T^{\text{jet}} < 45$ GeV (CMS) $\sum p_T^{\text{jet}} < 90$ GeV (ATLAS)

- In ATLAS, the two independent analyses (final states with 0 and ≥ 1 b -jet) are finally combined.

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

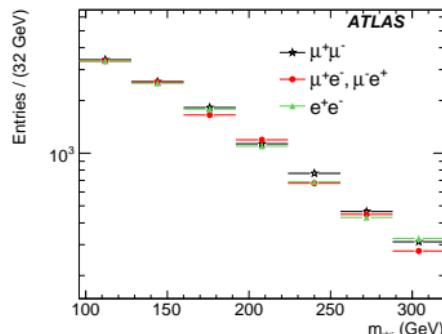


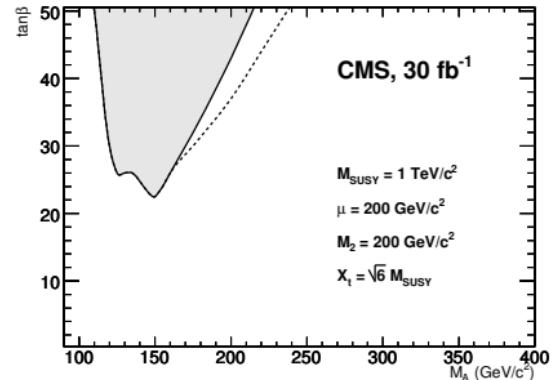
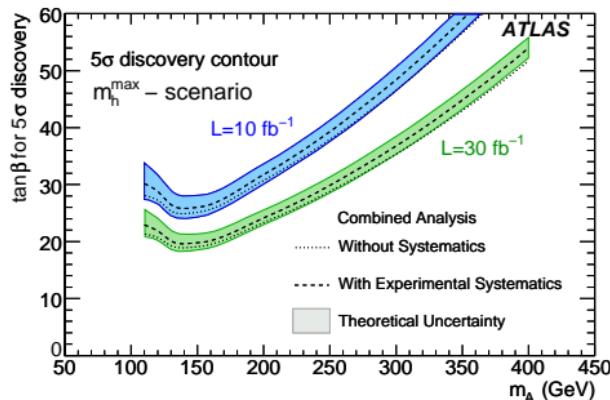
>1 b-jet analysis	ATLAS	CMS (hard b-tag)	CMS (soft b-tag)
Signal ($t\bar{t}$)	540 2670	462 5190	1272 7140

Twice larger $t\bar{t}$ in CMS, while signal and Z -bkg. are similar for ATLAS and CMS.

Systematic uncertainties mostly related to the jet energy scale and b -tagging; $\sim 5\text{-}10\%$.
Background estimation from data:

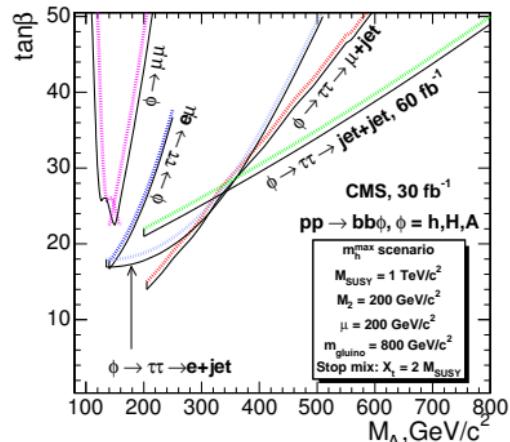
- Side-band fit,
- combined with additional information from the e^+e^- and $e^\pm\mu^\mp$ control samples.
(Signal-free samples with the same shape as for the $\mu^+\mu^-$ background.)





Comparison with the discovery reach
from $h/H/A \rightarrow \tau\tau$:

- $\mu\mu$ is a competitive channel.
- Combination of $\mu\mu$ and $\tau\tau$ can improve the discovery reach.
- $\mu\mu$ allows for the precise mass measurement.

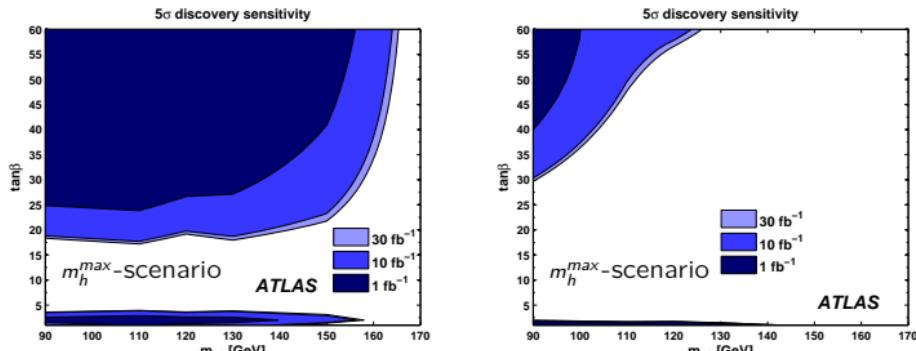


Main background processes: $t\bar{t}$, single top, $W + jets$, QCD multijets.

$$t\bar{t} \rightarrow (bH^\pm)(bW) \rightarrow (b\tau\nu)(bqq)$$

	$(b\tau_{jet}\nu\nu)(bqq)$	$(b\ell\nu\nu\nu)(bqq)$
Trigger	$\tau_{jet} + E_T^{\text{miss}}$	lepton + E_T^{miss}
Offline	τ_{jet} , large E_T^{miss} , lepton veto 2 b-jets, ≥ 2 non-tagged jets	isolated lepton, large(r) E_T^{miss} 2 b-jets, ≥ 2 additional jets
W & top reconstr.	by means of jet pairing; cuts on p_T^{t1}/p_T^{t2} , $\Delta\phi(t_1, t_2)$	angular and charge correlation; $100 < m_t^{\text{had}} < 300$ GeV
Further $t\bar{t}$ suppression	likelihood discriminant, 7 kinematics variables	$\cos\psi = 2m_{\ell b}^2/(m_T^2 - m_W^2) - 1$ against leptons from W
Signal Significance	From Likelihood discriminant and H^\pm transverse mass.	From transverse masses ^(*) of H^\pm and W .

(*) $m_T^{H^\pm}$: novel concept of the „generalized transverse mass”, arXiv:0801.1459v1 (2008).



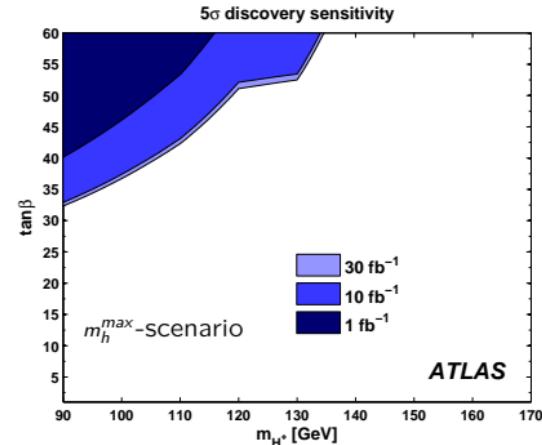
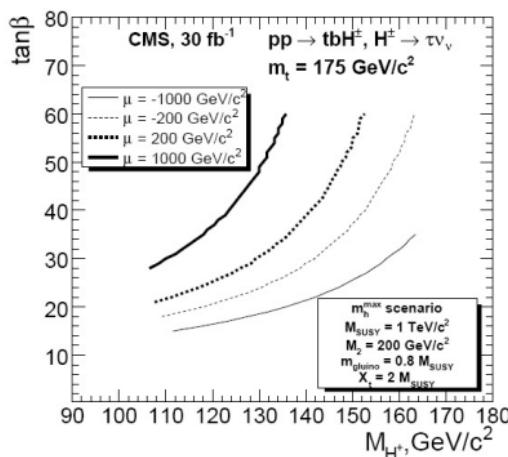
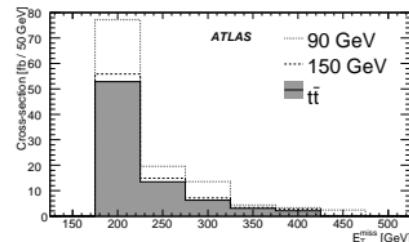
Light Charged Higgs, $m_{H^\pm} < m_{top}$ (II)

$$t\bar{t} \rightarrow (bH^\pm)(bW) \rightarrow (b\tau_{jet}\nu\nu)(b\ell\nu)$$

Complete event reconstruction is difficult due to 3ν , originating from both *top*-decays.

⇒ Signal is observed as an *excess of τ -leptons in $t\bar{t}$* , since $BR(H^\pm \rightarrow \tau^\pm \nu) > BR(w^\pm \rightarrow \tau^\pm \nu)$.

Trigger	lepton + E_T^{miss} (+3jets)(+ τ_{jet})
Offline	≥ 3 jets, ≥ 1 <i>b</i> -jets, ≥ 1 isolated lepton $\geq 1\tau_{jet}$, large E_T^{miss}
Kinematics	$p_T^\tau > 40$ GeV $Q_\ell + Q_\tau = 0$

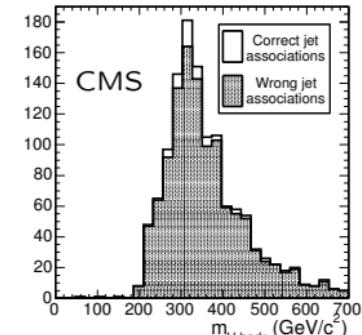


Heavy Charged Higgs, $m_{H^\pm} > m_{top}$

The search in $H^\pm \rightarrow \tau_{jet}\nu\nu$ decay mode is similar to the one for light charged Higgs.

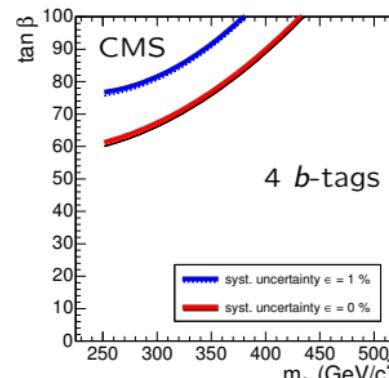
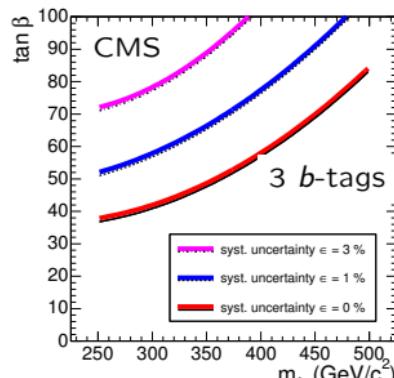
$$gg, gb \rightarrow t[b]H^\pm \rightarrow b\ell\nu[b]tb \rightarrow b\ell\nu[b]bqqb$$

Trigger	lepton + E_T^{miss}
Offline	= 1 isolated lepton, ≥ 5 jets, out of those ≥ 3 b -jets
W & top reconstr.	kinematic constraint on W -mass, jet association by combinatorial likelihood
Further $t\bar{t}$ suppression	likelihood discriminant, with several b -kinematics variables



This channel is extremely sensitive to systematic uncertainties.

⇒ Current analyses show a very low sensitivity in the MSSM parameter space.



H^\pm : Control Background Samples

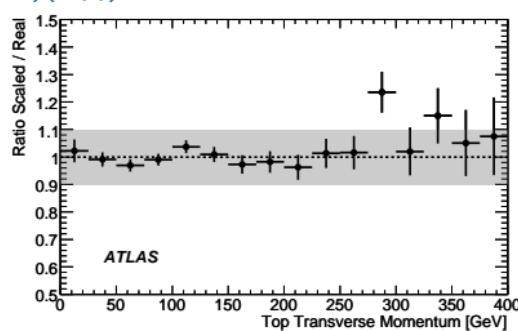
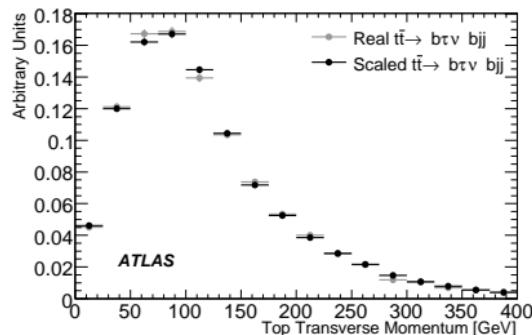
The dominant background for all H^\pm searches is the $t\bar{t}$ process.

- Theoretical scale uncertainty on the $t\bar{t}$ cross-section (NNLO): $\sim 10\%$.
- Experimental uncertainty: 10-40%.
Mostly affected by the jet energy scale and the b -tagging.

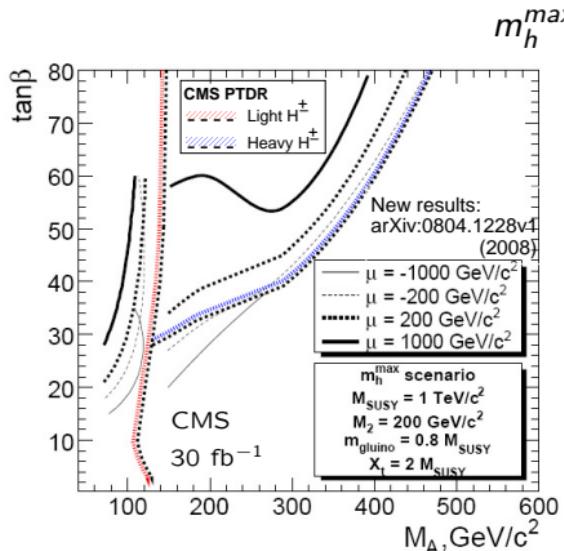
Need a reliable method for background estimation from control data.

- Control data samples: $t\bar{t} \rightarrow WbWb \rightarrow (\mu\nu b)(\mu\nu b)$, $t\bar{t} \rightarrow WbWb \rightarrow (\mu\nu b)(qqb)$.
- Replace the real muon(s) by an emulated τ -decay.
- The method can be used for all H^\pm searches with τ -s in the final state.

$$t\bar{t} \rightarrow (b\tau_{jet}\nu\nu)(bqq)$$

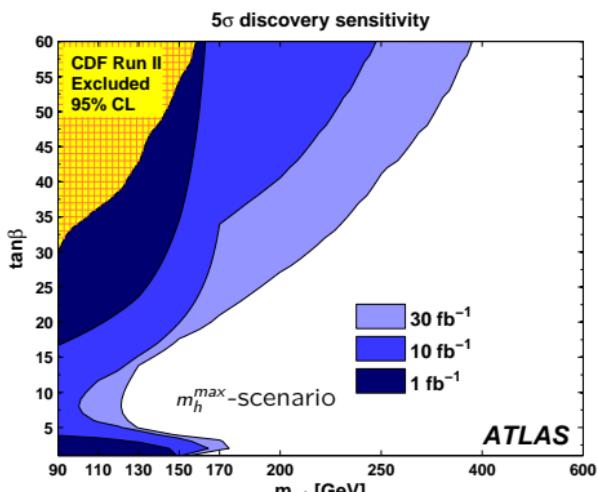


Experimental uncertainty on $t\bar{t}$ can be reduced down to less than 10%.



With 30 fb^{-1} :

- Light charged Higgs, $m_{H^\pm} < m_{top}$: Covered for nearly all $\tan\beta$.
- Heavy charged Higgs, $m_{H^\pm} > m_{top}$: Sensitivity only for large $\tan\beta$.



Summary

Discovery reach for MSSM Higgs bosons, explored by ATLAS and CMS:

- Most recent theoretical calculations and Monte Carlo generators.
- Detailed detector simulation.
- Detailed consideration of systematic uncertainties.
- Methods for the background estimation from the control data samples.

Neutral MSSM Higgs Bosons, $h/H/A$:

$h/H/A \rightarrow \tau\tau$ channel provides a good coverage of the $(m_A, \tan\beta)$ -plane.

- With 30 fb^{-1} :
 $\tan\beta$ -values above 15/20/50 are covered for $m_A=120/300/600 \text{ GeV}$ respectively.

$h/H/A \rightarrow \mu\mu$ is a competitive channel.

- Helps to increase the discovery reach. Allows for a precise mass reconstruction.

Charged MSSM Higgs Bosons, H^\pm :

Decay modes with $H^\pm \rightarrow \tau_{jet}\nu\nu$ provide the highest discovery reach.

Combining all channels, after 1 fb^{-1} of well understood data:

- Current Tevatron limits can be exceeded.

Combining all channels, after 30 fb^{-1} :

- $m_{H^\pm} < m_{top}$: Almost the whole parameter space is covered.
- $m_{H^\pm} > m_{top}$: Sensitive only for larger $\tan\beta$ values.