Beyond Standard Model Higgs searches at ATLAS

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Introduction

- In the **Standard Model** (SM) only 1 doublet of Higgs scalars is responsible for the electroweak symmetry breaking → there is only one neutral Higgs boson h^0.

- **Extensions of the SM**:
  - **2HDM models** predict the existence of 2 complex Higgs doublets resulting in 5 physical states: H^+, H^-, h^0, H^0, A^0
  - **nMSSM model** adds an additional superfield resulting in 7 physical states h_1, h_2, h_3, a_0, a_1, H^+, H^- → solves μ problem
  - Instead of a doublet a **triplet** of complex scalars field: h^0, $H^\pm$, $H^{\pm\pm}$ → explanation for neutrino masses and mixing

BSM Higgs searches at ATLAS

- **Charged Higgs boson searches:**
  - Charged Higgs
    - $H^{\pm} \rightarrow \tau\nu$ (important at $\tan\beta > 3$)
    - $H^{\pm} \rightarrow cs$ (important at $\tan\beta < 1$)
  - Doubly charged Higgs

- **Neutral Higgs Boson searches:**
  - $A/H/h \rightarrow \tau\tau$
  - 2HDM $H \rightarrow WW$
  - H to invisible
  - 4th-generation
  - Fermiophobic
  - nMSSM

BSM Higgs searches at ATLAS

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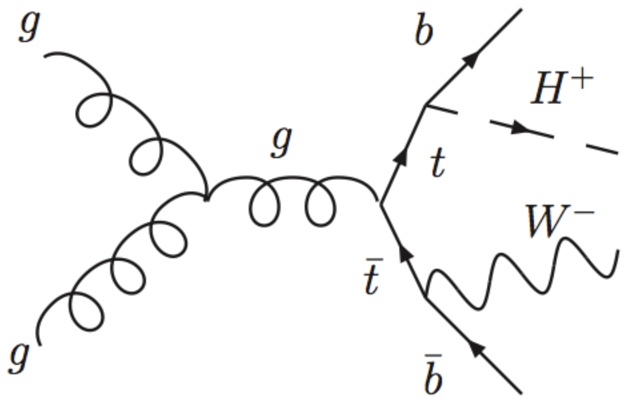
- **Neutral Higgs Boson searches:**
  - $A/H/h \rightarrow \tau\tau$ → 4.7-4.8 fb^{-1} at $\sqrt{s}$=7TeV
  - 2HDM $H \rightarrow WW$ → 13.0 fb^{-1} at $\sqrt{s}$=8TeV
  - H to invisible → 4.7 fb^{-1} at $\sqrt{s}$=7TeV + 13.0 fb^{-1} at $\sqrt{s}$=8TeV
  - ~~4th-generation~~ → excluded m_H= 119-593 GeV: ATLAS-CONF-2011-135
  - ~~Fermiophobic~~ → ATLAS-CONF-2012-013, ATLAS-CONF-2013-034
  - nMSSM → 4.9 fb^{-1} at $\sqrt{s}$=7TeV



- $H^{\pm} \rightarrow \tau\nu$
- $H^{\pm} \rightarrow cs$
- Doubly charged Higgs

Light H± ($m_{H\pm}$<m_t) => Main production mode: $pp \rightarrow t\bar{t} \rightarrow b\bar{b}W^{\mp}H^{\pm}$

CHARGED HIGGS

$H^{\pm} \rightarrow \tau\nu$

- ***Search through the violation of lepton universality***

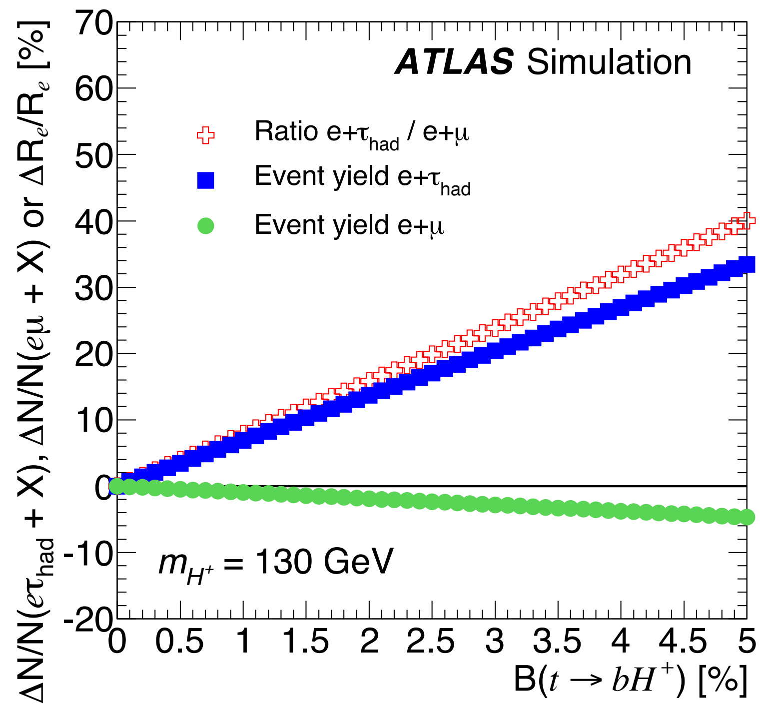
JHEP03(2013)076

➢ **Strategy:**
- W decays equally to e/μ/τ while $H^{\pm}$ decays predominantly to τ
- Look for excess w.r.t. SM in decay with τ_{had}

$$R_l = \frac{N(bb + l\tau_{had} + E_T^{miss})}{N(bb + ll' + E_T^{miss})}$$

- Ratio method cancels common systematics
- Ask for: 1 e/μ + another e/μ or a τ_{had}, >2 jets (2 b-tagged), E_T^{miss}>40GeV

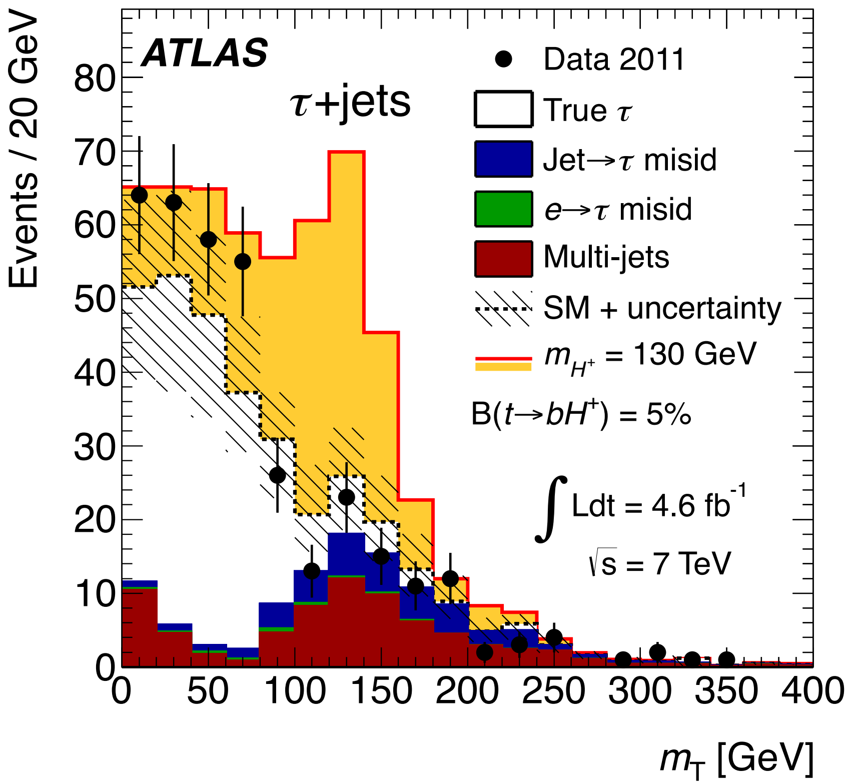
➢ **Main Backgrounds:**
- Misidentified leptons: data-driven estimation
- Misidentified l→τ from MC with SF from Zee CR
- Misidentified j→τ data-driven estimation in W CR



$H^{\pm} \to \tau\nu$

- ***Direct searches***

JHEP 1206 (2012) 039

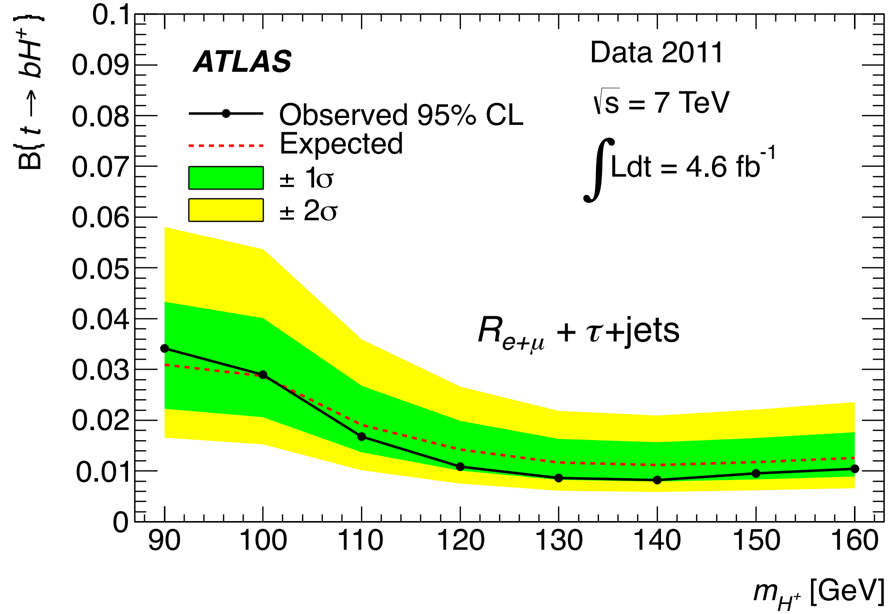


- **Strategy:**
  - W → jj + $H^{\pm}$ in hadronic τ
    Ask for: 1 τ_{had}, >4jets (>1 b-tagged), lep veto, E_T^{miss}>65GeV, m_{jjb} ∈ [120, 240] GeV
  - Final discriminant: $m_T(\tau_{had}, E_T^{miss})$
- **Main Backgrounds:**
  - True τ from embedding (from tt-like μ+jet event, replace μ with simulated τ)
  - Misidentified τ from MC with corrections from CR
  - Multijets: data-driven estimation

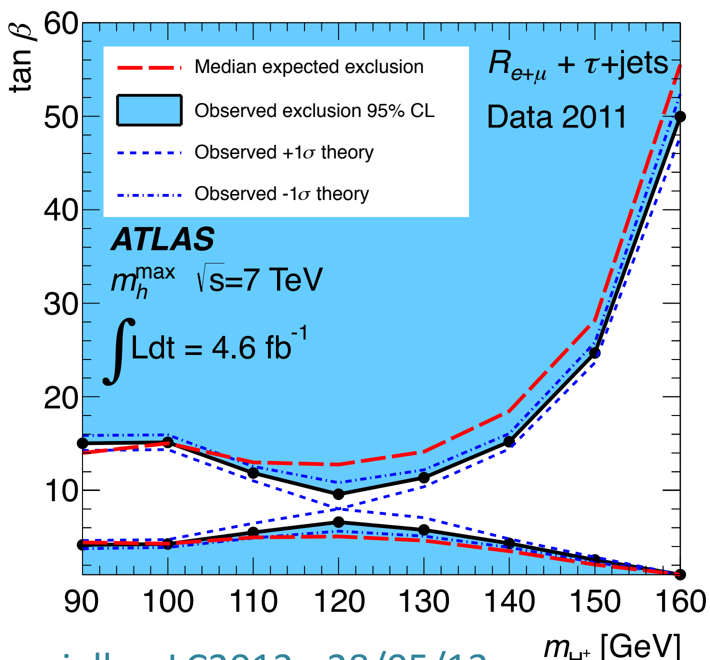
Limits and results interpretation

JHEP03(2013)076

- **Limits:**
  - Profile likelihood ratio with CLs technique and systematics uncertainty included as nuisance parameters
  - Limits on BR(t→bH$^{\pm}$) with the assumption BR(H$^{\pm}$→τν)=100%
  - τ+jets results are dominant in the whole range except for low $m_{H\pm}$
  - **Upper limits in the range 3.4%-0.8% for 90GeV<$m_{H\pm}$<160GeV**



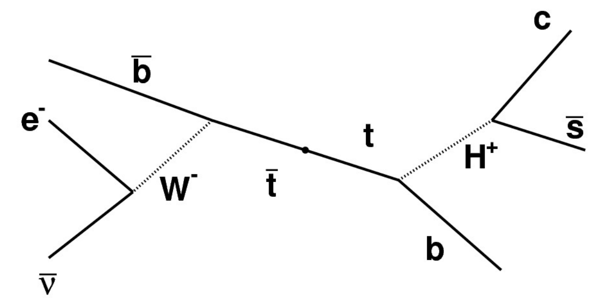
Combined analysis based on violation on lepton universality ($R_{e+\mu}$) and direct searches (τ+jets)



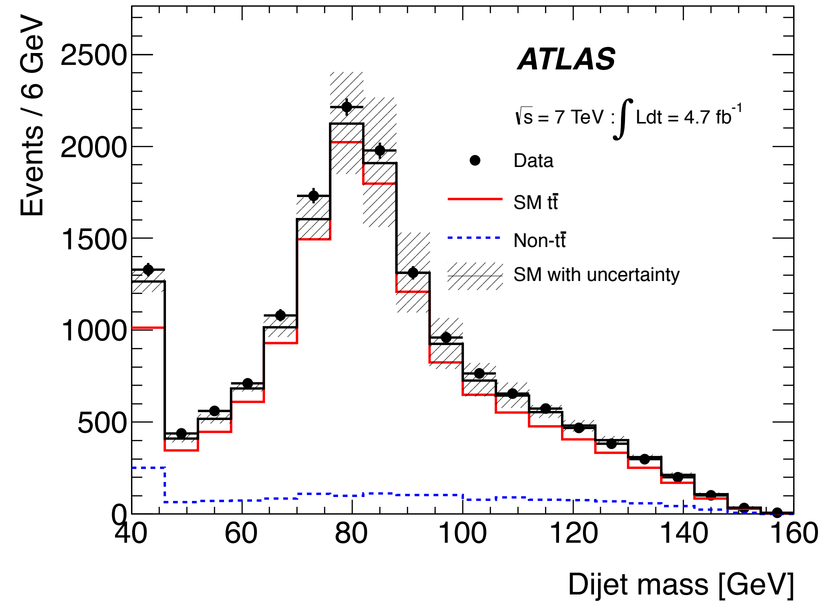
- **Interpretation in MSSM model:**
  - m_h^{max} scenario: parameters chosen such that maximum possible Higgs-boson mass m_h is obtained
  - tanβ → ratio of the 2 vev
  - Large regions of parameter space excluded
  - Unexcluded regions still compatible with 125 GeV SM Higgs boson

$H^{\pm} \rightarrow cs$

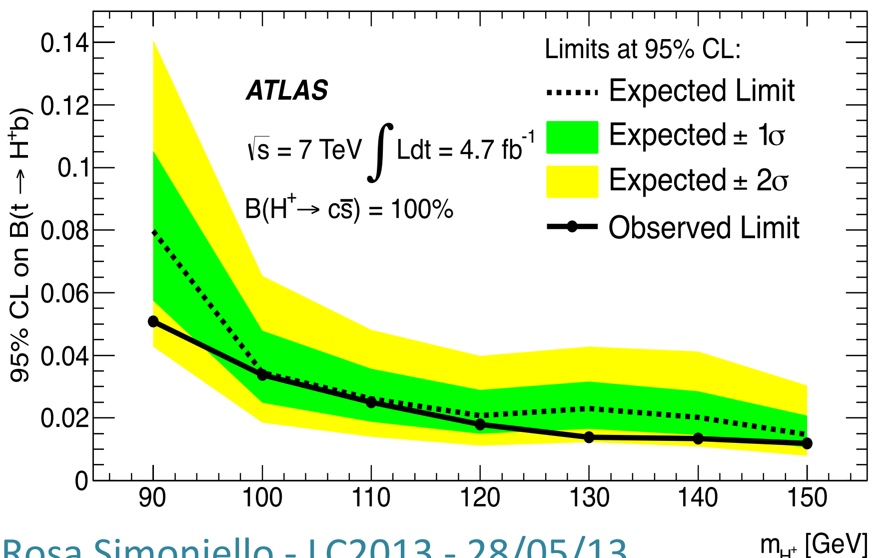
arXiv:1302.3694



- **Strategy:**
  - Ask for: 1 lepton, E_T^{miss}>25GeV, >4 jets (2 b-tagged)
  - Discriminating variable: m_{inv}(2jets)
  - Kinematic fit used to associate the jets for the bjj system and blν system
    → mass resolution ~ 12 GeV

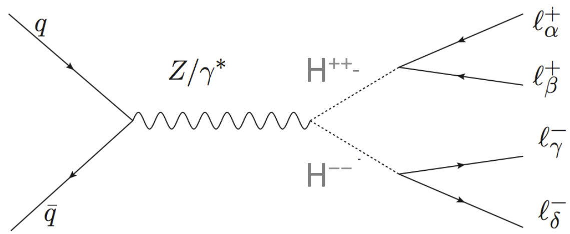


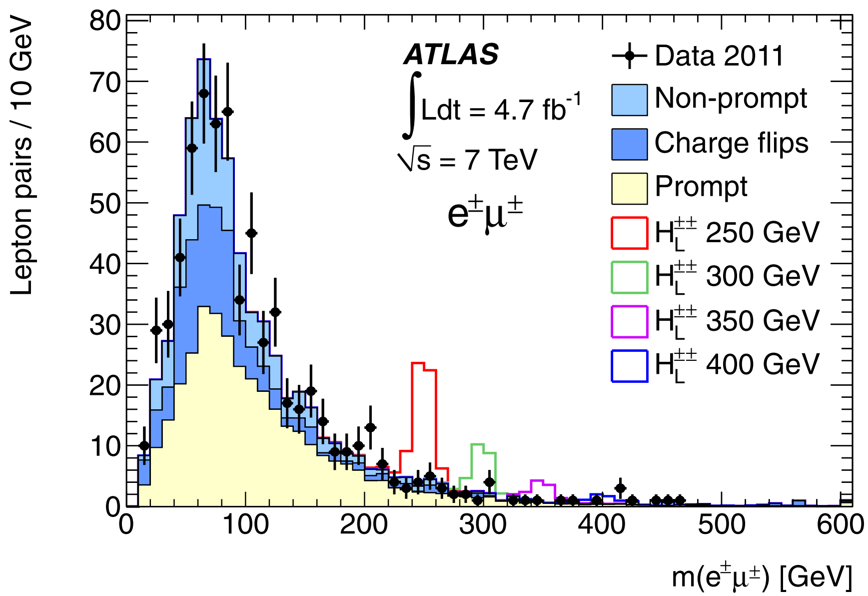
- **Main Backgrounds:**
  - ttbar (principally semileptonic decay) and single top from MC
  - QCD: data-driven using semi-isolation
  - W+jets: data-driven using charge asymmetry



- **Limits:**
  - Profile likelihood ratio with CLs technique and systematics uncertainty included as nuisance parameters
  - Limits on BR($t \rightarrow bH^{\pm}$) with the assumption BR($H^{\pm} \rightarrow cs$)=100%
  - **Upper limits in the range 5%-1% for 90GeV<$m_{H\pm}$<150GeV**

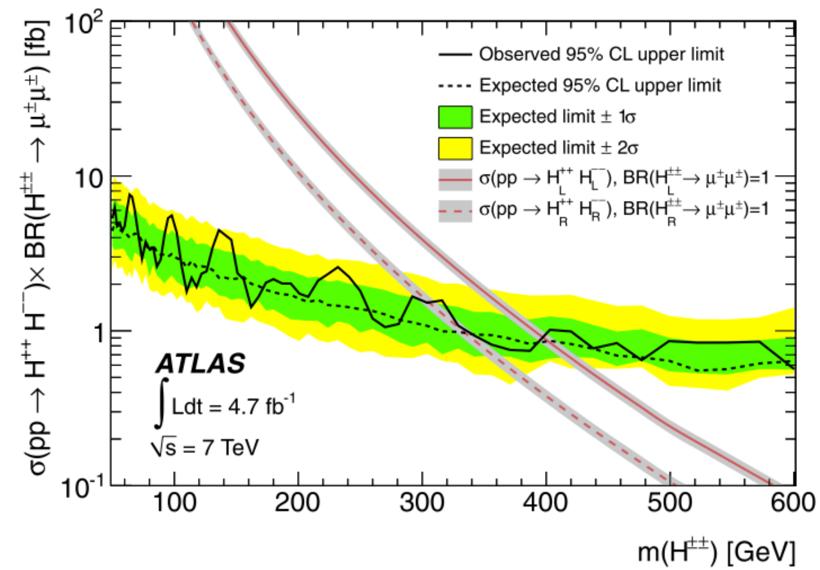
Doubly charged Higgs $H^{\pm\pm}$



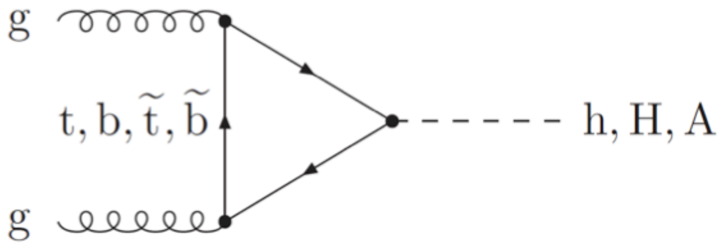


[Eur. Phys. J. C (2012) 72]

- **Strategy:**
  - Only "pair production" mode is considered (associated production depends on $m_{H\pm}$)
  - Look for a narrow resonance in the invariant mass of same-sign lepton pairs ($e^\pm e^\pm$, $e^\pm\mu^\pm$, $\mu^\pm\mu^\pm$)
- **Main Backgrounds:**
  - Prompt: Di-boson (mainly WZ) from MC
  - Non-prompt (semileptonic b, c decays, π showering) from data CR where one lepton fails part of selection
  - Charge flips rate corrected between data-MC comparison in Zee



- **Limits:**
  - Set upper limits on the cross section of $H^{\pm\pm}$ decaying into leptons pair
  - Assuming coupling to left-handed fermions, and a branching ratio of 100% for each final state, **masses below 409 GeV, 375 GeV, and 398 GeV are excluded for $e^\pm e^\pm$, $e^\pm\mu^\pm$, and $\mu^\pm\mu^\pm$**



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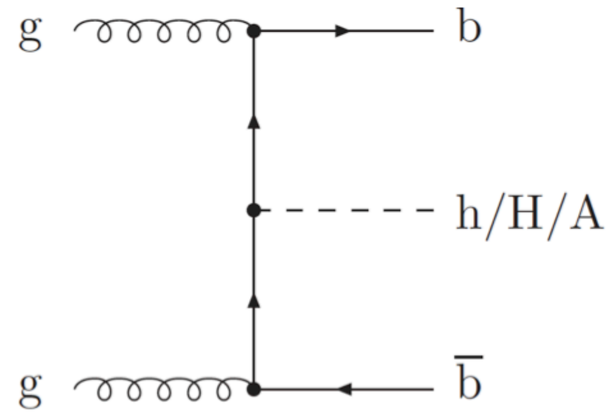


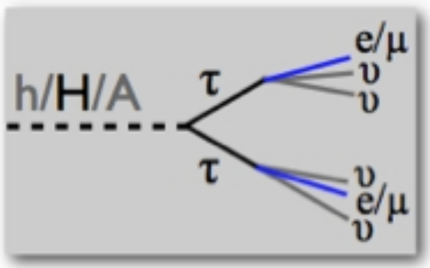
- h/H/A → ff’
  - BR(bb) ~ 90%
  - BR(ττ) ~ 10%
  - BR(μμ) ~ 0.04%
- H→WW
- H to invisible
- nMSSM

NEUTRAL HIGGS

h/H/A→ττ

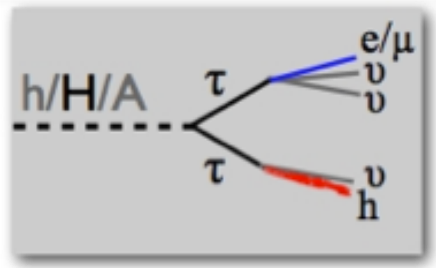
JHEP02(2013)095

lep-lep: 12.4%



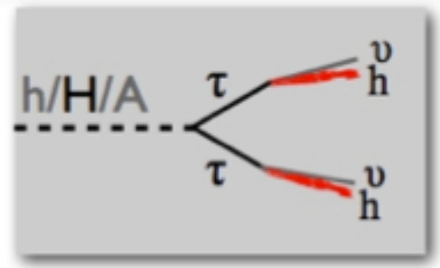
1 isolated electron,
1 isolated muon,
OS, $M^{e\mu}_{inv}$>30GeV

lep-had: 45.6%

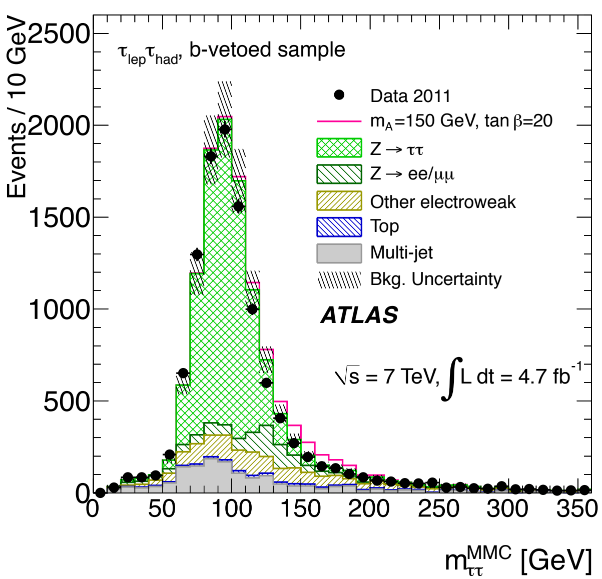


1 isolated lepton,
1 τ_{had} , OS,
$M_T(lep,E_T^{miss})$>30GeV

had-had: 42.0%



2 τ_{had} , OS,
lepton veto,
E_T^{miss}>25GeV



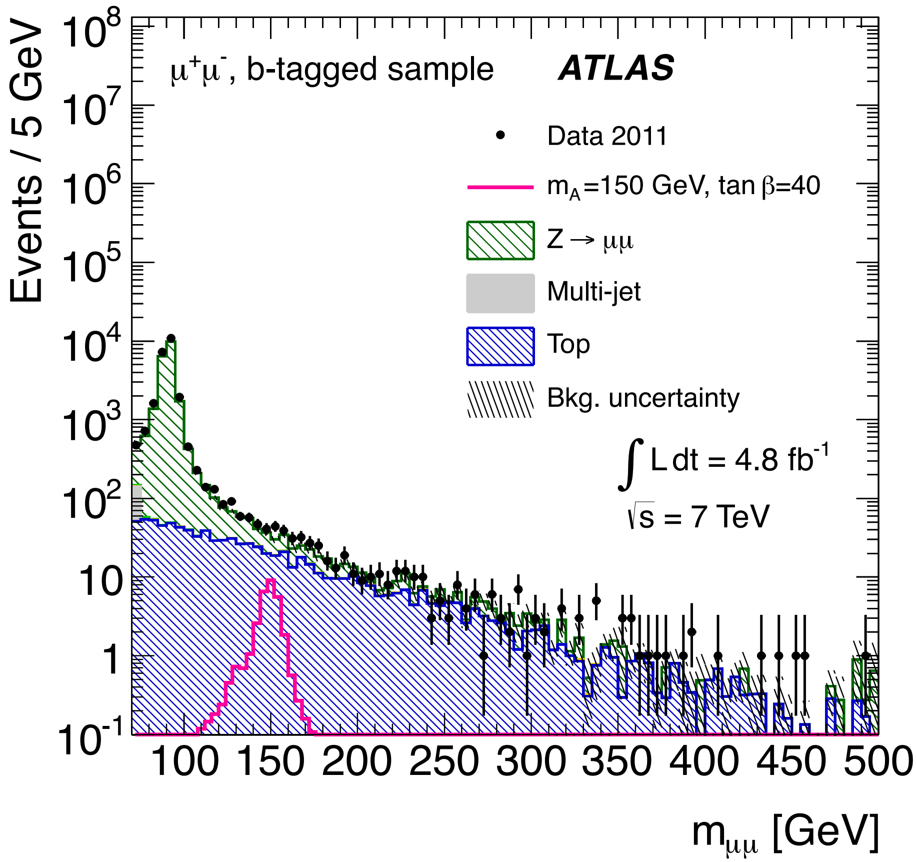
- **Strategy:**
  - MSSM context: 3 neutral Higgs bosons: h/H/A
  - Analysis divided in the 3 sub-channels: leplep, lephad, hadhad (where lepton means either electron or muon)
  - Each subchannel divided into 2 categories:
    - b-tagged sample: 1 b-jet (b-associated production)
    - b-vetoed sample
  - Final discriminant: MMC → estimator of the invariant mass of the ττ system
- **Common Backgrounds:**
  - Z→ττ: estimated from embedding (from Zμμ data replace μ with simulated τ)
  - QCD multijets: data-driven estimation with ABCD method

h/H/A→μμ

JHEP02(2013)095

- **Strategy:**
  - Low BR but clean signal and excellent mass resolution
  - Ask for 2 OS μ and separate events into 2 categories:
    - b-tag sample: at least 1 b-jet
    - b-vetoed
  - Discriminating variable: $m_{\mu\mu}$
- **Main Backgrounds:**
  - Resonant background: Z/γ* (51% in b-tag sample, 99% in b-vetoed sample)
  - Non-resonant background: ttbar

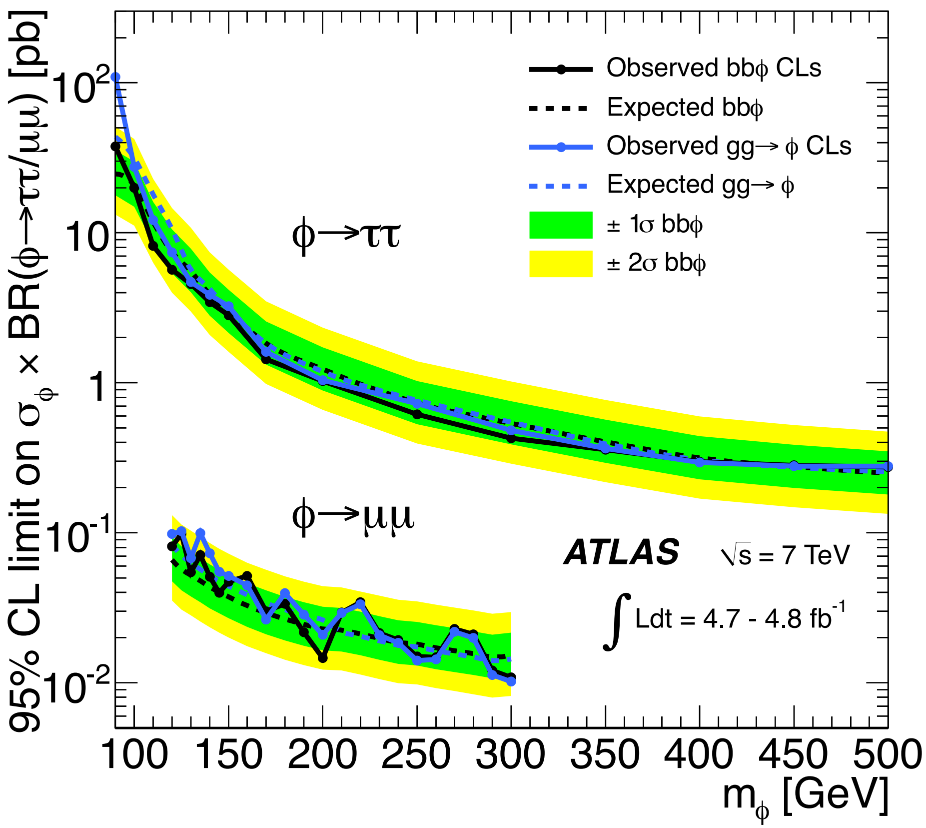
→ Estimated from local sideband fits in CR extrapolated in SR

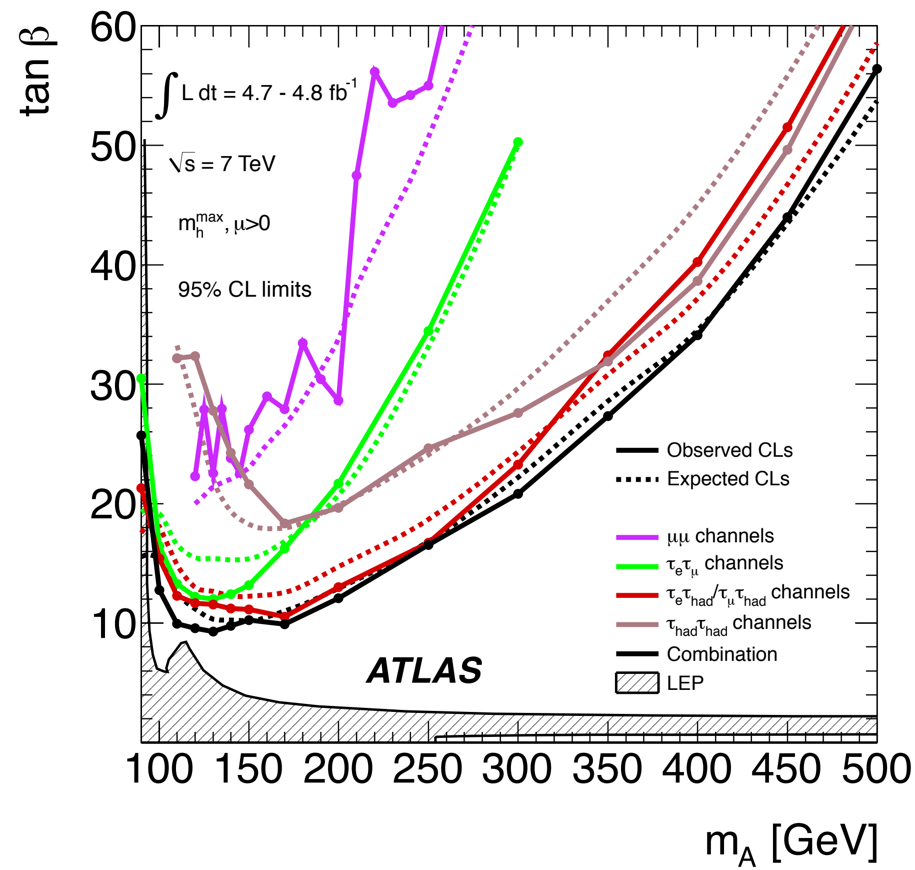


Combined limits

JHEP02(2013)095

- **Limits:**
  - The limits on the cross section for a single neutral Higgs boson times the branching fraction into τ and μ pairs can be set and can be interpreted in the m_h^{max} scenario of the MSSM.

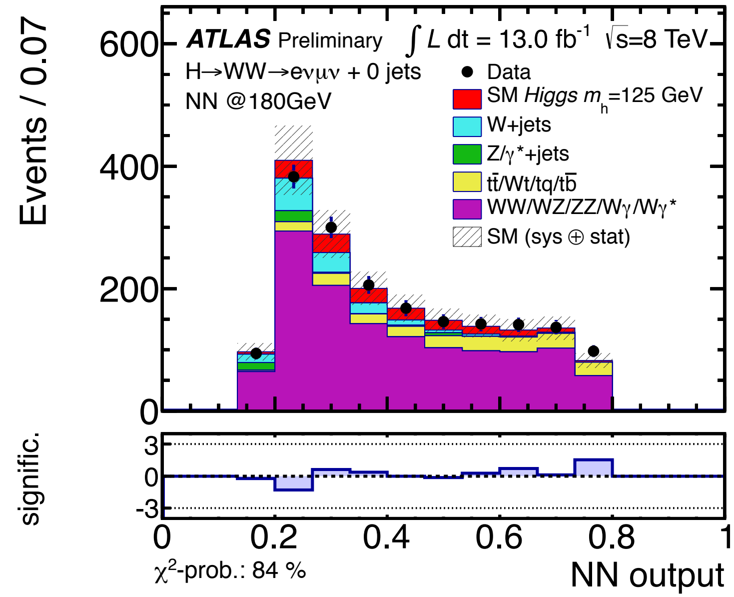




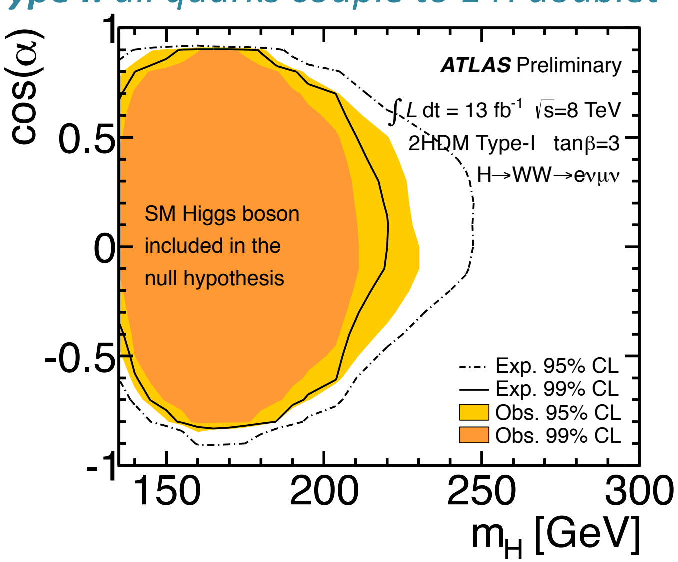
H→WW

ATLAS-CONF-2013-027

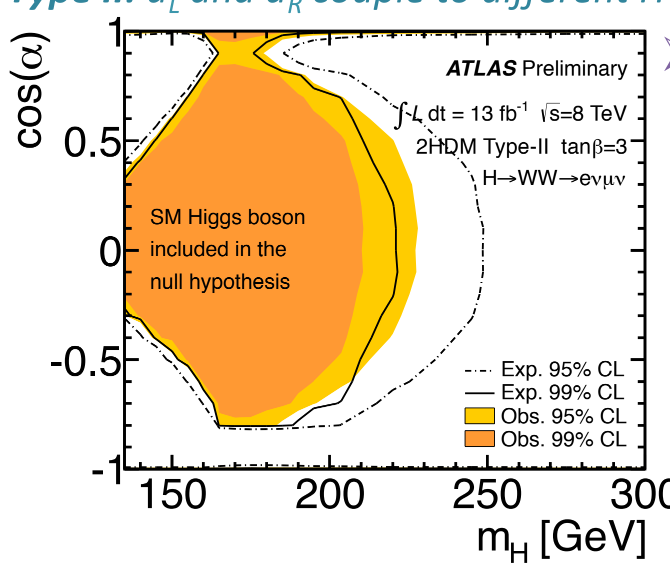
- **Strategy:**
  - Assuming the excess observed as 125 GeV is the h, search for the heavy H
  - Ask for OS eμ, E_T^{miss}
  - 2 categories: 0jets, 2 jets (no b-tagged)
  - Final discriminant: Neural Network (NN) output
  - NN trained for mH = 150, 180, 240 GeV
- **Main Backgrounds:**
  - Di-bosons and top from enriched CR
  - Z/γ+jets: from theory + data driven corrections for identification efficiency
  - W+jets data-driven estimation



Type I: all quarks couple to 1 H doublet



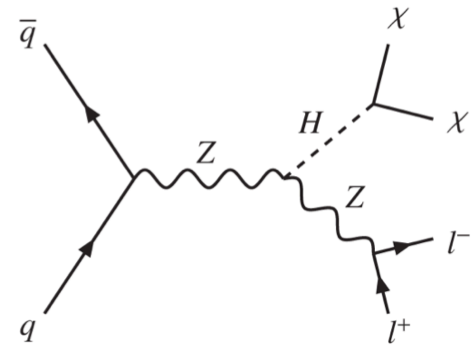
Type II: u_L and d_R couple to different H doublets



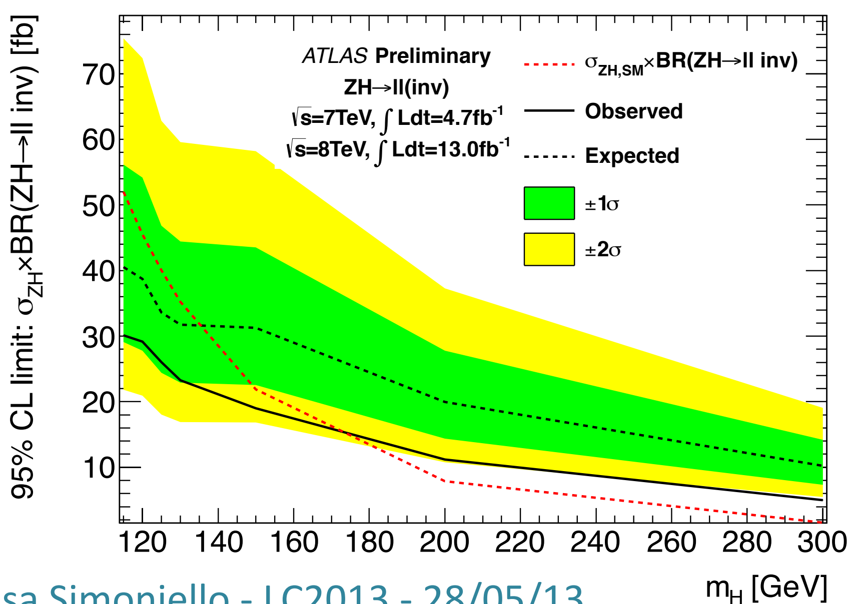
- **Limits:**
  - Signal rate depends on m_H, tanβ and cosα (α, β are the mixing angles of the 2 H doublets)
  - Tested different signal hypotheses and set limits for several tanβ in the plane cosα-m_H

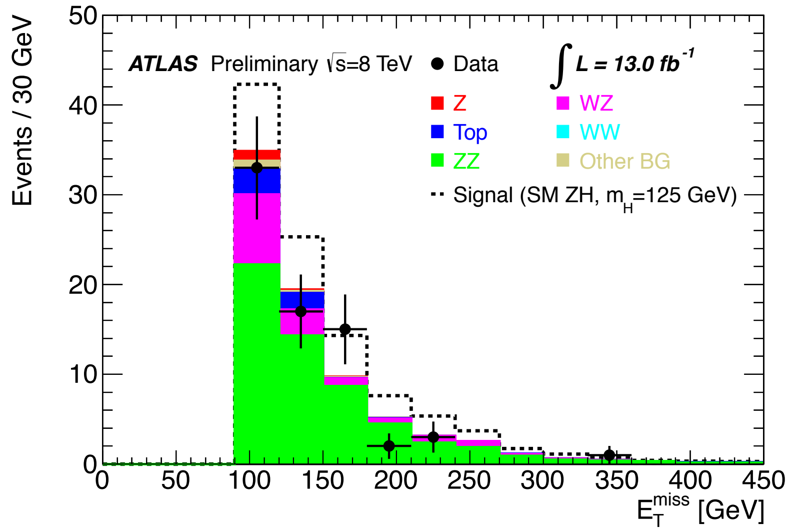
Higgs to invisible

ATLAS-CONF-2013-011



- **Strategy:**
  - Direct search → BR not measurable in the SM but in extended theories it can get a large contribution from the decay to the dark matter particles
  - electron or muon pair compatible with m_Z, veto on additional leptons or jets, E_T^{miss}>90GeV
  - Final discriminant: E_T^{miss}
- **Main Backgrounds:**
  - Irreducible ZZ → llνν (70% of the total background) from MC
  - WZ → lνll from MC



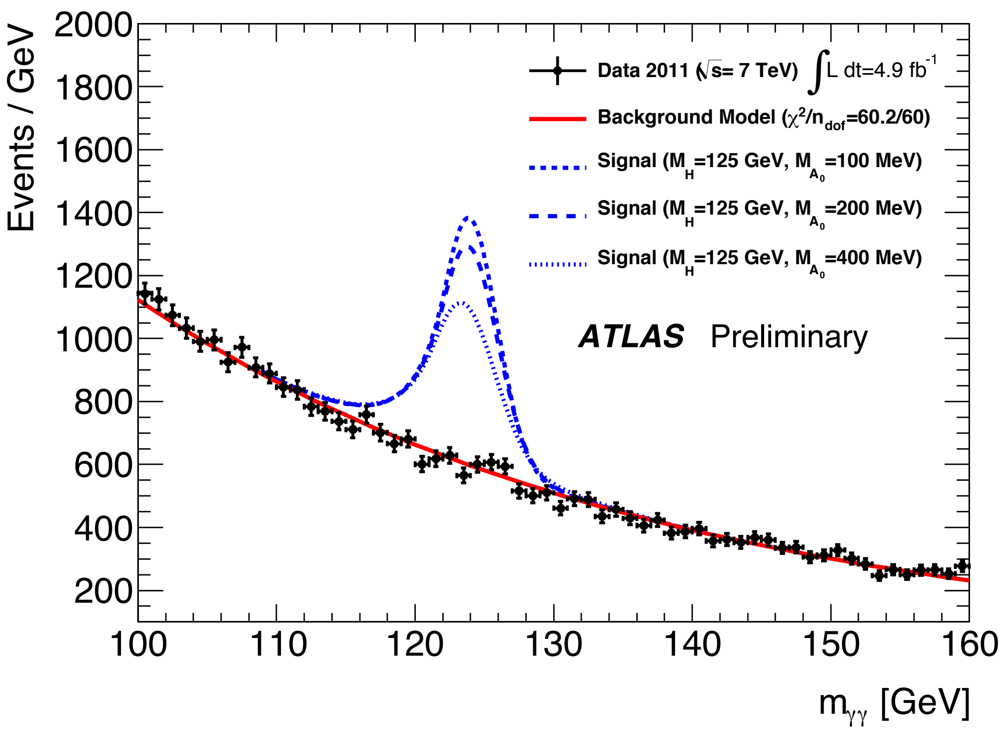


- **Limits:**
  - Assume SM ZH production for m_h = 125 GeV
  - Limits set on B(H → inv): B(H → inv)>65% is excluded at 95% CL

nMSSM

- **Theory:**
  - Additional supersymmetric field w.r.t. MSSM resulting in 7 observable bosons: 3 CP-even scalars *(h_1, h_2, h_3)*, 2 CP-odd scalars *(a_0, a_1)* and 2 charged scalars *(H^+, H^-)*

ATLAS-CONF-2012-079



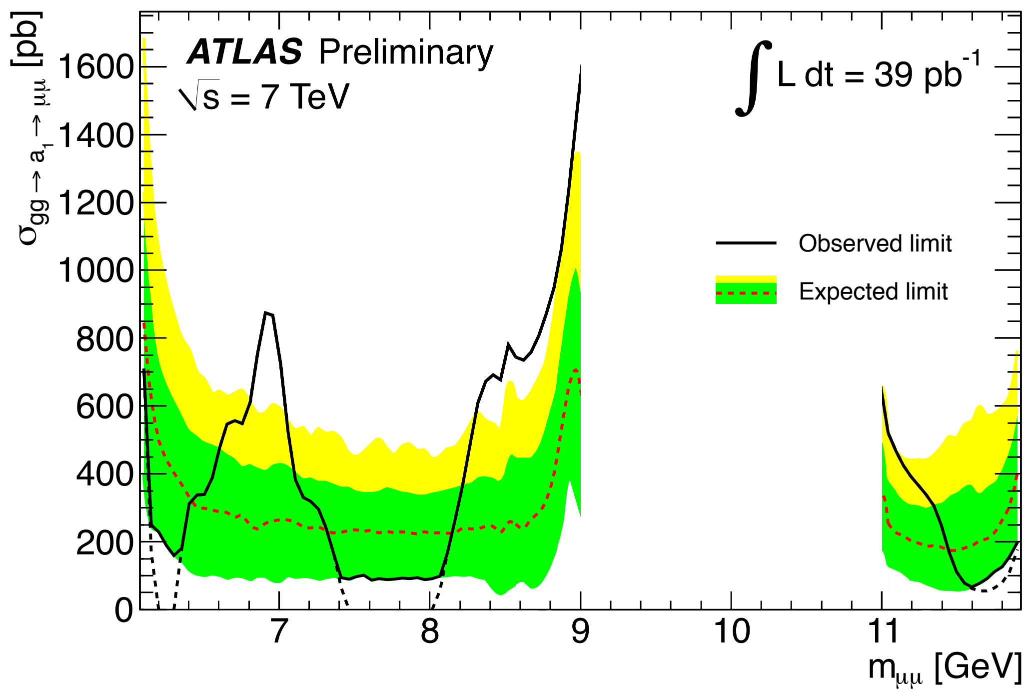
- **4 photons final state:**
  - 2011 data
  - $pp \rightarrow a_0 a_0 \rightarrow \gamma\gamma\gamma\gamma$
  - a_0 is expected to be very light: 100MeV-400MeV
  - a_0→ very collimated => mimic di-photons events
  - Final discriminant: $m_{\gamma\gamma}$
  - **Exclude σ(pp→H→4γ)>0.1pb (0.2 pb) for m_a = 100, 200 (400) MeV**

nMSSM

- **Theory:**
  - Additional supersymmetric field w.r.t. MSSM resulting in 7 observable bosons: 3 CP-even scalars *(h_1, h_2, h_3)*, 2 CP-odd scalars *(a_0, a_1)* and 2 charged scalars *(H^+, H^-)*

ATLAS-CONF-2011-020

- **Di-muons final state:**
  - 2010 data
  - $pp \rightarrow a_1 \rightarrow \mu^+\mu^-$
  - Expected light a1 mass: if 9.2 < m(a1) < 12 GeV can justify the anomalous μ magnetic moment
  - Ask for OS μ pair compatible with single particle decay Υ
  - Excluded region dominated by resonance
  - **No evidence for resonances** → set limits on σxBR, excess compatible with statistics fluctuation

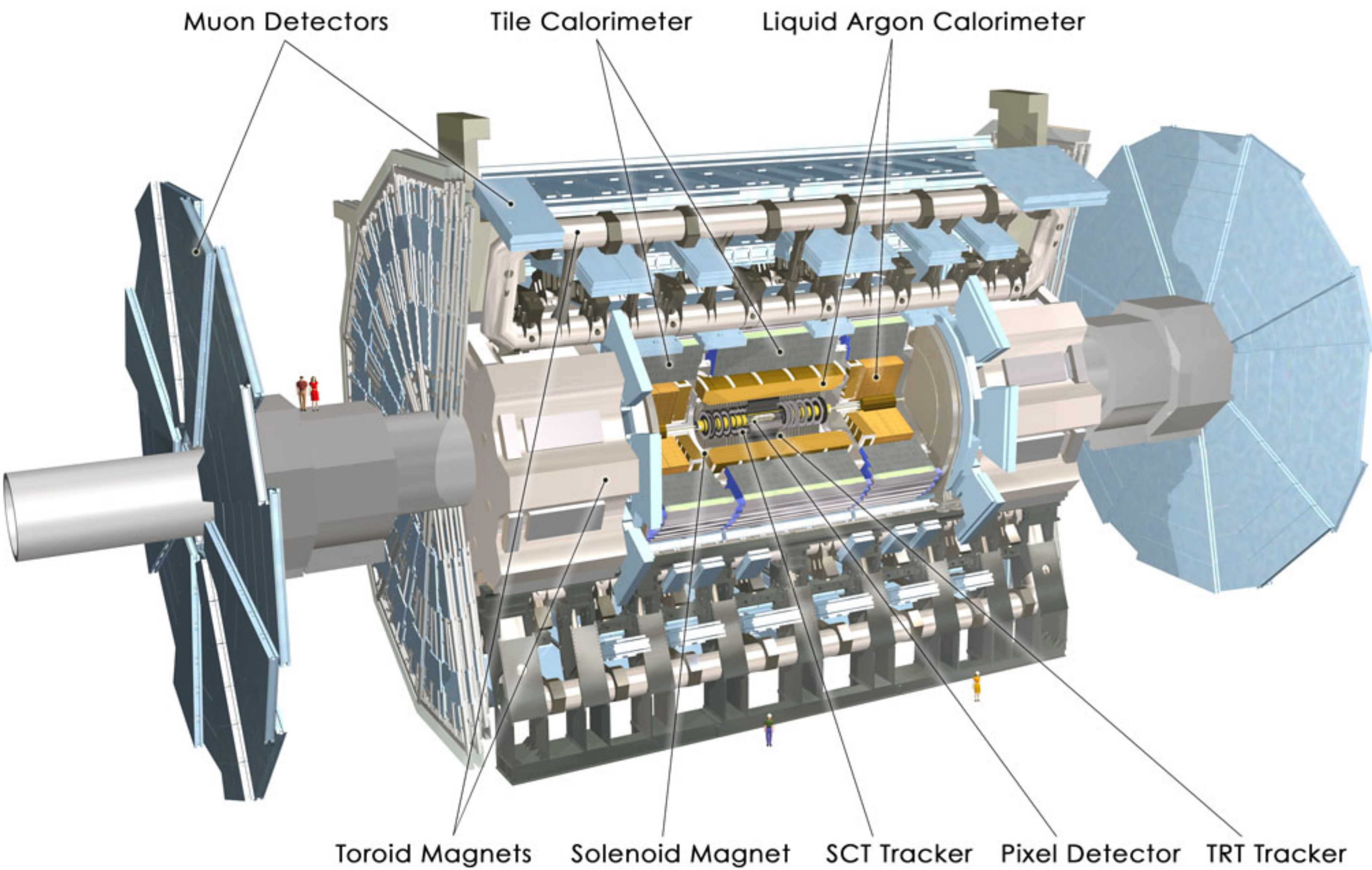


Conclusion and future plans

- The SM Higgs boson was discovered at the LHC, but there are theories extending the Standard Model that predict more Higgs bosons
- Set limits on branching ratio and cross section for processes predicted by extensions of SM
- Large regions of MSSM parameter space are excluded by searches of neutral and charged Higgs but still open regions of the phase space compatible with the observed 125 GeV SM Higgs boson.

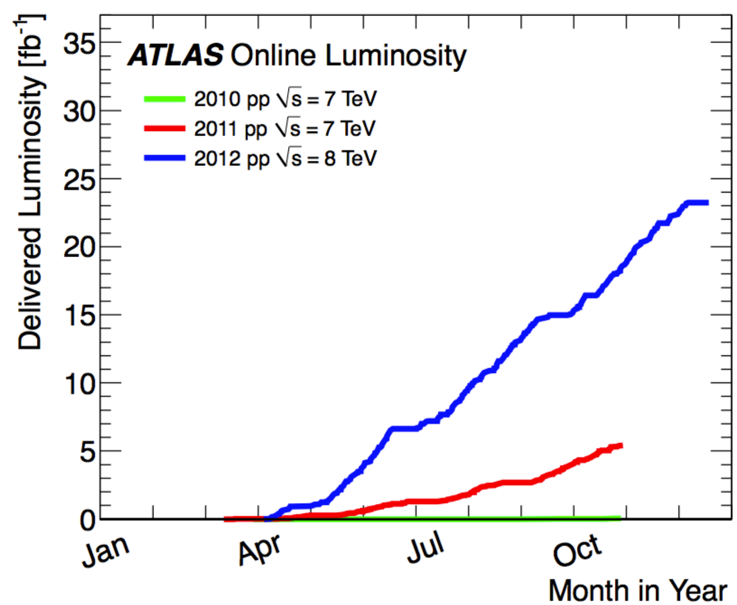
- Work ongoing to publish searches with the full 8TeV statistics
- Plan to explore new final states driven by theory and approach more generic benchmark models

BACK-UP


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

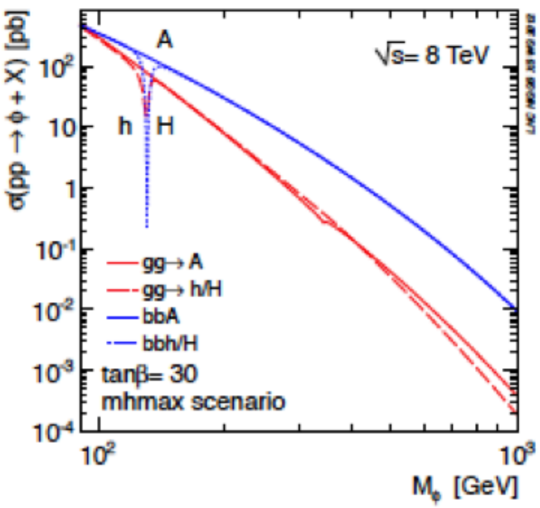
Run conditions

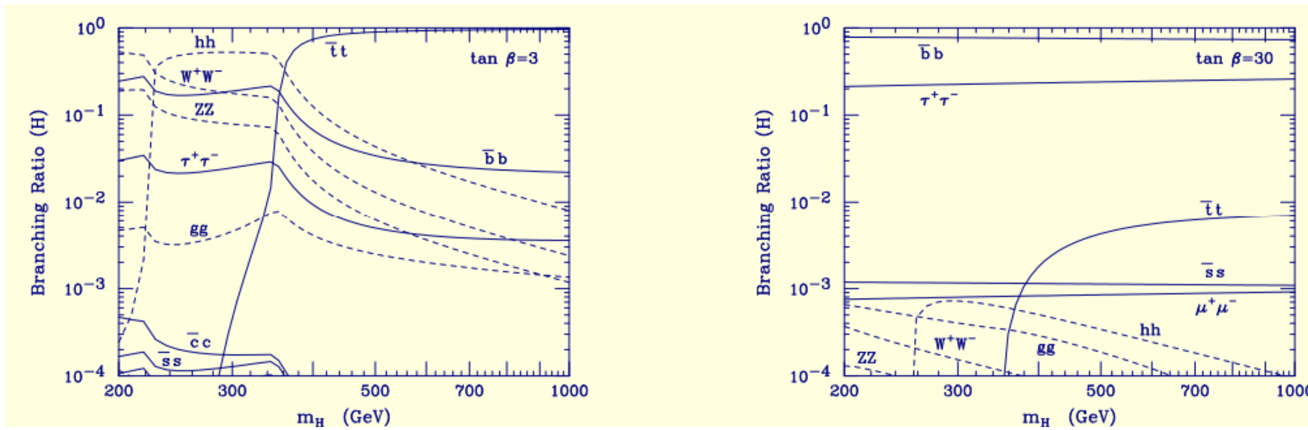
- **2010, √s =7 TeV, 36 pb-1**
- **2011, √s =7 TeV , 5.62 fb-1**
  - Peak luminosity 3.65x1033 cm-2s-1
  - 50 ns bunch spacing
  - Pileup: <μ > =6.3 - 11.6
- **2012, √s = 8 TeV, 23 fb-1**
  - Peak luminosity 7.73x1033 cm-2s-1
  - Pileup: <μ > = 20



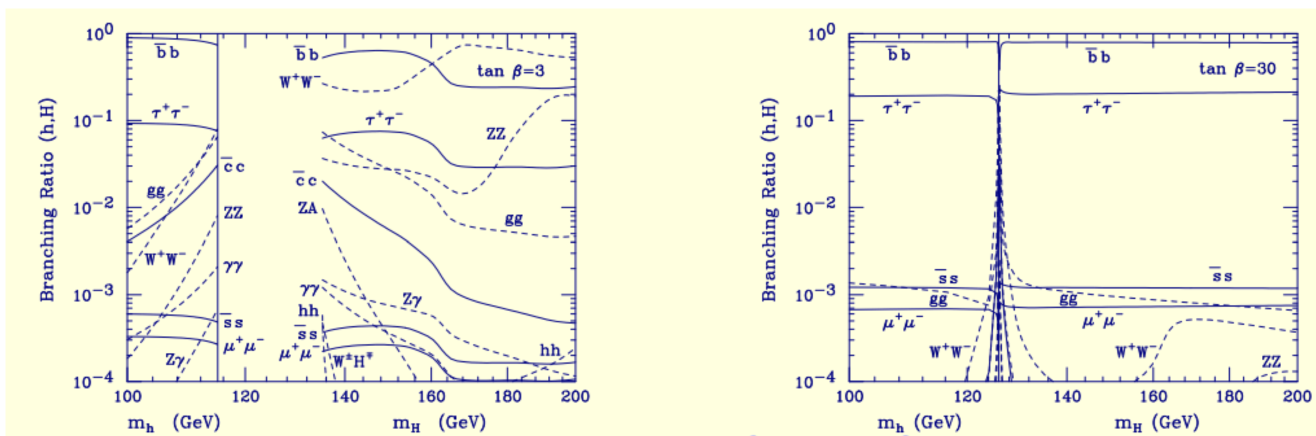
Theory: MSSM cross sections and BR

Neutral Higgs



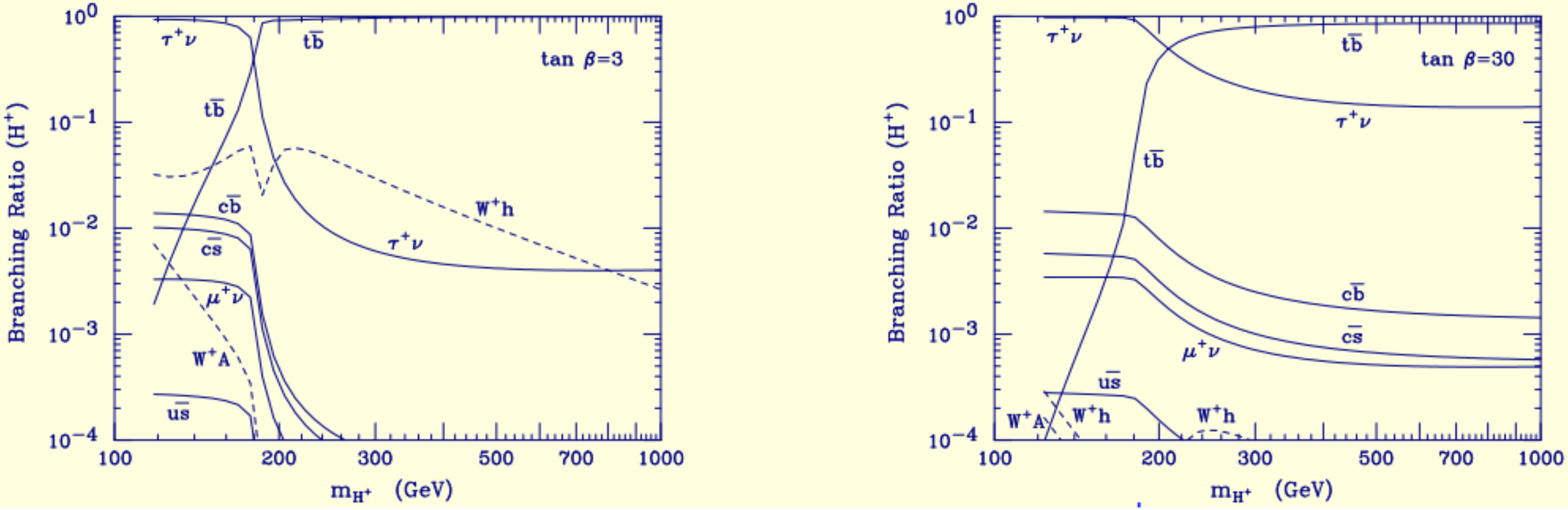


Coupling to down-fermions are $\tan^2\beta$ enhanced



Theory: MSSM cross sections and BR

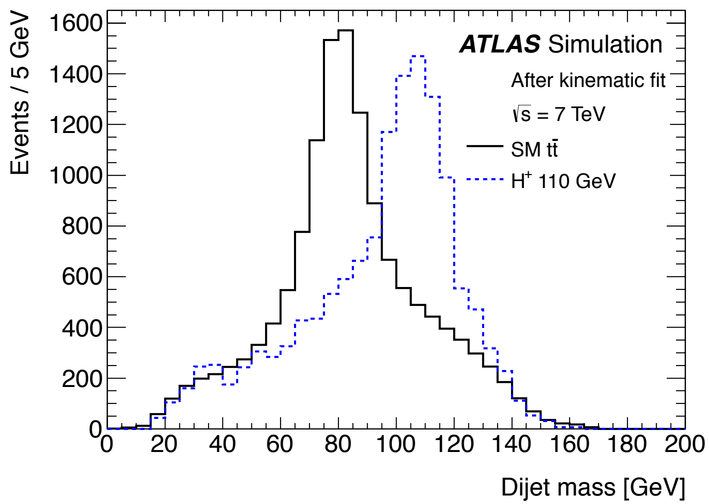
Charged Higgs



H+→cs: kinematic fit

- Compute all jets combinations and chosen the with the smallest χ^2

$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{\text{SEJ,fit}} - p_j^{\text{SEJ,meas}})^2}{\sigma_{\text{SEJ}}^2} + \sum_{k=jjb,b\ell\nu} \frac{(M_k - m_{\text{T}})^2}{\Gamma_t^2} .$$



- First row: take into account lepton and jet resolution
- Second row: take into account additional jets if any (njets>4) → SEJ: vector sum of the remaining jets in the event
- Third row: constrains the hadronic (jjb) and leptonic (blv) top-quark candidates to have a mass close to the top-quark mass

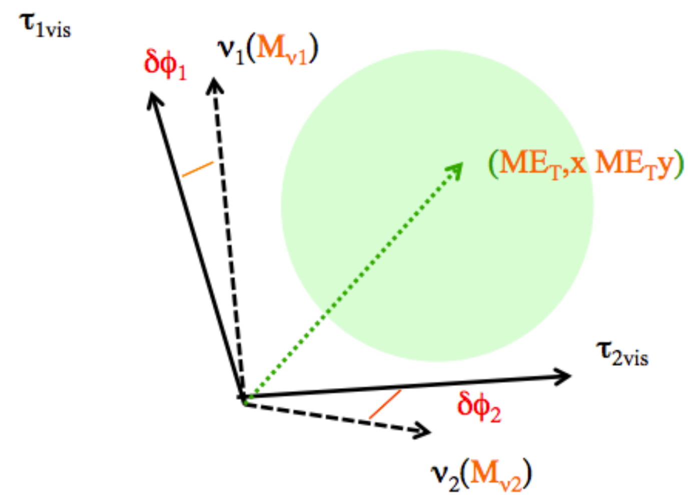
h/H/A→ττ: MMC

$$\not{E}_{T_x} = p_{\mathrm{mis}_1}\sin\theta_{\mathrm{mis}_1}\cos\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2}\sin\theta_{\mathrm{mis}_2}\cos\phi_{\mathrm{mis}_2}$$

$$\not{E}_{T_y} = p_{\mathrm{mis}_1}\sin\theta_{\mathrm{mis}_1}\sin\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2}\sin\theta_{\mathrm{mis}_2}\sin\phi_{\mathrm{mis}_2}$$

$$M_{\tau_1}^2 = m_{\mathrm{mis}_1}^2 + m_{\mathrm{vis}_1}^2 + 2\sqrt{p_{\mathrm{vis}_1}^2 + m_{\mathrm{vis}_1}^2}\sqrt{p_{\mathrm{mis}_1}^2 + m_{\mathrm{mis}_1}^2} - 2p_{\mathrm{vis}_1}p_{\mathrm{mis}_1}\cos\Delta\theta_{vm_1}$$

$$M_{\tau_2}^2 = m_{\mathrm{mis}_2}^2 + m_{\mathrm{vis}_2}^2 + 2\sqrt{p_{\mathrm{vis}_2}^2 + m_{\mathrm{vis}_2}^2}\sqrt{p_{\mathrm{mis}_2}^2 + m_{\mathrm{mis}_2}^2} - 2p_{\mathrm{vis}_2}p_{\mathrm{mis}_2}\cos\Delta\theta_{vm_2}$$



- Multiple neutrinos in the final state
- The unknown exceeds the number of constraints
- MMC use information about the τ decays in order to compute the invariant mass of the system requiring that the direction of the visible and invisible decay products are consistent with the mass and the kinematics of a τ decay:
  - MMC scan over the neutrino directions and pick the most likely value of $m_{\tau\tau}$, according to the probability density functions from simulated τ decays
- In order to compensate for the MET resolution it also allows to scan the MET inside its experimental resolution

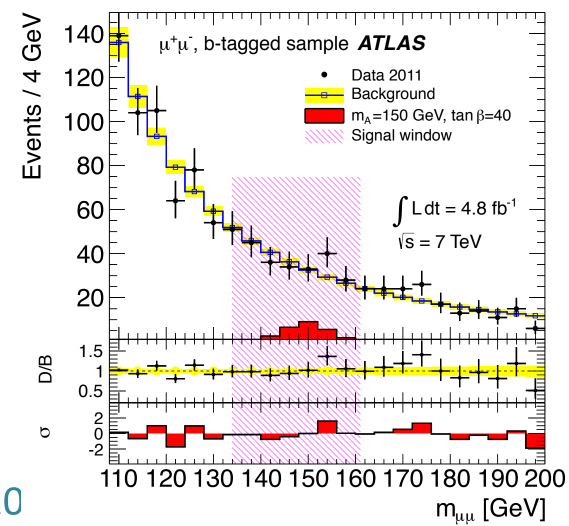
h/H/A→μμ: local sideband fit

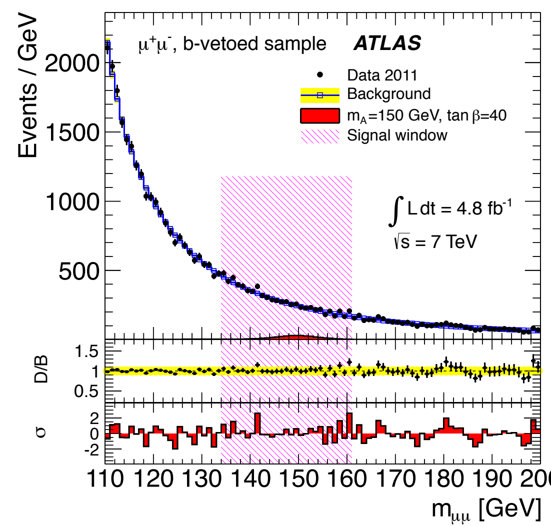
- The function describing the Z/g production is convoluted with a gaussian (to take into account finite mass resolution)

$$f_Z\left(x\,|A,B,m_Z,\Gamma_Z\right)=A\frac{1}{x^2}+B\frac{x^2-m_Z^2}{\left(x^2-m_Z^2\right)^2+m_Z^2\Gamma_Z^2}+\frac{x^2}{\left(x^2-m_Z^2\right)^2+m_Z^2\Gamma_Z^2}.$$

$$f_B\left(x\,|N_B,A,B,m_Z,\Gamma_Z,\sigma\right)=N_B\cdot\left[f_Z\left(x\,|A,B,m_Z,\Gamma_Z\right)\otimes\mathcal{F}_G\left(x\,|0,\sigma\right)\right]$$

- A parametrisation of the background shape is fitted to the μ+μ− invariant mass distribution
- Search windows are defined around each of the expected neutral Higgs bosons and are excluded from the fit
- The upper and lower boundaries of the search windows are defined by the $m_{\mu\mu}$ values where the cross-section predictions of the signal model are 10% of their maximum





H+→taunu (viol of lep univ) - Systematics

Systematic uncertainty	ΔR_e	ΔR_μ
Integrated luminosity	0.3%	0.3%
Electron trigger efficiency	0.1%	N/A
Electron reco. and ID efficiencies	0.2%	1.9%
Electron energy resolution	0.1%	<0.1%
Electron energy scale	0.1%	0.3%
Muon trigger efficiency	N/A	0.1%
Muon reco. and ID efficiencies	1.0%	0.1%
Muon momentum resolution	<0.1%	<0.1%
Muon momentum scale	0.1%	<0.1%
τ ID efficiency	3.9%	3.9%
τ energy scale	2.9%	3.0%
τ mis-ID (data-driven): number of associated tracks	2.1%	2.1%
τ mis-ID (data-driven): true τ_{had} contamination	0.2%	0.2%
τ mis-ID (data-driven): H^+ signal contamination	0.6%	0.6%
τ mis-ID (data-driven): event environment	1.3%	1.2%
τ mis-ID (data-driven): statistical uncertainties	3.3%	3.2%
τ mis-ID (data-driven): electron veto uncertainties	0.6%	0.3%
b-tagging	1.9%	2.3%
Jet vertex fraction	0.1%	0.4%
Jet energy resolution	0.4%	<0.1%
Jet energy scale	0.7%	0.5%
Jet reconstruction efficiency	0.1%	0.4%
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.3%	0.1%
$t\bar{t}$: cross section	0.7%	0.6%
$t\bar{t}$: generator and parton shower	5.7%	4.4%
$t\bar{t}$: initial- and final-state radiation	3.6%	3.7%
Backgrounds with misidentified leptons	3.5%	4.3%
Total (added in quadrature)	10.3%	10.1%

Table 4. Relative variation of the ratios R_e and R_μ in the SM-only hypothesis after shifting a particular parameter by its ±1 standard deviation uncertainty.

H+->taunu (direct search) - Systematics

τ+jets:	
Generator and parton shower ($b\bar{b}WH^+$)	5%
Generator and parton shower ($b\bar{b}W^+W^-$)	5%
Initial and final state radiation	19%

Table 7. Systematic uncertainties arising from the modelling of $t\bar{t} \to b\bar{b}W^+W^-$ and $t\bar{t} \to b\bar{b}WH^+$ events and the parton shower, as well as from initial and final state radiation.

τ+jets: true τ		
Embedding parameters	6%	3%
Muon isolation	7%	2%
Parameters in normalisation	16%	-
τ identification	5%	-
τ energy scale	6%	1%
τ+jets: jet $\to \tau$ misidentification		
Statistics in control region	2%	-
Jet composition	12%	-
Purity in control region	6%	1%
Object-related systematics	21%	2%
τ+jets: $e \to \tau$ misidentification		
Misidentification probability	22%	-
τ+jets: multi-jet estimate		
Fit-related uncertainties	32%	-
$E_{\mathrm{T}}^{\mathrm{miss}}$-shape in control region	16%	-

Table 8. Dominant systematic uncertainties on the data-driven estimates. The shape uncertainty given is the relative shift of the mean value of the final discriminant distribution. A "-" in the second column indicates negligible shape uncertainties.

H+→cs - Systematics

- Systematics on background estimation:
  - QCD multijets background (effects of pileup): 50%
  - W+jets background: 26%
- Uncertainties on the modelling of the detector and on theory:
  - luminosity: 3.9%
  - Trigger efficiency: 3.5% (elesctrons), 1% (muons)
  - Jet scale (1-4.6%) and resolution (16%)
  - B-jet identificaton efficiency (5-17%)
- Effect on the uncertenty on the top quark mass on the event rate: 1.9%

Systematic Source	
Shape dependent	
Jet energy scale	$\pm 9.5\%$
b-jet energy scale	$+0.3, -0.6\%$
c-jet energy scale	$+0.1, -0.3\%$
Jet energy resolution	$\pm 0.9\%$
MC generator	$\pm 4.3\%$
Parton shower	$\pm 3.1\%$
ISR/FSR	$\pm 8.8\%$
Shape independent	
b-tagging efficiency (b-jets)	$\pm 11\%$
b-tagging efficiency (c-jets)	$\pm 2.4\%$
b mistag rate	$\pm 1.8\%$
Lepton identification	$\pm 1.4\%$
Lepton reconstruction	$\pm 1.0\%$
t-quark mass	$\pm 1.9\%$
$t\bar{t}$ cross-section	$+10, -11\%$
Luminosity	$\pm 3.9\%$

Table 2 Effect of the systematic uncertainties on the event rate of $t\bar{t}$ background and signal ($m_{H^+} = 110$ GeV) events before any reduction from the likelihood fit, described in Sect. 6.

H++ - Systematics

- Dominant systematics on the backgrounds:
  - WZ, ZZ cross sections: 12%
  - ttV, WW cross sections: 50% (but their contribution is small)
  - Non-prompt and conversion background uncertainties: up to 40% at low mass
  - Limited statistics of MC or data for background estimation: dominating at high mass
  - Uncertainties on lepton identification, isolation and trigger efficiency are considered as weel but are not the dominant ones
- Uncertainty on pdf: ±1.6 %

h/H/A->tautau/mumu - Systematics

- Data-driven background estimation:
  - < 15% for tautau, < 5% for mummu
  - → Small w.r.t. other systematics
- Cross-section for signal and background samples (including syst due to pdf and renomralization and factorisation scales):
  - 10-20% for signal, 5% for W/Z background
- Acceptance modelling for simulated samples (includes effects of different UE tunes, pdf,…):
  - 2% to 20%
- Lepton identification and trigger:
  - electron identification: 3-6%
  - muon identification: <1.8%
  - tau_had identification: 4-8%
  - Trigger: <1% for electrons, 2-7% di-tau_had
- B-jet identification: 5-17%
- Energy scale and resolution:
  - electrons: 1-3%
  - muons:<1%
  - Tau_had/jets: ~3%
- Luminosity: 3.9%

H→WW - Systematics

Table 3: Relative systematic rate uncertainties for background processes in the 0-jet channel and the 2-jet channel. The uncertainties are rounded to full per cent, but all uncertainties that are smaller than 1% are rounded up. As described in the text above, the exact value of the luminosity uncertainty is 3.6% for each process. DY stands for Drell-Yan processes and the single top-quark processes are denoted $Wt/tq/t\bar{b}$.

Process		$WW/WZ/ZZ/W\gamma/W\gamma^*$	$t\bar{t}/Wt/tq/t\bar{b}$	DY/Z+jets
Jet modelling	0-jet bin	3%	14%	10%
	2-jet bin	11%	37%	12%
Lepton modelling	0-jet bin	2%	2%	6%
	2-jet bin	2%	2%	2%
Lumi	0-jet bin	4%	4%	4%
	2-jet bin	4%	4%	4%
PDF	0-jet bin	6%	6%	6%
	2-jet bin	5%	7%	5%
Generator	0-jet bin	1%	3%	–
	2-jet bin	2%	22%	–
Pile-up modelling	0-jet bin	2%	1%	2%
	2-jet bin	1%	1%	1%
Parton Shower	0-jet bin	–	7%	–
	2-jet bin	–	13%	–
Total	0-jet bin	8%	18%	14%
	2-jet bin	13%	46%	14%
Cross section		25%	22%	34%

H → invisible

Process	Estimation method	Uncertainty (%) 2011	2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	not used
Top quark	MC	90	not used
Top quark, WW and $Z \to \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

Table 2: Summary of the systematic uncertainties on each background and on the signal yield. The method used to estimate the backgrounds and the associated sources of systematic uncertainties are given. The total systematic uncertainties for each data taking period are given.

nMSSM: a0→4gammas - Systematics

- Systematics on the signal yield:
  - trigger efficiency: 4%
  - Signal identification efficiency: 10% per photon
  - Pileup: 2% per reconstructed photon object
  - Isolation cut efficiency: 5% per event
  - → the overall uncertainty on the signal yield is ±21%
- Systematics on the signal resolution:
  - Uncertainty on the constant term (for calo resolution): 12% on the $m_{\gamma\gamma}$ resolution
  - Uncertainty on the energy calibration: 6% on mass resolution
  - Pileup: 3% on mass resolution
  - Pointing resolution: 1%

nMSSM: a1→mumu - Systematics

Table 1: Systematic uncertainties affecting this analysis. The total uncertainty is obtained by adding the individual effects in quadrature.

Source	Relative Uncertainty (%) at $m(a_1)$ (GeV)							
	6.0	6.5	7.0	7.5	8.0	8.5	11.0	11.5
Luminosity	±3							
PYTHIA vs MC@NLO	±67	±55	±49	±40	±36	±32	±20	±20
Dimuon Efficiency	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+15}_{-14}$	$^{+15}_{-14}$
Trigger Correction	±8							
MC Statistics	±10	±10	±10	±10	±10	±10	±9	±9
Likelihood Ratio Modeling	±3							
Total (Pythia vs MC@NLO)	±70	±59	±53	±45	±41	±37	±28	±28