Search for charged Higgs bosons using other final states

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on behalf of the ATLAS collaboration

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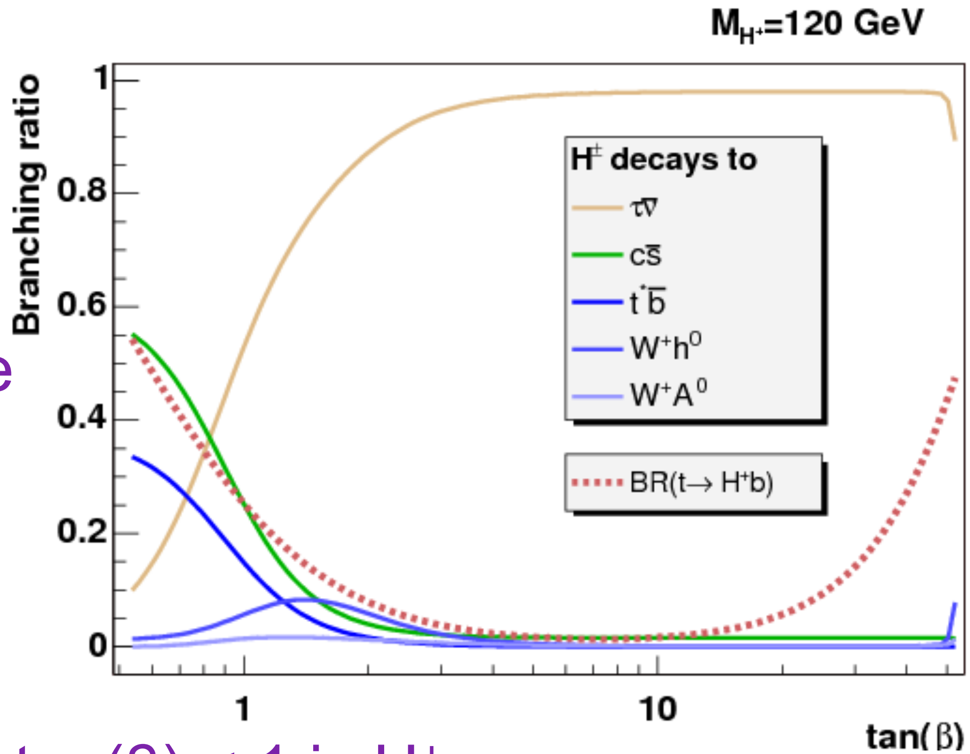
- Many extensions of the SM have more than one Higgs boson
- In generic 2HDMs (including the MSSM), there are 5 Higgs bosons, 2 of them charged
- For a light charged Higgs boson:



★ The dominant decay for tan(β) < 1 is $H^+ \rightarrow cs$

★ The dominant decay for tan(β) > 1 is $H^+ \rightarrow \tau\nu$

★ $H^+ \rightarrow Wh^\circ$ can also be sizeable and may appear in a multi-Higgs-boson cascade topology

In this talk:

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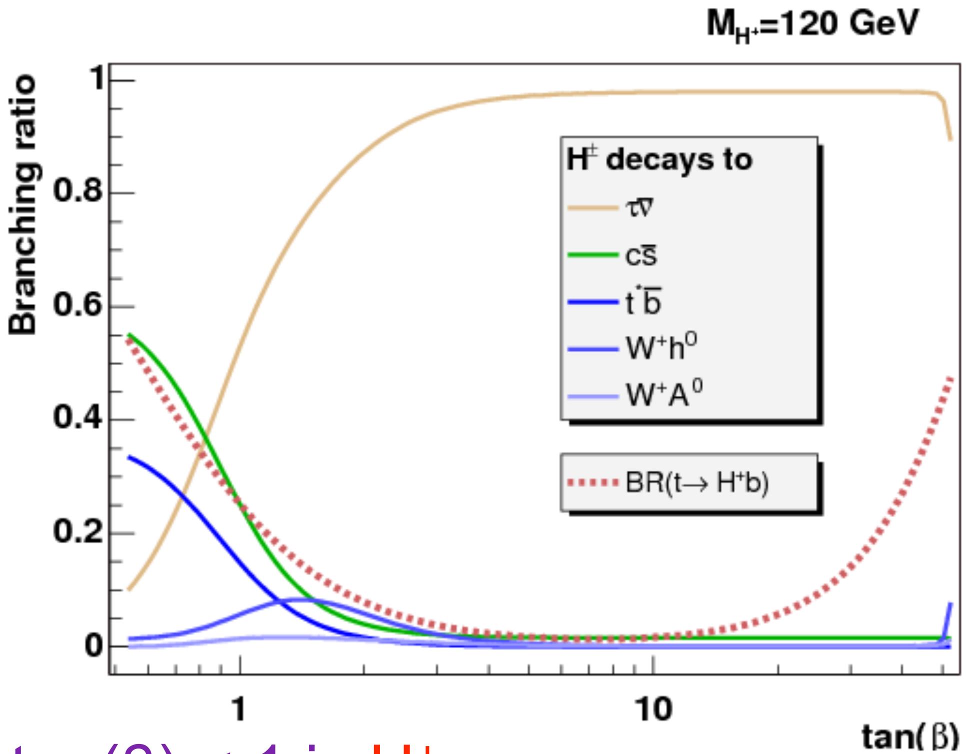
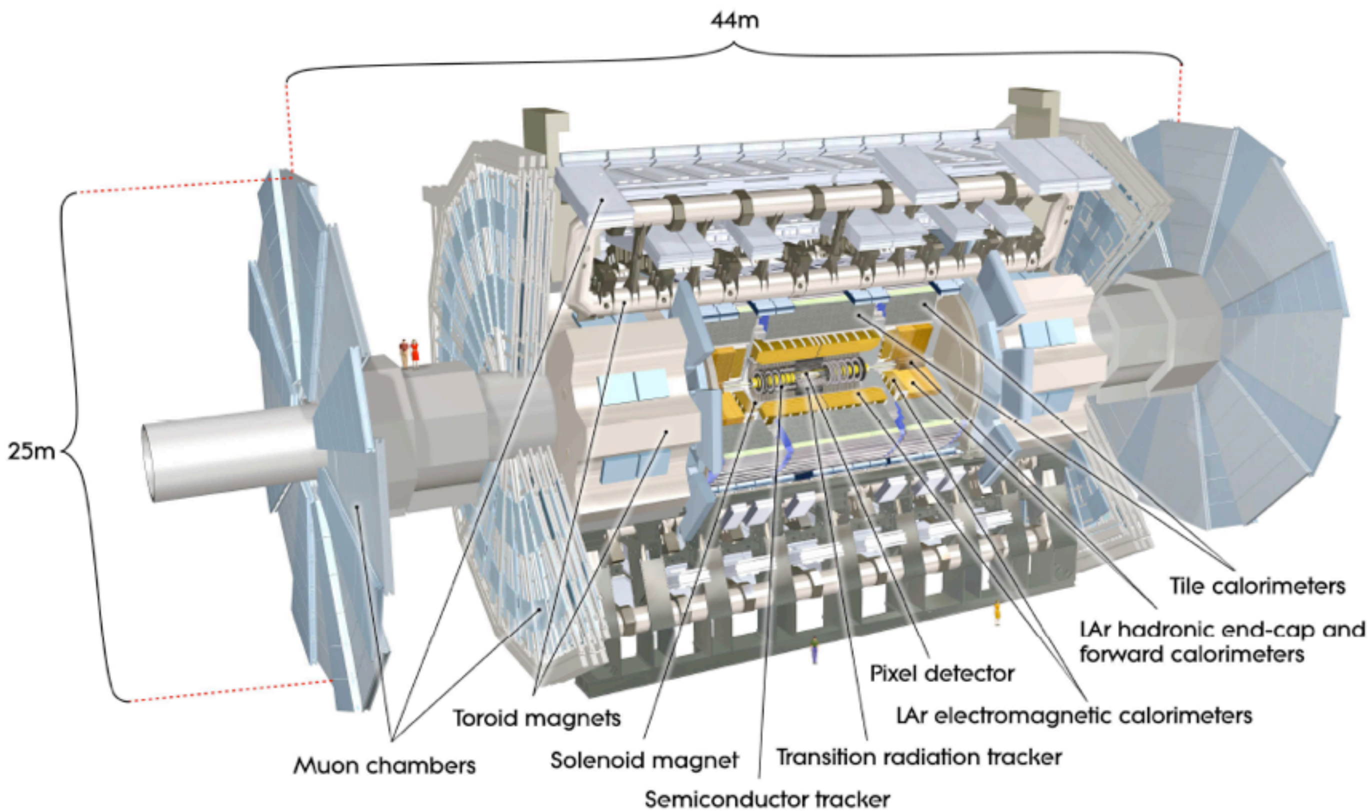


★ The dominant decay for tan(β) < 1 is H^+➔cs

★ The dominant decay for tan(β) > 1 is H^+➔$\tau\nu$ (ratio method)

★ H^+➔Wh° can also be sizeable and may appear in a multi-Higgs-boson cascade topology

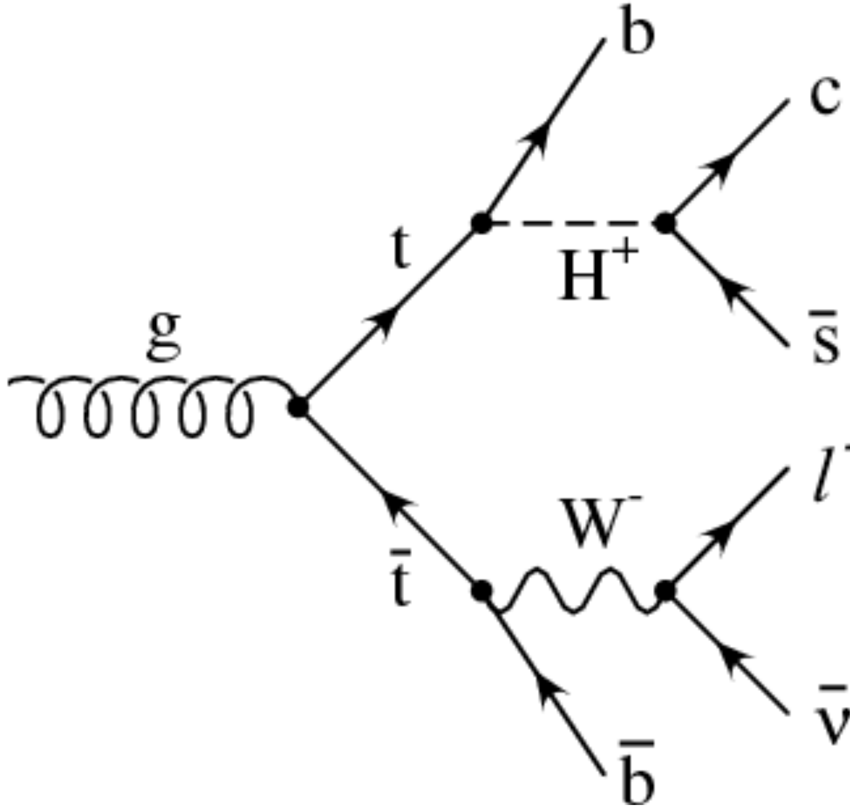
The ATLAS detector



Recorded data corresponding to an integrated luminosity of 20.3 fb^{-1} at $\sqrt{s}$=8 TeV and 4.7 fb^{-1} at $\sqrt{s}$=7 TeV in Run 1 of the LHC

H+->cs selection

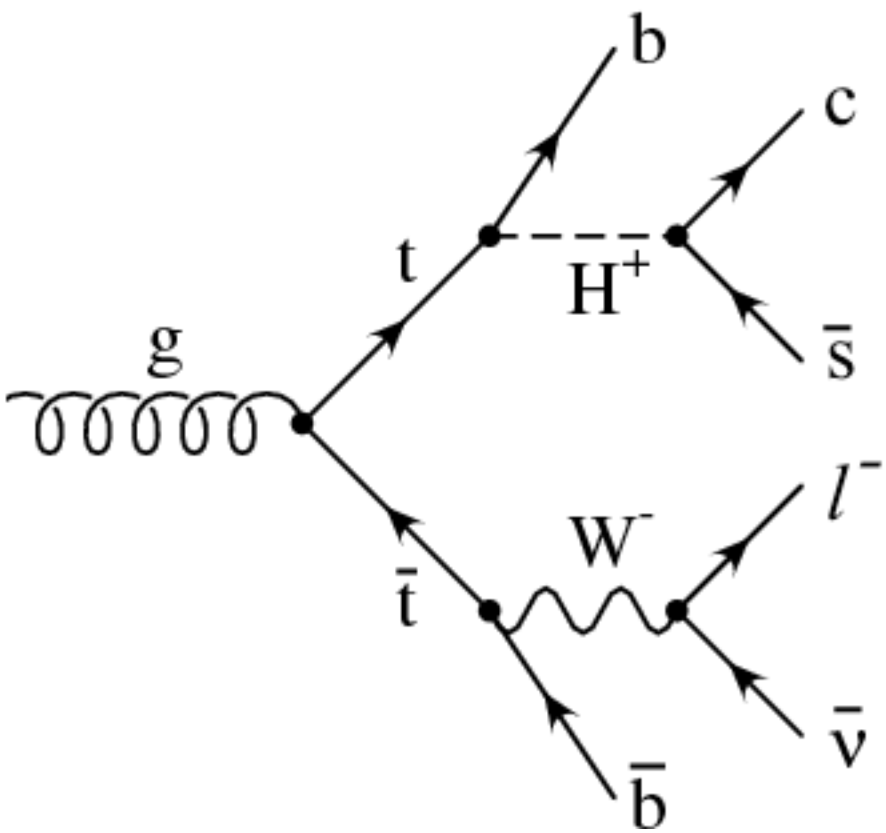
- Lepton + jets selection
- Jets:
  - ★ 4 or more jets (p_T > 25 GeV)
  - ★ 2 b-tagged jets (70% heavy flavour tagging efficiency)
- Electron channel:
  - ★ 1 electron with p_T > 25 GeV
  - ★ E_T^{miss} > 30 GeV
  - ★ m_T^e > 30 GeV
- Muon channel:
  - ★ 1 muon with p_T > 25 GeV
  - ★ E_T^{miss} > 20 GeV
  - ★ $E_T^{miss} + m_T^{\mu}$ > 60 GeV



$$m_T = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - \cos \Delta\phi)}$$

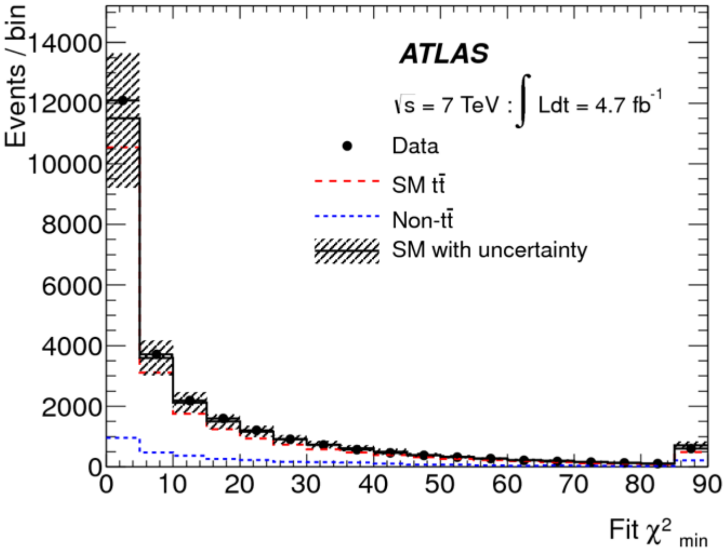
H+->cs kinematic fit

- Fully reconstruct the ttbar system
- Kinematic fitter used to reconstruct mass of dijets from W/H^+ boson candidates
- Lepton, E_T^{miss} and the 4 jets assigned to the decay particles of the ttbar system
- p_Z of the neutrino found by fixing m_W (real part taken)
- Invariant mass of the two systems (b/ν,bjj) to be within 1.5 GeV of the top-quark mass



H+->cs kinematic fit

- The combination with the smallest χ^2 value is selected
- The distribution agrees well with the simulation
- Events are required to have $\chi^2 < 10$

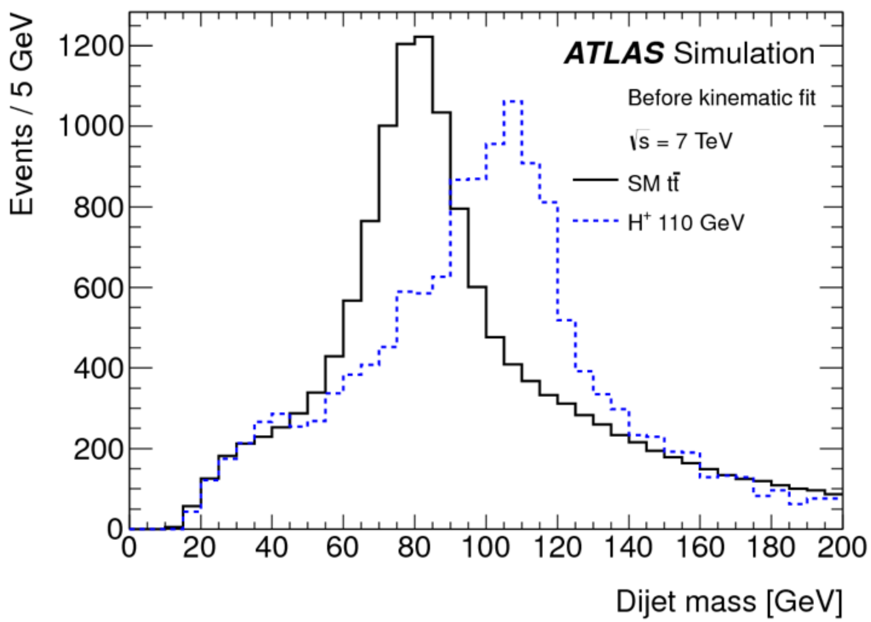


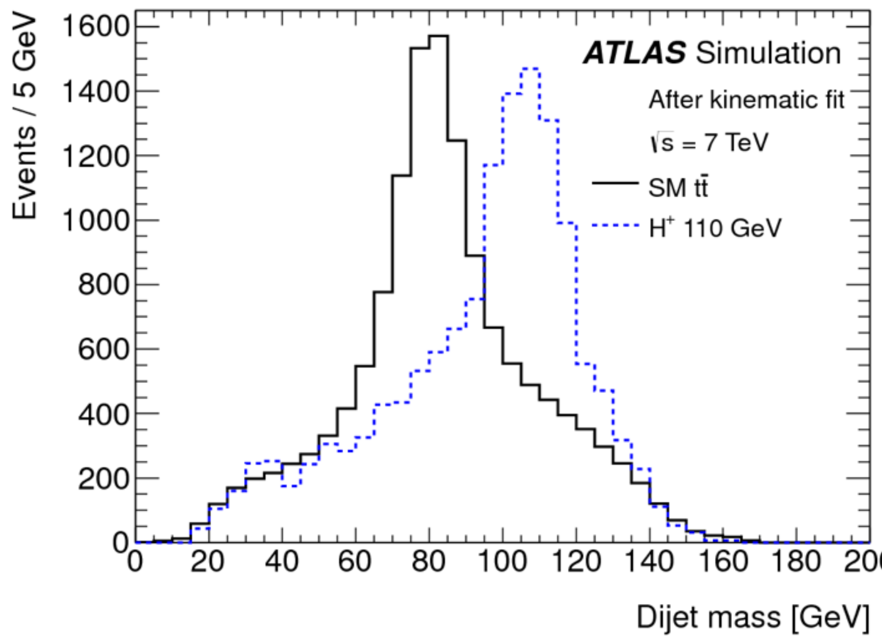
$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{(p_{\mathrm{T}}^{i,\text{fit}} - p_{\mathrm{T}}^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{\text{SEJ,fit}} - p_j^{\text{SEJ,meas}})^2}{\sigma_{\text{SEJ}}^2} + \sum_{k=jjb,b\ell\nu} \frac{(m_k - m_t)^2}{\Gamma_t^2}.$$

★ p_T of the lepton and 4 jets allowed to vary around the measured values
★ Vector sum of momenta of remaining jets
★ Constrains the hadronic and leptonic top-quark candidates

H+->cs kinematic fit

- This selection has an efficiency of 63% for SM ttbar events
- The fit results in a 20-30% improvement in the dijet mass resolution
- After the fit, there is a better discrimination between the mass peaks of the W and H^+ bosons





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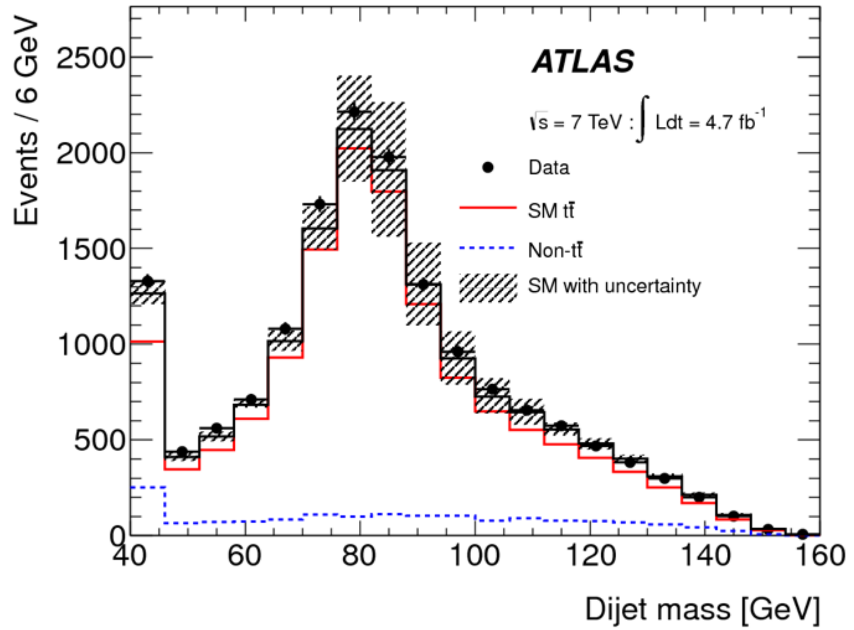
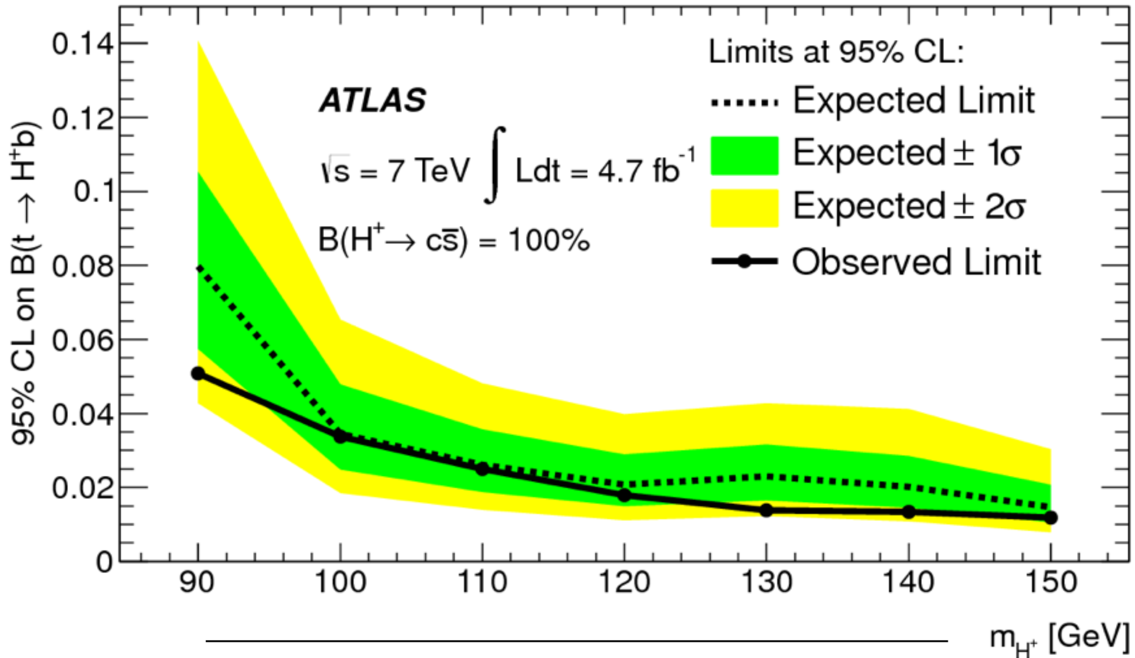
- The QCD multi-jet background is estimated using a data-driven method
- The dijet mass distribution is measured from a control region where leptons are isolated
- The W+jets background is estimated using the charge asymmetry method



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

H+->cs limits

- Upper limits on
- Br($t \rightarrow H^+b$) extracted as a function of m_{H+}
- It is assumed that the H^+ boson always decays to csbar
- The probability for the background to produce the observed mass distribution is 67-71%: no significant deviation from the background
- Br($t \rightarrow bH^+$) < 1.2% - 5.1% for m_{H+}=90 GeV to 150 GeV



Higgs mass	Expected limit (stat.⊕ syst.)	Observed limit (stat.⊕ syst.)
90 GeV	0.080	0.051
100 GeV	0.034	0.034
110 GeV	0.026	0.025
120 GeV	0.021	0.018
130 GeV	0.023	0.014
140 GeV	0.020	0.013
150 GeV	0.015	0.012

H+->$\tau\nu$ (ratio method)

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- Alternative method: measure the ratio of event yields between two ttbar final states
- This allows for the cancelation of most systematic uncertainties
  - ★ W bosons decay equally to leptons from the 3 generations
  - ★ H^+ boson may decay predominantly into $\tau\nu$
  - ★ An excess of ttbar events with at least one τ in the final state compared to events with only e or μ is a signature for the H^+ boson

$$R_l = \frac{\mathcal{B}(t\bar{t} \to b\bar{b} + l\tau_{\text{had}} + N\nu)}{\mathcal{B}(t\bar{t} \to b\bar{b} + ll' + N\nu)}.$$

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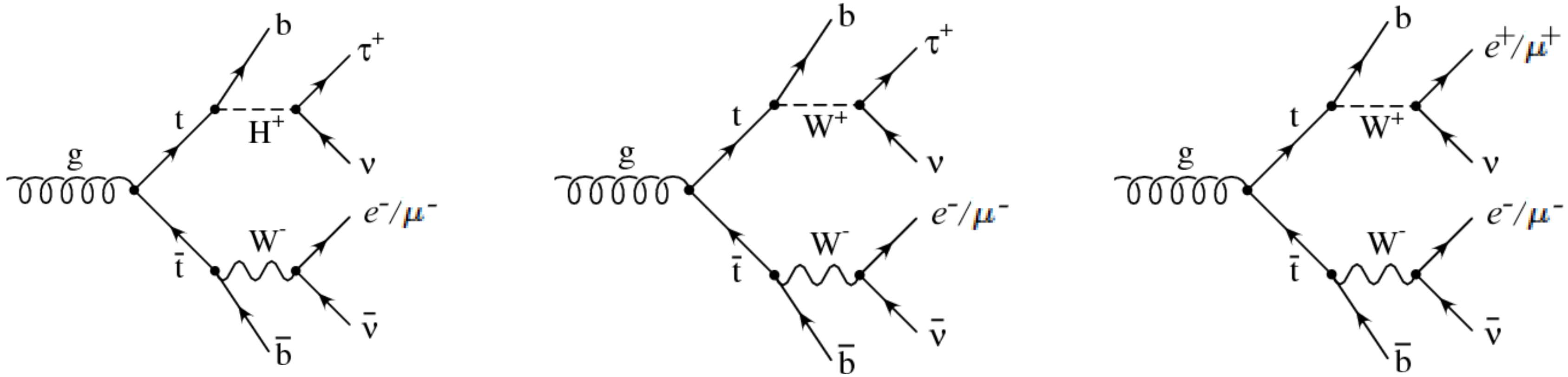

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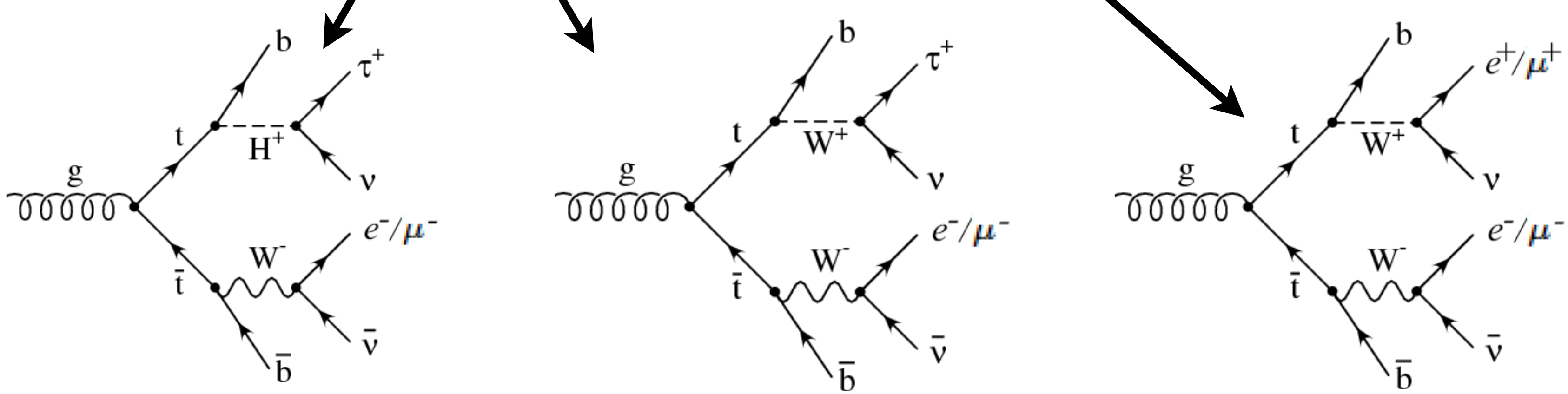
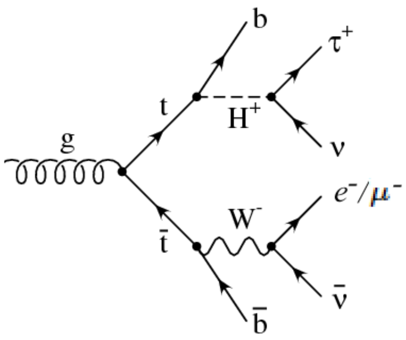
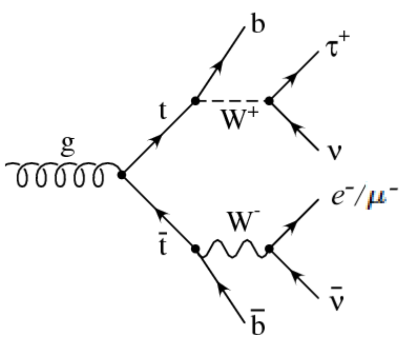
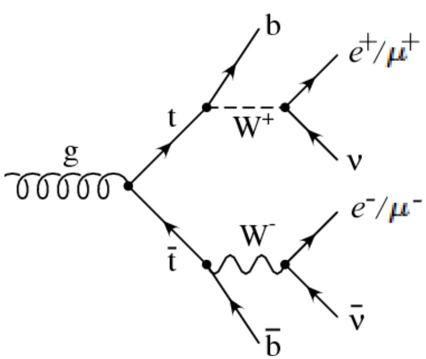


H+->$\tau\nu$ (ratio method) – Selection

- Jets:
  - ★ 2 or more jets (p_T > 20 GeV)
  - ★ Exactly 2 b-tagged jets
- Electron channel:
  - ★ 1 electron with E_T > 25 GeV - trigger matched
- Muon channel:
  - ★ 1 muon with p_T > 25 GeV - trigger matched
- Either:
  - ★ Exactly 1 τ-jet with p_T > 25 GeV or,
  - ★ Exactly one additional lepton (different flavour to the trigger matched)
- E_T^{miss} > 40 GeV
- Events are categorised depending on the single lepton trigger that was fired







H+->$\tau\nu$ (ratio method) - OS and SS events

- The majority of misidentified τ jets come from jets
- It is impossible to accurately predict the fraction of all jet types (light quarks, heavy quarks, gluons)

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• But, the influence of all jet types other than light quark jets can be eliminated by categorising events as OS or SS

- ★ OS: opposite sign (charge of the lepton compared to the charge of the τ jet)
- ★ SS: same sign (charge of the lepton compared to the charge of the τ jet)

H+->$\tau\nu$ (ratio method) – OS and SS events

http://atlas.ch

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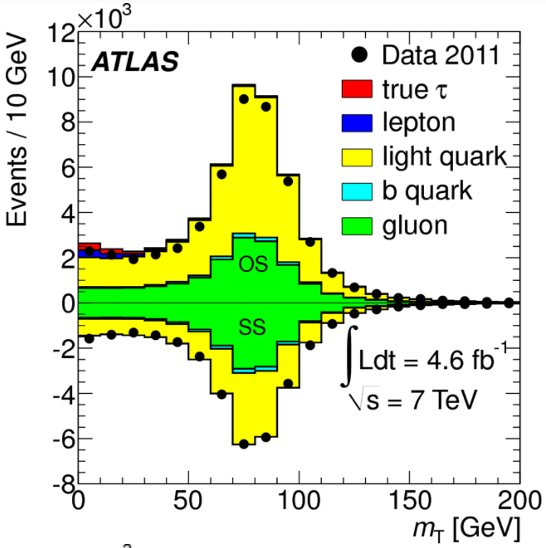
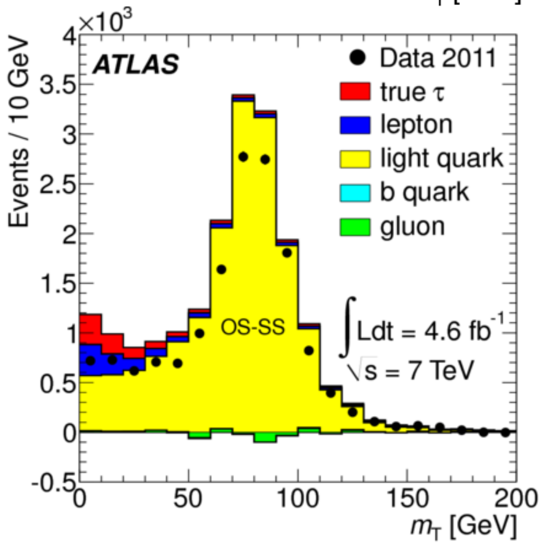
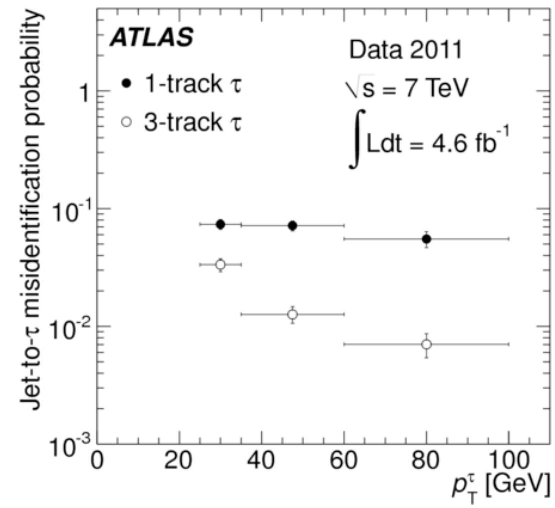
- It is impossible to accurately predict the fraction of all jet types (light quarks, heavy quarks, gluons)
- But, the influence of all jet types other than light quark jets can be eliminated by categorising events as OS or SS
- Assume heavy quarks and gluon jets misidentified as τ jets contribute equally to OS and SS events - assign negative weight to SS events. This is used throughout the whole analysis

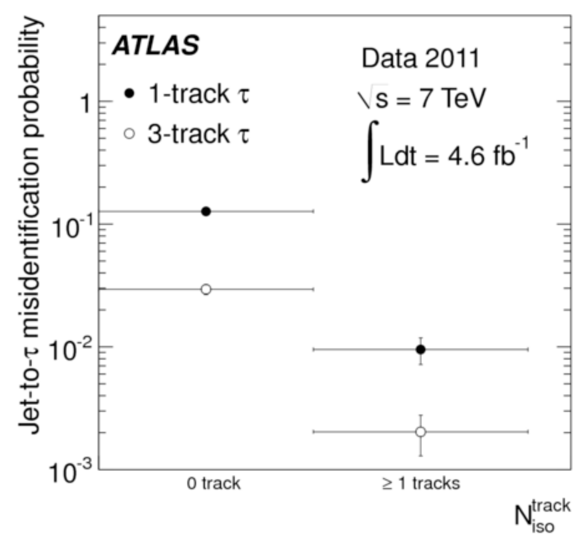




H+->$\tau\nu$ (ratio method) – Backgrounds

- Misidentified leptons
  - ★ Estimated from data using a loose selection on the leptons. Small contribution
- Misidentified τ jets
  - ★ Only 51% of selected τ jets in simulated ttbar events are matched to a truth τ
  - ★ Misidentification from heavy quarks and gluons removed by OS-SS
  - ★ Rate at which jets from light quarks are misidentified is measured in data using a W +2 jets selection and parametrised in bins of p_T^τ and number of tracks
- Backgrounds with real leptons and taus taken from simulation





H+->$\tau\nu$ (ratio method) – Results

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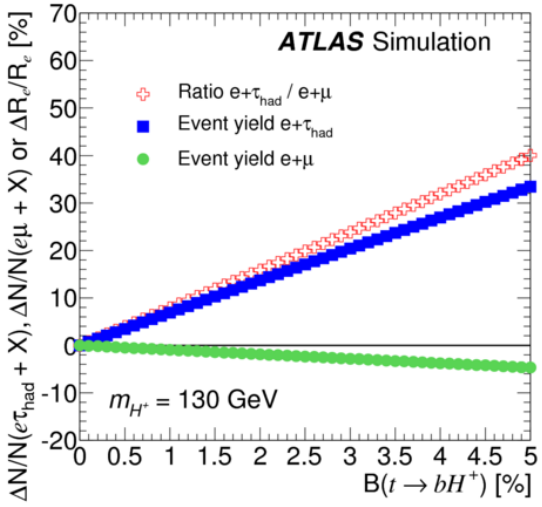
- The event yields are split into contributions from ttbar events and all other SM processes

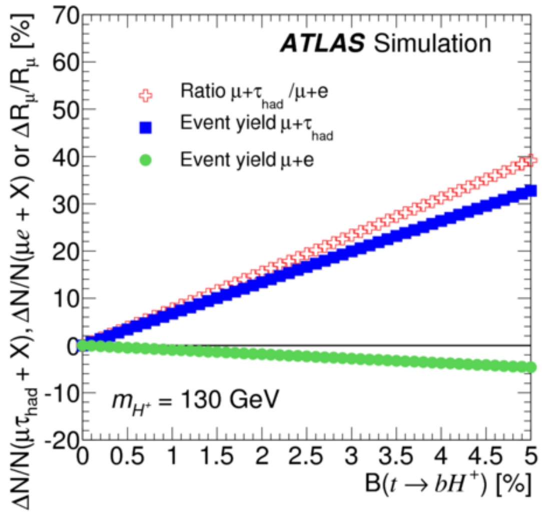
$$R_e = \frac{\mathcal{N}(e+\tau_{\text{had}})}{\mathcal{N}(e+\mu)} \qquad R_\mu = \frac{\mathcal{N}(\mu+\tau_{\text{had}})}{\mathcal{N}(\mu+e)}$$

- Predicted SM and measured ratios:

Ratio	R_e	R_μ
SM value	0.105 ± 0.012	0.166 ± 0.017
Measured value	0.115 ± 0.010 (stat)	0.165 ± 0.015 (stat)

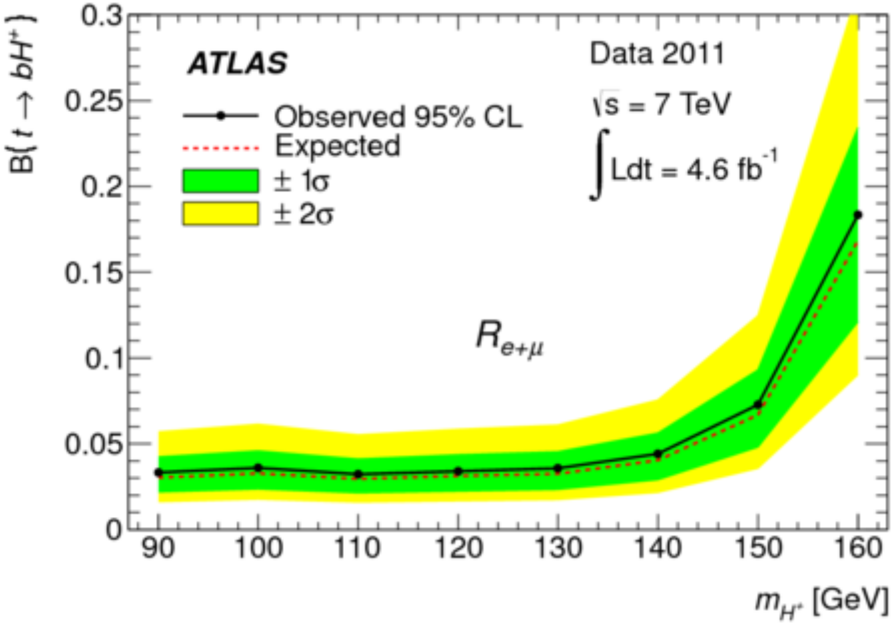
- Total systematic uncertainty ~10% for both
- Largest uncertainties: τ-ID efficiency, ttbar generator and parton shower variations and backgrounds with misidentified leptons
- Sensitivity of the analysis to charged Higgs bosons depends on the rate at which the ratios change with Br(t→b H$^+$)

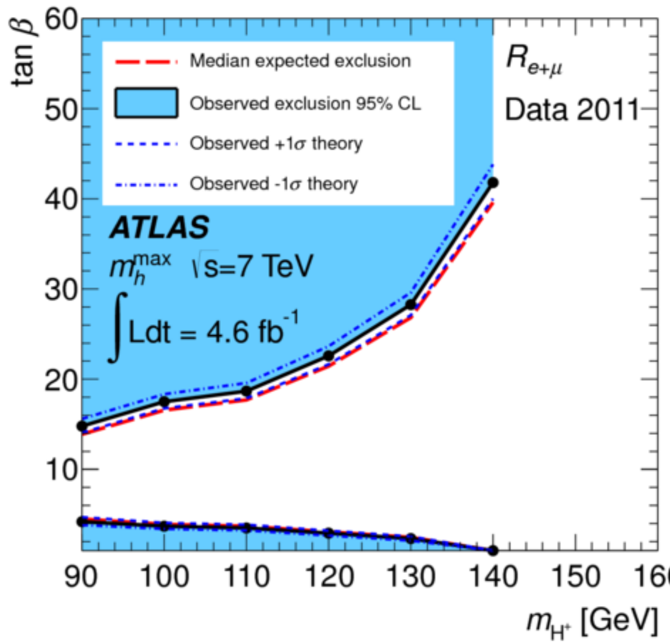




H+->$\tau\nu$ (ratio method) - Limits

- A profile likelihood ratio is used with R_e and R_μ as the discriminating variables
- Upper limits between 3.2%-4.4% can be placed on Br(t→b H^+)
- Limits for H^+ production can also be placed in the context of the m_h-max scenario of the MSSM





Multi-boson Higgs cascade

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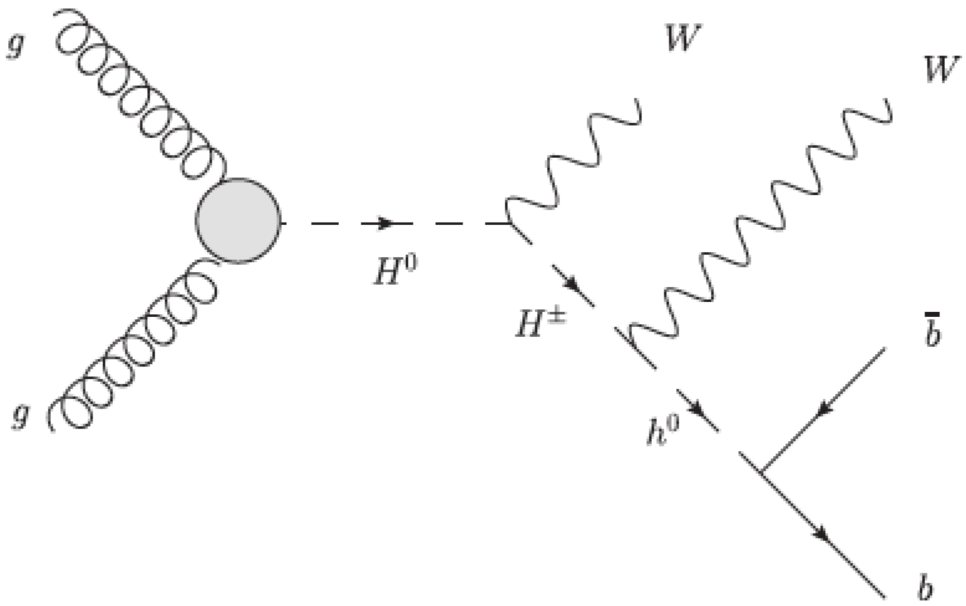
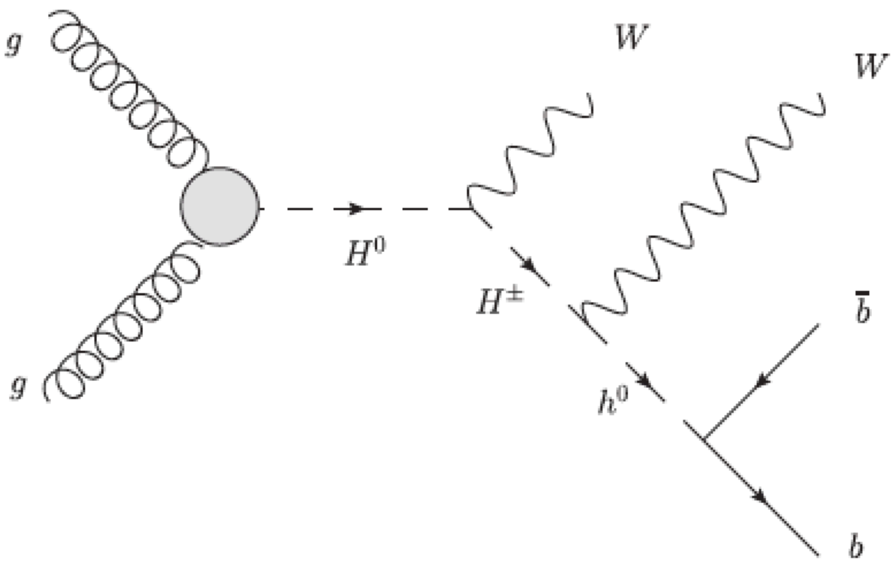
- Search for a multi-Higgs-boson cascade topology
- Assume there are other Higgs bosons but no particular model (m_{ho} assumed to be 125 GeV)
- Final state: W^+W^-bb



★ One of the W bosons is assumed to decay hadronically
★ The other W boson is assumed to decay leptonically
★ BDTs are used to distinguish the Higgs-boson cascade events from the ttbar events

Multi-boson Higgs cascade – Selection

- Lepton + jets selection
- Jets:
  - ★ 4 or more jets (p_T > 25 GeV)
  - ★ 2 b-tagged jets (70% heavy flavour tagging efficiency)
- Electron channel:
  - ★ 1 electron with p_T > 25 GeV
  - ★ E_T^{miss} > 30 GeV
  - ★ m_T^e > 30 GeV
- Muon channel:
  - ★ 1 muon with p_T > 25 GeV
  - ★ E_T^{miss} > 20 GeV
  - ★ $E_T^{miss} + m_T^{\mu}$ > 60 GeV



Multi-boson Higgs cascade – Reconstruction

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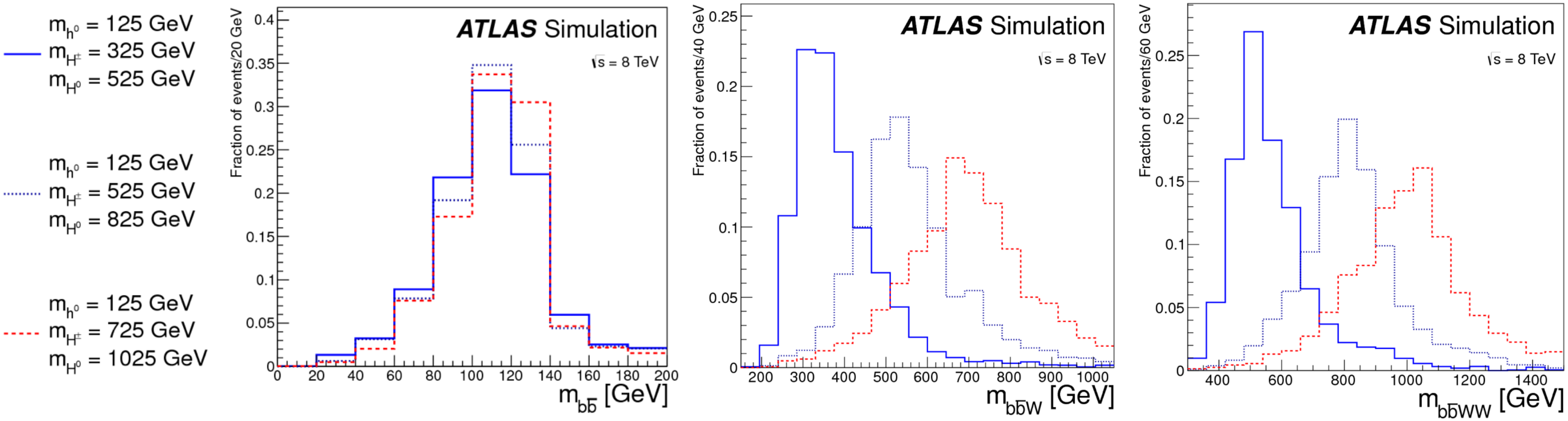
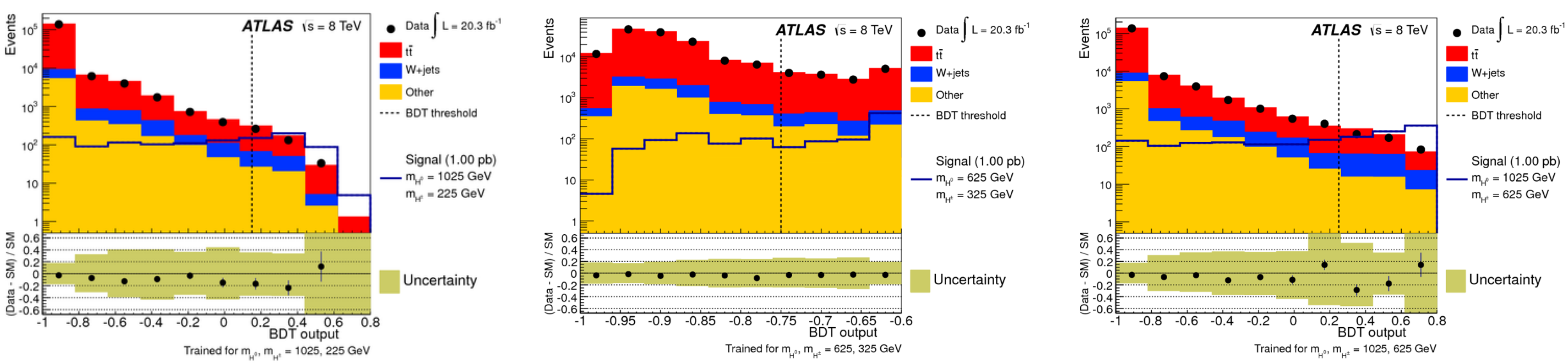
- First we identify the leptonically-decaying W
- The 2 b-tagged jets are used to reconstruct the lightest Higgs boson candidate (h^0)
- The hadronically-decaying W is identified from the remaining jets
- The charged Higgs boson candidate is constructed from the h^0 and the W boson which gives the largest m_{H+}
- The heavy neutral Higgs boson (H^0) is then formed as W^+W^-bb



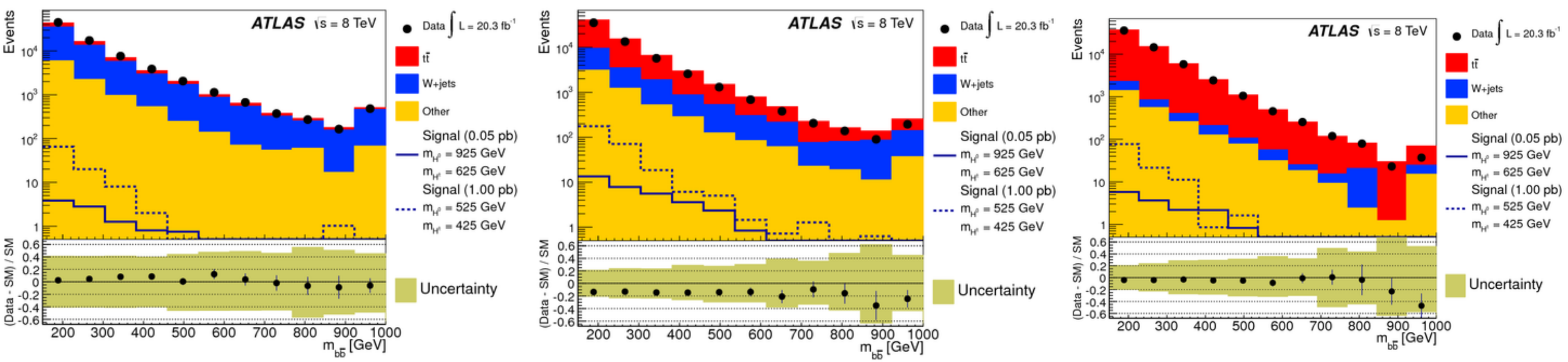
Multi-boson Higgs cascade – MVA

- A MVA is used to distinguish the Higgs-boson cascade from ttbar
- 7 kinematic variables chosen as input to the BDT:
  - ★ m_{bb}, m_{bbW}, m_{bbWW}
  - ★ ΔR_{bb}
  - ★ Hadronic and leptonic m_t and their difference
- A different BDT is trained for each signal mass hypothesis



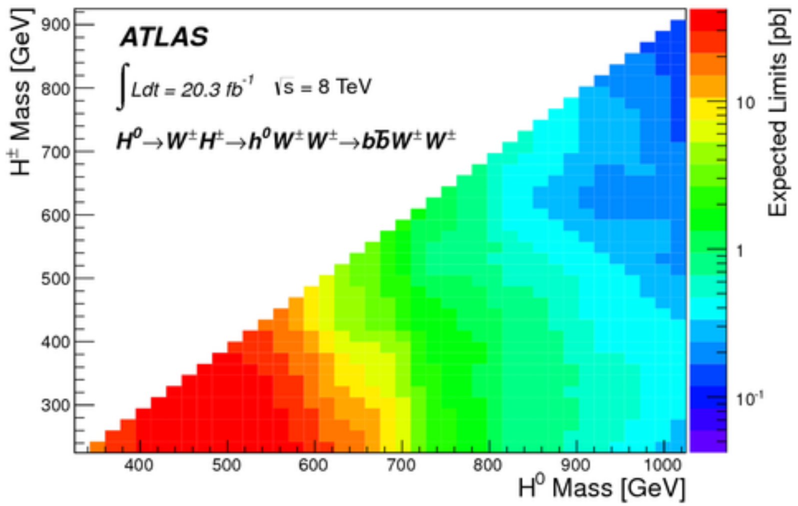
Multi-boson Higgs cascade – Backgrounds

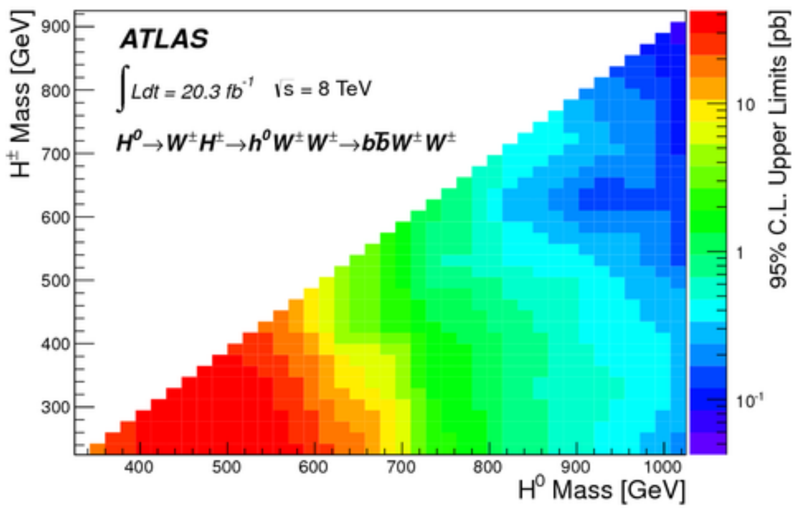
- 3 control regions are used to validate the modeling of the SM backgrounds:
  - ★ CR1: at least 4 jets, exactly 1 lepton and no b-tagged jets (W+jets)
  - ★ CR2: at least 4 jets, exactly 1 lepton and exactly 1 b-tagged jet (ttbar)
  - ★ CR3: at least 4 jets, exactly 1 lepton, at least 2 b-tagged jet and m_{bb} > 150 GeV (ttbar)



Multi-boson Higgs cascade – Results

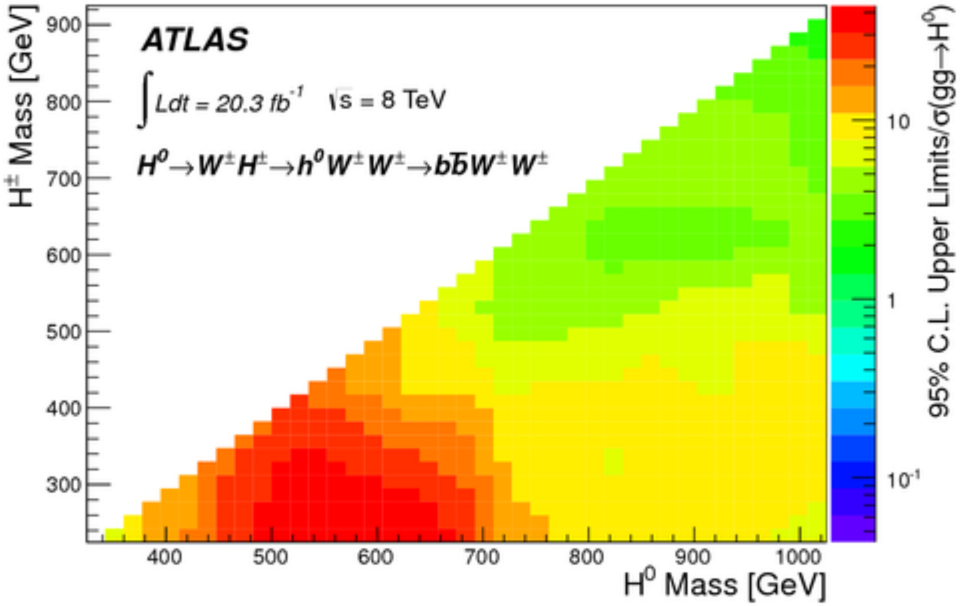
- The observed yields are found to be consistent with SM background expectations within uncertainties
- The 95% CL production cross section upper limits for the various signal hypothesis are obtained
- Compare limits to the production cross section of a heavy neutral SM-like Higgs boson
- The cross section upper limits observed are greater than the theoretical NNLO production cross sections for all mass points





Multi-boson Higgs cascade - Results

- Limits are not stringent enough to exclude models with SM-like production rates even with 100% BR for $H^0 \rightarrow H^+W^-$ and $H^\pm \rightarrow h^0W^+$ and SM values for Br(h0→bb)
- Ratio of observed upper limits and theoretical production cross section of the heavy Higgs boson
- Limits are more stringent in the high mass region (but still > 1)



Summary

- Three different ATLAS searches for a charged Higgs boson were presented in this talk
- No excess with respect to the SM predictions is found
- $Br(t \rightarrow bH^{+}) \times Br(H^{+} \rightarrow cs) < 1.2\% - 5.1\%$ (m_{H+}=90-150 GeV)
- $Br(t \rightarrow bH^{+}) \times Br(t \rightarrow \tau\nu) < 3.2\% - 4.4\%$ (m_{H+}=90-160 GeV)
- Limits on the production cross section times the branching ratio for $gg \rightarrow H^{0} \rightarrow WH^{+} \rightarrow W^{+}W^{-}h^{0} \rightarrow W^{+}W^{-}bb$ range from 0.065 to 43 pb as a function of m_{H+} and m_{H0}

References

- H± → csbar: Eur.Phys.J.C, 73 6 (2013) 2465
- Ratio method: JHEP 1303 (2013) 076 (2013)
- Higgs-boson cascade: Phys. Rev. D 89, 032002 (2014)

Back-up

The ATLAS detector

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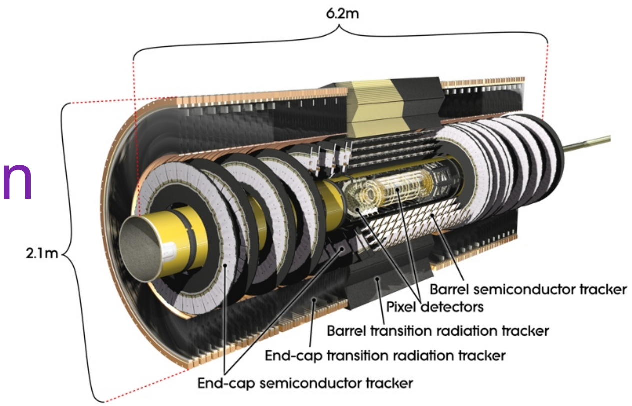
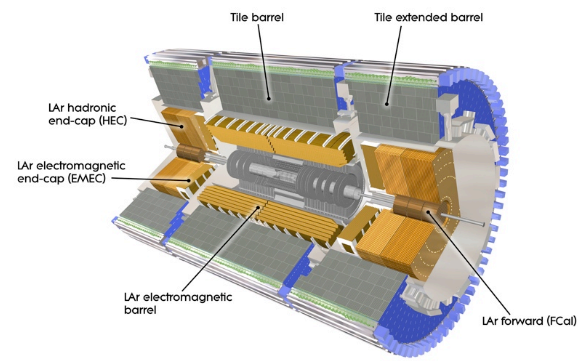
- Inner detector:
  - ★ Coverage up to $|\eta|<2.5$
  - ★ Provides additional z-vertex information
  - ★ Independent from the calorimeters
  - ★ Precision tracking and vertexing



- Calorimeters:
  - ★ High granularity calorimeter
  - ★ Fine longitudinal segmentation
  - ★ Readout cells: $\Delta\eta \times \Delta\phi \approx 0.025\times0.025$
  - ★ Good Had. calorimeter resolution
  - ★ Precise position measurement



- Muon spectrometer:
  - ★ Monitored drift tubes (MDT) for precision measurement
  - ★ RPCs for triggering

H+->cs kinematic fit (p_z^ν)

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- To obtain the longitudinal momentum of the neutrino:

$$\begin{aligned} m^2_{W,true} &= m^2_{\ell\nu} \\ &= m^2_\ell - 2(p^\ell_x p^\nu_x + p^\ell_y p^\nu_y) + 2E_\ell\sqrt{(E^{\rm miss}_{\rm T})^2 + (p^\nu_z)^2} - 2(p^\ell_z p^\nu_z). \end{aligned}$$

- Which leads to a quadratic equation:

$$a p^{\nu 2}_z + b p^\nu_z + c = 0$$

$$\begin{aligned} a &= E^2_\ell - p^{\nu 2}_z \\ b &= -2p^\nu_z\left(\frac{m^2_{W,true} - m^2_\ell}{2} + p^\ell_x p^\nu_x + p^\ell_y p^\nu_y\right) \\ c &= E^2_\ell E^{\rm miss\,2}_{\rm T} - \left(\frac{m^2_{W,true} - m^2_\ell}{2} + p^\ell_x p^\nu_x + p^\ell_y p^\nu_y\right)^2 \end{aligned}$$

- Two solutions for the longitudinal momentum are found:

$$p^\nu_{z\,1,2} = \frac{-b \pm \sqrt{d}}{2a} \qquad d = b^2 - 4ac$$

- For each solution a W boson candidate is constructed
- When complex solutions are returned, the real part is used

H+->cs results (dijet mass)

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- The dijet mass distribution is measured from a control region where leptons are isolated:
  - ★ p_T of tracks in a cone of radius ΔR excluding the lepton satisfies:

$$0.1 < p_{\mathrm{T}}^{\Delta R=0.3} / p_{\mathrm{T}}(e, \mu) < 0.3.$$

  - ★ Leptons are also required to have a large impact parameter w.r.t. the identified primary vertex:

$$0.2 \text{ mm} < |d_0| < 2 \text{ mm}$$

  - ★ Finally, an impact parameter significance:

$$|d_0|/\sigma_{d_0} > 3$$

H+->cs results (charge asymmetry)

- The W+jets background is estimated using the charge asymmetry method
  - ★ The ratio between the number of positively and negatively charged W bosons is well modeled: $Rmc = \frac{N_{W^+}}{N_{W^-}}$
  - ★ The difference between N_{W+} and N_{W-} from MC is replaced by the same difference but in data:

$$N_{W_{tot}} = \frac{N_{W^+} + N_{W^-}}{N_{W^+} - N_{W^-}} \times (N_{W^+} - N_{W^-})$$
$$N_{W_{tot}} = \frac{Rmc + 1}{Rmc - 1} \times (N_{Data^+} - N_{Data^-})$$

  - ★ The normalisation of the MC W+jets estimation to the data driven estimation is then:

$$SF = \frac{N_{W_{tot}DD}}{N_{W_{tot}MC}}$$

H+->cs limits (expected number of events)

- Likelihood function to estimate the expected number of events as a function of the branching ratio:

$$\mathcal{L}(\mathcal{B},\alpha) = \prod_i \frac{\nu_i(\mathcal{B},\alpha)^{n_i} e^{-\nu_i(\mathcal{B},\alpha)}}{n_i!} \prod_j \frac{1}{\sqrt{2\pi}} e^{-\frac{\alpha_j^2}{2}}$$

- n_i is the number of events in bin i of the dijet mass distribution and j labels the sources of systematic uncertainties
- The number of expected signal+background events in each bin:

$$\nu_i(\mathcal{B},\alpha) = 2\mathcal{B}(1-\mathcal{B})\sigma_{t\bar{t}}\mathcal{L}A^{H^+} S_i^{H^+} \prod_{j\neq b} \rho_{ji}^{H^+}(\alpha_j) + (1-\mathcal{B})^2\sigma_{t\bar{t}}\mathcal{L}A^{W} S_i^{W} \prod_{j\neq b} \rho_{ji}^{W}(\alpha_j) + n_i^N \rho_{bi}^N(\alpha_b)$$

- $\mathcal{B}$ → Br(t→bH⁺)
- $\mathcal{L}$ → Integrated luminosity
- A → Acceptance
- S_i → Describes the shape of the m_{jj} spectrum
- α_j → Nuisance parameters (systematic uncertainties)
- ρ_{ji} → Effect of α on the yields
- n_i^N → Expected # of non ttbar bkg events

H+->$\tau\nu$ (ratio method) – Selection – τ ID

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- τ candidates:
  - ★ Jets with 1 or 3 associated tracks and $E_T > 10$ GeV
  - ★ $p_T > 20$ GeV and $|\eta| < 2.3$
- Hadronic τ decays are identified using a likelihood criterion designed to discriminate against quark and gluon initiated jets
- A working point with an efficiency of about 30% for hadronically-decaying τ leptons in $Z \rightarrow \tau\tau$ events is chosen
- Rejection factor of about 100-1000 for jets
- Only τ candidates that fulfill the likelihood criterion are referred to as τ jets

H+->$\tau\nu$ (ratio method) – Reconstruction

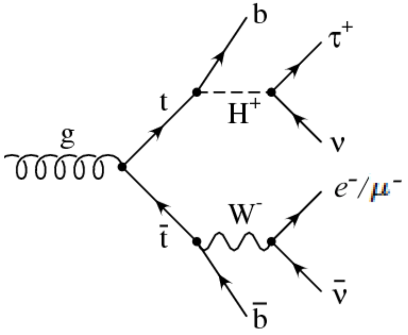
- m_{T2}^{H} is used as a selection variable
- It gives an event-by-event lower bound on the mass of the charged boson produced in the top decay

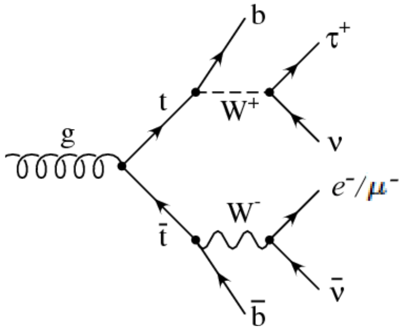
$$m_{T2}^{H} = \max_{\{\text{constraints}\}} \left[m_T^H(\vec{p}_{\mathrm{T}}^{\,H^+}) \right]$$

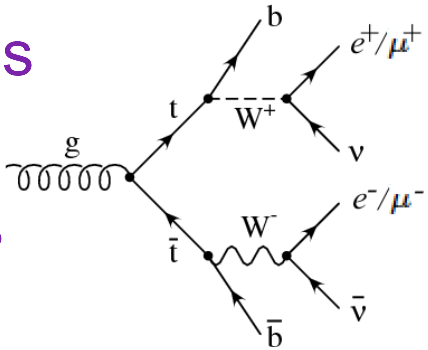
$$\left(m_T^H(\vec{p}_{\mathrm{T}}^{\,H^+})\right)^2 = \left(\sqrt{m_{\text{top}}^2 + (\vec{p}_{\mathrm{T}}^{\,H^+} + \vec{p}_{\mathrm{T}}^{\,b})^2} - p_{\mathrm{T}}^b\right)^2 - \left(\vec{p}_{\mathrm{T}}^{\,H^+}\right)^2$$

$$\begin{aligned} (p^{H^+} + p^b)^2 &= m_{\text{top}}^2, \\ (p^{\ell} + p^{\bar{\nu}_\ell})^2 &= m_W^2, \\ (p^{\ell} + p^{\bar{\nu}_\ell} + p^{\bar{b}})^2 &= m_{\text{top}}^2, \end{aligned} \qquad \begin{aligned} (p^{\bar{\nu}_\ell})^2 &= 0, \\ \vec{p}_{\mathrm{T}}^{\,H^+} - \vec{p}_{\mathrm{T}}^{\,\tau^+_{\text{had}}} + \vec{p}_{\mathrm{T}}^{\,\bar{\nu}_\ell} &= \vec{p}_{\mathrm{T}}^{\,\text{miss}} \end{aligned}$$

- The b-jets are assigned by selecting the combination that minimises the sum of the distances between the b-jet and either the lepton or the τ
- In simulated SM ttbar events, the efficiency of this association is about 70%







H+−>$\tau\nu$ (ratio method) – Backgrounds – miss ID leptons

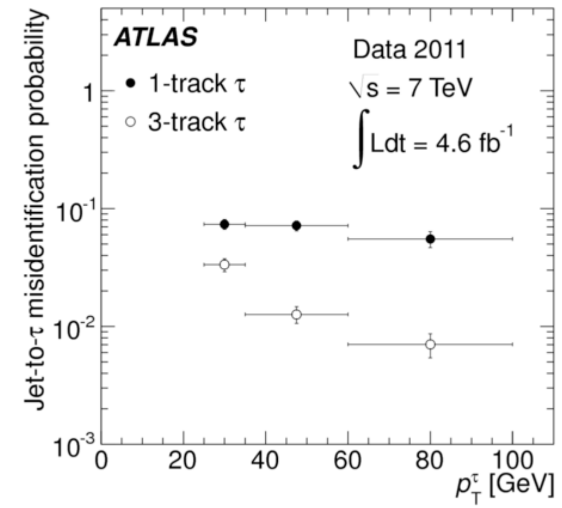
- Misidentified leptons - Estimated from data 2 samples:
  - ★ Tight: mostly real leptons - same selection as in the analysis
  - ★ Loose: mostly misidentified leptons - looser isolation and identification requirements on the leptons
- The efficiencies p_r and p_m to be detected as a tight lepton are determined from data
- The number of misidentified leptons passing the selection can be calculated by weighting each event in the data sample with one lose lepton according to:

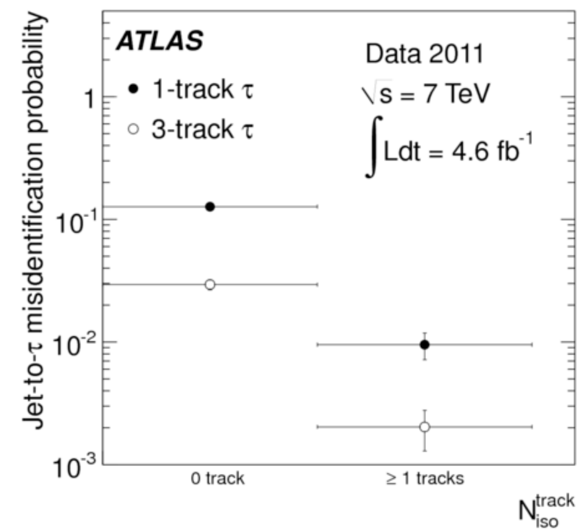
$$w_{\ell L} = \frac{p_{\mathrm{m}} p_{\mathrm{r}}}{(p_{\mathrm{r}} - p_{\mathrm{m}})}$$ ★ For a loose but not tight lepton

$$w_{\ell T} = \frac{p_{\mathrm{m}}(p_{\mathrm{r}} - 1)}{(p_{\mathrm{r}} - p_{\mathrm{m}})}$$ ★ For a tight lepton

- Misidentified τ jets
  ★ Rate at which jets from light quarks are misidentified is measured in data using a W +2 jets selection:
    ✦ Exactly 1 lepton with E_T or p_T > 25 GeV
    ✦ At least one τ candidate
    ✦ At least 2 jets in addition to the τ (not b-tagged)
    ✦ E_T^{miss} > 40 GeV
  ★ To reduce the contribution from events with a true τ:

$$m_T = \sqrt{2p_T^l E_T^{\text{miss}}(1-\cos\Delta\phi_{l,\text{miss}})} > 30 \text{ GeV}$$





H+->$\tau\nu$ (ratio method) - Results

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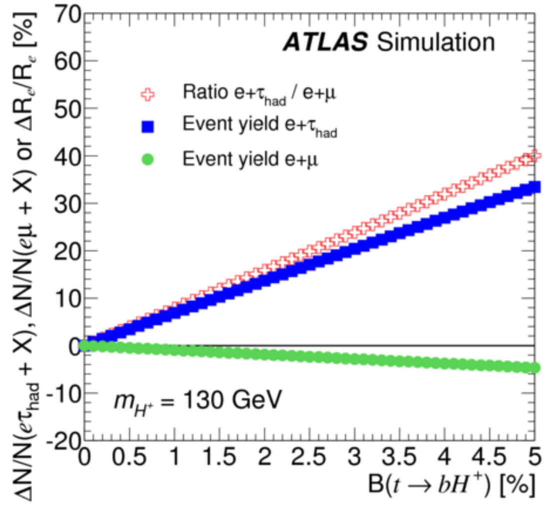
• Sensitivity of the analysis to charged Higgs bosons depends on the rate at which the ratios change with Br(t ➔b H^+):

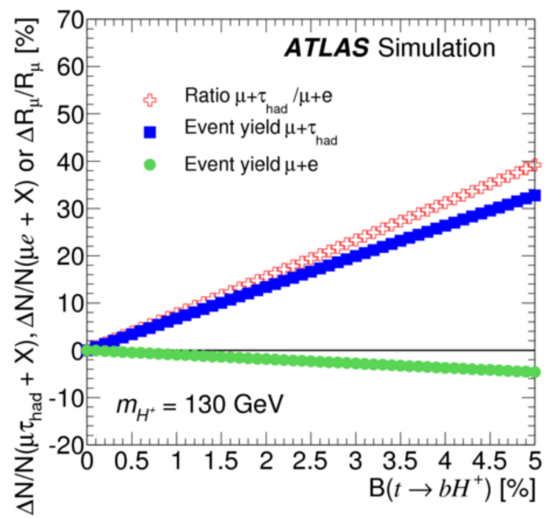
★ The presence of H^+➔ $\tau\nu$ in a fraction of the top decays leads to an increase of the number of ttbar events with a lepton and a τ

★ This leads to an increase of the ratios

★ For m_{H+}=150(160) GeV the rate at which the ratios change with the branching is 2(5) times smaller than for m_{H+}=130 GeV

★ The selection efficiencies are reduced for m_{H+} close to m_{top}





H+->$\tau\nu$ (ratio method) – Limits

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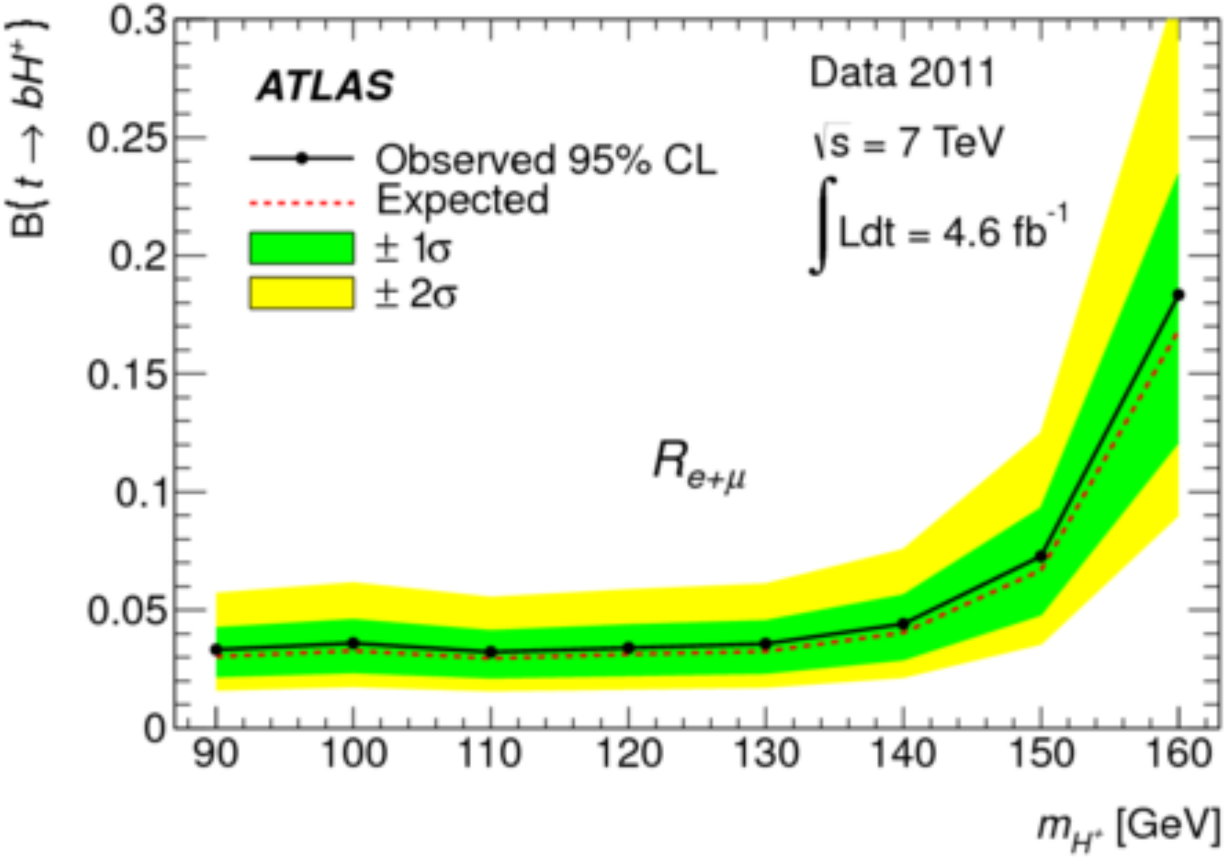
$$R_{e+\mu} = \frac{\mathcal{N}(e+\tau_{\rm had}) + \mathcal{N}(\mu+\tau_{\rm had})}{\mathcal{N}(e+\mu) + \mathcal{N}_{\rm OR}(\mu+e)}$$

→ Event yield after removing dilepton events that simultaneously fired both triggers



H+->$\tau\nu$ (ratio method) - Limits

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- Limits for H^+ production can also be placed in the context of the m_h-max scenario of the MSSM

★ Theoretical uncertainties considered: 5% for one loop EW corrections missing from calculations, 2% for missing two loop QCD corrections

★ If m_{h0}=125 GeV, it would imply tan(β)>3 and m_{H+} <155 GeV