International Workshop on Tau Lepton Physics, Manchester, 13-17 September 2010

$H \rightarrow \tau^+\tau^-$ AND $H^\pm \rightarrow \tau^\pm\nu_\tau$ WITH THE ATLAS DETECTOR AT THE LHC

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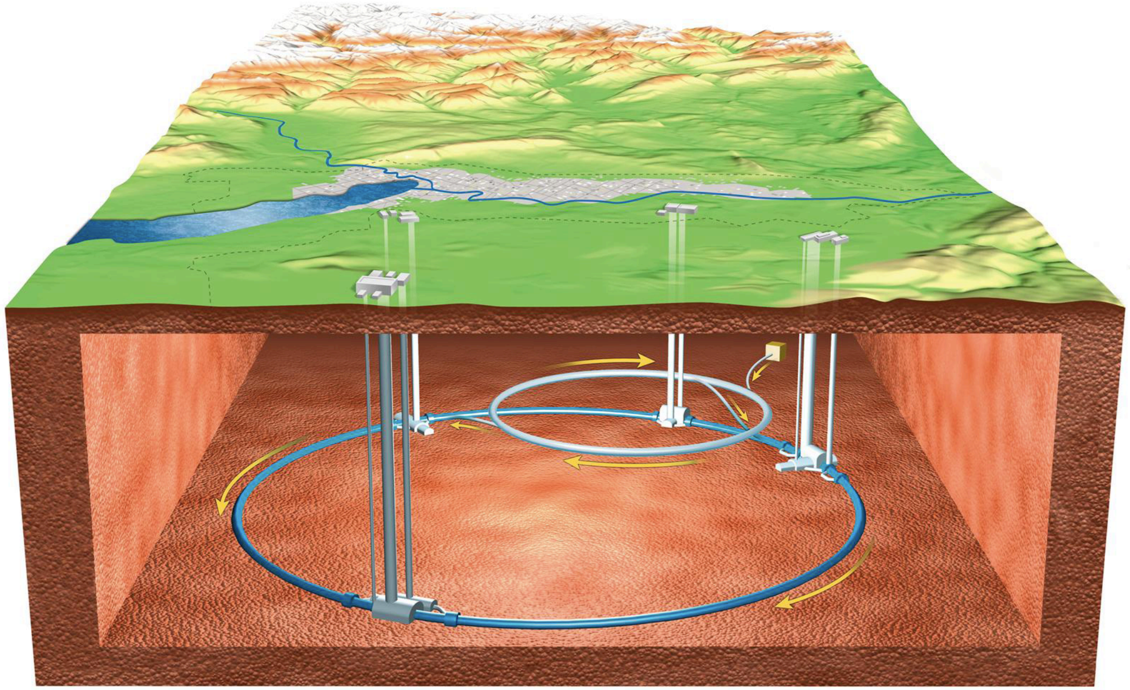
on behalf of the ATLAS Collaboration

Royal Holloway University of London

Outline

- ATLAS and LHC Status and Plans
- Higgs Physics at the LHC
- Recent ATLAS Results
  - $H \rightarrow \tau^+\tau^-$ in the Standard Model
  - $h/H/A \rightarrow \tau^+\tau^-$ in the MSSM
  - Charged Higgs: $H^\pm \rightarrow \tau^\pm \nu_\tau$
- Summary and Outlook



ATLAS and LHC Status and Plans

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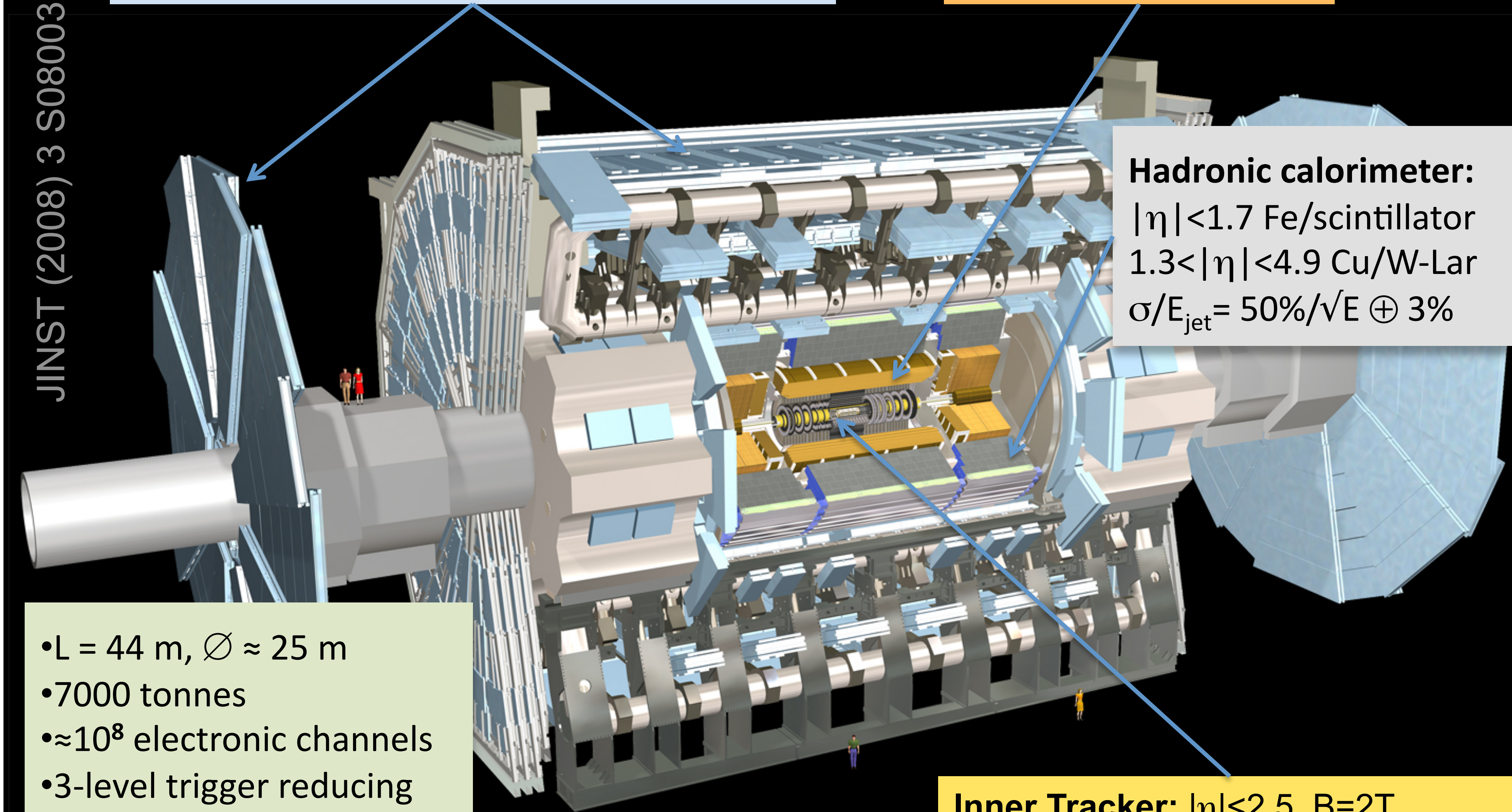
Muon Spectrometer: $|\eta|<2.7$
Air-core toroids and gas-based muon chambers
σ/p_T = 2% @ 50GeV to 10% @ 1TeV (ID+MS)

EM calorimeter: $|\eta|<3.2$
Pb-LAr Accordion
$\sigma/E = 10\%/\sqrt{E} \oplus 0.7\%$

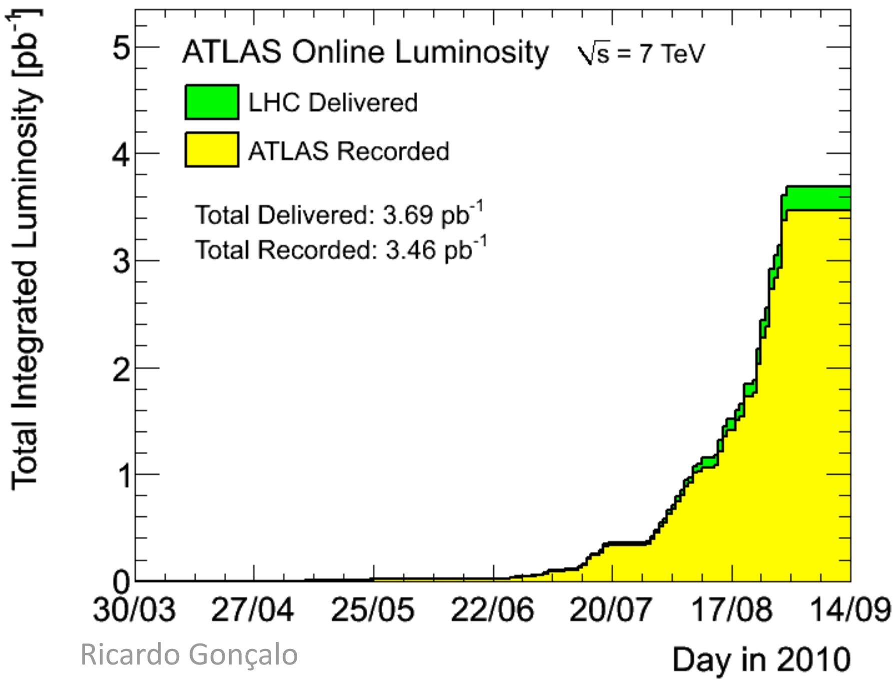


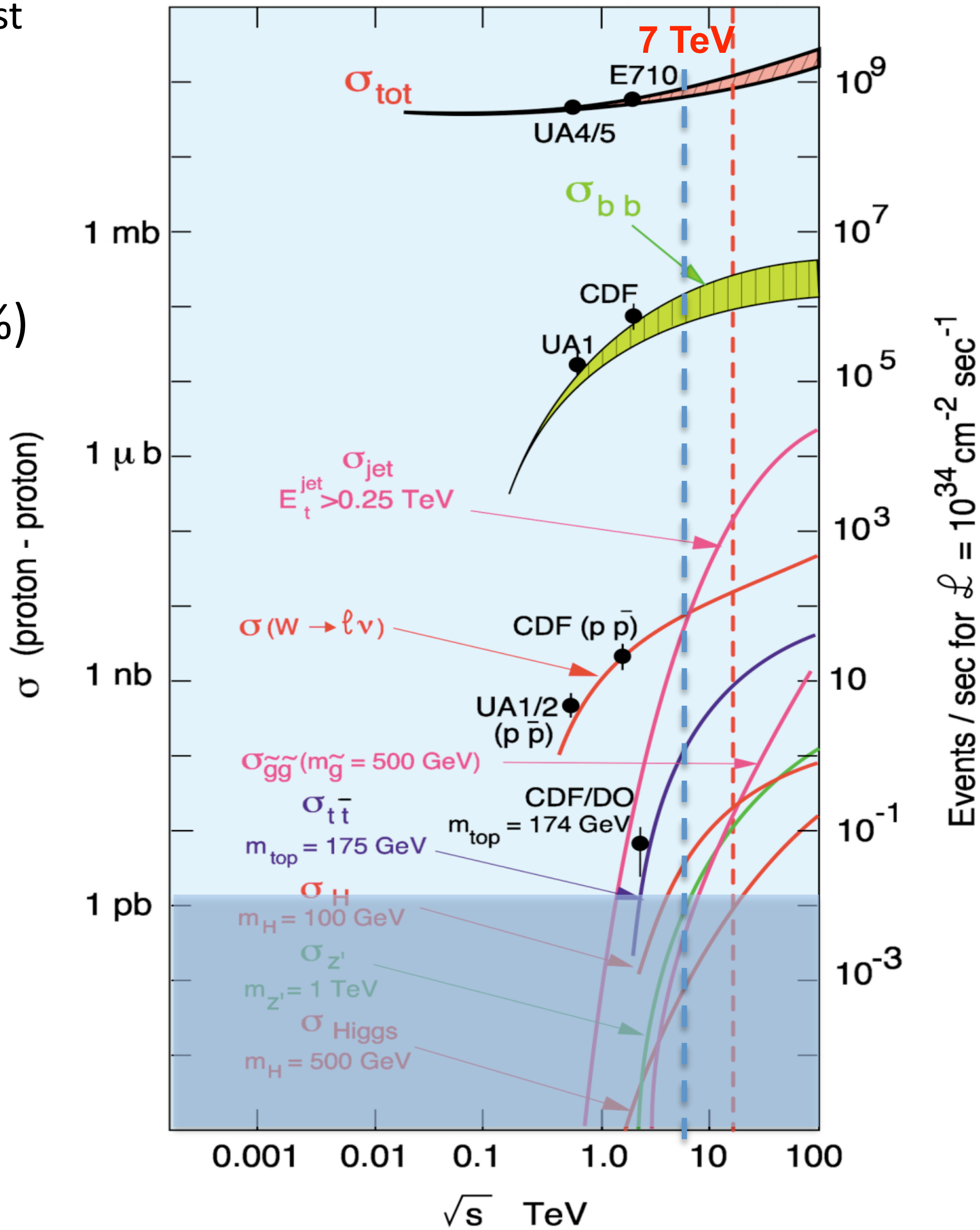
Hadronic calorimeter:
$|\eta|<1.7$ Fe/scintillator
$1.3<|\eta|<4.9$ Cu/W-Lar
$\sigma/E_{jet} = 50\%/\sqrt{E} \oplus 3\%$

- L = 44 m, ∅ ≈ 25 m
- 7000 tonnes
- ≈10^8 electronic channels
- 3-level trigger reducing 40 MHz collision rate to 200 Hz of events to tape

Inner Tracker: $|\eta|<2.5$, B=2T
Si pixels/strips and Trans. Rad. Det.
$\sigma/p_T = 0.05\%\ p_T\,(\text{GeV}) \oplus 1\%$

- LHC running smoothly at √s = 7 TeV
  - Crossed L = $10^{31} cm^{-2}s^{-1}$ milestone in August
  - Aim to achieve L = $10^{32} cm^{-2}s^{-1}$ in 2010
  - p-p run until 1 Nov., followed by heavy-ion run
  - Go to √s = 14 TeV in 2013 after shutdown
- ATLAS collected ∫Ldt ≈ 3.46 pb^{-1} (±11%)
  - At ≈ 94% efficiency and improving
  - First W and Z cross section measurements
  - Handful of top candidates seen
  - Expect to collect 1 fb^{-1} until end 2011





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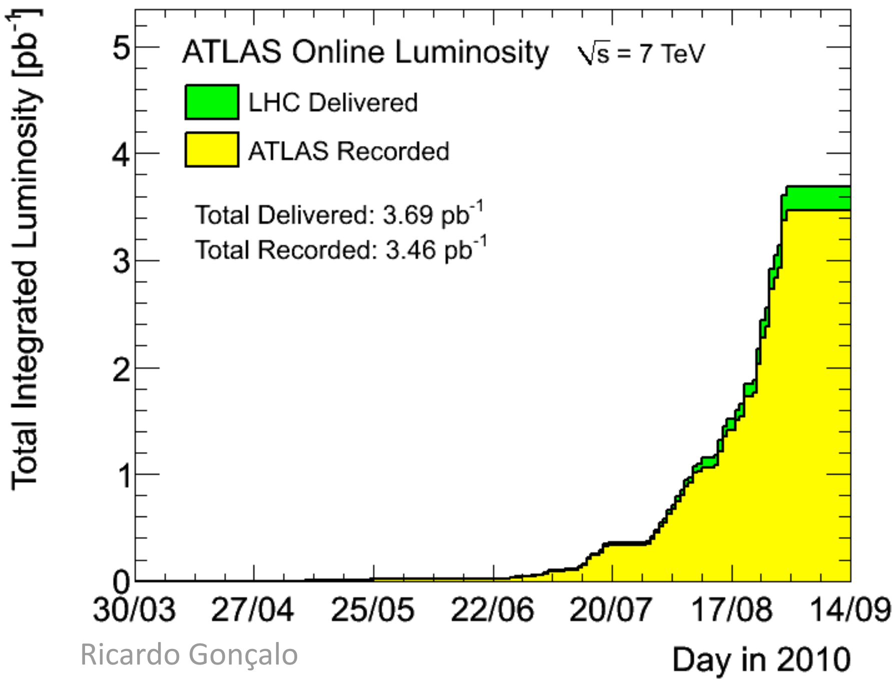

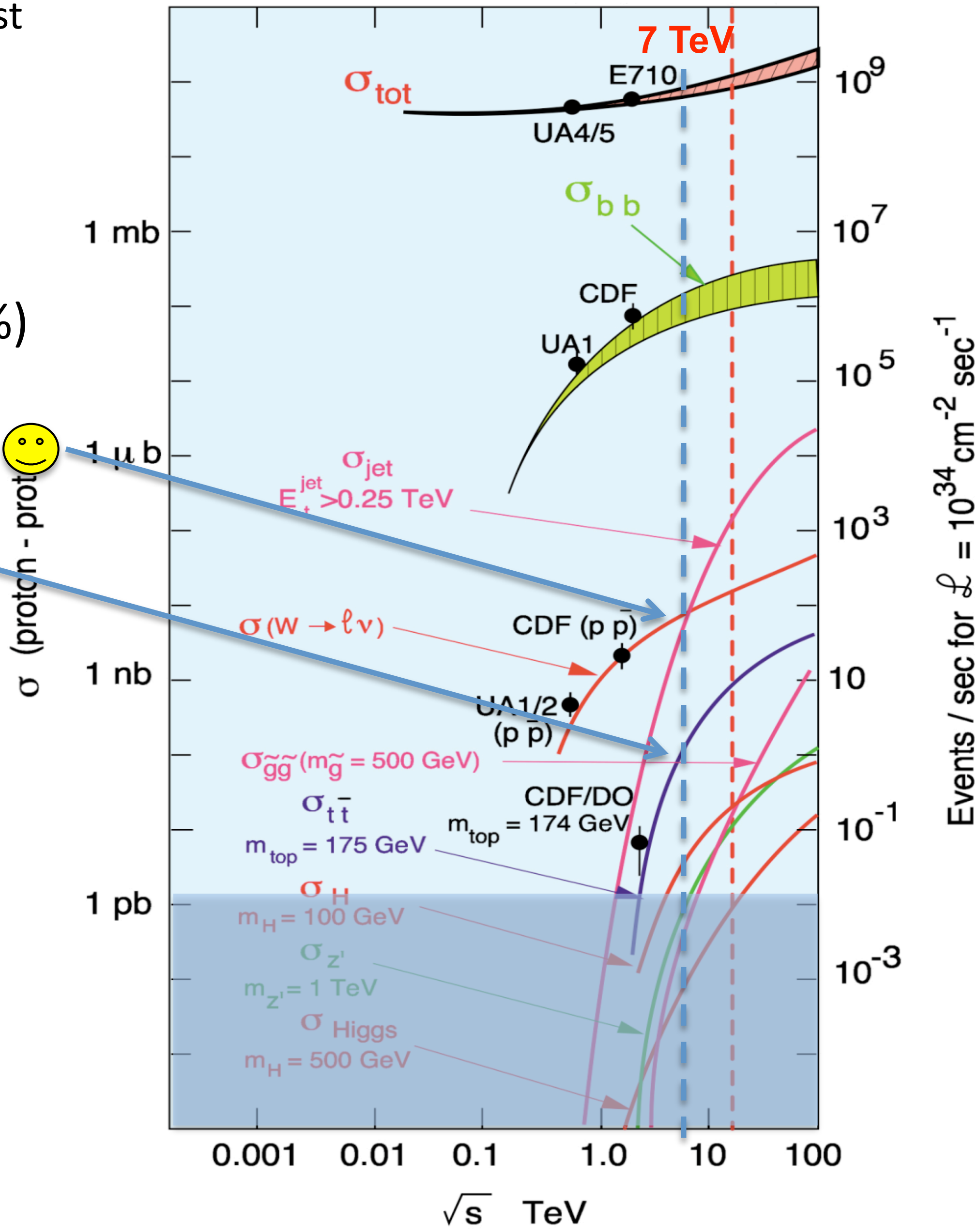

HIGGS PHYSICS AT THE LHC

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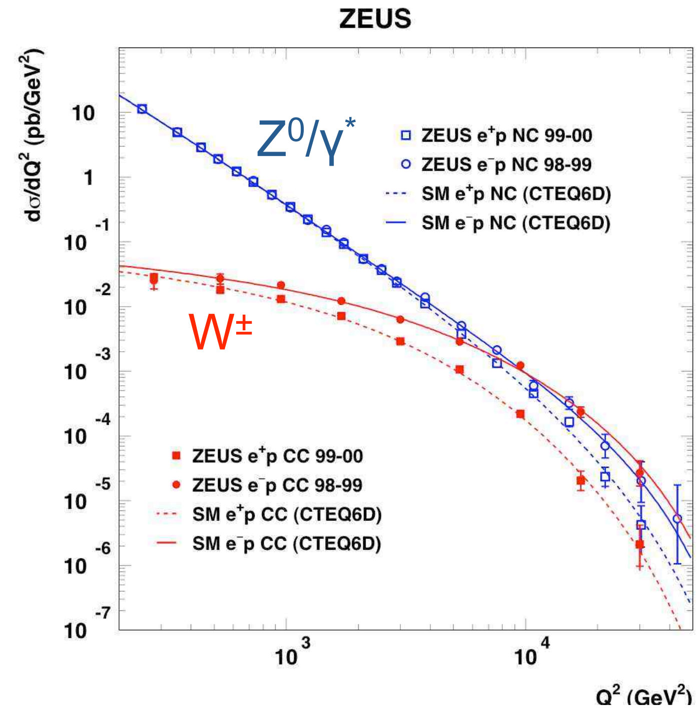
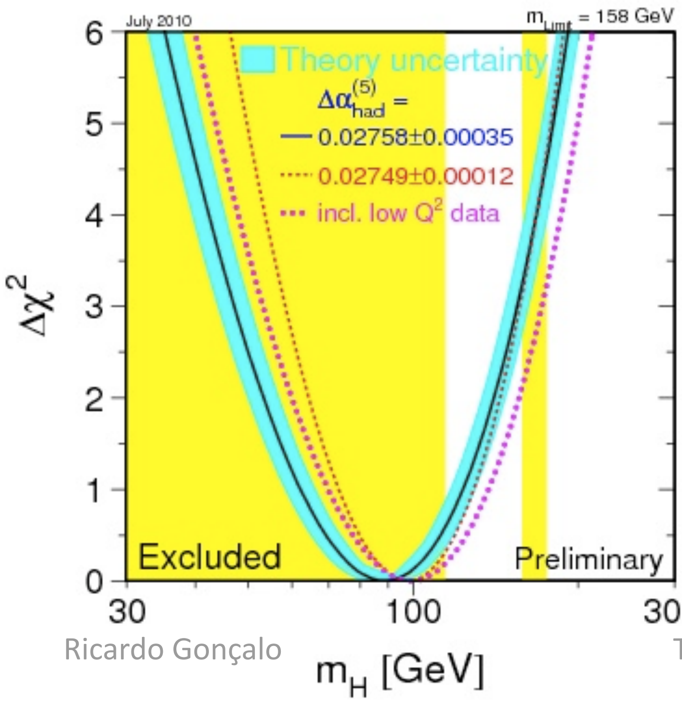
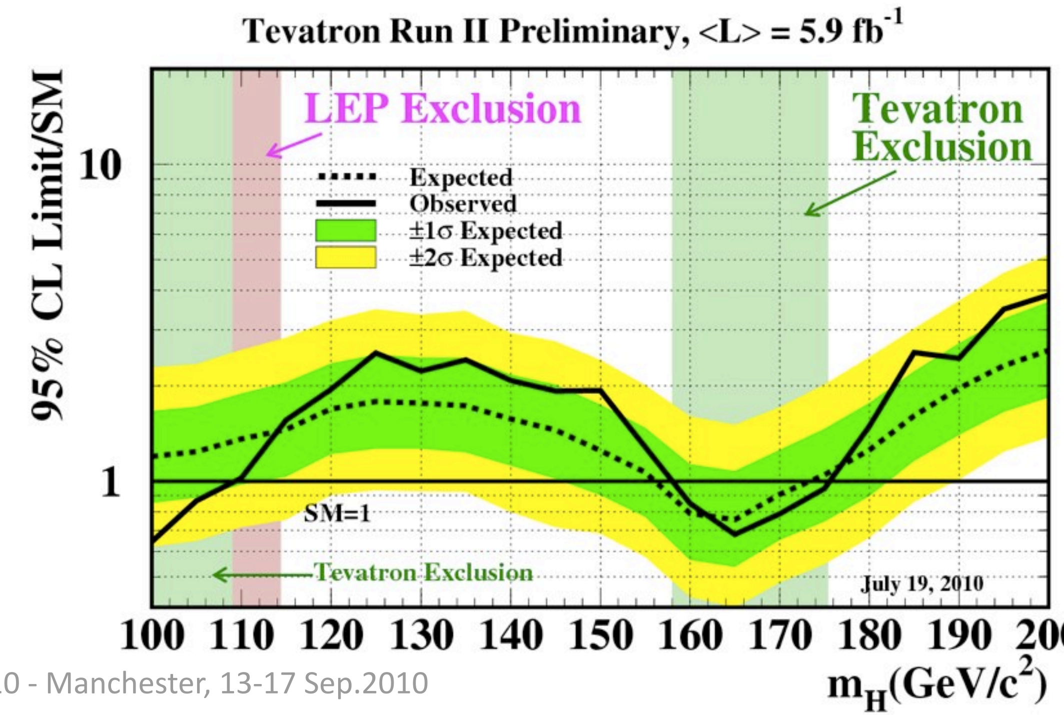
- Electroweak symmetry breaking/unification and the need to account for massive particles is clear from experimental data
- The **simplest model** of electroweak symmetry breaking predicts the existence of one **Higgs scalar**
  - The Higgs boson mass is the only free parameter
- Current mass limits as of July 2010:
  - LEP **excluded** mass range below **114.4 GeV/c^2**
  - EW fit: m_H = **89^{+35}_{-26} GeV/c^2**; including LEP: m_H < **185 GeV/c^2**
  - Tevatron **excluded** mass range of **158 – 175 GeV/c^2**



http://www-zeus.desy.de/physics/sfew/PUBLIC/sfew_results/preliminary/dis04/



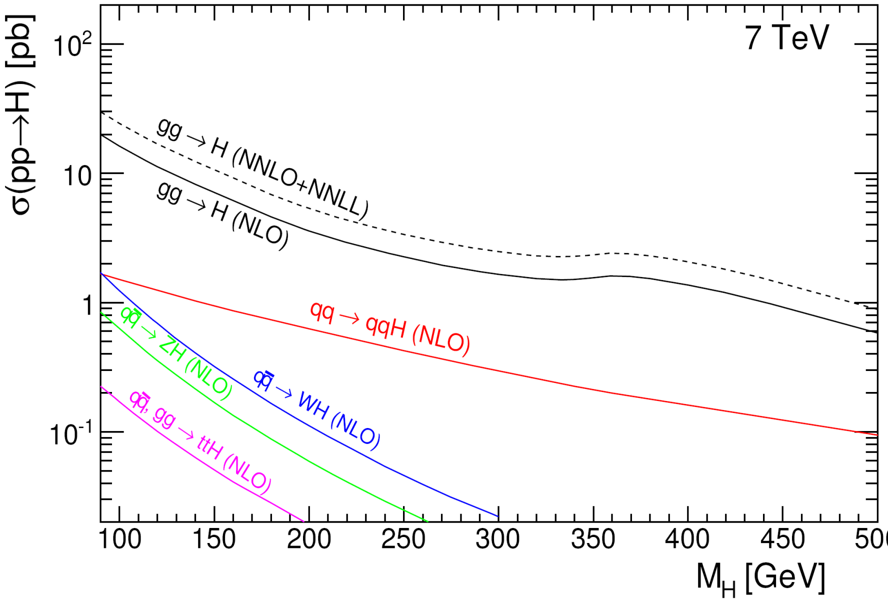
http://lepewwg.web.cern.ch/LEPEWWG/



http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_08hepex/

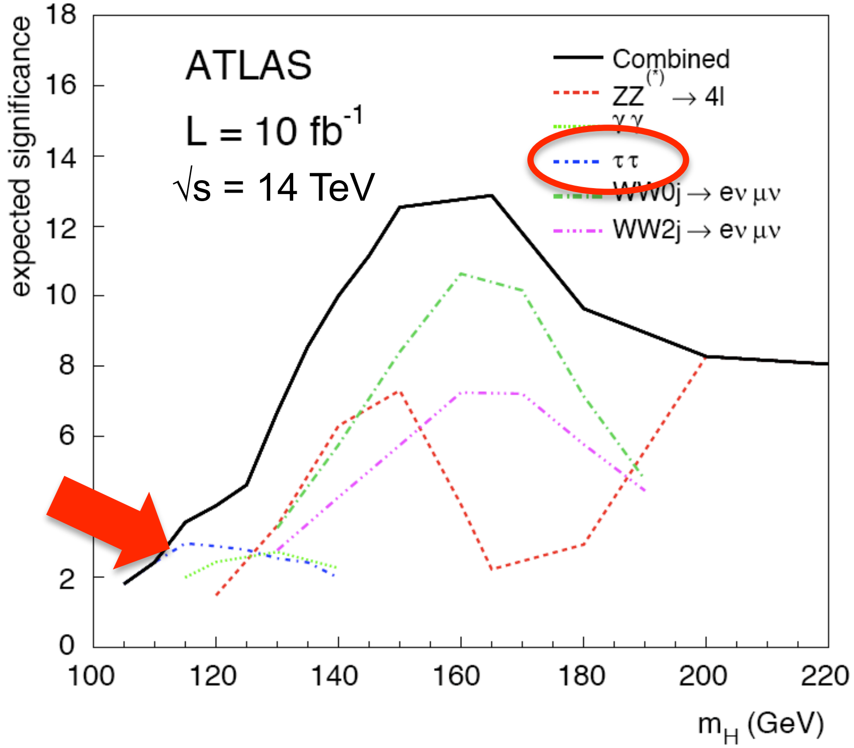
Standard Model Higgs:

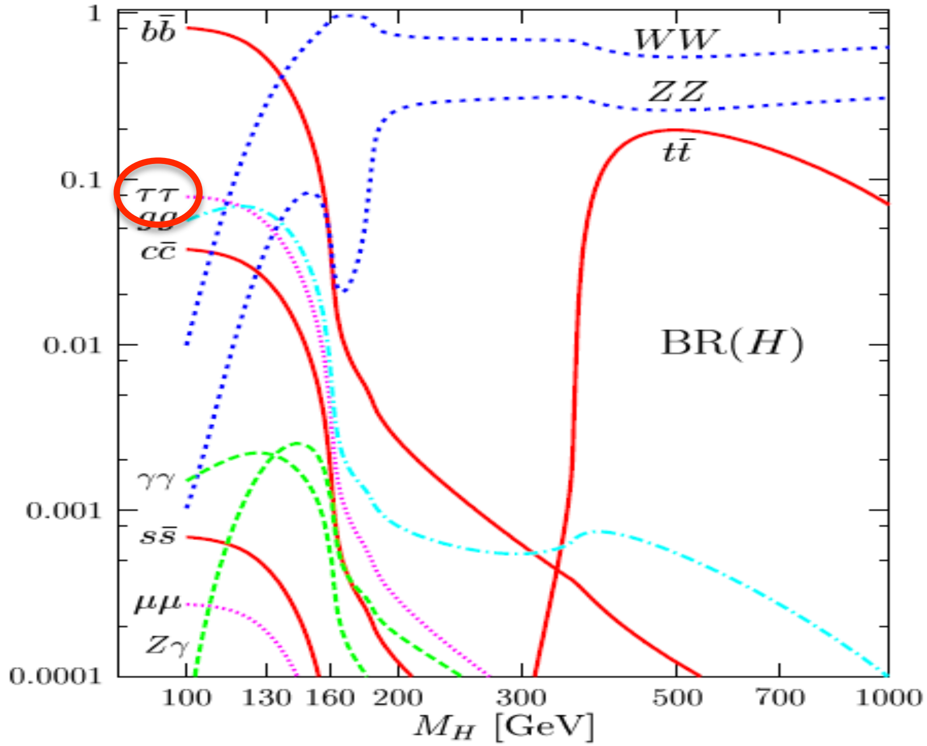
- Main production modes at the LHC:
  - Gluon fusion (gg→H)
  - ≈10x smaller: Vector boson fusion (qq->qqH)
- Main decay modes:
  - At low mass, H->bb is dominant (BR ≈ 90%), followed by H→ττ (BR ≈ 10%)
  - Above m_H ≈ 135 GeV/c^2 H→WW and H→ ZZ are the dominant decays
- At low m_H, H→ττ makes large contribution to ATLAS sensitivity



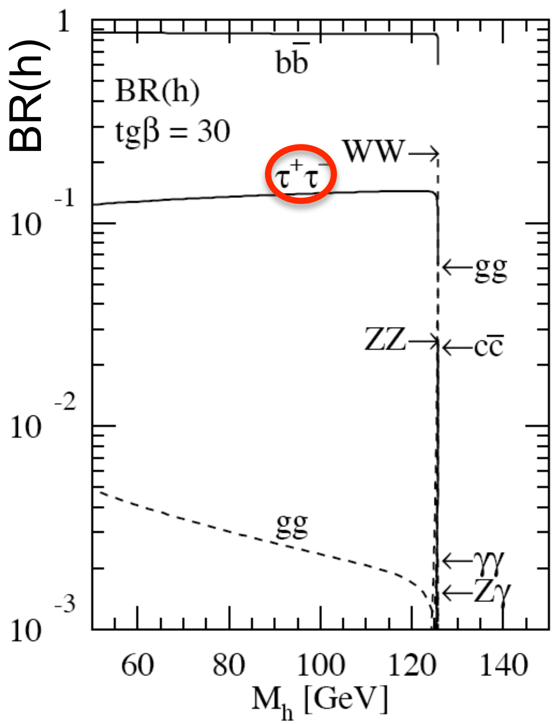
ATL-PHYS-PUB-2010-009

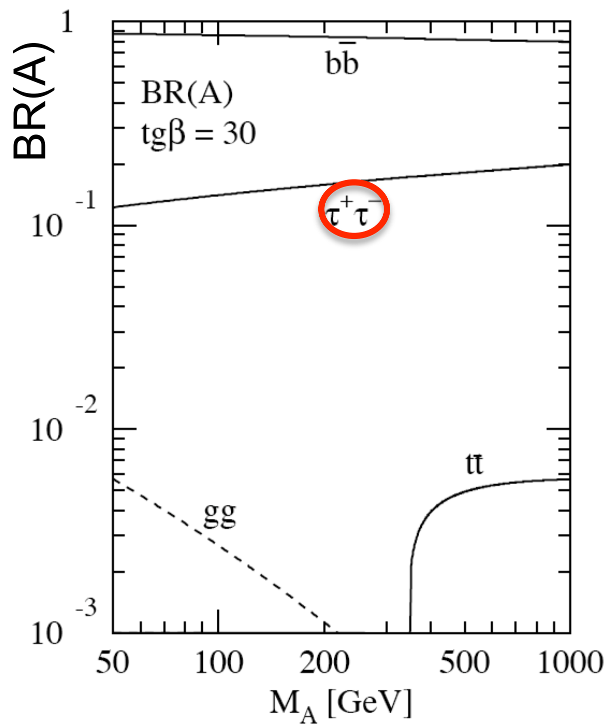
CERN-OPEN-2008-020

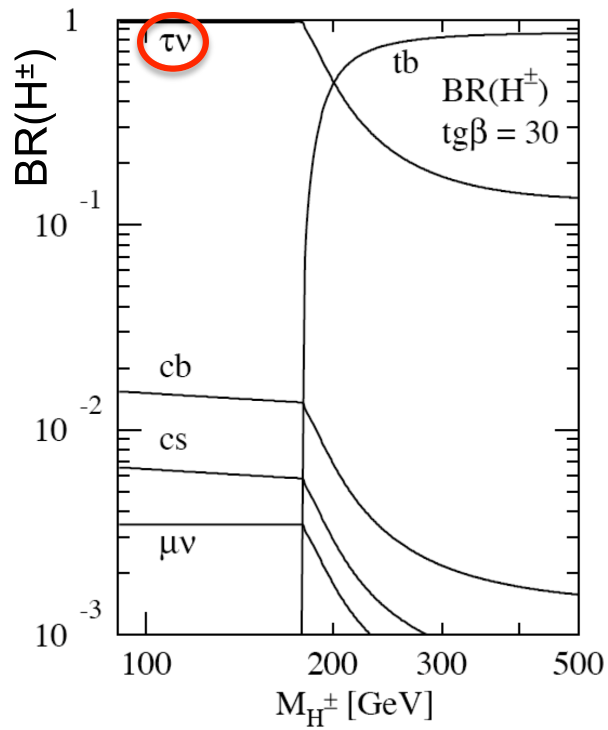




- In the MSSM, 2 Higgs doublets give 5 particles
  - Three neutral: h, H (CP-even), A (CP-odd); two charged: $H^{\pm}$
- At tree level $m_h < m_Z$ – after radiative corrections $m_h < 135$ GeV/c^2
- Important parameters: m_A, $\tan\beta = v_1/v_2$
  - As **tan β increases**, Higgs decays to **b quarks** and **tau** leptons **enhanced** over vector bosons
- Branching ratio to taus is O(10%) of one to bb in both SM and MSSM
  - But tau identification and triggering can be very advantageous over b-initiated jets
  - In case of charged Higgs bosons the dominant decay may involve a tau lepton
- Need the best possible tau trigger, ID and reconstruction that ATLAS can provide!
  - See talks by Stefania Xella and Anna Kaczmarska in previous session







M.Spira, Higgs Hunting workshop, Orsay, July 2010

ATLAS results in SM and MSSM

- The following slides summarize ATLAS results for $H \rightarrow \tau^+\tau^-$ (SM) and $h/H/A \rightarrow \tau^+\tau^-$ and $H^\pm \rightarrow \tau\nu_\tau$ (MSSM)
- All results shown (calculated at $\sqrt{s}$ = 14 TeV and $\sqrt{s}$ = 7 TeV) are based on Monte Carlo simulation
- Work currently focuses on understanding backgrounds to search channels
  - Particularly on establishing data-driven methods to determine these backgrounds

$H \to \tau^+\tau^-$ in the Standard Model

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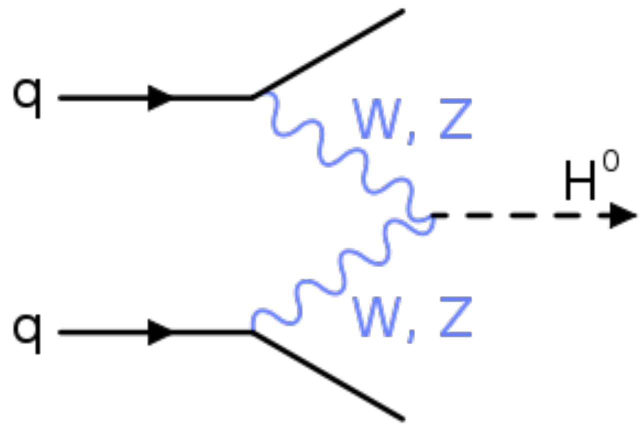
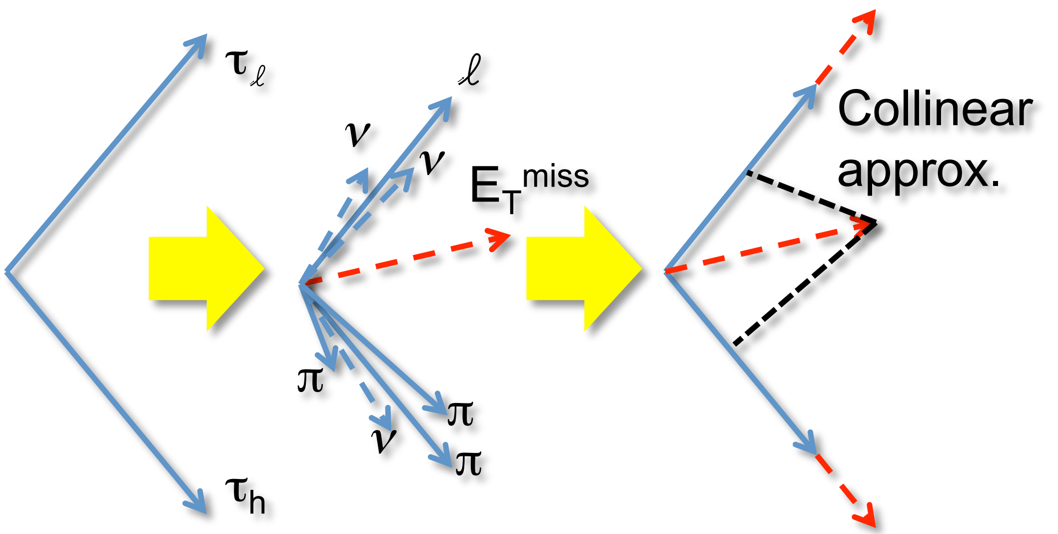
- Studied Vector Boson Fusion (VBF) production channel
  - Use discrimination power from 2 tag jets and clean inter-jet gap (tree level)



- Three channels ($\ell\ell$, ℓh, hh) for leptonic or hadronic τ decays
  - Trigger for hadron-hadron channel proved to be feasible
  - Background for this channel needs to be measured from data (in progress)

$$m_{\tau\tau} = \frac{m_{lh}}{\sqrt{x_l x_h}} \qquad x_h = \frac{E_h}{E_h + E_{\nu h}} \qquad x_l = \frac{E_l}{E_l + E_{\nu h}}$$

- $M_{\tau\tau}$ can be reconstructed in the collinear approximation with good resolution (δm ≈ 8 – 10 GeV/c²)
  - Assume τ decays to be only source of E_t^{miss}
  - Assume massles τ's



- Dominant background is $Z/\gamma^* \rightarrow \tau\tau$

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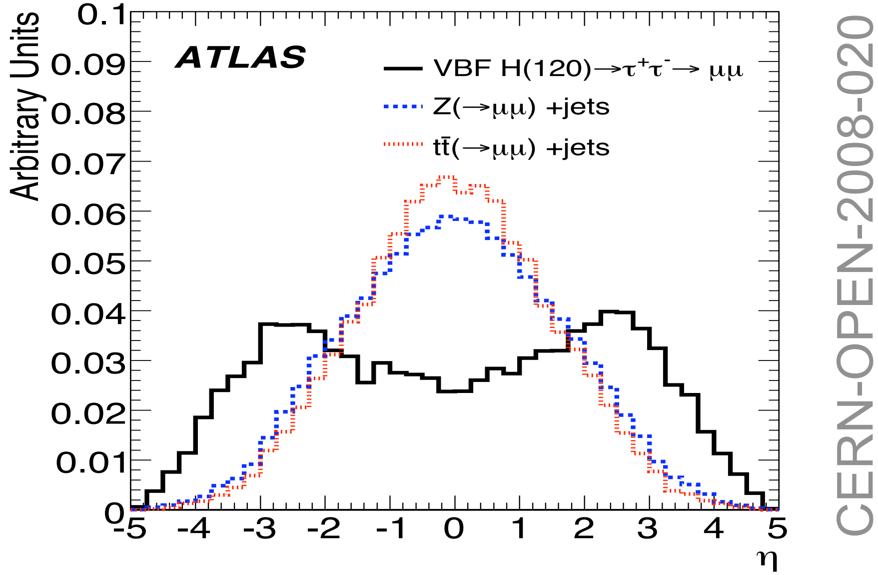

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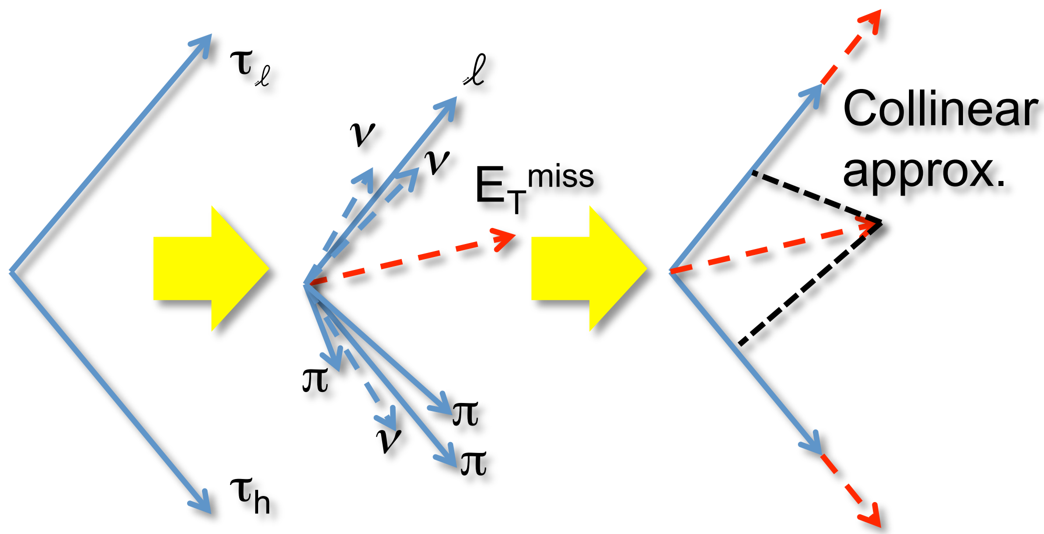
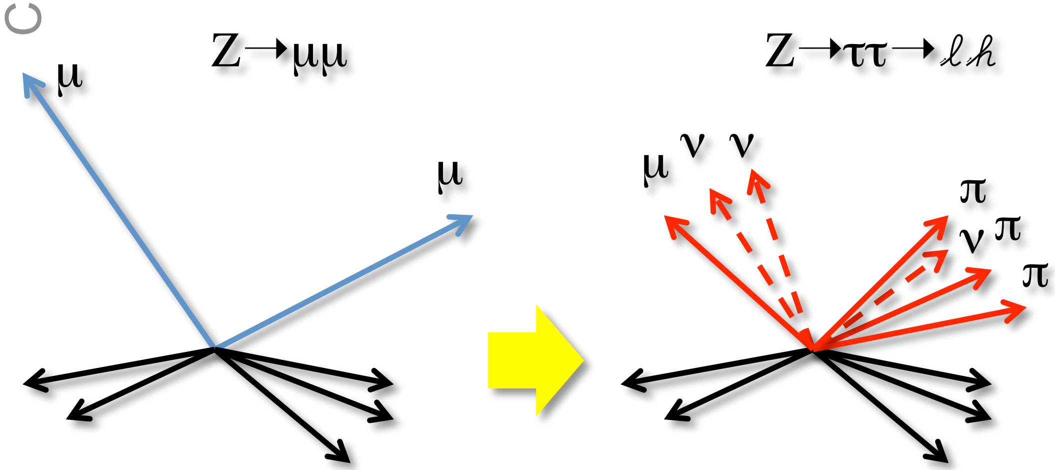
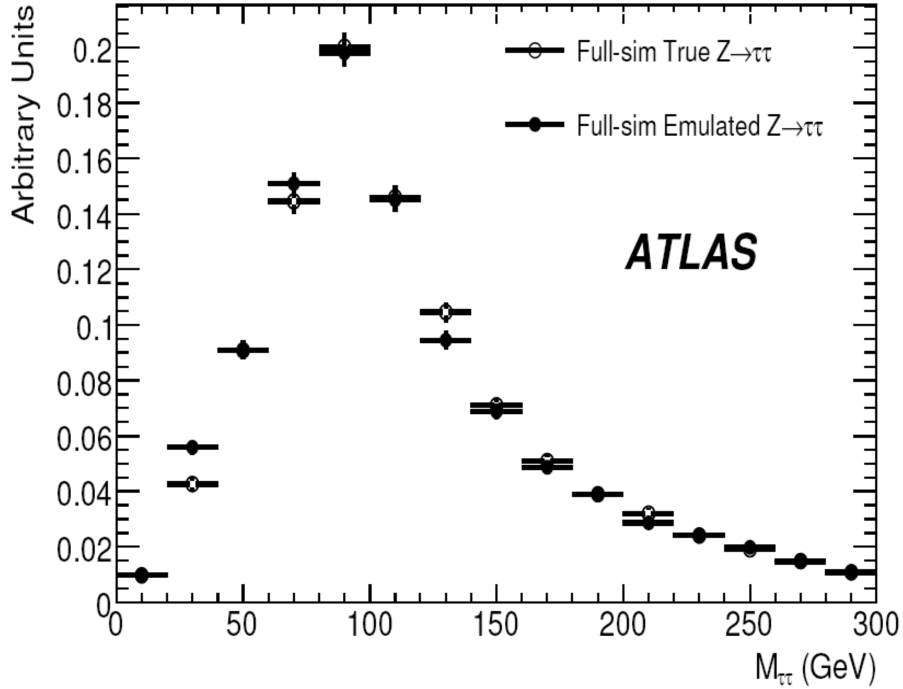
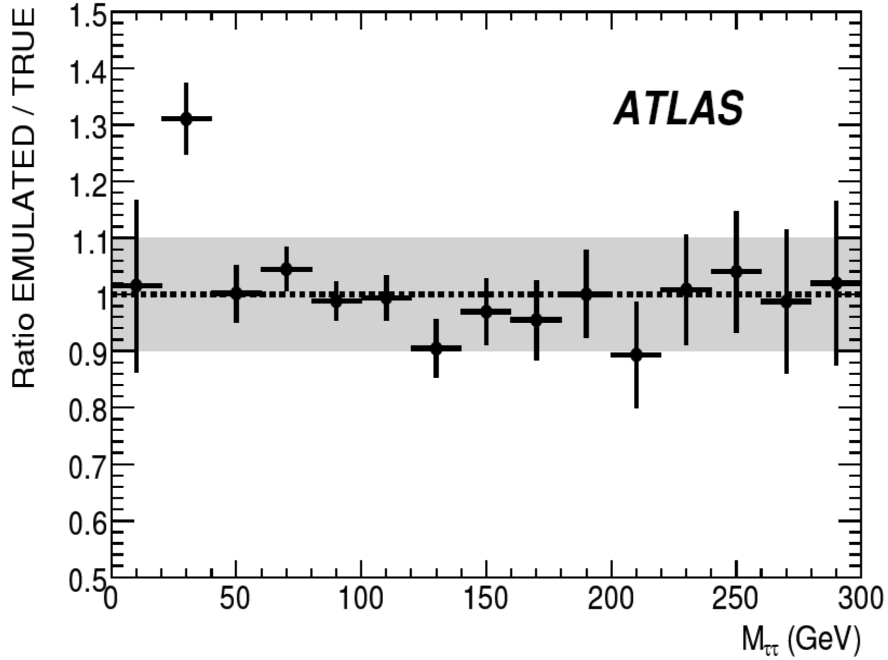


- Dominant background is Z/γ*→ττ

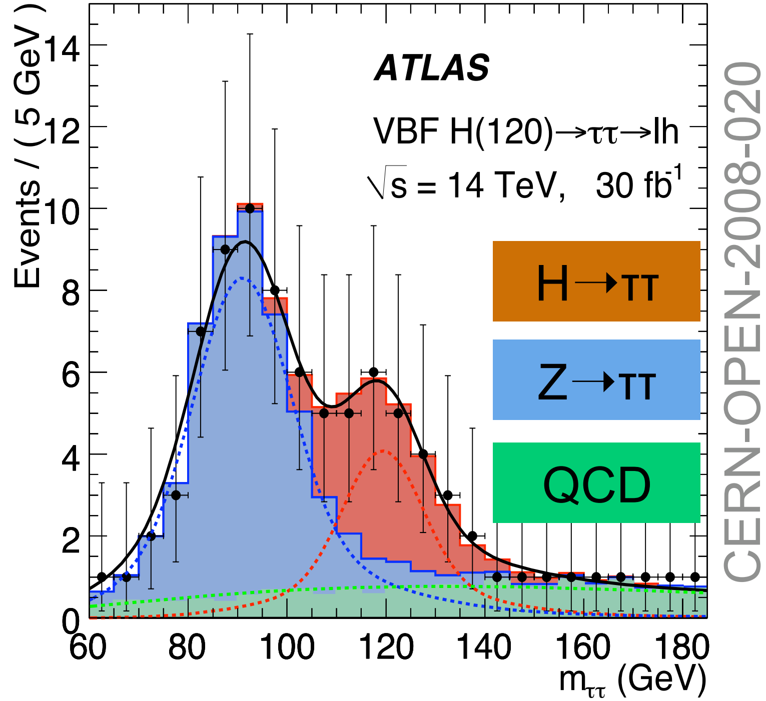
- High tail of the Z→ττ mass distribution extends into signal region
- Simulation shortcomings would impact on signal extraction – needs to be estimated from collision data:
  1. Select Z→μμ
  2. Take μ 4-momenta and decay as a τ in Tauola
  3. Run through detector simulation and merge back into event

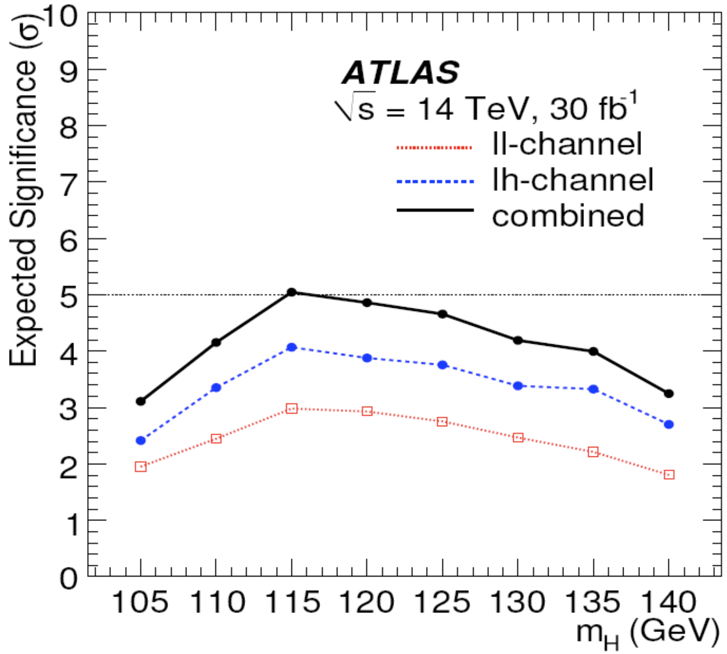






- $\ell\ell$ **event selection**: 2 leptons + tag jets + E_T^{miss}
  - Two leptons (e or μ) with opposite charge
  - Leptons not back to back and $0 < x_{l1}, x_{l2} < 0.75$ (for collinear approximation to work)
  - Two "tag" jets with $E_T > 40$ and 20 GeV in opposite hemispheres with $\Delta\eta_{jj} > 4.4$ and di-jet mass > 700 GeV/c^2
  - $E_T^{miss} > 40$ GeV
- ℓh **event selection**: e/μ + τ_h + tag jets + E_t^{miss}
  - Exactly one lepton (e or μ) with $p_T > 22$ GeV
  - One reconstructed hadronic tau (τ_h)
  - Lepton and τ_h not back to back and $0 < x_{l1}, x_{l2} < 0.75$ (for collinear approximation to work)
  - Transverse mass (lepton, E_T^{miss}) < 30 GeV
  - Two "tag" jets with $E_T > 40$ and 20 GeV in opposite hemispheres with $\Delta\eta_{jj} > 4.4$ and di-jet mass > 700 GeV/c^2
  - $E_T^{miss} > 30$ GeV
- **Combination** of $\ell\ell$ and ℓh:
  - 5σ discovery with 30 fb^{-1} at 14 TeV for $m_H \approx 115$ GeV/c^2
  - Systematic uncertainties of ≈20% in signal efficiency, dominated by jet energy scale





h/H/A $\rightarrow \tau^+\tau^-$ IN THE MSSM

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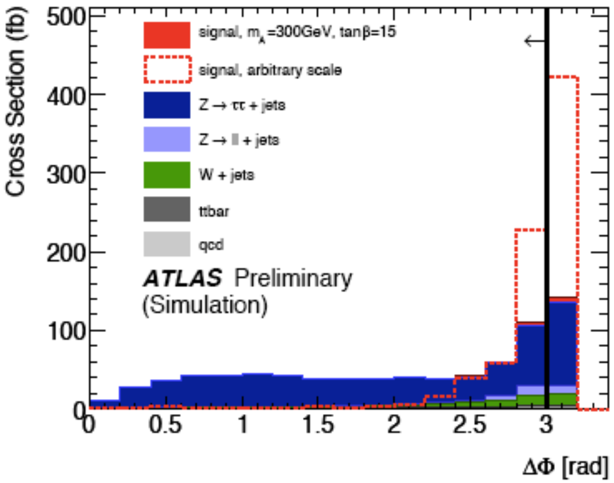
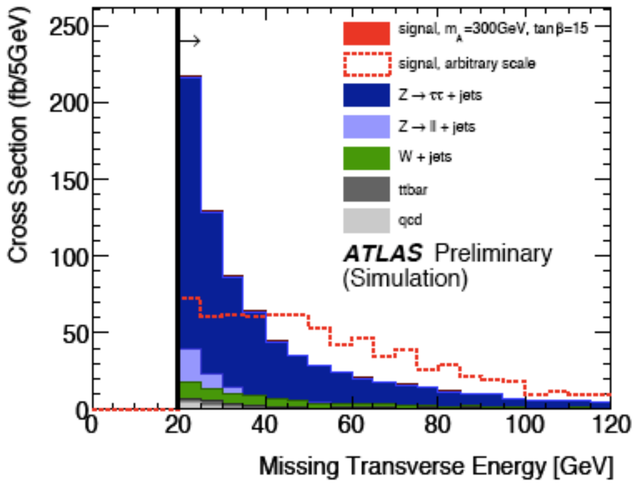
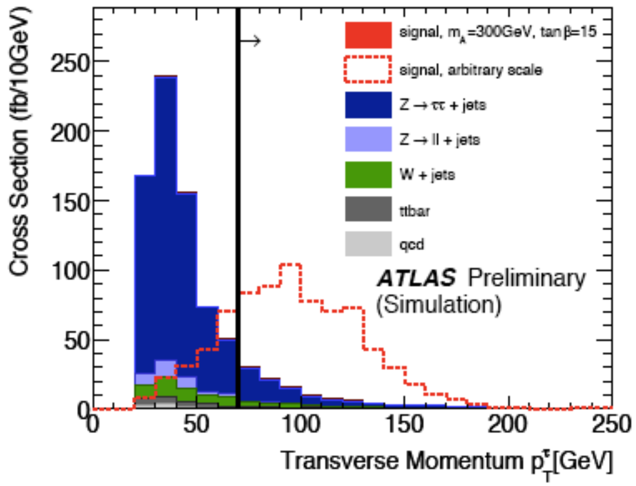
- Previously studied $h/H/A \rightarrow \tau^+\tau^- \rightarrow \ell^+\ell^- + 4\nu$ – lepton-lepton final state
  - m_h^{max} scenario and mass range 110 GeV/c² < m_A < 800 GeV/c² (CERN-OPEN-2008-020)
- New studies include lepton-hadron final state (ATL-PHYS-PUB-2010-011)
  - Similar analysis; focused on 150 GeV/c² < m_A < 800 GeV/c² (h ignored since $m_h \lesssim$ 135 GeV/c²)
- **Event selection**: $e/\mu + \tau_h + E_t^{miss}$
  - At least one e or μ with p_T > 24 GeV
  - Exactly one hadronic τ_h with opposite charge to e/μ
  - E_T^{miss} > 20 GeV; transverse mass: $M_T(\text{lepton}, E_T^{miss})$ < 25 GeV/c²
  - $m_{\tau\tau} > 0$ from collinear approximation and $0 < x_{l1}, x_{l2} < 1$
  - Separate sample into **b-tagged** and **non b-tagged** events to optimize separately using variables: $\mathbf{\Delta\phi_{l\tau}}$, $\mathbf{E_T^{miss}}$, $\mathbf{E_T^{\tau}}$ and $\mathbf{m_{\tau\tau}}$
- Re-do analyses for several masses between m_H = 150 GeV/c² and 800 GeV/c²
- Backgrounds: Z+jets and W+jets (non-b tagged) , ttbar (b-tag), QCD, single top

ATL-PHYS-PUB-2010-011

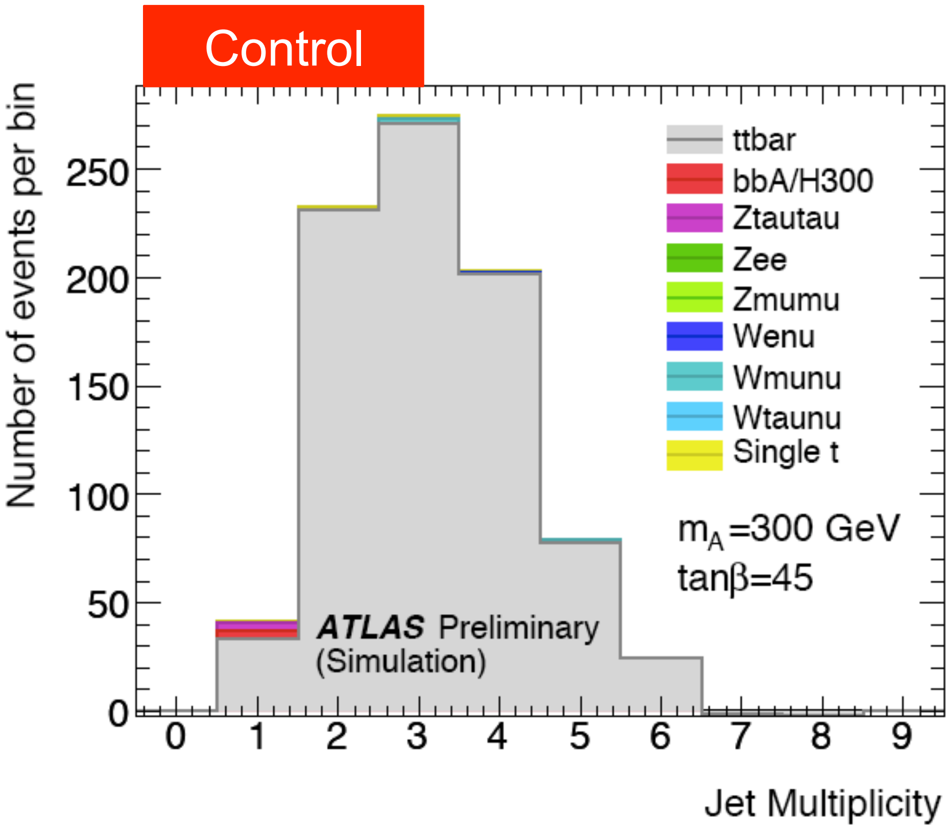


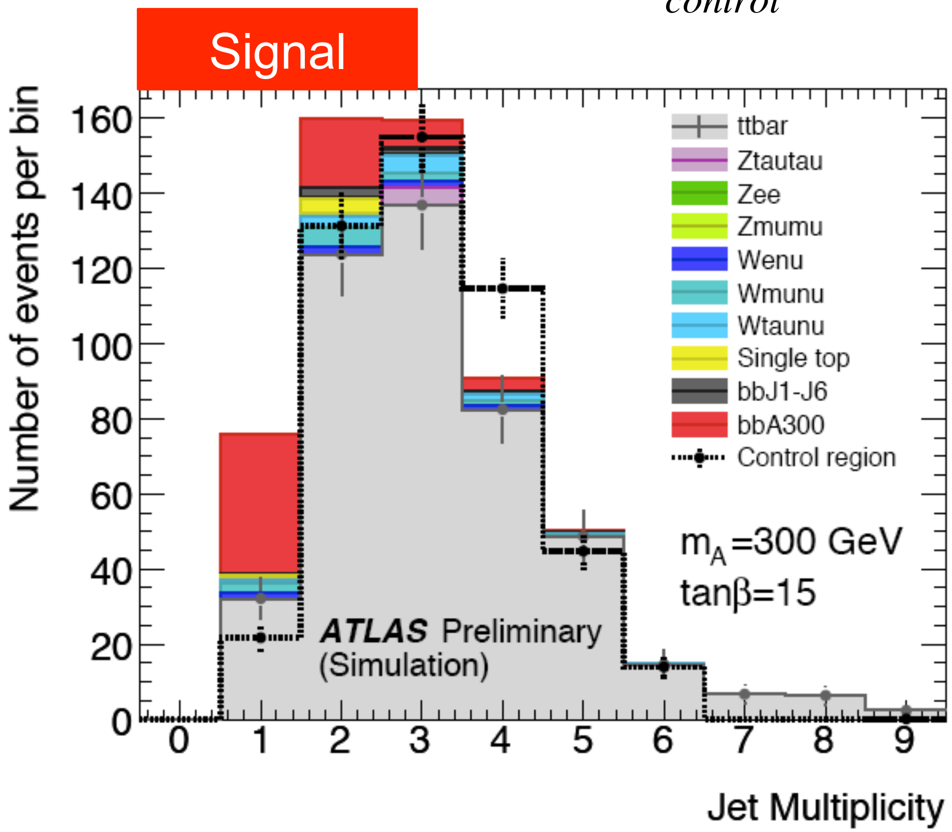




- Define strategies to determine backgrounds from collision data
- Example: ttbar background
  - Select control sample with high E_T^{miss} and no $M_{\tau\tau}$ cut
  - Other cuts similar to signal region
  - Bin events in number of reconstructed jets
  - Estimate ttbar in signal region through:

$$N_{signal}^{Njets<3} = N_{control}^{Njets<3} \frac{N_{signal}^{Njets>3}}{N_{control}^{Njets>3}}$$





- Combined b-tagged and non b-tagged analyses

- Improvement for $M_A > 150$ GeV/c^2 over older ATLAS analysis of di-lepton final state $\tau_l\tau_l$ (CERN-OPEN-2008-020)

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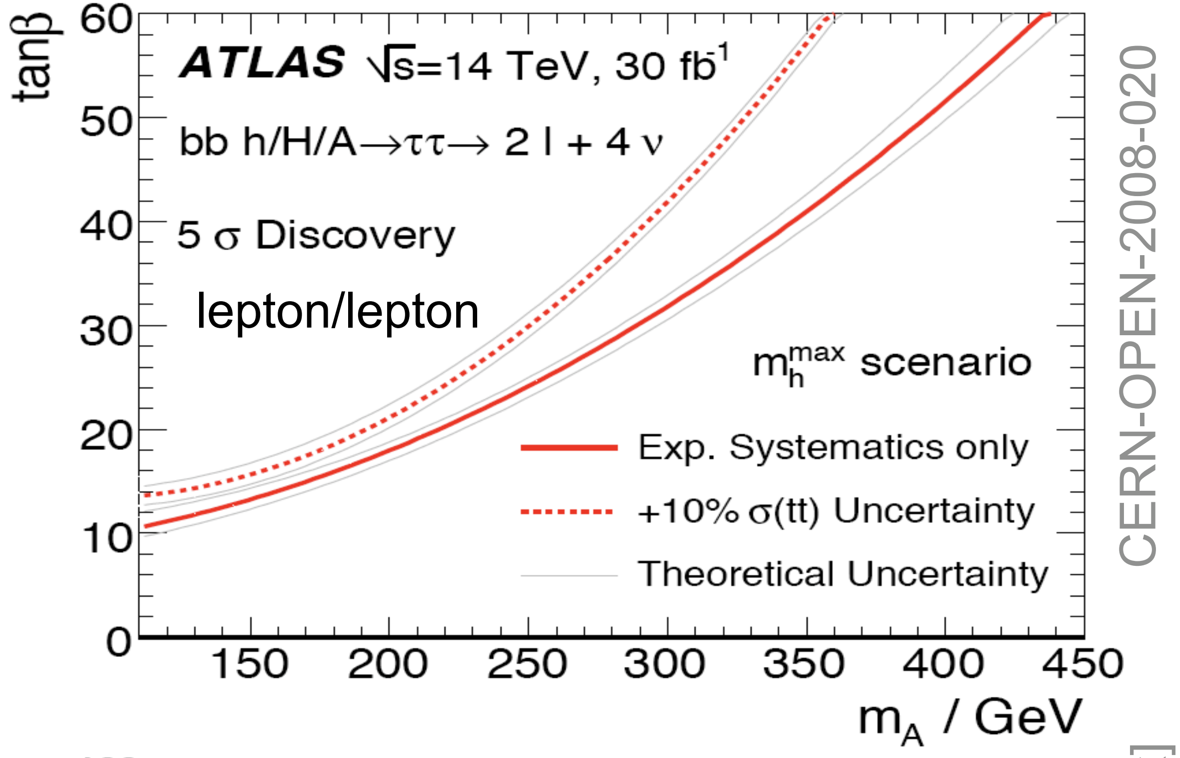

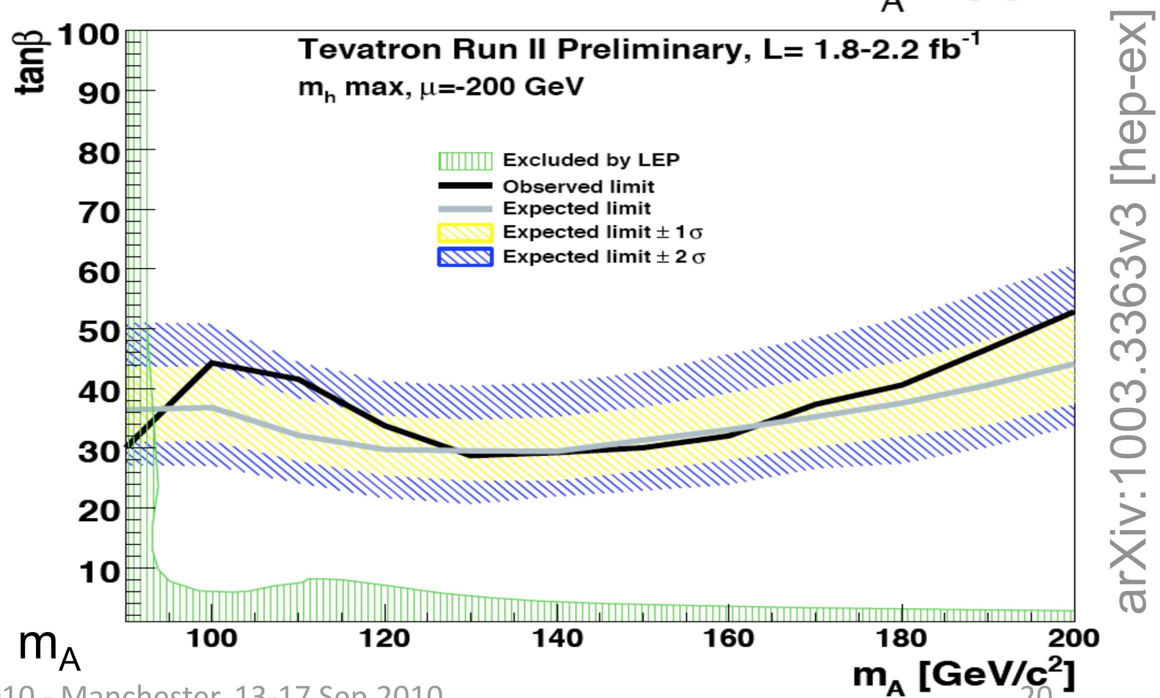

95% exclusion limit vs tanβ and m_A

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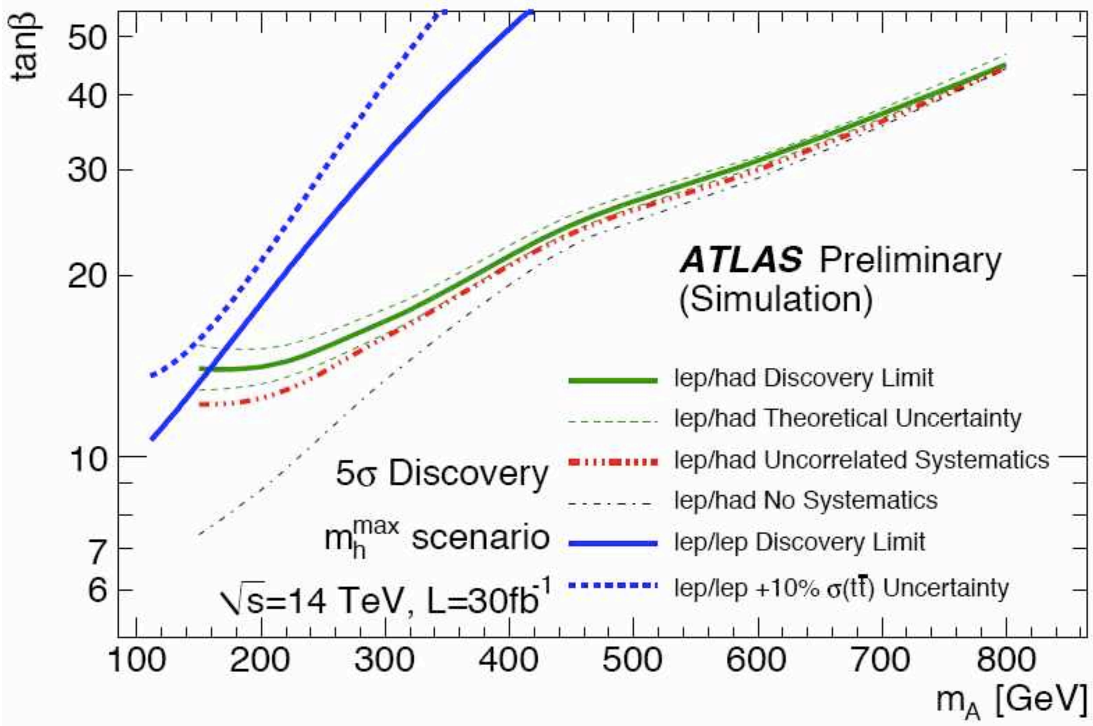

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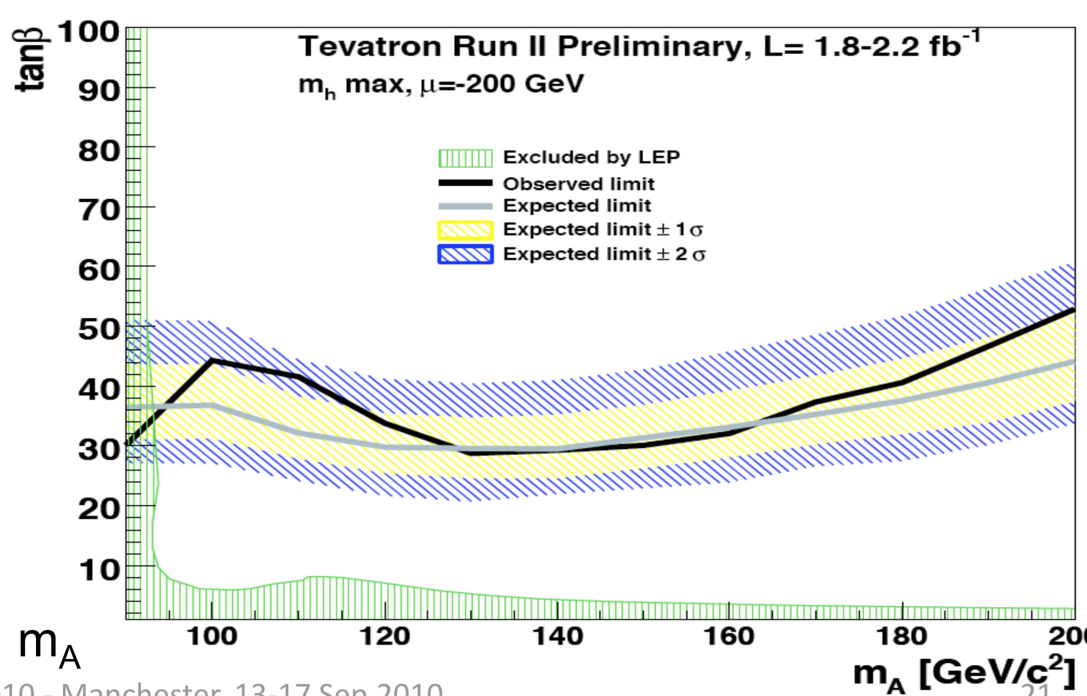


arXiv:1003.3363v3 [hep-ex]

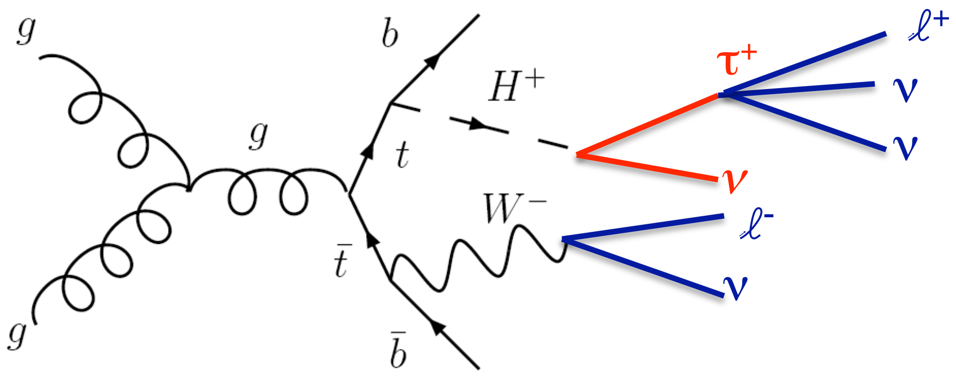
95% exclusion limit vs tanβ and m_A

CHARGED HIGGS: $H^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$

- Full simulation study done at $\sqrt{s}$ = 10 TeV and extrapolated to $\sqrt{s}$ = 7 TeV, 1 fb^{-1}
  - Cross sections scaled down and corrected for different acceptance when necessary

- Only light charged Higgs study being shown here: $m_{H+} < m_t$
  - For tan β > 1 BR($H^+ \rightarrow \tau\nu$) dominant; for tan β > 3 BR($H^+ \rightarrow \tau\nu$) > 90%

- Event Selection: 2 leptons + E_T^{miss} + 2 jets + kinematic cuts
  - Two leptons (e/μ) with opposite charge and with p_T^{l1} > 20 GeV and p_T^{l2} > 10 GeV
  - At least 2 jets with E_T > 15 GeV
  - Two jets with the highest b-jet probability assigned to be daughters of top and anti-top
  - E_T^{miss} > 50 GeV
  - Transverse mass of charge Higgs candidate
  - Lepton helicity angle θ_l^*: $\cos\theta_l^* < -0.6$ (on H^+ side)

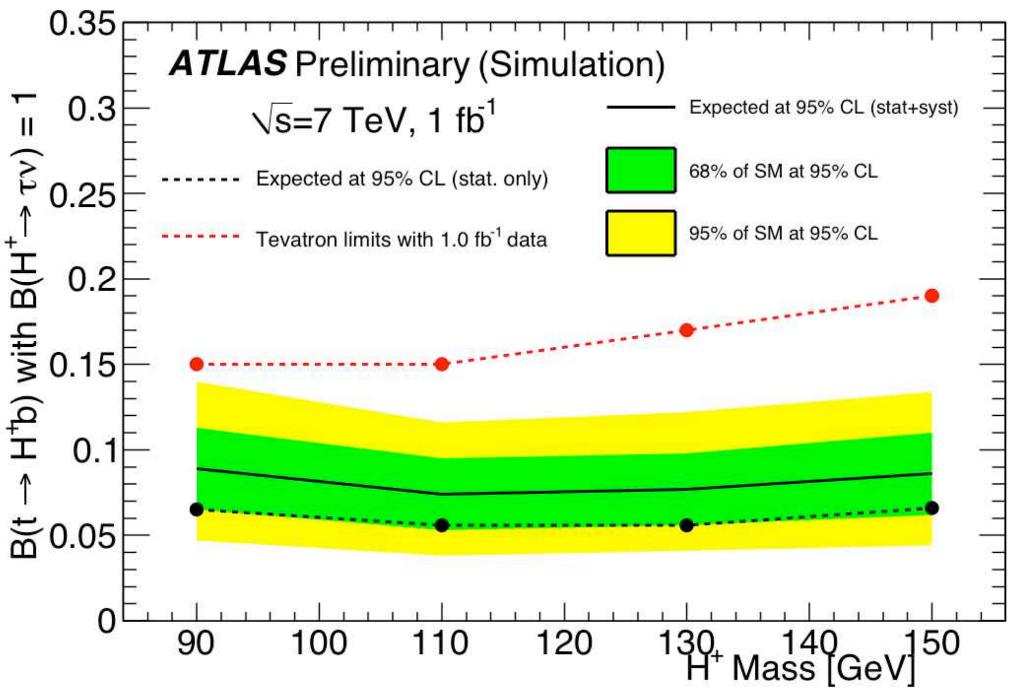


$$\cos\theta_\ell^* \approx \frac{4\, p_b \cdot p_\ell}{m_t^2 - m_W^2}$$

Results for √s = 7 TeV, 1 fb^{-1}:

- Upper limit on BR(t→bH⁺) assuming BR(H⁺→τν) = 1 versus m_{H+}
- Main background: ttbar (≈90%)
- Sensitivity evaluated separately for each mass point (m_{H+} = 90 – 150 GeV/c^2)
- Expected exclusion: BR(H⁺→τν) > 10% for mass range ≈90 – 150 GeV with 1 fb^{-1}
- Significant improvement on current Tevatron limits for this channel

ATL-PHYS-PUB-2010-006



Process	Number of events after no cut	all cuts
Signal $m_{H^+} = 90$ GeV	2.5×10^3	282
Signal $m_{H^+} = 110$ GeV	2.5×10^3	330
Signal $m_{H^+} = 130$ GeV	2.5×10^3	326
Signal $m_{H^+} = 150$ GeV	2.5×10^3	284
SM $t\bar{t}$ not hadronic	87.3×10^3	1194
Single top Wt-channel	5.7×10^3	55
Single top t-channel	20.4×10^3	43
Single top s-channel	0.9×10^3	3
$Z \to ll$ + jets	3.1×10^6	4
$W \to l\nu$ + jets	3.2×10^7	42
Wbb + jets	8.7×10^3	12
Zbb + jets	2.8×10^4	11

ATL-PHYS-PUB-2010-009

Conclusions and Outlook

- Low Higgs mass region is difficult experimentally – **taus will be an essential tool to achieve good sensitivity in this region**

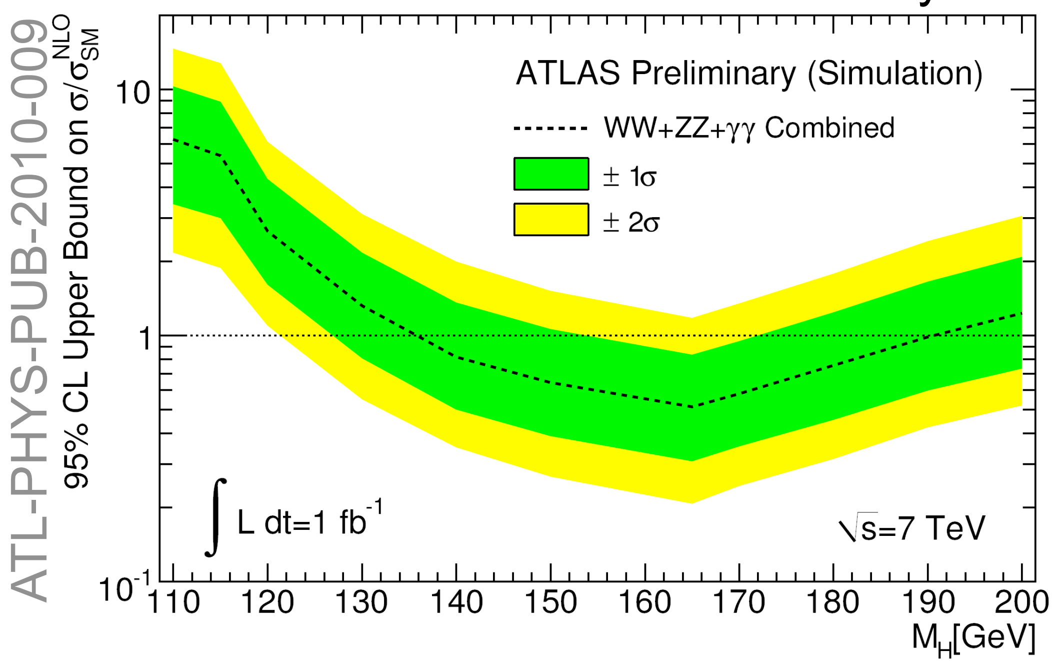
- An excellent, identification and reconstruction of tau leptons is essential

- Currently focusing on methods to determine backgrounds and estimate performance **from collision data**

- Charged Higgs search proved to be competitive with 1 fb^{-1} of data at √s = 7 TeV which we will collect by the end of 2011!

- **ATLAS will be able to exclude the Higgs in a wide region in both the SM and the MSSM with data from the current run.**

Note: WW + ϒϒ + ZZ results only

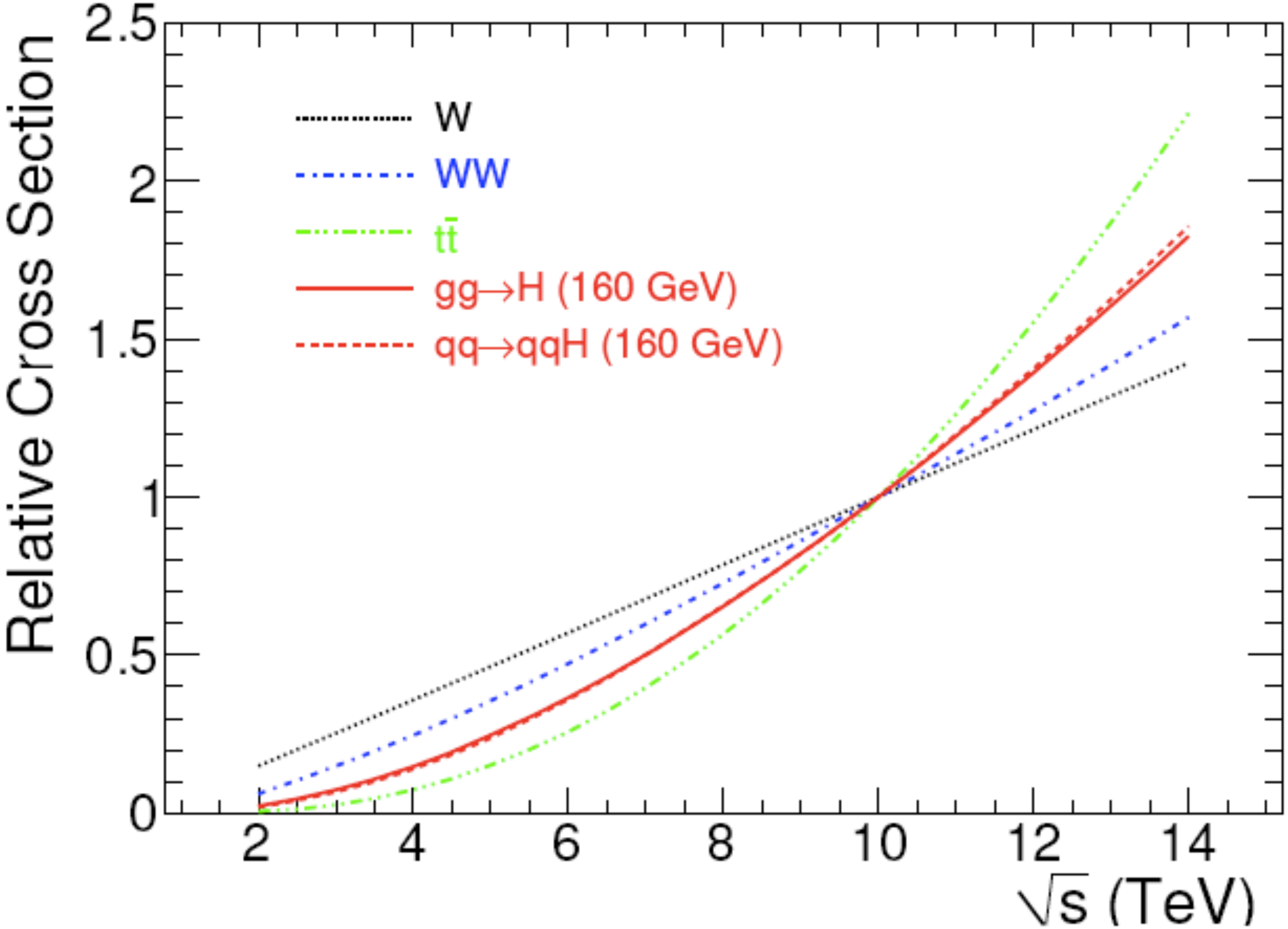


We've got a very exciting year ahead! Stay tuned!

BACKUP

Royal Holloway University of London

Calculated at NLO (MCFM)



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VBF $H \to \tau^+\tau^-$

Table 14: Estimated scale of systematic mis-measurements and their effect on the signal efficiency. † When varying the jet energy scale, only a 5% mis-measurement of the jet energy was used in manipulating the E_T^{miss} vector. See text for details.

Source	Relative uncertainty	Effect on signal efficiency
luminosity	$\pm 3\%$	$\pm$ 3%
muon energy scale	$\pm$ 1%	$\pm$ 1%
muon energy resolution	$\sigma(p_T) \oplus 0.011 p_T \oplus 1.7\ 10^{-4} p_T^2$	$\pm$ 0.5%
muon ID efficiency	$\pm$1 %	$\pm$ 2%
electron energy scale	$\pm$ 0.5%	$\pm$ 0.4 %
electron energy resolution	$\sigma(E_T) \oplus 7.3\ 10^{-3} E_T$	$\pm$ 0.3 %
electron ID efficiency	$\pm$ 0.2%	$\pm$ 0.4%
tau energy scale	$\pm$ 5%	$\pm$ 4.9%
tau energy resolution	$\sigma(E) \oplus 0.45\sqrt{E}$	$\pm$ 1.5%
tau ID efficiency	$\pm$ 5%	$\pm$ 5%
jet energy scale†	$\pm$ 7% ($\vert\eta\vert \leq 3.2$) $\pm$ 15% ($\vert\eta\vert \geq 3.2$) $\pm$ 5% (on E_T^{miss})	$^{+16\%}/_{-20\%}$
jet energy resolution	$\sigma(E) \oplus 0.45\sqrt{E}$ ($\vert\eta\vert \leq 3.2$) $\sigma(E) \oplus 0.67\sqrt{E}$ ($\vert\eta\vert \geq 3.2$)	$\pm$ 1%
b-tagging efficiency	$\pm$ 5%	$\pm$ 5%
forward tagging efficiency	$\pm$ 2 %	$\pm$ 2%
central jet reconstruction efficiency	$\pm$ 2 %	$\pm$ 2%
total summed in quadrature		$\pm$20%

h/H/A→τ⁺τ⁻ IN THE MSSM

Table 2: Summary of scale and resolution systematic variations in units of %. Numbers in parentheses indicate the variations for the b-tagged analysis when different from the non b-tagged analysis.

	Jet			τ			e			μ		
	ΔE↑	ΔE↓	$\Delta\sigma$(E)	ΔE↑	ΔE↓	$\Delta\sigma$(E)	ΔE↑	ΔE↓	$\Delta\sigma$(E)	Δp_T ↑	Δp_T ↓	$\Delta\sigma p_T$
Signal	0 (1)	0 (1)	1 (1)	1	2	2	0.5	0	0	0.5	0.5	0.5
$W \to e\nu$	0.5	0.5	1	< 5	< 6	2	1	1	0	2	3	0
$W \to \mu\nu$	0.5	0.5	1	< 5	< 6	2	1	1	0	2	3	0
$W \to \tau\nu$	0 (0.5)	0 (1)	1 (5)	< 5	< 6	1	0.5	0.5	0	0.5	0.5	0
$Z \to ee$	2	2	5	3	3	1	2	1	1	-	-	-
$Z \to \mu\mu$	0 (2)	0 (2)	3	< 6	< 7	2	-	-	-	5	5	0
$Z \to \tau\tau$	1	0	1	5	10	4	1	0.5	0	1	1	0.5
QCD	1 (3)	1 (2)	5	5	5	2	1	1	1	2	2	0
$b\bar{b}$-QCD	1 (3)	1 (2)	5	5	5	2	1	1	1	2	2	0
$t\bar{t}$	2 (3)	1	3	< 6 (< 10)	5 (< 7)	2	1	0	0	1	2	0

Table 3: Summary of efficiency and b-tagging systematic variations given in units of %. Numbers in parentheses indicate the variations for the b-tagged analysis when different from the non b-tagged analysis.

	$\Delta\varepsilon_e$	$\Delta\varepsilon_\mu$	$\Delta\varepsilon_\tau$	$\Delta\varepsilon_{b-\text{tag}}$	$\Delta f_{l-\text{jet}}$
Signal	0.1	0.5	5	0.5 (2.3)	0.3 (1.0)
$W \to e\nu$	0.2	-	5	0.0 (2.0)	0.1 (5.0)
$W \to \mu\nu$	-	1.0	5	0.0 (2.0)	0.1 (5.0)
$W \to \tau\nu$	0.2	0.5	5	0.0 (0.8)	0.1 (4.3)
$Z \to ee$	0.2	-	5	0.0 (1.8)	0.2 (6.0)
$Z \to \mu\mu$	-	1.0	5	0.0 (1.5)	0.2 (5.5)
$Z \to \tau\tau$	0.1	0.5	5	0.0 (1.8)	0.4 (3.2)
QCD	0.2	0.5	5	2.0 (3.0)	1.0 (3.0)
$t\bar{t}$	0.2	0.5	5	5.0 (2.0)	4.0 (1.5)

h/H/A→$\tau^+\tau^-$ IN THE MSSM

Source	Uncertainty (in %)	Effect (in %) on N_{bg}	Effect (in %) on ε_{sig}
Normalization	7	7	n/a
Trigger	1	< 1	1
Lepton ID efficiency	1	< 1	1
Lepton fake rate	1	1	1
Lepton energy scale	1	< 1	1
Jet energy scale	7-15	7	4
b-tagging efficiency	4	< 1	4
b-tagging fake rate	10	1	< 1
Total		10	6

Table 13: Systematic uncertainties and their effect on N_{bg} and ε_{sig}, expressed in %.