Search for exclusive and charged Higgs bosons

with ATLAS at the LHC

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Ph.D Thesis Defense

November 17, 2016

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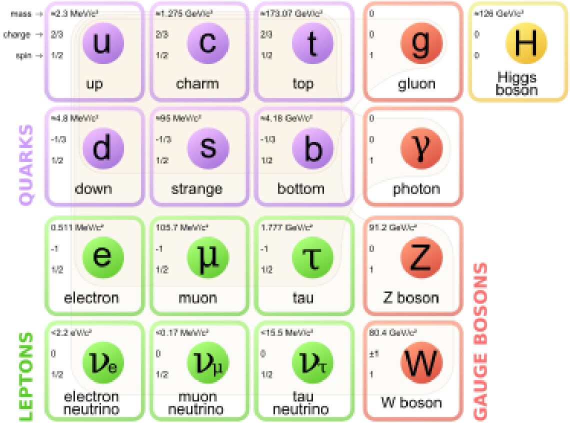
Introduction

The Standard Model (SM)

SM summarizes current understanding of matter and forces

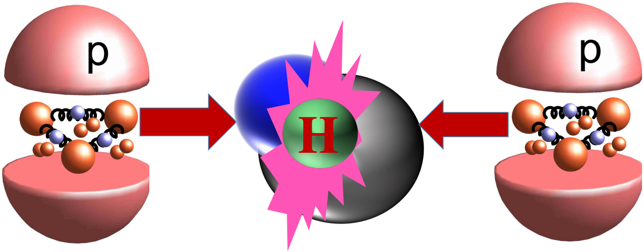


Also successful in making predictions

SM – experiments

Tested through scattering experiments – e.g proton scattering

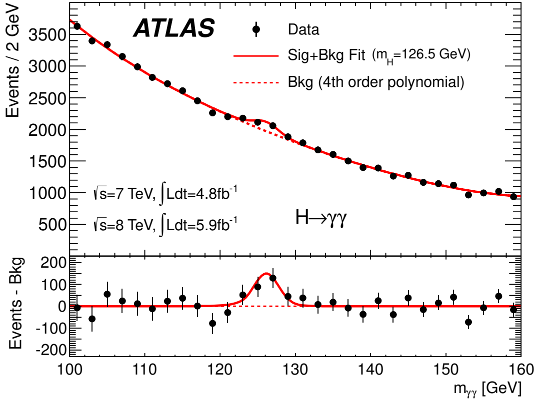
- Protons made up of quarks and gluons (partons)
  - Proton collision $\rightarrow$ parton collision
- Primary parton hard scatter expected to produce interesting physics
  - Proton remnant activity referred to as underlying events (UE)



- Bunches of protons collided to maximize probability of collision
- Multiple proton collisions per bunch
  - One primary and multiple pile-up collisions

SM Higgs boson – discovery and future prospects

Higgs boson discovered in 2012 – updated $m_H = 125.09 \pm 0.24$ GeV



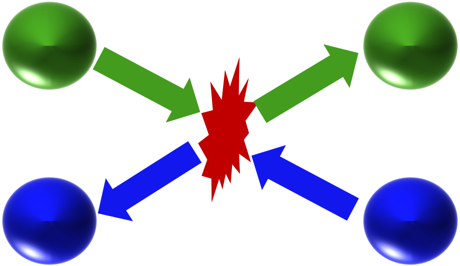
Efforts towards precision studies on its properties:

- Coupling constants, quantum numbers, invisible decays

Analysis channels with minimal backgrounds necessary

Exclusive Production – Candidate for precision studies

Exclusive processes have very little background contamination



- Scattering protons effectively do not exchange quantum numbers
- Only share momentum during collision
  - Shared momentum could create the SM Higgs boson
- No underlying event $\rightarrow$ cleanliness

Thesis Project I

Search for evidence of exclusive Higgs boson

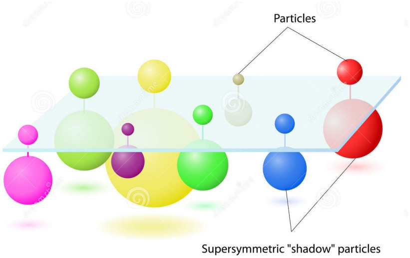
Shortfalls of the SM

"Failure is not fatal, but failure to change might be."

– John Wooden

- Absence of gravity
- Massless neutrinos
- Dark matter candidates
- CP violation in cosmology
- **Hierarchy problem – large differences in coupling constants at low energy scales**

Hierarchy problem could be addressed by SUperSYmmetric (SUSY) theories



Minimal Supersymmetric extension to Standard Model (MSSM)

Higgs sector now comprises 5 Higgs bosons:

- light Higgs, h^0– scalar
  - if h^0 is taken as the SM Higgs, MSSM is known as **hMSSM**
- heavy Higgs, H^0– scalar
- neutral Higgs, A^0– pseudo-scalar, CP-odd
- **charged Higgs**, $H^{\pm}$– scalar

Built on two Higgs doublet fields, rather than one Higgs field

- Entire parameter space of Higgs sector can be parametrized by:
  - $\tan\beta$ – ratio of vacuum expectation values of the two Higgs doublets
  - m_{H^+} – mass of $H^{\pm}$

Thesis Project II

$\boxed{\text{Search for evidence of charged Higgs boson}}$

The Experiment

The Large Hadron Collider (LHC)

27 km-long accelerator colliding bunches of protons

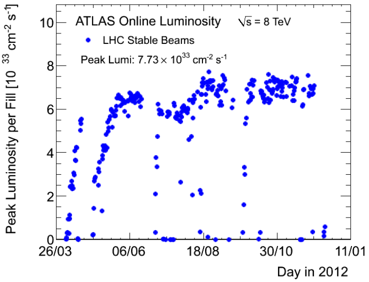
Parameter	Run I Value	Run II Value	Design Value
Beam Energy [TeV]	4	6.5	7
Bunch spacing [ns]	50	25	25
Protons per bunch	1.7×10^{11}	1.18×10^{11}	1.15×10^{11}
Average pile-up	20.7	22.9	20

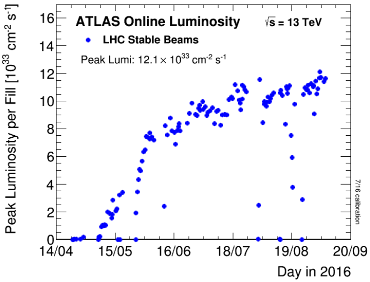
Has had 2 long runs : Run I (2011$\rightarrow$2012) and Run II (2015$\rightarrow$2016)

Goal is to optimally produce rare processes

- Performance quantified by instantaneous luminosity,

$$L = N_{process}/\sigma_{process}$$

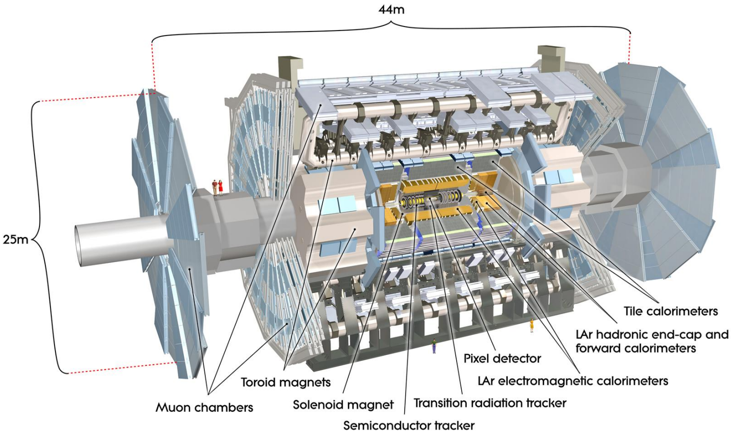




- Integrated luminosity $\mathcal{L} = \int_0^T L dt$ over time T quoted to correspond data collected

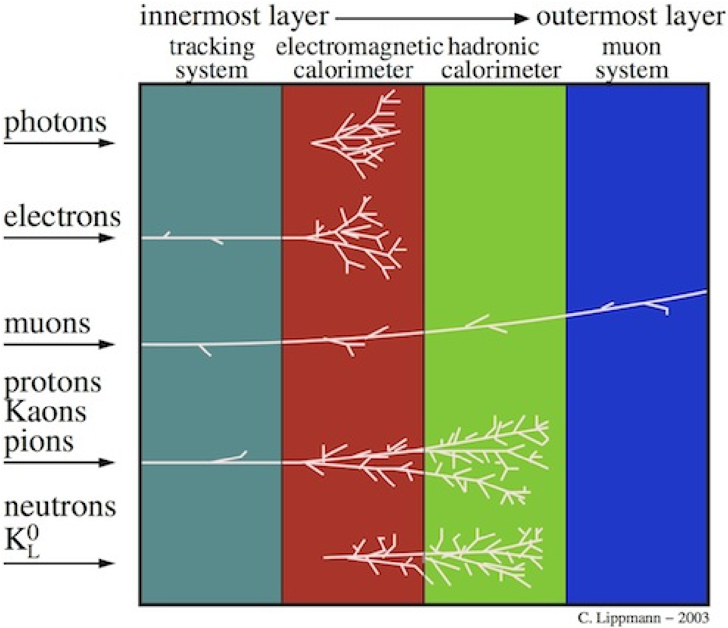
A Toroidal LHC ApparatuS (ATLAS)

Large all-purpose detector built around LHC collision point



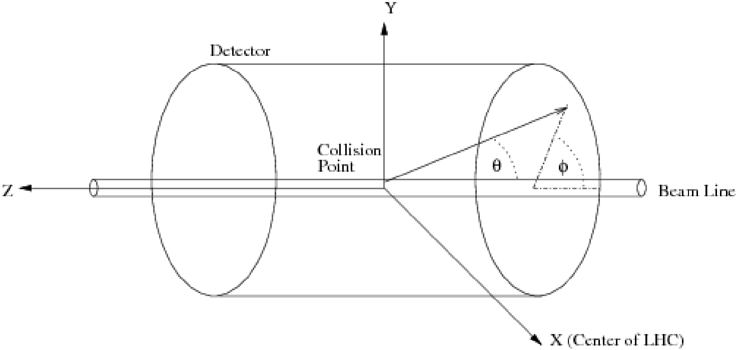
- Precision charged particle tracking
- Momentum and energy reconstruction

ATLAS – particle detection



ATLAS – coordinate system

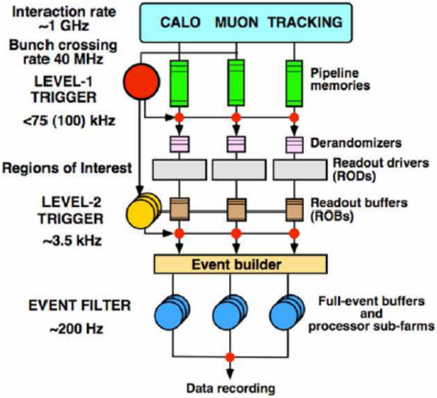
Cylindrical coordinate system



- Transverse plane $\longrightarrow$ (r, ϕ)
- Longitudinal plane $\longrightarrow$ pseudo-rapidity $\eta = -\ln\tan(\theta/2)$
- Metric $\longrightarrow$ angular distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

ATLAS – trigger system

Not all data can be collected and saved to disk; available space has limits

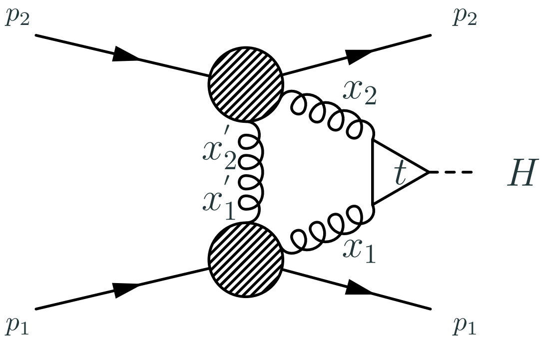


- Bunch crossing rate reduced from $\sim$ **40 MHz** to about $\sim$ **200 Hz**
- L2 and Event Filter combined into Higher Level Trigger (HLT) in Run II

Search for exclusive Higgs boson

Production

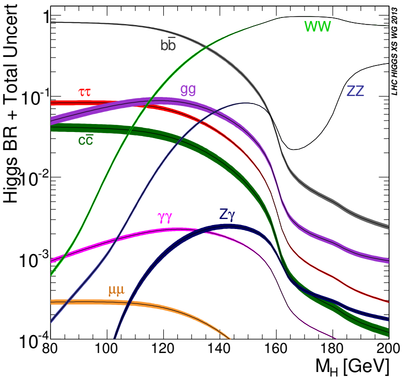
Protons remain intact after collision



- Higgs dominantly produced through standard gluon fusion
- Extra gluon exchanged maintains color in original protons
- Predicted 3 fb total production cross section at 8 TeV LHC

Decay channels

- Largest branching ratios:
  - $H \to b\bar{b}$
  - $H \to W^+W^-$
- Too much QCD multi-jets bkg. in $b\bar{b}$
  - Multi-jets too complex to model correctly
- W^+W^- is the optimal choice
- $W^\pm$ decay to leptons of different flavor, and charge



Complete decay channel : $gg \to H \to W^+W^- \to \ell^+\nu\ell'^-\bar{\nu}$

Major background processes

Backgrounds separated into inclusive and exclusive

Inclusive Backgrounds

- **Inc. *WW***: Non-diffractive direct production of W^+W^-
- **Top**: $t\bar{t}$ and single top
- **VV**: Non-diffractive direct production of $WZ, ZZ, W\gamma, Z\gamma$
- **V+jets**: Non-diffractive direct production of W/Z+jets

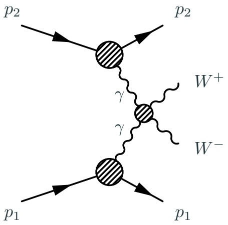
Exclusive Backgrounds

- **Excl. *WW***: Exclusive production of W^+W^-
  - E.g $\gamma\gamma \rightarrow W^+W^-$
- **Excl. *ll***: Exclusive and direct production of *ll*
  - E.g $\gamma\gamma \rightarrow \ell^+\ell^-$

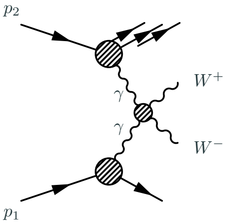
Major exclusive backgrounds

Exclusive backgrounds come in many forms!

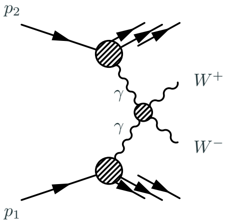
Elastic



Single Dissociative (SD)



Double Dissociative (DD)



- In all cases, proton remnants outside detector fiducial space
- Excl. *ll* production identical to excl. *WW*
- SD and DD difficult to model with MC
    - Estimated with data-driven methods

Event Selection [Signal region (SR) definition]

$$gg \rightarrow [H] \rightarrow [W^+][W^-] \rightarrow [l][l][E_T^{miss}]$$

- Lower bound on lepton p_T suppresses QCD and $W+$jets
- Lower bound on $m_{e\mu}$ suppresses QCD and Drell-Yan
- Upper bound on $m_{e\mu}$ exploits Higgs spin-0
  - Same as $\Delta\phi_{e\mu}$
- $p_T^{e\mu}$, suppresses QCD multijets, V+jets and

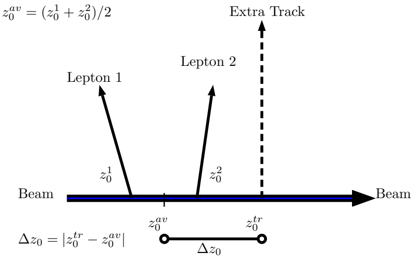
Signal Selection

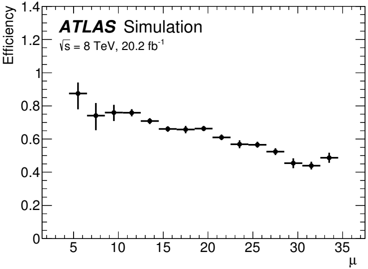
1. Oppositely charged $e\mu$
2. $p_T^{\ell 1} > 25$, $p_T^{\ell 2} > 15$ GeV
3. $10 < m_{e\mu} < 55$ GeV
4. $p_T^{e\mu} > 30$ GeV
5. $\Delta\phi_{e\mu} < 1.8$
6. $m_T < 140$ GeV
7. Exclusivity selection, Δz_0^{iso}

Exclusivity Selection, $\Delta z_0^{\mathrm{iso}}$

Exploit large gaps btwn protons and dilepton system

Expect no tracks in the large gaps





- For inclusive processes, expect extra tracks
  - Extra tracks from underlying event
- Optimal $\Delta z_0^{\mathrm{iso}} = 1$ mm, $\epsilon = 58 \pm 6\%$, rejection $= \mathcal{O}(10^3)$

$\Delta z_0^{\mathrm{iso}}$, validation

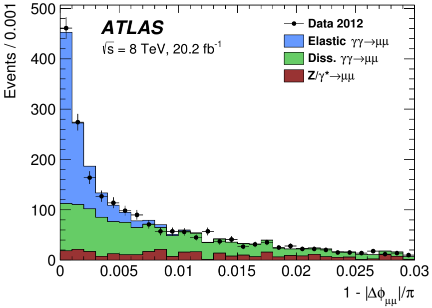
MC known to overestimate elastic $\gamma\gamma \to X$ (arxiv 1410.2983)

- **Strategy** : Derive scale factor f_{EL} from $\gamma\gamma \to \mu^+\mu^-$ data
  - f_{EL} is ratio of observed elastic $\gamma\gamma \to \mu^+\mu^-$ to MC prediction

$\gamma\gamma \to \mu^+\mu^-$ Selection

1. 2 μ with $p_{\mathrm{T}}^{\mu} > 20$ GeV
2. $45 < m_{\mu\mu} < 75$ GeV or $m_{\mu\mu} > 105$ GeV
3. $p_{\mathrm{T}}^{\mu\mu} < 3$ GeV and $\Delta z_0^{\mathrm{iso}} = 1.0$ mm

Drell-Yan only significant bkg



- Vary $p_{\mathrm{T}}^{\mu\mu}$ and $\Delta z_0^{\mathrm{iso}}$ to evaluate systematic uncertainties

$$\boxed{f_{\mathrm{EL}} = 0.76 \pm 0.04(\mathrm{stat.}) \pm 0.10(\mathrm{sys.})}$$

Previous measurements cover between 0.73 and 0.75

$\Delta z_0^{\mathrm{iso}}$, Pileup robustness

Effect of pile-up on exclusivity selection must be quantified

- **Strategy :** Evaluate f = Data/(Elastic+SD+DD) in two data regions
  - Nominal exclusivity vs. pile-up prone exclusivity

Nominal [$f = 0.73$]

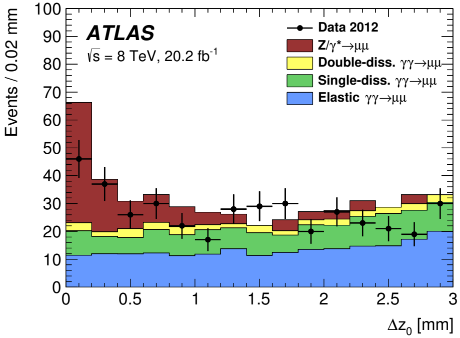
Excl. $\mu\mu$ sel. except :

1. acoplanarity < 0.0015
2. $\Delta z_0^{\mathrm{iso}} = 1.0$ mm

Pileup-prone [$f = 0.70$]

Similar to Nominal except :

1. 1 extra track with $\Delta z_0^{\mathrm{iso}} = 3.0$ mm



- 2 scale factors compatible at 10% ⇒ syst. error due to pile-up is 10%

Track Multiplicity in MC

Underlying event may not be modelled correctly in simulation

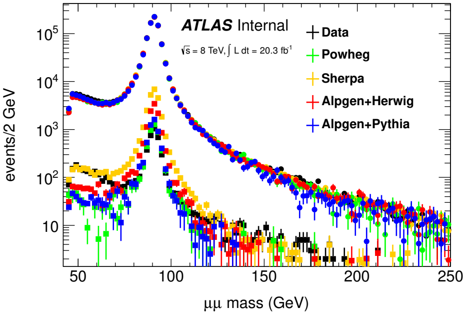
- **Strategy :** Extract scale factors ($\epsilon_{\text{Data}}/\epsilon_{\text{MC}}$) from Drell-Yan data

Selection

$\gamma\gamma \to \mu^+\mu^-$ selection except :

1. $80 < m_{\mu\mu} < 100$ GeV
2. No $p_{\text{T}}^{\mu\mu}$ selection

Exclusivity $\Delta z_0^{\text{iso}} = 1.0$ mm



- Rejection more in $Z/\gamma \to \mu^+\mu^-$ data than MC
- Systematics evaluated by varying MC generator across $m_{\mu\mu}$ (20%)

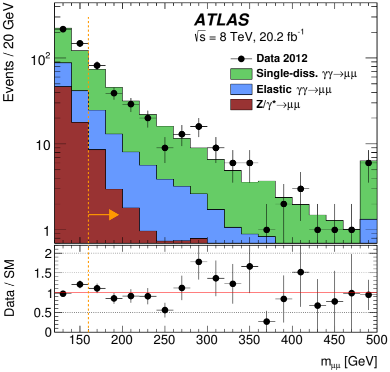
Estimation of SD and DD components

No simulation for SD and DD $\gamma\gamma \to W^+W^-$

- **Strategy :** Extract correction factor f_γ from excl. $\mu\mu$ data

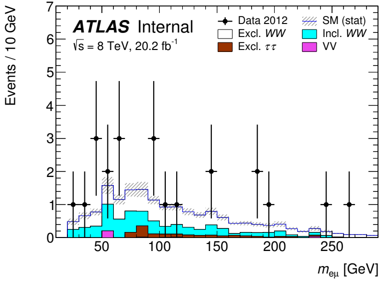
$$f_\gamma = \frac{\mathrm{N}_{\mathrm{Data}} - \mathrm{N}^{\mathrm{POWHEG}}_{\mathrm{Background}}}{\mathrm{N}^{\mathrm{HERWIG++}}_{\mathrm{Elastic}}} = 3.30$$

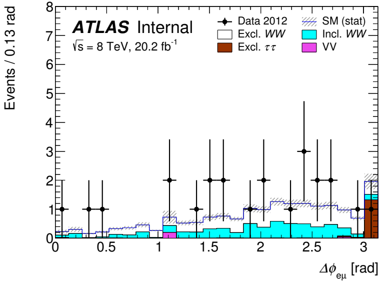
- Excl. *ll* similar to excl. *WW*

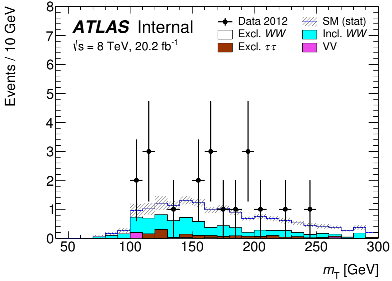


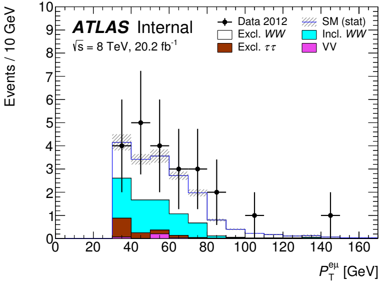
- Systematic uncertainty obtained by varying Drell-Yan by $\pm 20\%$
- Uncertainties mostly statistical, total being 7%

Validation regions – Excl. W^+W^-

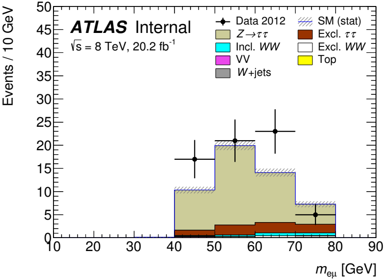


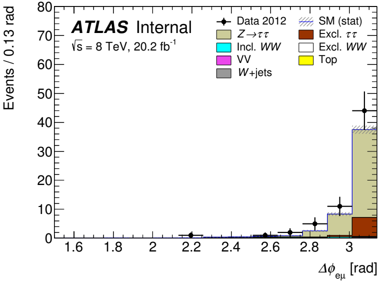


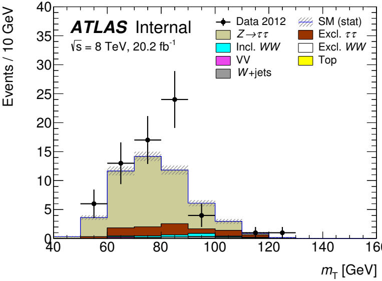


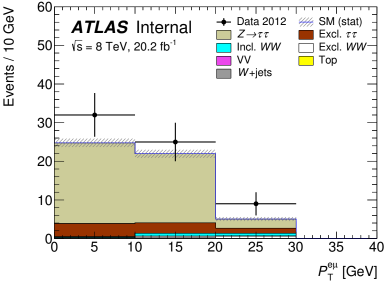


Validation regions – Incl. $Z \to \tau\tau$





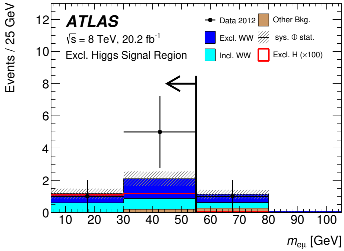


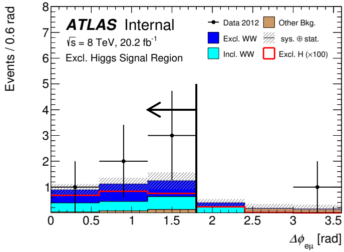


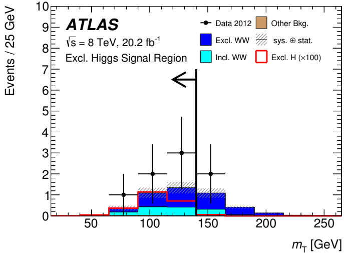
Results – Observed Event Yields

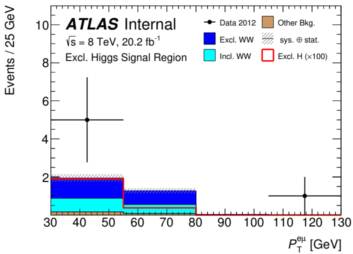
Excl. Higgs event yields

Data : 6 , Bkg : 3.0 ± 0.8, Signal : 0.023 ± 0.003









Results statistical interpretation – Observed Limits

- *Null hypothesis*: 6 events are compatible with the predicted 3 events
  - p-value of 0.13 – cannot reject null hypothesis
- Using interval estimation, limits can be set on σ_H
- Observed limit use real data
- Expected limit approximate data with expected sum of backgrounds

Upper Lim. σ_H (125 GeV) [pb] @ 95% CL

Observed : 1.2 pb , Expected : 0.7 pb

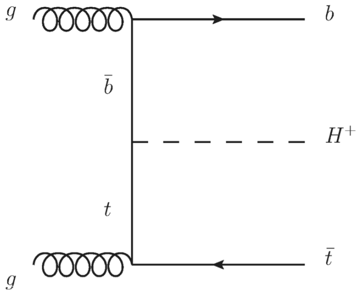
- Observed upper limit 1.1σ higher than expected.
- $400\times\sigma_H^{\text{predicted}}$, where $\sigma_H^{\text{predicted}} = 3.0$ fb

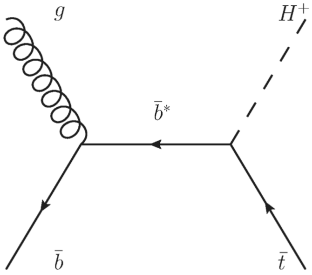
First ever upper limit on the exclusive Higgs

Search for charged Higgs boson

H^+ – Production Modes

For high m_{H^+}, H^+ produced in association with t quark

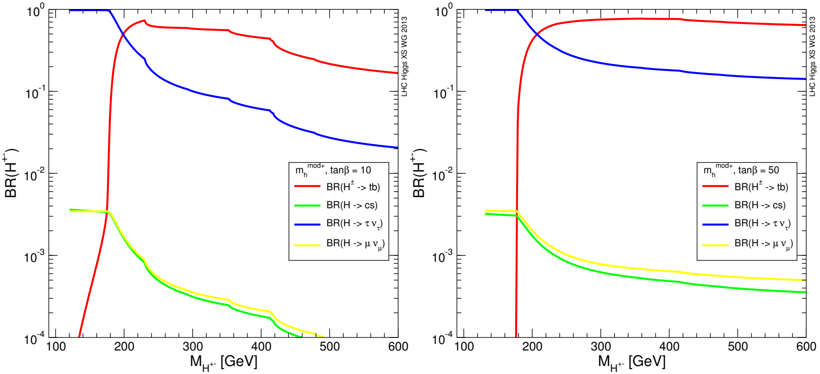




- 4-flavor scheme (left) also associated with a b quark
- Search scanned through m_{H^+} from 200$\rightarrow$2000 GeV

H^+ – Decay channels

For high m_{H^+}, $H^+ \to tb$ and $H^+ \to \tau\nu$ dominant decays



- $H^+ \to tb$ unfavorable – $t\bar{t}$ +X background, m_T unclear
- Chose $H^+ \to \tau\nu$ – backgrounds relatively easier to manage

τ lepton to decay hadronically – reconstructed as $\tau_{\text{had-vis}}$

$$gb \to [t][H^+] \to [(jj)b][(\tau_{\text{had-vis}} + E_T^{\text{miss}})]$$

$$gg \to [tb][H^+] \to [(jj)bb][(\tau_{\text{had-vis}} + E_T^{\text{miss}})]$$

- Backgrounds classified by type of $\tau_{\text{had-vis}}$
    - true τ, q/g faking τ, or e/μ faking τ

Background processes

1. **Top**: Sum of $t\bar{t}$ and single top
2. **W + jets**: $W^{\pm}$ produced in association with a jet
3. **Z + jets**: Z produced in association with a jet
4. **VV**: $WZ, ZZ, W\gamma$, or $Z\gamma$

$H^+ \to \tau\nu$ – Signal region (SR)

Looking for jets, b-jets, a $\tau_{\text{had-vis}}$, and E_T^{miss}

Signal Selection

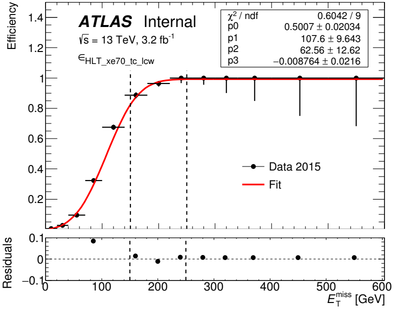
1. `HLT_xe70_tc_lcw`(`HLT_xe90_mht`)
2. At least one $\tau_{\text{had-vis}}$ with $p_T > 40$ GeV
3. At least 3 jets with $p_T > 25$ GeV
4. No μ or e
5. At least one b−tagged jet
6. $E_T^{\text{miss}} > 150$ GeV
7. $m_T > 50$ GeV

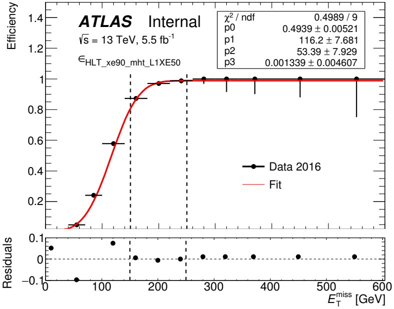
- Lower bound on $\tau_{\text{had-vis}}$ p_T suppresses most backgrounds
- Large E_T^{miss} – a construct of trigger efficiencies
- Large m_T expected since probing high m_{H^+}

Trigger Efficiency Studies

MC weighted according to trigger efficiency measured in data

- Orthogonal but similar control region in data used to measure trigger efficiency



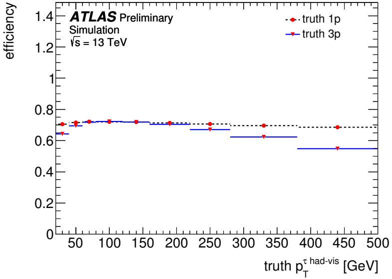


At 150 GeV $E_{\mathrm{T}}^{\mathrm{miss}}$, trigger efficiency above 80%

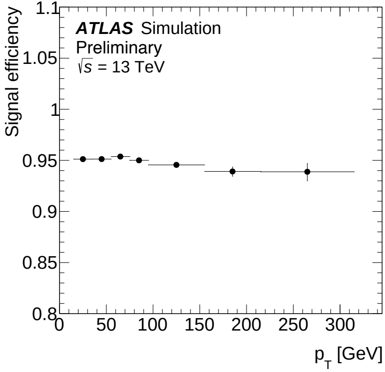
True τ background

Backgrounds from true τ events estimated using MC

- MC simulation corrected by scale factors to match data:
    - Reconstruction efficiency
    - QCD jet rejection
    - e/μ rejection
    - ...



Reco. Efficiency



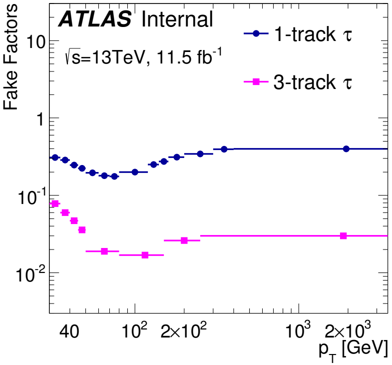
Jet to τ background

q/g ($N^{\text{anti-}\tau}_{\text{fakes}}$) extrapolated to $\tau_{\text{had-vis}}$ (N^{τ}_{fakes}) by Fake Factors

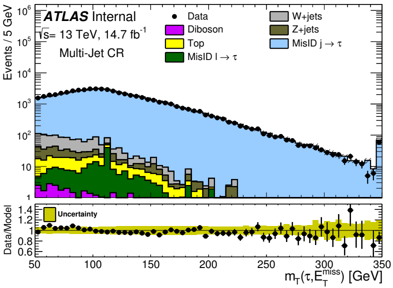
- FF measured in two sub-regions : $\tau_{\text{had-vis}}$-ID and anti-$\tau_{\text{had-vis}}$-ID

$$N^{\tau}_{\text{fakes}} = N^{\text{anti-}\tau}_{\text{fakes}} \times \text{FF}$$

$$\text{FF} = N_{\tau-\text{id}} / N_{\text{anti-}\tau\text{-id}}$$



- FF validated in region rich in QCD multi-jets



Major systematic uncertainties

Experimental and theoretical, depending on source

Theoretical

- QCD renormalization and factorization scales (μ_R, μ_F),
- choice of parton distribution functions (PDF)
- choice of parton shower and underlying event (PS and UE) tunes

Experimental

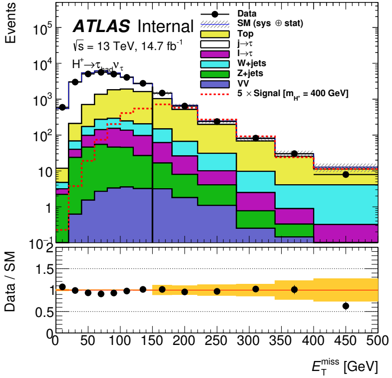
- Dominated by uncertainties on object reco. and ID
- Energy scales propagated to $E_{\mathrm{T}}^{\mathrm{miss}}$

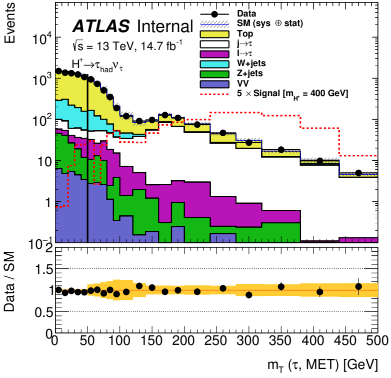
Variation	$t\bar{t}$ (%)	Signal (%)
PS and UE	16	10
μ_R, μ_F	5	5
PDF choice	5	1

Variation	$t\bar{t}$ (%)	Signal (%)
$\tau_{\text{had-vis}}$ ID efficiency	11	8
Jet energy scale	11	5
$\tau_{\text{had-vis}}$ energy scale	6	4

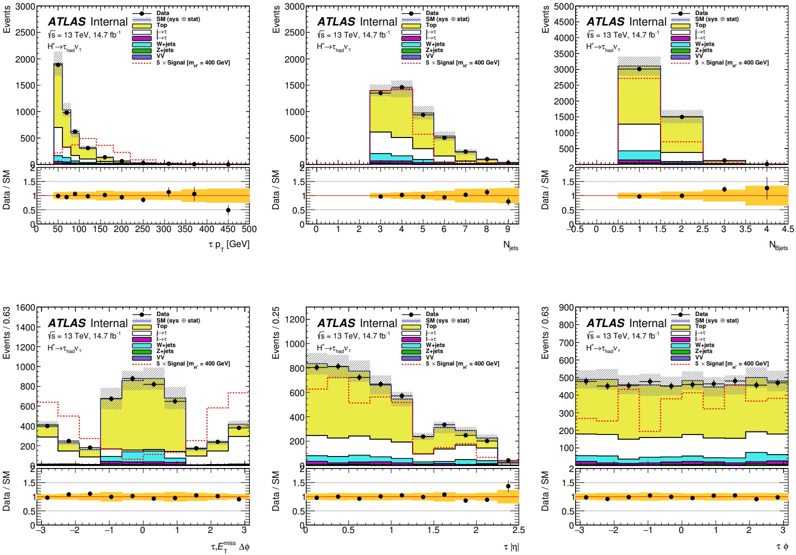
Results – Event yields in the SR

Observed events in the SR well within predictions



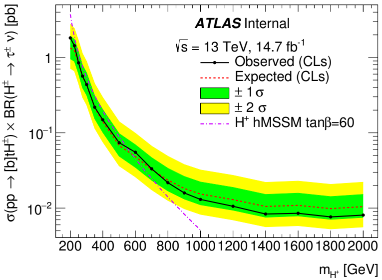


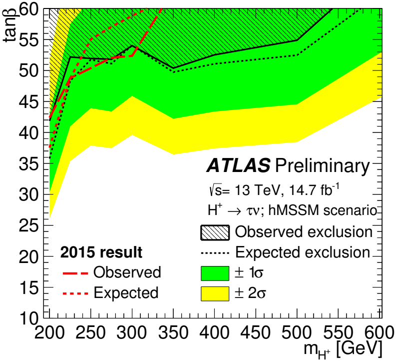
Results – Event yields in the SR



Results – Statistical interpretation, Limits

- Evaluation of observed yields (and m_T shape) against bkg-only hypothesis performed
  - Could not reject bkg-only hypothesis
- Limits on $\sigma^{true}_{H^+}$ set for m_{H^+} in 200→2000 GeV





In the hMSSM context, $\tan\beta = 60$ values are excluded for m_{H^+} in $200 \rightarrow 540$ GeV

Summary

Summary

- Undertook two major projects
  - Search for exclusive Higgs boson
  - Search for charged Higgs boson
- Contributed to detector development
  - Feasibility studies on ATLAS level 1 trigger
  - Optimization of RoIB for level 2 ATLAS trigger

- Found no evidence for the exclusive Higgs boson in LHC Run I data
  - Set the first ever limits on the production cross section
- Found no evidence for the charged Higgs boson in LHC Run II data
  - Set limits on the production cross section ($\times$ branching ratio to $\tau\nu$) in the 200$\rightarrow$200 GeV m_{H^+} range
  - In the hMSSM context, $\tan\beta = 60$ values excluded for m_{H^+} in $200 \rightarrow 540\ \ \mathrm{GeV}$

Thank you

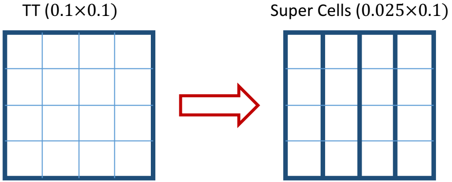
Level 1 (L1) trigger – the calorimeter

- L1 trigger decision based on multiplicity of physics objects and size of $E_{\mathrm{T}}^{\mathrm{miss}}$
    - e, μ, τ and jets
- Calorimeters made up of cells
    - however, full granularity not accessible at L1
- Reconstruction of physics objects performed using groups of cells
    - Trigger Towers – TT
- Objects distinguished based on shower shapes in the calorimeters
    - e.g, a τ shower is deeper than an e shower
- Maximum latency, 2.5 μs

Bunch crossing rate reduced from **40 MHz** to about **100 kHz**

L1 upgrade – feasibility studies (Summer 2012)

By how much would upgrading L1 calorimeter granularity improve L1?



Using supercells can we distinguish π^0 and e at L1?

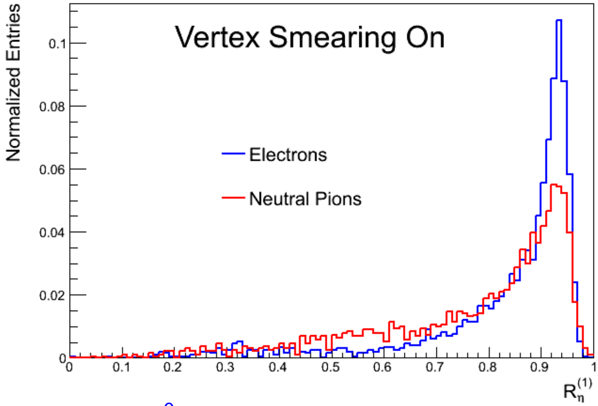
- **Strategy** : Come up with variables to describe shower shapes
  - e.g, ratio of energy of hottest supercell to sum of itself and two neighbors

$$R_\eta^{(1)} = \frac{E_0}{E_{+1} + E_0 + E_{-1}} \tag{1}$$

e shower narrower than $\pi^0 \longrightarrow$ expect $R_\eta^{(1)}$ to be larger for e than for π^0

L1 upgrade – feasibility studies (Summer 2012)

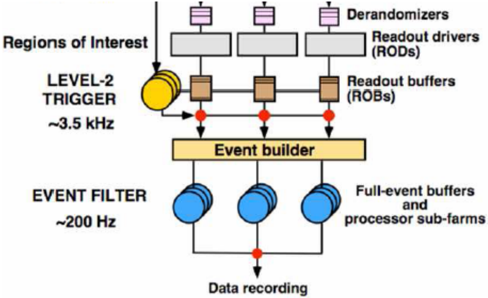
- Generated Monte Carlo (MC) samples of either single e or π^0
- Simulated passage of e/π^0 through ATLAS calorimeters
- Studied shower shapes of each using variables like $R_\eta^{(1)}$
  - More results at UTA hep web page



Cannot separate π^0 and e showers at L1 using supercells

L2 (HLT) upgrade – 2013→2014

Accepts/rejects events through a Regions of Interest (RoI) builder at 100 kHz

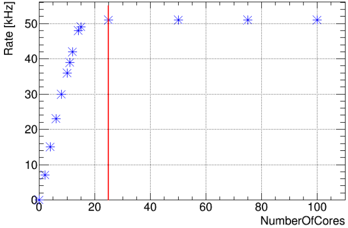


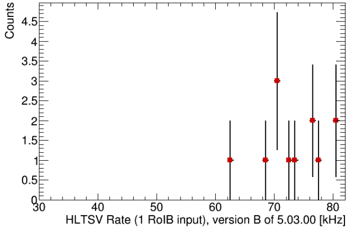
L2 and EF algorithms merged in Run II
– can this setup achieve a rate of 100 kHz?

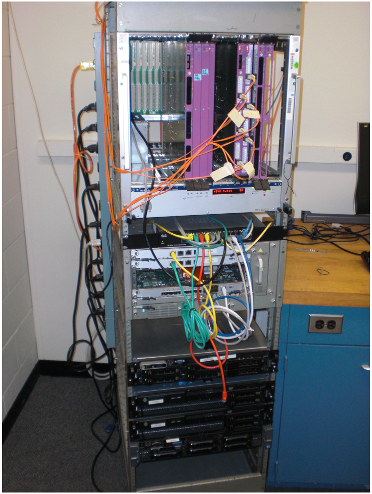
- **Project:** Optimize RoI Builder (RoIB) rate with Run II setup

HLT – Configuration optimization

Argonne National Laboratory has a test stand for HLT

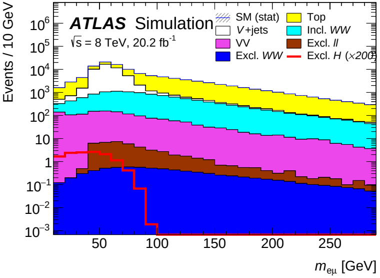


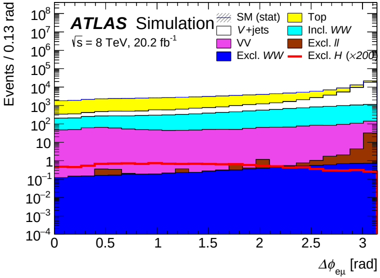


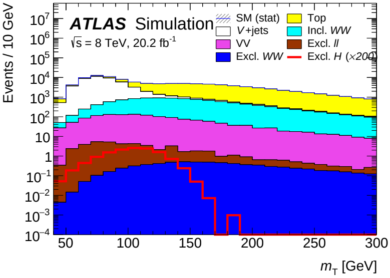


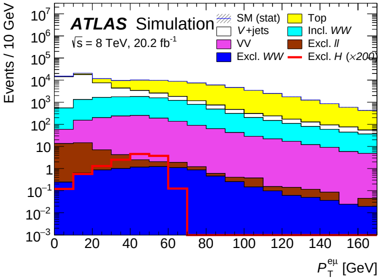
Achieved a rate of $\sim$ **80 kHz** – dependent on PC hardware

Kinematic Dists. after pre-selection





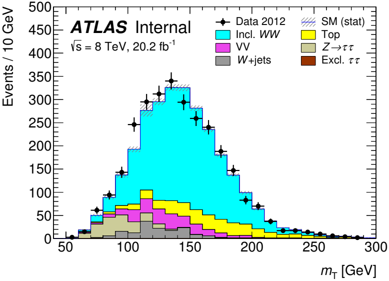


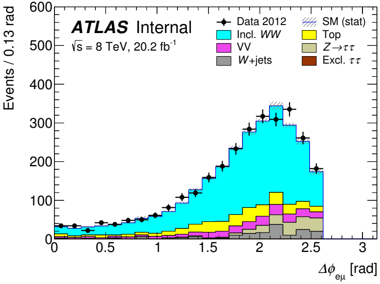


Inc. *WW* normalization

MC known to underestimate $q\bar{q} \to W^+W^-$ prediction

- Control region similar to signal region except:
  - $55 < m_{e\mu} < 110$ GeV and $\Delta\phi_{e\mu} < 2.6$



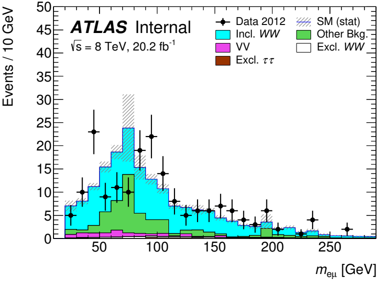


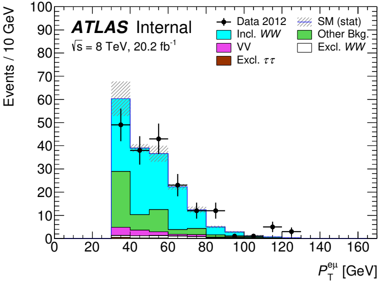
- $(20 \pm 5)\%$ more data was observed than is predicted
  - 1.20 ± 0.05(stat.) applied across the board as a scale factor

Inc. WW + Other

How much inclusive WW after exclusivity?

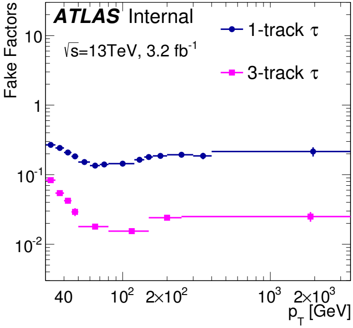
- Dedicated control region with incl. WW – loosen exclusivity to allow only 1 to 4 extra tracks
  - Other bkg such as $W+$jets, Drell-Yan, and Top irreducible
  - Exclusive processes well calibrated, so easy to subtract
- Extrapolate predictions to the 0-extra track exclusivity region

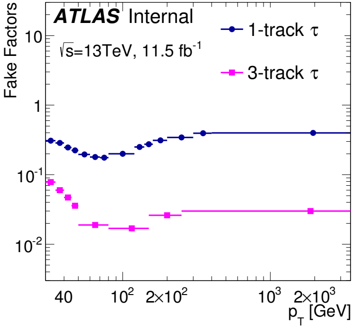


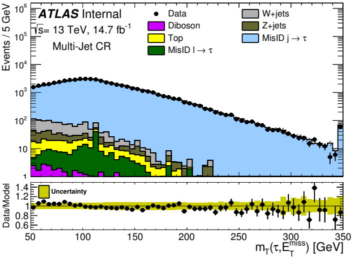


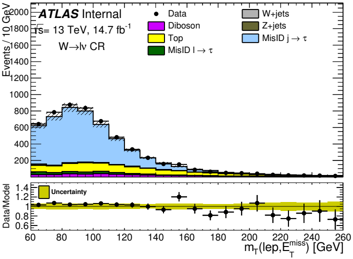
Extrapolation equivalent to applying a normalization factor of 0.79 to inclusive W^+W^-background

Jet to τ background – measured FF, validation









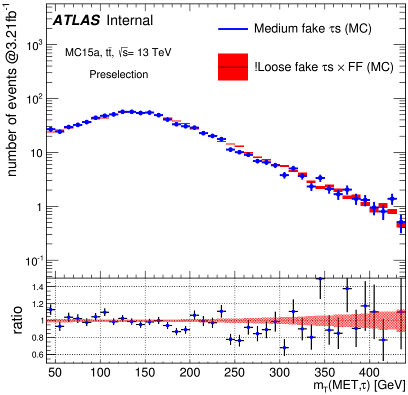
Jet to τ background – Fake Factors definition

From CR dominated by events with q/g-initiated jets ($N^{\text{anti-}\tau}_{\text{fakes}}$), extrapolate to SR events in which the jets pass $\tau_{\text{had-vis}}$ ID (N^{τ}_{fakes})

- Extrapolation factors known as *fake factors* (FF), where

$$\boxed{N^{\tau}_{\text{fakes}} = N^{\text{anti-}\tau}_{\text{fakes}} \times \text{FF}}$$

- FF measured in data (next slide)
- Pre-test FF by measuring them in $t\bar{t}$ MC and assessing performance on $t\bar{t}$ MC events that pass pre-selection



Jet to τ background – Fake Factors measurement

Region in which FF are **measured** must be different from the CR in which they are **applied**

- Measurement region comprises of τ-id and anti-τ-id sub-regions
  - In former jets pass τ ID and in latter they are not required to

$$\boxed{\mathrm{FF} = \frac{N_{\tau-\mathrm{id}}}{N_{\text{anti-}\tau\text{-id}}}}$$

- Here, FF measured in two regions:
  - **Multi-jet**: Dominated by events with QCD multi-jets
  - $\boldsymbol{W+}$ **jets**: Dominated by events with jets from $W+$ jets
- Fraction of q-initiated jets in multi-jets roughly the same as g-initiated jets
- Jets in $W+$ jets dominated by jets from light-flavored quarks
- Take measurements from multi-jets as nominal and use $W+$ jets measurements to evaluate impact of jet substructure

e/μ to τ background

Scale factors (SF) applied to simulated events with e/μ-matched $\tau_{\text{had-vis}}$

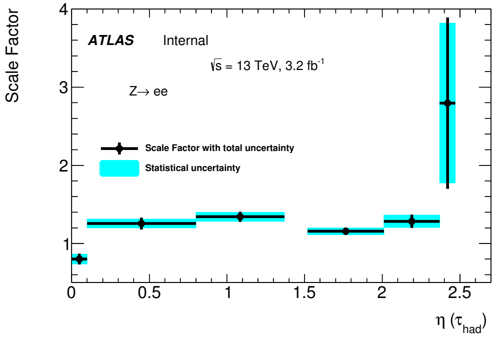
- SF dependent on and η and measured in $Z \to ee$ events in data

$Z \to ee$ Selection

1. One e, one $\tau_{\text{had-vis}}$
2. 0 b-jets, $m_T < 40$

- e tag, $\tau_{\text{had-vis}}$ probe

$$\text{SF} = \frac{\text{All sel.}}{\text{All sel.} - \tau_{\text{had-vis}}\ \text{sel.}}$$



- Non-$Z \to ee$ events subtracted from data before calculation of SF
- Measured SF range from 0.5% to 2.5%, depending on η

Major systematic uncertainties

Classified into *experimental* and *theoretical*, depending on source

Theoretical

- Dominated by uncertainties on:
  - QCD renormalization and factorization scales (μ_R, μ_F),
  - choice of parton distribution functions (PDF)
  - choice of parton shower and underlying event (PS and UE) tunes

Variation	$t\bar{t}$	Signal 400 GeV
PS and UE	16	10
μ_R, μ_F	5	5
PDF choice	5	1

Experimental

- Dominated by uncertainties on object reco. and ID
  - Propagated to $E_{\mathrm{T}}^{\mathrm{miss}}$; propagated to trigger efficiency

Variation	$t\bar{t}$	Signal 400 GeV
$\tau_{\text{had-vis}}$ ID efficiency	11	8
$\tau_{\text{had-vis}}$ energy scale	6	4
$\tau_{\text{had-vis}}$ reconstruction efficiency	3	2
$\tau_{\text{had-vis}}$-lepton OLR	1	2
Jet energy scale	11	5
$b-$tagging efficiency	2	2
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft term scale/resolution	2	2
Trigger efficiency	3	1

Uncertainties impact on limits

Impact of various sources of uncertainty on the expected 95% CL exclusion limit

Category	Source of systematic uncertainty	Impact on the expected limit (in %)	
		$m_{H^+} = 200$ GeV	$m_{H^+} = 1000$ GeV
Experimental	luminosity	1.5	0.9
	trigger	< 0.1	< 0.1
	$\tau_{\text{had-vis}}$	1.0	1.4
	jet	3.0	0.2
	$E_{\mathrm{T}}^{\text{miss}}$	< 0.1	< 0.1
Fake factors	FF	0.8	4.7
Signal and background models	$t\bar{t}$ modelling	13.2	3.5
	H^+ signal modelling	1.4	1.4

Largest impact was from modelling $t\bar{t}$ background processes