Searches for new physics in events with multiple leptons with the ATLAS detector

Anthony Hawkins on behalf of the ATLAS Collaboration

Lund University

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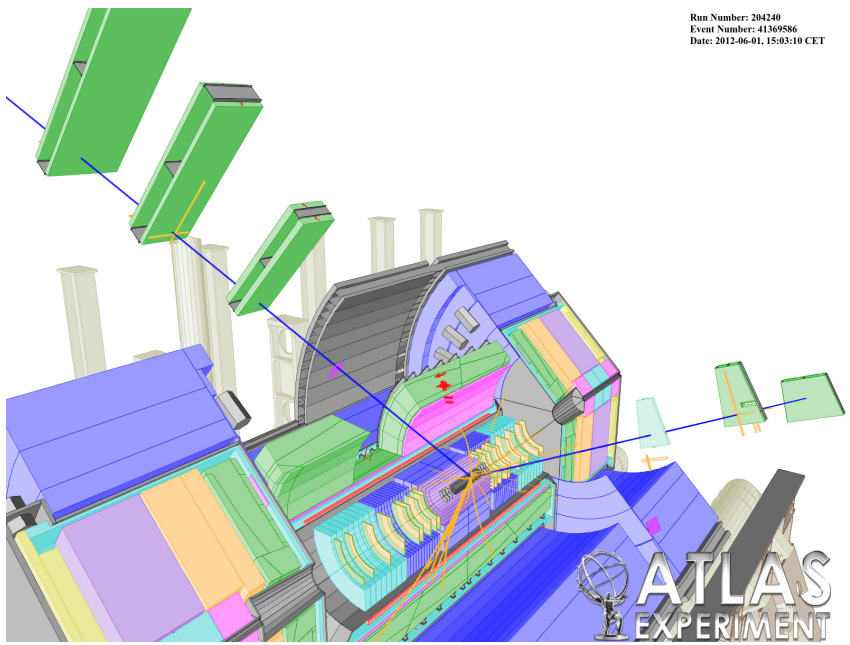
Physics motivation

- Leptons are clean, prompt, well isolated and high momenta probes.
- There are a plethora of models for beyond the Standard Model (BSM) physics which have partially or full semi-leptonic final states.
- Large signal to background ratio $\rightarrow$ multilepton signatures are perfect for probing BSM physics.

Analyses Covered

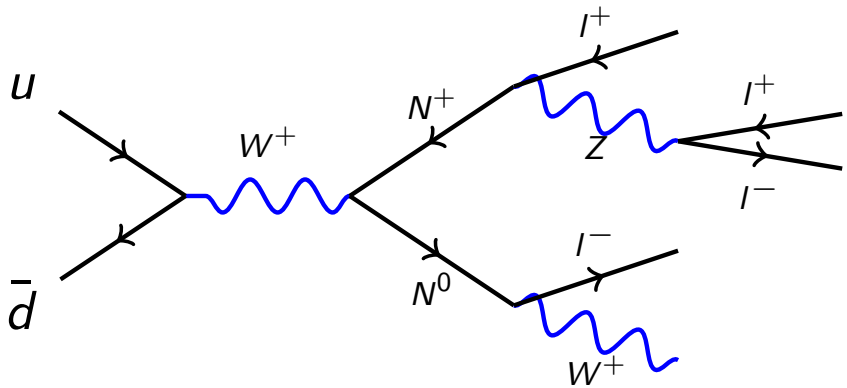
- Search for Type III Heavy Fermions (5.8 fb^{-1})
- Search for excited electrons and muons (13 fb^{-1})
- Search for new phenomena with multilepton events (20.3 fb^{-1})
- Search for a WZ resonance (20.3 fb^{-1})



Search for type III heavy fermions

Motivation

- Need to extend SM such that neutrinos acquire mass.
- Introduce Majorana and even Dirac mass terms.
- Introduce a see-saw mechanism to explain light neutrinos.
- Type I : Heavy Singlet Neutrino invoked.
- Type II: Generated in Higgs Sector by a Higgs triplet.
- **Type III**: Introduces at least two fermionic triplets.



Final state phenomenology

- A direct search for the $N^{\pm}$ is performed by reconstructing $N^{\pm} \to Z\ell$, here the Z decays leptonically to two opposite-sign same flavour leptons (e, μ)
- Four charged lepton final states (where a pair is from the Z) are dominated by $N^{\pm} \to Z\ell$ and $N^0 \to W^{\pm}\ell^{\mp}$ ($\approx$ 70%-90%) where the rest come from $N^{\pm}N^{\mp}$ pair production.

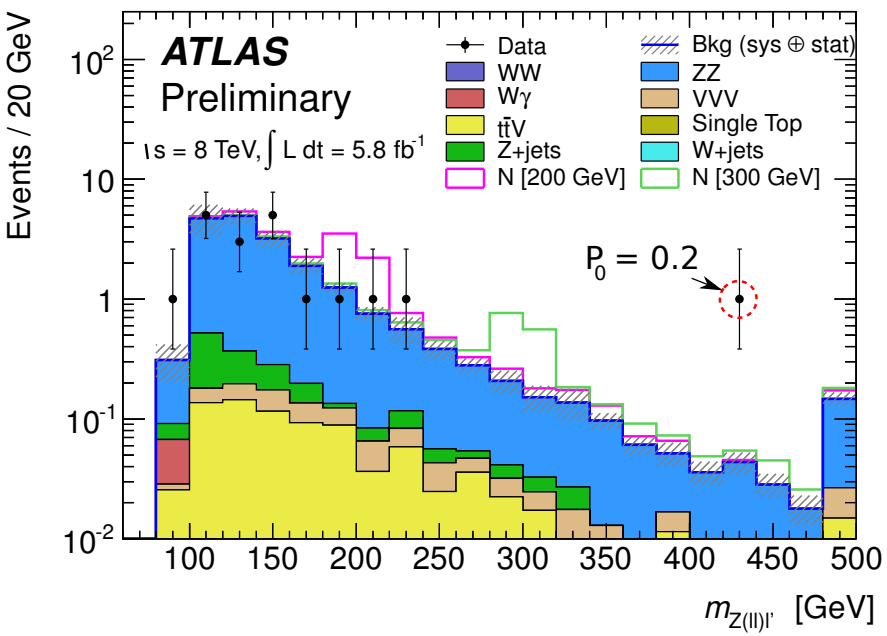
Type III Search

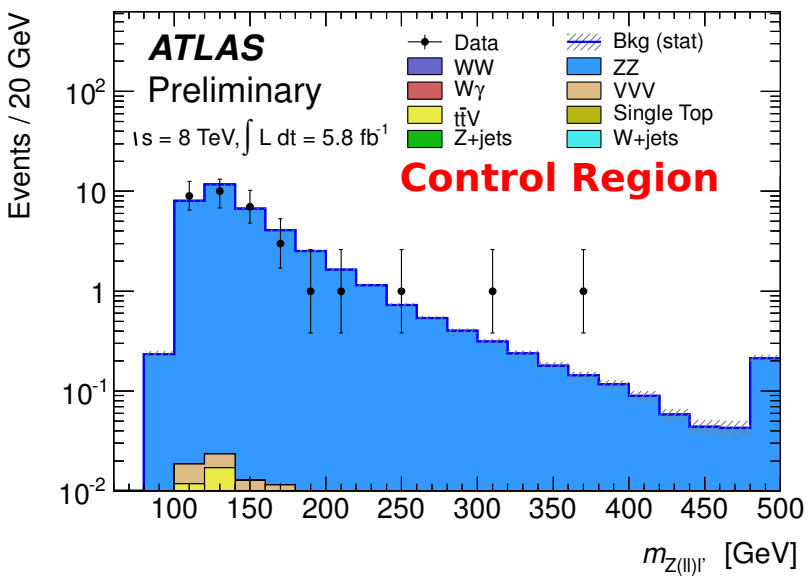
SM Backgrounds

- SM ZZ^* production (MC normalised in CR)
- SM VVV production (MC)
- $t\bar{t}V$ and Z+ jets (MC)

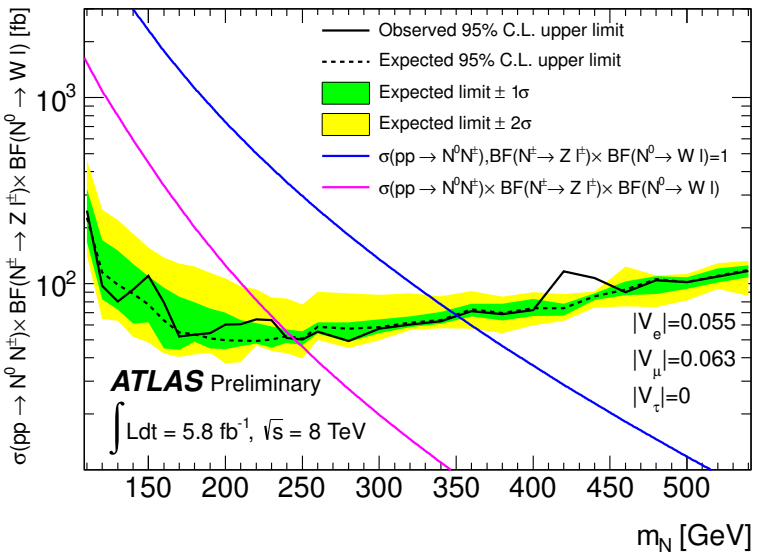
Selection

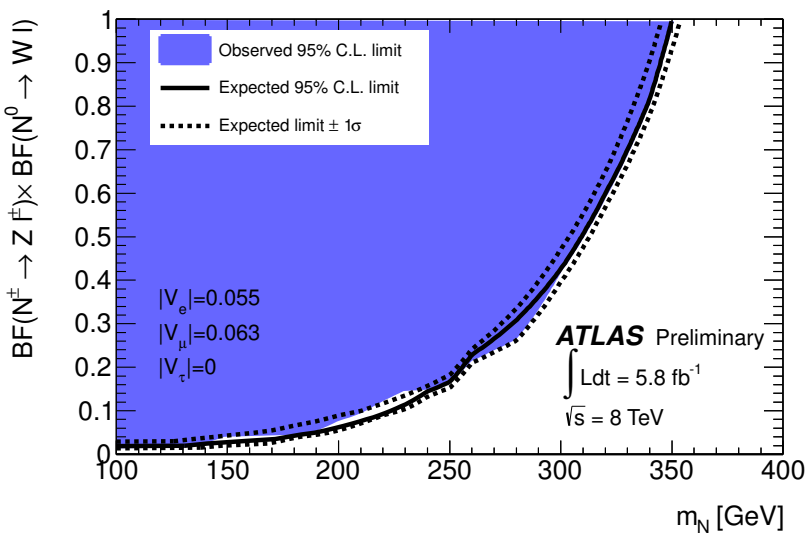
- Dominant Signal Process: $N^{\pm} \to Z\ell$ and $N^0 \to W^{\pm}\ell^{\mp}$
- Events with 4 or more prompt, isolated leptons.
- 2 opposite sign Same Flavour leptons with mass with 10 GeV of Z.
- Third lepton is that closest to Z candidate mass pair in phi.
- Fourth lepton is the highest p_T lepton remaining.
- Veto a second Z to surpress background.





Type III Search





Luminosity 5.8fb^{-1}

Limits Assuming $|V_e| = 0.055$, $|V_\mu| = 0.063$ and $|V_\tau| = 0$

Lower limit on mass of the N states of **245 GeV** at 95% confidence level

ATLAS-CONF-2013-019

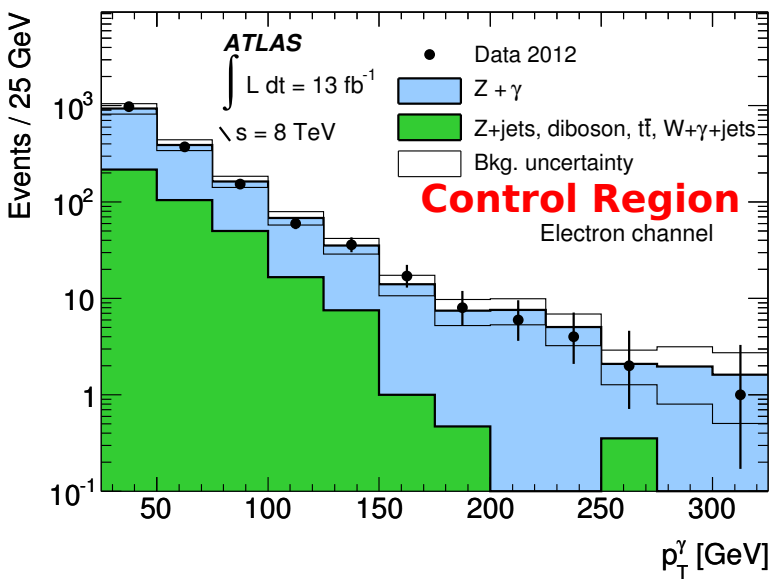
Search for excited electrons and muons

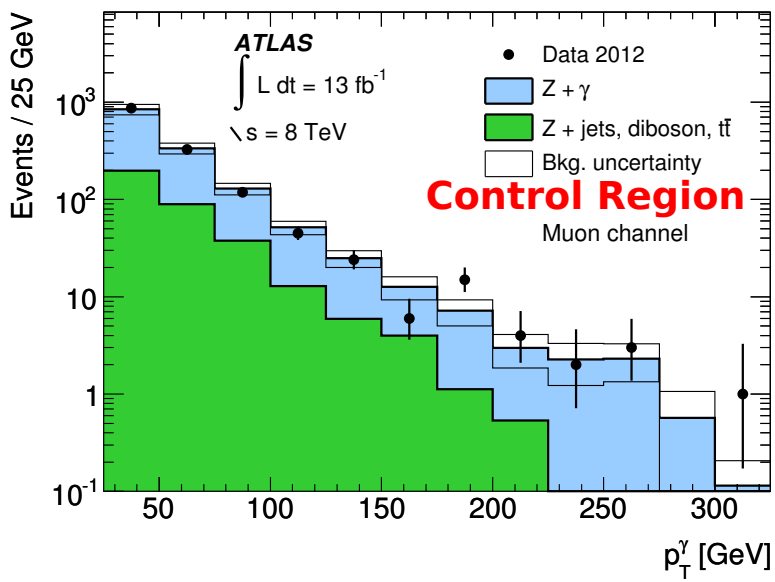
Motivation and selection

- SM does not provide explaination for generational structure or mass hierarchy.
- Fermion compositeness aims to explain these issues.
- Excited leptons are a direct consequence of the compositeness.
- Assume excited leptons (ℓ^*) are produced in contact interactions, hence their masses must be less than the compositeness scale Λ.
- Looking for events where $pp \to \ell\ell^* \to \ell\ell\gamma$.

SM Backgrounds

- Z + jets (MC sample normalised in CR to account for misidentification of jets as photons)
- $Z + \gamma$ * (MC)
- $t\bar{t}$ and diboson processes (MC)
- $W + \gamma$ + jets (MC sample normalised with a likelihood fit to account for the misidentification of jets to electrons)

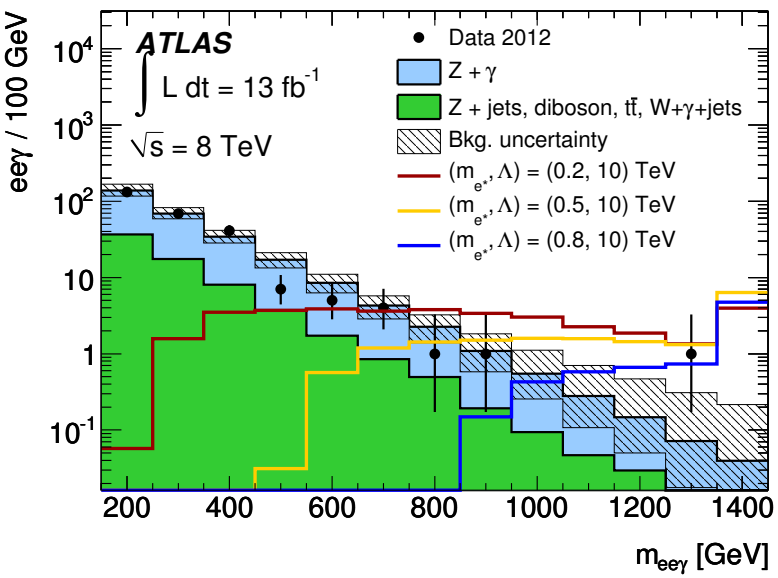


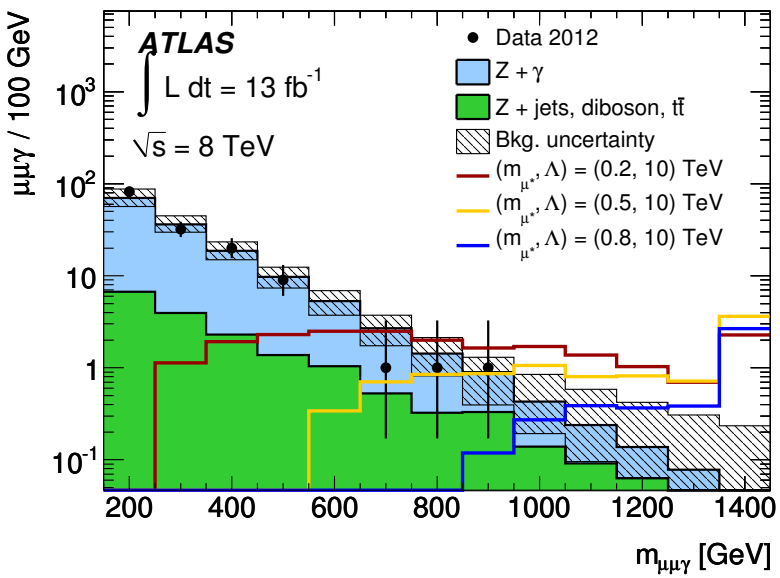


Search for excited electrons and muons

$m_{ee\gamma}$ Region (GeV)	Background	Data
> 350	69^{+18}_{-16}	60
> 450	34^{+11}_{-10}	19
> 550	17^{+7}_{-6}	12
> 650	$8.7^{+4.8}_{-3.4}$	7
> 750	$4.4^{+3.4}_{-2.0}$	3
> 850	$2.2^{+2.5}_{-1.1}$	2
> 950	$1.1^{+1.7}_{-0.6}$	1
> 1050	$0.5^{+1.2}_{-0.4}$	1

$m_{\mu\mu\gamma}$ Region (GeV)	Background	Data
> 350	40^{+11}_{-10}	32
> 450	21^{+7}_{-6}	12
> 550	11^{+5}_{-4}	3
> 650	$5.9^{+3.5}_{-2.6}$	3
> 750	$3.2^{+2.6}_{-1.6}$	2
> 850	$1.7^{+2.0}_{-0.9}$	1
> 950	$0.9^{+1.5}_{-0.6}$	0
> 1050	$0.5^{+1.0}_{-0.3}$	0

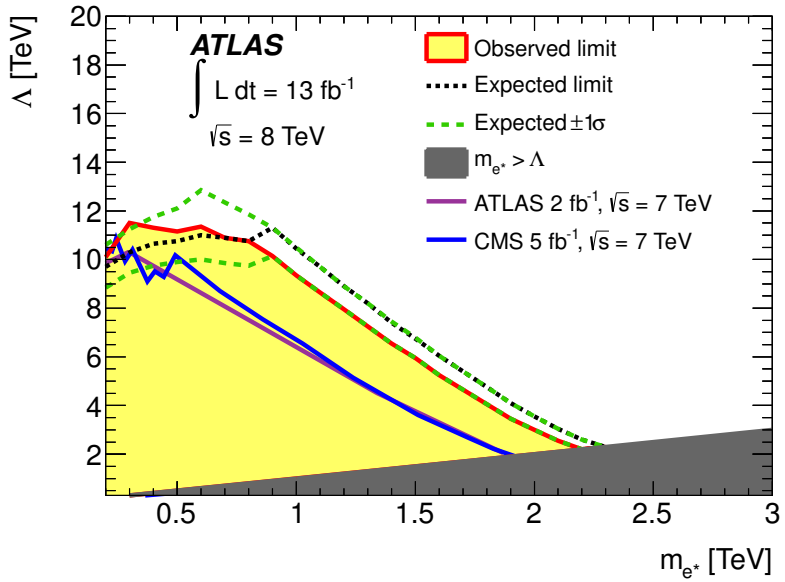


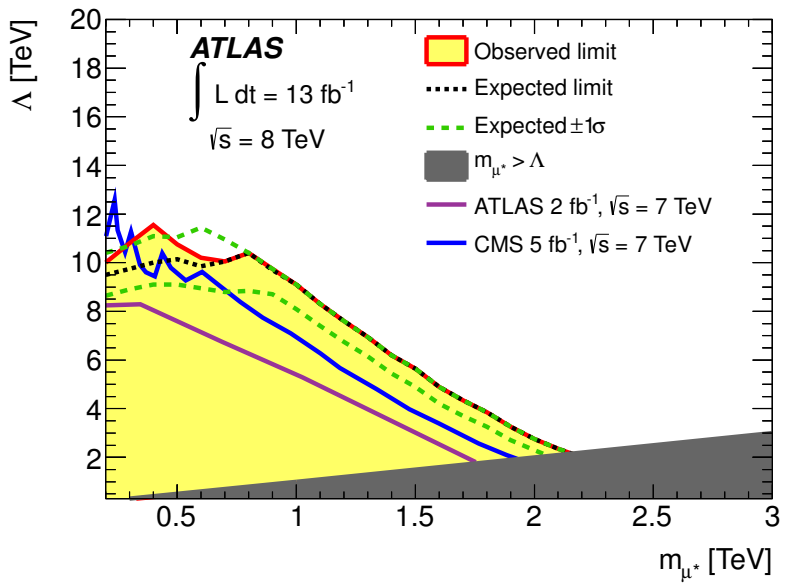


Search for excited electrons and muons

- Use the results to set exclusion limits in the compositeness scale (Λ) vs excited-lepton mass ($m_{\ell*}$).
- Filled area is excluded at 95% confidence limit.
- No limits set in the dark region where $m_{\ell*} > \Lambda$ and model not applicable.

Luminosity $13 fb^{-1}$
In the case $\Lambda = m_{\ell*}$ masses of excited electrons and muons below **2.2 TeV** excluded.
For $m_{\ell*} \geq 0.8 TeV$ the respective upper limits on $\sigma B(\ell^* \to \ell\gamma)$ are 0.75 fb and 0.90 fb for the e^* and μ^* searches.
New J. Phys. 15 (2013) 0

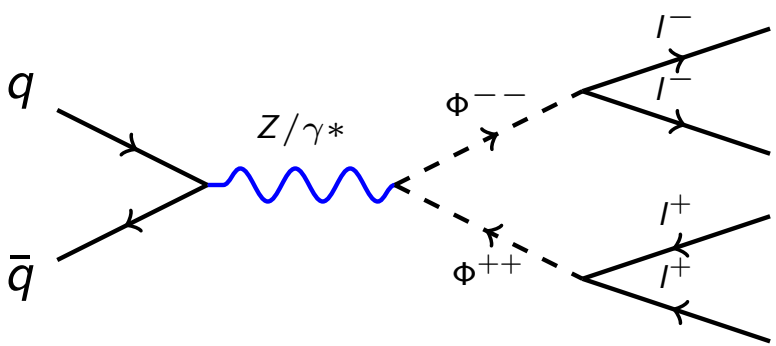




Search for new phenomena with multilepton events

Motivation and Selection

- Generic search for anomalous production of events with at least 3 charged leptons.
- Great probe for BSM theories such as: Fourth-gen quarks, excited neutrinos, Doubly Charged Higgs, SUSY...



SM backgrounds

- Prompt (WZ, ZZ $t\bar{t}+W/Z$ - MC)
- Drell-Yan + γ - MC
- Non-Prompt / Fake (Data driven estimate)

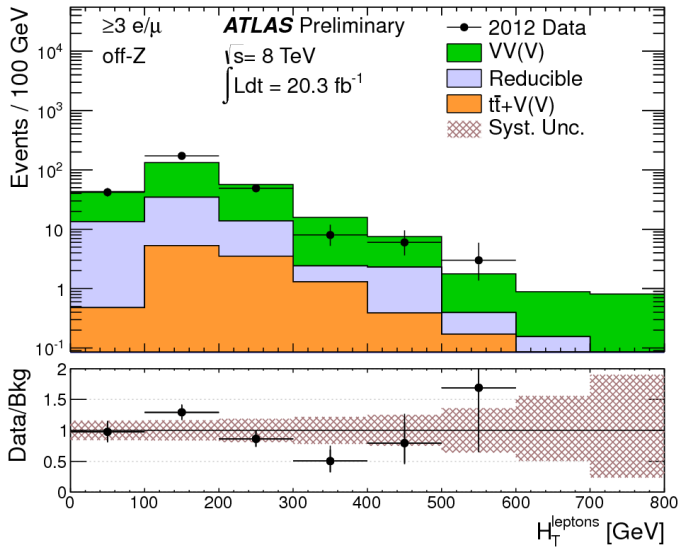
Observables

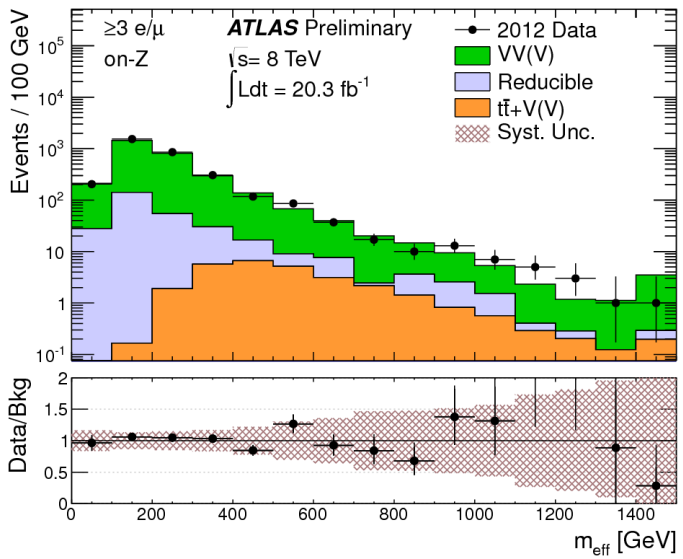
- $\mathbf{H_T^{leptons}}$ is the scalar sum of the transverse momenta of the three leading leptons.
- Min $\mathbf{p_T^{\ell}}$ is the minimum p_T of the three leading leptons in the event.
- $\mathbf{H_T^{jets}}$ is the sum of the transverse momenta of all selected jets in the event.
- Effective mass, $\mathbf{m_{eff}}$, is the scalar sum of E_T^{miss}, H_T^{jets} and the transfer momenta of all identified leptons.
- $\mathbf{m_T^W} = \sqrt{2p_T^{\ell}E_T^{miss}(1-cos(\delta\phi)}$ where $\delta\phi$ is the ϕ seperation of ℓ and E_T^{miss}

Multilepton search

	≥ 3 e/μ	2 e/μ + ≥1 τ_{had}
Off Z	260±10±40 280	1200±10±290 1193
On Z	3100±40±500 3199	17000±40±4000 14733

Event Numbers



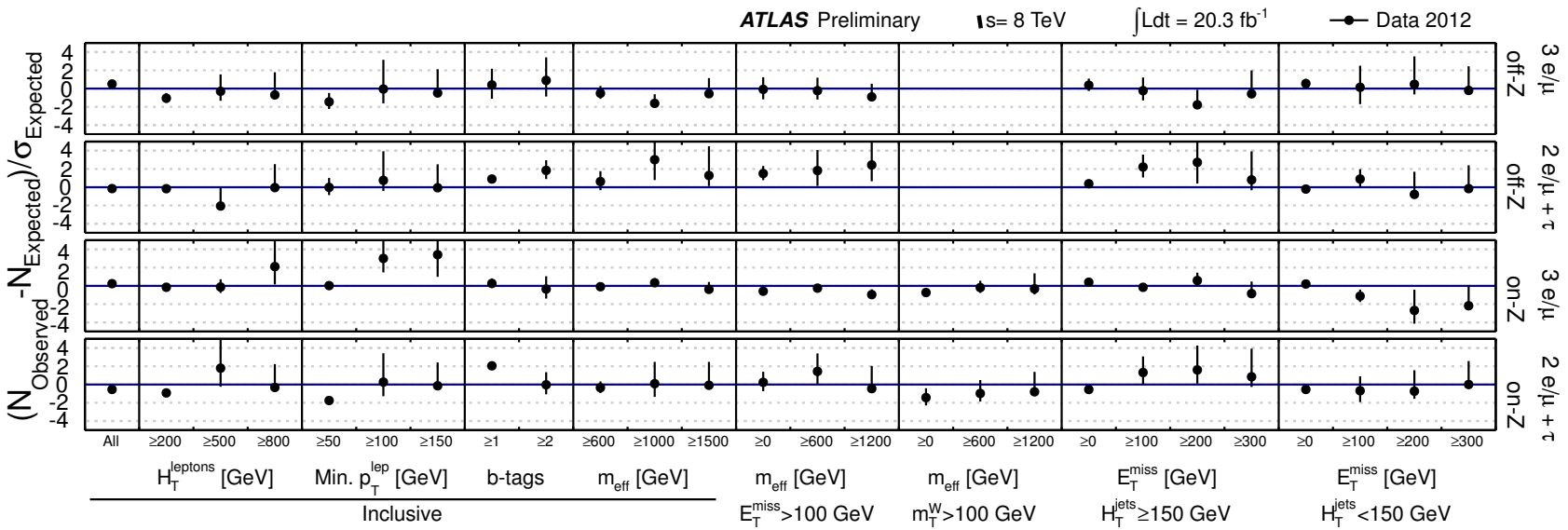


Results

- Signal region split into four regions.
- In each region many variables are analysed: m_{eff}, $H_T^{leptons}$, m_T, E_T^{miss}, p_T and number of b-tags and limits set.

Multilepton Search

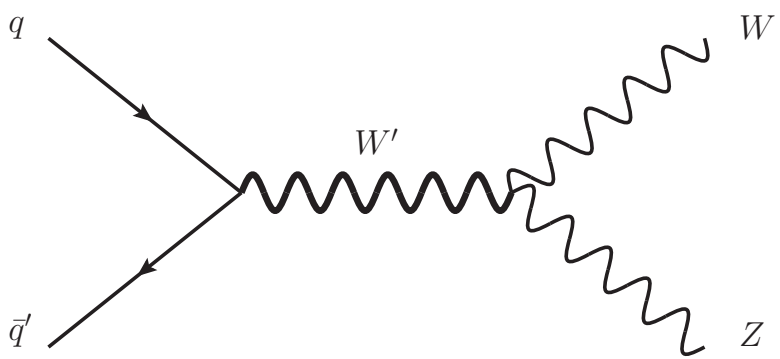
- $\sigma_{95}^{fid} = \frac{N_{95}}{\epsilon_{fid} \int Ldt} = \frac{\sigma_{95}^{vis}}{\epsilon_{fid}}$
- The fiducial cross-section for a given process can be calculated if one knows the visible cross-section and the per lepton fiducial efficiency.
- **ATLAS-CONF-2013-070**



Search for a WZ resonance in the fully leptonic channel

Motivation and Selection

- Essential complement to the investigation of the source of electroweak symmetry breaking.
- SM with low mass Higgs still has naturalness problem, suggesting only an effective theory.
- Extensions of SM solving this such as Little Higgs Models, Technicolor and GUT all predict high mass diboson resonances.
- Looking for events with final state $\ell'\ell'\nu\ell$ ($\ell' = e, \mu$)



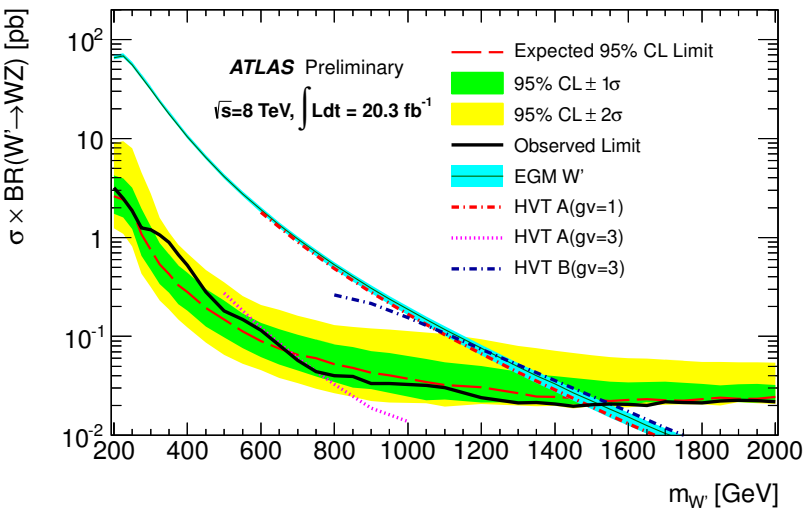
SM Backgrounds

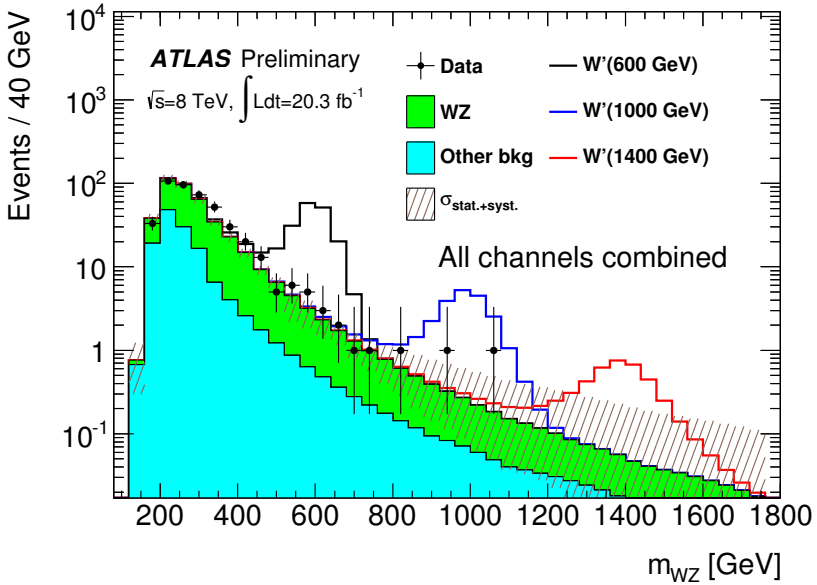
- SM WZ and ZZ production (MC)
- $t\bar{t} + W/Z$ (MC)
- $Z\gamma$ (MC)
- $\ell\ell'$ + jets (Data-driven fake estimate)

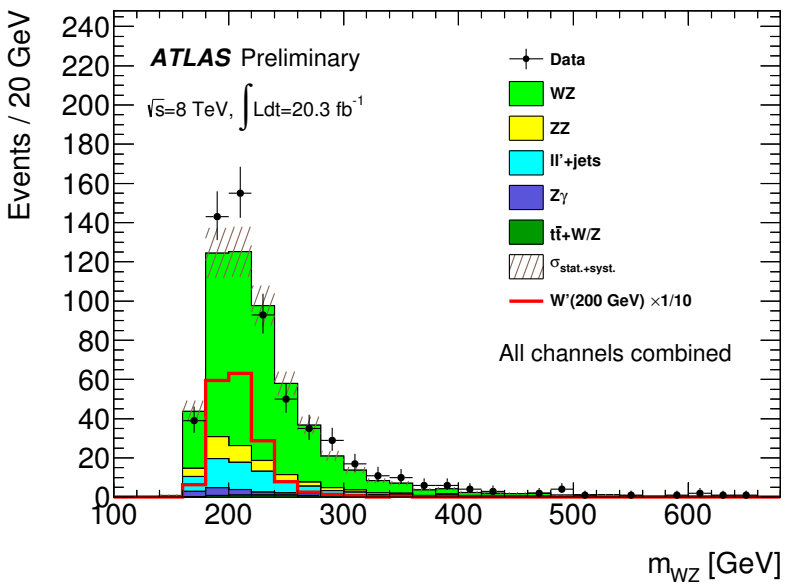
Selection

- Strictly 3 prompt and isolated leptons ($p_T > 25$ GeV)
- $E_T^{miss} > 25$ GeV
- Two Opposite Sign same flavour leptons required within 20 GeV of Z mass
- Lepton coming from W has more stringent selection
- 2 signal regions defned, High Mass SR1 (tuned for $m_{W'} \geq 250$ GeV) and Low Mass SR2 (tuned for $m_{W'} \leq 250$ GeV)

WZ Resonance Search







Luminosity 20.3fb^{-1}
Mass limit for the W' of 1.53 TeV found
ATLAS-CONF-2014-015

Summary and Outlook

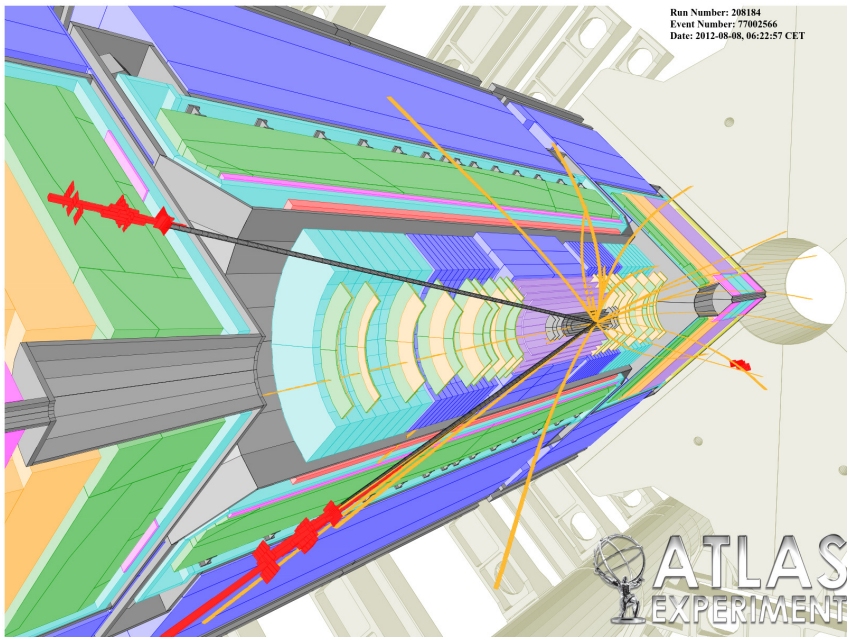
- Prompt isolated leptonic final states are invaluable probes for BSM physics
- A plethora of exotic models have (and are) being probed using ATLAS data. Both specific model searches and more inclusive searches.
- Some of the most recent searches have been summarised and reviewed here.
- **Coming to a conference near you...**:
  - Same sign inclusive dilepton search
  - Type II heavy majorana neutrino search

Thanks for listening

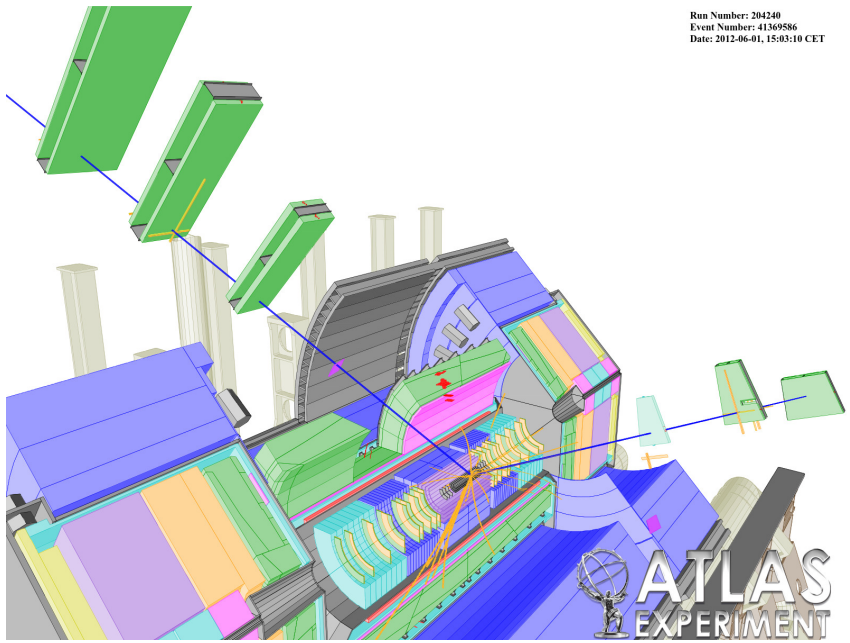
Back Up Slides

BACK UP

Excited Lepton events



Dielectron and photon event



Dimuon and photon event

Excited Lepton Cuts

Electrons

- Electron $p_T > 40(30)$ GeV for leading (subleading)
- Electron (muon) $|\eta| < 2.47$
- Electron candidates are "medium"
- Isolated and prompt
- No jet overlap

Photons

- Photon $p_T > 30$ GeV
- Photon $|\eta| < 2.37$
- Photon candidates are "tight"
- Well Isolated
- No jet overlap

Muons

- Muon $p_T > 25$ GeV for both
- Muon $|\eta| < 2.5$
- Isolated and prompt
- No jet overlap

Event Cuts

- Z-veto ($m_{\ell\ell} > 110 GeV$)
- $m_{\ell\ell\gamma} > 1050 GeV$ for $m_{\ell*} \geq 900 GeV$
- $m_{\ell\ell\gamma} > m_{\ell*} + 150 GeV$ for $m_{\ell*} < 900 GeV$

Type III Cuts

Lepton Cuts

- Lead Lepton $p_T > 25$ GeV (in order to pass trigger)
- Three subleading leptons $p_T > 10 GeV$
- Electron (muon) $|\eta| < 2.47(2.5)$
- Electron candidates are "tight"
- Muon candidates have combined tracks (ID and MS)
- Isolated and prompt
- No jet overlap

Event Cuts

- $80 GeV < Z_{cand} < 100 GeV$
- Third lepton closest in ϕ to the Z_{cand}
- Fourth lepton is the highest p_T leftover
- Events with a second Z_{cand} vetoed

WZ Resonance Cuts

Lepton Cuts

- Lepton $p_T > 25$ GeV (in order to pass trigger)
- Electron (muon) $|\eta| < 2.47(2.5)$
- Electron candidates are "medium"
- Muon candidates have combined tracks (ID and MS)
- Isolated and prompt
- No jet overlap

Event Cuts

- Select events with strictly three leptons
- Veto events with a fourth lepton of $(> 20GeV)$
- $E^T_{miss} > 25GeV$
- $70GeV < Z_{cand} < 110GeV$
- If two Z_{cand} chose the pair of leptons whose combined mass is closest to the Z pole mass
- Longtitudinal neutrino momentum is calculated assuming the full E^T_{miss} is from the neutrino and the lepton from the W and neutrino invariant mass is eual to the pole mass of the W boson
- Electrons from the W have a more stringent "tight" cut to surpress Z+jet backgrounds.
- For SR1 $\delta y(W, Z) < 1.5$ and $\delta(\ell, E_T^{miss}) < 1.5)$
- For SR2 $\delta y(W, Z) < 1.5$ and $\delta(\ell, E_T^{miss}) > 1.5)$

Multilepton Analysis Cuts

Electrons and muons

- Lead electron/muon $>$ 26 GeV
- Additional electron/muon $>$ 15 GeV
- Electron (muon) $|\eta| < 2.47 (< 2.4)$
- Electron candidates are "tight"
- Muon candidates have both inner detector and muon spectrometer hits
- $|d_0/\sigma(d_0)|$ ¡ 3 mm for leptons
- $z_0 sin(\theta) < 0.5$mm for leptons
- Both electrons and muons are isolated
- No jet overlap

Taus

- $p_T^{vis} \geq 20 GeV$
- $|\eta^{vis}| < 2.47$
- Here *vis* indicates the visible products of tau decays.
- Hadronic decaying taus are selected by a projecive likelihood identification algorithm.
- Algorithm trained seperately for *one prong* and *three prong* taus.

Event cuts

- Leptons within an opposite sign dilepton pair with $m_{\ell\ell} < 15 GeV$ are vetoed due to low mass resonances.
- Z veto used to discrimanate signal regions is defined as opposite sign same flavour dilepton pairs within 20 GeV of the Z boson mass.

Observables

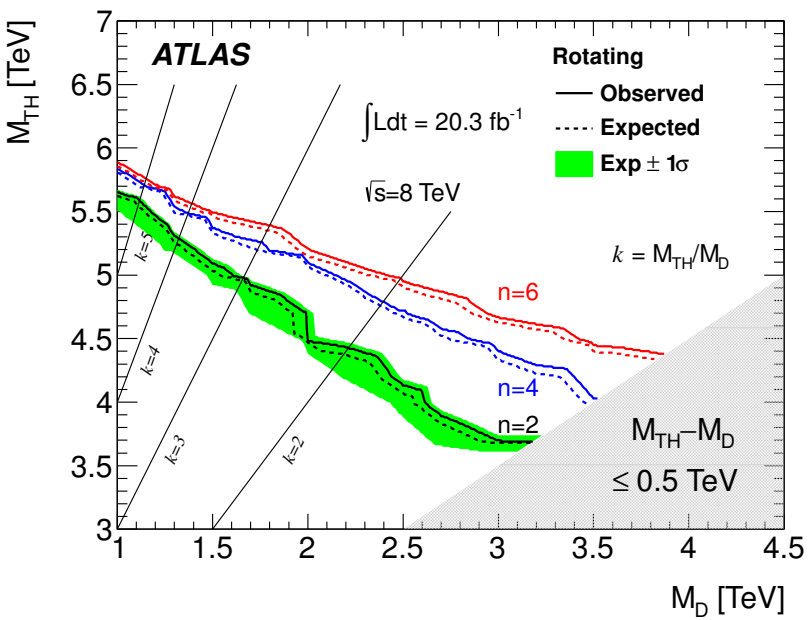
- $H_T^{leptons}$ is the scalar sum of the transverse momenta of the three leading leptons.
- Min p_T^{ℓ} is the minimum p_T of the three leading leptons in the event.
- H_T^{jets} is the sum of the transverse momenta of all selected jets in the event.
- Effective mass, m_{eff}, is the scalar sm of E_T^{miss}, H_T^{jets} and the transfer momenta of all identified leptons.
- $m_T^W = \sqrt{2 p_T^{\ell} E_T^{miss} (1 - cos(\delta\phi)}$ where $\delta\phi$ is the ϕ seperation of ℓ and E_T^{miss}

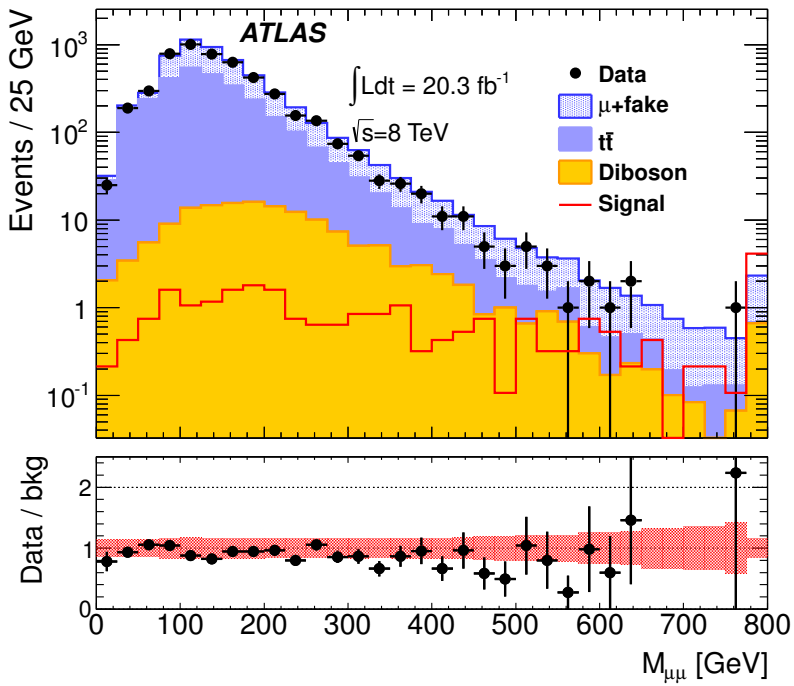
Same-Sign Dimuon Black Hole Search

Motivation

- Hierarchy Problem in SM
- Theories with Extra Dimensions solve problem
- Theories can lead to micrscopic black holes on the TeV scale.
- Search for same-sign dimuon pairs with high track multiplicity

- Luminosity 20.3 fb^{-1}
- 0.6 ± 0.2 events predicted 0 observed.
- Limits sets on various model at 95% C.L.
- **arXiv:1308.4075**





Fake Matrix Method

- Define a set of tight and loose object selection criteria. (Using Isolation, D_0, medium++ e.t.c.)
- Determine the *real efficiency* r, i.e the probability for a real, prompt lepton to pass the tight selection. This is done using real data.
- Determine the *fake rate* f, i.e the probability for a fake, non-prompt lepton to pass the tight selection. This is done using MC truth.
- Let N_{TT} denote the number of events with two tight leptons, N_{TL} the number of events with one tight and one loose lepton.
- Let N_{RR} denote the number of events with two real leptons, N_{RF} the number of events with one real and one fake lepton.

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \cdot \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix}$$

Systematic Uncertainties

- The following sources of systematic uncertainty are considered (where applicable).

- Luminosity
- Cross section
- Jet Energy Scale
- Jet Energy Resolution
- Trigger Reweighting
- b-tag Efficiency
- Generator
- Parton Shower
- PDF

- Electron Efficiency
- Electron Energy Resolution
- Electron Energy Scale
- Muon Efficiency
- Muon Energy Resolution
- Muon Energy Scale
- Muon MS Momentum
- Muon ID Momentum