MICHIGAN STATE UNIVERSITY

Searches for New Physics in events with multiple leptons using the ATLAS detector

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Introduction

- Many varied models for new physics have signatures with multiple leptons in their final state.
- This talk will cover analyses searching for (where ℓ = e or μ):

Two Same Flavour Leptons + γ, originating from qqll contact interactions with an excited lepton $(\ell^{\pm})(\ell^{\mp})(\gamma)$.

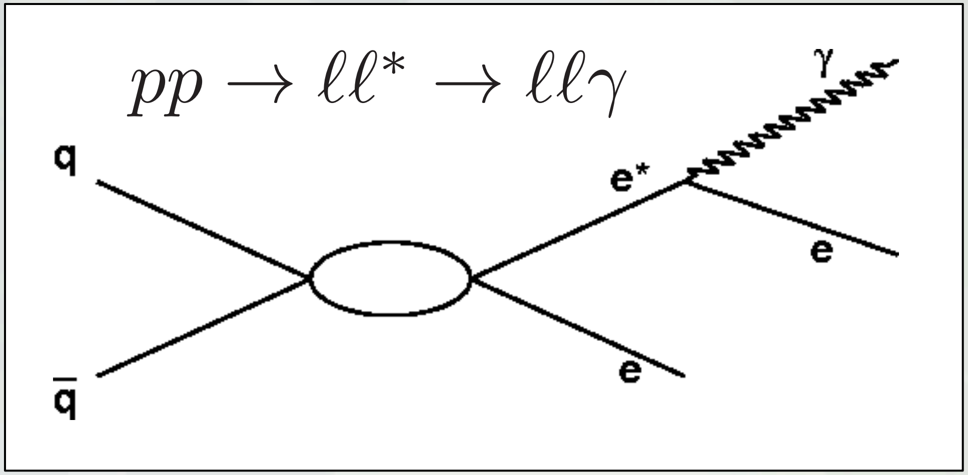
Three Leptons, allowing for any of the combinations $(\ell)(\ell)(\ell|\tau)$ in a fiducial region to conduct a model independent search for new physics.

Four Leptons, as a result of heavy leptons in the Type III Seesaw model. $(Z^0 \rightarrow \ell^+\ell^-)(\ell^+)(\ell^{\pm})$.

Excited Leptons

Compositeness at a binding energy scale, Λ, could help explain the generational structure and mass hierarchy of quarks and leptons.

Consequently, Excited Leptons (ℓ^*) under the LL isoscalar model, would be predominantly produced via a four-fermion contact interaction at the LHC.



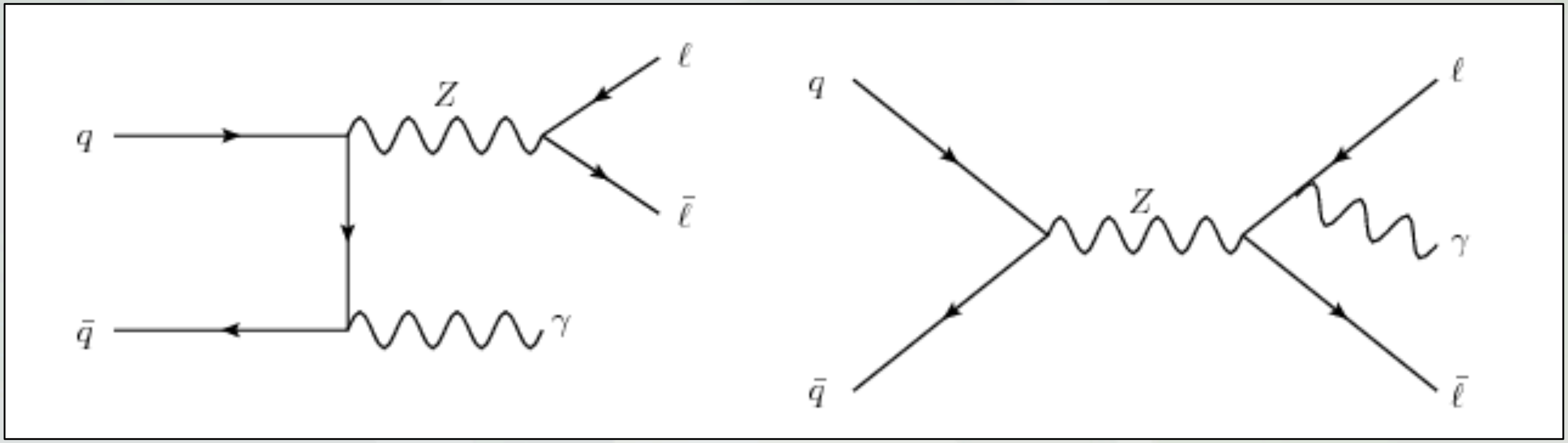
This search focuses on a final state with two same flavour opposite sign leptons, plus a photon. Kinematical properties of the signal are determined by two unknown parameters:

The excited lepton mass, m_{ℓ^*}, and compositeness scale, Λ. Valid for $m_{\ell^*} < \Lambda$.

Excited Leptons: Backgrounds

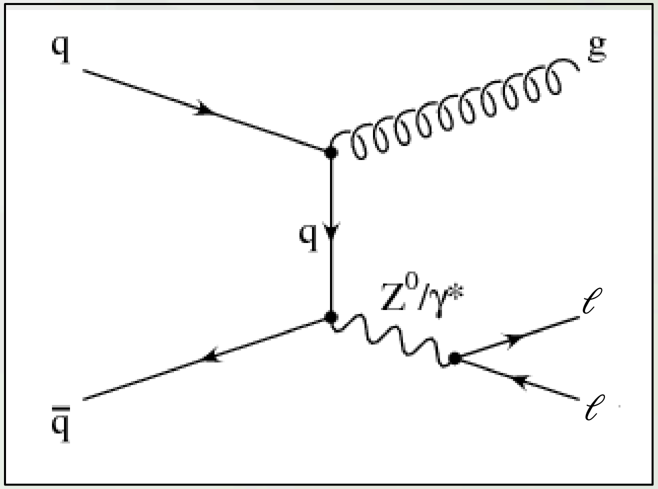
The dominant backgrounds to this search come from:

Irreducible (Z+ɣ)



Reducible (Z+Jets)

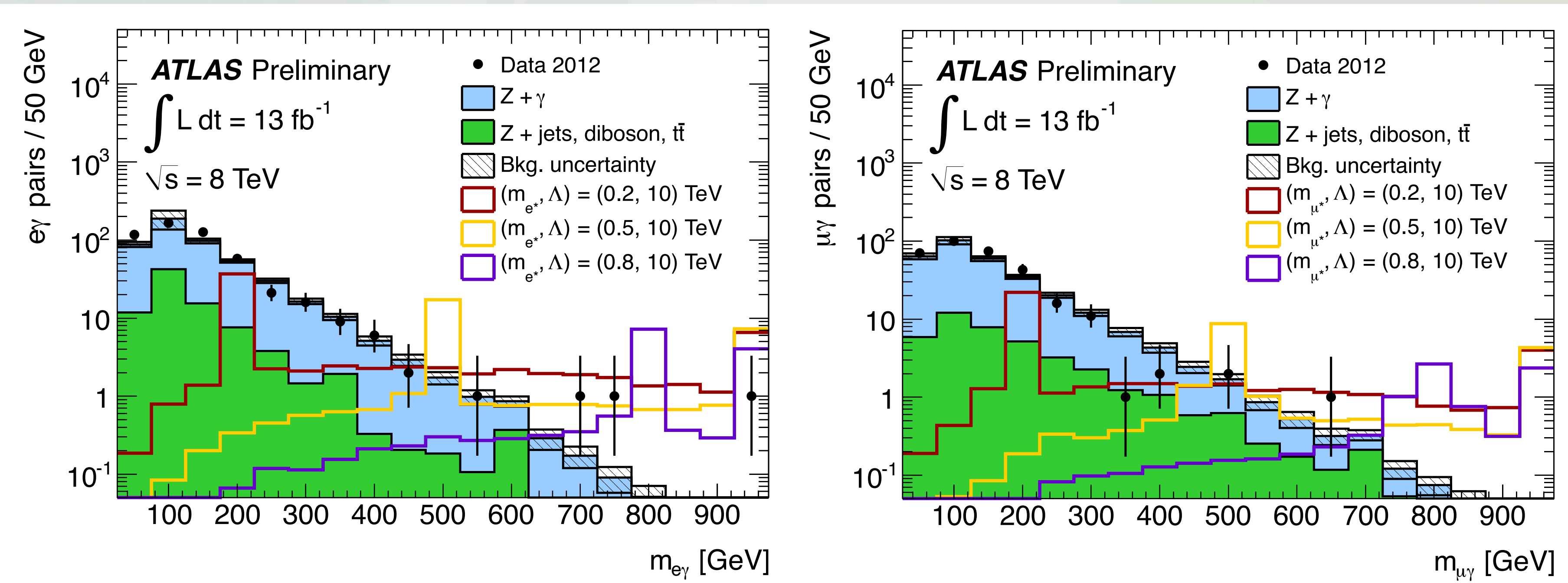
- Jets may fake a photon, causing signal contamination.
- However this background can be suppressed by imposing stringent quality requirements on the photon candidate.



Excited Leptons: Event Selection

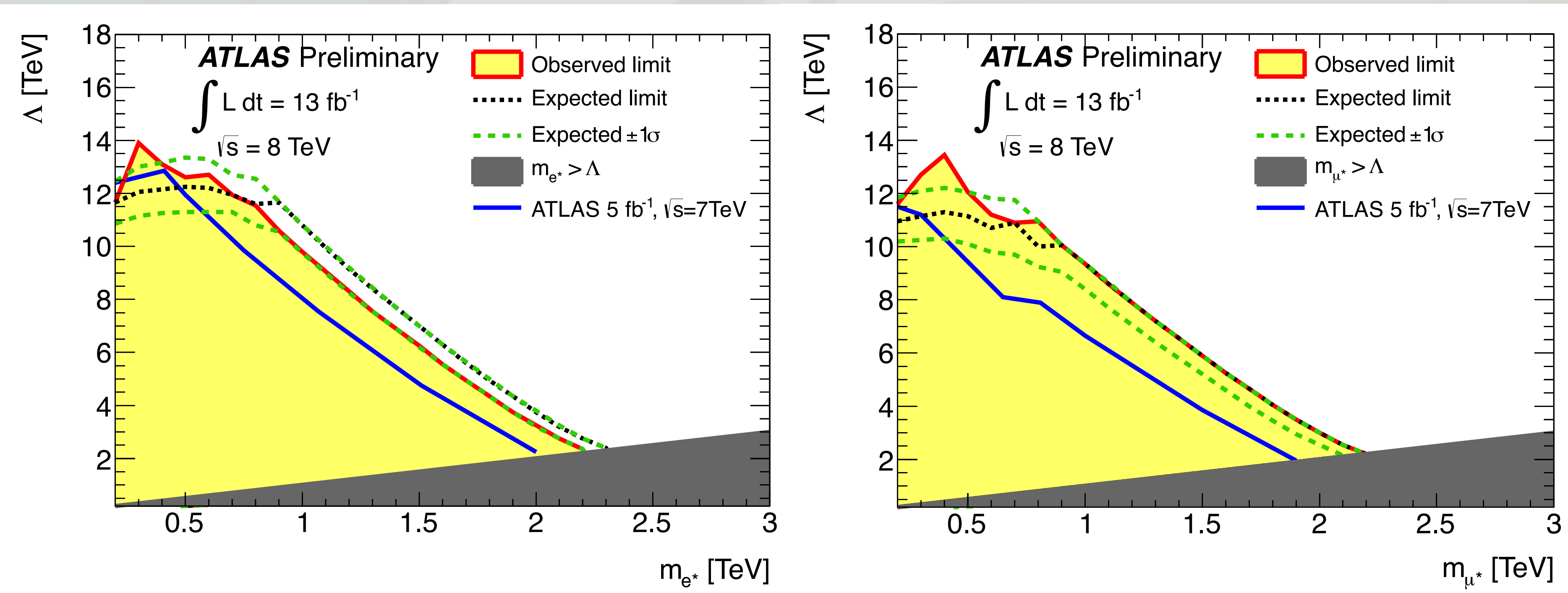
- Require at least two same flavour leptons + a photon in the event.
- Lepton (e/μ) criteria include a minimum p_T threshold, a fiducial volume cut, and *medium* quality requirements with isolation conditions.
- The photon criteria have similar p_T and fiducial thresholds, but with *tight* ID and isolation requirements.

All backgrounds are estimated with MC. Data/MC comparisons suggest that the jet misID rate is overestimated in simulation, therefore the Z+jets prediction is scaled to data in the signal-depleted region: $70 < m_{\ell\ell} < 110$ GeV (max 3% signal).



Excited Leptons: Statistical Interpretation

- As no significant excess is observed over the SM background prediction, exclusion limits on $\sigma(pp \to \ell\ell^*) \times B(\ell^* \to \ell\gamma)$ are set at 95% CL using a Bayesian approach, with a flat positive prior in σB.



- Statistical and Systematic Uncertainties are taken into account, with the Reco/ID ε and luminosity uncertainties assumed to be fully correlated between signal and background, and others uncorrelated.

- m(ℓ*) limit in special case of Λ = m(ℓ*) excludes e* and μ* below 2.2 TeV.

Three Charged Leptons

A model-independent search for new phenomena in events with ≥ 3 charged leptons. Such events are rare in the SM, dominated by WZ/ZZ production, so any excess would be very interesting!

This analysis attempts to remain model independent, and complement similar searches by:

➡ Avoiding model optimisation.
➡ Creating various possible interesting signal regions.
➡ Presenting results as upper limits on event yields in a fiducial volume.

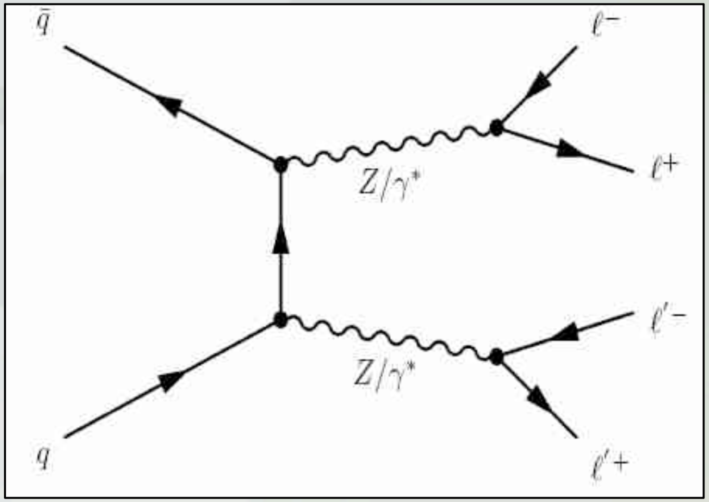
The highlights of this analysis compared to similar/previous searches are:

➡ Use Low lepton (e|μ) p_T threshold: 15 GeV minimum.
➡ Include channels with hadronic τ decays.
➡ Probe many kinematic variables of interest.
➡ Provide per-Lepton efficiencies so limits can be set on specific models.

Three Charged Leptons: Backgrounds

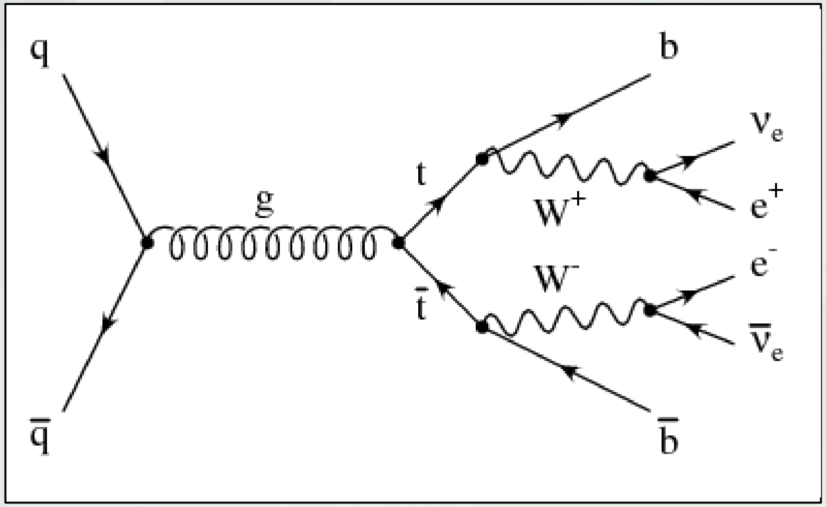
Irreducible: Events with 3 prompt leptons modelled with MC.

- WZ/ZZ.
- tt+W/Z, tt+WW.
- Z + (γ→ℓℓ).
- Triboson (negligible contributions).
- Higgs (negligible contributions).



Reducible: Events with up to 2 prompt leptons, and at least 1 non-prompt or fake candidate. Estimated using Data-Driven Fake-Factors method.

- Z+Jets, W+Jets.
- tt, single top.
- Multijets, etc.



N = Pass Nominal
D = Fail Nominal, Pass Relaxed Cuts.
fake-factor (f) = N/D

Method in a Nutshell:

- **Measure** f in background-dominated region (p_T, η, jets).
- **Apply** f in signal-like events.
- **Correct** background estimate for prompt leptons that are misidentified as D (using MC).

Three Charged Leptons: Event Selection

Define four mutually exclusive signal channels, based on:

$\geq 3\ell$ (off-Z), $\geq 3\ell$ (on-Z), $2\ell+\tau$ (off-Z), $2\ell+\tau$ (on-Z).

(On-Z ≡ $|m(\ell\ell)-m(Z)| < 20$ GeV) (Off-Z ≡ $|m(\ell\ell)-m(Z)| > 20$ GeV)

Reject All OSSF pairs with $m(\ell^+\ell^-) < 15$ GeV.

Lepton selection requires minimum p_T threshold, within a fiducial volume and *tight* lepton flavour ID. e/μ also require calorimeter and track isolation.

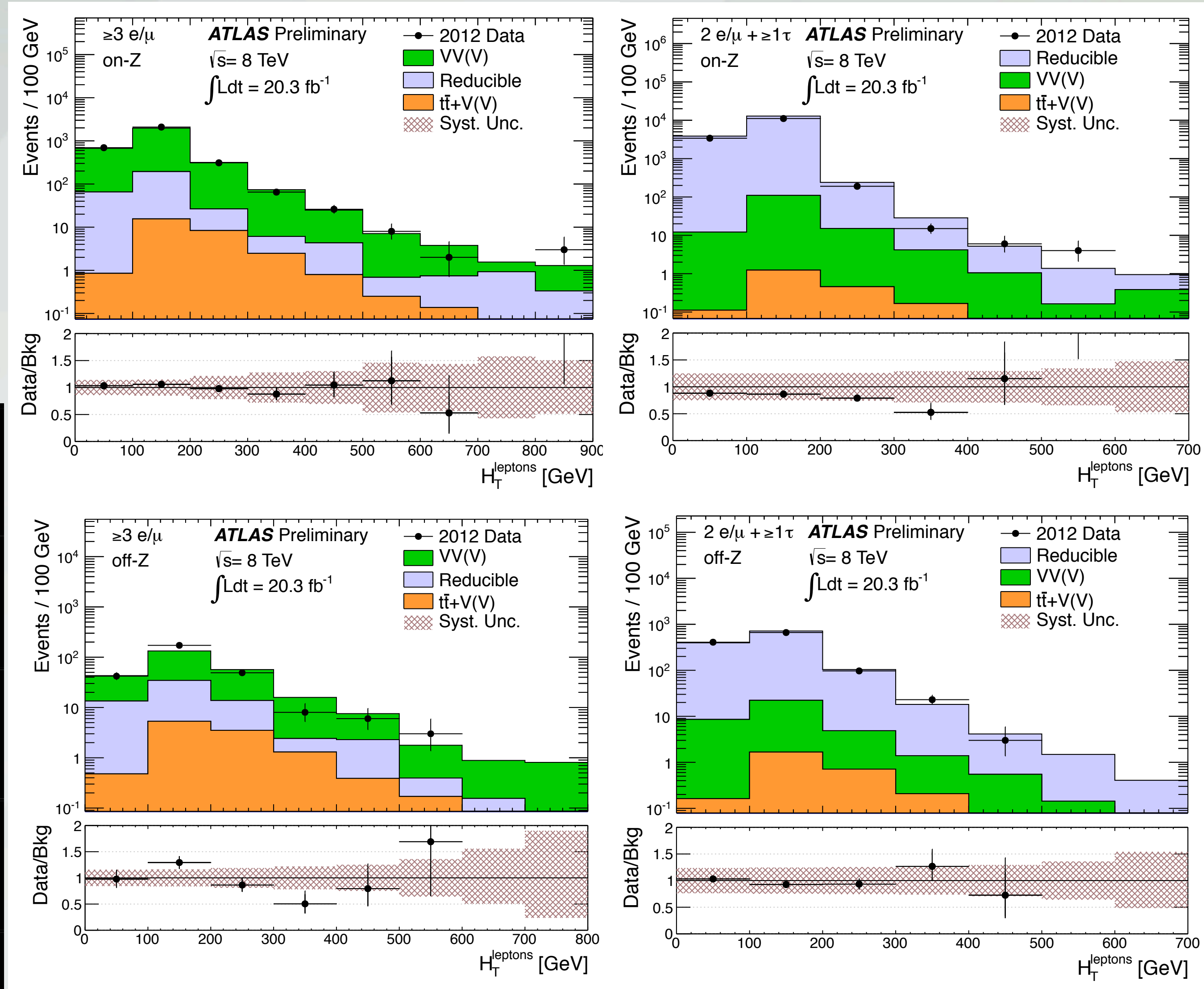
Variable	Signal Region Definition				Additional Requirements
H_T^{leptons}	Inclusive	≥ 200 GeV	≥ 500 GeV	≥ 800 GeV	
Min. p_T^{ℓ}	Inclusive	≥ 50 GeV	≥ 100 GeV	≥ 150 GeV	
E_T^{miss}	Inclusive	≥ 100 GeV	≥ 200 GeV	≥ 300 GeV	$H_T^{\text{jets}} < 150$ GeV
E_T^{miss}	Inclusive	≥ 100 GeV	≥ 200 GeV	≥ 300 GeV	$H_T^{\text{jets}} \geq 150$ GeV
m_{eff}	Inclusive	≥ 600 GeV	≥ 1000 GeV	≥ 1500 GeV	
m_{eff}	Inclusive	≥ 600 GeV	≥ 1200 GeV		$E_T^{\text{miss}} \geq 100$ GeV
m_{eff}	Inclusive	≥ 600 GeV	≥ 1200 GeV		$m_T^W \geq 100$ GeV, on-Z
b-tags	Inclusive	≥ 1	≥ 2		

After categorisation, inspect kinematic quantities of interest in each channel. Total of 94 independent signal regions!

Three Charged Leptons: Event Yields

- Distributions available for H_T, m_{eff}, E_T^{miss}, N_{btags}, M_T.
- No significant excess is observed compared to SM expectation.

Channel	Total Expected	Observed
≥ 3e/μ On-Z	3075 ± 36 ± 512	3199
≥ 3e/μ Off-Z	259 ± 8 ± 41	280
≥ 2e/μ+τ On-Z	17005 ± 43 ± 4213	14733
≥ 2e/μ+τ Off-Z	1237 ± 11 ± 293	1193



Three Charged Leptons: Statistical Interpretation

- 95% CL upper limits are extracted using the CL_s method with RooStats.

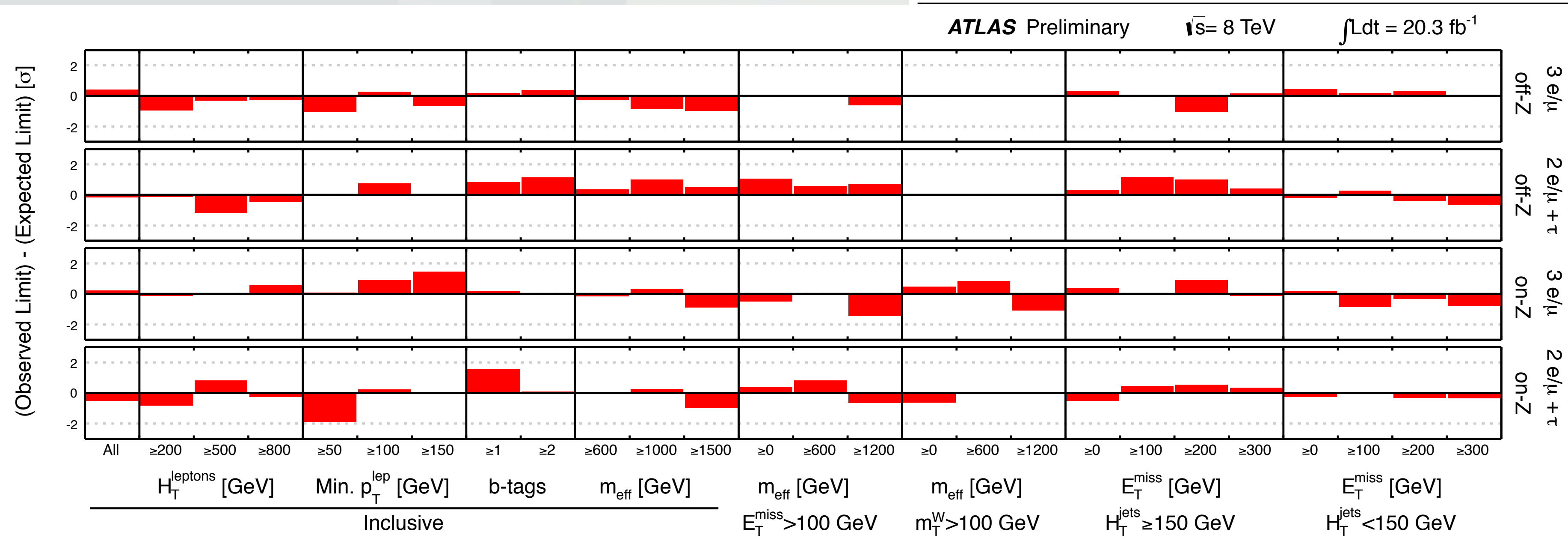
$$1 - CL_b = p(Q \leq Q_{obs}|H_0)$$

$$CL_{s+b} = p(Q \geq Q_{obs}|H_1)$$

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

- Efficiencies are not included in these limits, meaning this represents the *visible* σ, which can be converted to model specific limits using fiducial efficiencies ($\sigma_{95} = \sigma_{95}^{vis} / \varepsilon^{fid}$).

Source of uncertainty	Uncertainty
Trigger efficiency	1%
Electron energy scale	<1%
Electron energy resolution	<1%
Electron identification	2%
Electron non-prompt/fake backgrounds	9%
Muon momentum scale	<1%
Muon momentum resolution	<1%
Muon identification	<1%
Muon non-prompt/fake backgrounds	5%
Tau energy scale	2%
Tau identification	2%
Tau non-prompt/fake backgrounds	25%
Jet energy scale	5%
Jet energy resolution	4%
Luminosity	2.8%
Cross-section uncertainties	34%
Total uncertainty	11 – 35%



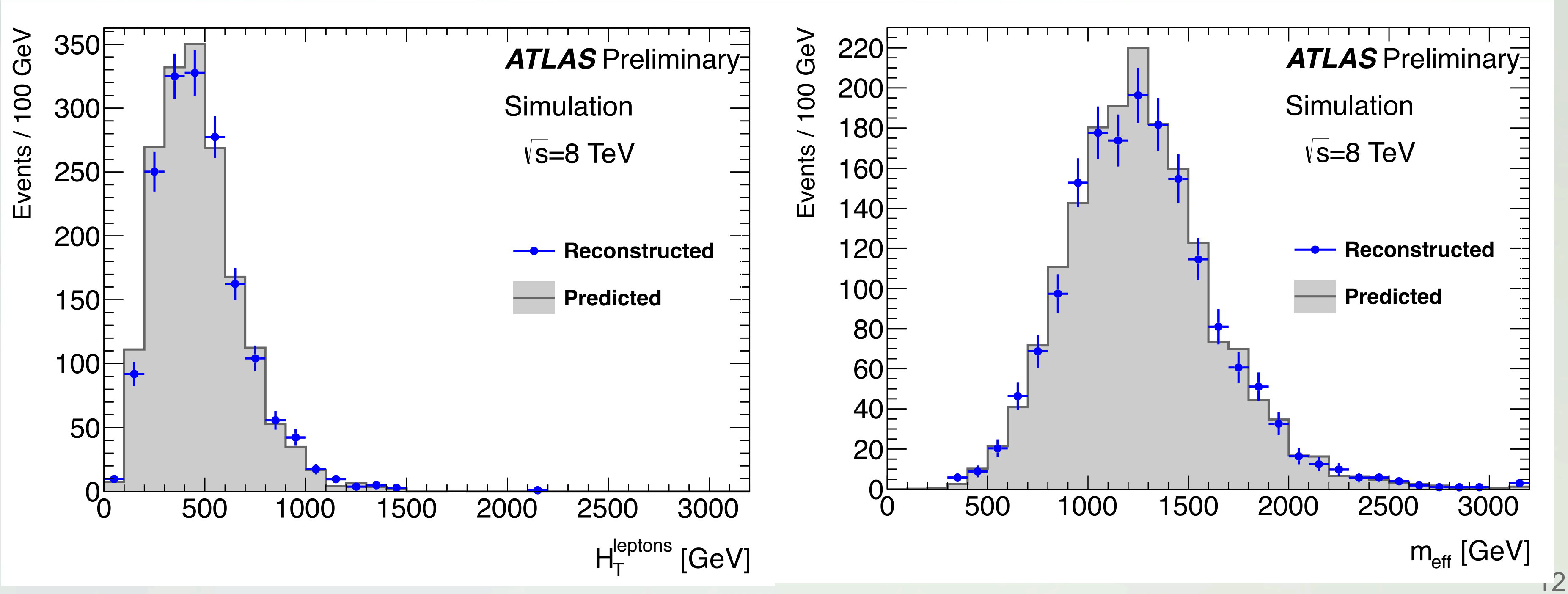
Three Charged Leptons: Single Lepton Efficiencies

1. Define a fiducial volume at the particle level.
2. Provide per-Lepton efficiencies (ε^{fid}) within that fiducial volume as a function of p_T and η.
3. Show that this is a sufficient parameterisation for a few new physics models.

95% CL upper limits on the σ for a given new physics process is then:

$$\sigma_{95} = \frac{N_{95}}{\epsilon^{\mathrm{fid}} \int \mathcal{L} dt}$$

(Example: d_4 model (m = 800 GeV), 3L channel)

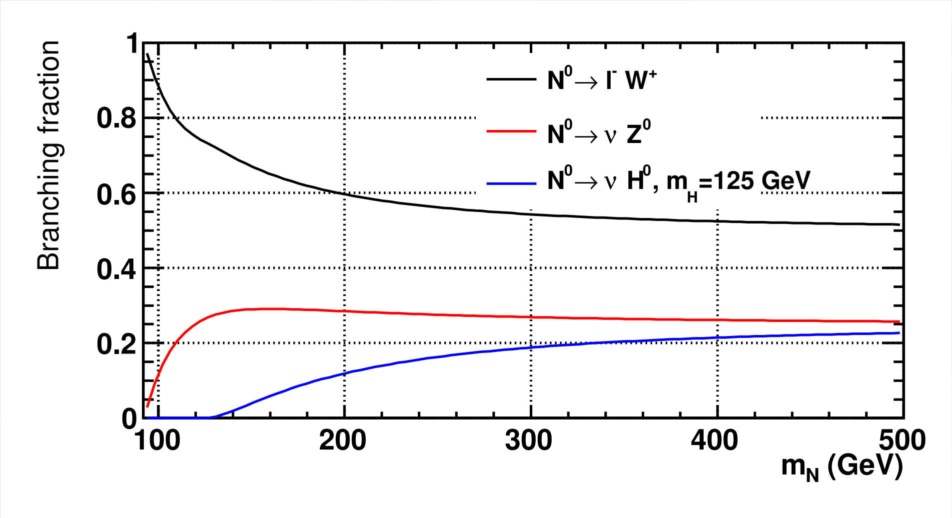


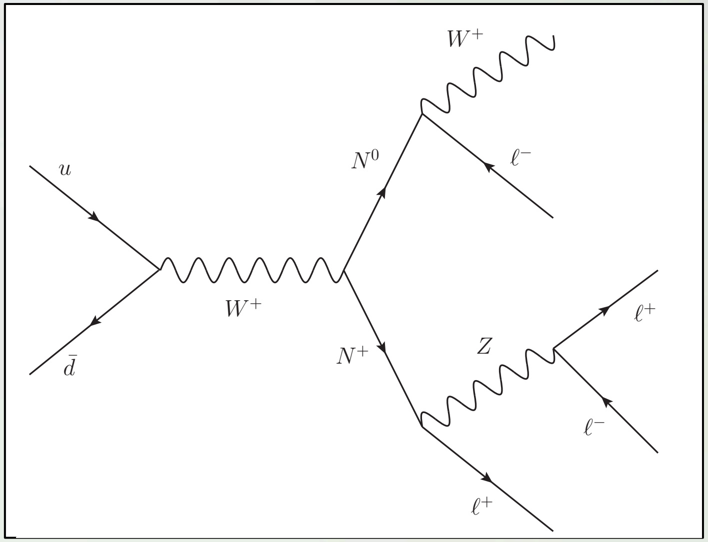
Four Charged Leptons

Neutrino masses within the Higgs mechanism would require an extremely small Yukawa coupling. To provide a more natural solution, so-called Seesaw models introduce heavy right-handed leptons.

In the Type-III Seesaw Mechanism, at least two fermionic triplets generate the neutrino masses. The lightest triplet of which introduces (N^0, $N^\pm$) with approximately degenerate masses.

These states couple to gauge bosons allowing for a non-negligible production cross-section at the LHC as well as m_N of O(100 GeV).





Four Charged Leptons: Event Selection

For the reconstruction of heavy triplet events in this analysis, leptons are split into three categories, with the Z+Bachelor leptons used to reconstruct the $N^{\pm}$ and look for signal:

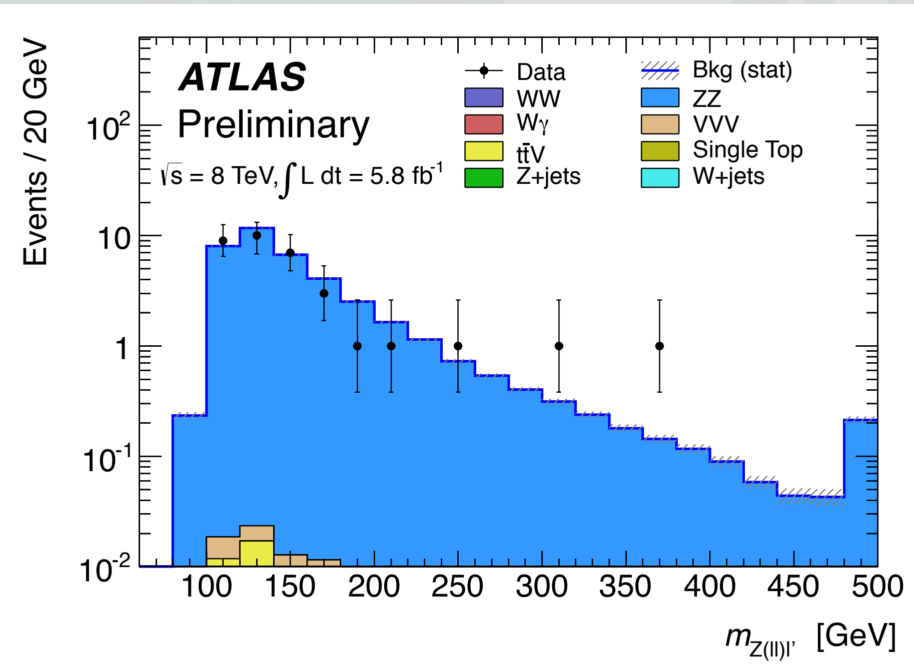
- **Z-candidate Leptons**: Two same flavour opposite sign leptons, consistent with having originated from a Z-boson.
- **Bachelor Lepton**: The lepton which most likely originated from $N^{\pm}$.
- **Fourth Lepton**: The highest p_T lepton remaining in the event. Most likely to have originated from the direct or cascade decay of N^0.

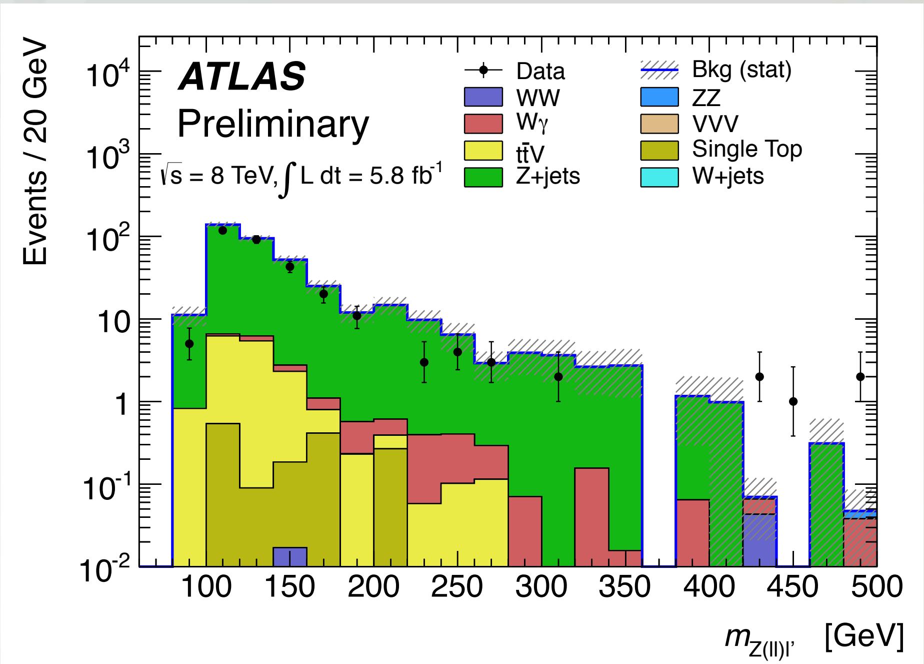
Additionally lepton candidates are required to pass the criteria:

- Single Lepton Trigger.
- Leading $p_T > 25$ GeV, all other leptons $p_T > 10$ GeV.
- $|\eta| < 2.47$ (2.50) for Electrons (Muons), excluding crack region.
- Isolation: $\Delta R < 0.3$ (0.4), $p_T^{iso}/p_T < \sim 15\%$.
- Electron ID *Tight* | Muon inner detector track hit requirements.

Four Charged Leptons: Backgrounds

The only significant background to this process is from $ZZ \rightarrow 4\ell$, although Z+Jets , W+Jets, Triboson and tt also represent a possible source of background and cannot be overlooked.

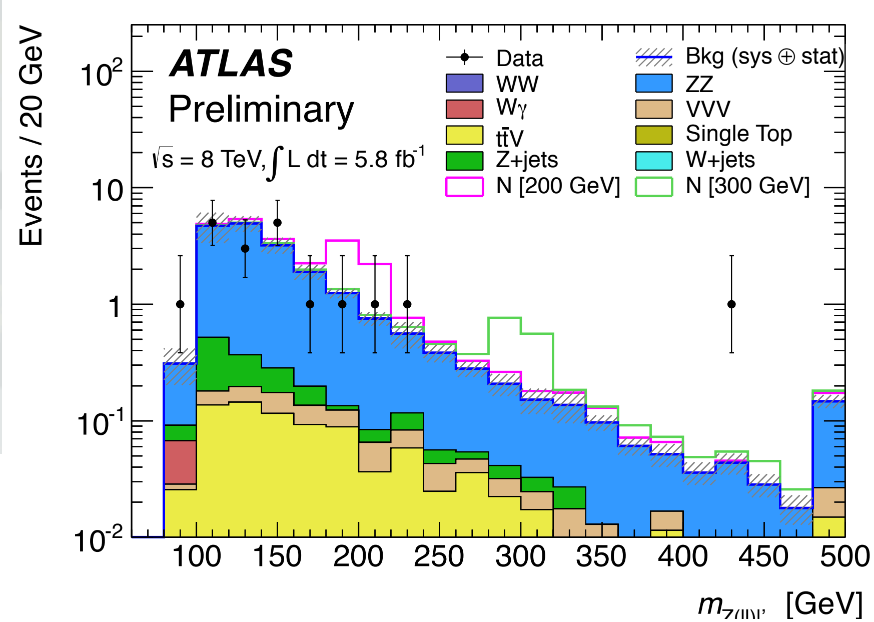


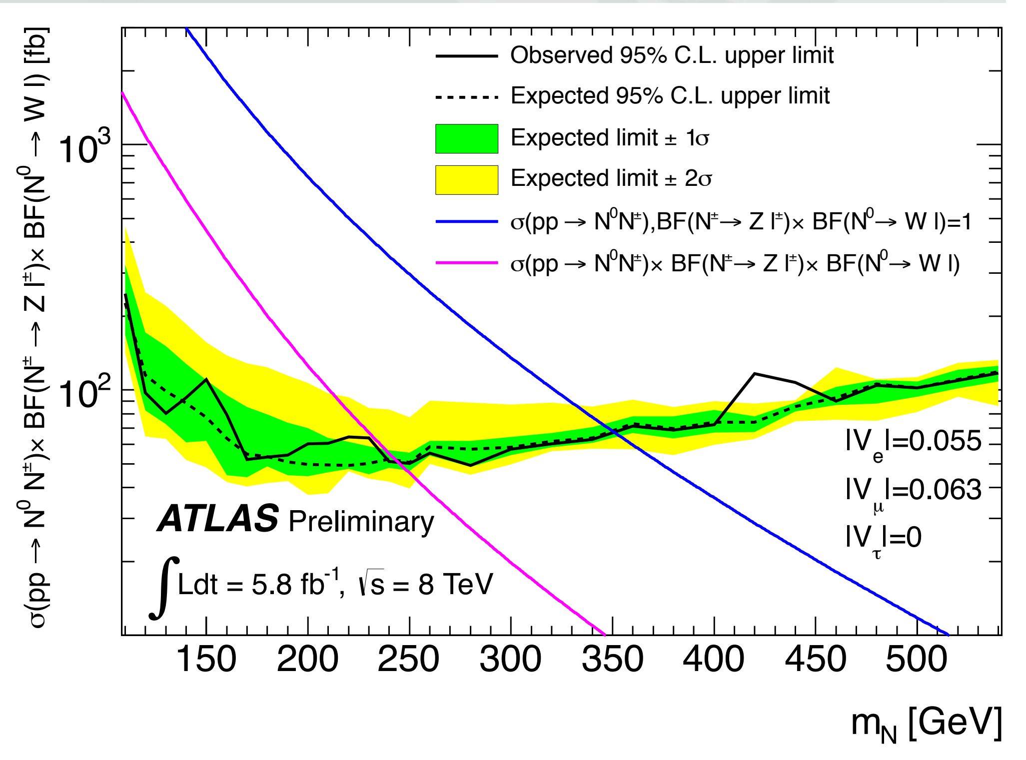


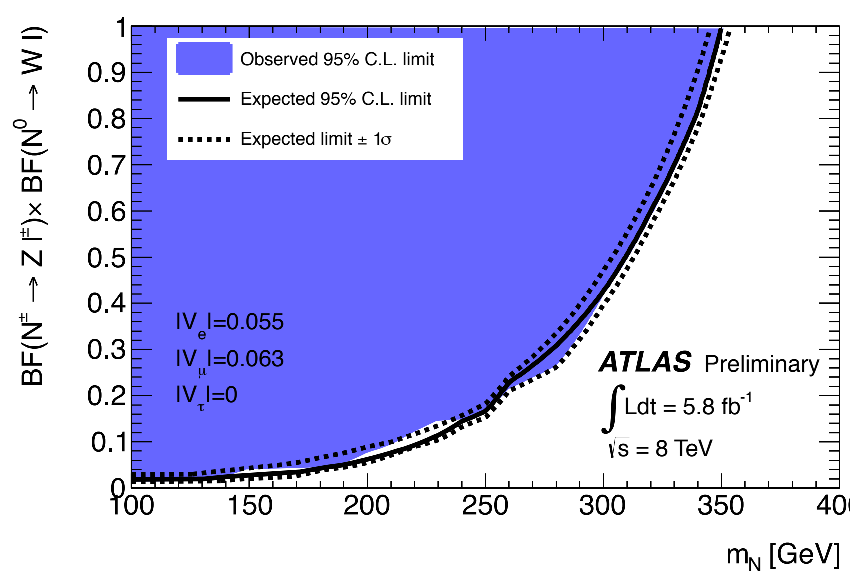
Reconstructed $N^{\pm}$ mass in the ZZ (left) and Z+Jets (right) control region. Determined using $|M_{\ell(3)\ell(4)} - M_Z| < 10$GeV, and looser track parameter / isolation requirements respectively.

Four Charged Leptons: Statistical Interpretation

- No significant signal-like excess is observed compared to SM expectation.
- 95% CL upper limits on the signal cross-section are extracted using the CL_s method with RooStats.







Summary and Conclusions

Searches for new physics with the ATLAS detector involving multiple leptons, is a rich and interesting area of research.

Two Same Flavour Leptons + γ. Analysis used 13.1 fb^{-1} of 8 TeV data, and set exclusion limits on qqll* contact interaction compositeness scale as a function of excited lepton mass.

Three Leptons. Analysis used 20.3 fb^{-1} of 8 TeV data, presented results in a model-independent way, and provided single lepton efficiencies as a function of p_T and η, to enable derivation of model-dependent limits.

Four Leptons. Analysis used 5.8 fb^{-1} of 8 TeV data, to search for evidence of a Type-III Seesaw mechanism by reconstructing $N^{\pm}$ in association with an additional charged lepton from N^0. With the absence of a signal-like excess, limits were set of the $N^{\pm}$ mass.

All analyses have strived to make continual improvements to their analysis and we continue to search for new physics!

References

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Search for excited electrons and muons with 13 fb^{-1} of proton–proton collisions at sqrt(s) = 8 TeV with the ATLAS detector.

ATLAS-CONF-2012-146

Search for New Physics in Events with Three Charged Leptons with the ATLAS detector.

ATLAS-CONF-2013-079

Search for Type III Seesaw Model Heavy Fermions in Events with Four Charged Leptons using 5.8 fb^{-1} of sqrt(s) = 8 TeV data with the ATLAS Detector

ATLAS-CONF-2013-019

Backup

Excited Leptons

m(ℓ ℓ γ) Distribution