Searches for New Phenomena in Events with Multiple Leptons with the ATLAS Detector

TÜLİN VAROL
University of Massachusetts, Amherst
On Behalf of the ATLAS Collaboration

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OUTLINE

- Introduction
- Excited e/μ Search
- Trilepton Search
- Type-III SeeSaw Heavy Fermions Search
- Conclusion

INTRODUCTION

- Multi-lepton final states are predicted by many extensions to the Standard Model

- Two leptons: Excited e/μ searches with two same flavour leptons with additional photon contribution in the final state $(\ell^{\pm})(\ell^{\mp})(\gamma)$

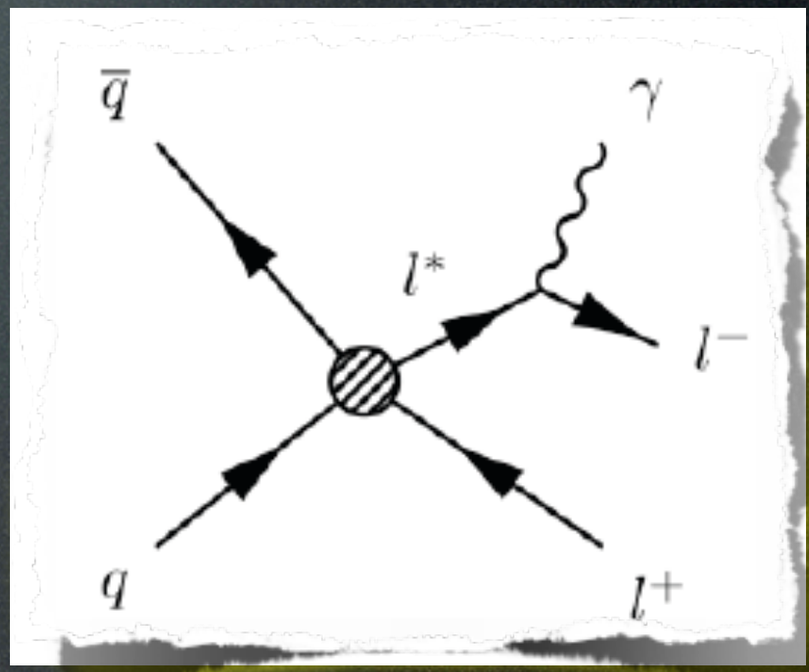
- Three leptons: A generic search with three charged leptons in the final state $(\ell)(\ell)(\ell \text{ or } \tau)$

- Four leptons: A search for heavy neutrinos with four leptons in the final state $(Z^0 \to \ell^+\ell^-)(\ell^{\pm})(\ell^{\pm})$

Excited e/μ: Introduction

Search for lepton compositeness

- **Motivation:** Mass hierarchy and the generational structure of quarks and leptons
- **SM leptons:** Ground states
- **Excited state ℓ^*:** Consequence of lepton compositeness



Effective Theory

- ℓ^* produced via contact interactions
- Effective model holds for $m_{\ell^*} < \Lambda$

Unknown parameters

- Compositeness scale Λ
- Mass of excited leptons m_{ℓ^*}

Studied Channel: $\mathrm{pp} \to \ell\ell^* \to \ell\ell\gamma$

Excited e/μ: Background Determination

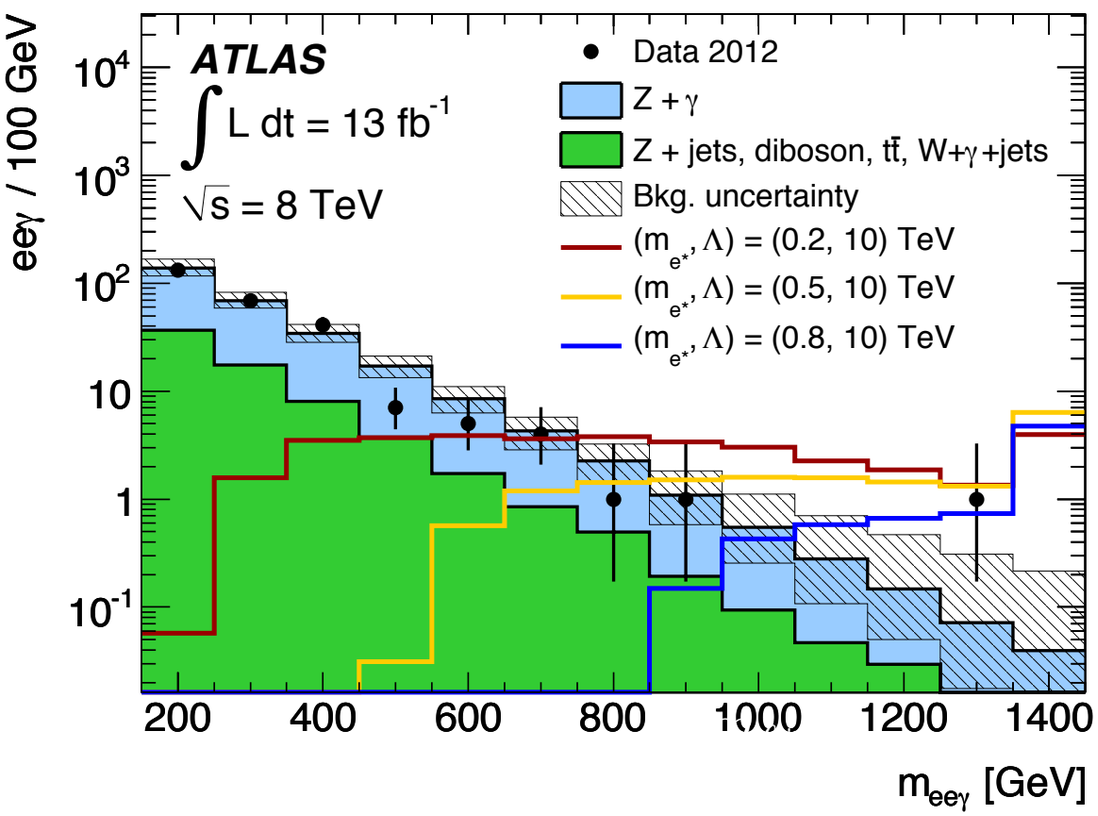
Event Selection

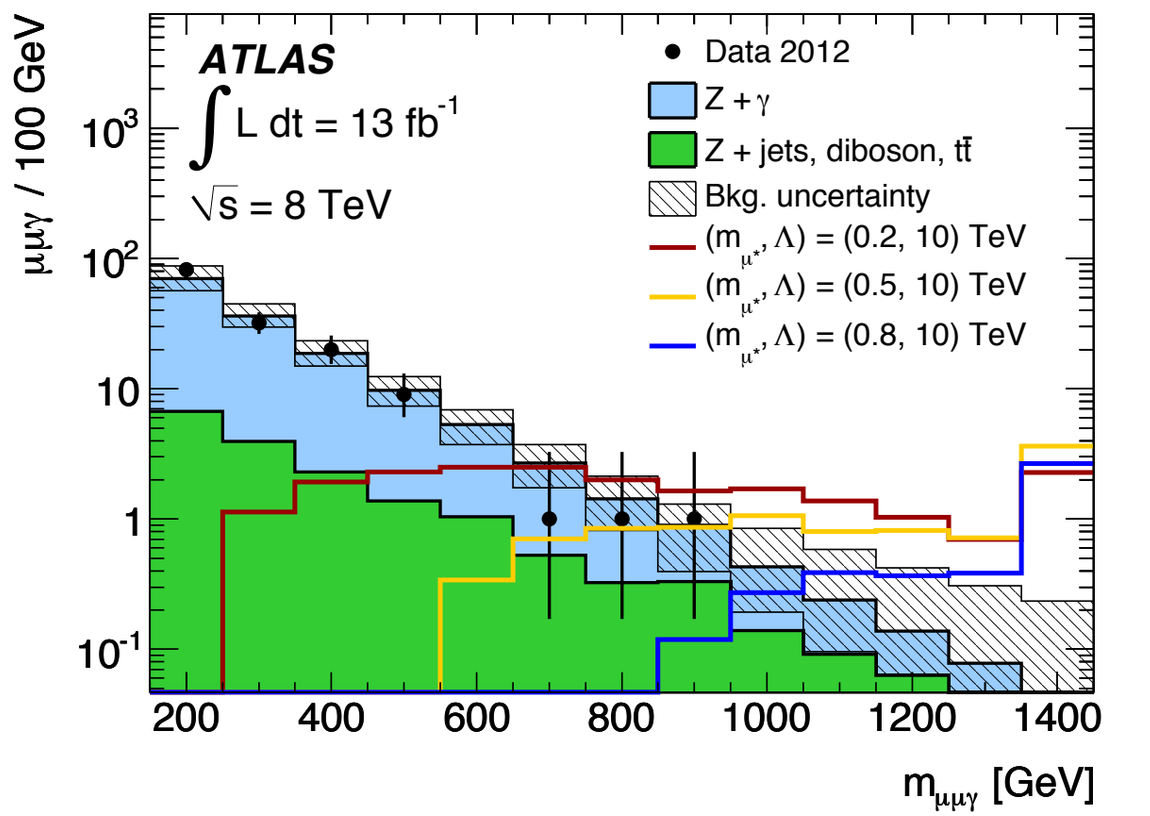
- Two lepton candidates and a photon candidate
- $m_{\ell\ell}$ > 110 GeV, suppressing Z+γ

Signal Regions

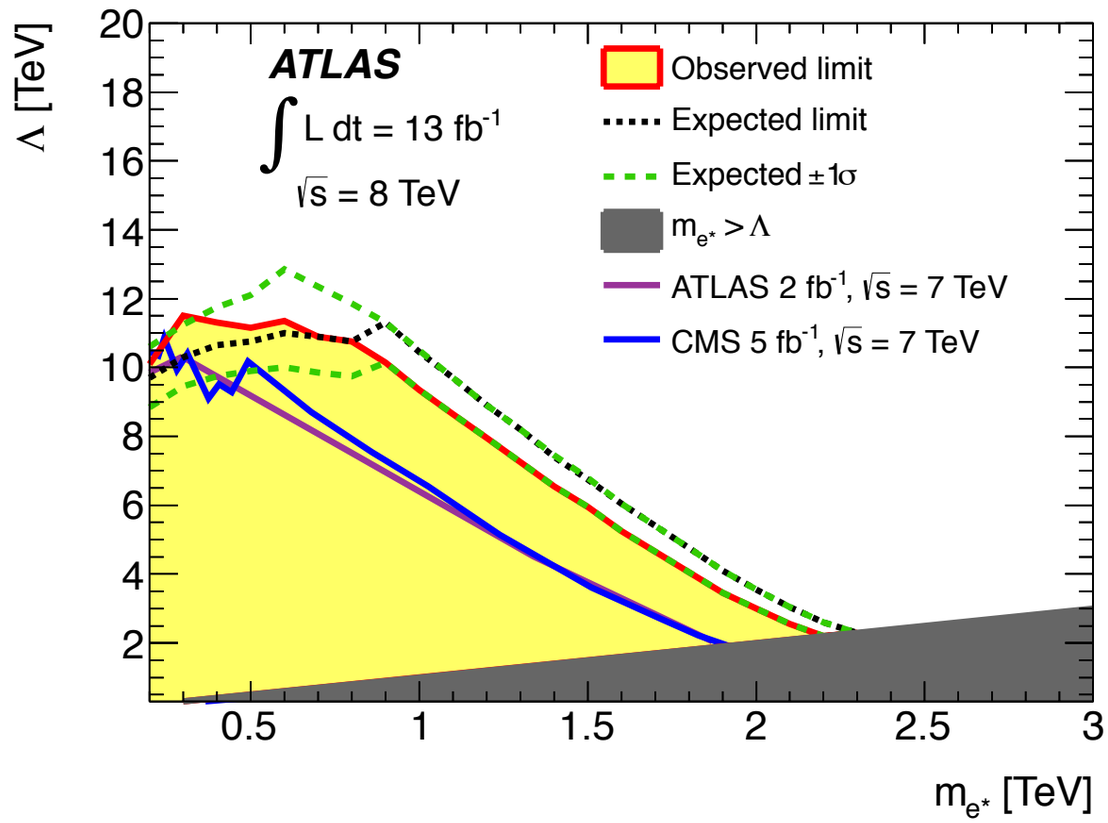
- $m_{\ell\ell\gamma} > m_{\ell^*}$ + 150 GeV, if $m_{\ell^*} < 900$ GeV
- $m_{\ell\ell\gamma} > 1050$ GeV, if $m_{\ell^*} \geq 900$ GeV

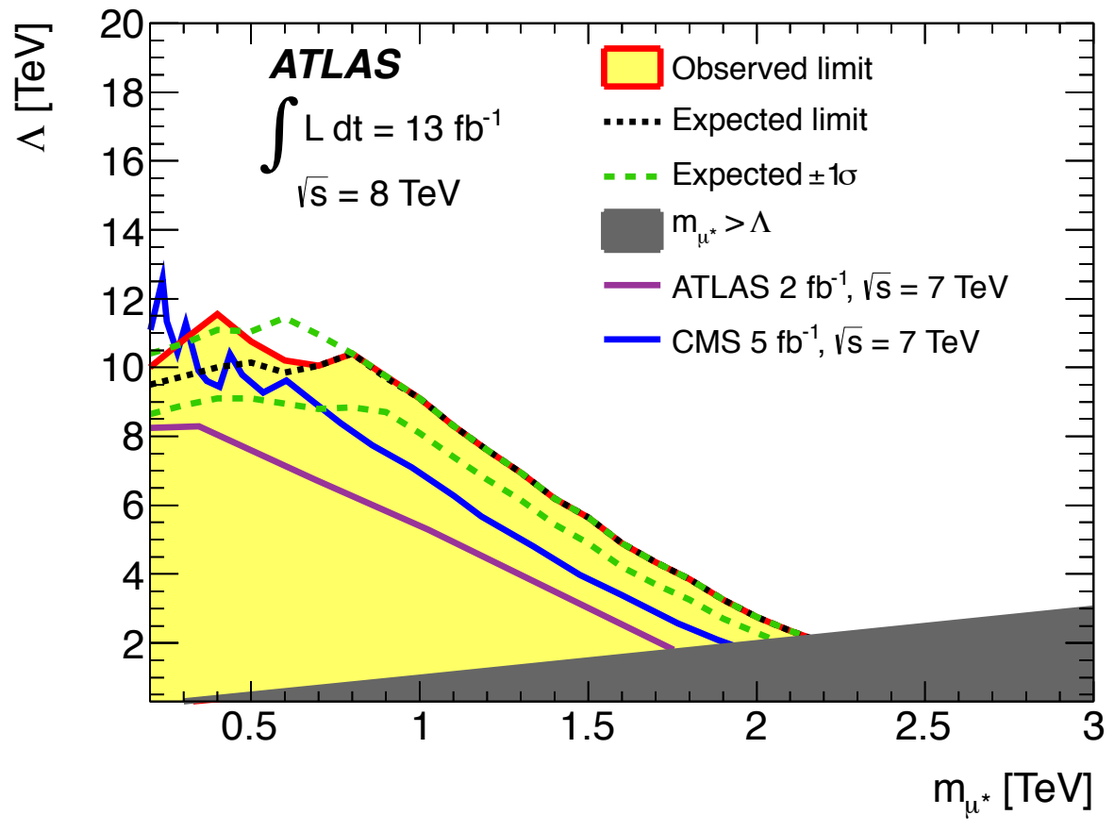
- **Z+γ:** dominant irreducible
- **Z+jets:** reducible
- **W+γ+jets:** for electron channel only
- **Diboson, ttbar:** small contributions





Excited e/μ: Results





- No significant excess is observed in the signal region
- 95% upper limits are set on $\sigma(\mathrm{pp} \to \ell\ell^*) \times \mathfrak{B}(\ell^* \to \ell\gamma)$
- For $m_{\ell^*} = \Lambda$, $m_{\ell^*} < 2.2$ TeV excluded

Three Charged Leptons: Introduction

- A model-independent search for new phenomena with ≥ 3 charged leptons
- Rare SM events
  - Dominated by WZ/ZZ production
  - Any excess would be interesting
- Complementary search for previous analysis
  - Avoiding optimization for specific models
  - Creating signal regions for various possible signatures
  - Presenting results as upper limits on event yields in a fiducial volume

Three Charged Leptons: Signal Regions

Define four mutually exclusive signal channels

On-Z ≥ 3 e/μ
On-Z 2 e/μ + ≥ 1 τ_{had}
Off-Z ≥ 3 e/μ
Off-Z 2 e/μ + ≥ 1 τ_{had}

On-Z: $|m_{\ell\ell} - m_Z| < 20$ GeV

Off-Z: $|m_{\ell\ell} - m_Z| > 20$ GeV

Minimum p_T, isolation, hit quality and fiducial volume requirements are applied to leptons

Variable	Definition
$H_T^{leptons}$	Sum of 3 lepton p_T
H_T^{jets}	Sum of jet p_T
E_T^{miss}	Missing transverse energy
m_{eff}	$H_T^{leptons} + H_T^{jets} + E_T^{miss}$

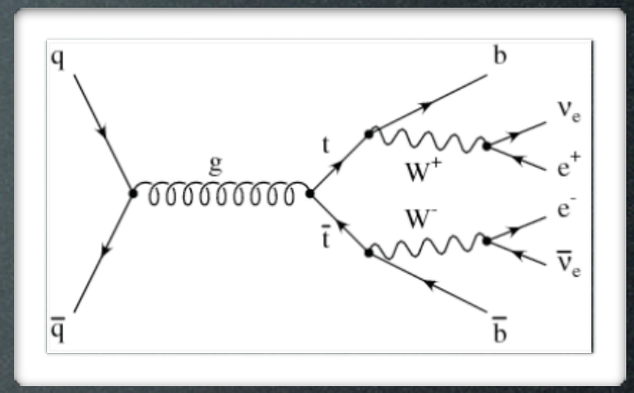
Variable	Signal Region Definition			Additional Requirements
$H_T^{leptons}$	Inclusive	≥200 GeV	≥ 500 GeV	≥ 800 GeV	
Min. p_T^{ℓ}	Inclusive	≥ 50 GeV	≥ 100 GeV	≥ 150 GeV	
E_T^{miss}	Inclusive	≥100 GeV	≥ 200 GeV	≥ 300 GeV	$H_T^{jets} < 150$ GeV
E_T^{miss}	Inclusive	≥100 GeV	≥ 200 GeV	≥ 300 GeV	$H_T^{jets}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

94 signal regions in total

Three Charged Leptons: Backgrounds

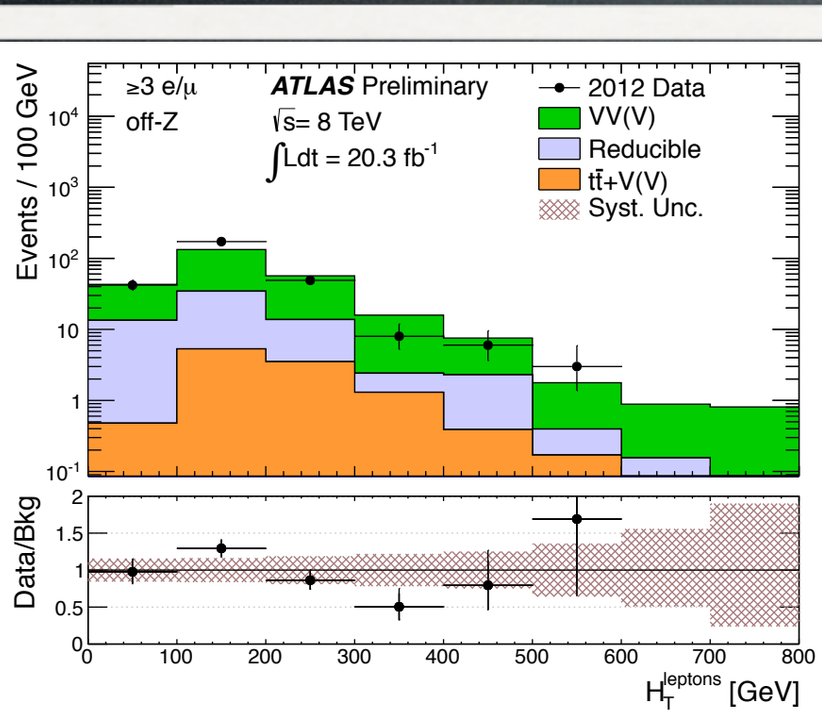
Irreducible backgrounds:

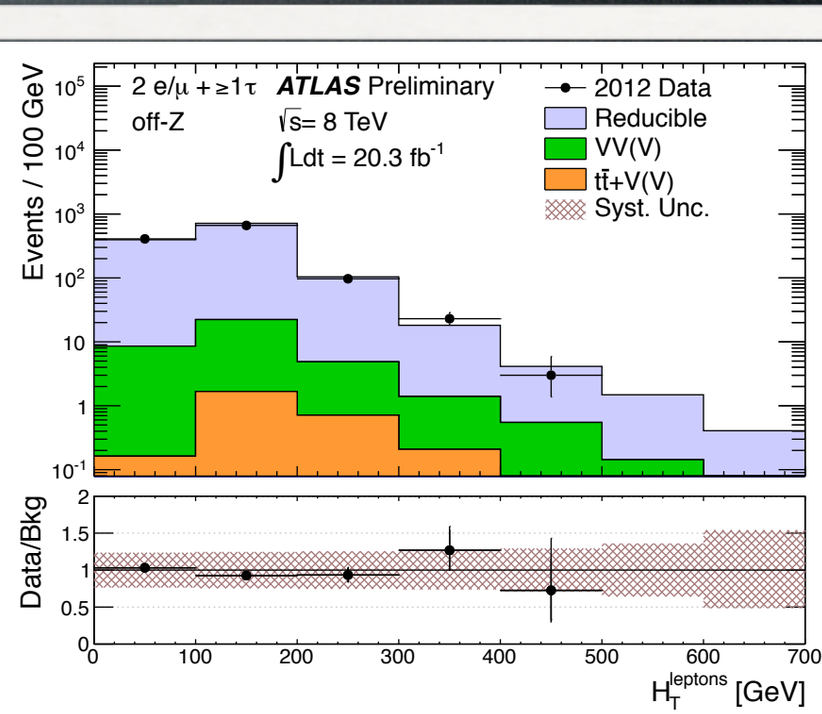
- Prompt leptons produced in the hard interaction:
  - WZ, ZZ, ttbar+W/Z processes
- Z+γ ($\gamma \rightarrow$ e)



Reducible backgrounds:

- Events with up to 2 prompt leptons with at least 1 non-prompt lepton
  - Non-isolated, fake lepton candidates
  - Z+jets, W+jets, tt, single top, multijets
  - Estimated by using data-driven fake factor method





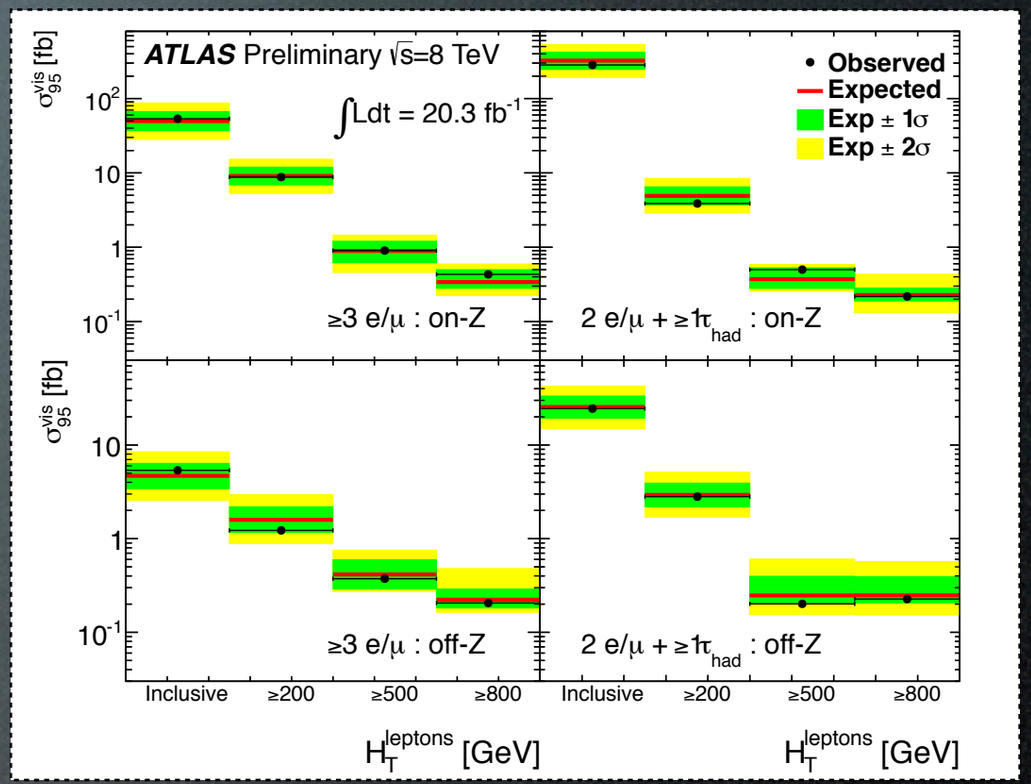
- Distributions are shown in terms of $H_T^{leptons}$, H_T^{jets}, m_{eff} and E_T^{miss}
- No significant deviation from the expected background is observed

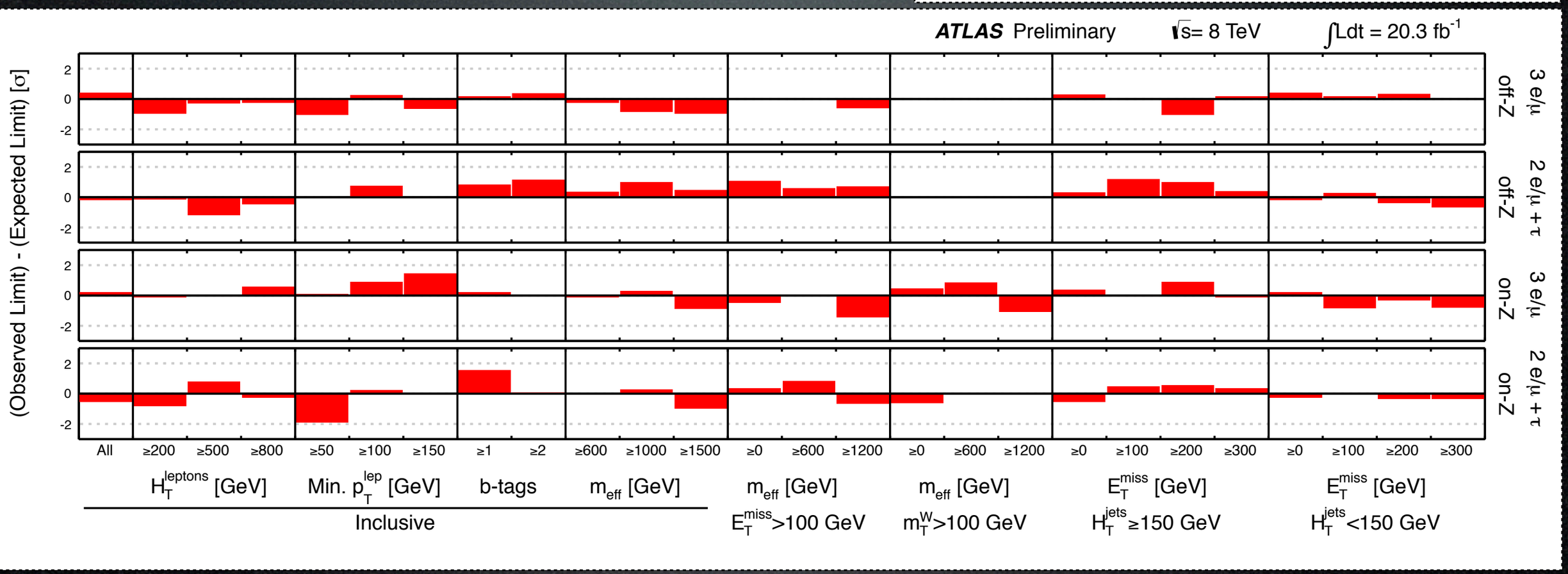
Three Charged Leptons: Results

- The 95% C.L upper limits set on the number of events from non-SM sources (N_{95})
- CL_s method is used
- The N_{95} limits are converted into limits on the "visible cross section"

$$\sigma_{vis}^{95} = \frac{N_{95}}{\int Ldt}$$

- No significant deviation is observed in any signal region under study

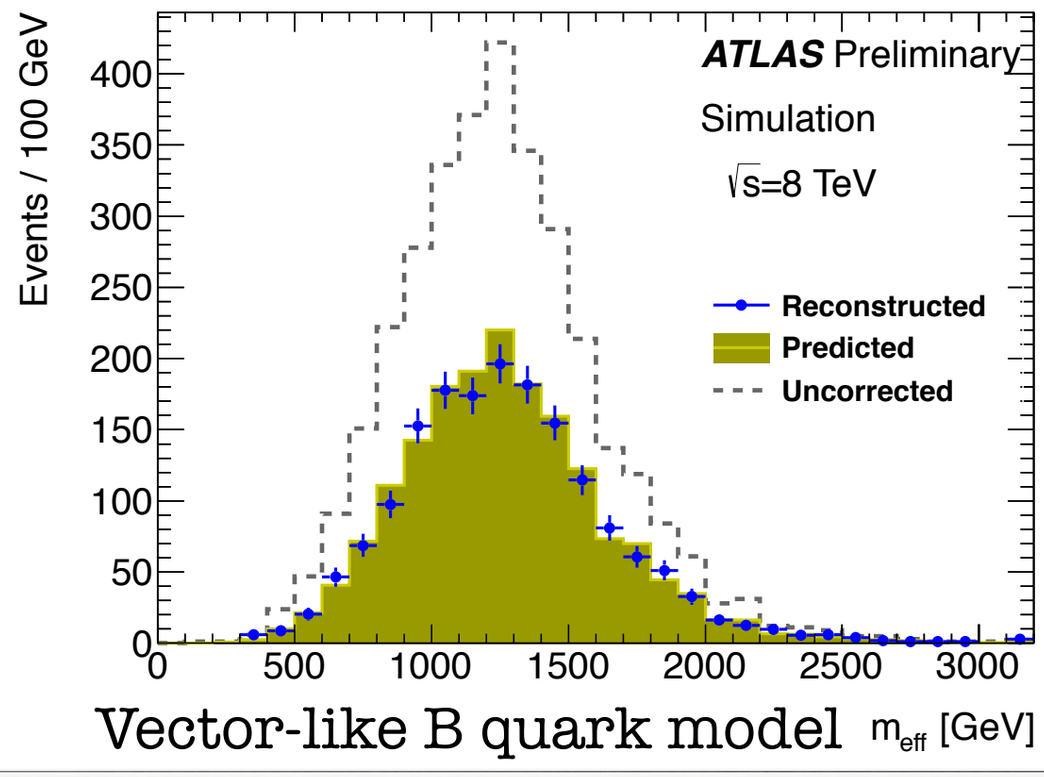




Three Charged Leptons: Model Testing

- Allow to set limits on specific models by using model independent limits given in terms of σ_{vis}
  - Define a fiducial volume at the particle level for a chosen model
  - Provide single lepton efficiencies (ε_{fid}) as a function of p_T and η in that fiducial volume
  - A 95% upper-limit on the cross section in the new model is then defined as;

$$\sigma_{95}^{fid} = \frac{N_{95}}{\epsilon_{fid} \int Ldt} = \frac{\sigma_{95}^{vis}}{\epsilon_{fid}}$$



Type-III SeeSaw: Introduction

- In the Standard Model (SM) neutrinos are massless
- From neutrino oscillation experiments:
  - At least two neutrinos of all three generations are massive

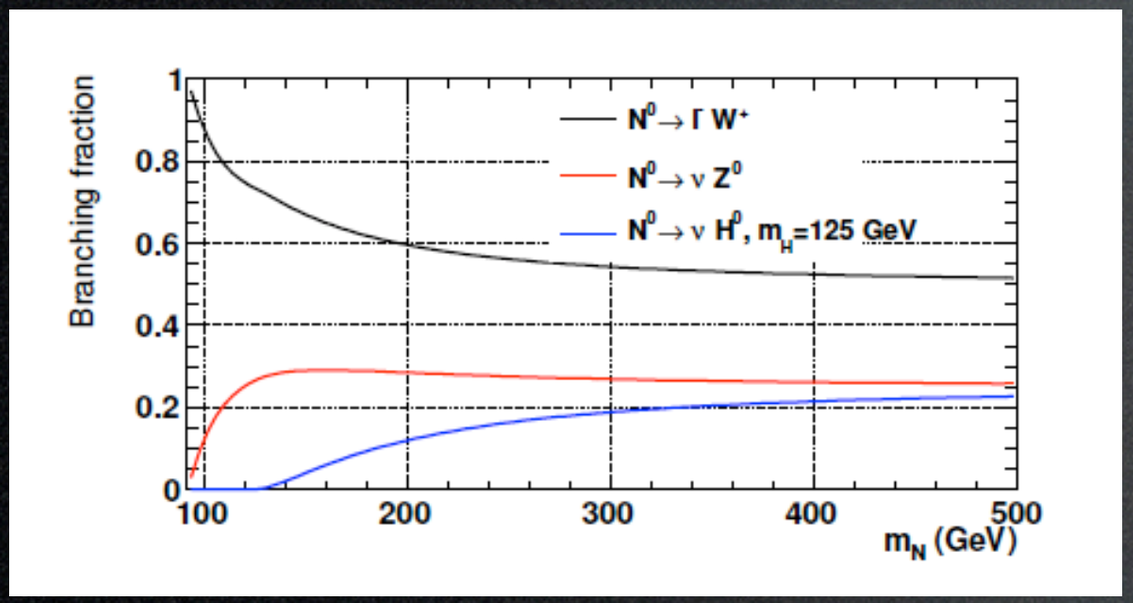
CONTRADICTION

The origin and smallness of neutrino masses ?

- SeeSaw models are proposed as an effective framework in order to provide answers to these puzzles

Type-III SeeSaw Mechanism

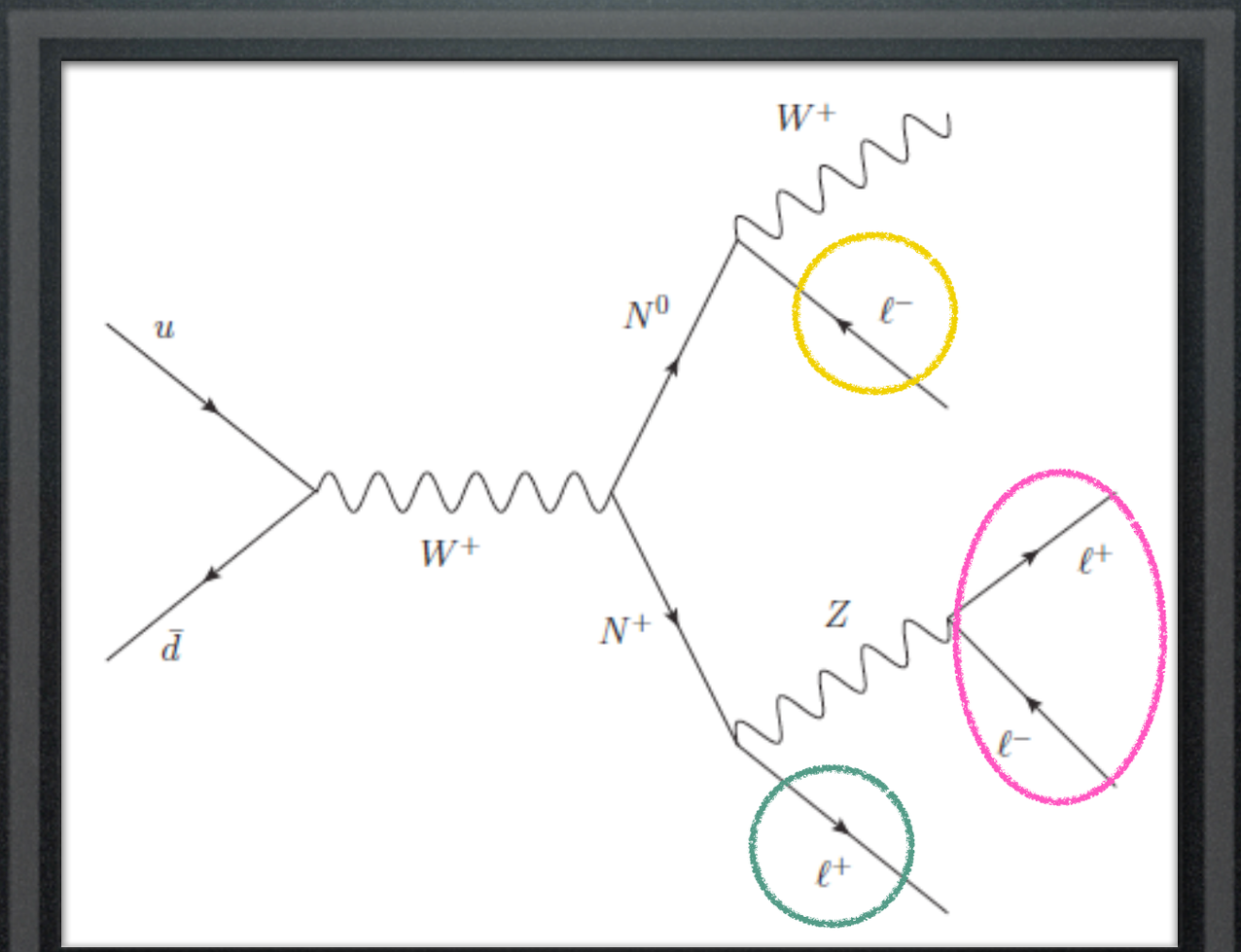
- Introduces at least two fermionic triplets that generate neutrino masses
- The lightest fermionic triplet; N^+ and N^-, N^0 - Approximately degenerate masses
- N^0 and $N^\pm$ decay into a W, Z or H and accompanying charged or neutral lepton



- $pp \to N^0 + N^\pm \to \ell^\pm W^\mp + \ell^\pm Z$
- $pp \to N^+ + N^- \to \ell^- Z + \ell^+ Z$
- $pp \to N^+ + N^- \to \ell^+ Z + \nu_\ell W^-$
- $pp \to N^+ + N^- \to \nu_\ell W^+ + \ell^- Z$
- $pp \to N^0 + N^\pm \to \nu_\ell Z + \nu_\ell W^\pm$

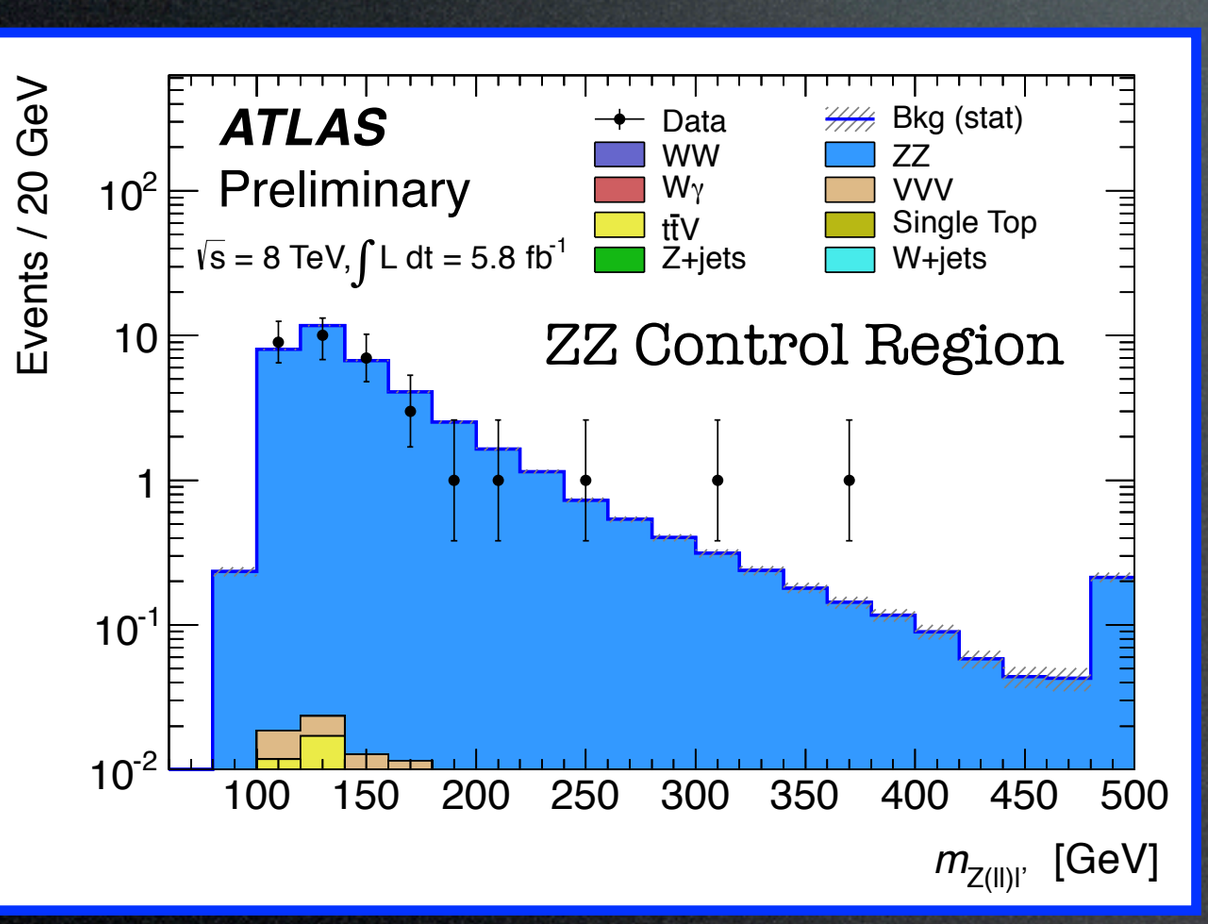
Type III SeeSaw: Event Selection

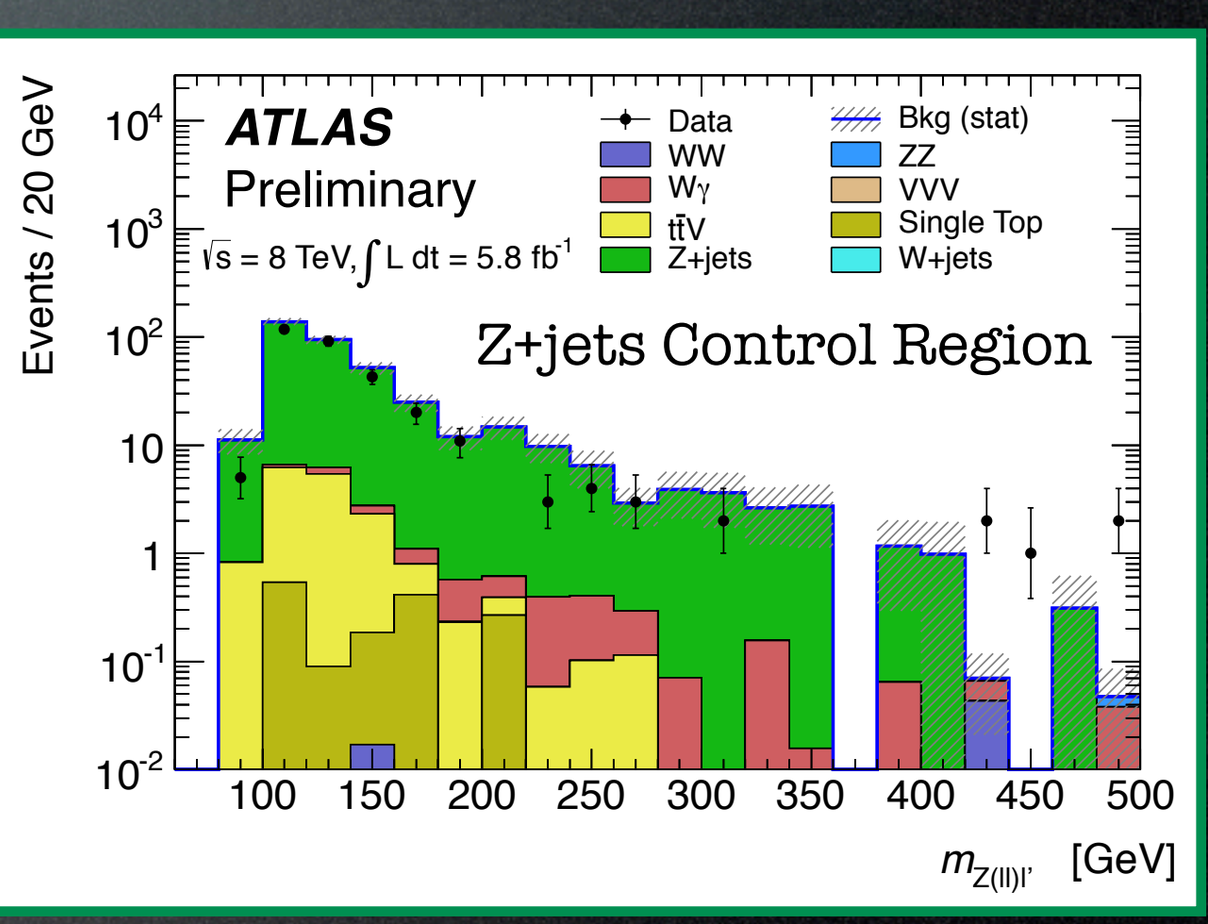
- At least four leptons (e or μ) in the event
  - **Z candidate:** 2 leptons with opposite sign and same flavour, invariant mass within ±10 GeV of the Z mass
  - **Bachelor lepton:** Third lepton candidate, closest in ϕ to the reconstructed Z
  - **Fourth lepton:** Highest p_T e or μ candidate remaining in the event



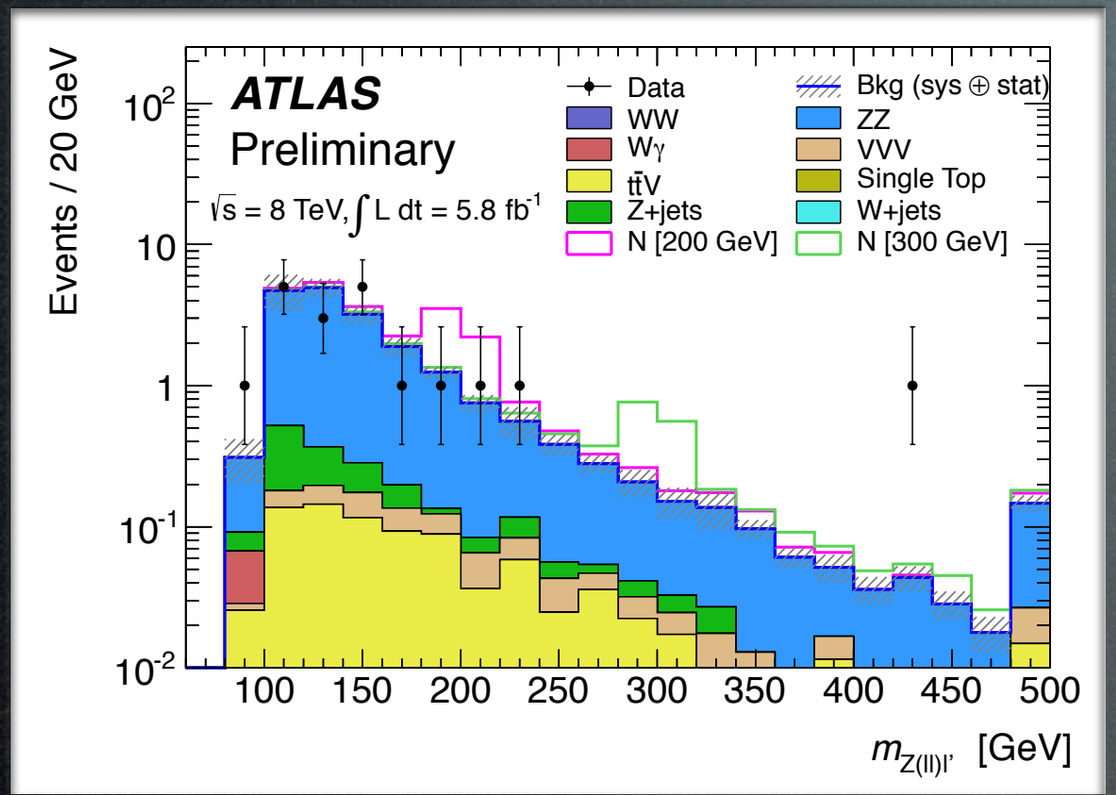
Type III SeeSaw: Backgrounds

- **MC based estimates**
  - **ZZ(*)** - dominant background
    - Veto events with a second Z boson with $|m_{\ell^+\ell^-} - m_Z| < 10$ GeV
    - Remains a small and irreducible contribution from ZZ*
  - **Z+jets** (Z+bb/cc) - small contribution
    - Validated with data in the control region
  - **ttV, VVV** - small contribution

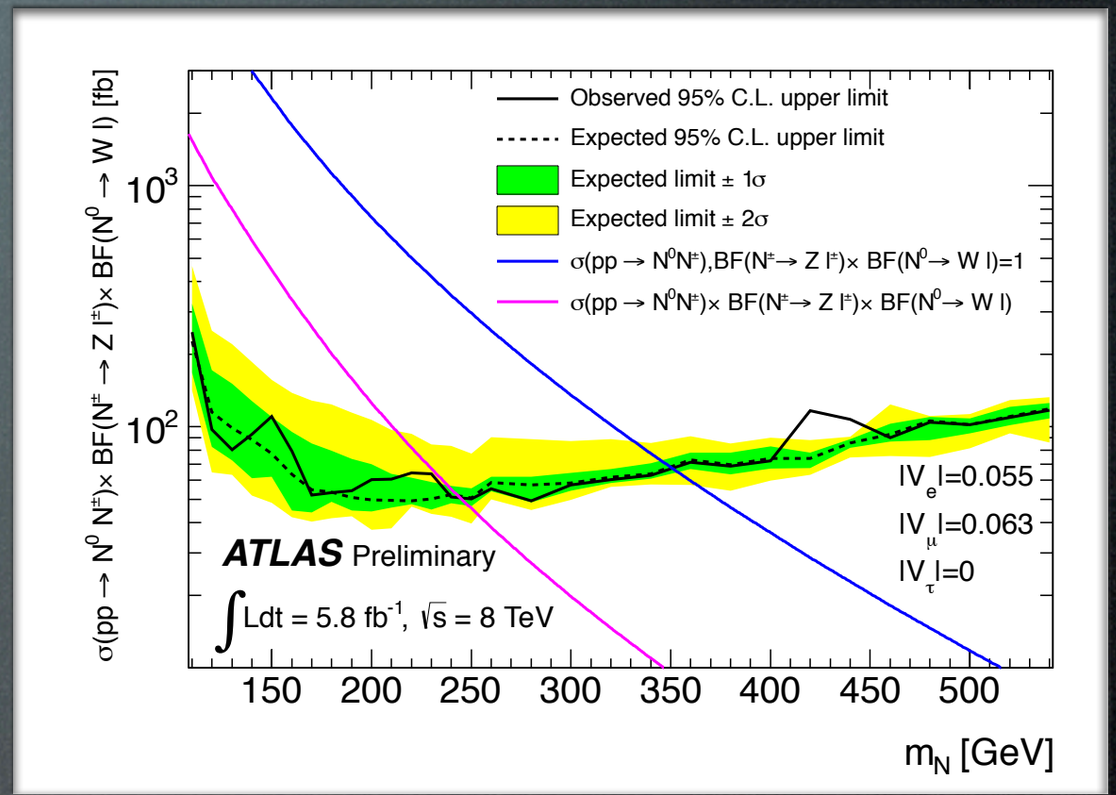




Type III SeeSaw: Results



m_N distribution
p_0 at 420 GeV = 0.2



Exclusion limits on m_N

- No significant deviation from the SM is observed
- 95% upper limits are placed on $\sigma\mathscr{B}$ by using the CLs method
- Limits depend on $\mathfrak{B}(\mathrm{N}^{\pm} \to \mathrm{Z}\ell^{\pm})\mathfrak{B}(\mathrm{N}^{0} \to \mathrm{W}^{\mp}\ell^{\pm})$
- For $\mathscr{B}$ = 1, m_N up to 350 GeV is excluded (same as expected)
- For nominal mass dependent $\mathscr{B}$, m_N up to 245 GeV is excluded (243 GeV expected)

CONCLUSIONS

- Presented three recent ATLAS analyses with multi-lepton final states
- No significant excesses observed

Two lepton final states - Excited e/μ search:

- Analysis is performed with 13 fb^{-1} of $\sqrt{s}$ = 8 TeV data
- An upper limit is set at 95% CL on the excited lepton mass
  - For $m_{\ell^*} = \Lambda$, $m_{\ell^*} > 2.2$ TeV

Three lepton final states - Model independent search:

- Analysis is performed with 20.3 fb^{-1} of $\sqrt{s}$ = 8 TeV data
- Provided model independent limits on σ_{vis}
  - Limits vary from 0.19 fb^{-1} to 340 fb^{-1}
- Single lepton efficiencies are provided in terms of p_T and η to derive model-dependent limits

Four lepton final states - Type-III SeeSaw model heavy fermions search:

- Analysis is performed with 5.8 fb^{-1} of $\sqrt{s}$ = 8 TeV data
- Limits are set on the mass of the N states at 95% CL
  - For $\mathcal{B}$ = 1, m_N > 350 GeV
  - For nominal mass dependent $\mathcal{B}$, m_N > 245 GeV

REFERENCES

- "Search for excited electrons and muons in $\sqrt{s}$ = 8 TeV proton-proton collisions with the ATLAS detector" New J. Phys. 15 093011

- "Search for New Phenomena in Events with Three Charged Leptons at $\sqrt{s}$ = 8 TeV with the ATLAS detector" ATLAS-CONF-2013-070

- "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

BACK UP

Excited e/μ: Event/Object Selection

ee

- γγ trigger
- $p_T^{leading,subleading}$ > {40 GeV, 30 GeV}
- |η| < 2.47, crack region excluded
- Electron medium ID
- Isolation: E_T^{el} (ΔR = 0.2) < 7 GeV

μμ

- Single muon trigger
- $p_T^{\mu_1,\mu_2}$ > 25 GeV
- Muon hit quality requirements
- Muon Spectrometer three station hits
- Impact parameter requirements
- Isolation: Σp_T (ΔR = 0.3) / p_T^{μ} < 5%
- Opposite sign pair

γ

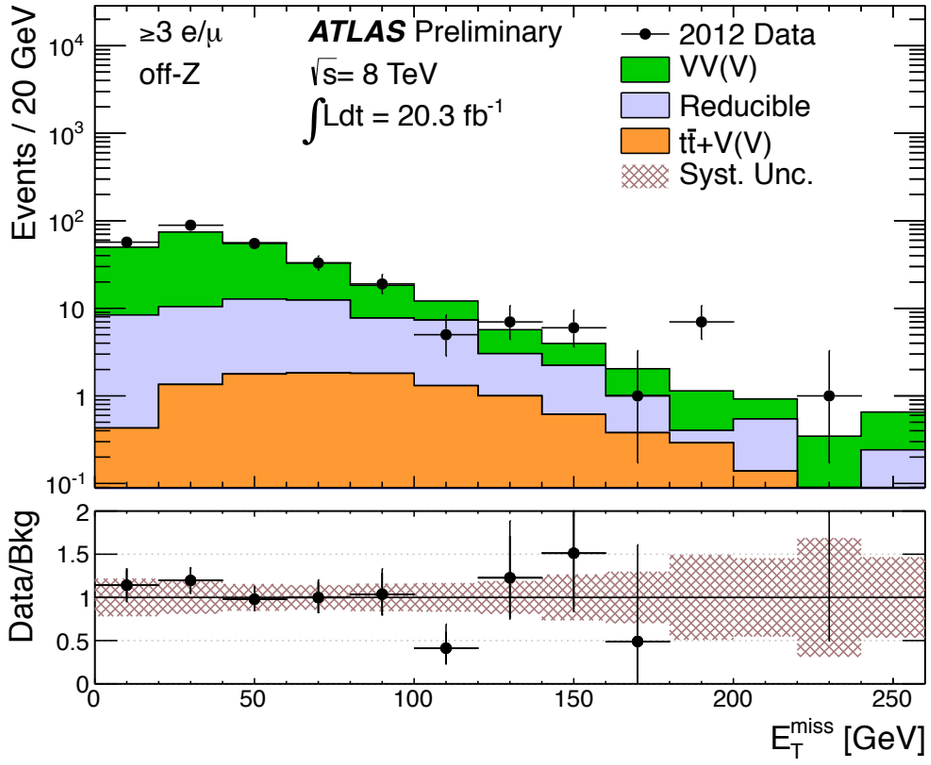
- p_T^{γ} > 30 GeV
- |η| < 2.47, crack region excluded
- Tight photon definition
- Isolation: E_T^{iso} (ΔR = 0.4) < 10 GeV
  or E_T^{iso}/p_T^{γ} < 1%
- ΔR (l, γ) > 0.7

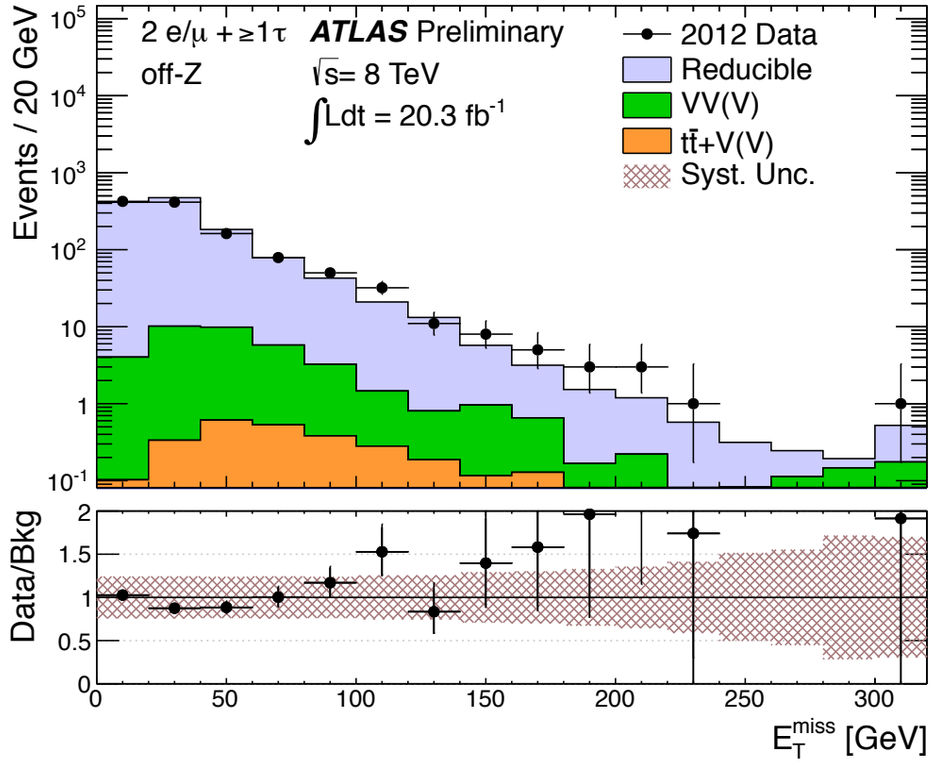
Three Charged Leptons: Systematic Uncertainties

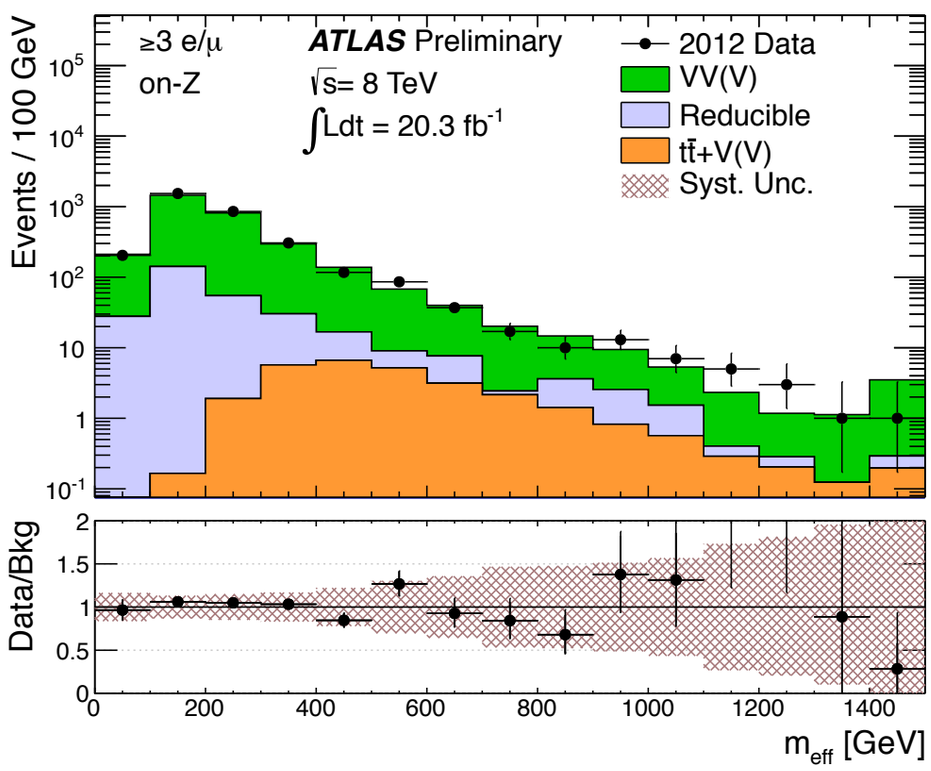
Sample systematics from most representative signal regions

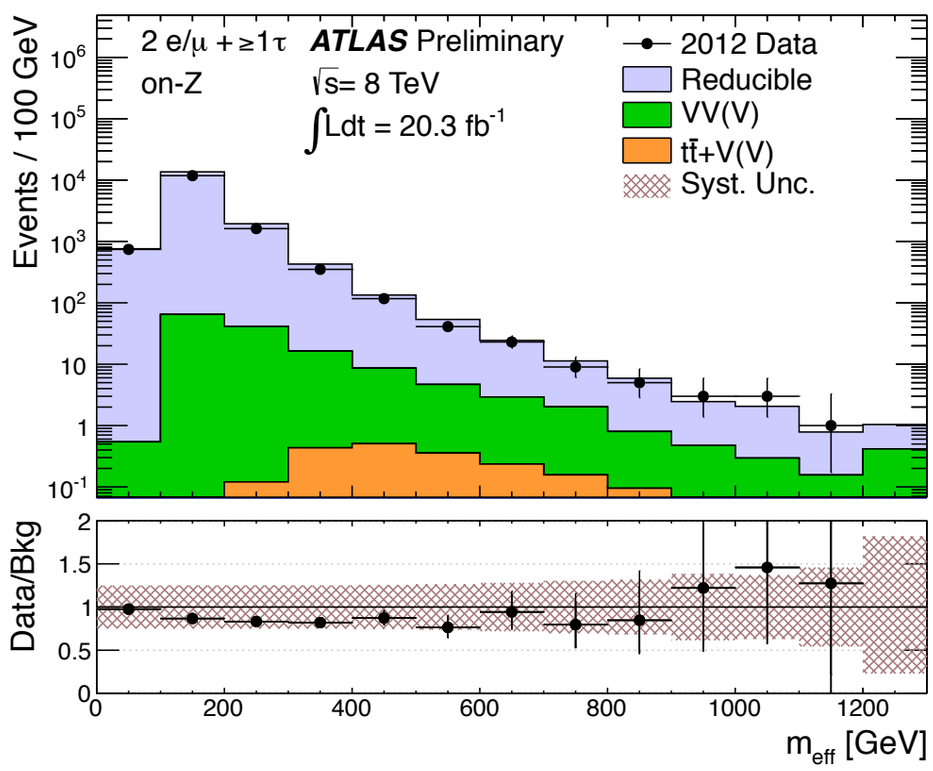
Source of uncertainty	Uncertainty
Trigger efficiency	1%
Electron energy scale	<1%
Electron energy resolution	<1%
Electron identification	2%
Electron non-prompt/fake backgrounds	9%
Muon momentum scale	<1%
Muon momentum resolution	<1%
Muon identification	<1%
Muon non-prompt/fake backgrounds	5%
Tau energy 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: Other Distributions

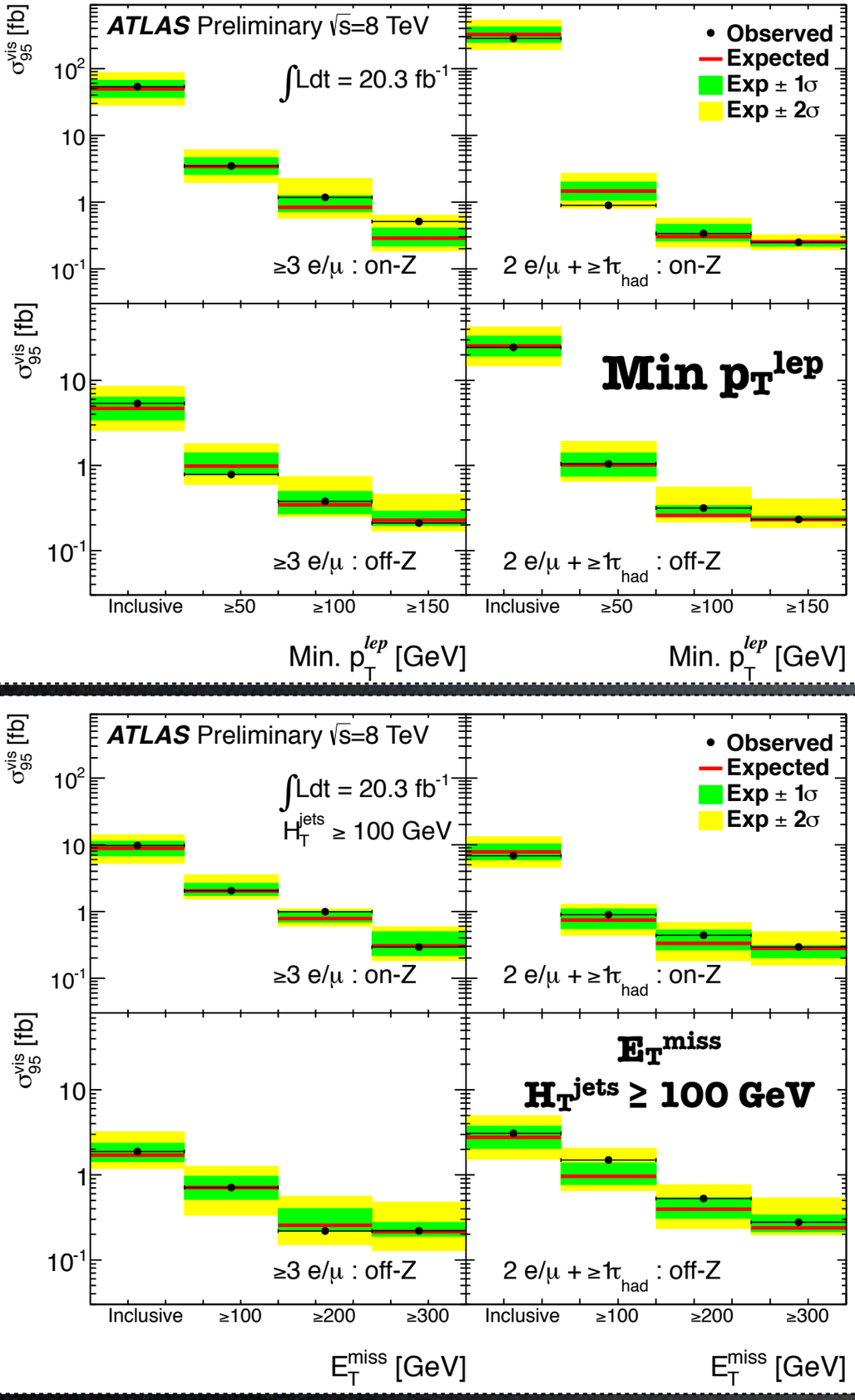


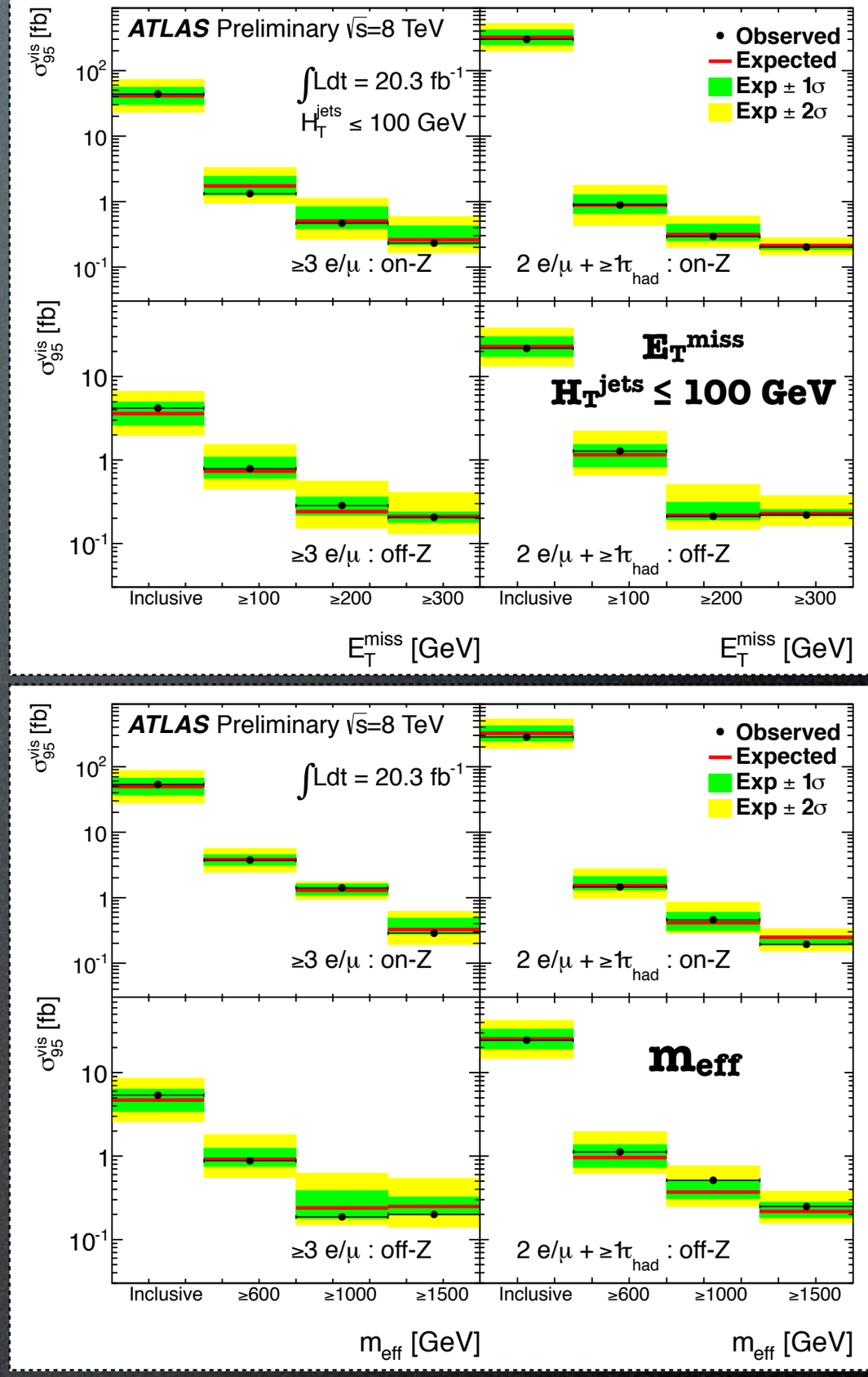




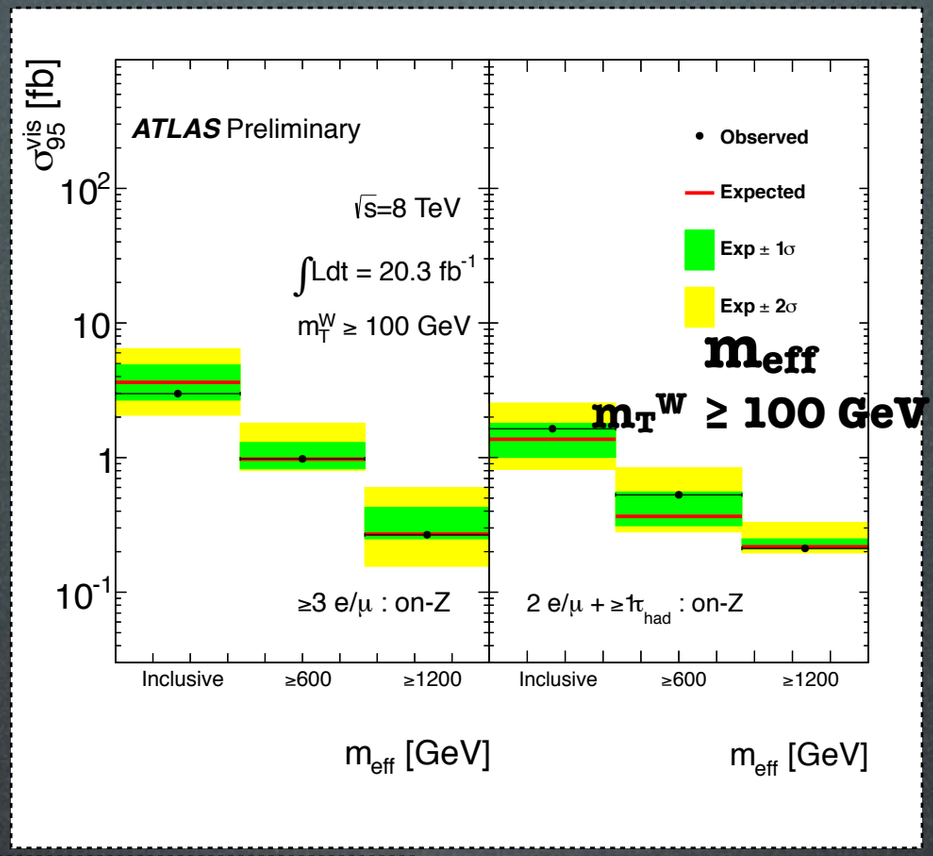


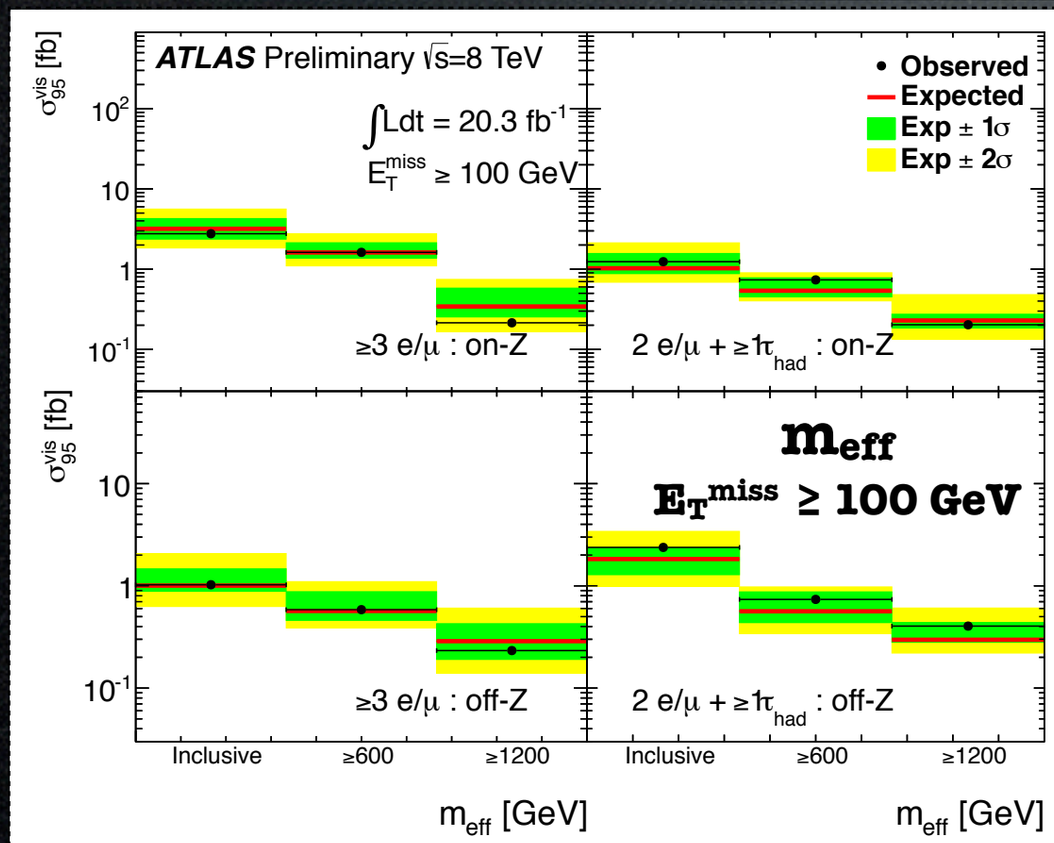
Three Charged Leptons: All Limits I

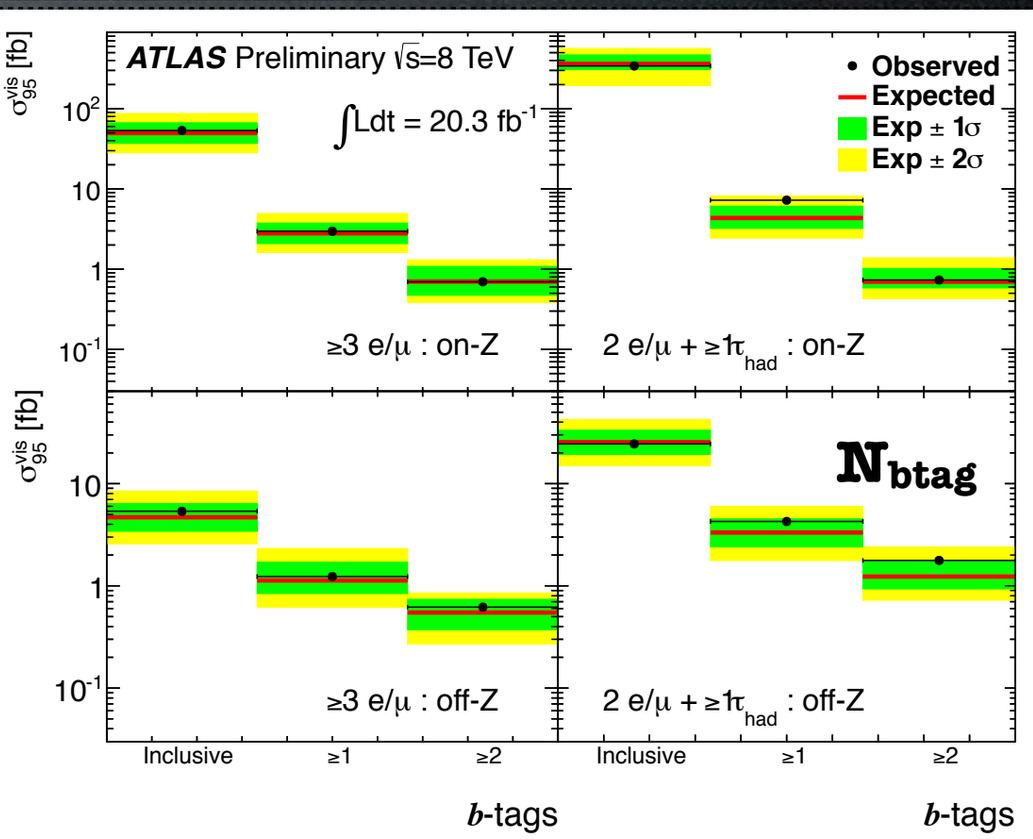




Three Charged Leptons: All Limits II







Type III SeeSaw: Systematic Uncertanties

Summary of the systematic uncertainties on the normalisation of the signal (m_N = 120 GeV) and background contributions, given in percentages

	ZZ	Z+jets	VVV	$t\bar{t}V$	Signal [120 GeV]
E_e Resolution	0.2	–	< 0.1	< 0.1	0.3
E_e Scale	0.1	–	0.3	0.6	0.6
e Identification	2.7	2.8	2.8	2.7	2.7
μ Res. ID	0.1	–	< 0.1	1.7	0.1
μ Res. Spectr.	0.1	–	< 0.1	1.7	0.1
E_μ Scale	< 0.1	–	< 0.1	5.8	0.2
Shape	–	100	–	–	–
Scale Factor	–	370	–	–	–
Fast sim.	–	–	–	–	6.8
Signal PDF	–	–	–	–	0.9
Cross Section	6.4	11	100	50	–
Total	7.0	390	100	50	7.4

The luminosity uncertainty is 3.6%