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

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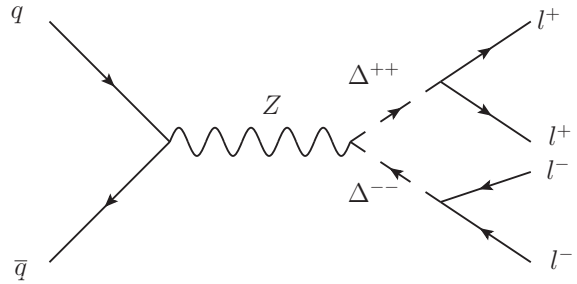
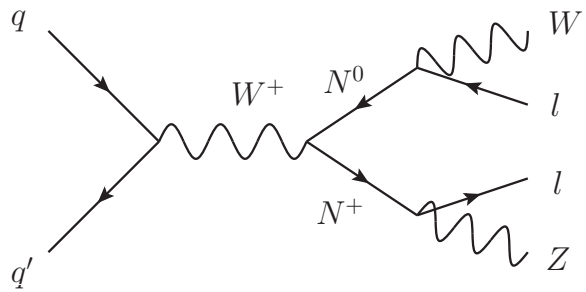
Introduction

Overview

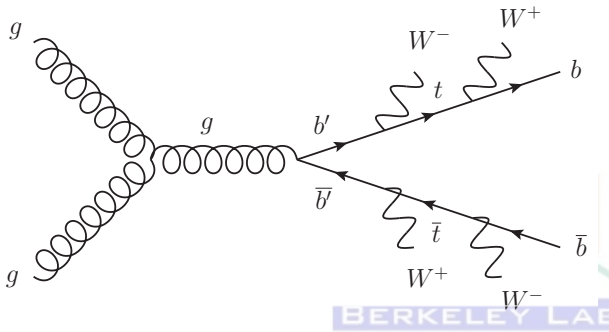
- Many models of BSM phenomena predict final states with several leptons:
  - Composite fermions.
  - Type III seesaw.
  - $H^{\pm\pm}$.
  - Fourth generation quarks.
  - Diboson resonances (EGM, SSM, RS).
  - SUSY.



(a) Doubly-Charged Higgs



(b) Type III Seesaw/Majorana ν

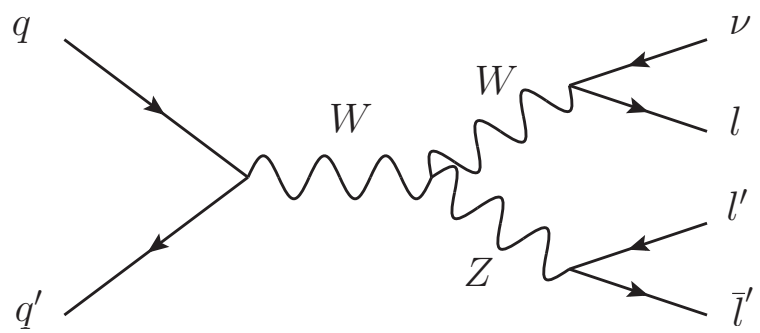


(c) 4th gen. quark

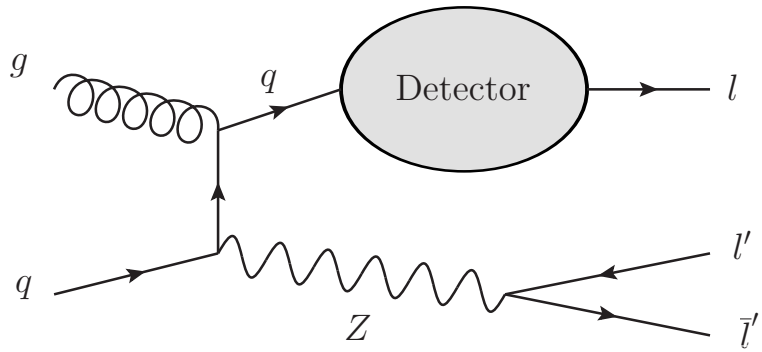
Introduction

Multilepton Backgrounds

- Searches profit from low SM backgrounds, especially when requiring:
  - Prompt lepton production: track consistent with primary vertex.
  - Isolation: limits on calorimeter energy/tracks near lepton candidate (e.g. $< 10\%$ of lepton p_T).
  - Strict identification criteria: shower shapes, good tracks, central η.
  - Rare topologies, e.g. same sign or ≥ 3 leptons.
- Primary backgrounds:
  - Irreducible SM: diboson production, $t\bar{t} + V$, ...
  - Non-prompt/fake: misidentified jets, semileptonic heavy flavor decays.



(a) WZ



(b) Fake Leptons

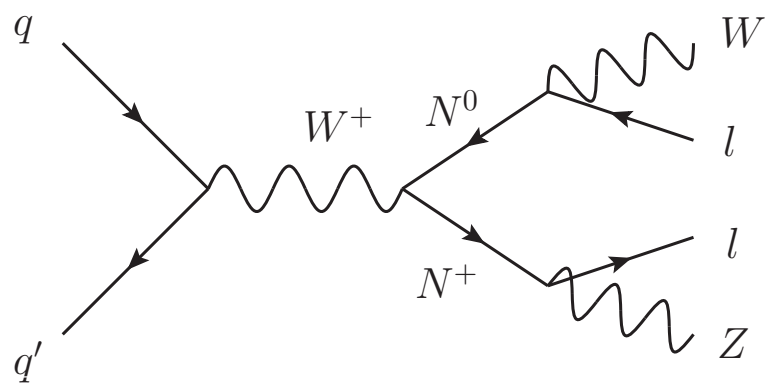
Searches

Search Name	Signature	$\int Ldt$	$\sqrt{s}$	Reference
Type III Seesaw Heavy Fermions	$4l$	5.8 fb^{-1}	8 TeV	ATLAS-CONF-2013-019
Excited e/μ	$l\bar{l}\gamma$	13 fb^{-1}	8 TeV	ATLAS-CONF-2012-146
Model-Independent Trilepton	$3l$	4.6 fb^{-1}	7 TeV	hep-ex/1211.6312
Model-Independent Same-Sign Dilepton	$l^{\pm}l^{\pm}$	4.7 fb^{-1}	7 TeV	hep-ex/1210.4538

Type III Seesaw: Analysis Overview

- Generate neutrino masses with fermionic triplets:

$$\Sigma = \begin{pmatrix} \frac{1}{\sqrt{2}}N^0 & N^+ \\ N^- & -\frac{1}{\sqrt{2}}N^0 \end{pmatrix}$$



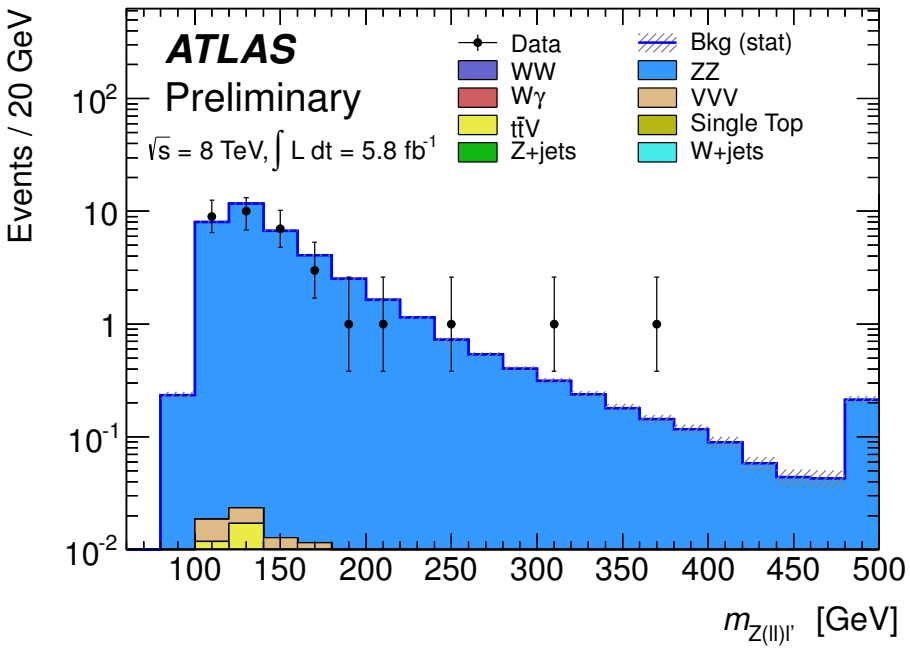
Event Reconstruction

- Search for $N^0 N^\pm$ pair production, with
  - $N^\pm \to Z l'^\pm \to l^+ l^- l'^\pm$
  - $N^0 \to W^\pm l^\mp$
- $p_T(l_1) > 25$ GeV, $p_T(l_{>1}) > 10$ GeV.
- Four-lepton ordering:
  - l_1, l_2 within ± 10 GeV of m_Z.
  - l_3 =closest in ϕ to Z.
  - l_4 =highest p_T remaining.
- Reconstruct $m_{N^\pm} = m_{Z(ll)l'}$.

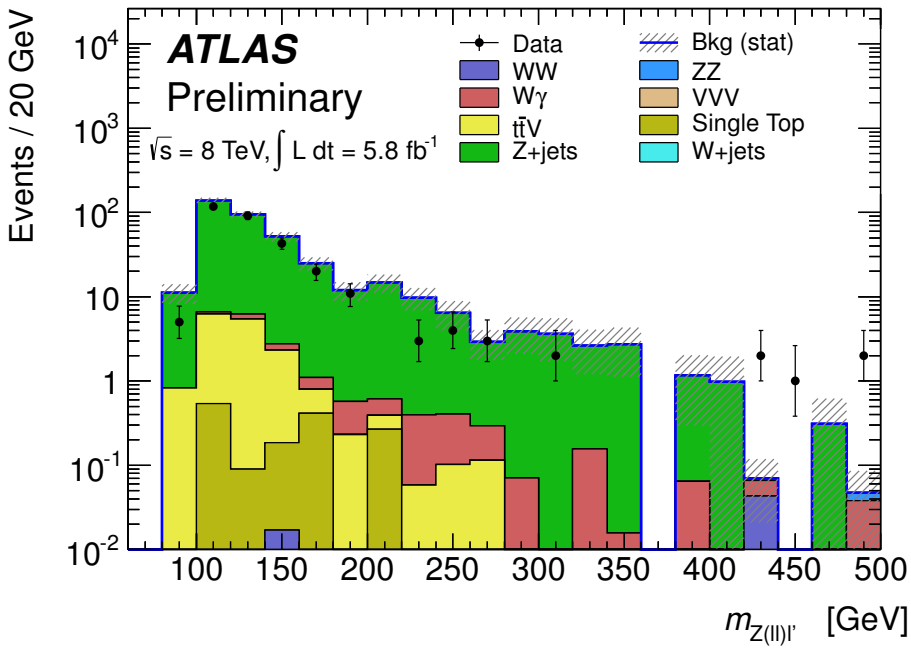
Type III Seesaw: Backgrounds

- Veto events with a second l^+l^- pair with $|m_{l^+l^-} - m_Z| < 10$ GeV.
- Dominant background remaining is ZZ^* ($\mathcal{O}(1)$ event from Z+jets).
- MC-driven estimates.

Control Regions

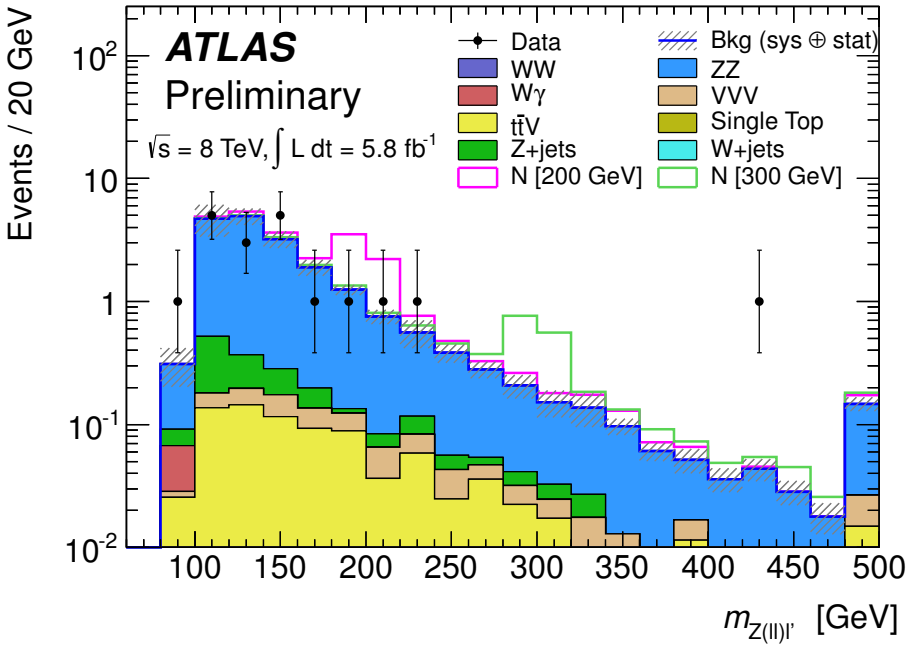


(a) ZZ, with second Z boson on-shell.

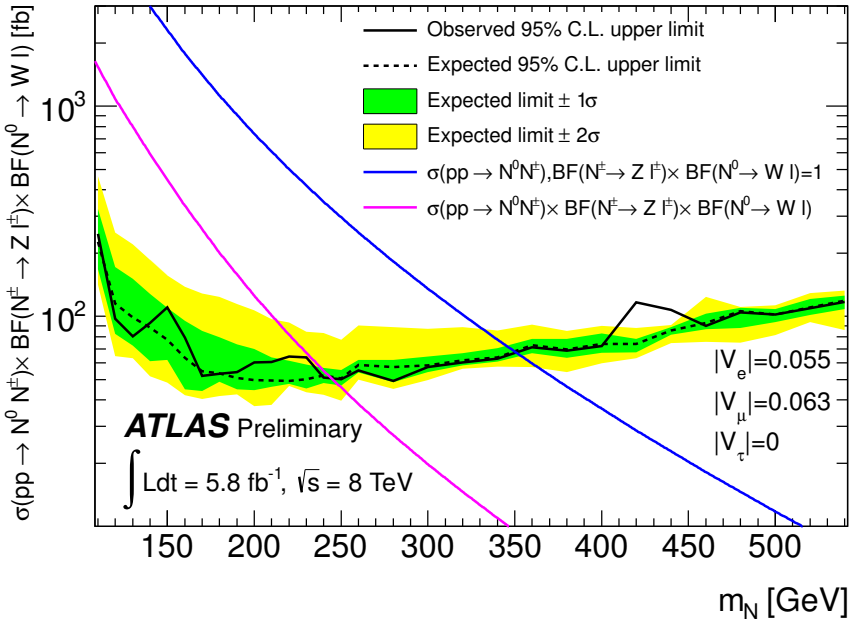


(b) Z+jets, with third lepton satisfying $\frac{d_0}{\sigma_{d_0}} > 4$ and $\frac{p_T^{cone30}}{p_T} > 0.2$.

Type III Seesaw: Results



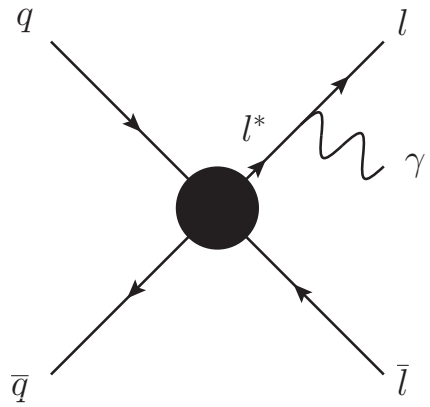
(a) m_N distribution (last bin inc. overflow). p_0 at 420 GeV$= 0.2$.



(b) Exclusion limits on m_N

- Limits depend on branching fraction $\mathscr{B}(N^{\pm} \to Zl^{\pm})\mathscr{B}(N^0 \to W^{\pm}l^{\mp})$.
- Assuming $\Pi\mathscr{B} = 1$, $m_{N^{\pm}} < 350$ GeV (350 GeV expected) is excluded.
- Assuming nominal mass-dependent $\Pi\mathscr{B}$, $m_{N^{\pm}} < 245$ GeV excluded (243 GeV expected).

Excited e/μ: Analysis Description



Search for excited e^*/μ^* using $l\bar{l}\gamma$ final state.

Leptons and Photons

- Leptons:
  - $p_T > \begin{cases} 40\text{ GeV}, 30\text{ GeV} : e \\ 25\text{ GeV} : \mu \end{cases}$
  - Good quality lepton tracks.
- Photons:
  - $p_T > 30$ GeV.
  - Unconverted and converted.
  - $R(l,\gamma) > 0.7$ between photon and signal leptons.
- All objects isolated.

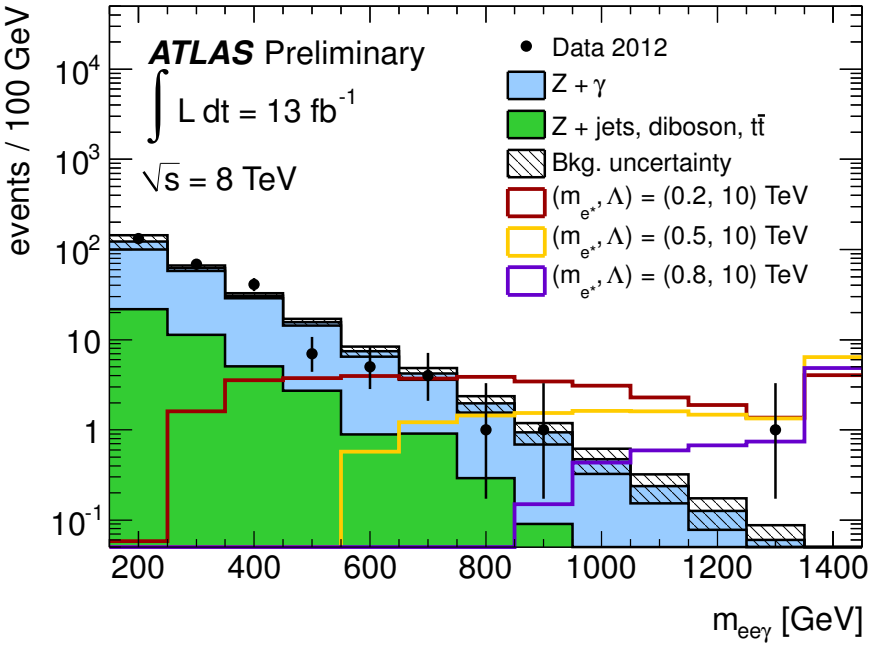
Event Selection

- $m_{l\bar{l}} > 110$ GeV: suppresses Drell-Yan$+\gamma$.
- Signal regions:

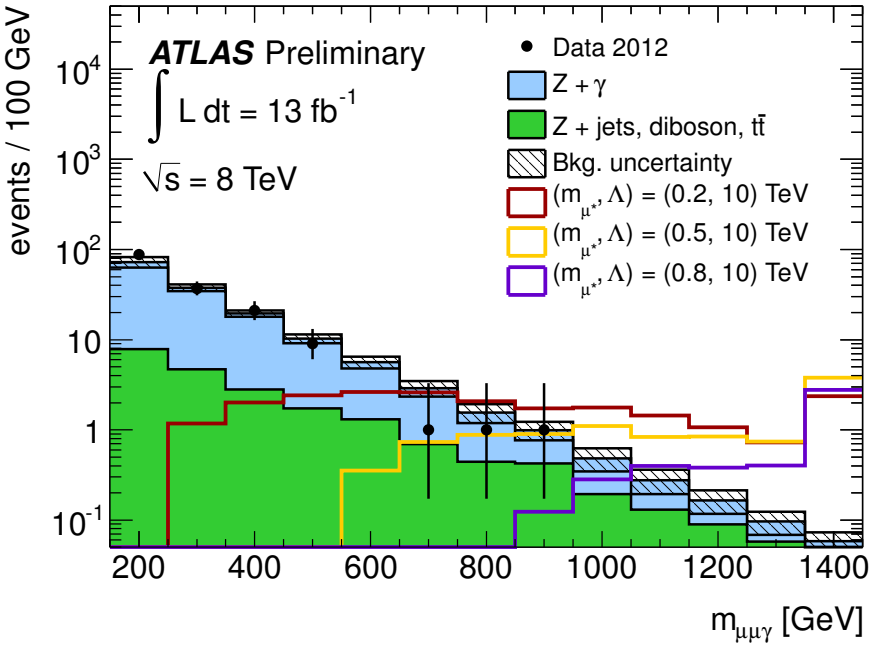
$$m_{l\bar{l}\gamma} > \begin{cases} m_{l^*} + 150\text{ GeV} : m_{l^*} < 900\text{ GeV} \\ 1050\text{ GeV} : m_{l^*} > 900\text{ GeV} \end{cases}$$

- Dominant systematic uncertainty: poor MC statistics with $m_{l\bar{l}} > 110$ GeV $\Rightarrow$ fit MC background shape.

Excited e/μ: Results



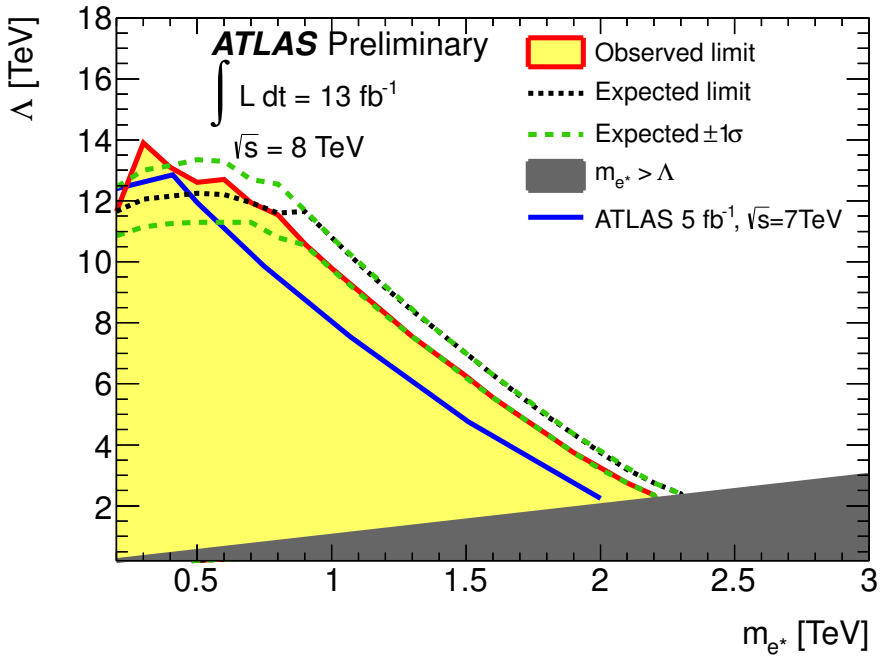
(a) e^*



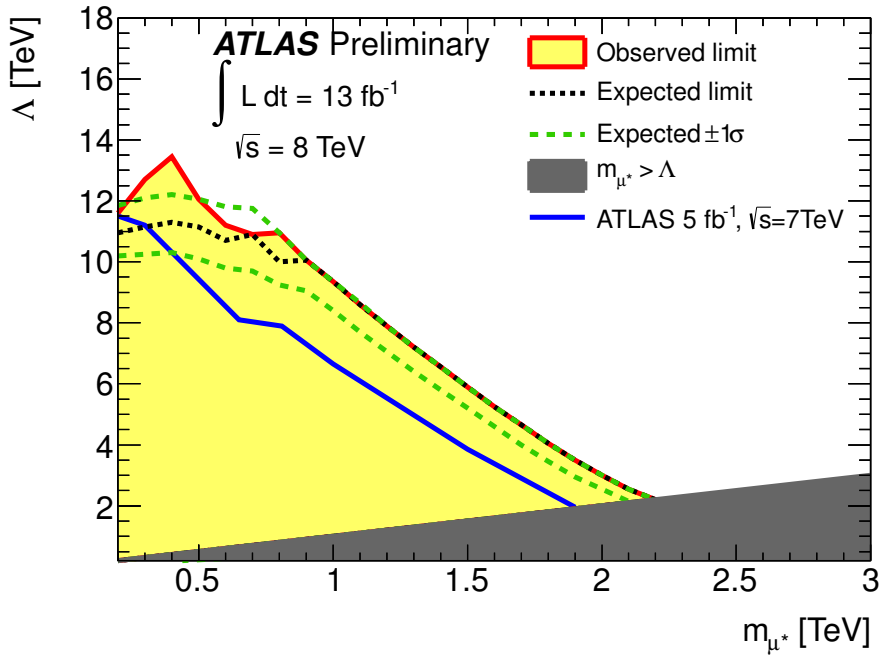
(b) μ^*

- Dominant background is $Z+\gamma$, with smaller contributions from Z+jets, diboson, and $t\bar{t}$.
- No significant excesses observed.
- $p_0 = 0.16$ for $m_{ll\gamma} > 1050$ GeV (e^*).

Excited e/μ: Results



(a) e^*



(b) μ^*

- Limits presented as function of excited lepton mass, m_{l^*}, and scale of compositeness, Λ.
- For $m_{l^*} = \Lambda$, $m_{l^*} < 2.2$ TeV excluded.
- Limit degrades significantly as Λ increases above m_{l^*}.

Trilepton Search: Introduction

Overview

- Exploit low backgrounds to search for non-SM excesses in many channels.
- Require events to have ≥ 3 leptons:

$$\begin{pmatrix} e \\ \mu \end{pmatrix} + \begin{pmatrix} e \\ \mu \end{pmatrix} + \begin{pmatrix} e \\ \mu \\ \text{Single-Prong } \tau \end{pmatrix}$$

- Absent significant excess, present 95% CL limits as functions of:

Variable	Definition
H_T^{leptons}	Sum of 3 lepton p_T
H_T^{jets}	Sum of jet p_T
$\not{E}_T$	Missing transverse energy
m_{eff}	$H_T^{\text{leptons}} + H_T^{\text{jets}} + \not{E}_T$

Trilepton Search: Signal Regions

- Define many signal regions:

On-Z	$\geq 3\, e/\mu$
On-Z	$2\, e\mu + \tau_{\text{had}}$
Off-Z	$\geq 3e/\mu$
Off-Z	$2\, e\mu + \tau_{\text{had}}$

(a) Categories

$\otimes$

Variable	Lower Bound (GeV)	Add'l Requirement
H_T^{leptons}	$0, 100, 150, 200, 300$	-
$\not{E}_T$	$0, 50, 75$	$H_T^{\text{jets}} < 100$ GeV
$\not{E}_T$	$0, 50, 75$	$H_T^{\text{jets}} \geq 100$ GeV
m_{eff}	$0, 150, 300, 500$	-
m_{eff}	$0, 150, 300, 500$	$\not{E}_T > 75$ GeV

(b) Signal Regions

- Estimate WZ/ZZ and Drell-Yan$+\gamma$/conversion backgrounds from MC.
- Estimate non-prompt/non-isolated/fake contribution (reducible) using data-driven technique.
- In 76 category/signal regions, set 95% CL limits on non-SM production, σ_{vis}^{95}.

Trilepton Search: Fake Factor Method

- "Reducible": non-prompt, non-isolated, or fake leptons. Primarily Z+jets.
- Characterize reducible leptons with fake factors: collect reducible leptons using a loosened selection, and measure fraction that pass full selection criteria.

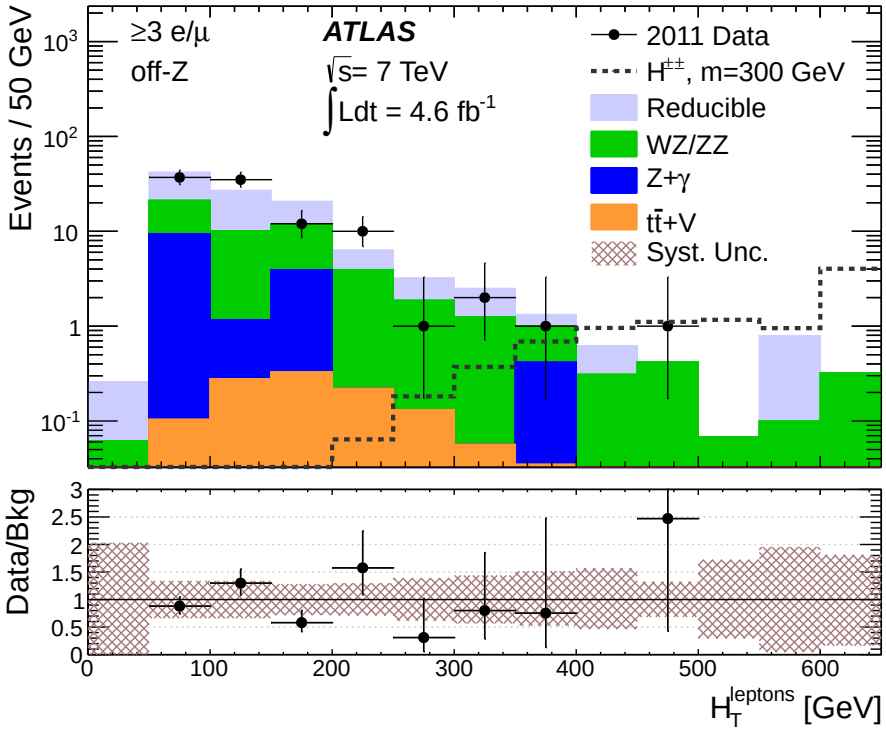
Fake Factor Definitions

Lepton	Fake Source	$f(p_T, \eta, ...)$
e	Light hadrons	$\frac{N(\text{Tight ID})}{N(\text{Medium ID \&\& fail tight ID})}$
$e,\ \mu$	$b/c-$hadron decay	$\frac{N(\text{Isolated})}{N(\text{Non-Isolated})}$
τ	Low track multiplicity jets	$\frac{N(\text{Tight ID})}{N(\text{Medium ID \&\& fail tight ID})}$

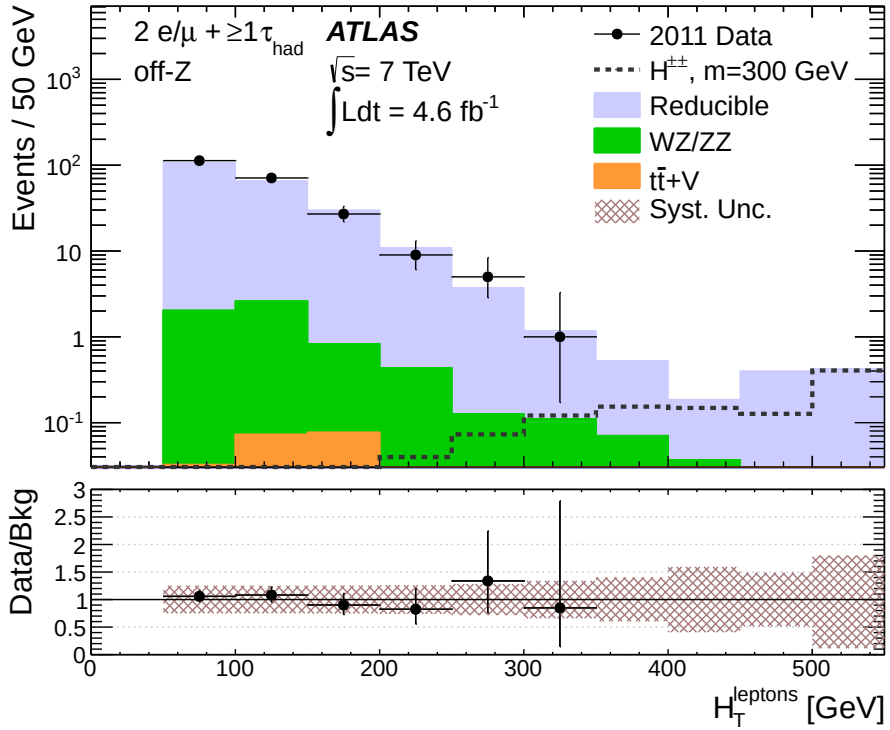
- Single-lepton background prediction:

$$N_N^{\text{signal}}(p_T, \eta, ...) = f^{\text{control}}(p_T, \eta) \times N_D^{\text{signal}}(p_T, \eta, ...)$$

Trilepton Search: Example Plots



(a) $\geq 3e\mu$



(b) $2e\mu + \tau_{\text{had}}$

Figure: H_T^{leptons} distribution for off-Z signal channel, with expected contribution from a 300 GeV $H^{\pm\pm}$.

Trilepton Search: Visible Cross Section Limits

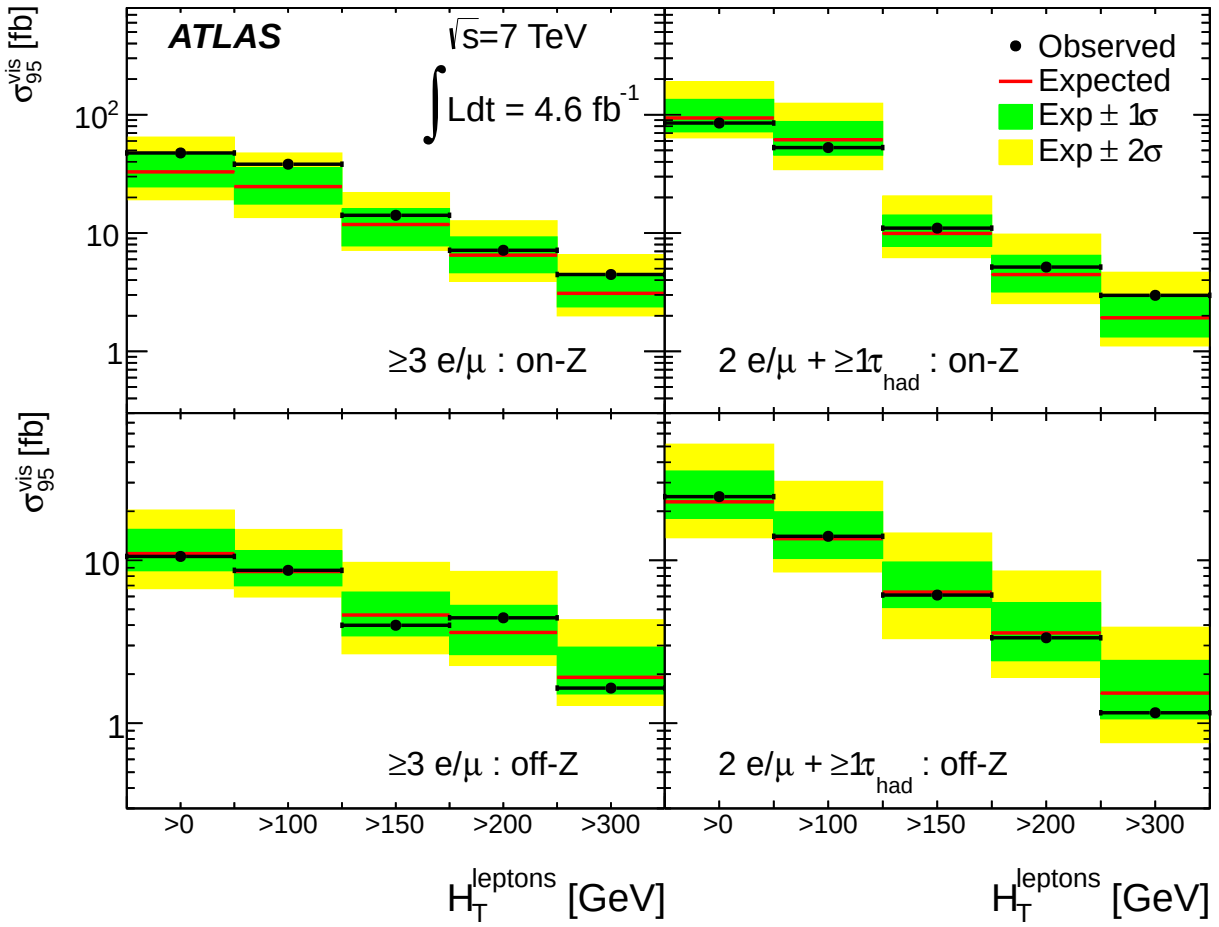
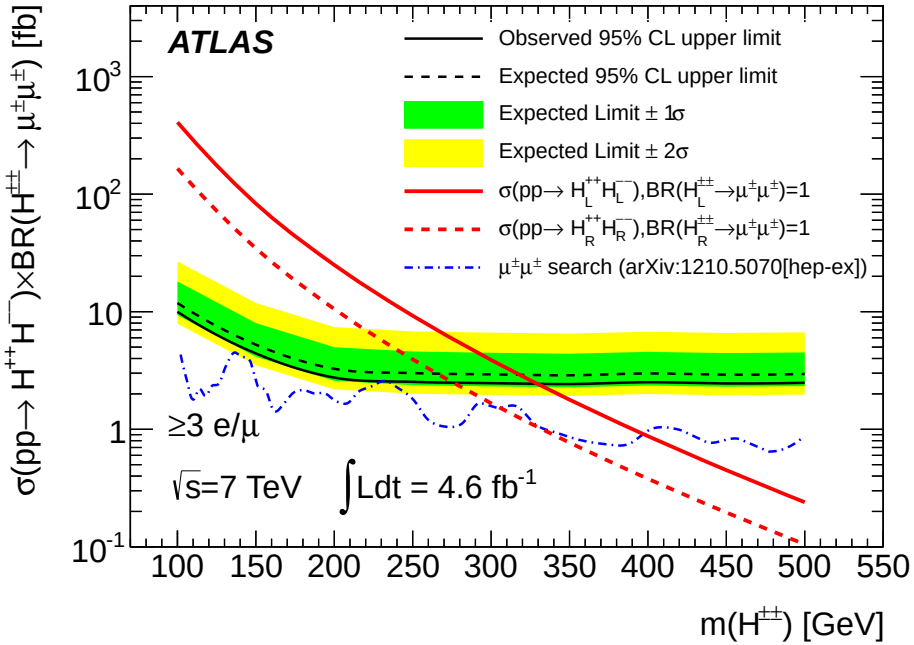


Figure: Observed and expected 95% confidence level upper limits, σ_{95}^{vis}, on non-SM trilepton event production, vs. H_T^{leptons}.

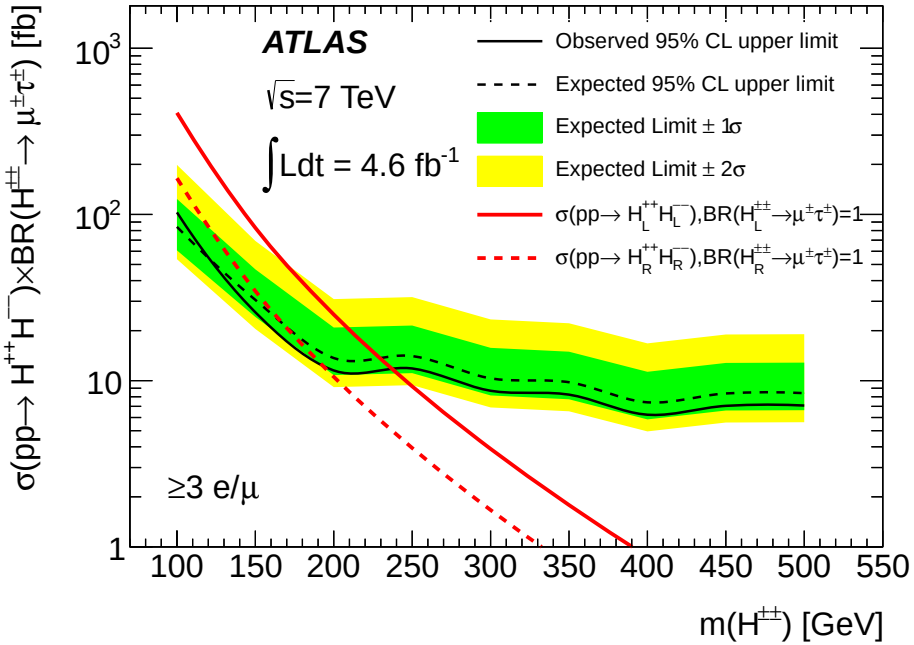
All limits + lepton efficiencies available at http://hepdata.cedar.ac.uk/view/ins1204447.

Trilepton Search: Limits

- With parametrized lepton efficiencies, $\sigma_{95}^{\text{vis}} \rightarrow \sigma_{95}^{\text{fid}}$ for a given model.



(a) $H^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$: comparison with same-sign dilepton analysis



(b) $H^{\pm\pm} \rightarrow \tau^{\pm}\mu^{\pm}$: new limits

Search	Expected limit	Observed limit
$H_L^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$ SS dilepton	401 GeV	398 GeV
$H_L^{\pm\pm} \rightarrow \mu^{\pm}\mu^{\pm}$ trilepton	319 GeV	330 GeV
$H_L^{\pm\pm} \rightarrow \tau^{\pm}\mu^{\pm}$ trilepton	229 GeV	237 GeV

Conclusion

- Presented three recent ATLAS analyses utilizing low background, multilepton final states.

  Model-driven searches can exploit final states to minimize backgrounds. Model-independent searches benefit from data-driven background techniques.

- Model-independent search results available for general model testing.
- No significant excesses observed.
- Many more analyses to follow using full 8 TeV dataset.

Search	Energy	Dataset	Limit
Heavy Fermions	8 TeV	5.8 fb^{-1}	350 GeV ($\Pi\mathscr{B} = 1$) 245 GeV ($\Pi\mathscr{B} = f(m_N)$)
Excited e^*/μ^*	8 TeV	13 fb^{-1}	2.2 TeV ($m_{l^*} = \Lambda$)
Model-Independent Trilepton	7 TeV	4.6 fb^{-1}	E.g. $m_{H_L^{\pm\pm}} < 330$ GeV
Model-Independent $l^{\pm}l^{\pm}$	7 TeV	4.7 fb^{-1}	E.g. $m_{H^{\pm\pm}{}_L} < 398$ GeV

References

- "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.
- "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 phenomena in events with three charged leptons at $\sqrt{s} = 7$ TeV with the ATLAS detector". arXiv:hep-ex/1211.6312.
- "Search for anomalous production of prompt like-sign lepton pairs at $\sqrt{s} = 7$ TeV with the ATLAS detector". arXiv:hep-ex/1210.4538.

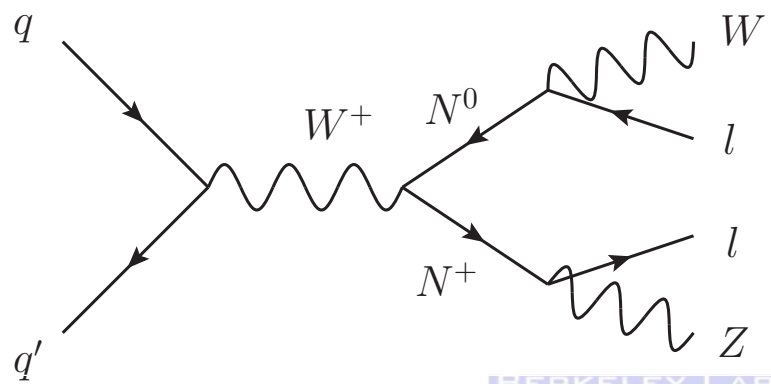
Type III Seesaw: Overview

- Generate neutrino masses with ≥ 2 fermionic triplets:

$$\Sigma = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 \end{pmatrix}$$

$$\mathscr{L} \ni \begin{cases} \mathrm{Tr}\left[\overline{\Sigma} i \not{D} \Sigma\right] & : \text{ Kinetic term + } W/Z \text{ interactions} \\ -\frac{1}{2}\mathrm{Tr}\left[\overline{\Sigma} M_\Sigma \Sigma^c + \overline{\Sigma^c} M_\Sigma^* \Sigma\right] & : \text{ Majorana mass} \\ -\tilde{\phi}^\dagger \overline{\Sigma} \sqrt{2} Y_\Sigma L & : \text{ Yukawa interactions} \end{cases}$$

- $m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$.
- Production via gauge couplings.
- Decay via SM lepton - heavy lepton mixing.



Type III Seesaw: Systematic Uncertainties

	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

Excited e/μ: Backgrounds

Background Procedure

- Primary backgrounds ($Z+\gamma$, Z+jets) taken from MC.
- Verified in signal-depleted control region: $70\ \text{GeV} < m_{ll} < 110\ \text{GeV}$.
- Z+jets normalization scaled using control region.
- Backgrounds fit with exponential, $\exp\left(p_0 + p_1 m_{ll\gamma}\right)$.

Channel	Z+jets Scale Factor
e^*	0.51 ± 0.09
μ^*	0.65 ± 0.09

Region [GeV]	$Z+\gamma$	Z+jets	Other	Total MC	Data
$m_{ee} < 110$	1254 ± 20	360 ± 70	18.9 ± 1.4	1633 ± 70	1633
$m_{ee} > 110$	208 ± 10	24 ± 8	19.7 ± 1.6	252 ± 13	263
$m_{\mu\mu} < 110$	1118 ± 20	416 ± 60	17.7 ± 1.2	1552 ± 60	1552
$m_{\mu\mu} > 110$	137 ± 8	15 ± 5	8.3 ± 1.3	160 ± 10	159

Excited e/μ: Systematic Uncertainties

Source	e^*		μ^*	
Extrapolation	NA	18%	NA	21%
Theory	NA	6%	NA	6%
Luminosity	3%	3%	3%	3%
Efficiency	4%	4%	4%	4%
Total	6%	20%	6%	23%

(c) $m_{l^*} = 200$ GeV

Source	e^*		μ^*	
Extrapolation	NA	230%	NA	200%
Theory	NA	8%	NA	8%
Luminosity	3%	3%	3%	3%
Efficiency	6%	4%	6%	5%
Total	7%	230%	7%	200%

(d) $m_{l^*} = 2$ TeV

Same-Sign Dilepton: Introduction

Overview

- Low-background, model-independent search using well-identified, prompt, isolated, and energetic leptons.
- Final state:

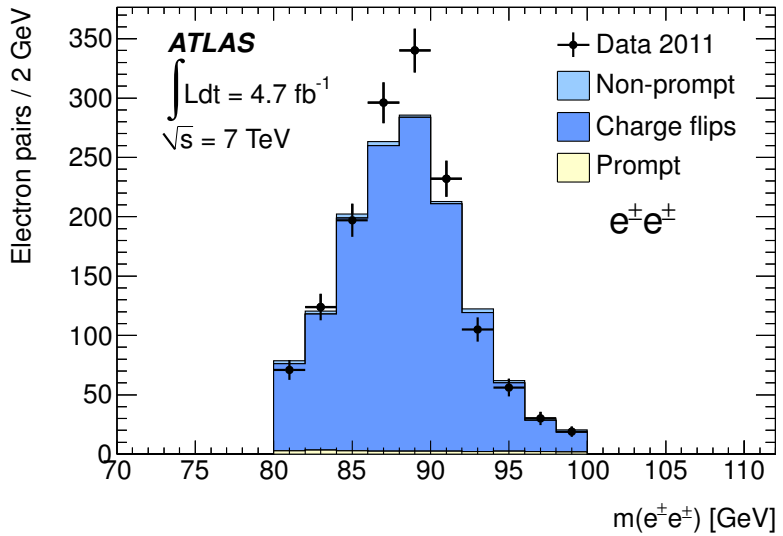
$$e^{\pm}e^{\pm} \oplus \mu^{\pm}\mu^{\pm} \oplus e^{\pm}\mu^{\pm}$$

- Scan m_{ll} for excesses beyond SM predictions.
- Primary backgrounds:

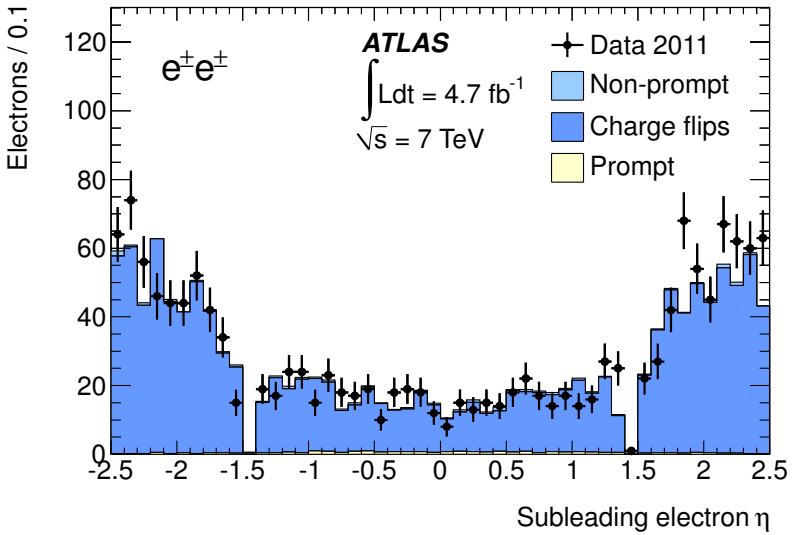
Source	Estimation
Prompt (diboson, $t\bar{t}+V$)	MC
Charge mis-ID (e)	Data-driven: $\frac{\pm\pm}{\pm\mp}$ with $\lvert m_{ll} - m_Z \rvert < 10$ GeV
Non-prompt/fake	Data-driven: fake factors

Same-Sign Dilepton: Charge Flip Control Region

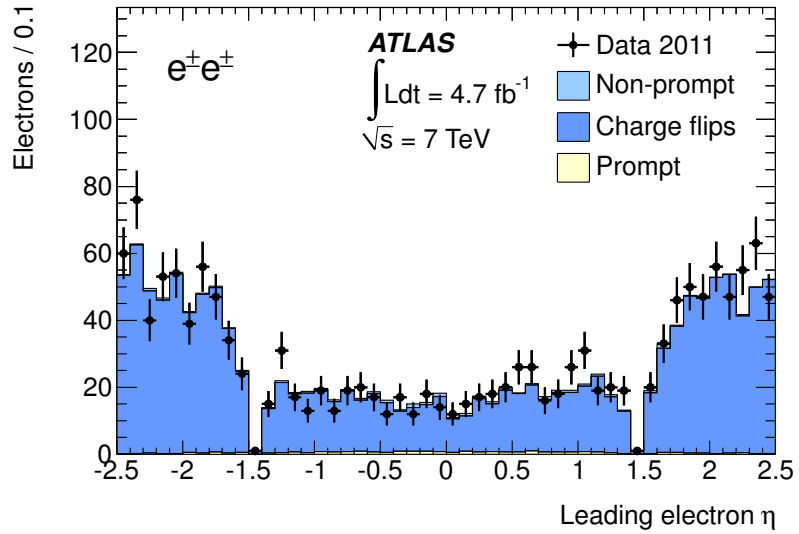
- Validation charge flip background in $l^{\pm}l^{\pm}$ region with $|m_{ll} - m_Z| < 10$ GeV.



(a) m_{ll}



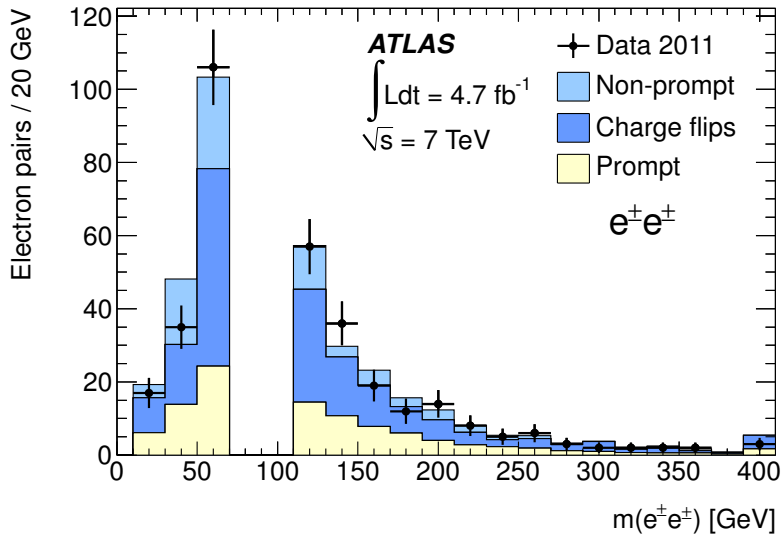
(b) Leading lepton p_T



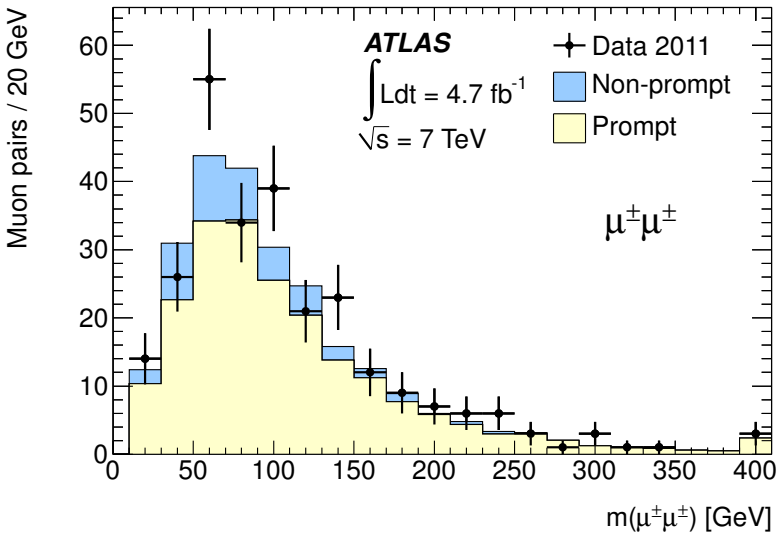
(c) Leading lepton η

Same-Sign Dilepton: m_{ll} Spectra

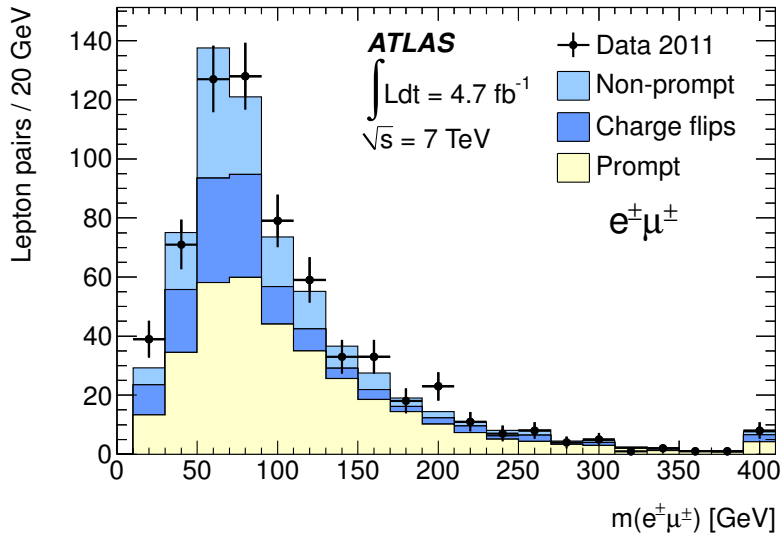
- Good agreement seen in all channels.



(a) ee



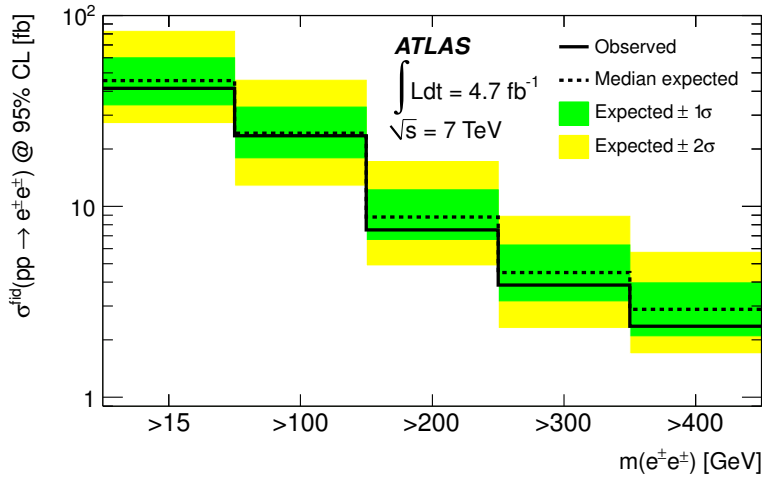
(b) $e\mu$



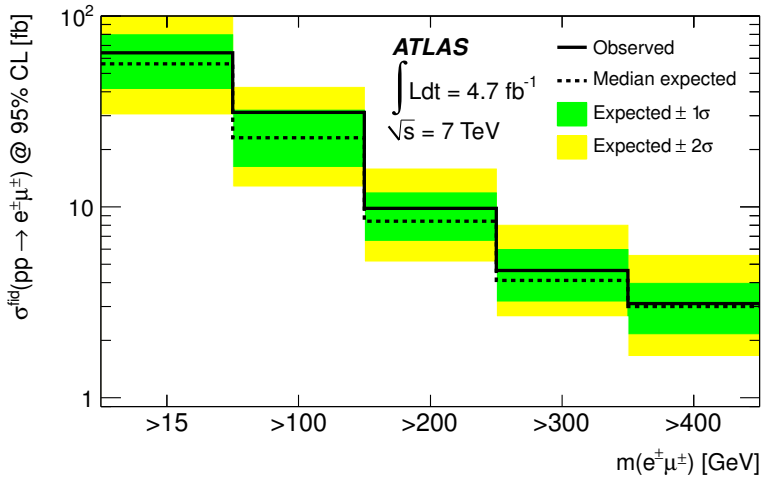
(c) $\mu\mu$

Same-Sign Dilepton: Fiducial Cross Sections

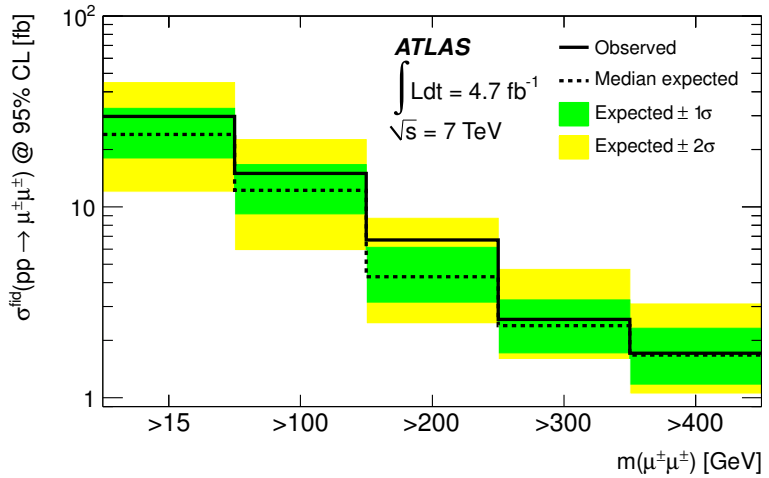
- With no excesses, set limits on fiducial cross sections for new physics.



(a) ee



(b) $e\mu$



(c) $\mu\mu$