Searching for New Physics with Multilepton Events at the LHC

Some recent results from ATLAS

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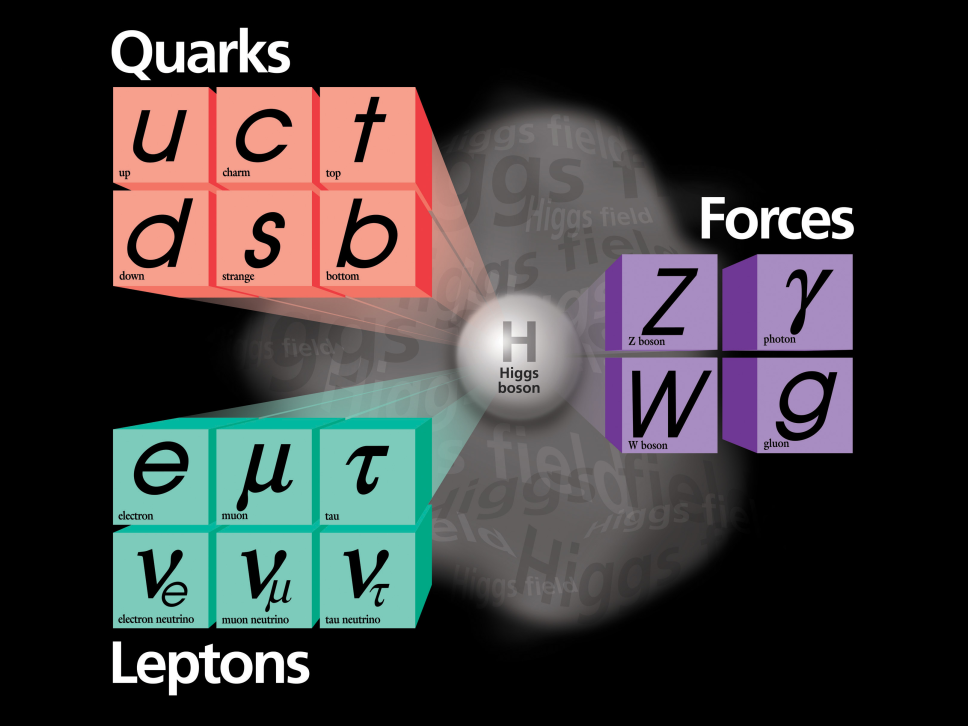
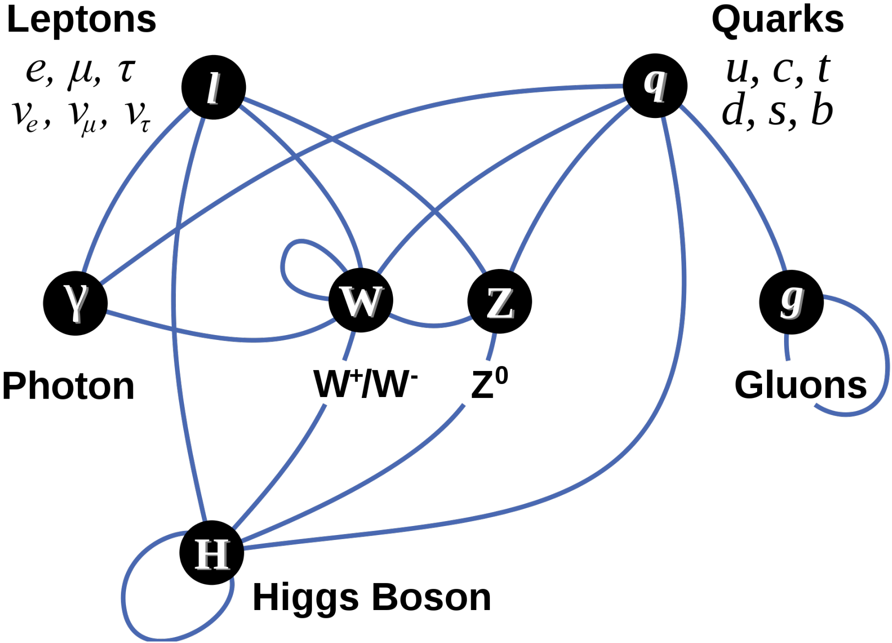
October 30, 2012

- Multileptons?
  - The Standard Model
  - ...and Beyond?
- A Generic Search for New Physics
  - Search strategy
  - The LHC and ATLAS
  - Backgrounds
  - Results
  - Interpretation
- Prospects and Conclusions

Multileptons?

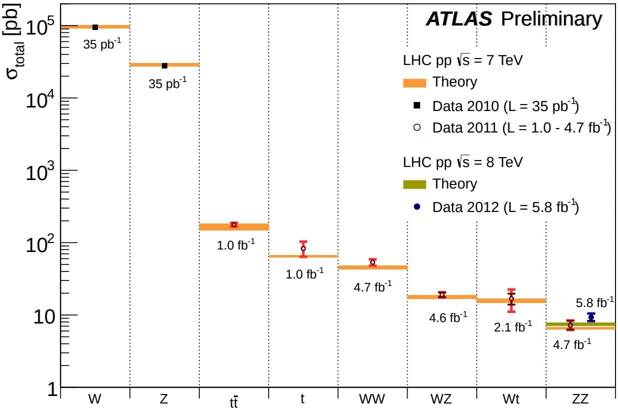


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Higgs field
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons


Leptons
e, μ, τ
ν_e, ν_μ, ν_τ
Quarks
u, c, t
d, s, b
l
q
γ
W
Z
g
Photon
W^+/W^-
Z^0
Gluons
H
Higgs Boson

The Standard Model

After the Tevatron, LEP, and run-1 of the LHC:
the Standard Model still going strong!



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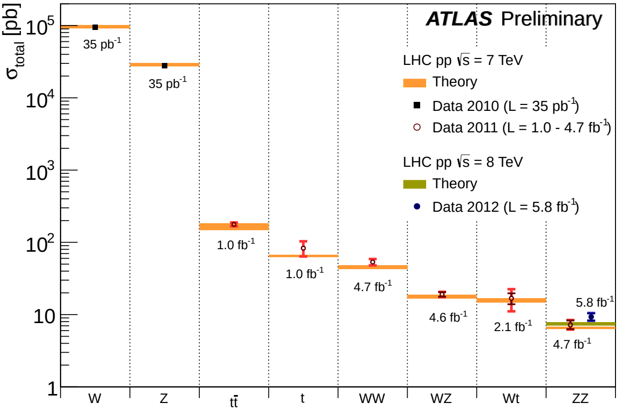
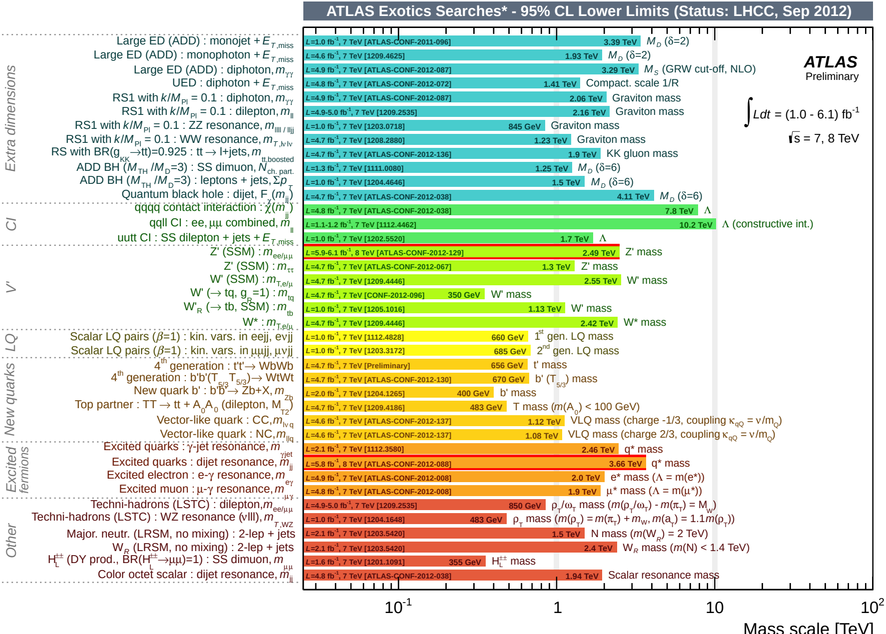
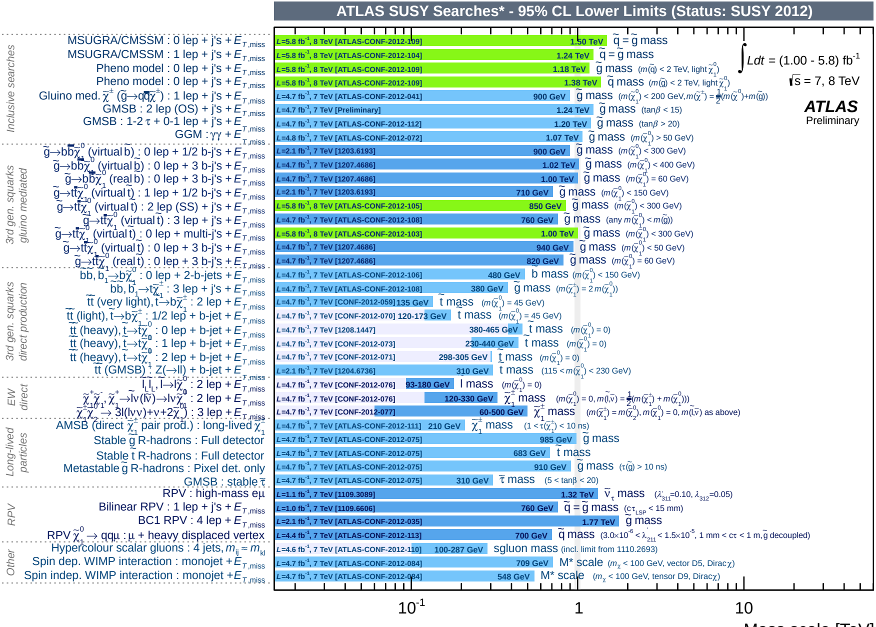


But what about: neutrino mass > 0? hierarchy problem? dark matter/energy?



*Only a selection of the available mass limits on new states or phenomena shown

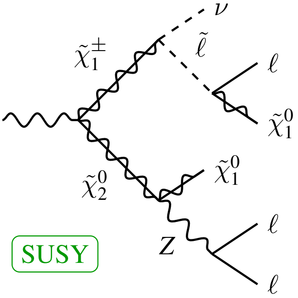


*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

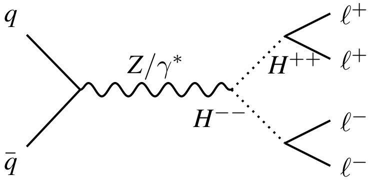
Prompt leptons are convenient probes of SM and BSM physics:

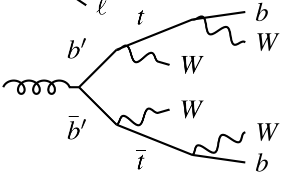
- Rare at hadron colliders
- Emerge (almost) unperturbed from the hard scatter
- "Easy" to trigger, reconstruct, identify

Events with 3+ leptons present in many new physics scenarios:

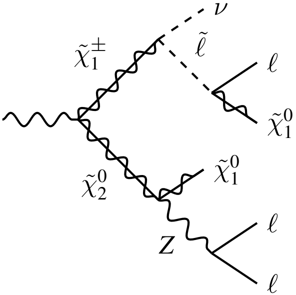


doubly-charged Higgs

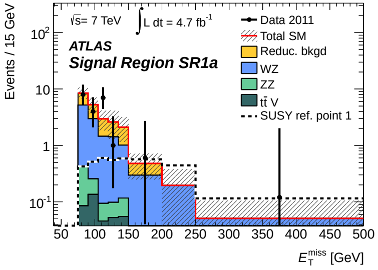


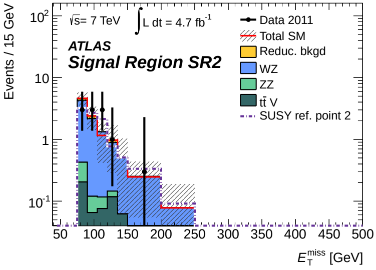


fourth-generation quark

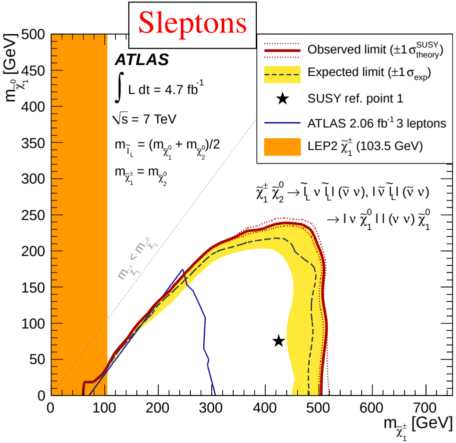


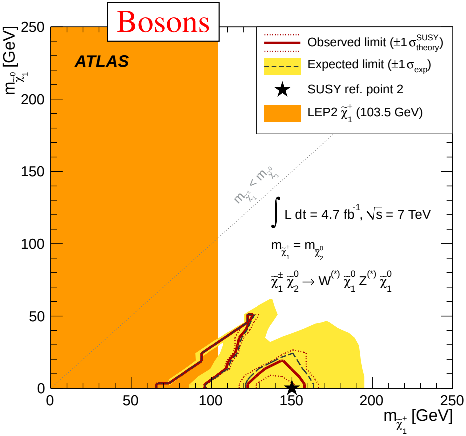
- Direct gaugino ($\tilde{\chi}_1^{\pm}$,$\tilde{\chi}_2^0$) search
- Require 3 leptons, $E_T^{miss} > 75$ GeV
- Signal regions target different decays:
  - via sleptons: Z veto, b veto
  - via bosons: Z requirement, $m_T > 90$





SUSY Direct Gaugino Search





A Generic Search for New Physics

Search Strategy

Our goals:

- Assume as little as possible about nature of new physics (NP)
  - Include all (known) lepton flavors: e, μ, and τ
- Keep sensitivity by separating data into **channels**
  - Separate events with/without a Z
  - Separate events with 3+ e/μ from those with 2 e/μ and $\geq 1\tau$
- Probe different (hopefully interesting) kinematic **signal regions**
  - $H_{\mathrm{T}}^{\mathrm{leptons}}$: sum of lepton p_{T}
  - $E_{\mathrm{T}}^{\mathrm{miss}}$: Missing transverse energy
  - $H_{\mathrm{T}}^{\mathrm{jets}}$: sum of jet p_{T}
  - m_{eff}: transverse activity
  - Counting experiment in each region

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Variable	Lower Bounds [GeV]	Additional Requirement
$H_{\mathrm{T}}^{\mathrm{leptons}}$	0, 100, 150, 200, 300	
$E_{\mathrm{T}}^{\mathrm{miss}}$	0, 50, 75	$H_{\mathrm{T}}^{\mathrm{jets}} < 100$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}}$	0, 50, 75	$H_{\mathrm{T}}^{\mathrm{jets}} \geq 100$ GeV
m_{eff}	0, 150, 300, 500	
m_{eff}	0, 150, 300, 500	$E_{\mathrm{T}}^{\mathrm{miss}} \geq 75$ GeV

How Inclusive Can We Be?

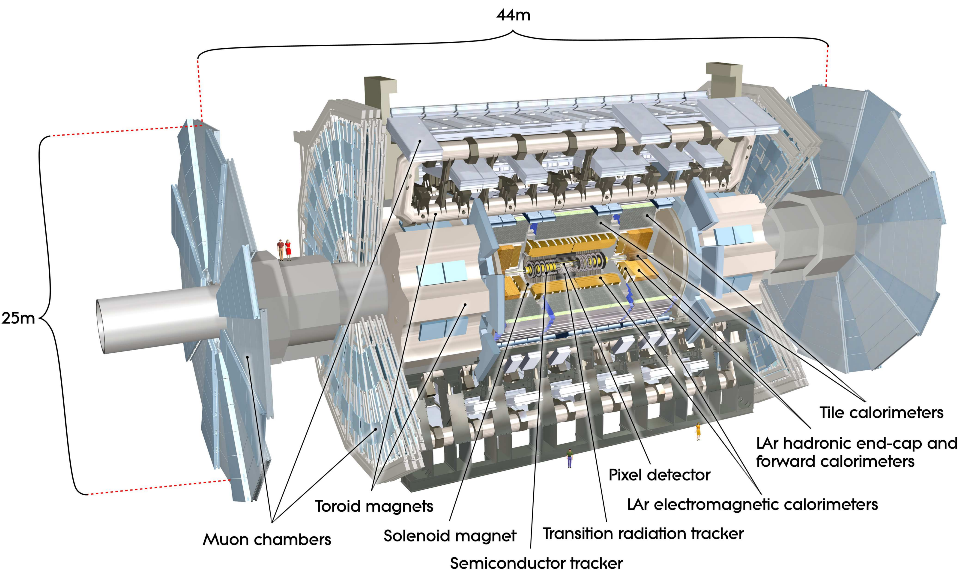
Model-independent analysis, but need to make *some* assumptions!

- Require **energetic**, **prompt**, and **isolated** leptons:
  - **Energetic**
    - $p_{\mathrm{T}} > 10$ for e/μ,
    - $p_{\mathrm{T}} > 15$ for τ
  - **Prompt**: leptons emerge from hard scatter
  - **Isolated**: leptons have no nearby hadronic activity

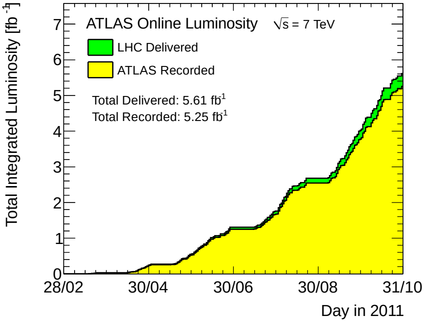
This means our **primary backgrounds** will be:

- SM WZ and ZZ production
- Rarer processes like $t\bar{t} + W/Z$
- $Z + \gamma$ where $\gamma \rightarrow e$
- "Fake" leptons from Z+jets and W+jets

A Toroidal LHC ApparatuS

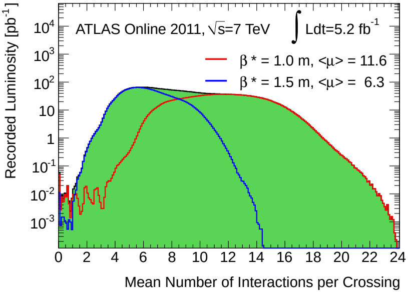


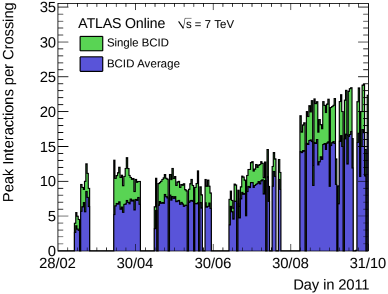
$\sqrt{s} = 7$ TeV data in 2011

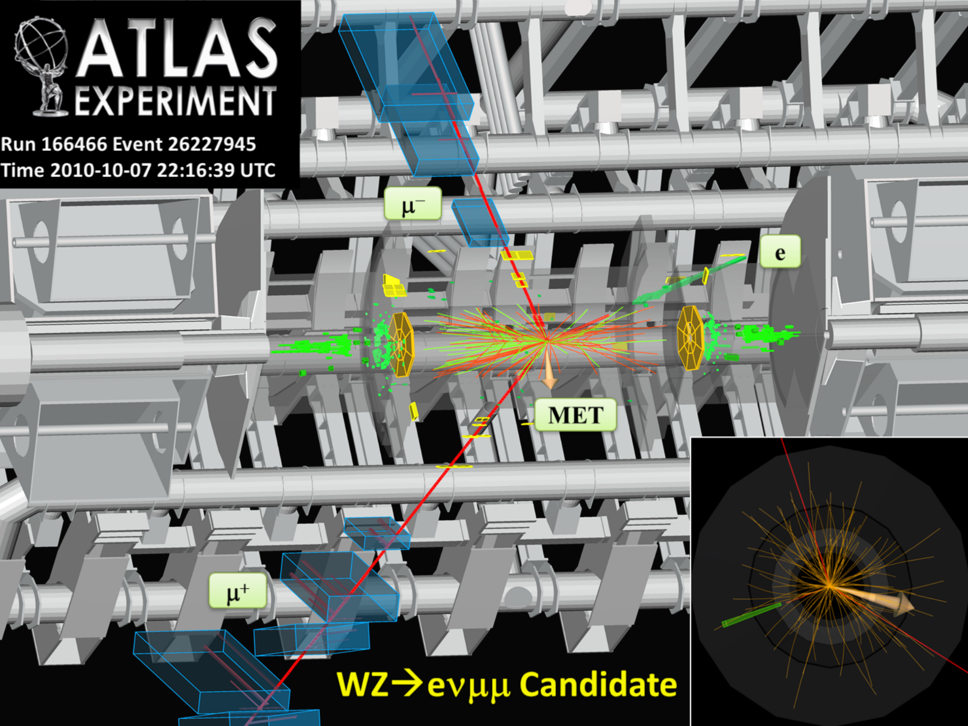


Impressive performance by the LHC:

- $\left(\int_{2011} \mathcal{L}dt\right) > 100 \times \left(\int_{2010} \mathcal{L}dt\right)$
- Exciting opportunity!
- Pileup still relatively low
  - Signs of things to come in September

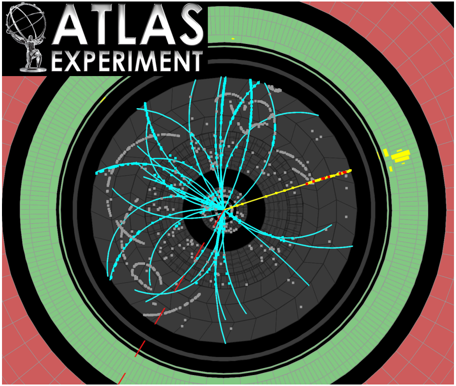


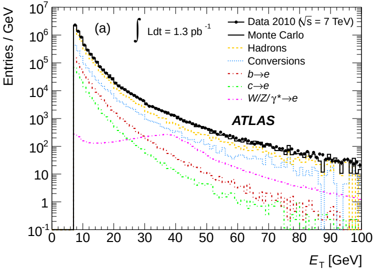



ATLAS
EXPERIMENT
Run 166466 Event 26227945
Time 2010-10-07 22:16:39 UTC
μ⁻
e
MET
μ⁺
WZ→eνμμ Candidate

Electrons made from clusters and tracks:

- Contributions from:
  - Prompt electrons (W/Z)
  - Light flavor jets
  - Semileptonic heavy flavor
  - Photon conversions
- Background rejection, triggering a challenge!





Cut-based identification:

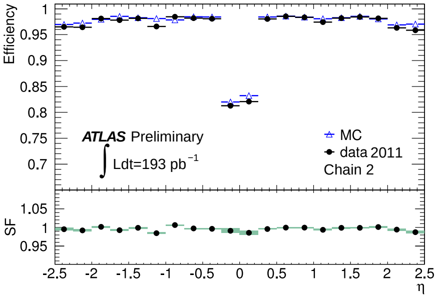
- ID hits on track
  - TRT for $e/\pi^{\pm}$ discrimination
- Calo shower shapes

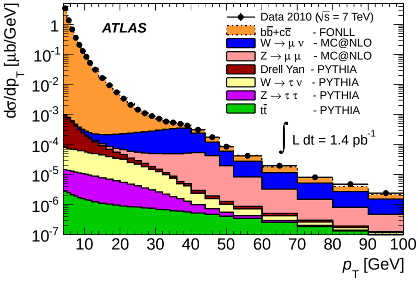
"Tight" working point has 80% efficiency.

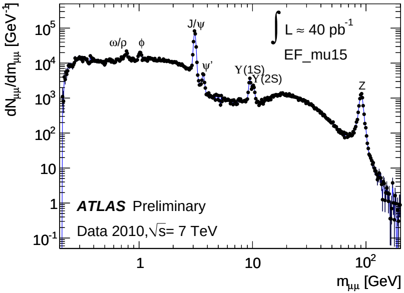
Muons

Muons have ID and muon spectrometer hits

- High efficiency to $|\eta| < 2.5$
- $\approx$all candidates are real muons
  - Prompt muons (W/Z)
  - decays in flight
  - semileptonic heavy flavor

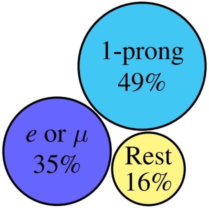


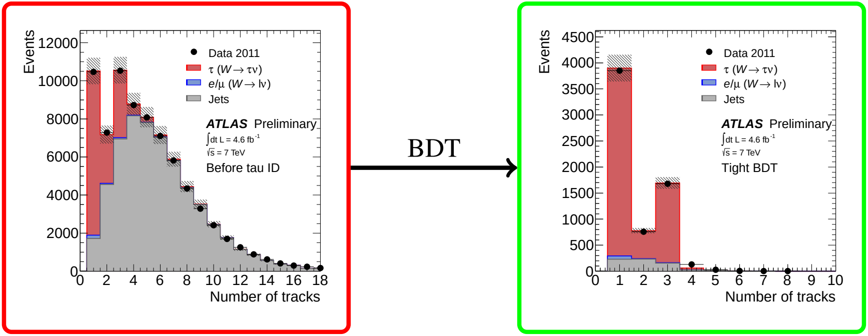




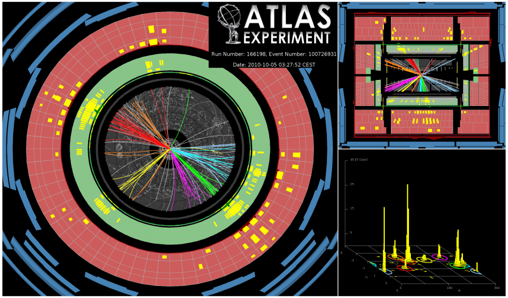
Hadronic Taus

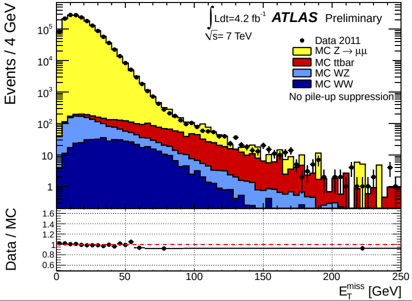
- Taus decay leptonically and hadronically
  - Hadronic: 1-prong and 3-prong
- Difficult to distinguish from jets
  - Shower-shapes, track properties, etc.
- Boosted Decision Tree (BDT) used
  - "Tight" working point, 30% effic. for 300x rejection





- Anti-k_t, $R = 0.4$
- $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 4.9$
- Jet Vertex Fraction
  - Jets in ID acceptance have tracks from PV
- b-tags with MV1 algorithm
  - NN discriminant with several taggers as input





- Corrections to $E_{\mathrm{T}}^{\mathrm{miss}}$ from leptons, jets, soft terms
- Pileup suppression not used
  - Used more heavily in 2012

Backgrounds

3 classes of backgrounds:

- **Irreducible**: SM processes producing three prompt leptons
  - WZ/ZZ production
  - $t\bar{t}+W$ and $t\bar{t}+Z$
  - WWW, $H \to ZZ \to 4\ell$ - negligible for this search
- **Isolated, Non-prompt**:
  - $Z+\gamma$, where $\gamma \to ee$
- **Non-isolated and/or non-prompt**:
  - Jets faking leptons
  - Dalitz decays
  - Semileptonic heavy-flavor decays

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  - $t\bar{t} + W$ and $t\bar{t} + Z$
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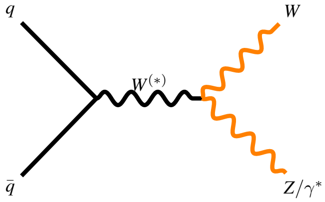
- **Isolated, Non-prompt**:
  - $Z + \gamma$, where $\gamma \to ee$

MC

- **Non-isolated and/or non-prompt**:
  - Jets faking leptons
  - Dalitz decays
  - Semileptonic heavy-flavor decays

Data

Irreducible Backgrounds

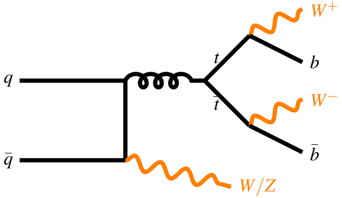


Dominant: WZ/ZZ

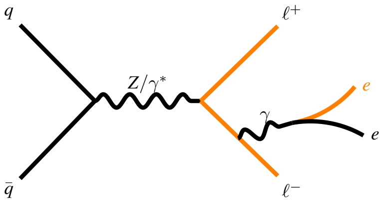
- Using SHERPA for VV+3 jets
- Includes γ^* contributions

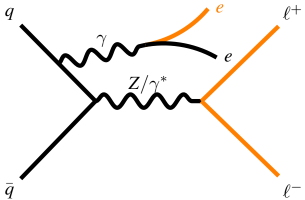
Rarer processes:

- $t\bar{t} + V$ (MADGRAPH)
- WWW, $H \to ZZ$ (negligible)

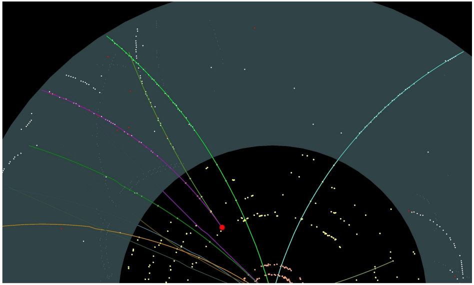


$Z + \gamma$





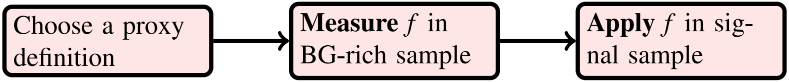
- Suppressed by tracking requirements on electrons
- Modeled with PYTHIA



"Fake factor" method:

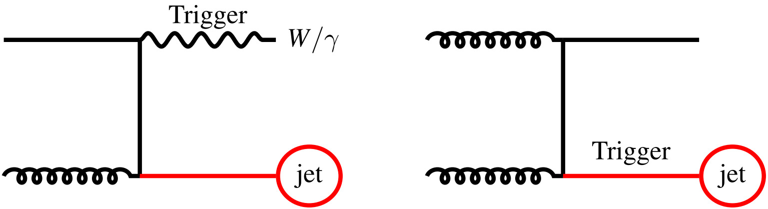
- Weight signal-like events that fail cuts to estimate background
  - Leptons that fail cuts are "proxies" for ID'd leptons
- Weights (Fake factors, f) determined from data, small corrections with MC
- Reweighted events provide full kinematic distributions
  - More than "just" estimating $N_{\text{background}}$

$$f = \frac{\text{fully identified leptons}}{\text{proxy leptons}}$$



Reducible Backgrounds (2)

Background Dominated: Proxies



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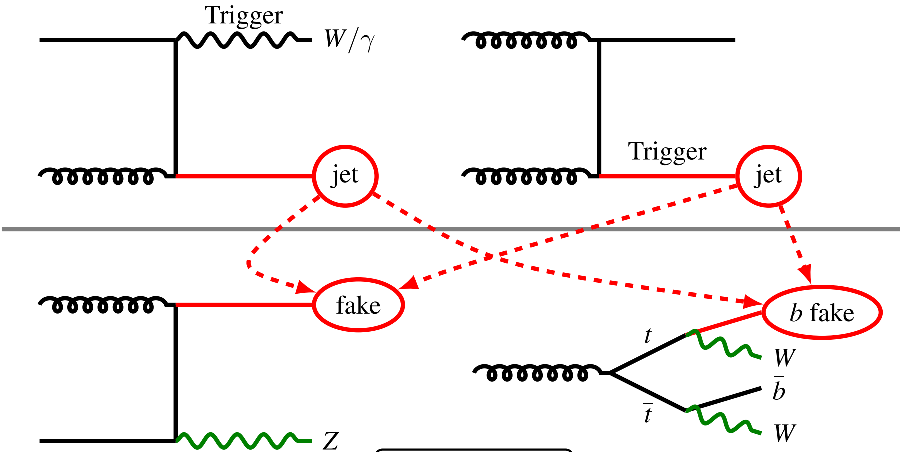
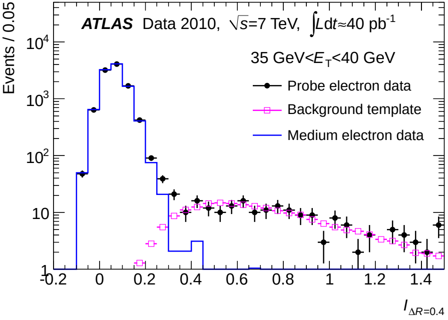


Signal-Like

Reducible Backgrounds (3)

	e	μ	τ
Proxy	Anti-ID **or** Anti-Iso	Anti-Iso	Anti-ID
$p_T < 25$ GeV	W+jet		γ+jet
$p_T \geq 25$ GeV	$b\bar{b}$, multijet		



Bin f to remove bias:

- p_T
- $|\eta|$
- MV1 (HF content)

$$f(\ell) = \frac{f(p_T)f(\eta)f(\text{MV1})}{\langle f \rangle^2}$$

$\langle f(e) \rangle = 0.15$, $\langle f(\mu) \rangle = 0.2$, $\langle f(\tau) \rangle = 0.05$

Lepton Selection:

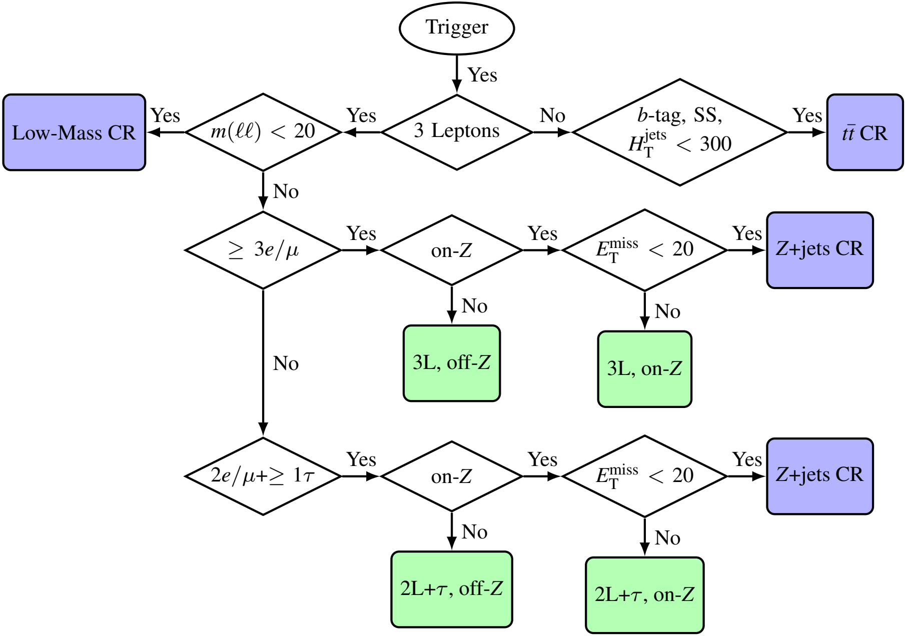
Cut	Electrons	Muons	Taus
Leading/Trigger E_T	$E_T \geq 25$ GeV	$p_T \geq 25$ GeV	-
Trigger Acceptance	$(\|\eta\| < 1.37) \|\| (1.52 \leq \|\eta\| < 2.47)$	$\|\eta\| < 2.4$	-
Subleading E_T	$E_T \geq 10$ GeV	$p_T \geq 10$ GeV	$E_T \geq 15$ GeV
$\|\eta\|$ Acceptance	$(\|\eta\| < 1.37) \|\| (1.52 \leq \|\eta\| < 2.47)$	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
ID class	Tight++	Tight	1p, BDT−Tight
Calorimeter Isolation	$\frac{\texttt{Etcone30}}{E_T} < 0.14$	$\frac{\texttt{Etcone30}}{p_T} < 0.14$	-
Track Isolation	$\frac{\texttt{ptcone30}}{E_T} < 0.13$	$\frac{\texttt{ptcone30}}{p_T} < 0.15$	-
$\|z_0 \sin(\theta)\|$	< 1mm	< 1mm	-
$\|\frac{d_0}{\sigma(d_0)}\|$	< 10	< 3	-

- Require at least 2 e/μ, at least one triggerable
  - Third can be e, μ, or τ
- "On-Z": $|m(\ell^+\ell^-) - m(Z)| < 20$ or $|m(\ell^+\ell^-\ell') - m(Z)| < 20$

Our plan:

- Estimate backgrounds, keeping data blind
- Check agreement in **control regions**
- Look at **signal regions**

Event Selection and Classification

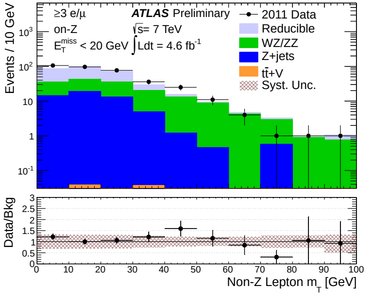


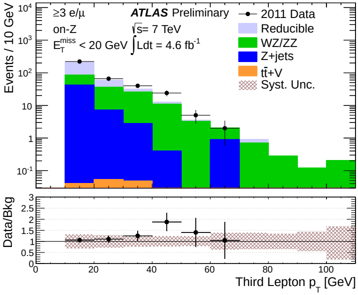
Z+jets Control Region

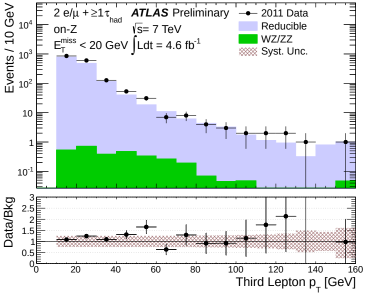
Low-$E_{\mathrm{T}}^{\mathrm{miss}}$ trilepton CR:

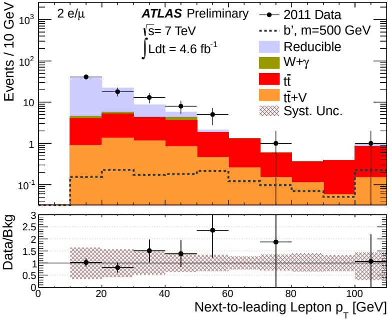
- 3 leptons, all fully-identified
- $|m(\ell^+\ell^-) - m(Z)| < 10$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} < 20$ GeV

Channel	Irreducible	Reducible	Total	Observed
$\geq 3e/\mu$	165 ± 26	160 ± 50	320 ± 60	359
$2e/\mu + \geq 1\tau$	3.0 ± 0.6	1480 ± 360	1480 ± 360	1696





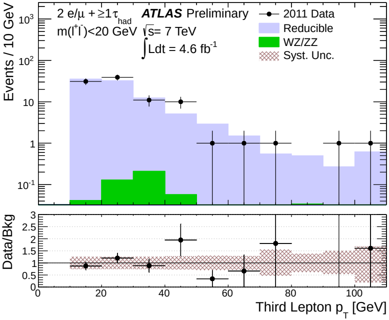




$t\bar{t}$ Control Region

- 2 leptons (same-sign)
- ≥ 1 b-tag
- $H_T^{\text{jets}} < 300$

Channel	Irreducible	Reducible	Total	Observed
$2e/\mu$	25 ± 4	58 ± 23	83 ± 23	87
$1e/\mu + 1\tau$	1.9 ± 0.4	107 ± 27	109 ± 27	103



Low-mass Drell–Yan CR:

- 3 leptons
- OSSF pair, $m(\ell^+\ell^-) < 20$ GeV
- Probes contributions from low-mass resonances, "onia", and $W\gamma^*$

Channel	Irreducible	Reducible	Total	Observed
$2e/\mu$	25 ± 4	58 ± 23	83 ± 23	87
$1e/\mu + 1\tau$	1.9 ± 0.4	107 ± 27	109 ± 27	103

Systematics

Source of uncertainty	Uncertainty	
Trigger efficiency	(≤ 1) –	1%
Electron energy scale	(≤ 1) –	13%
Electron energy resolution	(≤ 1) –	1%
Electron identification	(≤ 1) –	3%
Electron non-prompt/fake backgrounds	(≤ 1) –	13%
Muon momentum scale	(≤ 1) –	1%
Muon momentum resolution	(≤ 1) –	7%
Muon identification	(≤ 1) –	1%
Muon non-prompt/fake backgrounds	(≤ 1) –	**51%**
Tau energy scale	(≤ 1) –	4%
Tau identification	(≤ 1) –	4%
Tau non-prompt/fake backgrounds	(≤ 1) –	**24%**
Jet energy scale	(≤ 1) –	6%
Jet energy resolution	(≤ 1) –	3%
Soft $E_{\mathrm{T}}^{\mathrm{miss}}$ terms	(≤ 1) –	14%
Luminosity		3.9%
Cross-section uncertainties	(≤ 1) –	**14%**
Statistical uncertainties	1 –	**25%**
Total uncertainty	11 –	**56%**

Results!

Reminder: Search Strategy

Our goals:

- Assume as little as possible about nature of new physics (NP)
  - Include all (known) lepton flavors: e, μ, and τ
- Keep sensitivity by separating data into **channels**
  - Separate events with/without a Z
  - Separate events with 3+ e/μ from those with 2 e/μ and $\geq 1\tau$
- Probe different (hopefully interesting) kinematic **signal regions**
  - H_T^{leptons}: sum of lepton p_T
  - E_T^{miss}: Missing transverse energy
  - H_T^{jets}: sum of jet p_T
  - m_{eff}: transverse activity
  - Counting experiment in each region

Variable	Lower Bounds [GeV]	Additional Requirement
H_T^{leptons}	0, 100, 150, 200, 300	
E_T^{miss}	0, 50, 75	$H_T^{\text{jets}} < 100$ GeV
E_T^{miss}	0, 50, 75	$H_T^{\text{jets}} \geq 100$ GeV
m_{eff}	0, 150, 300, 500	
m_{eff}	0, 150, 300, 500	$E_T^{\text{miss}} \geq 75$ GeV

Results

Most inclusive signal regions:

Flavor Chan.	Z Chan.	Expected			Observed
$\geq 3e/\mu$	off-Z	**107** $\pm$	7 $\pm$	24	**99**
$\geq 3e/\mu$	on-Z	**510** $\pm$	10 $\pm$	70	**588**
$2e/\mu+\geq 1\tau$	off-Z	**220** $\pm$	5 $\pm$	50	**226**
$2e/\mu+\geq 1\tau$	on-Z	**1060** $\pm$	10 $\pm$	260	**914**

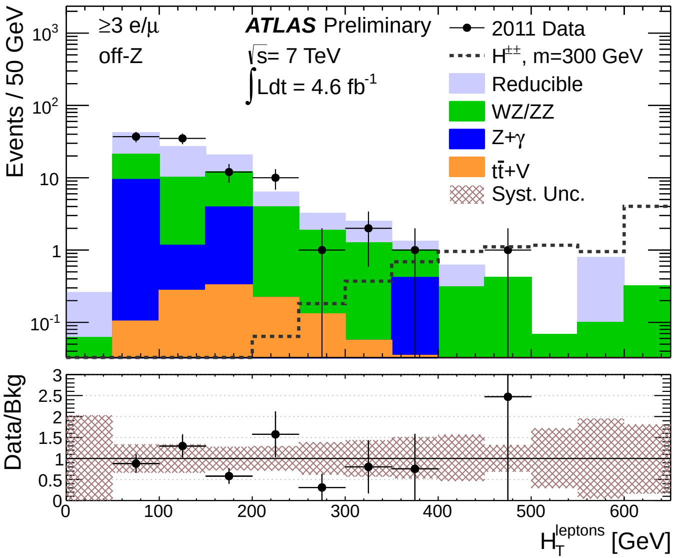
Generally good agreement with expectations:

- Not a surprise: most inclusive regions are almost always not the most sensitive to NP

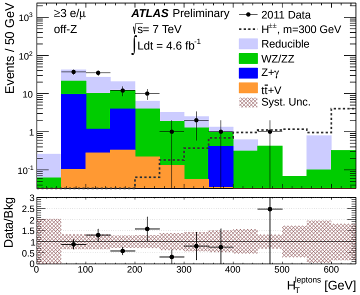
$m_{\text{eff}} > 500$ GeV:

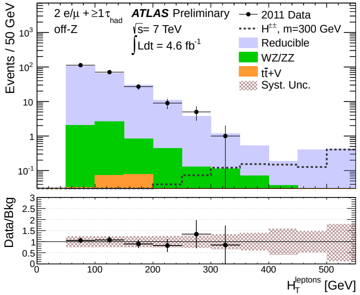
Flavor Chan.	Z Chan.	Expected			Observed
$\geq 3e/\mu$	off-Z	**6.5** $\pm$	1.2 $\pm$	2.5	**5**
$\geq 3e/\mu$	on-Z	**25** $\pm$	2 $\pm$	3	**29**
$2e/\mu+\geq 1\tau$	off-Z	**7.0** $\pm$	0.7 $\pm$	1.6	**6**
$2e/\mu+\geq 1\tau$	on-Z	**8.7** $\pm$	0.8 $\pm$	2.0	**5**

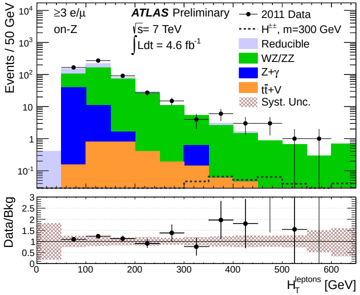
H_T^{leptons} - Off-Z

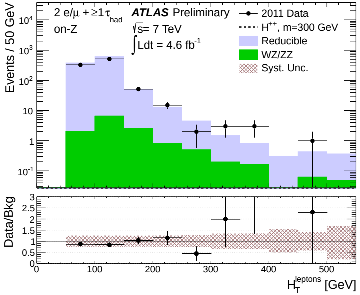


H_T^{leptons} - All Channels



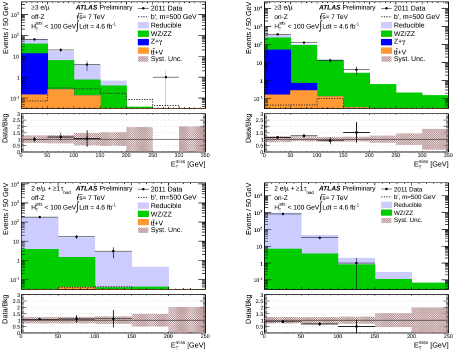




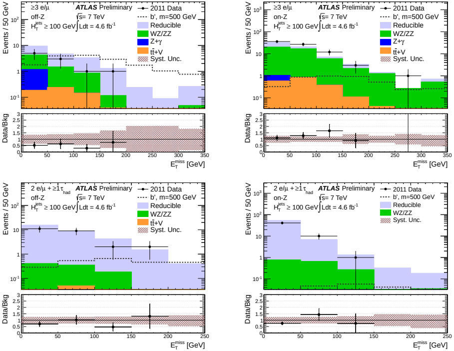


More Results

E_T^{miss}, $H_T < 100$ GeV

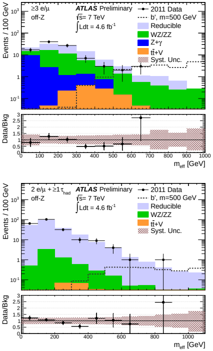


E_T^{miss}, $H_T \geq 100$ GeV

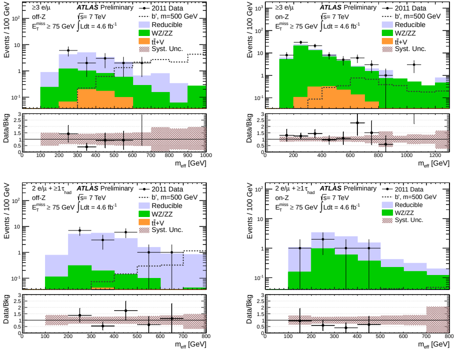


More Results

m_{eff}



$m_{\text{eff}}, E_{\text{T}}^{\text{miss}} > 75$ GeV



Limits

We see qualitatively that there's no new physics - let's quantify it.

- Extract 95% CL upper limits on events from NP (N_{95})
    - CL_s method
- Set limits on "visible cross section"

$$\sigma_{95}^{\mathrm{vis}} = \frac{N_{95}}{\int \mathcal{L} \mathrm{d}t}$$

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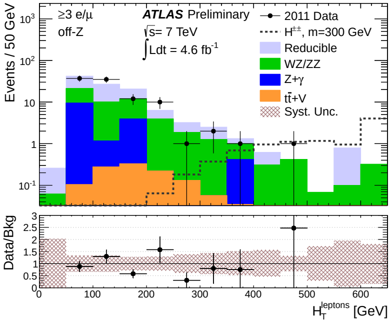
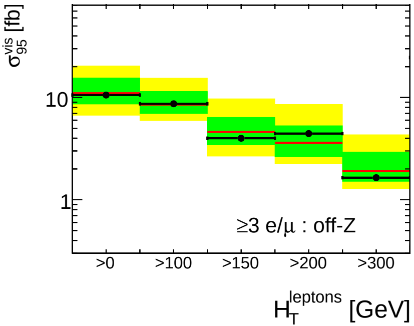
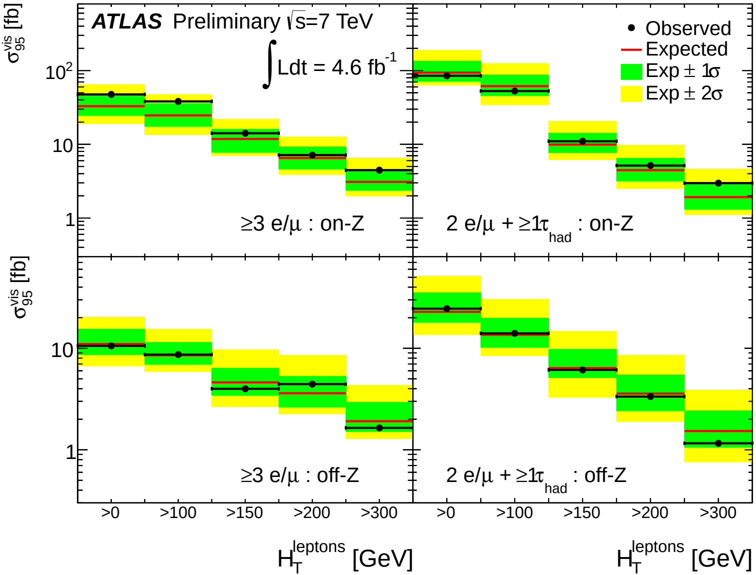
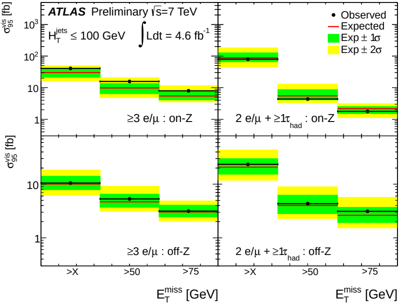


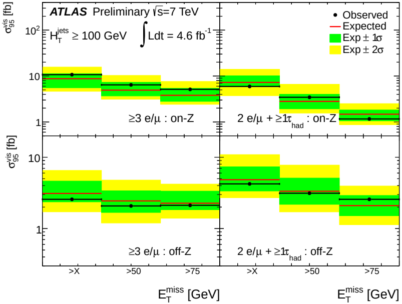


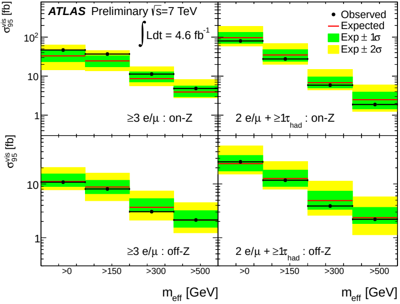


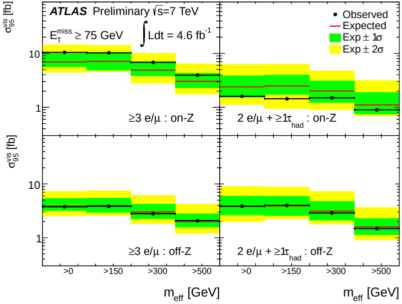
ATLAS Preliminary √s=7 TeV
∫Ldt = 4.6 fb⁻¹
Observed
Expected
Exp ± 1σ
Exp ± 2σ
σ95vis [fb]
10²
10
1
≥3 e/μ : on-Z
2 e/μ + ≥1τhad : on-Z
≥3 e/μ : off-Z
2 e/μ + ≥1τhad : off-Z
>0
>100
>150
>200
>300
HTleptons [GeV]

More Limits


ATLAS Preliminary √s=7 TeV
$H_T^{jets} \leq 100$ GeV
$\int Ldt = 4.6\ fb^{-1}$
Observed
Expected
Exp ± 1σ
Exp ± 2σ
≥3 e/μ : on-Z
2 e/μ + ≥1τ_had : on-Z
≥3 e/μ : off-Z
2 e/μ + ≥1τ_had : off-Z
σ_{95}^{vis} [fb]
>X
>50
>75
E_T^{miss} [GeV]


ATLAS Preliminary √s=7 TeV
$H_T^{jets} \geq 100$ GeV
$\int Ldt = 4.6\ fb^{-1}$
Observed
Expected
Exp ± 1σ
Exp ± 2σ
≥3 e/μ : on-Z
2 e/μ + ≥1τ_had : on-Z
≥3 e/μ : off-Z
2 e/μ + ≥1τ_had : off-Z
σ_{95}^{vis} [fb]
>X
>50
>75
E_T^{miss} [GeV]


ATLAS Preliminary √s=7 TeV
$\int Ldt = 4.6\ fb^{-1}$
Observed
Expected
Exp ± 1σ
Exp ± 2σ
≥3 e/μ : on-Z
2 e/μ + ≥1τ_had : on-Z
≥3 e/μ : off-Z
2 e/μ + ≥1τ_had : off-Z
σ_{95}^{vis} [fb]
>0
>150
>300
>500
m_{eff} [GeV]


ATLAS Preliminary √s=7 TeV
$E_T^{miss} \geq 75$ GeV
$\int Ldt = 4.6\ fb^{-1}$
Observed
Expected
Exp ± 1σ
Exp ± 2σ
≥3 e/μ : on-Z
2 e/μ + ≥1τ_had : on-Z
≥3 e/μ : off-Z
2 e/μ + ≥1τ_had : off-Z
σ_{95}^{vis} [fb]
>0
>150
>300
>500
m_{eff} [GeV]

So, what now?

How can someone use these results?

$$\frac{N_{95}}{\int \mathcal{L}\mathrm{d}t} = \sigma_{95}^{\mathrm{fid}} \geq \sigma_{\mathrm{NP}}^{\mathrm{total}} \times \mathcal{A} \times \epsilon$$

- $\sigma_{\mathrm{NP}}^{\mathrm{total}}$: Total cross section of New Physics process
- $\mathcal{A}$: Acceptance – fraction of events we *can* see
- ϵ: Efficiency – of events we *can* see, fraction of events we *should* see

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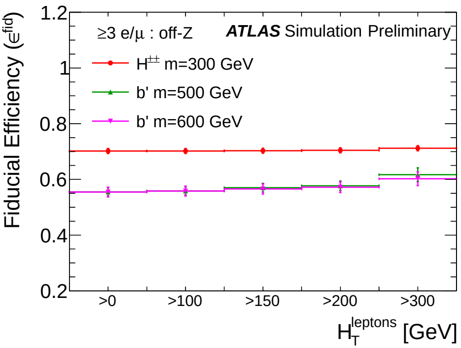
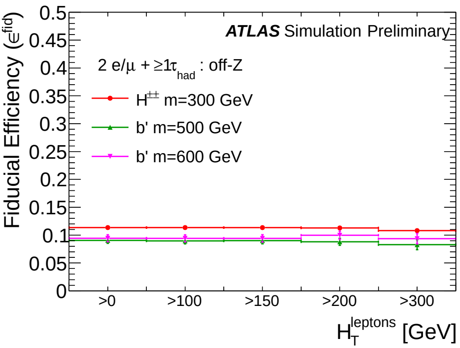




Getting around model dependence

Efficiencies should also be model-independent!

- Fiducial volume at particle level: $\mathcal{A}$
  - $p_{\rm T}$, $|\eta|$ requirements
  - Isolation requirements using stable particles
  - No special treatment for pileup!
- Measure ϵ in MC
  - SM *WZ* events

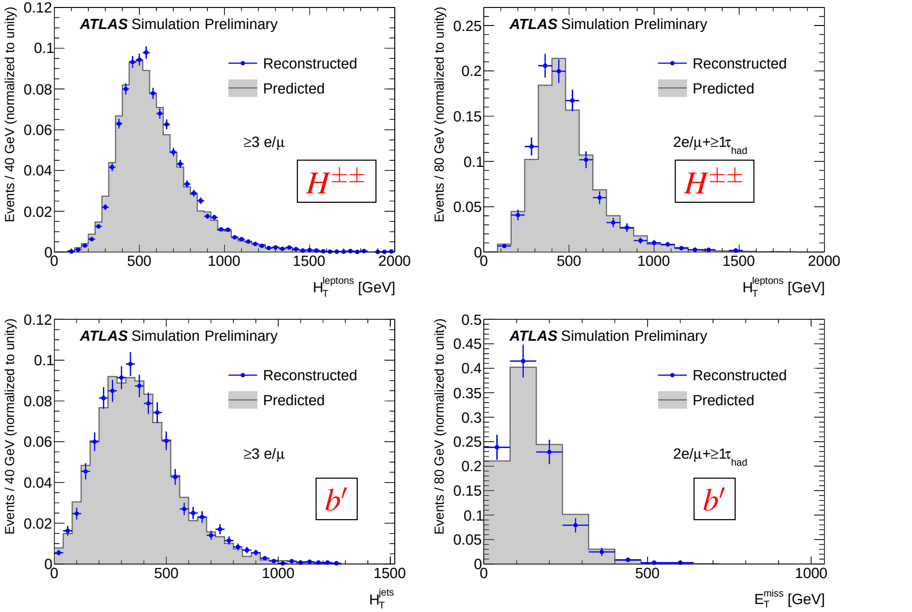
$\|\eta\|$	Prompt e	$\tau\to e$	$\tau_{\rm h}$
0.0–0.1	0.675±0.003	0.52±0.01	0.210±0.009
0.1–0.5	0.757±0.001	0.595±0.005	0.195±0.004
0.5–1.0	0.747±0.001	0.581±0.005	0.179±0.004
1.0–1.5	0.666±0.002	0.494±0.006	0.138±0.004
1.5–2.0	0.607±0.002	0.465±0.006	0.170±0.004
2.0–2.5	0.591±0.002	0.475±0.007	0.163±0.005

$p_{\rm T}$ [GeV]	Prompt e	$\tau\to e$	$\tau_{\rm h}$
10–15	0.394±0.003	0.381±0.004	0.025±0.002
15–20	0.510±0.003	0.515±0.005	0.147±0.004
20–25	0.555±0.003	0.542±0.006	0.225±0.005
25–30	0.626±0.002	0.601±0.007	0.229±0.006
30–40	0.691±0.002	0.673±0.006	0.215±0.005
40–50	0.738±0.002	0.729±0.008	0.206±0.006
50–60	0.774±0.002	0.76±0.01	0.202±0.008
60–80	0.796±0.002	0.77±0.01	0.198±0.008
80–100	0.830±0.002	0.82±0.02	0.21±0.01
100–200	0.850±0.003	0.81±0.02	0.23±0.02
200–400	0.878±0.009	0.85±0.07	0.19±0.05

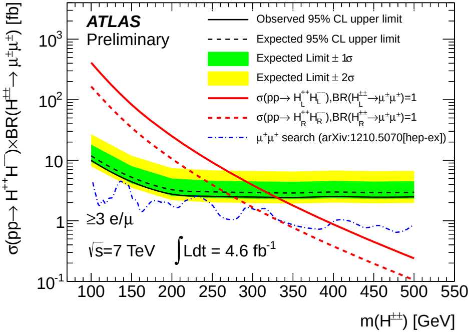
$p_{\rm T}$	Prompt μ		$\tau\to\mu$	
[GeV]	$\|\eta\|>0.1$	$\|\eta\|<0.1$	$\|\eta\|>0.1$	$\|\eta\|<0.1$
10–15	0.852±0.002	0.47±0.02	0.66±0.004	0.36±0.02
15–20	0.896±0.002	0.51±0.01	0.71±0.005	0.38±0.02
20–25	0.912±0.001	0.52±0.01	0.734±0.005	0.43±0.03
25–30	0.921±0.001	0.50±0.01	0.750±0.006	0.39±0.03
30–40	0.927±0.001	0.507±0.007	0.779±0.005	0.46±0.03
40–50	0.928±0.001	0.513±0.008	0.784±0.007	0.45±0.04
50–60	0.932±0.001	0.532±0.009	0.79±0.01	0.37±0.05
60–80	0.932±0.001	0.524±0.009	0.81±0.01	0.43±0.06
80–100	0.932±0.002	0.51±0.01	0.77±0.02	0.53±0.09
100–200	0.930±0.002	0.50±0.01	0.83±0.02	0.47±0.12
200–400	0.919±0.007	0.45±0.05	0.59±0.11	-

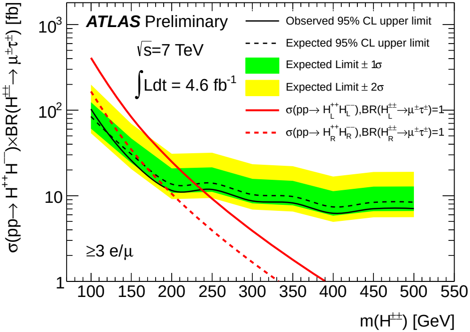
$$\epsilon^{\rm fid} = \epsilon_{\ell 1}\epsilon_{\ell 2}\epsilon_{\ell 3} \pm (10\% \text{ for } 3e/\mu,\ 20\% \text{ for } 2e/\mu+\tau)$$

Fiducial Efficiencies - Closure



$H^{\pm\pm}$ Limits



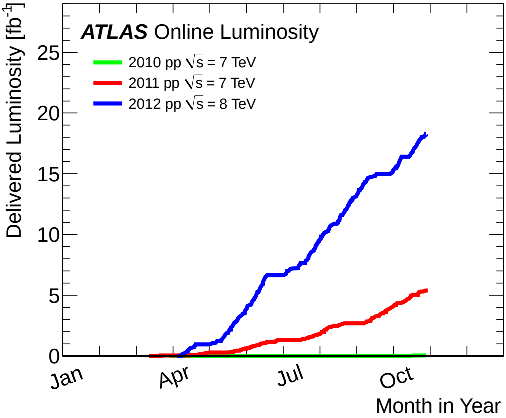


Use σ_{95}^{vis} limits and ϵ^{fid} to constrain $H^{\pm\pm}$:

- $H^{\pm\pm} \to \mu^\pm\mu^\pm$: 3 e/μ, off-Z, $H_{\text{T}}^{\text{leptons}} > 300$ GeV
- $H^{\pm\pm} \to \mu^\pm\tau^\pm$: 3 e/μ, off-Z
  - $H_{\text{T}}^{\text{leptons}} > 300$ GeV for most masses
  - $H_{\text{T}}^{\text{leptons}} > 200$ GeV for $m(H^{\pm\pm}) = 100$ GeV

Prospects and Conclusions

ATLAS in 2012



Many improvements over 2011:

- Electron reconstruction using brem-fitting algorithms
- Pileup-suppression for isolation, $E_{\mathrm{T}}^{\mathrm{miss}}$
- $\approx \times 5$ more data at 8 TeV

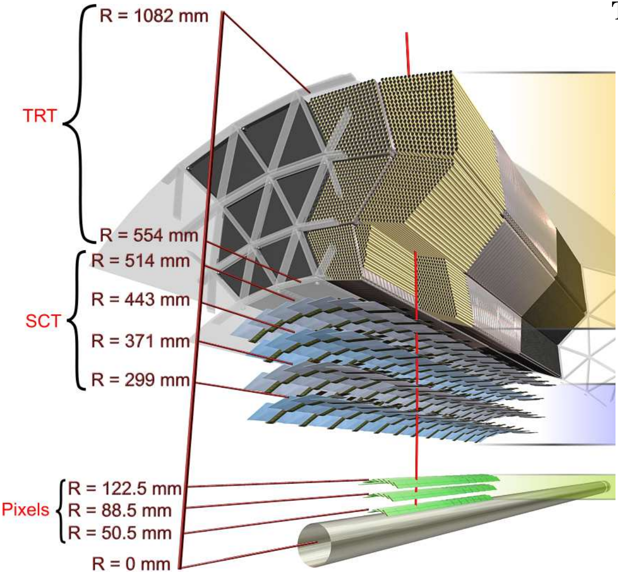
Conclusions

The hunt for New Physics continues....

- LHC searches setting strong limits on possible BSM scenarios
  - SUSY is on the ropes
  - Simpler extensions of SM have even stronger constraints
- Signature based searches are important
- Multilepton final states remain compelling
  - Clean signatures in complex environment
  - Sensitive to a variety of BSM scenarios
- 2012 will be exciting!

Bonus

Inner Detector



Transition Radiation Tracker

- 350k channel tracker
- 4mm (diameter) straws
- TR detection: $e/\pi^{\pm}$ discrimination
- $\approx$36 hits on track
- $\approx 130\mu$m resolution

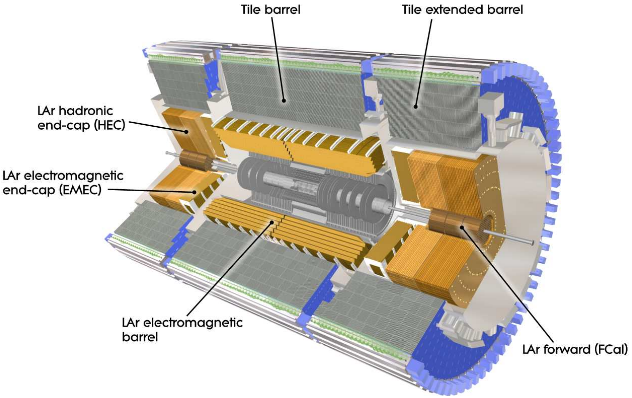
Semi-Conductor Tracker

- 6.3M channels
- 4 cylinders, 8 hits/track
- $\approx 17\mu$m resolution

Pixel Tracker

- 80M channels, 3 layers
- $\approx 10\mu$m resolution

Calorimetry



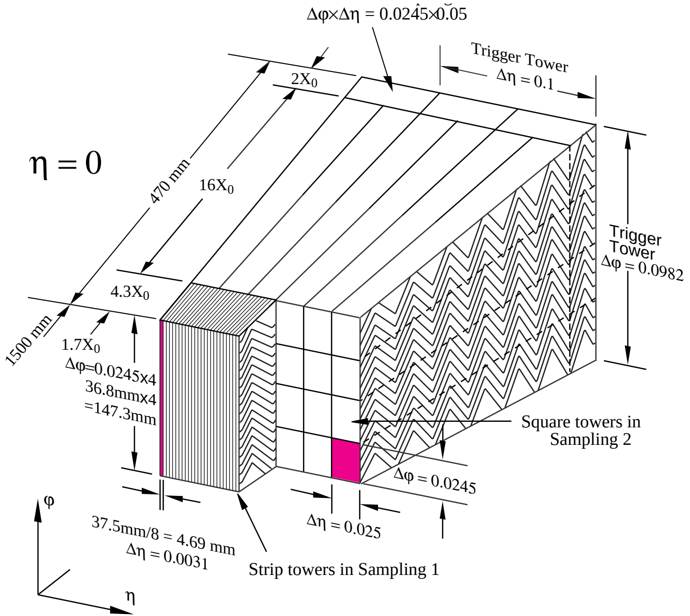
EM Calorimeter

- PB-LAr Accordion
- $\Delta E/E = \left(10\%/\sqrt{E}\right) \oplus .7\%$
- $.025 \times .025$ cells $(\eta \times \phi)$
- Angular res.: 50 mrad / $\sqrt{E}$

Hadronic Calorimeter

- Fe-scintillator for $|\eta| < 1.7$
  - $\Delta E/E = \left(50\%/\sqrt{E}\right) \oplus 6\%$
- Cu-LAr for $1.5 < |\eta| < 3.2$
  - $\Delta E/E = \left(50\%/\sqrt{E}\right) \oplus 3\%$

Liquid Argon Calorimeter



Four-Lepton Cases

$$\epsilon^{\text{fid}} = \epsilon_1\epsilon_2\epsilon_3+\epsilon_1\epsilon_2(1-\epsilon_3)\epsilon_4+\epsilon_1(1-\epsilon_2)\epsilon_3\epsilon_4+(1-\epsilon_1)\epsilon_2\epsilon_3\epsilon_4$$

- Assumes always at least one lepton satisfies trigger criteria

Yields

Table: Results for the H_T^{leptons} signal regions. Irreducible sources include all backgrounds estimated with MC simulation. Results are presented in number of expected events as $N \pm$ (statistical uncertainty) $\pm$ (systematic uncertainty).

$H_T^{\text{leptons}} \geq$	Irreducible	Reducible	Total Exp.	Observed
		$\geq 3e/\mu$, off-Z		
0 GeV	$54 \pm 4 \pm 7$	$54 \pm 6 \pm 23$	$107 \pm 7 \pm 24$	99
100 GeV	$32 \pm 2 \pm 4$	$32 \pm 4 \pm 16$	$65 \pm 4 \pm 16$	62
150 GeV	$22 \pm 1 \pm 3$	$15 \pm 2 \pm 8$	$37 \pm 3 \pm 8$	27
200 GeV	$9.7 \pm 0.6 \pm 1.5$	$6 \pm 2 \pm 4$	$16 \pm 2 \pm 4$	15
300 GeV	$3.6 \pm 0.5 \pm 0.5$	$2.5 \pm 1.2 \pm 1.8$	$6.2 \pm 1.3 \pm 1.9$	4
		$2e/\mu + \geq 1\tau$, off-Z		
0 GeV	$6.4 \pm 0.4 \pm 1.0$	$214 \pm 5 \pm 50$	$220 \pm 5 \pm 50$	226
100 GeV	$4.4 \pm 0.3 \pm 0.6$	$109 \pm 3 \pm 26$	$113 \pm 3 \pm 26$	113
150 GeV	$1.7 \pm 0.2 \pm 0.3$	$46 \pm 2 \pm 11$	$47 \pm 2 \pm 11$	42
200 GeV	$0.8 \pm 0.1 \pm 0.1$	$17 \pm 1 \pm 4$	$17 \pm 1 \pm 4$	15
300 GeV	$0.2 \pm 0.1 \pm 0.0$	$2.5 \pm 0.4 \pm 0.6$	$2.7 \pm 0.4 \pm 0.6$	1
		$\geq 3e/\mu$, on-Z		
0 GeV	$389 \pm 5 \pm 50$	$120 \pm 8 \pm 40$	$508 \pm 10 \pm 70$	588
100 GeV	$285 \pm 4 \pm 40$	$71 \pm 6 \pm 26$	$356 \pm 7 \pm 50$	422
150 GeV	$122 \pm 2 \pm 17$	$14 \pm 3 \pm 7$	$136 \pm 4 \pm 18$	151
200 GeV	$49 \pm 1 \pm 7$	$5 \pm 2 \pm 4$	$54 \pm 2 \pm 8$	60
300 GeV	$12.3 \pm 0.7 \pm 1.6$	$0.5 \pm 0.5 \pm 0.5$	$12.7 \pm 0.9 \pm 1.7$	18
		$2e/\mu + \geq 1\tau$, on-Z		
0 GeV	$13.2 \pm 0.5 \pm 2.2$	$1050 \pm 10 \pm 260$	$1060 \pm 10 \pm 260$	914
100 GeV	$11.1 \pm 0.5 \pm 1.9$	$670 \pm 10 \pm 160$	$680 \pm 10 \pm 160$	587
150 GeV	$4.5 \pm 0.3 \pm 0.8$	$66 \pm 2 \pm 16$	$71 \pm 2 \pm 16$	75
200 GeV	$1.8 \pm 0.2 \pm 0.3$	$19 \pm 1 \pm 5$	$21 \pm 1 \pm 5$	24
300 GeV	$0.5 \pm 0.1 \pm 0.1$	$3.0 \pm 0.5 \pm 0.8$	$3.5 \pm 0.5 \pm 0.8$	7

Yields

Table: Results for the $E_{\mathrm{T}}^{\mathrm{miss}}$, H_{T}<100 GeV signal regions. Irreducible sources include all backgrounds estimated with MC simulation. Results are presented in number of expected events as $N \pm$ (statistical uncertainty) $\pm$ (systematic uncertainty).

$E_{\mathrm{T}}^{\mathrm{miss}} \geq$	Irreducible	Reducible	Total Exp.	Observed
		$\geq 3e/\mu$, off-Z		
0 GeV	46 ±4 ±6	41 ±5 ±16	86 ±6 ±17	89
20 GeV	28 ±4 ±3	28 ±4 ±12	56 ±6 ±12	65
50 GeV	7.5 ±0.5 ±1.0	15 ±2 ±7	22 ±2 ±7	25
75 GeV	3.0 ±0.3 ±0.4	7 ±2 ±4	10 ±2 ±4	10
		$2e/\mu + \geq 1\tau$, off-Z		
0 GeV	5.3 ±0.4 ±0.9	184 ±4 ±40	190 ±4 ±40	202
20 GeV	4.4 ±0.3 ±0.7	93 ±3 ±20	98 ±3 ±20	91
50 GeV	1.5 ±0.2 ±0.2	17 ±1 ±4	19 ±1 ±4	20
75 GeV	0.6 ±0.1 ±0.1	8.0 ±0.8 ±1.8	8.5 ±0.8 ±1.8	10
		$\geq 3e/\mu$, on-Z		
20 GeV	340 ±5 ±50	100 ±7 ±31	439 ±9 ±60	509
50 GeV	105 ±2 ±14	14 ±3 ±5	119 ±3 ±14	144
75 GeV	40 ±1 ±5	5 ±1 ±2	46 ±2 ±6	57
		$2e/\mu + \geq 1\tau$, on-Z		
20 GeV	11.3 ±0.5 ±1.9	984 ±10 ±240	1000 ±10 ±240	862
50 GeV	4.6 ±0.3 ±0.7	43 ±2 ±11	48 ±2 ±11	33
75 GeV	2.0 ±0.2 ±0.3	4.1 ±0.6 ±1.0	6.1 ±0.6 ±1.0	4

Yields

Table: Results for the $E_{\mathrm{T}}^{\mathrm{miss}}$, $H_{\mathrm{T}} \geq$ 100GeV signal regions. Irreducible sources include all backgrounds estimated with MC simulation. Results are presented in number of expected events as $N \pm$ (statistical uncertainty) $\pm$ (systematic uncertainty).

$E_{\mathrm{T}}^{\mathrm{miss}} \geq$	Irreducible	Reducible	Total Exp.	Observed
		$\geq 3e/\mu$, off-Z		
0 GeV	7.7 $\pm 0.8 \pm 1.2$	13 $\pm 2 \pm 7$	21 $\pm 2 \pm 7$	10
20 GeV	6.0 $\pm 0.6 \pm 0.9$	12 $\pm 2 \pm 6$	18 $\pm 2 \pm 6$	8
50 GeV	3.2 $\pm 0.3 \pm 0.5$	8 $\pm 2 \pm 5$	11 $\pm 2 \pm 5$	5
75 GeV	2.2 $\pm 0.2 \pm 0.3$	7 $\pm 2 \pm 4$	9 $\pm 2 \pm 4$	5
		$2e/\mu + \geq 1\tau$, off-Z		
0 GeV	1.1 $\pm 0.1 \pm 0.2$	30 $\pm 2 \pm 7$	31 $\pm 2 \pm 7$	24
20 GeV	1.1 $\pm 0.1 \pm 0.2$	23 $\pm 1 \pm 6$	25 $\pm 1 \pm 6$	20
50 GeV	0.7 $\pm 0.1 \pm 0.1$	14.5 $\pm 1.1 \pm 3.4$	15.2 $\pm 1.1 \pm 3.4$	13
75 GeV	0.5 $\pm 0.1 \pm 0.1$	9.3 $\pm 0.8 \pm 2.2$	9.8 $\pm 0.8 \pm 2.3$	8
		$\geq 3e/\mu$, on-Z		
20 GeV	49 $\pm 1 \pm 7$	20 $\pm 4 \pm 10$	69 $\pm 4 \pm 12$	79
50 GeV	29 $\pm 1 \pm 4$	7 $\pm 2 \pm 3$	36 $\pm 2 \pm 5$	43
75 GeV	17.4 $\pm 0.7 \pm 2.1$	5 $\pm 1 \pm 2$	22 $\pm 2 \pm 3$	28
		$2e/\mu + \geq 1\tau$, on-Z		
20 GeV	1.9 $\pm 0.2 \pm 0.4$	61 $\pm 2 \pm 15$	63 $\pm 2 \pm 15$	52
50 GeV	1.1 $\pm 0.1 \pm 0.2$	7.8 $\pm 0.8 \pm 1.9$	8.9 $\pm 0.8 \pm 1.9$	11
75 GeV	0.7 $\pm 0.1 \pm 0.1$	2.7 $\pm 0.4 \pm 0.7$	3.4 $\pm 0.5 \pm 0.7$	1

Yields

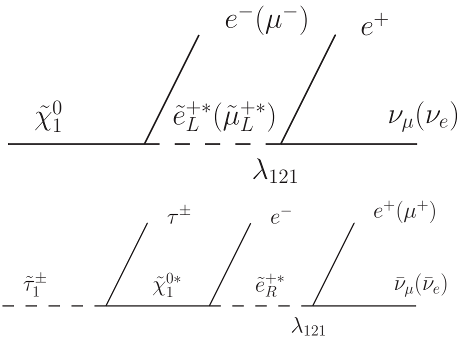
Table: Results for the m_{eff} signal regions. Irreducible sources include all backgrounds estimated with MC simulation. Results are presented in number of expected events as $N \pm$ (statistical uncertainty) $\pm$ (systematic uncertainty).

$m_{\text{eff}} \geq$	Irreducible	Reducible	Total Exp.	Observed
		$\geq 3e/\mu$, off-Z		
0 GeV	54 $\pm 4 \pm 7$	54 $\pm 6 \pm 23$	107 $\pm 7 \pm 24$	99
150 GeV	32 $\pm 2 \pm 4$	43 $\pm 4 \pm 20$	75 $\pm 4 \pm 20$	64
300 GeV	12.0 $\pm 0.9 \pm 1.6$	16 $\pm 2 \pm 8$	28 $\pm 3 \pm 8$	15
500 GeV	3.3 $\pm 0.2 \pm 0.5$	3.2 $\pm 1.2 \pm 2.4$	6.5 $\pm 1.2 \pm 2.5$	5
		$2e/\mu + \geq 1\tau$, off-Z		
0 GeV	6.4 $\pm 0.4 \pm 1.0$	214 $\pm 5 \pm 50$	220 $\pm 5 \pm 50$	226
150 GeV	4.4 $\pm 0.3 \pm 0.7$	106 $\pm 3 \pm 24$	111 $\pm 3 \pm 24$	101
300 GeV	1.3 $\pm 0.2 \pm 0.2$	31 $\pm 2 \pm 7$	32 $\pm 2 \pm 7$	25
500 GeV	0.4 $\pm 0.1 \pm 0.2$	6.6 $\pm 0.7 \pm 1.6$	7.0 $\pm 0.7 \pm 1.6$	6
		$\geq 3e/\mu$, on-Z		
0 GeV	390 $\pm 5 \pm 50$	120 $\pm 8 \pm 40$	510 $\pm 10 \pm 70$	588
150 GeV	270 $\pm 3 \pm 40$	57 $\pm 6 \pm 22$	330 $\pm 7 \pm 40$	399
300 GeV	73 $\pm 1 \pm 10$	16 $\pm 3 \pm 8$	89 $\pm 4 \pm 13$	103
500 GeV	22.2 $\pm 0.9 \pm 2.8$	3 $\pm 1 \pm 1$	25 $\pm 2 \pm 3$	29
		$2e/\mu + \geq 1\tau$, on-Z		
0 GeV	13.2 $\pm 0.5 \pm 2.2$	1050 $\pm 10 \pm 260$	1060 $\pm 10 \pm 260$	914
150 GeV	10.7 $\pm 0.5 \pm 1.8$	360 $\pm 5 \pm 90$	370 $\pm 5 \pm 90$	309
300 GeV	2.9 $\pm 0.3 \pm 0.4$	47 $\pm 2 \pm 12$	50 $\pm 2 \pm 12$	42
500 GeV	0.9 $\pm 0.2 \pm 0.1$	7.7 $\pm 0.8 \pm 1.9$	8.7 $\pm 0.8 \pm 2.0$	5

Yields

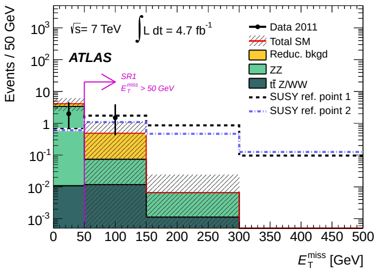
Table: Results for the m_{eff}, high-E_T^{miss} signal regions. Irreducible sources include all backgrounds estimated with MC simulation. Results are presented in number of expected events as $N \pm$ (statistical uncertainty) $\pm$ (systematic uncertainty).

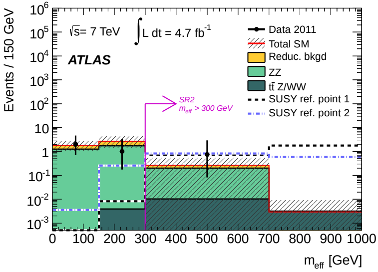
$m_{\text{eff}} \geq$	Irreducible	Reducible	Total Exp.	Observed
		$\geq 3e/\mu$, off-Z		
0 GeV	5.1 ±0.4 ±0.7	13 ±2 ±8	18 ±2 ±8	15
150 GeV	5.1 ±0.4 ±0.7	13 ±2 ±8	18 ±2 ±8	15
300 GeV	3.7 ±0.3 ±0.5	10 ±2 ±6	13 ±2 ±6	9
500 GeV	1.7 ±0.2 ±0.2	2.9 ±1.1 ±2.3	4.5 ±1.1 ±2.3	4
		$2e/\mu+ \geq 1\tau$, off-Z		
0 GeV	1.0 ±0.2 ±0.1	17 ±1 ±4	18 ±1 ±4	18
150 GeV	1.0 ±0.2 ±0.1	17 ±1 ±4	18 ±1 ±4	18
300 GeV	0.6 ±0.1 ±0.1	11.9 ±0.9 ±2.9	12.4 ±0.9 ±2.9	11
500 GeV	0.2 ±0.1 ±0.1	3.2 ±0.5 ±0.8	3.4 ±0.5 ±0.8	2
		$\geq 3e/\mu$, on-Z		
0 GeV	58 ±1 ±7	10 ±2 ±4	68 ±2 ±8	85
150 GeV	58 ±1 ±7	10 ±2 ±4	68 ±2 ±8	85
300 GeV	32 ±1 ±4	6 ±1 ±2	37 ±2 ±4	47
500 GeV	11.8 ±0.6 ±1.4	2.2 ±1.1 ±0.7	14.0 ±1.3 ±1.6	18
		$2e/\mu+ \geq 1\tau$, on-Z		
0 GeV	2.7 ±0.3 ±0.4	6.8 ±0.7 ±1.6	9.5 ±0.8 ±1.7	5
150 GeV	2.7 ±0.3 ±0.4	6.7 ±0.7 ±1.6	9.4 ±0.8 ±1.7	4
300 GeV	1.6 ±0.2 ±0.2	3.5 ±0.5 ±0.9	5.0 ±0.5 ±0.9	2
500 GeV	0.6 ±0.1 ±0.1	0.4 ±0.1 ±0.1	1.0 ±0.2 ±0.1	0

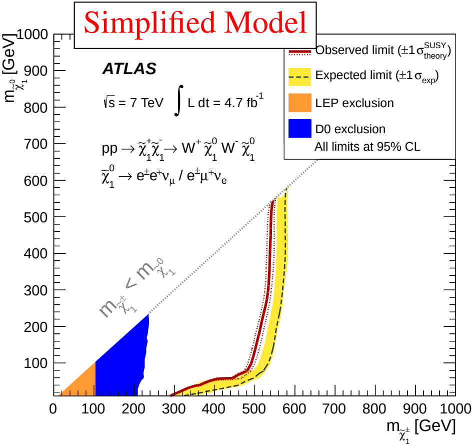


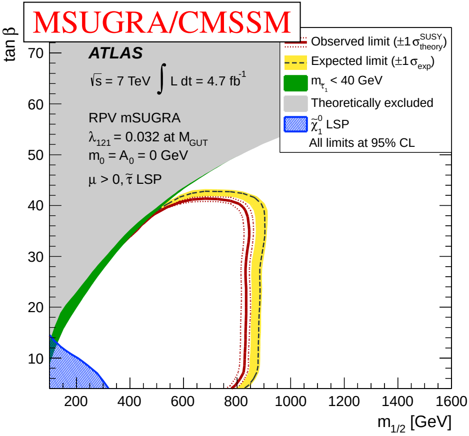
R-Parity Violating (RPV) search:

- Little/no $E_{\mathrm{T}}^{\mathrm{miss}}$
- Here, LSP→leptons

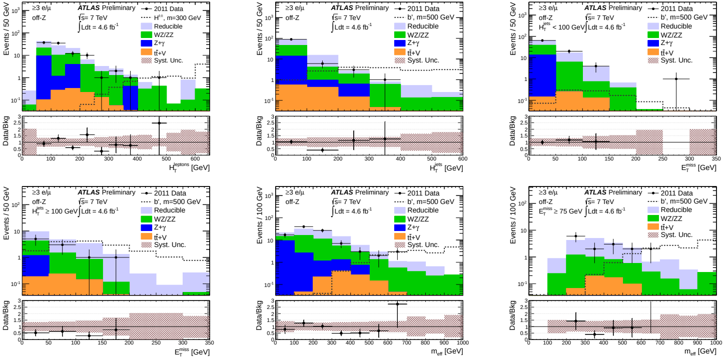




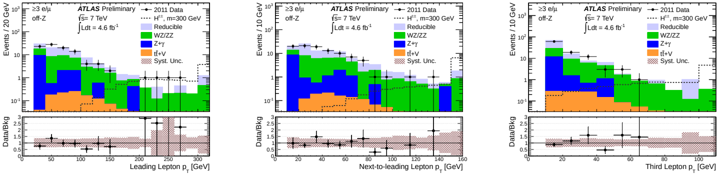

Simplified Model
ATLAS
√s = 7 TeV ∫ L dt = 4.7 fb-1
pp → χ̃1+χ̃1- → W+ χ̃10 W- χ̃10
χ̃10 → e±e∓νμ / e±μ∓νe
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
LEP exclusion
D0 exclusion
All limits at 95% CL
m χ̃1± < m χ̃10
m χ̃10 [GeV]
m χ̃1± [GeV]


MSUGRA/CMSSM
ATLAS
√s = 7 TeV ∫ L dt = 4.7 fb-1
RPV mSUGRA
λ121 = 0.032 at MGUT
m0 = A0 = 0 GeV
μ > 0, τ̃ LSP
Observed limit (±1 σ SUSY theory)
Expected limit (±1 σexp)
m τ̃1 < 40 GeV
Theoretically excluded
χ̃10 LSP
All limits at 95% CL
tan β
m1/2 [GeV]

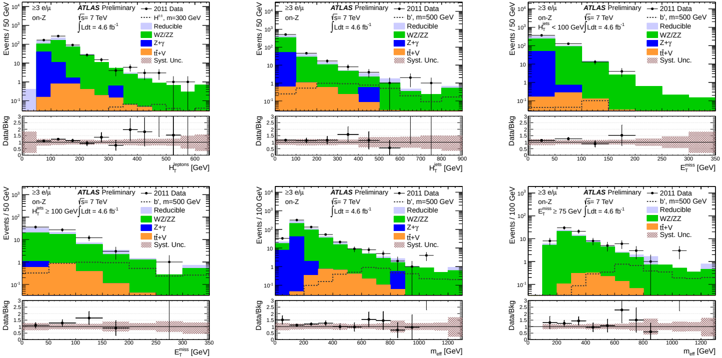
$\geq 3e/\mu$, off-Z Distributions



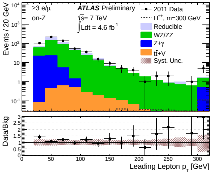
$\geq 3e/\mu$, off-Z Distributions

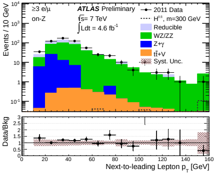


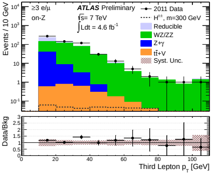
$\geq 3e/\mu$, on-Z Distributions

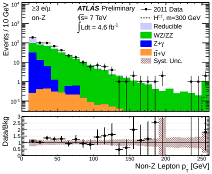


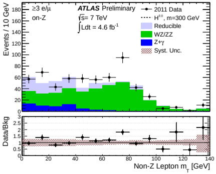
$\geq 3e/\mu$, on-Z Distributions



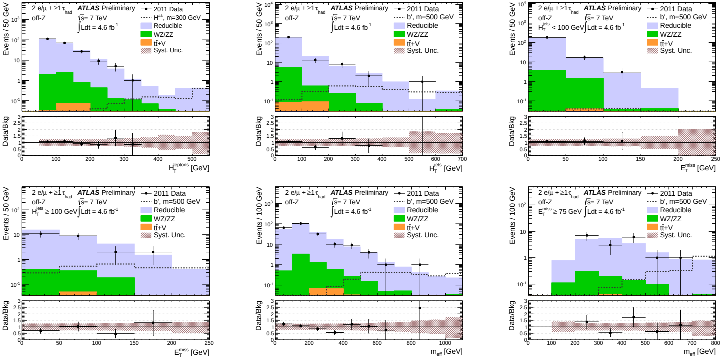




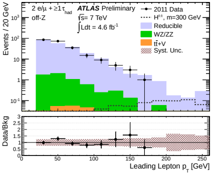


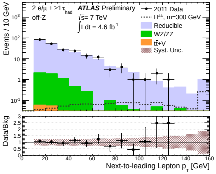


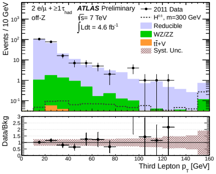
$2e/\mu + \geq 1\tau$, off-Z distributions



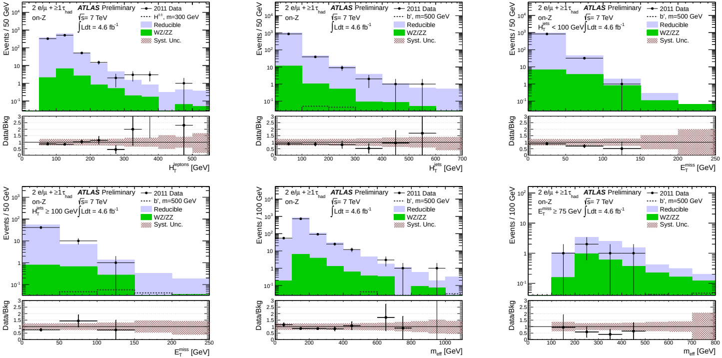
$2e/\mu + \geq 1\tau$, off-Z distributions



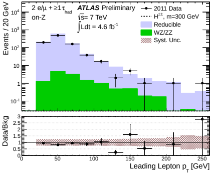


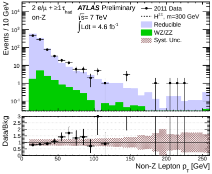


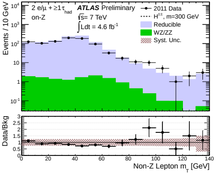
$2e/\mu + \geq 1\tau$, on-Z distributions



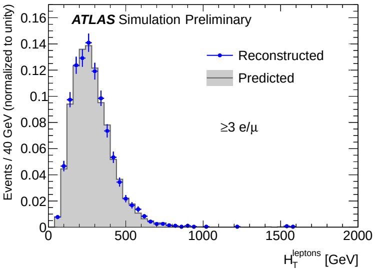
$2e/\mu + \geq 1\tau$, on-Z distributions

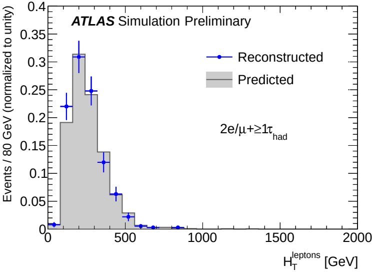


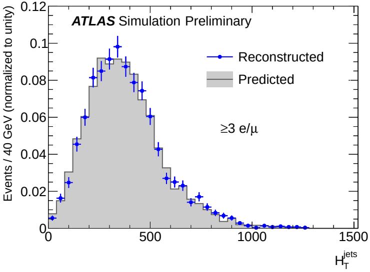


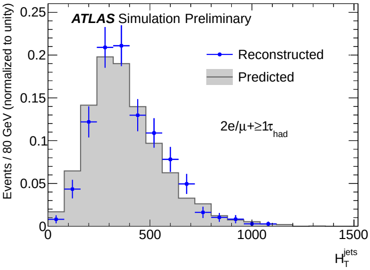


Fiducial Efficiencies









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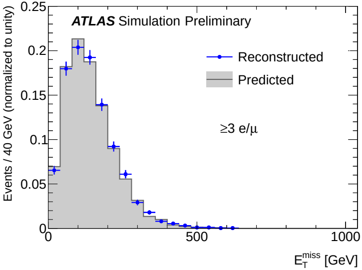

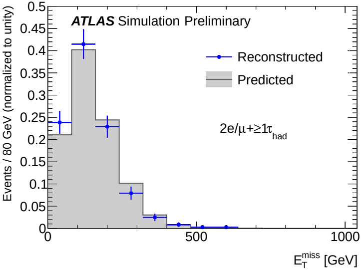

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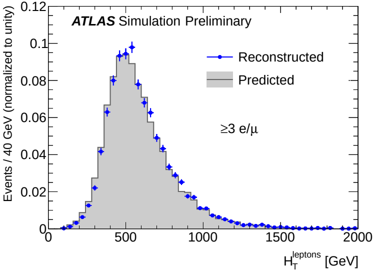

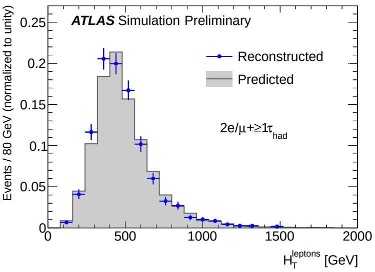

Fiducial Efficiencies