Search for Lepton Flavor Violation at ATLAS

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On behalf of ATLAS
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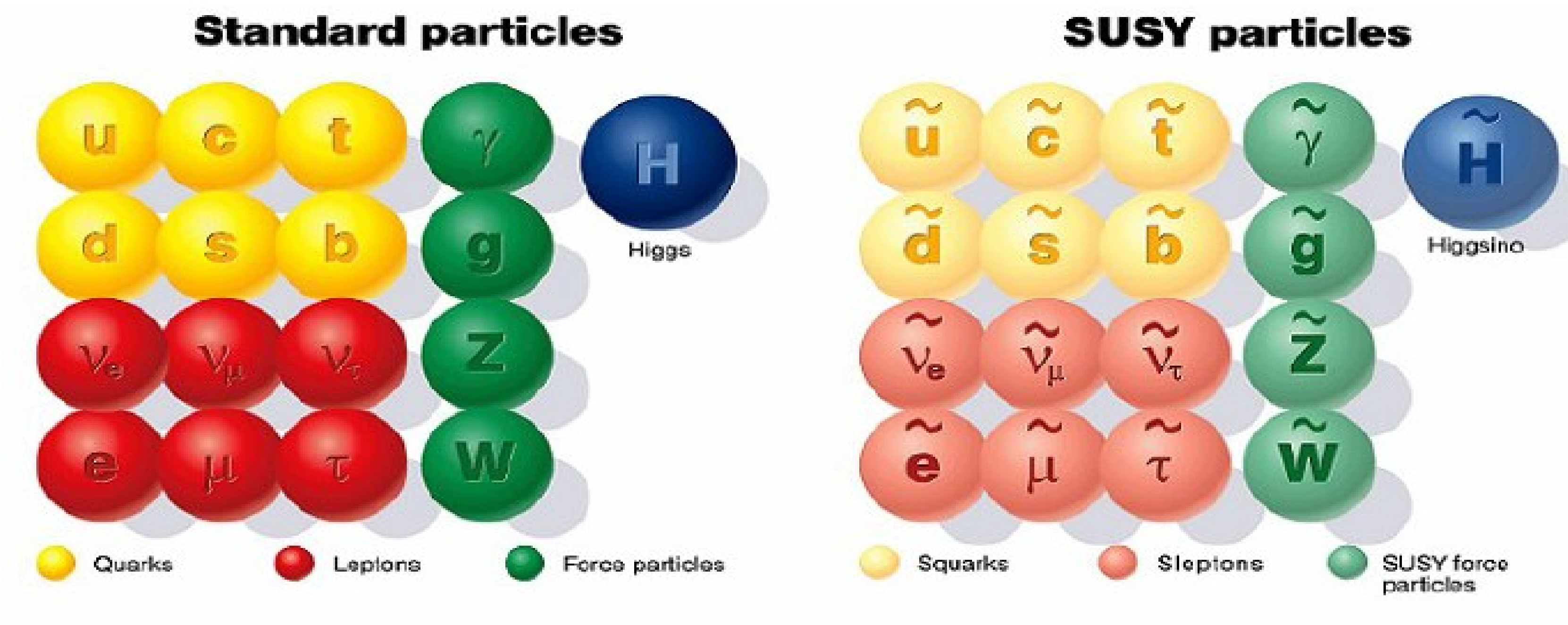
SUSY and R-Parity



- Hierarchy problem
- Dark matter/Energy
- neutrino mass

The last possible space-time symmetry

- R-Parity

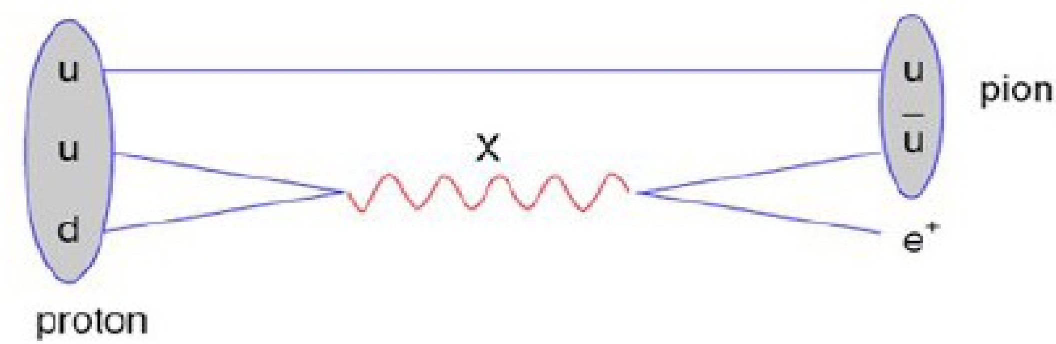
$$R=(-1)^{3B+L+2S}$$

- For SM particle: R = +1
- For SUSY particle: R = -1

R-Parity violating(RPV) and lepton flavor violating(LFV)

- Both "B" and "L" are conserved in SM, but not necessary in SUSY

  ✓ Proton Decay



RPV

✓ neutrino mass form experimental observations

$$\begin{aligned}
\Delta m_{21}^2 &= (7.6 \pm 0.2) \times 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m_{32}^2| &= (2.4 \pm 0.1) \times 10^{-3}\ \mathrm{eV}^2 \\
\sin^2 2\theta_{12} &= 0.87 \pm 0.03 \\
\sin^2 2\theta_{23} &> 0.92
\end{aligned}$$

the neutrino oscillation

The flavor of neutrino is actually a mixing of three mass eigen-states.

Topic of this slides

LFV

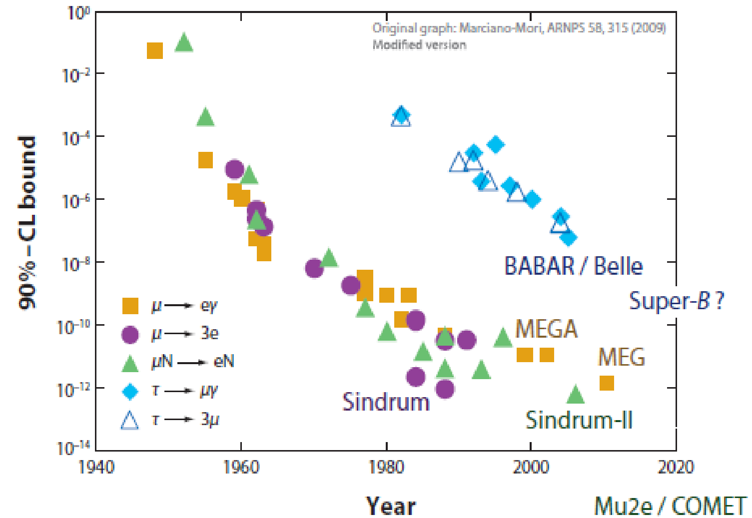
Outline

- Overview of LFV
- LFV search topics at ATLAS
- LFV search details
- Summary

Overview of LFV search

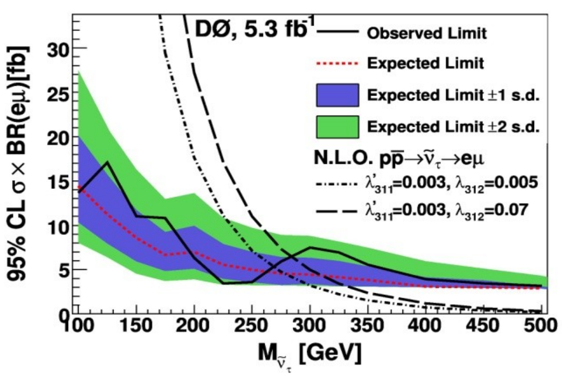
Low energy experiments

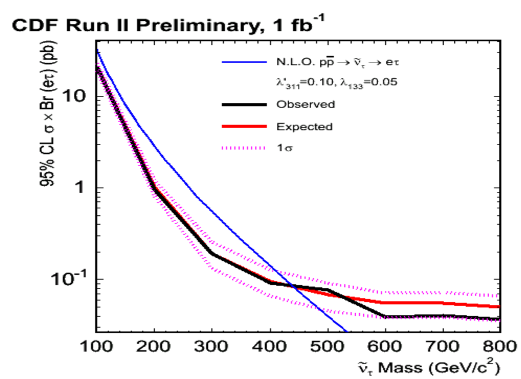
- The sensitivity in the search for rare lepton flavor violating (LFV) reactions has been increased by many orders of magnitude over the years

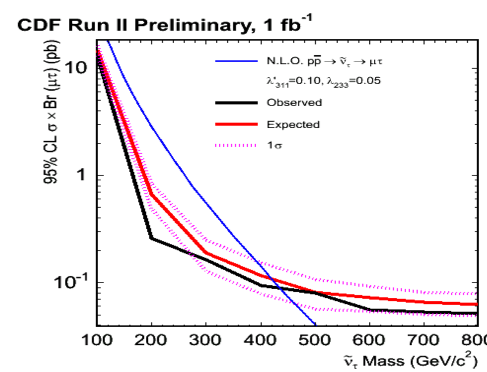


History of searches for selected lepton flavor violating processes

- Both CDF (1fb^{-1}: eμ, $\mu\tau$, eτ) and D0 (5 fb^{-1}: eμ) have performed searches for a SUSY LFV sneutrino resonance and extra gauge symmetry Z' particle







High energy experiments

LFV topics at ATLAS

- SUSY $\tilde{\nu}_{\tau}$ to eμ/eτ/μτ search
  - ✓ 7TeV 35pb^{-1}, publication on PRL : Phys. Rev. Lett.106,251801
  - ✓ 7TeV 1fb^{-1}, publication on EPJC: EPJC Vol.71, 12(2011)1809
  - ✓ 7TeV 5fb^{-1}, publication on PLB : PLB_29354
- Z'→ eμ search
  - ✓7TeV 35pb^{-1}, published together with $\tilde{\nu}_{\tau}$ on PRL
  - ✓ 7TeV 1fb^{-1}, published together with $\tilde{\nu}_{\tau}$ on EPJC
- stop →eμ continuum search
  - ✓ 7TeV 2fb^{-1}, publication on EPJC: Eur. Phys. J. C (2012) 72:2040
- (≥)4-lepton search
  - ✓ 7TeV, 5fb^{-1}, published on JHEP: JHEP12(2012)124
  - ✓ 8TeV, 21fb^{-1}, conference note for Moriond: ATLAS-CONF-2013-036
- μ+displaced vertex
  - ✓ 7TeV 35pb^{-1}, published on PLB: Physics Letters B 707 (2012) 478-496
  - ✓ 7TeV 5fb^{-1}, published on PLB: Physics Letters B 719 (2013) 280-298

LFV search details

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

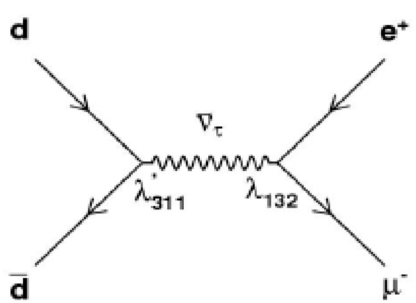
35pb^{-1}, 1fb^{-1} analyses focused on eμ channel only
5fb^{-1} analysis is extended to eμ/eτ/μτ channels(τ: only hadronic decay)

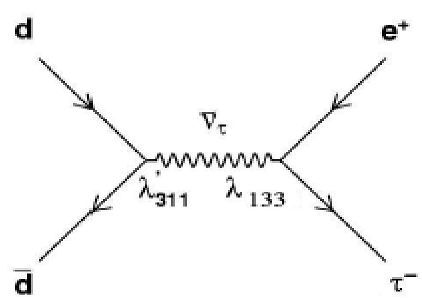
- A generic search for a heavy resonance decaying into eμ, μτ or eτ final states
- RPV Lagrangian:

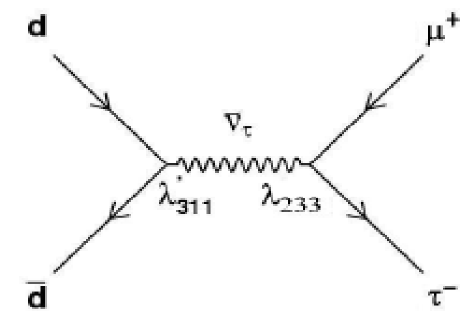
Decay

$$\mathcal{L}_{\not R} = \frac{1}{2}\lambda_{ijk}(\bar{\nu}^c_{Li}e_{Lj}\tilde{e}^*_{jL} + e_{Li}\bar{\nu}^c_{Lj}\tilde{e}^*_{Rk} + \nu_{Li}e_{Lj}\bar{e}_{Rk} - e_{Li}\tilde{\nu}_{Lj}\bar{e}_{Rk}) +$$
$$\lambda'_{ijk}(\bar{\nu}^c_{Li}d_{Lj}\tilde{d}^*_{Rk} - e^c_{Ri}u_{Lj}\tilde{d}^*_{Rk} + \nu_{Li}\tilde{d}_{Lj}\bar{d}_{Rk} - e_{Li}\tilde{u}_{Lj}\bar{d}_{Rk} +$$
$$\tilde{\nu}_{Li}d_{Lj}\bar{d}_{Rk} - \tilde{e}_{Li}u_{Lj}\bar{d}_{Rk}) + h.c.$$

Production







- Small backgrounds due to the requirement of two different flavor leptons
- RPV couplings: λ'_{311}, λ_{i3k} $(i \neq k)$, other RPV couplings are assumed to be zero.

$\tilde{\nu}_\tau$ →eμ/eτ/μτ resonance search

Trigger

Based on a single electron or mu trigger

- 2010 trigger

Table 5: Triggers used for the $e\mu$ analysis in 2010 data.

Period	Triggers used
A-E3	L1_EM14||L1_MU10
E4-G1	EF_e15_medium||EF_mu10_MG
G2-I1(167576)	EF_e15_medium||EF_mu13_MG
I1(167607)-I2	EF_e15_medium||EF_mu13_MG_tight

- 2011 trigger **1fb^{-1}**

EF_e20_medium || EF_mu18

- 2011 trigger **5fb^{-1}**

Period	Run numbers	EF trigger	Int. luminosity [pb^{-1}]
$e\mu$ channel and $e\tau$ channel			
D-J	179725-186755	EF_e20_medium	1695
K	186873-187815	EF_e22_medium	562
L-M	188921-191933	EF_e22vh_medium1	2393
$\mu\tau$ channel			
D-I	179725-186493	EF_mu18_MG	1469
J-M	186516-191933	EF_mu18_MG_medium	3181

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Event selection

- Single electron OR single muon trigger
- Data quality cuts
- Good primary vertex
- Exactly one electron and one muon with opposite charge (veto the 3nd lepton)

- dphi(l_1,l_2)>2.7
- Pt(e/μ)>Pt(τ)

Added in 7TeV, 5fb^{-1} analysis

Objects' selections followed mainly the recommendations from ATLAS performance group

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

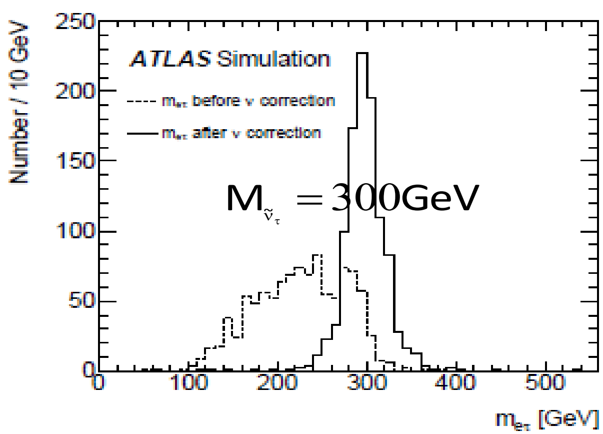
Reconstruction of di-lepton invariant mass

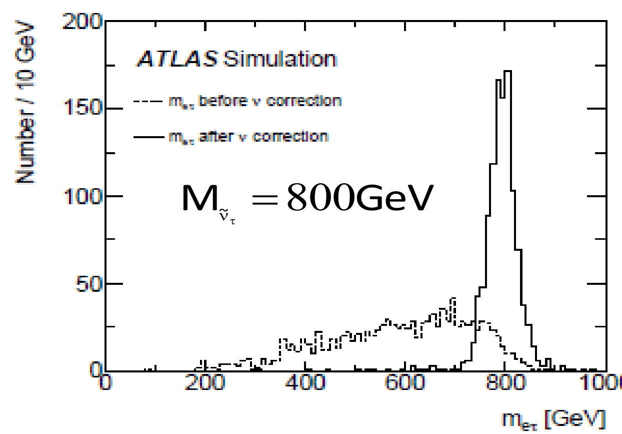
For eμ channel, it's pretty easy

For eτ and μτ channel, there's missing energy

- missing energy is from only one ν
- τ decay finals are heavily boosted due to large $M_{\tilde{\nu}_\tau}$
- neutrino and the resultant jet are approximately collinear

Reconstruct the ν by supposing $\eta_\nu = \eta_{\tau_{had}}$ ⇨ **Collinear approximation**





Dashed line: before ν correction Solid line: after ν correction

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Background estimation

- **Physics background**
  - $Z \rightarrow \tau\tau$
  - $Z \rightarrow ee$
  - $Z \rightarrow \mu\mu$
  - ttbar
  - WW/WZ/ZZ
  - single top

Well known processes

Use the corrected MC simulation to predict their contributions

- **jet fake background**
  - Wjet
  - QCD multijet

MC often doesn't provide good predictions of these fake bkgd

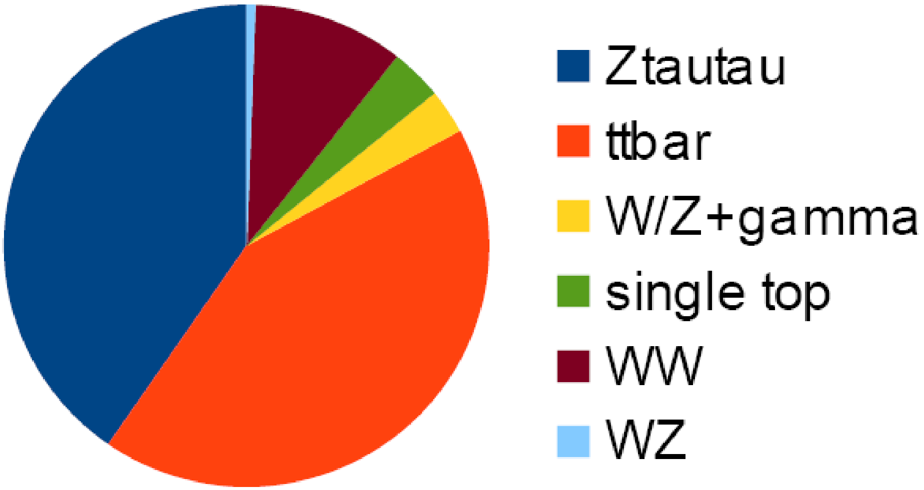
Use data driven method to Estimate their contributions

$\tilde{\nu}_\tau$ →eμ/eτ/μτ resonance search

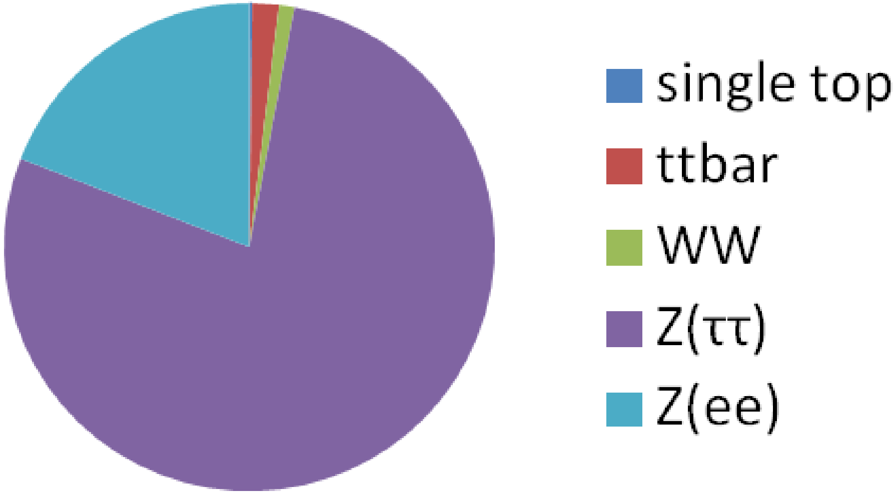
Background estimation: Physics background

Got from corrected MC simulation

Example plots



Physics backgrounds
fraction in 1fb^{-1} analysis (eμ channel)



Physics backgrounds
fraction in 5fb^{-1} analysis (eτ channel)

$\tilde{\nu}_\tau \to e\mu/e\tau/\mu\tau$ resonance search

Background estimation: jet fake background

Back

For $35pb^{-1}$ & $1fb^{-1}$ study, **Matrix method** is used

- Matrix method
  - 2x2 matrix

$$\begin{cases} N_L = N_R + N_F \\ N_T = \varepsilon N_R + f N_F \end{cases} \Rightarrow \quad N_R^T = \frac{N_T - f N_L}{\varepsilon - f}\varepsilon \qquad N_F^T = \frac{\varepsilon N_L - N_T}{\varepsilon - f} f$$

  - 4x4 matrix

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_e r_\mu & r_e f_\mu & f_e r_\mu & f_e f_\mu \\ r_e(1-r_\mu) & r_e(1-f_\mu) & f_e(1-r_\mu) & f_e(1-f_\mu) \\ (1-r_e)r_\mu & (1-r_e)f_\mu & (1-f_e)r_\mu & (1-f_e)f_\mu \\ (1-r_e)(1-r_\mu) & (1-r_e)(1-f_\mu) & (1-f_e)(1-r_\mu) & (1-f_e)(1-f_\mu) \end{bmatrix} \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

L: loose selection
T:tight selection
R: real lepton
F: fake lepton
ϵ: real lepton efficiency
f: fake lepton fake rate

- ε: from Z(→ee/μμ) control sample
  - “tag & probe” method
- f: from di-jet control sample
  - leptons which are back-to-back with a jet
  - E_t^{miss} <15GeV; M_T<30GeV

Isolation (Etcone40 for e/Ptcone40 for μ) is used as the discriminate variable from “Loose” to “Tight”

More details: Phys. Rev. Lett.106,251801

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Background estimation:

For 35pb^{-1} & 1fb^{-1} study

35pb^{-1}

Process	Number of events
$Z/\gamma^* \to \tau\tau$	54 ± 7
$t\bar{t}$	57 ± 9
WW	13.4 ± 1.7
Single top	4.6 ± 0.9
WZ	0.79 ± 0.11
Instrumental background	33^{+30}_{-10}
Total background	163^{+34}_{-18}
Data	160

1fb^{-1}

Process	Number of events
$t\bar{t}$	1580 ± 170
Jet fake	1175 ± 120
$Z/\gamma^* \to \tau\tau$	750 ± 60
WW	380 ± 31
Single top	154 ± 16
$W/Z + \gamma$	82 ± 13
WZ	22.4 ± 2.3
ZZ	2.48 ± 0.26
Total background	4145 ± 250
Data	4053

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Background estimation: jet fake background

For 5fb^{-1} study, a "**Charge based**" method is used(specially used for τ channels)

$$
\begin{aligned}
N^{os} &= N^{os}_{QCD} + N^{os}_{W+jet} + N^{os}_{Z\to\tau\tau} + N^{os}_{others} \\
&= r_{QCD} \times N^{ss}_{QCD} + r_{W+jet} \times N^{ss}_{W+jet} + r_{Z\to\tau\tau} \times N^{ss}_{Z\to\tau\tau} + r_{others} \times N^{ss}_{others}
\end{aligned}
$$

Others:
Zll, ttbar, WW, single top

$$r_{QCD} = \frac{N^{os}_{QCD}}{N^{ss}_{QCD}} = 1,$$

→ **assumption**

$$
\begin{aligned}
r_{W+jet} &= \frac{N^{os}_{W+jet}}{N^{ss}_{W+jet}} = 1 + k_{W+jet}, \\
r_{Z\to\tau\tau} &= \frac{N^{os}_{Z\to\tau\tau}}{N^{ss}_{Z\to\tau\tau}} = 1 + k_{Z\to\tau\tau}, \\
r_{others} &= \frac{N^{os}_{others}}{N^{ss}_{others}} = 1 + k_{others},
\end{aligned}
$$

OS: opposite sign events
SS : same sign events

$$N^{OS} = N^{SS}_{total} + k_{wjet} * N^{SS}_{wjet} + k_{Z\tau\tau} * N^{SS}_{Z\tau\tau} + k_{others} * N^{SS}_{others}$$

$k_{wjet} * N^{SS}_{wjet}$: largely based on collision data control samples

$k_{Z\tau\tau} * N^{SS}_{Z\tau\tau} + k_{others} * N^{SS}_{others}$: Got from MC

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Background estimation: jet fake background

For 5fb^{-1} study, a "**Charge based**" method is used(specially used for τ channels)

Derivative for k_{W+jet}

determined in a control region of *W+jets* events.
same cuts applied for signal +
an additional requirement of *ETmiss > 30 GeV.*

$$k_{W+jet} = r_{W+jet} - 1 = \frac{n^{os,data}_{high\ E_T^{miss}} - n^{os,MC}_{others,high\ E_T^{miss}}}{n^{ss,data}_{high\ E_T^{miss}} - n^{ss,MC}_{others,high\ E_T^{miss}}} - 1$$

Derivative for $k_{W+jet} \times N^{ss}_{W+jet}$

N^{ss}_{W+jet} : Determined in the same control region

$$k_{W+jet} \times N^{ss}_{W+jet} = k_{W+jet} \times (n^{ss,data}_{high\ E_T^{miss}} - n^{ss,MC}_{others,high\ E_T^{miss}}) \times \frac{n^{ss,MC}_{W+jet,all}}{n^{ss,MC}_{W+jet,high\ E_T^{miss}}}$$

A factor obtained from W+jets MC to correct MET from >30GeV to ALL MET region

For more details: arXiv:1212.1272

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Background estimation:

For $5fb^{-1}$ study

	$m_{\ell\ell'} < 200$ GeV			$m_{\ell\ell'} > 200$ GeV		
Process	$N_{e\mu}$	$N_{e\tau}$	$N_{\mu\tau}$	$N_{e\mu}$	$N_{e\tau}$	$N_{\mu\tau}$
$Z/\gamma^* \rightarrow \tau\tau$	1880 ± 150	4300 ± 600	5300 ± 600	8 ± 1	24 ± 3	28 ± 4
$Z/\gamma^* \rightarrow ee$		1050 ± 80			44 ± 3	
$Z/\gamma^* \rightarrow \mu\mu$			3030 ± 290			29 ± 3
$t\bar{t}$	760 ± 110	96 ± 18	94 ± 14	251 ± 30	90 ± 15	70 ± 13
Diboson	260 ± 27	57 ± 8	60 ± 7	71 ± 8	26 ± 3	24 ± 3
Single top	87 ± 8	11 ± 2	9 ± 1	39 ± 4	10 ± 2	8 ± 1
W+jets	420 ± 260	3500 ± 700	3200 ± 600	90 ± 40	370 ± 80	470 ± 110
multijet	37 ± 13	2200 ± 700	730 ± 230	6 ± 2	150 ± 50	24 ± 18
Total background	3440 ± 300	11200 ± 900	12400 ± 800	460 ± 60	720 ± 80	650 ± 90
Data	3345	11212	12285	498	795	699

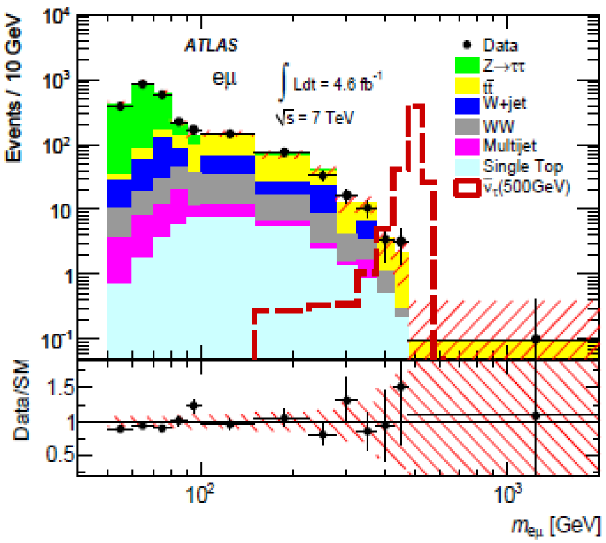
Z(→ll), ttbar, Wjet are the dominant backgrounds

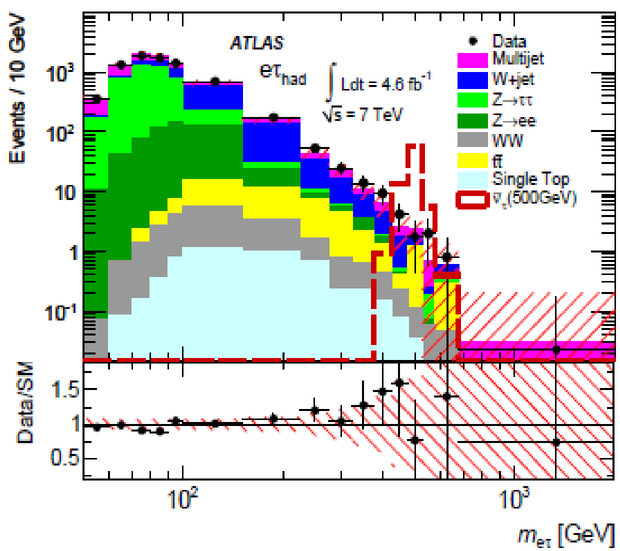
Good agreement between data and expectation

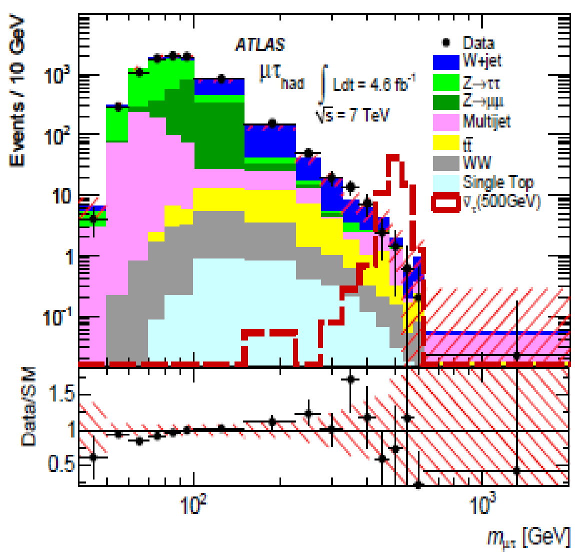
$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Control plots: data Vs. MC

Plots for 5fb^{-1}







Invariant mass of eμ

Invariant mass of eτ

Invariant mass of μτ

Reasonable Agreement

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

For $5fb^{-1}$

systematics

eμ channel

Sources	Uncertainties $m(e,\mu) < 200$ GeV	Uncertainties $m(e,\mu) > 200$ GeV
MC cross-section	3.5%	5.6%
Trigger	1.0%	0.9%
Luminosity	1.2%	1.7%
Electron ID	2.6%	1.5%
Muon ID	1.3%	1.1%
Electron scale and resolution	1.0%	1.1%
Muon resolution	0.8%	1.1%
Missing E_T uncertainty	4.2%	6.5%
Electron Charge misID	1.0%	1.3%
r_{QCD}	0.1%	0.1%
MC W+jet shape uncertainty	0.6%	0.9%
MC $t\bar{t}$ shape uncertainty	1.8%	1.7%
MC Statistics	5.3%	10.2%
Total systematics	6.9%	9.4%

eτ channel

Sources	uncertainties with $m(e,\tau) < 200$ GeV	uncertainties with $m(e,\tau) > 200$ GeV
MC cross-section	2.0%	2.1%
Trigger	0.6%	0.4%
Luminosity	1.2%	0.9%
Electron ID	1.3%	1.1%
Tau ID	4.7%	2.8%
Electron scale and resolution	0.9%	1.1%
τ scale	2.0%	2.7%
Missing E_T uncertainty	4.2%	6.2%
Electron charge misID	0.8%	1.5%
r_{QCD}	2.0%	2.1%
MC W+jet shape uncertainty	2.7%	3.6%
MC Statistics	1.9%	6.7%
Total systematics	7.8%	9.1%

μτ channel

Sources	uncertainties with $m(\mu,\tau) < 200$ GeV	uncertainties with $m(\mu,\tau) > 200$ GeV
MC cross-section	2.8%	3.0%
Trigger	1.0%	0.8%
Luminosity	1.8%	0.7%
Tau ID	2.8%	3.5%
Muon ID	1.1%	0.9%
Tau scale	2.6%	3.6%
Muon resolution	1.1%	0.9%
r_{QCD}	0.6%	0.3%
Missing E_T uncertainty	3.4%	8.6%
MC W+jet shape uncertainty	1.6%	3.8%
MC Statistics	1.8%	8.6%
Total systematics	6.6%	11.3%

$\tilde{\nu}_\tau$ →eμ/eτ/μτ resonance search

Limit setting

Bayesian method is used to set limits for $\tilde{\nu}_\tau$ search

- Bayesian theorem

$$P(s|n) = \frac{\iint P(n|s,b,\varepsilon)P(s)P(b)P(\varepsilon)\mathrm{d}b\mathrm{d}\varepsilon}{\iiint P(P(n|s,b,\varepsilon))P(s)P(b)P(\varepsilon)\mathrm{d}s\mathrm{d}b\mathrm{d}\varepsilon}$$

$$\int_0^{S_{up}} P(s|n)\mathrm{d}s = 1-\alpha$$ (1-α = 95%)

- Flat prior for signal cross section and Gamma prior for background and efficiency

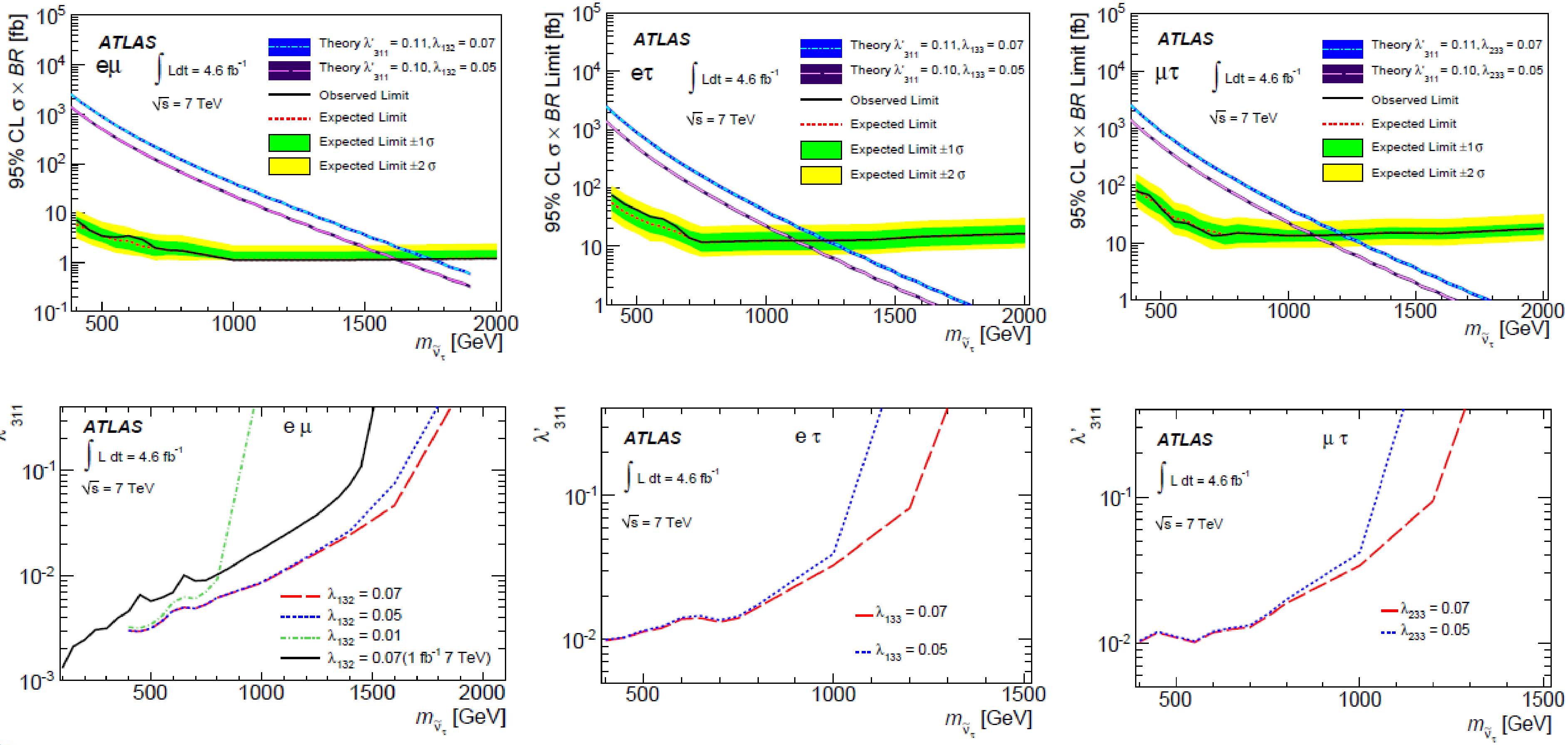
$$\mathrm{Gamma}(k,\theta) = f(x;k,\theta) = \frac{1}{\theta^k}\frac{1}{\Gamma(k)}x^{k-1}e^{-\frac{x}{\theta}}$$

$$\text{for } x \geq 0 \text{ and } k,\theta > 0$$

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Limits to new physics

For $5 fb^{-1}$



eμ channel
eτ channel
μτ channel

$\tilde{\nu}_\tau$ →eμ/eτ/μτ resonance search

Limits to new physics @ 95% C.L.

Analysis	Limit on σ x Br. eμ channel	Limit on σ x Br. eτ channel	Limit on σ x Br. μτ channel	Limit on λ'_{311} eμ channel	Limit on λ'_{311} eτ channel	Limit on λ'_{311} μτ channel
$35pb^{-1}$@ATLAS	>660GeV			$<2.4\times10^{-2}$		
$1fb^{-1}$@ATLAS	>1.3TeV			$<5.6\times10^{-3}$		
$5fb^{-1}$@ATLAS	>1.6TeV	>1.1TeV	>1.1TeV	$<3.0\times10^{-3}$	$<1.1\times10^{-2}$	$<1.1\times10^{-2}$
$1fb^{-1}$@CDF	>550GeV	>440GeV	>440GeV	$<2.6\times10^{-2}$	$<4.5\times10^{-2}$	$<5.5\times10^{-2}$

Limits on σ x Br. : @ $\lambda'_{311}=0.10$, $\lambda_{i3k}=0.05$

Limit on λ'_{311} : @ M=500GeV, $\lambda_{i3k}=0.05$

Summary for $\tilde{\nu}_\tau$ resonance search

- Performed 3 studies based on different integrated luminosities, and made 3 publications
  - $35pb^{-1}$: Phys. Rev. Lett.106,251801
  - $1fb^{-1}$: EPJC Vol.71, 12(2011)1809
  - $5fb^{-1}$: PLB(accepted) arXiv:1212.1272
- The data are found to be consistent with standard model predictions
- Limits are placed on the cross section times branching ratio for an RPV SUSY sneutrino. These results considerably extend previous constraints from Tevatron experiments

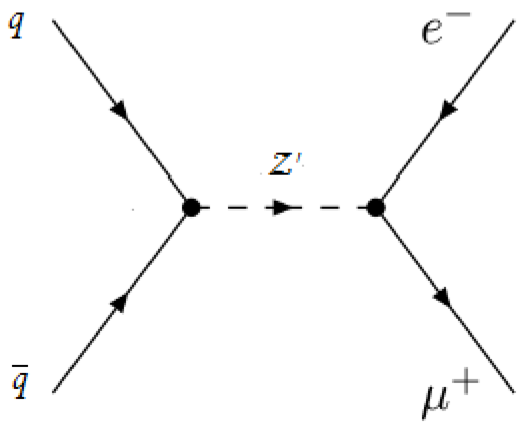
Z'→eμ resonance search at ATLAS

There are two analyses based on 35pb^{-1} and 1fb^{-1} which made 2 publications together with tau sneutrino resonance search.

extension to the SM
extra U(1) gauge symmetry } Z'

Sequential Standard Model (SSM)

$$\sigma(Z' \to l_i^- l_j^+) = \frac{g_z^2}{4\pi} \frac{(Q_{ij}^l)^2}{144} \frac{M^2}{(M^2 - M_{Z'}^2)^2 + M_{Z'}^2 \Gamma_{Z'}^2}$$



M: invariant mass of the lepton pair

$M_{Z'}$: the mass and of the Z'

$\Gamma_{Z'}$: total width of the Z'

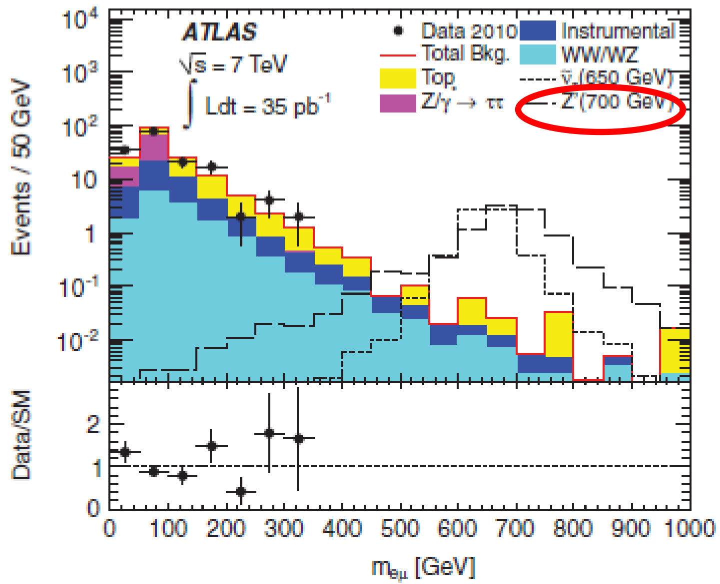
g_Z : the gauge coupling of the Z boson

Q^l_{ij}: i,j =1,2 (1for e, 2 for mu)

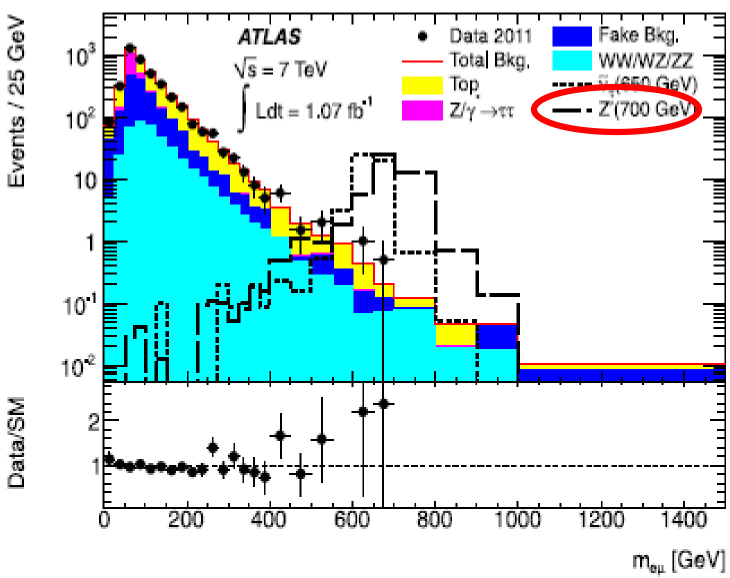
Z'→eμ resonance search at ATLAS

Event selection and Background estimation

- Event topology is exactly the same with $\tilde{\nu}_\tau$ analysis
- For both event selection and background estimation, we followed the same method for tau sneutrino search



Invariant mass of eμ @ 35pb^{-1}



Invariant mass of eμ @ 1fb^{-1}

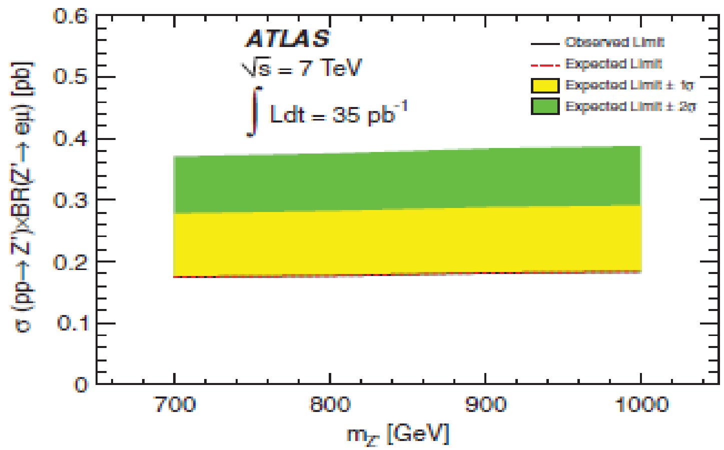
Data and MC are in reasonable agreement !

Z'→eμ resonance search at ATLAS

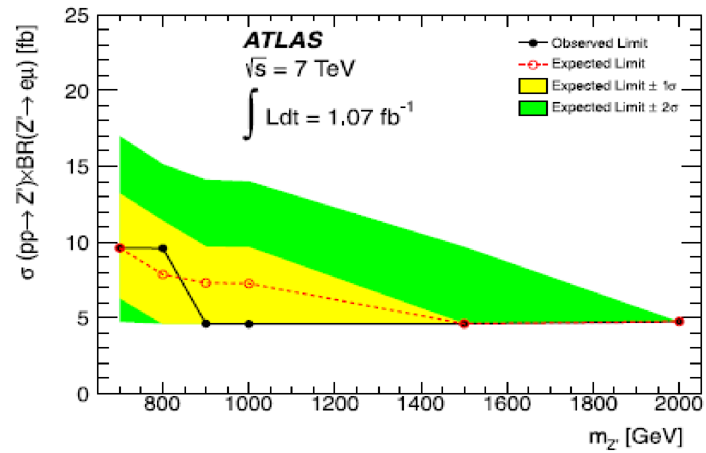
Limits on Z' search

Mass (GeV)	N_{data}	Lumi (pb^{-1})	σ(Lumi) (pb^{-1})	ϵ_{sig}	$\sigma(\epsilon_{sig})$	$N_{Bkg.}$ (expected)
700	0	35.2	3.9	0.503	0.012	0.67
800	0	35.2	3.9	0.496	0.012	0.67
900	0	35.2	3.9	0.486	0.012	0.67
1000	0	35.2	3.9	0.481	0.011	0.67

Mass (GeV)	Search Window (GeV)	N_{data}	ϵ^{sig}_{selc}	$\sigma(\epsilon^{sig}_{selc})$	$N_{Bkg.}$
700	550-850	3	0.594	0.014	2.8
800	600-1000	3	0.610	0.014	2.3
900	700-1100	0	0.610	0.014	1.2
1000	750-1250	0	0.614	0.014	0.9
1500	1100-1800	0	0.610	0.014	0.2
2000	1600-2400	0	0.592	0.014	0



Limit on σ x Br. Vs. $m_{z'}$ @ 35pb^{-1}



Limit on σ x Br. Vs. $m_{z'}$ @ 1fb^{-1}

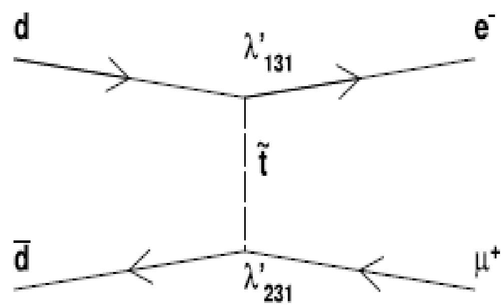
stop→eμ continuum search at ATLAS

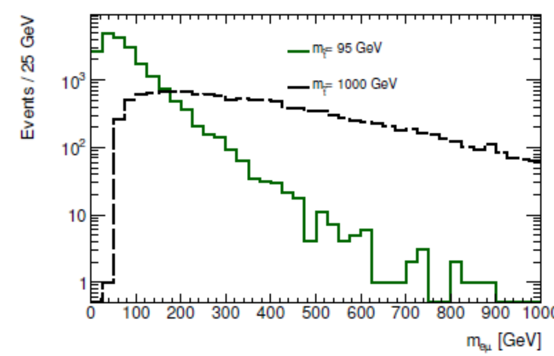
- A search for eμ final states in the t-channel
- Exchange of an R-parity violating scalar top quark
- Continuum search using 2.1 fb^{-1} of 7TeV data(2011)

Lagrangian

$$\mathcal{W} = -\lambda'_{ijk}\tilde{u}_j \bar{d}_k \ell_i$$

$\tilde{u}$: the up-type squark field
d: the down-type quark field
l: the lepton field
λ: the coupling at the production vertex
i, j, k: fermion generations





Invariant mass of stop

$$\frac{d\sigma}{dt} = \frac{|\lambda'_{131}\lambda'_{231}|^2 \hat{t}^2}{64 N_c \pi \hat{s}^2 \left(\hat{t} - m_{\tilde{t}}^2\right)^2},$$

where $\hat{s}$ and $\hat{t}$ are the usual Mandlestam variables in the $d\bar{d}$ center-of-mass frame, $N_c = 3$ is the color factor, and $m_{\tilde{t}}^2$ is the scalar top mass.

stop→eμ continuum search at ATLAS

Objects & event selection

- Single electron OR single muon trigger
- Data quality cuts
- Good primary vertex
- Exactly one GOOD electron and one GOOD muon with opposite charge

GOOD electron:

- Author 1 or 3
- $p_{\mathrm{T}} > 25$ GeV
- $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ (fiducial region)
- isEM::Tight
- $p_{\mathrm{T}}^{cone20} / p_{\mathrm{T}} < 0.10$
- $E_{\mathrm{T}}^{cone20} / p_{\mathrm{T}} < 0.15$
- $\Delta R(\mu) > 0.2$

GOOD muon:

- Staco muon (author 6)
- $p_{\mathrm{T}} > 25$ GeV
- $|\eta| < 2.4$
- Combined muon
- Pass MCP recommended muon selection criteria:
  - Require b-hits if expected
  - Number of pixel hits+number of crossed dead pixel sensors > 1
  - Number of SCT hits+number of crossed dead SCT sensors >= 6
  - Number of pixel holes + number of SCT holes < 3
  - For $|\eta| < 1.9$, require $n > 5$ and $n_{TRT\,outliers} < 0.9n$ and for $|\eta| > 1.9$, require $n_{TRT\,outliers} < 0.9n$ if $n > 5$, where $n = n_{TRT\,hits} + n_{TRT\,outliers}$ and $n_{TRT\,hits}$ denotes the number of TRT hits on the muon track and $n_{TRT\,outliers}$ denotes the number of TRT outliers on the muon track
- $p_{\mathrm{T}}^{cone20} / p_{\mathrm{T}} < 0.10$
- $E_{\mathrm{T}}^{cone20} / p_{\mathrm{T}} < 0.15$

stop→eμ continuum search at ATLAS

Background estimation

- **physics backgrounds :**

  Got from corrected MC simulations

- **"jet fake" backgrounds**

  Followed exactly the same method with tau sneutrino search: **4x4 matrix method**

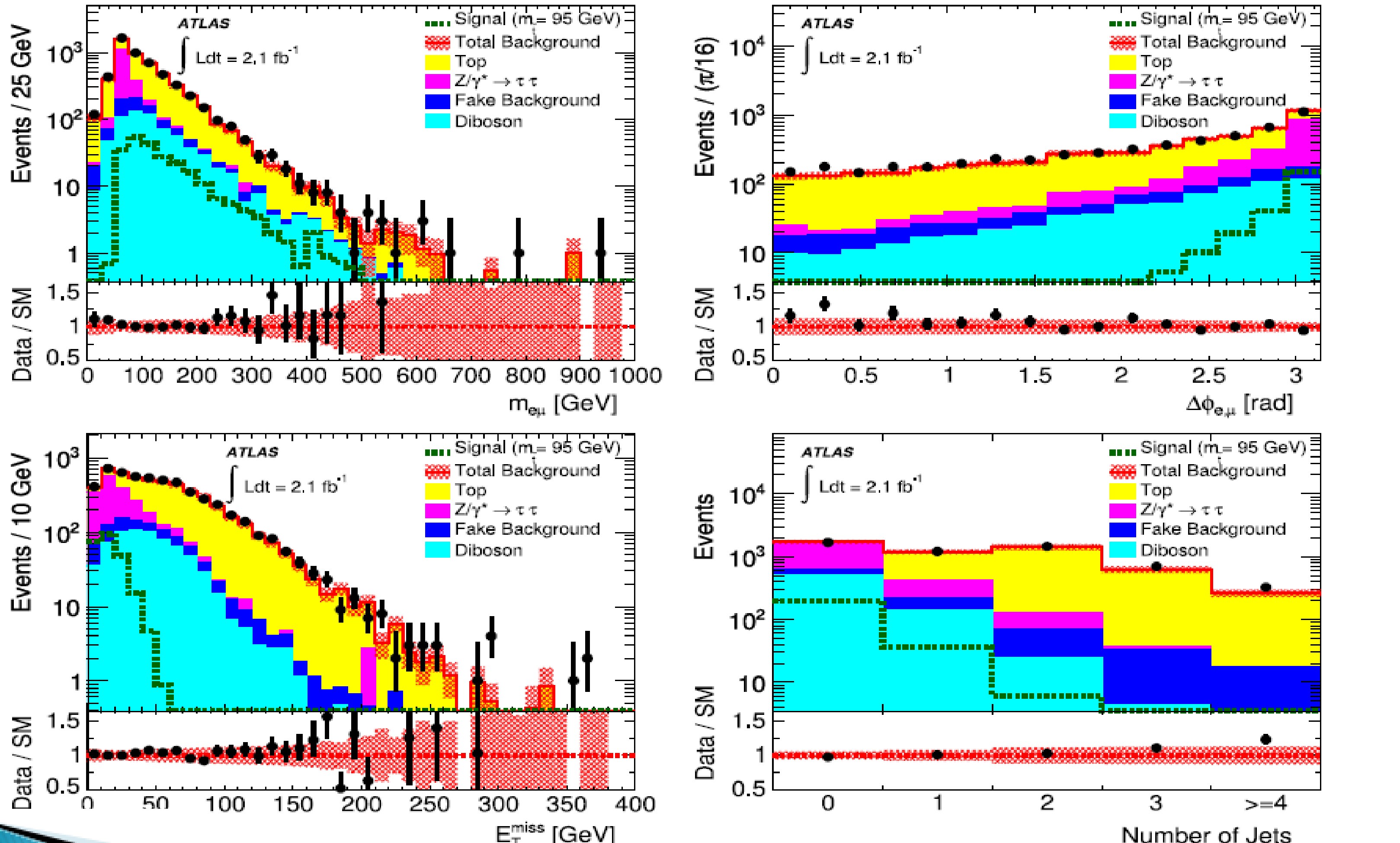
Details on slide 14

Process	Preselection
$t\bar{t}$	2800 ± 400
$Z/\gamma^* \to \tau\tau$	1210 ± 110
WW	640 ± 50
Fake background	290 ± 40
Single top	270 ± 40
WZ	36 ± 4
$W/Z + \gamma$	20 ± 7
ZZ	4.0 ± 0.4
Total background	5300 ± 400
Data	5387
Signal ($m_{\tilde{t}} = 95$ GeV)	240 ± 15
Signal ($m_{\tilde{t}} = 500$ GeV)	3.05 ± 0.18
Signal ($m_{\tilde{t}} = 1000$ GeV)	0.305 ± 0.018

Event observation and sig/Background estimation

stop→eμ continuum search at ATLAS

Data Vs. MC



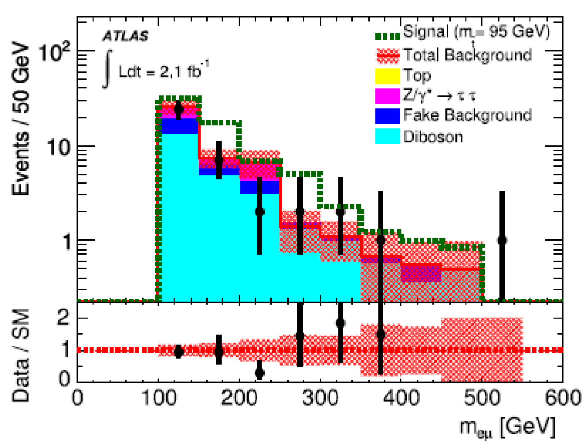
stop→eμ continuum search at ATLAS

Further event selection

Due to **no mass peak**, it's not enough to use only the invariant mass distribution of eμ to provide adequate separation of signal and bkgd

$$\begin{cases} m_{e\mu} > 100\text{GeV} \\ \Delta\phi_{e\mu} > 3.0 \\ E_T^{miss} < 25\text{GeV} \\ N_{jet} = 0 \end{cases}$$

→ **Optimized by maximizing the significance**



Process	Final selection
WW	23.4 ± 3.3
$Z/\gamma^* \to \tau\tau$	10 ± 4
Fake background	9.6 ± 1.9
WZ	0.76 ± 0.31
$t\bar{t}$	0.25 ± 0.17
Single top	0.22 ± 0.20
$W/Z + \gamma$	0.04 ± 0.04
ZZ	0.042 ± 0.028
Total background	44 ± 6
Data	39
Signal ($m_{\tilde{t}} = 95$ GeV)	67 ± 5
Signal ($m_{\tilde{t}} = 500$ GeV)	1.28 ± 0.08
Signal ($m_{\tilde{t}} = 1000$ GeV)	0.124 ± 0.008

stop→eμ continuum search at ATLAS

Systematics

Source	Fractional Uncertainty	Applicable To
Luminosity	3.7%	Signal + All Background
Trigger	1%	Signal + All Background
Electron reco and ID efficiency	2%	Signal + MC Background
Muon reco and ID efficiency	1%	Signal + MC Background
Jet energy scale	3.6%	Signal + MC Background
Electron energy smearing	0.9%	Signal + MC Background
Muon momentum smearing	0.3%	Signal + MC Background
Theoretical cross section	5 - 15%	MC Background Only
E_T^{miss} Uncertainty	12.2%	Signal + MC Background Only
MC Shape Uncertainty	13%	*WW* Background Only
Matrix method	15.0%	Instrumental Only

The mainly systematic sources are:
Missing Et, WW MC shape and jet-fake background estimation

stop→eμ continuum search at ATLAS

Limit setting

- **Since no excess is observed in data, limits are set on $\sigma_{sTop \to e\mu}$**

  $m_{e\mu}$ distribution in a single bin for $m_{e\mu} > 400$ GeV is used

- **A modified-frequentist approach is used**

  using a binned log-likelihood ratio (LLR)

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

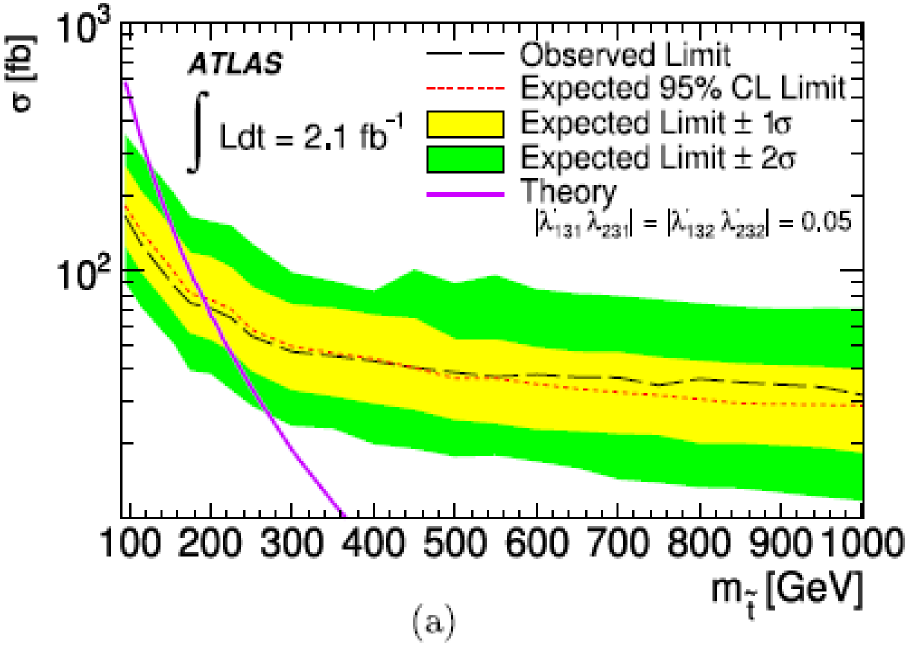
$$CL_{s+b} = \int_{LLR(s+b|x)}^{\infty} P(s+b|x')\, d(LLR(s+b|x'))$$

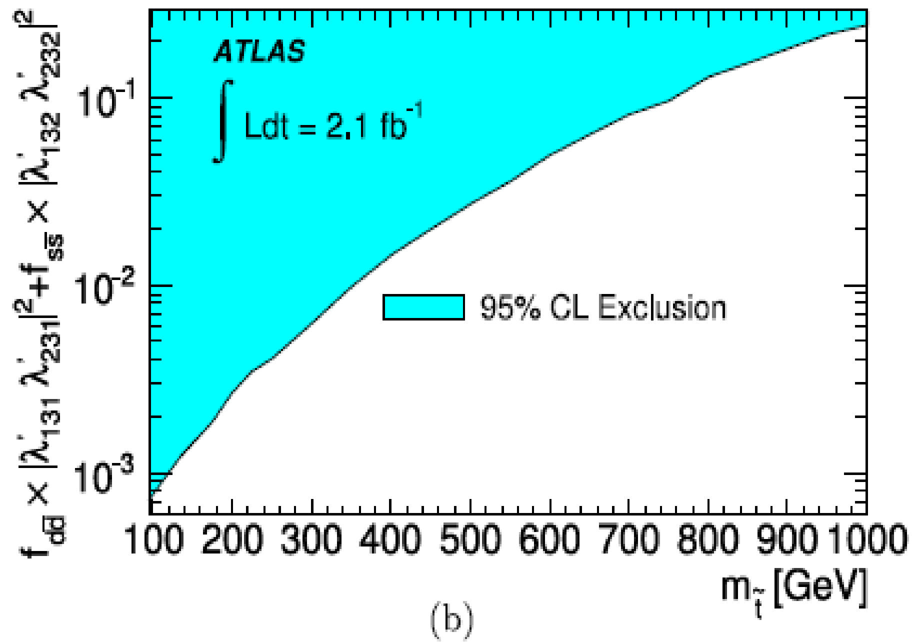
$$CL_b = \int_{LLR(b|x)}^{\infty} P(b|x')\, d(LLR(b|x'))$$

s: signal
b: bkgd
x’: data

stop→eμ continuum search at ATLAS

Limits for stop search





observed 95 % CL upper limits on σ(stop → eμ)

Excluded region for the PDF weighted sum of couplings

M_{stop}=95GeV

(≥)4-lepton RPV search

- "Leptons" refers to electrons or muons
- including those from τ decays
- does not include τ leptons that decay hadronically

Super-potential term

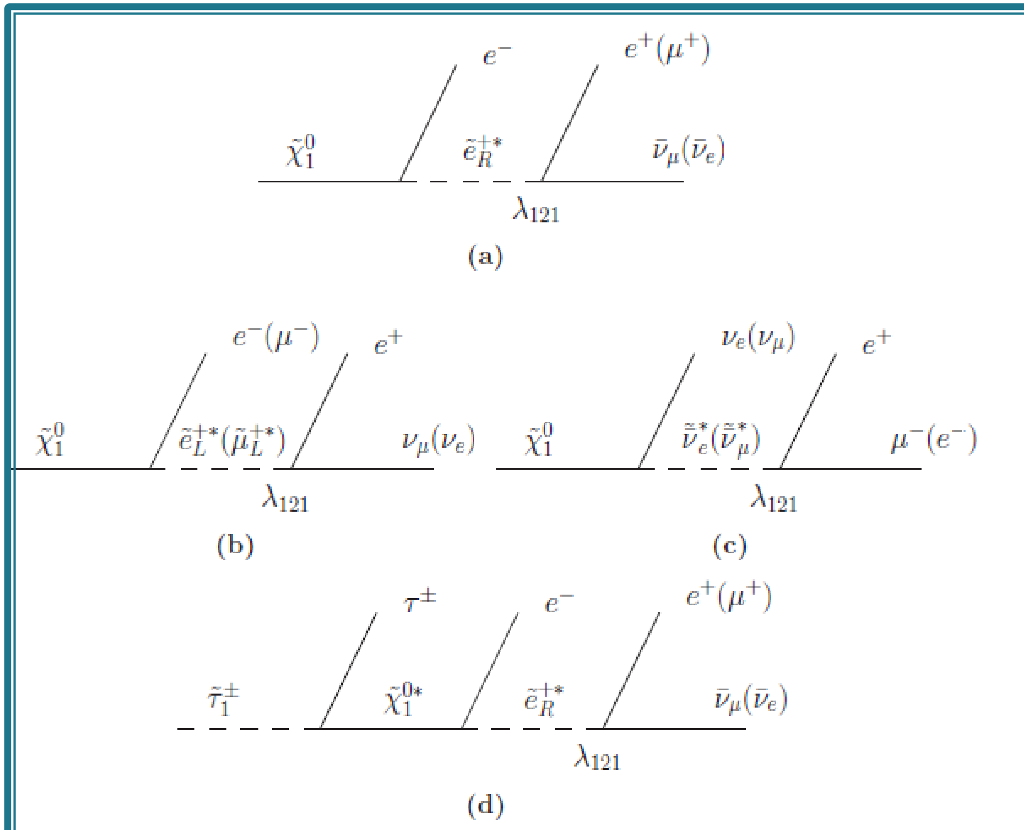
$$W_{RPV} = \lambda_{ijk} L_i L_j \bar{E}_k$$

- i,j,k refer to the lepton generations
- L:lepton SU(2) doublet super-fields

Several scenarios, eg.
Pair production of

$\tilde{\chi}_i^\pm \to W^{(*)} + \tilde{\chi}_1^0$
$\tilde{g} \to q\bar{q}'\tilde{\chi}_1^0$
} "simplified model"

$\tilde{\tau}_1^\pm \to \tau^\pm \tilde{\chi}_1^0$ ➡ "MSUGRA model"



(≥)4-lepton RPV search

Objects & event pre-selection

- Single e/μ trigger and double e/μ trigger
- Data quality cuts
- Good primary vertex

Electron
- pT>10GeV, |η|<2.47,remove crack
- tight
- calo isolation & track isolation

Jet
- AntiKt4
- pT>20GeV, |η|<2.5
- JVF>0.75

Muon
- pT>10GeV, |η|<2.4
- |d0| and |z0| requirement
- calo isolation & track isolation
- track quality

Tau(hadronic)
- pT>20GeV, |η|<2.5
- JetBDTSigLoose
- electronVeto

dR(jet,lepton)>0.4

Signal region selection

2 signal regions

7TeV, 5fb^{-1}

Selection	SR1	SR2
Number of leptons	≥ 4	≥ 4
Z-candidate	veto	veto
E_T^{miss}/GeV	> 50	–
m_{eff}/GeV	–	> 300

$$m_{eff} = E_T^{miss} + \sum_\mu p_T^\mu + \sum_e E_T^e + \sum_j E_T^j.$$

8TeV, 21fb^{-1}

SR	N($\ell = e, \mu$)	N(τ)	Z Candidate	E_T^{miss}[GeV]		m_{eff}[GeV]	Scenario
SR0noZb	≥4	≥0	extended veto	>75	or	>600	RPV
SR1noZ	=3	≥1	extended veto	>100	or	>400	RPV

(≥)4-lepton RPV search

Background estimation

Same strategy for both 7TeV and 8TeV analyses

Irreducible background

events with four real, isolated leptons

- ZZ
- $t\bar{t}Z$
- $t\bar{t}WW$

Estimated from corrected MC samples

reducible background

process has at least one "fake" lepton
- ✓ Jet fake
- ✓ γ conversion

estimated using a weighting method

$$[N_{\text{data}}(3\ell_S+\ell_L)-N_{\text{MCirr}}(3\ell_S+\ell_L)]\times F(\ell_L)$$
$$-[N_{\text{data}}(2\ell_S+\ell_{L_1}+\ell_{L_2})-N_{\text{MCirr}}(2\ell_S+\ell_{L_1}+\ell_{L_2})]\times F(\ell_{L_1})\times F(\ell_{L_2})$$

ℓ_S: signal leptons
ℓ_L: loose leptons, which are tagged leptons failing the signal lepton requirements

$$F=\sum_{i,j}(\alpha^i\times R^{ij}\times f^{ij})$$

i is the type of fake (heavy-flavour leptons or conversion electrons)

j is the process category the fake originates from (top quark or W/Z boson)

Got from MC →
f^{ij} ratio of tagged leptons faked as "signal" vs. "loose"
R^{ij} Weighting factor according to fractional contribution of the process

α^i fake ratio measured in data divided by that in simulation

More details: JHEP12(2012)124

(≥)4-lepton RPV search

Background estimation

7TeV, 5fb^{-1}

Selection	SR1	SR2
SUSY ref. point 1	6.5 ± 0.6	7.1 ± 0.7
SUSY ref. point 2	4.2 ± 0.6	4.5 ± 0.6
ZZ	0.14 ± 0.11	0.51 ± 0.30
$t\bar{t}Z$	0.023 ± 0.014	0.029 ± 0.016
$t\bar{t}WW$	0.0044 ± 0.0035	0.005 ± 0.004
Σ Irreducible	0.17 ± 0.12	0.54 ± 0.31
Reducible	0.8 ± 0.8	0.18 ± 0.26
Σ SM	**1.0 ± 0.8**	**0.7 ± 0.4**
Data	**3**	**2**
p_0-value (σ)	0.05 (1.7)	0.07 (1.5)
σ_{vis} obs (exp)	1.3 (0.8)	1.1 (0.7)

8TeV, 21fb^{-1}

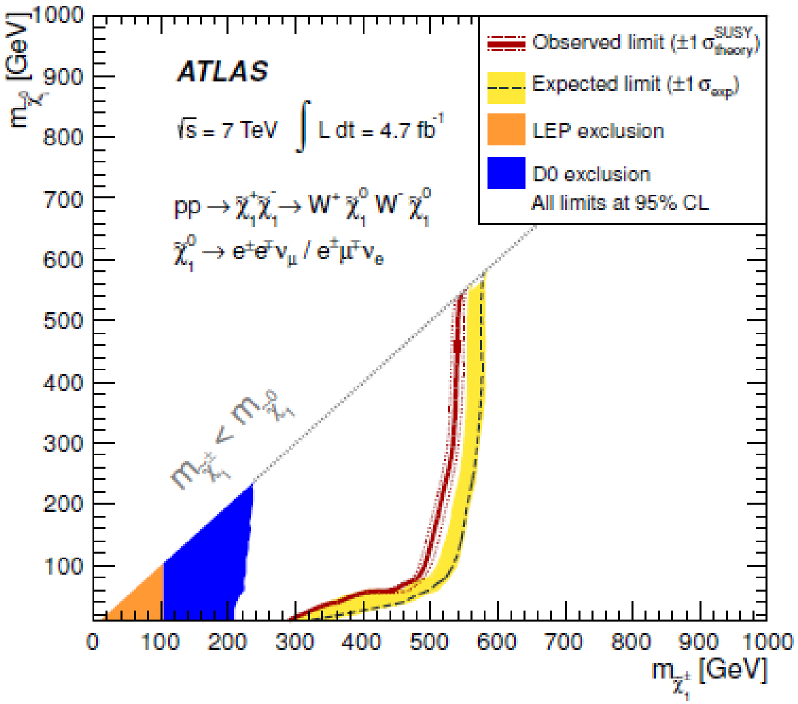
Sample	SR0noZb	SR1noZ
ZZ	0.50 ± 0.26	0.19 ± 0.05
ZWW	0.08 ± 0.08	0.05 ± 0.05
$t\bar{t}Z$	0.75 ± 0.35	0.16 ± 0.12
Higgs	0.22 ± 0.07	0.23 ± 0.06
Irreducible Bkg.	1.6 ± 0.6	0.62 ± 0.21
Reducible Bkg.	$0.05^{+0.14}_{-0.05}$	1.4 ± 1.3
Total Bkg.	1.6 ± 0.6	2.0 ± 1.3
Data	1	4
p_0-value	0.5	0.15

No significant excess of events is found in the signal regions.

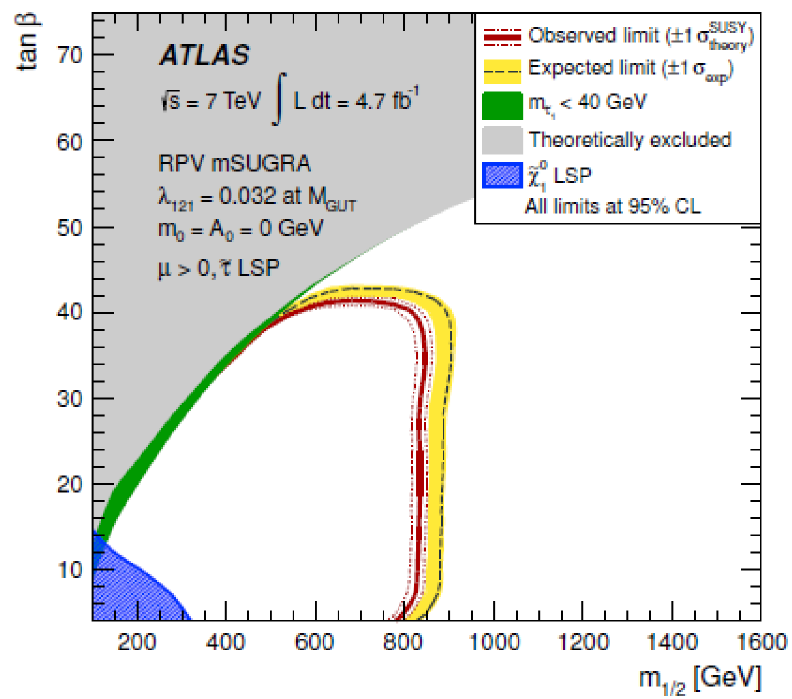
(≥)4-lepton RPV search

Limit setting results

7TeV, $5fb^{-1}$



"simplified model"



"MSUGRA model"

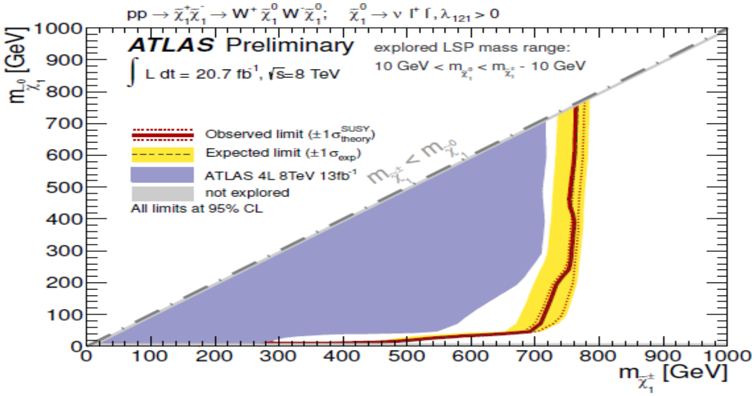
Chargino masses up to 540GeV are excluded for LSP masses above 300GeV

$m_{1/2}$ below 820GeV are excluded when $10 < \tan\beta < 40$

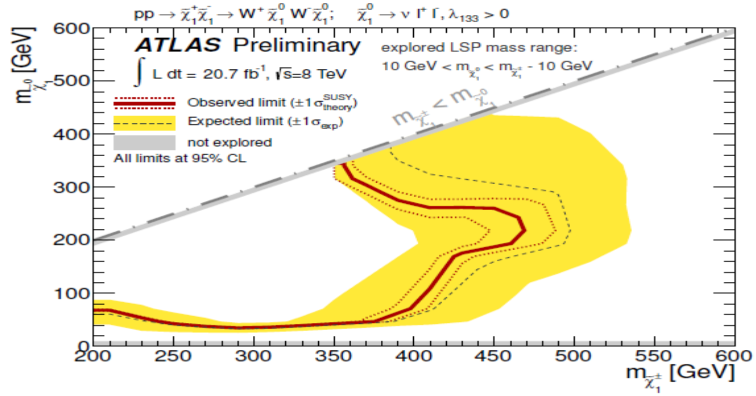
(≥)4-lepton RPV search

Limit setting results

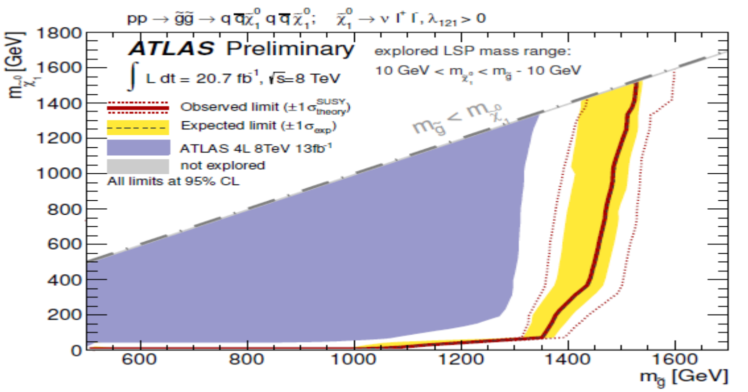
8TeV, 21fb^{-1}



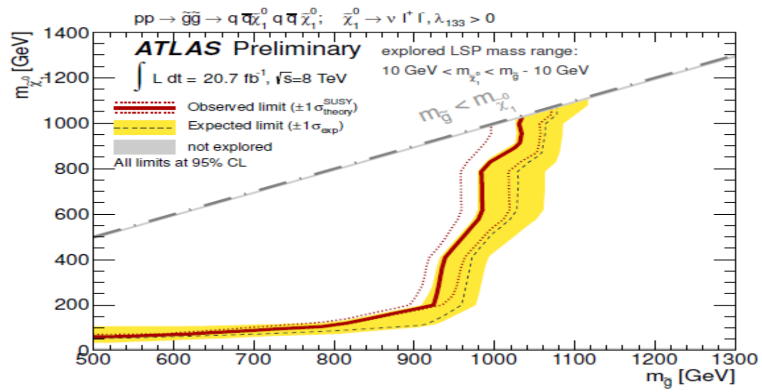
(a) Wino $\lambda_{121} \neq 0$



(b) Wino $\lambda_{133} \neq 0$



(c) Gluino $\lambda_{121} \neq 0$



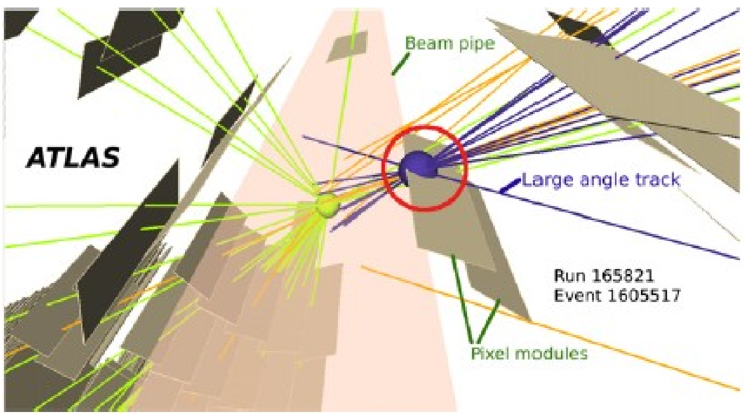
(d) Gluino $\lambda_{133} \neq 0$

- Wino model: NLSP masses of up to ~ 750GeV (~ 400GeV) are excluded
- Gluino model: NLSP masses of up to ~ 1400GeV (~ 1000GeV) are excluded

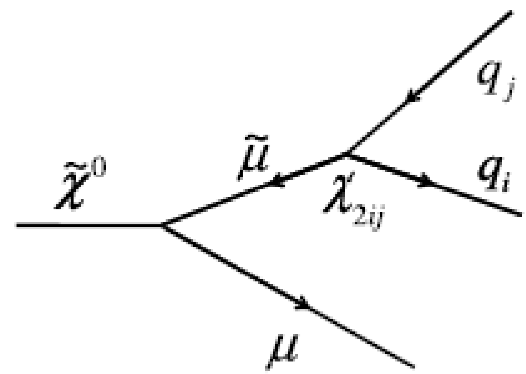
for λ_{121} (λ_{133})

Muon + displaced vertex search

- Search for long-lived, heavy particles in final states with a high pT muon and multi-track **displaced vertex** (a distance of order millimeters to tens of centimeters from IP)
- performed 2 searches with 2010 35pb^{-1} and 2011 5fb^{-1} respectively



An example of DV with a high-pT track



SUGRA scenario,

Under such a scenario, processes are simulated in which a pair of squark is produced:

$$\tilde{q}\tilde{q} / \bar{\tilde{q}}\bar{\tilde{q}} / \tilde{q}\bar{\tilde{q}} \rightarrow qq / \bar{q}\bar{q} / q\bar{q} + \tilde{\chi}^0\tilde{\chi}^0$$

Muon + displaced vertex search

Event selection

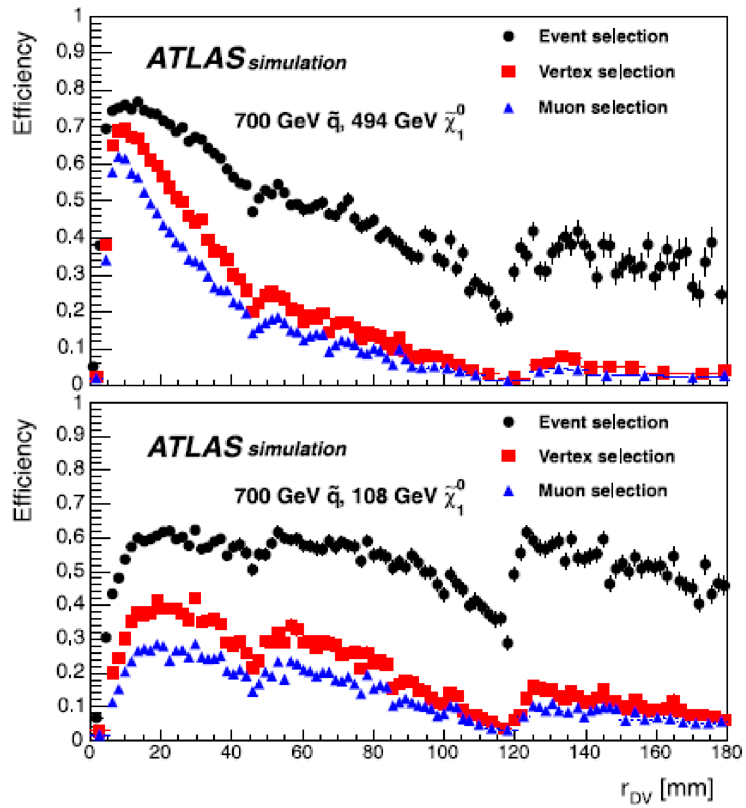
- Event pass L1_mu40 trigger
- PV: $n_{track}>4$; $|z|<200mm$

Displaced Vertex(DV) selection

- In pixel region
- vertex recon quality
- transverse distance from PV >4mm
- $n_{track}>3$
- m_{DV} > 10 GeV
- veto vertices within regions of high-density material

Muon selection

- staco mu
- pT>45GeV(>50GeV for 2011 data)
- $|\eta|<1.07$
- |d0|>1.5mm(for 2011 data)
- Match with L1 trigger
- SCT&TRT hits requirement

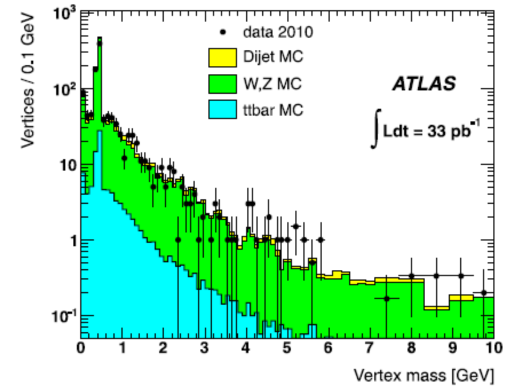


The efficiency as a function of r_{DV} for vertices in the signal MC samples

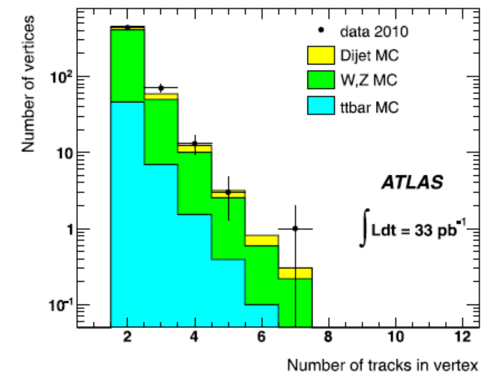
Muon + displaced vertex search

Background estimation

Data Vs Mc in the control region, $m_{DV} < 10$ GeV and before applying the material veto



- Background events to satisfy all the selection criteria is extremely low
- use background MC samples to estimate the number of data events of each background type

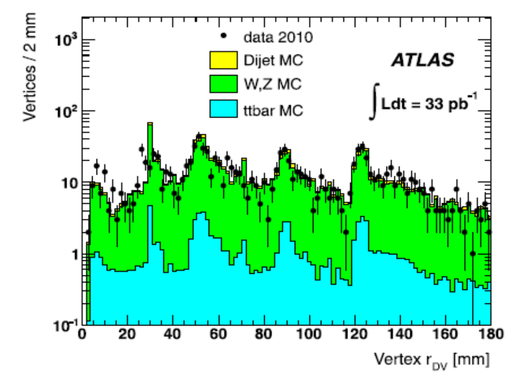


In 2010 data:

no events are observed in data
fewer than 0.03 background events are expected

In 2011 data:

no events are observed in data
fewer than 0.06 background events are expected



More details: Physics Letters B 719 (2013) 280-298

Muon + displaced vertex search

systematics

Dominant sources

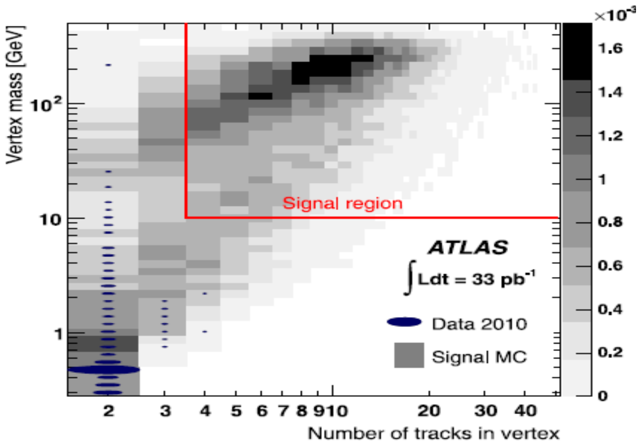
•performance of vertex reconstruction algorithm

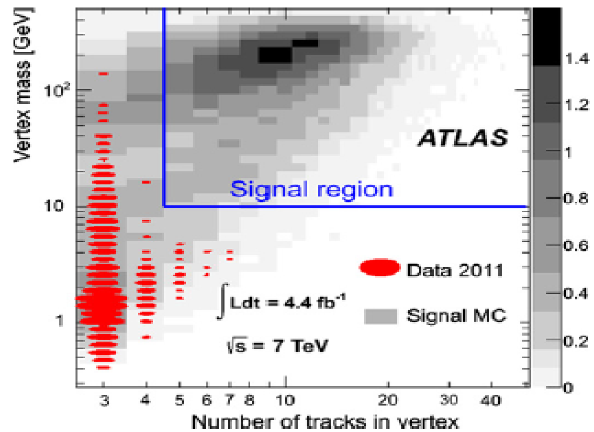
• Pileup

• Signal PDF

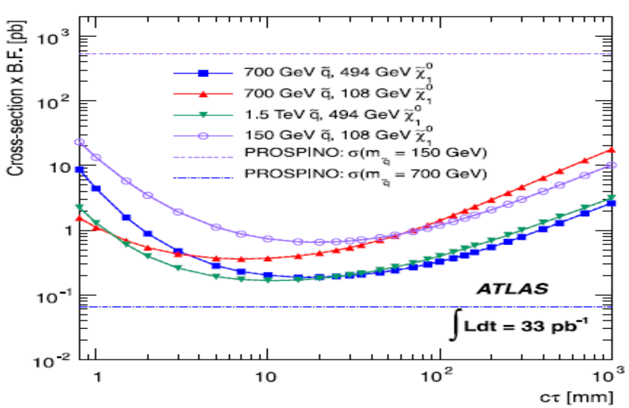
Muon + displaced vertex search

Results

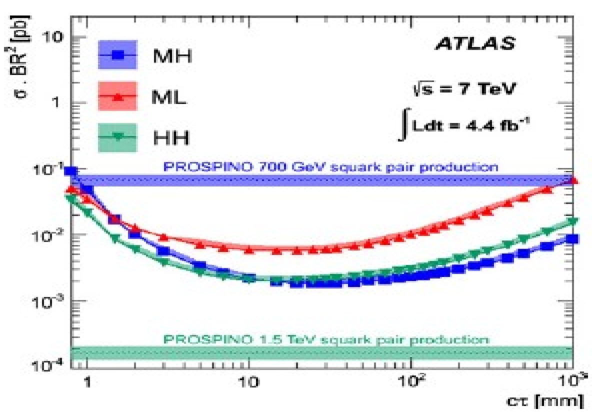




Vertex mass vs. vertex track multiplicity for displaced vertices



2010 33pb^{-1}



2011 4.4fb^{-1}

Upper limits at 95% CL on the σ x Br. vs. the neutralino lifetime times c (light speed)

Summary

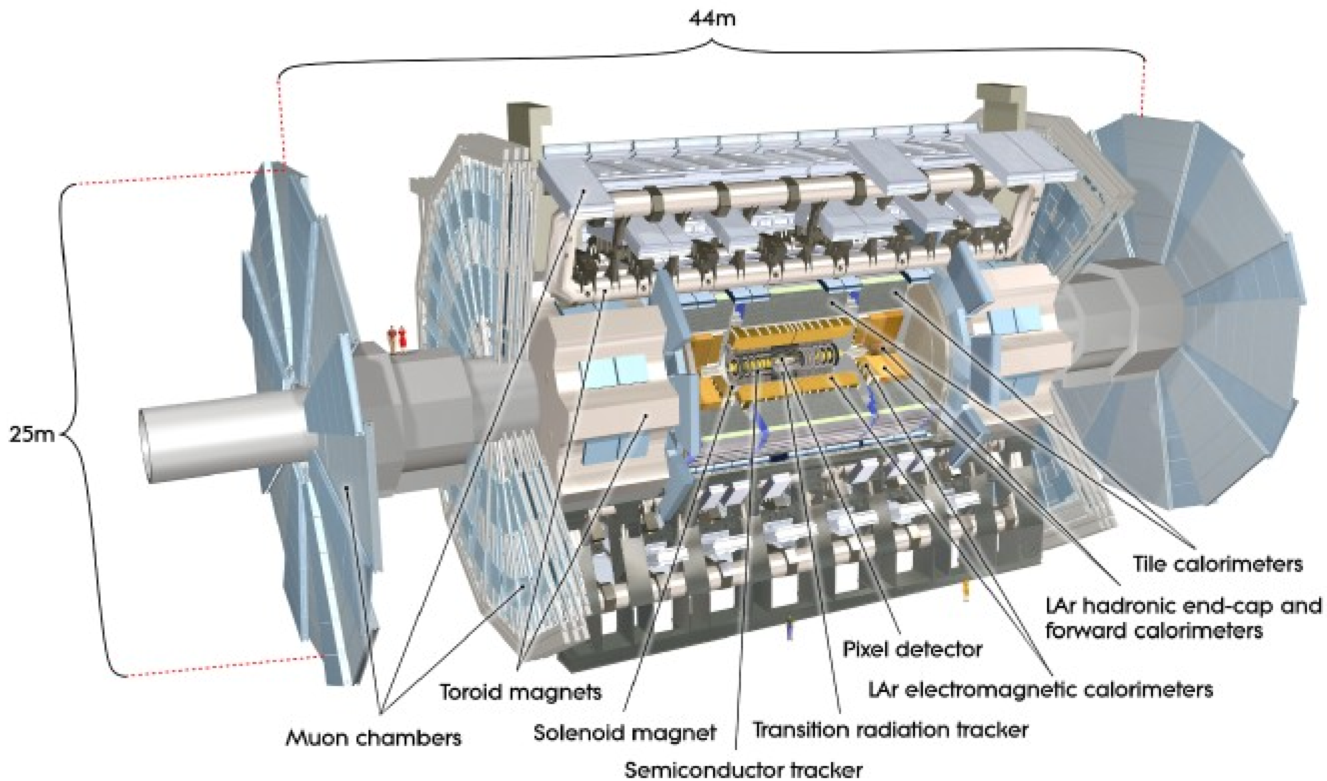
- We have performed 5 studies aiming at LFV search based on 7TeV/8TeV datasets, and made 7 publications

- Data are found to be consistent with standard model predictions, thus limits are set based on different models

- 8TeV analyses for LFV are on their way, and more topics are included

Backup

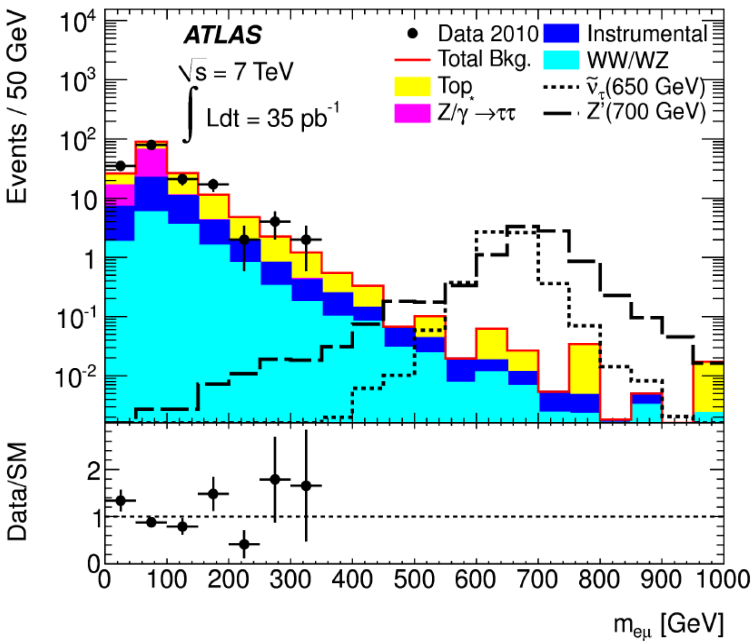
The ATLAS detector



$\tilde{\nu}_\tau$ →eμ/eτ/μτ resonance search

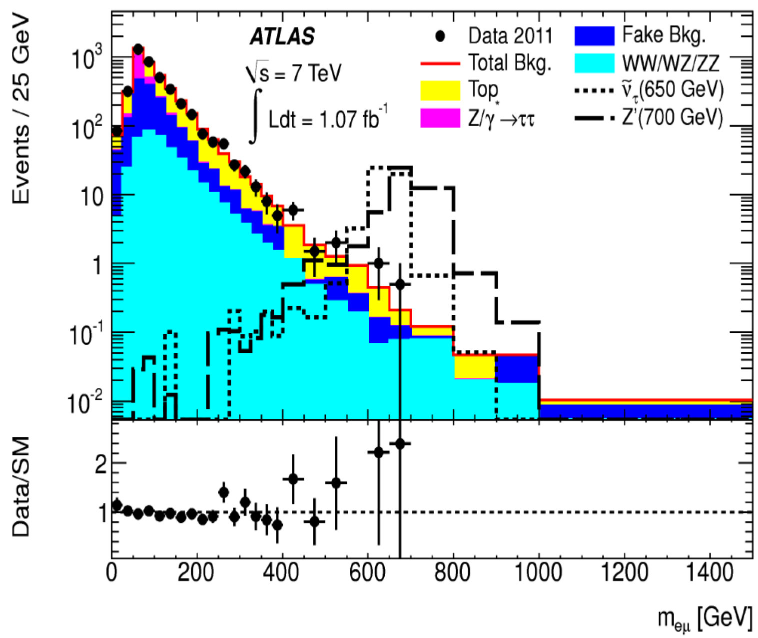
Control plots: data Vs. MC

Plots for 35pb⁻¹



Invariant mass of eμ

Plots for 1fb⁻¹



Invariant mass of eμ

Reasonable Agreement

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

systematics

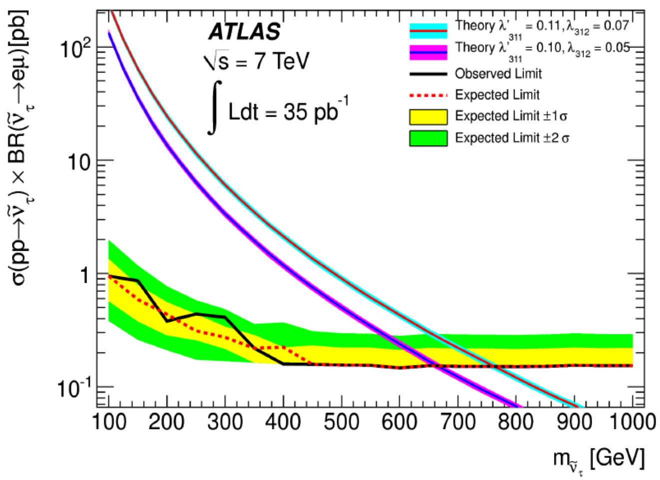
Source	Relative uncertainty
Luminosity	3.7% (11% for 2010 data)
Trigger efficiency	1%
Electron Reco & ID efficiency	2%
Muon Reco & ID efficiency	1%
$Z/\gamma^* \rightarrow \tau\tau$ cross section	5%
WW and WZ cross section	7%
ZZ cross section	5%
Ttbar cross section	10%
Single top	9%
$W\gamma$, $Z\gamma$ cross section	10%

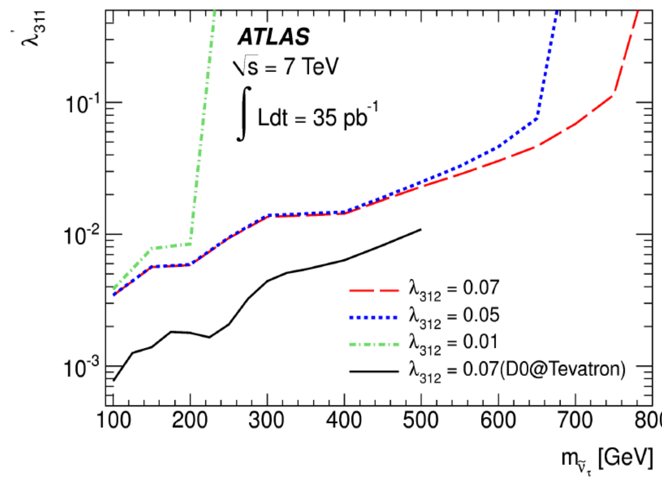
For $35pb^{-1}$ & $1fb^{-1}$

$\tilde{\nu}_\tau \rightarrow e\mu/e\tau/\mu\tau$ resonance search

Limits to new physics

limits for 35pb^{-1}





limits for 1fb^{-1}