Yield extraction of a 4th generation signal with the ATLAS detector

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GK blockcourse
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1. Introduction to a 4th family of fermions
   - Motivation
   - Search signature
   - Particle and event selection
2. Counting analysis
   - Idea
   - Control samples
   - Estimation of control ratios and signal yields
3. Results for b' (300 GeV)
   - Mixing sample
   - Signal and control regions
   - Result
   - Convergences
4. Summary

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Motivation

Present situation:

- Number of families not fixed by the Standard Model
- Z-resonance (LEP I): $N_\nu = 3$ with $m_\nu < m_Z/2$
- If ν_4 exists: $m_{\nu_4} \gtrsim m_Z/2$

With a fourth generation:

- Possible way to explain baryogenesis
  (Fok et al, Phys.Rev.D78:075023,2008; Hou, Chin. J. Phys.47:134, 2009)
- Higher Higgs mass (up to 600GeV) possible
  (Kribs et al, Phys.Rev.D76:075016,2007)

Direct limits

Current mass limits on short living particles @ 95% CL:

Particle	m_{min} [GeV]	Experiment
ℓ_4	100	LEP
ν_4 (Dirac)	90.3	LEP
ν_4 (Majorana)	80.5	LEP
t'	311	Tevatron
b'	325	Tevatron

Consequence for us:

- Looking for 4th generation quarks with m $\geq$ 300GeV

Tiny mixing angles between 4th and other families
$\Rightarrow$ **particles could have long lifetime:**

- Mass limit depends on CKM elements and mass of other heavy quark (Hung el all,, Phys.Rev.D77:037302,2008)

Search signature

Assumption: m(b')-m(t) > m(W), $V_{tb'}$ sufficiently large wrt $V_{ub'}$ and $V_{cb'}$

Final states of t' and b' decay with sizable branching fraction:

m(t') > m(b')	m(t')-m(b') > m(W)	$b'\bar{b}' \to t\bar{t} + 2W \to b\bar{b}2W^+2W^-$ $t'\bar{t}' \to b'\bar{b}' + 2W \to b\bar{b}3W^+3W^-$
	m(t')-m(b') < m(W)	$b'\bar{b}' \to tW^-\bar{t}W^+ \to b\bar{b}2W^+2W^-$ $t'\bar{t}' \to bW^+\bar{b}W^-$
m(b') > m(t')	m(b')-m(t') > m(W)	$b'\bar{b}' \to t'W^-\bar{t}'W^+ \to b\bar{b}2W^+2W^-$ $b'\bar{b}' \to tW^-\bar{t}W^+ \to b\bar{b}2W^+2W^-$ $t'\bar{t}' \to bW^+\bar{b}W^-$
	m(b')-m(t') < m(W)	$b'\bar{b}' \to tW^-\bar{t}W^+ \to b\bar{b}2W^+2W^-$ $t'\bar{t}' \to bW^+\bar{b}W^-$

Search scenario

Decay channels:

- $b'\bar{b}' \to t\bar{t} + W^+W^- \to b\bar{b} + 2W^+2W^-$
- $t'\bar{t}' \to b'\bar{b}' + W^+W^- \to t\bar{t} + 2W^+2W^- \to b\bar{b} + 3W^+3W^-$

$\Rightarrow$ Exclusive reconstruction difficult but inclusive multilepton final state interresting

$\Rightarrow$ b' final states: $\ell^\pm\ell^\pm/3\ell$ + jets

$\Rightarrow$ t' final states: $\ell^\pm\ell^\pm/3\ell$ + jets

$\Rightarrow$ rare standard model signatures

- signature also used in "Search for A Fourth Generation b' Quark in tW Final State at CMS in pp Collisions at $\sqrt{s} = 10$ TeV" (CMS PAS EXO-09-012)

Lepton selection

Leptons

particle	p_T^{min} [GeV]	$\lvert\eta^{max}\rvert$	E_T^{cone20} [GeV]
$e^\pm$	20	< 2.5	< 8
$\mu^\pm$	20	< 2.5	< 10

- E_T^{cone20}: Energy sum in a cone R $= \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.2$
- Muons: $\chi^2/NDoF < 5$ for matching between tracks in Muon Spectrometer and Inner Detector

Jet selection

Jets

- Cone jet algorithm with $\Delta R < 0.4$
- Remove misidentified jets in a cone $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.2$ and $|\eta| < 2.5$ with $e^\pm$, $\mu^\pm$, γ and $\tau^\pm$
- $E_T^{jet} > 25$GeV in order to suppress jets from underlying event

Event selection

Missing energy:

- Use for calculation:
  - Jets
  - Muons
  - Correction function for dead material (cryostat)
  - Calorimeter cells in $e^{\pm}$, $\tau^{\pm}$, γ
- $\not{E}_T > 20 GeV$

Leptons and jets

- **Electrons and muons** : $P_T^{leading} > 35\text{GeV}$
- **Jets** : $E_T^{leading} > 85\text{GeV}$

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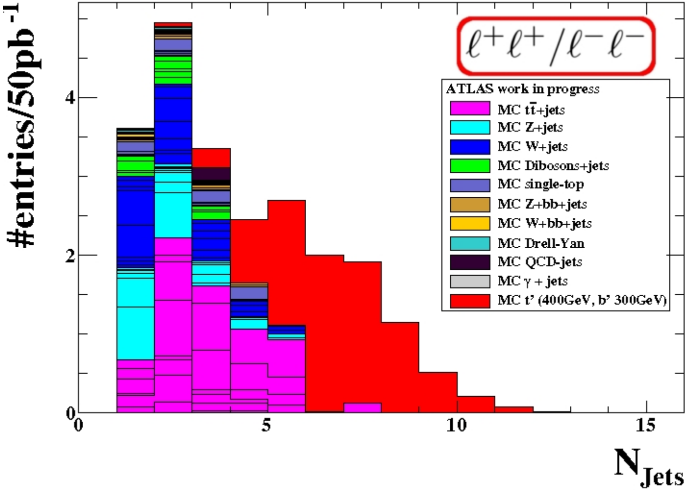
Motivation



$\Rightarrow$ How to reliably estimate the background on data?

Idea

Procedure

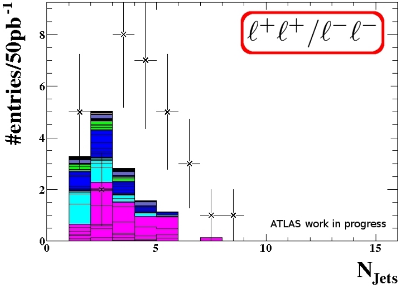
- Long term: Likelihood fit in N_{Jets}
- This talk: Counting analysis (N_{Jets} only used as control distribution)
- Two issues:
  1. Control of background cross sections (included in this talk)
  2. Lepton fake rates (long term)

Test of procedure using MC pseudo-data

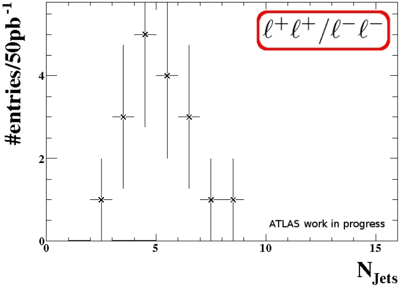
- Mixing sample is used as pseudo-data
- Selecting randomly events from each MC background and signal sample corresponding to specific luminosity (here: $50pb^{-1}$) and assuming specific cross section ($N = \sigma \cdot L$)
- Using the remaining events as the MC prediction

Subtracting background

- Counting of observed entries on data in specific **signal region (SR)** and subtraction of MC background
- **Signal region**: Lepton category (same sign dileptons)



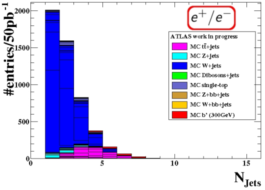
$\Rrightarrow$



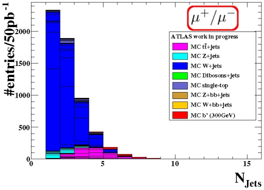
$$\boxed{N^{Sig} = N^{Data} - N^{MC}}$$

Control samples

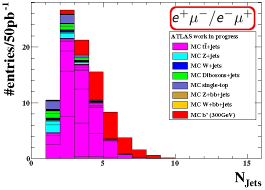
Lepton categories and dominating background



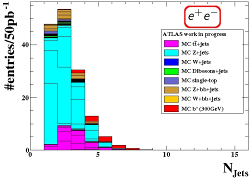
CR for $W \rightarrow e\nu$



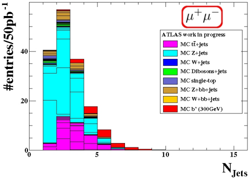
CR for $W \rightarrow \mu\nu$



CR for $t\bar{t}$



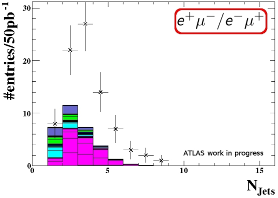
CR for $Z \rightarrow ee$



CR for $Z \rightarrow \mu\mu$

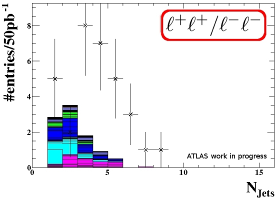
Controlling background

- Control main backgrounds in **control regions (CR)**
- **Same event cuts** as SR but **different lepton categories**
- Modifying MC predictions by control ratios



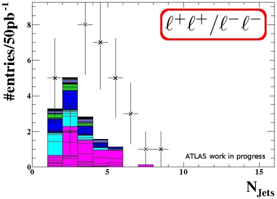
Control region for $t\bar{t}$

Pseudo-data: $\sigma_{t\bar{t}} \longrightarrow k_\sigma \cdot \sigma_{t\bar{t}}$ (here: $k_\sigma = 3$)



Signal region

$\Rrightarrow$



Signal region (corrected)

Estimation of control ratios and signal yields

Calculation - Iteration 0

$$N^0_{Sig} = N^{SR}_{data} - \sum_i \left(N^{SR}_{MC,i} \cdot \mathbf{R^0_i} \right) - \sum_{i_{other}} N^{SR}_{MC,i_{other}}$$

$$\mathbf{R^0_i} = \frac{N^{CR,i}_{data}}{N^{CR,i}_{MC,i}}$$

- $N_{MC(data)}$: Number of entries in N_{Jets} histogram of MC (data) sample
- $\sum_i$: Sum over data-driven corrected BG samples
- $\sum_{i_{other}}$: Sum over other, uncorrected BG
- $\mathbf{R^0_i}$: Correction factor for sample i, also calculated for signal in SR

Estimation of control ratios and signal yields

Calculation - Iteration k

$$R_i^0 = \frac{N_{data}^{CR,i}}{N_{MC,i}^{CR,i}} \quad \Rightarrow \quad R_i^k = \frac{N_{data}^{CR,i} - \sum_{\mathbf{m} \neq \mathbf{i}} \mathbf{R}_{\mathbf{m}}^{\mathbf{k-1}} \cdot \mathbf{N}_{\mathbf{MC},\mathbf{m}}^{\mathbf{CR}}}{N_{MC,i}^{CR,i}}$$

- $\sum_{\mathbf{m}}$: **Sum over all BG (corrected and uncorrected) and MC signal sample**
- $\mathbf{R}_{\mathbf{m}}^{\mathbf{k-1}}$: Correction factor of previous iteration for sample m ($= 1$ for uncorrected BG), also calculated for signal in SR

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Mixing sample

Modified cross sections σ in mixing sample generation by factor k_σ

$$\sigma \longrightarrow k_\sigma \cdot \sigma$$

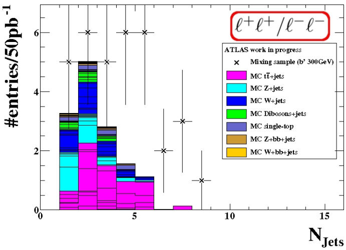
Modification of cross sections in production of mixing sample

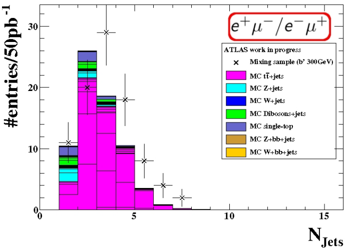
Modified sample	Modification factor k_σ
b' (300 GeV)	1.15
$We\nu$+jets (MC)	0.9
$W\mu\nu$+jets (MC)	0.9
Zee+jets (MC)	0.9
$Z\mu\mu$+jets (MC)	0.9
$t\bar{t}$+jets (MC)	1.15
Dibosons+jets	0.9

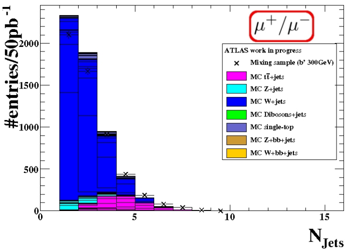
Expected result from MC signal sample

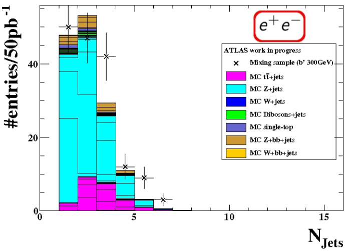
Expecting $\mathbf{21.6 \pm 0.3}$ signal events

Signal and control regions **before** correction procedure

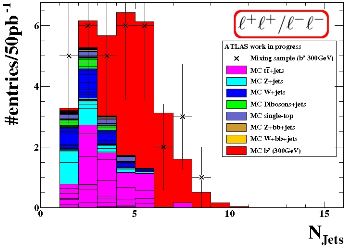


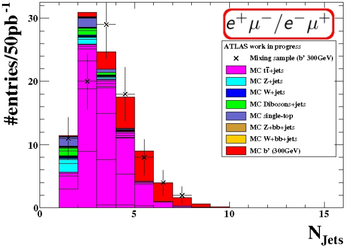


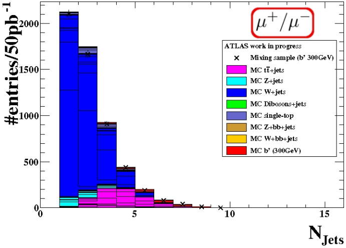


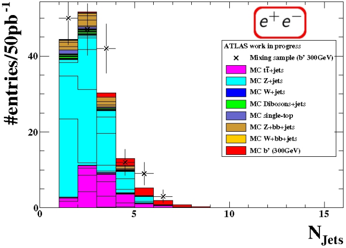


Signal and control regions **after** correction procedure







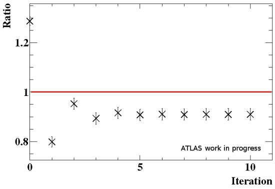


Result for b' (300 GeV) @ $50pb^{-1}$, $\sqrt{s} = 10$ TeV

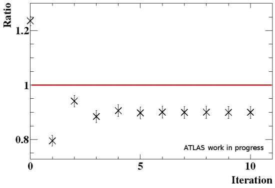
Results

Sample	Events	Final R_i^k	k_σ
data	34 ± 6		
$We\nu$+jets (MC)	0.6 ± 0.2	0.91 ± 0.02	0.9
$W\mu\nu$+jets (MC)	1.6 ± 0.3	0.90 ± 0.02	0.9
Zee+jets (MC)	2.6 ± 0.4	0.95 ± 0.06	0.9
$Z\mu\mu$+jets (MC)	0.11 ± 0.04	0.90 ± 0.05	0.9
$t\bar{t}$+jets (MC)	6.5 ± 0.9	1.0 ± 0.2	1.15
other (MC)	2.2 ± 0.9		
Result	20 ± 6		
Expected	21.6 ± 0.3		

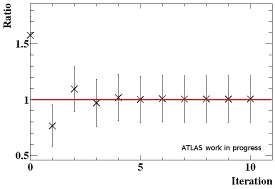
Convergence plots of control ratios



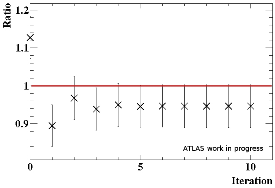
Ratio for $W \rightarrow e\nu$



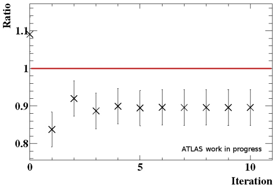
Ratio for $W \rightarrow \mu\nu$



Ratio for $t\bar{t}$



Ratio for $Z \rightarrow ee$



Ratio for $Z \rightarrow \mu\mu$

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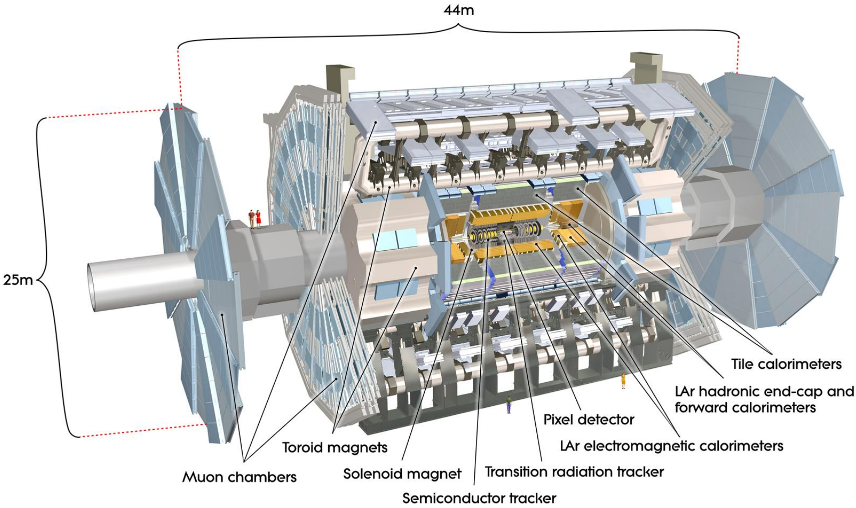
Summary

- $\ell^{\pm}\ell^{\pm}/3\ell$ + jets are good search signatures
- Data driven analysis for extraction of 4th generation signal developed
- Generally applicable on analysis where background and signal pass the same event selection cuts but contribute with different efficiencies in different event categories (here: lepton charges and multiplicities)
- Signal yield limited by statistics in SR $\rightarrow$ Errors on control ratios negligible
- Stability: Control ratios converge after few iteration steps
- Test with pseudo-data shows no bias for control ratios and signal yield
- Not shown: Works als with no signal in pseudo data

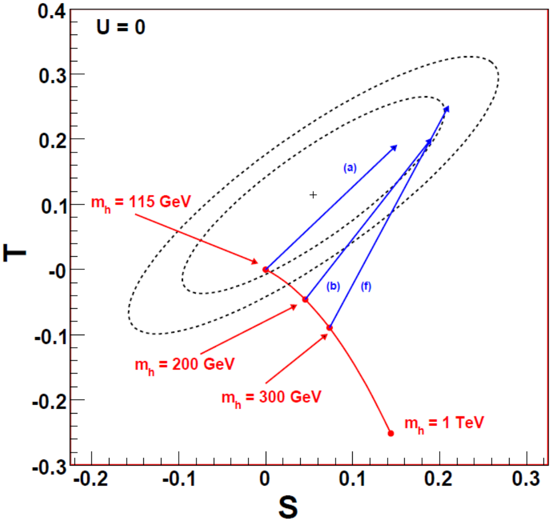
Thank you !!!

Backup slides

ATLAS detector



ST-Ellipse



U = 0
T
S
0.4
0.3
0.2
0.1
-0
-0.1
-0.2
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
m_h = 115 GeV
m_h = 200 GeV
m_h = 300 GeV
m_h = 1 TeV
(a)
(b)
(f)

Particle selections

Electrons

- Standard (HighPt), tight electrons
- $P_T > 20$ GeV, $|\eta| < 2.5$, $E_T^{cone20} < 8$ GeV

Muons

- STACO muons
- $\chi^2/ndf < 5$
- $P_T > 20$ GeV, $|\eta| < 2.5$, $E_T^{cone20} < 10$ GeV

Jets

- Cone4H1Tower jets
- Overlap removal with e, μ, τ, γ within $\Delta R < 0.2$
- $E_T > 25$ GeV, $|\eta| < 2.5$

Background samples

Control regions and the dominating background

- e^+/e^- : $We\nu$+jets
- μ^+/μ^- : $W\mu\nu$+jets
- e^+e^- : Zee+jets
- $\mu^+\mu^-$: $Z\mu\mu$+jets
- $e^+\mu^-/e^-\mu^+$: $t\bar{t}$+jets

Uncorrected samples

- $W\tau\nu$+jets, $W+bb$+jets
- $Z\tau\tau$+jets, $Z+bb$+jets
- WW+jets, WZ+jets, ZZ+jets
- Single top (s-channel, t-channel, Wt-production)

b' (varied σ) analysis: Signal region

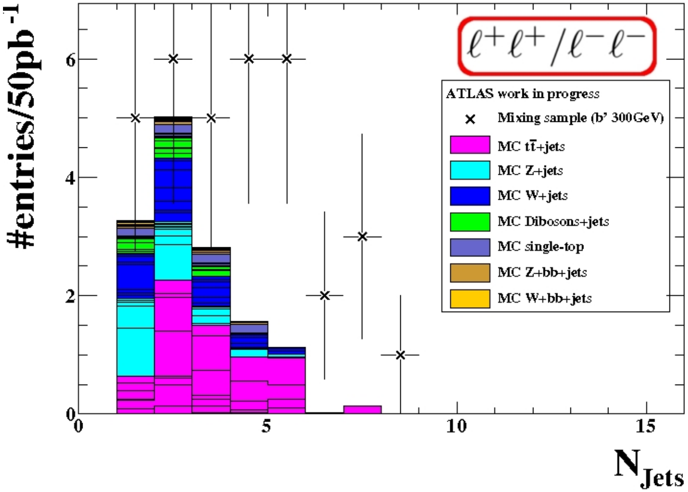


Figure: l^+l^+/l^-l^- SR

b' (varied σ) analysis: $We\nu$ and $W\mu\nu$ control region

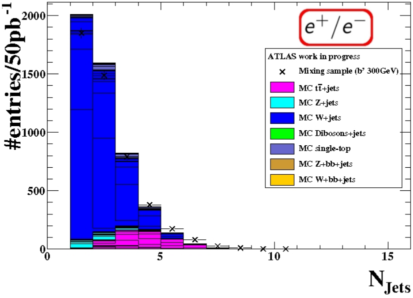


Figure: $We\nu$+jets control region

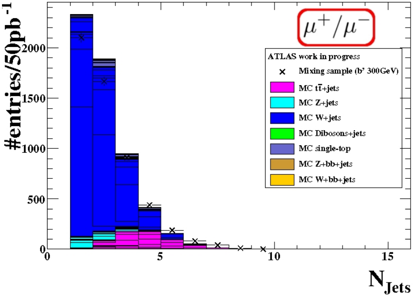


Figure: $W\mu\nu$+jets control region

b' (varied σ) analysis: Zee and $Z\mu\mu$ control region

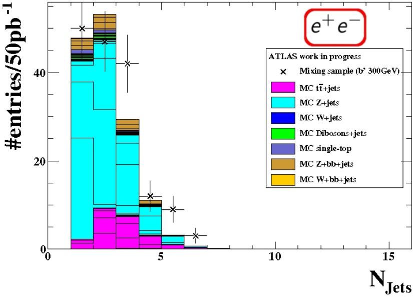


Figure: Zee+jets control region

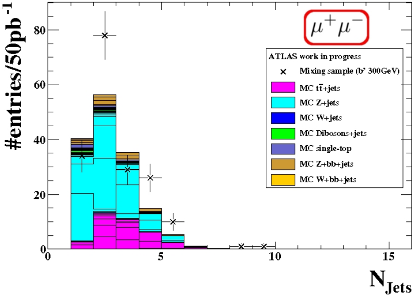


Figure: $Z\mu\mu$+jets control region

b' (varied σ) analysis: $t\bar{t}$ control region

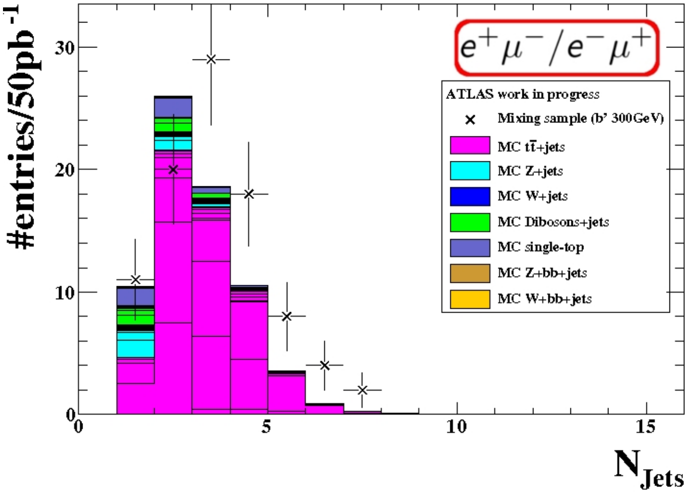


Figure: $t\bar{t}$ control region

b' analysis: Result for b' (300 GeV) @ $50 pb^{-1}$

Results (b' 300 GeV)

Sample	Events	Final R_i^k
data	32 ± 6	
$We\nu$+jets (MC)	0.7 ± 0.2	1.01 ± 0.02
$W\mu\nu$+jets (MC)	1.8 ± 0.3	1.01 ± 0.02
Zee+jets (MC)	2.8 ± 0.5	1.03 ± 0.06
$Z\mu\mu$+jets (MC)	0.11 ± 0.04	0.93 ± 0.05
$t\bar{t}$+jets (MC)	5.9 ± 0.8	0.9 ± 0.2
other (MC)	2.2 ± 0.9	
Result	19 ± 6	
Expected	18.4 ± 0.3	

b' analysis: Signal region

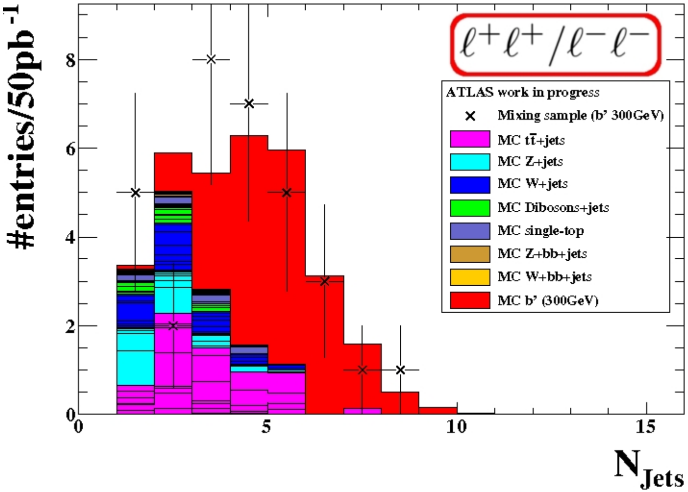


Figure: Signal region

b' analysis: $We\nu$ and $W\mu\nu$ control region

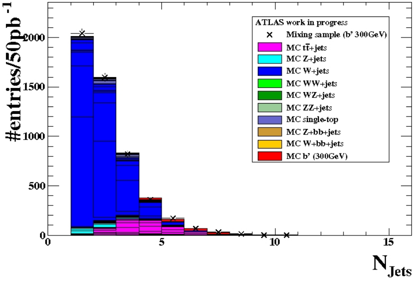


Figure: $We\nu$+jets control region

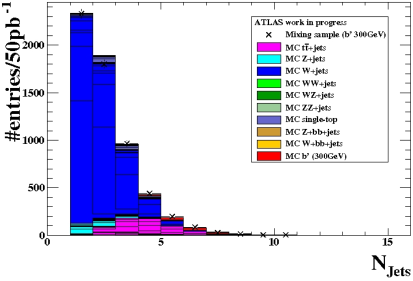


Figure: $W\mu\nu$+jets control region

b' analysis: *Zee* and $Z\mu\mu$ control region

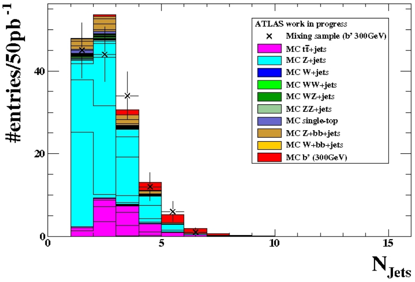


Figure: *Zee*+jets control region

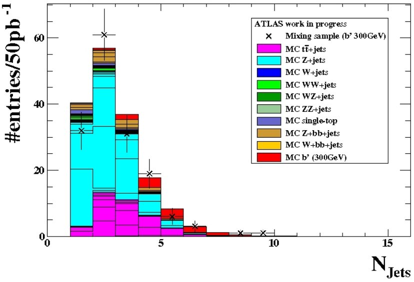


Figure: $Z\mu\mu$+jets control region

b' analysis: $t\bar{t}$ control region

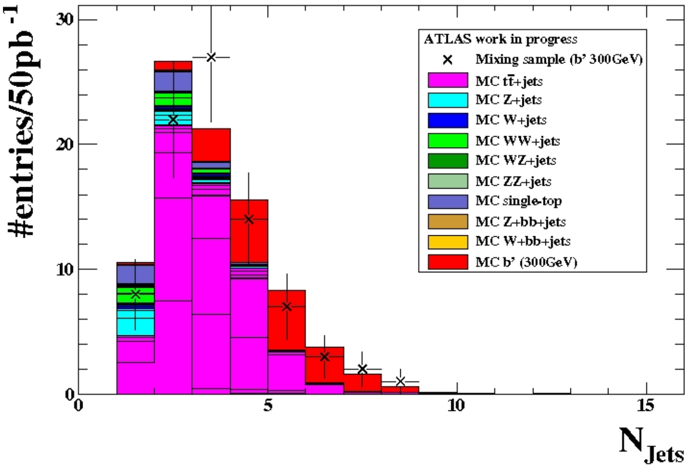


Figure: $t\bar{t}$ control region

b' analysis: Convergence of b' signal ratio

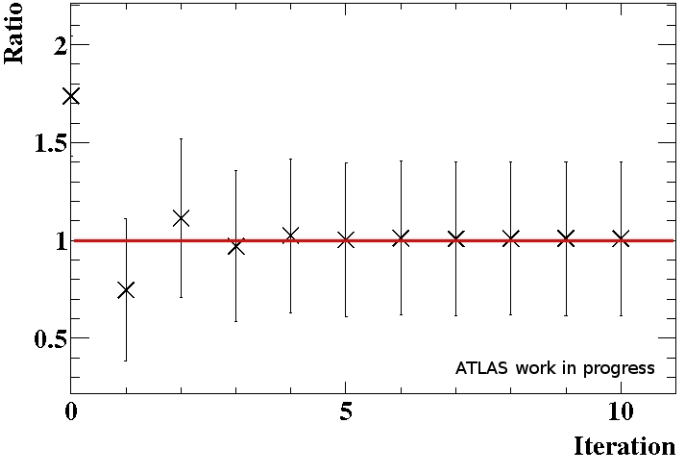
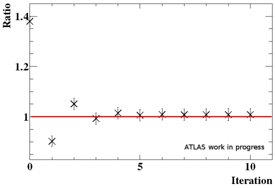
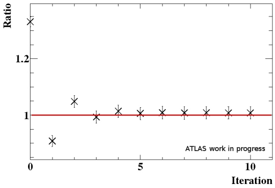


Figure: Ratio for b' signal

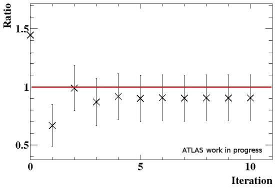
b' analysis: Convergence plots of control ratios



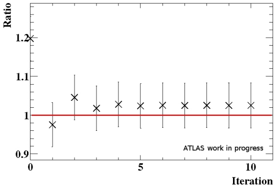
Ratio for $W \to e\nu$



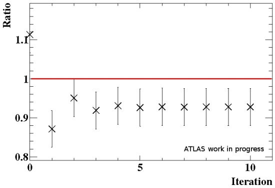
Ratio for $W \to \mu\nu$



Ratio for $t\bar{t}$



Ratio for $Z \to ee$



Ratio for $Z \to \mu\mu$

b' analysis: Trilepton categories

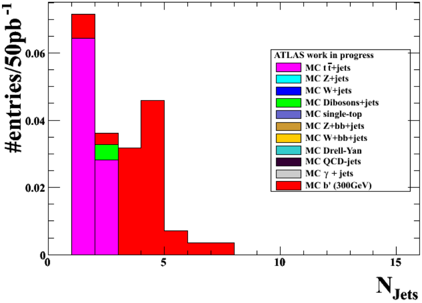


Figure: $l^+l^+l^+/l^-l^-l^-$

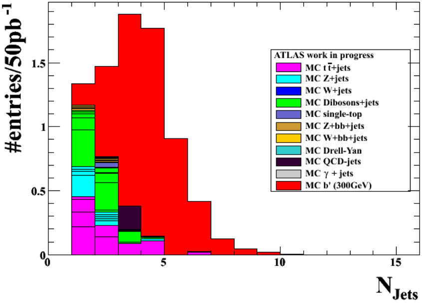


Figure: $l^+l^+l^-/l^-l^-l^+$

t' analysis: Result for t' (400 GeV) @ $50pb^{-1}$

Results (t' 400 GeV)

Sample	Events	Final R_i^k
data	23 ± 5	
$We\nu$+jets (MC)	0.7 ± 0.2	1.00 ± 0.02
$W\mu\nu$+jets (MC)	1.8 ± 0.3	1.01 ± 0.02
Zee+jets (MC)	2.8 ± 0.5	1.04 ± 0.06
$Z\mu\mu$+jets (MC)	0.11 ± 0.04	0.93 ± 0.05
$t\bar{t}$+jets (MC)	5.9 ± 0.7	0.9 ± 0.2
other (MC)	2.2 ± 0.9	
Result	10 ± 5	
Expected	8.39 ± 0.07	

t' analysis: Result for t' (400 GeV) @ $50pb^{-1}$

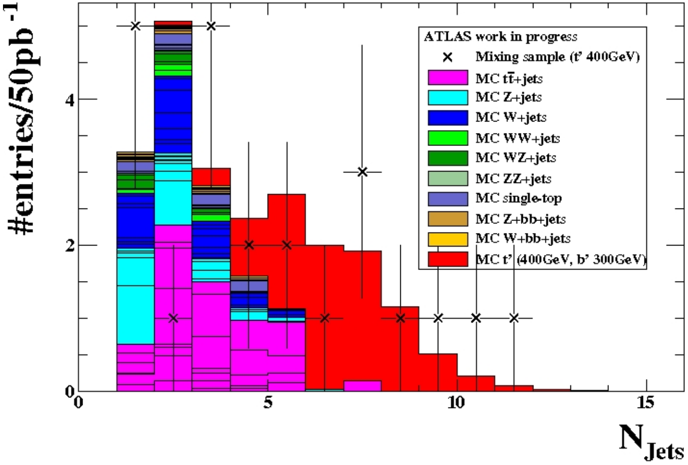


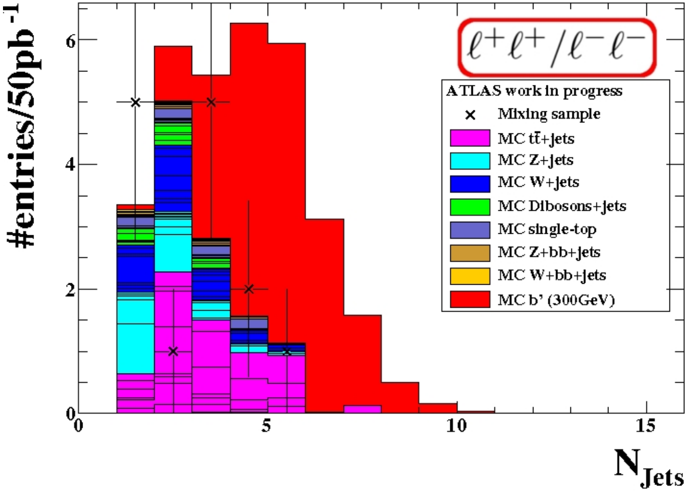
Figure: Signal region

b' (without signal) analysis: Results

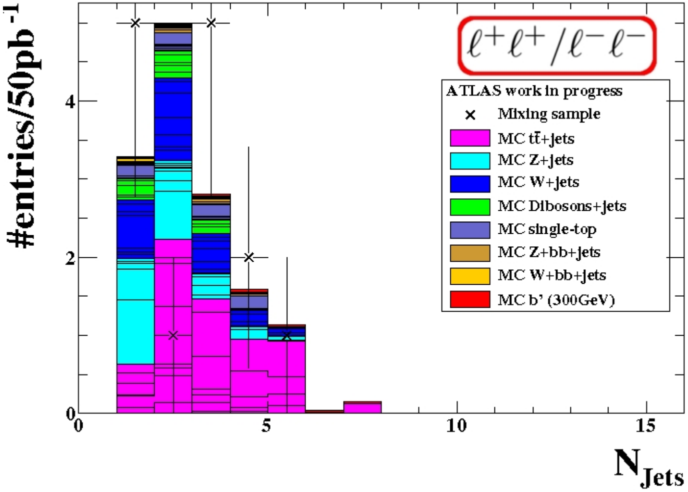
Results @ $50pb^{-1}$

Sample	Events	Final R_i^k
data	14 ± 4	
$We\nu$+jets (MC)	0.7 ± 0.2	1.00 ± 0.02
$W\mu\nu$+jets (MC)	1.8 ± 0.3	1.00 ± 0.02
Zee+jets (MC)	2.8 ± 0.5	1.03 ± 0.06
$Z\mu\mu$+jets (MC)	0.11 ± 0.04	0.92 ± 0.05
$t\bar{t}$+jets (MC)	6.3 ± 0.8	1.0 ± 0.2
other (MC)	2.2 ± 0.9	
Result	0 ± 4	
Expected	0	

b' (w/o signal) analysis: Signal region **before** correction



b' (w/o signal) analysis: Signal region **after** correction



b' (w/o signal) analysis: $t\bar{t}$ CR before/after correction

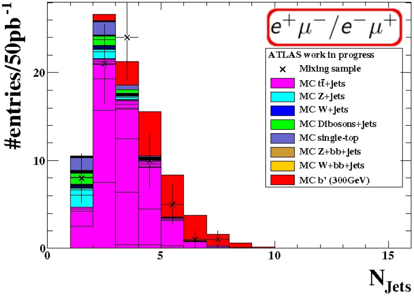


Figure: Before correction

$\Rightarrow$

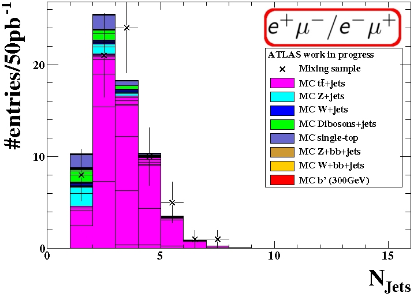


Figure: After correction

SR with $\not{E}_T > 0$ GeV

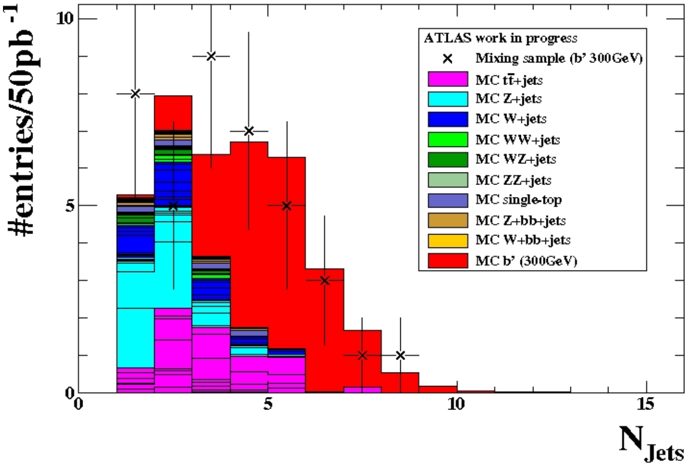


Figure: l^+l^+/l^-l^- SR without cut on $\not{E}_T$

SR with $E_T^{LeadingJet} < 85$ GeV

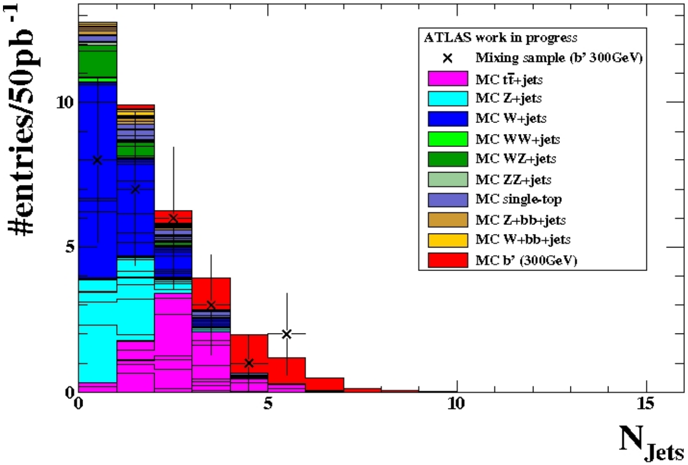


Figure: l^+l^+/l^-l^- SR with anti-cut on leading jet E_T

SR with $E_T^{LeadingJet} < 85$ GeV and $P_T^{LeadingLep} > 0$ GeV

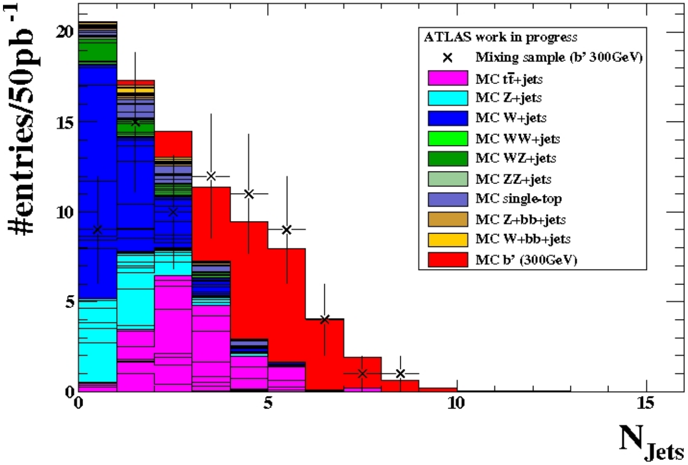


Figure: l^+l^+/l^-l^- SR with anti-cut on leading jet E_T and no cut on leading lepton P_T