

# Search for Heavy Vector-like Quarks at ATLAS

Sam Meehan on behalf of the ATLAS Collaboration  
University of Chicago  
DPF 2011 – August 9

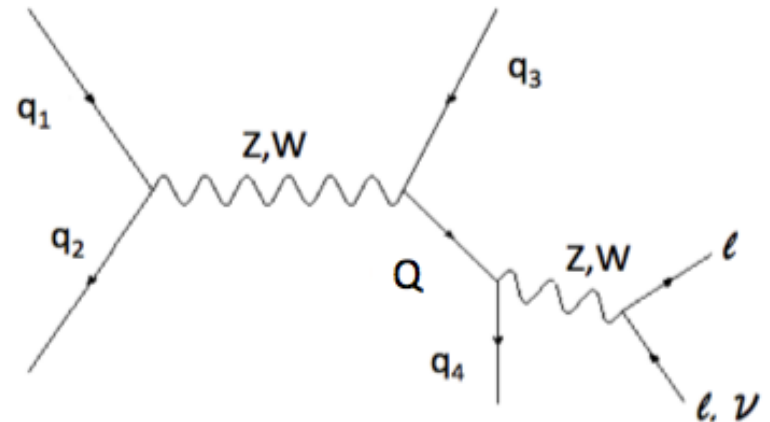
# Motivation

- “Heavy vector-like quarks” : Heavy fermions whose left and right components transform the same under  $SU(2)$  symmetries
- Other 4<sup>th</sup> generation models offers solution to fine tuning of Higgs mass but usually made to couple to top sector
- Cancellations by strong EWSB or existence of higher dimensions can allow for coupling of vector like quark (Q) to light generations
- Searched for at Tevatron : *arxiv:1010.1466 (2010)*
- Theory fully developed in : *arxiv:1102.1987v1 (2010)*  
*arxiv:0806.3966v2 (2008)*
-

# Theoretical Model

- Couplings controlled by single parameter in the Lagrangian ( $\tilde{\kappa}_{Qq}, M_Q$ )

M (GeV)	$\sigma_Q \times \text{BR}$ (pb)	
	W channel	Z channel
225	33.7	3.29
300	12.8	1.33
400	4.52	0.479
500	1.89	0.2
600	0.891	0.0927
700	0.462	0.0482
800	0.252	0.026
900	0.143	0.0143
1000	0.0846	0.00841

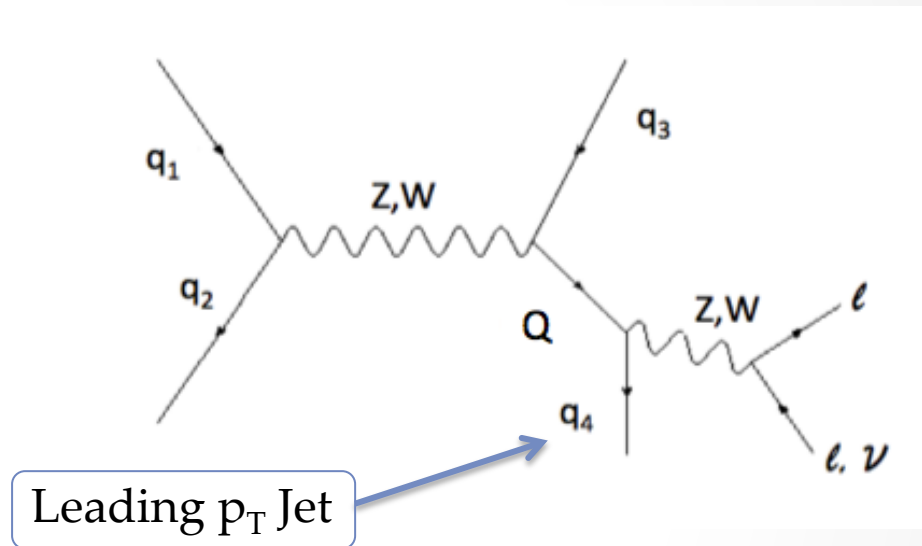


SM Backgrounds	
W channel	Z channel
W+jets	Z+jets
QCD	ttbar
ttbar	Single top
Z+jets	Diboson
Single top	W+jets
Diboson	

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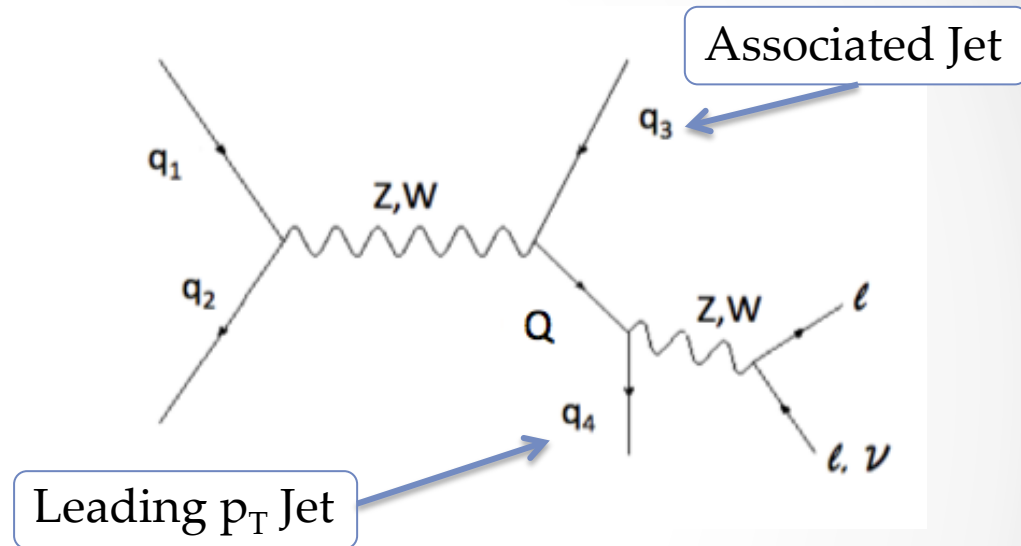


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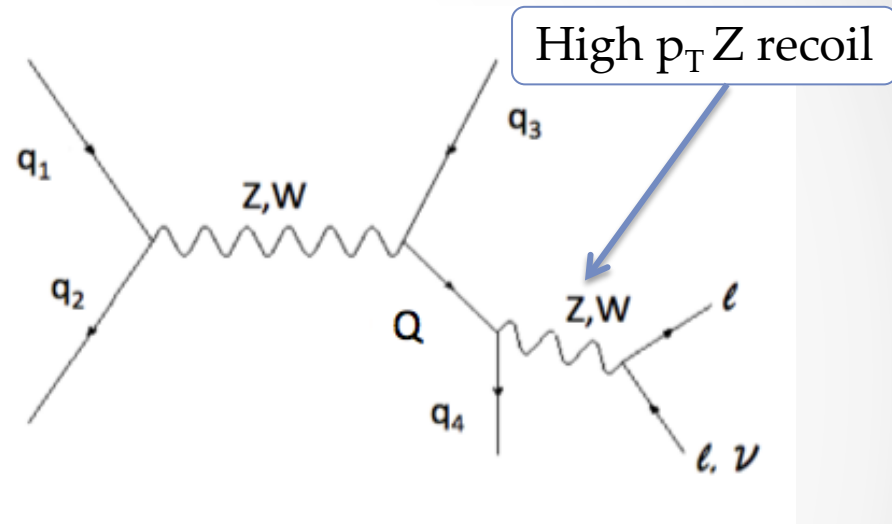


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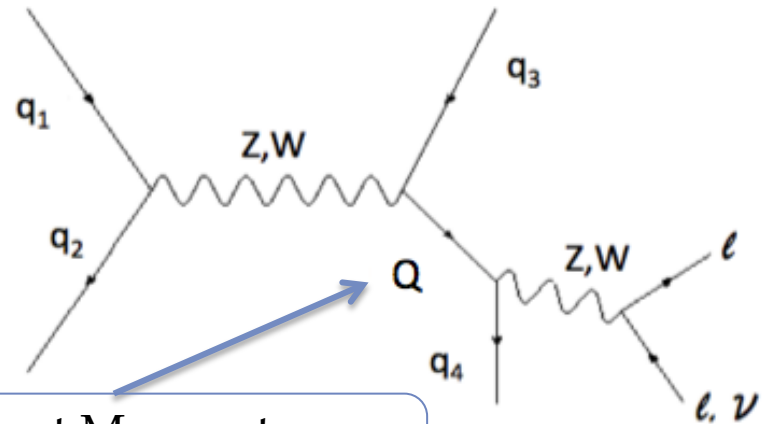


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Reconstruct  $M_Q$  spectrum from W/Z and leading  $p_T$  jet

SM Backgrounds	
W channel	Z channel
W+jets	Z+jets
QCD	ttbar
ttbar	Single top
Z+jets	Diboson
Single top	W+jets
Diboson	

# Object Selection

## Electrons:

- Trigger : 20 GeV electron object
- $|\eta| < 2.47$
- $E_T > 25$  GeV
- $E_T(\text{isolation})/E_T < 0.1$

## Muons:

- Trigger : 18 GeV muon object
- $|\eta| < 2.4$
- $E_T > 25$  GeV
- $p_T(\text{isolation})/p_T < 0.1$

## MET:

- Veto events with poor quality high  $p_T$  jets to ensure good quality of MET

## Jets:

- Anti-kt reconstructed ,  $R = 0.4$
- $|\eta| < 4.5$
- $p_T > 25$  GeV
- $|\text{JetVertexFraction}| > 0.75$

## Selection:

- Z Channel
  - Exactly two oppositely charged leptons with  $66 \text{ GeV} < M(\ell\ell) < 116 \text{ GeV}$
- W Channel
  - $\text{MET} > 50$  GeV
  - Exactly one lepton with  $M_T(\ell, \text{MET}) > 40$  GeV

$Q \rightarrow W + \text{Jet}$   
Channel

# Background Estimation

- Electroweak backgrounds (W/Z+jets, ttbar, single top, diboson) *from MC*
- W+jets *number of parton (NP) samples reweighted* by fitting  $N_{\text{jet}}$  distribution of MC to data floating NP sample weights
- Perform *fit of QCD templates + EW to data* to obtain QCD normalization
- Test SM background understanding in control regions of dominant backgrounds (W+jets & QCD)

# Signal/Control Regions

- W+jets Control Region

- MET > 50 GeV
- $M_T(W) > 40$  GeV
- $\Delta \phi(\ell, MET) > 2.4$

- QCD Control Region

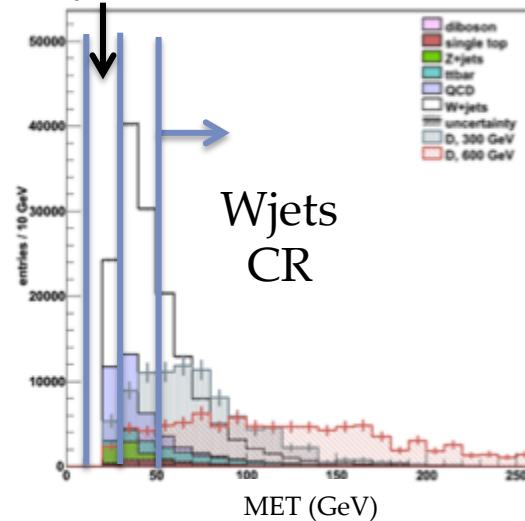
- $10 \text{ GeV} < MET < 30 \text{ GeV}$
- $M_T(W) > 40$  GeV

- Signal Region

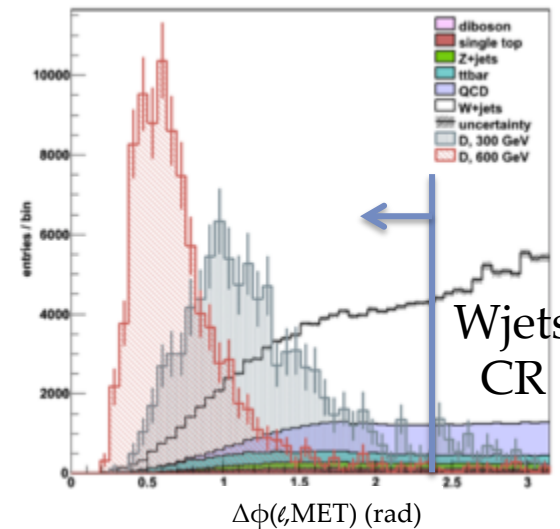
- MET > 50 GeV
- $M_T(W) > 40$  GeV
- $\Delta \phi(\ell, MET) < 2.4$
- $p_T(\text{LeadJet}) > 50$  GeV
- $|\Delta \eta(\text{LeadJet}, \text{Assoc. Jet})| > 1$
- Njets  $\geq 2$

→ = Signal Region

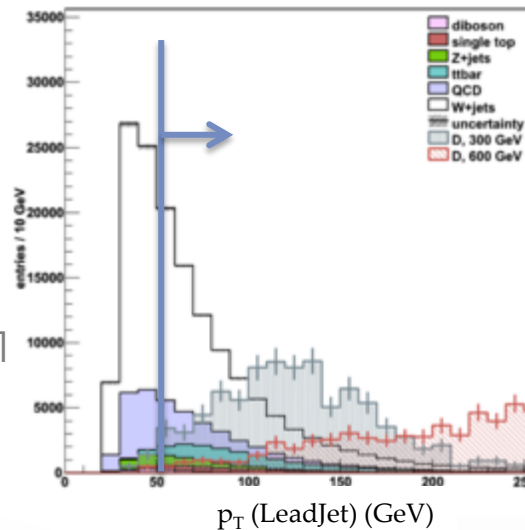
QCD CR



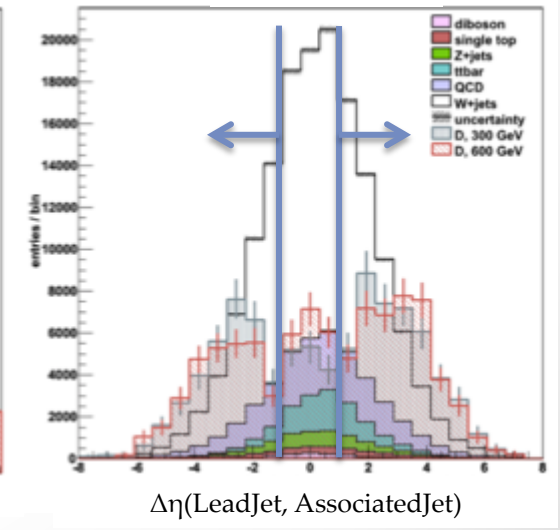
Wjets CR



Wjets CR



$p_T(\text{LeadJet})$  (GeV)



$\Delta \eta(\text{LeadJet}, \text{AssociatedJet})$

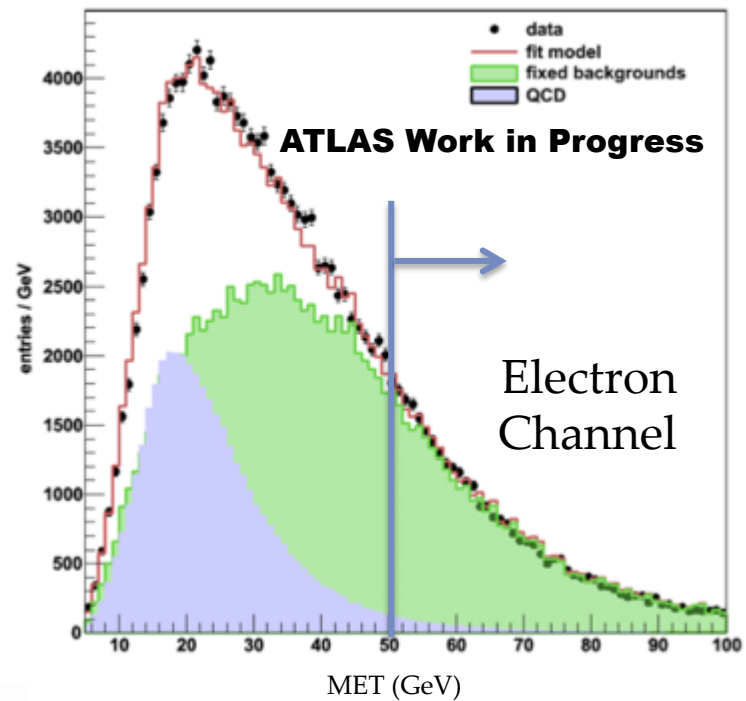
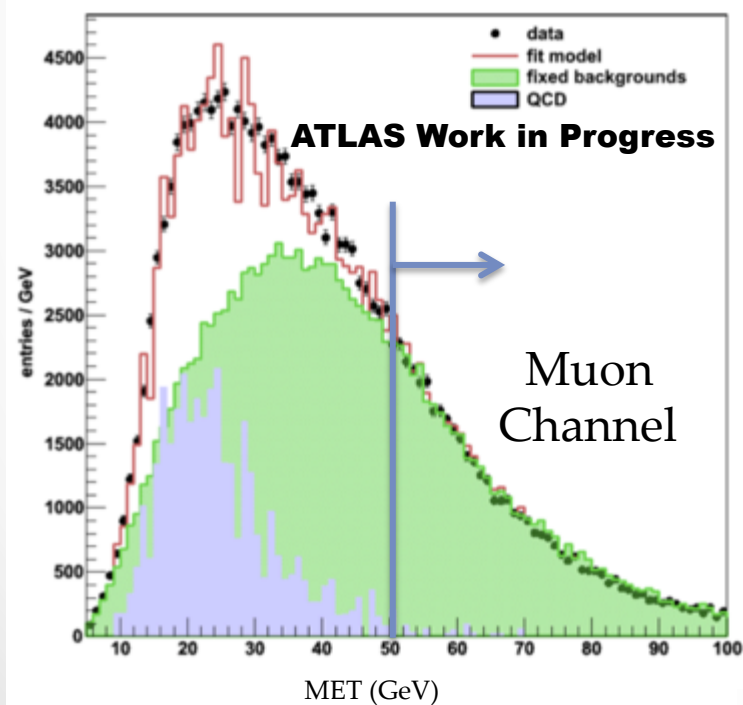
Plots shown for electron channel

# QCD Modeling

- Fix EW backgrounds (relatively) and float QCD and EW normalizations in fit of MET after baseline W selection
  - Electron QCD Template : taken from data by relaxing electron reconstruction quality to medium and **not** tight
  - Muon QCD Template : taken from Pythia bbar MC sample

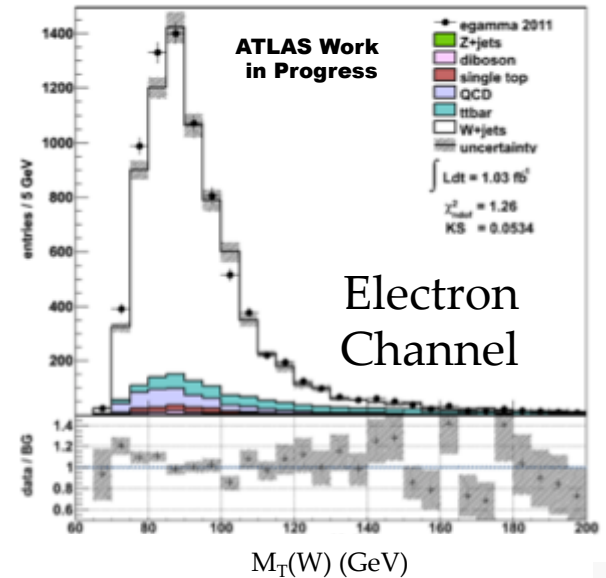
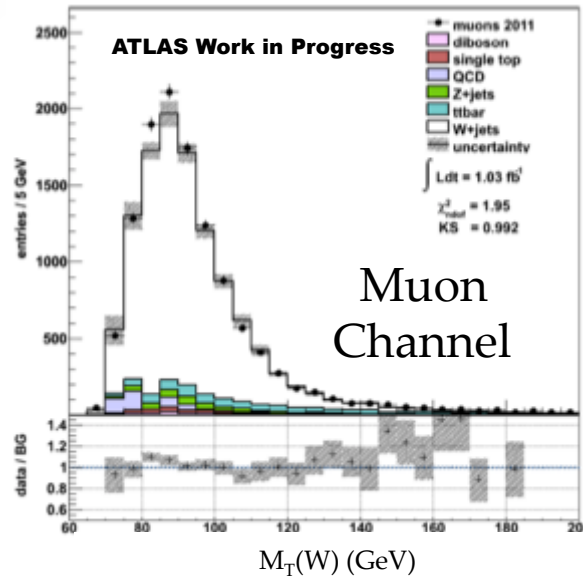
$\%QCD(\mu, \text{post MET cut}) = 2.7 \%$

$\%QCD(e, \text{post MET cut}) = 5.8 \%$

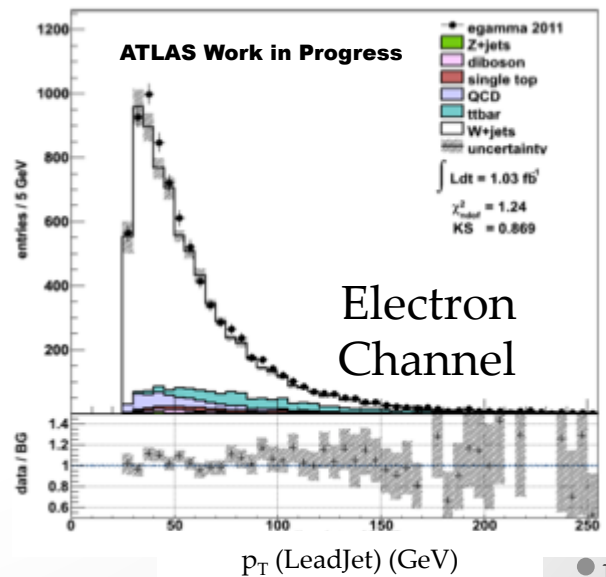
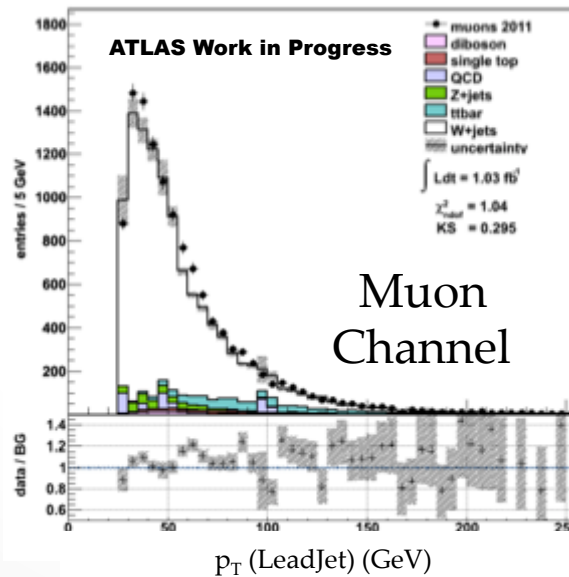


# W+jets Control Region

$M_T(\ell, MET)$

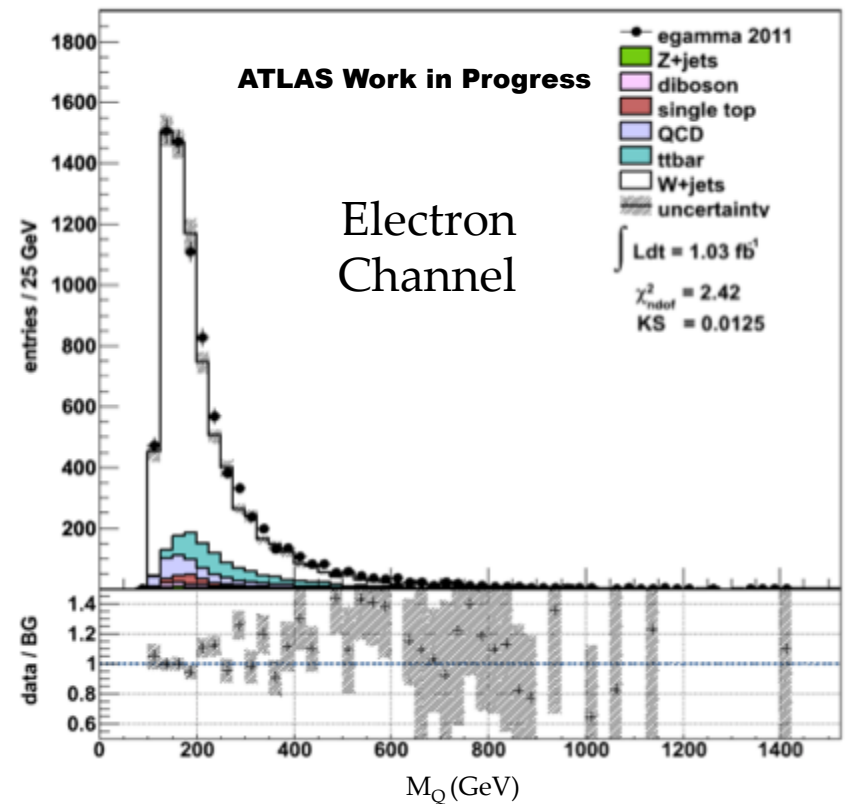
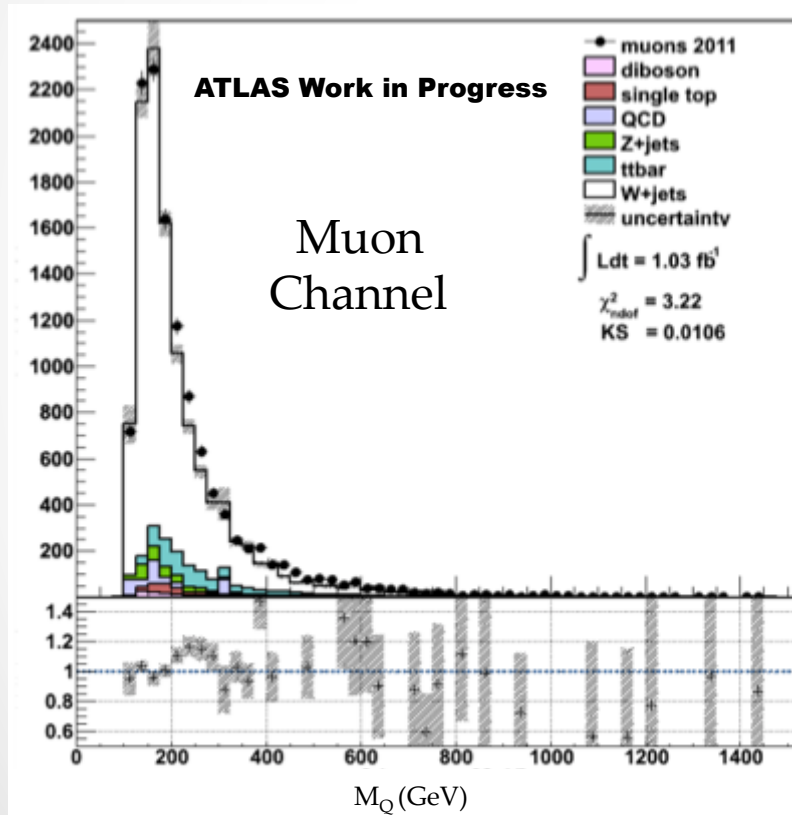


$p_T(\text{Lead Jet})$



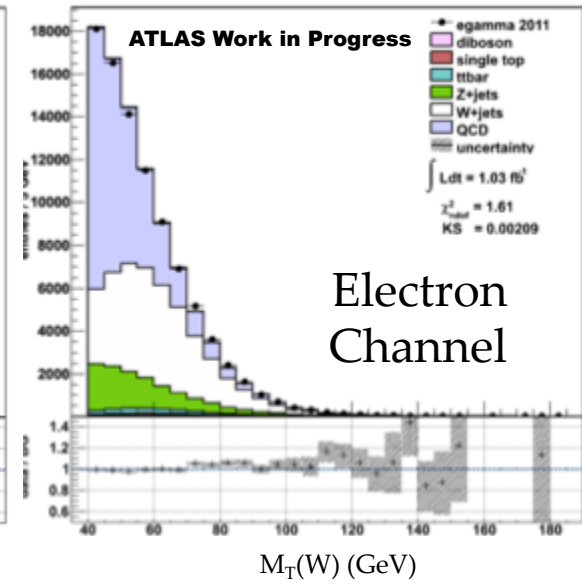
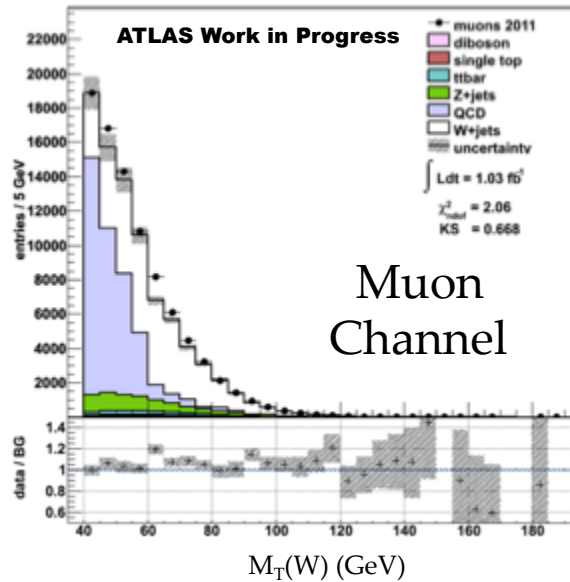
# W+jets Control Region

Heavy Quark Mass :  $\ell + \text{MET} + \text{LeadJet}$

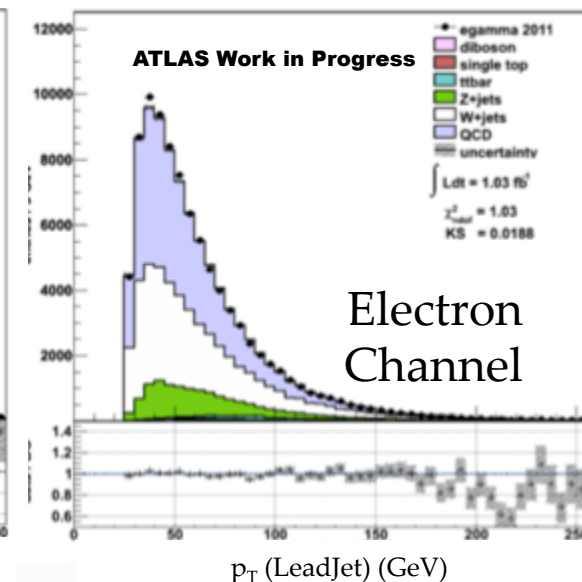
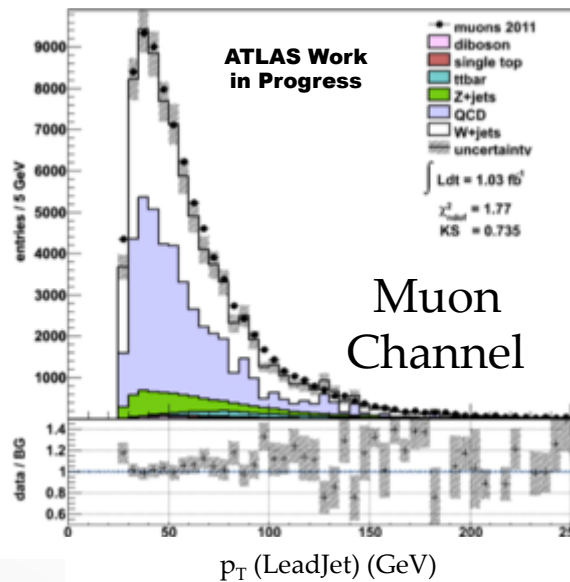


# QCD Control Region

$M_T(\ell, MET)$

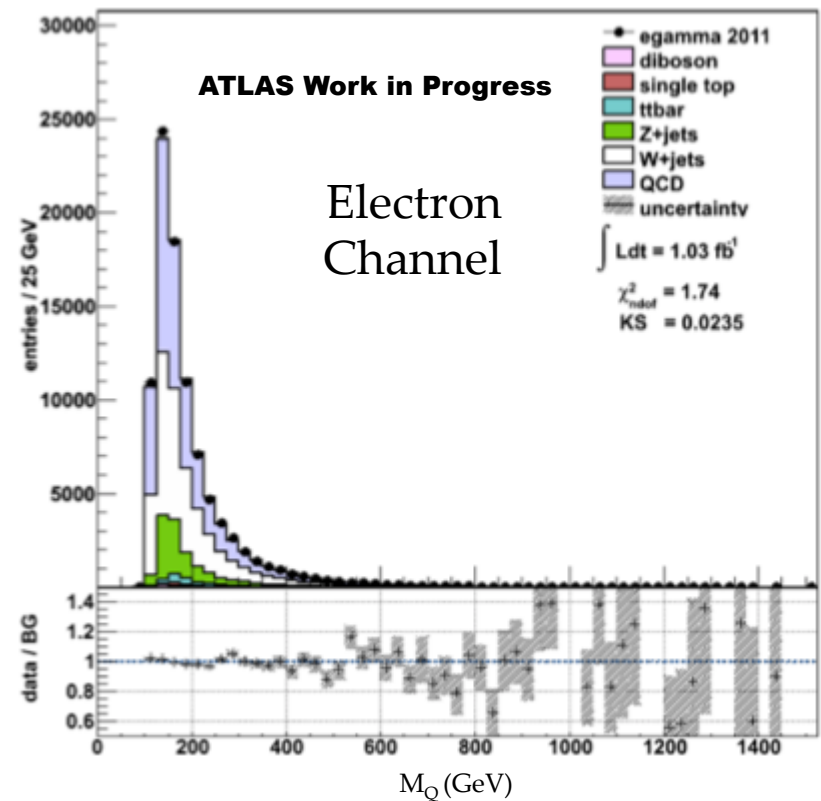
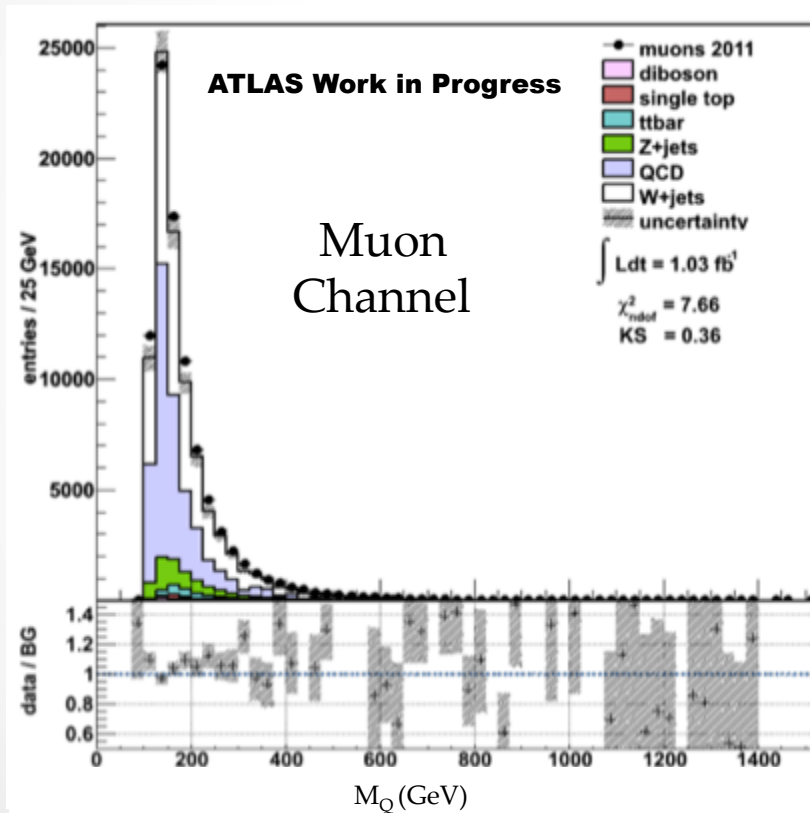


$p_T(\text{Lead Jet})$



# QCD Control Region

Heavy Quark Mass :  $\ell + \text{MET} + \text{LeadJet}$

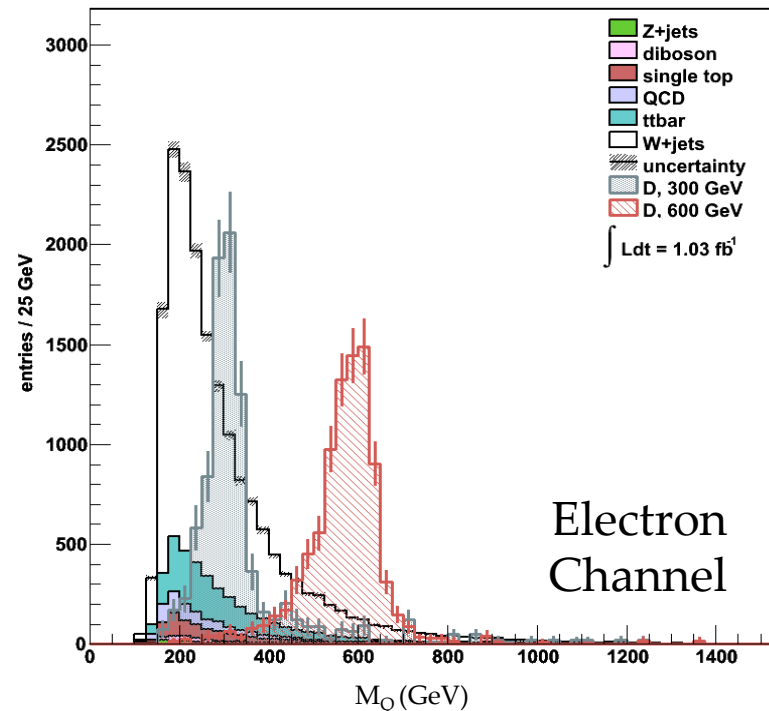
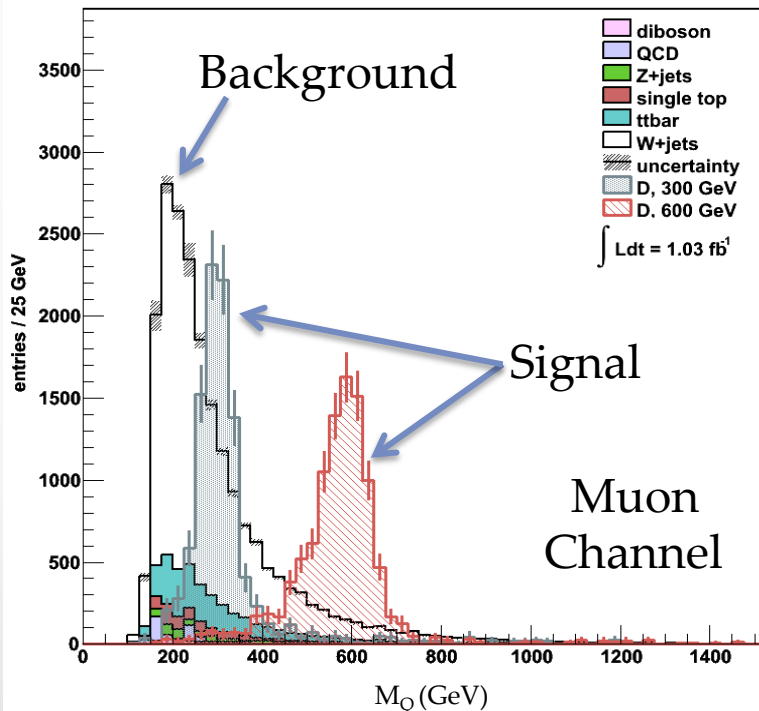


# Signal Region Expectations

	Muon Channel	Electron Channel
W+jets	16600 ± 2500	14100 ± 2300
ttbar	2560 ± 70	2300 ± 70
QCD	334 ± 130	680 ± 270
Single top	743 ± 50	684 ± 50
Z+jets	440 ± 70	124 ± 20
Diboson	181 ± 24	163 ± 24
Q = 300 GeV	1210	1460
Q = 600 GeV	130	133

## NOTE :

300 GeV signal cross section multiplied by factor of 7  
 600 GeV signal cross section multiplied by factor of 70



$Q \rightarrow Z + \text{Jet}$   
Channel

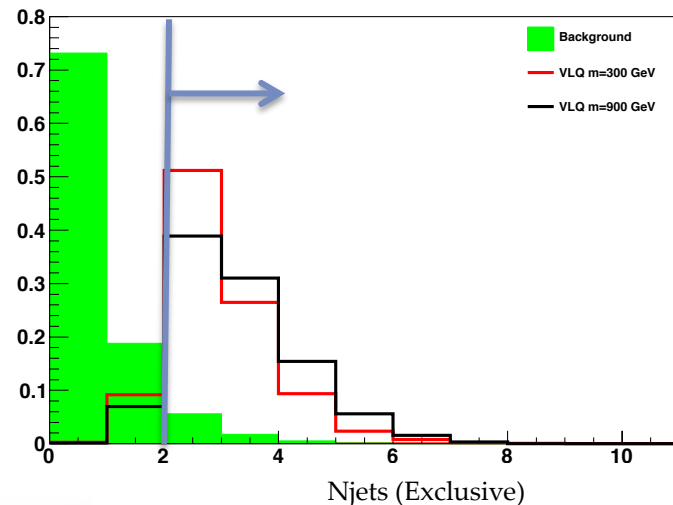
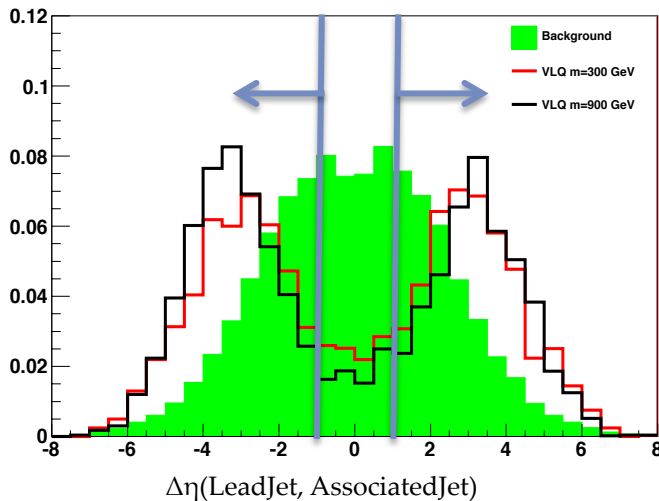
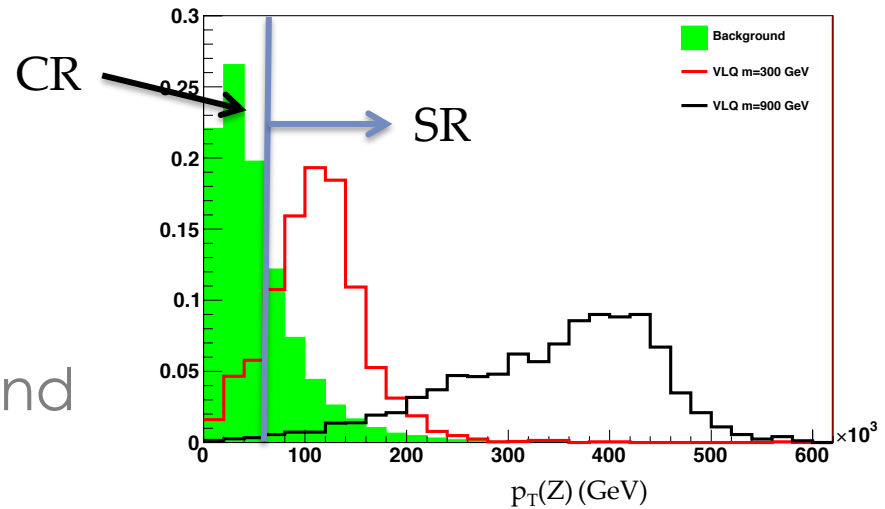
# Background Estimation

- All SM backgrounds (W/Z+jets, ttbar, single top, diboson) obtained *from MC*
- QCD contribution determined by reversing isolation cut on leptons and fitting the dilepton mass
  - Contribution at ~1% level
- Test SM background understanding in control regions of dominant backgrounds (Z+jets)

# Signal/Control Region

- Signal Region:
  - $N_{\text{jets}} \geq 2$
  - $|\Delta \eta (\text{LeadJet}, \text{FarJet})| > 1$
  - $p_T(\ell) > 50 \text{ GeV}$
- Reverse  $p_T(\ell)$  cut for testing Z+jets background

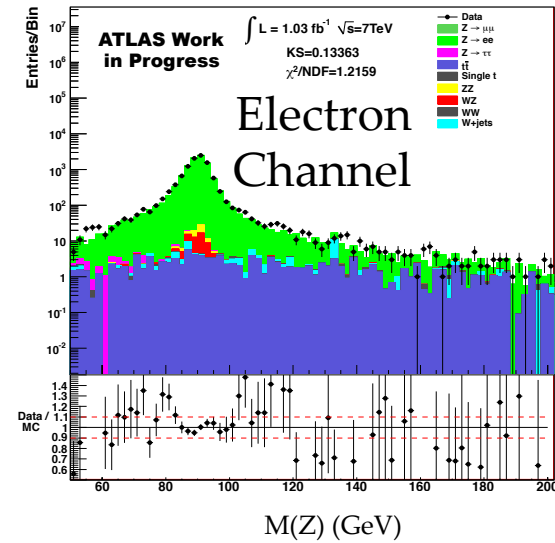
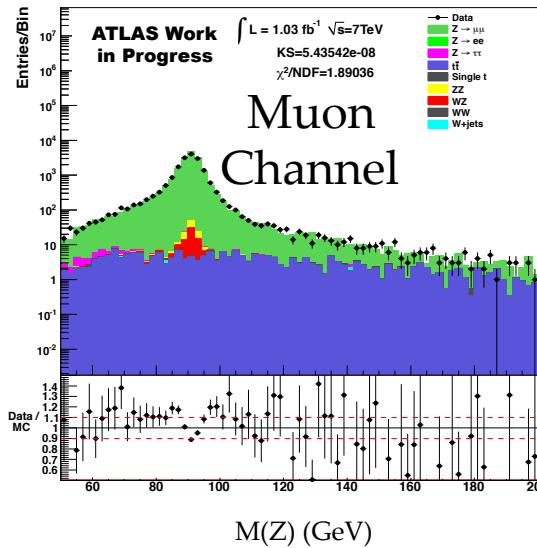
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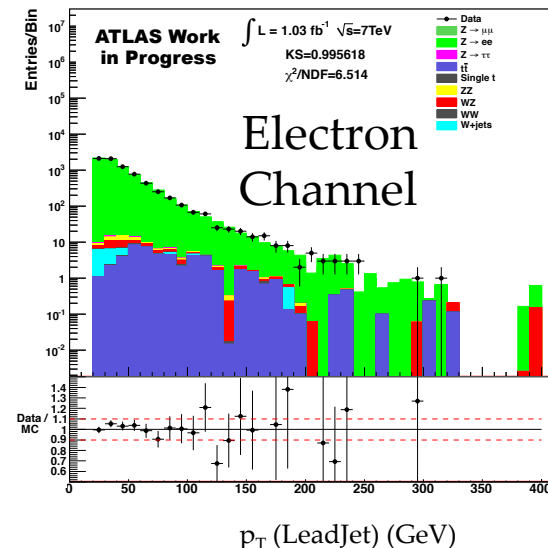
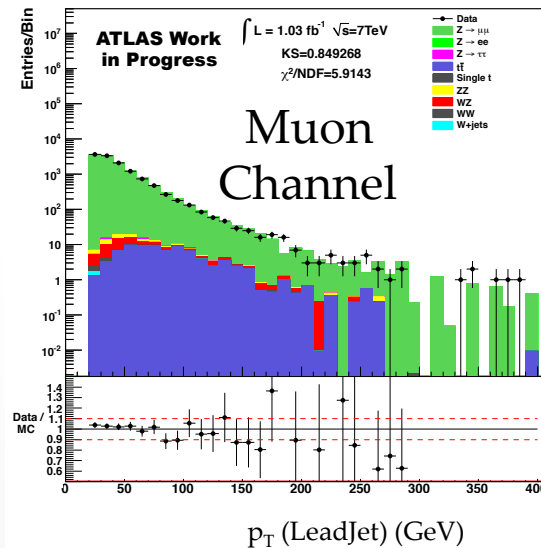
Plots shown for muon channel

# Z+jets Control Region

$M(ee)$  Peak

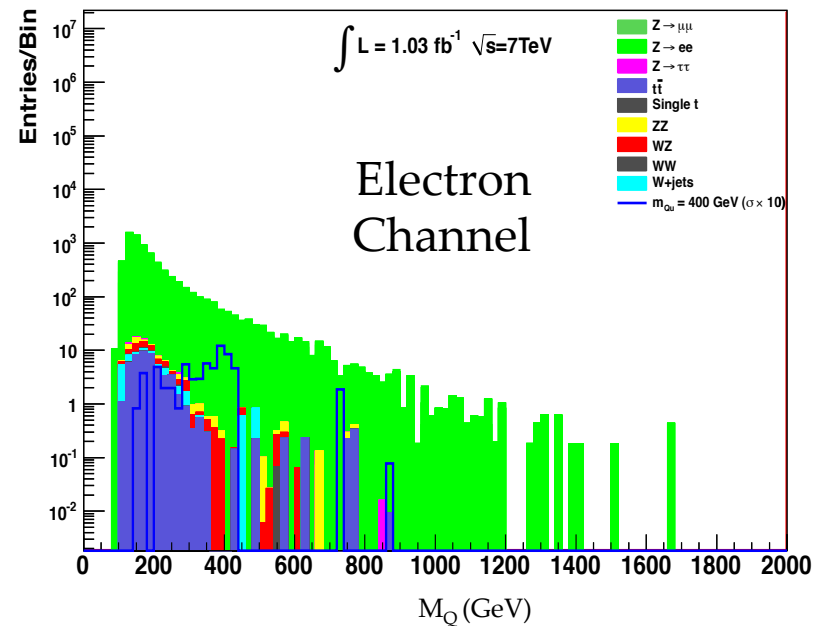
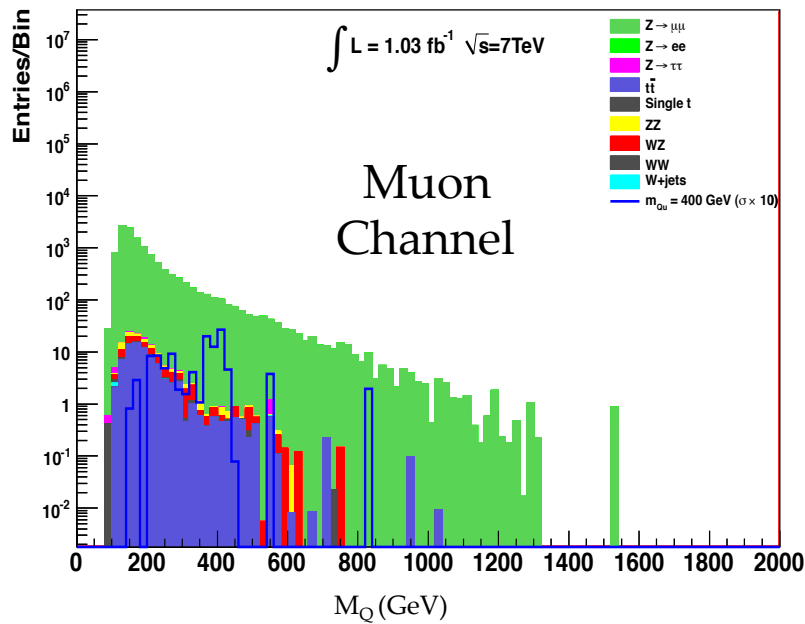


$p_T(\text{Lead Jet})$



# Z+jets Control Region

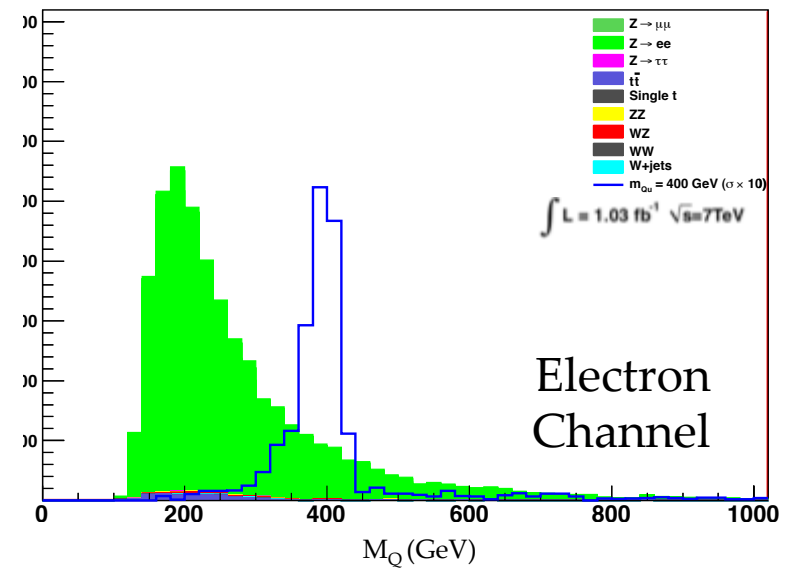
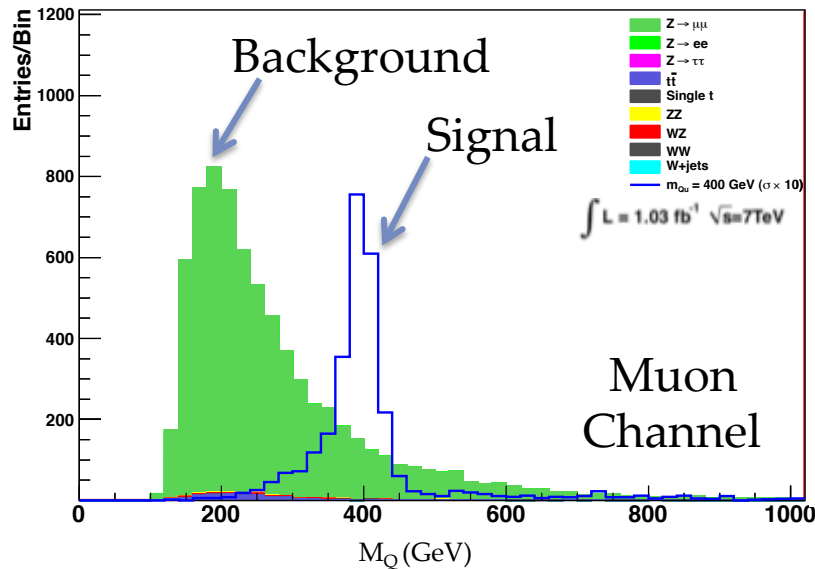
Heavy Quark Mass :  $\ell + \ell + \text{LeadJet}$



# Signal Region Expecations

	Muon Channel	Electron Channel
<b>Z+jets</b>	7196 $\pm$ 1220	4511 $\pm$ 770
<b>W+jets</b>	0 $\pm$ 0.3	7.8 $\pm$ 1.3
<b>ttbar</b>	126 $\pm$ 3	84 $\pm$ 3
<b>Diboson</b>	72 $\pm$ 6	49 $\pm$ 4
<b>Single top</b>	0.4	0.09
<b>Q = 400 GeV</b>	107	73

**NOTE :** 400 GeV signal cross section multiplied by factor of 10



# Systematic Uncertainties

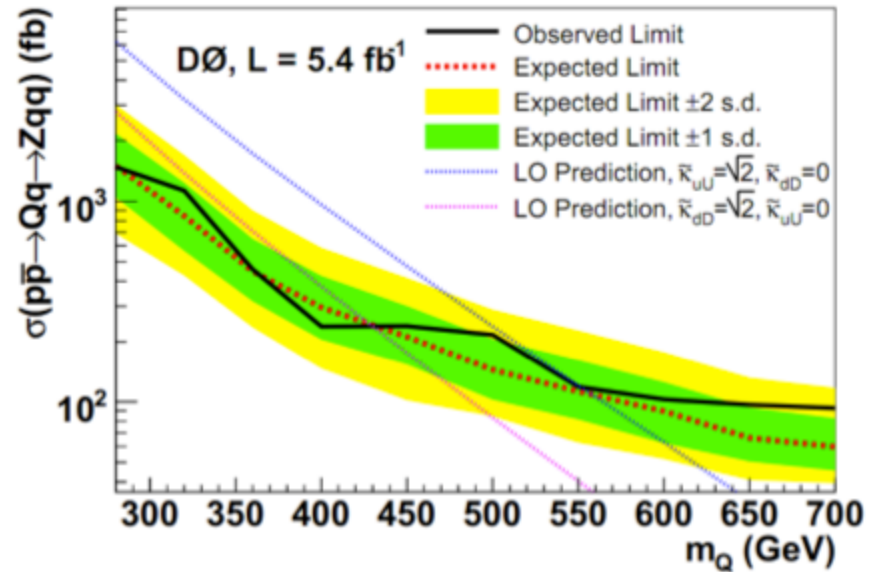
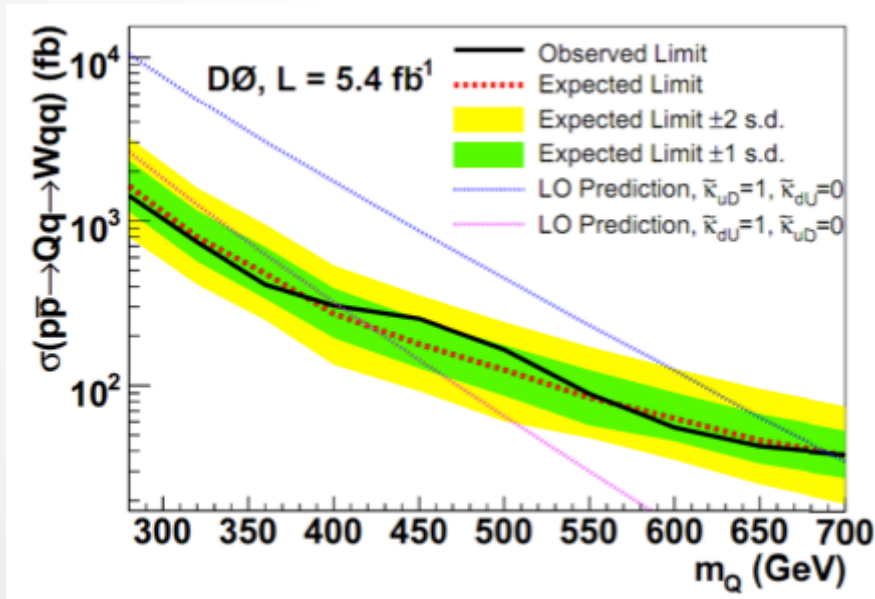
	<b>Signal Normalization Uncertainty</b>	<b>BG Normalization Uncertainty</b>
<b>Jet Energy Scale *</b>	5% at M=225 GeV to 3% at M=1TeV	16% (W+jets) to 3% (ttbar)
<b>Jet Energy Resolution</b>	< 1%	< 1%
<b>QCD Normalization</b>	N/A	40% - on QCD component only
<b>Lepton Energy Scale</b>	< 1%	< 1%
<b>MC Statistics</b>	5%	1% (W+jets) to 6% (diboson)

\* Atlas JES ranges from 4.6% at  $p_T = 20$  GeV to 2.5% at  $p_T \geq 60$  GeV

\* W+jets Shape uncertainty taken from reweighting fit of W+jets NP samples

# Tevatron Limits

- Set by D0 at Tevatron with  $5.4 \text{ fb}^{-1}$  of Data (2010)



W Channel Limit  $\sim 680$  GeV    Z Channel Limit  $\sim 560$  GeV

# Conclusions

- We hope to be sensitive up to masses of  $\sim 800$  GeV –  $900$  GeV with  $\sim 1$  fb<sup>-1</sup> of data
- Working to more fully understand systematic uncertainties before setting observed limits
- Continue search as more data arrives in 2011

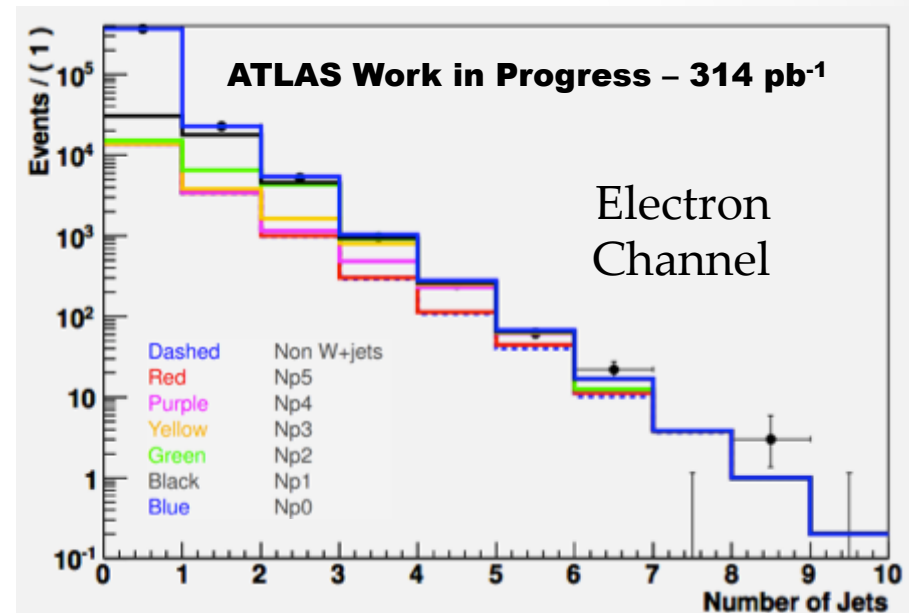
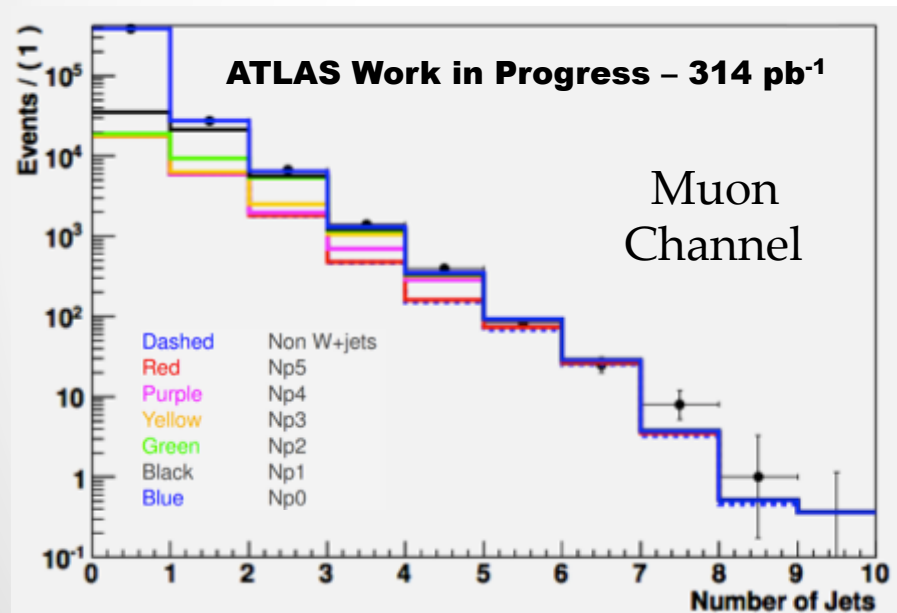
# Acknowledgements

- Thank you to everyone at Atlas and the LHC
- Thank you to Vector-Like Quark Analysis Group:
  - University of Chicago : Florencia Canelli, Mark Oreglia, Joe Tuggle, Jordan Webster
  - Columbia University : Alex Penson
  - University of Montreal : Georges Azuelos, Merlin Davies
  - University of Sheffield : Tulay Cuhadar Donszelmann
  - University of California, Irvine : Gokhan Unel

# Backup Slides

# W+jets Reweighting

- Rescale six parton number (NP) samples of W+jets MC by floating reweights and fitting Njet distribution to data



# W+jets Reweighting

Sample	Top group (2010)	My fit (electrons & muons combined)
Np0	$.978 \pm .004$	$.9186 \pm .0013$
Np1	$1.107 \pm .015$	$.977 \pm .011$
Np2	$1.147 \pm .047$	$.989 \pm .027$
Np3	$.86 \pm .16$	$.87 \pm .10$
Np4	$1.63 \pm .44$	$1.98 \pm .32$
Np5	$.95 \pm .58$	$.4 \pm .6$