Searches for 2nd generation pair leptoquarks
using LHC Run-I data from ATLAS detector at 8 TeV

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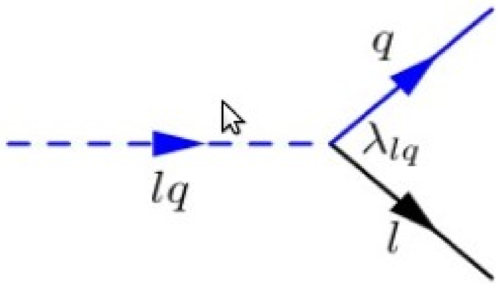
What are leptoquarks?

"Leptoquark" is a generic name for states which couple directly to a quark and a lepton.



- Assuming SU(3)C × SU(2)L × U(1)Y invariant and renormalizable interactions, every leptoquark:
  - belongs to a colour triplet representation of SU(3)C
  - carries both a baryon and a lepton numbers

- The quantum numbers used to classify the different leptoquark states allowed by the symmetries are:
  - S: spin (0 or 1)
  - I_W: weak isospin (0, ½ or 1)
  - Q: electric charge (fractional)
  - F: fermion number (0 or -2)
  - H: chirality of the lepton (L or R)

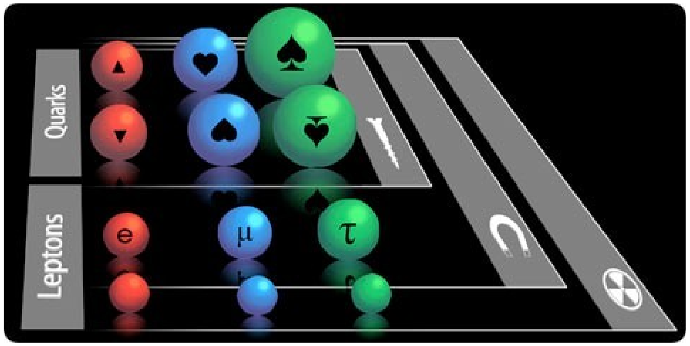
Many possible leptoquarks…

Type	Spin	I_{3W}	F=3B+L	Q	Decay	Coupling	βe
S_{1L}	0	0	-2	-1/3	e-u, νd	λL, -λL	1/2
S_{1R}	0	0	-2	-1/3	e-u	λR	1
S_{1R}	0	0	-2	-4/3	e-d	λR	1
S_{3L}	0	1	-2	-4/3	e-d	-.{2 λL	1
				-1/3	e-u, νd	- λL, - λL	1/2
				2/3	νu	.{2 λL	0
R_{2L}	0	1/2	0	-5/3	e-u	λL	1
				-2/3	νu	λL	0
R_{2R}	0	1/2	0	-5/3	e-u	λR	1
				-2/3	e-d	-λR	1
R_{2L}	0	1/2	0	-2/3	e-d	λL	1
				1/3	νd	λL	0
V_{2L}	1	1/2	-2	-4/3	e-d	λL	1
				-1/3	νd	λL	0
V_{2R}	1	1/2	-2	-4/3	e-d	λR	1
				-1/3	e-u	λR	1
V_{2L}	1	1/2	-2	-1/3	e-u	λL	1
				2/3	νu	λL	0
U_{1L}	1	0	0	-2/3	e-d, νu	λL, λL	1/2
U_{1R}	1	0	0	-2/3	e-d	λR	1
U_{1R}	1	0	0	-5/3	e-u	λR	1
U_{3L}	1	1	0	-5/3	e-u	.{2 λL	1
				-2/3	e-d, νu	- λL, λL	1/2
				1/3	νd	.{2 λL	0

- The most general $\mathbf{L}_{\mathbf{eff}}$ can describe up to 24 different leptoquarks for each generation!
- Generally, only a subset of these possible leptoquarks are contained in a particular model

⇒ **Important to look at each channel to discriminate between models**

Is the apparent symmetry relating quarks and leptons fundamental or accidental?



This question has inspired many BSM theories which naturally contain leptoquarks

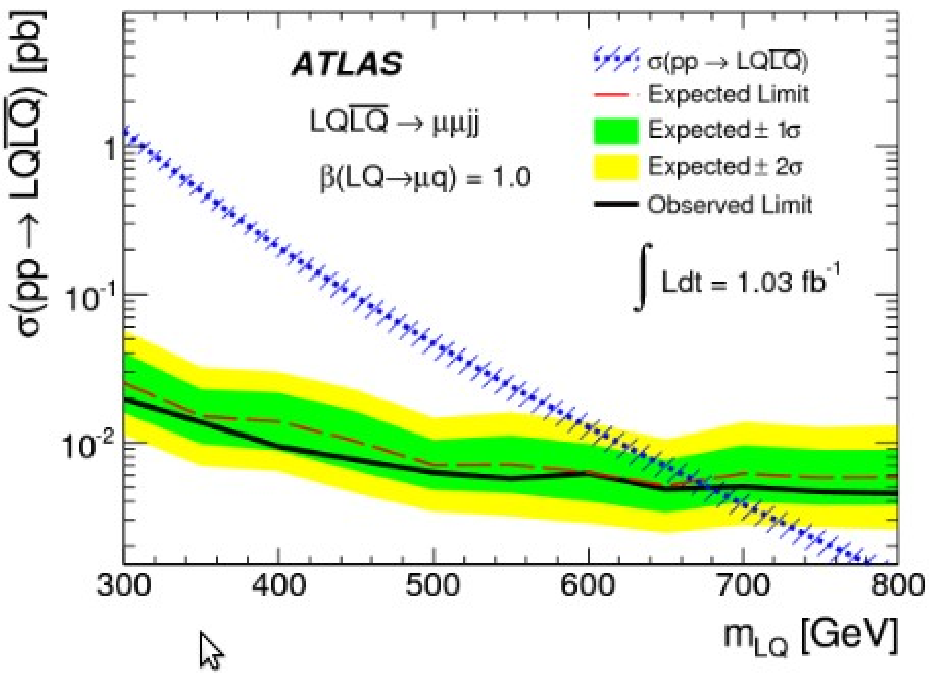
- composite models with quark and lepton substructure
- extended technicolor
- GUTs with different gauge groups (SU(5), SU(15), E6, etc)

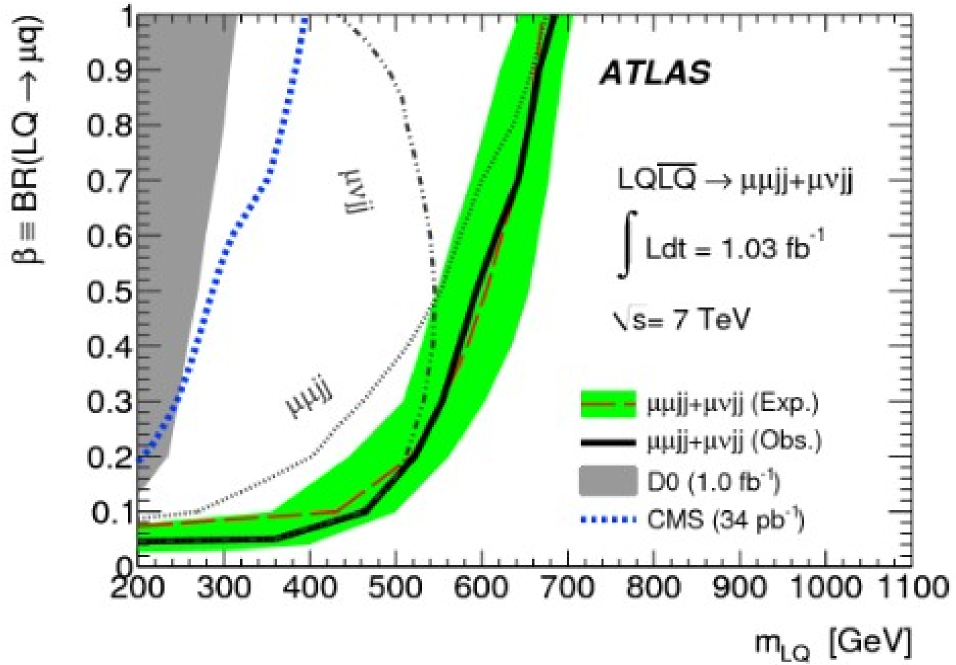
Leptoquarks can be light enough to be observable if:

- lepton **and** baryon numbers are conserved (no proton decay)
- couplings to fermions are chiral (helicity suppression of $\pi^+ \rightarrow e + \nu_e$)
- couplings are family diagonal (avoid FCNC)

branching ratio and exclusion limits

- branching ratio, β, of an LQ decaying to a charged lepton (or neutrino) and a jet is unconstrained by the theory
- studying LQ channel with β=0.5 give us the opportunity to exclude LQs in a 2D plane (LQ_{mass} vs β) by combining results with β=1 channel

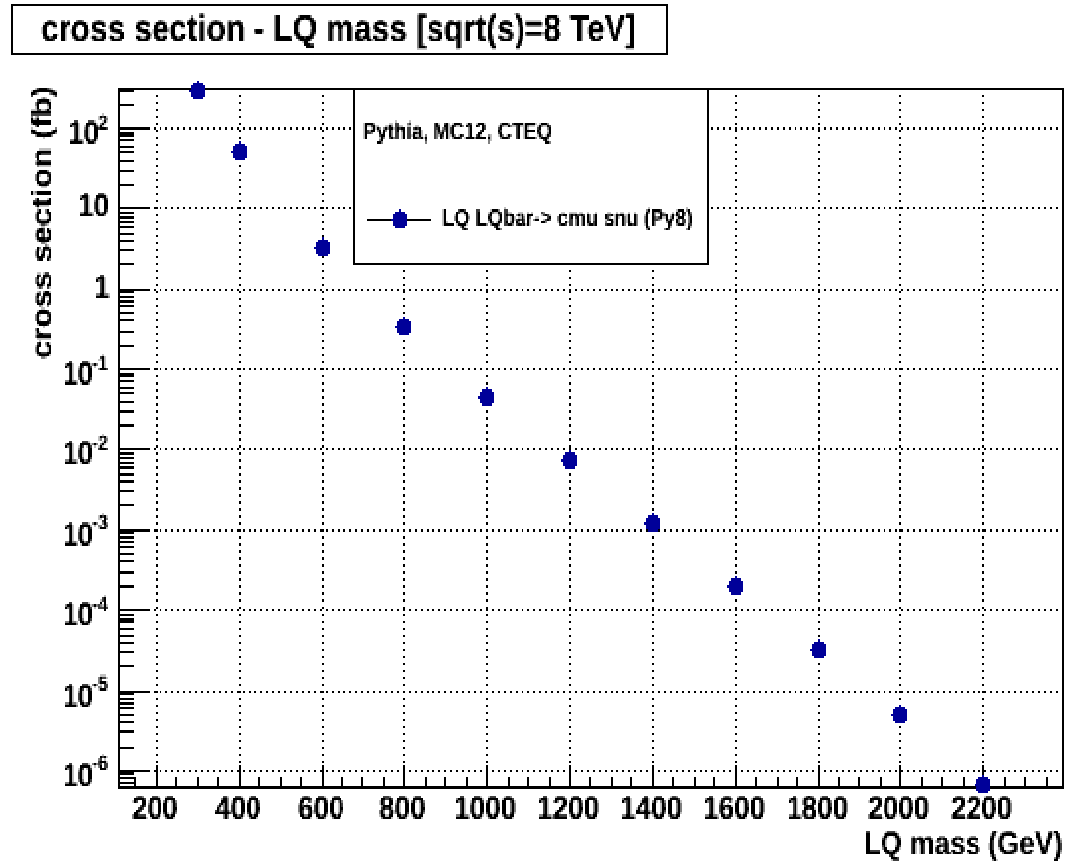




* **plots from 2012 ATLAS Note** "*Searches for second generation leptoquarks in dimuon plus jets and muon, MET plus jets final states using the ATLAS detector*"

lepton-MET-jj channel LQ production cross sections

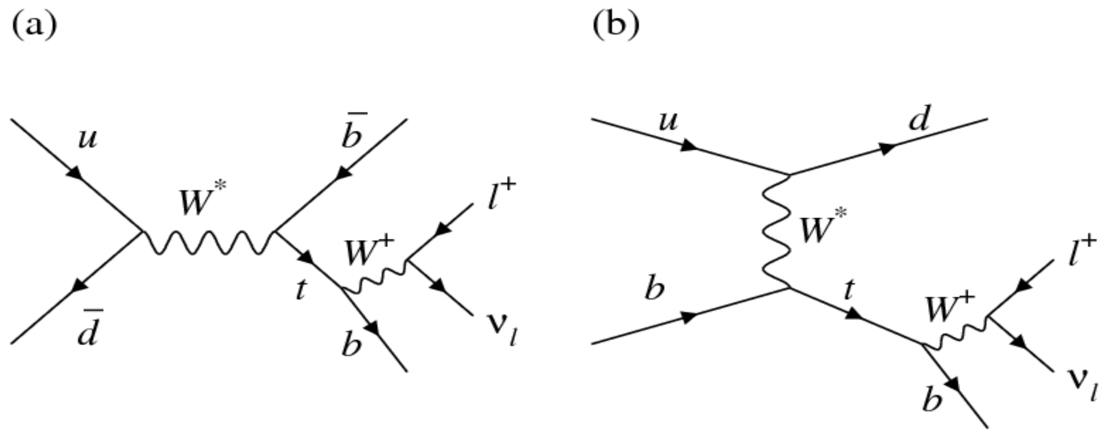
LQ mass (GeV)	LQ LQbar→cmu snu (fb)
300	287.1
400	50.0
600	3.208
800	3.408^10^{-1}
1000	4.621^10^{-2}
1200	7.143^10^{-3}
1400	1.175^10^{-3}
1600	1.959^10^{-4}
1800	3.170^10^{-5}
2000	4.877^10^{-6}



- Generator: Pythia 8
- PDF: CTEQ 6.1
- calculated only in LO

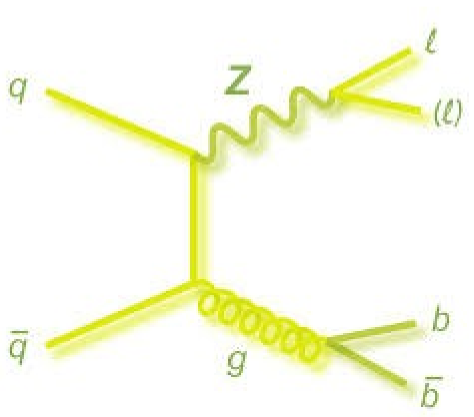
SM background: V+jets

W+jets



main background in lepton+MET+jets channel

Z+jets



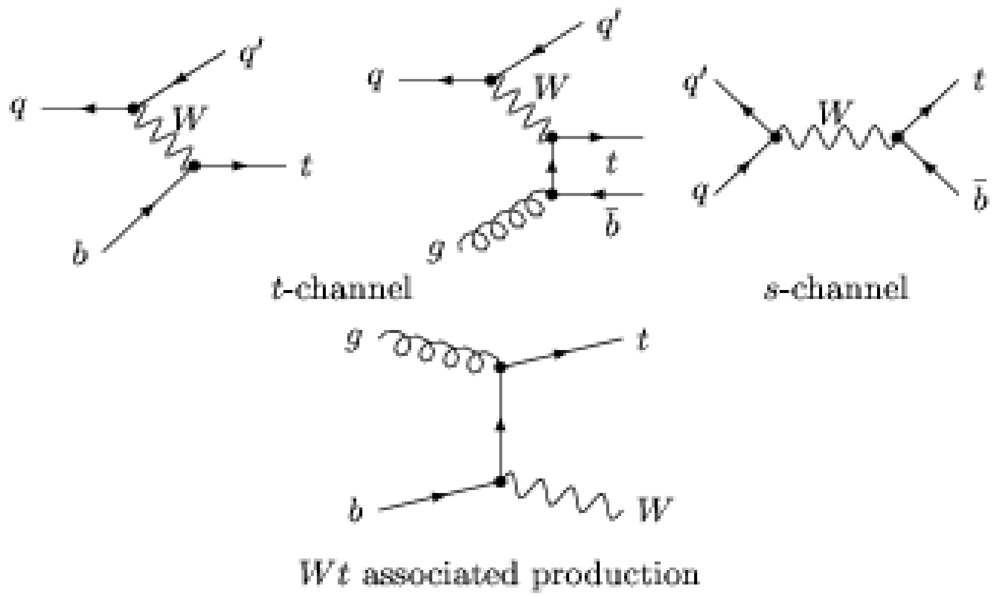
V+jets (vector bosons) = W+jets + Z+jets

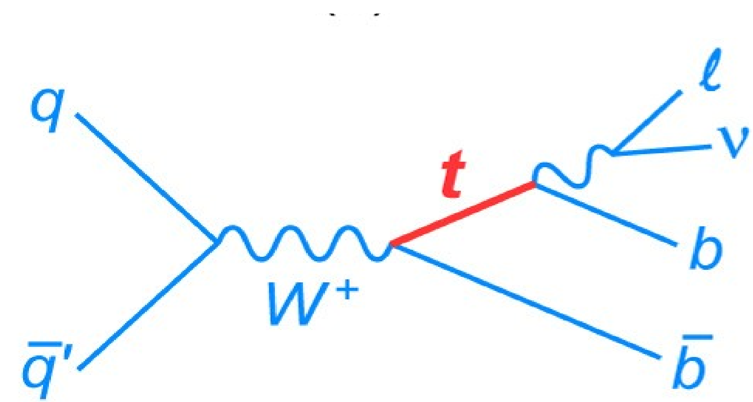
V+jets total cross section ~11,450 pb

the most dominant background for jet jet mu nu channel

SM background: top

single top (s-channel, t-channel, W-t)

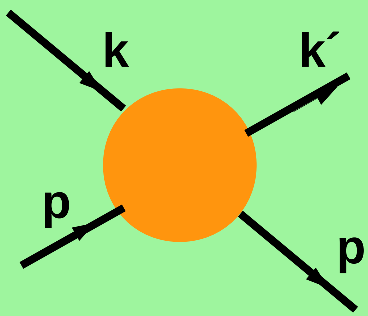




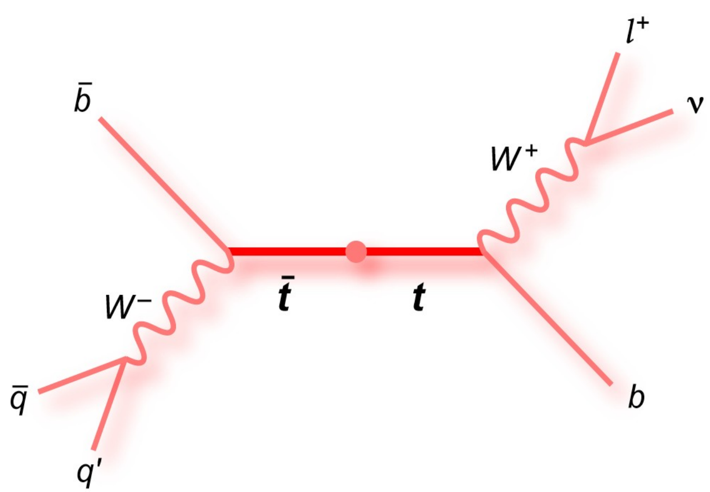
where <u>s-channel</u> and <u>t-channel</u> refer to Mandelstam constants

$s = (k+p)^2$

$t = (k-k')^2$



ttbar



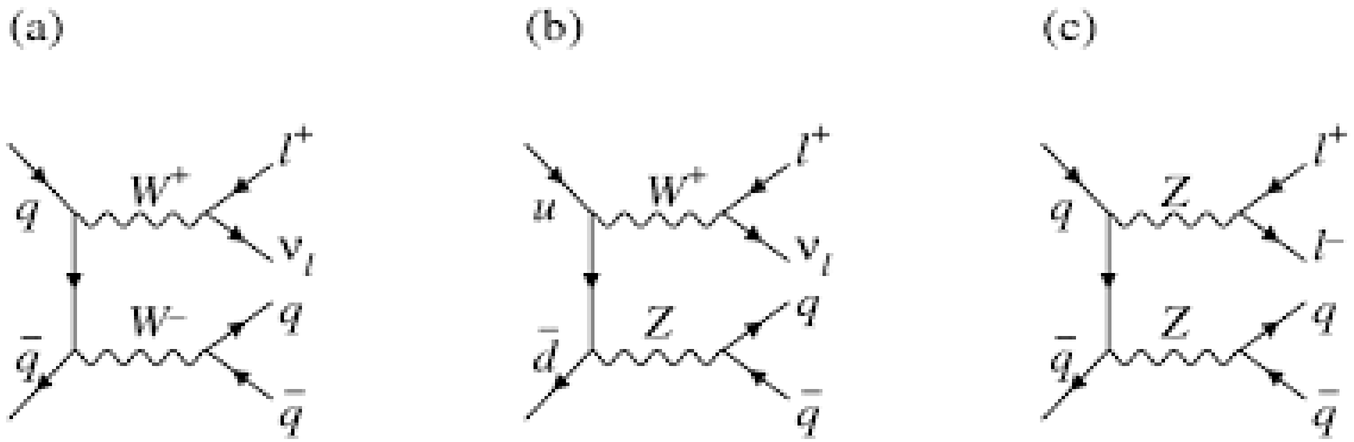
top = single top + ttbar

top total cross section ~170 pb

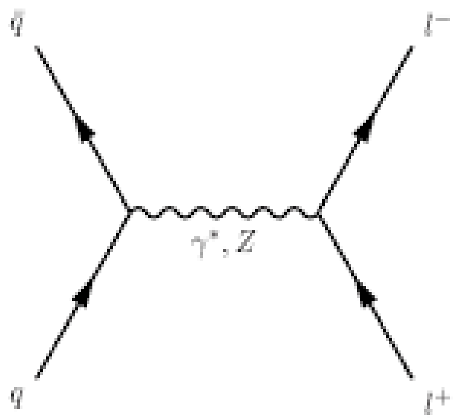
the next most dominant background for jet jet mu nu channel

SM background: Diboson

diboson (WW, WZ, ZZ)



Drell - Yan



diboson cross section ~ 90 pb

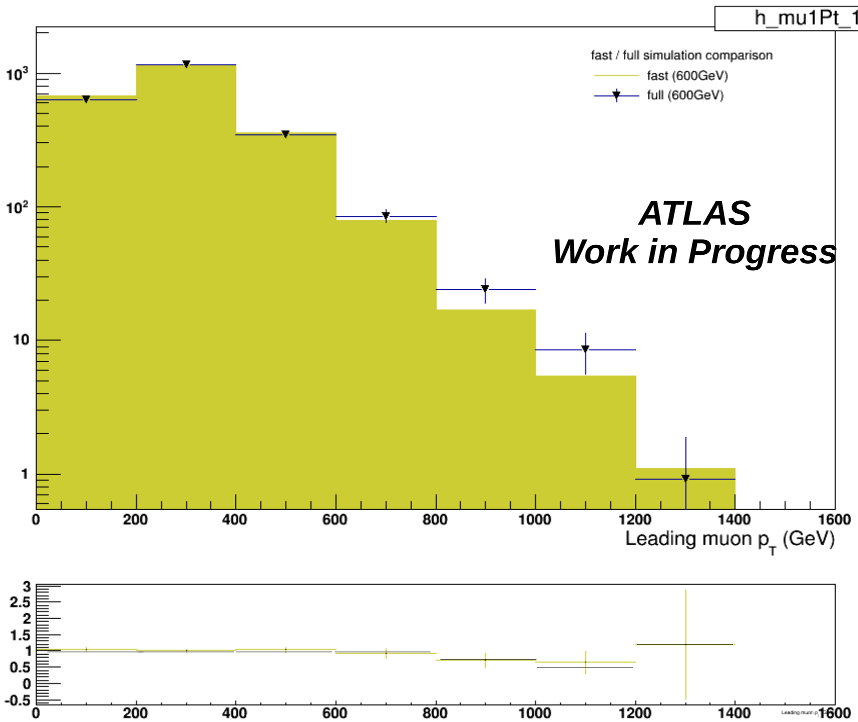
Drell – Yan cross section ~ 13 pb

signal simulation, validation

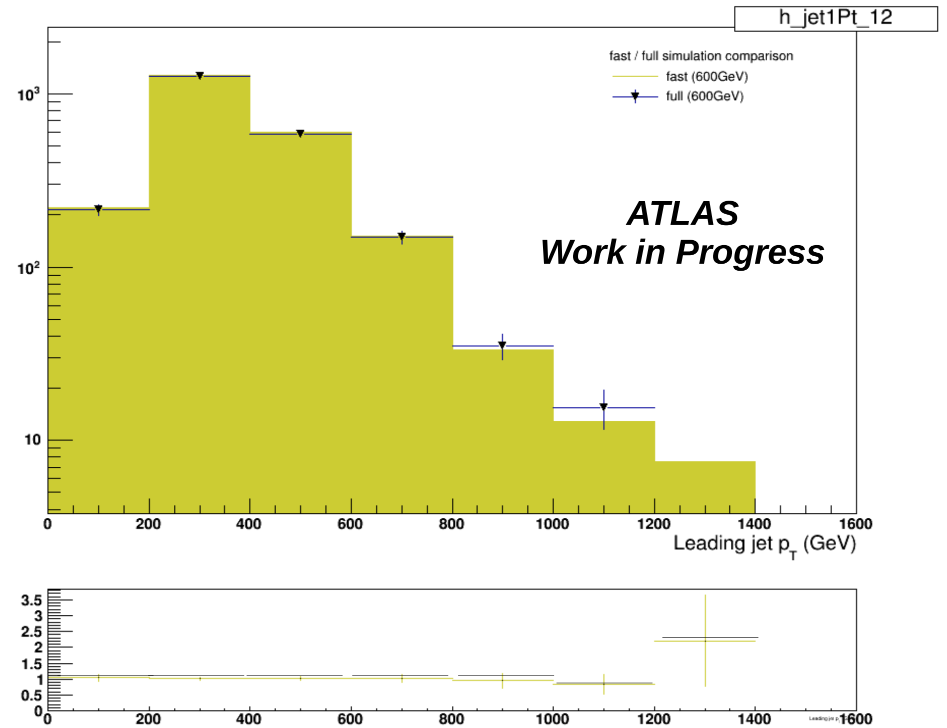
- Pythia 8 generator has been used for signal simulation
- CTEQ 6.1 is PDF used
- simulation has been performed in fast and full mode for comparison
- no significant differences between two modes are observed (following plots), signal final production request was made for fast simulation

fast / full simulation comparison plots for signal at 300GeV

muon p_T



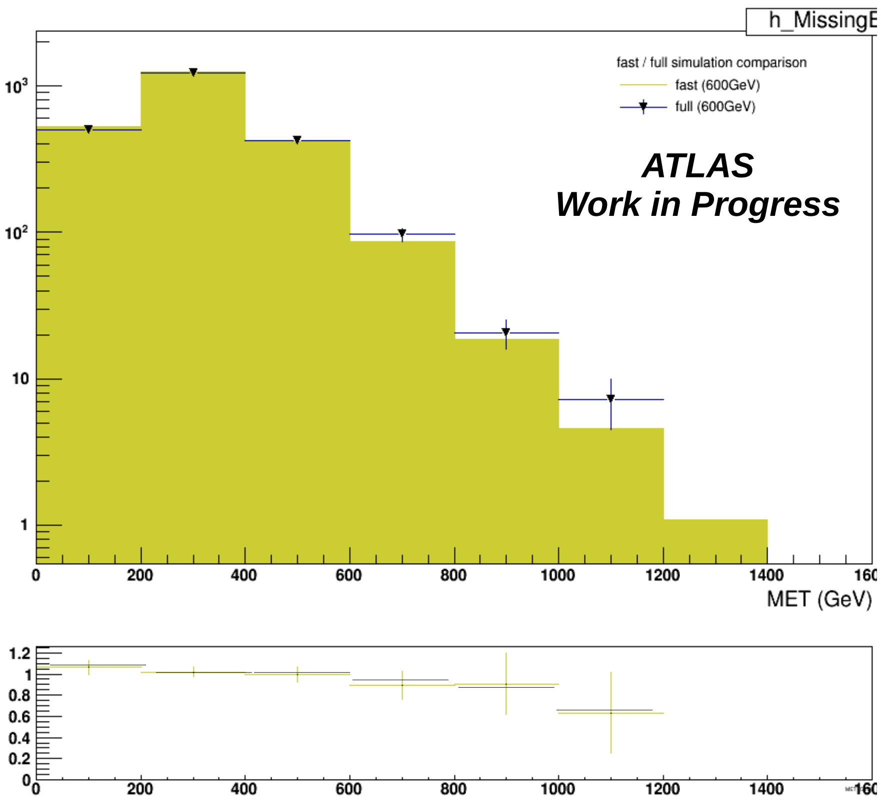
leading jet p_T



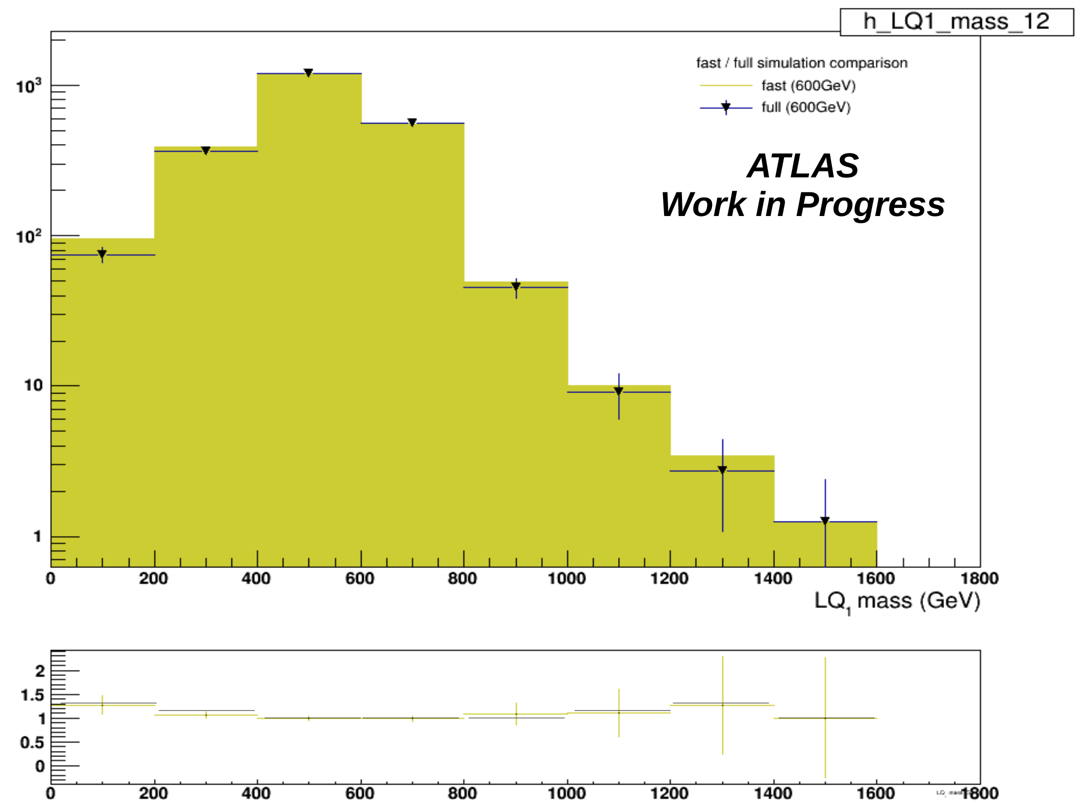
no significant differences between two modes are observed

fast / full simulation comparison plots for signal at 300GeV

missing transverse energy (MET)



leading LQ mass



some kinematic variables used in the analysis

- leptons' transverse momentum (L_T) is the total sum of muon and neutrino momentum-components

$$L_T = (p_T)_{muon} + MET$$

- hadrons' transverse momentum (H_T) is the total sum of two jets momentum-components

$$H_T = (p_T)_{leading\ jet} + (p_T)_{subleading\ jet}$$

- total sum over all particles' momenta (S_T)

$$S_T = (p_T)_{muon} + (p_T)_{leading\ jet} + (p_T)_{subleading\ jet} + MET$$

therefore....

$$S_T = H_T + L_T$$

- transverse mass (M_T) is derived by using the same components as L_T in the equation

$$M_T = sqrt\,[\,2 * (p_T)_{muon} * MET * (1\text{-}\cos\Delta\varphi)]$$

where MET is missing transverse energy (neutrino 's energy) and Δφ is the angle between muon 's and neutrino 's trajectories in the same event

- M_T variable is used to distinguish between events with and without leptonic decay of a real W boson. It is a function of visible momenta (muon 's and MET 's), therefore its value depends on W boson 's decay. The result is that M_T 's value can be used as a lower limit of W mass (parent particle)

object and event selection (LQ signal at 300GeV)

muon selection		
1. all muons		10119.97
2. central muons (type)	(selected only central muons)	9892.23
3. p_T	(pass muons with $p_T > 30.0$ GeV)	9697.40
4. |eta|	(pass muons with pseudorapidity < 2.5 , up to ~10^o if beam axis corresponds to 0^o)	9697.40
5. blayer		9697.40
6. pixel		9697.40
7. sct	(MCP quality cuts, e.g pixel sensors, SCT sensors, TRT etc)	9697.40
8. si		9697.40
9. trt		9697.40
10. z0*sin(theta)	(longitudinal impact parameter)	9694.84
11. d0sig	(transverse impact parameter)	9591.74
12. trkiso	(make sure the selected muon is well isolated (p_T cone))	9431.85
13. 3-station	(at least 3 MDT hits in inner, middle and outer stations, increase muon efficiency through MCP recommendations in high p_T muons ("good" muon))	8091.40
14. trigmatch	(make sure that our selected muon is the one that fired the muon trigger)	7972.31

MCP recommended quality cuts

object and event selection (LQ signal at 300GeV)

jet selection		
1. all jets weighted		32252.52
2. energy > 0	(not noise channel)	32252.52
3. jet quality	(not a bad jet)	32252.52
4. p_T	(pass jets with pT > 20.0 GeV)	32252.52
5. |eta|	(pass jets with pseudorapidity < 2.8 (up to ~7^o if beam axis corresponds to 0^o))	32252.52
6. vertex fraction	(express the possibility our track comes from a particular vertex)	31711.72
7. p_T	(pass jets with pT > 30.0 GeV)	31711.72
8. muon – jet overlap	(make sure our jet is well isolated)	31711.72
9. electron – jet overlap	(make sure our jet is well isolated)	31711.72

object and event selection (LQ signal at 300GeV)

Event selection (μνjj preselection)		
1. events after trigger	(the event has been fired by muon trigger)	9748.43
2. bad event & tile error	(event cleaning cuts)	9748.43
3. muons > 0	(make sure there is at least 1 muon in the event)	7780.57
4. signal muons = 1	(make sure there is exactly 1 muon in the event (our channel: μνjj))	7777.93
5. pass trigger	(using the EF_mu18_MG_medium trigger algorithm)	7775.03
6. triggered matched	(make sure that our selected muon is the one that fired the muon trigger)	7614.65
7. 2nd lepton veto	(make sure there is exactly 1 muon and no electron in the event)	7614.65
8. jets >= 2	(make sure there are at least 2 jets in the event)	7614.65
9. MET	(missing transverse energy must be over a lower limit)	7350.99
10. Δφ (leading jet, MET)	(rejecting events with misreconstructed MET ("back to back" jet-ν))	6956.69
11. Δφ (muon, MET)	(rejecting events with misreconstructed MET ("back to back" muon-ν))	5666.71
12. M_T	(rejecting events with transverse mass M_T of muon-ν smaller than 40 GeV)	5649.37
13. S_T (rejecting events with scalar transverse mass S_T smaller than 300 GeV)		5609.45

Control regions (CR)

Every event must fulfill each CR 's requirements:

- CR A (Wjets): number of jets = 2
  $S_T < 225.$
  $40. < M_T < 120.$

- CR B (Wjets): number of jets >= 3
  $S_T < 225.$
  $40. < M_T < 120.$

- CR C (ttbar): number of jets >= 4
  $40. < M_T < 120.$
  leading jet $p_T > 50.$
  subleading jet $p_T > 40.$

in CRs most backgrounds - except one in each case - are excluded in order to be easier fitting real data and MC simulated events

Control regions (CRs)

- in control regions most backgrounds except one in each case are excluded in order to be easier fitting real data and MC simulated events

- the first and second CRs (A and B) are almost the same, except the requested number of jets

  why is that: W boson has a leptonic and a hadronic decay

  $$W \rightarrow l\ \nu_l \ \textit{(leptonic decay)}$$
  $$W \rightarrow q\ q \ \textit{(hadronic decay)}$$

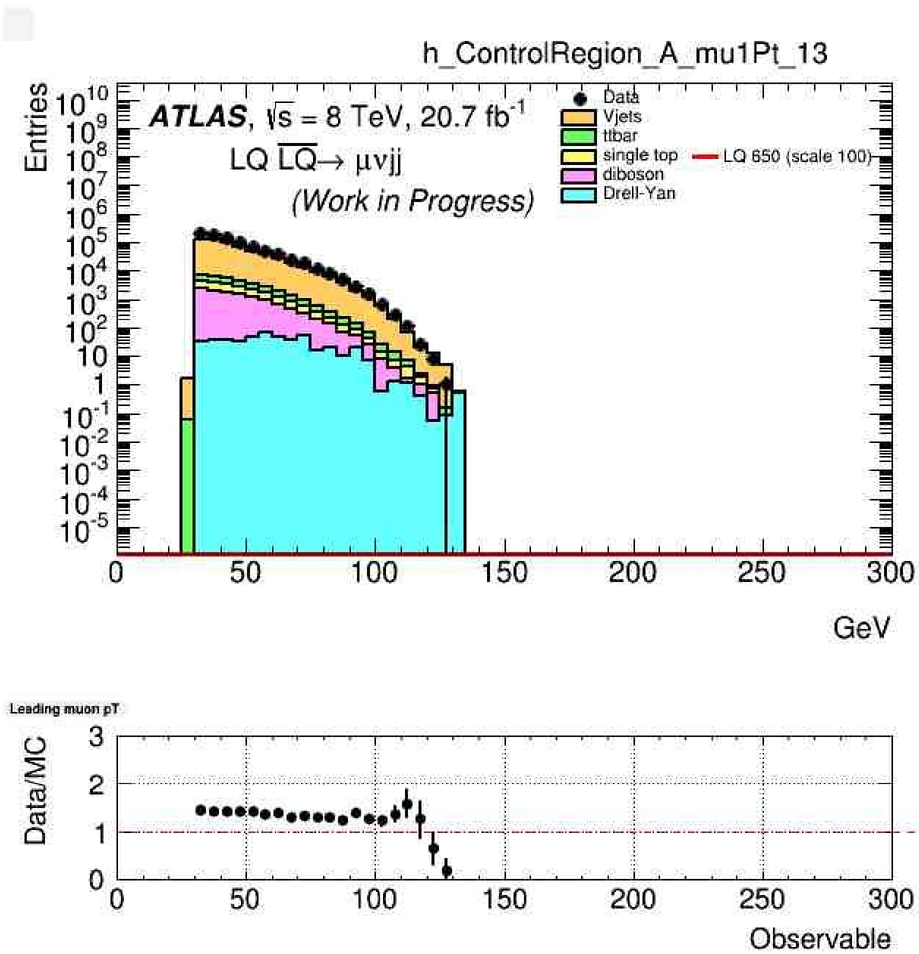
  the first corresponds to CR A, the second to CR B

- M_T variable request has a width of 80 GeV around main value of W boson mass ~80 GeV in order not to "kill" many events and have a sufficient statistic

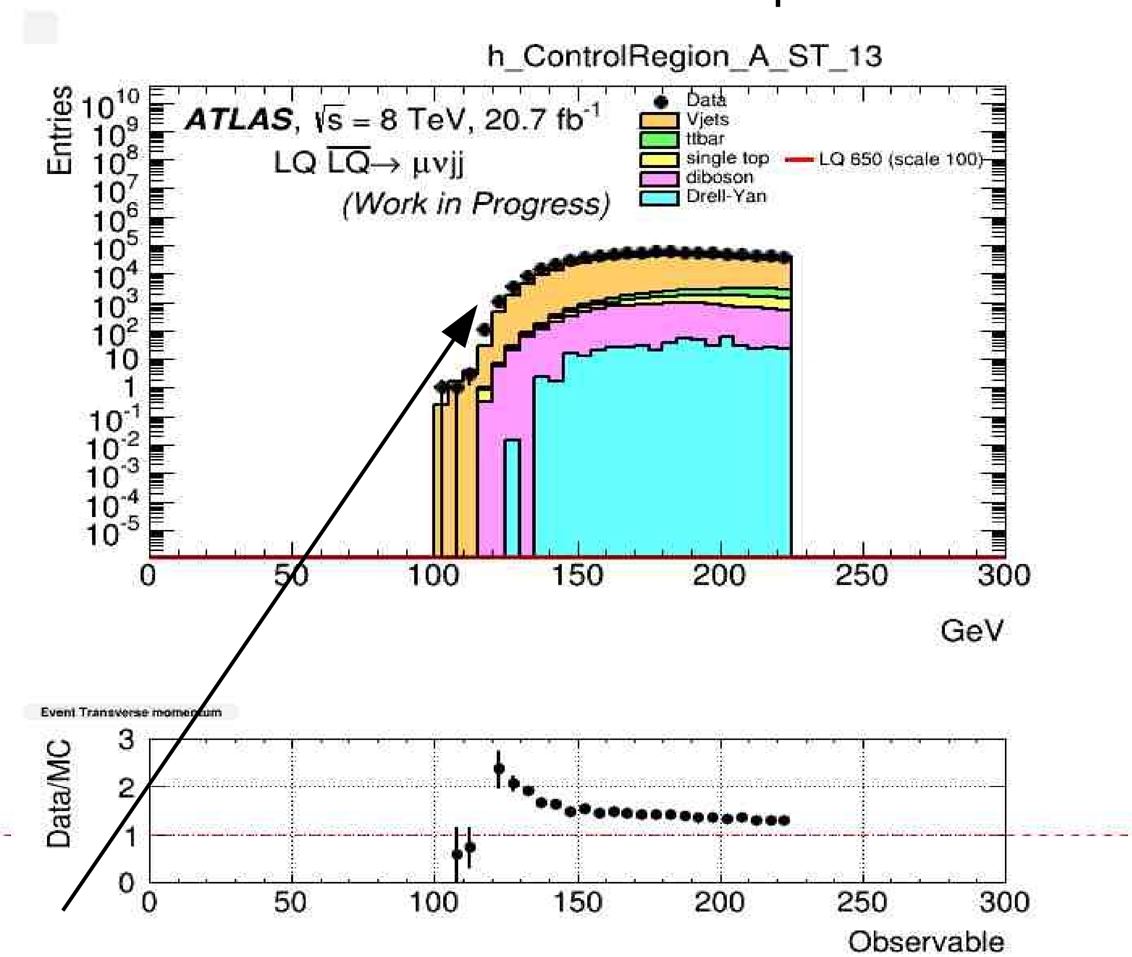
Control region plots

CR_A

muon p_T



total transverse momentum (S_T)

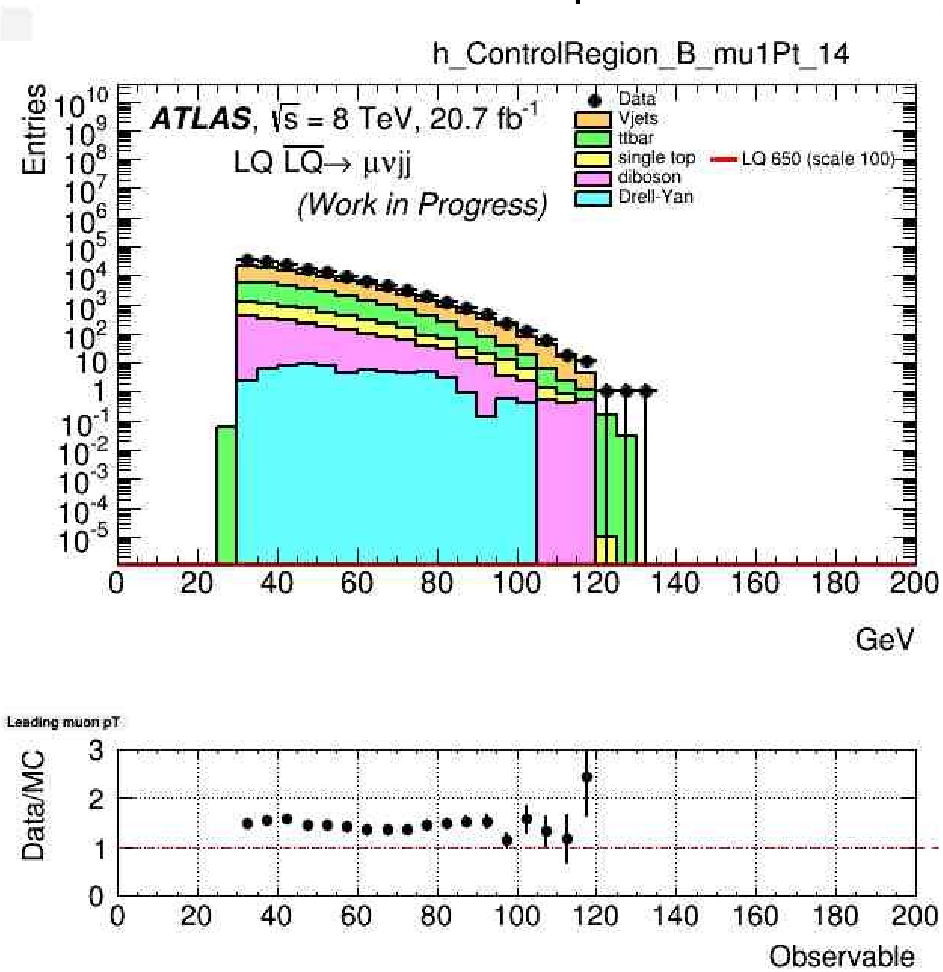


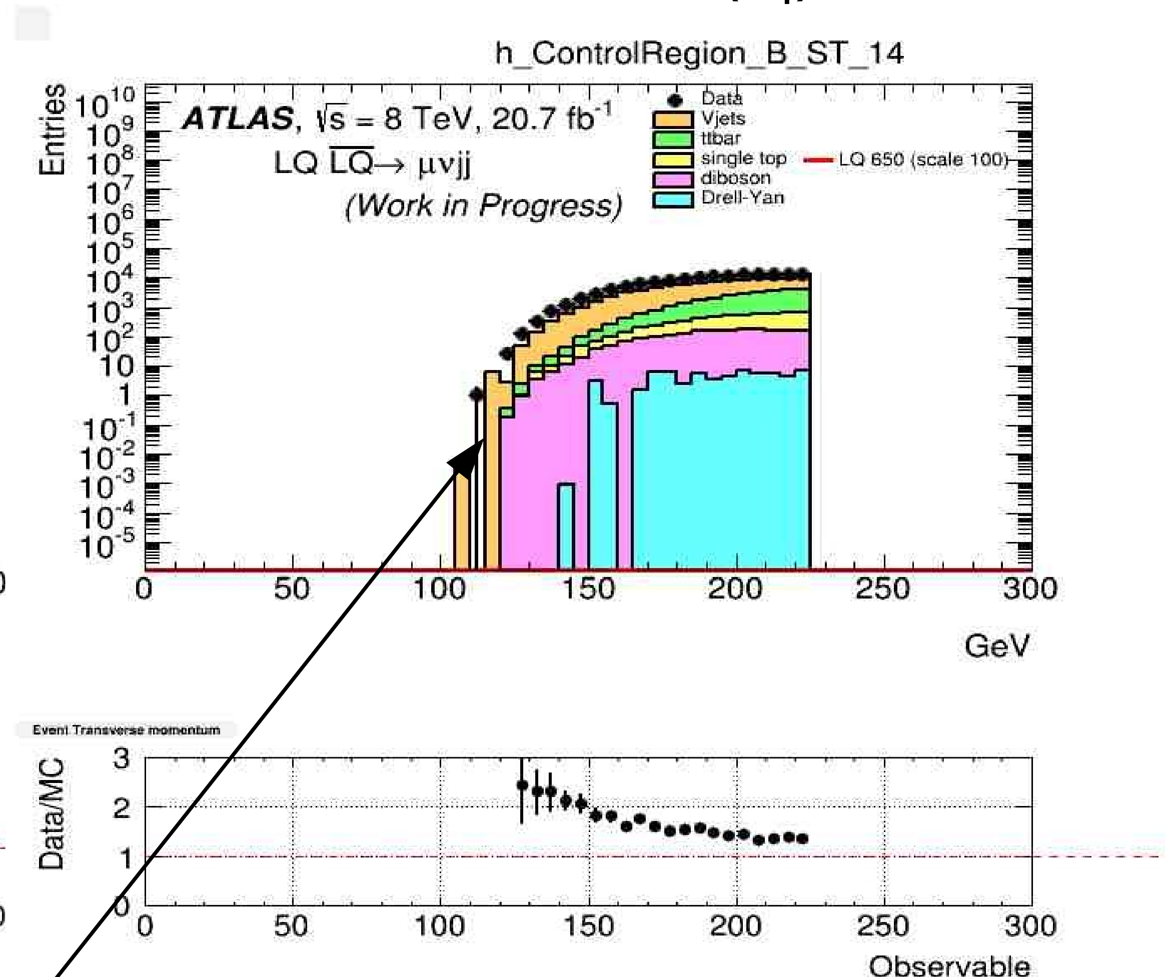
* NOT satisfying fitting, especially in low energy bins *;*
further investigation is required

CR_B

muon p_T

total transverse momentum (S_T)





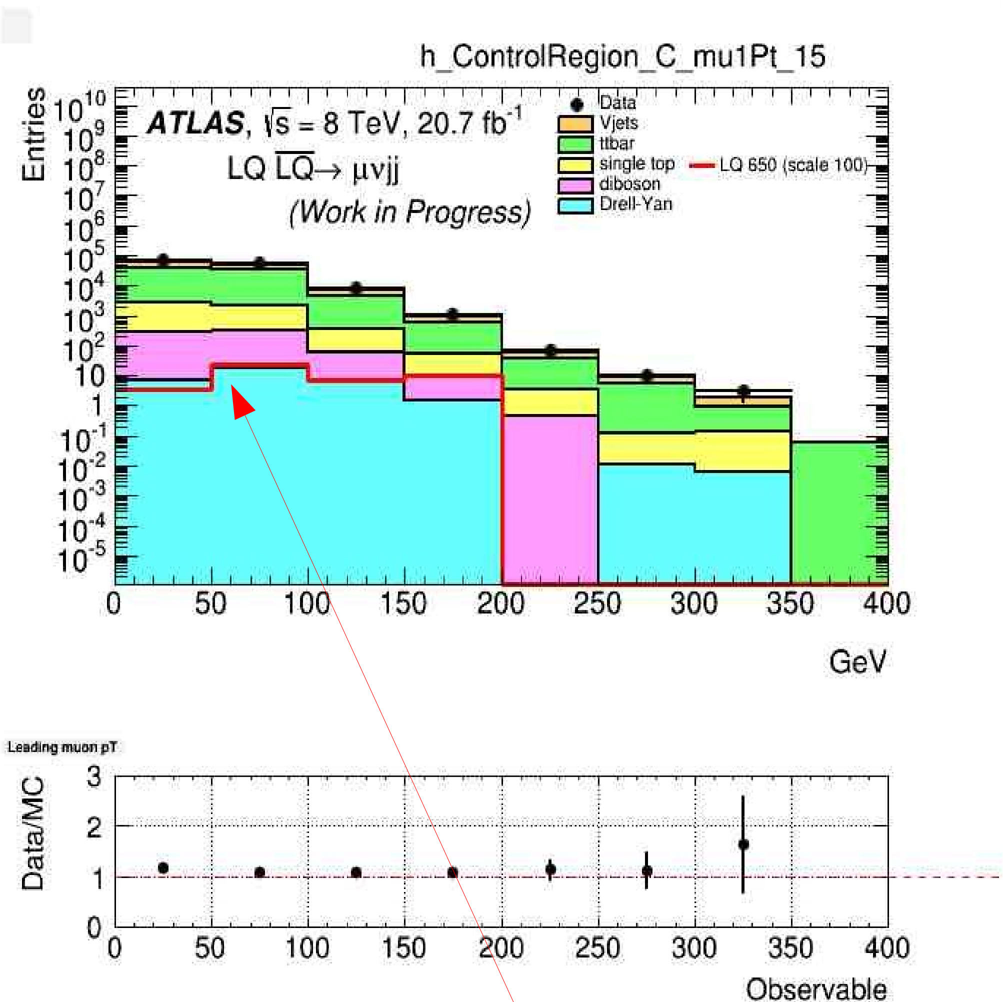
* NOT satisfying fitting, especially in low energy bins ; *further investigation is required*

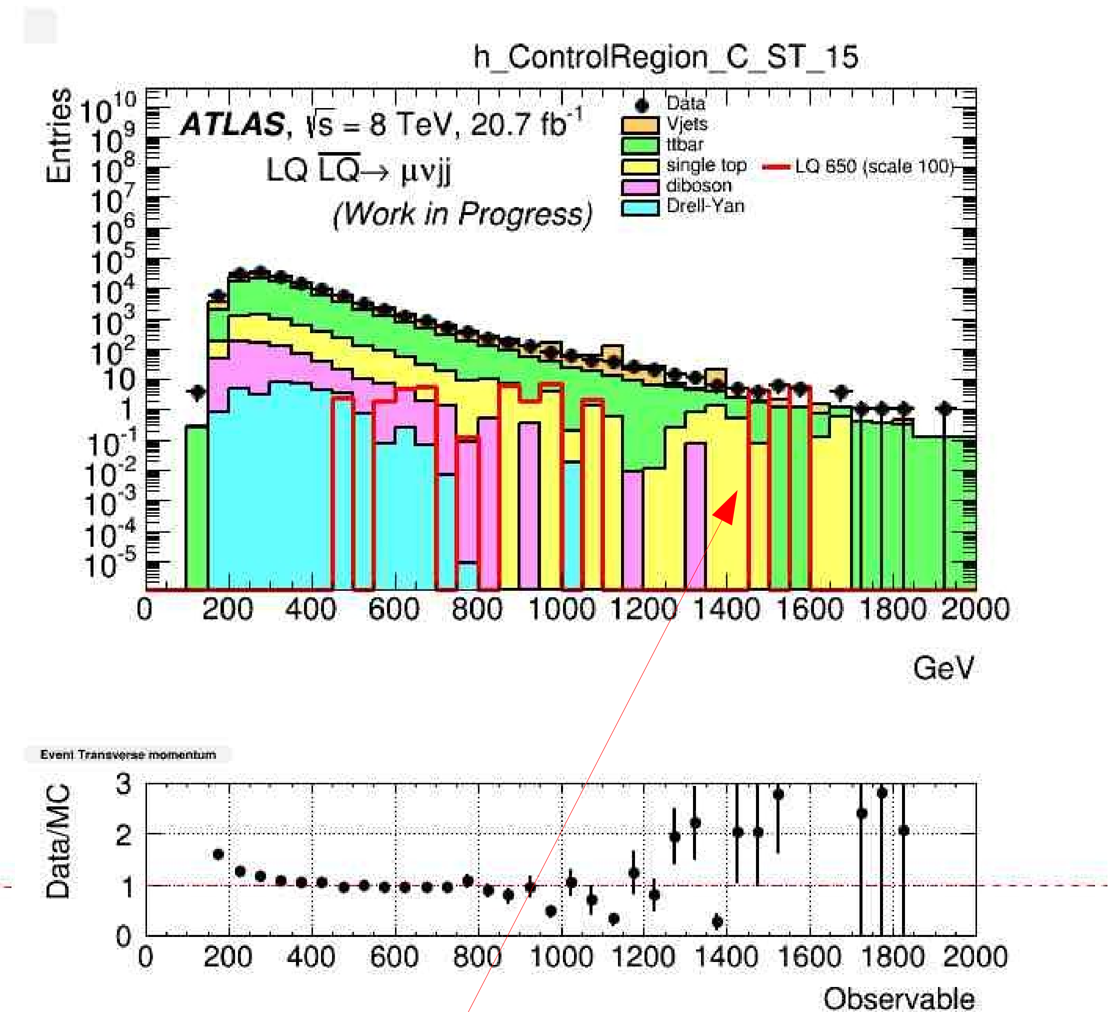
Control region plots

CR_C

muon p_T

total transverse momentum (S_T)





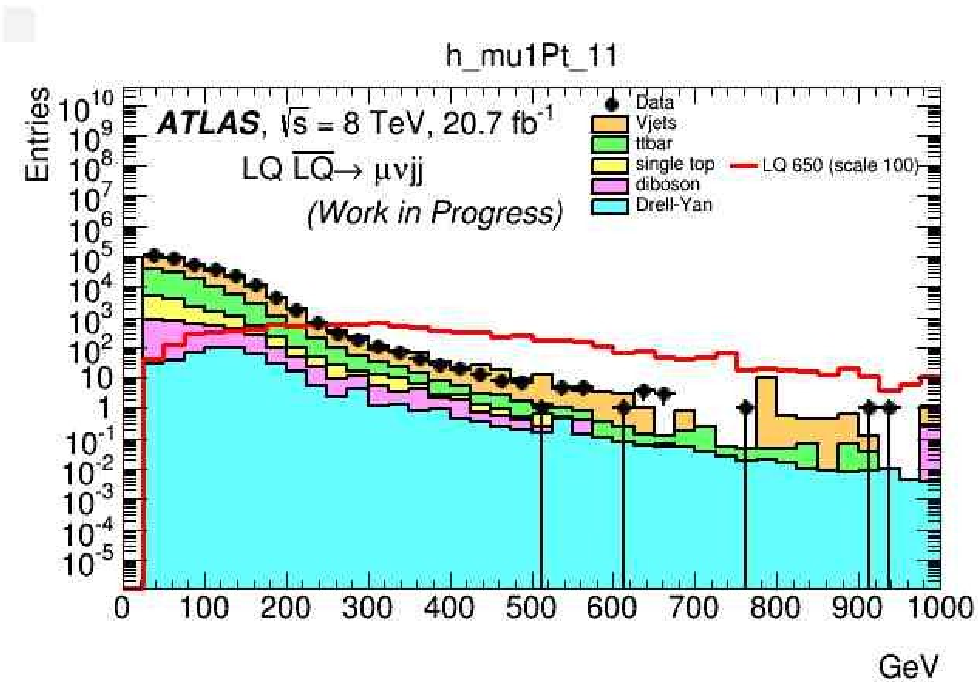
with red line LQ signal at 650 GeV is depicted

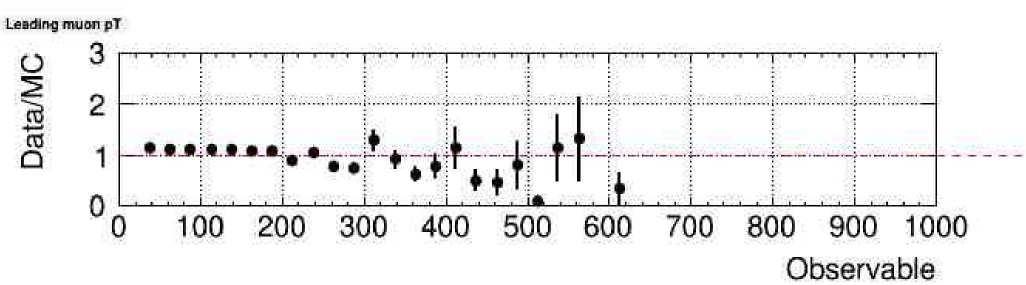
plots after event preselection

reminder

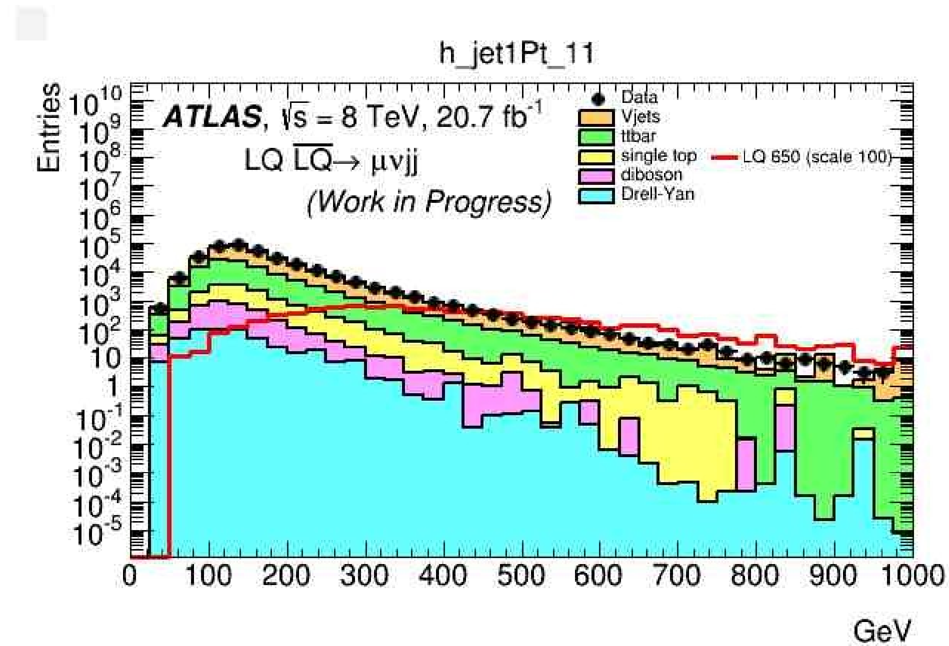
- p_T > 30.0 GeV (muon)
- p_T > 20.0 GeV (jet)
- M_T > 50.0 GeV (event)
- S_T > 300.0 GeV (event)

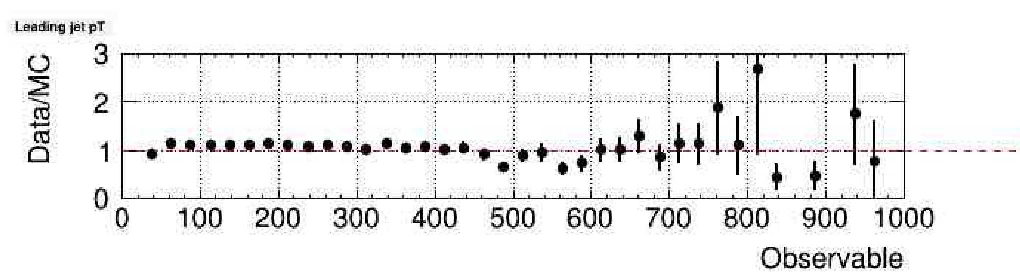
muon p_T





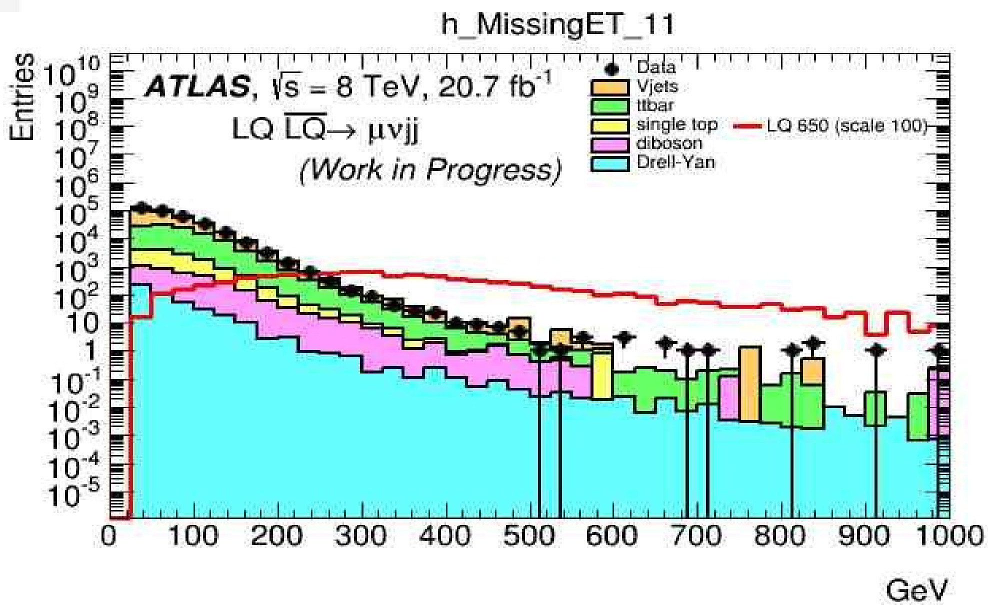
leading jet p_T

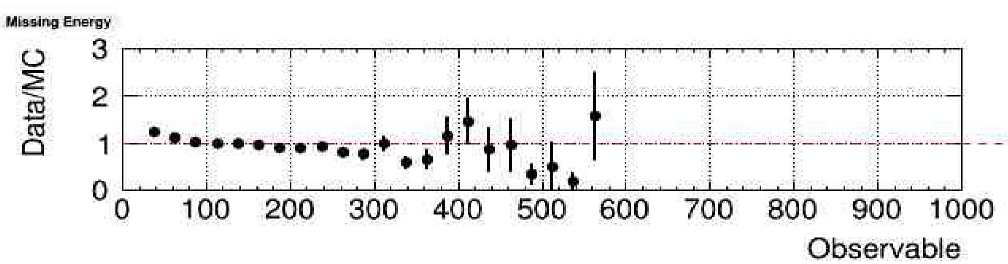




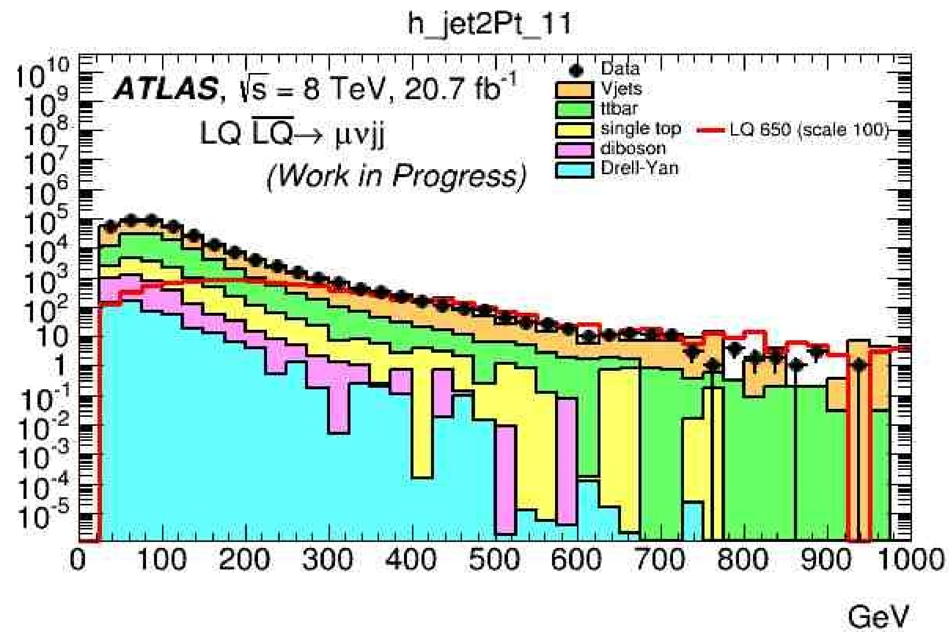
plots after event preselection

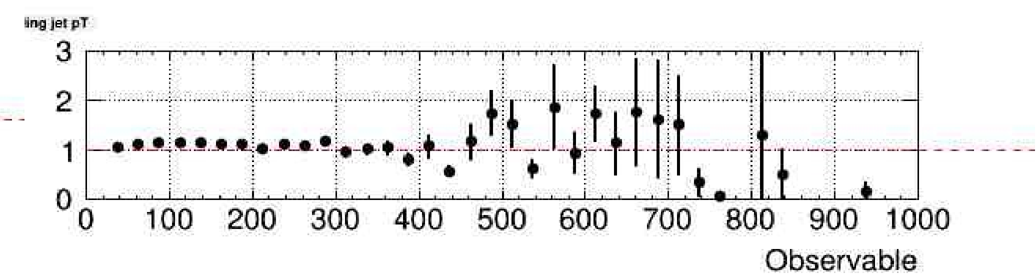
transverse missing energy (MET)





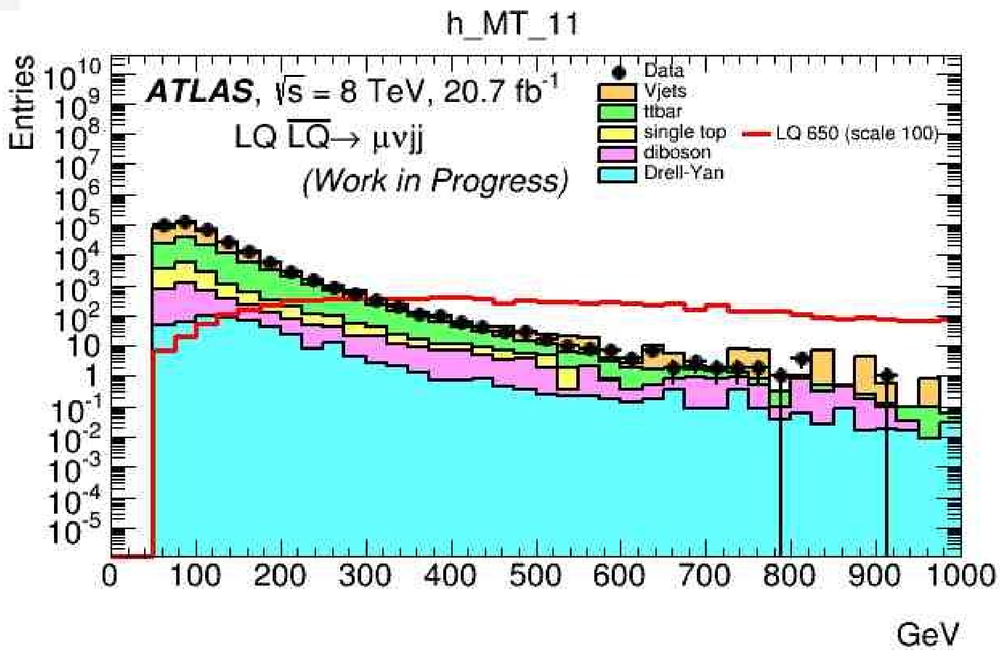
subleading jet p_T

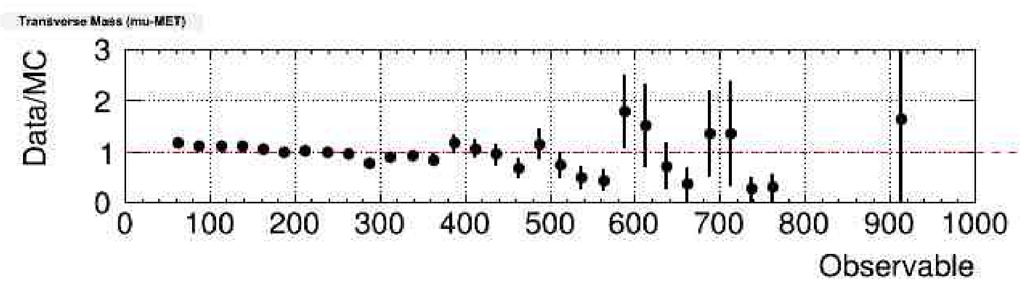




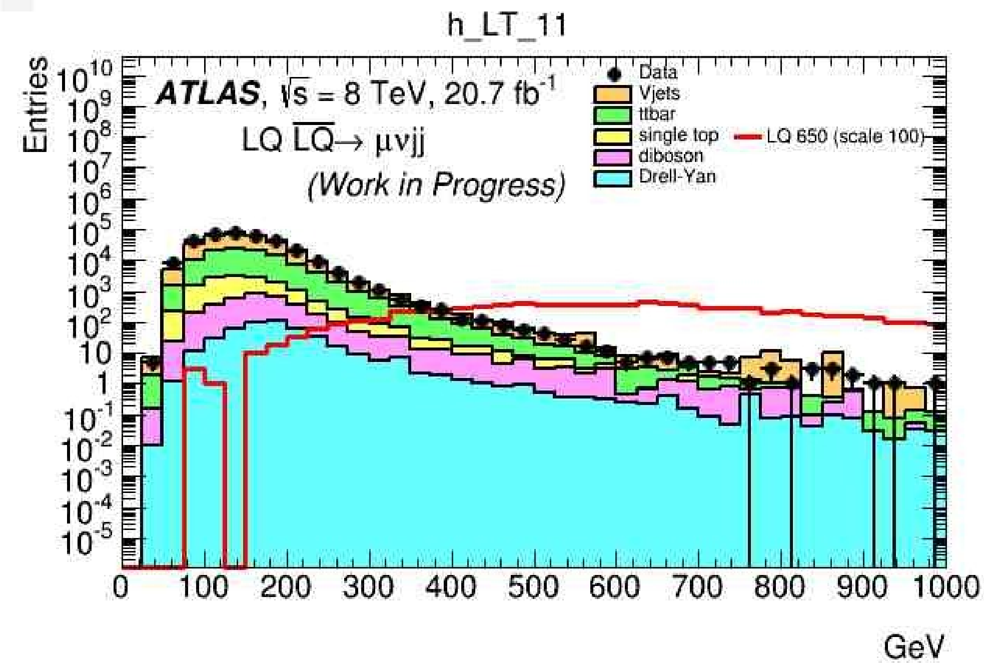
plots after event preselection

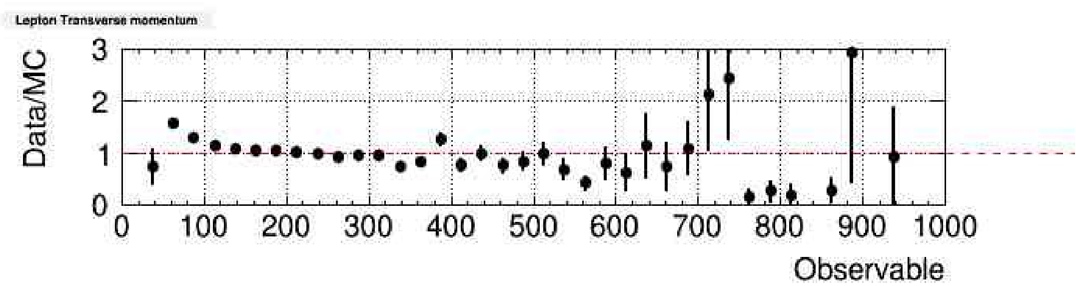
leptons' transverse mass (M_T)





leptons' transverse momentum (L_T)

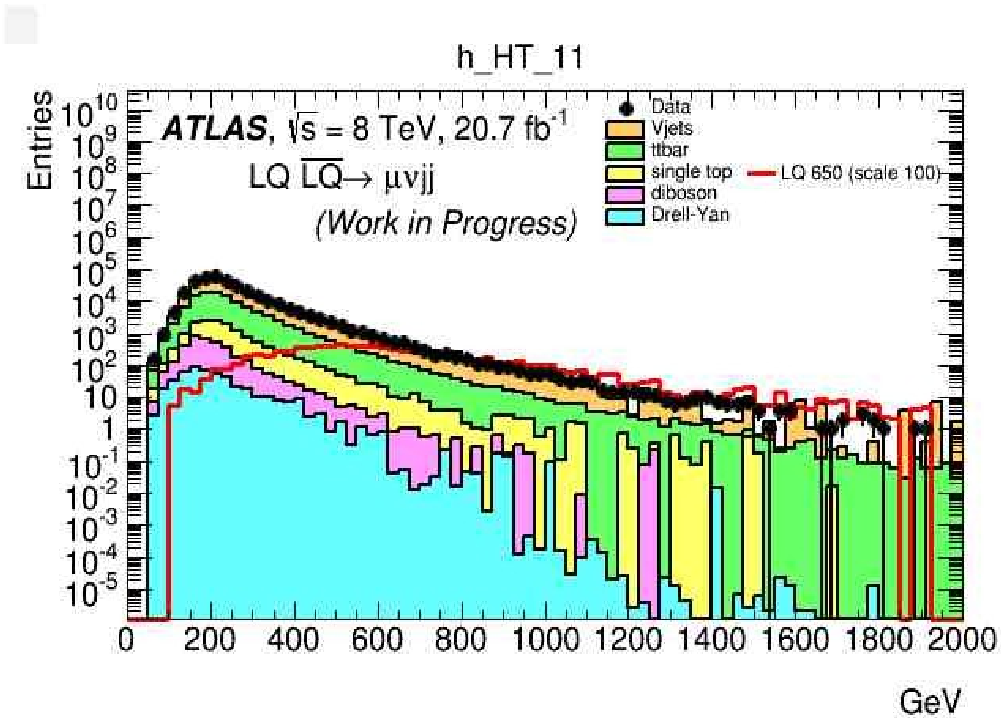


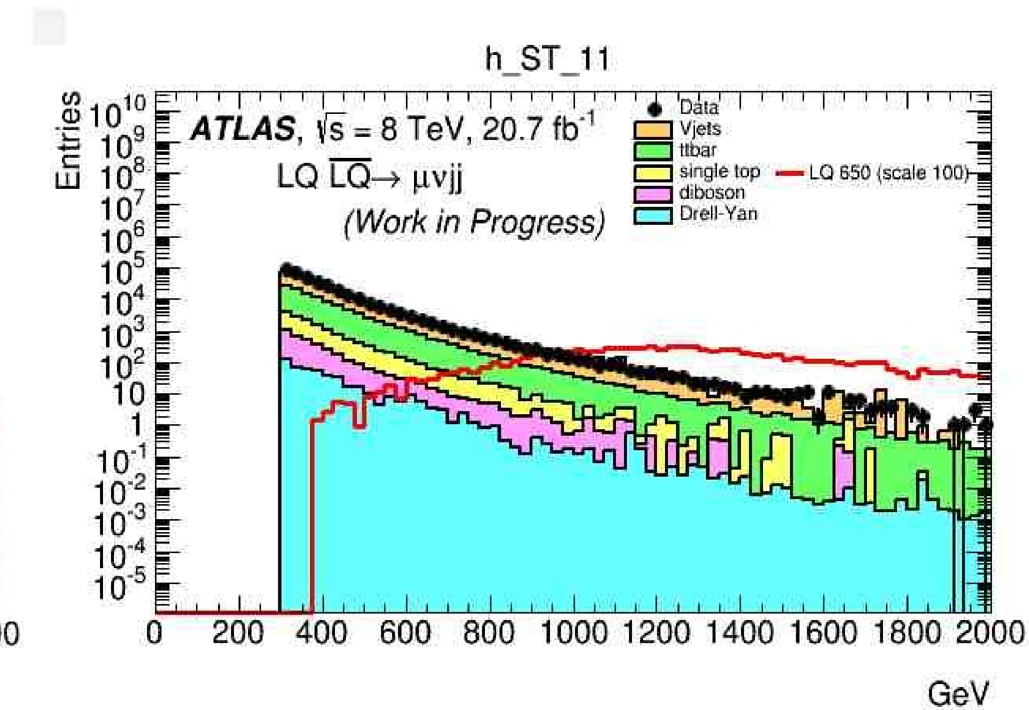


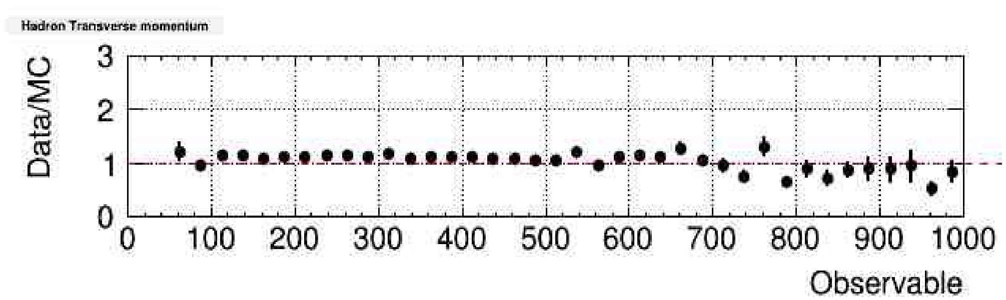
plots after event preselection

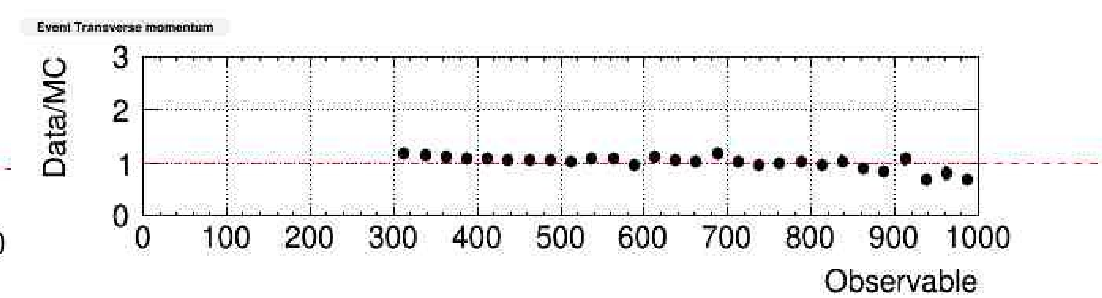
hadrons' transverse momentum (H_T)

total transverse momentum (S_T)









some conclusions on preselection

- in general we observe rather good agreement between real data and MC simulated background, especially in low energy bins

- some disagreement, mainly in higher energy bins, is possibly due to binning effect and low statistics

LQ reconstructed mass

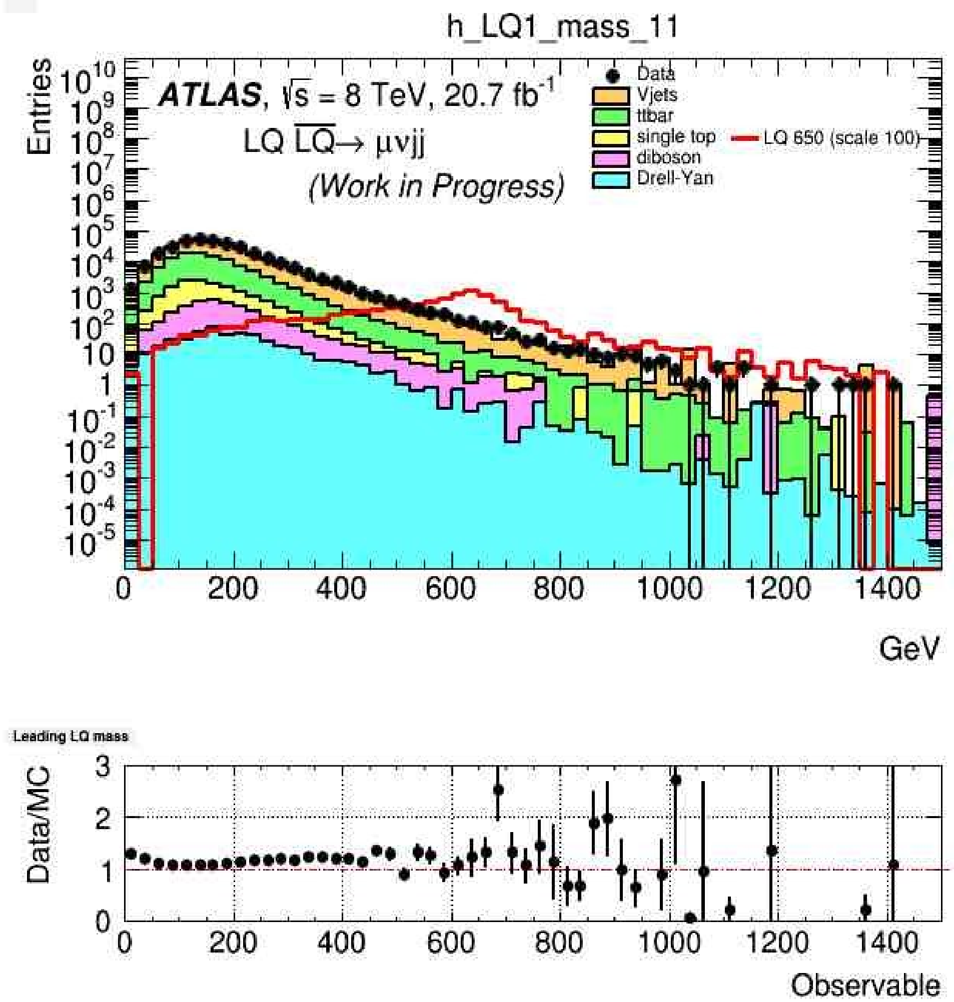
- in each event two LQ masses are constructed by combining leading jet with muon and subleading jet with neutrino (missing energy) or vice versa

- theoretically, the two LQ masses should be almost the same. In each case, both combinations are made and finally the combination selected is that with the minimum mass difference (*mass window method*)

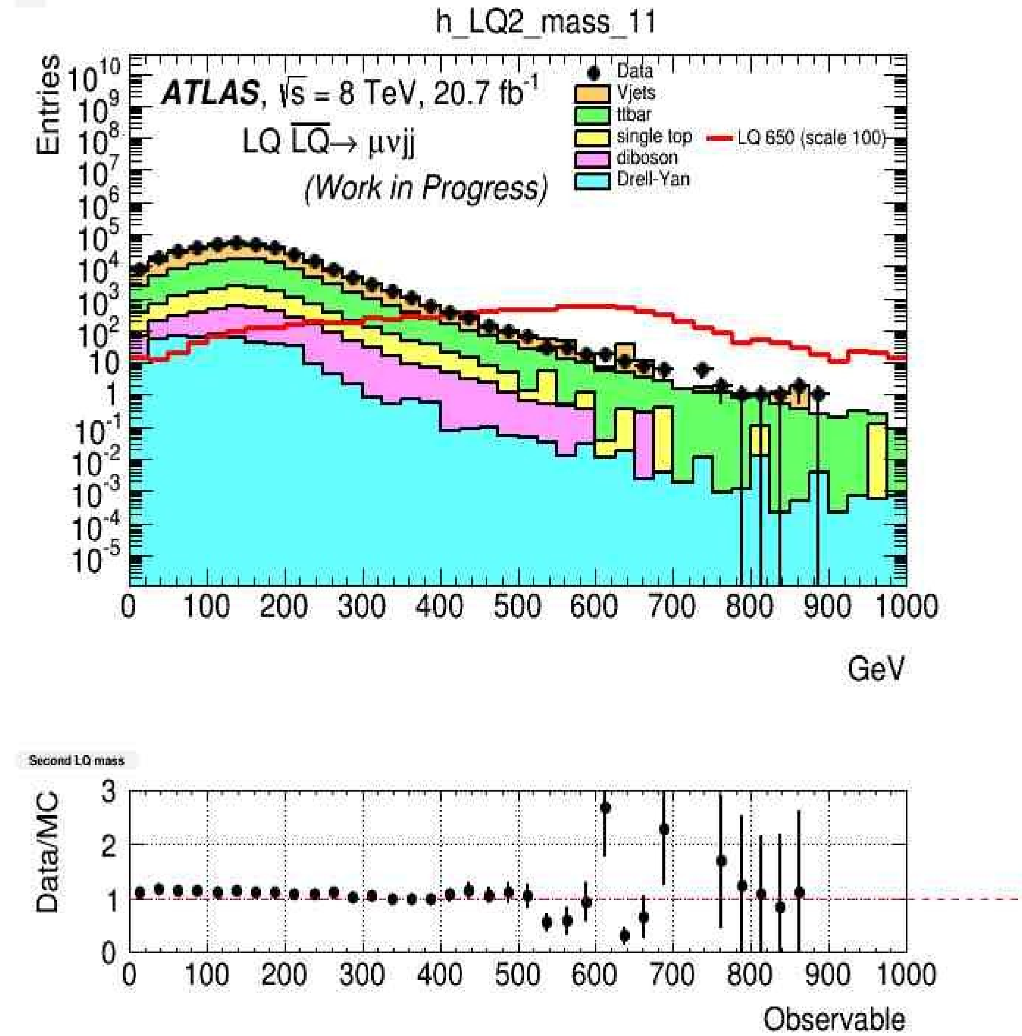
- another method is to calculate the average LQ mass derived directly from the sum of lepton 's momentum, jets' momentum and missing energy

LQ reconstructed mass plots

leading LQ mass



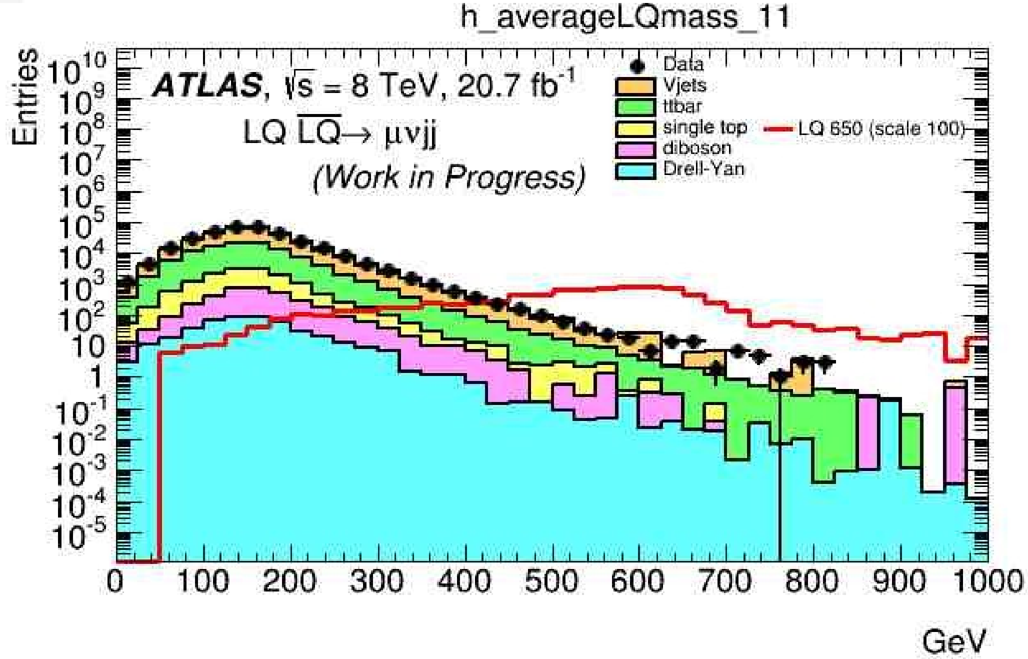
subleading LQ mass

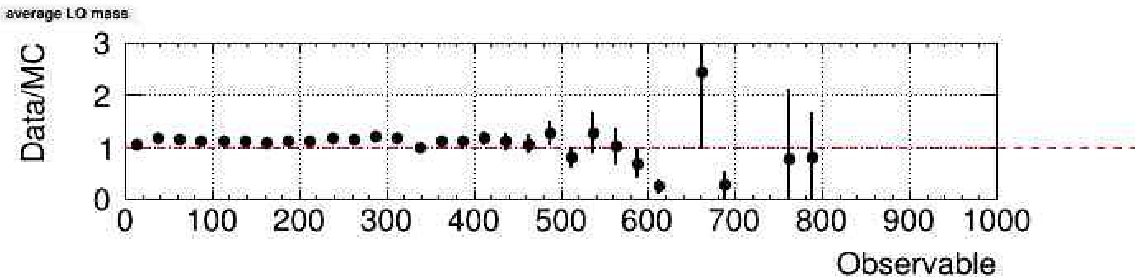


plots acquired through mass window method

LQ reconstructed mass plots

average LQ mass





average LQ mass = (leading LQ mass + subleading LQ mass) /2

significance and efficiency results for different LQ mass points

Definitions

- ***significance = signal / sqrt(background)*** (1)
- ***efficiency = signal / total signal*** (2)

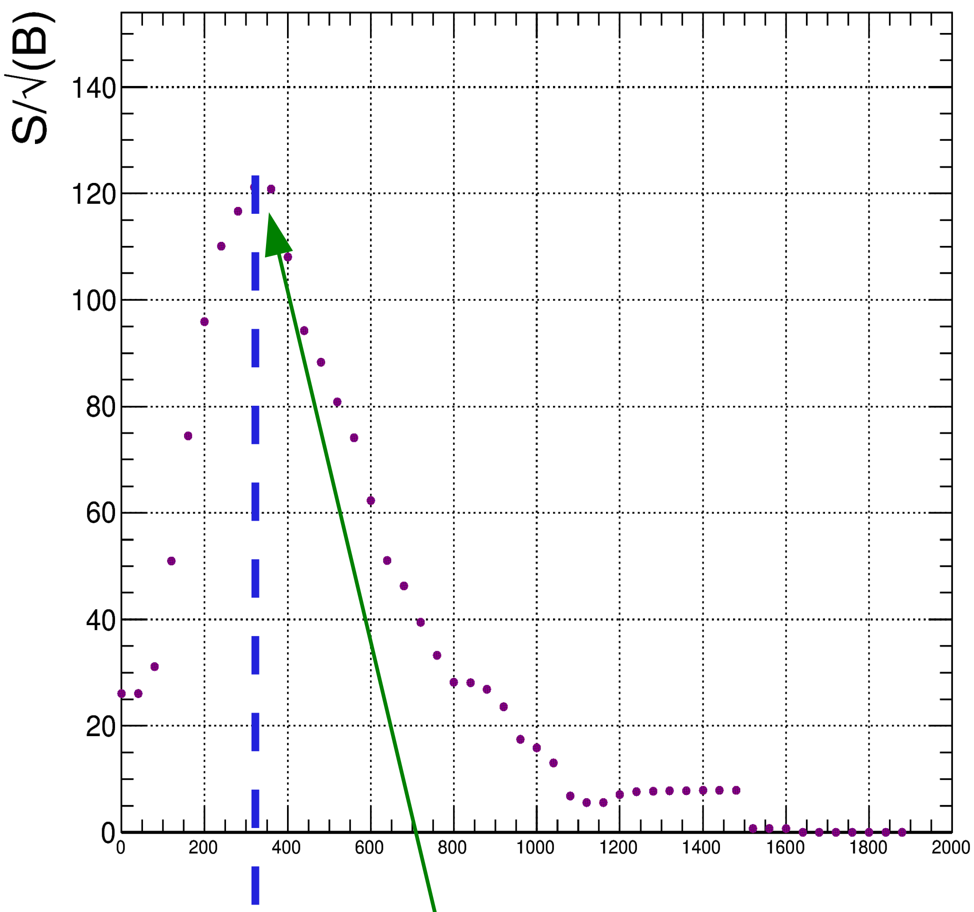
For significance calculation it was used as well the definition

$$Z = \sqrt{2\left[(s+b)\ln\left(1+\frac{s}{b}\right)-s\right]}$$

for comparison with eq.1 . The results are proved to be very similar.

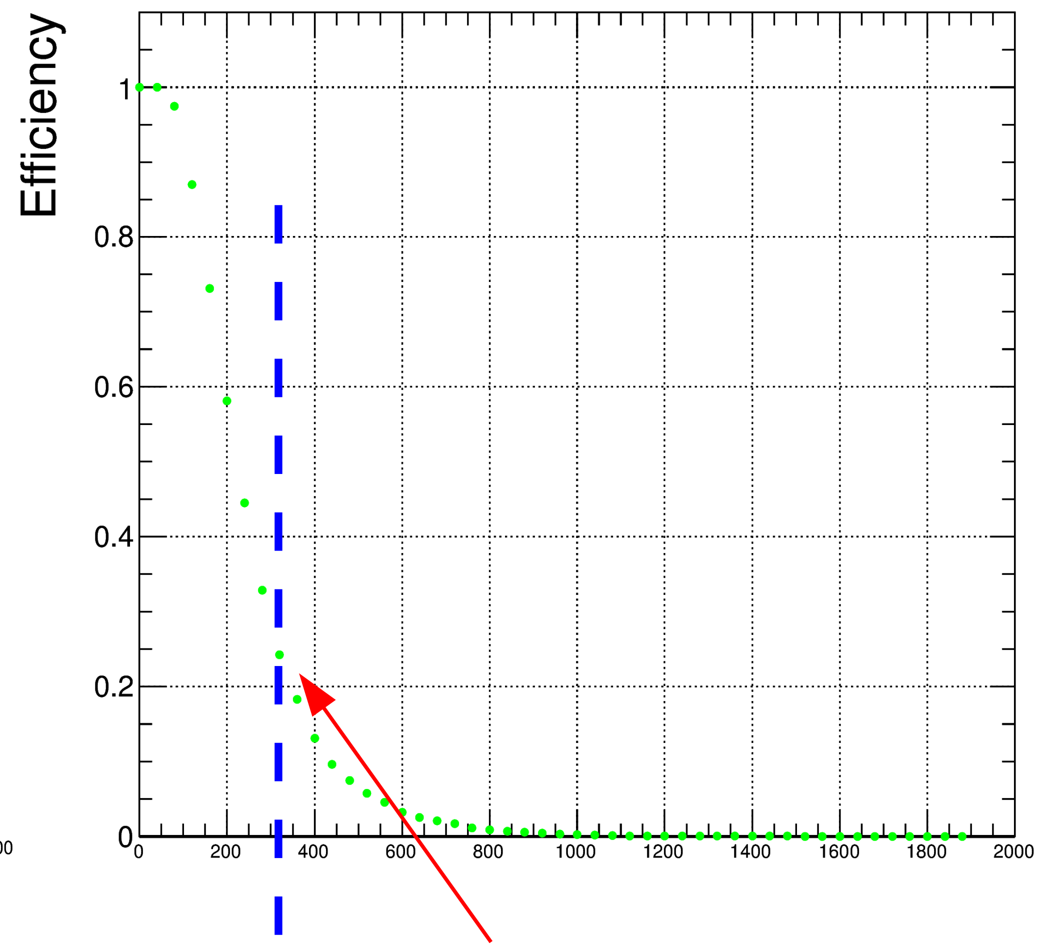
300GeV mass point plots

M_T significance



maximum M_T significance ~121 for M_T ~320 GeV

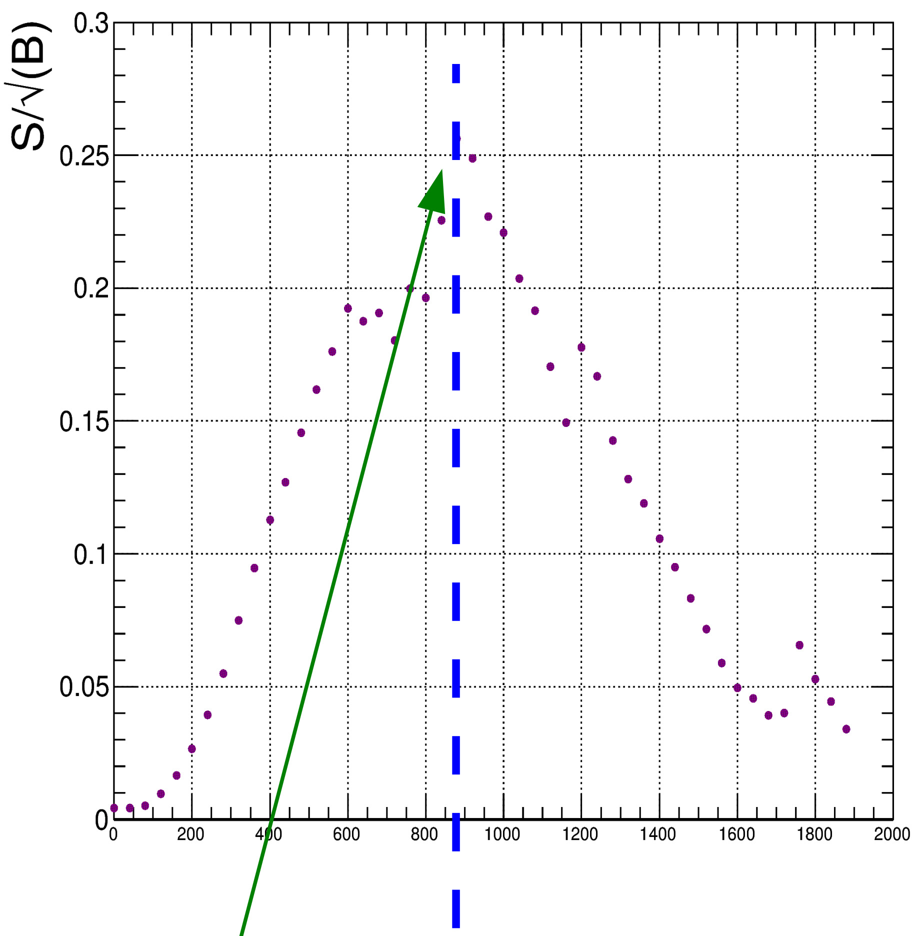
M_T efficiency



M_T eficiency ~0.24 for maximum significance at 300 GeV signal LQ sample

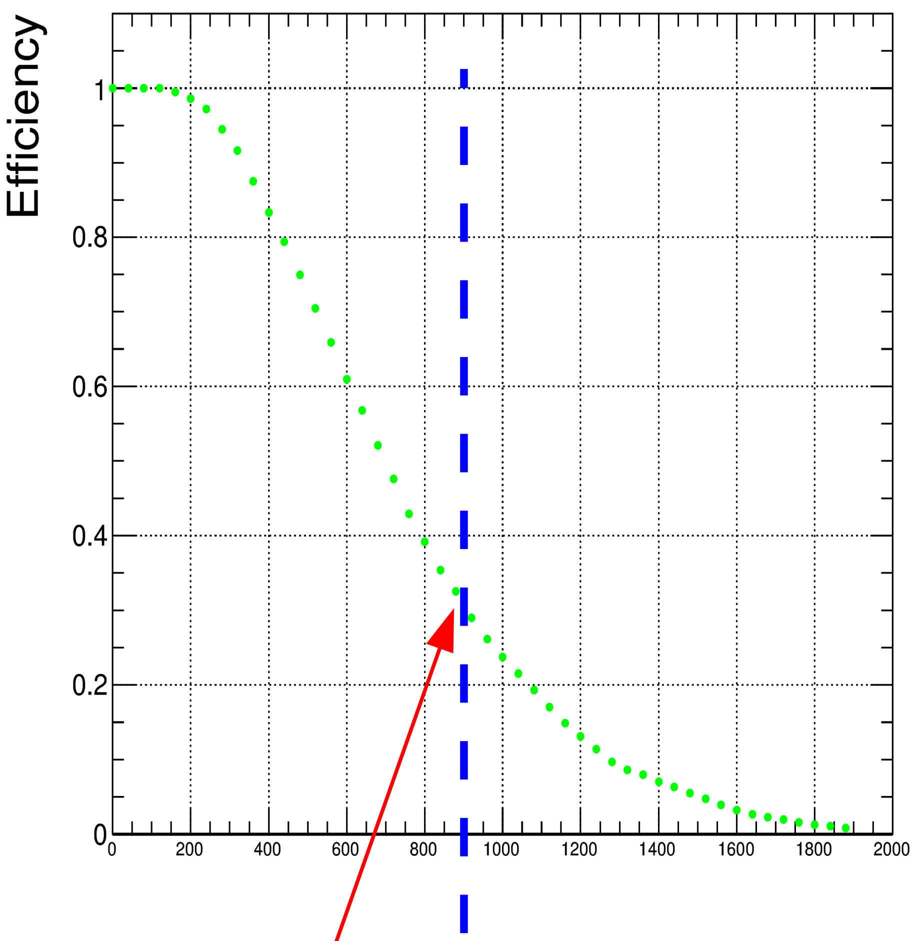
1000GeV mass point plots

M_T significance



maximum M_T significance ~0.26 for M_T ~880 GeV

M_T efficiency



M_T eficiency ~0.33 for maximum significance at 1000 GeV signal LQ sample

significance / efficiency table

(GeV)	M_T		S_T		leading LQ mass	
mass point	***signif.***	***effic.***	***signif.***	***effic.***	***signif.***	***effic.***
300	121.211 *(M_T~320)*	0.243	63.268 *(S_T~560)*	0.621	51.218 *(lq_{mass}~240)*	0.722
500	14.942 *(M_T~480)*	0.308	8.463 *(S_T~880)*	0.599	6.510 *(lq_{mass}~440)*	0.585
800	1.202 *(M_T~880)*	0.211	0.860 *(S_T~1400)*	0.586	0.735 *(lq_{mass}~680)*	0.618
900	0.557 *(M_T~880)*	0.240	0.484 *(S_T~1800)*	0.160	0.346 *(lq_{mass}~760)*	0.552
1000	0.256 *(M_T~880)*	0.325	0.222 *(S_T~1800)*	0.306	0.191 *(lq_{mass}~880)*	0.557
1200	0.051 *(M_T~920)*	0.447	0.025 *(S_T~1840)*	0.349	0.047 *(lq_{mass}~1040)*	0.420

** for LQ mass point 800GeV and on, significance appears smaller than 1; further investigation is required*

work still to be done and future plans (Run II)

Step 1: add QCD background through data driven methods

Step 2: adding systematics

Step 3: exclusion limits calculation

- CMS 2014: *in electron-neutrino-jet-jet topology there is indication of an excess at ~650 GeV at 8 TeV, it would be interesting to be further investigated in Run II up to 13 TeV*

excess at ~650 GeV (first generation LQ)