Searches for vector-like quarks and ttbar resonances with the ATLAS detector

Jordan Webster on behalf of ATLAS

Joint with the TOP & Exotics groups

26 April 2013

Key References:
ATLAS-CONF-2012-136
ATLAS-CONF-2012-137
ATLAS-CONF-2013-018
arXiv:1211.2202

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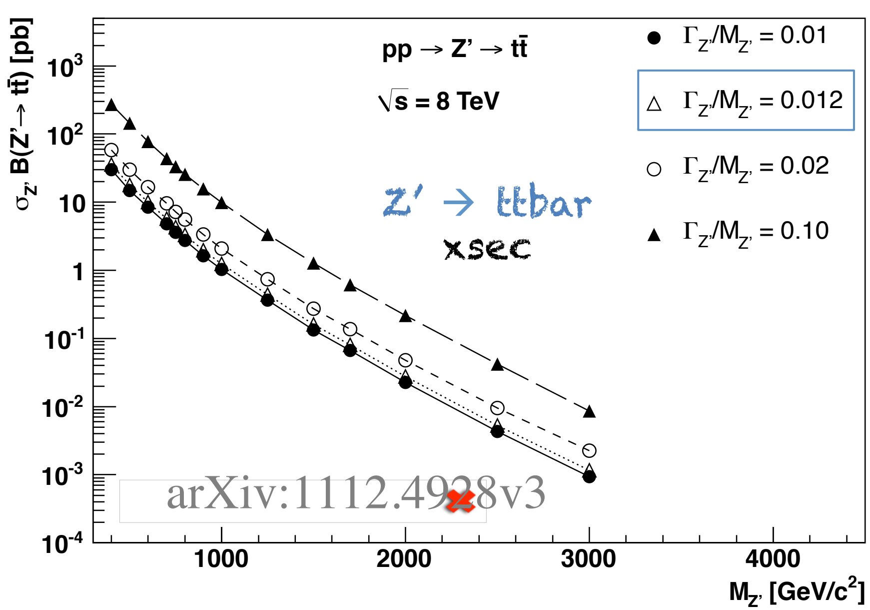
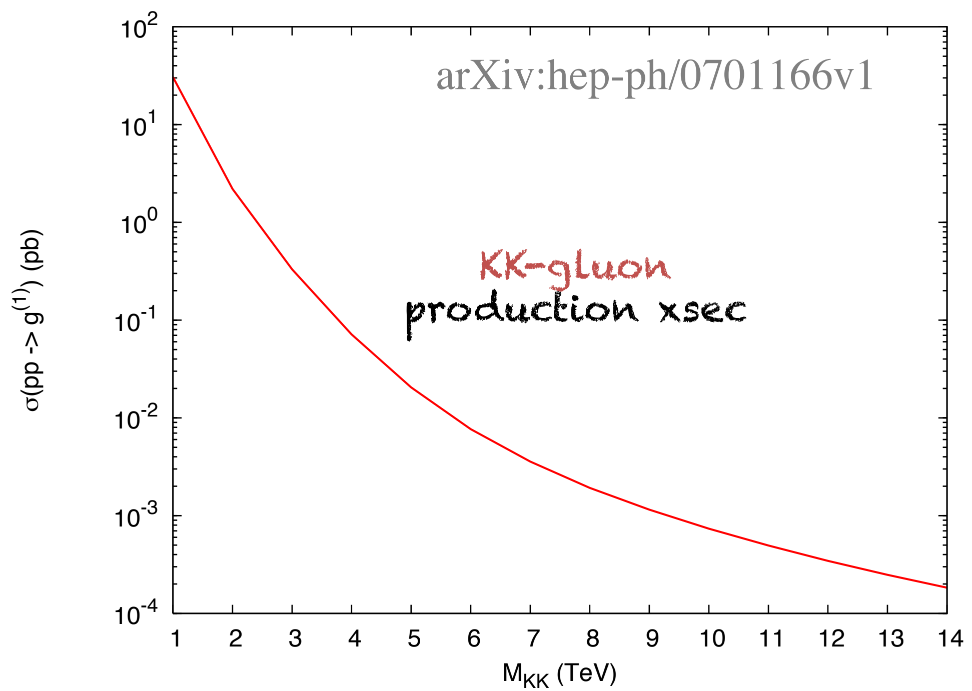
Motivation

- **Narrow Z'** (EWSB)
  - Predicted by **topcolor** assisted technicolor [arXiv:hep-ph/9411426v2]
  - Can be leptophobic and **decay to ttbar**
- **Kaluza-Klein gluon** (Hierarchy problem)
  - Predicted by Randall-Sundrum **warped extra dimension** [arXiv:hep-ph/0701166v1]
  - Most strongly coupled of KK modes, decays primarily to ttbar
- **Vector like quarks**
  - Pair produced t' singlet/doublet, coupling to 3rd generation [arXiv:0907.3155v2]
  - Singly produced degenerate doublet, coupling to light quarks [arXiv:1102.1987]





Final states to work with

$t\bar{t} \rightarrow \ell + E_T^{miss} + \text{jets}$

- Z', KK-gluons
- High pT jets
- Handle on multi-jet background

$t\bar{t} \rightarrow \text{jets}$

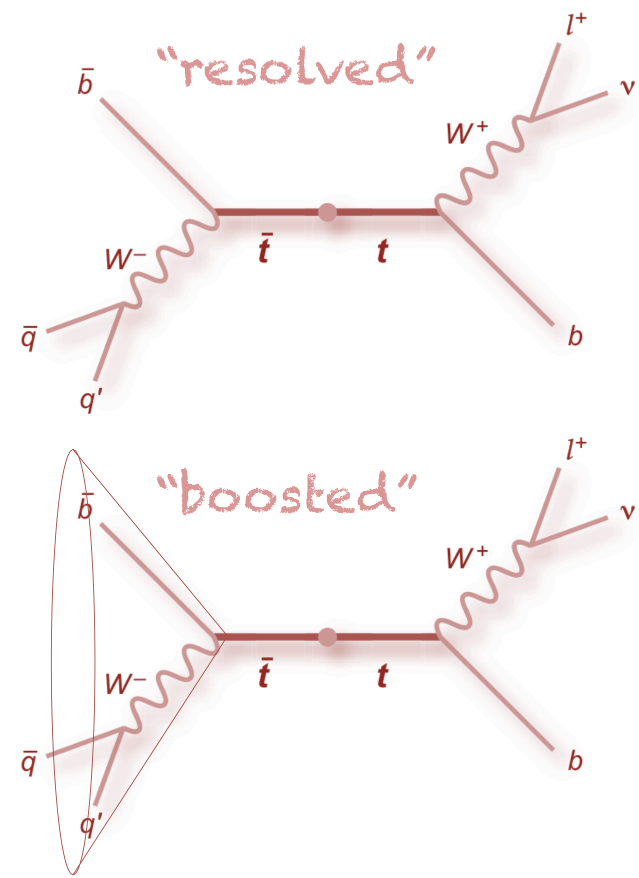
- Z', KK-gluons
- Very high pT jets
- Handle on leptonic backgrounds
- Substructure

$t'\bar{t}' \rightarrow HtHt, ZtHt, WbHt \; (H \rightarrow bb)$

- Islated lepton + high jet multiplicity

$Q + \text{jet} \rightarrow W + \text{jets}, Z + \text{jets}$

- Isolated lepton(s) + at least 2 jets



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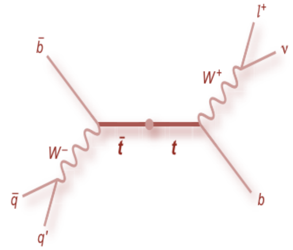

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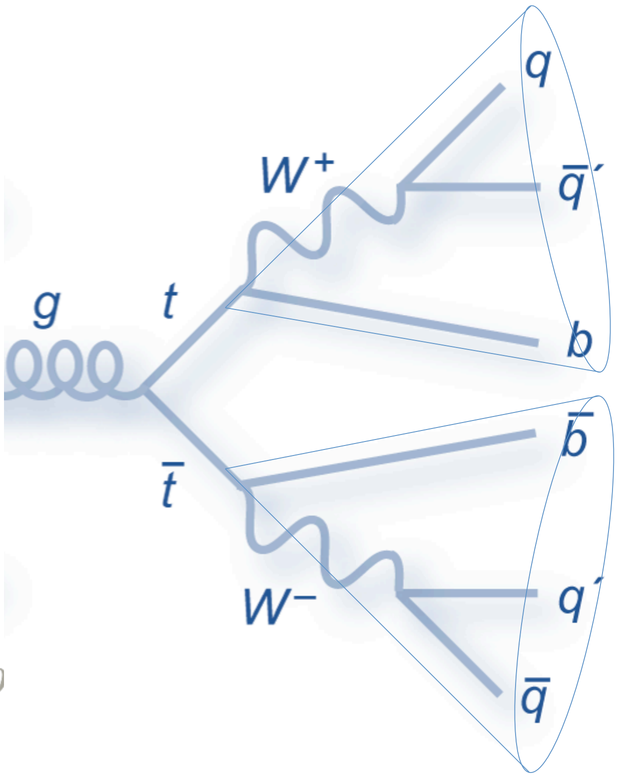

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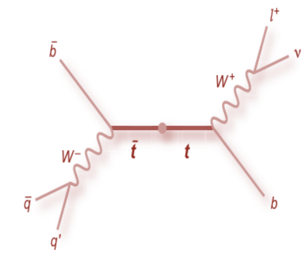
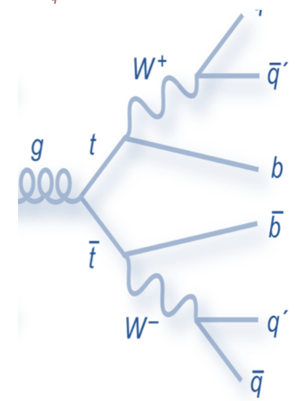
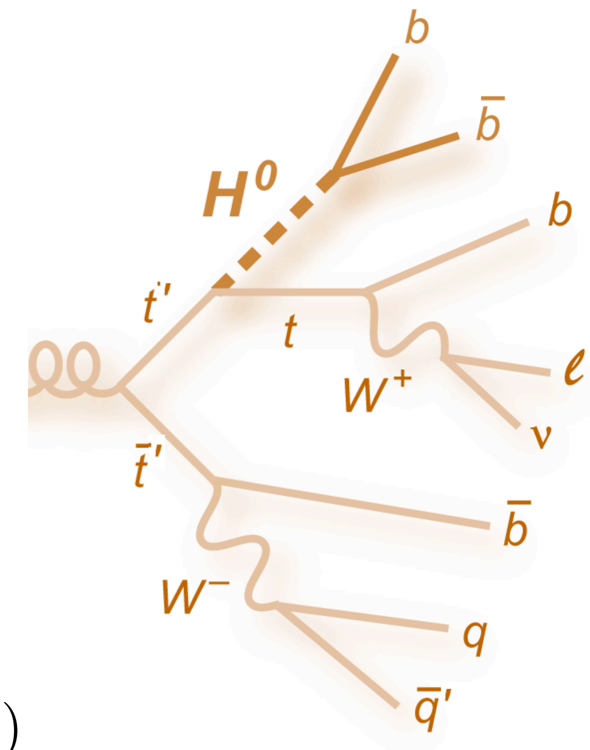
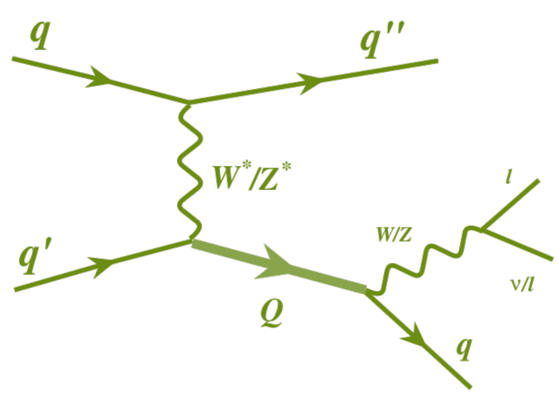
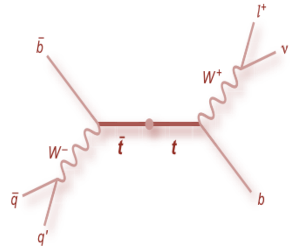






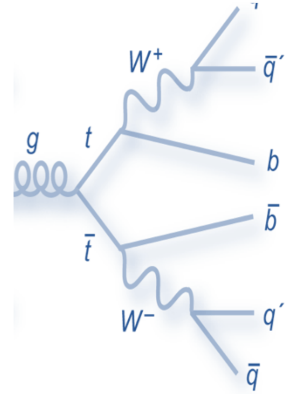


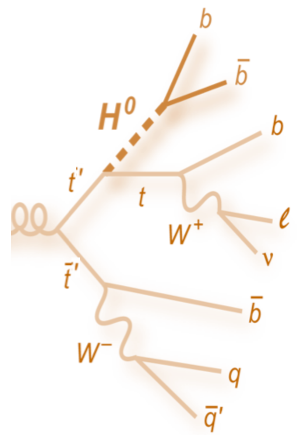
Analysis toolbox

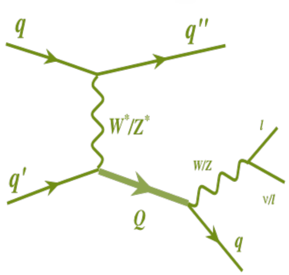


Complicated final states ➔ lots of fun analysis techniques!

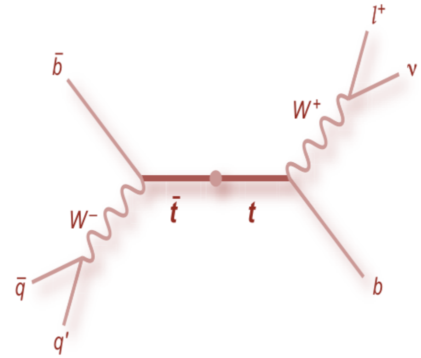
- **b-tagging**
- **Fat jets**
- **Jet substructure**
  - HEPTopTagger – re-clustering
  - Top Template Tagger – topology matching
- **Data-driven background estimation**
  - Matrix method for multi-jet background
  - W charge asymmetry method for W+jets background







ttbar → lepton + jets



Data: 4.66 fb^{-1}, 7 TeV

Selection:

- Triggered either by single lepton or single fat jet trigger, $p_T > 240$ GeV
- Exactly one isolated lepton with $p_T > 25$ GeV, $|\eta| < 2.5$ (2.47 for electrons)
- MET > 20 – 35 GeV depending on lepton flavor
- Require 1 boosted R=1.0 jet + a b-jet – OR IF FAILS – 4 resolved R=0.4 jets (3 if one has $m_T > 60$ GeV)

Model:

- ttbar – MC@NLO, Herwig
- Single top – MC@NLO, Herwig // AcerMC, Pythia
- W/Z+jets – Alpgen, **W+jets normalization from data**
- Diboson – Herwig, Jimmy
- Multijet events – **data-driven** from matrix method
- Signal model from Monte Carlo (LO*k-factor) – Z' (Pythia), KK-gluon (Madgraph)

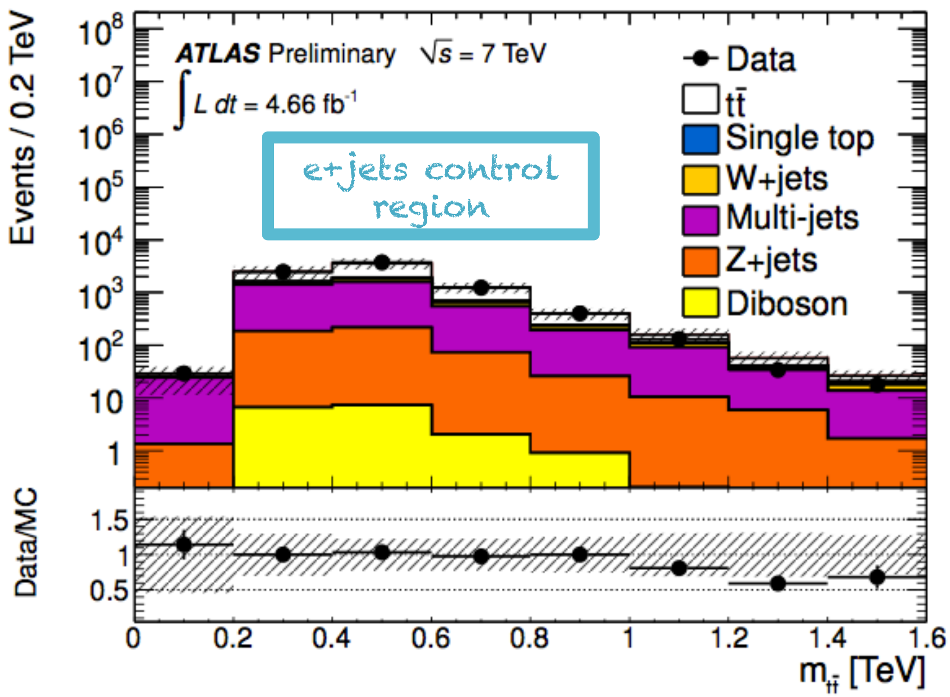
ttbar → lepton + jets

Event reconstruction

- In the case of 3 – 4 resolved jets, a chi-square algorithm is used to select the jet corresponding to semi-leptonically decaying top

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h-W}}{\sigma_{t_h-W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{\text{diff}\,p_T}}\right]^2$$

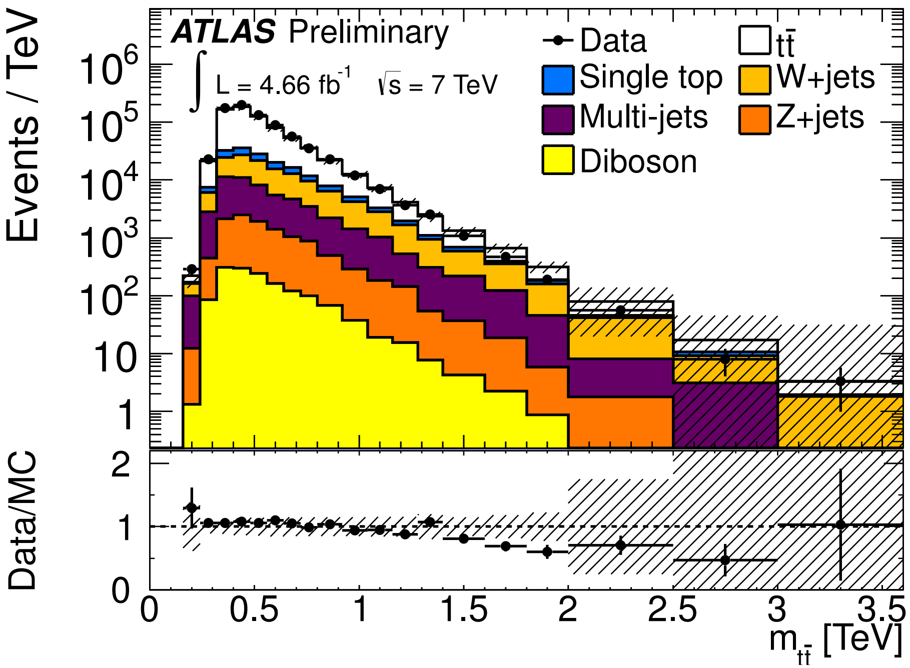
  - Correctly matches partons in 65% of ttbar events passing selection

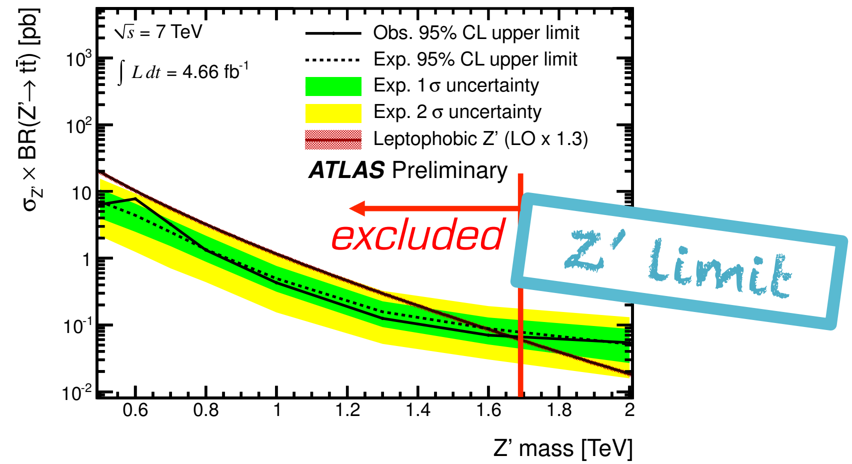


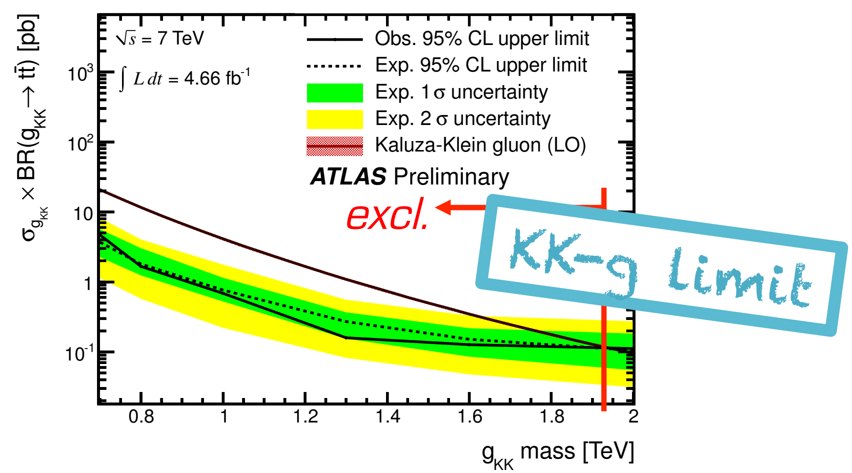
ttbar → lepton + jets

Systematics

- ttbar xsec – 11%
- W+jets normalization – 10% (resolved) to 20% (boosted)
- Multijets normalization – 60%
- JES – 8% to 17% on background yield





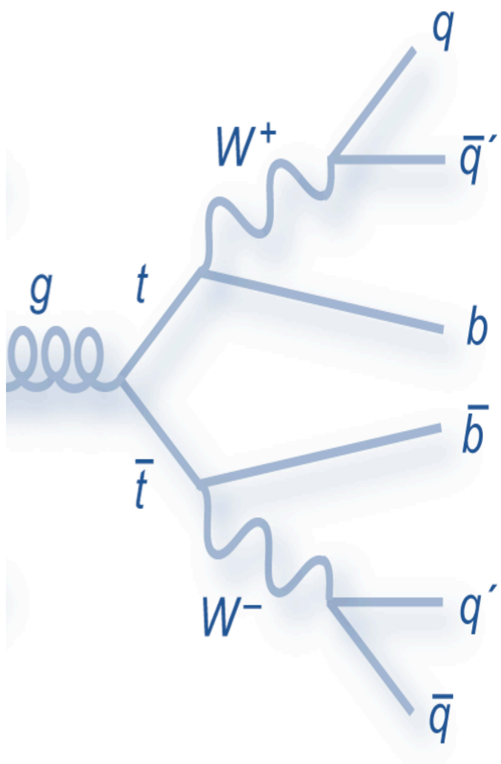


ttbar → jets

Data: 4.7 fb^{-1}, 7 TeV

Selection:

- Events triggered by high E_T jets, or large jet multiplicity
- Want at least 2 fat jets tagged as tops
  - HEPTopTagger – jet $p_T > 200$ GeV
  - Top Template Tagger – jet $p_T > 450$ GeV
- Each fat jet must have an associated b-tagged jet nearby



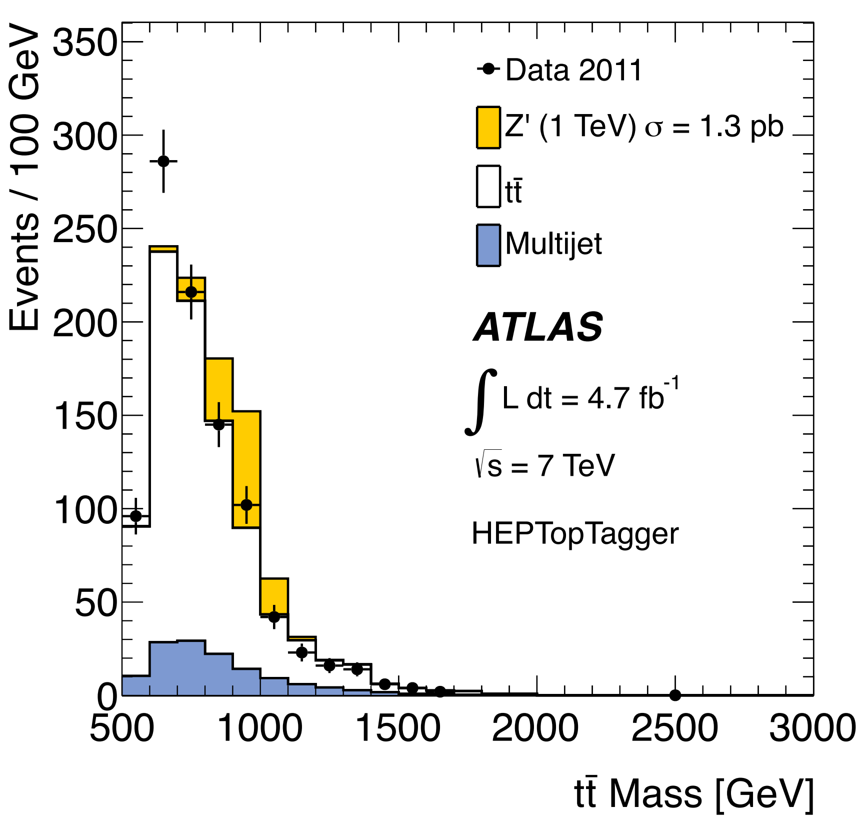
Model:

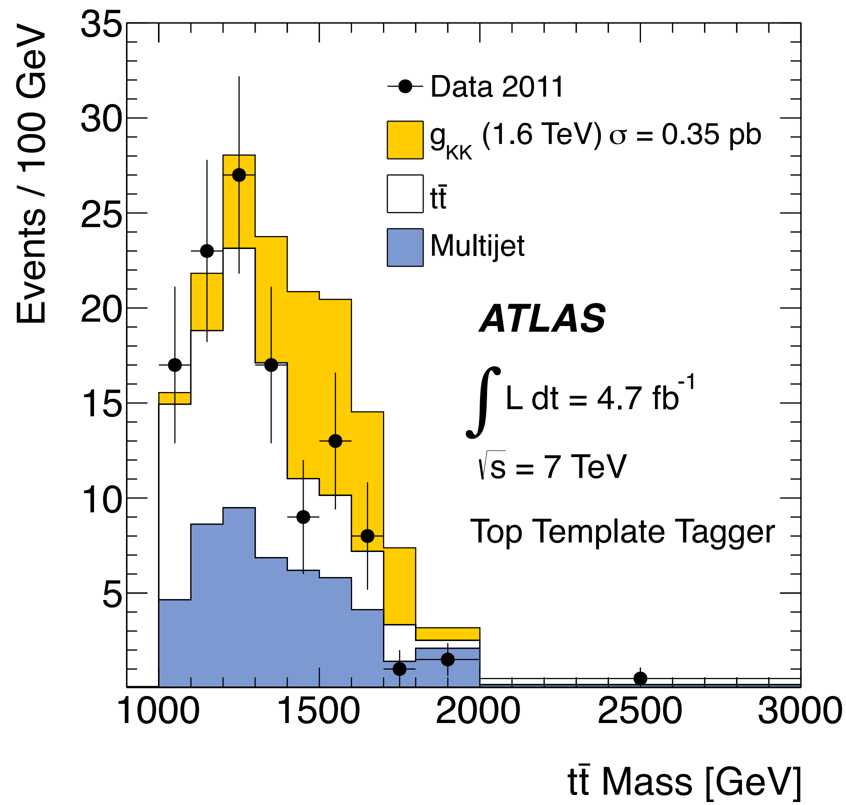
- ttbar – MC@NLO, Herwig
- Multijet events – **data-driven** from control region extrapolation
- Signal model from Monte Carlo (LO) – Z' (Pythia), KK-gluon (Madgraph)

ttbar → jets

Systematics

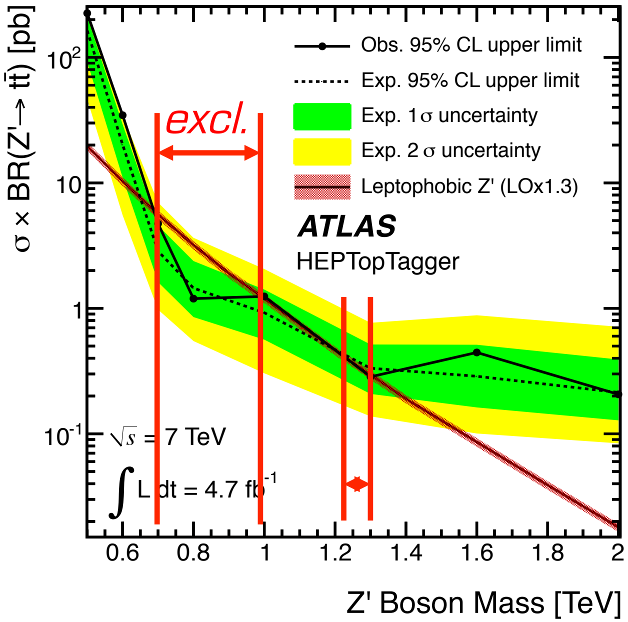
- Largest uncertainties from
  - b-tagging efficiency – as large as 50% at very high p_T
  - JES – 2.3% to 6.8%



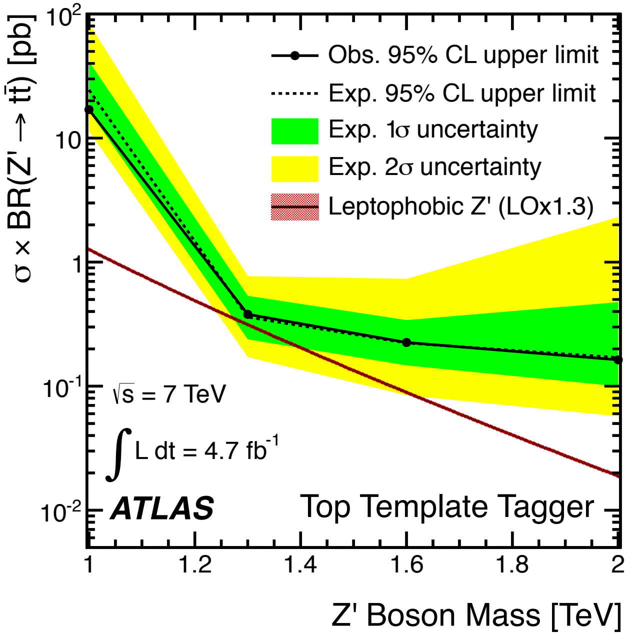


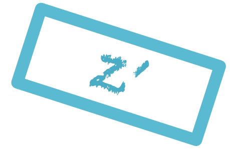
95% CL Limits

ttbar → jets
HEPTopTagger

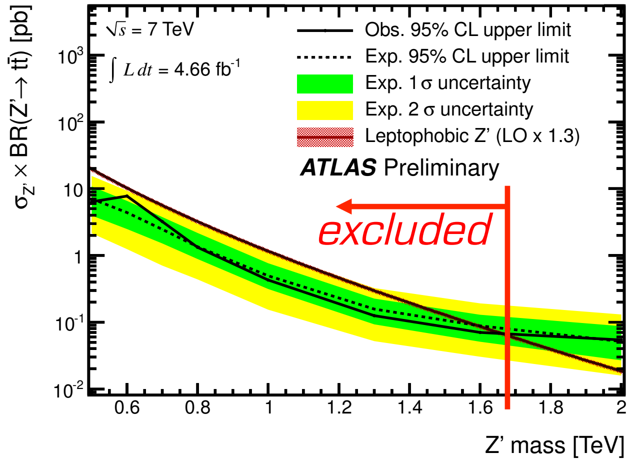


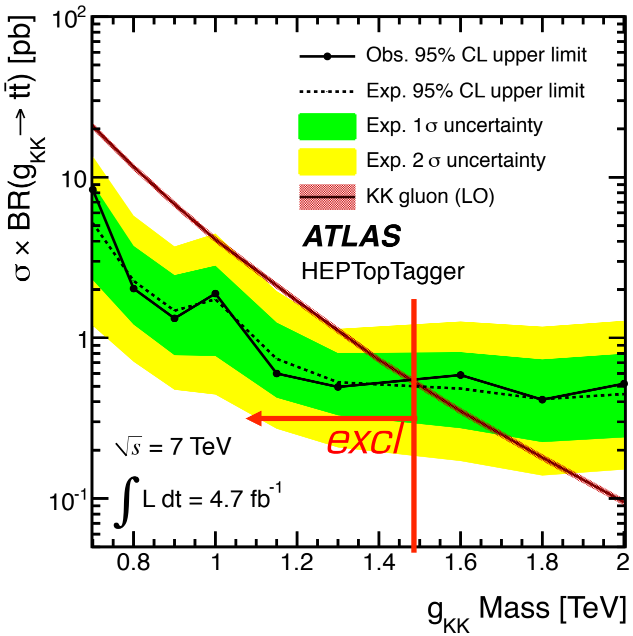
ttbar → jets
Top Template Tagger

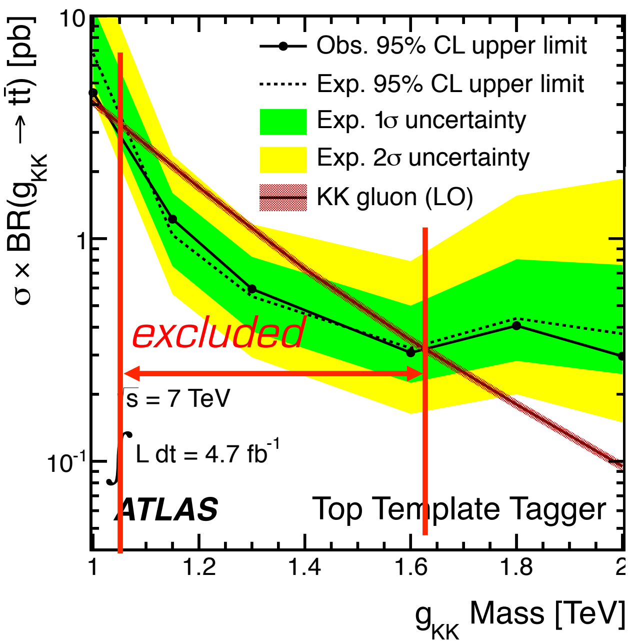


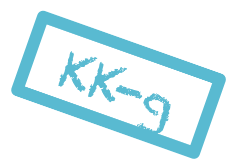


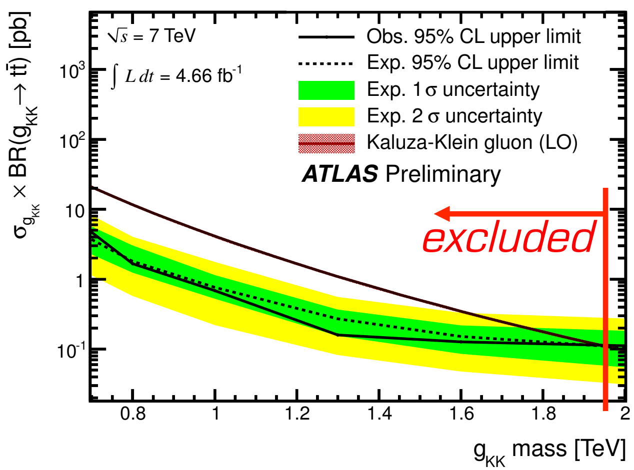
ttbar → lepton + jets











Pair produced VLQs

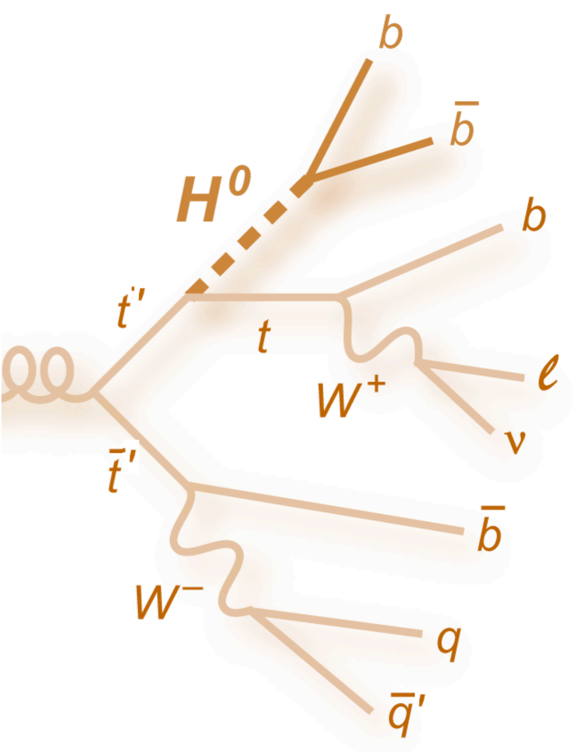
Data: 14.3 fb^{-1}, 8 TeV

Selection:

- Single lepton trigger
- Exactly 1 isolated lepton with $p_T > 25$ GeV, $|\eta| < 2.5$ (2.47 for electrons)
- MET > 20 GeV
- At least 6 jets with at least 2 b-tags

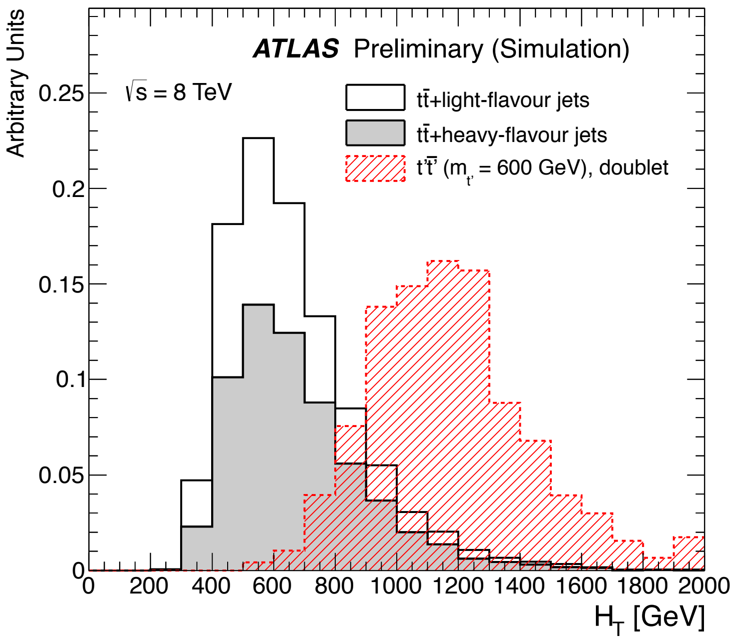
Model:

- ttbar + jets – Alpgen, Herwig
- W/Z+jets – Alpgen, **W+jets normalization from data**
- Multijet events – **data-driven** using matrix method
- Single top – MC@NLO, Herwig // AcerMC, Pythia
- ttV – Madgraph, Pythia
- ttH (125 GeV) – Pythia
- Diboson – Herwig
- t' signal - Protos



Pair produced VLQs

- Discrimination from H_T = scalar sum of all p_T in event

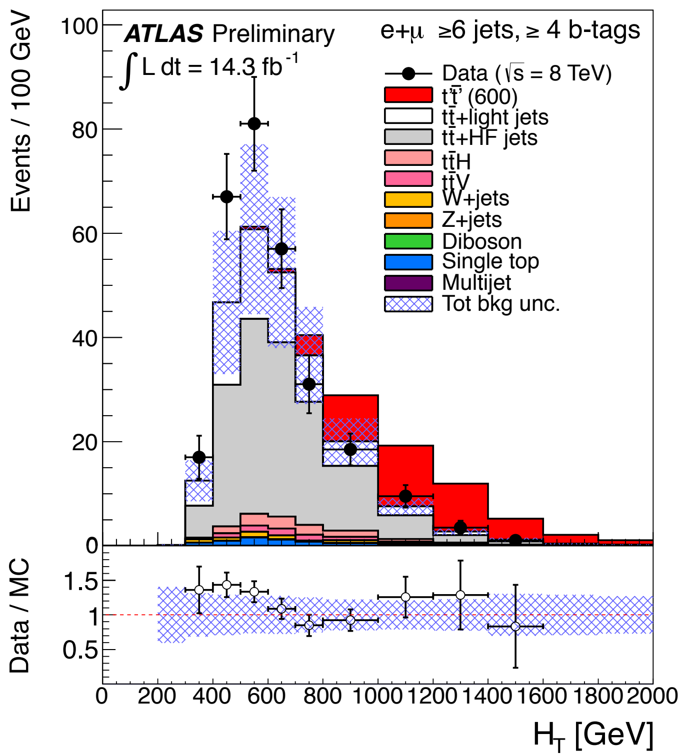


Systematics

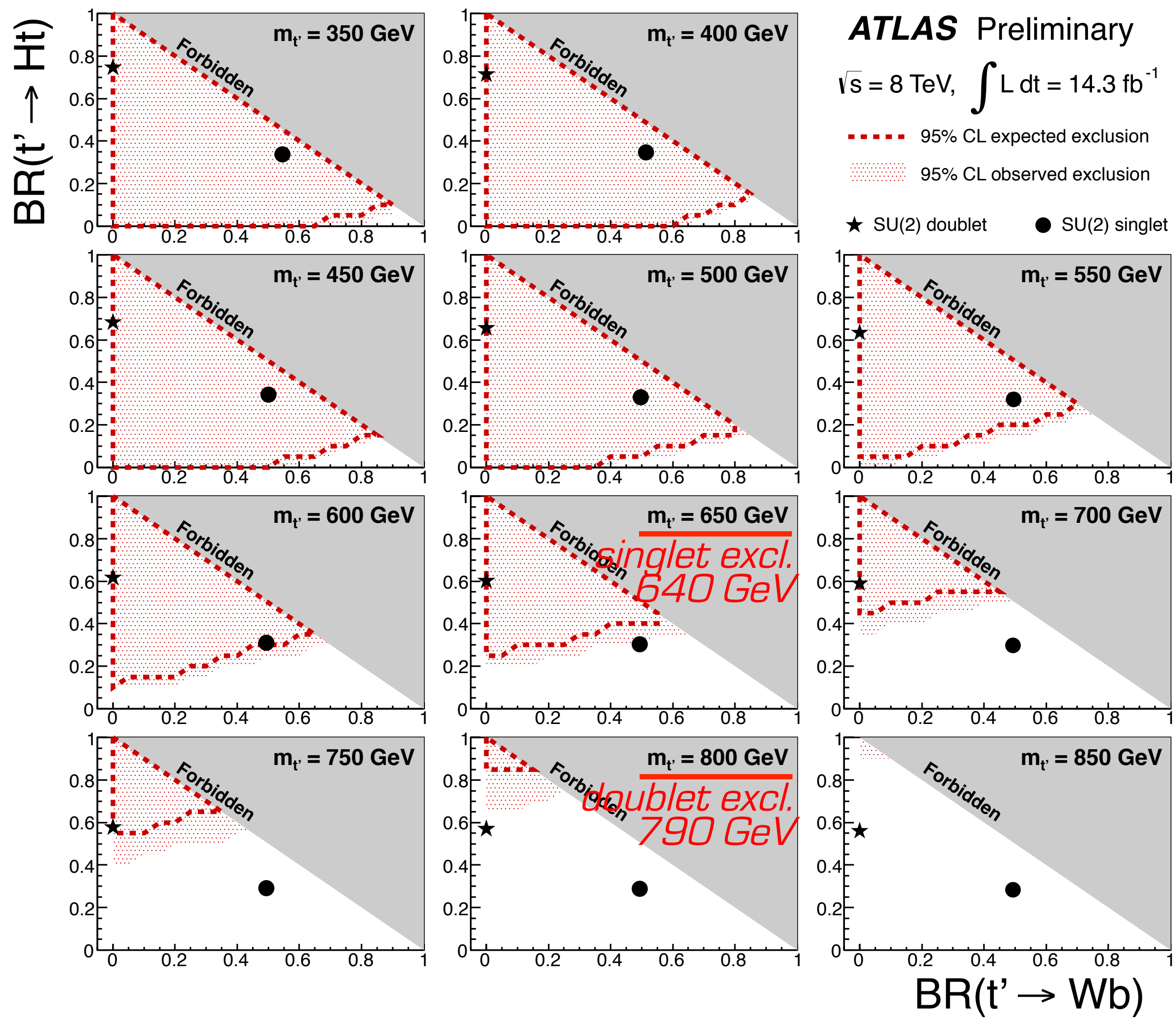
- Uncertainty on **background** normalization largest for ≥ 4 b-tags, 42%
  - Dominant uncertainties from ttbar modeling/xsec (32%), b-tag/c-tag efficiency (16%/11%), and JES (11%)
- Uncertainty on **signal** normalization largest for ≥ 4 b-tags, 21%
  - Dominated by b-tag efficiency

Pair produced VLQs

At least 4 b-tags

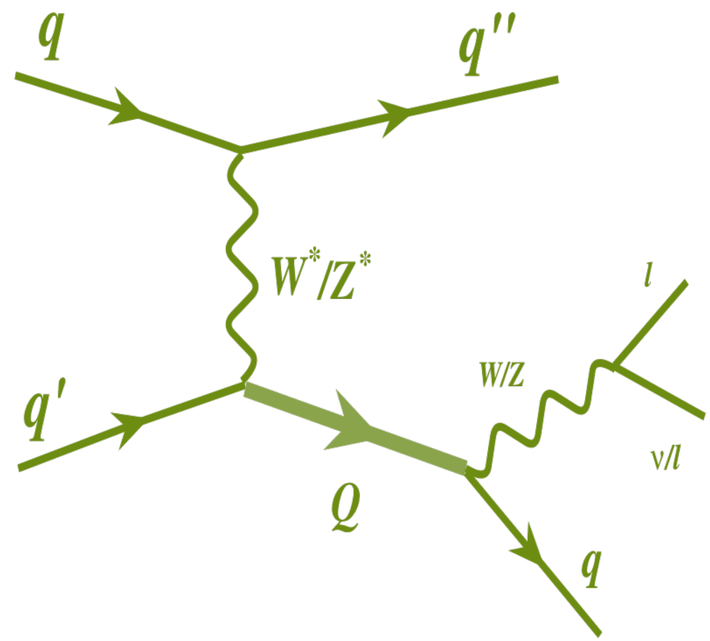


t' 95% CL limits



Singly produced VLQs

Data: 4.64 fb^{-1}, 7 TeV



Selection:

- Single or 2 lepton trigger depending on channel
- Select W or Z decaying to lepton(s)
- 2 or more jets, one with p_T > 60 GeV

Model:

- **Function fit to data**
- MC used to determine fit function, optimize cuts
  - W/Z+jets – Alpgen, Herwig
  - ttbar – MC@NLO, Herwig
  - Diboson – Herwig
- Signal generated seperately in W/Z channels in Madgraph

Singly produced VLQs

Modeling

- Final background estimation comes from a fit to data using form

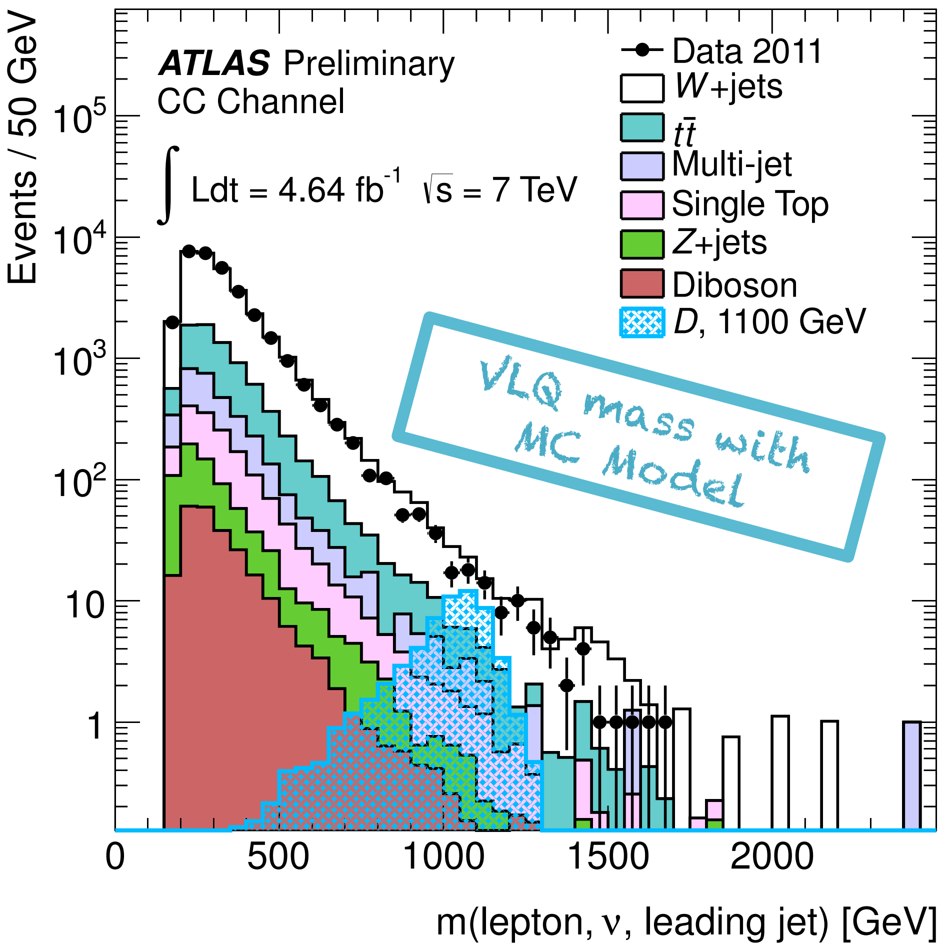
$$f(m; p_{0,1,2,3}) = p_0 \cdot \frac{(1-x)^{p_1}}{x^{p_2+p_3 \cdot \ln(x)}}$$

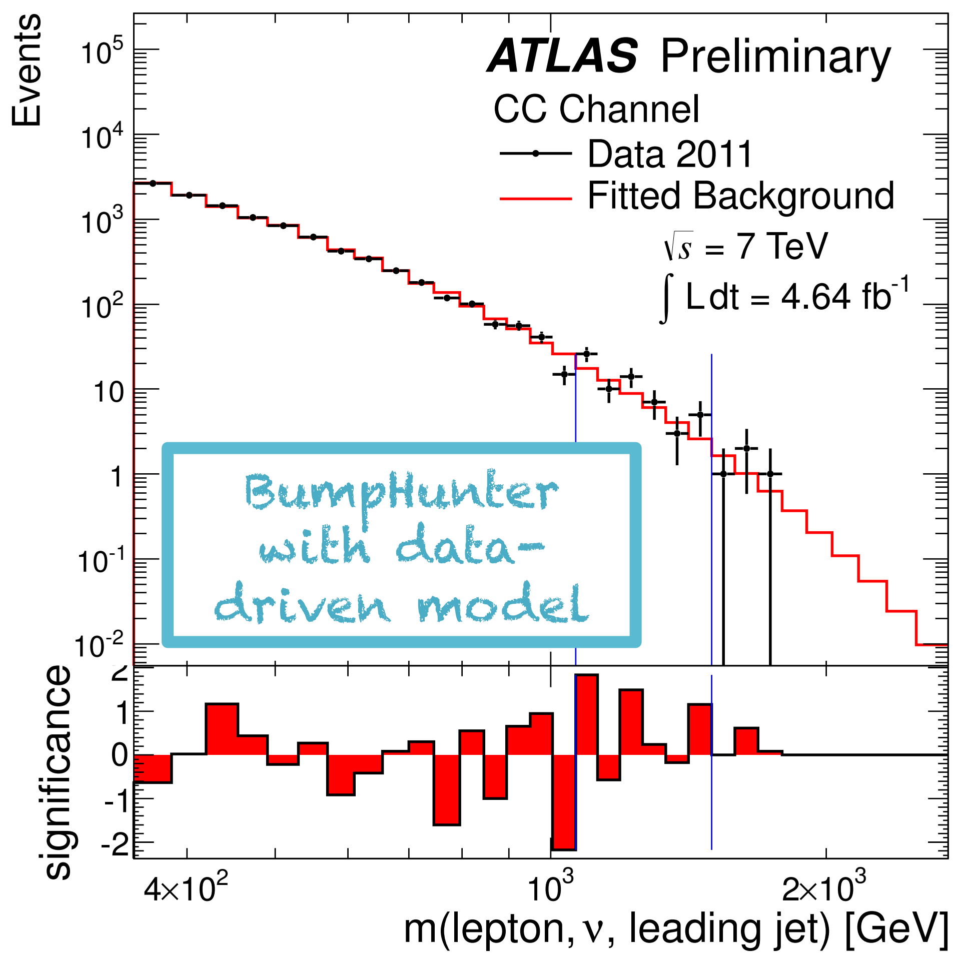
  - Cross-checked on MC and in control regions
- A set of optimized rectangular cuts on uncorrelated variables
  - Acceptance ranges from 13 – 42%

Systematics

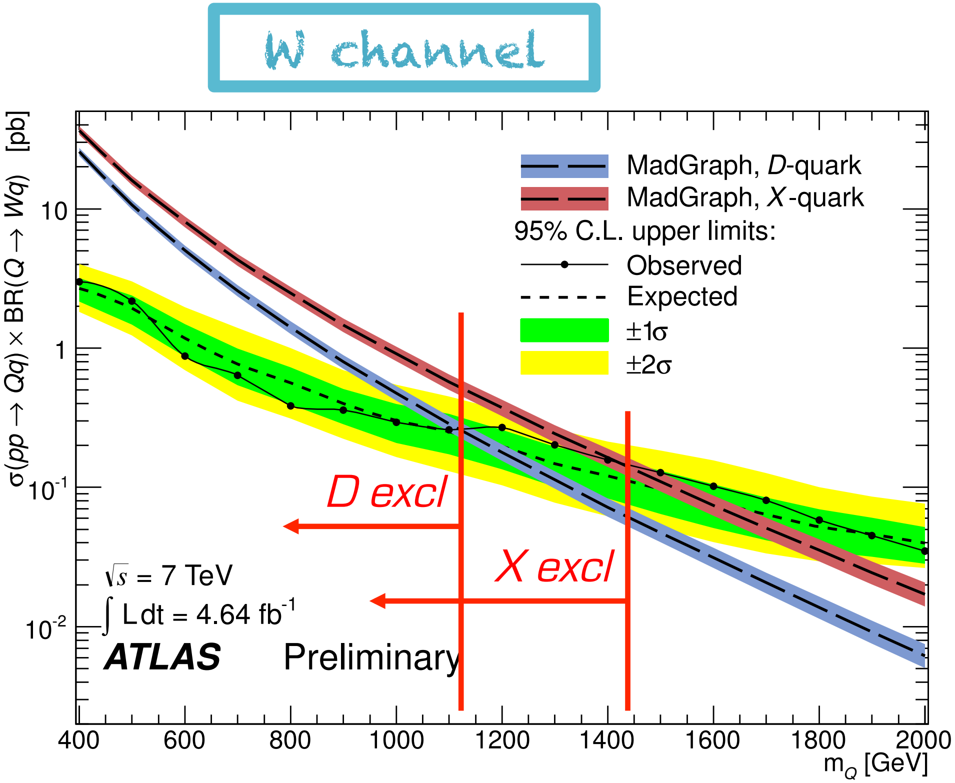
- Fit uncertainty varies from 5 – 15% across m_{VLQ} distribution
- Dominant signal normalization uncertainties from JES
  - 5 – 8% overall

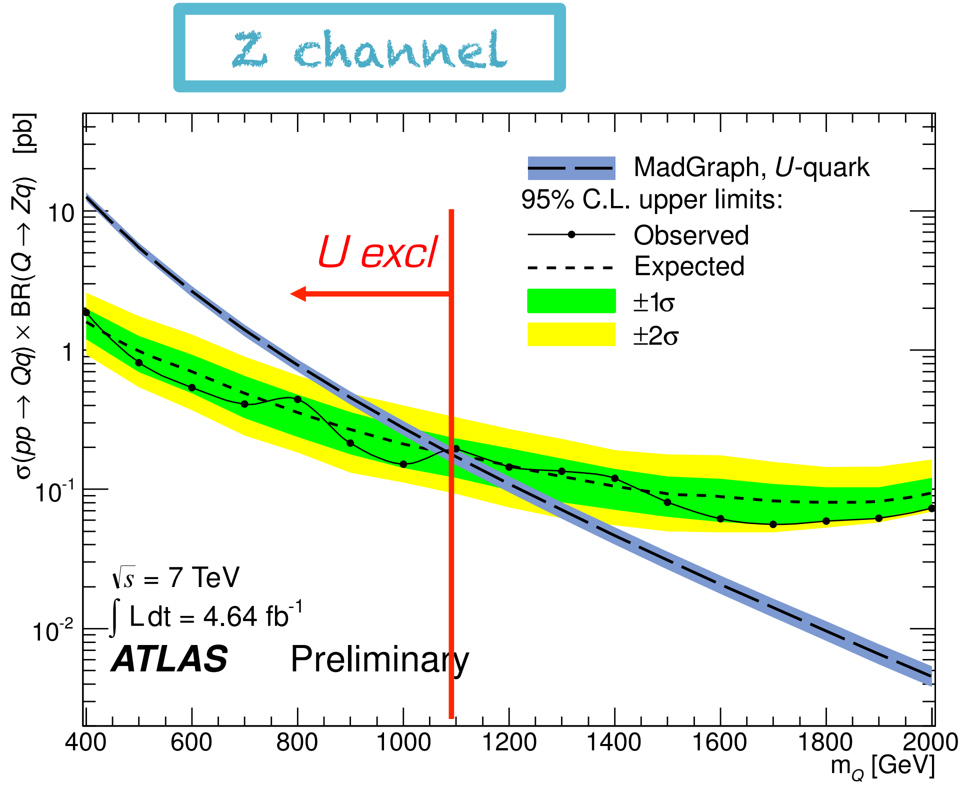
Singly produced VLQs – W channel





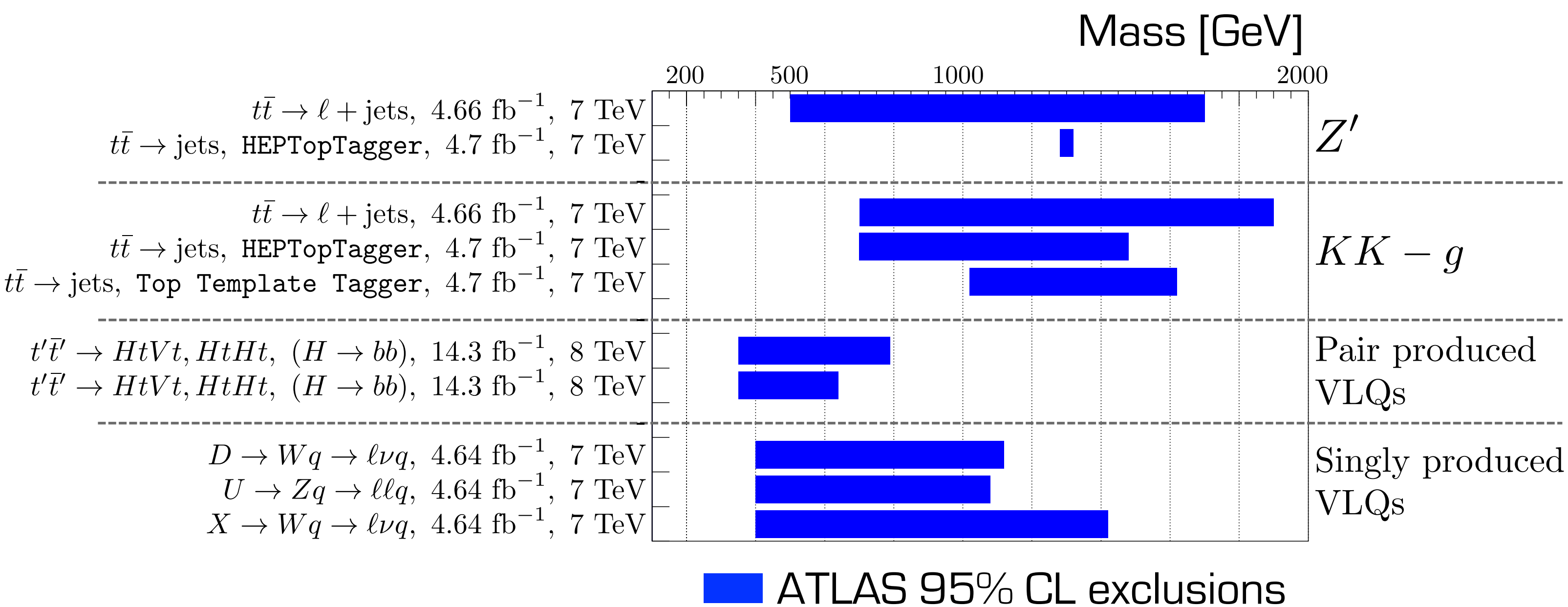
Singly produced VLQs





Conclusion

- ATLAS results in these channels are so far consistent with SM
- Limits set on ttbar resonance models and VLQs



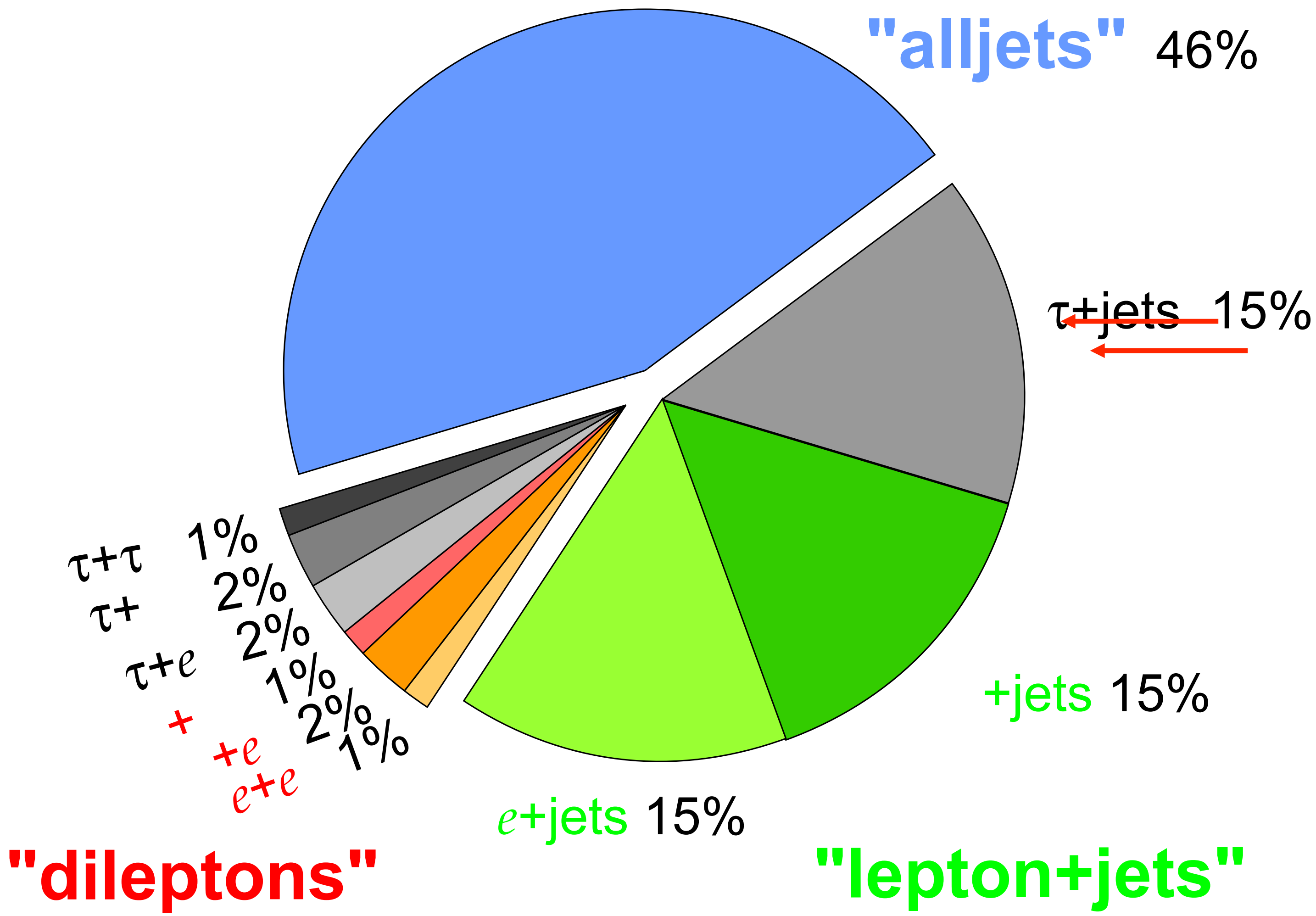
- MV tools for hadronic top tagging, b-tagging, jet substructure, are shown to be robust and expand the possibility for creativity in top channels

- Room for updates, higher energy data will offer a nice boost in sensitivity!

SECTION

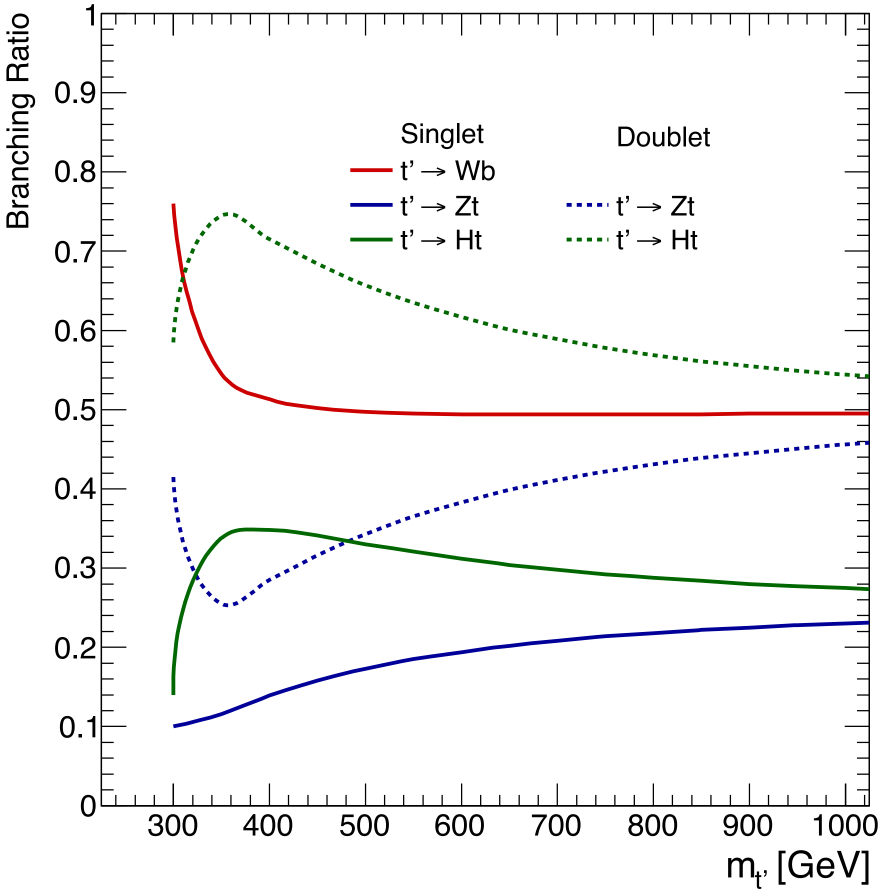
BACKUP

Top Pair Branching Fractions

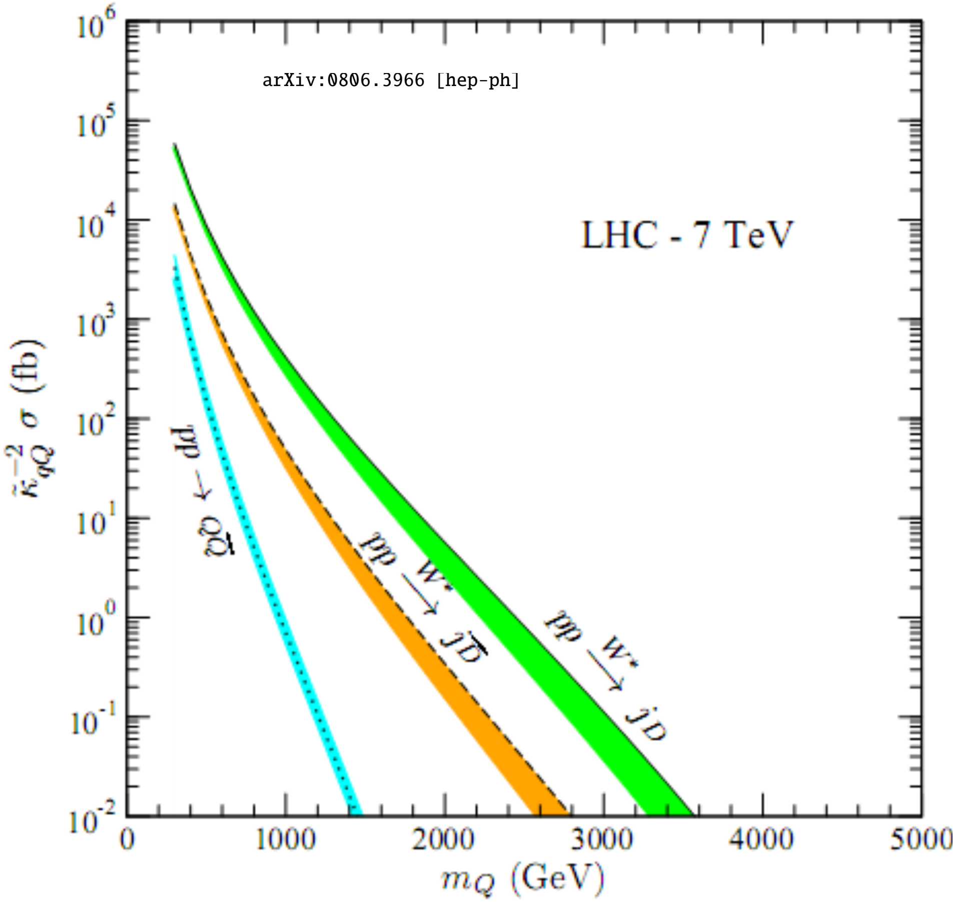


VLQ theory plots

Coupling to 3rd generation

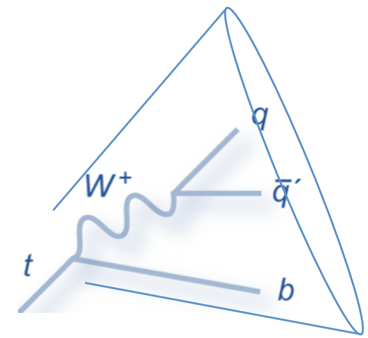


Coupling to light quarks



ttbar → jets

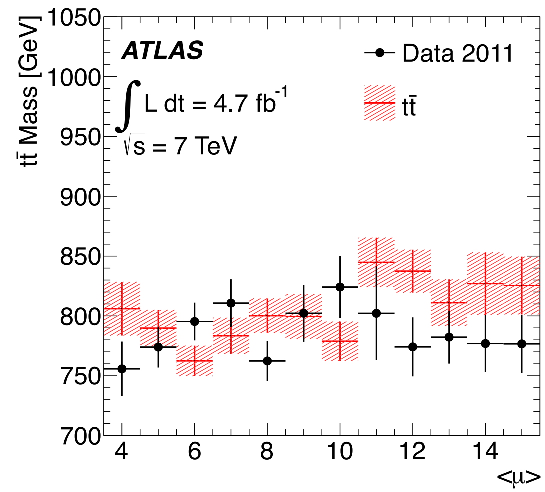
Reconstructing hadronically decaying tops



HEPTopTagger

- Driven by jet substructure and the C/A jet algorithm
- Use R = 1.5 jets, $p_T > 200$ GeV
- Maximum efficiency on signal:

$$\varepsilon^2_{b\text{-tag, max}} \cdot \varepsilon^2_{\text{top-tag, max}} \approx 10\%$$

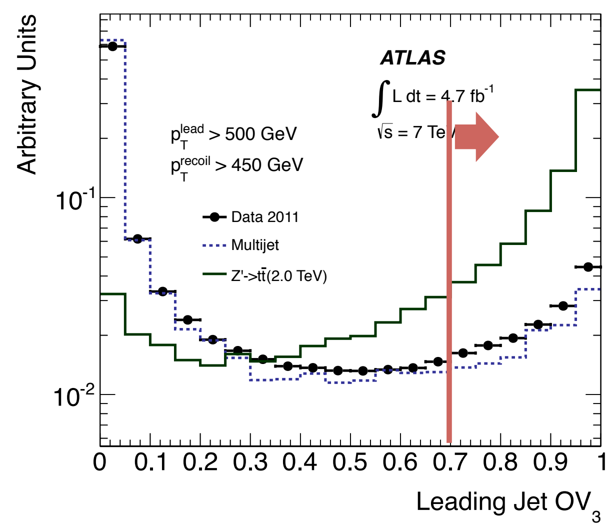


Top Template Tagger

- Compare jet topology to library of 300K templates

$$OV_3 = \max_{\{\tau_n\}} \exp\left[-\sum_{i=1}^{3} \frac{1}{2\sigma_i^2}\left(E_i - \sum_{\substack{\Delta R(\text{topo},i)\\<0.2}} E_{\text{topo}}\right)^2\right]$$

- Use R = 1.0 jets, $p_T > 450$ GeV
- Efficiency for top quark selection near 75%



ttbar → jets – more multi-jet details

Data-driven components

- Control regions defined by loosening t/b-tag
  - Taking advantage of the fact that the t/b tags are uncorrelated

- For HEPTopTagger selection
  - Multi-jet shape averaged over control regions with 2 top-tags, normalization from region with 1 top-tag (< 2 b-tags)

    ➔ $130 \pm 70\ (\mathrm{stat.}\oplus\mathrm{syst.})$ multijet events in SR

- For Top Template Tagger selection
  - Multi-jet prediction from iterative technique, avoiding directly using data from regions with potential BSM contamination

    ➔ 53 +/- 3 (stat) multijet events in SR

ttbar → jets : control regions

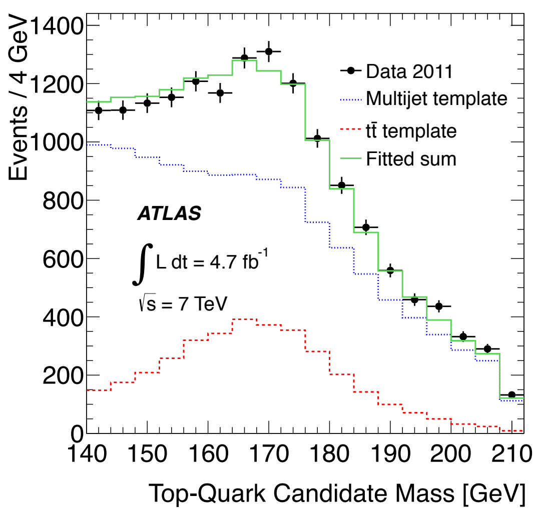
HEPTopTagger Analysis

	1 top-tag	≥ 2 top-tags
no b-tag	U(0.3%)	V(2.4%)
1 b-tag	W(3.2%)	X(24.3%)
≥ 2 b-tags	Y(22.5%)	Z(80.9%)

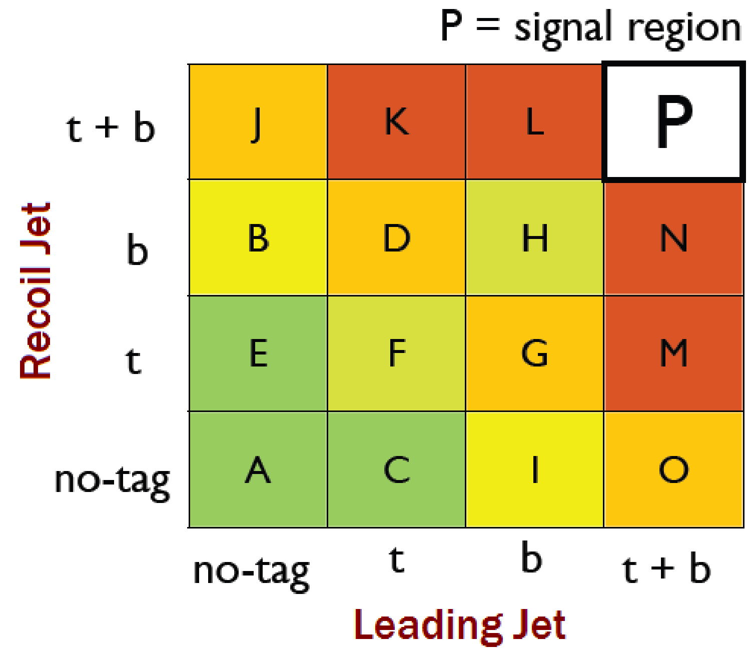
multijet
$$\frac{dn_Z}{dm_{t\bar{t}}} = \left(\frac{1}{n_U} \times \frac{dn_V}{dm_{t\bar{t}}} + \frac{1}{n_W} \times \frac{dn_X}{dm_{t\bar{t}}}\right) \times \frac{n_Y}{2}$$

Ttbar normalization validation

Correction factor = 1.01 +/- 0.09



Top Template Tagger Analysis



ttbar → lepton + jets – Data-driven methods

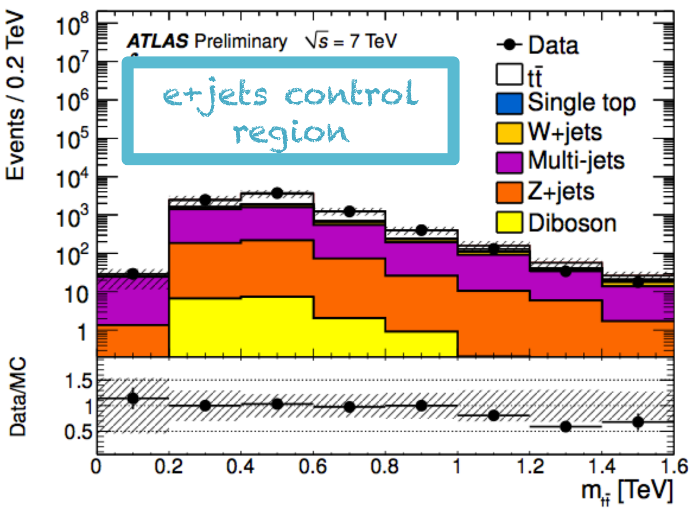
Data-driven components

- W+jets normalization scaled to agree with data, using a ratio of estimated and predicted charge uncertainty

$$N_{W^+} + N_{W^-} = \left(\frac{r_{\mathrm{MC}} + 1}{r_{\mathrm{MC}} - 1}\right)(D_{\mathrm{corr}+} - D_{\mathrm{corr}-})$$

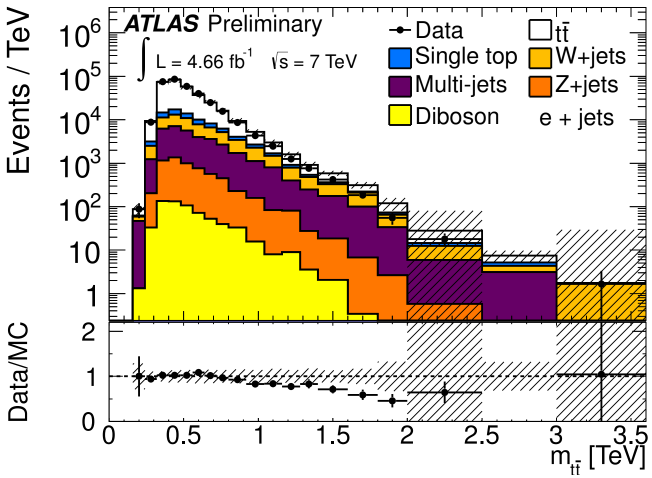
- Multijet normalization and shape from **matrix method**, cross-checked with jet-electron method
  - validated in low MET control region

$$\begin{aligned} N^{\mathrm{loose}} &= N^{\mathrm{loose}}_{\mathrm{real}} + N^{\mathrm{loose}}_{\mathrm{fake}}, \\ N^{\mathrm{tight}} &= \epsilon_{\mathrm{real}} N^{\mathrm{loose}}_{\mathrm{real}} + \epsilon_{\mathrm{fake}} N^{\mathrm{loose}}_{\mathrm{fake}}, \end{aligned}$$

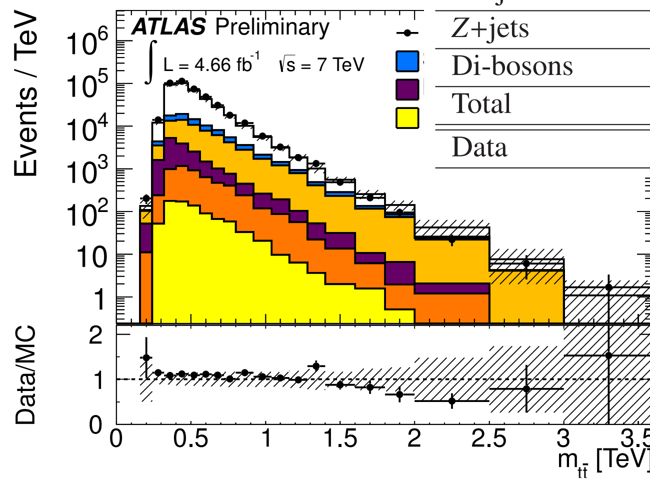


ttbar → lepton + jets results in separate channels

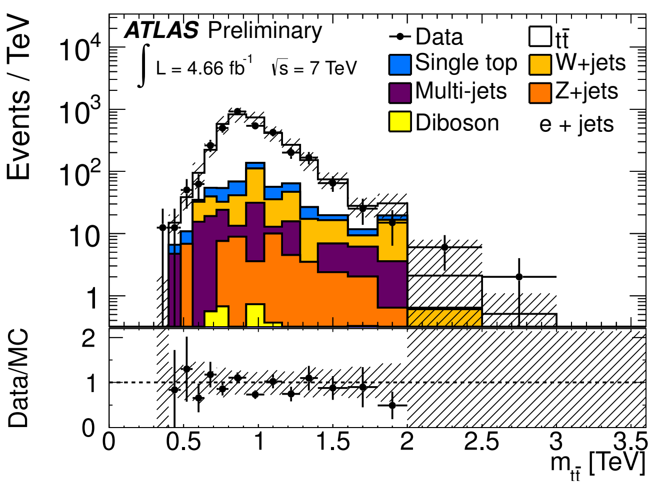
Type	Resolved selection	Boosted selection
$t\bar{t}$	44 000 ± 4 700	950 ± 100
Single top	3 250 ± 250	49 ± 4
Multi-jets e+jets	2 500 ± 1 500	12 ± 7
Multi-jets μ+jet	1 010 ± 610	20 ± 12
W+jets	6 940 ± 730	82 ± 15
Z+jets	840 ± 410	11 ± 5
Di-bosons	124 ± 43	0.88 ± 0.30
Total	58 700 ± 5 300	1 120 ± 100
Data	61 954	1079

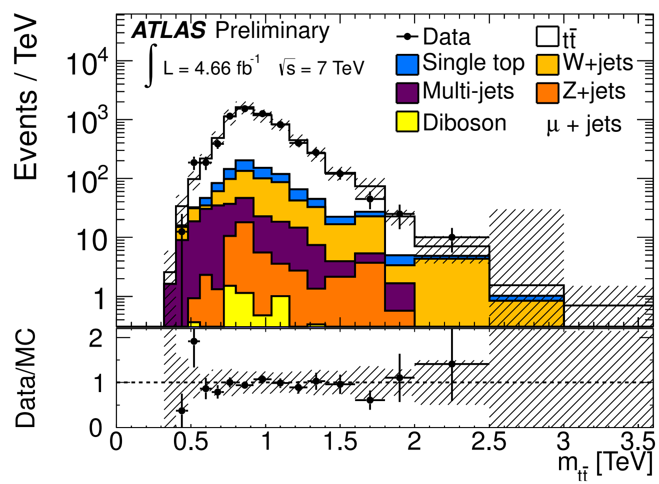


(a) e+jets channel, resolved selection.



(b) μ+jets channel, resolved selection.





ttbar → lepton + jets systematics summary

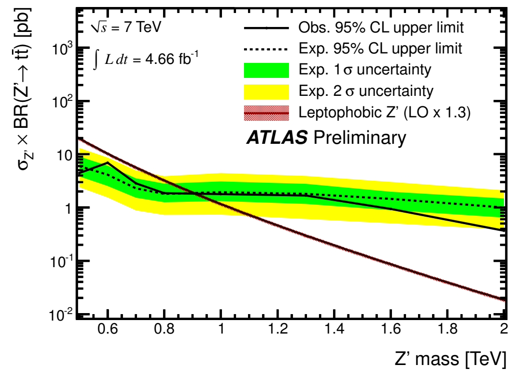
Impact on Systematic effect	*Resolved selection* yield [%]		*Boosted selection* yield [%]	
	total bgr.	Z'	total bgr.	Z'
ISR/FSR	0.3	–	5.9	–
PDF	3.5	–	7.9	–
$t\bar{t}$ normalization	8.0	–	9.0	–
EW Sudakov	1.9	–	4.2	–
$t\bar{t}$ higher order QCD corr.	1.2	–	9.0	–
W + heavy flavor	1.3	–	1.2	–
Multi-jets norm, e+jets	2.6	–	0.6	–
Multi-jets norm, μ+jets	1.0	–	1.1	–
Parton shower	0.2	–	7.3	–
JES, anti-k_t $R = 0.4$ jets	7.8	2.9	0.5	0.5
JES, anti-k_t $R = 1.0$ jets	0.2	4.8	17.0	2.8
b-tag efficiency	3.8	7.7	6.0	3.5
c-tag efficiency	1.2	0.6	0.1	2.5
Mistag rate	1.0	0.3	0.7	0.1

ttbar resonance searches – more limit info

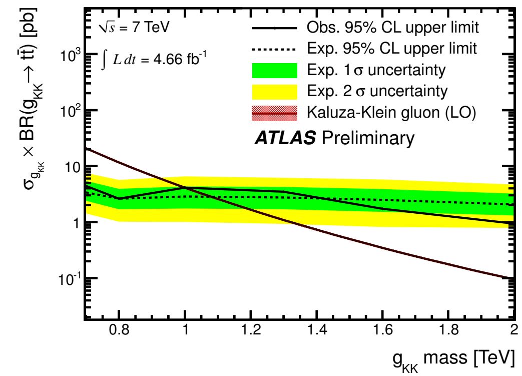
ttbar → jets exclusions

Model	Obs. Limit (TeV)	Exp. Limit (TeV)
HEPTopTagger		
Z'	$0.70 < m_{Z'} < 1.00$ $1.28 < m_{Z'} < 1.32$	$0.68 < m_{Z'} < 1.16$
KK gluon	$0.70 < m_{g_{KK}} < 1.48$	$0.70 < m_{g_{KK}} < 1.52$
Top Template Tagger		
KK gluon	$1.02 < m_{g_{KK}} < 1.62$	$1.08 < m_{g_{KK}} < 1.62$

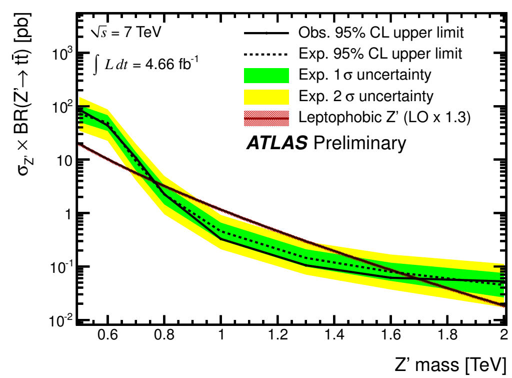
ttbar → lepton + jets limits in separate "resolved" and "boosted" searches

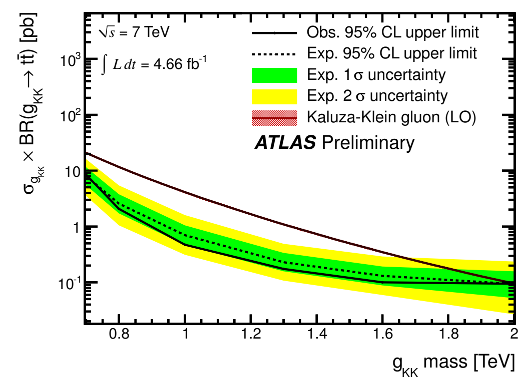


(a) Z', resolved selection.



(b) g_{KK}, resolved selection.





Pair produced VLQ treatment of systematics

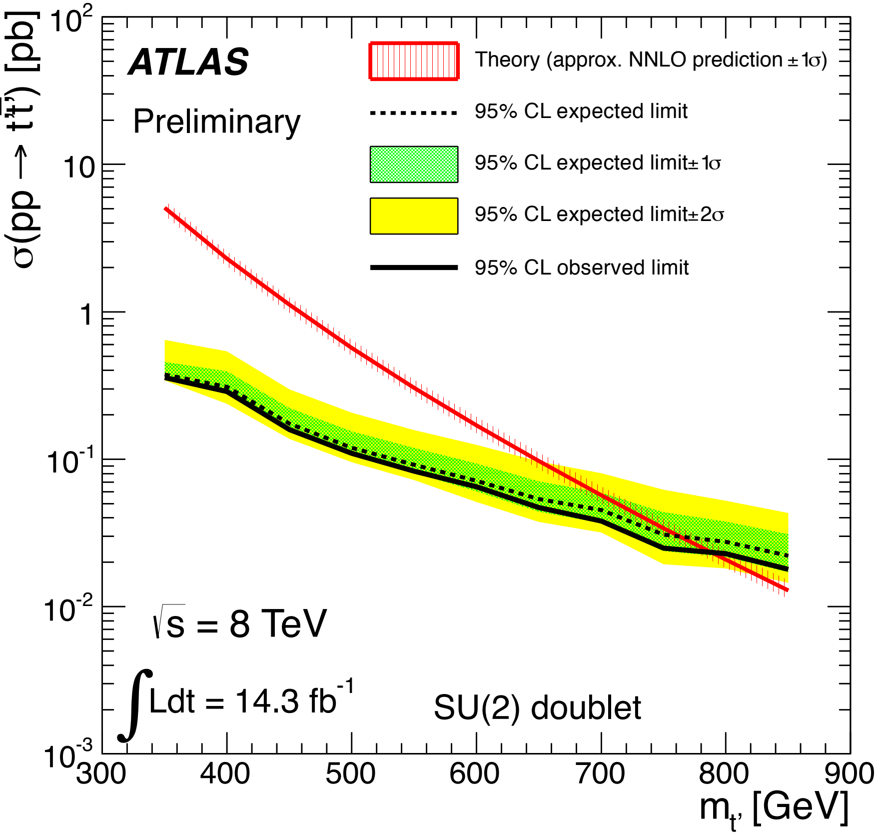
Systematic uncertainty	Type	Components
Luminosity	N	1
Lepton ID+reco+trigger	N	1
Jet vertex fraction efficiency	S	1
Jet energy scale	SN	8
Jet energy resolution	SN	1
b-tagging efficiency	SN	9
c-tagging efficiency	SN	5
Light jet-tagging efficiency	SN	1
$t\bar{t}$ cross section	N	1
$t\bar{t}V$ cross section	N	1
$t\bar{t}H$ cross section	N	1
Single top cross section	N	1
Dibosons cross section	N	1
V+jets normalisation	N	1
Multijet normalisation	N	1
$t\bar{t}$ modelling	SN	3
$t\bar{t}$+heavy-flavour fractions	N	1

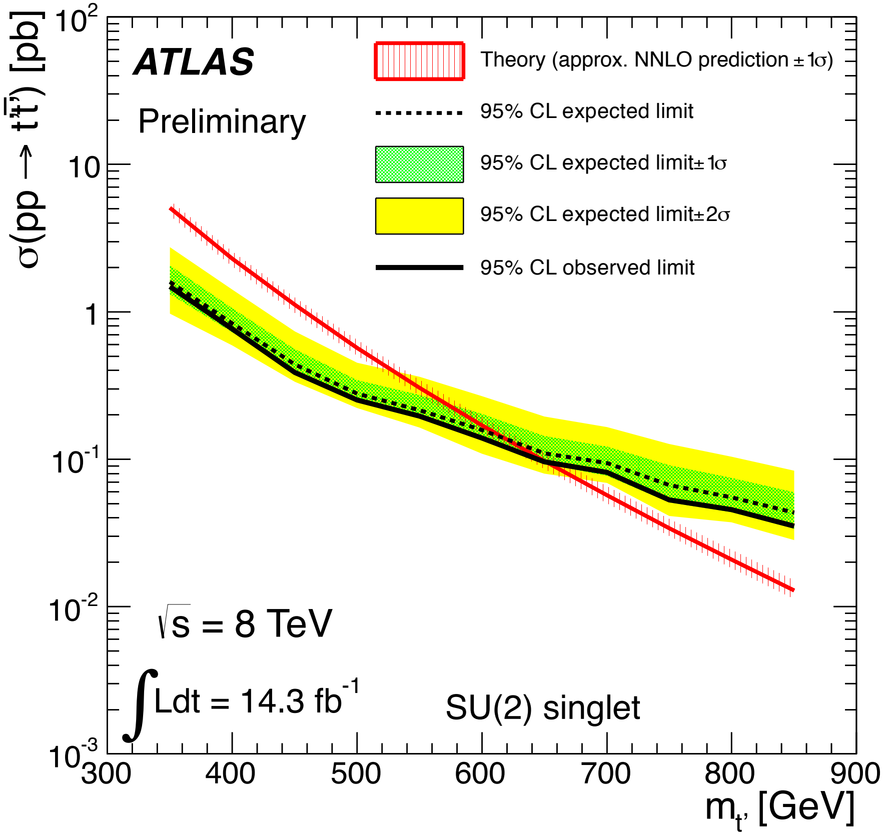
Table 2: List of systematic uncertainties considered. A “N” means that the uncertainty is taken as normalisation-only for all processes and channels affected. A “SN” means that the uncertainty is taken as both shape and normalisation, although for small backgrounds only the normalisation uncertainty is considered. Some of the systematic uncertainties are split into several different components for a more accurate treatment.

Pair produced VLQ yields

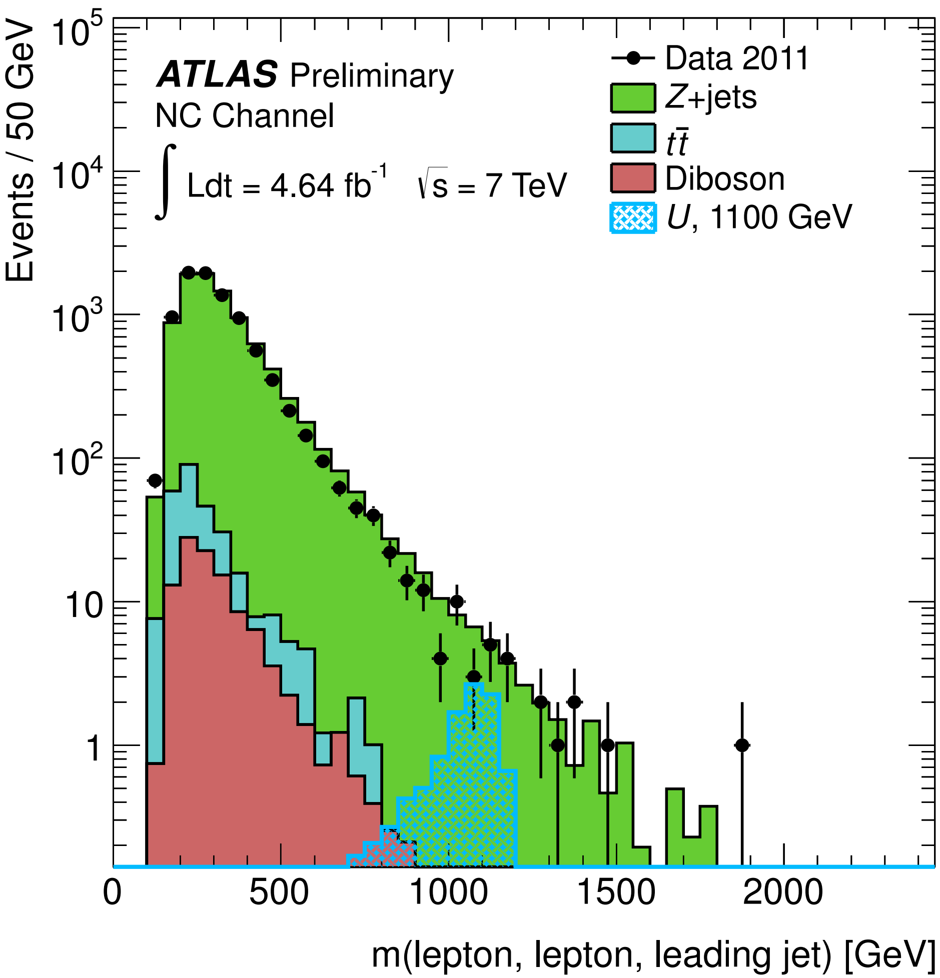
	≥ 6 jets, 2 b-tags	≥ 6 jets, 3 b-tags	≥ 6 jets, ≥ 4 b-tags
$t\bar{t}$+heavy-flavour jets	1500 ± 900	900 ± 400	170 ± 70
$t\bar{t}$+light-flavour jets	9600 ± 1000	1900 ± 350	75 ± 22
W+jets	250 ± 130	50 ± 30	5 ± 3
Z+jets	50 ± 40	9 ± 6	0.5 ± 0.9
Single top	300 ± 70	75 ± 18	7 ± 3
Diboson	1.7 ± 0.6	0.3 ± 0.1	0.03 ± 0.03
$t\bar{t}V$	70 ± 20	36 ± 12	7 ± 3
$t\bar{t}H$	28 ± 4	31 ± 6	12 ± 3
Multijet	49 ± 23	1.7 ± 0.8	0.15 ± 0.06
Total background	11860 ± 260	2990 ± 210	270 ± 60
Data	11885	2922	318
Doublet			
$t'\bar{t}'$(400)	550 ± 70	1100 ± 100	790 ± 160
$t'\bar{t}'$(600)	4.3 ± 1.2	94 ± 7	79 ± 18
$t'\bar{t}'$(800)	0.12 ± 0.05	10.7 ± 0.8	9.1 ± 2.1
Singlet			
$t'\bar{t}'$(400)	290 ± 30	650 ± 80	330 ± 70
$t'\bar{t}'$(600)	2.3 ± 0.4	61 ± 7	36 ± 9
$t'\bar{t}'$(800)	0.06 ± 0.01	6.9 ± 0.7	4.2 ± 1.1

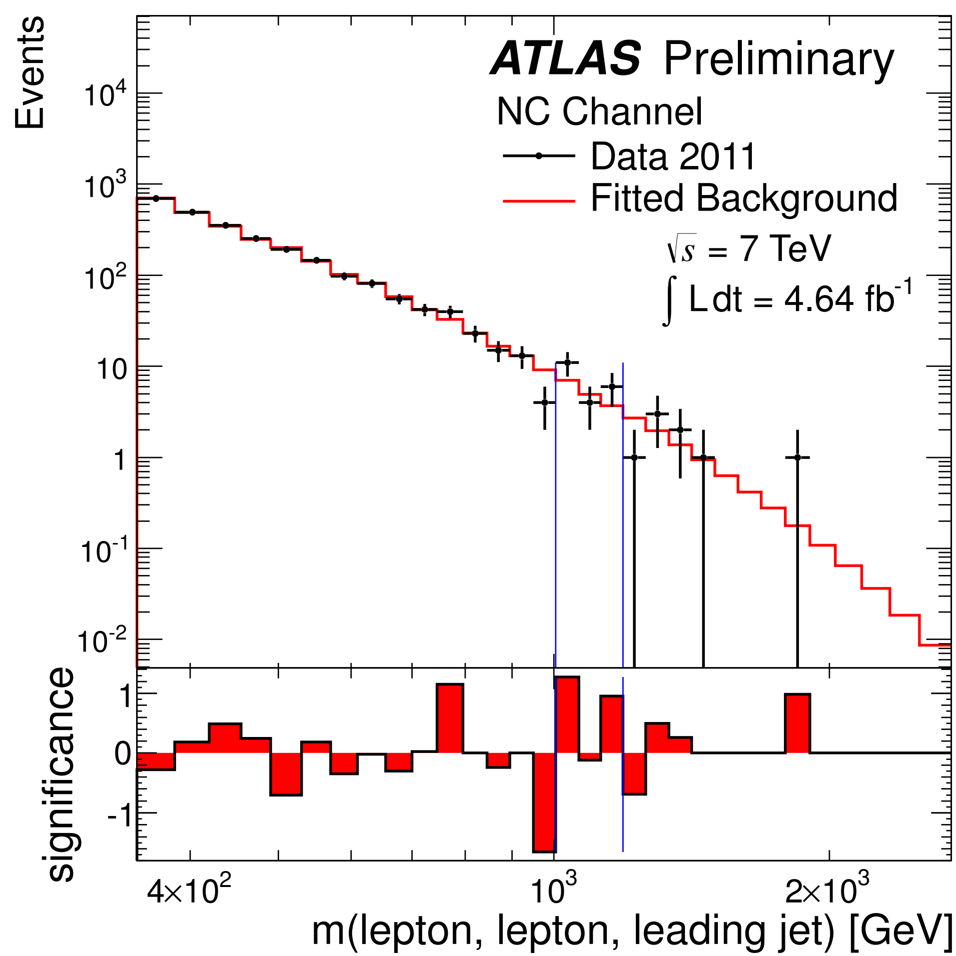
Pair produced VLQ model dependent limits



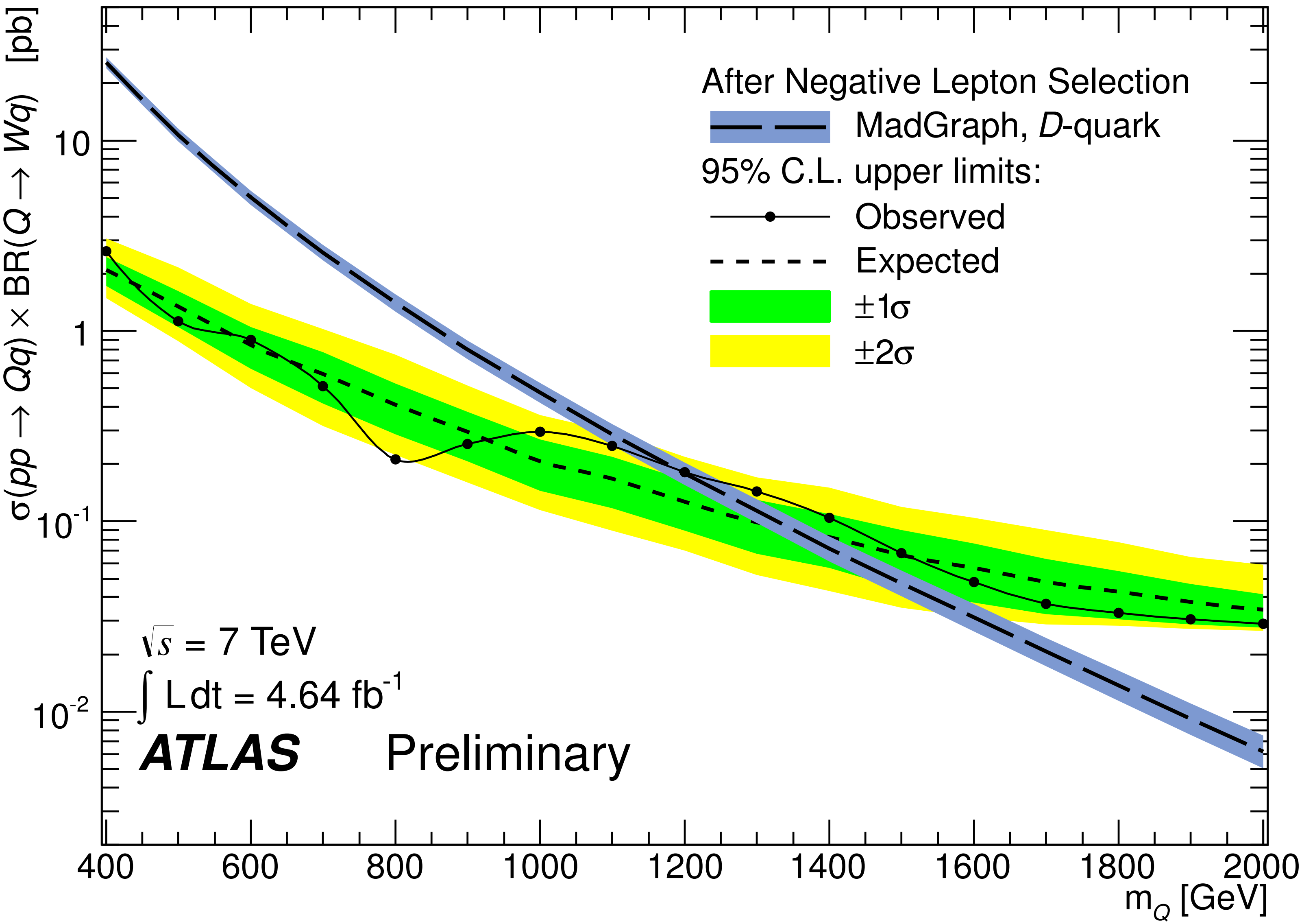


Singly produced VLQ NC results



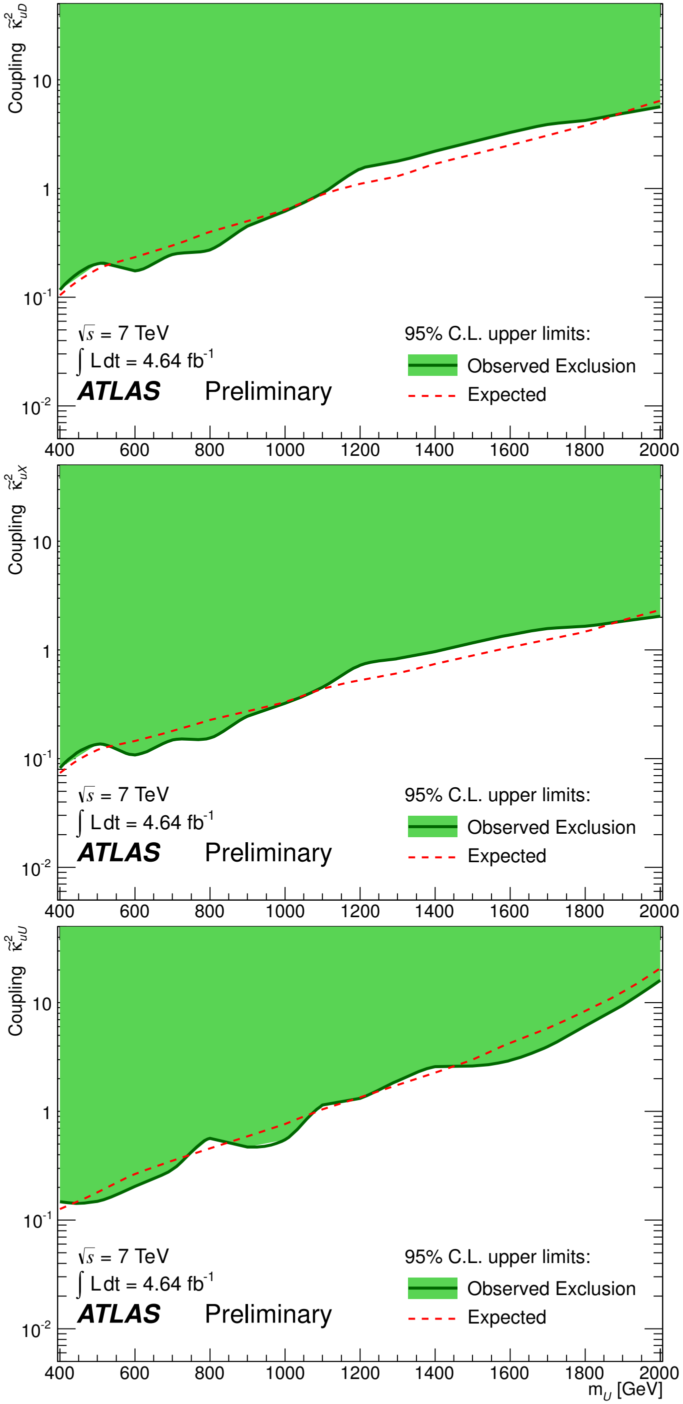


Singly produced VLQ limits with negative lepton selection

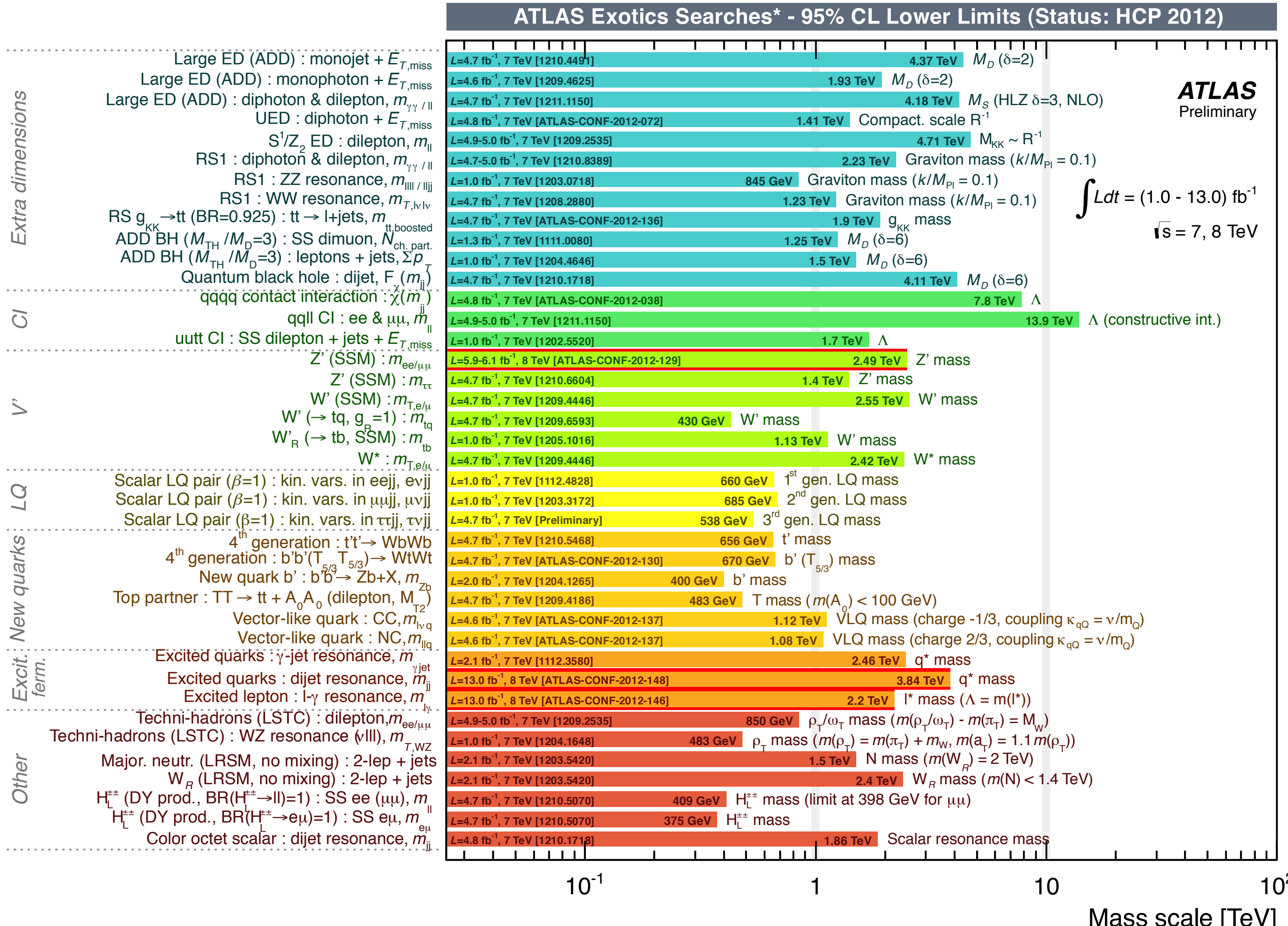


Singly produced VLQ coupling limits

$$\kappa_{qQ} = (v/m_Q)\tilde{\kappa}_{qQ}$$



Mass reach summary



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