Exotic Searches at the LHC

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Outline

- Introduction
- Overview of Searches
- Conclusion and Outlook

Introduction

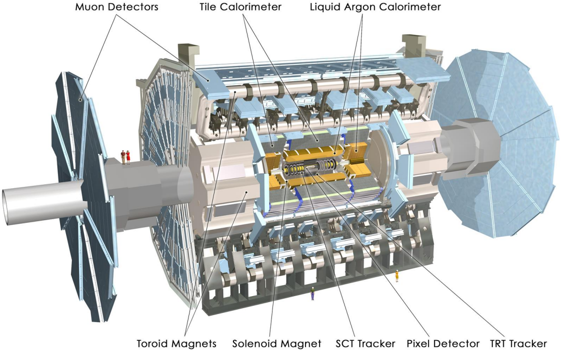
- Exotics (non-SUSY) Searches are a large part of the LHC Programme:
  - 47 (46) ATLAS (CMS) Publications
  - If something new had been found you would already know about it!
- Easy for a talk discussing this wide programme to become a fashion parade of exotic models and searches
- Here I will present what I consider to be the edited highlights
- Prefer to focus on the final states explored, rather than the models excluded

Introduction

The ATLAS and CMS detectors at the LHC:

- precise calorimetry:
  - Hadronic jets
  - electrons
- Precise tracking:
  - Muons
  - *b*-jet tagging
- Excellent solid-angle coverage:
  - E_T^{miss}

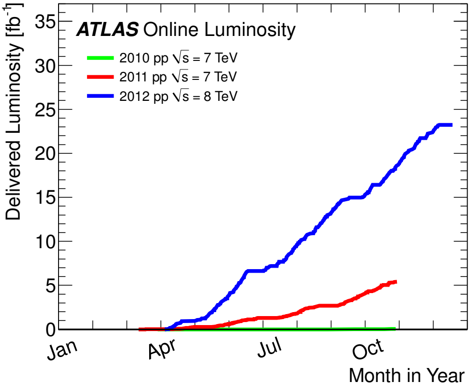
Versatile detectors for finding new physics in a variety of final states



Luminosities

The LHC has been performing excellently since 2010:

- $\sim 35\,\mathrm{pb}^{-1}$ of 7 TeV *pp* collisions/experiment 2010
- $\sim 5\,\mathrm{fb}^{-1}$ of 7 TeV *pp* coliisions/experiment 2011
- $\sim 20\,\mathrm{fb}^{-1}$ of 8 TeV *pp* coliisions/experiment 2012



Only one exotics publication (CMS) from 2012 data so far...

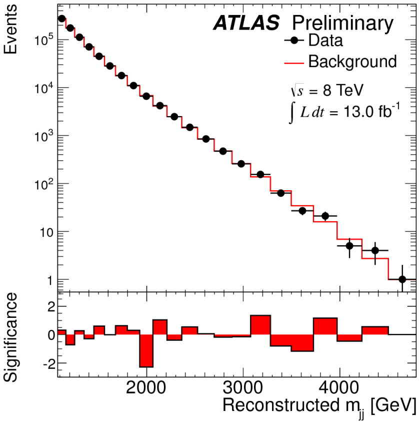
- First go for the potential early discoveries:
  - large-cross-section processes
  - simple final states
- Then tougher targets:
  - smaller cross-sections
  - complex signatures
- Make sure to check the rest with:
  - model independent searches
  - precision measurements

First, the low hanging fruit:

- large cross section:
  - dijets
- simple (clean) final states
  - l^+l^-
  - $l\nu$

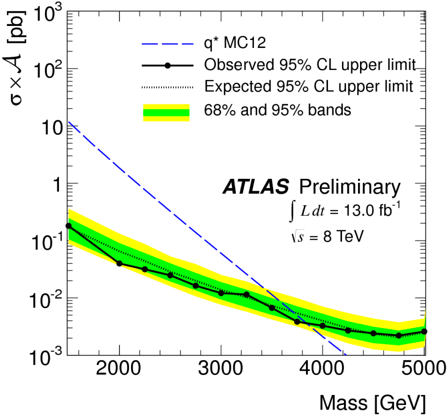
ATLAS-CONF-2012-148 Search for new physics in dijets
13 $\mathbf{fb^{-1}}$ @ 8 TeV

- Require two central jets $|y| < 2.8$
- Reduce t-channel-like processes $|y_{1,2}| < 2.8$, $|y^*| < 0.6$
- $|m_{jj}| > 1000$ GeV
- Search for a bump in the m_{jj} spectrum



Dijets

- limits set on excited quark production
- Furthermore model-independent limits (assuming a Gaussian signal) set
- Application to set limits on NP models beyond those directly considered is possible



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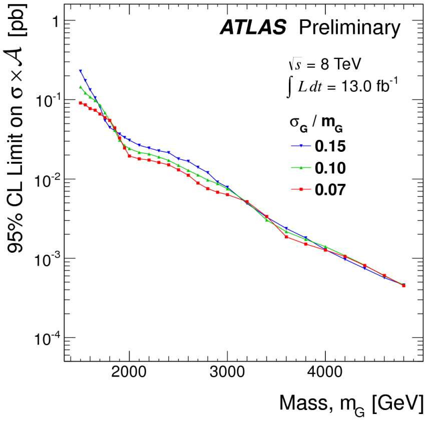
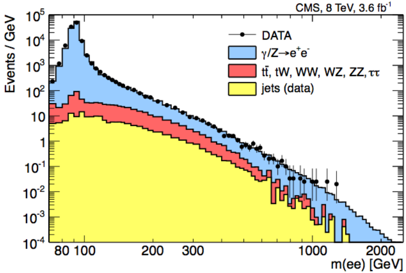
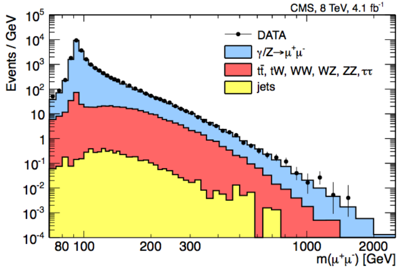


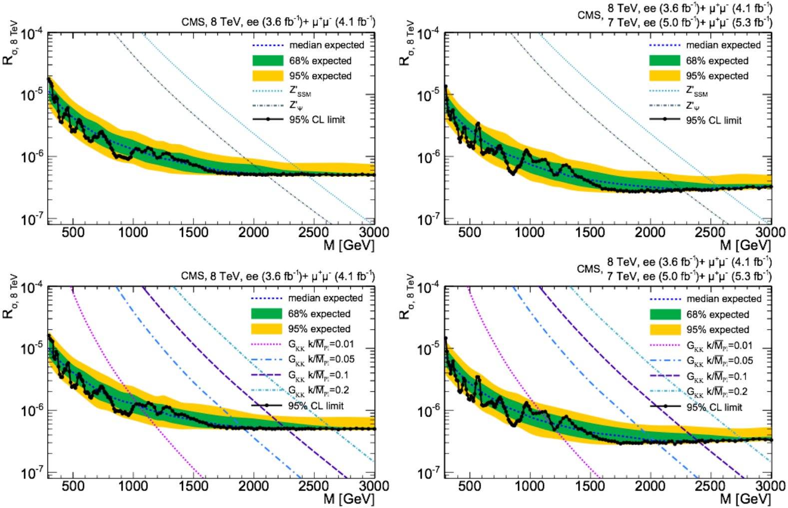
Another early search channel is l^+l^-:

- Only 8 TeV Exotica publication (1212.6175) with 4 fb^{-1} by CMS
- Select two high p_T leptons
- Search invariant mass spectrum
- Set limits on models
- ATLAS CONF note with 6 fb^{-1} also available (ATLAS-CONF-2012-129)





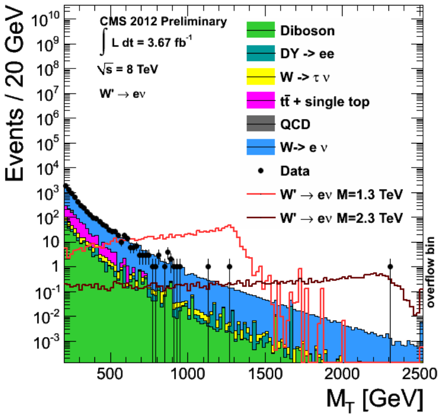
l^+l^-


CMS, 8 TeV, ee (3.6 fb^{-1})+ $\mu^+\mu^-$ (4.1 fb^{-1})
median expected
68% expected
95% expected
Z'$_{SSM}$
Z'$_\psi$
95% CL limit
CMS, 8 TeV, ee (3.6 fb^{-1})+ $\mu^+\mu^-$ (4.1 fb^{-1})
7 TeV, ee (5.0 fb^{-1})+ $\mu^+\mu^-$ (5.3 fb^{-1})
G_{KK} k/$\overline{M}_{Pl}$=0.01
G_{KK} k/$\overline{M}_{Pl}$=0.05
G_{KK} k/$\overline{M}_{Pl}$=0.1
G_{KK} k/$\overline{M}_{Pl}$=0.2
$R_{\sigma, 8\ TeV}$
M [GeV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
500
1000
1500
2000
2500
3000

l^+l^-

Usually slower to access: $l\nu$ (E_T^{miss})

- CMS-PAS-EXO-12-010
- Select a high-p_T lepton
- Require E_T^{miss} that balances p_T^l
- Search m_T distribution for excesses
  - e-channel
  - μ-channel



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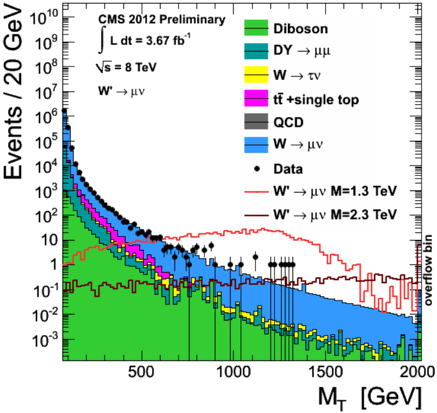
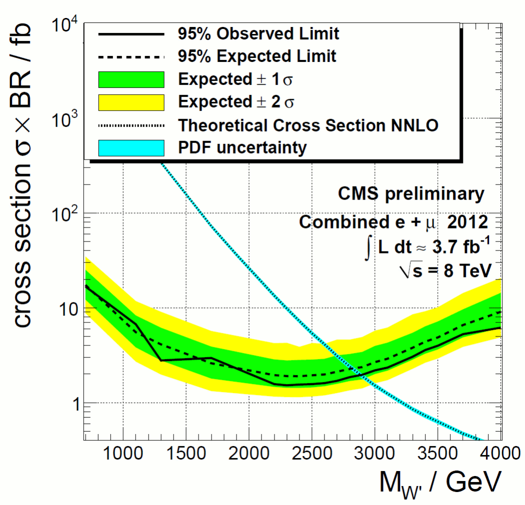



95% Observed Limit
95% Expected Limit
Expected ± 1σ
Expected ± 2σ
Theoretical Cross Section NNLO
PDF uncertainty
CMS preliminary
Combined e + μ 2012
∫L dt ≈ 3.7 fb⁻¹
√s = 8 TeV
cross section σ × BR / fb
M_W' / GeV
10⁴
10³
10²
10
1
1000
1500
2000
2500
3000
3500
4000

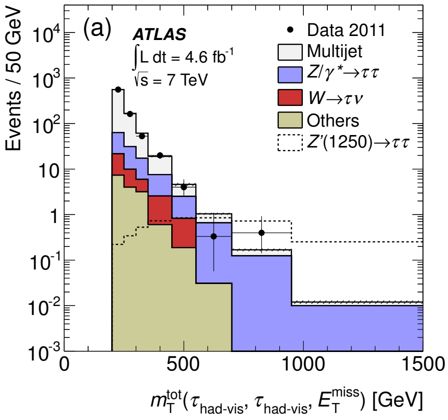
As data sets become better understood, more challenging quarry can be approached:

- Final states with τs and bs
- Complex multi-object final states
- Processes with very small expected cross sections
- Final states with boosted heavy objects

arXiv:1210.6604

search for resonant $\tau^+\tau^-$:

- Use four channels:
  - $\tau_h\tau_h$ (42%)
  - $\tau_h\mu$ (23%)
  - $\tau_h e$ (23%)
  - $e\mu$ (6%)
- Opposite charge τ candidates
- Require τs back to back in transverse plane
- Use M_T to discriminate signal and background



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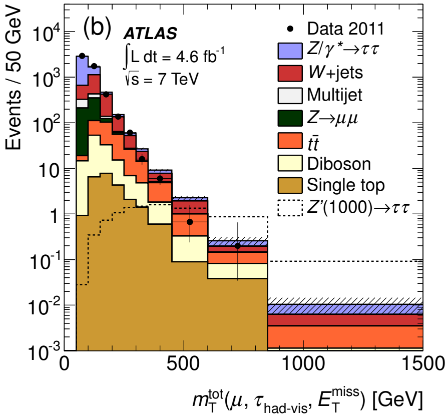

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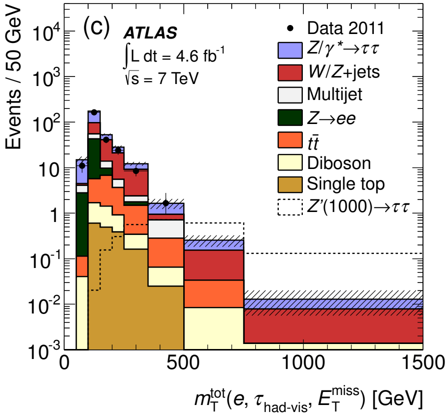

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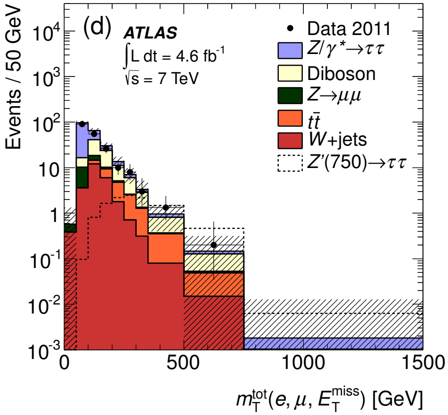
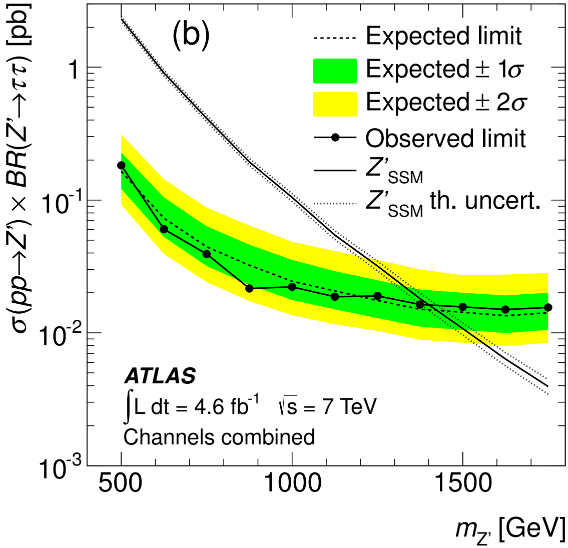
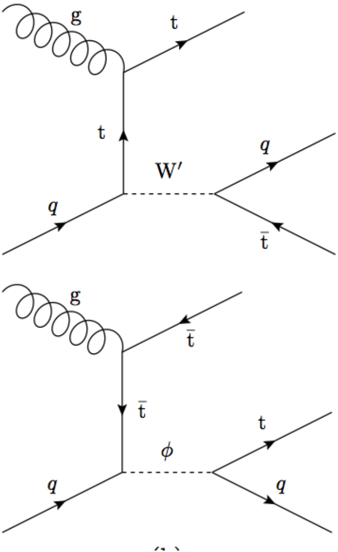




- Channels are combined to set a cross-section $\times\mathcal{BR}$ limit on $Z' \to \tau^+\tau^-$
- SSM Z' used as a benchmark

Example of a complex final state: top-associated new physics

- Search for: $pp \to tX, X \to t$+jet
- looking for a top+jet resonance
- Several proposed models like this to account for large Tevaton A_{FB}
- Search focusses on W'-like particles:
  - Color singlet $tW', W' \to \bar{t}d$
  - Di-quark color triplet $\bar{t}\phi, \phi \to tu$

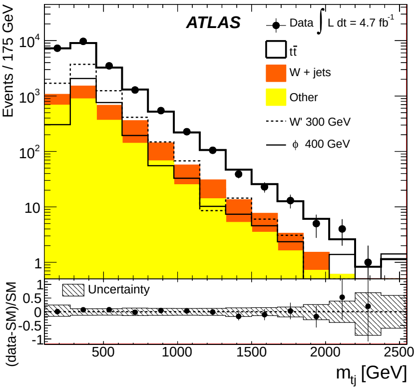


$t + X, X \to td$

arXiv:1209.6593

Strategy:

- Select $t\bar{t}$ l+jets events in the standard way
- require an extra jet
- Assign jets to top quarks using a kinematic likelihood fitter
- Exploit charge-asymmetry in NP production by looking at m_{tj} vs $m_{\bar{t}j}$



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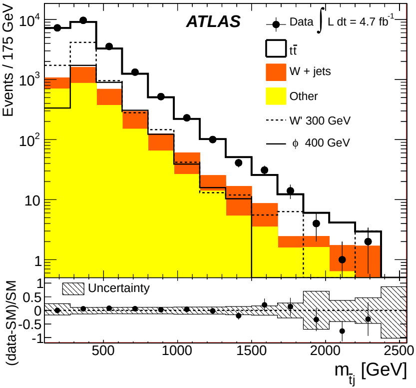
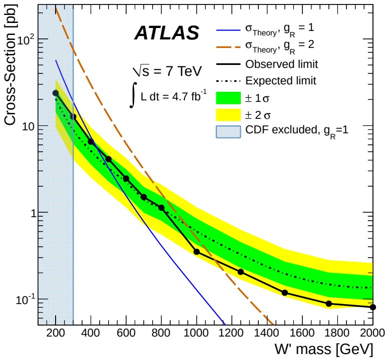
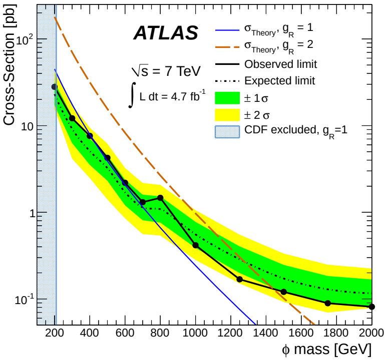
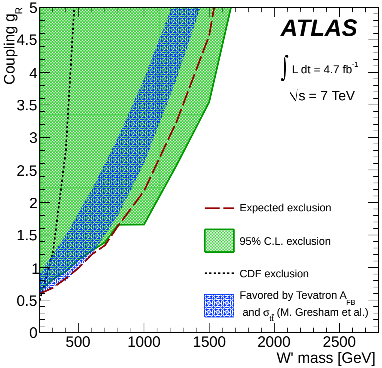


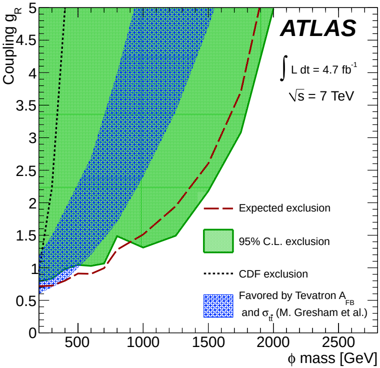
Limits on cross-section$\times\mathcal{BR}$:





Limits on cross-section$\times\mathcal{BR}$ and also on allowed coupling (g_R):

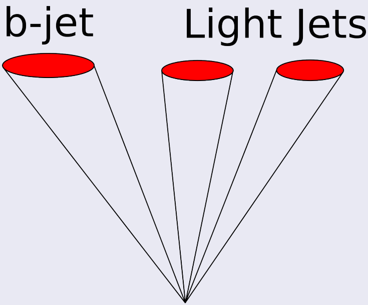




When pushing to higher energies, new factors come into play:

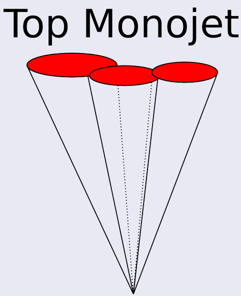
Low Energy tops

$t \to bW$, $W \to qq'$ gives three distinct "jets":



High Energy tops

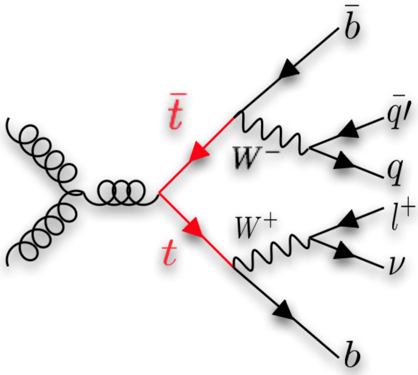
top decay system is highly boosted and reconstructed as only one jet:



Need new techniques to identify these boosted objects

An ideal test case is a search for high-mass particles decaying to $t\bar{t}$:

- Use the l+jets topology
- lepton and E_T^{miss} cuts ensure sample is quite pure
- Can search for new physics
- can verify that jet substructure variables are well described

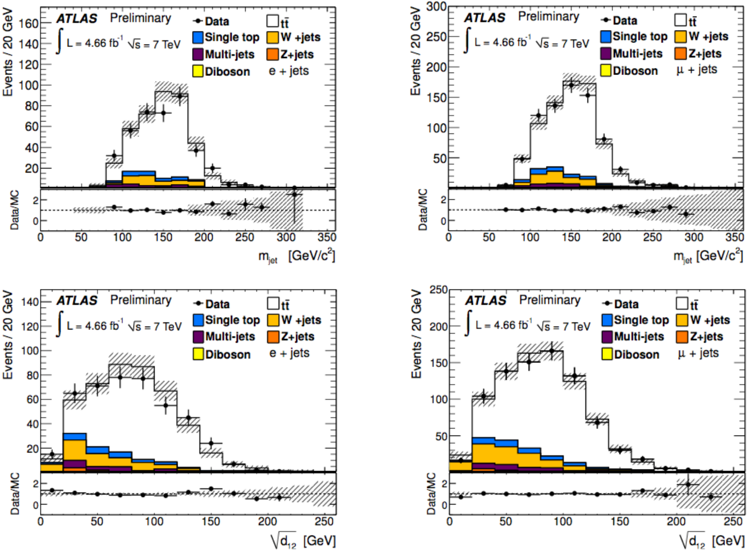


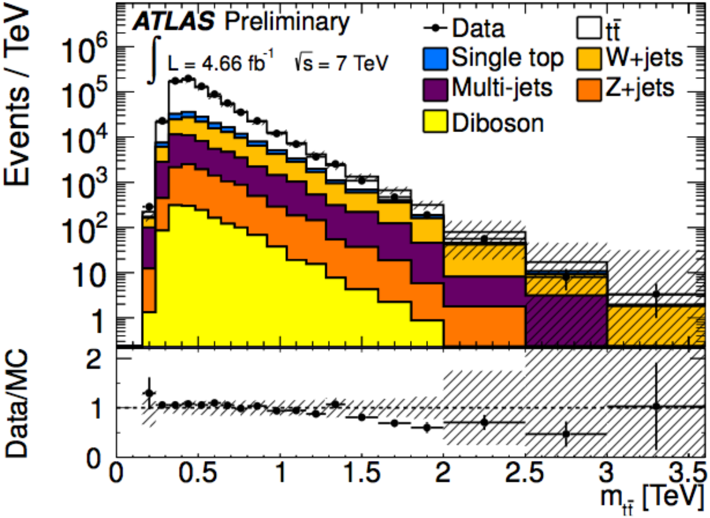
ATLAS-CONF-2012-136

Search strategy adopted by ATLAS, combines two selections:

- **Resolved**
  - lepton
  - E_T^{miss}
  - $\geq$ 3 jets
  - $\geq$ 1 b-jet
- **Boosted:**
  - lepton
  - E_T^{miss}
  - $\geq$ 1 large-R jet with $p_T > 350$ GeV and large jet-mass
  - $\geq$ 1 b-jet

$Z' \to t\bar{t}$


ATLAS Preliminary
$\int L = 4.66\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7$ TeV
Data
$t\bar{t}$
Single top
W +jets
Multi-jets
Z+jets
Diboson
e + jets
μ + jets
Events / 20 GeV
Data/MC
m_{jet} [GeV/c^2]
$\sqrt{d_{12}}$ [GeV]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Data
tt̄
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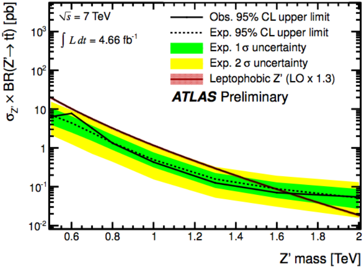
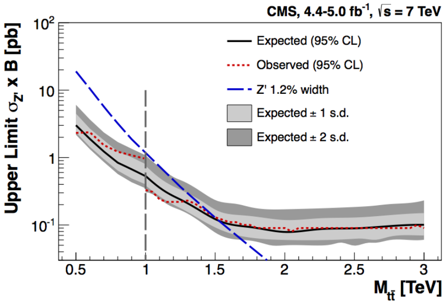
m_tt̄ [TeV]





(ATLAS limit on a TC2 Z' compared to CMS from arXiv:1209:4397 - both experiments can perform this kind of search)

As well as relatively dedicated searches, there is an increasing trend towards producing results that are more widely applicable:

- Fiducial cross section limits
- Limits associated with parametrised efficiency
- Global searches for any discrepancies

These offer the chance to catch new physics that we hadn't thought of and they give others the potential to test new models agaianst existing searches.

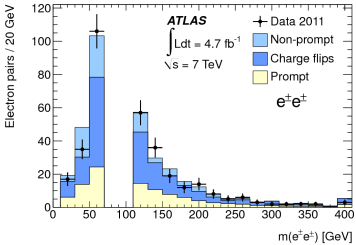
$l^+ l^+$

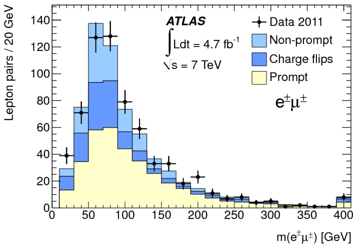
Many, many models predict signatures with same-sign leptons in the final state, but

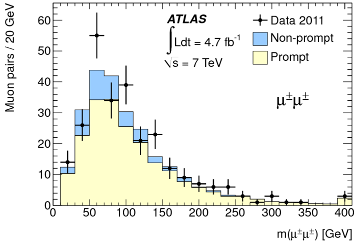
- There's probably no __________ (insert model here)
- So let's stop over-optimising and enjoy setting fiducial cross-section limits

arXiv:1210.4358

l^+l^+







- Select events with like-sign lepton pairs $ee,\mu\mu.e\mu$
- in ee channel exclude mass window around Z (large charge-flip background there)
- No requirement on E_T^{miss}

l^+l^+

Mass range	95% C.L. upper limit [fb]					
	expected	observed	expected	observed	expected	observed
	$e^\pm e^\pm$		$e^\pm\mu^\pm$		$\mu^\pm\mu^\pm$	
$m > 15$ GeV	46^{+15}_{-12}	42	56^{+23}_{-15}	64	$24.0^{+8.9}_{-6.0}$	29.8
$m > 100$ GeV	$24.1^{+8.9}_{-6.2}$	23.4	$23.0^{+9.1}_{-6.7}$	31.2	$12.2^{+4.5}_{-3.0}$	15.0
$m > 200$ GeV	$8.8^{+3.4}_{-2.1}$	7.5	$8.4^{+3.4}_{-1.7}$	9.8	$4.3^{+1.8}_{-1.1}$	6.7
$m > 300$ GeV	$4.5^{+1.8}_{-1.3}$	3.9	$4.1^{+1.8}_{-0.9}$	4.6	$2.4^{+0.9}_{-0.7}$	2.6
$m > 400$ GeV	$2.9^{+1.1}_{-0.8}$	2.4	$3.0^{+1.0}_{-0.8}$	3.1	$1.7^{+0.6}_{-0.5}$	1.7
	e^+e^+		$e^+\mu^+$		$\mu^+\mu^+$	
$m > 15$ GeV	$29.1^{+10.2}_{-8.6}$	22.8	$34.9^{+12.2}_{-8.6}$	34.1	$15.0^{+6.1}_{-3.3}$	15.2
$m > 100$ GeV	$16.1^{+5.9}_{-4.3}$	12.0	$15.4^{+5.9}_{-4.1}$	18.0	$8.4^{+3.2}_{-2.4}$	7.9
$m > 200$ GeV	$7.0^{+2.9}_{-2.2}$	6.1	$6.6^{+3.5}_{-1.8}$	8.8	$3.5^{+1.6}_{-0.7}$	4.3
$m > 300$ GeV	$3.7^{+1.4}_{-1.0}$	2.9	$3.2^{+1.2}_{-0.9}$	3.2	$2.0^{+0.8}_{-0.5}$	2.1
$m > 400$ GeV	$2.3^{+1.1}_{-0.6}$	1.7	$2.4^{+0.9}_{-0.6}$	2.5	$1.5^{+0.6}_{-0.3}$	1.8
	e^-e^-		$e^-\mu^-$		$\mu^-\mu^-$	
$m > 15$ GeV	$23.2^{+8.6}_{-5.8}$	25.7	$26.2^{+10.6}_{-7.6}$	34.4	$12.1^{+4.5}_{-3.5}$	18.5
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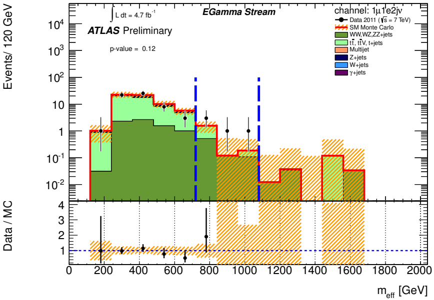
- Evaluate efficiency in fiducial region using several models:
  - SS top
  - $H^{\pm\pm}$
  - $W_R \to lN_R$
  - $b'b' \to WtWt$
- Use most conservative choice for fiducial limit
- Alternative approach for 3 lepton search in: arXiv:1211.6312:
  - $\sigma_{\rm vis}$ sections provided
  - Parametrised lepton efficiencies also given

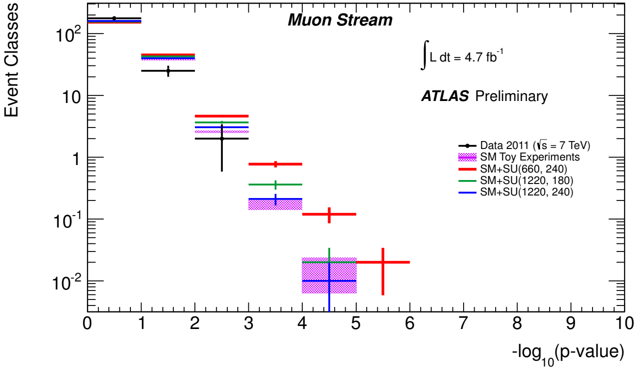
Making sure we don't miss anything big: ATLAS-CONF-2012-107

Define physics objects:

- **electrons**: $p_T > 25$ GeV , $|\eta| < 2.47$
- **muons** : $p_T > 20$ GeV , $|\eta| < 2.4$
- **jets** : $p_T > 50$ GeV , $|\eta| < 4.9$
- **b-jets** : b-tagged jet
- **photons** : $p_T > 40$ GeV , $|\eta| < 2.37$
- **neutrinos** : $E_T^{\text{miss}} > 130$ GeV



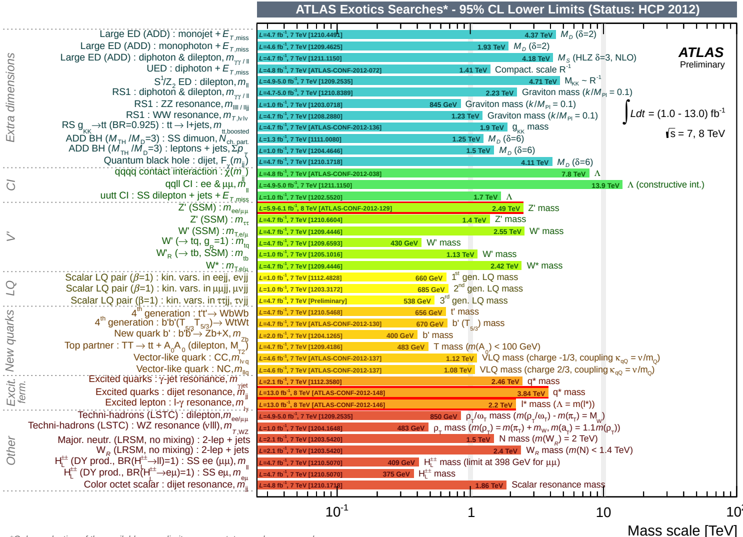
Systematically look at all possible multi-object final states for regions of largest discrepancy (655)



(Also there is an earlier CMS general search: CMS-PAS-EXO-10-021)

Summary

Summary



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

- Wide range of NP signatures explored
- Extremely strong constraints on many benchmark models
- Still no sign of new physics
- Plenty to explore in the 8 TeV data
- Need to look everywhere, surprises can always be lurking where you weren't expecting them...


Allison Pearson
Talking offence is the new national sport
Features page 25

Peter Oborne
Tony Blair has failed in the Middle East and should quit
Comment page 22

Pep Guardiola
Why he turned his back on England
See Sport pages 1-3

The Daily Telegraph

Thursday, January 17, 2013 telegraph.co.uk

Horse meat in burgers for years

MATT

Crash helicopter 'was out of control'

Briton dies, many held, in al-Qaeda revenge raid

Both Collaborations pushing hard for new and updated results in the next few weeks!

Bonus features!

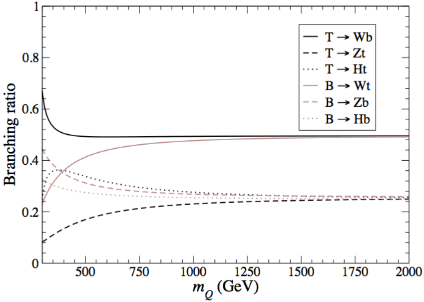
Extra slides and goodies follow...

Heavy Quark Searches

- Are Heavy quark searches in trouble?
  - **yes** - for the bog-standard chiral 4th generation
  - **no** - for Vector-like quarks
- Future of such searches is to explore the parameter space for VLQs

Vector-like quarks are not your daddy's quarks[1]:

- Charges allowed $-4/3, -1/3, 2/3, 5/3$
- both chiralities have the same transformation properties under the electroweak group
- Don't have Yukawa couplings to Higgs Bosons
- Can decay to qW, qZ, qH
- motivated by e.g. extra-dimension models, composite Higgs

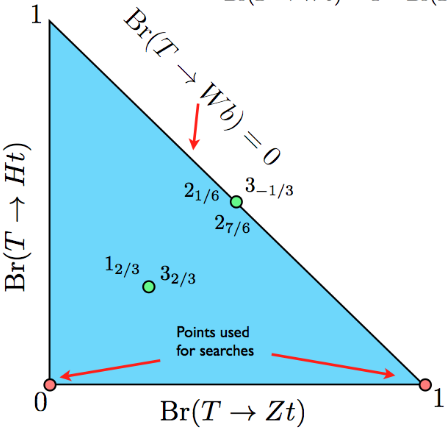


"As good (or bad) a model as a sequential 4$^{\text{th}}$ generation"

[1] See e.g. arXiv:0907:3155

Still important parameter space to explore:[2]

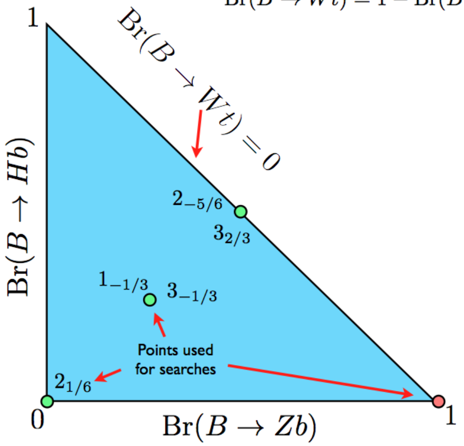
$$\mathrm{Br}(T \to Wb) = 1 - \mathrm{Br}(T \to Zt) - \mathrm{Br}(T \to Ht)$$



[2]Figure from Juan-Antonio Aguilar-Saavedra

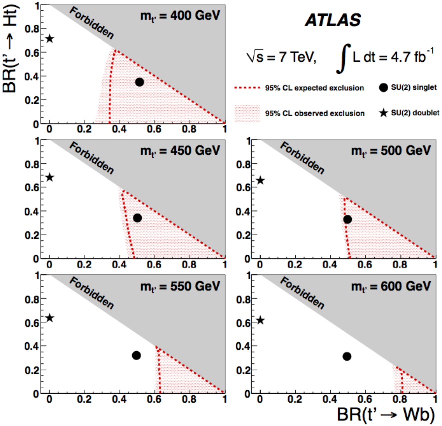
Still important parameter space to explore:[3]

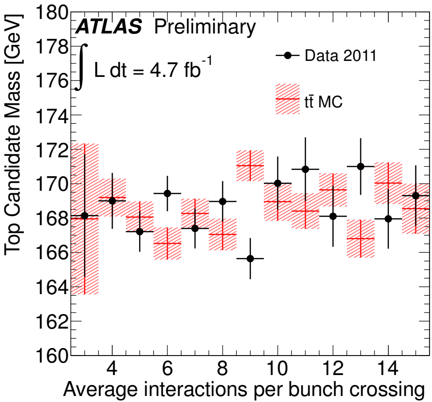
$$\mathrm{Br}(B \to Wt) = 1 - \mathrm{Br}(B \to Zb) - \mathrm{Br}(B \to Hb)$$



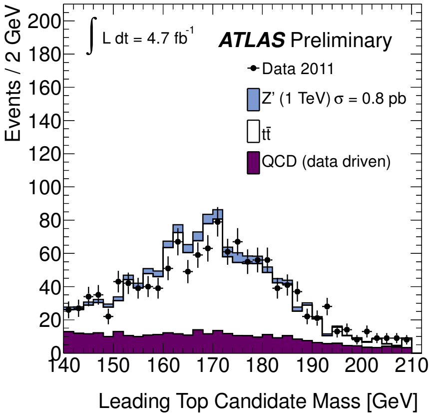
[3] Figure from Juan-Antonio Aguilar-Saavedra

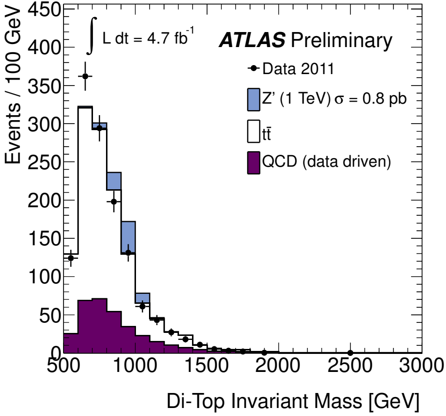
first generic heavy quark search form ATLAS arXiv:1210.5468:

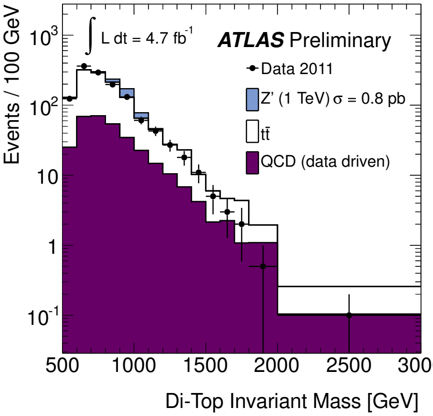


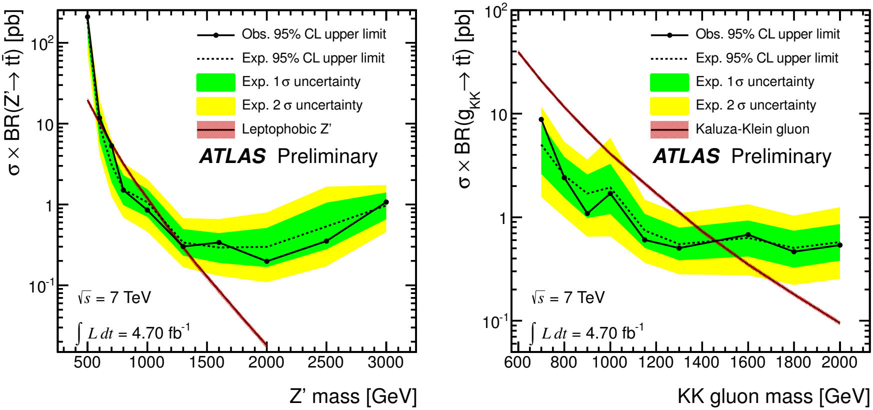


Technique based on HepTopTagger:
Phys.Rev.Lett.104:111801,2010 (Pile-up resistant)


$\int$ L dt = 4.7 fb^{-1}
ATLAS Preliminary
Data 2011
Z' (1 TeV) σ = 0.8 pb
$t\bar{t}$
QCD (data driven)
Events / 2 GeV
Leading Top Candidate Mass [GeV]
0
20
40
60
80
100
120
140
160
180
200
140
150
160
170
180
190
200
210


Events / 100 GeV
∫ L dt = 4.7 fb-1
ATLAS Preliminary
Data 2011
Z' (1 TeV) σ = 0.8 pb
tt̄
QCD (data driven)
Di-Top Invariant Mass [GeV]


Events / 100 GeV
∫ L dt = 4.7 fb-1
ATLAS Preliminary
Data 2011
Z' (1 TeV) σ = 0.8 pb
tt̄
QCD (data driven)
Di-Top Invariant Mass [GeV]


Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1σ uncertainty
Exp. 2 σ uncertainty
Leptophobic Z'
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 4.70 fb^{-1}
$\sigma \times$ BR(Z'→ $t\bar{t}$) [pb]
Z' mass [GeV]
Obs. 95% CL upper limit
Exp. 95% CL upper limit
Exp. 1σ uncertainty
Exp. 2 σ uncertainty
Kaluza-Klein gluon
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV
$\int L\,dt$ = 4.70 fb^{-1}
$\sigma \times$ BR(g_{KK} → $t\bar{t}$) [pb]
KK gluon mass [GeV]