SEARCH Workshop, University of Maryland, March 17-19, 2012

Searches for Exotic Heavy Quarks and $t\bar{t}$ Resonances in ATLAS

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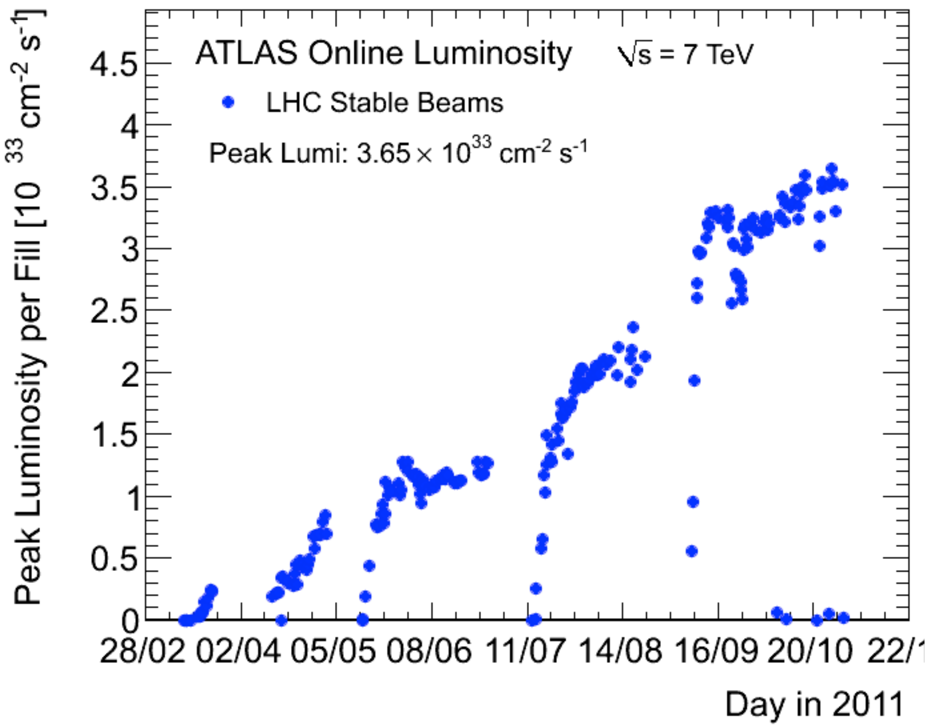
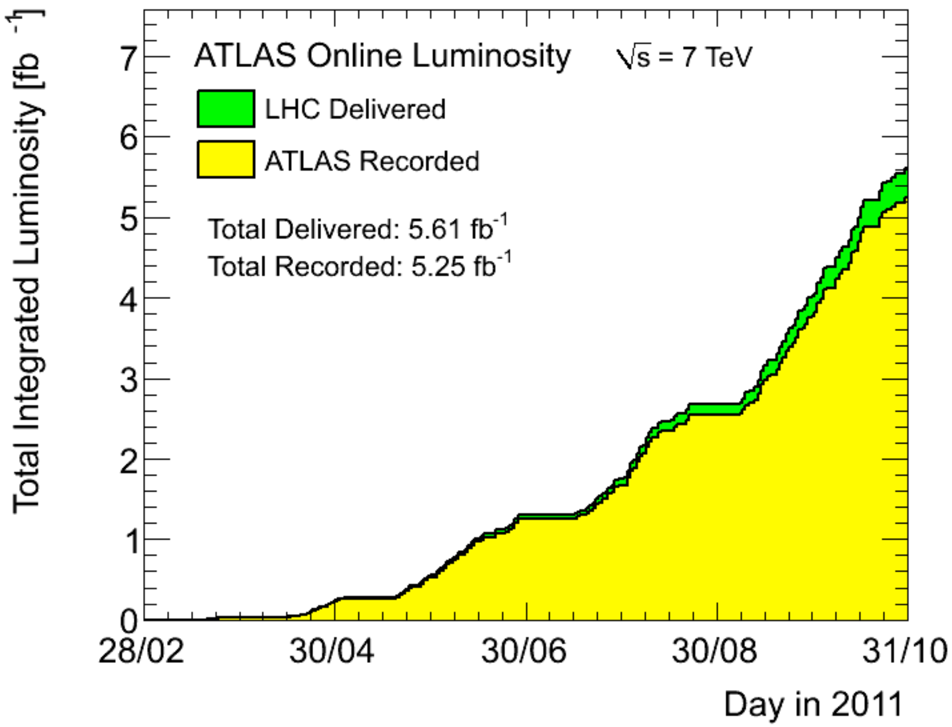
For the ATLAS Collaboration

Dataset





- 2011 ATLAS Dataset:
  - Peak instantaneous luminosity: 3.7×10^{33} $cm^{-2}s^{-1}$
  - Integrated luminosity: ~5.3 fb^{-1} recorded

    ➔ 4.7 fb^{-1} after all data quality requirements (these analyses use full detector!)

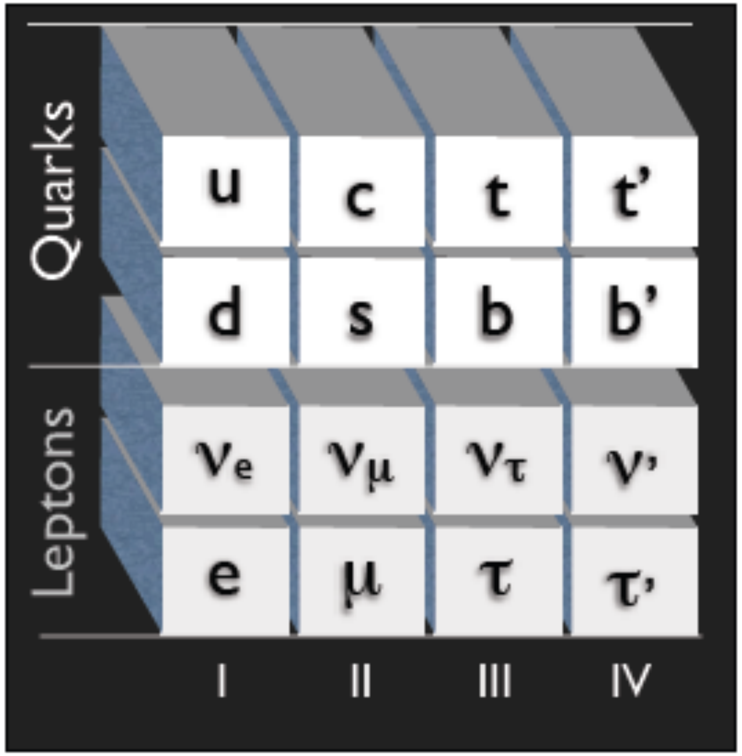
- Results presented here consider dataset recorded up to August 2011:

  ➔ ~1-2 fb^{-1} in analysis
- Analyses using full 2011 dataset are underway and should be available soon.

Exotic Heavy Quarks

4^{th} Generation Quarks

- SM doesn't predict # of fermion generations:
  - Upper bound from QCD asymptotic freedom: #families < 9.
  - CKM constraints fairly weak.
- SM4 = SM + 4^{th} generation family of fermions with 100 GeV < M < 600 GeV. Above 600 GeV large Yukawa couplings render model non-perturbative.
- In this talk will focus on heavy quarks
- Who ordered that?
  - Consistent w/ precision EW data and allowing for a heavier Higgs boson (up to ~500 GeV).
  - Extended CKM matrix could provide enough CP-violation to explain matter-antimatter asymmetry.
  - Can explain some anomalies in CP-violation measurements in B-physics.



$$\mathrm{CKM}_{4\times4} = \begin{bmatrix} 0.97377\pm0.00027 & 0.2257\pm0.0021 & 0.00431\pm0.00030 & <0.044 \\ 0.230\pm0.011 & 0.957\pm0.095 & 0.0416\pm0.0006 & <0.46 \\ 0.0074\pm0.0008 & 0.0406\pm0.0027 & >0.78 & <0.47 \\ <0.063 & <0.46 & <0.47 & >0.57 \end{bmatrix}$$

t'→Wq (q=d,s,b)

b'→Wq (q=u,c,t)

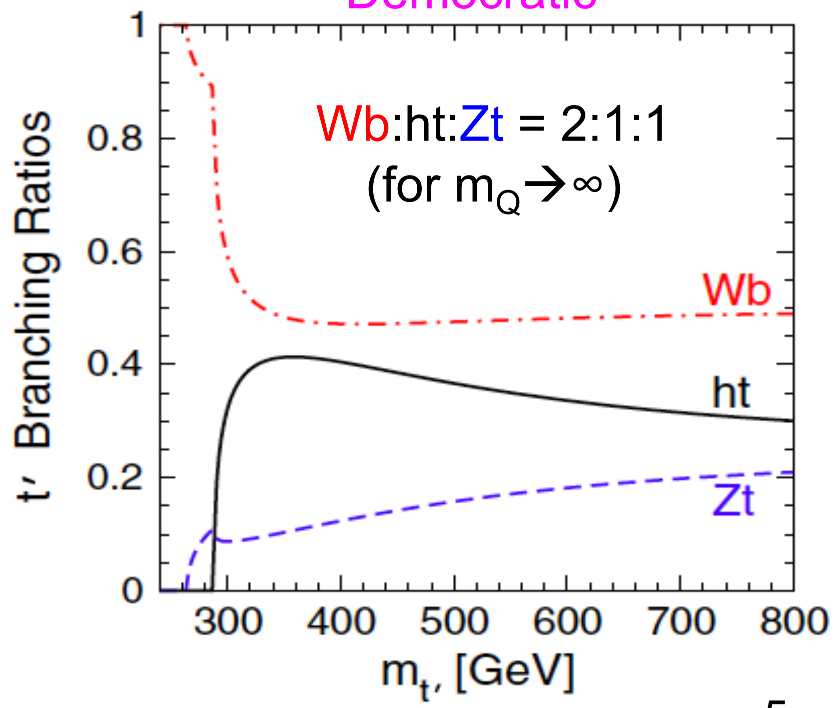
Vector-like Quarks

- Vector-like quarks: left and right components transform the same under $SU(2)_L$
  ➔ can couple to SM particles without upsetting precision EW and flavor constraints.
- Vector-like quarks in a doublet need to be nearly degenerate in mass.
- Predicted by many models: extra-dimensions, Little Higgs, GUTs,…
- Since mixing with other quarks is ~m/M, they preferentially couple to the 3rd generation.
- Quite a few possibilities to explore! Branching ratios can be quite model-dependent.

JHEP 11, 030 (2009) *(triplets not included)*

	Label	Charge	Decay mode
T singlet	T_S	+2/3	$T \to W^+b$, Zt, ht
B singlet	B_S	-1/3	$B \to W^-t$, Zb, hb
(T,B) doublet	TB_d	(+2/3, -1/3)	$T \to W^+b$, Zt, ht $B \to W^-t$, Zb, hb
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+t$ $T \to Zt$, ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, hb $Y \to W^-b$

"Democratic"



PRD 81, 035004 (2010)

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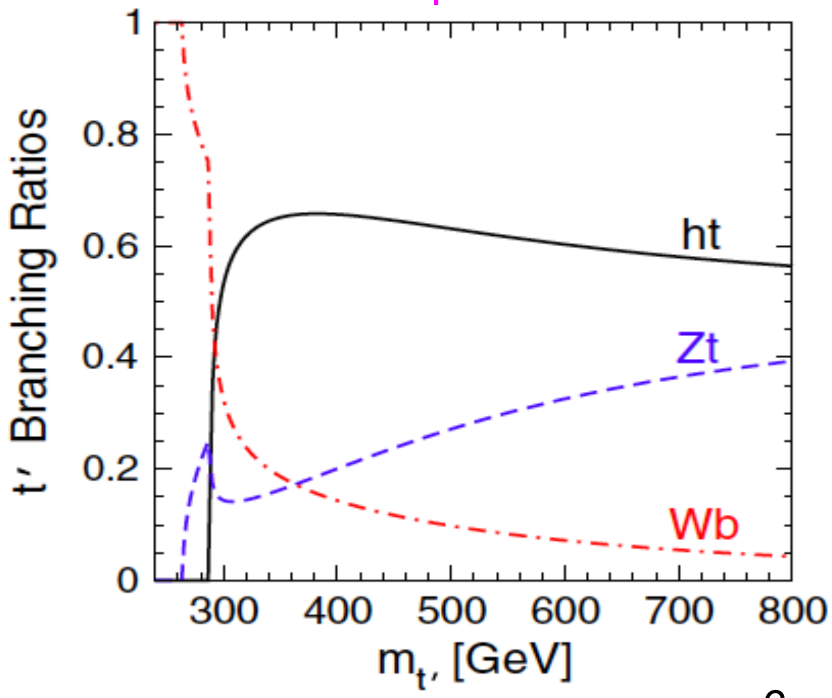
(X,T) doublet	XT_d	(+5/3, +2/3)	$X \to W^+t$ $T \to Zt$, ht
(B,Y) doublet	BY_d	(-1/3, -4/3)	$B \to Zb$, hb $Y \to W^-b$

"W-phobic"

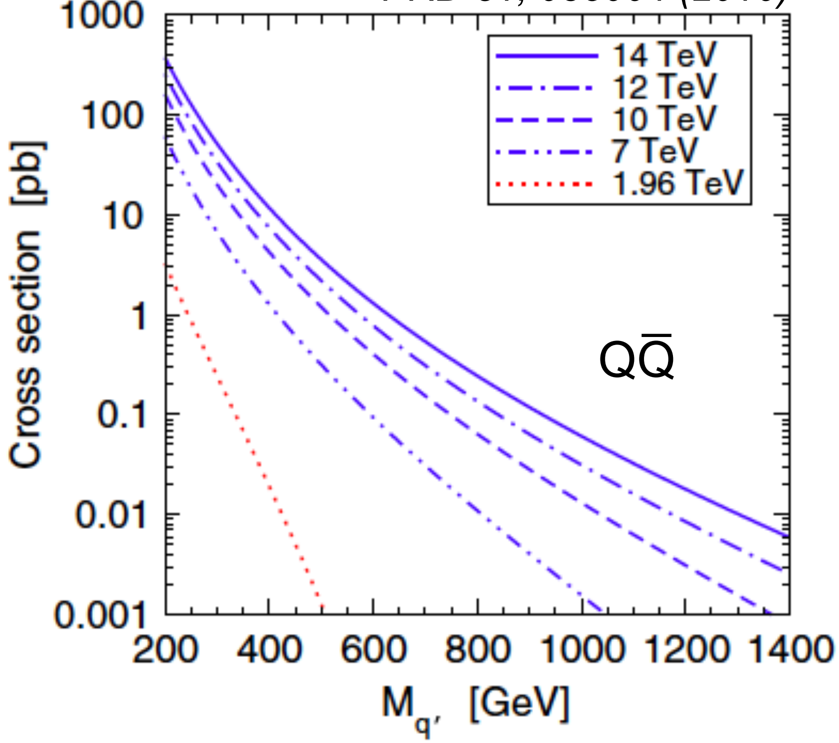


PRD 81, 035004 (2010)

Heavy Quark Production

- Up to masses ~1 TeV, dominant production is in pairs via the strong interaction:
  $\sqrt{s}$=7 TeV: $\sigma(Q\bar{Q})$ ~ 1.5 pb for m_Q~400 GeV vs $\sigma(t\bar{t})$ = 160 pb
  $\sqrt{s}$=14 TeV: $\sigma(Q\bar{Q})$ ~ 8 pb for m_Q~400 GeV vs $\sigma(t\bar{t})$ = 880 pb
- Many models involving vector-like quarks also have new heavy spin-1 colored particles (e.g. G') which can enhance significantly the cross section.
- For masses above ~1 TeV the dominant production mode is single via the EW interactions (model-dependent, but also opportunity to measure weak couplings of heavy quarks!).

PRD 81, 035004 (2010)



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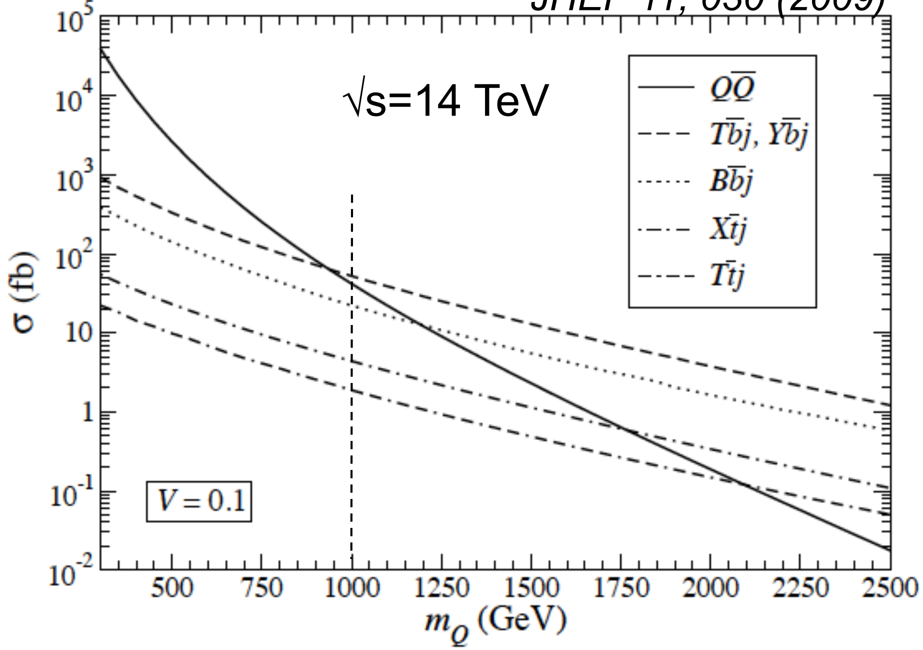


In this talk will focus on pair production

Signatures: 4th Generation Quarks

- 4^{th} generation models have a restricted list of available signatures that simplify the search strategy: $T\bar{T} \to WbWb$, $B\bar{B} \to WtWt$

				TB_d		
4 leptons	4l (0Z)			$B\bar{B}$		
3 leptons	3l (0Z)			$B\bar{B}$		
OS dileptons	l^+l^- (0Z)			$T\bar{T}$, $B\bar{B}$		
SS dileptons	$l^\pm l^\pm$			$B\bar{B}$		
lepton+jets	$l^\pm$ (4j)			$T\bar{T}$		
	$l^\pm$ ($\geq$6j)			$B\bar{B}$		

Signatures: Vector-like Quarks

- If we consider VLQ models, there are many signatures that could be exploited, and which are ultimately needed to both enhance discovery potential and model discrimination.

		T_S	B_S	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	$B\bar{B}$
	4l (1Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	$B\bar{B}$
	4l (0Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	$B\bar{B}$
3 leptons	3l (1Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	
	3l (0Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	
OS dileptons	l^+l^- (1Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	$B\bar{B}$
	l^+l^- (0Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	$B\bar{B},Y\bar{Y}$
SS dileptons	$l^\pm l^\pm$		$B\bar{B}$	$B\bar{B}$	XX	
lepton+jets	$l^\pm$ (4j)	$T\bar{T}$		$T\bar{T}$	$T\bar{T}$	$Y\bar{Y}$
	$l^\pm$ ($\geq$6j)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	

New channels: 4l (2Z), 4l (1Z), 3l (1Z), l^+l^- (1Z)

- Of course, some of them are more challenging or powerful than others…

Signatures Covered in This Talk

		T_S	B_S	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	$B\bar{B}$
	4l (1Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	$B\bar{B}$
	4l (0Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	$B\bar{B}$
3 leptons	3l (1Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	
	3l (0Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	
OS dileptons	l^+l^- (1Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T}$	$B\bar{B}$
	l^+l^- (0Z)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	$B\bar{B},Y\bar{Y}$
SS dileptons	$l^\pm l^\pm$		$B\bar{B}$	$B\bar{B}$	XX	
lepton+jets	$l^\pm$ (4j)	$T\bar{T}$		$T\bar{T}$	$T\bar{T}$	$Y\bar{Y}$
	$l^\pm$ ($\geq$6j)	$T\bar{T}$	$B\bar{B}$	$T\bar{T},B\bar{B}$	$T\bar{T},XX$	

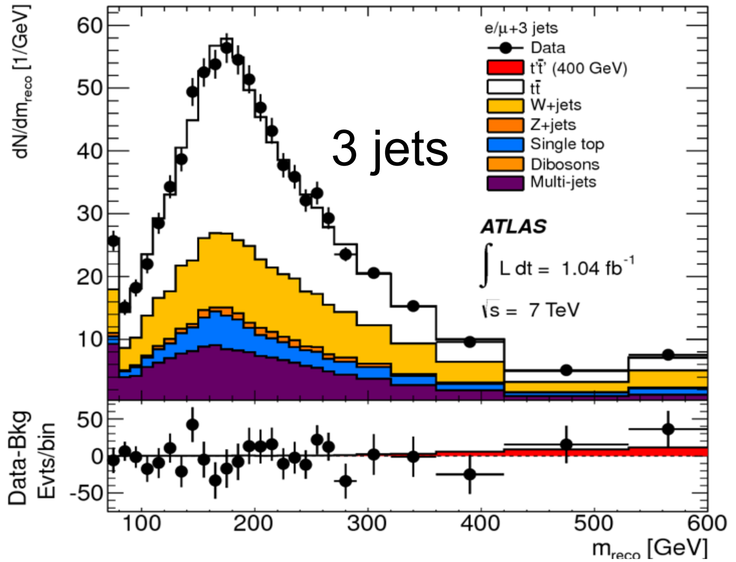
Up-type quarks

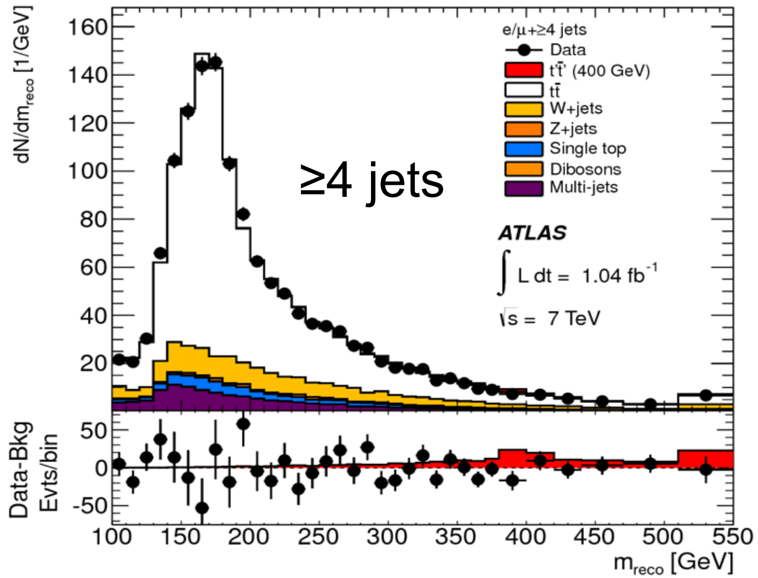
$T\bar{T} \rightarrow WbWb$ (lepton+jets)

1 fb^{-1}

arXiv:1202.3076 [hep-ex]

- Signature: l + E_T^{miss} + 3/≥4 jets (l=e,μ)
- Event selection:
  - =1 e/μ, $p_T(e)$>25 GeV, $p_T(\mu)$>20 GeV
  - e(μ)+jets: E_T^{miss}>35(20) GeV
  - E_T^{miss}+$M_T(W)$>60 GeV
  - ≥3 jets with p_T>25 GeV, |η|<2.5; p_{T1}>60 GeV
  - ≥1 b-tagged jets
- Background: dominated by $t\bar{t}$+jets (modeled with MC@NLO).
- Strategy:
  - Loose event selection to maximize signal acceptance.
  - Consider 3-jet events to help constrain background systematics.
  - Analyze separately four analysis channels (e, μ)x(3 jets, ≥4 jets) and combine at the end.
- Observable: reconstructed heavy quark mass (m_{jjj} in 3-jet bin, mass from kinematic fitting in ≥4–jet bin).





$T\bar{T} \rightarrow WbWb$ (lepton+jets)

- Exploit high-statistics in background-dominated “sidebands” to constrain impact of systematic uncertainties (a.k.a. “profiling”).
- Dominant systematic uncertainties:
  - Jet energy scale
  - $t\bar{t}$ modeling: ISR/FSR, NLO generator (*), fragmentation model (*)

(*) Not profiled

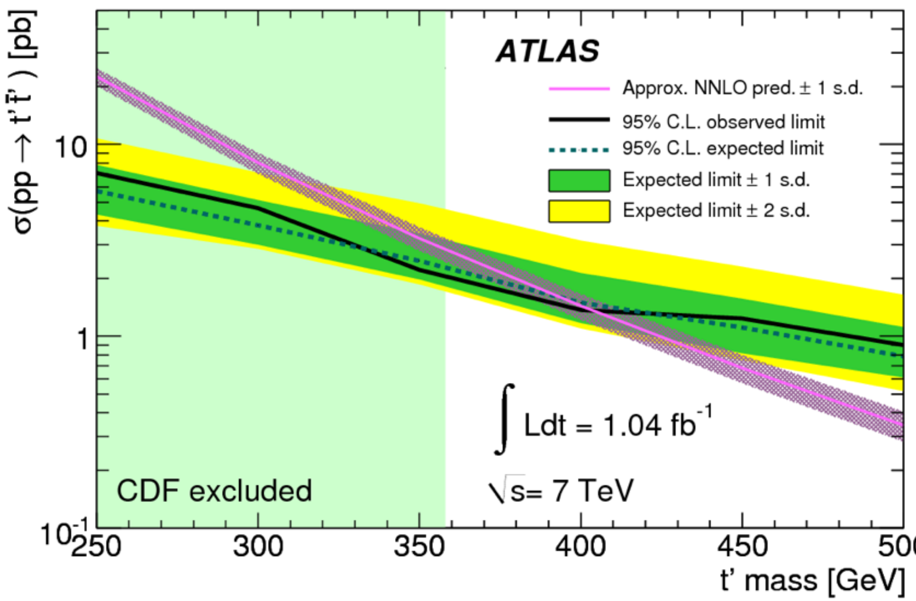
- Hypothesis testing: CL_s method via MCLimit, profiling of (some) systematic uncertainties.
- **Limit at 95% C.L.:**

m_T>404 GeV (>394 GeV expected)

Limits under assumption BR(T→Wb)=1 due to b-tagging requirement; perfectly applicable to Y→W⁻b (Q=-4/3).

Data in good agreement with background expectation

	$e+\geq 4$ jets	$\mu+\geq 4$ jets
$t\bar{t}$	4470 ± 920	5900 ± 1200
W+jets	830 ± 580	1160 ± 790
Z+jets	86 ± 56	83 ± 46
Single top	262 ± 70	325 ± 79
Dibosons	12 ± 5	17 ± 5
Multi-jet	320 ± 320	340 ± 340
Total prediction	6000 ± 1100	7800 ± 1400
Data	6145	8149
$t'\bar{t}'$(400 GeV)	102.0 ± 10.5	98.1 ± 11.1

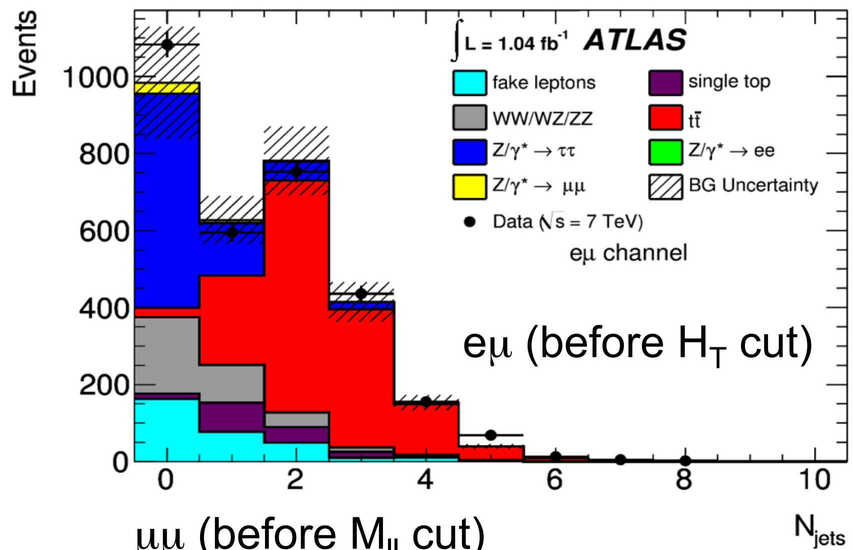


$T\bar{T} \rightarrow WqWq$ (OS dilepton+jets)

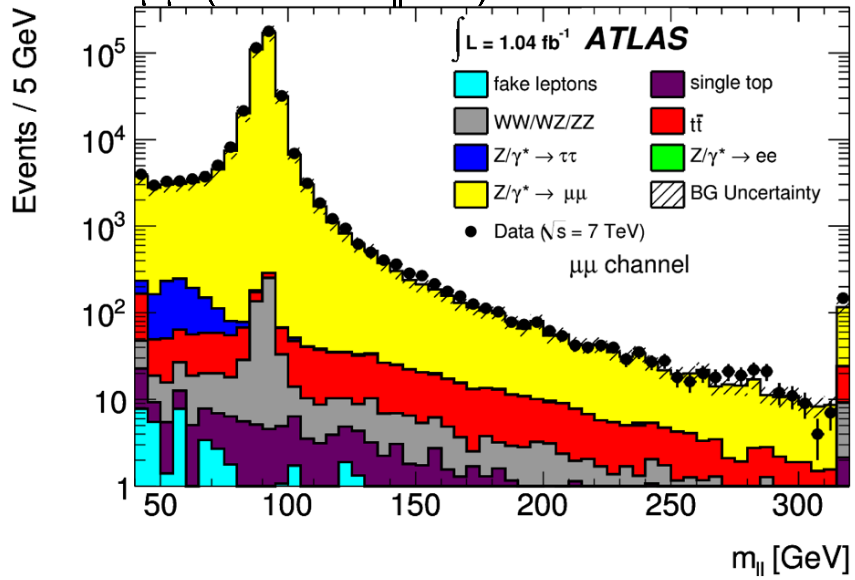
1 fb^{-1}

arXiv:1202.3389 [hep-ex]

- Signature: $l^+l'^- + E_T^{miss}$ + ≥2 jets ($l,l'=e,\mu$)
- Event pre-selection:
  - =2 opposite-sign leptons: ee, $\mu\mu$ or $e\mu$
  - $p_T(e)>25$ GeV, $p_T(\mu)>20$ GeV
  - ≥2 jets with $p_T>25$ GeV, $|\eta|<2.5$
  - $e\mu$-only: $H_T>130$ GeV
  - $ee/\mu\mu$-only:
    - $M_{ll}>15$GeV, $|M_{ll}-M_Z|>10$ GeV
    - $E_T^{miss}>60$ GeV
- Background: dominated by $t\bar{t}$+jets (modeled with MC@NLO).
- Strategy:
  - Reconstruct heavy quark mass under collinear approximation.
  - Apply tight final selection to suppress background.
  - No high-statistics sidebands available so no benefit from profiling of systematics.

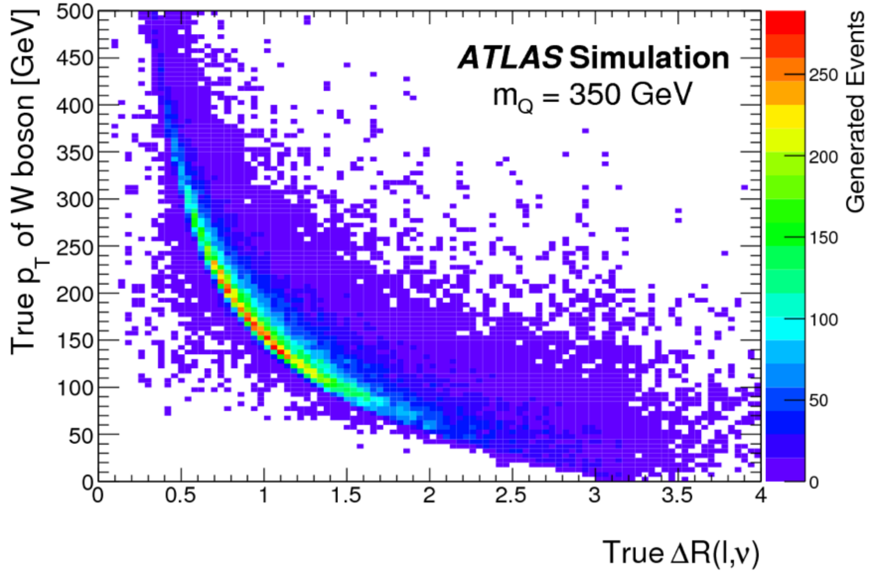


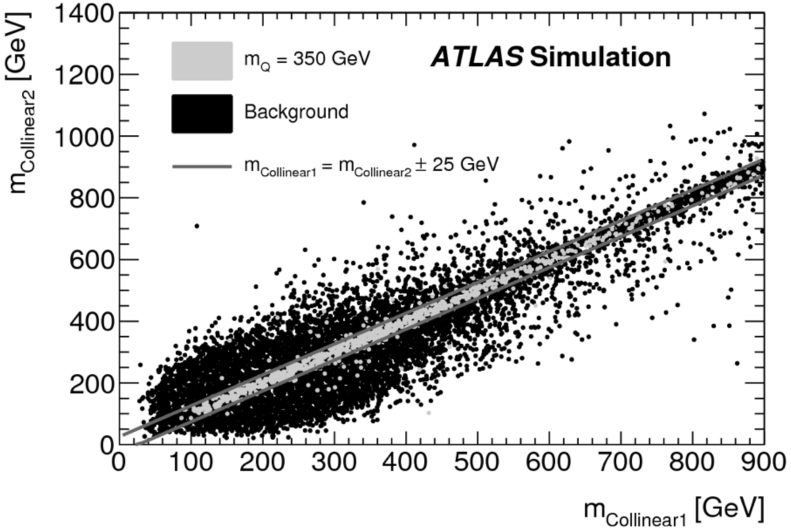
$\mu\mu$ (before M_{ll} cut)

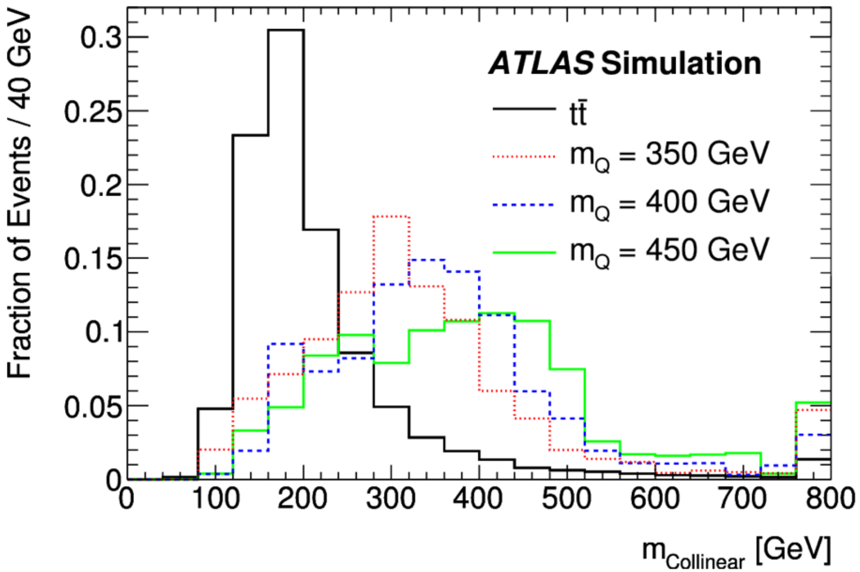


$T\bar{T} \rightarrow WqWq$ (OS dilepton+jets)

- Observable: average reconstructed heavy quark mass.
  ➔ exploits small angle between lepton and neutrino in boosted W decays from signal.
  - Assume two heavy quarks with the same mass decaying semileptonically.
  - Assume E_T^{miss} entirely comes from ν's.
  - Perform MINUIT fit allowing for non-zero $\Delta\eta(l,\nu)$ and $\Delta\phi(l,\nu)$.
  - Keep solution that minimizes $|m_{coll1}-m_{coll2}|$ and remove events with $|m_{coll1}-m_{coll2}|>25$ GeV.







$T\bar{T} \rightarrow WqWq$ (OS dilepton+jets)

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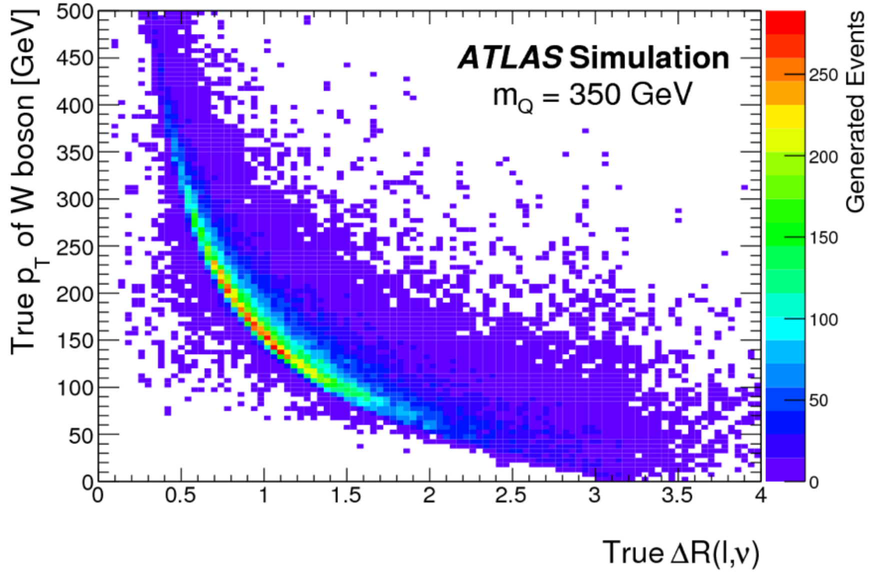
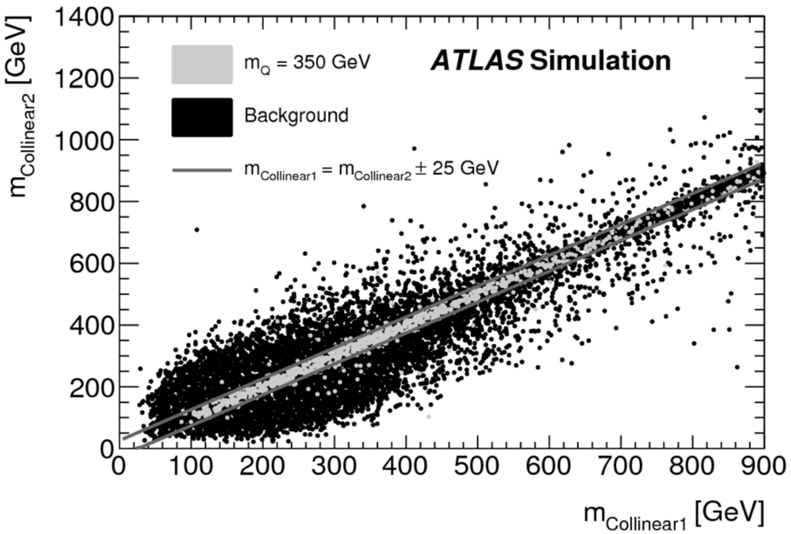
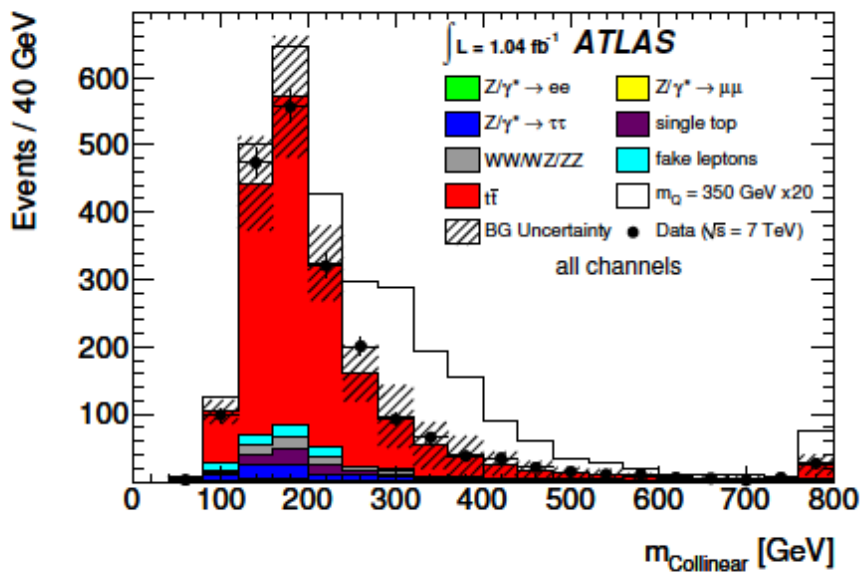
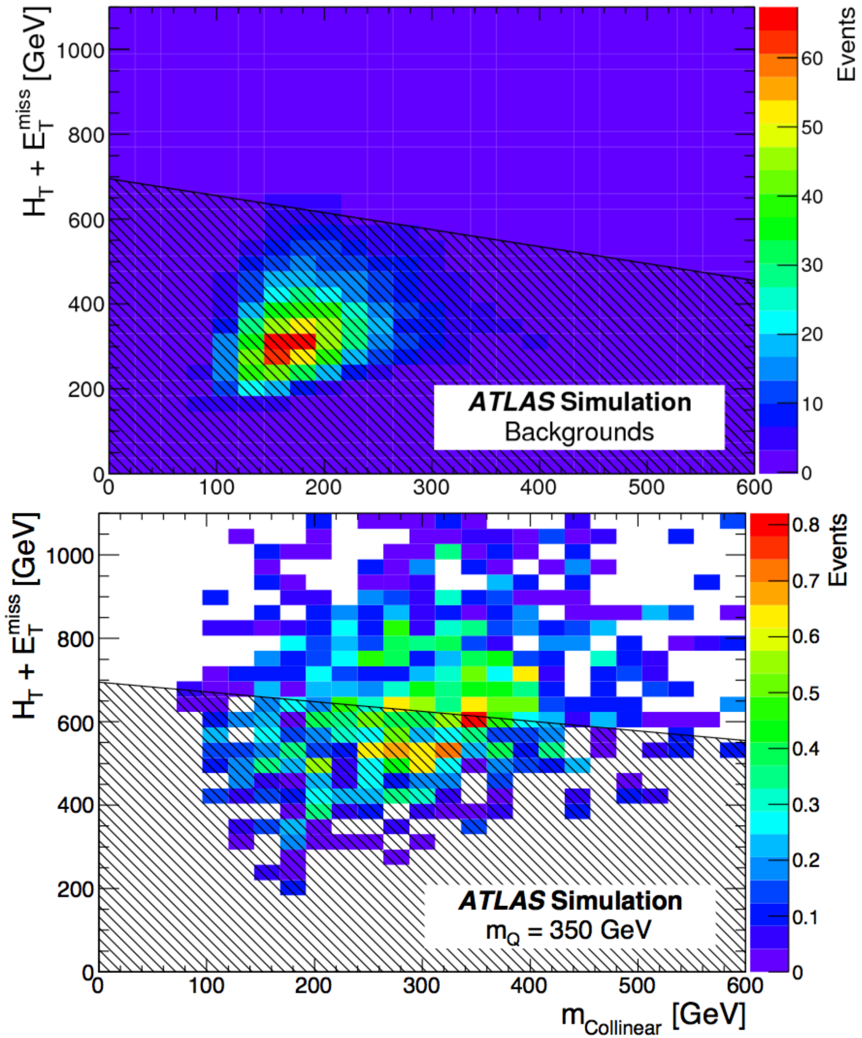


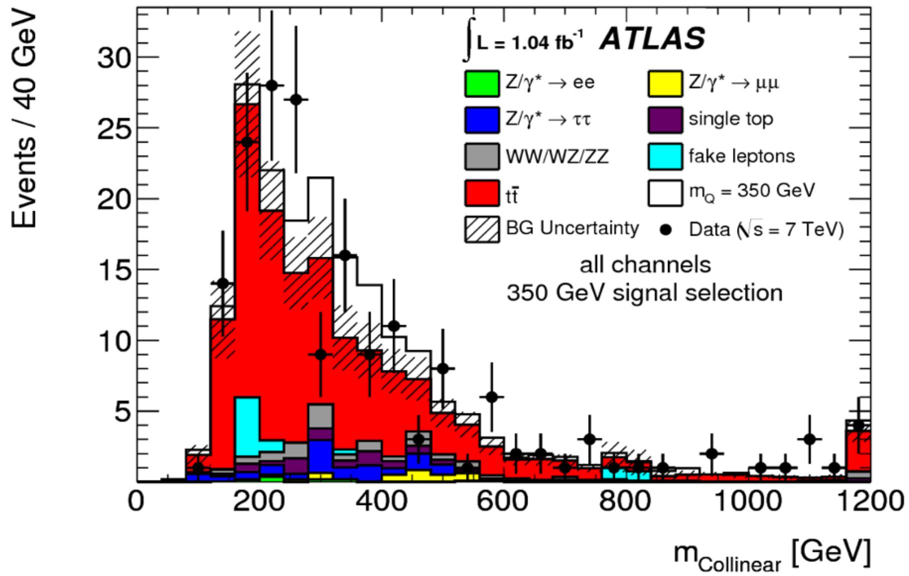




$T\bar{T} \rightarrow WqWq$ (OS dilepton+jets)

- Further selection cuts to optimize $S/\sqrt{(S+B)}$:
  - On plane $H_T + E_T^{miss}$ vs m_{coll}
  - On leading jet p_T and E_T^{miss}





m_Q (GeV)	Expected Background	Expected Signal	Observed Data
300	300^{+40}_{-40}	95^{+14}_{-12}	315
350	148^{+22}_{-18}	35^{+5}_{-4}	180
400	75^{+11}_{-10}	$17.1^{+2.5}_{-2.1}$	89
450	49^{+8}_{-6}	$8.4^{+1.2}_{-1.0}$	57
500	30^{+5}_{-4}	$4.4^{+0.6}_{-0.5}$	36

Data in good agreement with background expectation

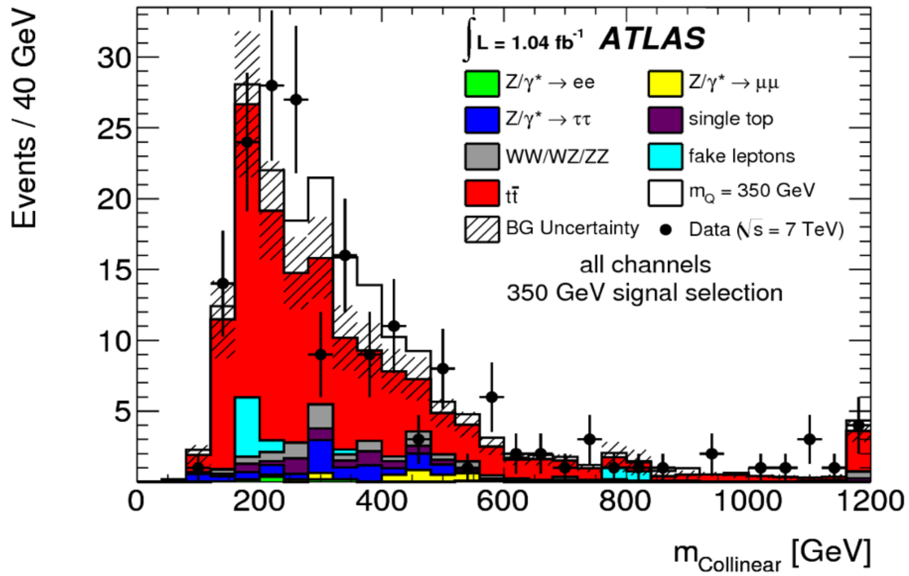
$T\bar{T} \rightarrow WqWq$ (OS dilepton+jets)

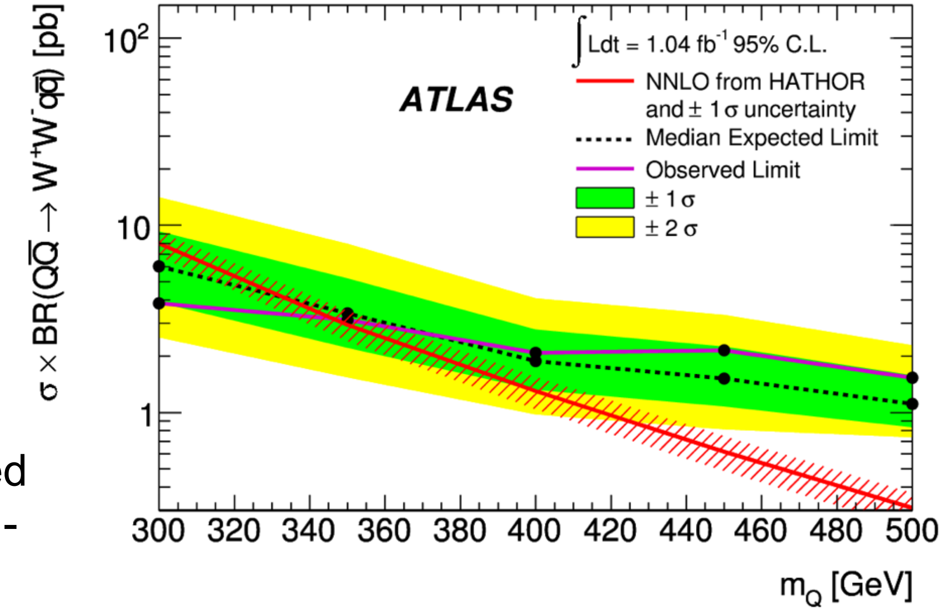
- Further selection cuts to optimize $S/\sqrt{(S+B)}$:
  - On plane $H_T + E_T^{miss}$ vs m_{coll}
  - On leading jet p_T and E_T^{miss}

- Main systematics:
  - Jet energy scale
  - $t\bar{t}$ modeling: ISR/FSR

- Hypothesis testing: CL_s method via MCLimit, no profiling of systematic uncertainties.
- **Limit at 95% C.L.:**
  $m_T > 350$ GeV (>335 GeV expected)
  Limits applicable to $T \rightarrow W^+ q$ (q=d,s,b), $B \rightarrow W^- q$ (q=u,c) and $Y \rightarrow W^- b$.

- B-tagging requirement would give improved sensitivity at the expense of greater model-dependence.





$T\bar{T} \rightarrow tA_0 tA_0$ ($t\bar{t}+E_T^{miss}$)

1 fb^{-1}

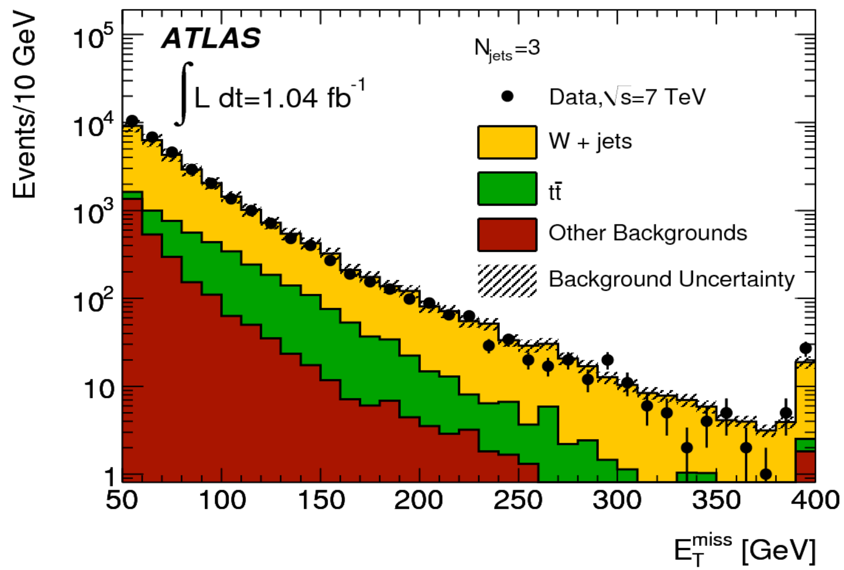
PRL 108, 041805 (2012)

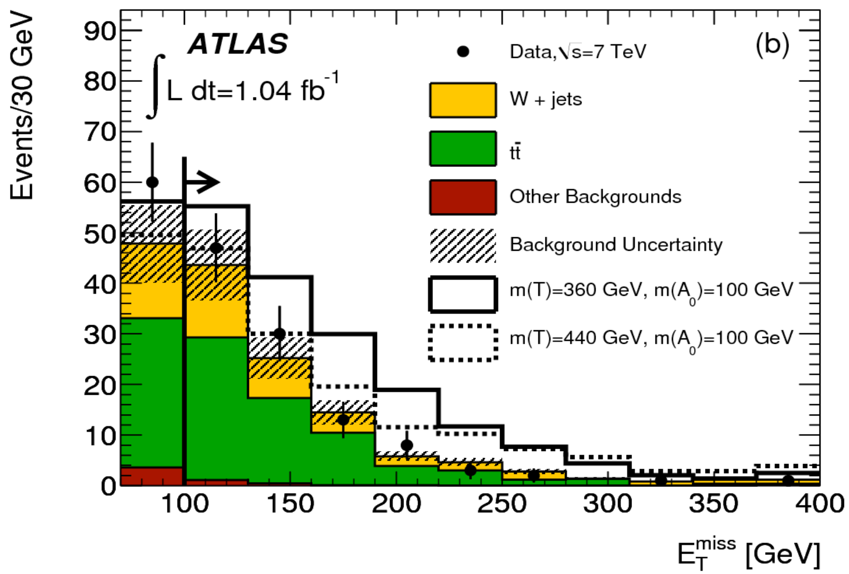
- Signature: l + E_T^{miss} + ≥4 jets (l=e,μ)

- Event selection:
  - =1 e/μ, p_T(e)>25 GeV, p_T(μ)>20 GeV
    2nd lepton/isolated track veto
  - E_T^{miss}>100 GeV
  - M_T(W)>150 GeV
  - ≥4 jets with p_T>25 GeV, |η|<2.5

- Background: dominated by dileptonic $t\bar{t}$ (modeled with MC@NLO), followed by single-lepton $t\bar{t}$ and W+jets (calibrated to data in low M_T(W) region).

- Strategy:
  - Loose 2nd lepton veto to suppress dominant dileptonic $t\bar{t}$ background.
  - High E_t^{miss} and M_T(W) to suppress single-lepton $t\bar{t}$ and W+jets.
  - Cut-and-count analysis.





$T\bar{T} \rightarrow tA_0tA_0$ ($t\bar{t}+E_T^{miss}$)

- Observable: total yield after selection.
- Dominant systematic uncertainties:
  - Jet energy scale
  - 2^{nd} lepton veto in dileptonic $t\bar{t}$
  - Single-lepton backgrounds at high $M_T(W)$
- Hypothesis testing: Bayesian method using MCLimit.
- **Limit at 95% C.L.:**

  m_T>420 GeV (for m_{A0}=10 GeV)

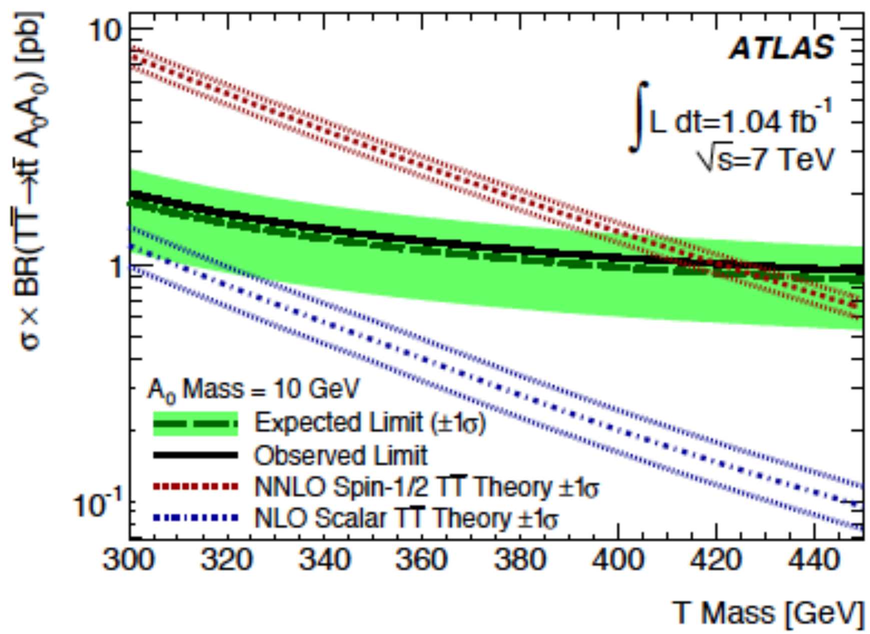
  m_T>370 GeV (for m_{A0}=140 GeV)

  No sensitivity yet for scalar models (~x6 lower σ).

  Search could be applied to $T\bar{T} \rightarrow WbZt$, $ZtZ\bar{t}$ (w/ $Z \rightarrow \nu\nu$) or $T\bar{T} \rightarrow Wbht$, $ht h\bar{t}$ ($h \rightarrow$ invisible).

Data in good agreement with background expectation

Source	Number of events
Dilepton $t\bar{t}$	62 ± 15
Single-lepton $t\bar{t}/W$+jets	33.1 ± 3.8
Multi-jet	1.2 ± 1.2
Single top	3.5 ± 0.8
Z+jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105



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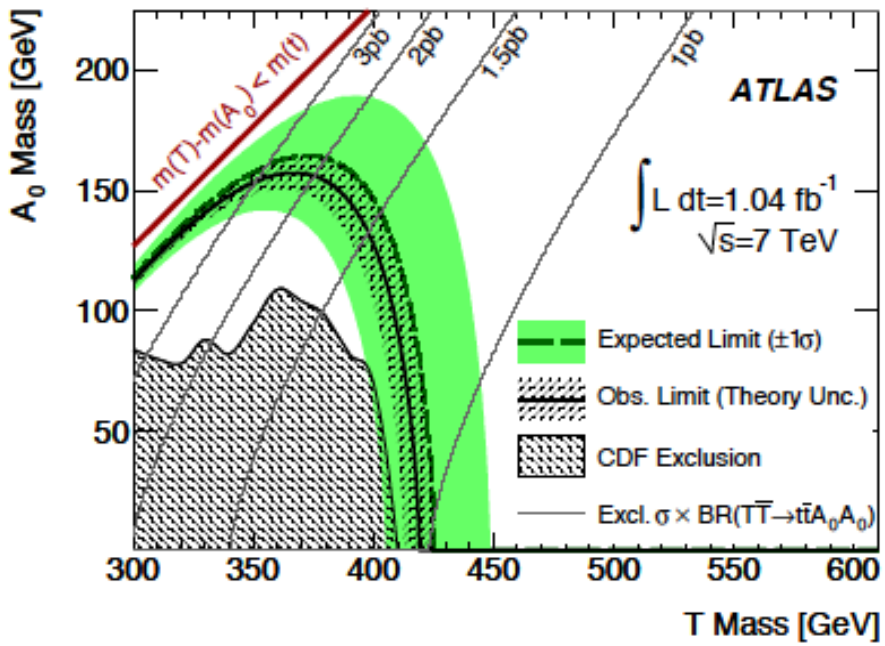
  m_T>370 GeV (for m_{A0}=140 GeV)
  No sensitivity yet for scalar models (~x6 lower σ).

Search could be applied to $T\bar{T} \rightarrow WbZt$, $ZtZ\bar{t}$ (w/ $Z \rightarrow \nu\nu$) or $T\bar{T} \rightarrow Wbht$, $hth\bar{t}$ ($h \rightarrow$ invisible).

Data in good agreement with background expectation

Source	Number of events
Dilepton $t\bar{t}$	62 ± 15
Single-lepton $t\bar{t}/W$+jets	33.1 ± 3.8
Multi-jet	1.2 ± 1.2
Single top	3.5 ± 0.8
Z+jets	0.9 ± 0.3
Dibosons	0.9 ± 0.2
Total	101 ± 16
Data	105



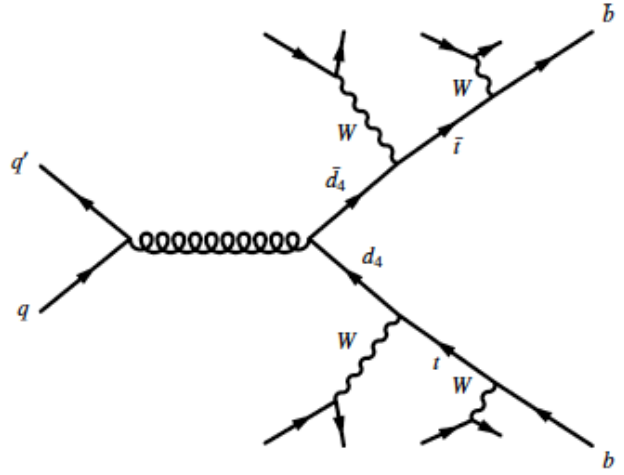
Down-type quarks

$B\bar{B}\rightarrow WtWt$ (lepton+jets)

1 fb^{-1}

arXiv:1202.6540

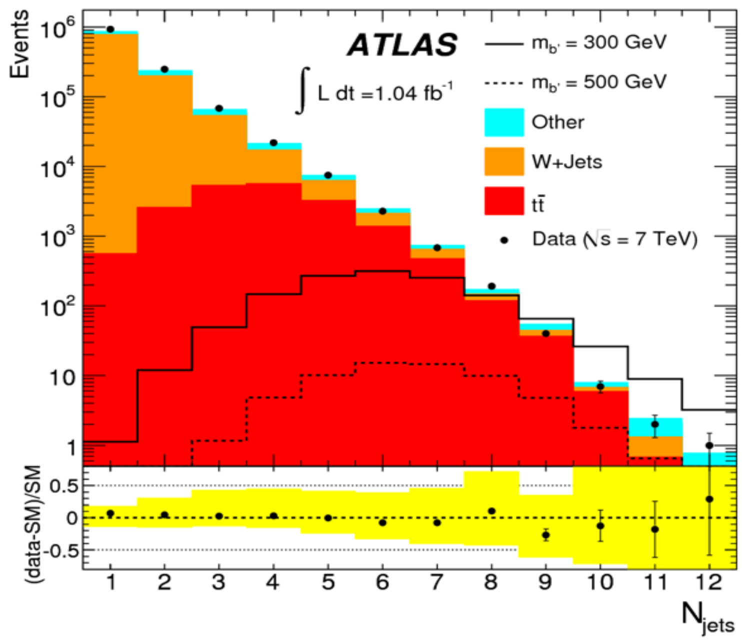
- Signature: l + E_T^{miss} + ≥6 jets (l=e,μ)
- Event selection:
  - =1 e/μ, $p_T(e)$>25 GeV, $p_T(\mu)$>20 GeV
  - e(μ)+jets: E_T^{miss}>35(20) GeV
  - E_T^{miss}+$M_T(W)$>60 GeV
  - ≥6 jets with p_T>25 GeV, |η|<2.5



- Background: dominated by $t\bar{t}$+jets (modeled with ALPGEN up to 3 explicit partons).

  W+jets next most important background.

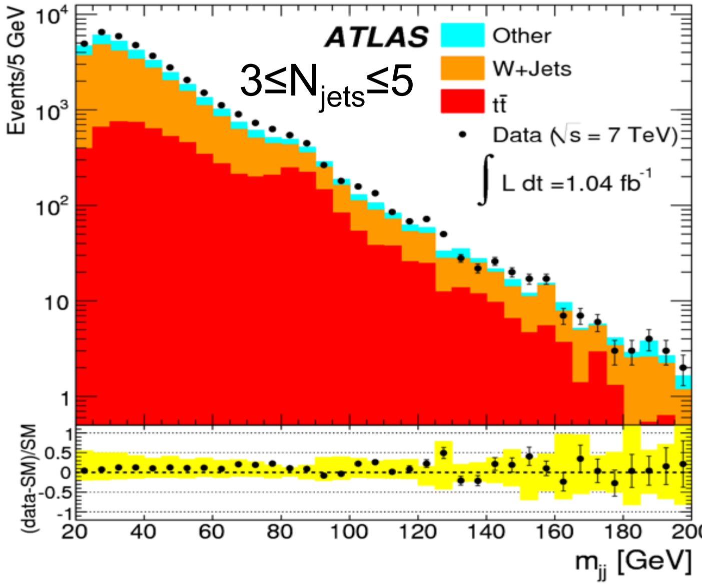
- Strategy:
  - High jet multiplicity requirement to suppress background.
  - Identify high-p_T $W\rightarrow q\bar{q}'$ bosons via invariant mass of nearby jets.

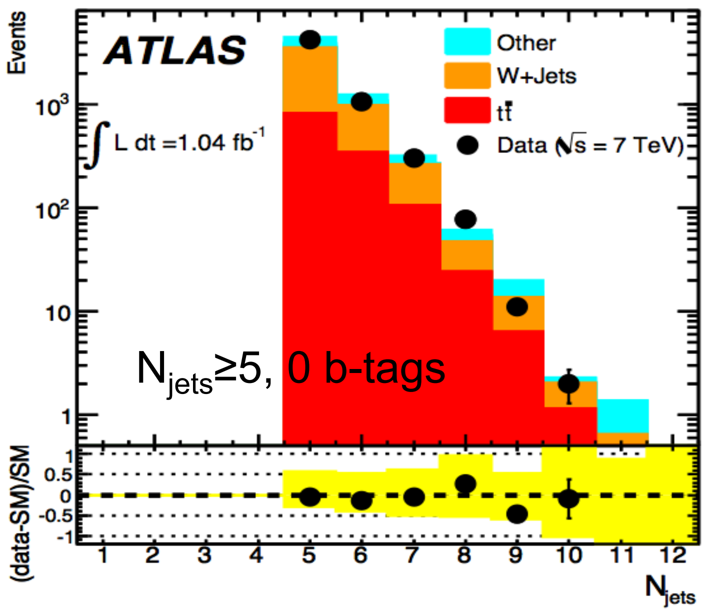


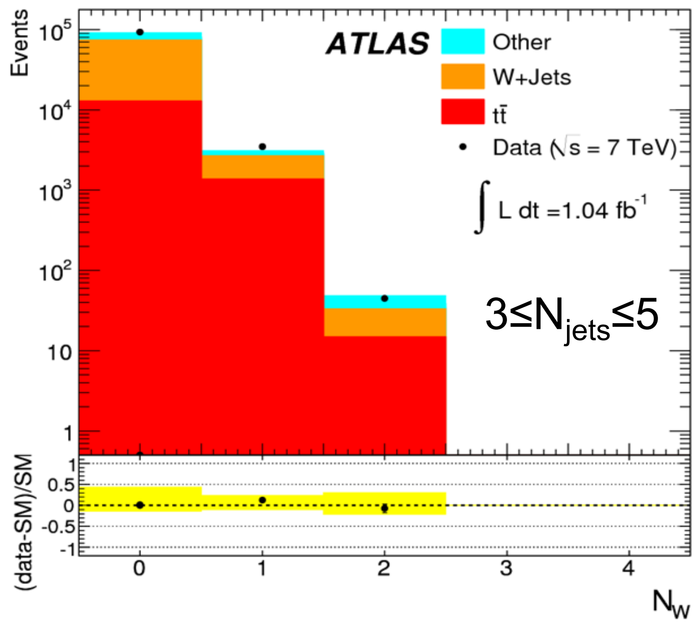
$B\bar{B} \rightarrow WtWt$ (lepton+jets)

- Hadronic W boson identification:
  - Consider jet pairs with $\Delta R(j,j)<1.0$.
  - Count number of such jet pairs with invariant mass in 70-100 GeV range (N_W).
  - ➔ ~80% efficient for $W \rightarrow jj$ decays with $p_T(W)>250$ GeV.

- Background modeling validated in several signal-depleted control samples.







$B\bar{B} \rightarrow WtWt$ (lepton+jets)

- Observable: distribution of number of hadronic W boson candidates (0,1,≥2) in 3 different N_{jet} bins (6, 7, ≥8).

- Dominant systematic uncertainties:
  - W+jets normalization
  - $t\bar{t}$ modeling: ISR/FSR,
  - Jet energy scale (*)

    (*) Not profiled

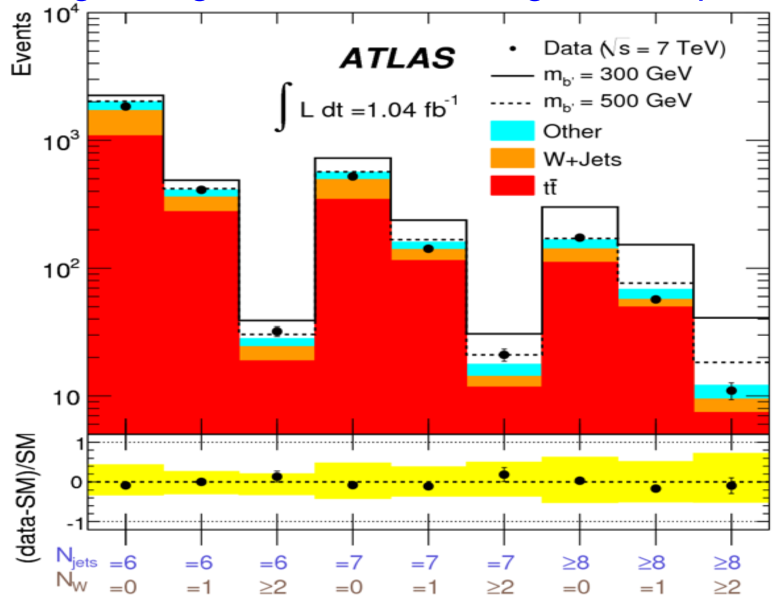
- Hypothesis testing: CL_s method via MCLimit, profiling of (some) systematic uncertainties.

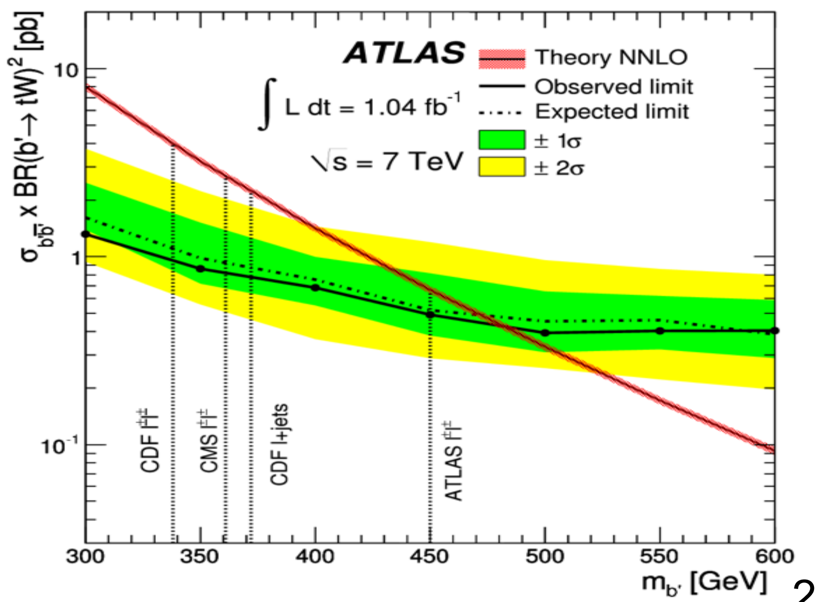
- **Limit at 95% C.L.:**

  m_B>480 GeV (>470 GeV expected)

  Limits applicable to $B \rightarrow W^- t$ (Q=-1/3) and $X \rightarrow W^+ t$ (Q=+5/3).

Data in good agreement with background expectation



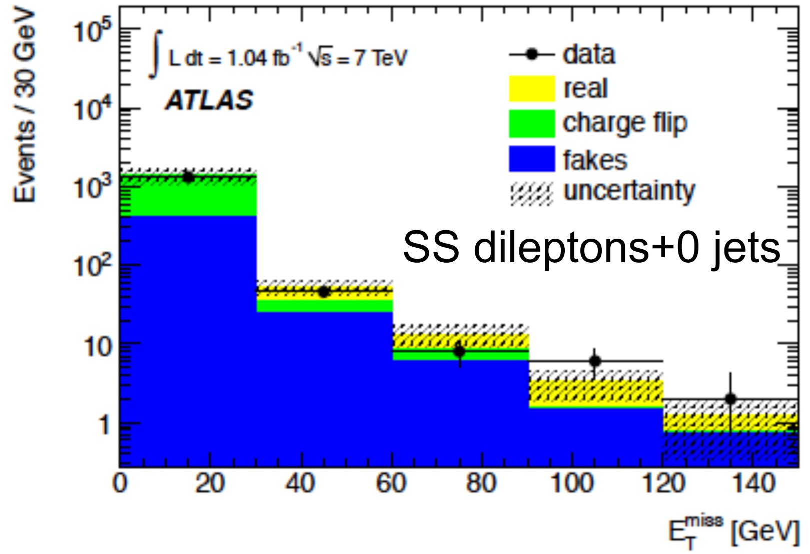


$B\bar{B} \rightarrow WtWt$ (SS dilepton+jets)

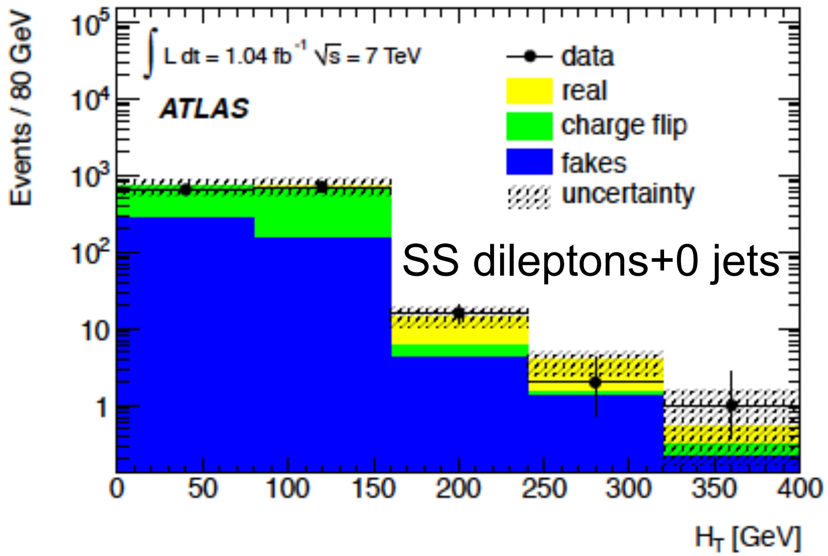
1 fb^{-1}

arXiv:1202.5520 [hep-ex]

- Signature: $l^{\pm}l'^{\pm}$ + E_T^{miss} + ≥2 jets ($l,l'=e,\mu$)
- Event pre-selection:
  - ≥2 same-sign leptons: ee, $\mu\mu$ or eμ
  - $p_T(e)>25$ GeV, $p_T(\mu)>20$ GeV
  - ≥2 jets with $p_T>20$ GeV, $|\eta|<2.5$
  - ee/$\mu\mu$ only: $M_{ll}>15$GeV, $|M_{ll}-M_Z|>10$ GeV
  - $E_T^{miss}>40$ GeV
  - $H_T>350$ GeV



- Backgrounds:
  - Physics: dibosons (real leptons)
  - Instrumental: $t\bar{t}$+jets, W+jets (one fake lepton or charge flip)
    ➔ estimated from data



- Strategy:
  - Low-background search, main issue is accurate instrumental bckg estimation.
  - Cut-and-count analysis.

$B\bar{B} \rightarrow WtWt$ (SS dilepton+jets)

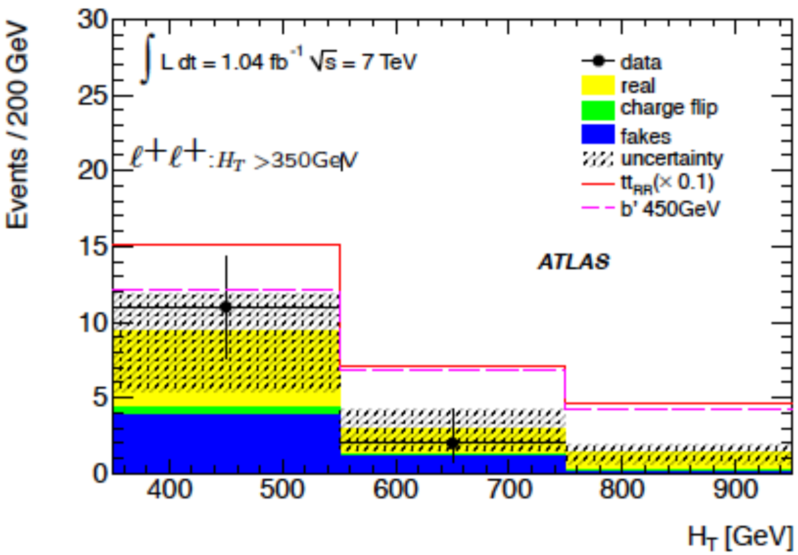
- Observable: total yield after selection.
  Analyze separately different lepton channels as well as charge configurations (l^+l^+ background > l^-l^- background).

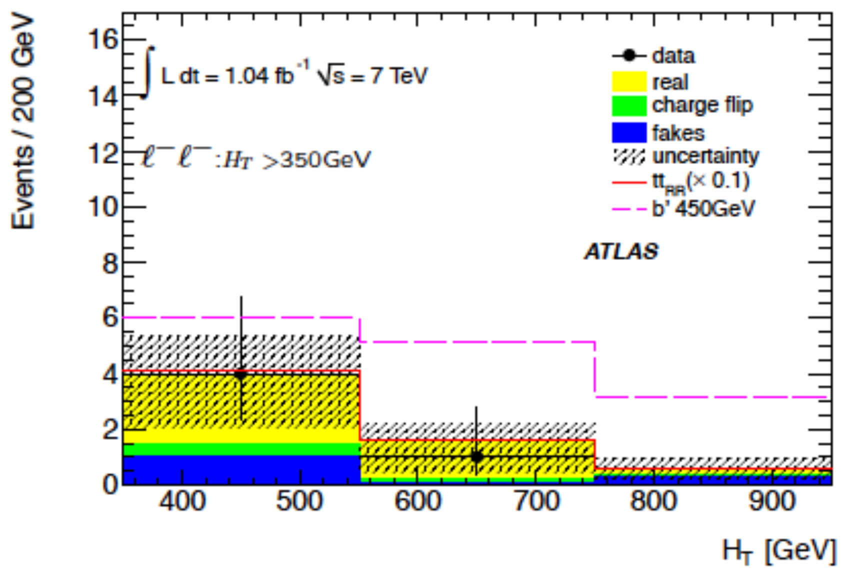
- Dominant systematic uncertainties:
  - Jet energy scale and resolution
  - Fake lepton background
  - Charge flip background

Data in good agreement with background expectation

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
Fake	$0.8 \pm 0.6^{+0.2}_{-0.4}$	$1.0 \pm 0.3^{+0.6}_{-0.4}$	$3.3 \pm 1.1^{+1.6}_{-1.4}$
Charge flip	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0.0}$	$0.4 \pm 0.1^{+0.3}_{-0.1}$
Real	$1.9 \pm 0^{+0.7}_{-1.5}$	$1.6 \pm 0^{+0.7}_{-0.9}$	$4.4 \pm 0^{+1.3}_{-3.1}$
Total	$3.0 \pm 0.6^{+0.8}_{-1.5}$	$2.6 \pm 0.3^{+0.9}_{-1.1}$	$8.1 \pm 1.1^{+2.2}_{-3.4}$
Data	2	1	10
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.7 \pm 0 \pm 0.4$	$5.0 \pm 0 \pm 0.7$

	e^-e^-	$\mu^-\mu^-$	$e^-\mu^-$
Fake	$0.2 \pm 0.3 \pm 0.1$	$0.7 \pm 0.3^{+0.6}_{-0.3}$	$0.5 \pm 0.2^{+0.7}_{-0.3}$
Charge flip	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0}$	$0.3 \pm 0.1^{+0.2}_{-0.1}$
Real	$0.8 \pm 0^{+0.3}_{-0.6}$	$1.0 \pm 0^{+0.4}_{-0.6}$	$2.3 \pm 0^{+0.8}_{-1.9}$
Total	$1.4 \pm 0.3^{+0.4}_{-0.6}$	$1.7 \pm 0.3 \pm 0.7$	$3.1 \pm 0.2^{+1.1}_{-1.9}$
Data	1	2	2
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.1 \pm 0 \pm 0.3$	$4.3 \pm 0 \pm 0.5$





$B\bar{B}$→WtWt (SS dilepton+jets)

- Observable: total yield after selection.
  Analyze separately different lepton channels as well as charge configurations (l^+l^+ background > l^-l^- background).

- Dominant systematic uncertainties:
  - Jet energy scale and resolution
  - Fake lepton background
  - Charge flip background

- Hypothesis testing: CL_s method via Collie, no profiling of systematic uncertainties.

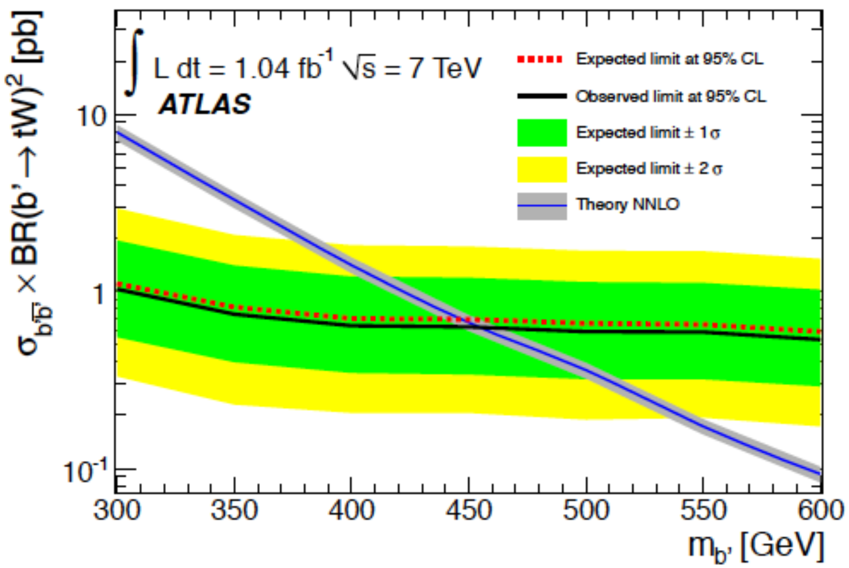
- **Limit at 95% C.L.:**
  m_B>450 GeV (>450 GeV expected)
  Limits applicable to B→W⁻t (Q=-1/3) and X→W⁺t (Q=+5/3).

➔ comparable sensitivity to lepton+jets!

Data in good agreement with background expectation

	e^+e^+	$\mu^+\mu^+$	$e^+\mu^+$
Fake	$0.8 \pm 0.6^{+0.2}_{-0.4}$	$1.0 \pm 0.3^{+0.6}_{-0.4}$	$3.3 \pm 1.1^{+1.6}_{-1.4}$
Charge flip	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0.0}$	$0.4 \pm 0.1^{+0.3}_{-0.1}$
Real	$1.9 \pm 0^{+0.7}_{-1.5}$	$1.6 \pm 0^{+0.7}_{-0.9}$	$4.4 \pm 0^{+1.3}_{-3.1}$
Total	$3.0 \pm 0.6^{+0.8}_{-1.5}$	$2.6 \pm 0.3^{+0.9}_{-1.1}$	$8.1 \pm 1.1^{+2.2}_{-3.4}$
Data	2	1	10
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.7 \pm 0 \pm 0.4$	$5.0 \pm 0 \pm 0.7$

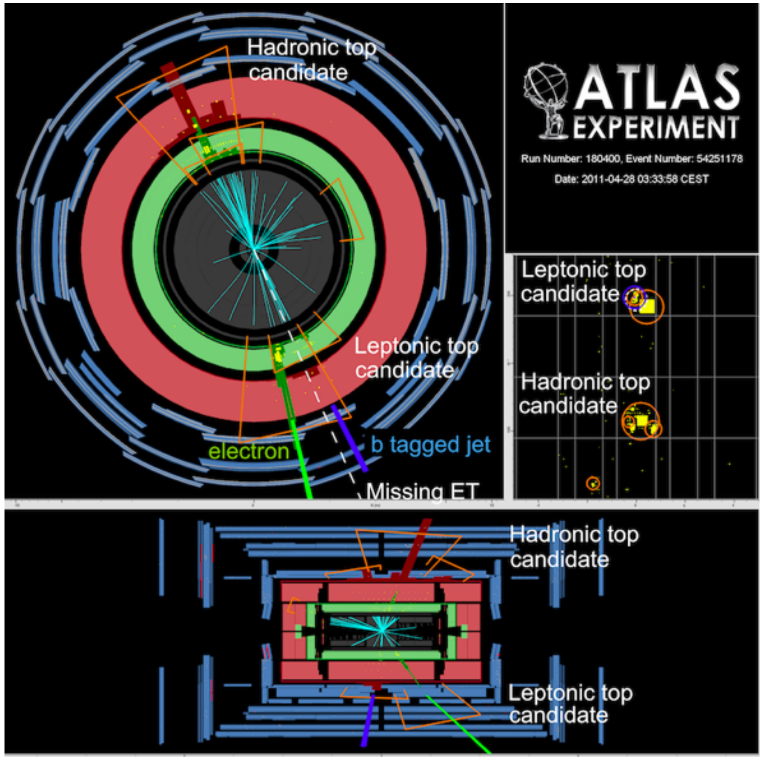
	e^-e^-	$\mu^-\mu^-$	$e^-\mu^-$
Fake	$0.2 \pm 0.3 \pm 0.1$	$0.7 \pm 0.3^{+0.6}_{-0.3}$	$0.5 \pm 0.2^{+0.7}_{-0.3}$
Charge flip	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0}$	$0.3 \pm 0.1^{+0.2}_{-0.1}$
Real	$0.8 \pm 0^{+0.3}_{-0.6}$	$1.0 \pm 0^{+0.4}_{-0.6}$	$2.3 \pm 0^{+0.8}_{-1.9}$
Total	$1.4 \pm 0.3^{+0.4}_{-0.6}$	$1.7 \pm 0.3 \pm 0.7$	$3.1 \pm 0.2^{+1.1}_{-1.9}$
Data	1	2	2
b' 450 GeV	$1.8 \pm 0 \pm 0.3$	$2.1 \pm 0 \pm 0.3$	$4.3 \pm 0 \pm 0.5$

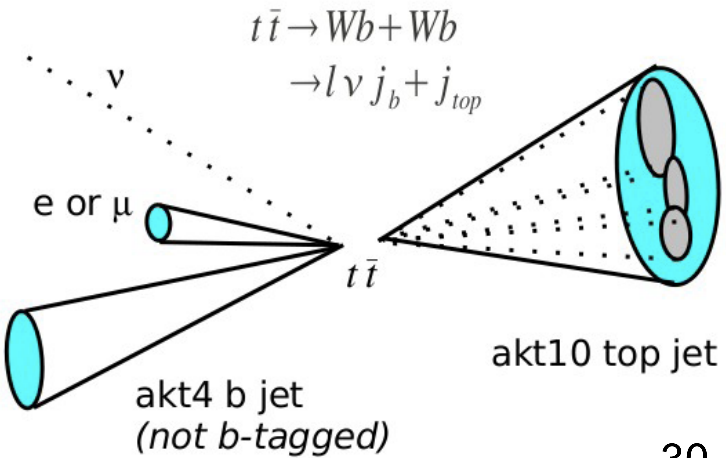


$t\bar{t}$ Resonances

$t\bar{t}$ Resonances: Introduction

- Many models of New Physics predict $t\bar{t}$ resonances. Current searches focus on two benchmarks:
  - Leptophobic Topcolor Z' as proxy for "narrow" resonances.
  - Randall-Sundrum KK gluon as proxy for "wide" resonances.
- For very massive resonances W boson and even top decay products can be reconstructed as single "fat jet" ("boosted topology").
- Searches presented here correspond to (mostly) "resolved topologies".
  - Similar acceptance to "boosted topologies" beyond ~1 TeV, much higher acceptance for lower masses.
  - Acceptance drops at high mass because of lepton isolation (both types of searches).





$t\bar{t}$ Resonances (lepton+jets)

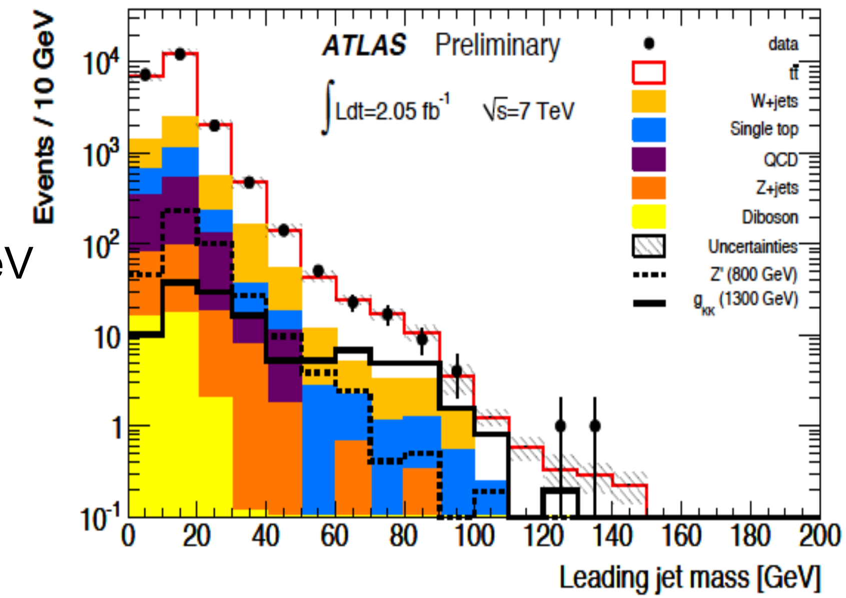
2 fb^{-1}

ATLAS-CONF-2012-029

- Signature: l + E_T^{miss} + ≥4 jets (l=e,μ)
- Event selection:
  - =1 e/μ, p_T(e/μ)>25 GeV
  - e+jets: E_T^{miss}>35 GeV, M_T(W)>25 GeV
  - μ+jets: E_T^{miss}>20 GeV, E_T^{miss}+M_T(W)>60 GeV
  - If one jet has mass m_{jet}>60 GeV:
    - ≥3 jets with p_T>25 GeV, |η|<2.5

    else

    - ≥4 jets with p_T>25 GeV, |η|<2.5
  - Leading jet p_T>60 GeV
  - ≥1 b-tagged jets
- Background: dominated by $t\bar{t}$+jets (modeled with MC@NLO).

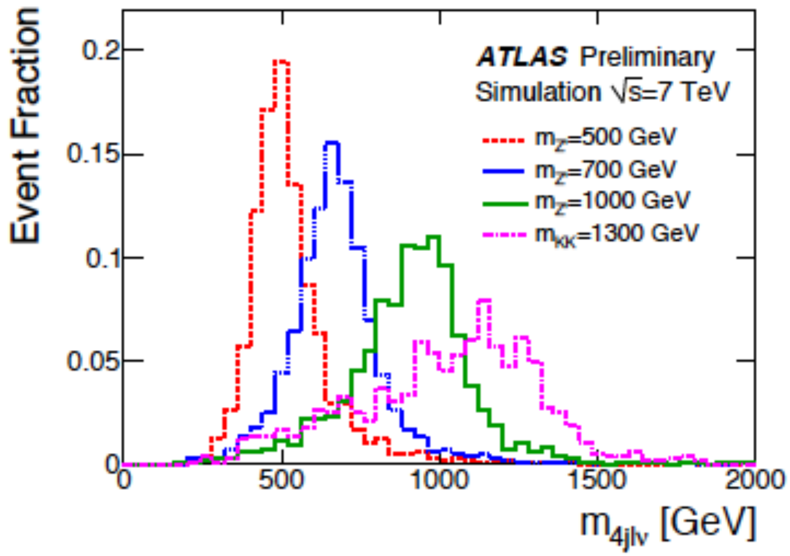


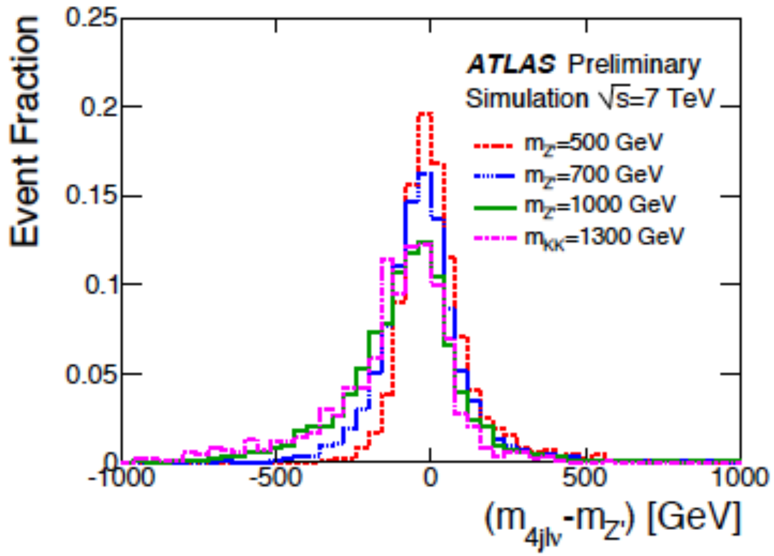
	Electron channel	Muon channel
$t\bar{t}$	7830 ± 750	10000 ± 960
Single top	470 ± 50	570 ± 60
W plus jets	1120 ± 540	1450 ± 700
Z plus jets	85 ± 40	90 ± 45
Diboson	18 ± 1	18 ± 1
Multijet	350 ± 170	470 ± 240
Total expected	9860 ± 940	12600 ± 1210
Data observed	9622	12706
Z', m = 800 GeV	200	224
g_{KK}, m = 1300 GeV	59	65

Data in good agreement with background expectation

$t\bar{t}$ Resonances (lepton+jets)

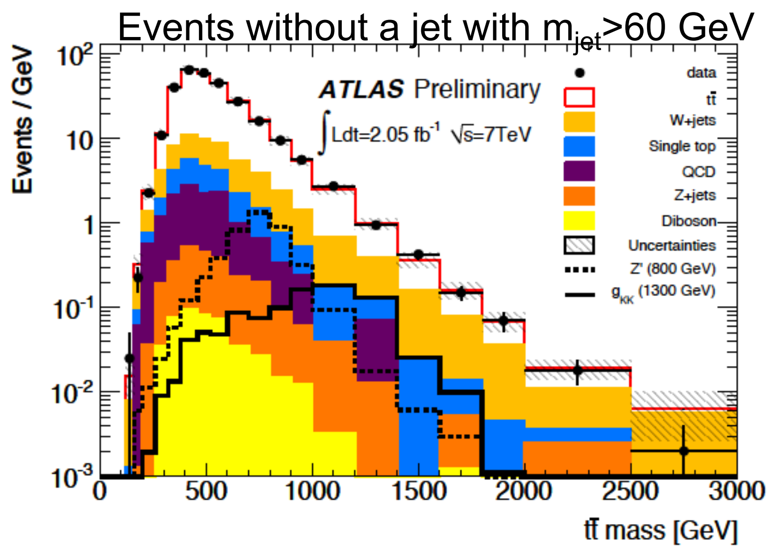
- $t\bar{t}$ Mass reconstruction:
  - $p_z(\nu)$ via W mass constraint (quadratic eq):
    - If no real solution, E_T^{miss} adjusted to get null discriminant
    - If two solutions, pick smallest $|p_z(\nu)|$
  - Events without a jet with m_{jet}>60 GeV
    ➔ no assignment of jets to top or anti-top:
    - 3 or 4 hardest jets added to leptonic W
    - Jets compatible with ISR (far from other objects) excluded
  - Events with a jet with m_{jet}>60 GeV:
    - Form hadronic top quark candidate by combining massive jet with closest jet
    - Form leptonic top quark candidate by combining leptonic W with closest jet

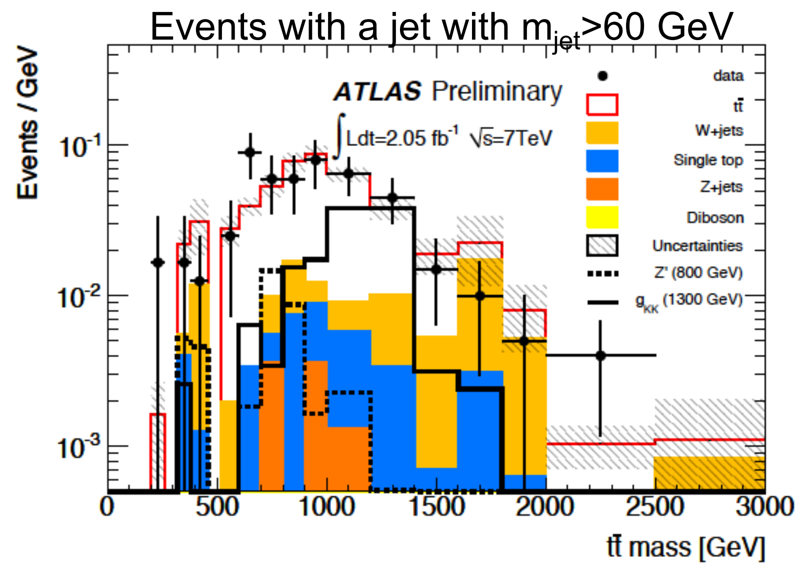




- Dominant shape systematic uncertainties:
  - B-tagging efficiency (~16-19%)
  - Jet energy scale (3-4%)
  - ISR/FSR (8.5%)

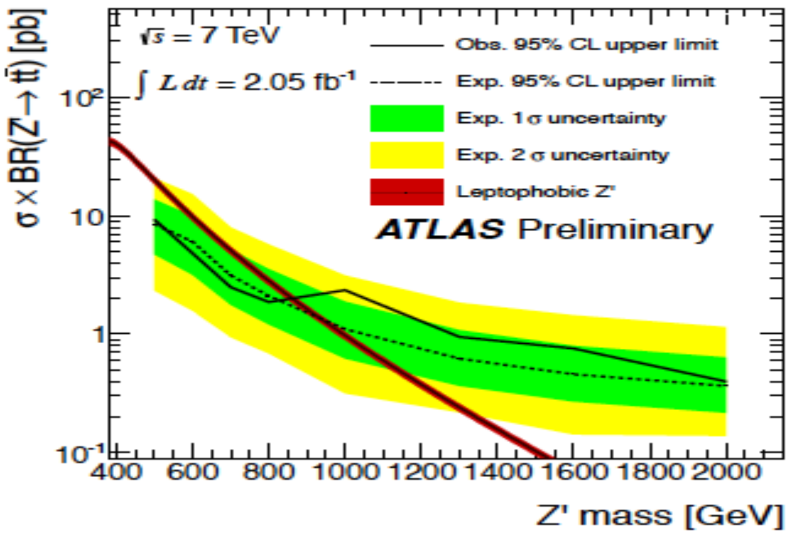
$t\bar{t}$ Resonances (lepton+jets)





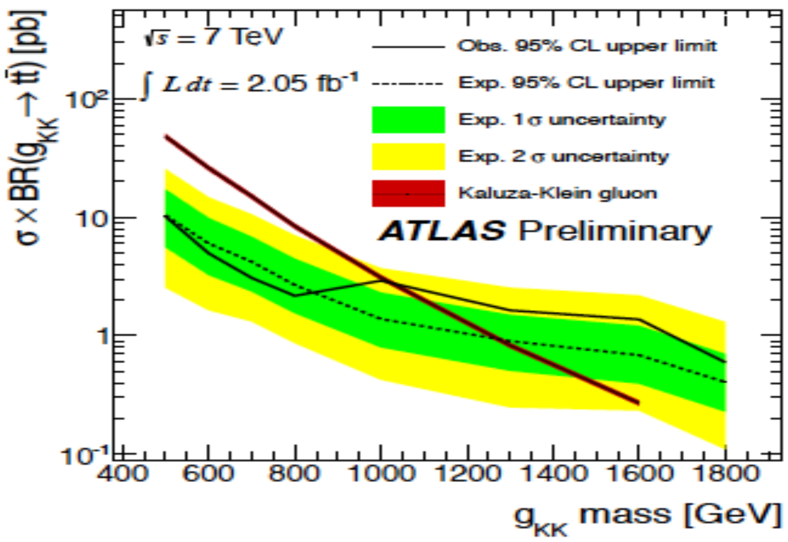
- Hypothesis testing: Bayesian method

Leptophobic Z' (Γ/M=1.2%)



500<$m_{Z'}$<860 GeV excluded @ 95% C.L.

KK Gluon



500<m_{gKK}<1025 GeV excluded @ 95% C.L.

$t\bar{t}$ Resonances (dilepton+jets)

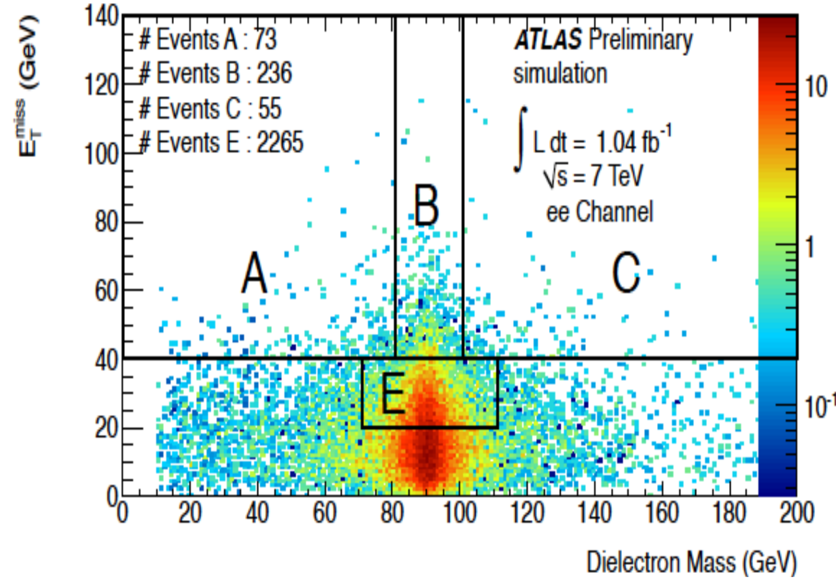
$1\ fb^{-1}$

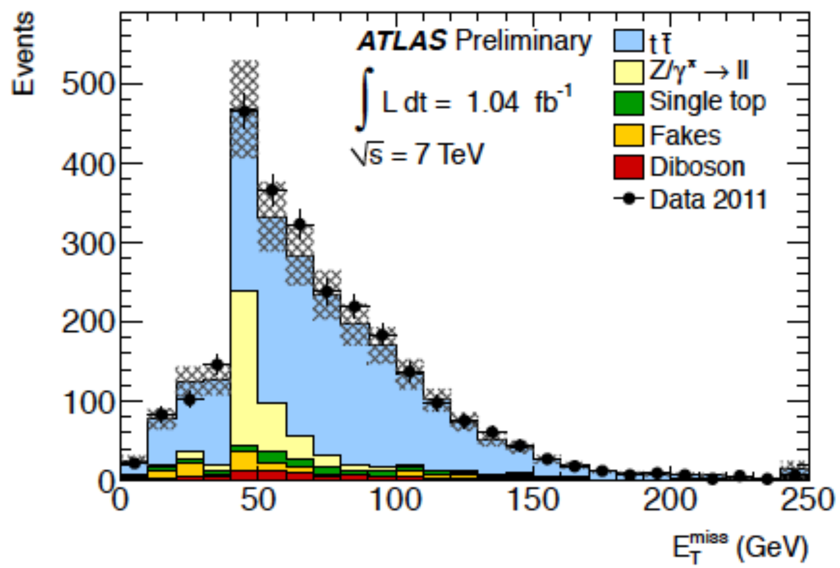
ATLAS-CONF-2011-123

- Signature: $l^{+}l'^{-}$ + E_T^{miss} + ≥2 jets ($l,l'=e,\mu$)

- Event pre-selection:
  - =2 opposite-sign leptons: ee, $\mu\mu$ or eμ
  - $p_T(e)>25$ GeV, $p_T(\mu)>20$ GeV
  - ≥2 jets with $p_T>25$ GeV, $|\eta|<2.5$
  - eμ-only: $H_T>130$ GeV
  - ee/$\mu\mu$-only:
    - $M_{ll}>15$GeV, $|M_{ll}-M_Z|>10$ GeV
    - $E_t^{miss}>40$ GeV

- Background:
  - Dominated by $t\bar{t}$+jets (modeled with MC@NLO).
  - Z+jets background normalized using data-driven techniques.





$t\bar{t}$ Resonances (dilepton+jets)

- tt mass reconstruction not possible due to missing neutrinos.
  ➔ Use $H_T + E_T^{miss}$ as observable instead.

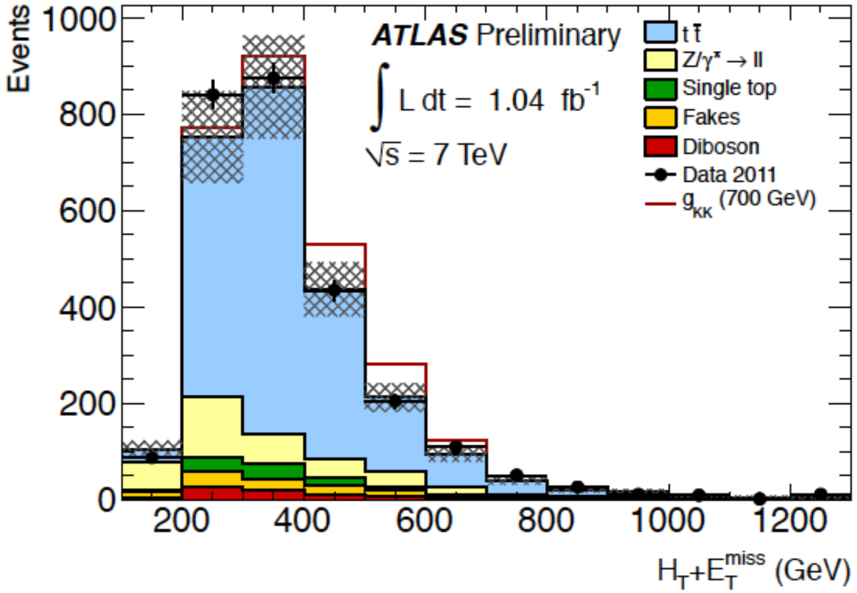
- Dominant shape syst. uncertainties:
  - Jet energy scale
  - $t\bar{t}$ modeling: ISR/FSR, NLO generator, fragmentation model

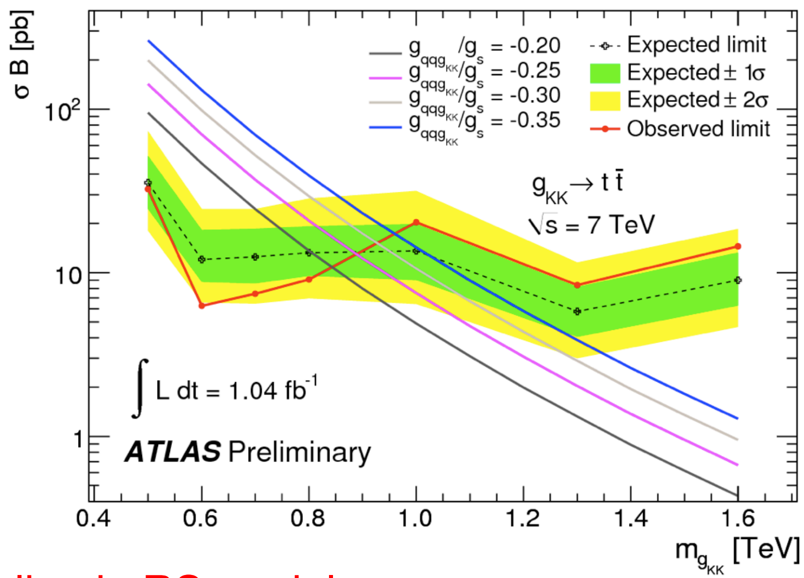
- Hypothesis testing: Bayesian method

- **Limits at 95% C.L.:**

	Mass Limit (TeV)	
$g_{qqg_{KK}}/g_s$	Expected	Observed
-0.20	0.80	0.84
-0.25	0.88	0.88
-0.30	0.95	0.92
-0.35	1.02	0.96

Default coupling in RS model





Summary and Conclusions

- Wide range of searches for pair-production of exotic heavy quarks ongoing in ATLAS, reaching sensitivities of ~400-500 GeV with 1 fb^{-1} of data at $\sqrt{s}$= 7 TeV.

  Still, much ground remains to be covered, both in terms of additional search channels as well as combination and interpretation of results.

- Searches for $t\bar{t}$ resonances in (mostly) “resolved topologies” reaching sensitivities to masses up to 1.0 TeV with ≤2 fb^{-1} of data at $\sqrt{s}$= 7 TeV.

  Entering era of “boosted top” analyses.

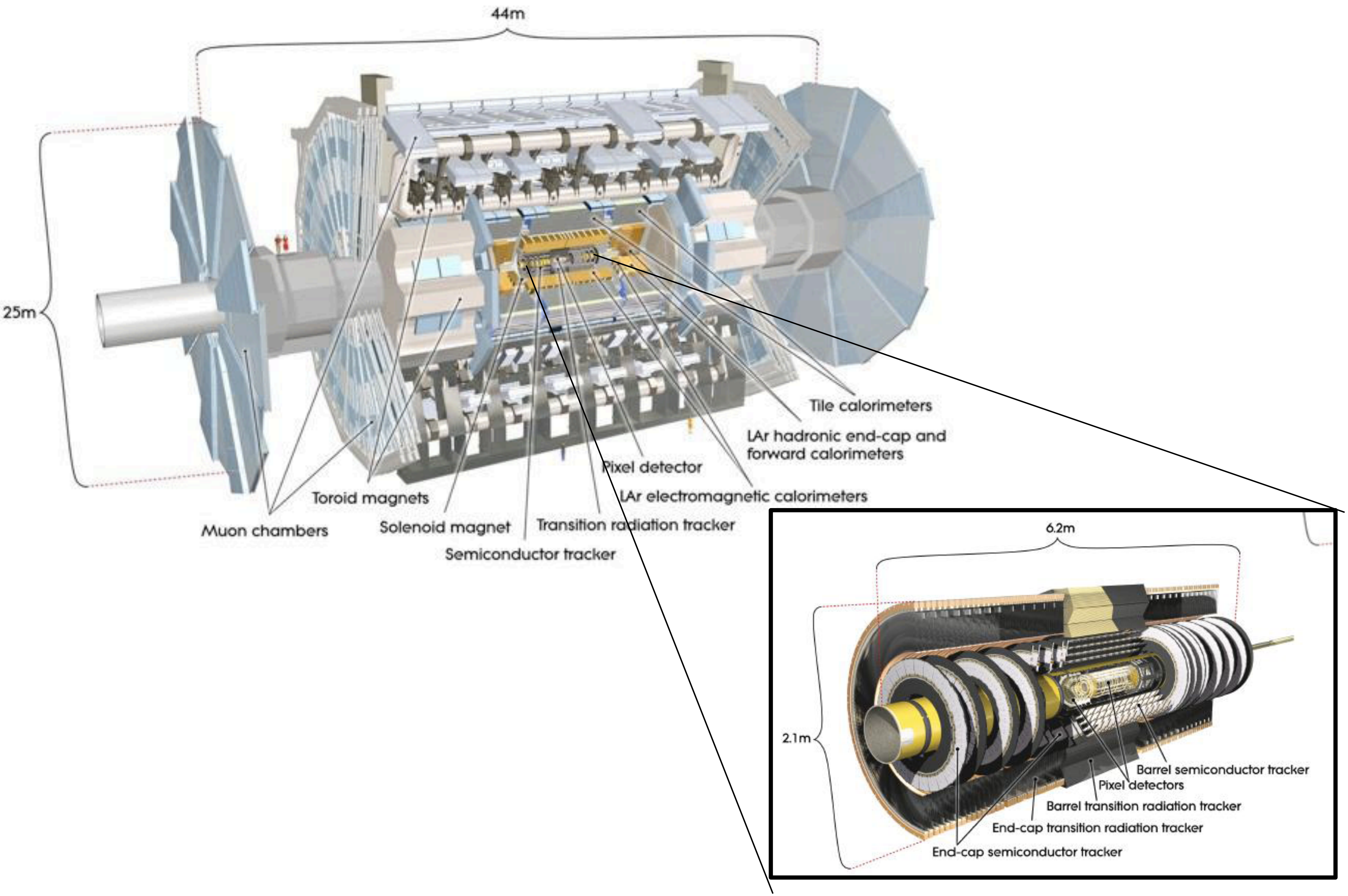
- Very exciting prospects ahead!
  - Up to x5 increase in statistics from analyses using full 2011 dataset.

    Also re-optimized/broader scope analyses and new channels!
  - At least 15 fb^{-1} at $\sqrt{s}$=8 TeV by the end of 2012.

Stay Tuned!

Backup

ATLAS Detector



What's Missing

- Let's consider the "more generic" scenario of vector-like quarks and take a look at what signatures/scenarios are being probed by the existing dedicated searches.

		T_S	B_S	TB_d	XT_d	BY_d
4 leptons	4l (2Z)	TT	BB	TT,BB	TT	BB
	4l (1Z)	TT	BB	TT,BB	TT	BB
	4l (0Z)	TT	BB	TT,BB	TT,XX	BB
3 leptons	3l (1Z)	TT	BB	TT,BB	TT	
	3l (0Z)	TT	BB	TT,BB	TT,XX	
OS dileptons	l^+l^- (1Z)	TT	BB	TT,BB	TT	BB
	l^+l^- (0Z)	TT	BB	TT,BB	TT,XX	BB,YY
SS dileptons	$l^\pm l^\pm$		BB	BB	XX	

- Of course, some of them are more challenging or powerful than others…

What's Missing

- Let's consider the "more generic" scenario of vector-like quarks and take a look at what signatures/scenarios are being probed by the existing dedicated searches.

	T_S	B_S	TB_d	XT_d	BY_d
4l (2Z)	TT	BB	TT,BB	TT	BB
4l (1Z)	TT	BB	TT,BB	TT	BB
4l (0Z)	TT	BB	TT,BB	TT,XX	BB
3l (1Z)	TT	BB	TT,BB	TT	
3l (0Z)	TT	BB	TT,BB	TT,XX	
l^+l^- (1Z)	TT	BB	TT,BB	TT	BB
l^+l^- (0Z)	TT	BB	TT,BB	TT,XX	BB,YY
$l^\pm l^\pm$		BB	BB	XX	

4 leptons

3 leptons

OS dileptons

SS dileptons

Existing analyses

- Obvious omission: trilepton searches have sensitivity comparable to the most powerful channels and often allow to identify the new quark.

What's Missing

- Let's consider the "more generic" scenario of vector-like quarks and take a look at what signatures/scenarios are being probed by the existing dedicated searches.

		T_S	B_S	TB_d	XT_d	BY_d
lepton+jets	$l^{\pm}$ ($1V_{had}$,2b)	TT		TT	TT	YY
	$l^{\pm}$ ($>1V_{had}$,2b)		BB	BB	XX	
	$l^{\pm}$ (4b)	TT	BB	TT,BB	TT	
	$l^{\pm}$ (6b)	TT		TT	TT	
multi-b-jets	Multijet (4b)	TT	BB	TT,BB	TT	BB
	Multijet (6b)	TT	BB	TT,BB	TT	BB

- Of course, some of them are more challenging or powerful than others…

What's Missing

- Let's consider the "more generic" scenario of vector-like quarks and take a look at what signatures/scenarios are being probed by the existing dedicated searches.

		T_S	B_S	TB_d	XT_d	BY_d
lepton+jets	$l^{\pm}$ ($1V_{had}$,2b)	TT		TT	TT	YY
	$l^{\pm}$ ($\geq 1V_{had}$,2b)		BB	BB	XX	
	$l^{\pm}$ (4b)	TT	BB	TT,BB	TT	
	$l^{\pm}$ (6b)	TT		TT	TT	
multi-b-jets	Multijet (4b)	TT	BB	TT,BB	TT	
	Multijet (6b)	TT	BB	TT,BB	TT	BB

Existing analyses

- Obvious omissions:
  - Searches targeting FCNC decays: Q→Hq, Zq, needed to maximize sensitivity to a VLQ (pure CC decays are ≤25% of total decay rate) and to establish unambiguously VLQ nature of any discovered heavy quark.
  - Multijet/multi-b searches: challenging but very interesting in their own!

Producing "Model-Indep" Results?

- For the most part our searches so far have been, not only model-dependent, but often in the context of unrealistic models, e.g.:
  - Assume BR=1 for particular heavy quark decay modes.
  - Neglect additional signals that would be present in any realistic model (e.g. in 4^{th} gen models there are two quarks, not one which in principle can contribute in the signal region depending on the final event selection and observable used).

- Given the large number of possible signatures to explore, it's hard to imagine we can in general design "model-indep" searches for VLQs, but we can sometimes alleviate some of the model assumptions by carefully designing the search.

  A good example: *QQ→Zb+X*
  - *Leptonic Z allows to focus on Q decay modes containing Z bosons with small contamination from other decay modes.*
  - *Reconstructed Zb system "enough" to suppress backgrounds and build a sensitive observable so don't really need to look at the "rest of the event".*

  Designing event selections which are very inefficient for most but a subset of decay modes may also be a way to have a "cleaner" interpretation (e.g. SS dileptons mainly sensitive to B/X quarks, l+6 b-tag searches only sensitive to T→tH, etc).

- In the case of 4^{th} gen models, it's possible to relax assumptions on the V_{Qq} elements (e.g. by not using b-tagging requirements or producing limits on BR vs m_Q plane).

Towards a Combined Search

- This seems a better idea than performing “inclusive searches” since:
  - The result is going to be model-dependent anyway.
  - Can make use of existing analysis efforts as inputs.
  - Will at the end have better sensitivity.

  But not so quick….

- Since multiple analyses would have to be combined there is a higher degree of coordination required:
  - Ensure orthogonality of selections
  - Ensure all searches use the same set of signals
  - The combination is made difficult unless all searches use similar background predictions (e.g. ttbar MC@NLO vs ALPGEN), assign consistent set of systematics, provide inputs in same format, etc.

- But this may well be a worthy effort as the discovery of exotic heavy quarks may require to combine multiple channels. With or without signals, deriving constraints on model parameter space and/or model discrimination will require the ability to produce such combination.