4th Generation Quarks Searches with the ATLAS Detector

Lorenzo Feligioni
On behalf of the ATLAS Collaboration

ICHEP2012 Melbourne

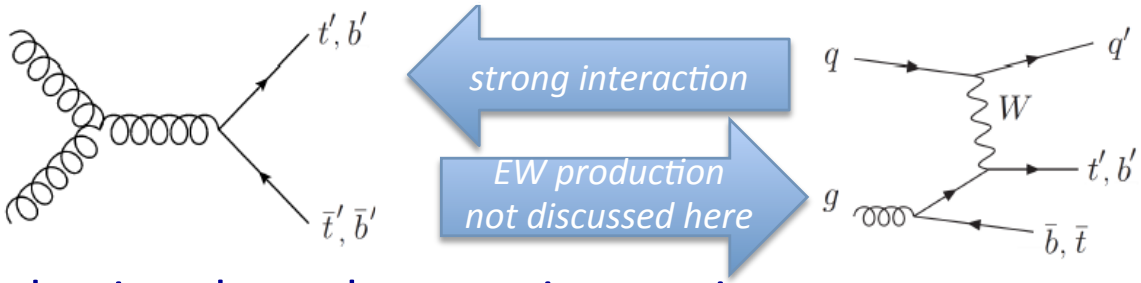
Outline:

- Why 4 generations?
- Phenomenology at the LHC
- Searches at ATLAS
- Conclusions and Outlook

Why a 4th generation?

- 4th generation not excluded by the electroweak precision data.
  - small mass splitting between the 4th generation quarks is preferred: $|m_{t'} - m_{b'}| < m_W$.
- Measurement from LEP: $N_\nu = 2.92 \pm 0.05$
  - but $N(gen) > 3$ if heavy neutrino mass > 0.5 m_Z
- BAU: 4th generation could enhance CP violation
- Many interesting phenomena may occur at the LHC
  - presence of 4th generation affects Higgs production rate and decay modes

Phenomenology at the LHC



- Main production through strong interaction
  - single *t'* production in the *t*-channel suppressed if 3-4 CKM mixing element is negligible
- Decay channel
  - *t'*: assuming $|m_{t'} - m_{b'}| < m_W$, *t'* predominantly decays in W boson and down type quarks
  - *b'*: if $m_{b'} > m_t + m_W$ *b'* decay mostly as $b' \rightarrow Wt \rightarrow WWb$
- Analysis presented here:
  - $t't' \rightarrow WbWb \rightarrow bbqq'lv$
  - $b'b' \rightarrow WtWt \rightarrow bbWWWW \rightarrow bbqq'qq'qq'lv$
  - $QQ \rightarrow WqWq \rightarrow qqlvlv$ [where *Q* denotes a generic heavy quark]
- 4^{th} generation quarks can also originated more exotic signatures
  - See talk on Vector-Like-Quarks by M. Davies

t't'→WbWb→bbqq'l ν

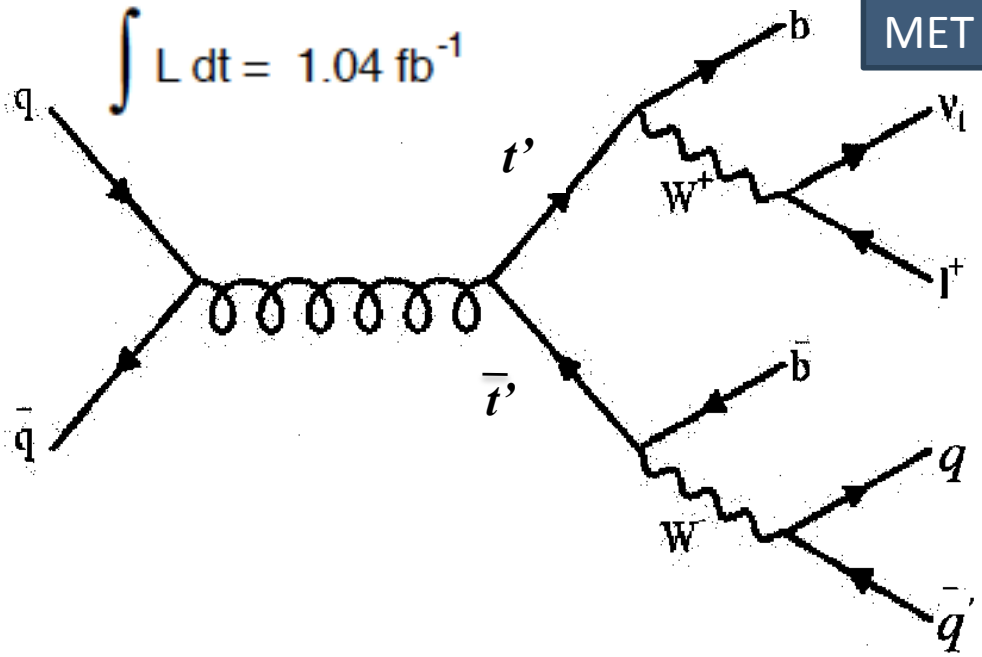
pre-selection

arXiv:1202.3076

At least one jet is *b*-tagged
$\varepsilon(b)$~70%, rejection~100

Neutrino detected as missing transverse energy

MET > 35 GeV [electron channel]
MET > 20 GeV [muon channel]



Exactly one lepton in the event
Muon: p_T > 20 GeV, |η| < 2.5
Electron: p_T > 25 GeV, |η|<2.47

Jet multiplicity
At least 3 jets p_T > 25, |η| <2.5
At least one jet p_T > 60

MET + m_T > 60 GeV, where m_T is transverse mass lepton and MET

$t't' \rightarrow WbWb \rightarrow bbqq'l\nu$

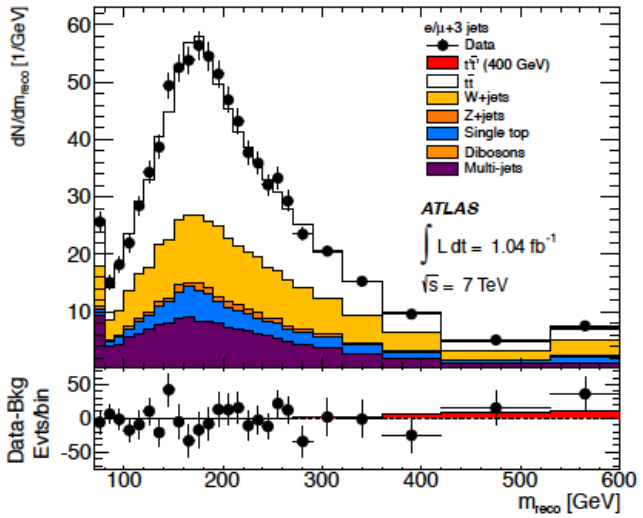
Agreement after pre-selection

	e+3 jets	μ+3 jets	e+$\geq$4 jets	μ+$\geq$4 jets
$t\bar{t}$	2320 ± 460	3000 ± 630	4470 ± 920	5900 ± 1200
W+jets	1440 ± 790	2200 ± 1200	830 ± 580	1160 ± 790
Z+jets	92 ± 53	118 ± 62	86 ± 56	83 ± 46
Single top	382 ± 68	554 ± 94	262 ± 70	325 ± 79
Dibosons	28 ± 7	37 ± 11	12 ± 5	17 ± 5
Multi-jet	520 ± 520	550 ± 550	320 ± 320	340 ± 340
Total prediction	4800 ± 1000	6500 ± 1500	6000 ± 1100	7800 ± 1400
Data	4533	6421	6145	8149
$t't'(400\ \mathrm{GeV})$	20.0 ± 3.3	21.0 ± 3.6	102.0 ± 10.5	98.1 ± 11.1

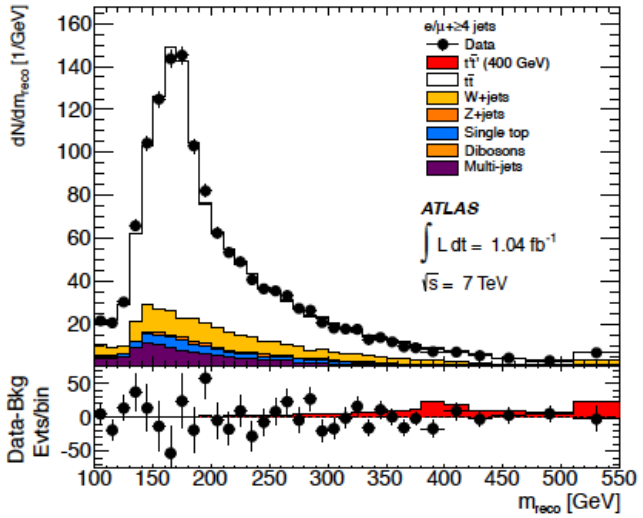
- Signal is modeled using PYTHIA 6.421
  - masses generated between 200 GeV to 600 GeV in steps of 50 GeV
- Main Background after pre-selection
  - top quark: estimated using simulated events with MC@NLO
  - W+Jets shape from simulation ALPGEN v2.13 and normalization from data
  - multi-jet events estimated from data using matrix method (normalization and shape)

$t't' \rightarrow WbWb \rightarrow bbqq'l\nu$ Discriminant

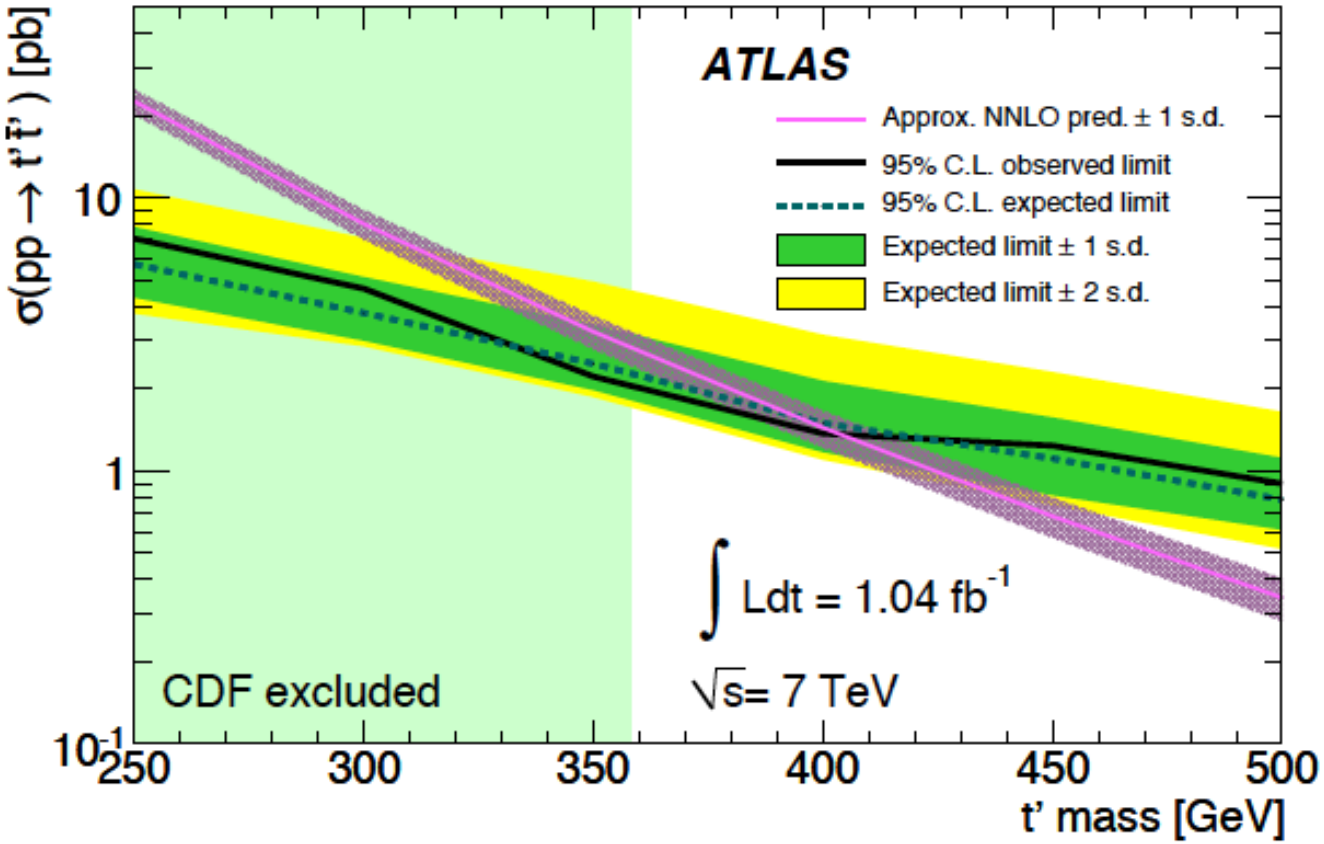
- Reconstructed heavy quark mass m_{reco} is the discriminating variable
  - in the case of events with >=4 jets combination minimizing a kinematic fit is taken
- Systematic uncertainties:
  - large contribution from *tt*
    - theoretical cross section, fragmentation models
  - W+jets systematics derived in 2 jet bin
    - associated to extrapolation to higher multiplicity and heavy flavor content
  - other major sources are *b*-tagging and QCD multi-jet evaluation
- Profile likelihood
  - per bin signal and background predictions are parameterized using 12 nuisance parameters representing major sources of systematic uncertainties
  - after the fit m_{reco} is shown in the right



(a)



$t't' \rightarrow WbWb \rightarrow bbqq'l\nu$ results



Assuming BR($t' \rightarrow Wb$)=1 observed (expected) 95% CL limit $m_{t'}$>404 (394) GeV

$b'b' \rightarrow ttWW \rightarrow bbqqqqql\nu$

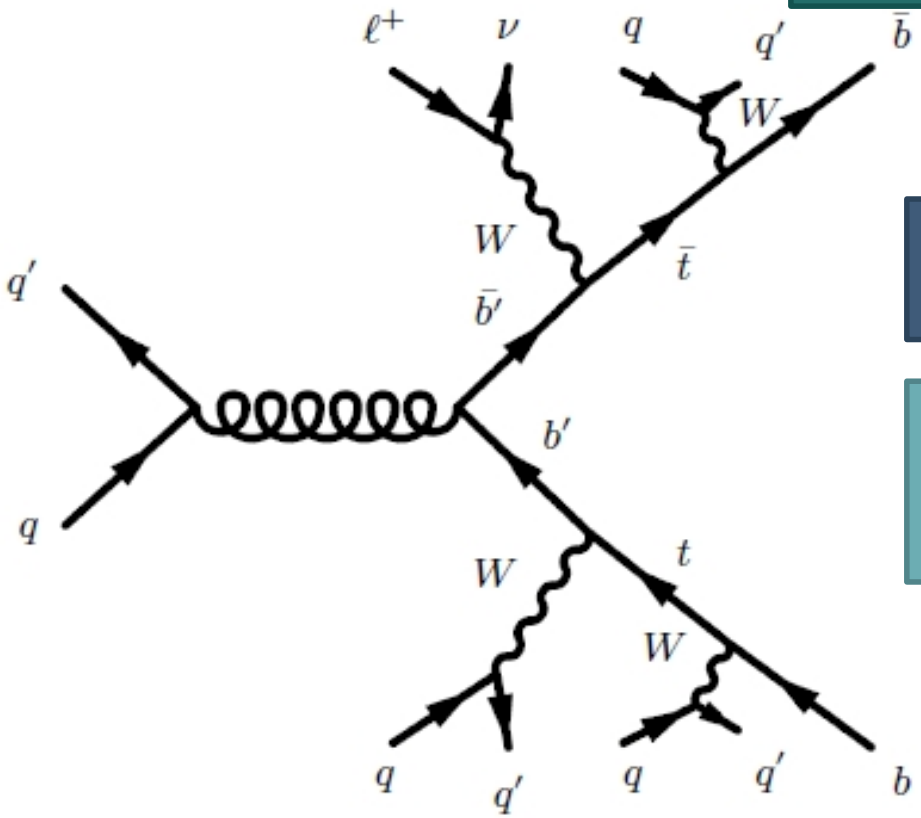
pre-selection

arXiv:1202.6540

Exactly one lepton in the event
Muon: $p_T > 20$ GeV, $|\eta|<2.5$
Electron: $p_T > 25$ GeV, $|\eta|<2.47$

Neutrino detected as missing transverse energy

MET > 35 GeV [electron channel]
MET > 20 GeV [muon channel]



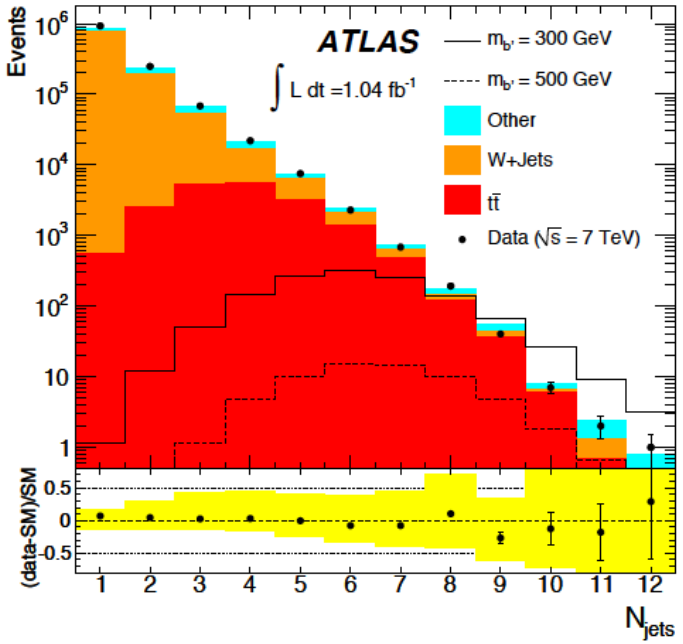
Jet multiplicity
At least 6 jets $p_T > 25$ GeV, $|\eta| < 2.5$

MET + $m_T > 60$ GeV,
where m_T is transverse mass lepton and MET

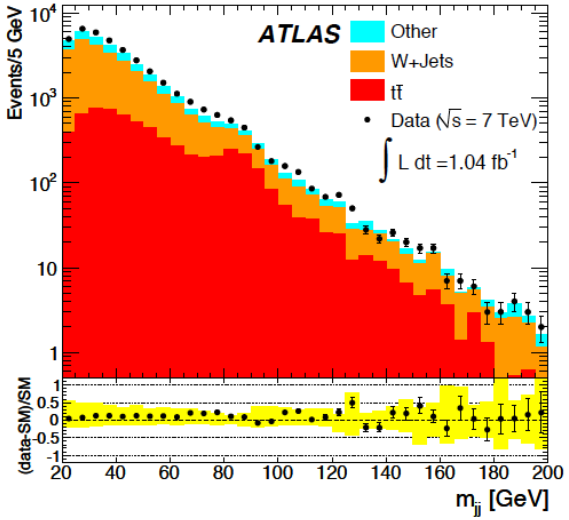
$b'b' \rightarrow ttWW \rightarrow bbqqqqqql\nu$

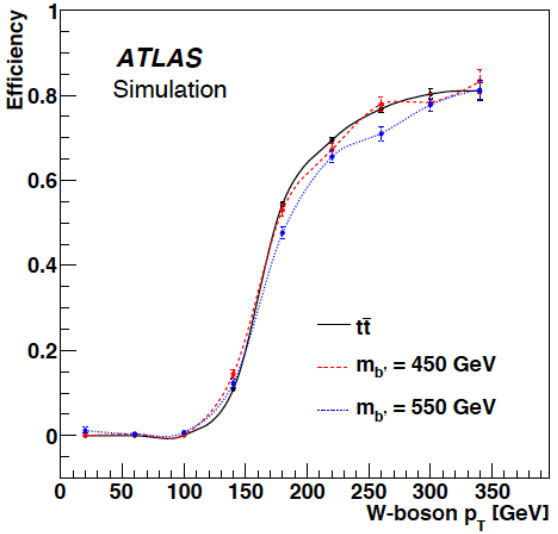
Agreement after pre-selection

- Signal is modeled using PYTHIA 6.421
  - masses generated between 300 to 600 GeV cross section for *b'* production ~3.2 pb at $m_{b'}$=350 GeV and 0.33 pb at 500 GeV
  - signal efficiency of 11.2% and 13.5% for $m_{b'}$ of 350 GeV and 500 GeV respectively
- Main Background after preselection
  - *tt* simulated using ALPGEN
    - rate from data in low jet multiplicity region
  - W+jets shape from simulation ALPGEN v2.13 and normalization from data
  - diboson ALPGEN normalized to NLO calculation
  - *tt*+vector boson production is modeled with MADGRAPH
  - multi-jet events estimated from data using matrix method (normalization and shape)

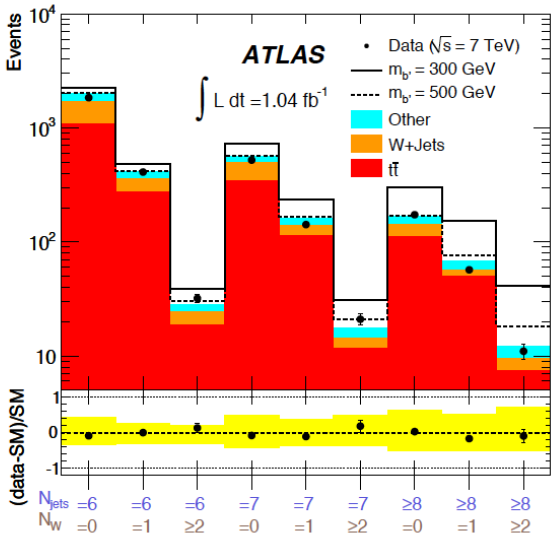


$b'b' \rightarrow tt\,WW \rightarrow bbqqqqqql\nu$ Discriminant



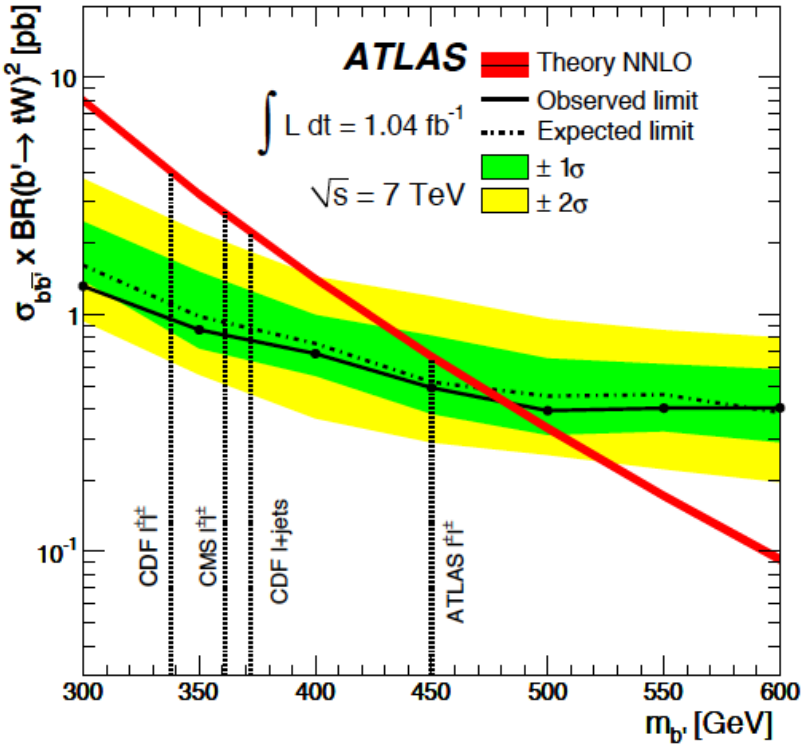


- Events where a *b′* is produced are identified by the large number of hadronic "semi-boosted" *W* bosons
  - medium energy *b′* regime these can be identified by two jets having ΔR < 1.0 and mass compatible with *W* boson
  - goodness of simulation checked on signal depleted samples (low jet multiplicity)
- 9 exclusive bins of different jet and hadronic *W* multiplicity used
- Profile likelihood used to fit signal and background contribution within systematic unc.



b'b'→ttWW→bbqqqqqql ν results

N_{jet}	N_W	Expected background	Observed events	b' 350 GeV	b' 500 GeV
6	0	2060^{+850}_{-750}	1839	80	5
6	1	410^{+104}_{-150}	410	47	8
6	≥ 2	28^{+10}_{-16}	32	7	2
7	0	570^{+320}_{-230}	521	60	4
7	1	166^{+49}_{-68}	142	46	7
7	≥ 2	$17.9^{+6.6}_{-6.8}$	21	11	3
≥ 8	0	170^{+180}_{-70}	173	56	3
≥ 8	1	69^{+33}_{-27}	57	50	8
≥ 8	≥ 2	$12.1^{+8.6}_{-5.2}$	11	22	6



Assuming BR($t' \rightarrow Wb$)=1 observed (expected) 95% CL limit $m_{b'}$>480 (470) GeV

QQ→WWqq→qqlvlv

pre-selection

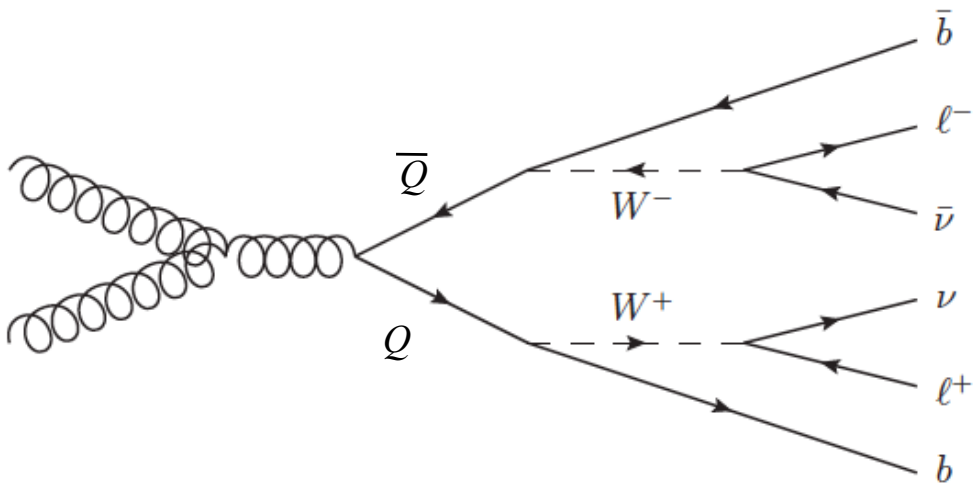
arXiv:1202.3389

Exactly two leptons in the event
Muon: p_T>20 GeV, |η| < 2.5
Electron: p_T > 25 GeV, |η| <2.47

$\int L\,dt = 1.04\ fb^{-1}$

Neutrino detected as missing transverse energy

same flavor events (ee, μμ) MET > 60 GeV
different flavor (eμ) HT > 130 GeV



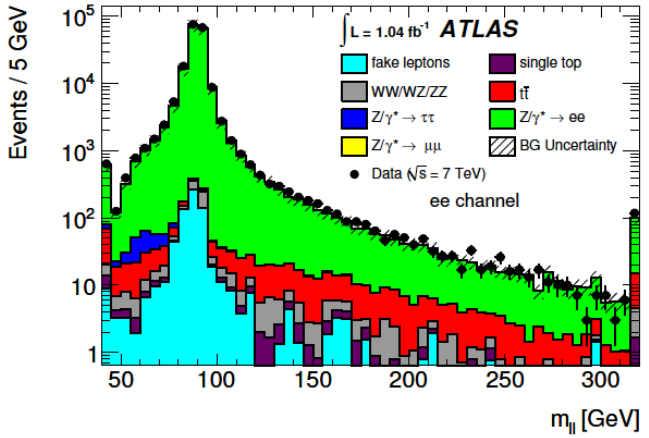
Dilepton invariant mass for same flavor events must be > 15 GeV and outside the Z mass peak 81 GeV to 101 GeV

Jet multiplicity
At least 2 jets p_T> 25 GeV, |η| <2.5

QQ→WWqq→qqlvlv

Agreement after pre-selection

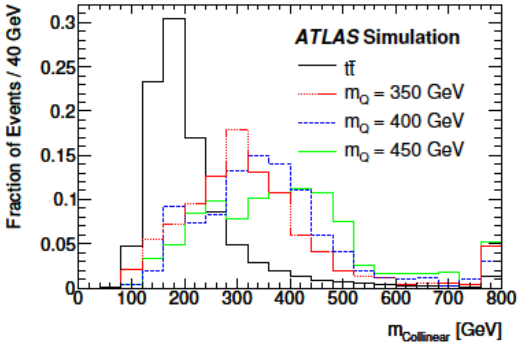
- Signal is modeled using PYTHIA 6.421
  - cross section for QQ' NNLO ranges from 0.3 pb to 8.0 pb depending on the mass
- Main Background after pre-selection
  - top production simulated using MC@NLO
  - Z/γ* + jets from ALPGEN
    - normalization factor from same flavor lepton events inside Z mass window
  - multi-jet events
    - matrix method using electron and muon loose to tight efficiency for real electrons and fakes:
      - Fakes muons: b/c decays
      - Fake electrons: b/c decays, ϒ conversions, π^0's

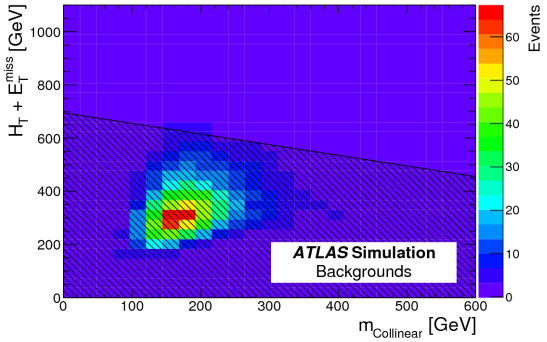


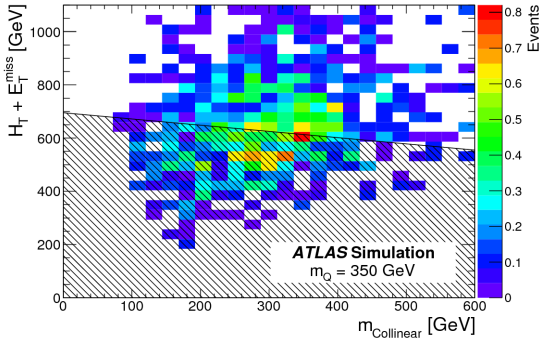
Process	ee		$e\mu$		$\mu\mu$	
$t\bar{t}$	190	$^{+40}_{-30}$	1140	$^{+250}_{-200}$	370	$^{+80}_{-70}$
single-top	9.4	$^{+2.2}_{-1.9}$	60	$^{+14}_{-11}$	24	$^{+5}_{-5}$
$Z/\gamma^* \to ee$	6.3	$^{+2.0}_{-1.9}$	0.0	$^{+0.1}_{-0.0}$	0.0	$^{+0.1}_{-0.0}$
$Z/\gamma^* \to \mu\mu$	0.0	$^{+0.1}_{-0.0}$	2.2	$^{+1.1}_{-1.1}$	17	$^{+5}_{-4}$
$Z/\gamma^* \to \tau\tau$	7.3	$^{+2.4}_{-2.2}$	62	$^{+15}_{-12}$	16	$^{+4}_{-4}$
WW, WZ, ZZ	8.7	$^{+2.2}_{-1.9}$	49	$^{+11}_{-10}$	12.7	$^{+3.0}_{-2.6}$
fake leptons	3.7	± 2.8	70	± 40	0.5	± 0.8
Total Bg	230	$^{+50}_{-40}$	1380	$^{+310}_{-250}$	440	$^{+90}_{-80}$
Observed	243		1410		460	

$QQ \rightarrow WWqq \rightarrow qqlvlv$ Discriminant

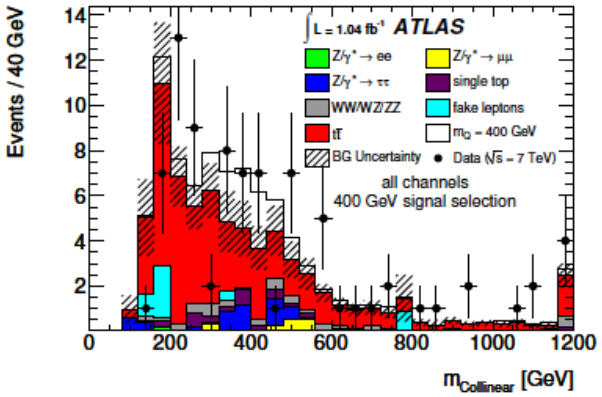
- Discriminating variable $m_{Collinear}$
  - mass for heavy quarks reconstructed
  - collinear approximation for neutrinos taken into account when fitting masses using same mass constraint for heavy quark and real W mass
  - higher correlation for heavy quark production w.r.t. background events
    - $| m_{collinear1} - m_{collinear2} | < 25$ GeV
- Final Event Selection
  - pre-selection used to discriminate against *Z+jet* production
  - additional signal mass dependent cuts, HT+MET and leading jet p_T's, are put in place to discriminated against top quark production.



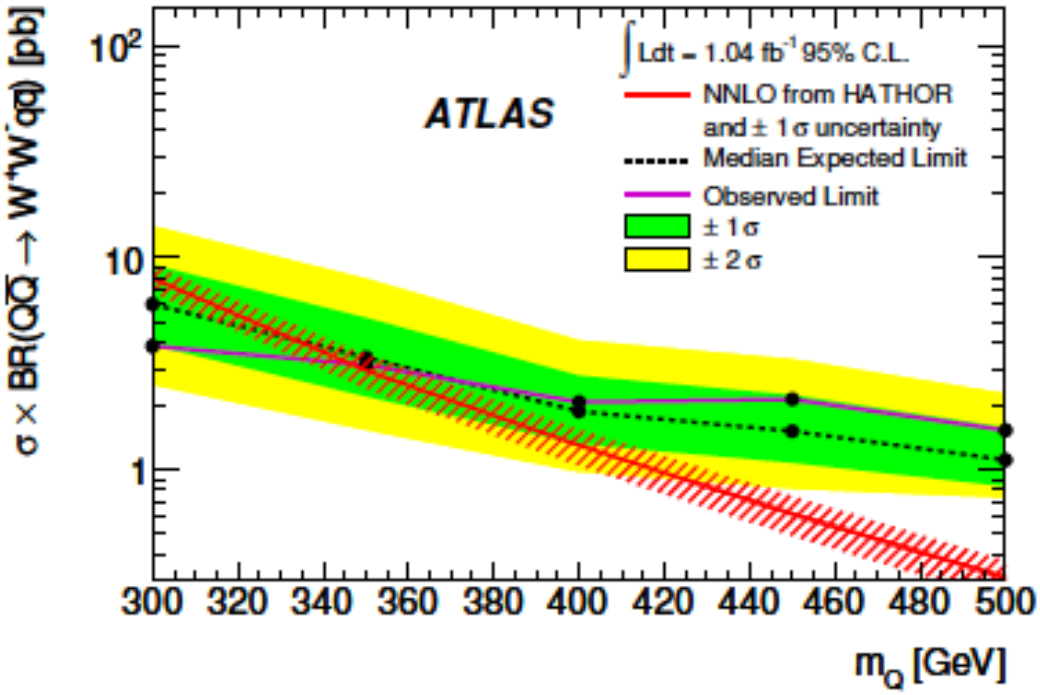




QQ→WWqq→qqlvlv results



Background	$+1\sigma$ Unc.	-1σ Unc.
$t\bar{t}$	7 %	10 %
single-top	7 %	7 %
$Z/\gamma^* \to ee$	60 %	30 %
$Z/\gamma^* \to \mu\mu$	40 %	30 %
$Z/\gamma^* \to \tau\tau$	40 %	40 %
WW, WZ, ZZ	5 %	5 %
fake leptons	50 %	50 %



- Sources of systematic uncertainty come from lepton reconstruction efficiencies, jet energy scale and pile up effect (particularly true for MET estimation)
  - acceptance for signal and background from simulation carry associated uncertainty on choice of generator and either theoretical calculation or data driven rate estimation
- Assuming BR($Q \to Wq$)=1 observed (expected) 95% CL limit m_Q>350 (335) GeV

Conclusions and Outlook

- ATLAS actively searched for 4th generations quarks
- Analyses with 1 fb-1 data have excluded at 95% CL the following new heavy quarks:
  - observed (expected) limit for t': $m_{t'} < 404$ (394) GeV
    - Assuming BR($t' \rightarrow Wb$) = 1
  - observed (expected) limit for b': $m_{b'} < 480$ (470) GeV
    - Assuming BR($b' \rightarrow Wt$)=1
  - observed (expected) limit for Q: $m_{Q} < 350$ (335) GeV
    - Assuming BR ($Q \rightarrow Wq$)=1
- More results in the pipeline with full 2011 dataset
- Sequential 4th generation can be ruled out using full 2012 dataset
  - constraints from Higgs production and decay rates
- Direct Searches more challenging in the high mass region or in case of small 3-4 mixing angle
  - unexplored phase space could exists even after 2012 data taking