

# ATLAS Exotic top and fourth generation searches

Clément Helsens

IFAE Barcelona

For the ATLAS Collaboration

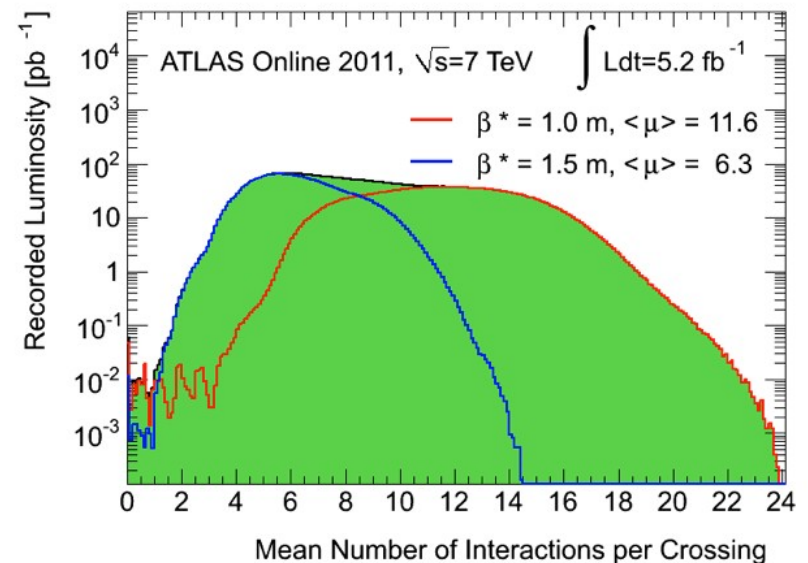
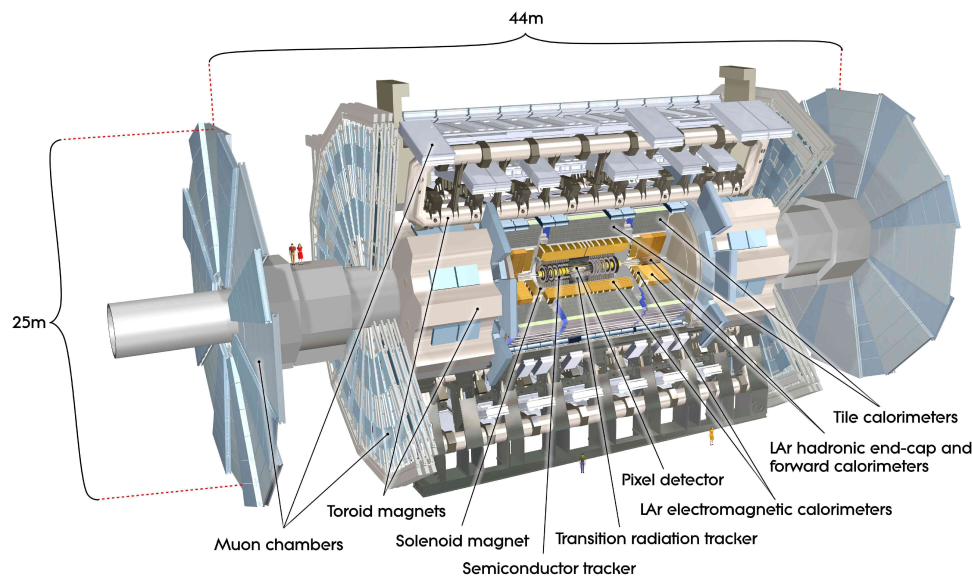
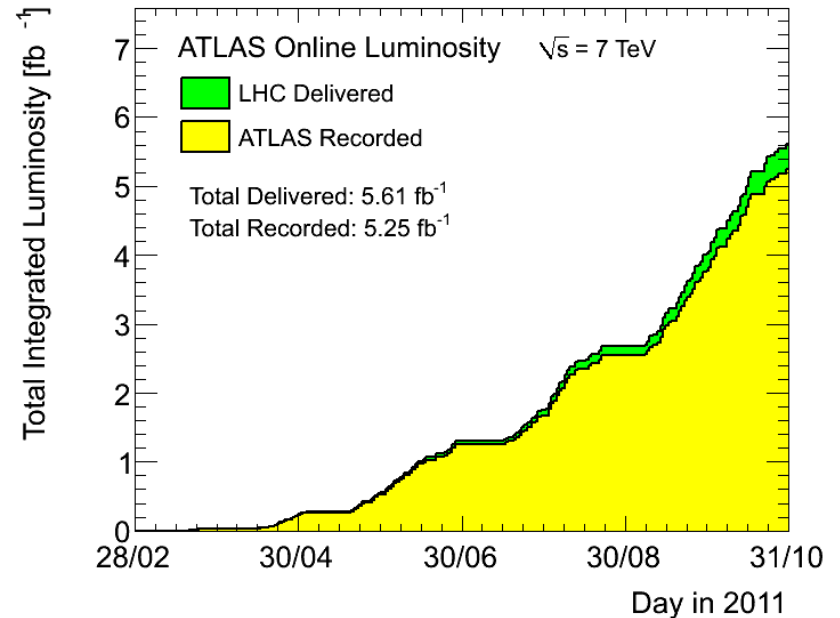
March 29 2012

Next Implications of LHC Physics  
Workshop



# ATLAS and LHC Data

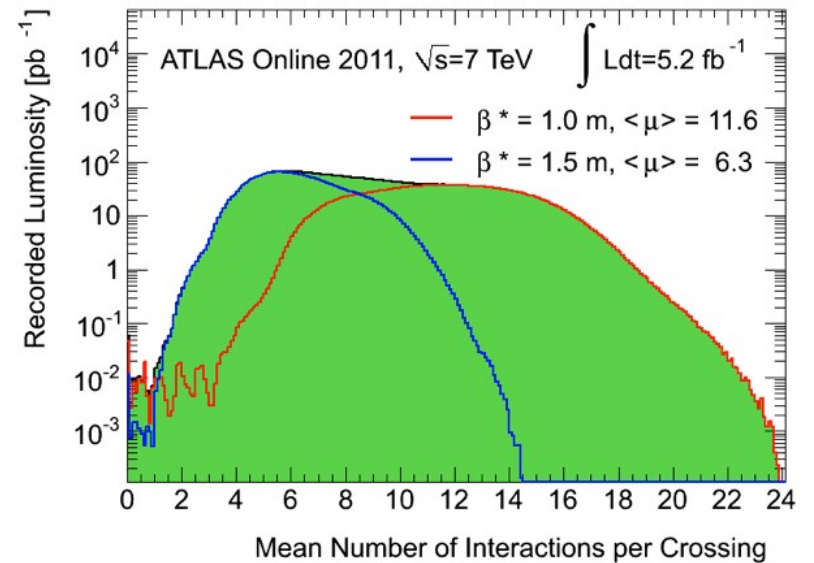
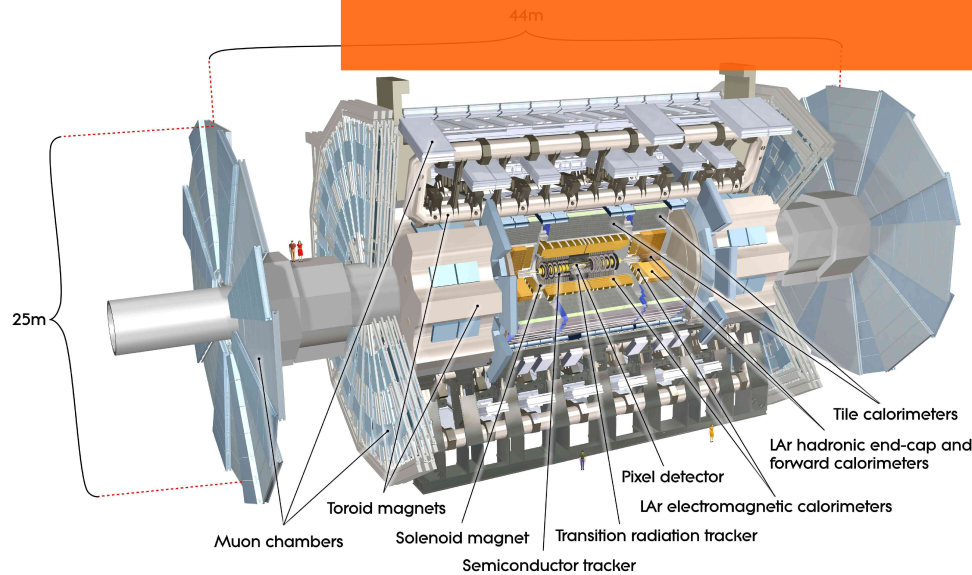
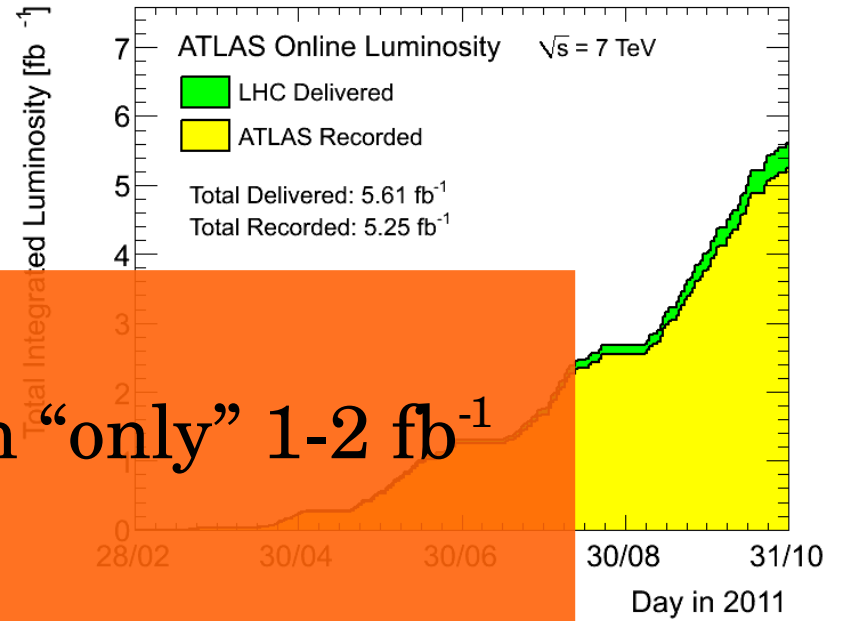
- Data collected in 2011 → up to  $5.25 \text{ fb}^{-1}$
- Maximum instantaneous luminosity  $3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Pileup up to  $n_{\text{vtx}} = 24$  (depending on the LHC)
- Luminosity uncertainty down to 3.4%



# ATLAS and LHC Data

- Data collected in 2011 → up to  $5.25 \text{ fb}^{-1}$
- Maximum instantaneous luminosity  $3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$
- Pileup up to  $\langle n_{\text{vtx}} \rangle = 24$  (depending on the LHC)
- Luminosity uncertainty today is 2.1%

Today's results with "only"  $1\text{-}2 \text{ fb}^{-1}$



# 4<sup>th</sup> generation quarks

- SM doesn't predict number of fermion generations:
  - Upper bound from QCD asymptotic freedom: number of families  $< 9$  ( $< 16$  quarks).
  - CKM constraints fairly weak.
- SM4 = SM + 4<sup>th</sup> generation family of fermions with  $100 \text{ GeV} < M < 600 \text{ GeV}$ . 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  $\sim 500 \text{ GeV}$ ).
  - Extended CKM matrix could provide enough CP-violation to explain matter-antimatter asymmetry.
  - Can explain some anomalies in CP-violation measurements in B-physics.
- Vector like quarks could produce similar and richer variety of signature

Quarks	u	c	t	t'
	d	s	b	b'
Leptons	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$\nu'$
	e	$\mu$	$\tau$	$\tau'$
	I	II	III	IV

$$CKM_{4 \times 4} = \begin{bmatrix} 0.97377 \pm 0.00027 & 0.2257 \pm 0.0021 & 0.00431 \pm 0.00030 & < 0.044 \\ 0.230 \pm 0.011 & 0.957 \pm 0.095 & 0.0416 \pm 0.0006 & < 0.46 \\ 0.0074 \pm 0.0008 & 0.0406 \pm 0.0027 & > 0.78 & < 0.47 \\ < 0.063 & < 0.46 & < 0.47 & > 0.57 \end{bmatrix}$$

Assume  $|mt' - mb'| < mW$

Signatures

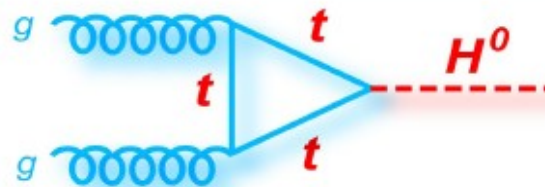
$t' \rightarrow Wq$  ( $q=d,s,b$ )

$b' \rightarrow Wq$  ( $q=u,c,t$ )



# Higgs and 4<sup>th</sup> generations 1/3

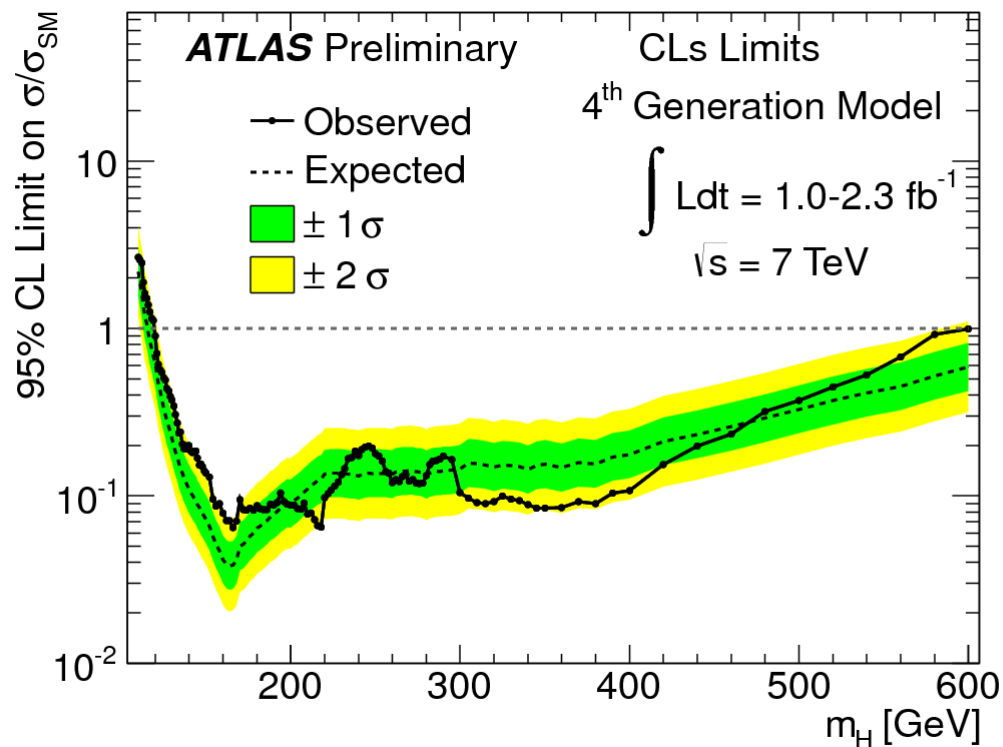
- 4<sup>th</sup> generation quarks can come with or without the Higgs boson
- If Higgs exist and considering SM4
  - Higgs couples to the new heavy quarks in the standard way
  - Substantial enhancement of the  $gg \rightarrow H$  cross section
  - Leads to dramatic exclusion on the Higgs  $\rightarrow$  4<sup>th</sup> family in big trouble
- Data seems to indicate that both fourth family and SM Higgs cannot both exist
- If 4<sup>th</sup> family is discovered  $\rightarrow$  SM Higgs is in deep troubles
- Also models of VLQ with a Higgs but suppression of SM branching ratio  $\rightarrow$  Higgs only visible via heavy quark production



# Higgs and 4<sup>th</sup> generations 2/3

1-2.3fb<sup>-1</sup>

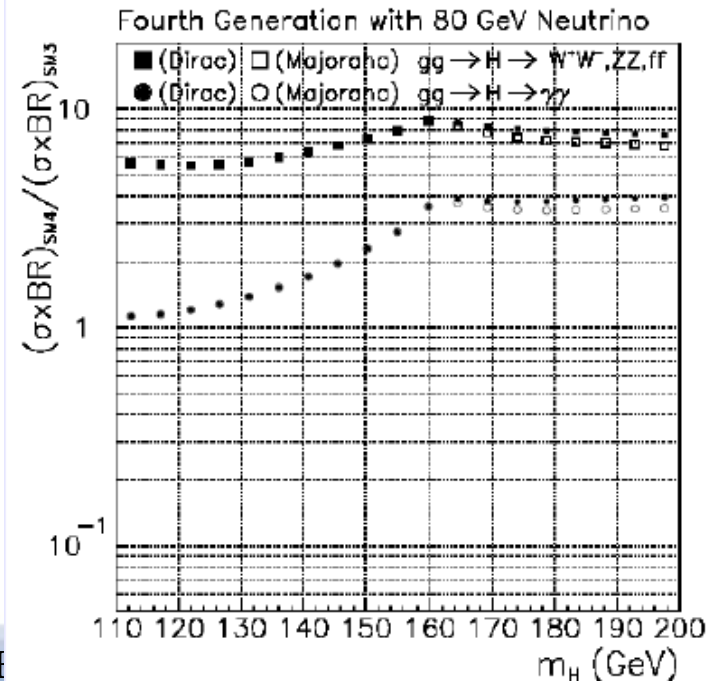
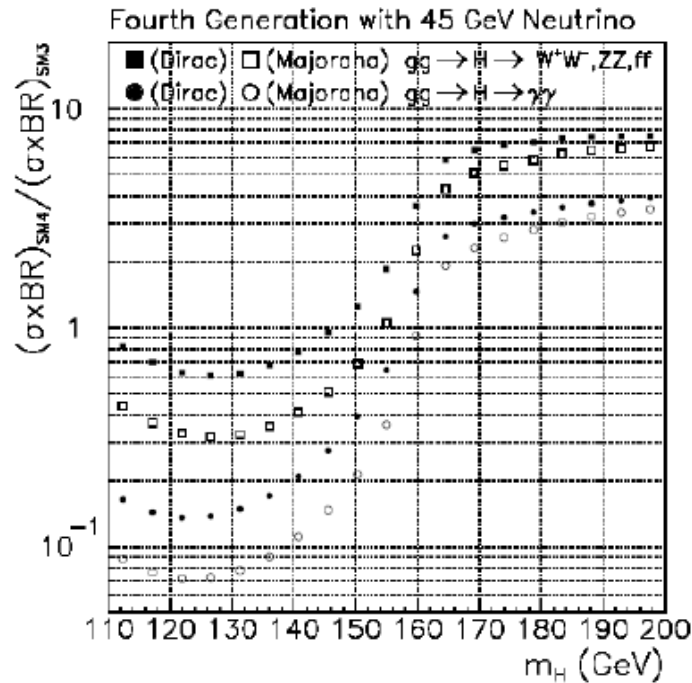
- Consider a 4<sup>th</sup> generation quark with a mass of 600GeV
- Exclude Higgs boson with  $m(H) > 119\text{GeV}$  and  $m(H) < 593\text{GeV}$
- If 125GeV excess is real  $\rightarrow$  difficult to have a 4<sup>th</sup> generation quarks



- $\rightarrow$  But, LHC limits not conservative

# Higgs and 4<sup>th</sup> generations 3/3

- Some room left for 4<sup>th</sup> generations and SM Higgs boson
  - 4<sup>th</sup> generation quarks also change the Higgs branching fractions
  - Heavy neutrino mass becomes a key parameter
  - SM4 with SM Higgs only possible
    - For very large Higgs masses > 600GeV
    - Small mass window → size depend on the heavy neutrino mass (Conservative limit from Z lineshape: Bulanov, Rozanov & Vysotsky (2003)  $m(\nu_4) > 46.7\text{GeV}$ )
    - → need to recalculate LHC Higgs limits with 4<sup>th</sup> generation neutrino mass = 46.7GeV



# Monte-Carlos

- Signal generated with Pythia
- Signal cross-sections from HATHOR (NNLO approximation)
- Backgrounds:
  - MC@NLO for  $t\bar{t}$ , single top, Alpgen for W/Z+jets, Herwig for dibosons
  - Alpgen used for  $t\bar{t}$  as well (for higher jet multiplicities)
  - For fake leptons: Obtained via data-driven techniques → loosening the lepton ID criteria and extracting tight vs loose efficiencies in control samples

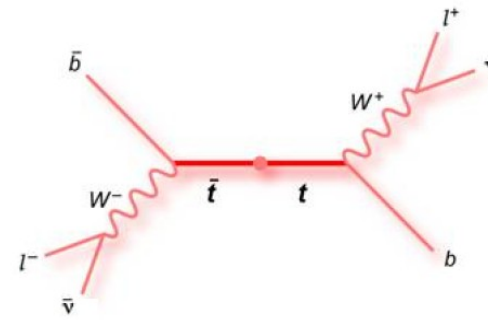
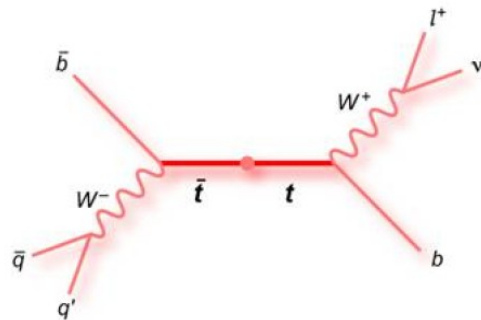


# Results Covered In This Talk

- **ATLAS results** → <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/>
  - Search for pair production of a heavy quark decaying to a W boson and a b quark in the lepton+jets channel with the ATLAS detector ([1.04fb-1](#), [arXiv:1202.3076](#))
  - Search for pair-produced heavy quarks decaying to Wq in the two-lepton channel at  $\sqrt{s} = 7$  TeV with the ATLAS detector ([1.04fb-1](#), [arXiv:1202.3389](#))
  - Search for same-sign top-quark production and fourth-generation down-type quarks in pp collisions at  $\sqrt{s} = 7$  TeV with the ATLAS detector ([1.04fb-1](#), [arxiv:1202.5520](#))
  - Search for down-type fourth generation quarks with the ATLAS Detector in events with one lepton and high transverse momentum hadronically decaying W bosons in  $\sqrt{s}=7$  TeV pp collisions ([1.04fb-1](#), [arxiv:1202.6540](#))
  - Search for New Phenomena in ttbar Events With Large Missing Transverse Momentum ([1.04fb-1](#), [arXiv:1109.4725](#))
  - Search for pair production of a new quark that decays to a Z boson and a bottom quark with the ATLAS detector ([2.0fb-1](#), [approved plots](#))
  - Search for a heavy vector-like quark coupling to light quarks in proton-proton collision at  $\sqrt{s} = 7$  TeV with the ATLAS detector ([1.04 fb-1](#), [arXiv:1112.5755](#))

# Common Selection

- Top/exotic analysis uses almost the same object definition/selection
- Cosmics, pileup rejection → > 4 tracks from the Primary Vertex
- Triggers → Single lepton triggers
- Jets → Topological clusters; Anti- $k_T$ ( $R=0.4$ );  $p_T > 25\text{GeV}$ ;  $|\eta| < 2.5$
- Electrons → Good isolated calo object; match to track;  $E_T > 25\text{GeV}$ ;  $|\eta| \in [0; 2.47]$  removing  $[1.37, 1.52]$
- Muons → Segment in the tracker and muon detector; isolated track;  $p_T > 20\text{GeV}$ ;  $|\eta| < 2.5$

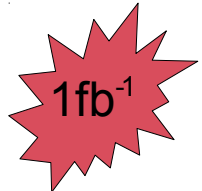


## Single-lepton

- 1 lepton exclusive (veto other flavor)
- jets with  $p_T > 25\text{GeV}$ ;  $|\eta| < 2.5$
- e:  $E_T^{\text{miss}} > 35\text{GeV}$ ;  $m_T(W) > 25\text{GeV}$
- $\mu$ :  $E_T^{\text{miss}} > 20\text{GeV}$ ;  $E_T^{\text{miss}} + m_T(W) > 60\text{GeV}$
- $\geq 1$  jet b-tagged if tagged analysis

## Di-leptonic

- At least 2 leptons
- jets with  $p_T > 25\text{GeV}$ ;  $|\eta| < 2.5$
- $ee/\mu\mu$  (same flavor) →  $|M_{ll} - M_Z| < 10\text{GeV}$ ; higher MET cut
- $e\mu$ :  $H_T > 130\text{GeV}$
- No b-tagging requirement

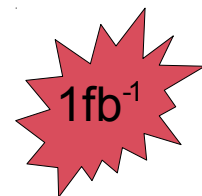


- Final state  $t't' \rightarrow WbWb \rightarrow jjb l\nu b$
- Strategy:  $\rightarrow$  stay as close as possible to the top group selection  $\rightarrow$  loose selection
- Event selection:
  - Single lepton triggers
  - Exactly 1 leptons  $p_T > 20\text{GeV}$ ; muon  $|\eta| < 2.5$ ; electron  $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$  (veto the other flavor)
  - Jets: Anti-kt 0.4,  $p_T > 25\text{GeV}$ ,  $|\eta| < 2.5 \rightarrow$  at least 3 jets; leading jet  $p_T > 60\text{GeV}$
  - $\text{ETMiss} > 20$  (30)GeV muon (electron);  $\text{ETMiss} + \text{MTW} > 60\text{GeV}$
  - Using the btagging ( $\geq 1\text{bjet}$  70% efficiency, optimize to get best  $S/\sqrt{B}$ )
- 1D kinematic Likelihood fit
  - Reconstructed top mass
  - 3 jet bin: just the invariant mass of the 3 jets
  - $\geq 4$  jets: using KL Fitter
    - Using leading 4 jets only
    - Floating 'top' mass
    - No Btagging information used
    - Only constrain both 'sides' to be similar

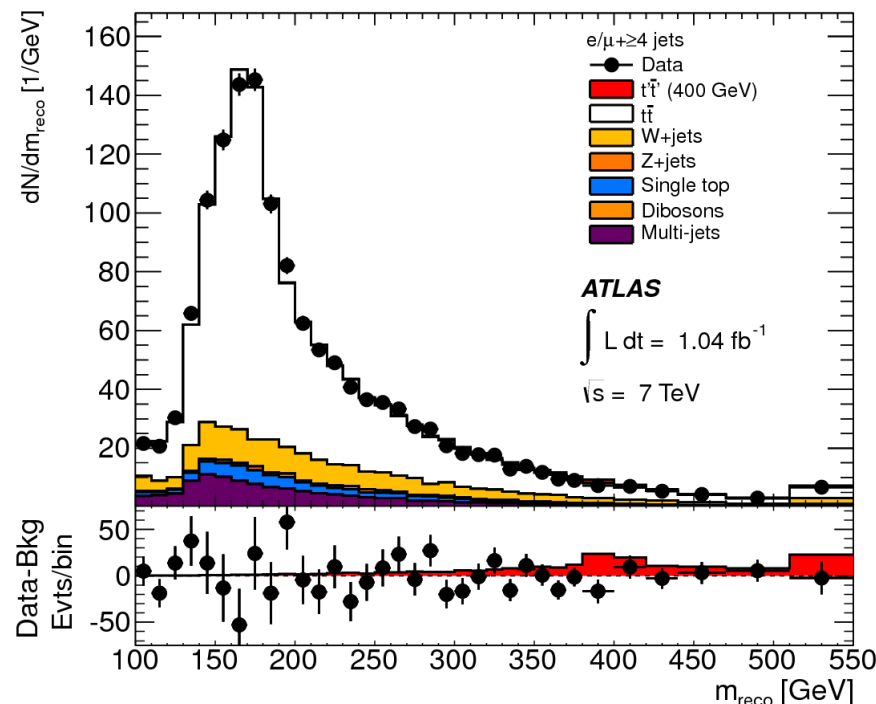
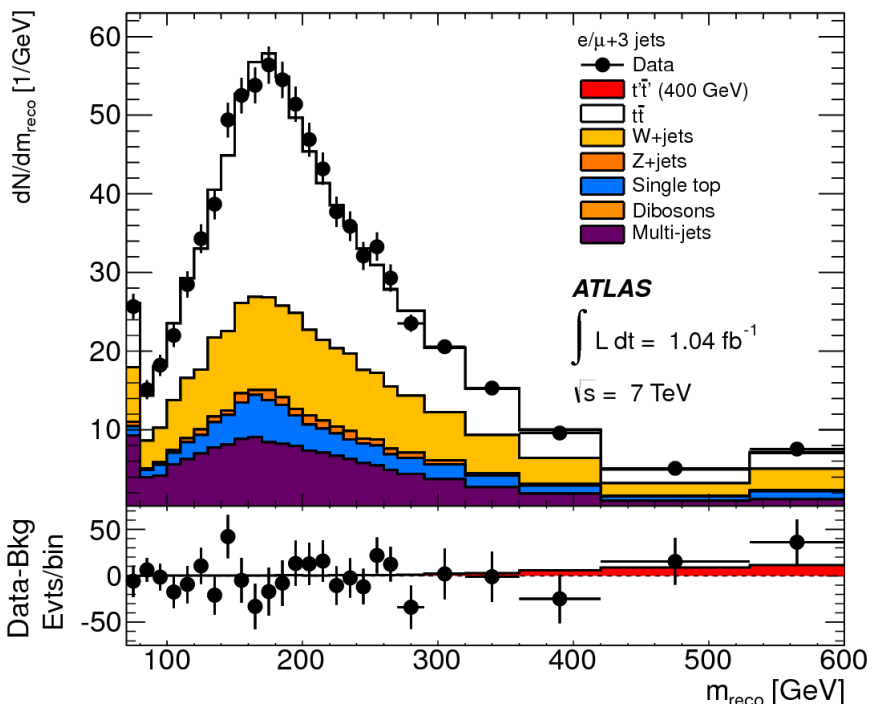
} Helps to constraint systematics with profiling

- Systematics treated as nuisance parameters
- 27 sources in total, 12 profiled
- Dominant systematics: Jet energy scale;  $t\bar{t}$  modeling: ISR/FSR, NLO generator (\*), fragmentation model (\*) (\*) = Not profiled
- A profile likelihood ratio is performed combining 3jet exclusive/4 jet inclusive channel for at least 1btag jet and electron and muon channels

arXiv:1202.3076



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



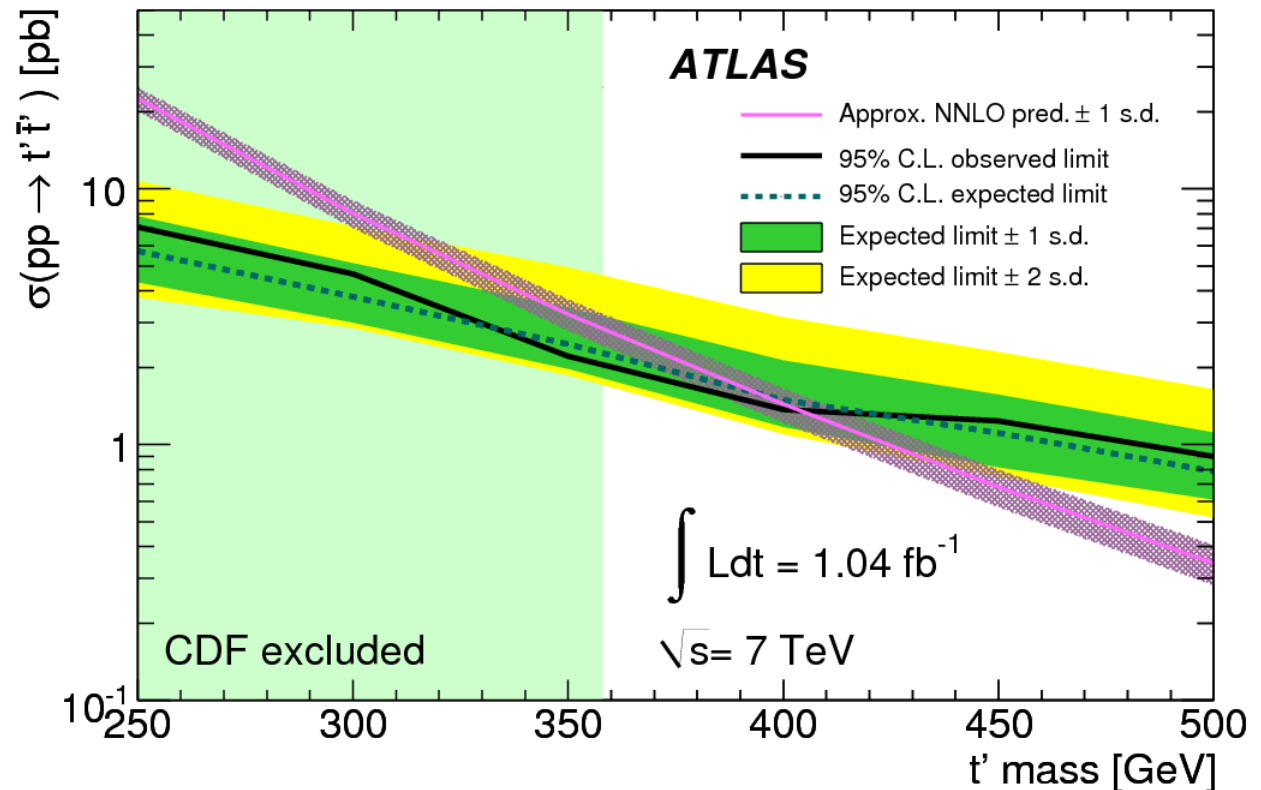


arXiv:1202.3076

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- No sign of excess  $\rightarrow$  set limits (mclimit)
  - Combined limit: electron/muon =3/ $\geq$ 4jets  $\rightarrow$  4 orthogonal channels
  - Observed limit:  $m_{t'}$  > 404GeV @ 95% C.L. Expected limit: 394GeV
  - Observed limit is within 1 $\sigma$  of the expected in the full mass range considered

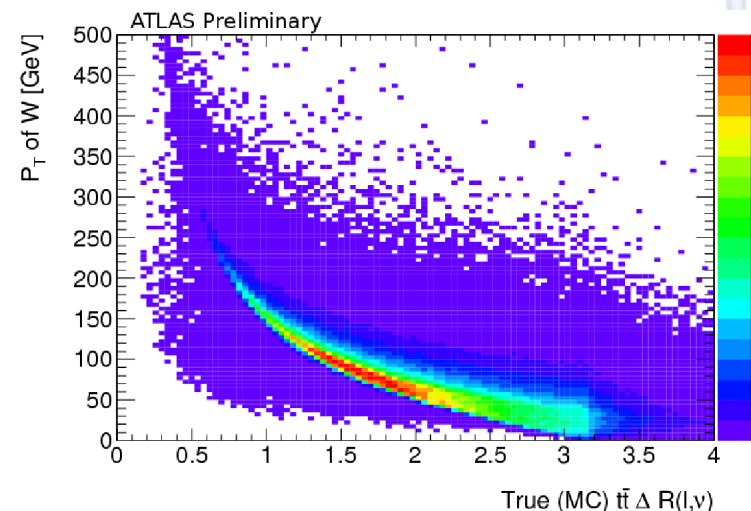
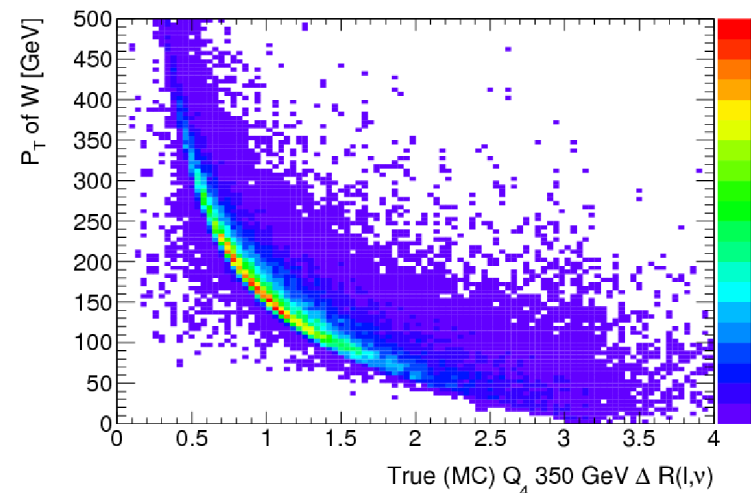
Applicable to VLQ  
 $Y \rightarrow W\text{-}b$  (Q=-4/3)



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arXiv:1202.3389

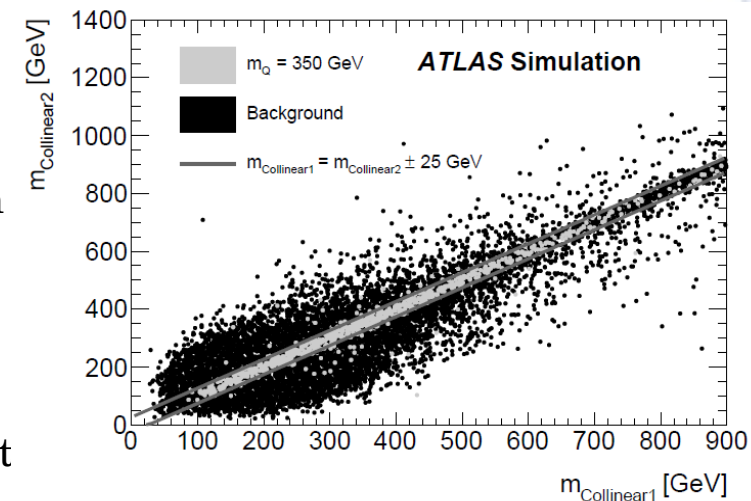
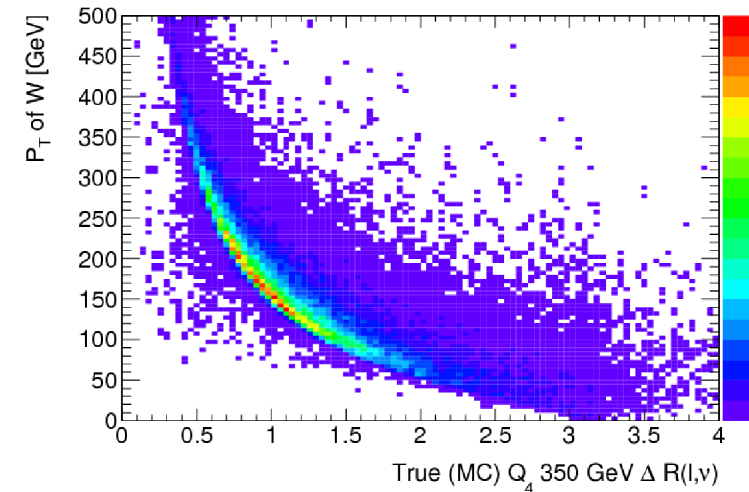
- Final state  $t't' \rightarrow WqWq \rightarrow l\nu q l\nu q$
- No assumption about the quark mixing  $t' \rightarrow Wq$
- Baseline selection:
  - Exactly 2 leptons  $p_T > 20\text{GeV}$ ; muon  $|\eta| < 2.5$ ; electron  $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - Lepton isolation:  $\sum ET(\Delta R < 0.2) < 3.5\text{GeV}$
  - Jets: Anti-kt 0.4,  $p_T > 25\text{GeV}$ ,  $|\eta| < 2.5 \rightarrow$  at least 2 jets
  - $ET_{\text{Miss}} > 60\text{ GeV}$  (ee/ $\mu\mu$ );  $HT(\text{MET} + \text{lep } p_T) > 130\text{GeV}$  (e $\mu$ )
  - For ee/ $\mu\mu \rightarrow M_{ll} > 15\text{GeV}$ ;  $|M_{ll} - M_Z| > 10\text{GeV}$
- Reconstruction of the heavy quark masses:
  - At high W  $p_T \rightarrow$  neutrino and lepton  $\sim$  collinear
  - Reconstruct both neutrinos by assuming solely contribution to MET
  - Reconstruct  $|\Delta\eta(l,\nu)|$  and  $|\Delta\Phi(l,\nu)|$  for each neutrino as a free parameter  $\rightarrow$  range [0,1]
  - Find the  $|\Delta\eta(l,\nu)|$  and  $|\Delta\Phi(l,\nu)|$  values and jet assignment that minimizes the differences between the two masses (collinear mass) and keep events with  $|m_1 - m_2| < 25\text{GeV}$



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arXiv:1202.3389

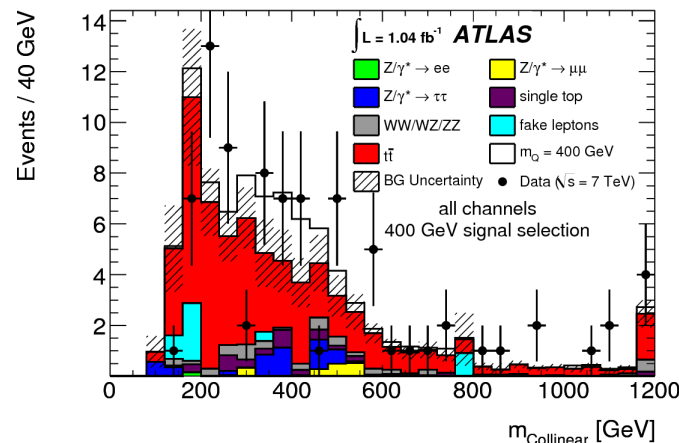
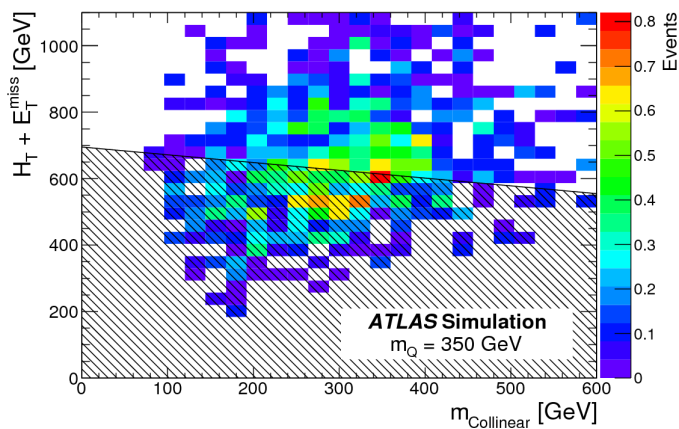
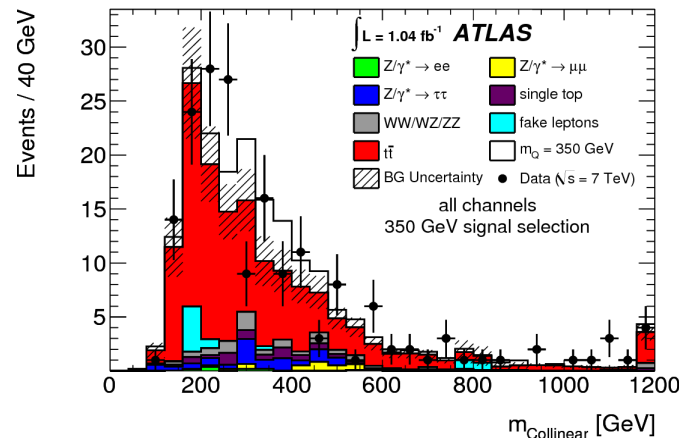
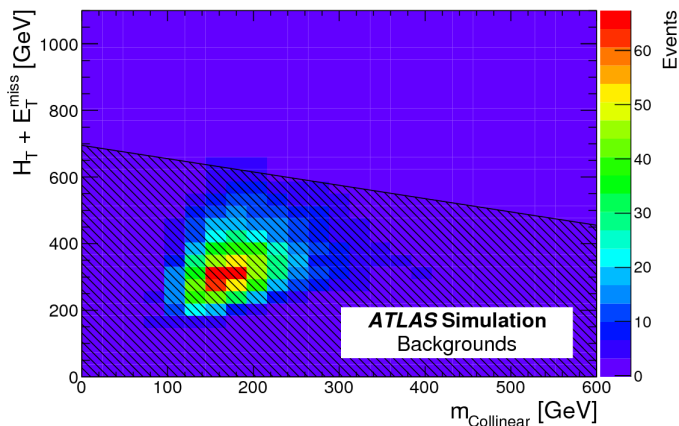
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$m_Q$ (GeV)	Triangle Requirement (GeV)
300	$H_T + E_T^{\text{miss}} > 610 - 0.4 \times m_{\text{Collinear}}$
350	$H_T + E_T^{\text{miss}} > 700 - 0.4 \times m_{\text{Collinear}}$
400	$H_T + E_T^{\text{miss}} > 790 - 0.4 \times m_{\text{Collinear}}$
450	$H_T + E_T^{\text{miss}} > 880 - 0.4 \times m_{\text{Collinear}}$
500	$H_T + E_T^{\text{miss}} > 970 - 0.4 \times m_{\text{Collinear}}$

$m_Q$ (GeV)	Jet $p_T$ (GeV)	$E_T^{\text{miss}}$ (GeV)
300	Leading jet $p_T > 80$	—
350	Leading jet $p_T > 120$	—
400	Leading jet $p_T > 130$	$E_T^{\text{miss}} > 70$
450	Leading jet $p_T > 130$	$E_T^{\text{miss}} > 70$
500	Leading jet $p_T > 130$	$E_T^{\text{miss}} > 70$



- **Final selection:**  
→ triangular cut in the  $M_{\text{coll}} - H_T$  plane (=  $H_{\text{thad}} + \text{lepton } p_T + \text{MET}$ )
- **Optimized for each  $t'$  mass**  
→ improve the signal/background discrimination
- →  $M_{\text{coll}}$  after triangular cut is used to discriminate signal and background

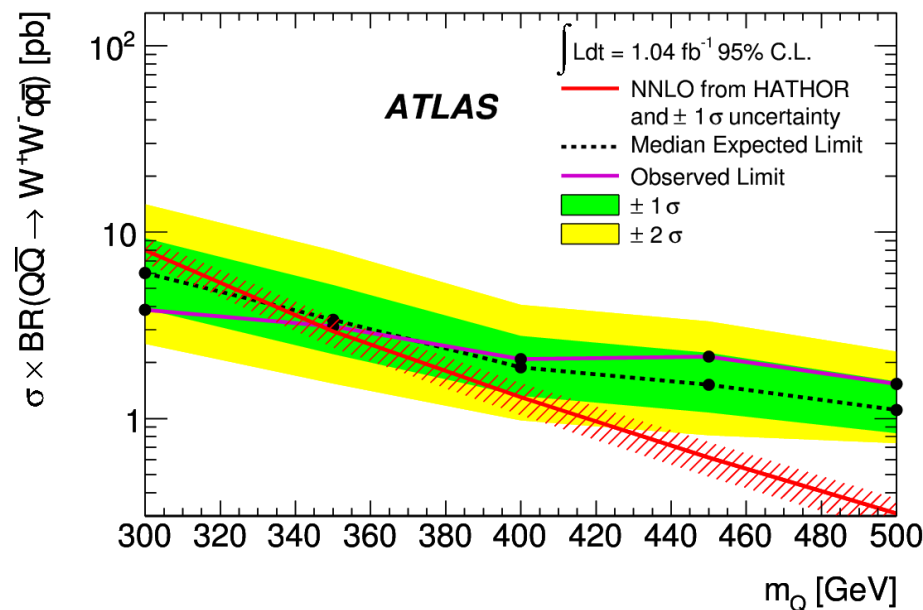


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arXiv:1202.3389

- Binned maximum likelihood used to set limit on the production cross section; Template fit using the Mcoll distribution
- Observed limit  $m(t') > 350\text{GeV}$  @ 95%CL

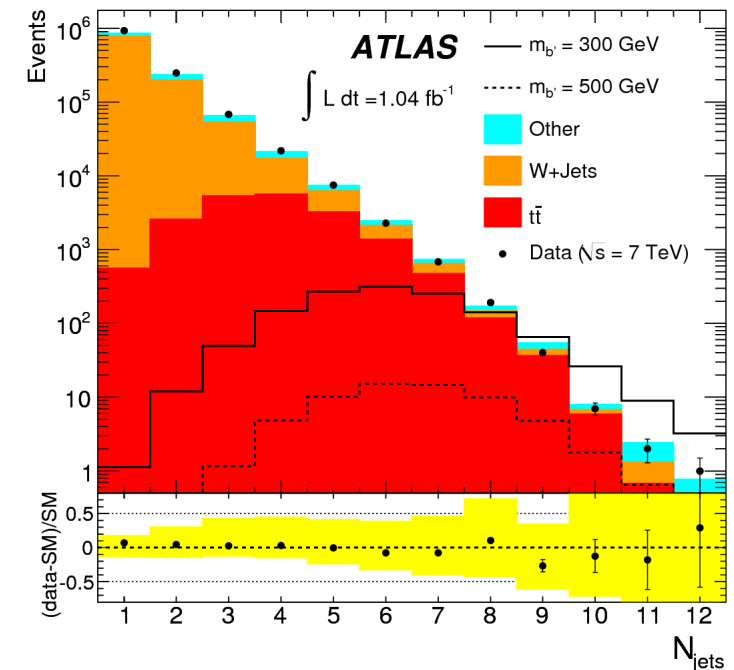
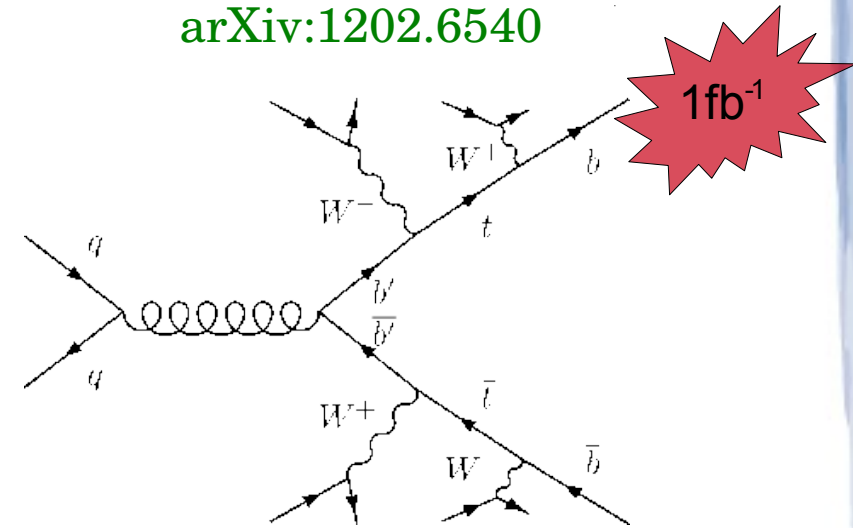
Source	+1 $\sigma$ Unc.	-1 $\sigma$ Unc.
Lepton trigger	1 %	1 %
Lepton ID and reconstruction	2 %	< 1 %
Jet reconstruction	3 %	3 %
Jet energy resolution	2 %	2 %
Jet energy scale	13 %	11 %
$\mu$ momentum resolution	2 %	2 %
$\mu$ momentum scale	1 %	2 %
$e$ energy resolution	1 %	1 %
$e$ energy scale	< 1 %	< 1 %
$e$ isolation pileup term	1 %	1 %
$e$ isolation $p_T$ term	< 1 %	< 1 %
$E_T^{\text{miss}}$ uncertainties	1 %	< 1 %
LAr readout problem	2 %	2 %
ISR/FSR: $t\bar{t}$	8 %	5 %
MC generator: $t\bar{t}$	1 %	< 1 %
MC fragmentation/model: $t\bar{t}$	1 %	1 %
Drell-Yan model	7 %	7 %



Applicable to to VLQ  
 $T \rightarrow Wq(q=d,s,b)$   $B \rightarrow Wq(q=u,c)$   
 and  $Y \rightarrow W-b$

arXiv:1202.6540

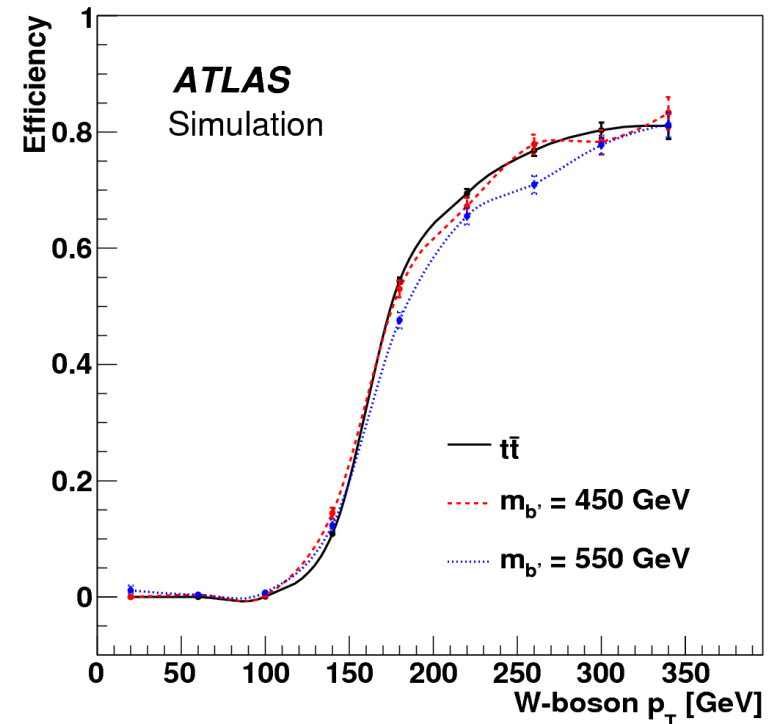
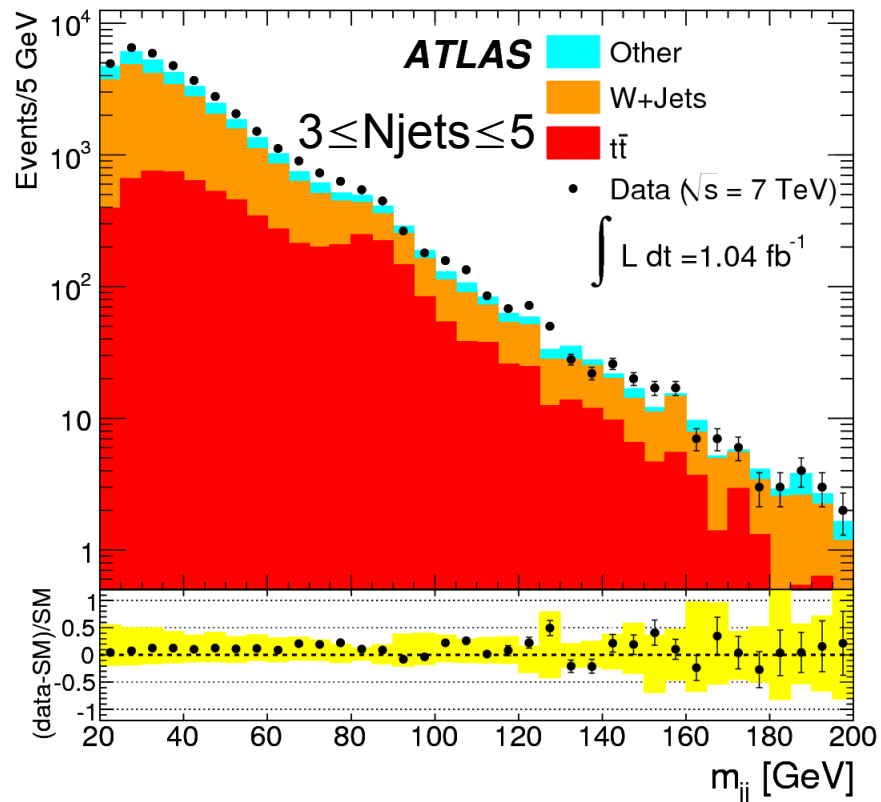
- Final state  $b\bar{b} \rightarrow WtWt \rightarrow WWbWWb \rightarrow 1\text{lep} + \text{MET} + \geq 6\text{jets}$
- Event selection:
  - Exactly 1 lepton (electron or muon) with tight selection criteria
  - Lepton  $p_T > 20(25)\text{GeV}$  muon(electron); muon  $|\eta| < 2.5$ ; electron  $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - $\text{ETMiss} > 20(35)\text{ GeV}$ ; muon(electron)
  - $\text{ETMiss} + \text{MTW}(\text{lep}) > 60\text{GeV}$
  - $\geq 6\text{jets}$  with  $p_T > 25\text{GeV}$  and  $|\eta| < 2.5$
- No b-tagging requirements
- High jet multiplicity  $\rightarrow$  suppress background
- Identify high  $p_T$  W bosons (close-by jets)

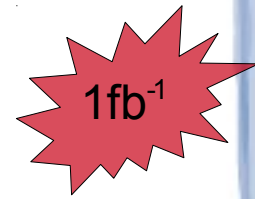


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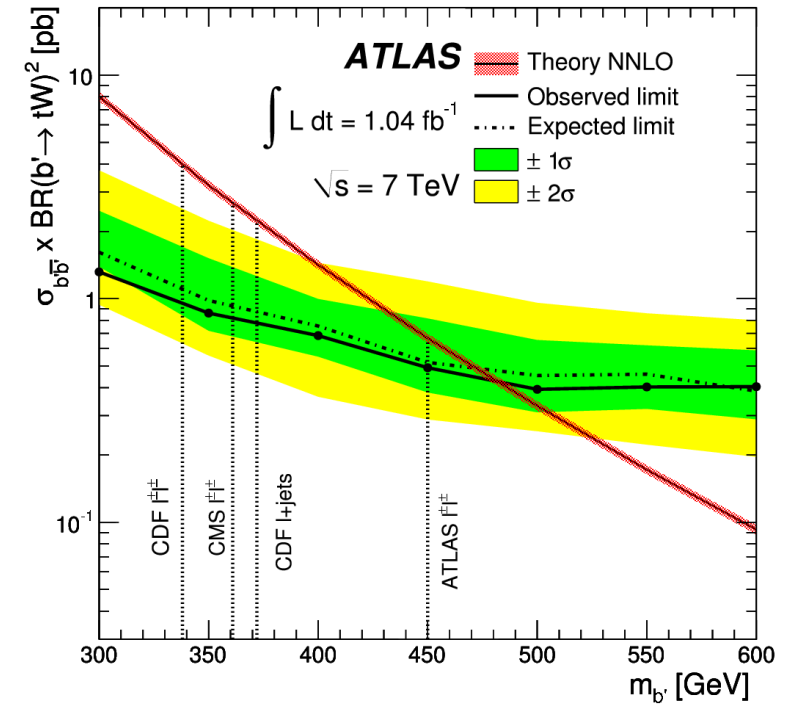
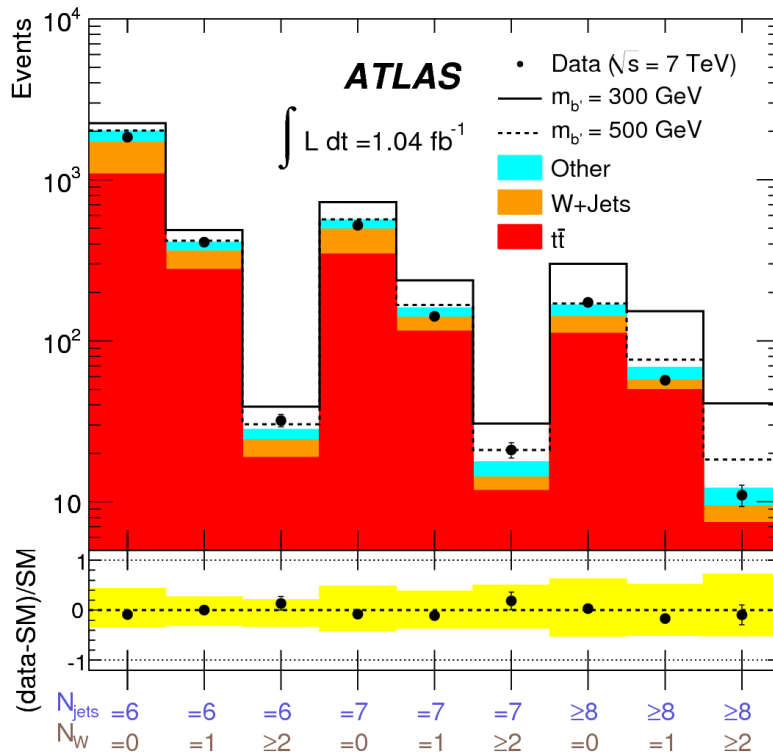
1fb<sup>-1</sup>

- Analysis based on high  $p_T$  hadronic W (2 jets collimated)
- Pair jets if  $DR(j,j) < 1$
- Count the number of W with  $70 < M_W < 100 \text{ GeV}$ 
  - $\rightarrow >75\%$  efficient for  $pt(W) > 250 \text{ GeV}$
- Very good Background modeling in several signal free regions





- Data in agreement with SM expectations  $\rightarrow$  Set limits
- Number of hadronic W boson candidate (0,1,  $\geq 2$ ) for 3 jet bins (6, 7,  $\geq 8$ )
- Mclimit used (Cls method with profile likelihood fit)
- Assuming  $BR(b' \rightarrow tW) = 1 \rightarrow m(b') > 480\text{GeV}$  @ 95% C.L.



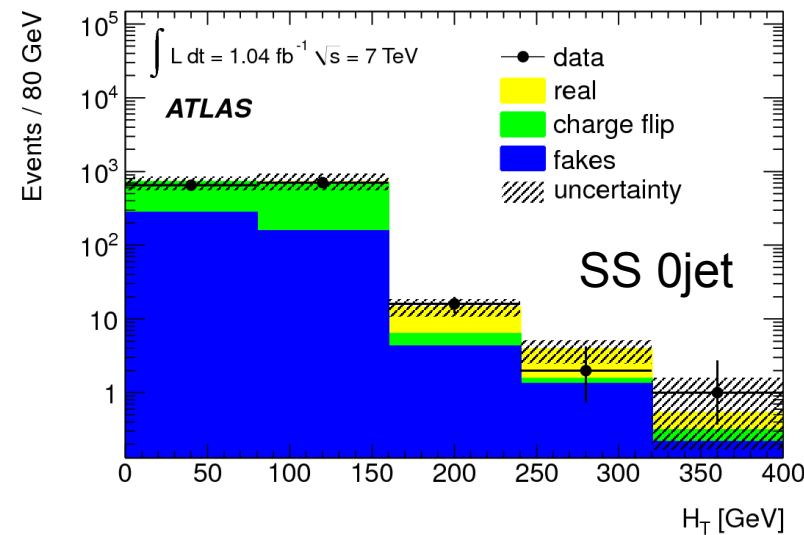
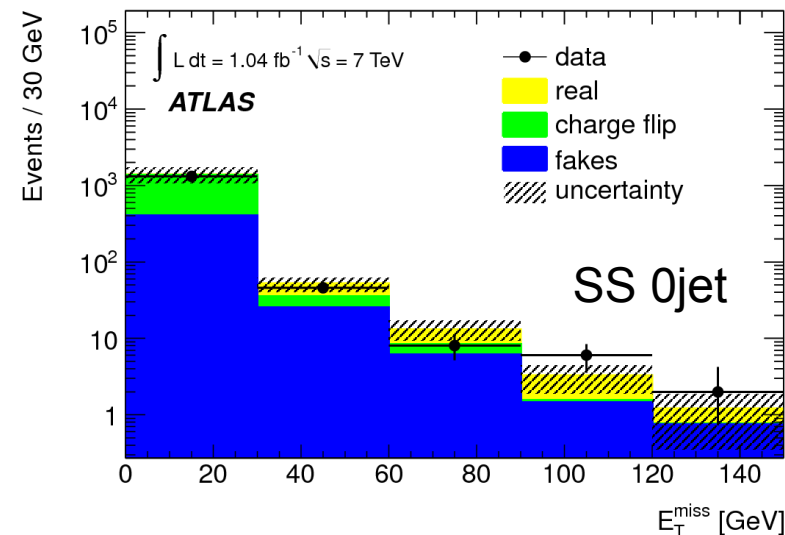
Applicable to VLQ  
 $B \rightarrow W-t$  ( $Q=-1/3$ ) and  
 $X \rightarrow W+t$  ( $Q=+5/3$ )



arXiv:1202.5520

1fb<sup>-1</sup>

- Final state  $b'b' \rightarrow WtWt \rightarrow WWbWWb \rightarrow 2SS$  leptons, MET,  $\geq 2$ jets
- Search for two same sign leptons ( $ee/e\mu/\mu\mu$ )
- Signature: 2 SS leptons, MET,  $\geq 2$ jets
- Pre-Selection:
  - 2 same sign leptons with tight identification criteria
  - Single lepton trigger
  - Lepton  $p_T > 20(25)\text{GeV}$  muon(electron); muon  $|\eta| < 2.5$ ; electron  $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - $ee/mumu \rightarrow M_{ll} > 15\text{GeV}$  and  $|M_{ll} - M_Z| > 10\text{GeV}$
  - Jets: 2 Anti-kt 0.4,  $p_T > 20\text{GeV}$ ,  $|\eta| < 2.5$
  - $ET_{\text{Miss}} > 40\text{ GeV}$
- No b-tagging requirements



- Background sources in the SM:

- Diboson (MC)  $\rightarrow$  irreducible background (Real leptons)
- $Ttbar$ ,  $W$ jets  $\rightarrow$  one fake lepton or charge flip  $\rightarrow$  data driven

- Dominant systematics:

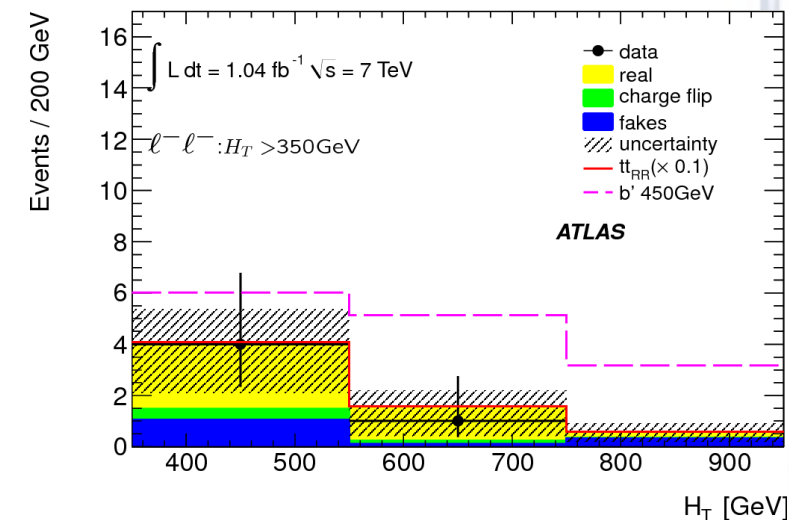
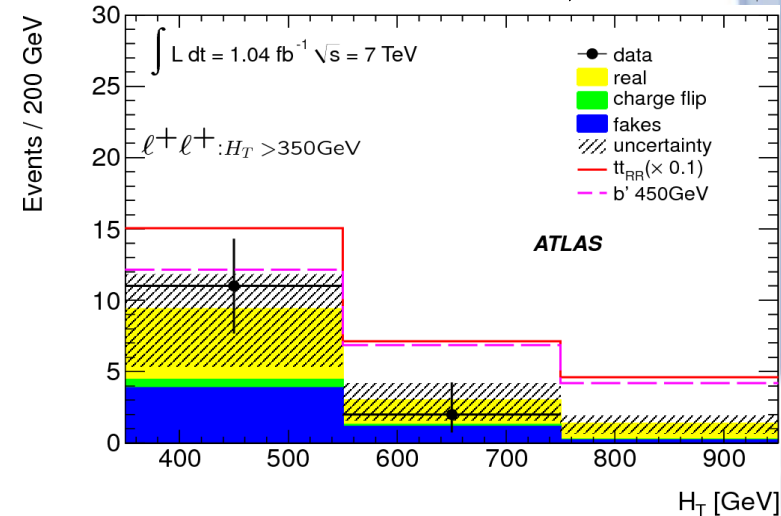
- Jet energy scale and resolution
- Fake lepton background
- Charge flip background

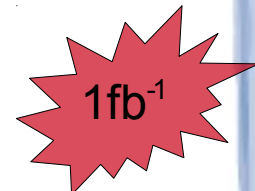
- Strategy:

- Signal region  $\rightarrow H_T > 350\text{GeV}$  (scalar sum of leptons and jets)
- Low background search  $\rightarrow$  accurate estimations
- Cut and count analysis

arXiv:1202.5520

1fb<sup>-1</sup>

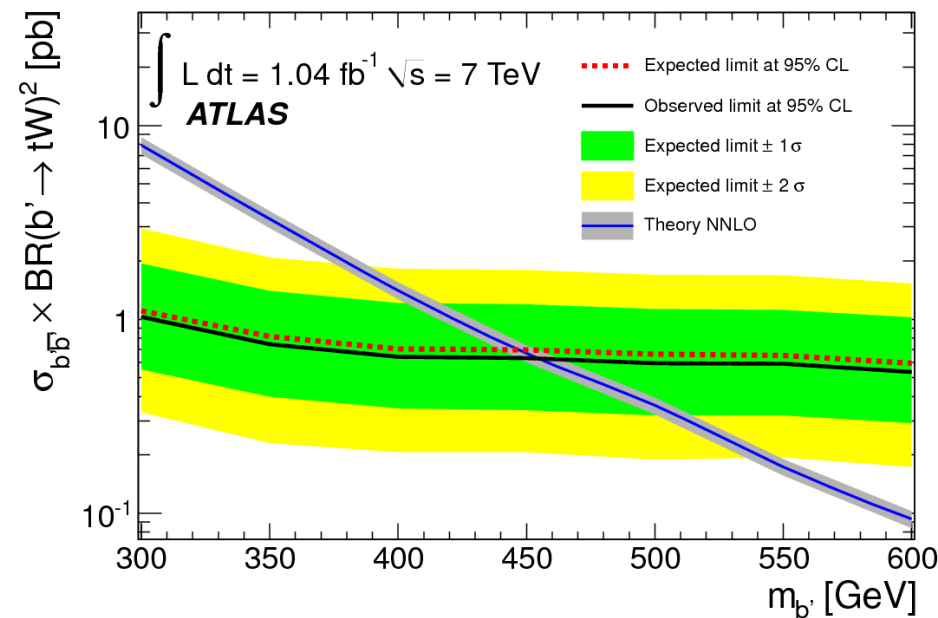




- A single bin counting experiment is used to set limit
- Data in agreement with SM expectations
- Limits setting using Collie package
- Confidence level interval are build using a Likelihood ratio test statistic
- Assuming  $BR(b' \rightarrow tW) = 1 \rightarrow m(b') > 450\text{GeV} @ 95\% \text{ C.L.}$

	$e^-e^-$	$\mu^-\mu^-$	$e^-\mu^-$
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
$b' 450 \text{ GeV}$	$1.8 \pm 0 \pm 0.3$	$2.1 \pm 0 \pm 0.3$	$4.3 \pm 0 \pm 0.5$

	$e^+e^+$	$\mu^+\mu^+$	$e^+\mu^+$
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	$0.3 \pm 0.1^{+0.3}_{-0.1}$	$0 \pm 0^{+0.01}_{-0}$	$0.4 \pm 0.1^{+0.3}_{-0.1}$
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
$b' 450 \text{ GeV}$	$1.8 \pm 0 \pm 0.3$	$2.7 \pm 0 \pm 0.4$	$5.0 \pm 0 \pm 0.7$



Applicable to VLQ  
 $B \rightarrow W-t$  ( $Q=-1/3$ ) and  
 $X \rightarrow W+t$  ( $Q=+5/3$ )

# $TT \rightarrow tA_0tA_0$ ( $tt + E_t^{\text{miss}}$ ) 1/2

1fb<sup>-1</sup>

arXiv:1109.4725

- Search for anomalous MET in  $tt$  (single lepton) events

Signature: 1lepton, MET,  $\geq 4$ jets

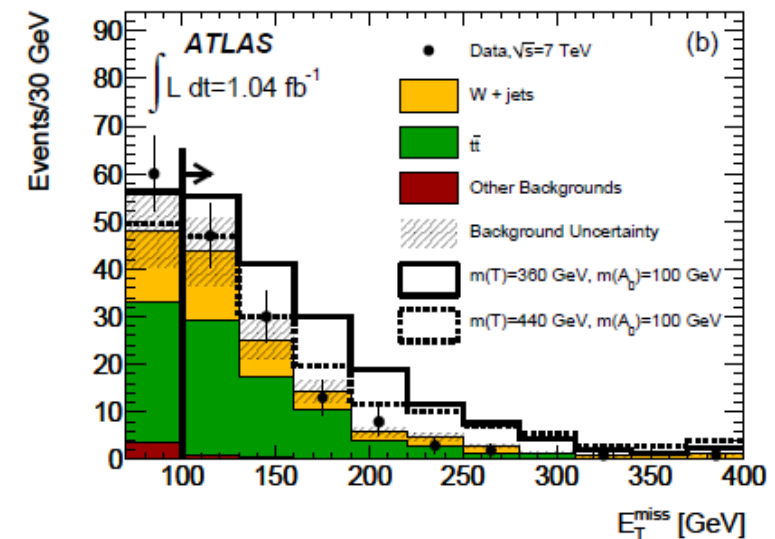
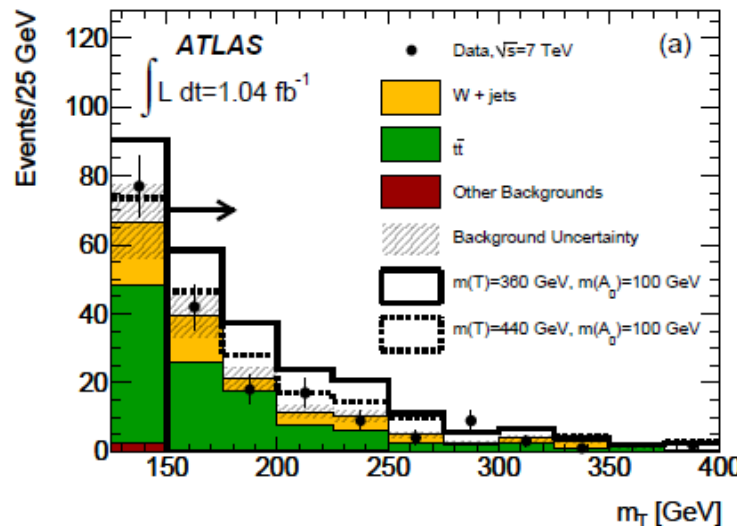
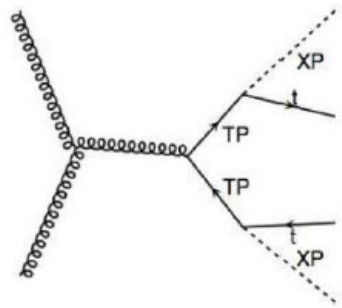
- Benchmark:  $TT$  pair with  $T \rightarrow tA_0$

- $A_0$  is a dark matter candidate
- Enhanced cross section due to spin states

- Signal region:

- $E_T^{\text{miss}} > 100\text{GeV}$ ,  $m_T > 150\text{GeV}$ , dilepton veto,  $p_T > 15\text{GeV}$ , tracks, loose electrons

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





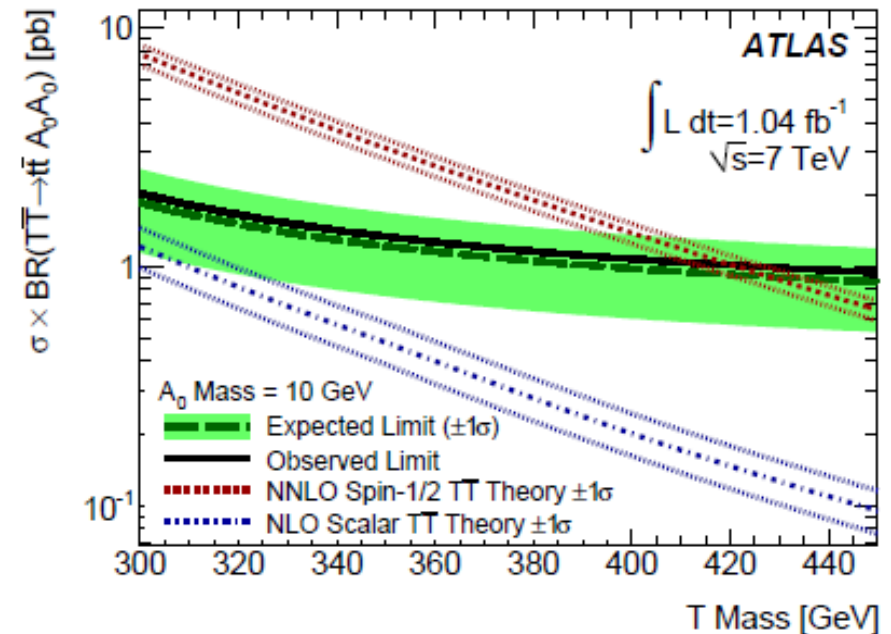
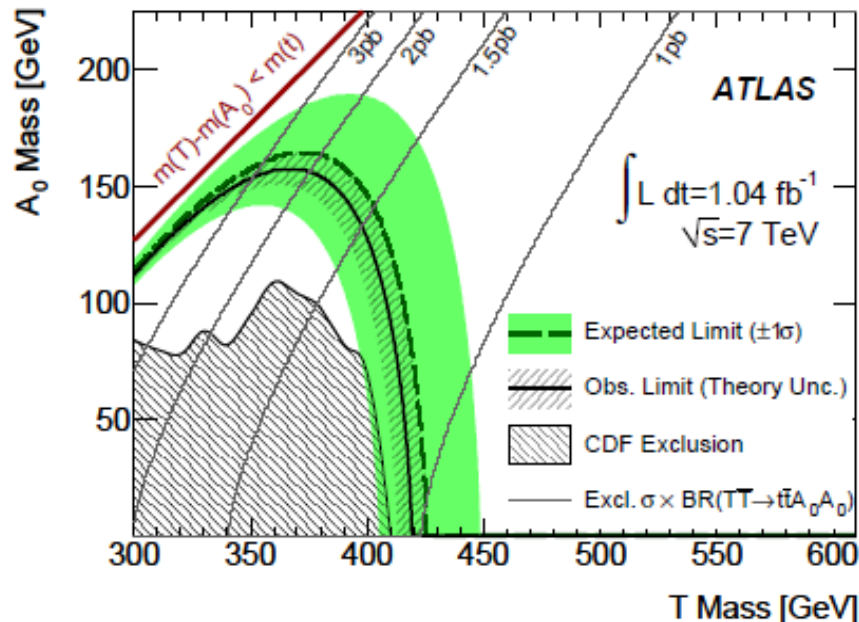
# TT → tA0tA0 (tt + E<sub>t</sub><sup>miss</sup>) 2/2

1fb<sup>-1</sup>

arXiv:1109.4725

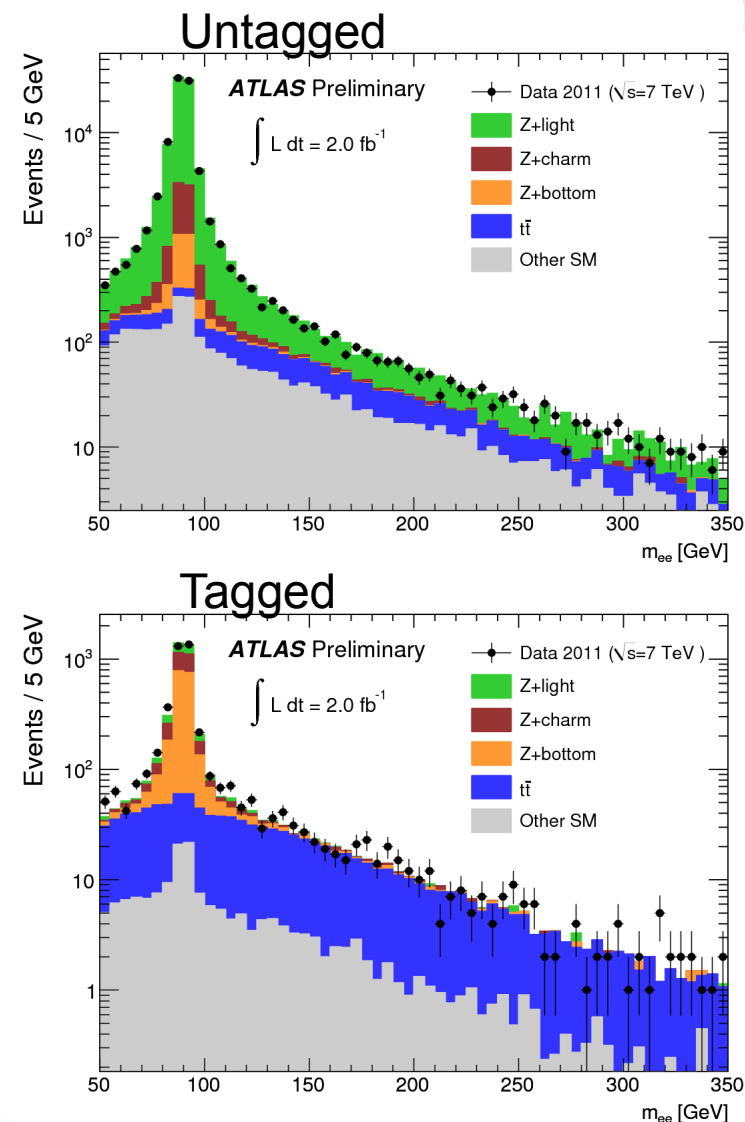
- Assuming BR(T → tA0) = 1
- Cut and count method used to set limit using frequentist confidence intervals
- 95% CL limits on TT pair production cross section (depend on A0 and T masses)
  - m(T) < 420 GeV for m(A0) < 10GeV
  - 330 < m(T) < 390 GeV for m(A0) < 140GeV

Could be applied to VLQ  
 TT → WbZt, ZtZt (with Z → νν)  
 TT → Wb Ht (H invisible)



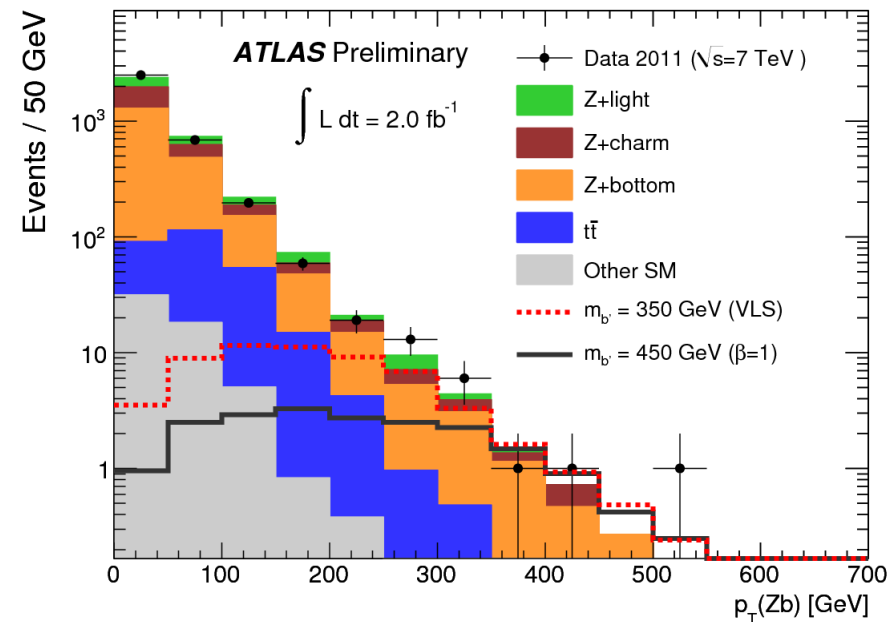
2fb<sup>-1</sup>

- Final state BB  $\rightarrow$  Zb + X  $\rightarrow$  llb + X
- Focus on a least one B  $\rightarrow$  Zb
- Using only electron channel: Z  $\rightarrow$  ee
- Preselection:
  - Single electron trigger (95%)
  - $\geq 2$  OS electrons
  - electron pT > 25GeV  $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
  - $\geq 1$ jet with pT>25GeV (antikt04)
  - $\geq 1$  bjet (60% efficiency)



2fb<sup>-1</sup>

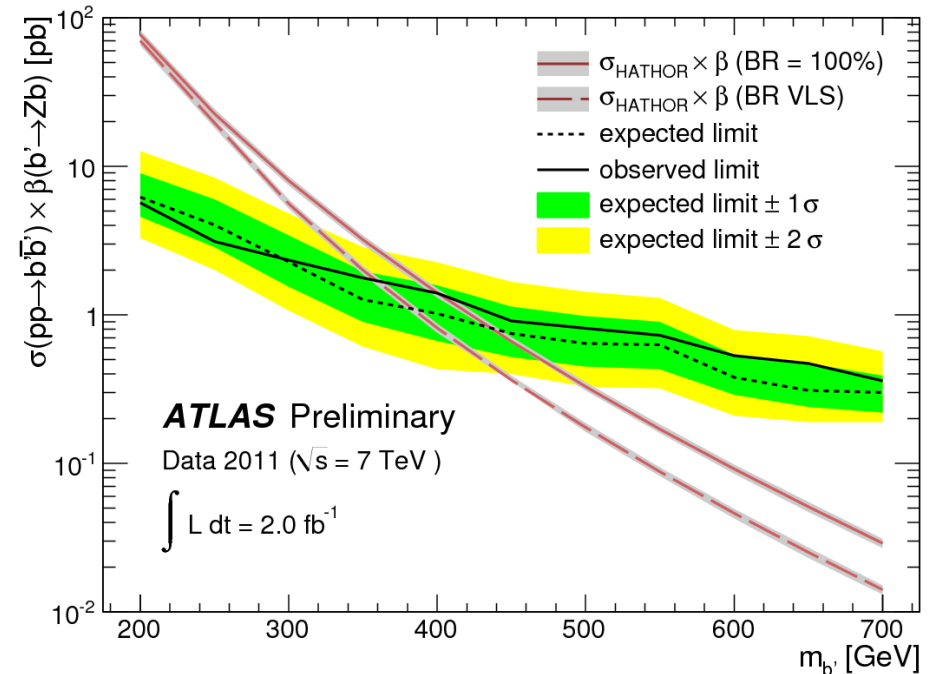
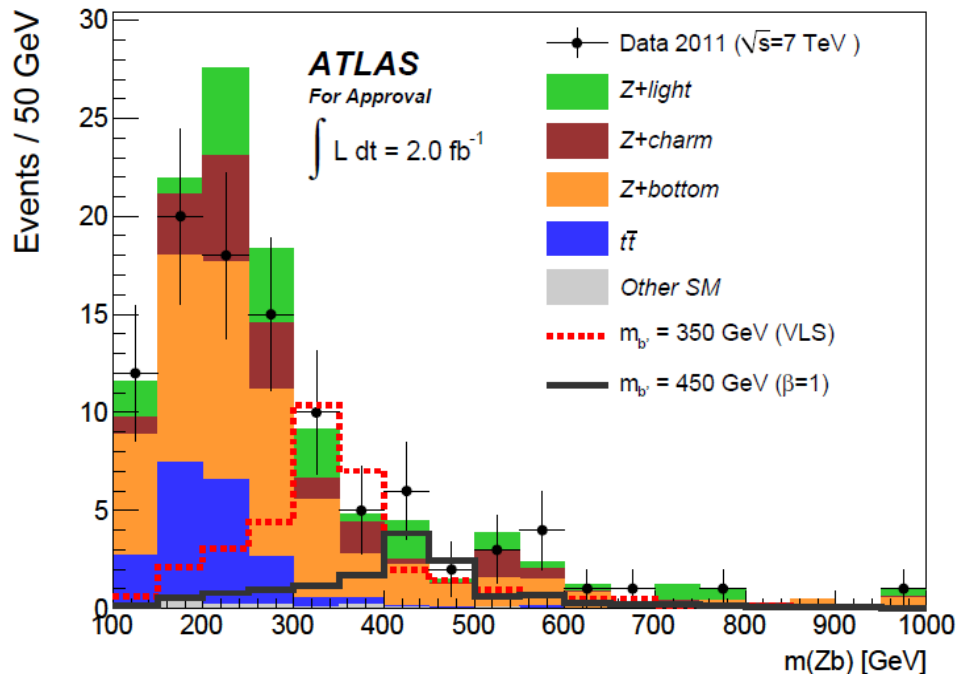
- Exploit boosted configuration of the Zb system
- Z candidate → 2OS electrons satisfying  $|M_{ee} - M_Z| < 15\text{GeV}$  (take the closest to MZ)
- B → Zb formed with Z and highest p<sub>T</sub> b jet
- Final selection:
  - p<sub>T</sub>(Zb) > 150GeV → heavy quarks produced with large p<sub>T</sub>



Source	Z+ ≥ 1 jet	Z+ ≥ 1 b-jet	p <sub>T</sub> (Zb) > 150 GeV
Z+light	74400 ± 7300	590 ± 140	19 ± 7
Z+charm	5340 ± 520	870 ± 210	18 ± 7
Z+bottom	2540 ± 250	1710 ± 270	52 ± 17
t $\bar{t}$	320 ± 40	220 ± 40	20 ± 4
Other SM	1010 ± 280	70 ± 20	1.6 ± 0.4
Total SM	83600 ± 8100	3460 ± 580	110 ± 30
<b>Data</b>	<b>80519</b>	<b>3466</b>	<b>100</b>
m <sub>B</sub> = 350 GeV	110 ± 12	93 ± 11	55 ± 7
m <sub>B</sub> = 450 GeV	27 ± 3	20 ± 2	14 ± 2

2fb<sup>-1</sup>

- Final discriminant M(Zb)
- 2 scenarios  $\rightarrow$  maximal mixing  $\beta=1$ ; Vector Like Singlet (VLS) solely mixing with 3<sup>rd</sup> generation (mass dependent  $\beta=0.9-0.5/200-700\text{GeV}$ )
- SM Higgs mass of 125GeV assumed
- Set limits with mclimit
- $m(b') > 400$  (358) GeV @ 95%C.L. For beta=1 (VLS)

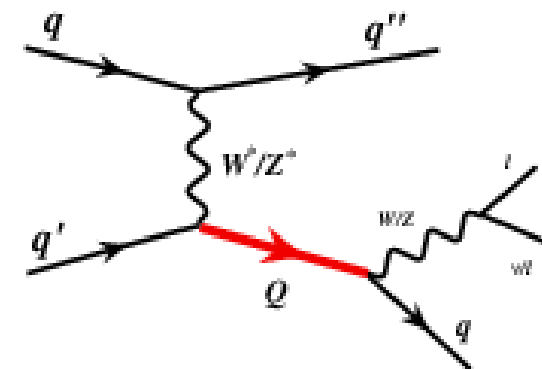
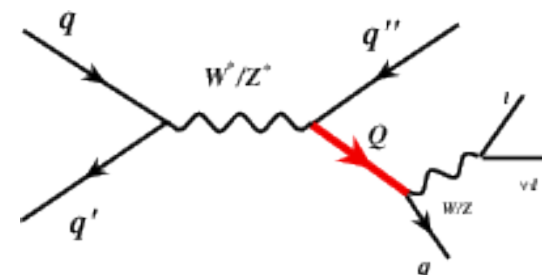




1fb<sup>-1</sup>

arXiv:1112.5755

- Search for vector like quarks (VLQ)  $Q$  singly produced both in
  - Charged Current (CC)  $pp \rightarrow Qq \rightarrow Wq_1q_2$
  - Neutral Current (NC)  $pp \rightarrow Qq \rightarrow Zq_1q_2$
- Assuming only leptonic decays of the gauge boson
- Both S and T channels contribute to the signal cross section
- Assume VLQ couples to first two generation only (2 degenerate VLQ doublets)  $\rightarrow$  potentially strong signal at the LHC
- Couplings  $K_{qQ} = (\nu/m_Q)K'_{qQ}$ 
  - $q$  is any light quark;  $Q$  is VLQ,  $m_Q$  VLQ mass
  - $\nu$  Higgs vev
  - $K'_{qQ} \rightarrow$  the model dependence of the  $qVQ$  vertex ( $V = W$  or  $Z$ )
- Consider only VLQs  $U$  and  $D$  of charge  $+2/3$  and  $-1/3$



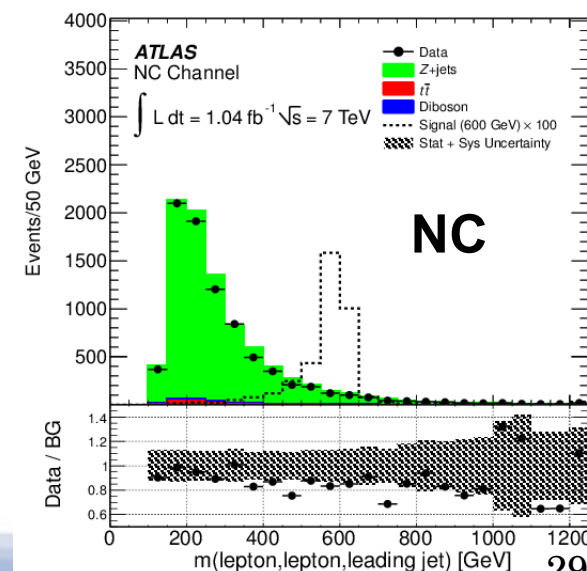
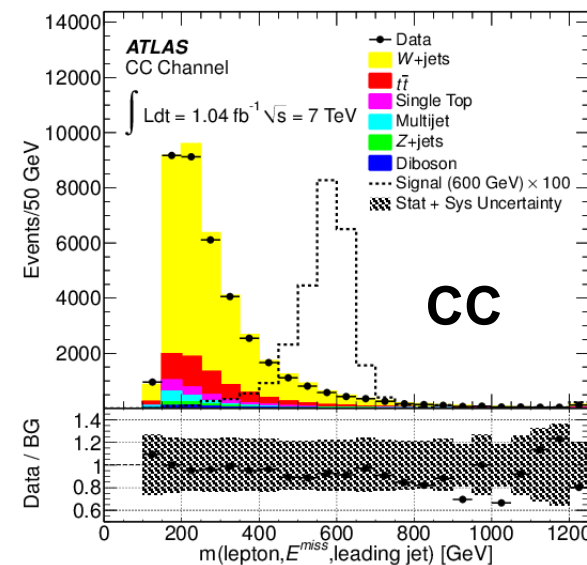
1fb<sup>-1</sup>

arXiv:1112.5755

- Event selection, considering electron and muon channels:
- Single lepton triggers
- Isolated electron,  $p_T > 25\text{GeV}$ ,  $|\eta| < 2.47 \notin 1.37 < |\eta| < 1.52$
- Isolated muon,  $p_T > 25\text{GeV}$ ,  $|\eta| < 2.5$
- Jets reconstructed with antiKT0.4
- Charge Current:
  - Exactly one lepton
  - $E_t^{\text{miss}} > 50\text{GeV}$
  - At least 2 jets with  $p_T > 50, 25\text{ GeV}$
  - $|\Delta\eta| > 1$  leading jet  $p_T$  and 2<sup>nd</sup> or 3<sup>rd</sup> jet
  - $m_T(W) > 40\text{GeV}$
  - $\Delta\Phi(l, E_t^{\text{miss}}) > 2.4$  (expect boosted Ws)
  - VLQ mass  $\rightarrow m(W, \text{jet})$  with leading jet  $p_T$  ( $\nu$  pz chosen to give the largest  $|\Delta\eta|$  between neutrino and leading jet  $p_T$ )

Neutral Current:

- Exactly two opposite charged same-flavor leptons
- $66 < M_{ll} < 116\text{GeV}$ ,  $p_T(l, l) > 50\text{GeV}$  (expect boosted Zs)
- At least 2 jets with  $p_T > 25\text{GeV}$
- VLQ mass  $\rightarrow m(l, l, \text{jet})$  with leading jet  $p_T$



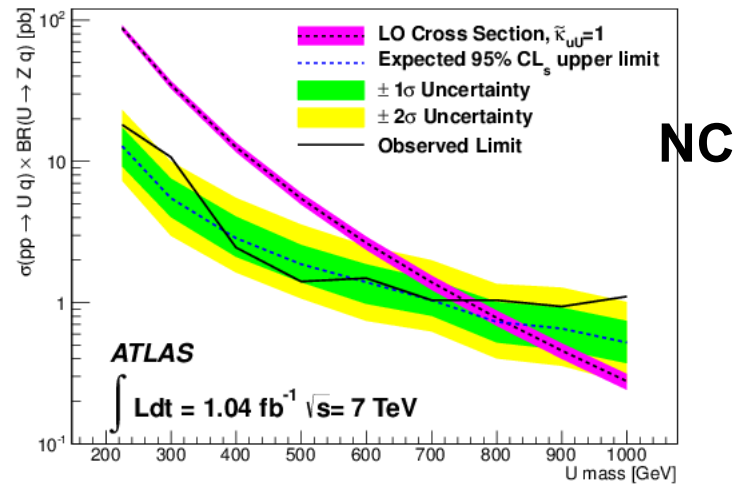
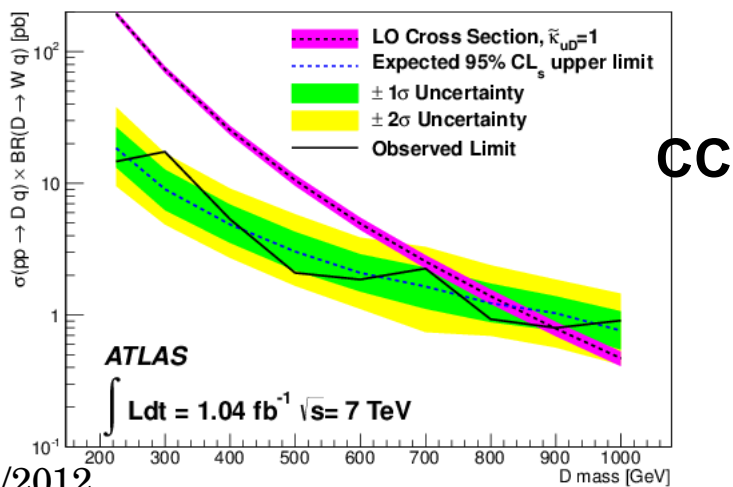
1fb<sup>-1</sup>

arXiv:1112.5755

- Cls method and binned maximum Likelihood
- Search performed by searching a signal peak on top of a smooth background
- No evidence of VLQ found
- Assuming  $K'_{uU} = K'_{uD} = 1$  set limits  $\rightarrow m_{VLQ} > 900(760)$  GeV for CC(NC) @95% C.L.
- **Tevatron limits**  $\rightarrow K'_{uU}=1$  690GeV (100% BR CC) ;  $K'_{uD}=\sqrt{2}$  550GeV (100% BR NC)

Process	Electron channel	Muon channel
$W$ +jets	14500 ± 100 ± 4400	16600 ± 100 ± 5000
$t\bar{t}$	2360 ± 50 ± 270	2530 ± 50 ± 290
Single Top	700 ± 30 ± 120	740 ± 27 ± 120
Multijet	670 ± 30 ± 270	340 ± 20 ± 410
$Z$ +jets	128 ± 11 ± 90	432 ± 21 ± 170
Diboson	174 ± 13 ± 53	198 ± 14 ± 62
Expected Total Background	18500 ± 100 ± 4400	20900 ± 100 ± 5100
Data	17302	20668
Expected Signal, $D(225$ GeV)	2360 ± 50 ± 350	2380 ± 50 ± 400
Expected Signal, $D(600$ GeV)	133 ± 12 ± 10	133 ± 12 ± 11
Expected Signal, $D(1000$ GeV)	14 ± 4 ± 1	14 ± 4 ± 1

Process	Electron Channel	Muon Channel
$Z$ +jets	3250 ± 60 ± 430	5350 ± 70 ± 700
$t\bar{t}$	58 ± 8 ± 3	90 ± 9 ± 5
Diboson	38 ± 6 ± 4	58 ± 8 ± 4
Expected Total Background	3350 ± 60 ± 430	5500 ± 70 ± 700
Data	3105	5070
Expected Signal, U(225 GeV)	192 ± 14 ± 9	339 ± 18 ± 19
Expected Signal, U(600 GeV)	15 ± 3.9 ± 0.6	23 ± 4.8 ± 0.7
Expected Signal, U(1000 GeV)	1.9 ± 1.4 ± 0.1	2.7 ± 1.6 ± 0.1



# Summary of the results

- 4<sup>th</sup> generation:
  - $b'b' \rightarrow Wt$  (100% BR) 480GeV (single lepton; 1.04fb<sup>-1</sup>, arxiv:1202.5520)
  - $b'b' \rightarrow Wt$  (100% BR) 450GeV (SS leptons; 1.04fb<sup>-1</sup>, arxiv:1202.6540)
  - $t't' \rightarrow Wb$  (100% BR) 404GeV (single lepton; 1.04fb<sup>-1</sup>, arXiv:1202.3076)
  - $t't' \rightarrow Wq$  (q=d,s,b) 350GeV (dilepton; 1.04fb<sup>-1</sup>, arXiv:1202.3389)
- Vector like quarks:
  - $BB \rightarrow Zb+X$  400(358)GeV  $\beta=1$ (VLS) (dilepton; 2fb<sup>-1</sup>)
  - $T \rightarrow Wq$  (no coupling to 3<sup>rd</sup> generation) 900GeV (1.04 fb<sup>-1</sup>, arXiv:1112.5755)
  - $T \rightarrow Zq$  (no coupling to 3<sup>rd</sup> generation) 750GeV (1.04 fb<sup>-1</sup>, arXiv:1112.5755)



# Conclusion and Outlook

- ATLAS performed the search for new heavy quarks in several decay channels
  - Search for new heavy quarks made a lot of quick progress at ATLAS
  - ATLAS limits are now the most stringent ones (published)
  - Unfortunately no sign of new physic yet :(
- Our program of heavy quark searches is barely covering the tip of the iceberg....
- We have a nice set of searches focusing on pair production but much territory remains to be explored (NC decay modes, boosted topologies, single production, etc).
- Very exciting prospects ahead!
  - Factor of 5 increase in statistics from analyses (2011 dataset).
  - Also re-optimized/broader scope analyses and new channels!
  - Up to 15 fb<sup>-1</sup> at  $\sqrt{s}=8$  TeV by then end of 2012.
- Lots of fun coming soon :)

# Bonus Slides

# New heavy quarks

- Over the past decades, Standard Model (SM) has been very successful in describing all the experimental measurements using “only” three generations of quarks and lepton family
- Many BSM models predict new heavy quarks: Extra-dimension, little higgs, new SM like generations, GUTs, etc...
- → Can be vector like, can have flavor changing neutral current decays, etc...
- Initial searches at the LHC focus mainly on pair produced heavy quarks, decaying mostly like the top-quark
- Benchmark model:
  - Simplest extension of the SM: 4<sup>th</sup> sequential generation of fermions

Quarks	u	c	t	t'
	d	s	b	b'
Leptons	$\nu_e$	$\nu_\mu$	$\nu_\tau$	$\nu'$
	e	$\mu$	$\tau$	$\tau'$
	I	II	III	IV

# Vector like quarks

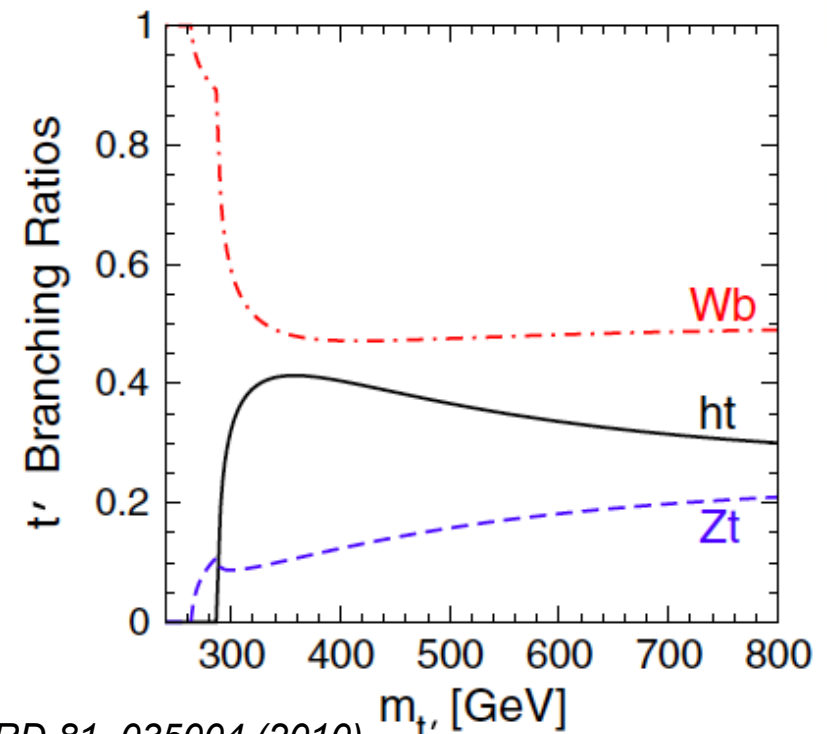
- Vector-like quarks: left and right components transform the same under  $SU(2)_L$   
→ can couple to SM particles without upsetting precision EW and flavor constraints.
- Vector-like quarks in a doublet → nearly degenerate in mass
- Predicted by many BSM models → extra-dimensions, Little Higgs, GUTs,...
- Mixing with other quarks is  $\sim m/M$  → preferentially couple to the 3<sup>rd</sup> generation.
- Quite a few possibilities to explore! BRs can be quite model-dependent.

“Democratic”

*JHEP 11, 030 (2009)*

Triplets not included

	Label	Charge	Decay mode
T singlet	$T_s$	+2/3	$T \rightarrow W^+b, Zt, Ht$
B singlet	$B_s$	-1/3	$B \rightarrow Wt, Zb, Hb$
(T,B) doublet	$TB_d$	(+2/3, -1/3)	$T \rightarrow W^+b, Zt, Ht$ $B \rightarrow Wt, Zb, Hb$
(X,T) doublet	$XT_d$	(+5/3, +2/3)	$X \rightarrow W^+t$ $T \rightarrow Zt, Ht$
(B,Y) doublet	$BY_d$	(-1/3, -4/3)	$B \rightarrow Zb, Hb$ $Y \rightarrow Wb$



*PRD 81, 035004 (2010)*



# Vector like quarks

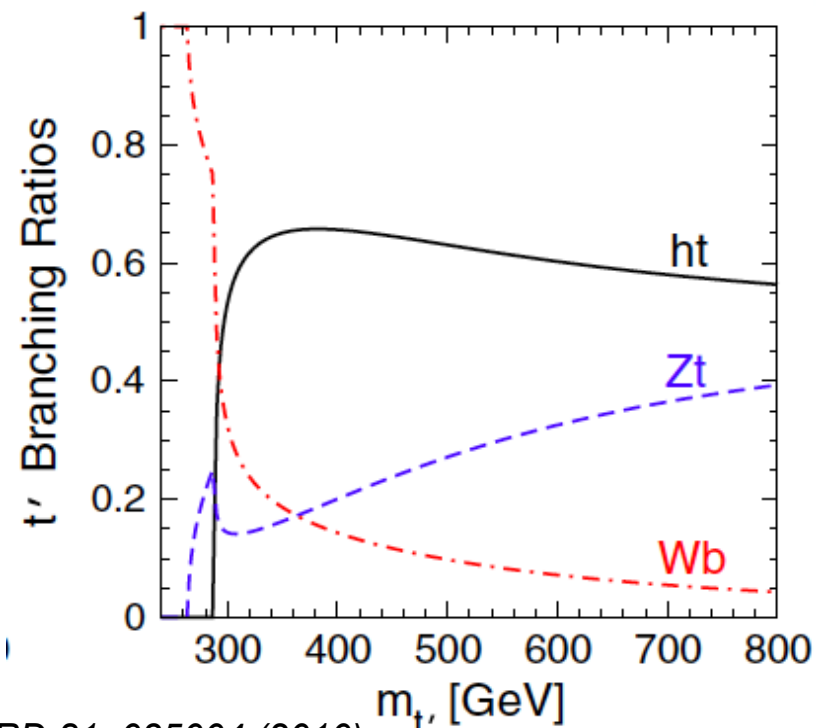
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“W-phobic”

JHEP 11, 030 (2009)

Triplets not included

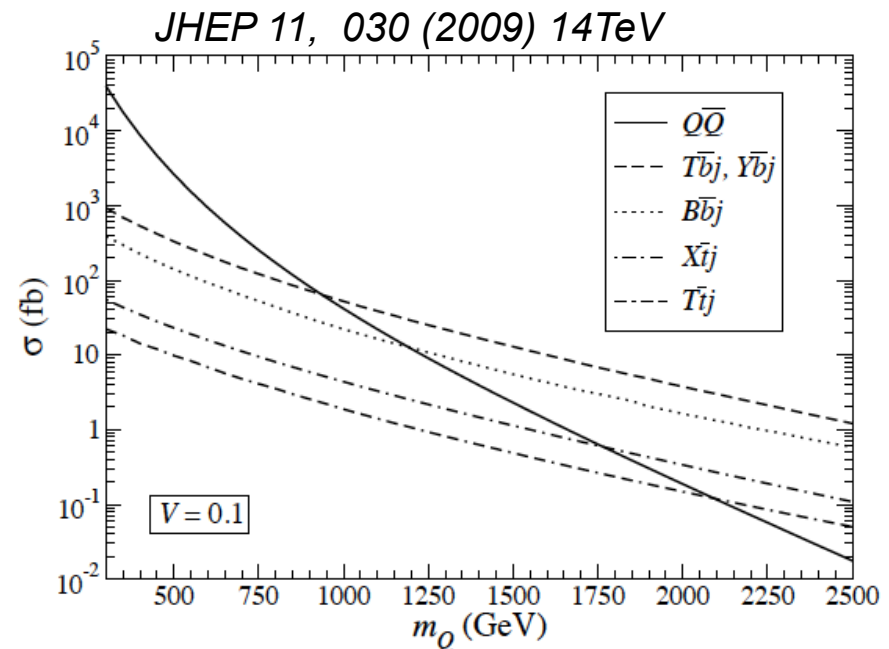
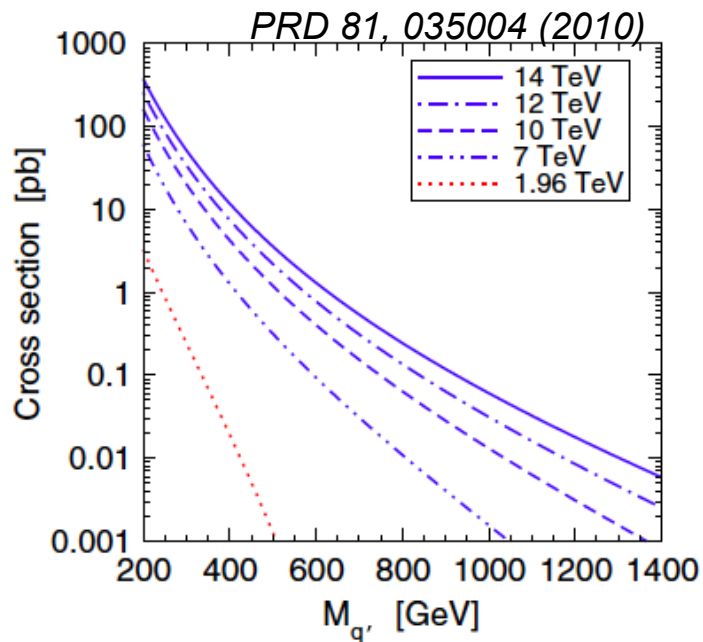
	Label	Charge	Decay mode
T singlet	$T_s$	+2/3	$T \rightarrow W^+b, Zt, Ht$
B singlet	$B_s$	-1/3	$B \rightarrow Wt, Zb, Hb$
(T,B) doublet	$TB_d$	(+2/3, -1/3)	$T \rightarrow W^+b, Zt, Ht$ $B \rightarrow Wt, Zb, Hb$
(X,T) doublet	$XT_d$	(+5/3, +2/3)	$X \rightarrow W^+t$ $T \rightarrow Zt, Ht$
(B,Y) doublet	$BY_d$	(-1/3, -4/3)	$B \rightarrow Zb, Hb$ $Y \rightarrow Wb$



PRD 81, 035004 (2010)

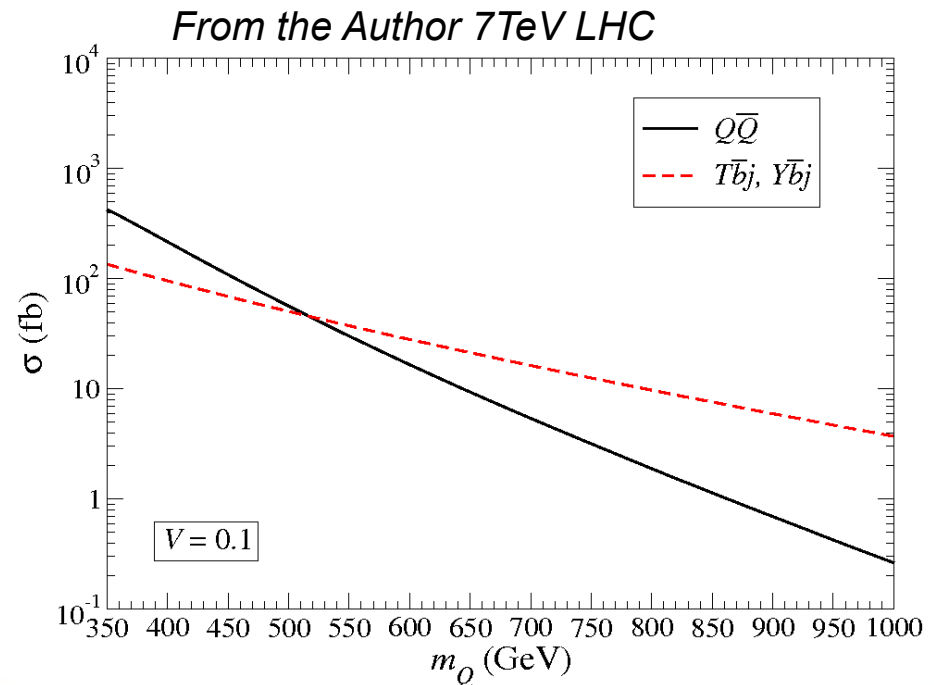
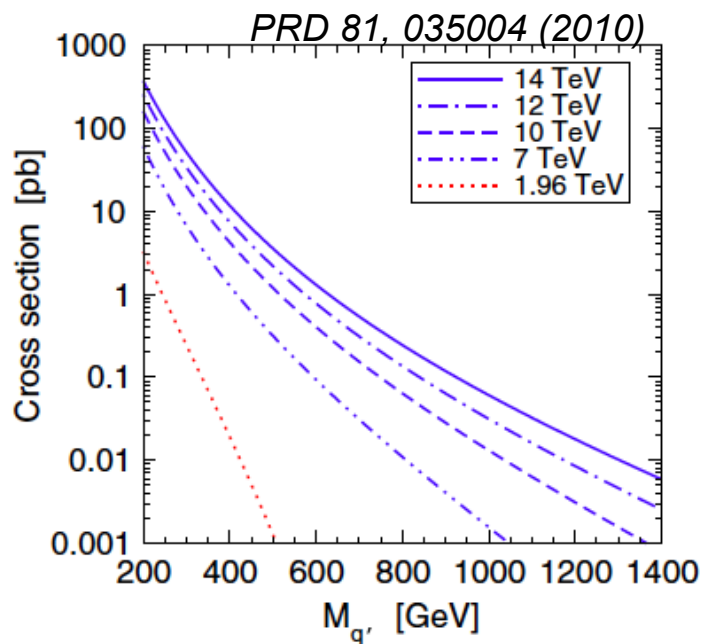
# Heavy quark production

- Up to masses  $\sim 1$  TeV, dominant production is in pairs via the strong interaction:
- $\sqrt{s}=7$  TeV:  $\sigma(Q\bar{Q}) \sim 1.5$  pb for  $m_Q \sim 400$  GeV vs  $\sigma(tt) = 160$  pb
- $\sqrt{s}=14$  TeV:  $\sigma(Q\bar{Q}) \sim 8$  pb for  $m_Q \sim 400$  GeV vs  $\sigma(tt) = 880$  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  $\sim 1$  TeV (14TeV LHC) the dominant production mode is single via the EW interactions (model-dep, but also opportunity to measure weak couplings of heavy quarks!).



# Heavy quark production

- Up to masses  $\sim 1$  TeV, dominant production is in pairs via the strong interaction:
- $\sqrt{s}=7$  TeV:  $\sigma(Q\bar{Q}) \sim 1.5$  pb for  $m_Q \sim 400$  GeV vs  $\sigma(tt) = 160$  pb
- $\sqrt{s}=14$  TeV:  $\sigma(Q\bar{Q}) \sim 8$  pb for  $m_Q \sim 400$  GeV vs  $\sigma(tt) = 880$  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  $\sim 1$  TeV (14TeV LHC; 0.5TeV for 7TeV LHC ) the dominant production mode is single via the EW interactions (model-dep, but also opportunity to measure weak couplings of heavy quarks!).



# Signatures: 4<sup>th</sup> generation quarks

- 4<sup>th</sup> Generation models → restricted list of available signatures, simplify the search strategy:  
 $t't' \rightarrow WbWb$ ,  $b'b' \rightarrow tWtW \rightarrow WbW WbW$

			$TB_d$		
4 leptons					
	4l (0Z)		BB		
3 leptons					
	3l (0Z)		BB		
OS dileptons					
	$l^+l^-$ (0Z)		TT, BB		
SS dileptons					
	$l^+l^\pm$		BB		
lepton+jets					
	$l^\pm$ (4j)		TT		
	$l^\pm$ ( $\geq 6j$ )		BB		

# 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.

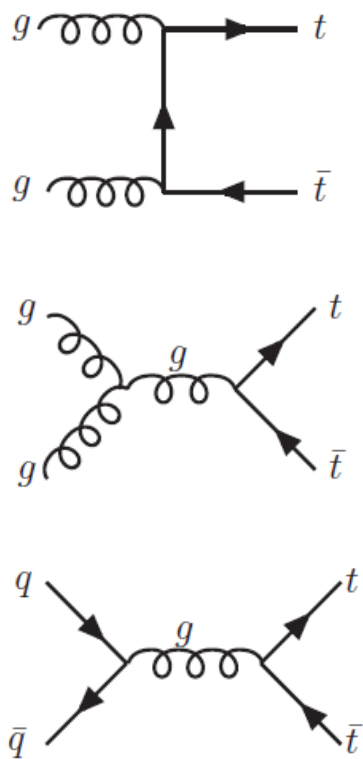
		$T_s$	$B_s$	$TB_d$	$XT_d$	$BY_d$
4 leptons	4l (2Z)	TT	BB	TT, BB	TT	BB
	4l (1Z)	TT	BB	TT, BB	TT	BB
	4l (0Z)	TT	BB	TT, BB	TT, XX	BB
3 leptons	3l (1Z)	TT	BB	TT, BB	TT	
	3l (0Z)	TT	BB	TT, BB	TT, XX	
OS dileptons	$l^+l^-$ (1Z)	TT	BB	TT, BB	TT	BB
	$l^+l^-$ (0Z)	TT	BB	TT, BB	TT, XX	BB, YY
SS dileptons	$l^{\neq}l^{\pm}$		BB	BB	XX	
lepton+jets	$l^{\pm}$ (4j)	TT		TT	TT	YY
	$l^{\pm}$ ( $\geq 6j$ )	TT	BB	TT, BB	TT, XX	

- Of course, some of them are more challenging or powerful than others... Could also split in number of b-jets and number of Higgs ( $120\text{GeV} \rightarrow \sim 60\% \text{ BR } H \rightarrow bb$ )



# Top Quark Pair Production

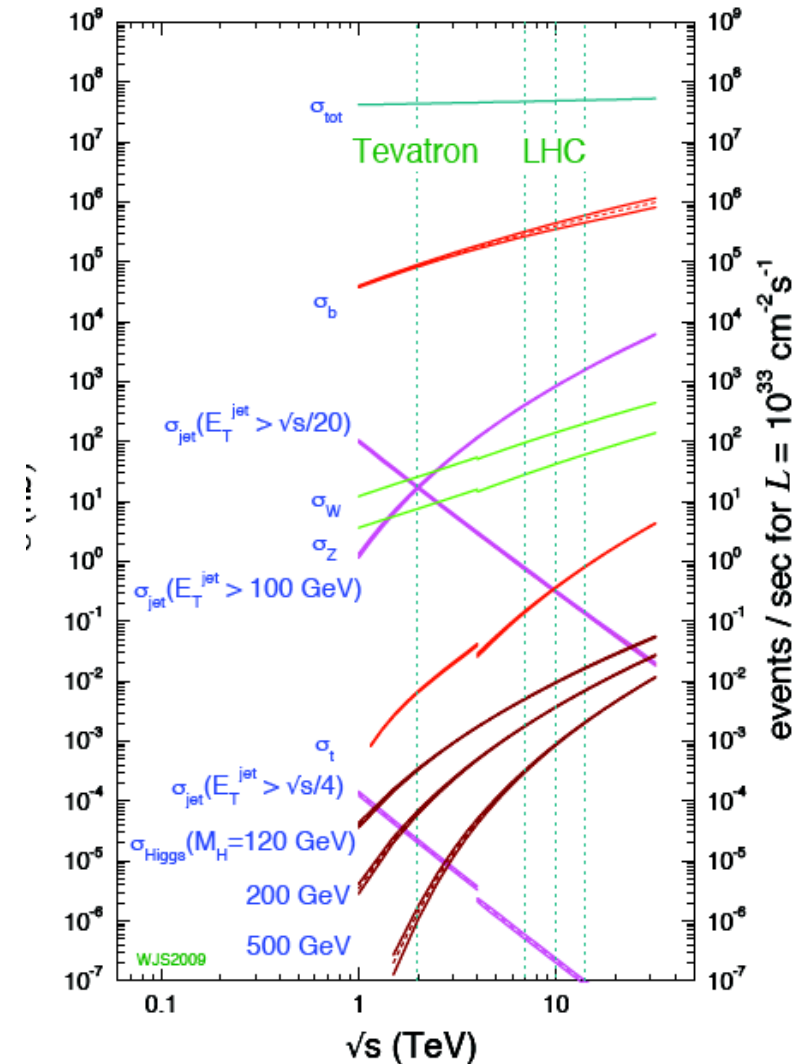
- $\sigma_{tt}$  (7 TeV LHC)  $\sim 165$  pb (172.5 GeV, Moch, Uwer, Langenfeld (Phys. Rev. D78 (2008) 034003, arXiv:0907.2527) =  $20 \sigma_{tt}$  (Tevatron)
- $5\text{fb}^{-1}$  @ 7 TeV already on tape  
 $\rightarrow$  825K ttbar pairs ( $\sim 10$  times Tevatron statistics)



Dominant at the LHC (80%)

Dominant at the Tevatron

proton - (anti)proton cross sections



# Top Quark Event Topology

- Almost all top quarks decay to  $t \rightarrow Wb$
- Final states classified by W decay modes  
 $W \rightarrow qq$  (2/3) or  $W \rightarrow l\nu$  (1/3)
  - All hadronic (no  $W \rightarrow l\nu$ )  $\rightarrow 4/9$  (~45%)
  - Semi-leptonic (1  $W \rightarrow l\nu$ )  $\rightarrow 4/9$  (only electron/muon considered  $\rightarrow$  ~31%)
  - Di-leptonic (2  $W \rightarrow l\nu$ )  $\rightarrow 1/9$  (only electron /muon considered  $\rightarrow$  ~5%)

$\bar{c}s$	electron+jets			muon+jets			tau+jets			all-hadronic		
$\bar{u}d$	electron+jets			muon+jets			tau+jets			all-hadronic		
$\tau^-$	$e\tau$	$\mu\tau$	$\tau\tau$	tau+jets			tau+jets			all-hadronic		
$\mu^-$	$e\mu$	$\mu\mu$	$\tau\mu$	muon+jets			muon+jets			all-hadronic		
$e^-$	$e\mu$	$e\mu$	$e\tau$	electron+jets			electron+jets			all-hadronic		
W decay	$e^+$	$\mu^+$	$\tau^+$	$u\bar{d}$			$c\bar{s}$			all-hadronic		

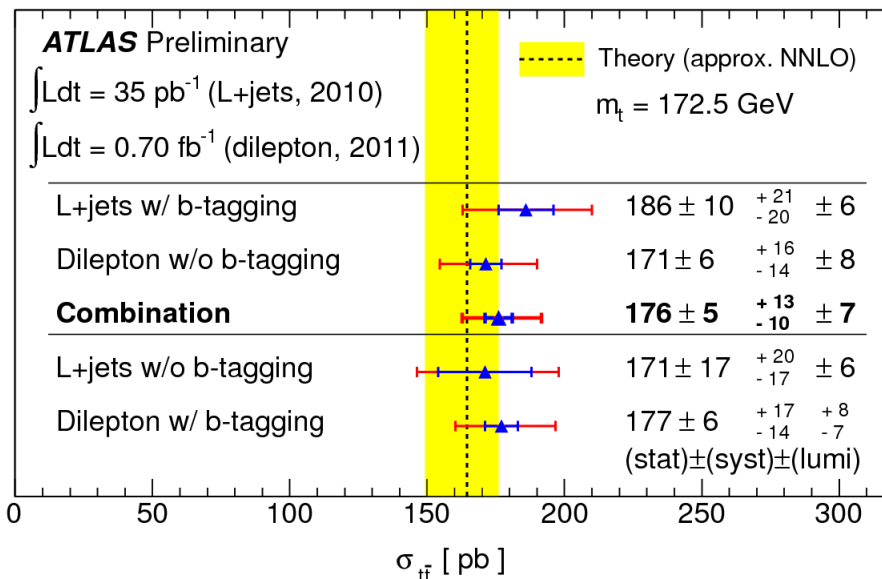
- The top-quark provides a virtual lab to search for new physics
  - Many tops have already been produced at LHC!!
  - Various properties of the top-quark have been measured
  - This helps us to provides procedures/tools to separate SM backgrounds from new physics

# Top Quark Physic Status (cross sections only...)

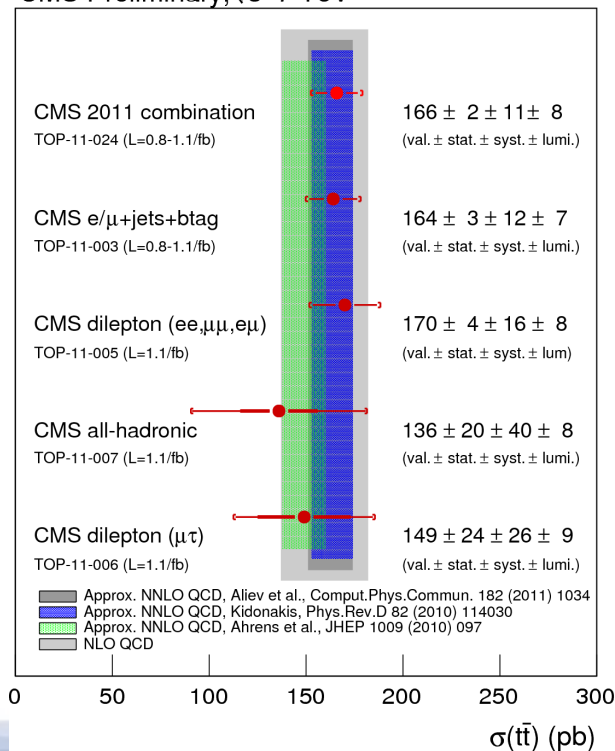


ATLAS

- Single lepton: (0.7fb-1)  $\sigma(ttbar) = 179.0 +9.8-9.7$  (stat+syst)  $\pm 6.6$ (lumi.)pb
- Dilepton: (0.7fb-1) :  $\sigma(ttbar) = 177 \pm 6$  (stat.)+17-14 (syst.)  $\pm 8$  (lum.)pb
- Combination (L+jets 35pb-1 and DL 0.7fb-1 no btag):  $\sigma(ttbar) = 176 \pm 5$ (stat.) +13-10(syst.)  $\pm 7$  (lumi.)pb.
- CMS combine L+jets, dilepton, mu+tau, all hadronic (0.8-1.1fb-1)  $\sigma(ttbar) = 165.8 \pm 2.2$  (stat.)  $\pm 10.6$  (syst.)  $\pm 7.8$  (lumi.) pb.
- → results with more luminosity coming soon approaching theoretical errors!

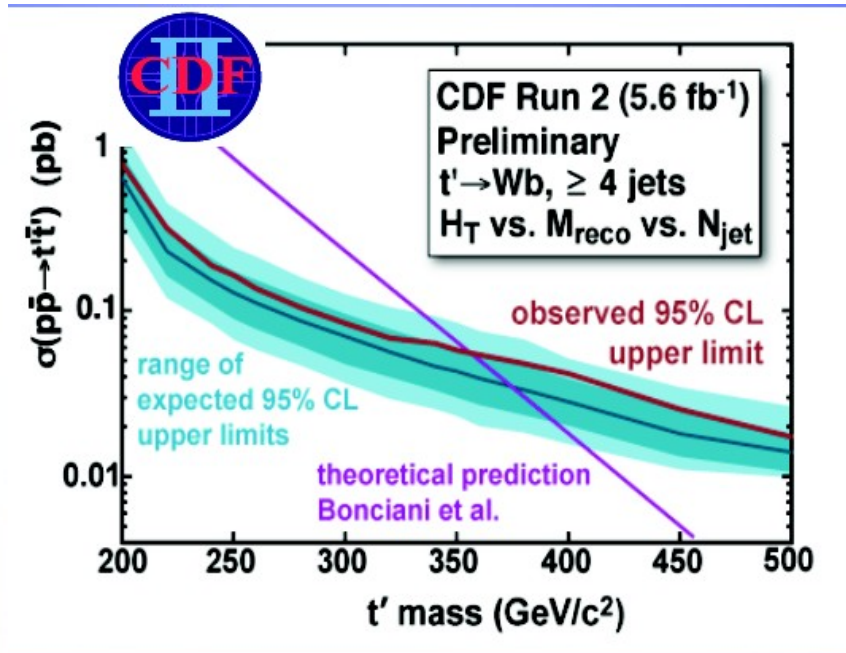


CMS Preliminary,  $\sqrt{s}=7 \text{ TeV}$

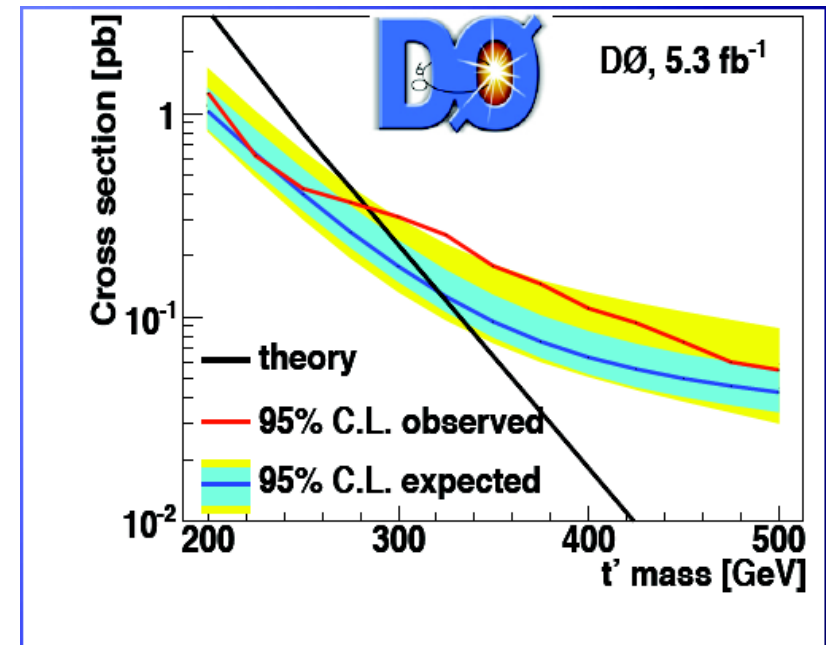


# Tevatron Results $t'$ (4<sup>th</sup> gen)

- $t' \rightarrow Wb, L+jets$  Channel
- No signal consistent with  $t'$  pair production



$m(t') > 358\text{GeV}$  (CDF) @ 95% C.L.



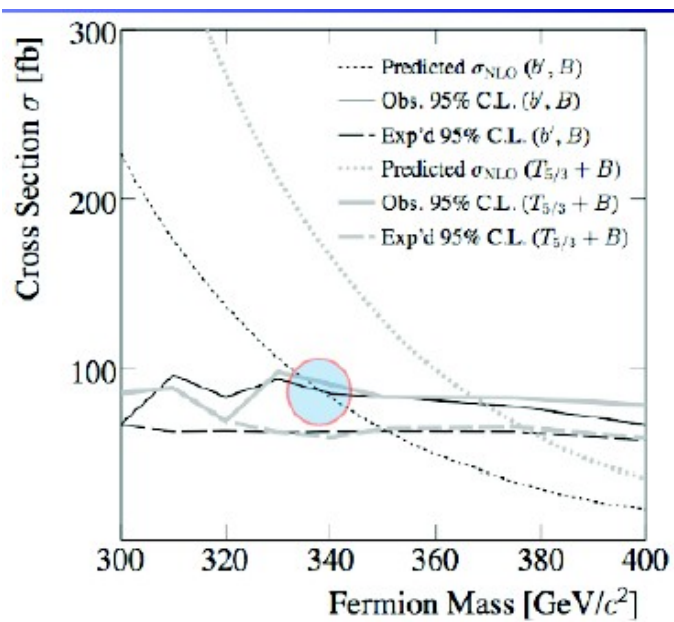
$m(t') > 285\text{GeV}$  (DO) @ 95% C.L.



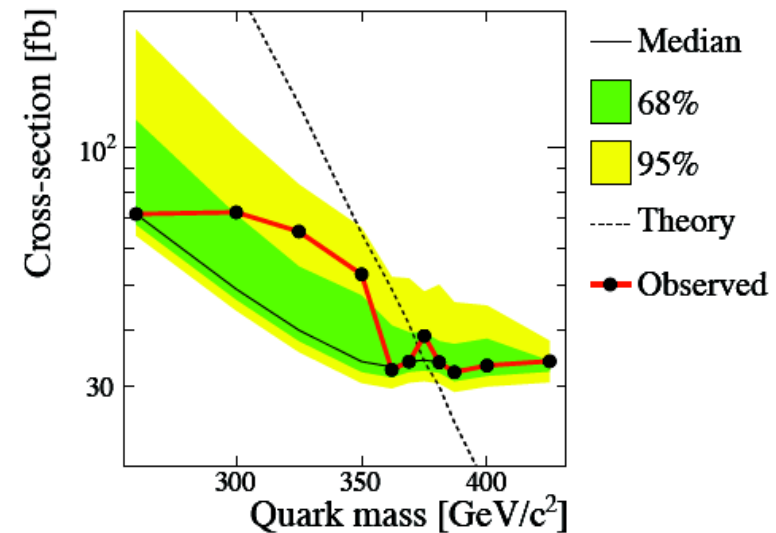
# Tevatron Results $b'$ ( $4^{\text{th}}$ gen)

- $b' \rightarrow Wt \rightarrow WWb, L+\text{jets}$  Channel and same-signed leptons
- No signal consistent with  $b'$  pair production

### Same-signed



### Lepton+jets



$m(b') > 338\text{GeV}$  (CDF) @ 95% C.L.

$m(b') > 372\text{GeV}$  (CDF) @ 95% C.L.



# CMS – Search for $b'$ 1/3

PAS-EXO-11-036



- $b'b' \rightarrow tWtW \rightarrow WbW WbW$ 
  - 2 same sign or three isolated leptons (e/mu) in the final state  $\rightarrow 7.3\%$  of the decay
  - Dilepton triggers  $\rightarrow 92\%$  (mu/mu),  $96\%$  (e/mu),  $>99\%$  (e/e)
  
- Selection criteria:
  - Muons:  $p_T > 20\text{GeV}$ ,  $|\eta| < 2.4$ ; isolation  $\Sigma ET(\Delta R < 0.3) - \text{pileup} < 0.15 * p_T$
  - Electron:  $p_T > 20\text{GeV}$ ,  $|\eta| < 2.4 \notin 1.44 < |\eta| < 1.57$ ; isolation  $\Sigma ET(\Delta R < 0.3) - \text{pileup} < 0.06 * p_T$ 
    - Select event with 2 opposite sign leptons or three leptons (2 of them opposite charge)
  - For same flavor leptons  $\rightarrow Z$  mass veto:  $|m_{ll} - m_Z| > 10\text{GeV}$
  - B-tagging based on IP significance  $\rightarrow 50\%$  b-tag efficiency;  $1\%$  mistag rate;  $n_{\text{bjet}} \geq 1$
  - Jets clustered using PF particles and Anti-kt with a cone of 0.5;  $p_T > 25\text{GeV}$ ;  $|\eta| < 2.4$ 
    - Same sign lepton  $\rightarrow n_{\text{jets}} \geq 4$ ; 3 lepton channel  $n_{\text{jets}} \geq 2$
  - $ST = \text{scalar sum of jet } p_T, \text{ lepton } p_T, \text{ MET}$ , should be  $> 500\text{GeV}$
  
- Signal selection efficiency:

$M_{b'}$ [GeV/ $c^2$ ]	cross section [pb]	same-sign dilepton		trilepton	
		efficiency [%]	yield	efficiency [%]	yield
350	3.20	$1.16 \pm 0.15$	42	$0.33 \pm 0.06$	12
400	1.41	$1.36 \pm 0.17$	22	$0.42 \pm 0.06$	6.7
450	0.662	$1.51 \pm 0.18$	11	$0.45 \pm 0.07$	3.4
500	0.330	$1.57 \pm 0.19$	5.9	$0.48 \pm 0.07$	1.8
550	0.171	$1.80 \pm 0.22$	3.5	$0.57 \pm 0.08$	1.1

# CMS – Search for $b'$ 2/3

PAS-EXO-11-036

**1fb<sup>-1</sup>**

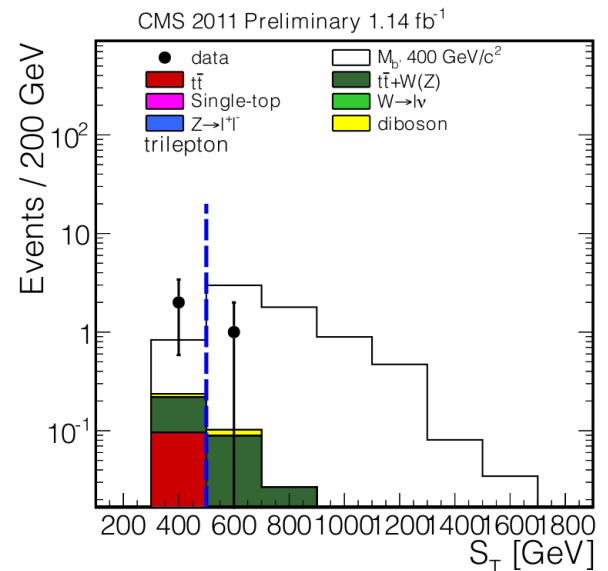
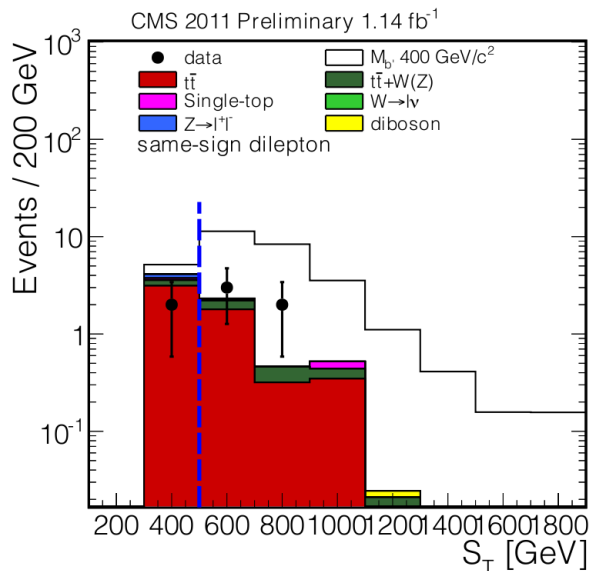
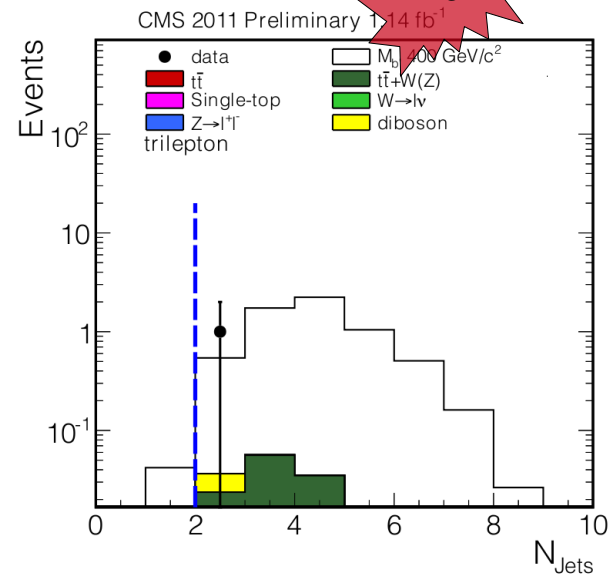
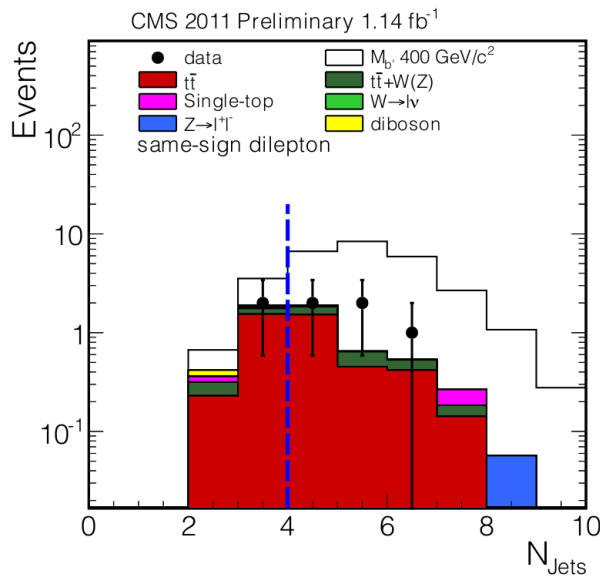
Backgrounds:

- Same sign 2 leptons → main contribution is from  $t\bar{t}$
- 3 leptons; main contribution  $t\bar{t}+W(Z)$

- Good modeling of the data, no sign of any excess → set limits

Expected/observed yields:

	Total BG in signal region	Data
2SS	4.4 +/- 1.4	5
3 lepton	0.16 +/- 0.09	1



# CMS – Search for $b'$ 3/3

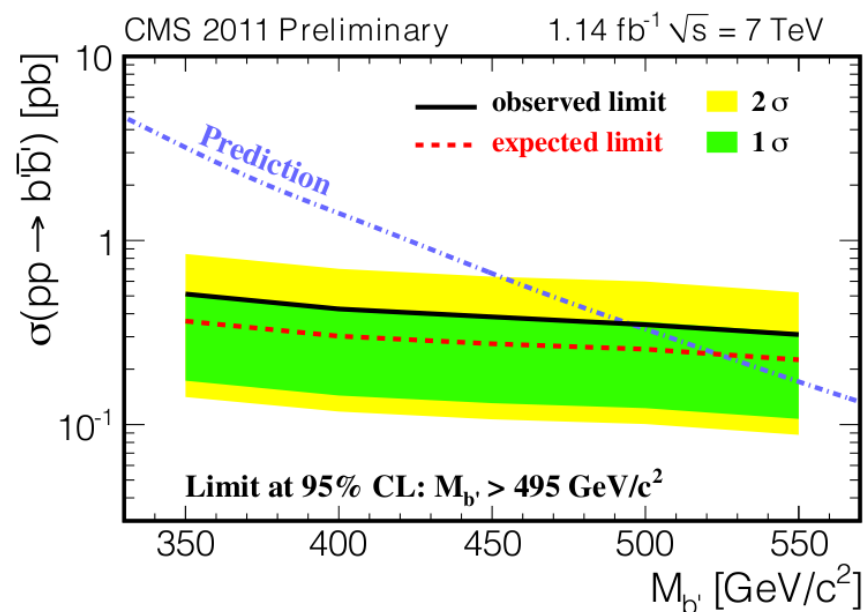
PAS-EXO-11-036

1fb<sup>-1</sup>

- Limits extracted using a cut and count method
- Bayesian method with log-normal prior for integration over the nuisance parameters
- Observed limit:  $m(b') > 495\text{GeV}$  @ 95%CL**

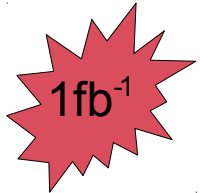
	Total BG in signal region	Data
2SS	4.4 +/- 1.4	5
3 lepton	0.16 +/- 0.09	1

	same-sign dilepton		trilepton	
	$\Delta\epsilon/\epsilon$	$\Delta B$	$\Delta\epsilon/\epsilon$	$\Delta B$
Accuracy of control-sample method	-	1.02	-	-
Control sample statistics	-	0.49	-	-
Integrated Luminosity	4.5%	0.03	4.5%	0.007
Background normalization	-	0.39	-	0.059
Lepton selection	4.4 – 4.5%	0.03	6.2 – 6.5%	0.010
b-tagging	10%	0.07	10%	0.016
Pile-up events	2.3%	0.35	3.4%	0.053
Jet energy scale	1.4 – 3.2%	0.12	0.4 – 4.3%	0.008
Jet energy resolution	0.8 – 2.4%	0.51	0.6 – 3.5%	0.010
Missing energy resolution	0.1 – 3.1%	0.10	0.6 – 6.0%	0.014
Trigger	2.3%	0.07	2.3%	0.004
PDF	0.3 – 0.7%	0.06	0.7 – 1.8%	0.005
Simulated sample statistics	3.1 – 4.0%	0.05	5.6 – 7.4%	0.025
Total	12 – 13%	1.4	14 – 17%	0.09



# CMS – Search for $t'$ dilepton 1/3

PAS-EXO-11-050



- Search for heavy top-like:  $t't' \rightarrow WbWb \rightarrow l\nu b l\nu b$  ( $l=e/\mu$ )
  
- Selection:
  - 2 (or more) opposite sign leptons;  $p_T > 20 \text{ GeV}$ ;  $|\eta| < 2.4$
  - Dilepton triggers efficiency  $\rightarrow$  100, 95, 90% for  $ee$ ,  $e\mu$ ,  $\mu\mu$ , respectively
  - Lepton isolation  $\rightarrow \Sigma ET(\Delta R < 0.3) < 0.15 * p_T$
  - Z mass veto for  $ee$ ,  $\mu\mu \rightarrow$  removed event if  $76 < M_{ll} < 106 \text{ GeV}$  or  $M_{ll} < 12 \text{ GeV}$
  - Jets: Anti-kt  $R=0.5$ ;  $p_T > 30 \text{ GeV}$ ;  $|\eta| < 2.5$  (separated by  $\Delta R > 0.4$  from selected leptons)
    - At least 2 jets and at least two of them b-tag
  - $ET_{\text{Miss}} > 30 \text{ GeV}$

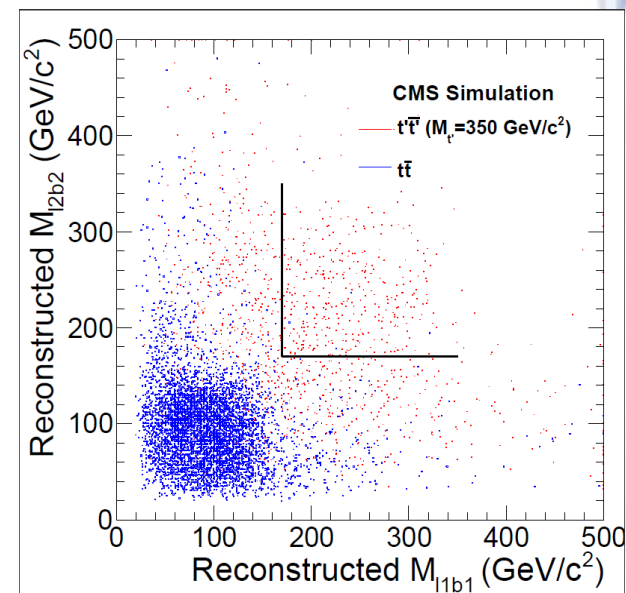
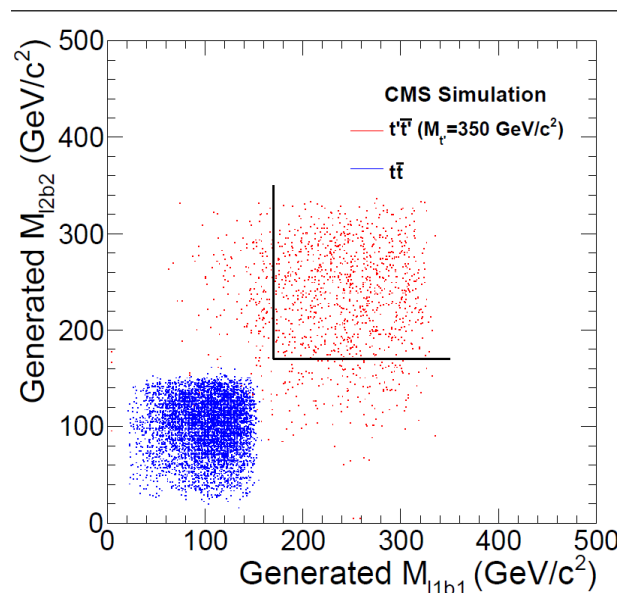
# CMS – Search for $t'$ dilepton 2/3

PAS-EXO-11-050

1fb<sup>-1</sup>

- Signal region:  
→ after basics selection  $t\bar{t}$  dominates...
- The invariant mass of lepton and b-jet is used as discriminant
- At generator level:  
→ clear distinction between  $t'$  and top
- At reconstruction level:  
→ pairing done with  $\min(\Delta R)$  between lepton and bjet
- $M_{lb} > 170\text{GeV}$  is applied for the two masses
  - → signal efficiency ~ 40%
  - →  $t\bar{t}$  very small...

Sample	ee	$\mu\mu$	$e\mu$	all
$t't', M_{t'} = 350\text{ GeV}/c^2$	$5.63 \pm 0.41$	$5.63 \pm 0.38$	$13.43 \pm 0.61$	$24.69 \pm 0.83$
$t'\bar{t}', M_{t'} = 400\text{ GeV}/c^2$	$2.51 \pm 0.18$	$2.92 \pm 0.19$	$6.33 \pm 0.28$	$11.76 \pm 0.38$
$t'\bar{t}', M_{t'} = 450\text{ GeV}/c^2$	$1.45 \pm 0.09$	$1.53 \pm 0.09$	$3.27 \pm 0.14$	$6.25 \pm 0.19$
$t\bar{t} \rightarrow \ell^+\ell^-$	$167.46 \pm 5.85$	$178.88 \pm 5.71$	$445.45 \pm 9.30$	$791.79 \pm 12.38$
$t\bar{t} \rightarrow \text{fake}$	$3.35 \pm 0.85$	$0.19 \pm 0.19$	$5.81 \pm 1.04$	$9.35 \pm 1.36$
W + jets	< 2	< 2	< 2	< 2
DY $\rightarrow \ell^+\ell^-$	$2.23 \pm 1.39$	$2.15 \pm 1.66$	< 1	$4.38 \pm 2.17$
Di-boson	$0.04 \pm 0.01$	$0.14 \pm 0.07$	$0.14 \pm 0.07$	$0.31 \pm 0.10$
Single top	$2.63 \pm 0.28$	$2.41 \pm 0.26$	$7.03 \pm 0.45$	$12.06 \pm 0.59$
Total simulated background	$175.70 \pm 6.08$	$183.76 \pm 5.96$	$458.43 \pm 9.37$	$817.88 \pm 12.66$
Data	184	182	512	878





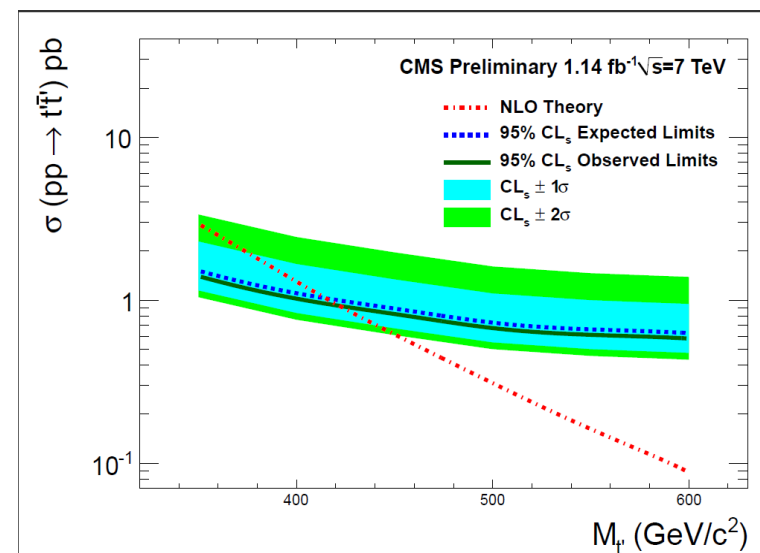
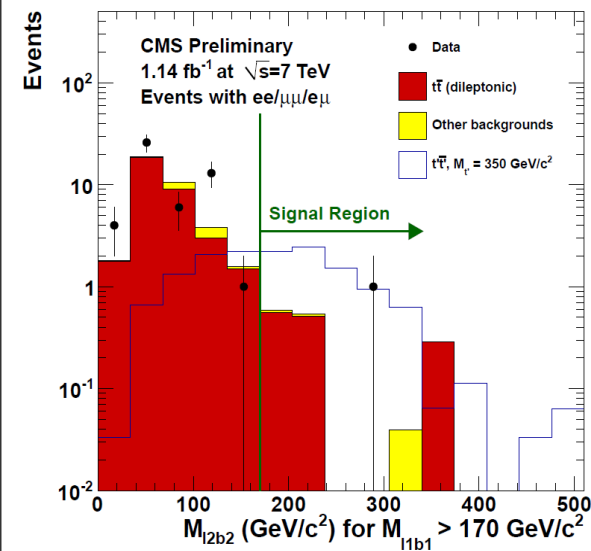
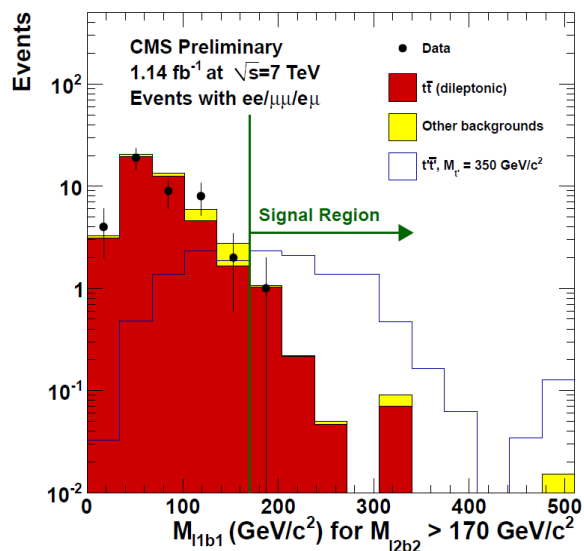
# CMS – Search for $t'$ dilepton 3/3

PAS-EXO-11-050

1fb<sup>-1</sup>

- 1 event observed; 1.62 expected
- 95% CL Limits extracted using Cut and count
- Observed limit  $\rightarrow m(t') > 422\text{GeV} @ 95\% \text{ CL}$
- Analysis updated to 4.7 fb<sup>-1</sup>,  $m(t') > 552\text{GeV} @ 95\% \text{ CL}$

Sample	Yield	Source
$t\bar{t} \rightarrow \ell^+\ell^-$	$1.35 \pm 0.67$	Data
Fake leptons	$0.0^{+0.4}_{-0.0}$	Data
$DY \rightarrow e^+e^-$ or $\mu^+\mu^-$	$0.07^{+0.13}_{-0.07}$	Data
$DY \rightarrow \tau^+\tau^-$	$0.11 \pm 0.11$	Simulation
Di-boson	$0.02 \pm 0.02$	Simulation
Single top	$0.07 \pm 0.04$	Simulation
Total prediction	$1.62^{+0.80}_{-0.70}$	
Data	1	



# CMS – Search for $t'$ single-lepton 1/3

PAS-EXO-11-051

0.5-0.8fb<sup>-1</sup>

- Final state  $t't' \rightarrow WbWb \rightarrow qqbl\nu b$
- Selection:
  - Isolated Electron  $pt > 30 - 45$  GeV (trigger threshold changed)  $|\eta| < 2.4 \notin 1.44 < |\eta| < 1.57$
  - Isolated Muon  $pt > 35$  GeV  $|\eta| < 2.1$
  - Jets: Anti-kt R=0.5  $\rightarrow$  4 jets 120, 90, 35, 35 GeV
  - MET  $> 20$  GeV
  - At least 1 btag jet

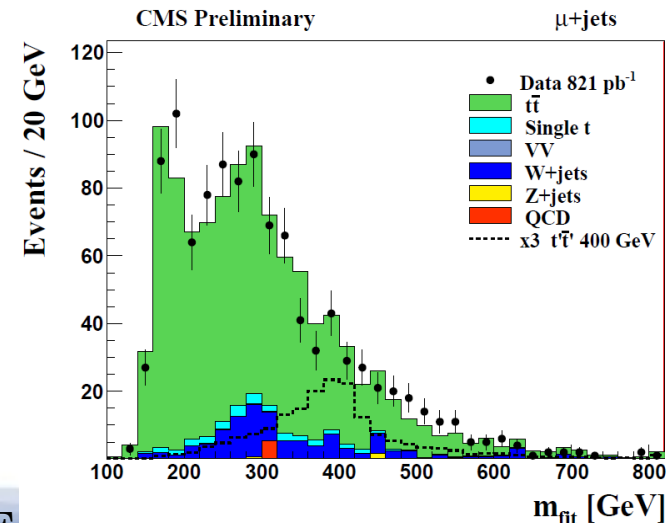
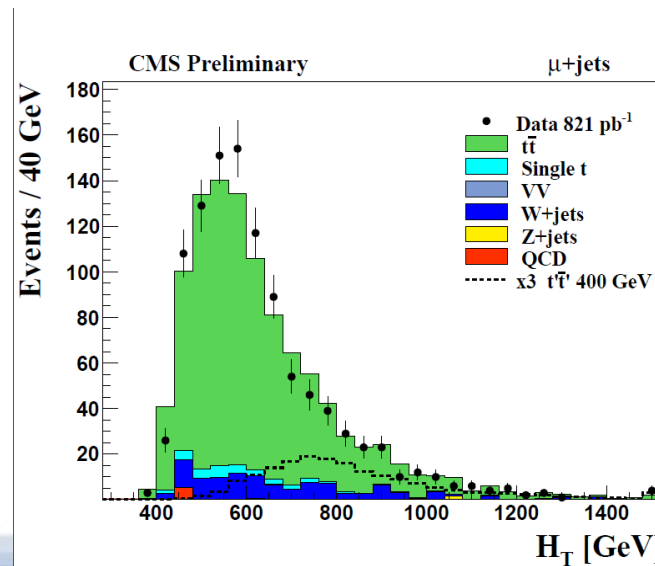
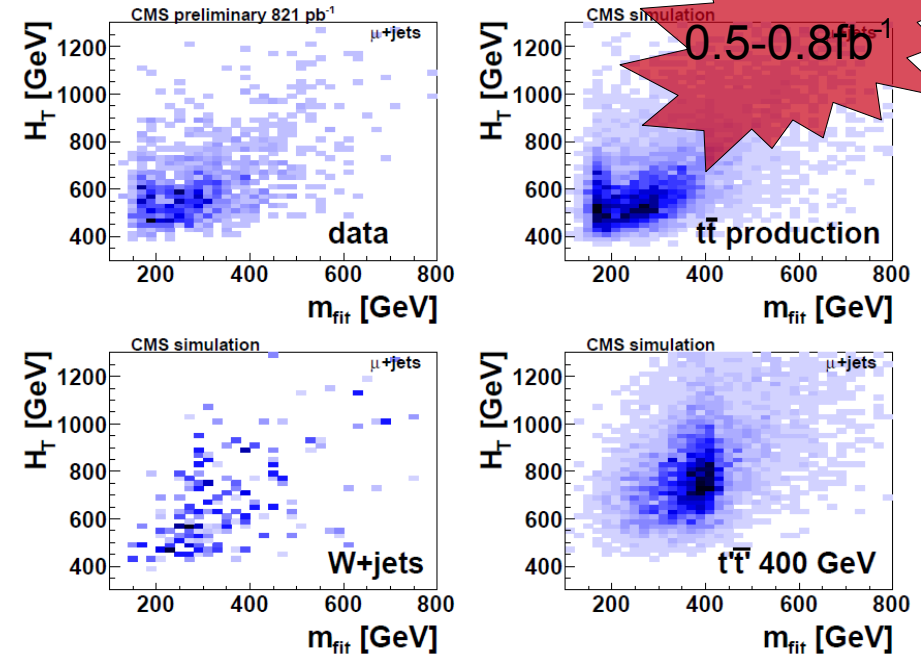
process	cross section	$e$ +jets eff.	$\mu$ +jets eff.
$t'\bar{t}'$			
$m_{t'} = 350$ GeV	3.20 pb	$3.7 \pm 0.4\%$	$4.5 \pm 0.3\%$
$m_{t'} = 400$ GeV	1.41 pb	$4.3 \pm 0.4\%$	$5.2 \pm 0.4\%$
$m_{t'} = 450$ GeV	0.66 pb	$4.8 \pm 0.4\%$	$5.6 \pm 0.4\%$
$m_{t'} = 500$ GeV	0.33 pb	$5.0 \pm 0.4\%$	$5.8 \pm 0.4\%$
CMS simulation			

process	cross section	$e$ +jets events	$\mu$ +jets events
$\mathcal{L}$		$573 \text{ pb}^{-1}$	$821 \text{ pb}^{-1}$
data		520	1054
$t\bar{t}$	158 pb	$456 \pm 91$	$907 \pm 114$
single $t$	33 pb	$14.5 \pm 3.5$	$30 \pm 6$
$W$ +jets	$30 \mu\text{b}$	$33.3 \pm 8.2$	$106 \pm 25$
$Z$ +jets	$2.9 \mu\text{b}$	$4.5 \pm 1.2$	$2.6 \pm 2.6$
$WW, WZ, ZZ$	67 pb		$2.1 \pm 0.6$
multijets		$2.5 \pm 1.2$	$5.7 \pm 5.5$
total background		$510 \pm 103$	$1054 \pm 145$

# CMS – Search for $t'$ single-lepton 2/3

PAS-EXO-11-051

- Mass reconstruction  $\rightarrow$  take four-jet combination out of the hardest 5 jets
- Use the  $W$  mass constraint and leptonic/hadronic  $t'$  mass should be equal
- A kinematic fit is performed by minimizing a  $\chi^2$  from the measured momenta of all the particles and their resolutions
- Fitted  $t'$  mass is used together with  $H_T \rightarrow$  2D discriminant unfolded in a 1D

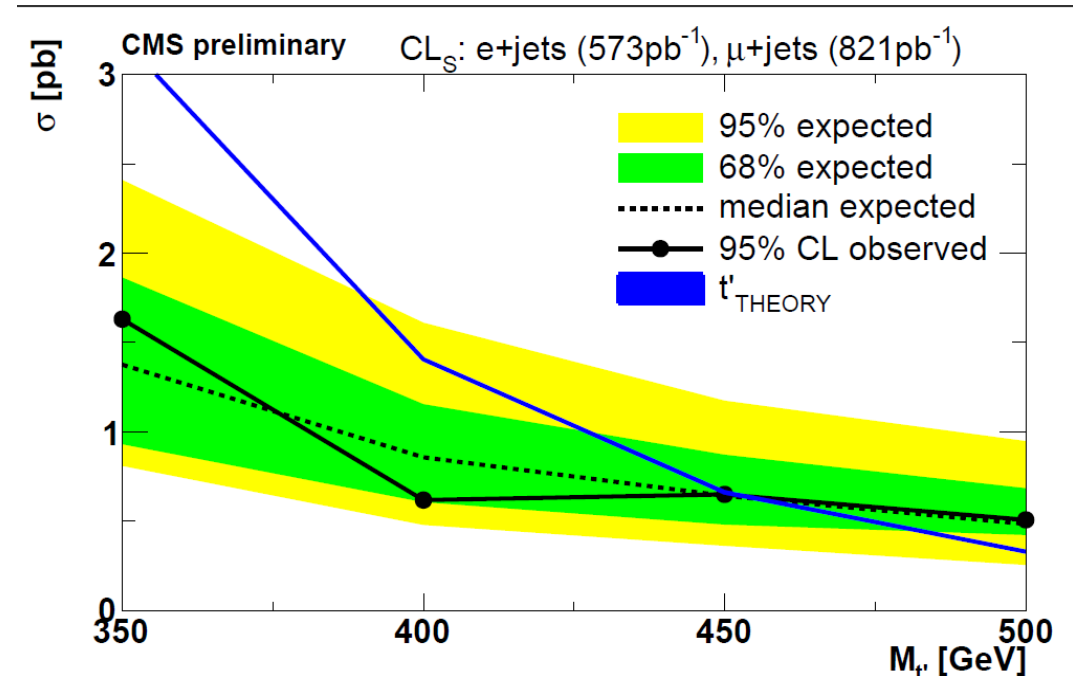
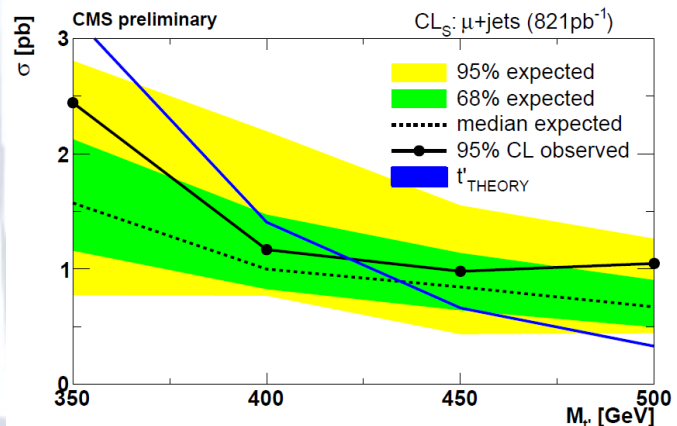
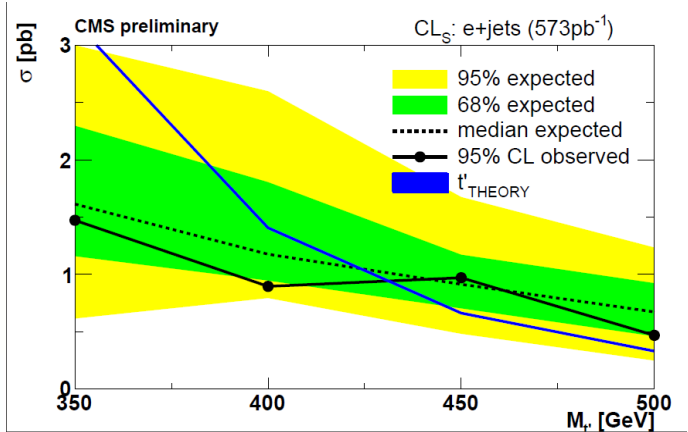


# CMS – Search for $t'$ single-lepton 3/3

PAS-EXO-11-051

0.5-0.8fb<sup>-1</sup>

- CLs method used to set limits on the  $t't'$  production cross section
- Assuming  $BR(t' \rightarrow Wb) = 1 \rightarrow m(t') > 450\text{GeV} @ 95\%CL$



1fb<sup>-1</sup>

PAS-EXO-11-054

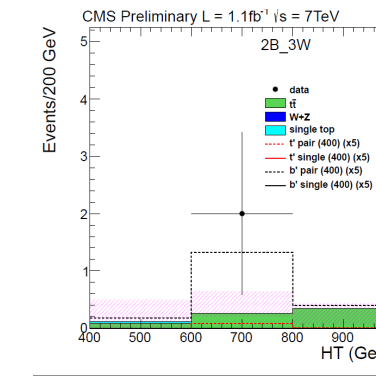
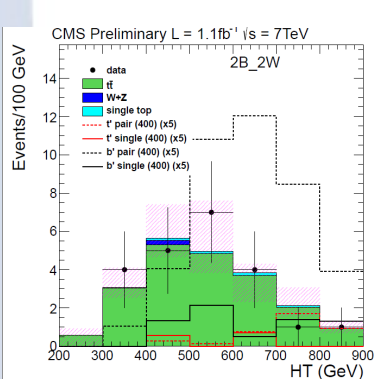
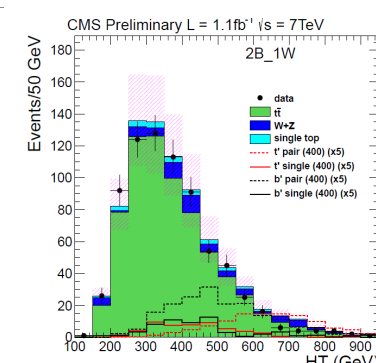
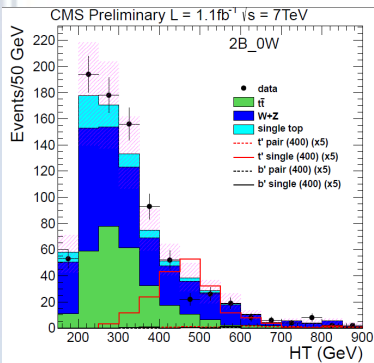
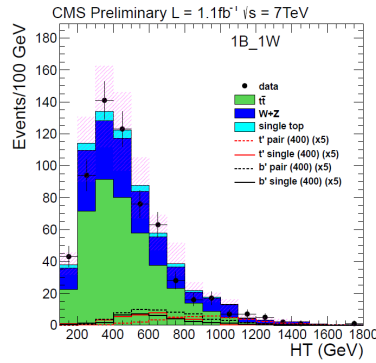
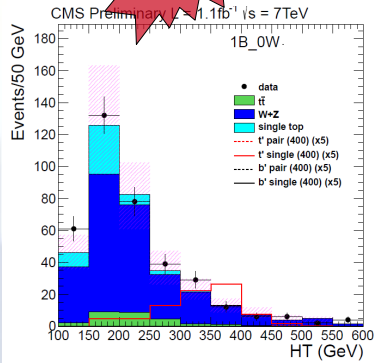
- This analysis presents the inclusive search of 4<sup>th</sup> generation up-down type quark from pair or single production ( $t'b \rightarrow Wb b$ ;  $b't \rightarrow WbW Wb$ ;  $t't' \rightarrow WbWb$ ;  $b'b' \rightarrow WbW WbW$ )
- Search is performed in the muon channel:
  - 1 isolated muon  $p_T > 40$  GeV;  $|\eta| < 2.1$ ; veto other isolated muons  $p_T > 10$  GeV,  $|\eta| < 2.5$ ; veto electrons  $p_T > 20$  GeV;  $|\eta| < 2.5$
  - Jets  $p_T > 30$  GeV;  $|\eta| < 2.5$ ;  $\geq 1$  to be a b-tag ( $|\eta| < 2.4$  tracker acceptance)
  - MET  $> 40$  GeV to reduce QCD multijet
- Search performed in 6 subsamples, based on nb-jet (==1,  $\geq 2$ ); nWhad (==0, ==1, ==2,  $\geq 3$ )
  - 1B\_0W  $\rightarrow$  single t' with 1 fwd/1central bjet; ==1 forward jet ( $2.4 < |\eta| < 5$ )  $p_T > 30$  GeV
  - 2B\_0W  $\rightarrow$  single t' with 2central bjets; ==0 forward jet ( $2.4 < |\eta| < 5$ )  $p_T > 30$  GeV
  - 1B\_1W  $\rightarrow$  t't' tt pair production with 1 b-jet failing ID;  $\geq 3$  jets in addition of the btag
  - 2B\_1W
  - 2B\_2W
  - 2B\_3W

}  $\rightarrow$  one additional bjet at least 2, 4, 6 additional jets



1fb<sup>-1</sup>

PAS-EXO-11-054



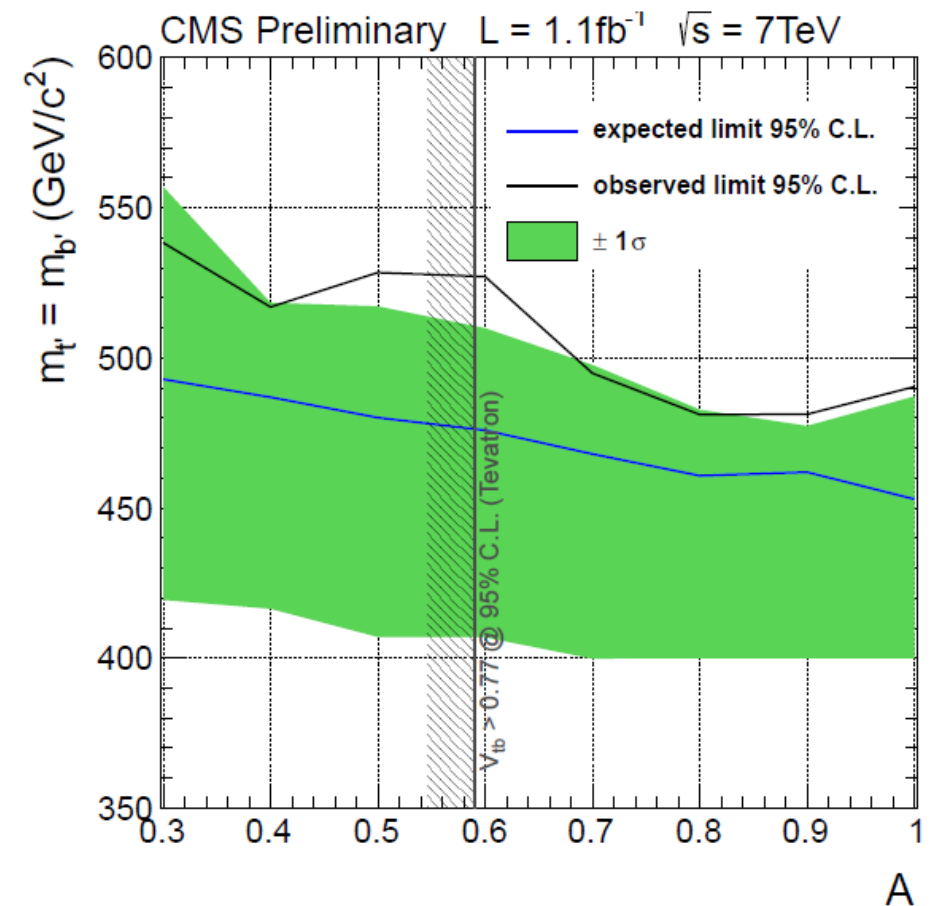
- HT discriminant is used = scalar sum of MET, muon pT, btag jets, Whad pT
- HT is sensitive to the presence of 4<sup>th</sup> generation quark
- A 4<sup>th</sup> generation quark would appear in the high tails of the HT distribution
- The 6 channels are combined into a single template histogram
- The 4 different signals processes are added into a single distribution for the signal

1fb<sup>-1</sup>

PAS-EXO-11-054

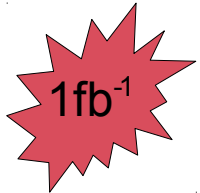
$$\text{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- Different templates of signal are made for each value of A and masses of the new quark
- The results are presented in the plane (A, m<sub>q4</sub>), where m<sub>q4</sub> is the degenerate mass of the quarks,  $A = |V_{tb}|^2$
- Using the CLs method is used to set limits together with a profile likelihood template fit
- For minimal off diagonal mixing, (A~1) between the third and the fourth generation,  $m_{t'} = m_{b'} > 490\text{GeV} @ 95\%CL$

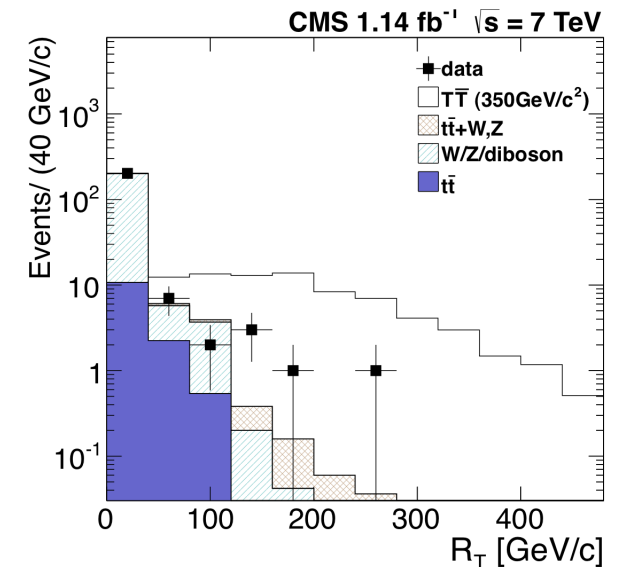
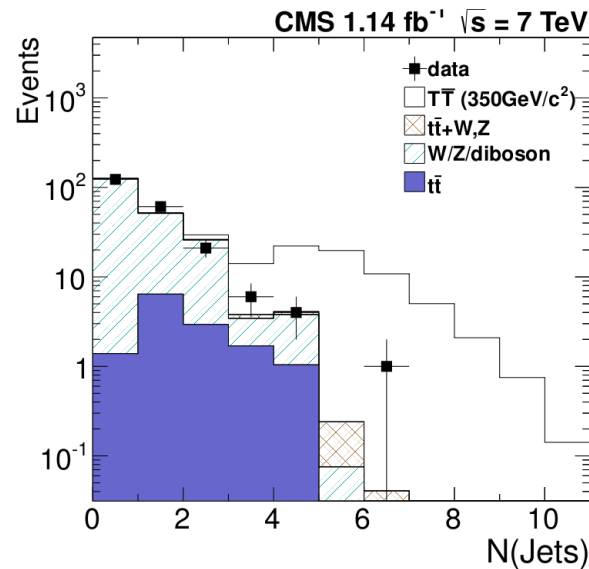
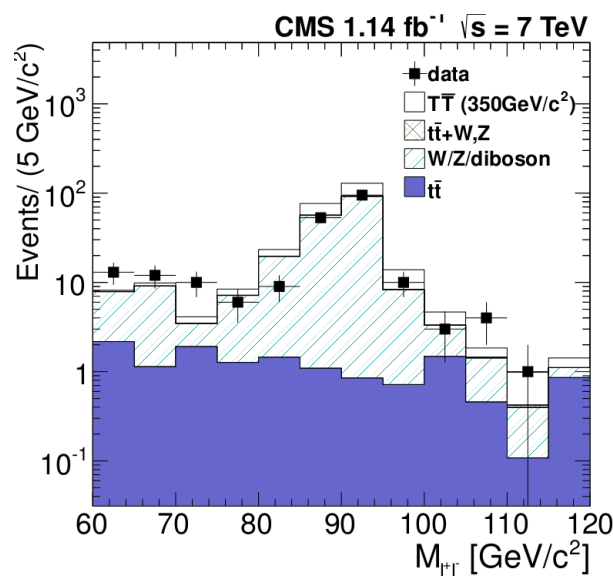


# Search for VLQ in $t+Z$ (pair prod.) 1/2

arXiv:1109.4985



- Search for a pair-produced heavy vector like quark  $T$  (VLQ) with charge  $2/3$
- 100% BR  $T \rightarrow tZ$ ;  $pp \rightarrow TT \rightarrow tZtZ \rightarrow WbZWbZ$
- Muon,  $p_T > 15\text{GeV}$  and  $|\eta| < 2.4$
- Electron  $> 20\text{GeV}$  and  $|\eta| < 2.5 \notin 1.44 < |\eta| < 1.57$
- Jets from particle flow, antikt 0.5;  $p_T > 25\text{GeV}$ ,  $|\eta| < 2.4$
- One leptonic  $Z \rightarrow 2$  OS, same flavored leptons (e or mu)  $60 < M_{ll} < 120\text{GeV}$
- At least 3 leptons and at least 2 jets
- $R_T > 80\text{GeV}$ , with  $R_T = \sum p_T(\text{jet } i) + \sum p_T(\text{lepton } i)$  ( $i \neq 1,2$ )



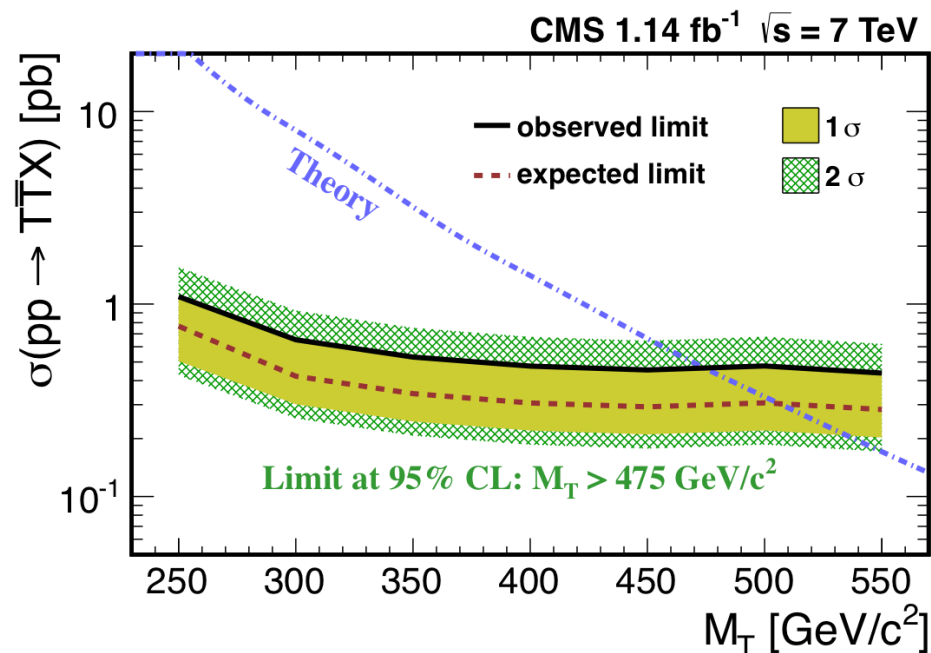
# Search for VLQ in $t+Z$ (pair prod.) 2/2

arXiv:1109.4985

1fb<sup>-1</sup>

- After full event selection two types of background remains:
  - Events with 2 prompt leptons and a non prompt lepton from a jet ( $B_{2l}$ ) → data driven
  - Events with 3 prompt leptons ( $B_{3l}$ )  $tt+Z$ , diboson → from MC
- Seven events observed in data, compatible with SM expectation → no evidence of VLQ
- Upper limit on the cross section calculated using a Bayesian method
- Assuming a BR of 100%  $T \rightarrow tZ$  set limits on the cross section
- Exclude  $m(\text{VLQ}) < 475 \text{ GeV}$  @ 95% C.L.

Channel	eee	ee $\mu$	$\mu\mu e$	$\mu\mu\mu$	Total
$B_{2l}$	$0.2^{+0.3}_{-0.2}$	$0.8 \pm 0.5$	$0.9 \pm 0.4$	$1.1 \pm 0.5$	$3.0 \pm 0.8$
$B_{3l}$	$0.3 \pm 0.1$	$0.3 \pm 0.1$	$0.5 \pm 0.2$	$0.5 \pm 0.2$	$1.6 \pm 0.5$
$B_{\text{total}}$	$0.5 \pm 0.3$	$1.1 \pm 0.5$	$1.4 \pm 0.5$	$1.7 \pm 0.6$	$4.6 \pm 1.0$
Data	0	2	2	3	7





# Producing model independent results

- For the most part LHC 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<sup>th</sup> 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:  $QQ \rightarrow Zb+X$ 
  - 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, 1+6 b-tag searches only sensitive to  $T \rightarrow tH$ , etc).

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