Search for Heavy Quarks with the ATLAS detector

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On behalf of the ATLAS collaboration

VIIIth Rencontres du Vietnam
Beyond the Standard Model

Quy Nhon, Vietnam 16-22 December 2012

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

Outline

1. Motivations for heavy quarks searches

   Implications of Higgs searches on fourth generation

   Vector-like Quarks

2. Analysis with Data 2011 – 7 TeV :
   - Heavy top :
     - ***t't'*** → ***WbWb*** **: lepton + jets**
   - Heavy bottom :
     - ***b'b'*** → ***WtWt*** → ***4W2b*** **: 2 same-sign leptons**

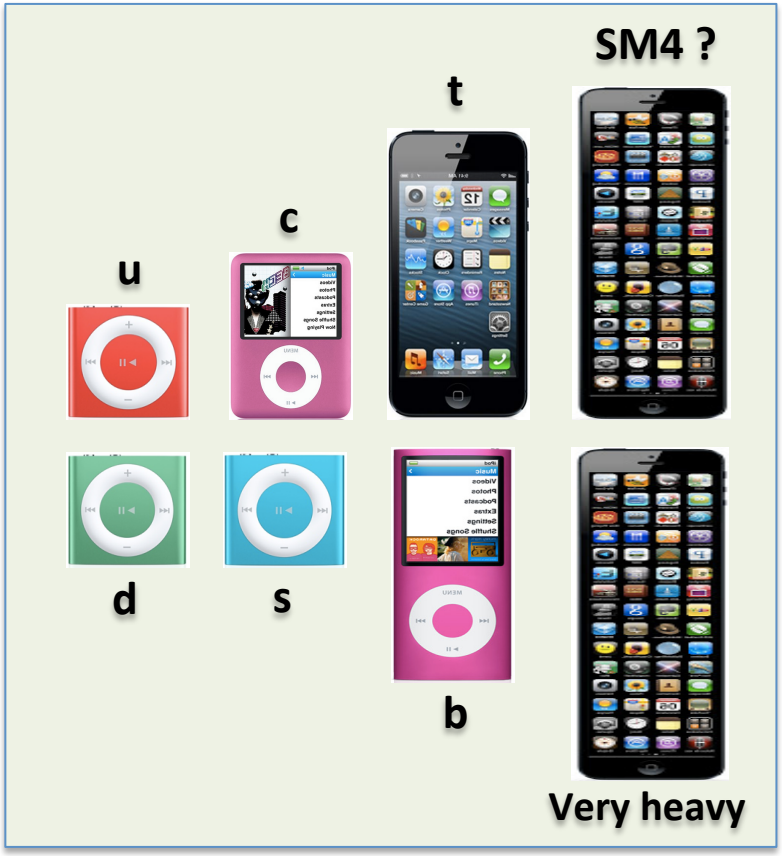
       (*similar signature as same-sign top quark pair, or* $T_{5/3}$ *pair, or four tops*)
   - **Vector-like quarks T,B**

     (*Fourth generation searches become a sub-set*)

3. Conclusion & Perspective

Motivations for Heavy Quarks Searches (1.1)

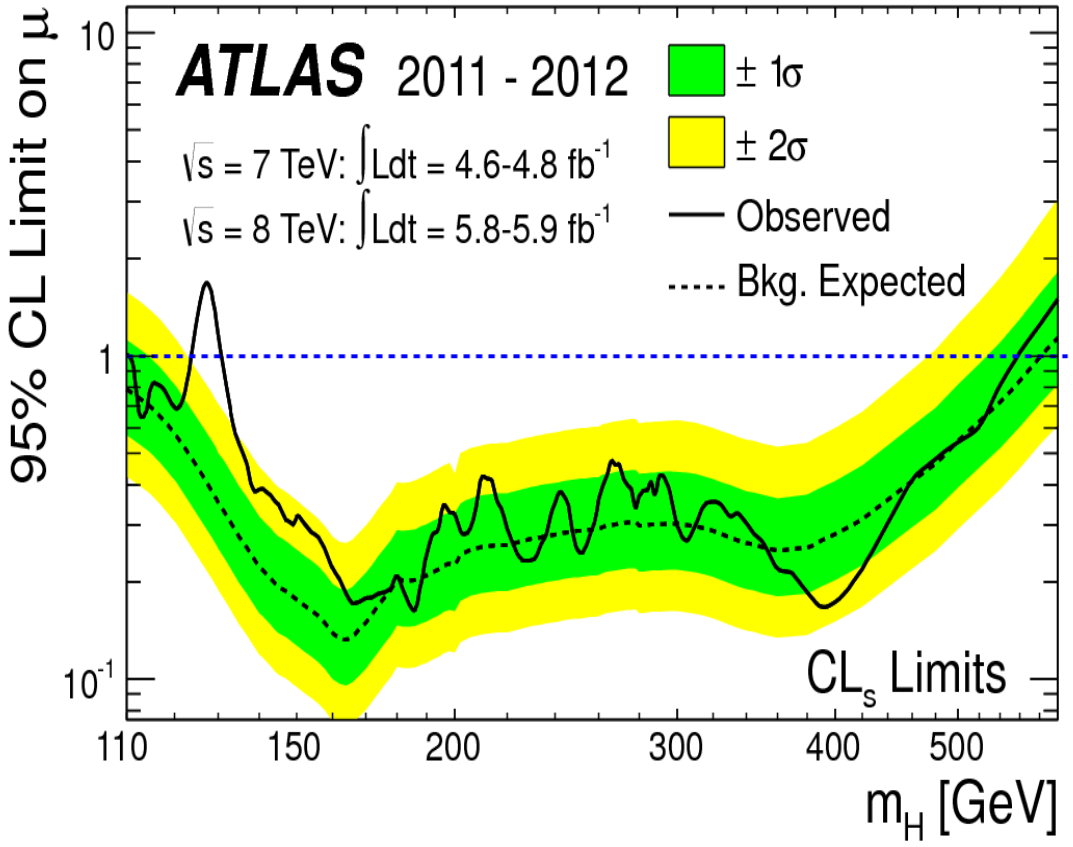
- Standard Model fourth generation (SM4) : simplest extension
- Beyond Standard Model extension



Motivation for searches :

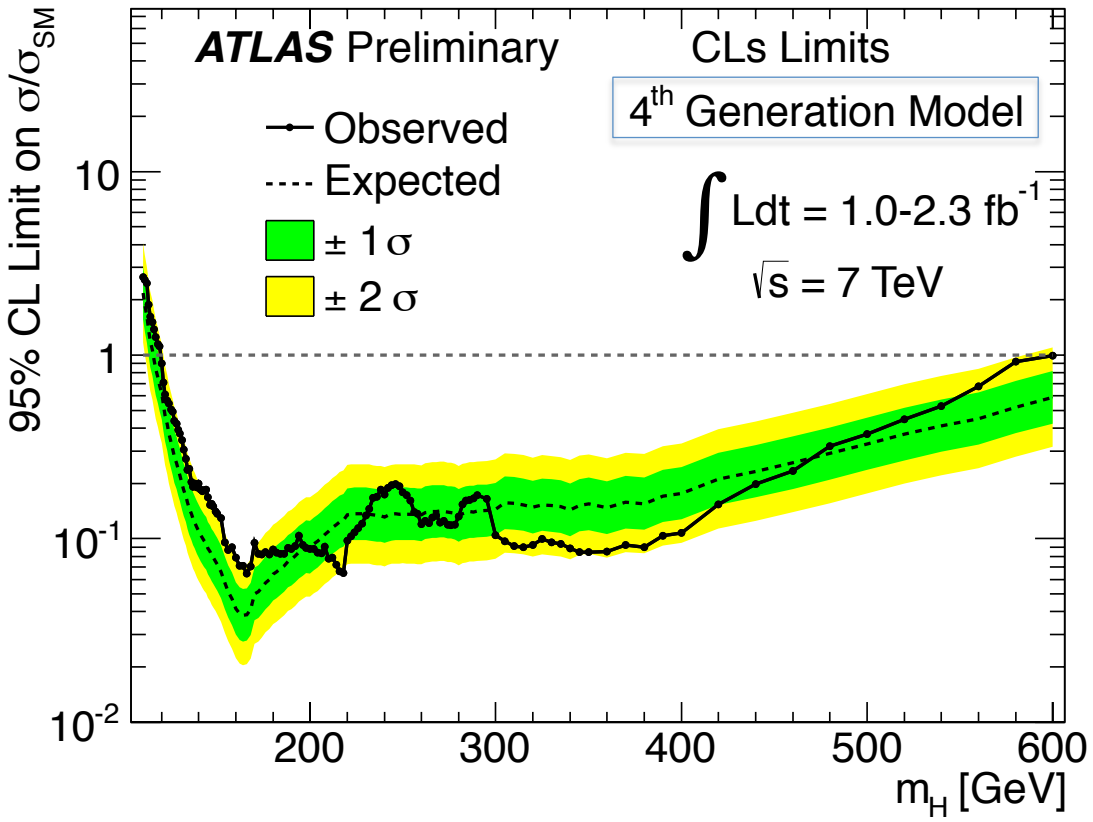
- SM does not predict number of generations
- New source of CP violation could explain matter-antimatter asymmetry
- Dynamical electroweak symmetry breaking
- Other theoretical aspects (Flavour hierarchy, Higgs boson mass naturalness ...)

Implications of Higgs Searches on Fourth Generation (1.2)



- Up to > 10 fb^{-1} : within SM3 all range excluded but a Higgs at 125 GeV

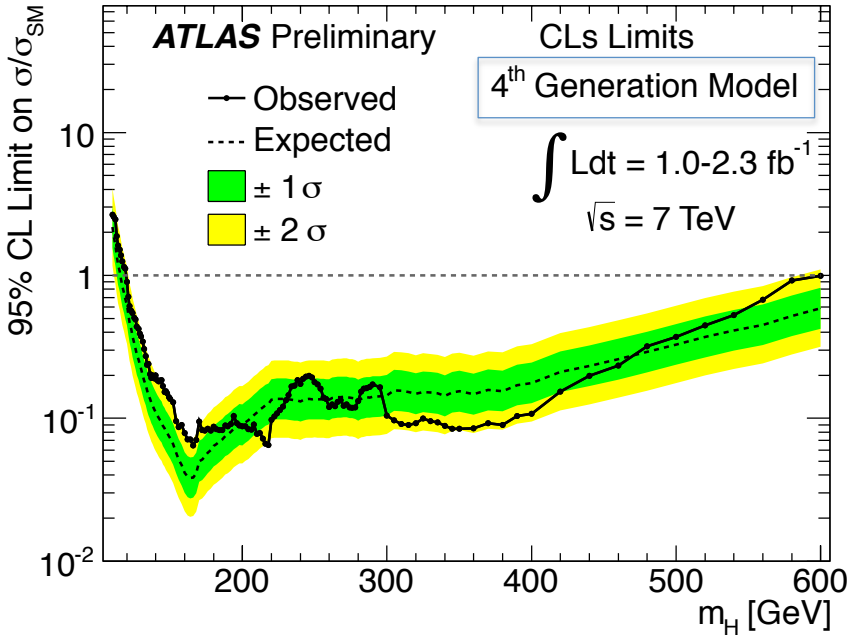
Implications of Higgs Searches on Fourth Generation (1.2)



ATLAS-CONF-2011-135

- With just 2.3 fb^{-1} within SM4 : m_H in all range 120 - 600 GeV is excluded

Implications of Higgs Searches on Fourth Generation (1.2)



ATLAS-CONF-2011-135

- Discovery of a Higgs boson with mass of 125 GeV and cross section compatible to SM3 rules out minimal SM4 (?)
- Direct searches for non-minimal models are still needed, e.g. :
  - Two-Higgs doublets
  - Vector-like Quarks

Vector-like Quarks (VLQ) (1.3)

- Left and Right components behave identically w.r.t. SU(2) × U(1)
  - ➢ Allows SM gauge invariant mass term
- Predicted in various models of physics Beyond Standard Model
- Mass generation not through Yukawa coupling to Higgs
  - – Looser constraint from Higgs cross section measurement
- Decay through Flavour Changing Charged & **Neutral** Currents

  $t' \rightarrow Wb, tH, tZ$ $\qquad\qquad$ $b' \rightarrow Wt, bH, bZ$

2. Analyses and results

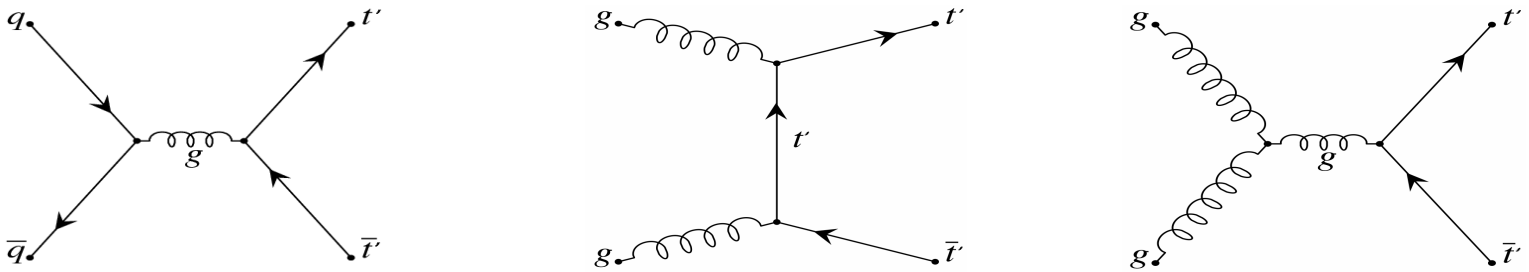
2.1. t't'→WbWb (Single Lepton + Jets)

2.2. ≥3W + 2b (Same Sign Leptons + Jets)

2.3. b'b' → Zb+X

2.4. Single Vector-like Quark Production

t't'→WbWb (Single Lepton + Jets) (2.1)

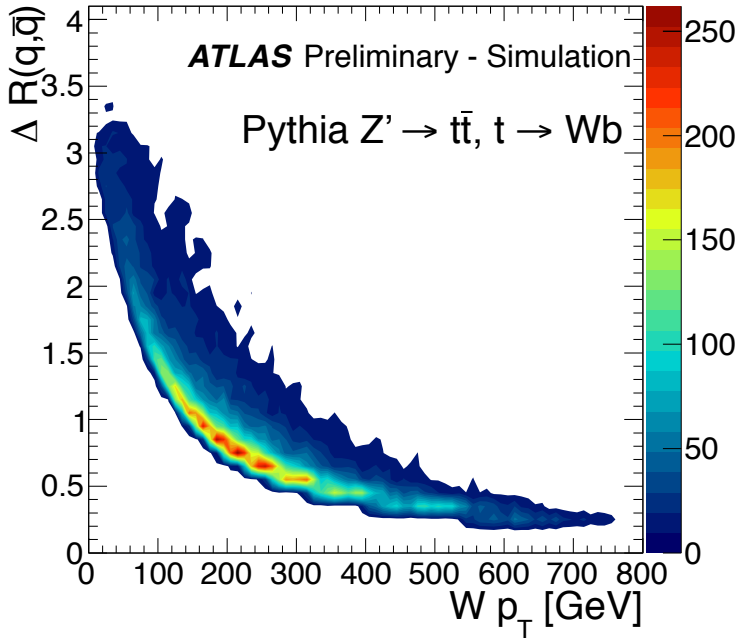


(For high mass *t'* : *q-qbar* annihilation dominant)

- Analysis published with 1fb^{-1} set an observed (expected) 95%CL lower limit on *t'* mass : $m_{t'} > 404$ (394) GeV with BR(*t'*→*Wb*) = 1

- High mass *t'* : *W* is boosted → 2 jets from hadronic *W* can be merged or very close to each other

- Strategy for analysis at 4.7 fb^{-1} changed to adapt to this scenario



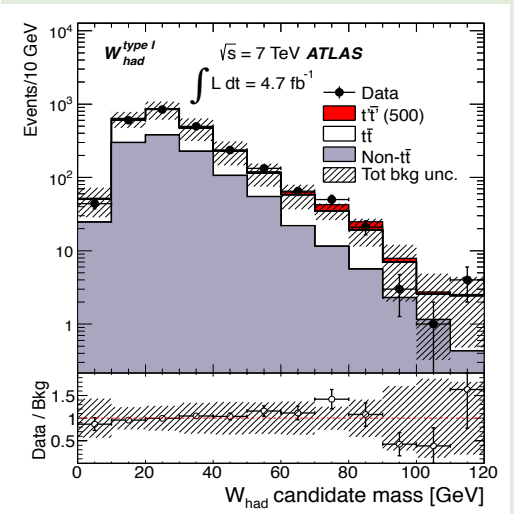
t't'→WbWb (Single Lepton + Jets) (2.1)

- Analysis for 4.7 fb^{-1} : Boosted W reconstruction
- Jet anti-k_t algorithm, size R = 0.4

Latest paper with 4.7 fb^{-1}
arXiv : 1210.5468

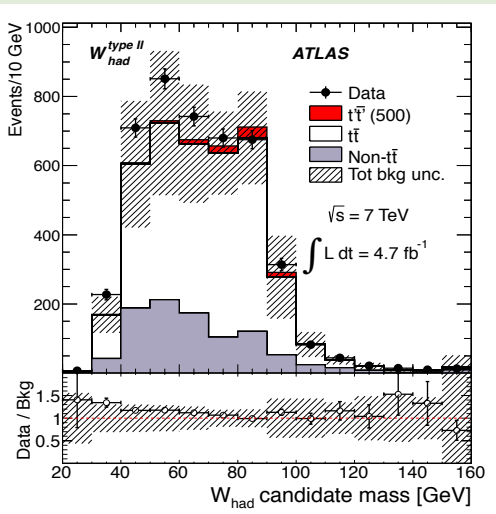
Channel 1

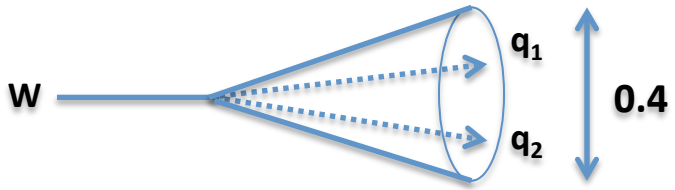
One jet
with
$p_T > 250$ GeV
and
$60 < m_j < 110$ GeV

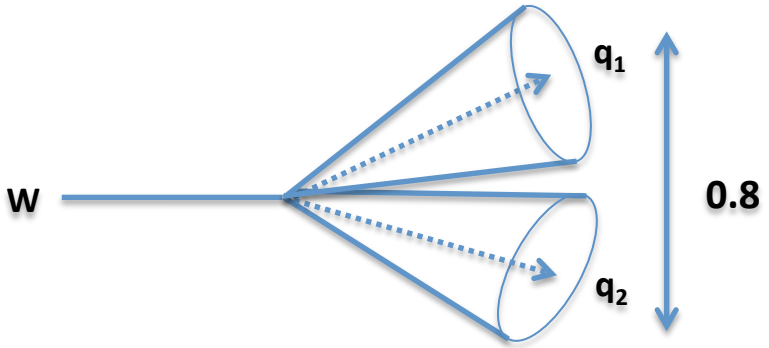


Channel 2

Dijet system
with
$p_T > 150$ GeV
$\Delta R(j,j) < 0.8$
$60 < m_{jj} < 110$ GeV







t't'→WbWb (Single Lepton + Jets) (2.1)

❖ **Analysis :** H_T (*) > 750 GeV & $p_T^{leading\ b\text{-}jet}$ > 160 GeV & $p_T^{subleading\ b\text{-}jet}$ > 60 GeV

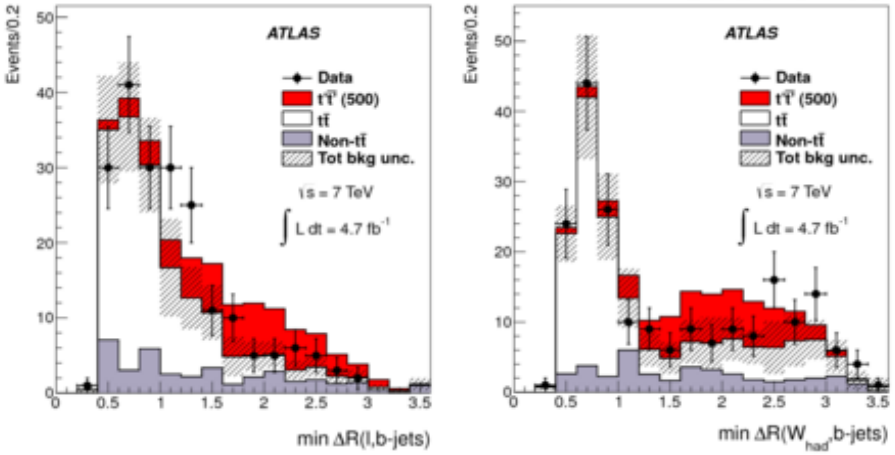
- Reconstruct hadronic *t'* mass m_{reco}
  - 4 combinations from one hadronic W, one leptonic W (2 neutrino solutions from W mass constraint) and 2 *b*-jets
  - Choose combination giving the smallest difference between hadronic and leptonic mass
  - Additional cuts :
    - minΔR(lepton – neutrino) < 1.4
    - minΔR(W – both *b*-jets) > 1.4

    & minΔR(lepton – both *b*-jets) > 1.4

➢ Help to reject boosted top events

(*) $H_T = E_T^{miss} + p_T^{lepton} + \sum_{j=1}^{4} p_T^{jet_j}$

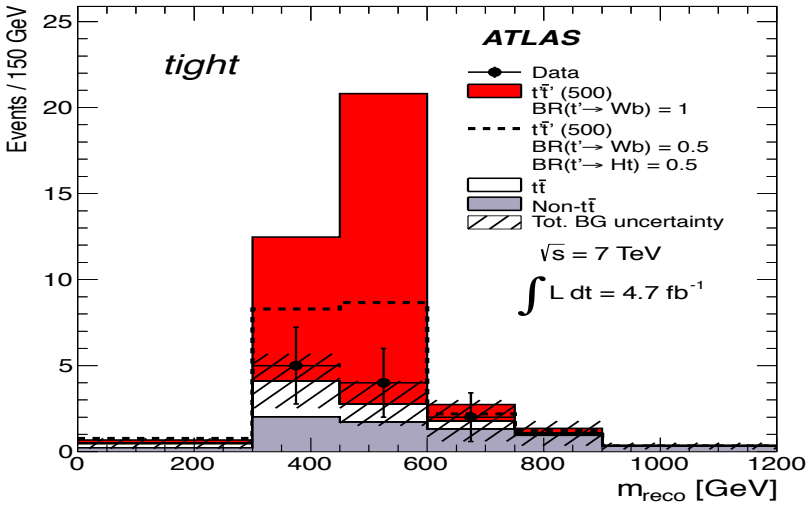
arXiv : 1210.5468



Distribution of minΔR(W – both b-jets) and minΔR(lepton – both b-jets)
Signal prefer to have high values

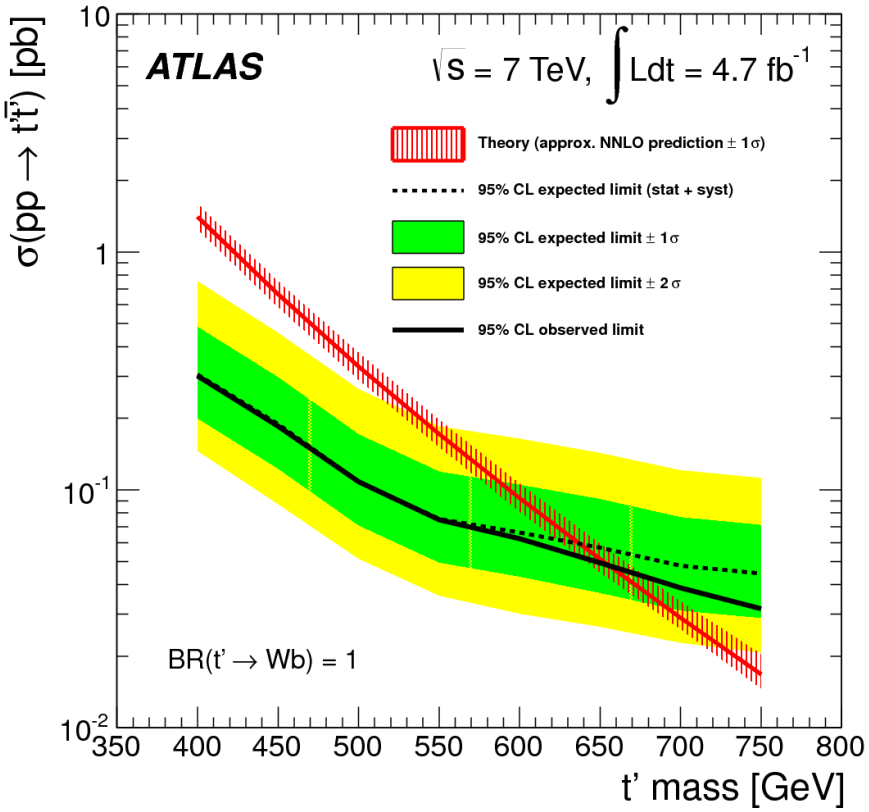
t't'→WbWb (Single Lepton + Jets) (2.1)

arXiv : 1210.5468



Distribution of m_{reco} after event selection and after applying isolation cuts

Total Bkg	**Data**	*t'* SM4 500 GeV	*t'* VLQ 500 GeV
11.3 ± 4.8	**11**	28.2 ± 3.6	11.2 ± 1.5



- **Result :**

  Observed (expected) limit :

  $m_{t'} > 656\ (638)$ GeV

  for BR($t' \rightarrow Wb$) = 1

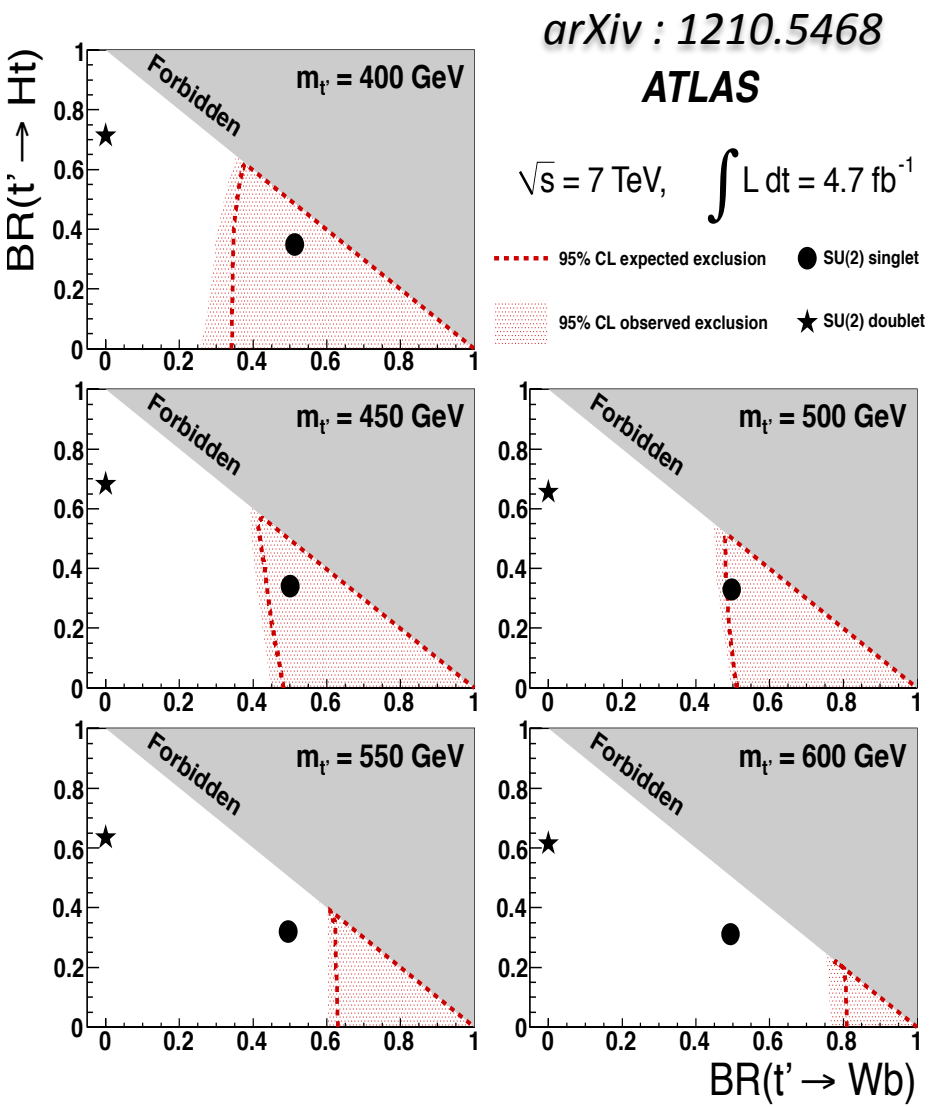
VLQ Interpretation from t't'→WbWb Analysis (2.1)

Heavy vector-like *t'* :

- Decay modes :
  - $t' \rightarrow Wb$
  - $t' \rightarrow tH$
  - $t' \rightarrow tZ$

(sum of 3 BRs equal 1, BR values are model dependent)

- t' SU(2) singlet (BR($t' \rightarrow Wb$) ≈ 0.5) with mass in range 400 – 500 GeV excluded

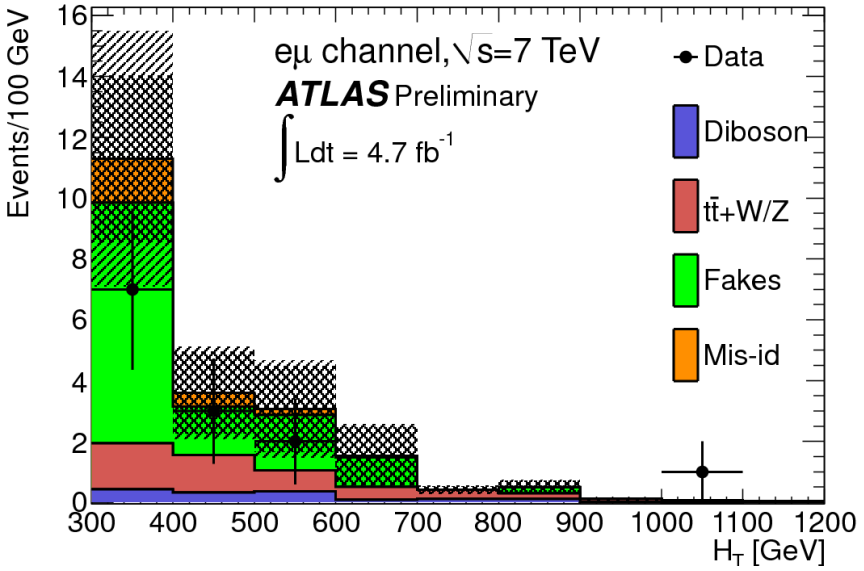


≥3W + 2b (Same Sign Leptons + Jets) (2.2)

ATLAS Note ATLAS-CONF-2012-137

- Preliminary result with 4.7 fb^{-1} :
  - Inclusive searches for 4 exotic processes ($b'b'$, $T_{5/3}T_{5/3}$, single $T_{5/3}$, 4 tops)

- **Event selection :**
  - ✓ At least 2 lepton candidates with same charge and at least 2 "good" jets
  - ✓ In *ee* or *μμ* channel : inv. mass of 2 leptons must exceed 15 GeV & $|m_{ll} - m_Z| > 10$ GeV
  - ✓ Missing transverse momentum exceed 40 GeV



Distribution of H_T after applying the selection except the H_T cut for eμ channel

- **Signal region :**

  Additional cut :

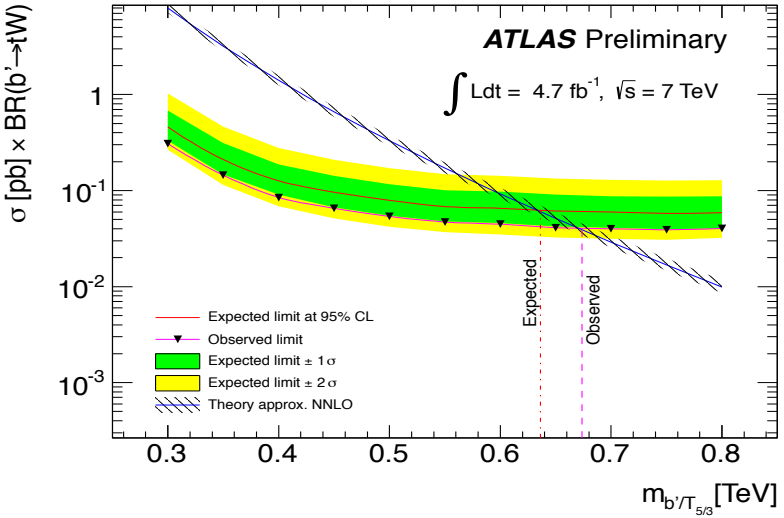
  H_T (jets+leptons) > 550 GeV

≥3W + 2b (Same Sign Leptons + Jets) (2.2)

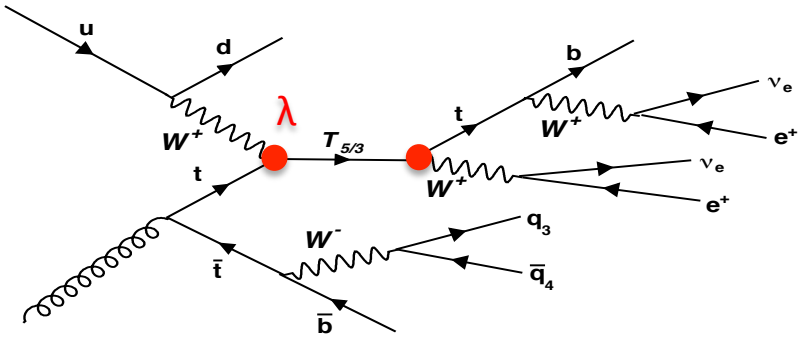
ATLAS Note ATLAS-CONF-2012-137

- **λ << 1 :**
  - No single production
  - $m_{b'}$ and $m_{T5/3\ (\text{pair production})}$ > 670 (640) GeV

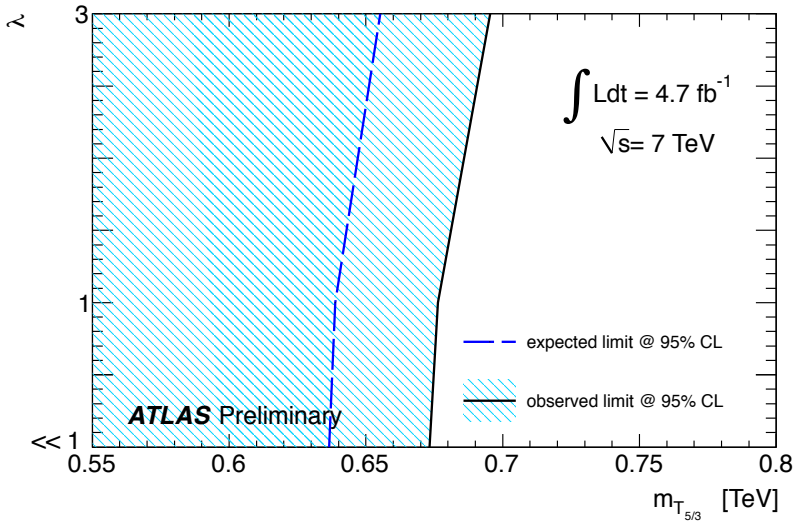
  ($T_{5/3}$ quasi-stable → R-hadrons-like searches)



- **λ ≥ 1 :** Single production added



- **λ = 1 :** $m_{T5/3}$ > 680 (640) GeV
- **λ = 3 :** $m_{T5/3}$ > 700 (660) GeV



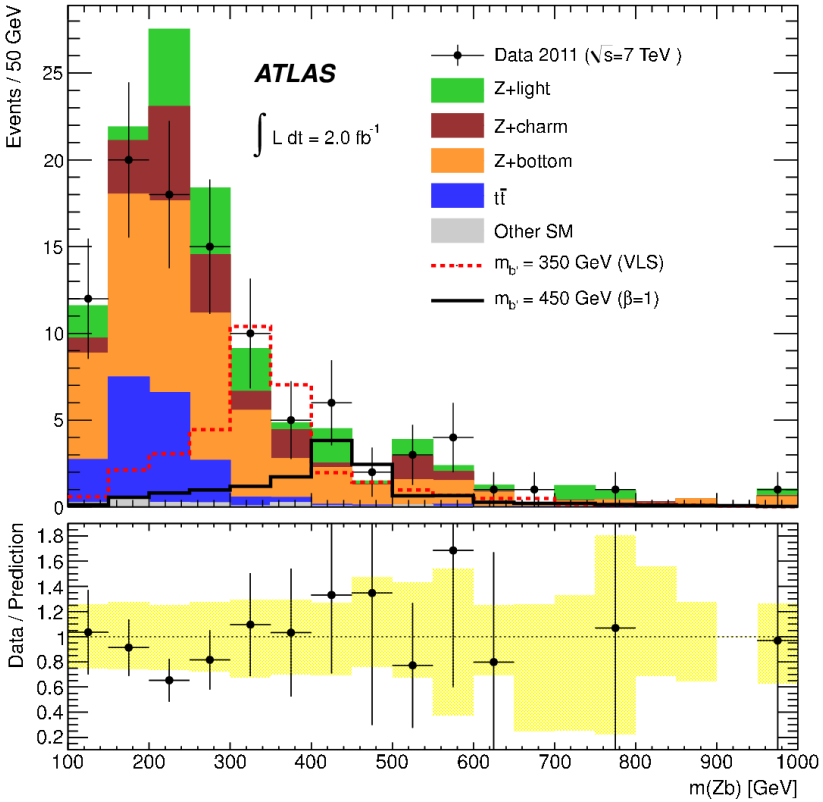
b'b' → Zb+... (2.3)

Latest paper with 2 fb^{-1}
arXiv : 1204.1265
Phys.Rev.Lett. 109 (2012) 071801

- **Event selection :**
  - ✧ At least 1 *b*-jet
  - ✧ Z candidate :
  - – At least two opposite-charge electron candidates and $|m_{ee} - m_Z| < 15$ GeV
  - – $p_T(Z,b\text{-jet}) > 150$ GeV

Total SM	**Data**	*b'* VLS 350 GeV	*b'* 450 GeV
110 ± 30	**100**	55 ± 7	14 ± 2

- **Reconstruct *m*(*Zb*) :**
  - – if more than one *b*-tagged jet choose the leading p_T



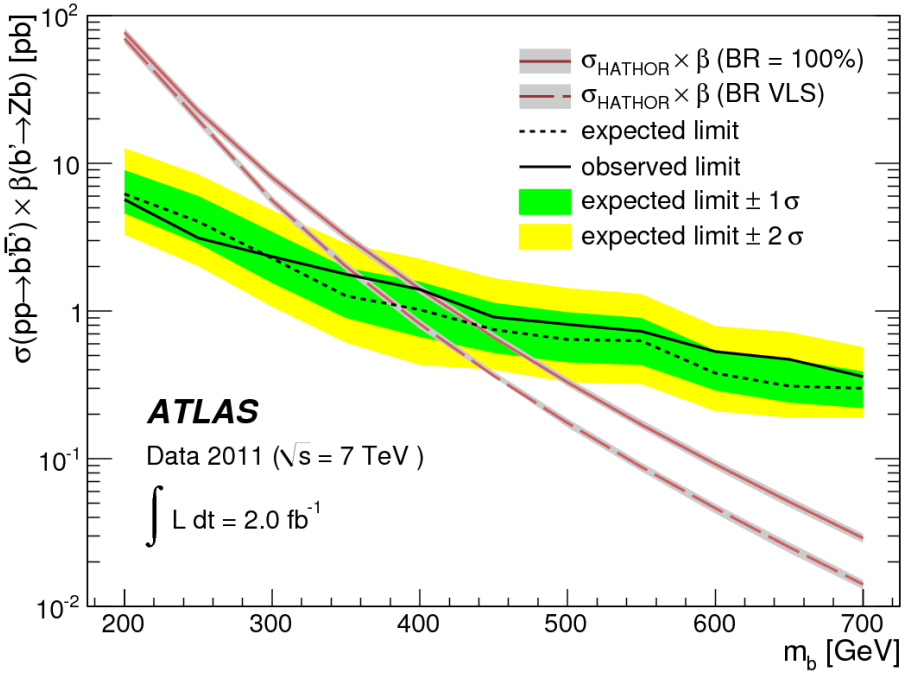
Mass distribution of b' candidate for events passing selection

b'b' → Zb+... (2.3)

arXiv : 1204.1265
Phys.Rev.Lett. 109 (2012) 071801

Result :

- *b'* with mass $m_{b'}$ < 400 GeV decaying entirely via b' → Z + b are excluded
- For vector-like singlet *b'* mixing solely with the third Standard Model generation : $m_{b'}$ > 358 GeV

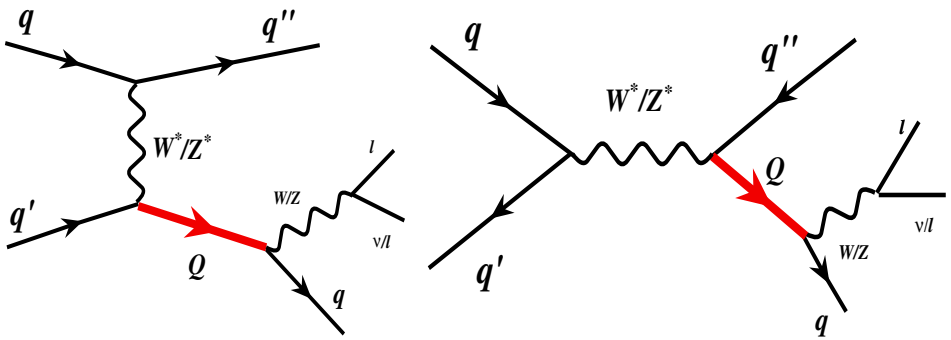


$\beta = 2 \times BR(b' \to Zb) - BR(b' \to Zb)^2$: Fraction of signal events with at least one *b'*→*Zb* decay as a function of BR(*b'*→*Zb*)

Single Vector-like Quark Production (2.4)

ATLAS Note ATLAS-CONF-2012-137

- Q can be U(+2/3), D(-1/3) or X(+5/3)
- Q decays to W/Z and light quarks
- 2 possible final states :
  - *Wu* (for D and X) :
    Charged Current (CC)
  - *Zu* (for U)
    Neutral Current (NC)



Single production of VLQ in t-channel and s-channel

➢ Analysis divided into 4 channels : CC or NC, electrons or muons in final state

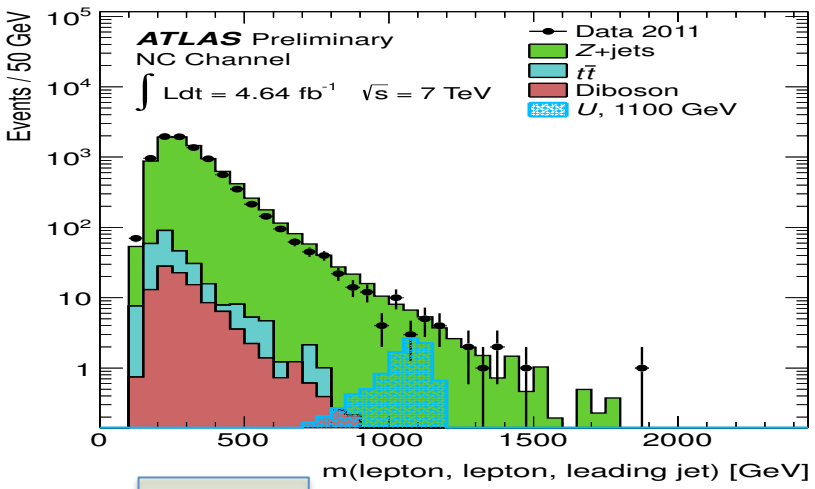
- **Event selection :**
  - At least 2 jets

CC	NC
- W reconstructed using lepton candidate and neutrino candidate - m_T^W > 40 GeV and |η(W)| < 2.5	- 2 same flavour, opposite sign leptons - 66 GeV < m_{ll} < 116 GeV

Single Vector-like Quark Production (2.4)

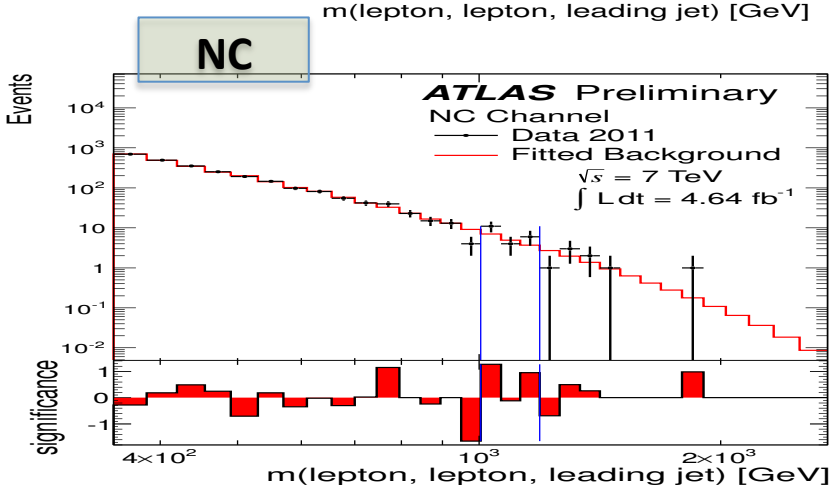
Results :

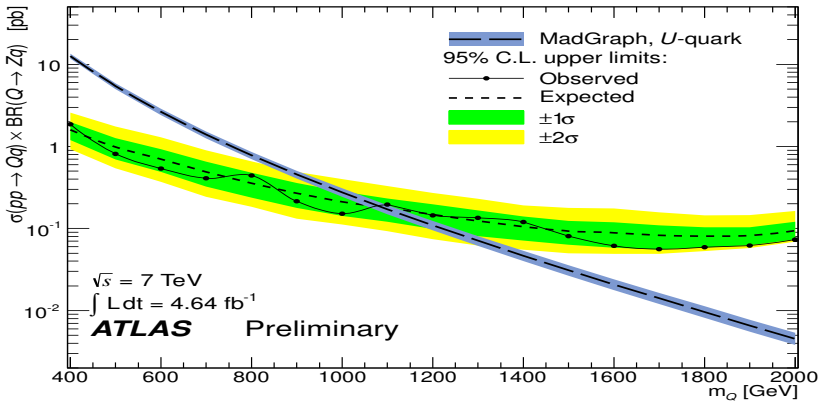
ATLAS Note ATLAS-CONF-2012-137



Comparison of data and expected SM backgrounds (combined electron and muon channels) for NC channel

Plot bottom-left : BumpHunter result show the most significant deviation region bounded by blue lines. The width of BumpHunter bin roughly equal to VLQ mass resolution

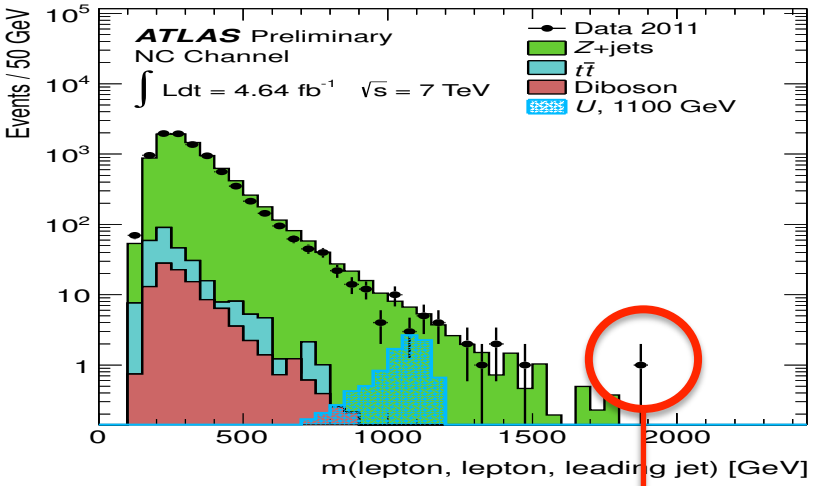




- U(+2/3) with mass below 1120 GeV excluded (NC)
- Mass of X(+5/3), D(-1/3) greater than 1420 GeV and 1080 GeV respectively

Single Vector-like Quark Production (2.4)

ATLAS Note ATLAS-CONF-2012-137



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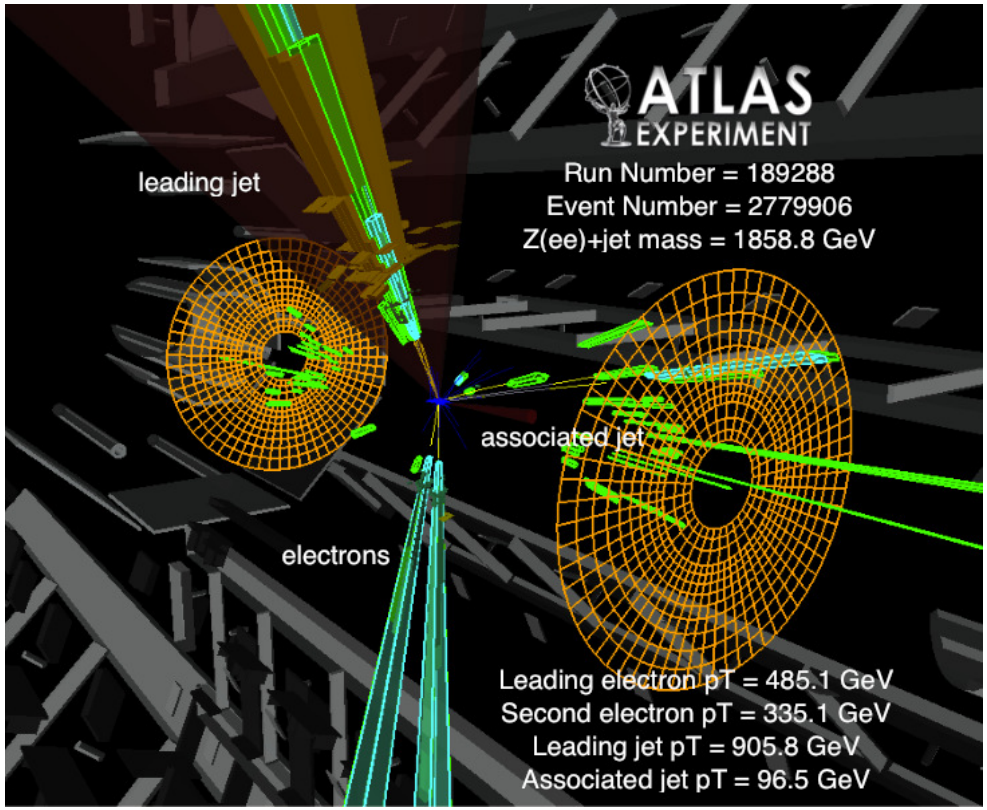
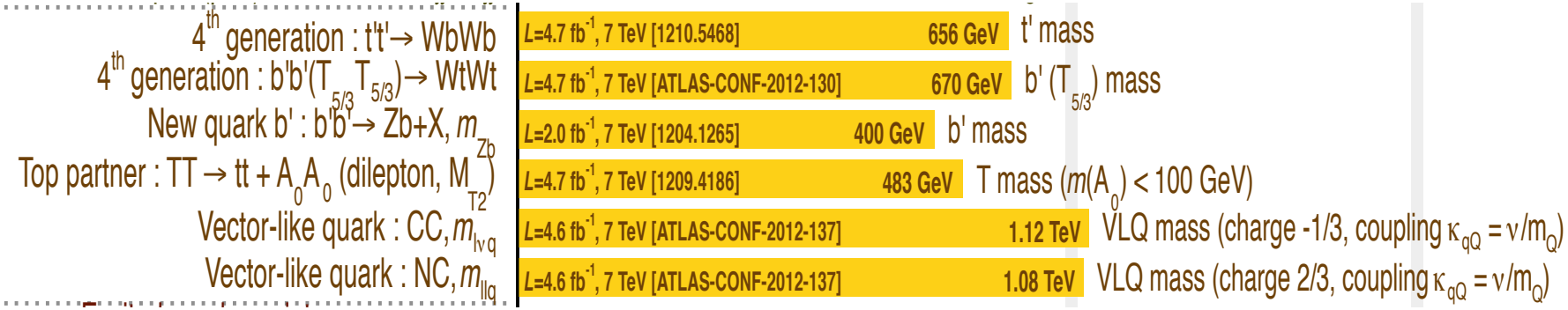


Conclusion & Perspective

- 2012 has seen a huge progress on various searches for New Physics
- So far no hint for signal !
- Limits were set for different models

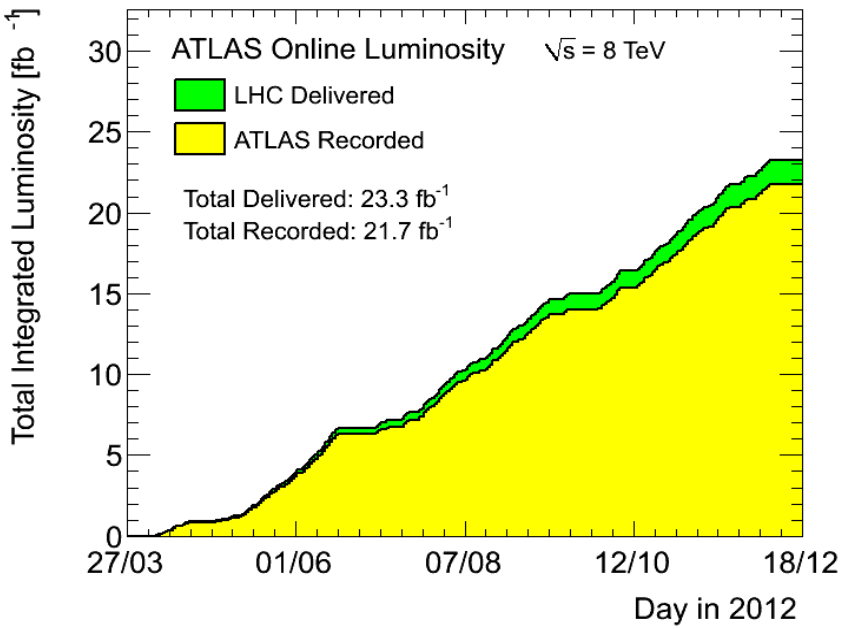


ATLAS Physics Summary Plot for HCP 2012

Conclusion & Perspective

- 2012 has seen a huge progress on various searches for New Physics
- So far no hint for signal !
- Limits were set for different models

✧ > 20fb^{-1} 8 TeV p-p physics run data from 2012 promises an exciting year of analysis !



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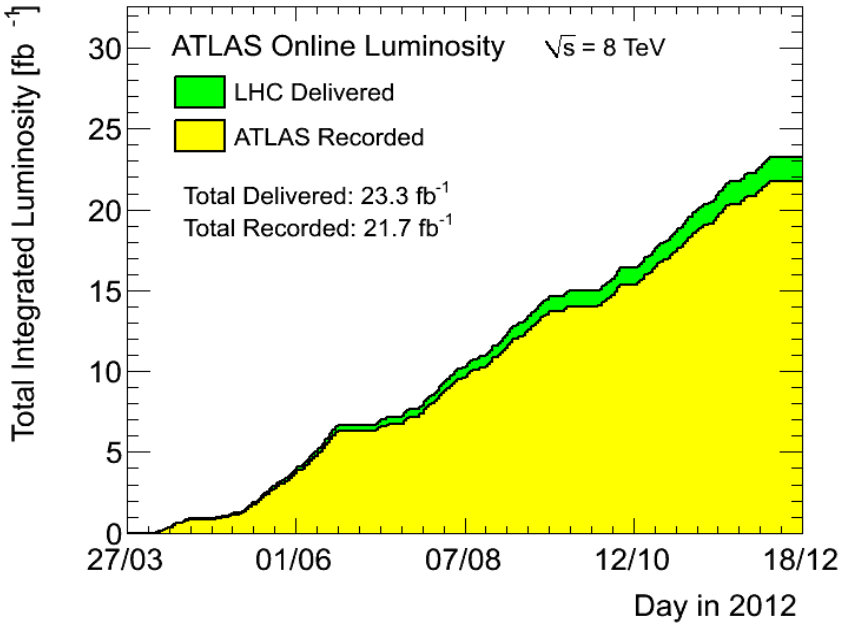
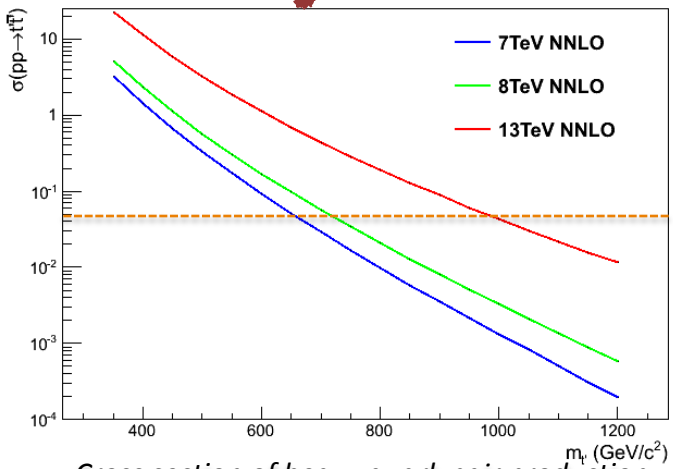




Cross section of heavy quark pair production (HATHOR – 1.3)

- @ 13 TeV :

  Significant enhancement of cross section

→ Discovery ☺

or

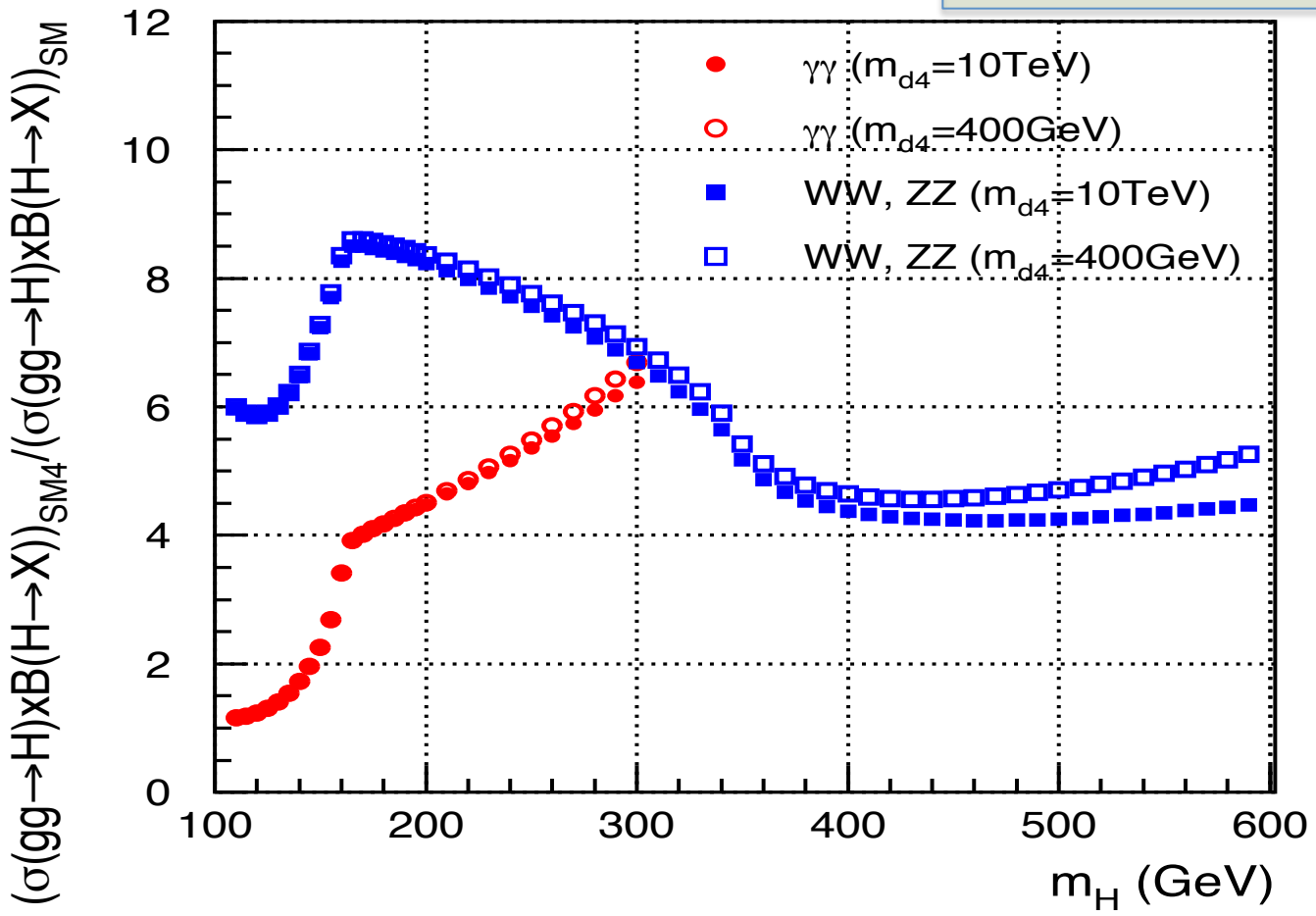
High Mass Exclusion

(Death of many BSM models !)

Backup slides

Implications of Higgs Searches on Fourth Generation

arXiv : 1105.1634



Fourth Generation quark pair production cross section (*pb*)

$m_{t'}$	7 TeV NNLO	8 TeV NNLO	13 TeV NNLO	14 TeV NLO
350	3.20	5.08	22.92	25.8
400	1.41	2.30	11.19	12.8
450	0.662	1.113	5.86	6.77
500	0.33	0.57	3.24	3.78
550	0.171	0.306	1.87	2.21
600	0.0923	0.1696	1.12	1.34
650	**0.0511**	0.0971	0.695	0.842
700	0.0290	**0.0569**	0.441	0.541
750	0.0168	0.0341	0.286	0.356
800	0.00988	0.0208	0.19	0.239
850	0.00589	0.01285	0.128	0.163
900	0.00355	0.00805	0.088	0.113
950	0.00216	0.00512	0.0611	0.0798
1000	0.00133	0.00328	0.043	**0.0568**

Some things about VLQ

$$\mathcal{L} = \bar{q}_L \not{\partial} q_L + \bar{t}_R \not{\partial} t_R$$

← elementary sector

$$+ \mathrm{Tr}\left\{\bar{\mathcal{Q}}\left(\not{\partial} - M_Q\right)\mathcal{Q}\right\} + \bar{\tilde{T}}\left(\not{\partial} - M_{\tilde{T}}\right)\tilde{T} + Y_* \,\mathrm{Tr}\{\bar{\mathcal{Q}}\mathcal{H}\}\,\tilde{T} + h.c$$

← composite sector

$$+ \Delta_L \, \bar{q}_L \left(T, B\right) + \Delta_R \, \bar{t}_R \tilde{T} + h.c.$$

← mixing terms

Yukawa lagrangian

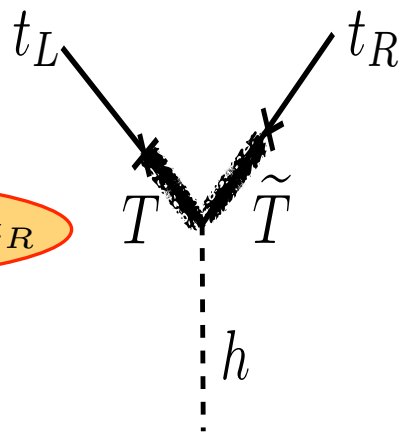
$$\mathcal{L}_{yuk} = Y_* Tr\{\bar{\mathcal{Q}}\mathcal{H}\}\tilde{T} = Y_* Tr\left(\begin{bmatrix} \bar{T} & \bar{B} \\ \bar{T}_{5/3} & \bar{T}_{2/3} \end{bmatrix}\begin{bmatrix} \phi_0^* & \phi_+ \\ -\phi_- & \phi_0 \end{bmatrix}\right)\tilde{T}$$

$$= Y_*\left(\bar{T}\phi_0^* - \bar{B}\phi_- + \bar{T}_{5/3}\phi_+ + \bar{T}_{2/3}\phi_0\right)\tilde{T}$$

Some things about VLQ

$$\begin{aligned}\mathcal{L}_{yuk} =& Y_* \sin\varphi_L \sin\varphi_R \left(\bar{t}_L \phi_0^\dagger t_R - \bar{b}_L \phi^- t_R\right) + Y_* \cos\varphi_L \sin\varphi_R \left(\bar{T} \phi_0^\dagger t_R - \bar{B} \phi^- t_R\right) \\ &+ Y_* \sin\varphi_L \cos\varphi_R \left(\bar{t}_L \phi_0^\dagger \tilde{T} - \bar{b}_L \phi^- \tilde{T}\right) + Y_* \sin\varphi_R \left(\bar{T}_{5/3} \phi^+ t_R + \bar{T}_{2/3} \phi_0 t_R\right) \\ &+ Y_* \cos\varphi_L \cos\varphi_R \left(\bar{T}_L \phi_0^\dagger \tilde{T}_R - \bar{B}_L \phi^- \tilde{T}_R\right) + Y_* \left(\bar{T}_R \phi_0^\dagger \tilde{T}_L - \bar{B}_R \phi^- \tilde{T}_L\right) \\ &+ Y_* \cos\varphi_R \left(\bar{T}_{5/3} \phi^+ T_R + \bar{T}_{2/3} \phi_0 \tilde{T}_R\right) + Y_* \left(\bar{T}_{5/3} \phi^+ T_L + \bar{T}_{2/3} \phi_0 \tilde{T}_L\right) + \ldots\end{aligned}$$

$$y_t = Y_* \sin\varphi_{q_L} \sin\varphi_{t_R}$$



$\tilde{T} \to Z_L t_L$ $\tilde{T} \to h\, t_L$ $\tilde{T} \to W_L b_L$	$Y_* \sin\varphi_L \cos\varphi_R$
$T_{2/3} \to Z_L\, t_R$ $T_{2/3} \to h\, t_R$	$Y_* \sin\varphi_R$
$T \to Z_L t_R$	$Y_* \cos\varphi_L \sin\varphi_R$
$B \to W_L t_R$	$Y_* \cos\varphi_L \sin\varphi_R$
$T_{5/3} \to W_L t_R$	$Y_* \sin\varphi_R$
$T_{5/3} \to Z_L t_R$	$Y_* \sin\varphi_R$

Some things about VLQ

	SM quarks	Singlets		Doublets			Triplets	
	$\begin{pmatrix} u \\ d \end{pmatrix}$ $\begin{pmatrix} c \\ s \end{pmatrix}$ $\begin{pmatrix} t \\ b \end{pmatrix}$	(U)	(D)	$\begin{pmatrix} X \\ U \end{pmatrix}$	$\begin{pmatrix} U \\ D \end{pmatrix}$	$\begin{pmatrix} D \\ Y \end{pmatrix}$	$\begin{pmatrix} X \\ U \\ D \end{pmatrix}$	$\begin{pmatrix} U \\ D \\ Y \end{pmatrix}$
$SU(2)_L$	$q_L = 2$ $q_R = 1$	1		2			3	
$U(1)_Y$	$q_L = 1/6$ $u_R = 2/3$ $d_R = -1/3$	$2/3$	$-1/3$	$7/6$	$1/6$	$-5/6$	$2/3$	$-1/3$
$\mathcal{L}_Y$	$-y_u^i \bar{q}_L^i H^c u_R^i$ $-y_d^i \bar{q}_L^i V_{CKM}^{i,j} H d_R^j$	$-\lambda_u^i \bar{q}_L^i H^c U_R$ $-\lambda_d^i \bar{q}_L^i H D_R$		$-\lambda_u^i \psi_L H^{(c)} u_R^i$ $-\lambda_d^i \psi_L H^{(c)} d_R^i$			$-\lambda_i \bar{q}_L^i \tau^a H^{(c)} \psi_R^a$	
$\mathcal{L}_m$	not allowed			$-M\bar{\psi}\psi$				

t't'->WbWb (single lepton + jets)

- Analysis strategy : Boosted W reconstruction

Selection:

- Electron :
  - Tight, p_T > 25 GeV & |η| < 2.47 not in the crack (1.37-1.52), isolated
- Muon :
  - p_T > 20 GeV & |η| < 2.5
- Jets :
  - Topocluster anti-kt, cone R = 0.4
  - p_T > 25 GeV & |η| < 2.5
- Event level cuts :
  - > 4 tracks from primary vertex (non-collision background rejection)
  - *e*-channel : E_T^{miss} > 35 GeV & $E_T^{miss} + m_T^W$ > 60 GeV
  - *mu*-channel : E_T^{miss} > 20 GeV & $E_T^{miss} + m_T^W$ > 60 GeV

t't'->WbWb (single lepton + jets)

m_{u_4} (GeV)	$\sigma(u_4\bar{u}_4)$ (pb)	Scale uncertainties (pb)	PDF and α_s uncertainties (pb)
400	1.406	+0.045/-0.083	+0.176/-0.138
450	0.662	+0.023/-0.040	+0.087/-0.065
500	0.330	+0.012/-0.020	+0.045/-0.032
550	0.171	+0.007/-0.010	+0.024/-0.017
600	0.092	+0.004/-0.006	+0.014/-0.009
650	0.051	+0.002/-0.003	+0.008/-0.005
700	0.029	+0.001/-0.002	+0.005/-0.003
750	0.017	+0.001/-0.001	+0.003/-0.002

Table 3: Theoretical cross section at NNLO for $u_4\bar{u}_4$ production as a function of m_{u_4} as computed by HATHOR, and scale and PDF uncertainties.

m_T (GeV)	BR(WbWb)	BR(WbtH)	BR(WbtZ)	BR(tHtZ)	BR(tHtH)	BR(tZtZ)
400	0.2625	0.3569	0.1427	0.0969	0.1217	0.0193
450	0.2518	0.3409	0.1583	0.1078	0.1161	0.0250
500	0.2468	0.3282	0.1717	0.1141	0.1092	0.0300
550	0.2448	0.3169	0.1827	0.1183	0.1029	0.0344
600	0.2441	0.3075	0.1923	0.1209	0.0972	0.0379

Table 2: Protos Branching Ratios (BR) for $T\bar{T}$ production as a function of m_T as computed by PROTOS.

b'b'→WtWt→4W2b (Same Sign Leptons + Jets)

Selection:

- Electron :
  - Tight, p_T > 25 GeV & |η| < 2.47 not in the crack (1.37-1.52), isolated
- Muon :
  - Combined with track, p_T > 20 GeV & |η| < 2.5, isolated, not overlap with jet
  - Back-to-back muon pairs removed
- Jets :
  - Topocluster anti-kt, cone R = 0.4
  - p_T > 25 GeV & |η| < 2.5
  - Remove jets overlapped with electron
- Event level cuts :
  - E_T^{miss} > 40 GeV

Heavy-quark and same-sign top-quark signal regions		
	$\ell^+\ell^+$ and $\ell^-\ell^-$	
$b'_{m_{b'}=350\ \text{GeV}}$	2.0%	
$b'_{m_{b'}=450\ \text{GeV}}$	2.5%	
$b'_{m_{b'}=550\ \text{GeV}}$	2.7%	
	$\ell^+\ell^+$	$\ell^-\ell^-$
tt_{LL}	0.7%	negligible
tt_{LR}	0.8%	negligible
tt_{RR}	0.8%	negligible
Low-mass Z' boson signal region		
$tt_{RR,m_{Z'}=100\ \text{GeV}}$	0.7%	negligible
$tt_{RR,m_{Z'}=150\ \text{GeV}}$	0.8%	negligible
$tt_{RR,m_{Z'}=200\ \text{GeV}}$	1.0%	negligible

b'b'→WtWt→4W2b (Same Sign Leptons + Jets)

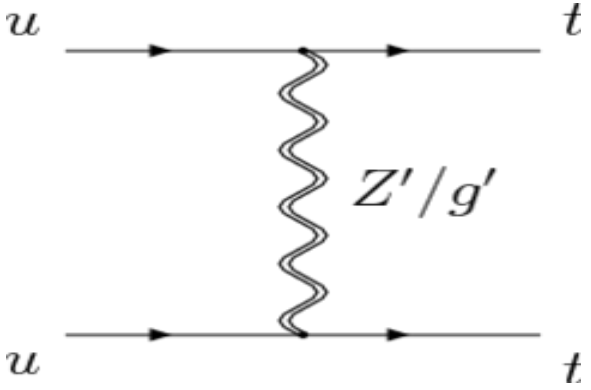
- Analysis also used to search for same-sign (s-s) top-quark pair production

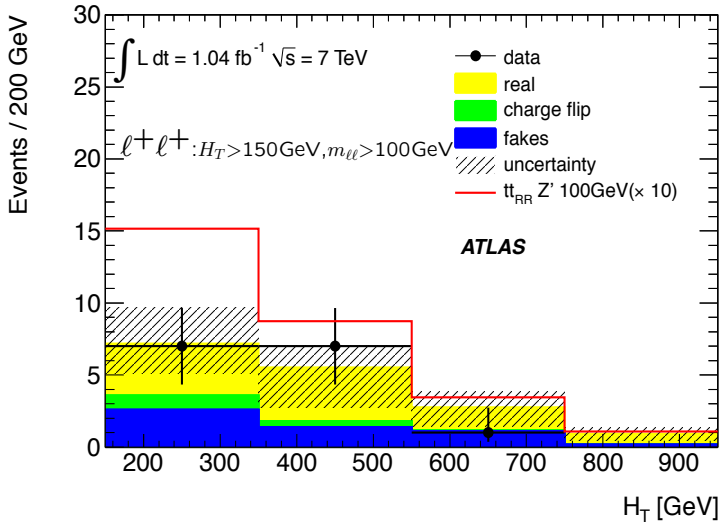
- **Event selection :**
  - At least 2 lepton candidates with same charge and at least 2 "good" jets
  - In *ee* or *μμ* channel : inv. mass of 2 leptons must exceed 15 GeV & $|m_{ll} - m_Z| > 10$ GeV
  - Missing transverse momentum > 40 GeV

- **3 signal regions :**
  - (1) Heavy quark signal region for *b'*, or s-s top-pair production from high-mass *Z'* exchange :

    H_T (jets+leptons) > 350 GeV
  - (2) Same-sign top-quark signal region : satisfies requirement of (1) but only for positively-charged leptons
  - (3) Low-mass *Z'* boson signal region : positively-charged leptons, $H_T > 150$ GeV, $m_{ll} > 100$ GeV

Latest paper with 1.04 fb^{-1}
arXiv : 1202.5520





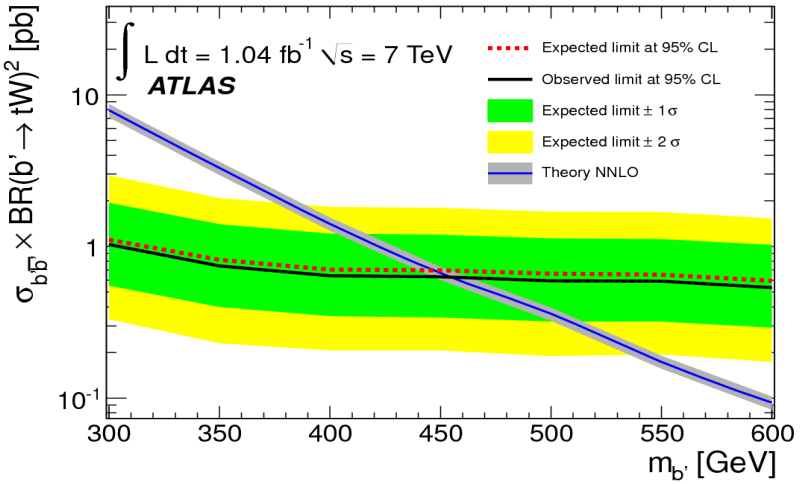
Comparison of observed data and expected SM backgrounds for H_T in region (3)

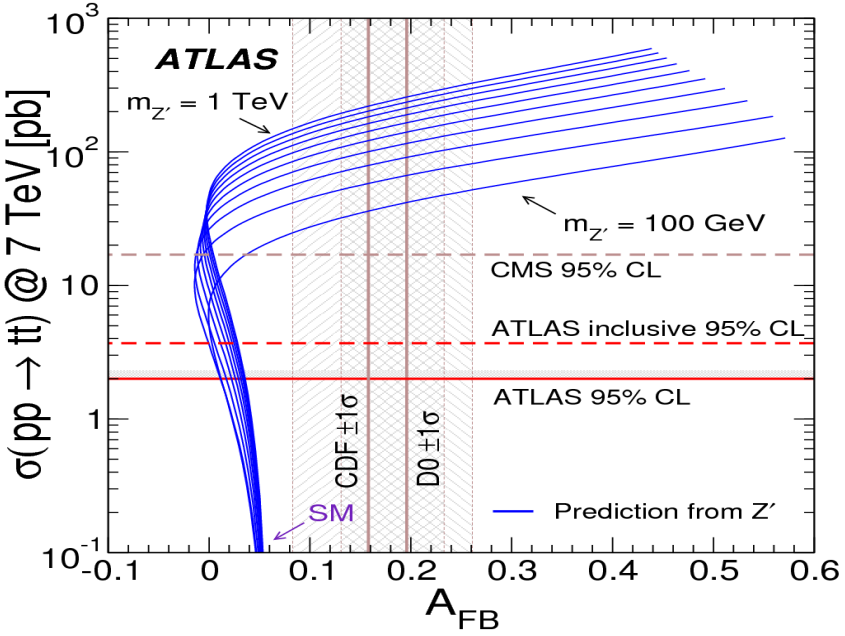
b'b'→WtWt→4W2b (Same Sign Leptons + Jets)

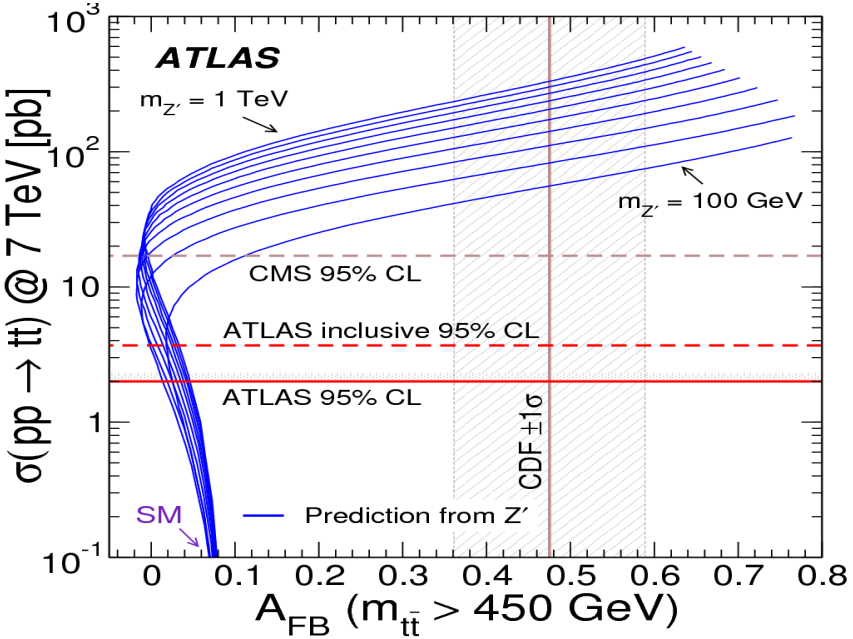
arXiv : 1202.5520

Results :

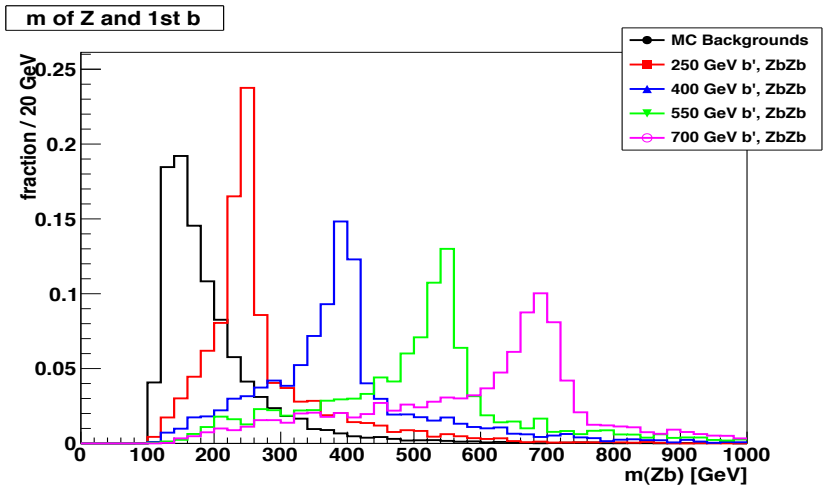
- Heavy down-type quark $m_{b'} > 450$ GeV
- For s-s top quarks production : Solid red line presents result from analysis, measurements of forward-backward production at Tevatron lie above SM expectation
  - Upper limit for cross section : 2pb



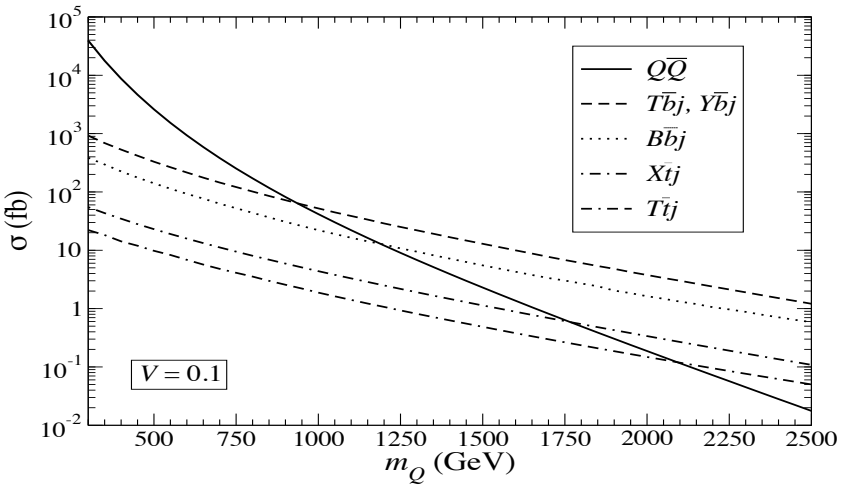




BB → Zb+X



Selection of objects is exactly the same as the 2 previous analyses.



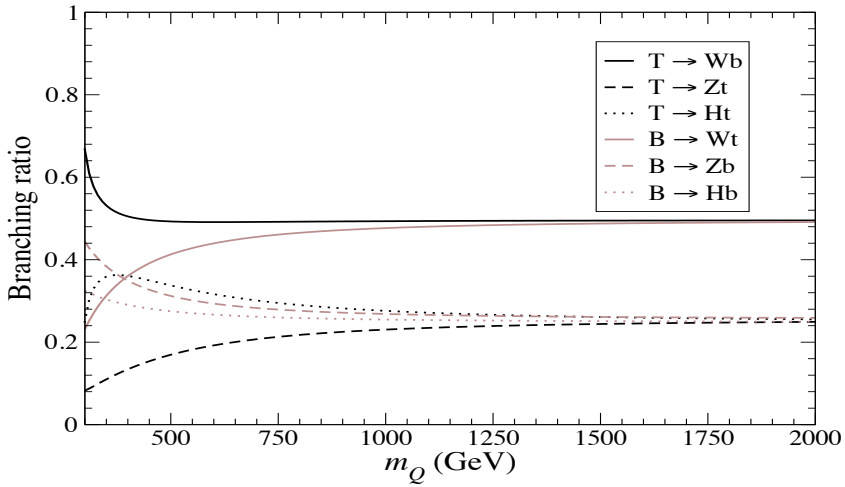


Figure 1. Left: Heavy quark production cross sections at LHC. Right: branching ratios for T and B decays.

Single Vector-like Quark Production

Selection:

- Object selection is the same as for the previous analyses
- Additional cuts :

CC Channel:

- $|\Delta\eta(W, \text{leading jet})| < 2.3$
- $|\Delta\phi(W, \text{leading jet})| > 2.1$ rad
- $|\Delta\phi(\ell, \text{E}_\text{T}^\text{miss})| < 1.3$ rad
- $|\Delta\eta(W, \text{associated jet})| > 1.6$
- $|\Delta\eta(\text{leading jet, associated jet})| > 1.3$
- $\text{E}_\text{T}^\text{miss} > 50$ GeV
- $p_\text{T}^\text{leading jet} > 60$ GeV

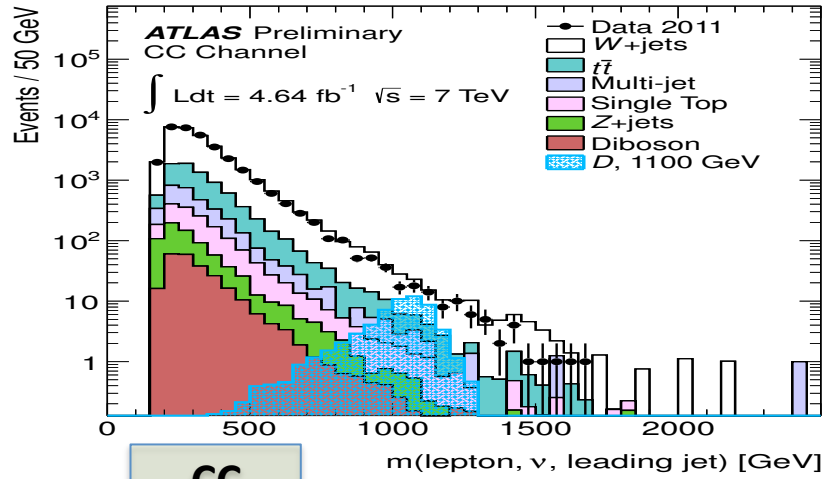
NC Channel:

- $|\Delta\phi(\ell, \ell)| < 1.5$ rad
- $|\Delta\eta(\ell, \ell)| < 1.6$
- $|\Delta\phi(Z, \text{leading jet})| > 2.1$ rad
- $|\Delta\eta(Z, \text{leading jet})| < 1.1$
- $|\Delta\eta(Z, \text{associated jet})| > 0.9$
- $|\Delta\eta(\text{leading jet, associated jet})| > 0.9$

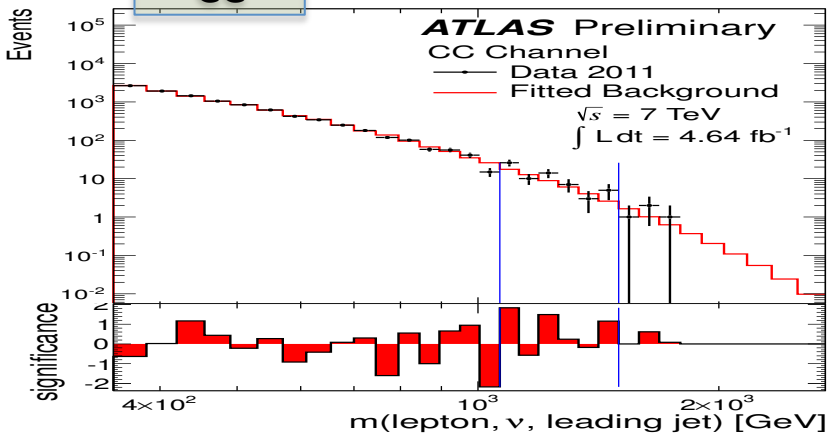
Single Vector-like Quark Production

Results :

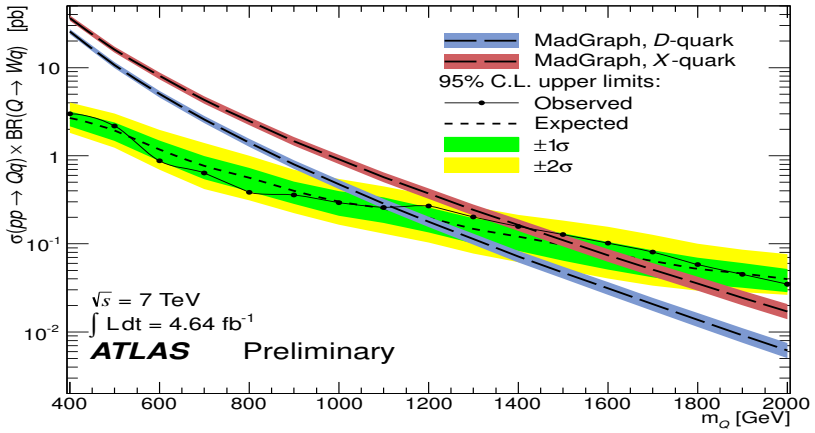
ATLAS Note ATLAS-CONF-2012-137



CC



Same kind of plots but for CC channel



- Mass of X(+5/3), D(-1/3) greater than 1420 GeV and 1080 GeV respectively
- U(+2/3) with mass below 1120 GeV excluded (NC)

Single Vector-like Quark Production

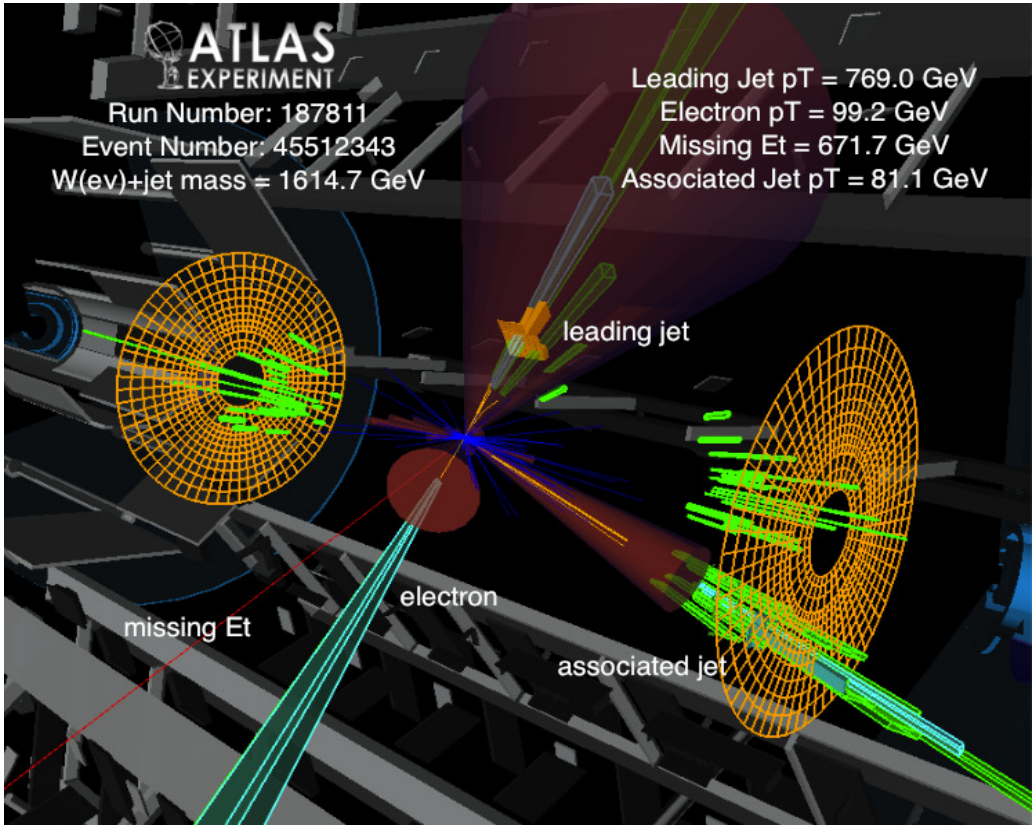


Figure 7: Event display for the $W \rightarrow e\nu$ channel event with the highest three body invariant mass. Here, the invariant mass of the three body system is $M(e, \nu, \text{leading jet}) = 1615$ GeV.

Single Vector-like Quark Production

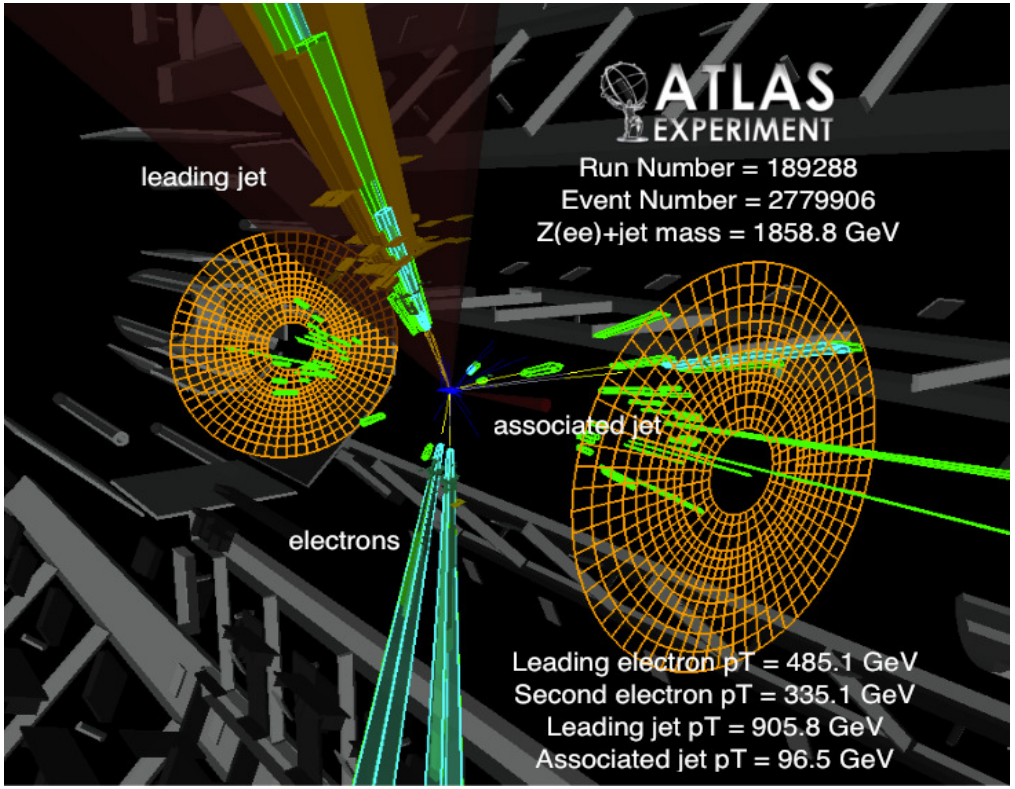


Figure 9: Event display for the $Z \rightarrow ee$ channel event with the highest three body invariant mass. Here, the invariant mass of the three body system is $M(e, e, \text{leading jet}) = 1859$ GeV.