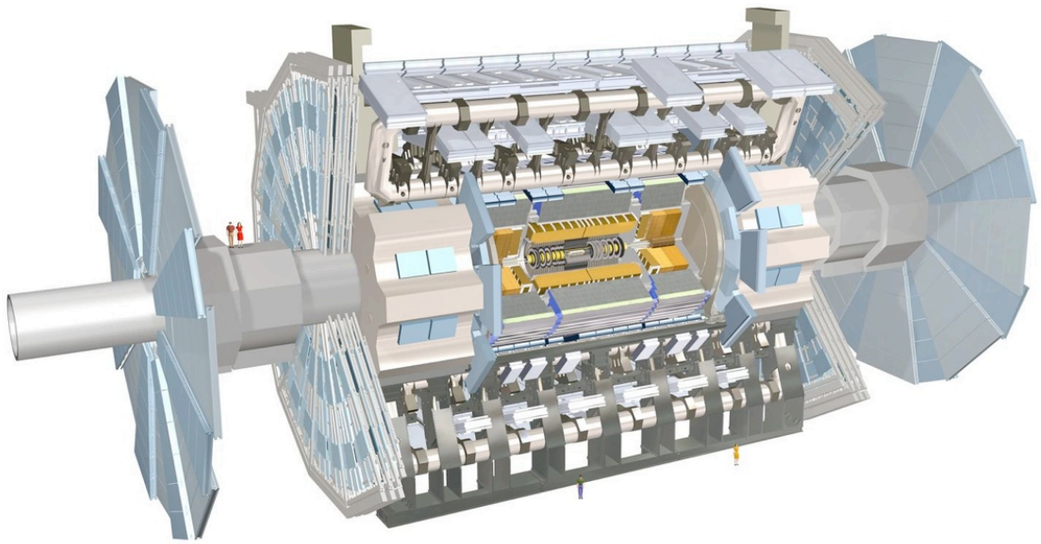
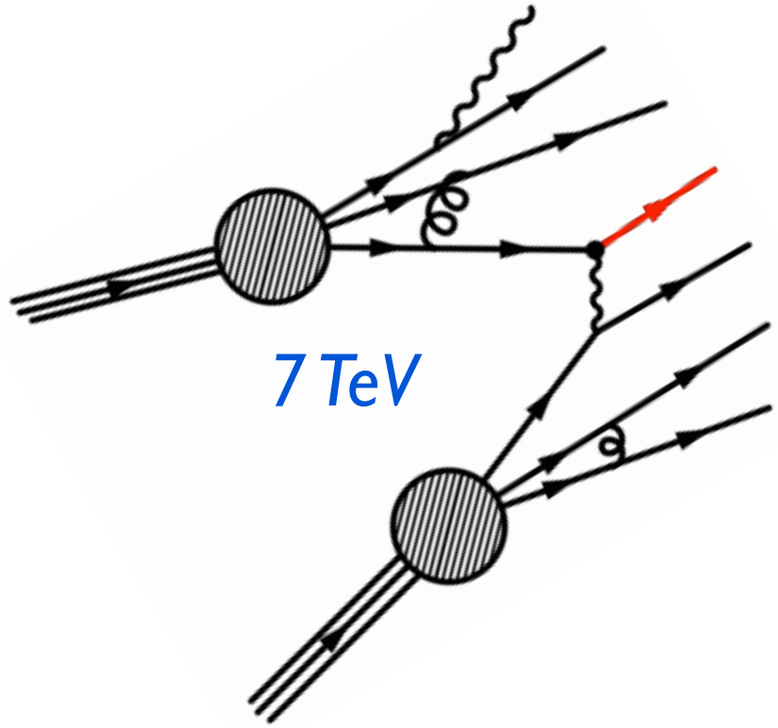
$$\frac{g}{\sqrt{2}} W_\mu^+ \left(\kappa_{uD} \bar{u}_R \gamma^\mu D_R + \kappa_{dD} \bar{d}_R \gamma^\mu U_R \right) + \frac{g}{2c_W} Z_\mu \left(\kappa_u U \bar{u}_R \gamma^\mu U_R + \kappa_{dD} \bar{d}_R \gamma^\mu D_R \right) + h.c.$$

Searches for vector-like quarks and Top-jet resonances with ATLAS

Merlin Davies

On behalf of the ATLAS collaboration



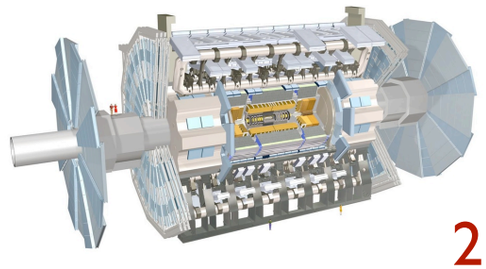


ATLAS EXPERIMENT

ICHEP 2012 - Melbourne

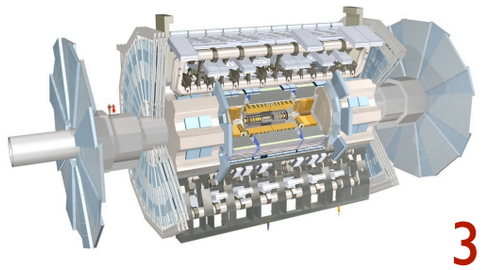
Université de Montréal

Overview



- **I will present the results of 3 ATLAS searches performed with 2011 data.**
- **Vector-like quark (VLQ) searches (2)**
  - Properties and theoretical motivations
  - **Pair production of vector-like quark singlets (VLS) decaying by neutral current** [arXiv:1204.1265]
    - $b' \rightarrow Zb$
  - **Single production of vector-like quarks coupling to light quarks** [Phys.Lett. B712 (2012) 22-39]
    - $qq \rightarrow D\,q \rightarrow Wu\,q$ *(CC channel)*
    - $qq \rightarrow U\,q \rightarrow Zu\,q$ *(NC channel)*
- ***Top+jet* resonance search (1)**
  - Theoretical Motivation
  - **Associated production of a top + jet resonance** [ATLAS-CONF-2012-096]
    - $g\,q \rightarrow X\,\bar{t} \rightarrow t\,j\,\bar{t}$

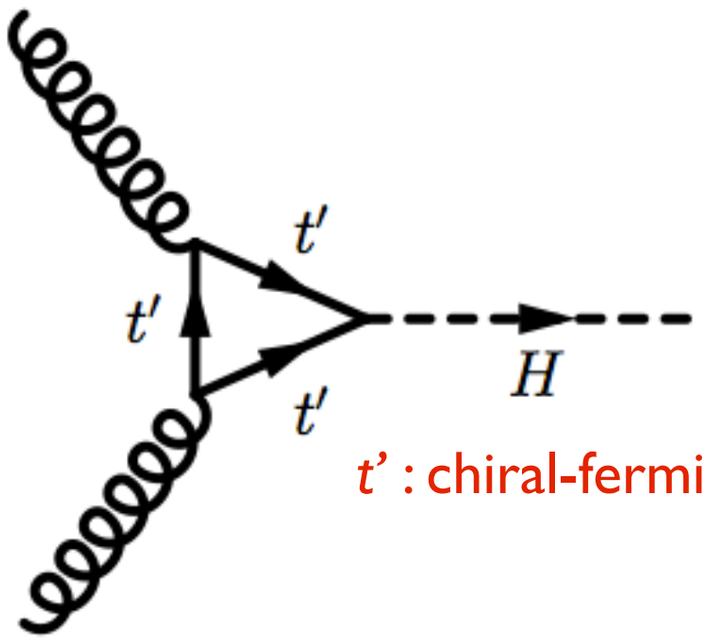
General properties of vector-like quarks



- The *Left* and *Right* components of vector-like quarks (*VLQ*) transform identically under the weak force:
  - **Chiral:** $\sim W_\mu \bar{\psi} \gamma^\mu (1-\gamma_5) \psi$ **Vector:** $\sim W_\mu \bar{\psi} \gamma^\mu \psi$
- Important Phenomenological Properties of 4th generation *chiral* quarks:
  - Increases by a factor of **~9** the Higgs' SM cross-section...
    We would have seen the Higgs long ago!
  - *Vacuum instability* : Their loop contributions to the Higgs' propagator can render λ negative!

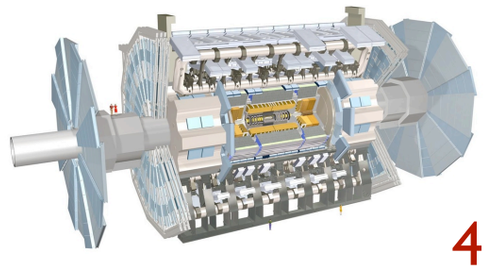
$$V(\phi) = -\frac{1}{2}\mu^2 \phi^\dagger \phi + \frac{1}{4}\lambda \left(\phi^\dagger \phi\right)^2$$

- **VLQ *evade* these problems because**
  - They don't have a Yukawa coupling to the Higgs
  - Contribute negligibly to the Higgs' self-coupling

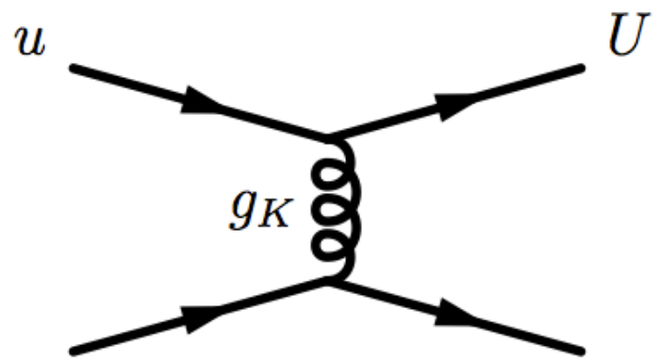


t' : chiral-fermion

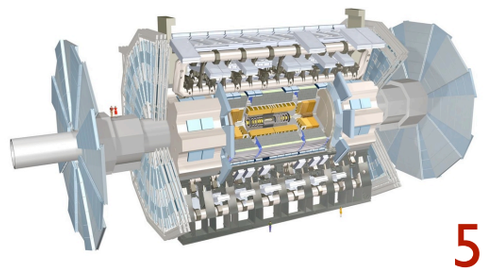
Models predicting the existence of VLQs



- In many ***BSM theories***, VLQ's play the role of top-partners to cancel the top's contribution to the Higgs' self-coupling.
  - **Little Higgs (with *T-Parity*)**
    - Higgs arises naturally as a Pseudo-Goldstone Boson
    - Global SU(5) symmetry breaking at the weak scale ~TeV
  - **Composite Higgs, or strongly interacting Higgs**
    - A new strong force exists where the Higgs is composite
    - Other new composite states are phenomenologically identical to VLQ at energies below the energy scale of this new interaction → VLQ can interact with light quarks via this new strong force
  - **Extra-dimension models**
    - Universal Extra Dimensions: Kaluza-Klein excitation of a chiral quark phenomenologically similar to a vector-like quark if the number of extra dimensions is odd.
  - **GUT E6, SO(10), and others...**
    - Within many of the breaking schemes of these large groups, the final result contain a piece identical to the SM, and another containing, among other fermion fields, new up and down type vector-like quarks (E(6) only has down-type VLQ).

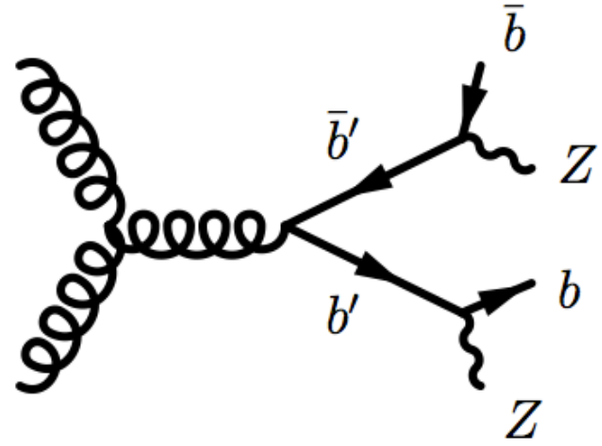


Vector-like quark search strategies



- Given the wide range of possible models predicting the existence of VLQ → We search for them while trying to stay as **model independent** as possible
- Although Vector-like quarks could exist as a series of singlets, doublets, and triplets, we chose to focus on *2 main possibilities* which were the basis of **2 searches performed by ATLAS** [arXiv:1204.1265, Phys.Lett. B712 (2012) 22-39]

1) A down-type vector-like quark singlet (VLS) coupling to 3rd generation and produced in pair pp → *b′b′* → *Zb (Zb,Wt, Hb)*



No requirement on the decay of the second b′

- The **probability** that at least one *b′* decays to *Zb* is parametrized by :

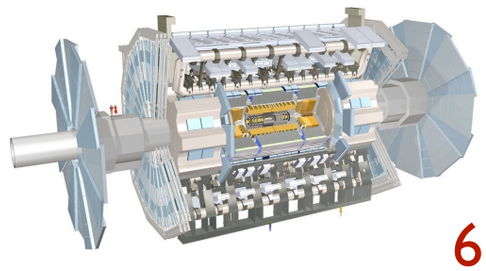
$$\beta = 2 \times BR(b' \to Zb) - BR(b' \to Zb)^2$$

- In the limit of high *b′* mass

$$BR(b' \to Wt) : BR(b' \to Hb) : BR(b' \to Zb) \longrightarrow 2:1:1$$

- For *b′* masses in the range [200, 700] GeV, β varies from 0.9 to 0.5

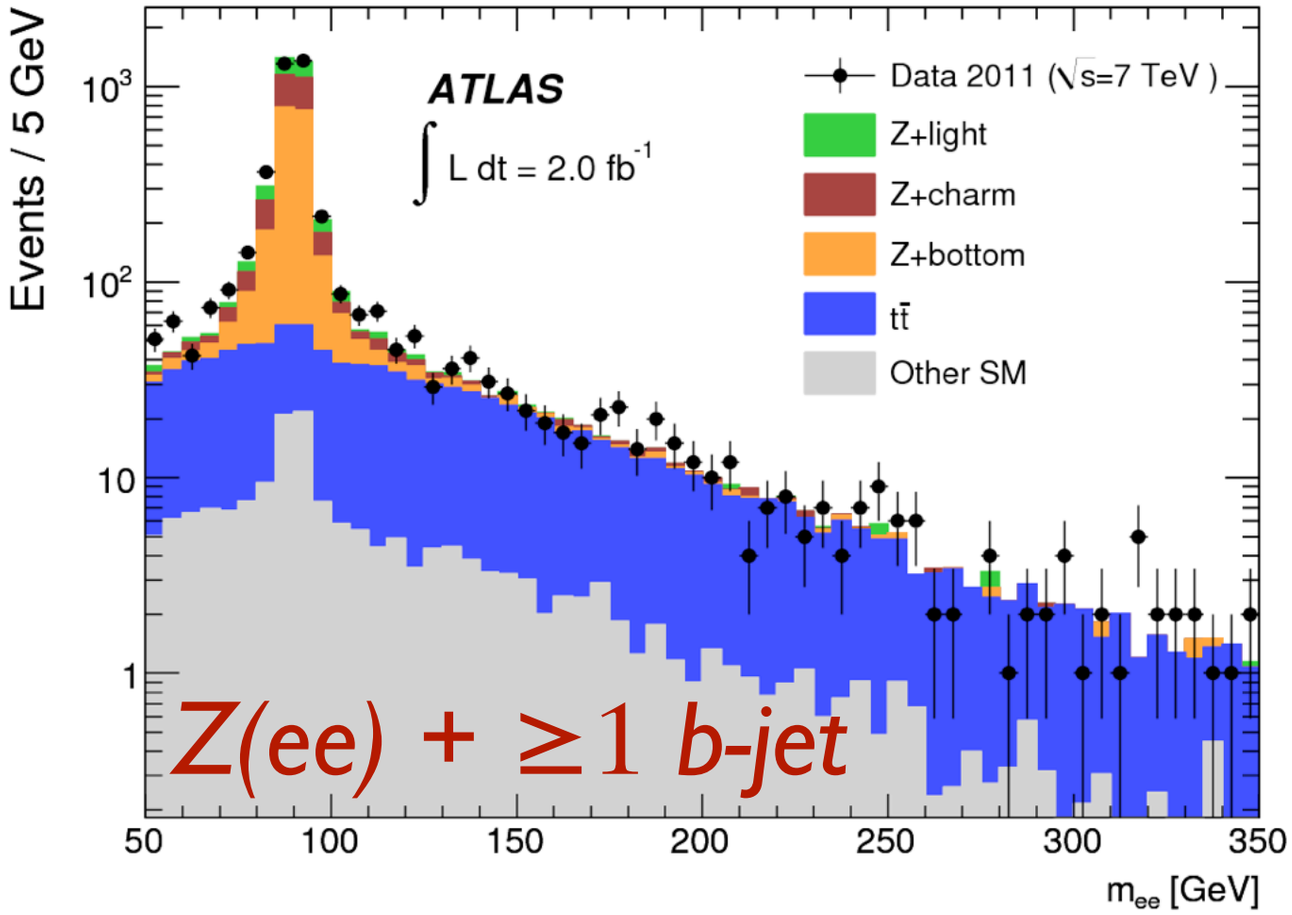
Search for Vector-Like Quark Singlet (VLS) in Pair Production



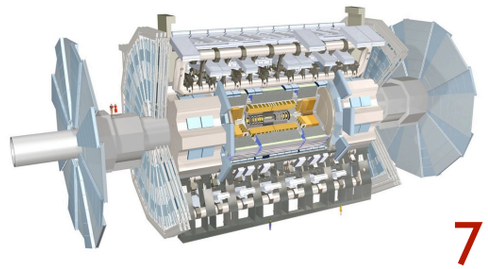
- Experimental Analysis with **2.0 fb^{-1} of 2011 data**

- **Looking for *Z(ee)* + > 1 b-jet events**
- **Electron cuts:**
  - p_T > 25 GeV
  - |η| < 2.47 while removing 1.37 < |η| < 1.52
  - **$|m_{ee} - m_Z|$ < 15 GeV**
- **Jet cuts:**
  - anti-k_t algorithm cone R = 0.4
  - A least 75% of the total track p_T point the selected vertex
  - |η| < 2.5
  - pT > 25 GeV
  - Require at least one *b*-tagged event
    - **60% efficiency for *b*-hadrons**
      - measured in ttbar events
    - **Rejection rate of 300 for light flavour jets**

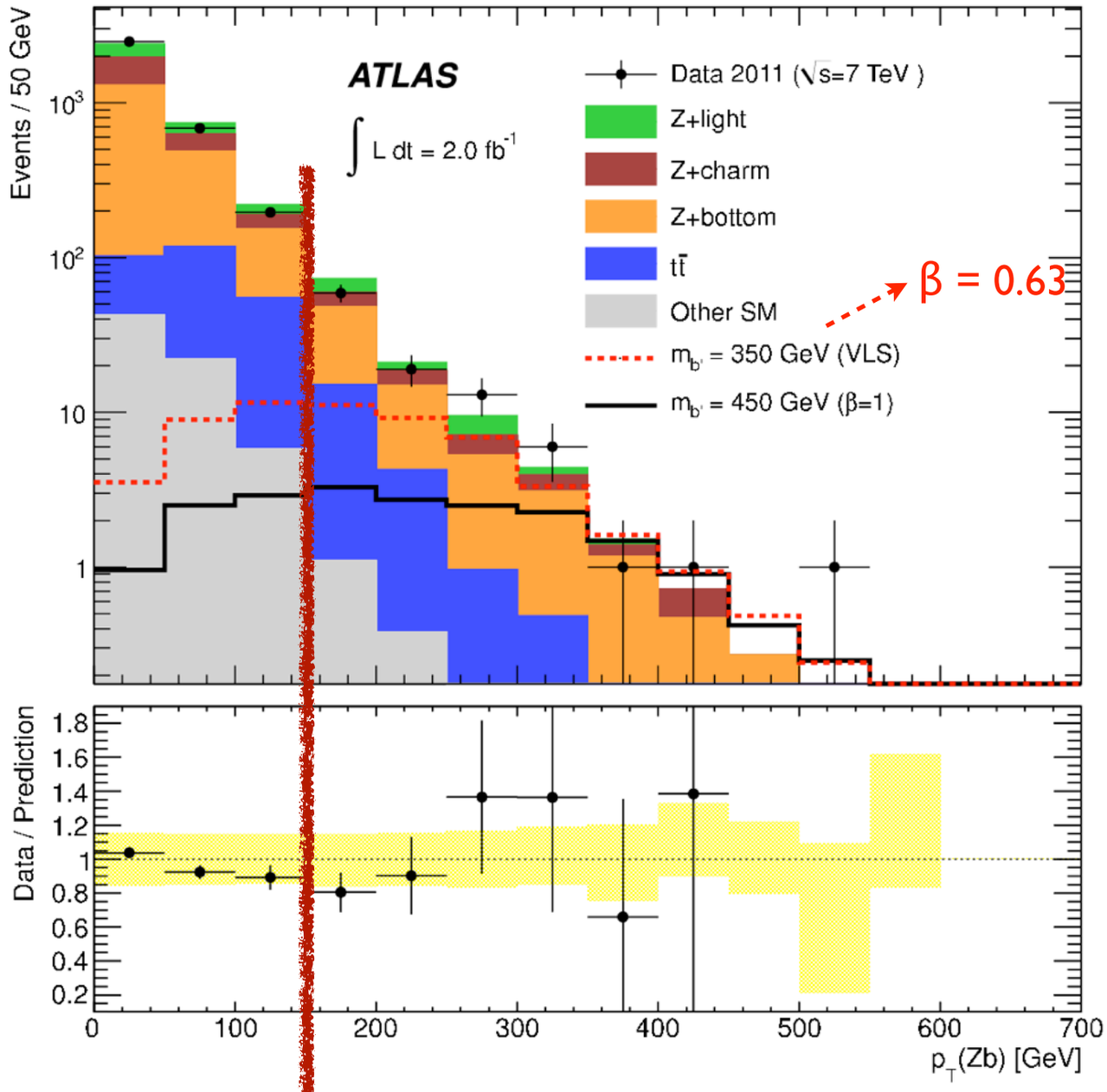
MC Generators Used:
Z+jets → AlgGen (scaled to NNLO[3])
→ Sherpa used as cross check
ttbar → MC@NLO (NNLO σ comp. using HATHOR[6])



Signal Region for VLS

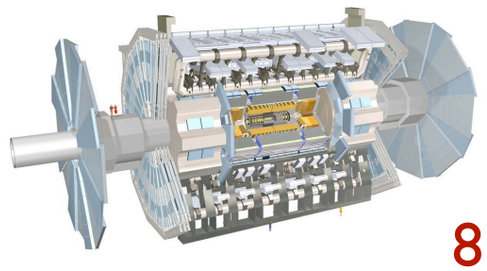


- Since we have ***back-to-back b'***, we place a cut
  - $p_T(Zb) > 150$ GeV
- Signals generated by MADGRAPH with the G4LHC extension
- Signal cross-sections vary from 80 *pb* to 30 *fb* in the range $m_{b'} = [200, 700]$ GeV

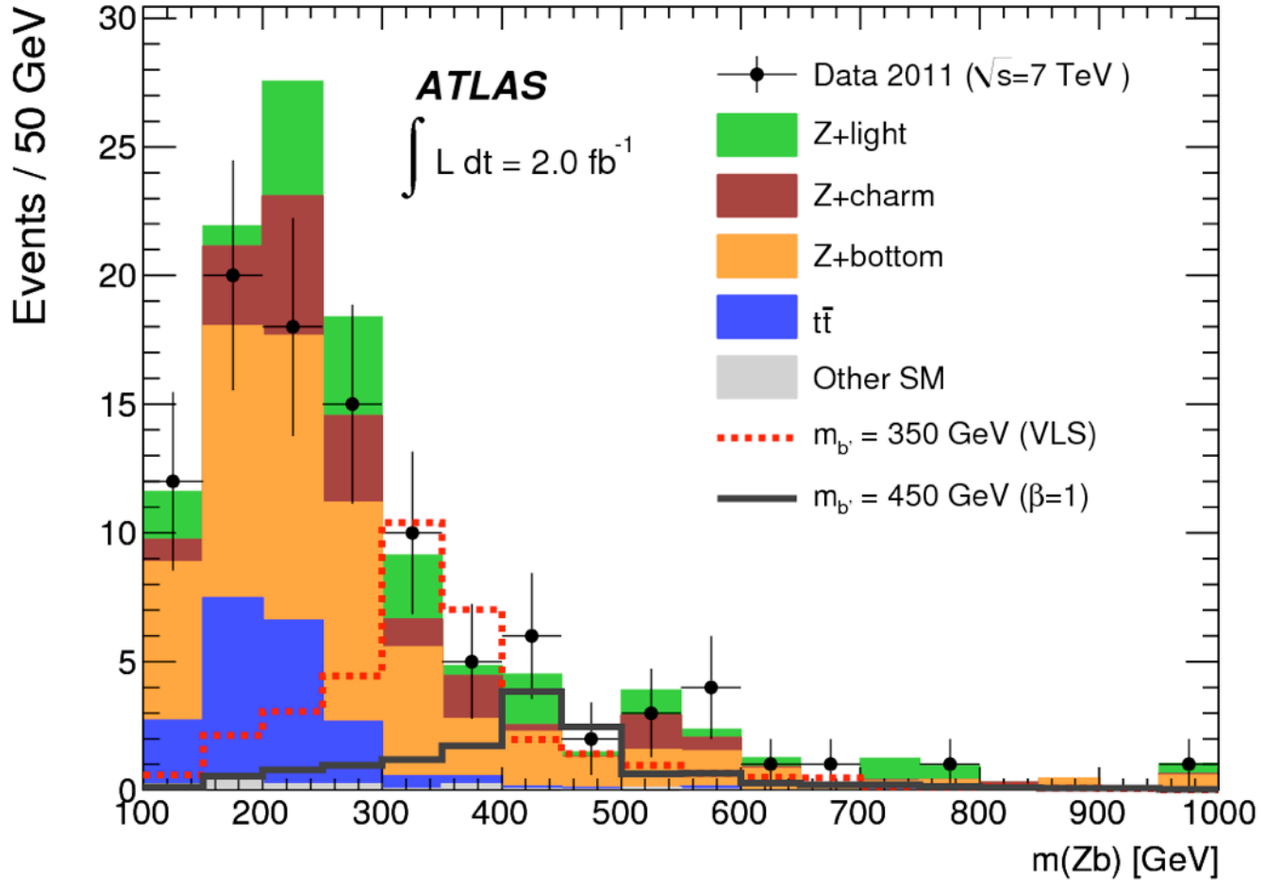


Signal Region

Results - Down-Type VLS Search

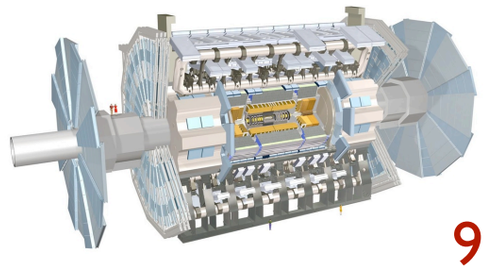


Source	Signal Region Yields
Z+light	19 ± 7
Z+charm	18 ± 7
Z+bottom	52 ± 17
ttbar	20 ± 4
Other SM	1.6 ± 0.4
Total SM	**110 ± 30**
DATA	**100**
mb' = 350 GeV	55 ± 7
mb' = 450 GeV	14 ± 2

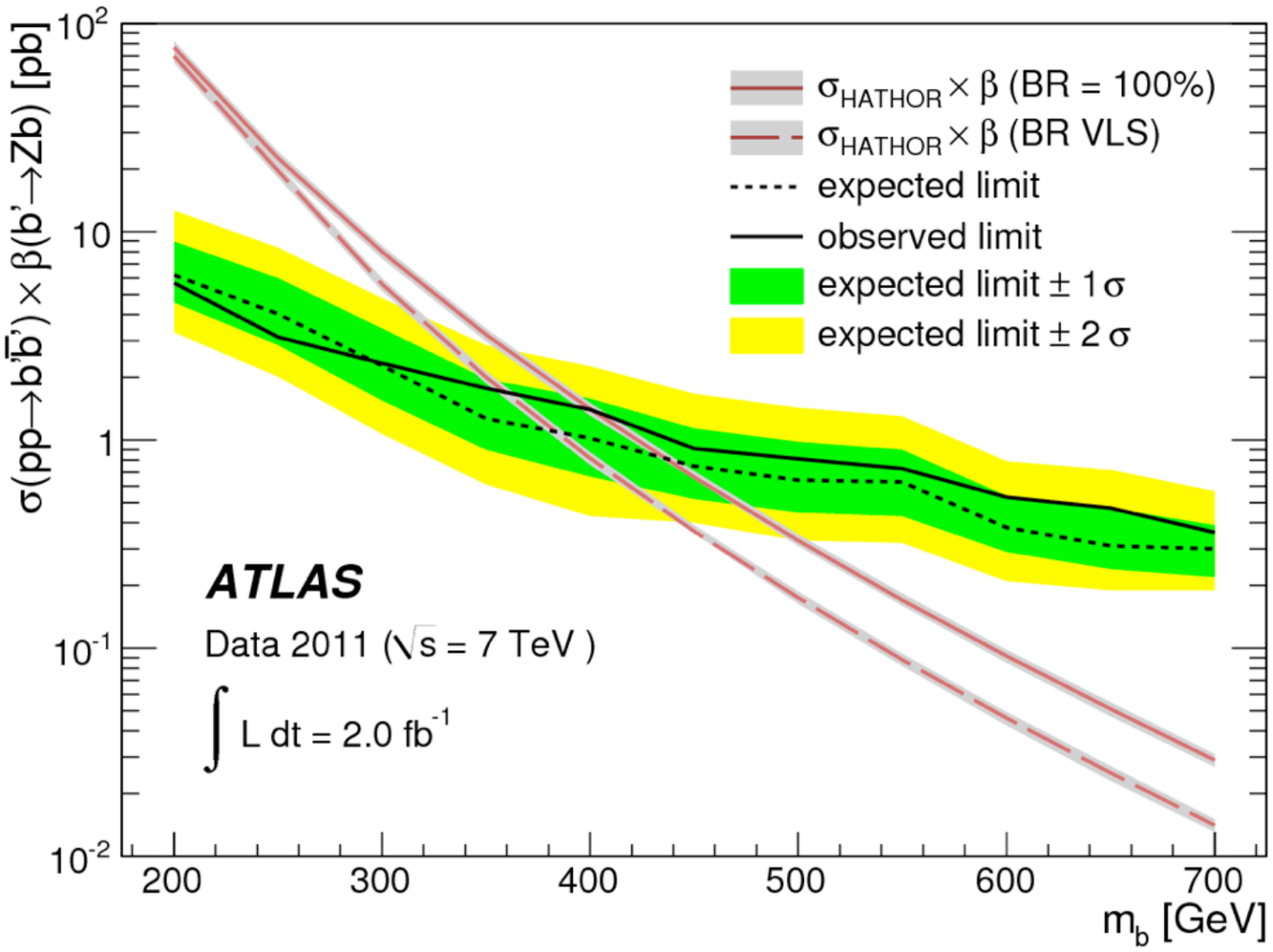


- **Important systematics:**
  - Renormalization and factorization scale (14%)
  - AlpGen vs Sherpa shape differences (12%)
  - b-tagging efficiency (12%)

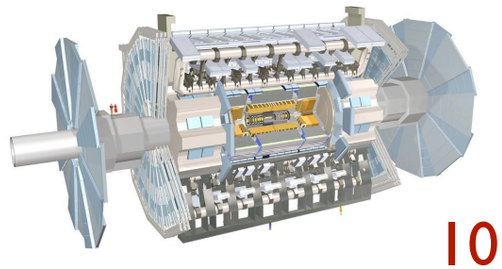
Results - Down-Type VLS Search



- Since no excess is found, we computed limits based on the CL_s modified frequentist approach
- Assuming VLS mixing solely to 3rd generation quarks and
- **β = 1**, we find
  - **$m_{b'}$ < 400 GeV at 95% C.L.**
- **β = 0.63**, we find
  - **$m_{b'}$ < 358 GeV at 95% C.L.**



Vector-like quark search strategies (Cont.)



2) VLQ are generally expected to couple to 3rd generation, but under some symmetries → it is possible to construct models with VLQ coupling primarily to light quarks.

- **One such model it to have a pair of VLQ doublets** [arXiv:0806.396]

$$\begin{pmatrix} U \\ D \end{pmatrix}, \begin{pmatrix} X \\ Y \end{pmatrix} \quad Q_U = \frac{2}{3}, Q_D = -\frac{1}{3}, Q_X = -\frac{5}{3} \text{ and } Q_Y = \frac{4}{3}$$

- If the mass of these VLQ doublets are *almost* degenerate, cancellations can occur between the mixing and coupling of VLQs to light quarks

- **A model independent Lagrangian can be written (focusing on *U, D*):**

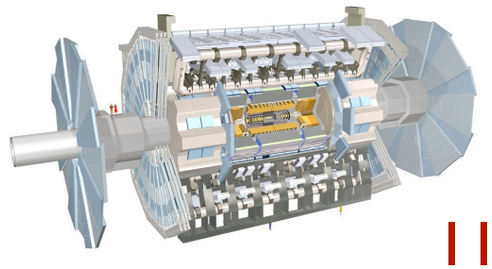
$$\frac{g}{\sqrt{2}} W_\mu^+ \left(\kappa_{uD} \bar{u}_R \gamma^\mu D_R + \kappa_{dD} \bar{d}_R \gamma^\mu U_R\right) + \frac{g}{2c_W} Z_\mu \left(\kappa_u U \bar{u}_R \gamma^\mu U_R + \kappa_{dD} \bar{d}_R \gamma^\mu D_R\right) + h.c.$$

- where the couplings $\kappa_{qQ} = \frac{v}{m_Q} \tilde{\kappa}_{qQ}$

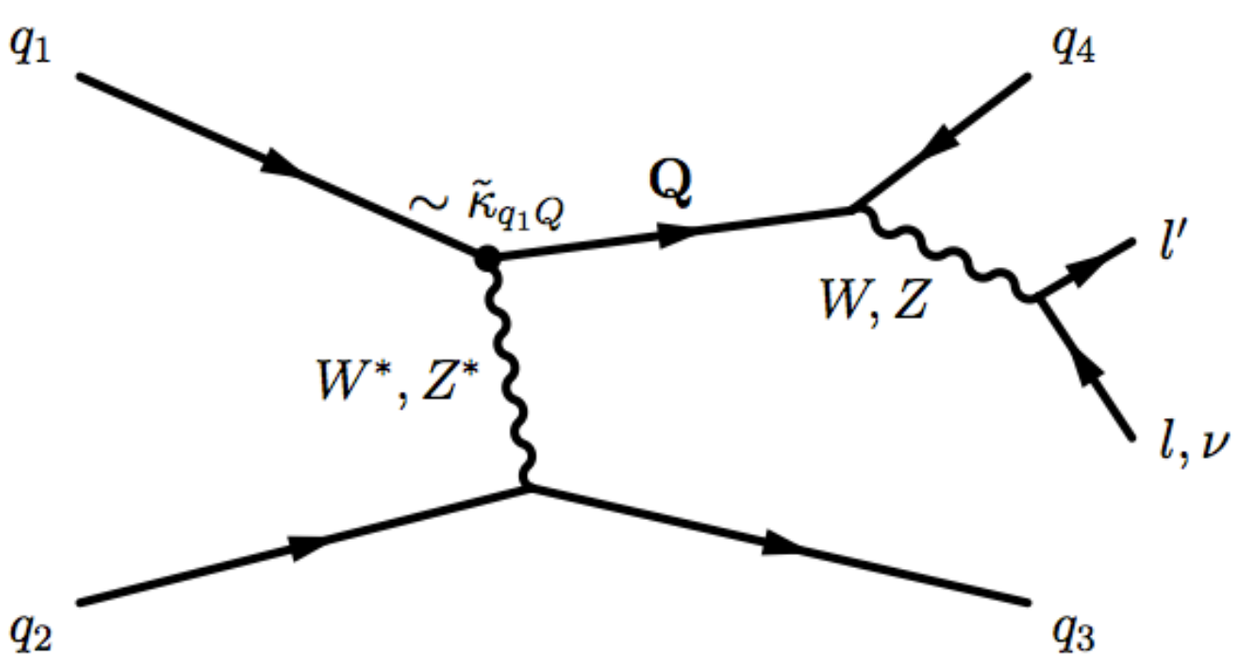
- In this degenerate VLQ doublet model, only mild *EW* constraints persists, in fact

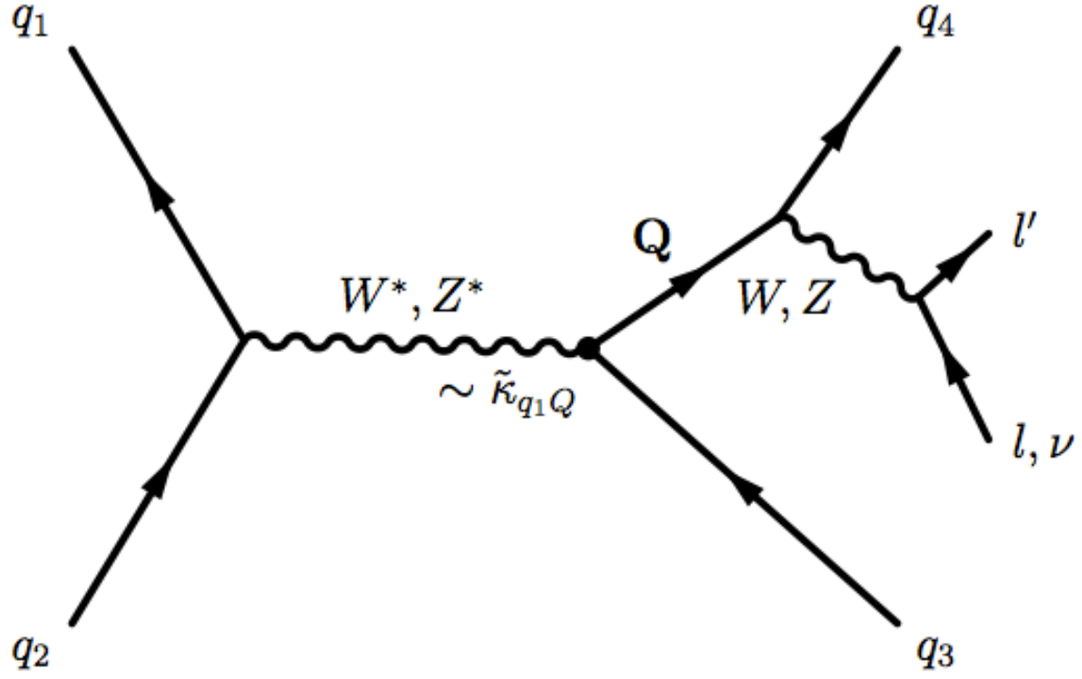
$$\tilde{\kappa}_{qQ} \sim 1$$

Vector-like quark search strategies (Cont.)

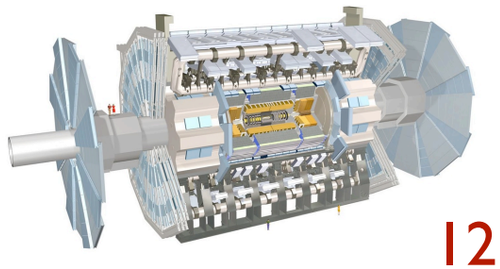


- Since the coupling $\tilde{\kappa}_{qQ}$ can be order ~1
  [Phys. Lett. B **669**, 39 (2008)]
  - *Single production* is a *more powerful* channel for this search *than pair production* → it is kinematically more favourable.

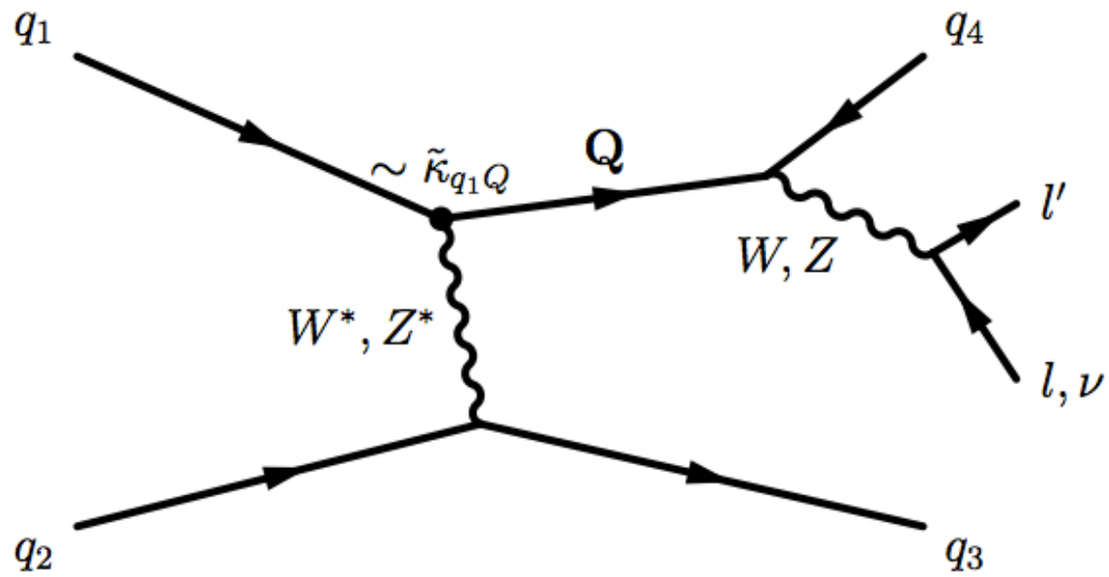




Search for VLQ coupling to light generations in single production



- Experimental Analysis with **1.04 fb^{-1} of 2011 data**
- **Looking for *W/Z* + 1 high p_T jet + 1 forward jet**
- Basic Electron/Muon cuts
  - p_T > 25 GeV
  - Isolated within a cone of ΔR = 0.2
- Basic Jet cuts
  - anti-k_t algorithm cone R = 0.4
  - Remove jets within ΔR = 0.5 with an electron
  - |η| < 4.5
  - p_T > 25 GeV

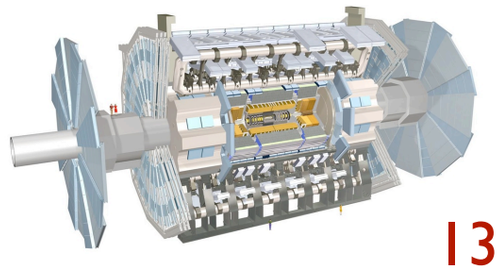


MC Generators Used:

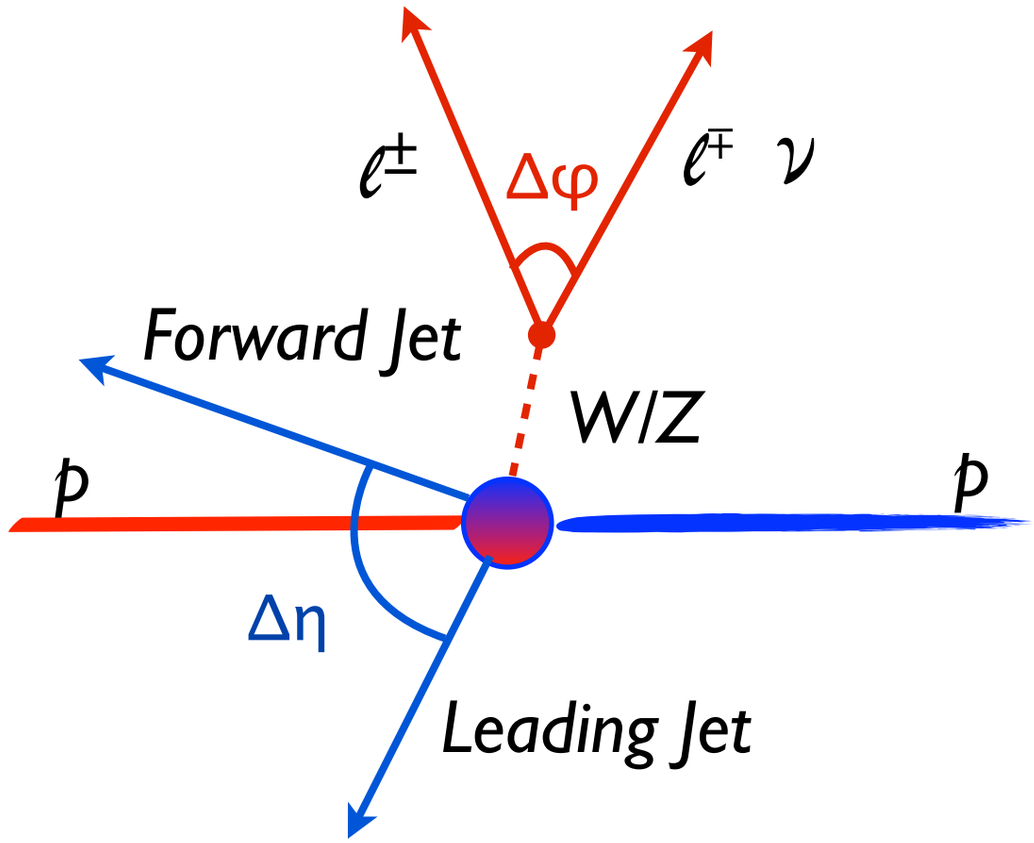
W/*Z*+*jets* → AlgGen (scaled to NNLO[3])

tt / single top / Di-bosons → MC@NLO

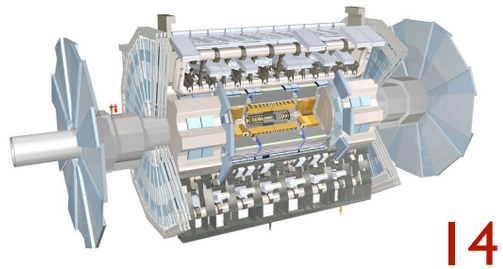
VLQ Signal Extraction - Signal Region

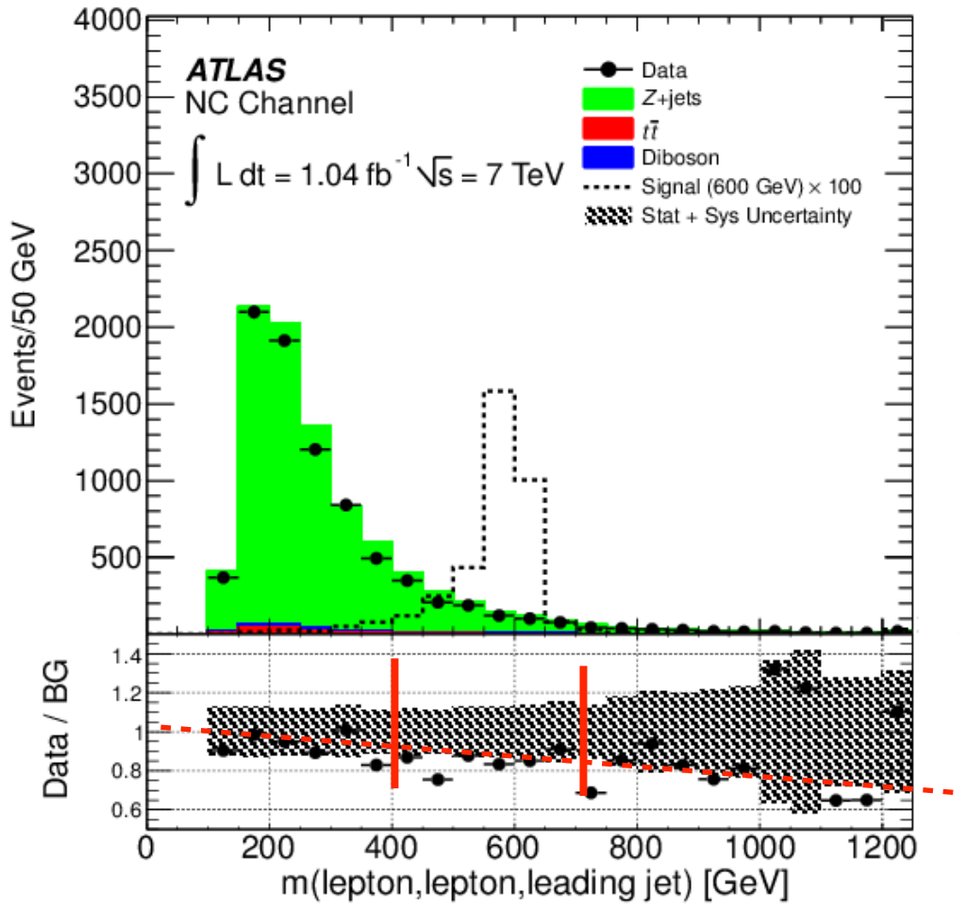


- **CC channel**
  - **Missing E_T > 50 GeV (reduce Multi-jet background)**
  - Leading Jet p_T > 50 GeV
  - N jets ≥ 2
  - **Δη(leading jet, forward jet) > 1.0**
  - $m_T(W)$ > 40 GeV
  - **Δφ(lepton, ν) < 2.4 rad**
  - Get Missing p_z solution for ν from $m(W)$ equation
- **NC Channel**
  - **$|m_{\ell\ell} - m_Z| < 25$ GeV**
  - **$p_T(Z) > 50$ GeV**
  - **Δη(leading jet, forward jet) > 1.0**
  - Leading Jet p_T > 50 GeV



Results - VLQ NC channel

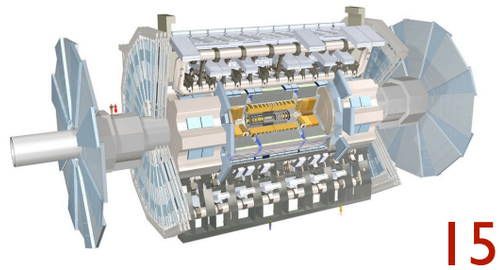




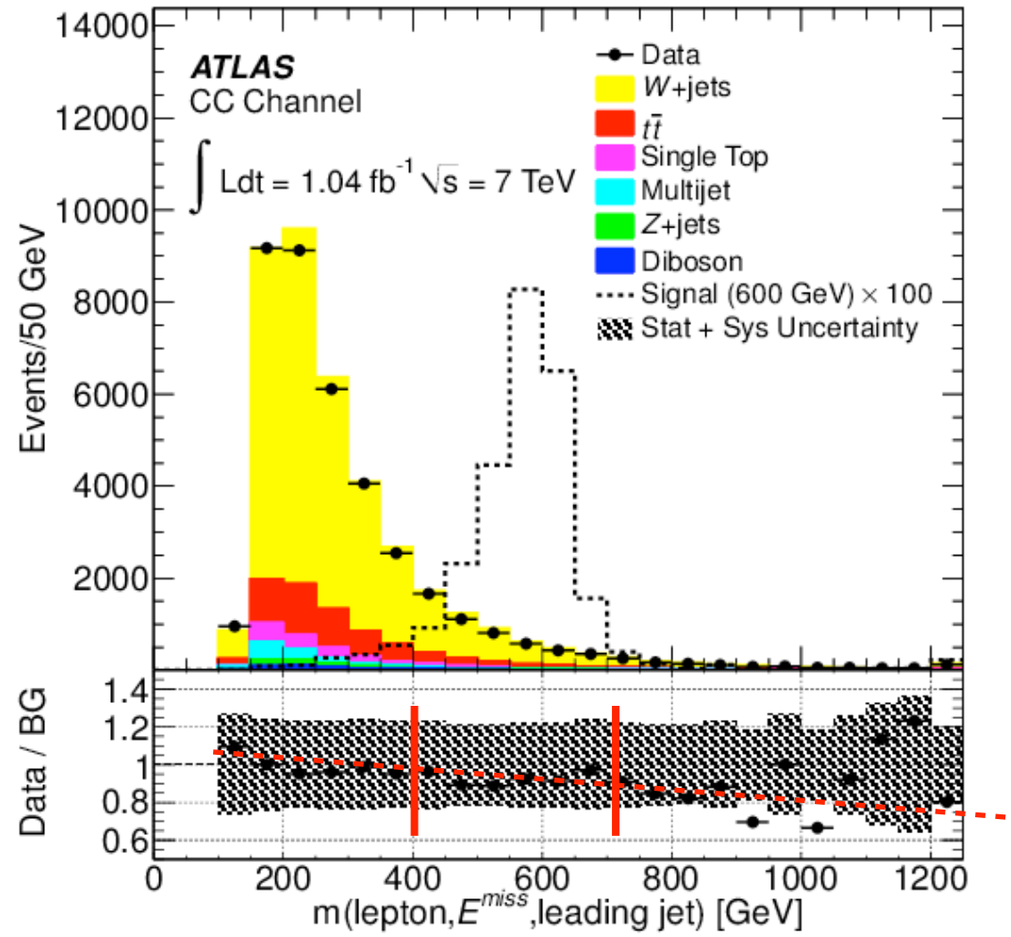
Source	Signal Region Yields
Z+jets	8600 ± 830
ttbar	148 ± 13
Dibosons	96 ± 11
Total SM	**8850 ± 67**
DATA	**8175**
m_U = 225 GeV	531 ± 31
m_U = 600 GeV	38 ± 6
m_U = 1000 GeV	4.6 ± 2.1

- **Due to a mis-modelling of the Z+jets background, a linear correction (--- in histogram above) is applied.**
  - We fitted the ratio Data/MC while excluding the range [m_U - 200, m_U + 100] GeV around each tested signal mass.
- **Main systematics:**
  - **Linear fit correction uncertainty**
  - Renormalization/Factorization Scales (4% to 12% depending on signal mass)
  - JES (20% on normalization and 5% on efficiency) (more sensitive to shape than normalization uncertainties)

Results - VLQ CC channel

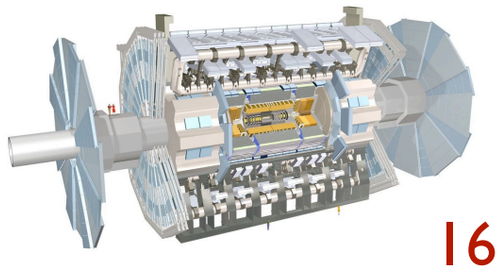


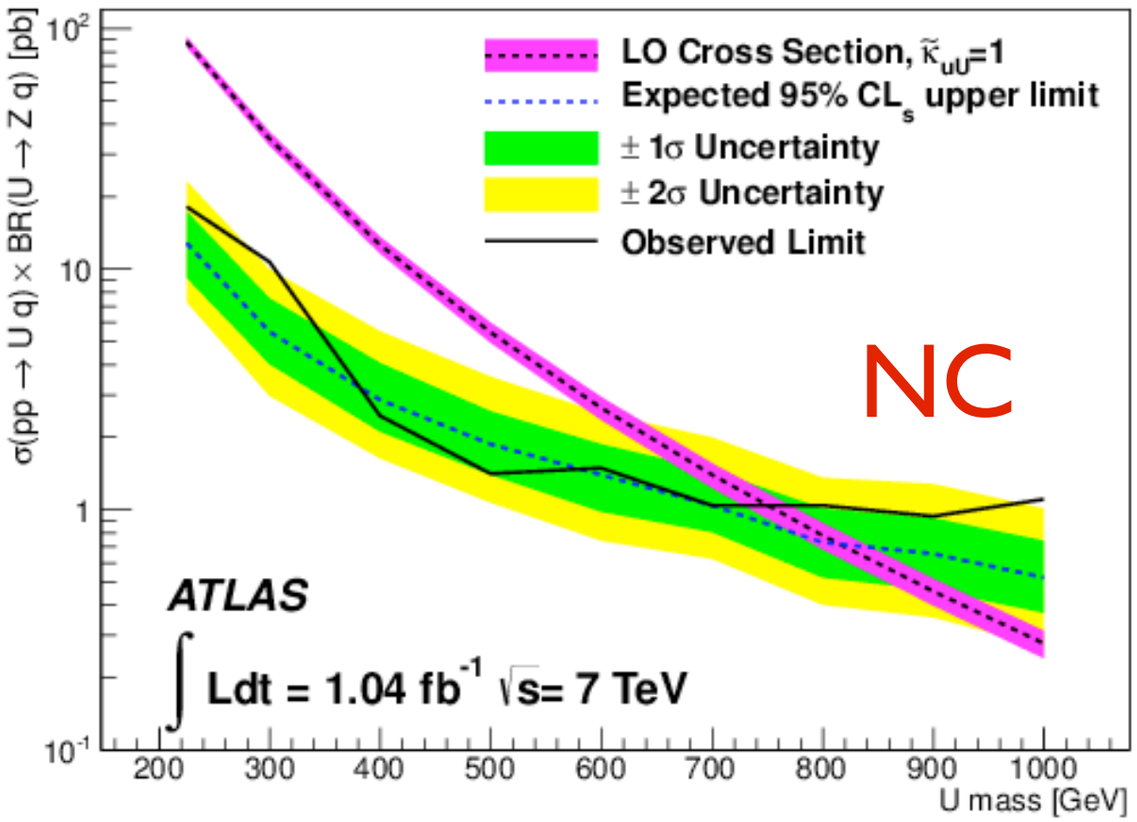
Source	Signal Region Yields
W+jets	31100 ± 6600
ttbar	4890 ± 400
Single Top	1440 ± 20
Multijet	1010 ± 50
Z+jets	560 ± 200
Dibosons	372 ± 84
Total SM	**39400 ± 6700**
DATA	**37970**
m_D = 600 GeV	266 ± 22
m_D = 1000 GeV	28 ± 6

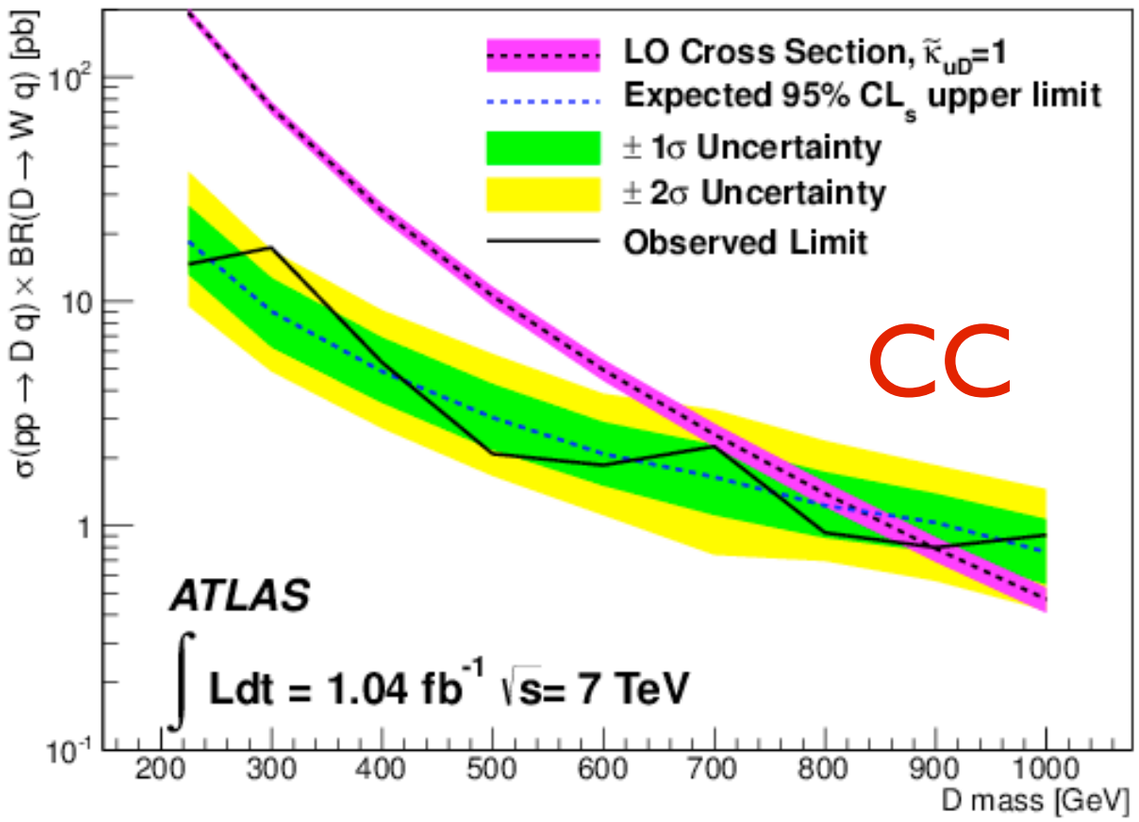


- **Same linear fit correction** method as in the NC is used here (--- in histogram above).
- **Multijet Background**: Use the missing E_T distribution between [10, 30] GeV and extract a data-driven template after subtracting all non-multijet contributions.
- **Main Systematics**: same as for the NC, but with additional uncertainties associated the multijet background estimation.

Results - VLQ Coupling to Light Generation







- Once again, no excess is found, we hence compute limits based on the *CL$_s$* method
  - **Assuming a coupling of**

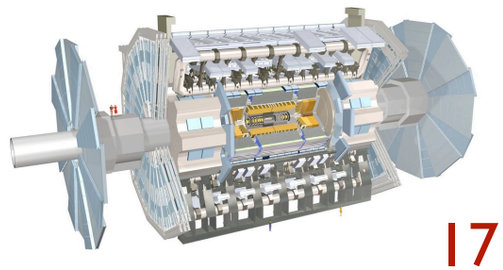
$$\tilde{\kappa}_{qQ} = 1$$

We obtain the limits:

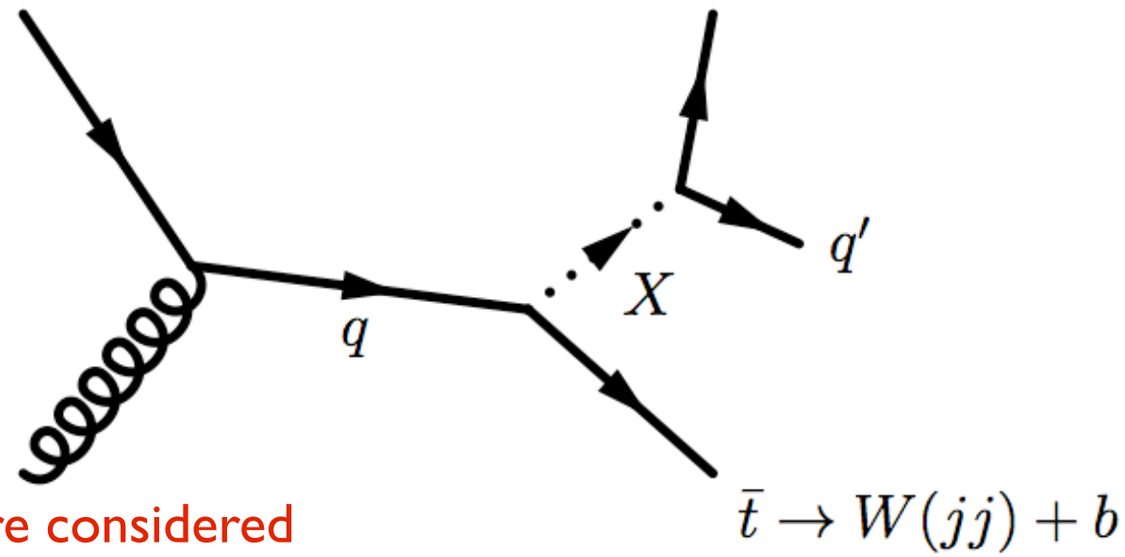
m_U < 760 (820) GeV at 95% C.L.

m_D < 900 (840) GeV at 95% C.L.

Search for Top-jet Resonances

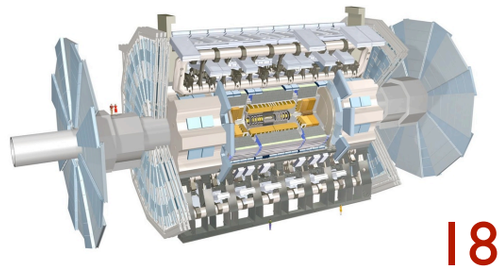


- One of the few discrepancies between SM expectations and observation is the *forward-backward asymmetry* measurements from the Tevatron [arXiv:1101.0034, arXiv:1107.4995]
  - Possible explanation: Top-flavour violating processes
  - Look for a new heavy resonance $X \to tj(\bar{t}j)$ produced in association with a top-quark (decaying to jets)

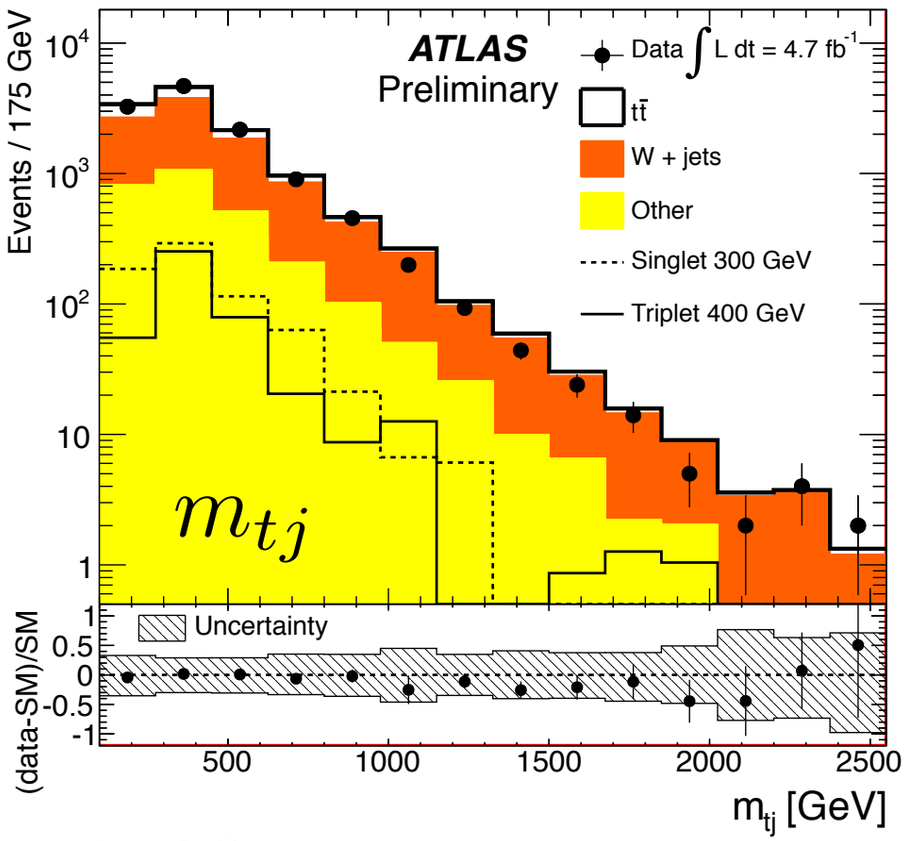


  - Two types of *X* resonances were considered
    - color singlet *W′* → *m(antitop+jet) resonance*
    - *di-quark* color triplet → *m(top+jet) resonance*
  - Assume these resonances have unit right-handed coupling to *tq*
  - The *X* resonance occurs in the m(top+jet) or m(antitop+jet) channel, but not in both! (important during limit setting)

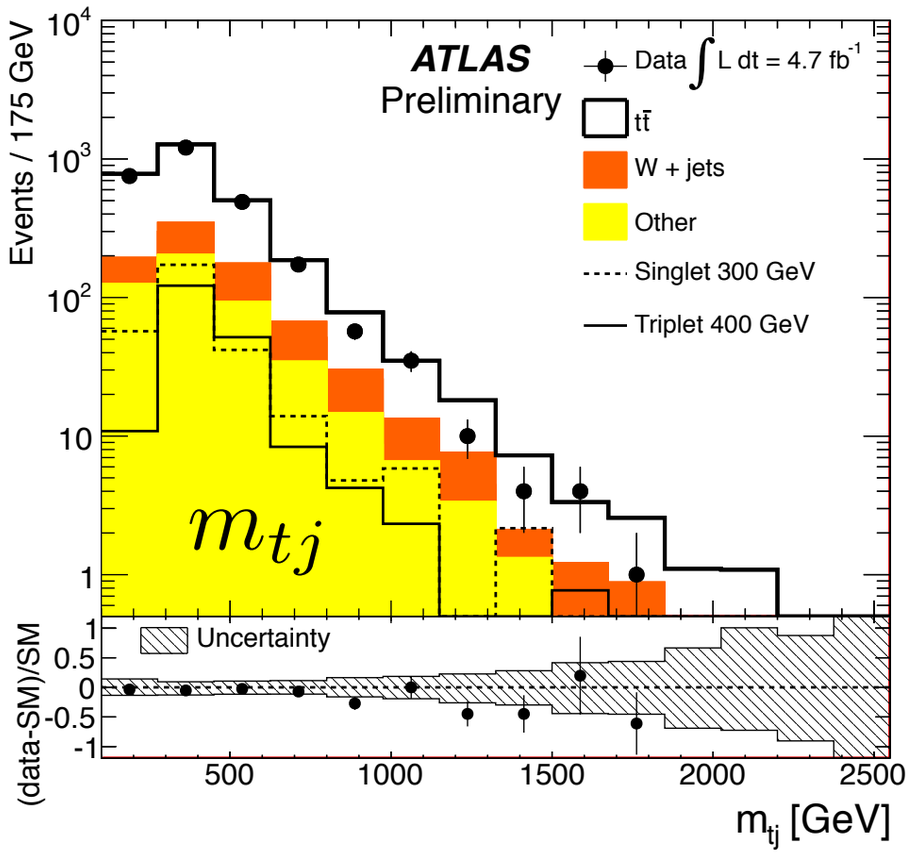
Control and Signal Region definitions



W+jet C.R.



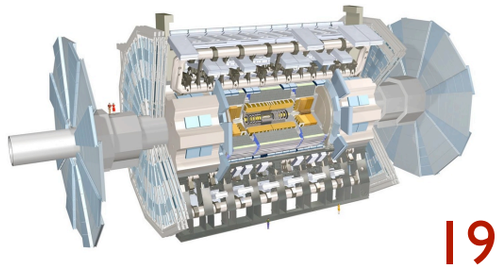
ttbar C.R.

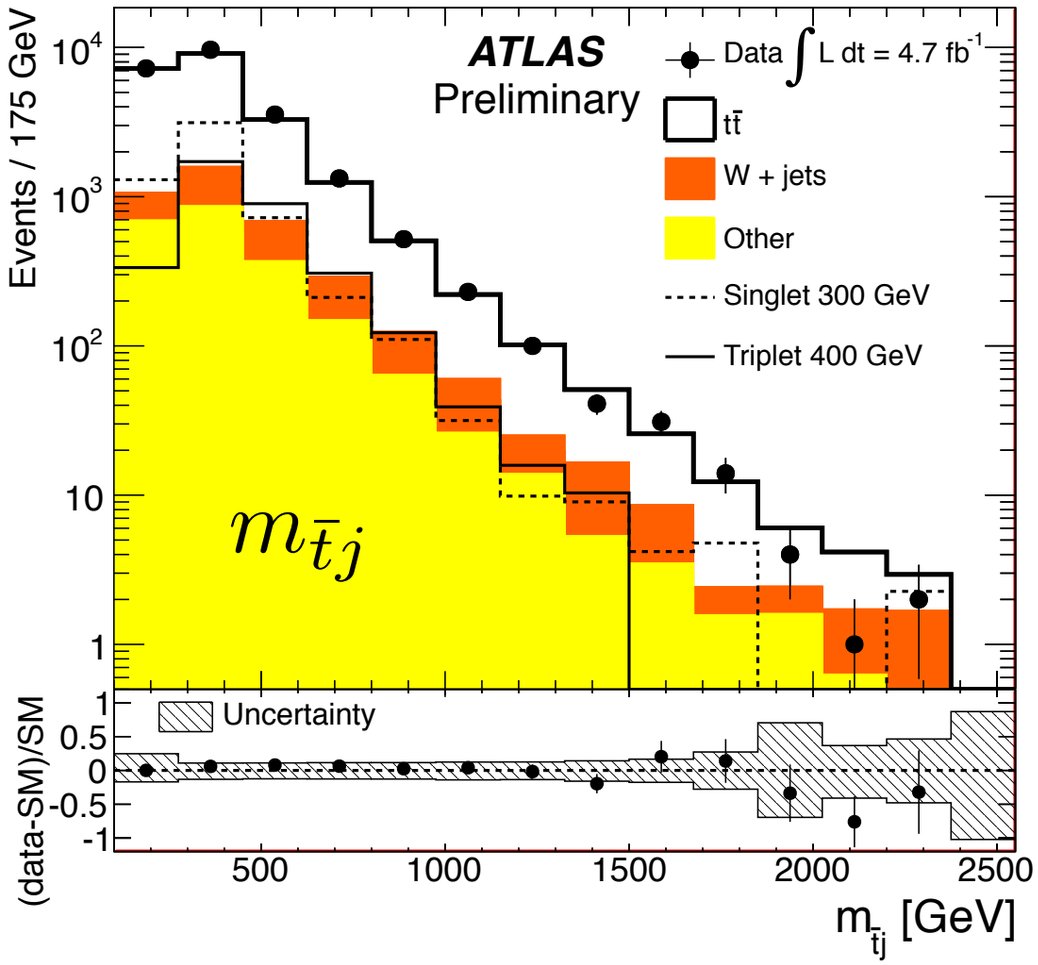


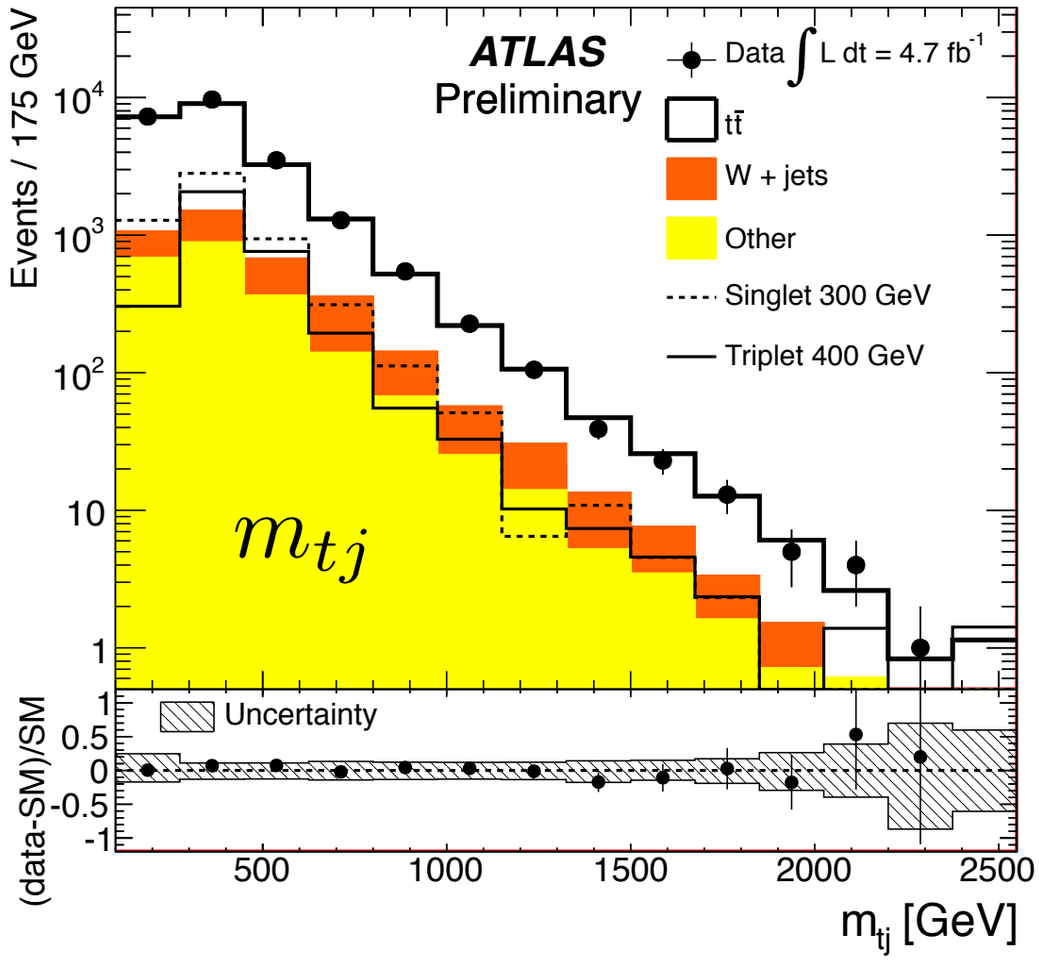
- ***Standard Cuts:***
  - Find events with exactly 1 lepton
    (E_T(el) > 25 GeV, p_T(μ) > 20 GeV)
  - *Missing E_T > 30(20) GeV in the electron(muon) channel*
  - *m_T(W) > 30 GeV (electron channel)*
  - *m_T(W) + Missing E_T > 60 GeV (muon channel)*

Cuts	W+jets CR	ttbar CR	**SR**
# Jets	≥ 5	4 + ≥ 1 soft	≥ **5**
# b-tagged Jets	0	≥ 1	≥ **1**

Top+jet Mass Spectrum - Signal Region



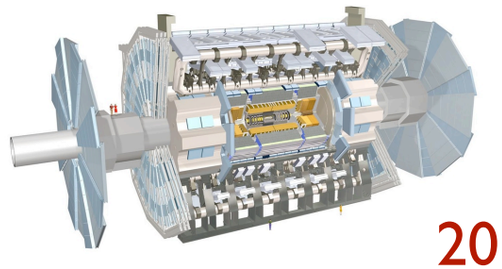


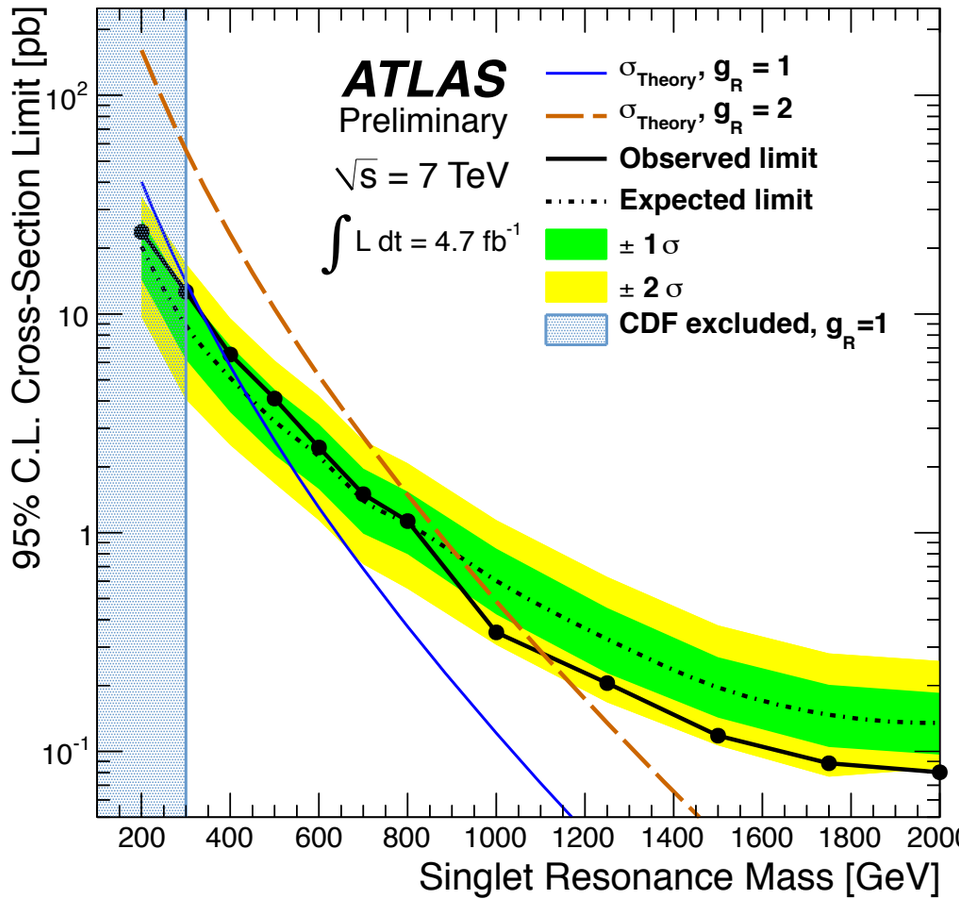


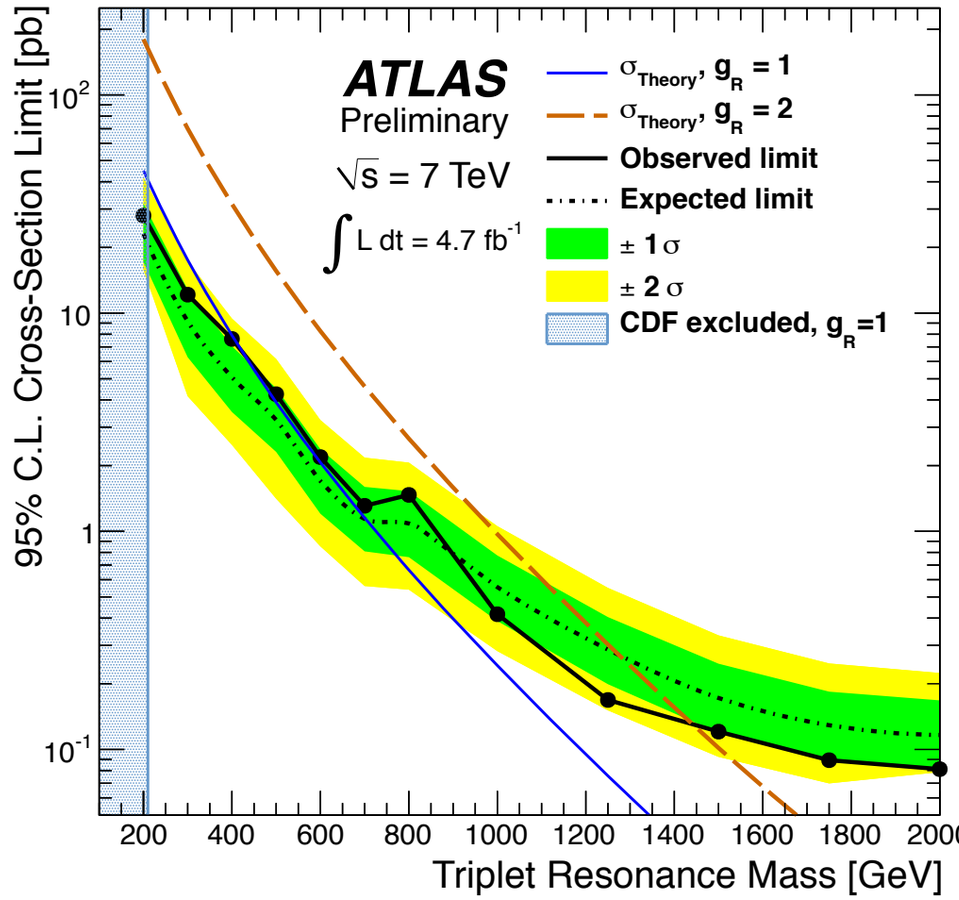
- Expected and Observed distributions of the **top+jet mass spectrum** with **4.7 fb^{-1} of 2011 data**
- Signals shown assume unit coupling (g_R) to the new resonance

- Main systematic contributors:
  - JES (10% on background, 21% on signal)
  - b-tagging efficiency (16%)

Limits on Top-jet Resonances

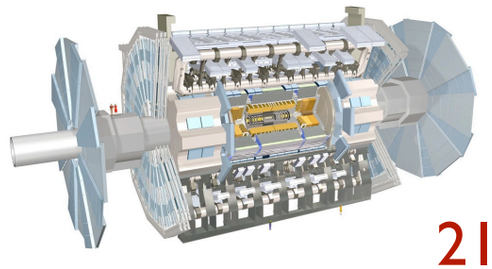




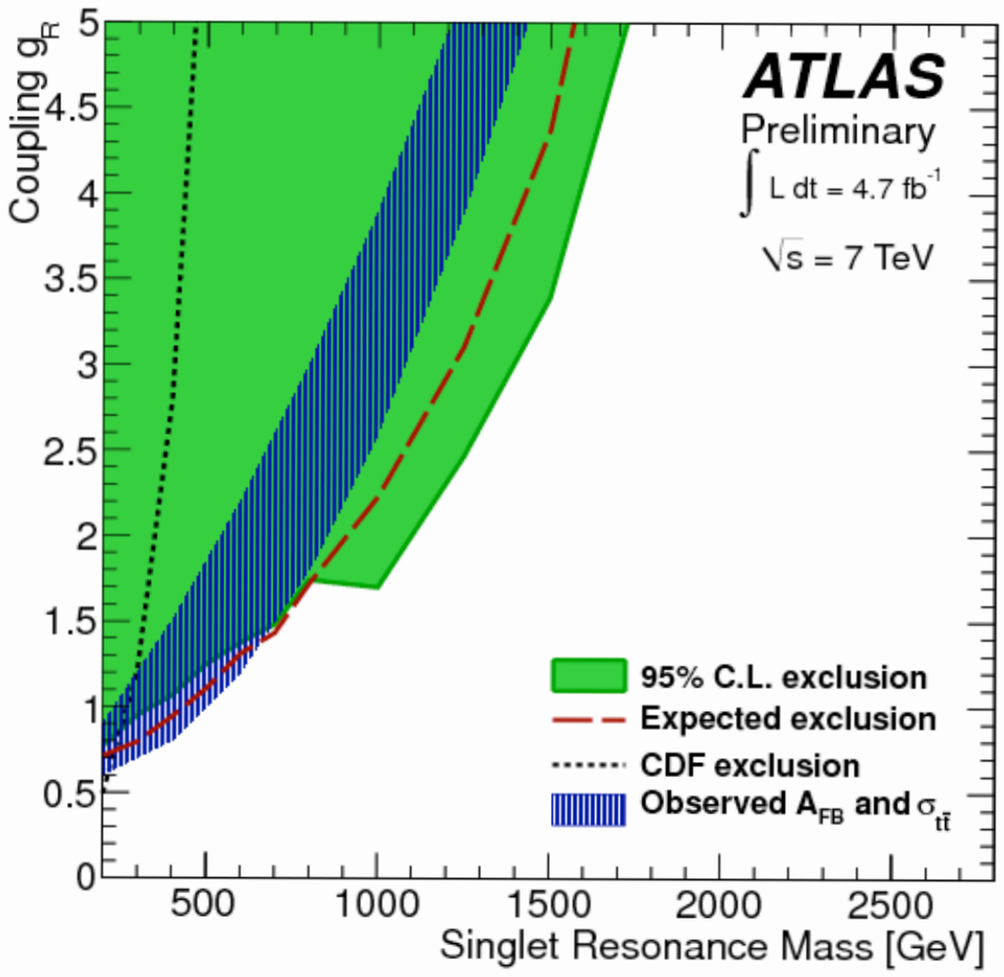


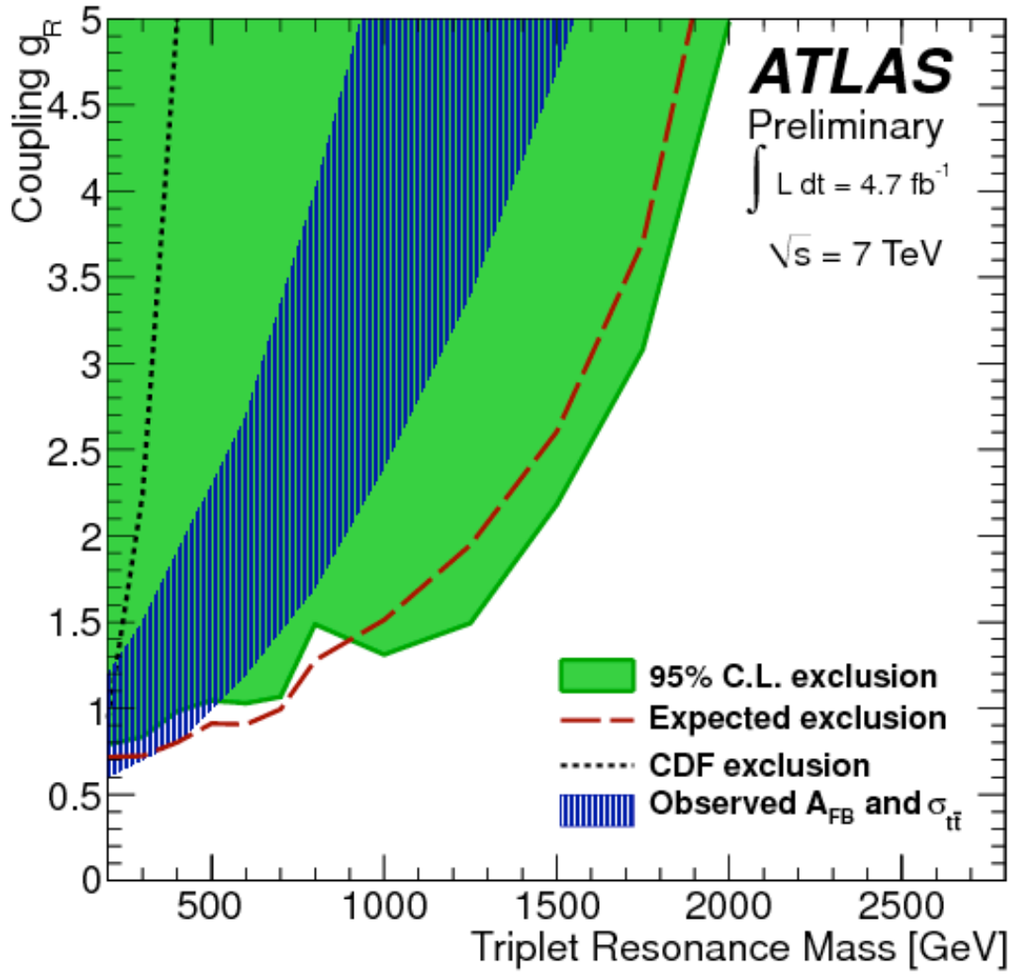
- Since no excess is observed, we computed limits on the color singlet W′ and color triplet models (*CL$_s$* method) while looking at a specific region in the $m_{tj} - m_{\bar{t}j}$ plane.
  - **With g_R = 1**
    - **$m_{W'}$ < 350 (450) GeV at 95% C.L. (singlet)**
    - **$m_{di\text{-}quark}$ < 430 (700) GeV at 95% C.L. (triplet)**

In terms of the coupling g_R

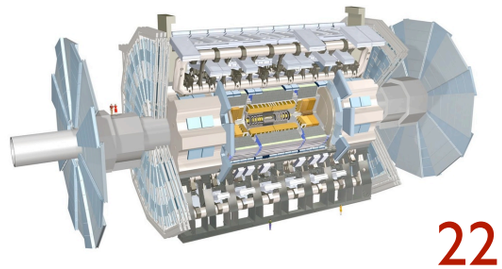


- The previous limits can be re-expressed in terms of g_R
- Assumes cross-sections scales as g_R^2

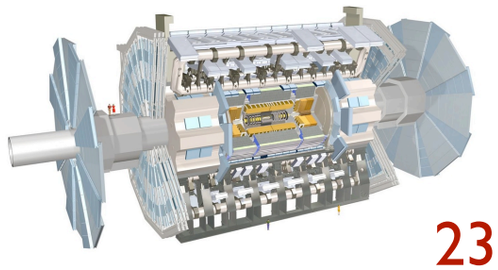




Summary



- **Two ATLAS searches for VLQ have been performed:**
  - Pair production of a VLS : $b' \rightarrow Z(ee)b$
    - m_{VLS} **< 400 GeV at 95% C.L.**
  - Single production of a VLQ doublet coupling to light quarks:
    - $qq \rightarrow D\,q \rightarrow Wd\,q$
      - $m_{D\text{-}type}$ **< 900 (840) GeV at 95% C.L.**
    - $qq \rightarrow U\,q \rightarrow Zu\,q$
      - $m_{U\text{-}type}$ **< 760 (820) GeV at 95% C.L.**
- **One ATLAS search for Top+jet resonance**
  - $g\,q \rightarrow X\,t \rightarrow \bar{t}\,j\,t$
    - $m_{W'}$ **< 350 (450) GeV at 95% C.L. (singlet)**
    - $m_{di\text{-}quark}$ **< 430 (700) GeV at 95% C.L. (triplet)**
- Stay tuned for results with the full 2011/2012 datasets



Thank You!