# Search for vector-like quarks

Romain Kukla, CPPM Marseille
*on behalf of the ATLAS collaboration*

7 déc. 2017

*SUSY 2017, Mumbai*

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

ATLAS
EXPERIMENT

# Outline

Introduction on top partners/vector-like quarks

Searches for pair production of VLQ T

- Search for TT $\rightarrow$ Ht
- Search for TT $\rightarrow$ Zt
- Search for TT $\rightarrow$ Wb

Search for single production of VLQ Y

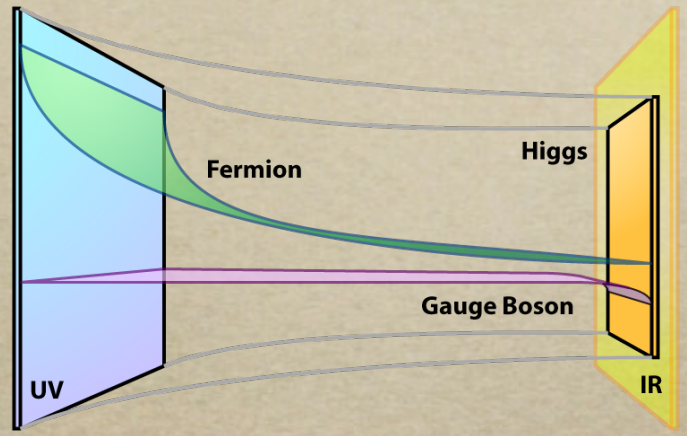
- Search for Y $\rightarrow$ Ht

# From top partners to VLQ

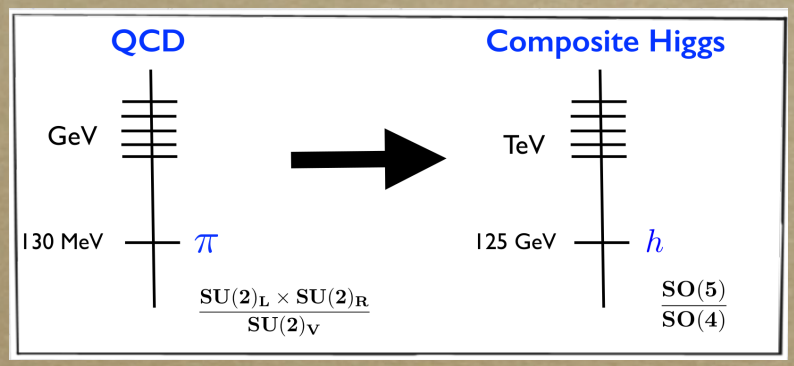
## What are vector-like quarks ?

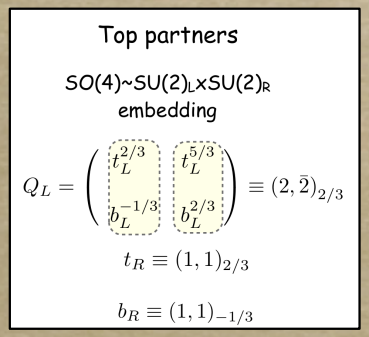
→ a « top partners » benchmark in the context of strongly coupled models

... originaly from holographic Higgs model from warped extra dimensions.




... then interpreted in terms of a SO(5)→SO(4) symmetry breaking (or larger), with various representations for collider phenomenology.



# Vector-like Quarks

## What are vector-like quarks ?

→ a « top partners » benchmark in the context of strongly coupled models

→ which stabilize the Higgs mass and solve the hierarchy problem thanks to strongly coupled dynamics in the extended symmetry.

→ they have a Dirac mass without the Higgs (before EWSB)

$$L_{mass} \sim -M\left(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L\right)$$

→ their couplings to the SM fields is of Yukawa-type.

$$L_{Yuk} \sim \frac{-\lambda v}{\sqrt{2}}\left(\bar{q}_L \psi_R - \bar{\psi}_R q_L\right)$$

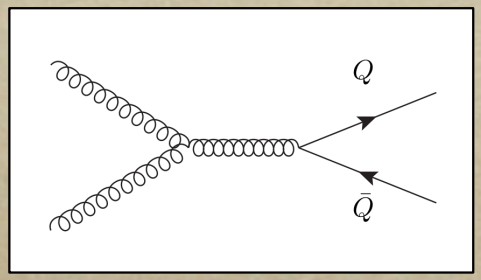
→ presented in singlets/doublets/triplets/fourplets depending on the model.

→ usually consist of $T, B, T_{2/3}, T_{5/3}, Y_{-4/3} \ldots$

The VLQ implementation fixes the maximal strength of the couplings to SM.

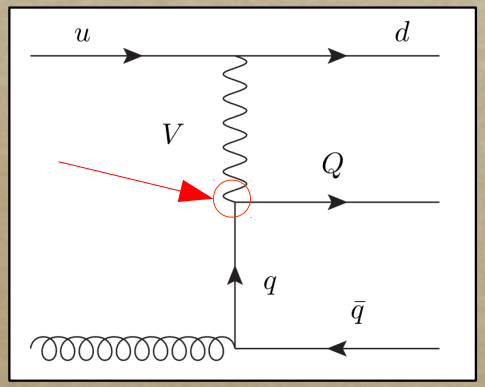
# VLQ : production and decays

## Two production modes :

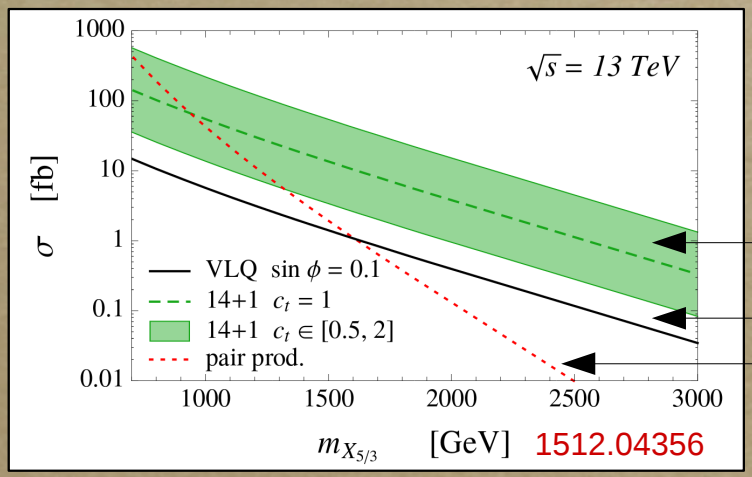



→ QCD pair production : essentially mass dependent

→ EW single production : scales with the coupling (model dependent)




Low mass = pair production mainly
High mass = single production becomes sizable/dominant




VLQ decay via charged and neutral currents to the 3rd generation : the heavier the SM quark is, the larger its coupling to VLQ is.

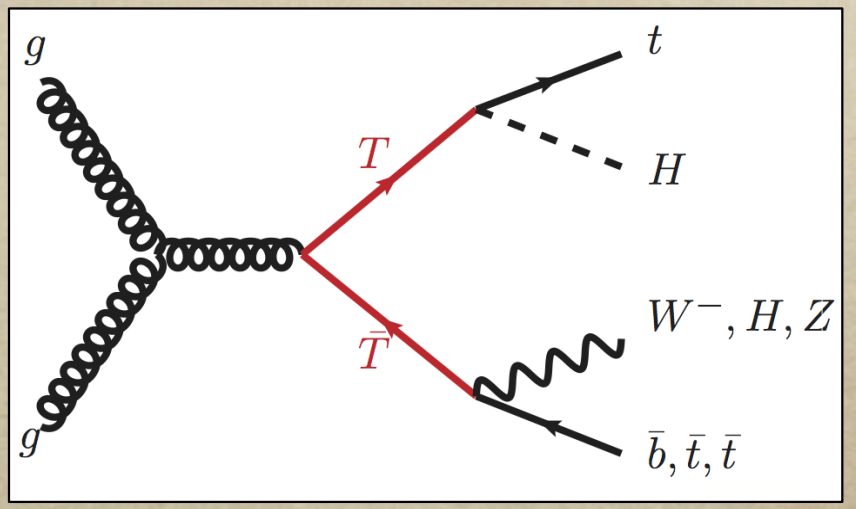
| VLQ | $W$-decay | $Z$-decay | $h$-decay |
|---|---|---|---|
| $T$ | $Wb$ | $Zt$ | $ht$ |
| $B$ | $Wt$ | $Zb$ | $hb$ |
| $T_{5/3}$ | $Wt$ | - | - |
| $Y_{-4/3}$ | $Wb$ | - | - |

# Search for TT→Ht+X (13.2 fb$^{-1}$)

ATLAS-CONF-2016-104

Aiming for both 0 or 1 lepton final states for T→Ht+X, 4top productions and ttH.

| Preselection requirements | | |
|---|---|---|
| Requirement | 1-lepton channel | 0-lepton channel |
| Trigger | Single-lepton trigger | $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger |
| Leptons | =1 isolated $e$ or $\mu$ | =0 isolated $e$ or $\mu$ |
| Jets | ≥5 jets | ≥6 jets |
| $b$-tagging | ≥2 $b$-tagged jets | ≥2 $b$-tagged jets |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV | $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV |
| Other $E_{\mathrm{T}}^{\mathrm{miss}}$-related | $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV | $\Delta\phi_{\mathrm{min}}^{4j} > 0.4$ |




Angular distance between MET and the 4 leading jets : removes completely QCD background.

SM backgrounds simulated using MC.
In 1-lep, the multijets contribution with an additionnal fake lepton is estimated with a data-driven method.

Signal regions cuts :

- Jet multiplicity
- b-tag (77%) multiplicity
- mass-tag multiplicity
  (R=1.0, m>100 GeV, pT > 300 GeV)
- kinematic variables

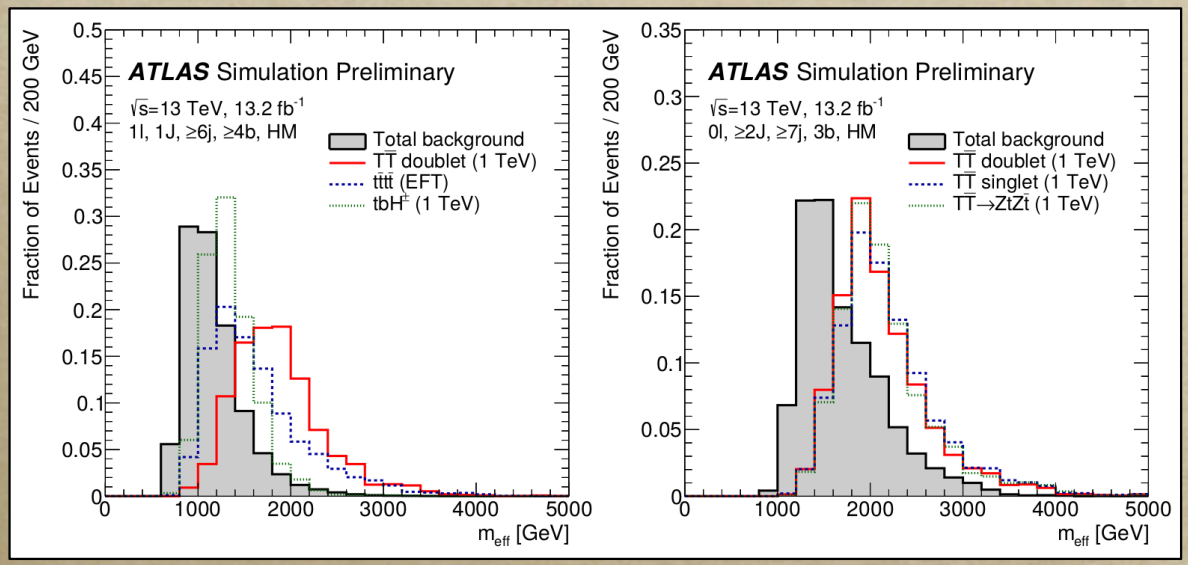
1-lepton $m_{bb}^{\mathrm{min}\Delta R} > 100$ GeV

0-lepton $m_{\mathrm{T,min}}^{b} > 160$ GeV

# Search for TT→Ht+X (13.2 fb$^{-1}$)

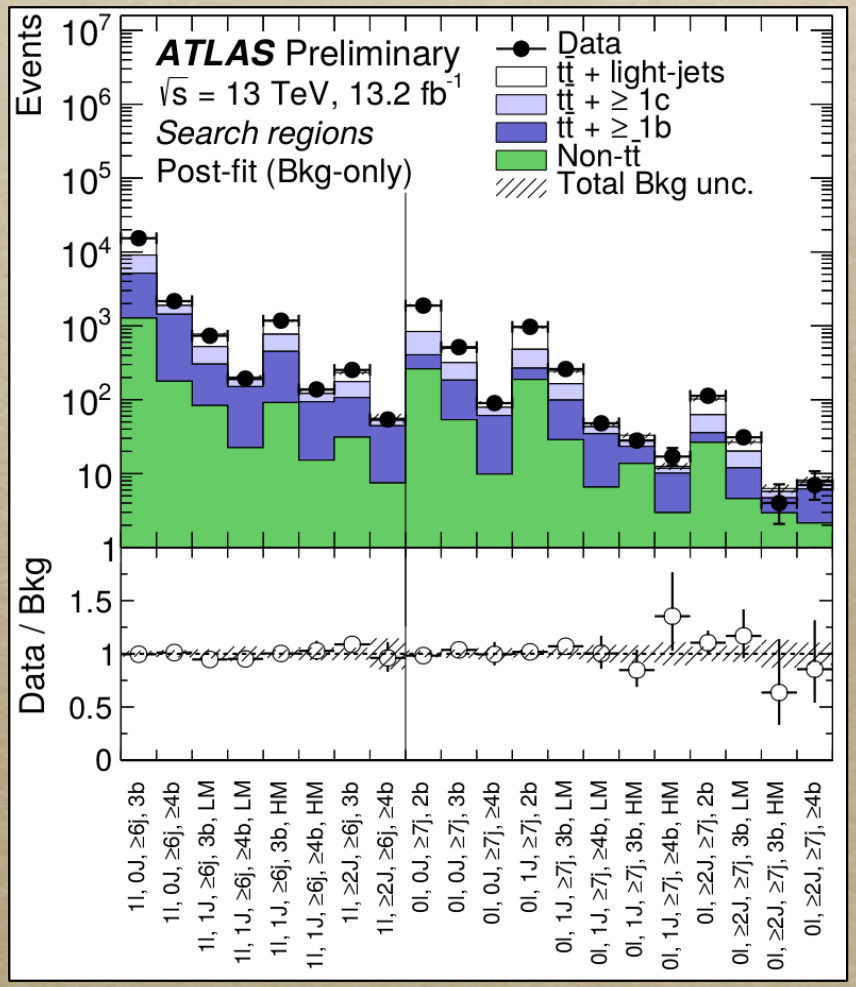
*ATLAS-CONF-2016-104*

## Further discrimination using $m_{eff}$ (scalar sum of all $p_T$)




1-lepton

0-lepton




Main sources of systematic errors :

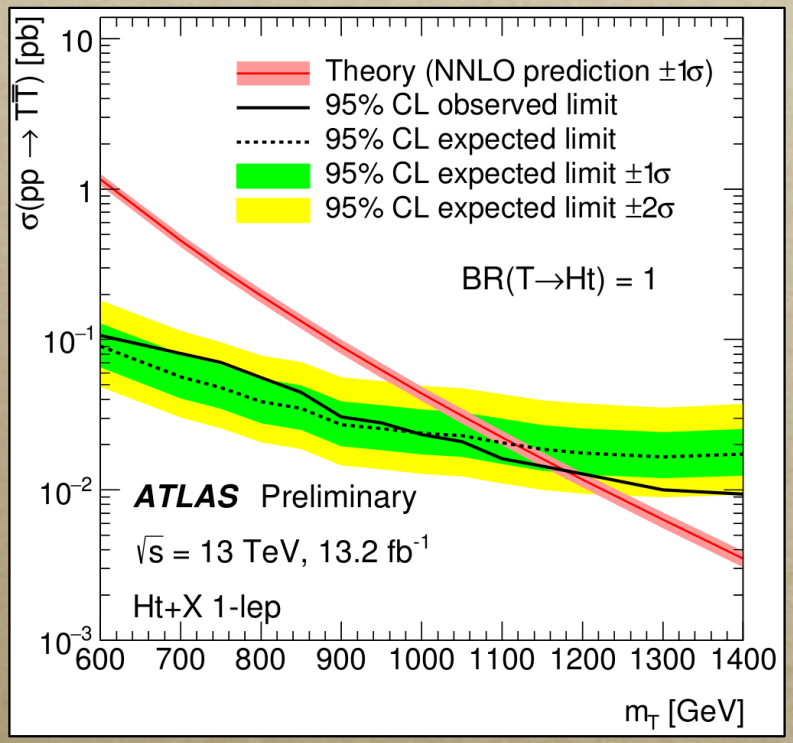
- tt+jets normalization
- b-tagging, c-tagging, light-jet tagging
- QCD data-driven method

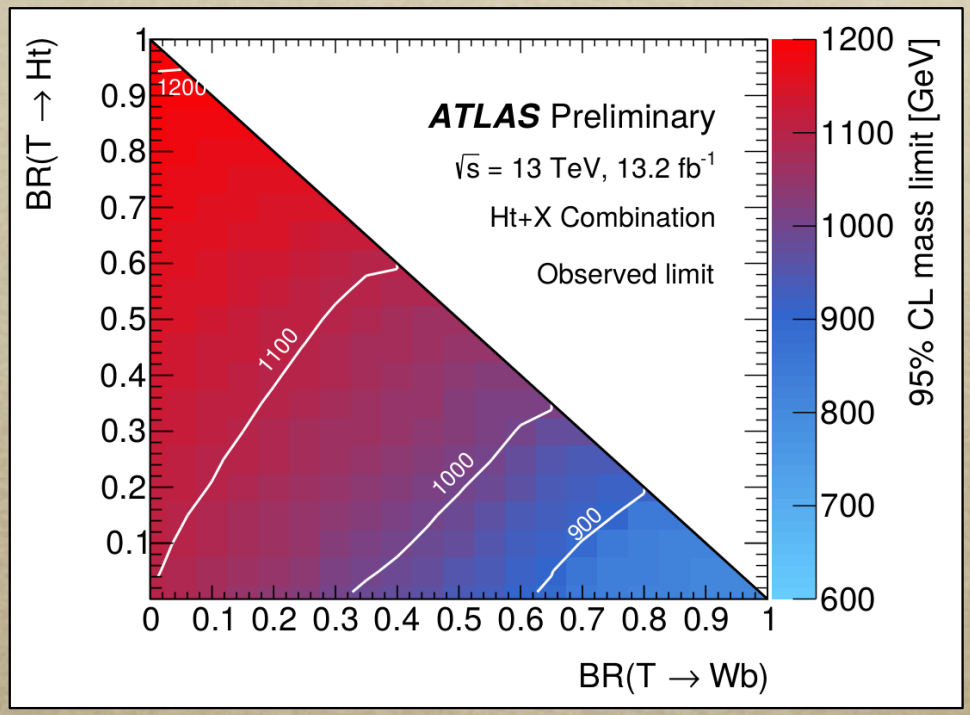
Fitting the $m_{eff}$ distribution helps to constrain systematics.

# Search for TT→Ht+X (13.2 fb$^{-1}$)

*ATLAS-CONF-2016-104*

## Combined result between 0 and 1 leptons signal regions




| Search | BR($T \to Ht$) = 1 |
|---|---|
| 1-lepton channel | 1180 (1120) |
| 0-lepton channel | 1090 (1070) |
| **Combination** | **1200 (1160)** |

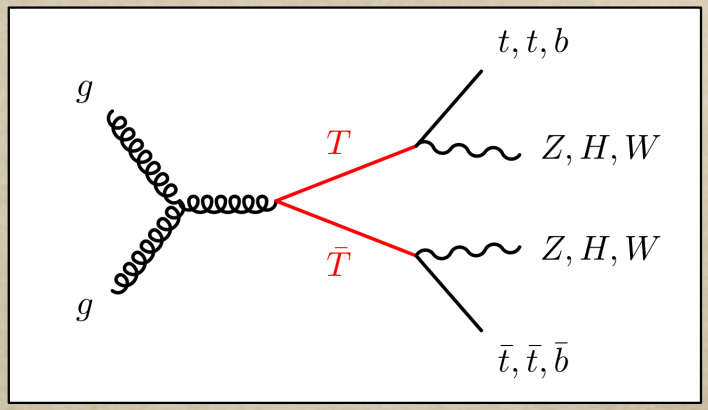
Observed (expected) lower mass limits in GeV

Recasts for other BR done by reweighting separately the signal MC samples.

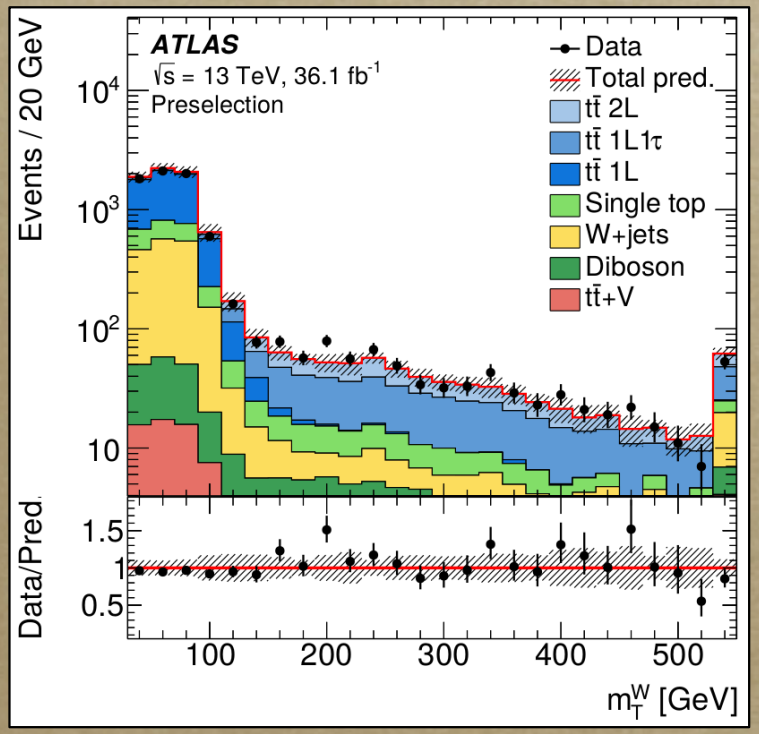
# Search for TT→Zt+X (36.1 fb$^{-1}$)

CERN-EP-2017-075

Analysis optimized for T→Z(νν)t , 1 lepton




Preselection :
MET > 300 GeV, at least 4 jets and 1 b-jet, angular separation between jets and MET.
$M_T^W$ > 30 GeV (170 GeV for the signal region)




$$m_{\mathrm{T}}^{W} = \sqrt{2 p_{\mathrm{T}}^{\mathrm{lep}} E_{\mathrm{T}}^{\mathrm{miss}} [1 - \cos(\Delta\phi)]}$$

Use of $m_T^W$ to reject ttbar 1L and W+jets.

$$m_{\mathrm{T2}} \equiv \min_{\vec{q}_{\mathrm{T}a}+\vec{q}_{\mathrm{T}b}=\vec{E}_{\mathrm{T}}^{\mathrm{miss}}} \{\max(m_{\mathrm{T}a}, m_{\mathrm{T}b})\}$$

$m_{T2}$ tries to estimate the masses of particles which produce the MET.

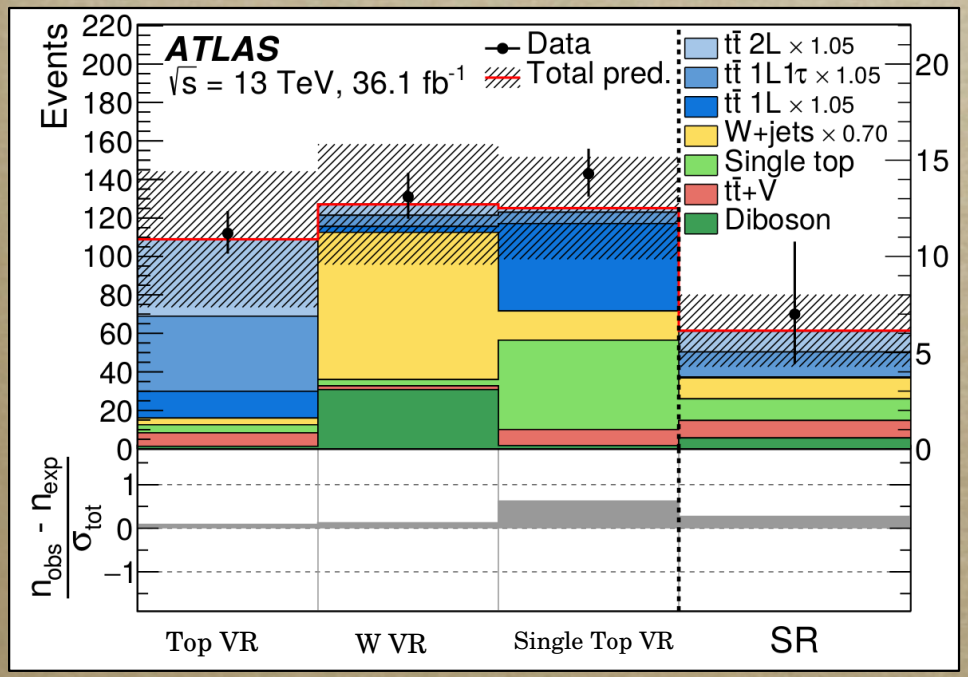
# Search for TT→Zt+X (36.1 fb$^{-1}$)

*CERN-EP-2017-075*

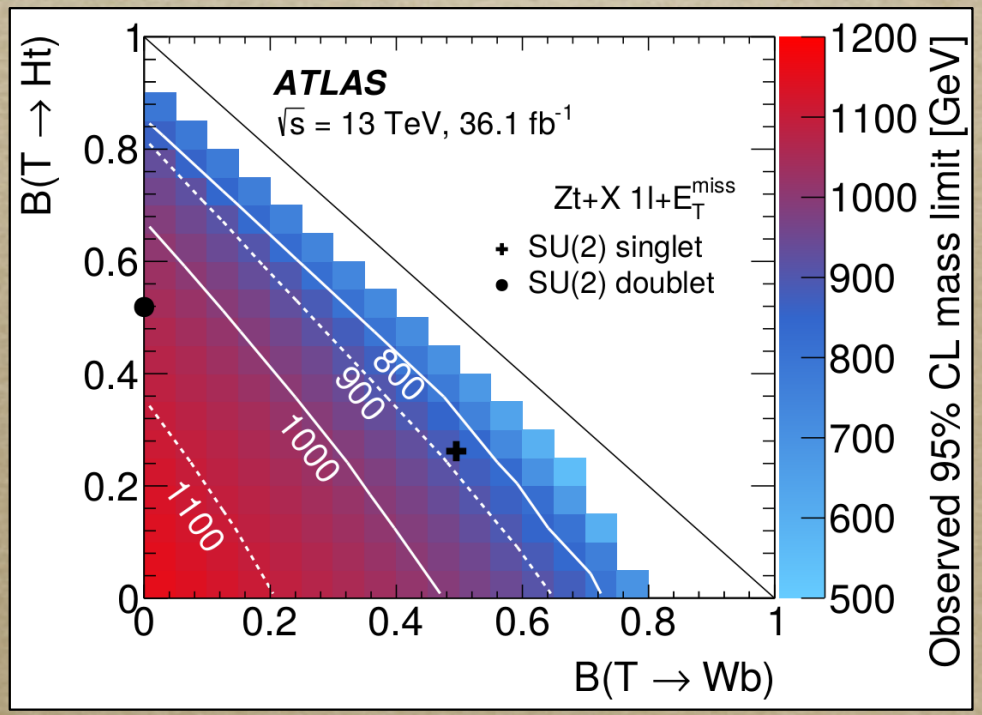
The main systematics are :
- tt modelisation
- VV scales
- Jet energy scale/resolution
- Flavour tagging

| Signal | Obs. 95% CL lower mass limit | Exp. 95% CL lower mass limit |
|---|---|---|
| $T \to Zt$ | 1.16 TeV | 1.17 TeV |
| Singlet | 0.87 TeV | 0.89 TeV |
| Doublet | 1.05 TeV | 1.06 TeV |

Events are reweighted to scan different BR choices and compute 95 % CL inferior mass limits.




The background normalizations are fitted in control regions and checked in validation regions.

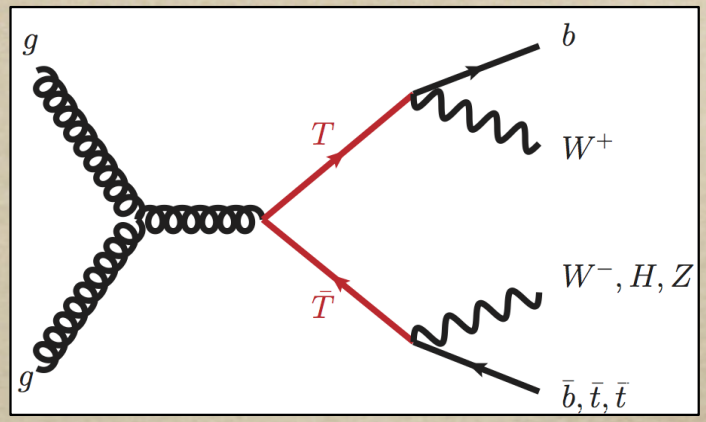


# Search for TT→Wb (36.1 fb$^{-1}$)

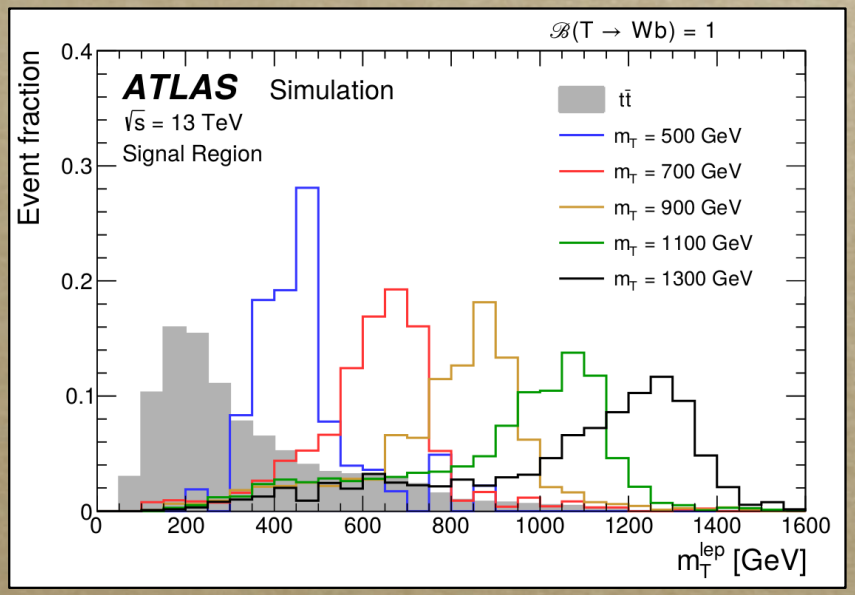
*CERN-EP-2017-094*

1 lepton channel, also sensitive to B→Wt.

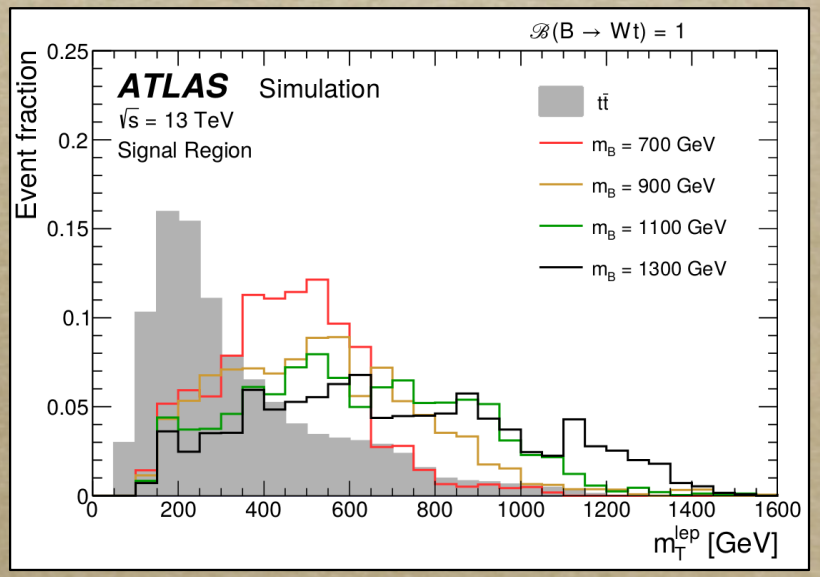
Preselection :
at least 3 jets,
≥1 b-tag,
MET ≥ 60 GeV
≥1 hadronic W candidate




A reconstruction of the hadronic and leptonic T 4-momenta is done using lepton, MET and jets minimizing |Δm|.




Very efficient for T

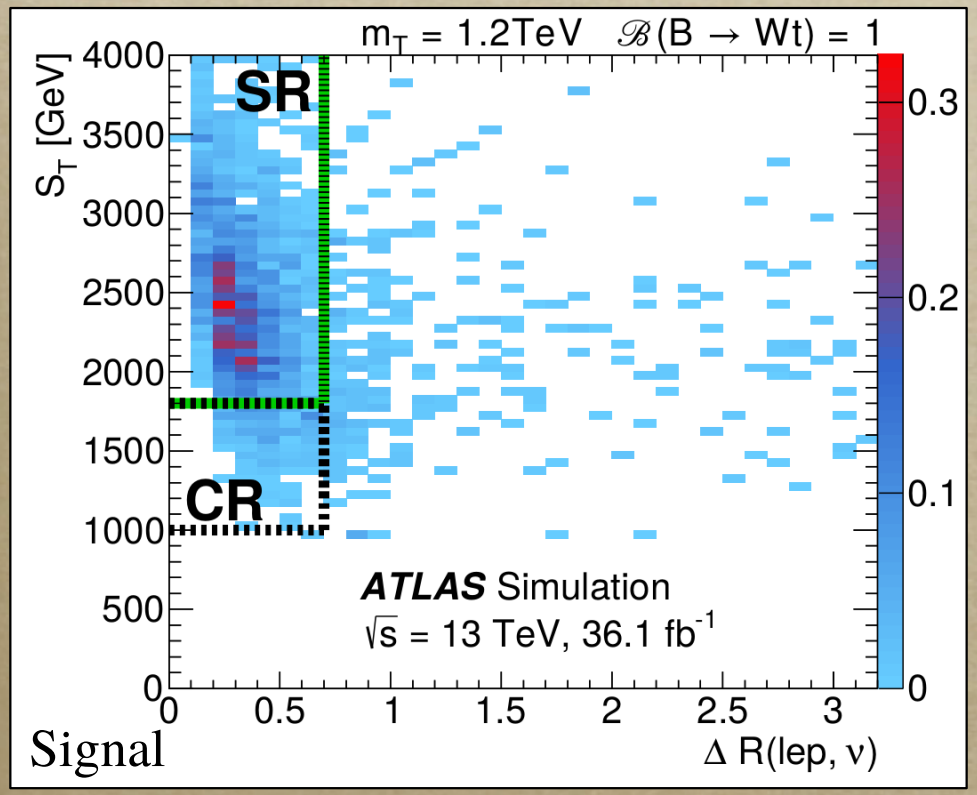


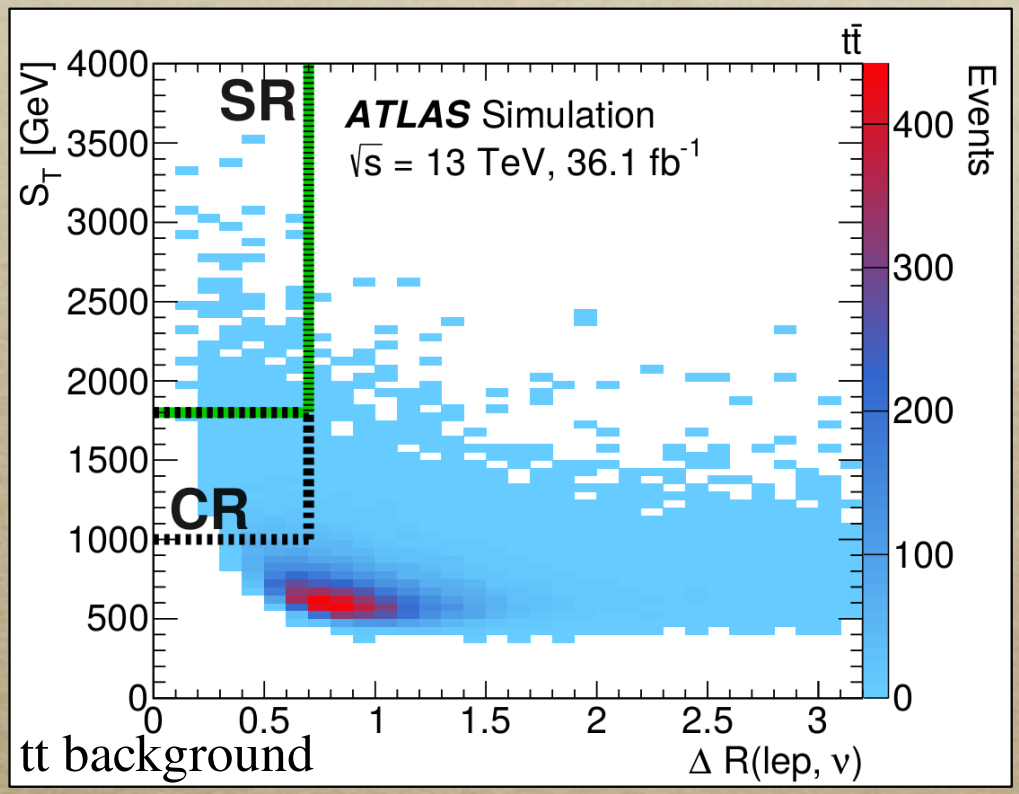

Worse mass resolution for B

# Search for TT→Wb (36.1 fb$^{-1}$)

*CERN-EP-2017-094*

The angular separation between the lepton and the MET, as well as the scalar sum of lepton and jets pT are used to define control / signal regions.



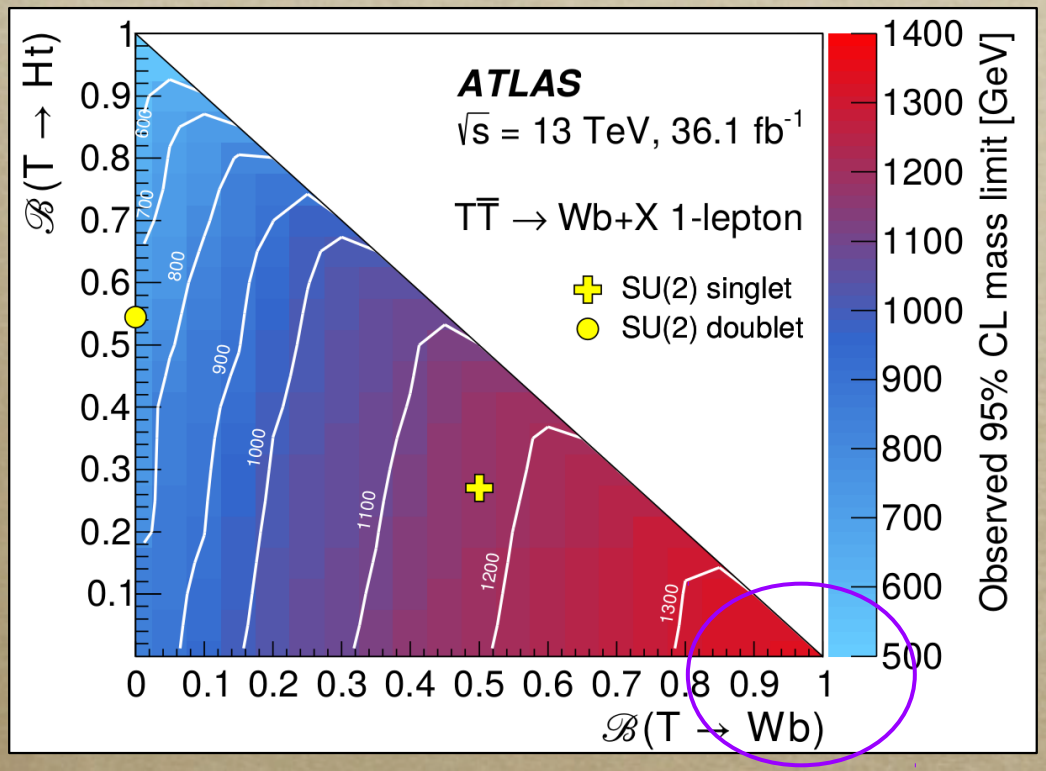

All SM backgrounds are simulating using MC apart from the fake lepton coming from QCD multijets processes for which the data-driven matrix method is used.

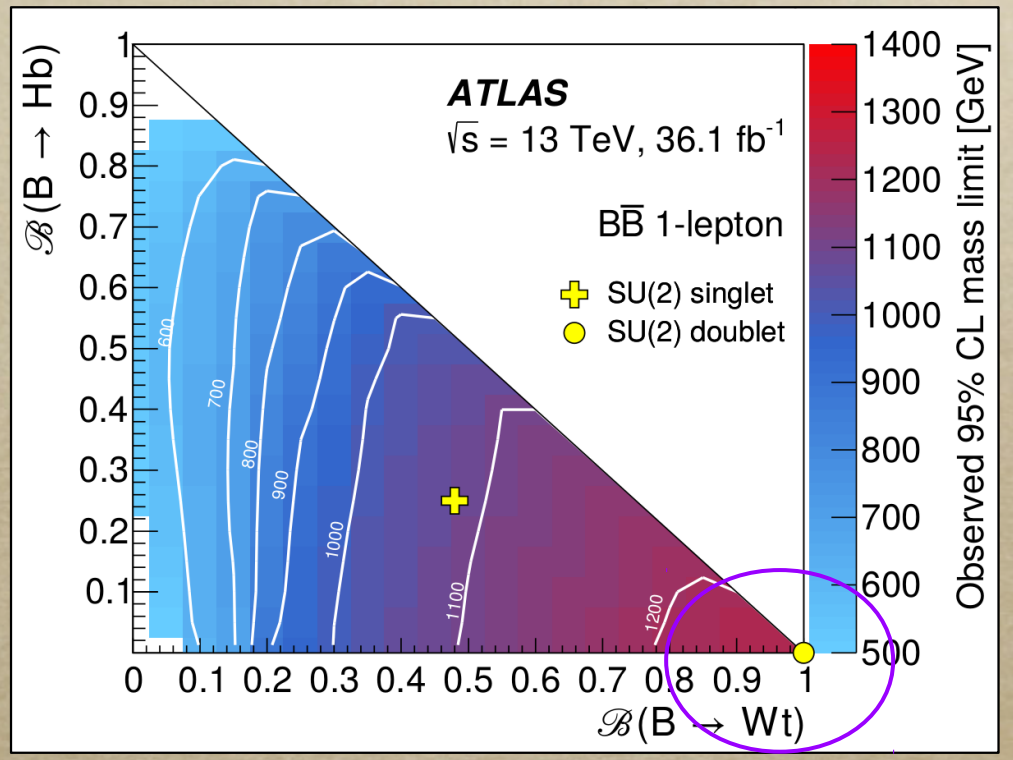
Main systematics : W+jets and data-driven QCD normalizations, tt modelling, JES, JER

# Search for TT→Wb (36.1 fb$^{-1}$)

*CERN-EP-2017-094*

$m_T^{lep}$ is used to test for the presence/absence of signal.



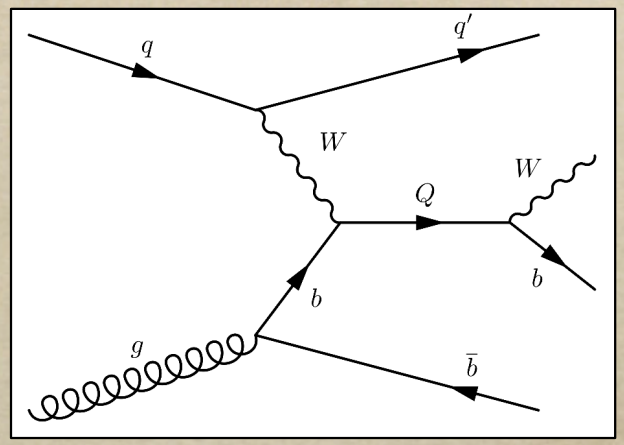




As the charge of the VLQ was not used, these BR(Wb) or BR(Wt) = 100 % can be used for limits on XX and YY production. (1250 GeV and 1350 GeV)

# Search for single Y (3.2 fb$^{-1}$)

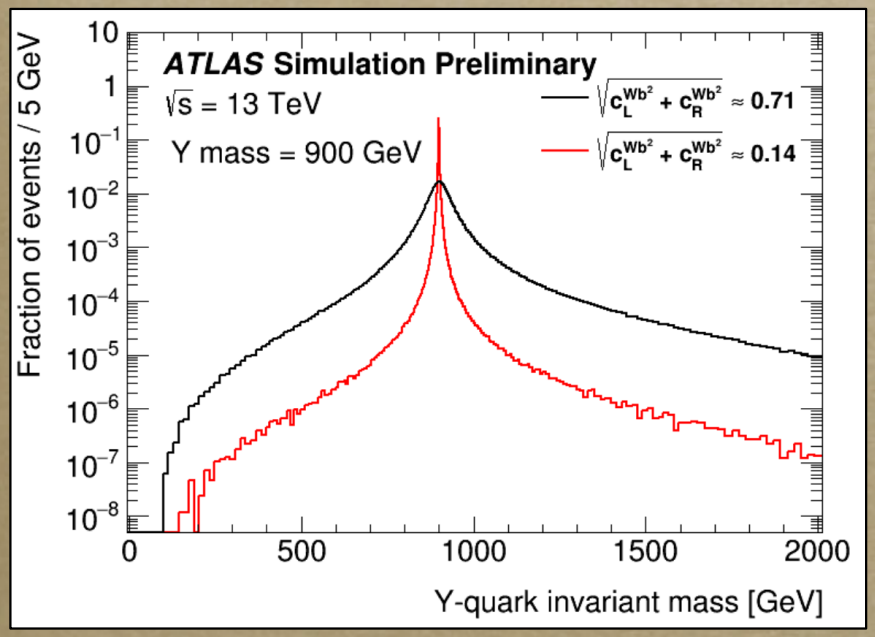
*ATLAS-CONF-2016-072*

Analysis optimized for single T/Y→Wb




In addition to mass, the coupling changes the width and the kinematics.
Here, $c_L$=$c_R$=0.5

Targeted topology : single lepton, one high pT b-tagged jet (350 GeV) and large MET (120 GeV)



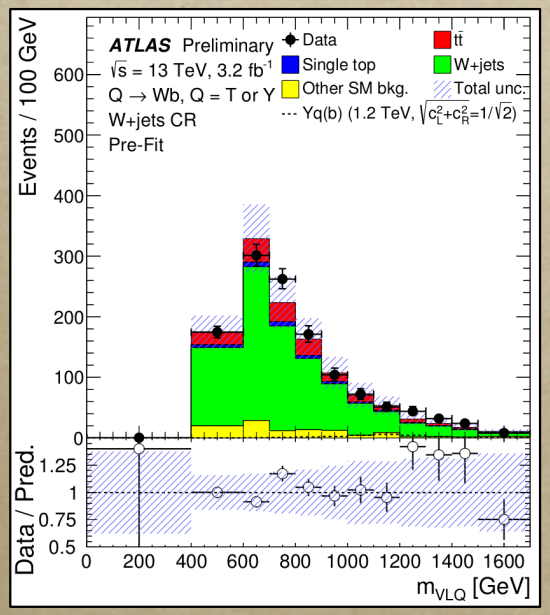

Veto on any additional hard jet to remove ttbar events. Cut on angular separation between the lepton and the leading b-tagged jet.
+ one forward jet criteria.

| Region | Selection cuts: Leading jet $p_T$ | Leading jet is $b$-tagged | $\Delta R$ (jet, $b$-tagged jet))< 1.2 or $\Delta R$ (jet, $b$-tagged jet) > 2.7 |
|---|---|---|---|
| SR | > 350 GeV | yes | 0 |
| $t\bar{t}$ CR | > 200 GeV | yes | ≥ 1 |
| $W$+jets CR | > 250 GeV | no | - |

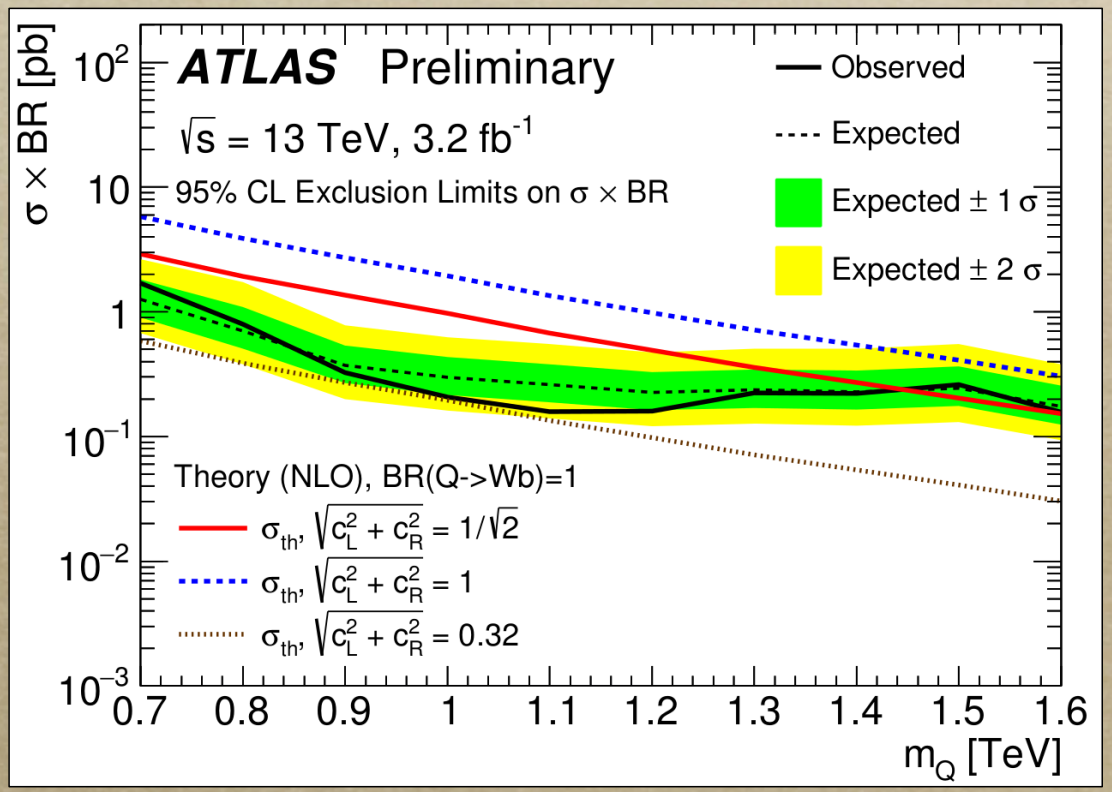
# Search for single Y (3.2 fb$^{-1}$)

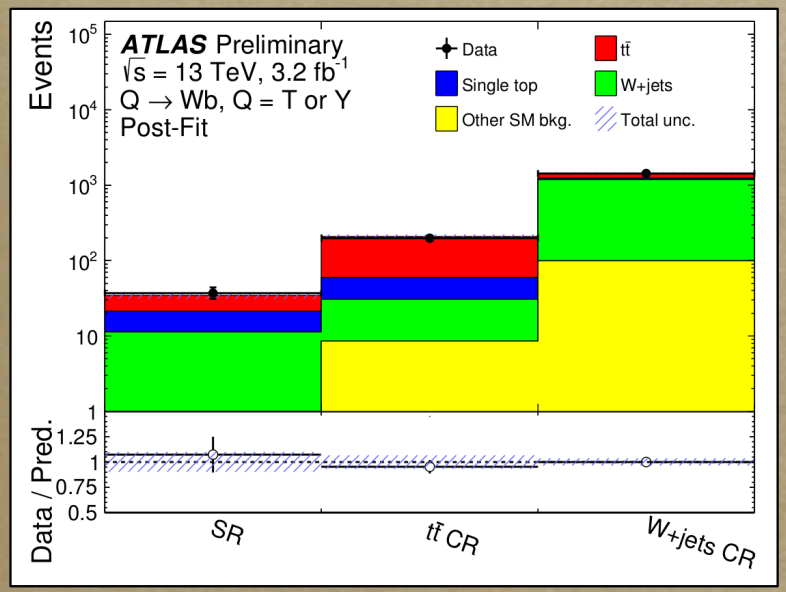
*ATLAS-CONF-2016-072*

The VLQ mass is reconstructed using its decay objects.




Main systematics : flavour tagging, JES, resolution, MET reconstruction, multijet data-driven method



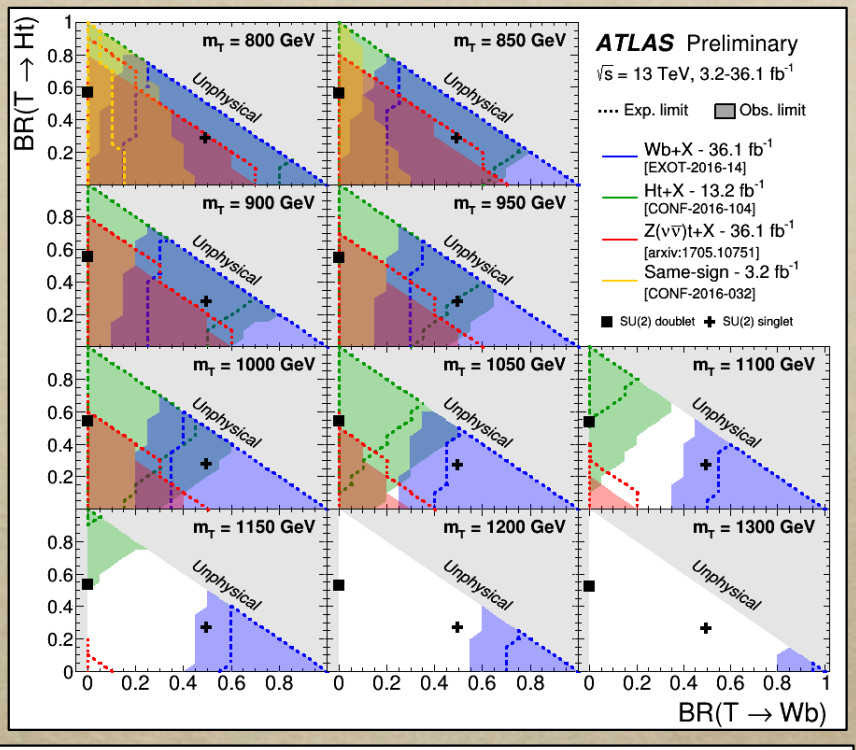

Several benchmarks are fitted (3 couplings values) and exclusion limits are extracted using the CL method.

# Conclusion

VLQ searches is a very rich program in ATLAS with dedicated analyses for each channel

Next step : combinaison of these results and studies on new channels.

No evidence for VLQ production at the LHC.




**ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits**

*Status: July 2017*

**ATLAS** Preliminary

$\int \mathcal{L}\,dt = (3.2 - 37.0)$ fb$^{-1}$ $\sqrt{s} = 8, 13$ TeV

| | Model | $\ell, \gamma$ | Jets† | $E_T^{miss}$ | $\int \mathcal{L}\,dt$[fb$^{-1}$] | Limit | | Reference |
|---|---|---|---|---|---|---|---|---|
| Heavy quarks | VLQ $TT \to Ht + X$ | 0 or 1 $e, \mu$ | ≥ 2 b, ≥ 3 j | Yes | 13.2 | T mass 1.2 TeV | $\mathcal{B}(T \to Ht) = 1$ | ATLAS-CONF-2016-104 |
| | VLQ $TT \to Zt + X$ | 1 $e, \mu$ | ≥ 1 b, ≥ 3 j | Yes | 36.1 | T mass 1.16 TeV | $\mathcal{B}(T \to Zt) = 1$ | 1705.10751 |
| | VLQ $TT \to Wb + X$ | 1 $e, \mu$ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | T mass 1.35 TeV | $\mathcal{B}(T \to Wb) = 1$ | CERN-EP-2017-094 |
| | VLQ $BB \to Hb + X$ | 1 $e, \mu$ | ≥ 2 b, ≥ 3 j | Yes | 20.3 | B mass 700 GeV | $\mathcal{B}(B \to Hb) = 1$ | 1505.04306 |
| | VLQ $BB \to Zb + X$ | 2/≥3 $e, \mu$ | ≥2/≥1 b | – | 20.3 | B mass 790 GeV | $\mathcal{B}(B \to Zb) = 1$ | 1409.5500 |
| | VLQ $BB \to Wt + X$ | 1 $e, \mu$ | ≥ 1 b, ≥ 1J/2j | Yes | 36.1 | B mass 1.25 TeV | $\mathcal{B}(B \to Wt) = 1$ | CERN-EP-2017-094 |
| | VLQ $QQ \to WqWq$ | 1 $e, \mu$ | ≥ 4 j | Yes | 20.3 | Q mass 690 GeV | | 1509.04261 |
| | VLQ $T_{5/3}T_{5/3} \to WtWt$ | 2(SS)/≥3 $e,\mu$ | ≥1 b, ≥1 j | Yes | 3.2 | $T_{5/3}$ mass 990 GeV | | ATLAS-CONF-2016-032 |

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/

# Backup

7 déc. 2017

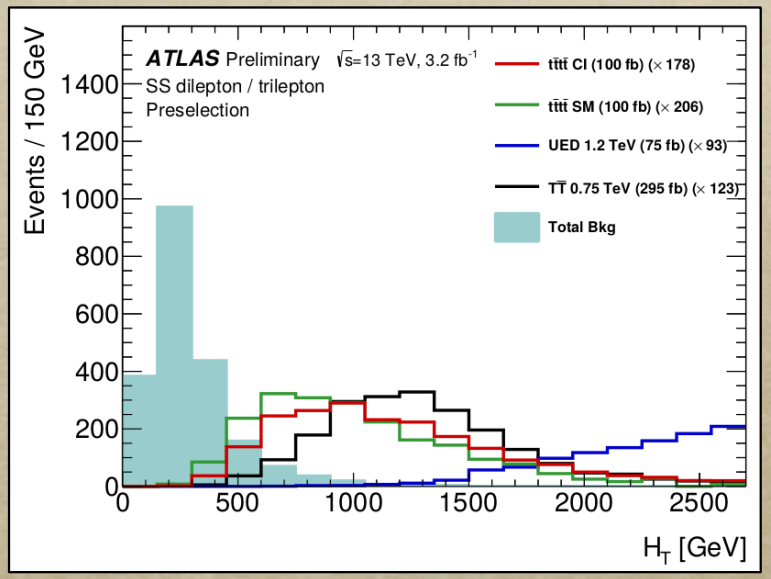
# Search for BB, TT, XX (3.2 fb$^{-1}$)

*ATLAS-CONF-2016-032*

2 same-sign leptons or 3 leptons

Main SM background from MC, 2 data-driven methods for fake/non-prompt leptons and electron charge flip processes.

| | Electrons | Muons | Jets |
|---|---|---|---|
| Trigger | 1 electron, $p_T > 24$ GeV | 1 isolated muon, $p_T > 20$ GeV or 1 muon, $p_T > 50$ GeV | |
| $p_T$ | $> 25$ GeV | $> 25$ GeV | $> 25$ GeV |
| $\|\eta\|$ | $< 1.37$ or $1.52 < \|\eta\| < 2.47$ | $< 2.5$ | $< 2.5$ |
| Object ID | tight | medium | – |
| Vertex match | $\|d_0\|/\sigma(d_0) < 5$ <br> $\|\Delta z_0 \sin\theta\| < 0.5$ mm | $\|d_0\|/\sigma(d_0) < 3$ <br> $\|\Delta z_0 \sin\theta\| < 0.5$ mm | JVT requirement (if $\|\eta\| < 2.4$ and $p_T < 50$ GeV) |
| Isolation | track and calorimeter | track | – |
| Multiplicity | 2 same-charge leptons or $\geq 3$ leptons | | – |

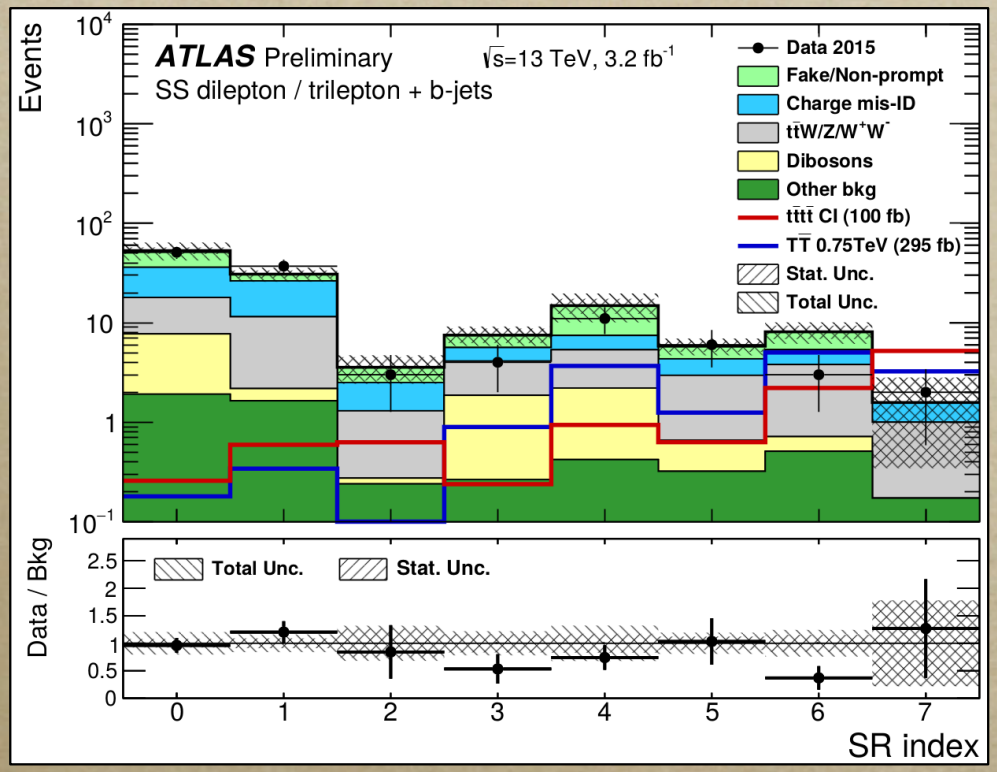



| Definition | | | Name |
|---|---|---|---|
| $e^\pm e^\pm + e^\pm \mu^\pm + \mu^\pm \mu^\pm + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_{\text{jets}} \geq 2$ | | | |
| $400 < H_T < 700$ GeV | $N_b = 1$ | $E_T^{\text{miss}} > 40$ GeV | SR0 |
| | $N_b = 2$ | | SR1 |
| | $N_b \geq 3$ | | SR2 |
| $H_T \geq 700$ GeV | $N_b = 1$ | $40 < E_T^{\text{miss}} < 100$ GeV | SR3 |
| | | $E_T^{\text{miss}} \geq 100$ GeV | SR4 |
| | $N_b = 2$ | $40 < E_T^{\text{miss}} < 100$ GeV | SR5 |
| | | $E_T^{\text{miss}} \geq 100$ GeV | SR6 |
| | $N_b \geq 3$ | $E_T^{\text{miss}} > 40$ GeV | SR7 |

Signal regions defined using a categorisation using MET, HT, jets and b-tagged jets multiplicities to probe different final states.

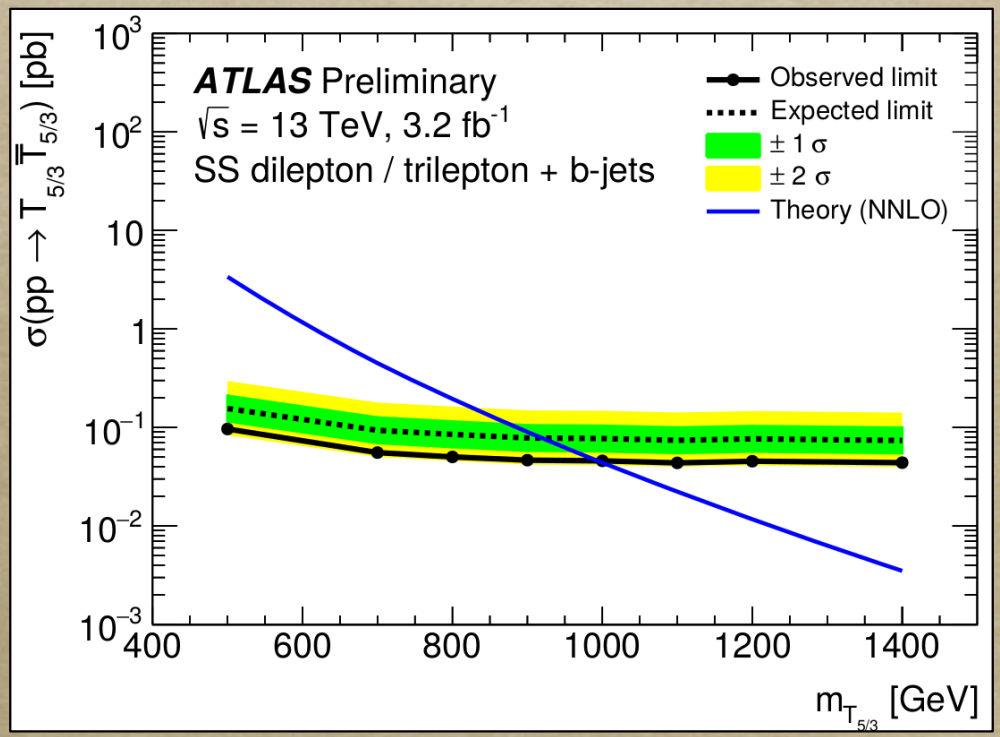
# Search for BB, TT, XX (3.2 fb$^{-1}$)

*ATLAS-CONF-2016-032*




Main systematics for data-driven :

- electron charge flip 25 %
- Fakes/non-prompts 54 %




Limits are computed using the combined signal regions, for BB, TT and XX. For B and T, the samples are reweighted to probe other Brs, but the overall limits are weaker than the 1 lepton analysis.