Search for new quarks with the ATLAS detector

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Outline

- Motivation
- Summary of results from Run1 at 8 TeV
- Selected recent results at $\sqrt{s} = 13$ TeV with 3.2 fb^{-1}
  - Events with b-jets and same-sign leptons :
    - VLQ TT, BB, $T_{5/3}T_{5/3}$ and 4-top analysis
      ATL-CONF-2016-032
  - lepton+jets final state:
    - Vector-like TT pair and four tops
      ATL-CONF-2016-013, **ATL-CONF-2016-020**
  - Single production
    - VLQ $T/Y \rightarrow Wb$
      ATL-CONF-2016-072

Heavy quarks

- Fourth generation chiral quarks are ruled out
  - precision electroweak measurements
  - in context of SM,
    - would enhance Higgs production by a factor ~ 9
    - contributes to Higgs quartic coupling λ and leads to vacuum instability
- Vector-like quarks
  - unlike SM, both L and R chiralities are in the same SU(2) representation: singlets, doublets or triplets
  - mass does not arise from Yukawa couplings

$$T^{2/3}_{L,R},\quad B^{-1/3}_{L,R}$$

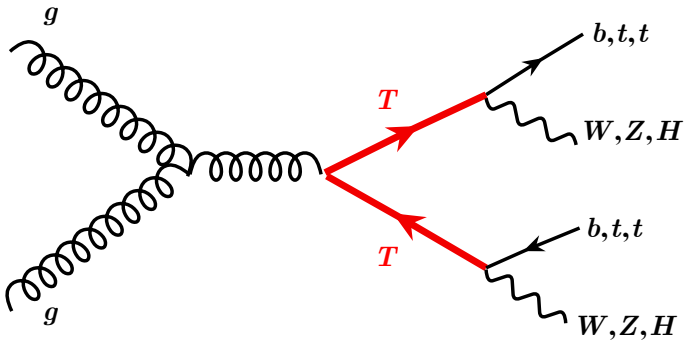
$$\begin{pmatrix} T^{5/3} \\ T^{2/3} \end{pmatrix}_{L,R},\quad \begin{pmatrix} T^{2/3} \\ B^{-1/3} \end{pmatrix}_{L,R},\quad \begin{pmatrix} B^{-1/3} \\ Y^{-4/3} \end{pmatrix}_{L,R}$$

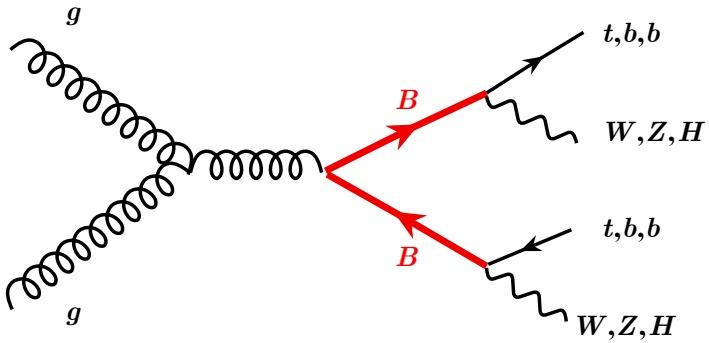
Aguilar-Saavedra et al., 1306.0572

$$\begin{pmatrix} T^{5/3} \\ T^{2/3} \\ B^{-1/3} \end{pmatrix}_{L,R},\quad \begin{pmatrix} T^{2/3} \\ B^{-1/3} \\ Y^{-4/3} \end{pmatrix}_{L,R}$$

  - top partners enter in radiative corrections and protect Higgs mass from quadratic divergence with Q^2: composite Higgs models, Little Higgs, extra dimensions

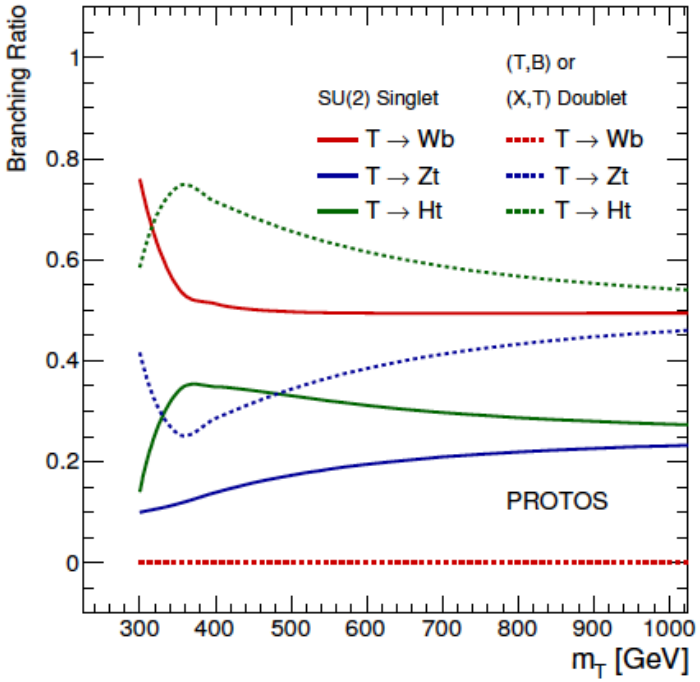
Pair production of 3rd generation partners

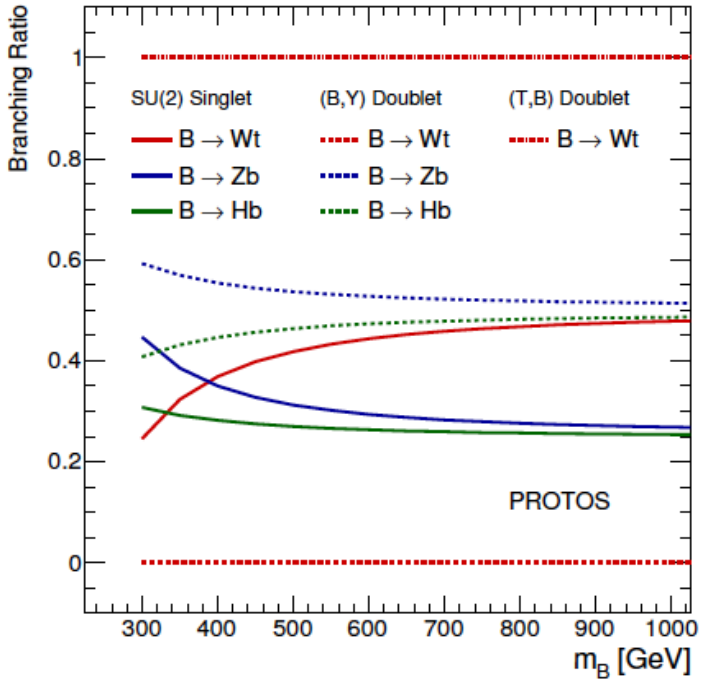




In the limit of very high mass, the vlq' BR's follow

$$BR(Q \to Wq) : BR(Q \to Zq) : BR(Q \to Hq) = 2 : 1 : 1$$



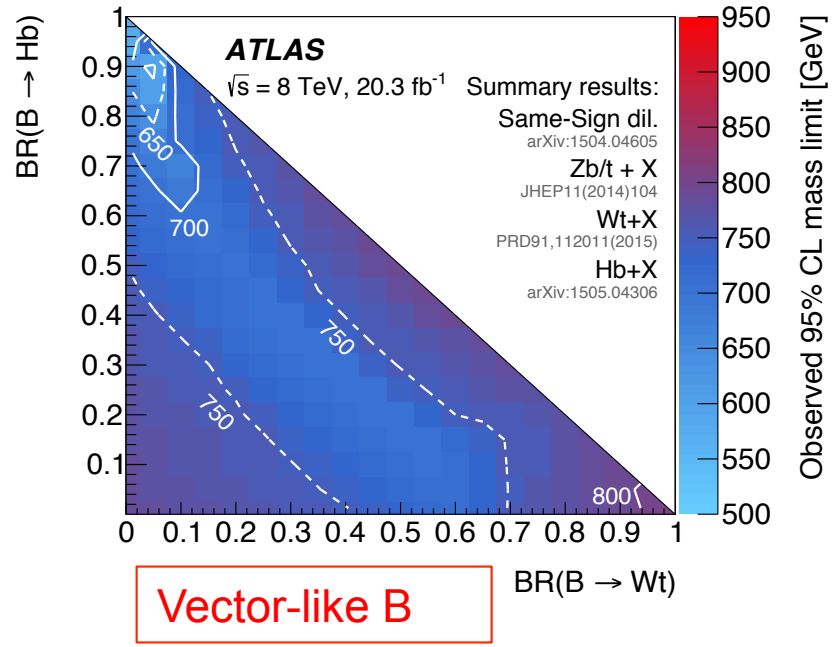


no mixing between $B_{-1/3}$ and b for $(T,B)_R$ doublet in these plots $\left(\theta_R^d = 0\right)$

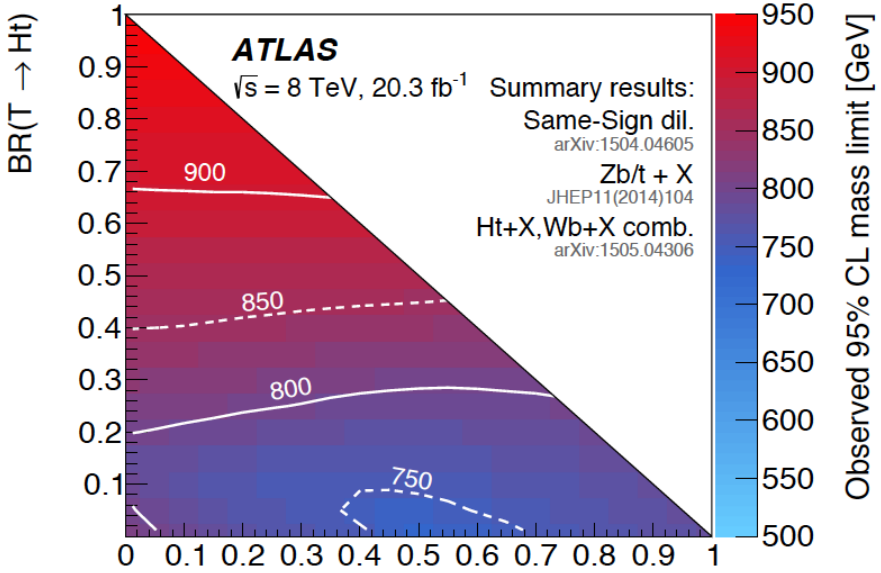
Aguilar-Saavedra, 1306.0752

Previous limits at 8 TeV from ATLAS

- pair-production in Run I:
  - same-sign dileptons: JHEP10(2015) 150, (1504.04605)
    - m(B, singlet) > 620 GeV
    - m(T, singlet) > 590 GeV
    - m($T_{5/3}$) > 750 GeV
  - Zb/t + X: JHEP11(2014)104, (1409.5500)
    - m(B in (B,Y) doublet) > 755 GeV
  - Wt + X: PRD91, 112011 (2015)
    - m($T_{5/3}$) > 840 GeV
  - Q → Hb, Ht,Wb + X: JHEP08(2015) 105, (15050.04306)
    - m(T in (T,B) doublet) > 855 GeV
    - m(Y in (B,Y) doublet) > 770 GeV
    - m(B, singlet) > 735 GeV
- single production
  - T/Y – Wb (1602.05606)
    - m(T/Y) > 950 GeV (for coupling =1)
- single production via heavy gluon
  - G* → Bb → Hbb → 4b (1602.06034)
    - m(B) vs m(G*)



Vector-like B



Vector-like T

b-jets, same-sign leptons, missing E_T

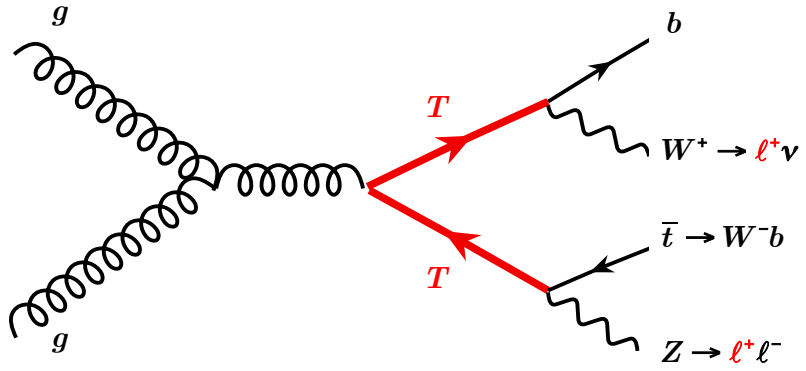
ATLAS-CONF-2016-032

- Vector-like quarks:
  - $T\bar{T}, B\bar{B}$

    $B \to Wt, Zb, Hb$

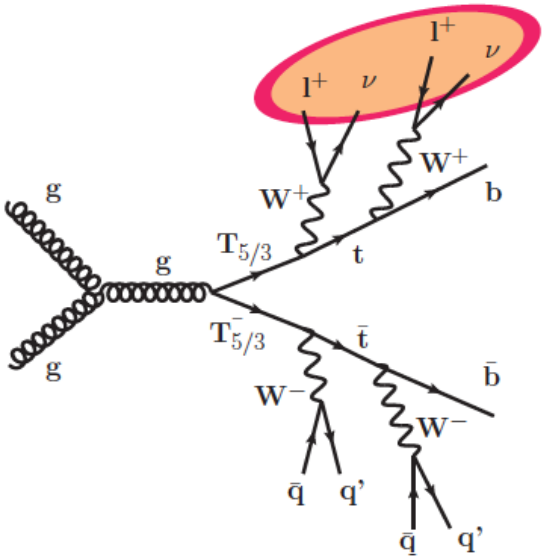
    $T \to Wb, Zt, Ht$

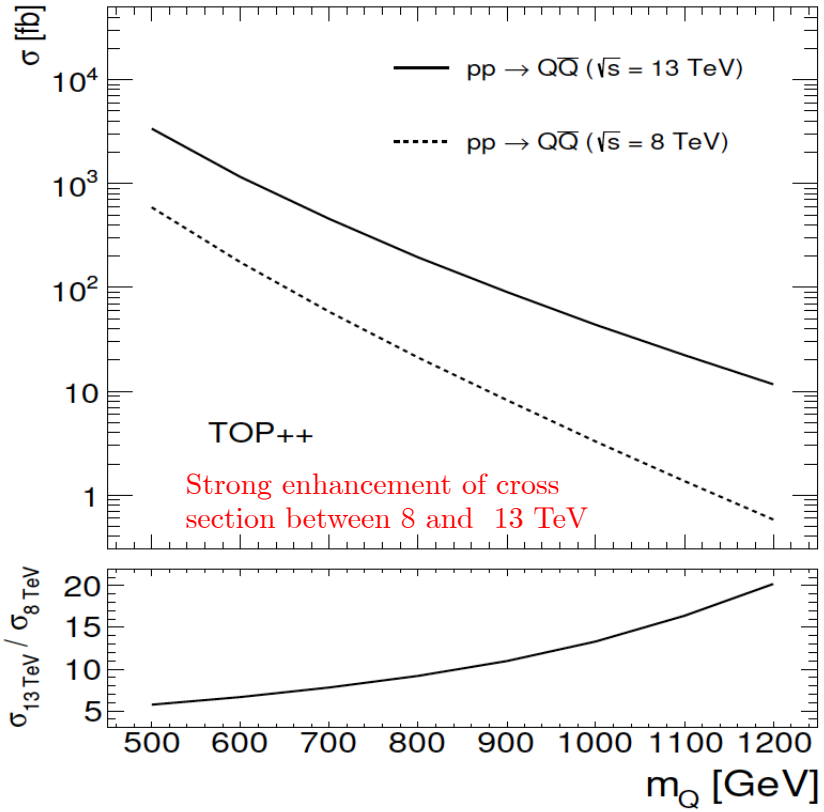
    Events generated with **PROTOS** cross section at NNLO



  - $T_{5/3}\bar{T}_{5/3}$ (doublet)

    $BR(T_{5/3} \to Wt) = 100\%$

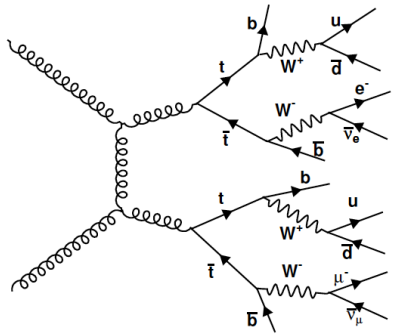




b-jets, same-sign leptons, missing E_T

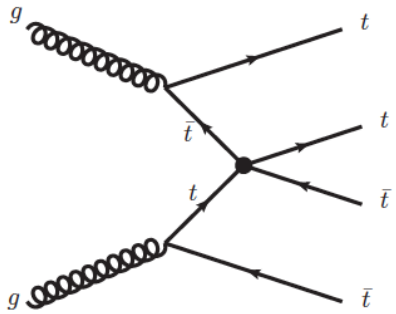
ATLAS-CONF-2016-032

- 4-top
  - SM: low cross section: ~9.2 fb at 13 TeV
    - same sign leptons, missing E_T, multiple light-quark and b jets



  - contact interaction
    - compositeness, sgluons, …

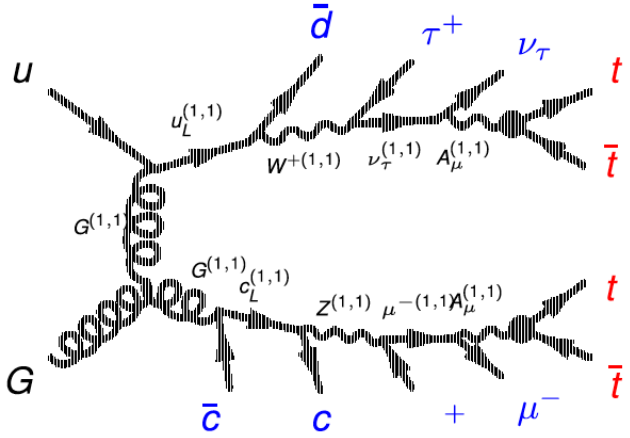
$$\mathcal{L}_{4t} = \frac{C_{4t}}{\Lambda^2} \left(\bar{t}_R \gamma^\mu t_R\right) \left(\bar{t}_R \gamma_\mu t_R\right)$$



  - two universal extra dimensions under real projective plane geometry (2UED/RPP)
    - KK parity conservation $(-1)^{k+\ell}$
    - dark matter candidate

$$m_{KK} \equiv m^{(1,0)} = \frac{1}{R_4} \qquad \xi = \frac{R_4}{R_5} \qquad m^{(1,1)} = \sqrt{1+\xi^2}\, m_{KK}$$

Cacciapaglia et al., 0907.4993



b-jets, same-sign leptons, missing E_T

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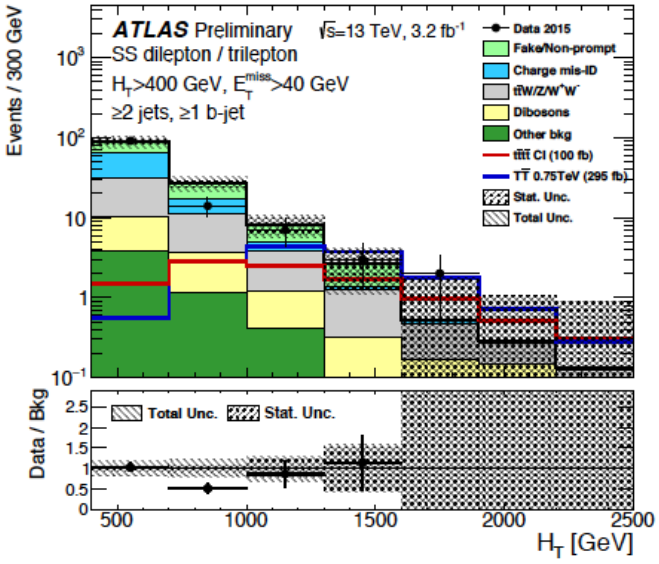
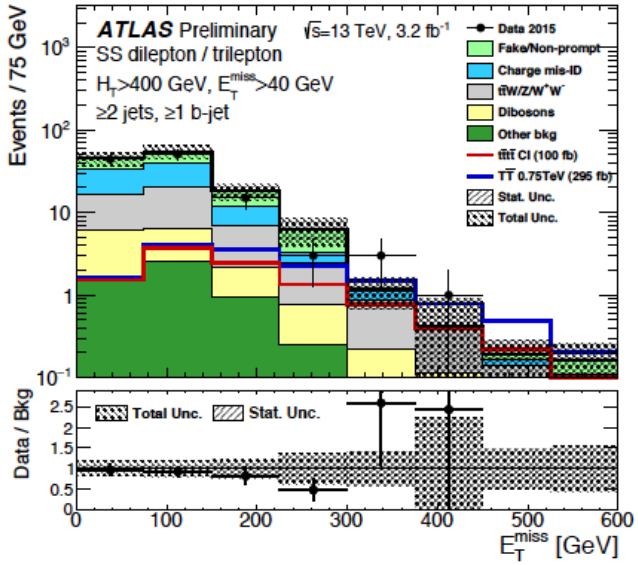
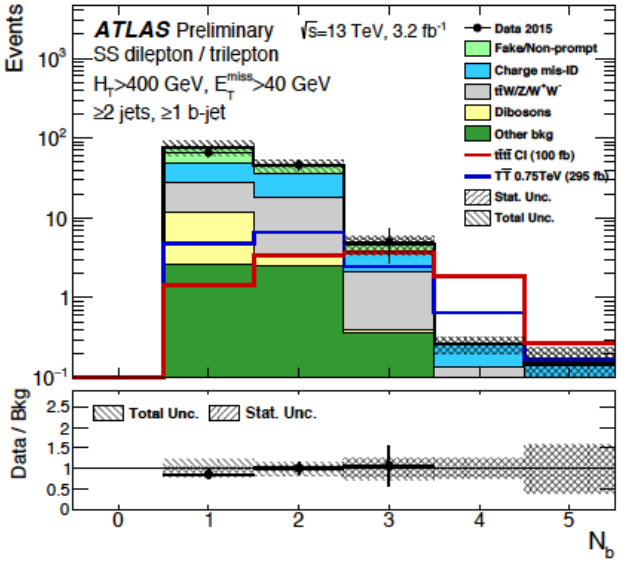
- Signal Basic signatures:
  - same-sign leptons, high H_T, MET, number of jets, b-jets → 8 event categories for signal regions





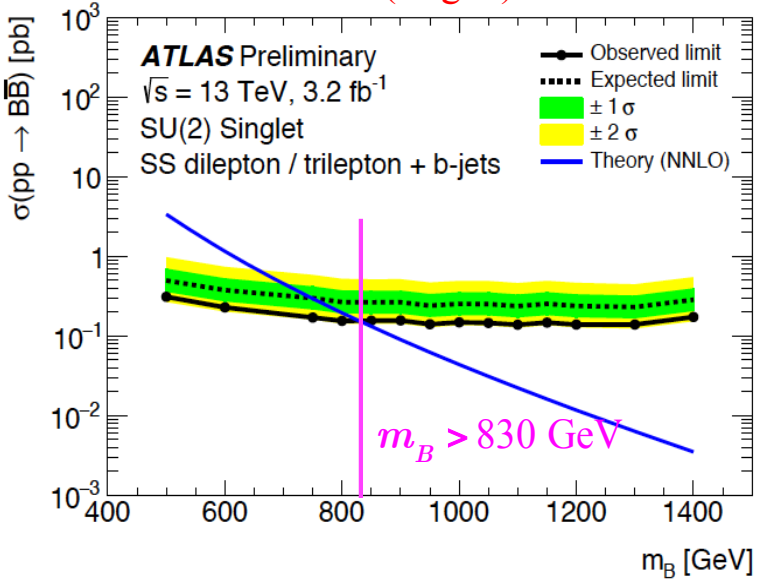


- Backgrounds
  - $t\bar{t}V, ttWW, t\bar{t}H$ MadGraph *rescaled to NLO* VV, VVV Sherpa
    → systematic uncertainties on cross section 8-57%, depending on signal region
  - Detector-related backgrounds
    - charge mis-ID
      - probability measured in $Z \rightarrow ee$ events, as a function of p_T and η
      - background estimated from opposite sign ee and $e\mu$ events
      - systematic uncertainty ~ 3-8 % of total background
    - non-prompt and fake leptons
      - estimated by matrix method: measure how "loose" and "tight" leptons relate to "real" and "fake" leptons and derive the fraction of "fake" leptons in the data.
      - systematic uncertainty ~ 13-26% of total background

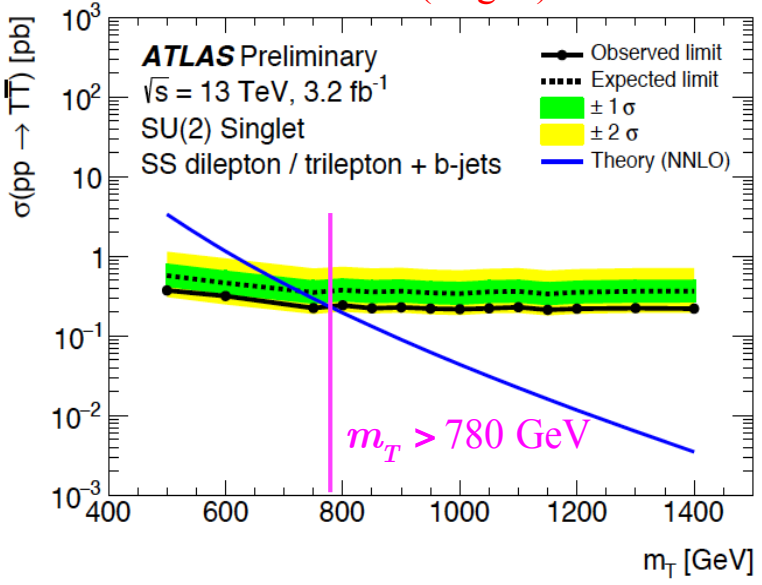
Limits for B and T VLQ's

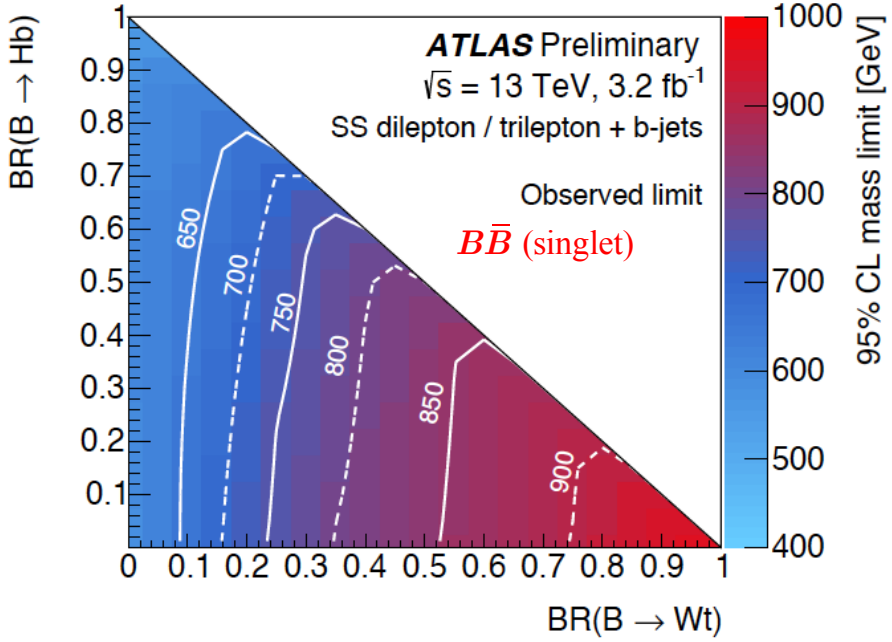
ATLAS-CONF-2016-032

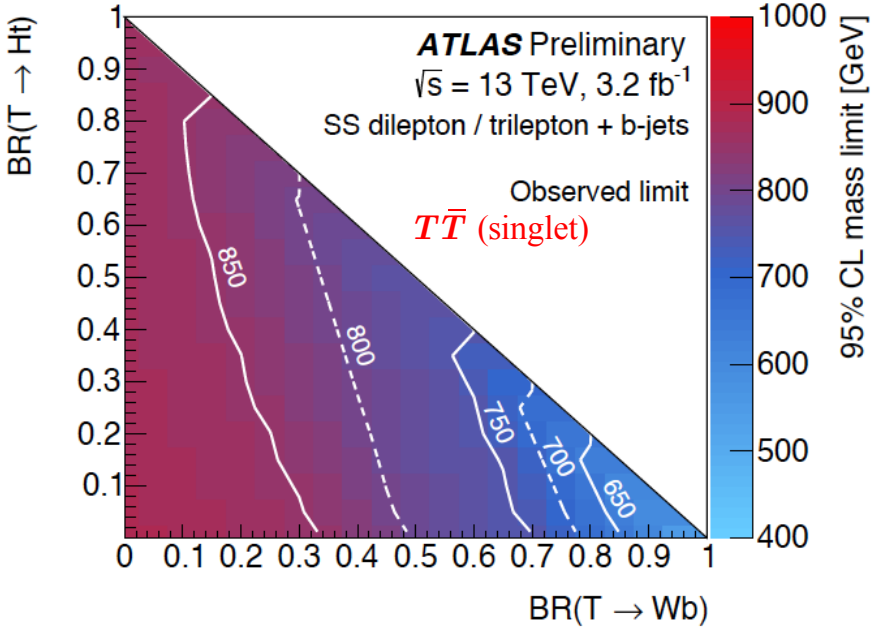
$B\bar{B}$ (singlet)



$T\bar{T}$ (singlet)

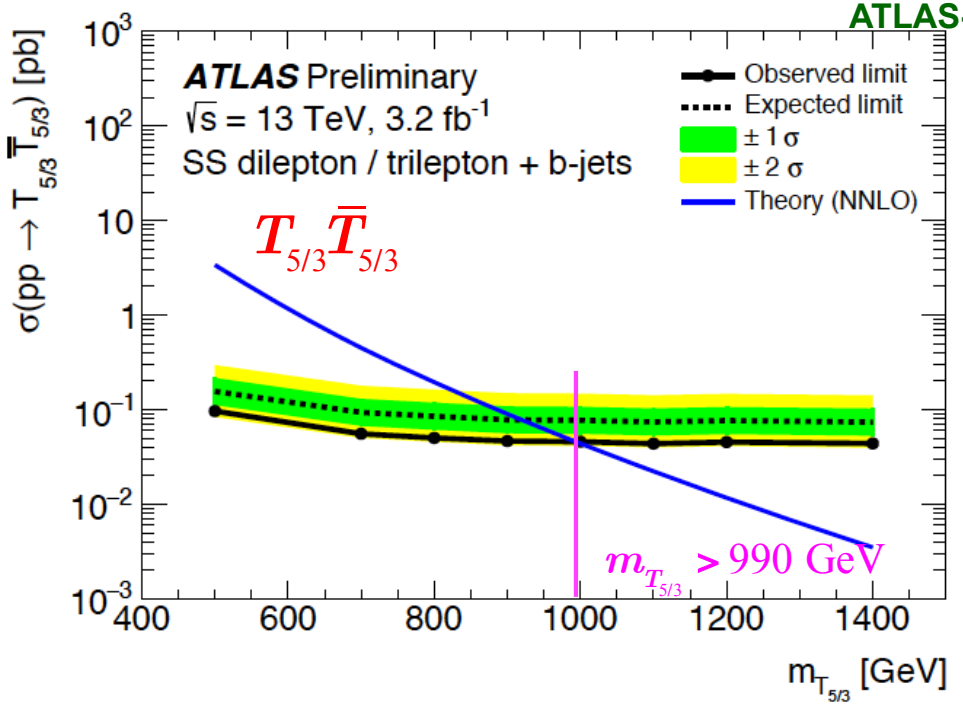






$T_{5/3}$, 4-t contact and 2UED/RPP

ATLAS-CONF-2016-032

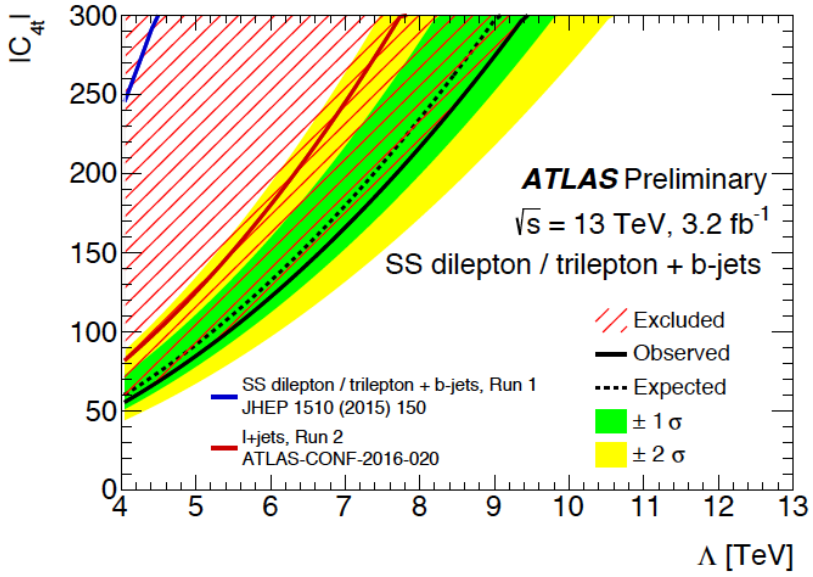


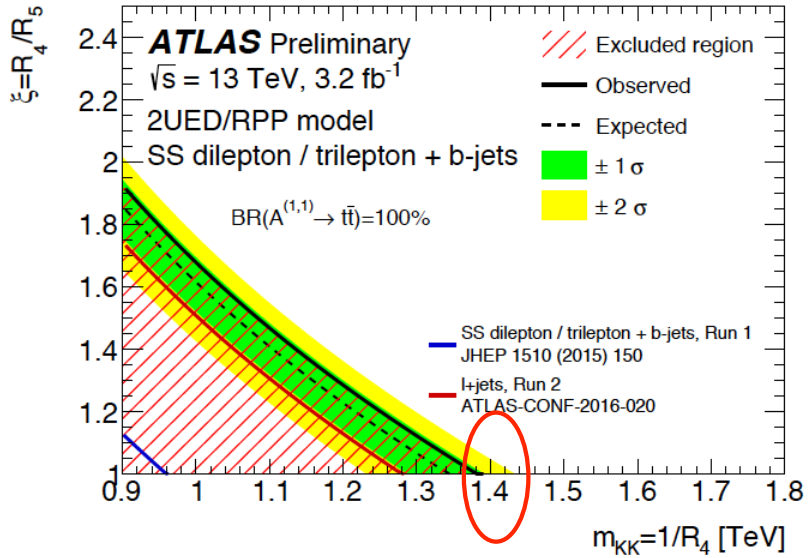
$\sigma(pp \to 4t) < 95$ fb (SM kinematics)

< 67 fb (contact interaction)

$C_{4t}/\Lambda^2 < 3.5$ TeV^{-2}

$m_{KK} > 1.4$ TeV ($R_4 = R_5$)





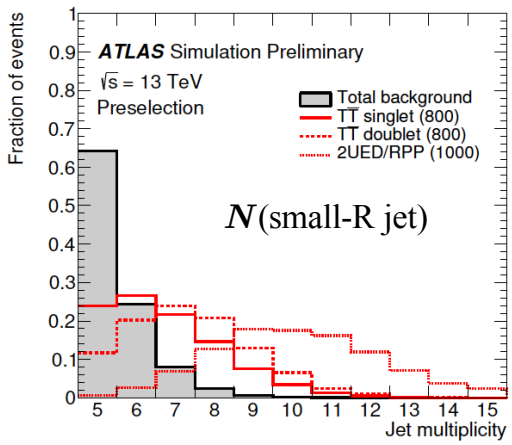
$m_{KK} >$ 4 TeV for symmetric 2UED/RPP case

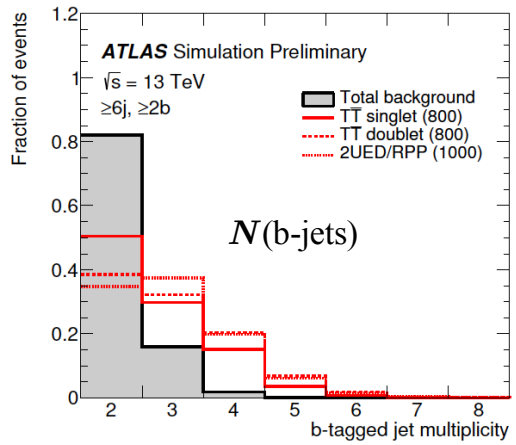
VLQ, 4-tops, in lepton + jets

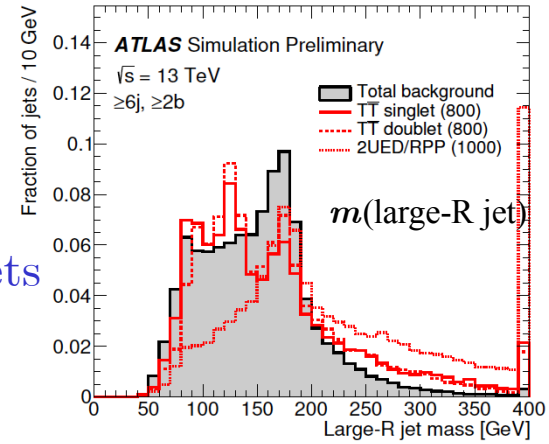
$T\bar{T} \rightarrow HtHt, HtZt, HtWb$

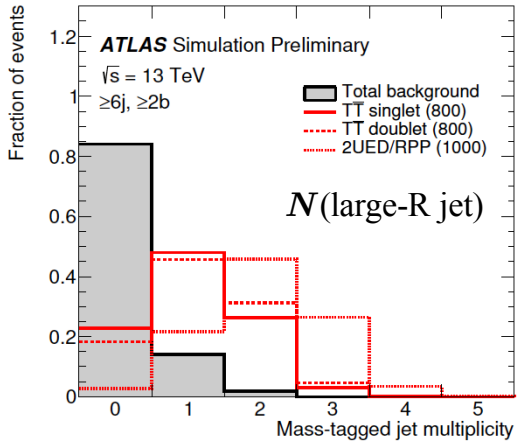
also : $ZtZt, ZtWb, Z \rightarrow b\bar{b}$

- Selection:
  - one isolated lepton
  - $E_T^{miss} > 20$ GeV
  - $m_T(W) > 60$ GeV
- **ATL-CONF-2016-013**
  - up to 6-8 jets, ≥ 2 b-tagged
  - 0-2 high mass jets from boosted tops when $p_T(\text{top}) > 300$ GeV
  - large-R jets (R=1.0) with at least 2 small-R (R=0.4) subjets
    - trimmed: remove small-R subjets with $p_T < 5\%$ of p_T of large-R jet
- **ATL-CONF-2016-20**
  - 4-top analysis
  - 9-10 jets
  - at least 3-4 b-jets

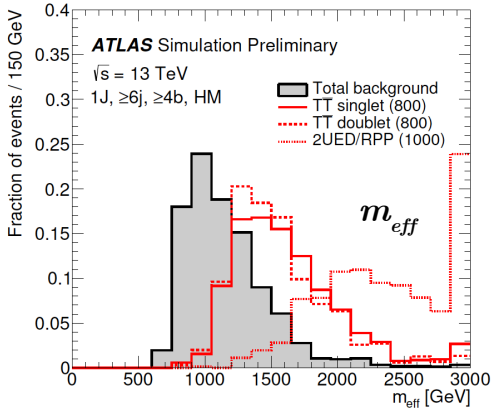








$$m_{eff} = \sum_{\ell,j,\text{miss}} p_T^i$$



VLQ, 4-tops, in lepton + jets

ATLAS-CONF-2016-013
ATLAS-CONF-2016-020

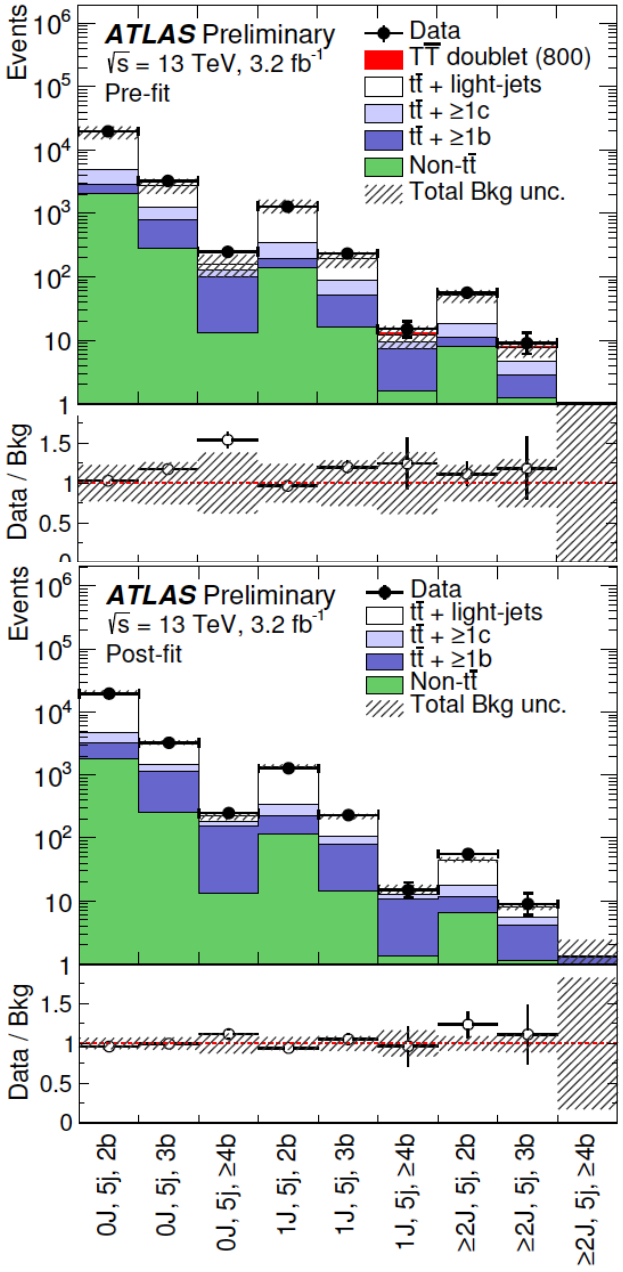
- Backgrounds

  $t\bar{t}$ + *jets*, Wt → Powheg-Box, MadGraph, *rescaled to NNLO*

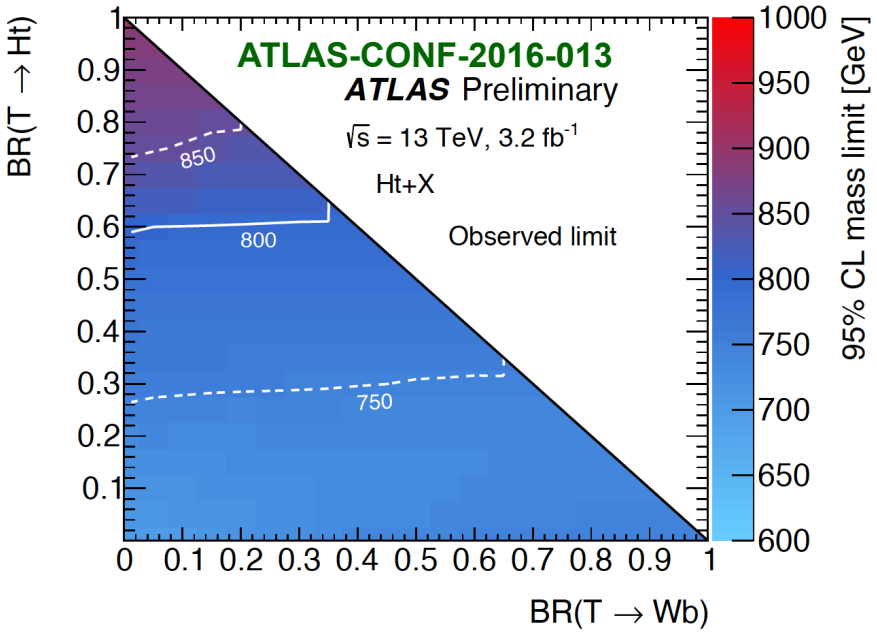
  W + *jets*, VV → Sherpa2.1, *rescaled to NNLO*

  ttV, ttH MadGraph5_aMC@NLO

- Systematic uncertainties
  - luminosity, 5%
  - lepton reconstruction, ~ 1.7%
  - jet energy scale, resolution, ~6% (signal), ~13% (tt background)
  - heavy-flavor jet tagging efficiencies
  - main background modelling uncertainties
    - tt, ~ 6%
    - tt + b's, ~50%
    - V+jets, dibosons, ~ 5%
    - ttV, ttH, 11-13%
    - misidentified lepton: 50%
- Limit extraction
  - Likelihood fit of all signal regions, with systematic errors as nuisance parameters



VLQ, 4-tops, in lepton + jets: limits



$m_T > 900$ GeV (if BR$(T \to Ht) = 1$)

> 750 GeV (T singlet)

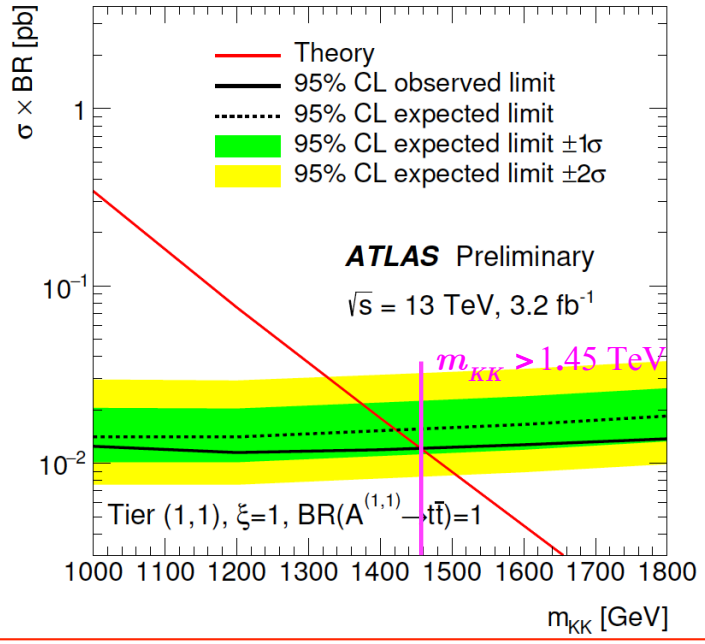
> 800 GeV (T in doublet)

$\sigma(pp \to 4t) < 190$ fb (SM kinematics)

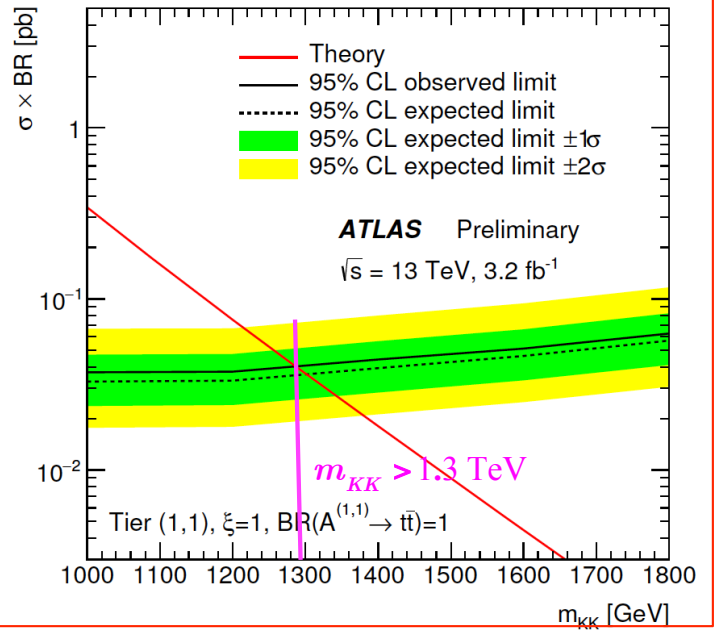
< 140 fb (contact interaction)

$|C_{4t}|/\Lambda^2 < 4.8$ TeV^{-2}

small- and large-R jets: **ATLAS-CONF-2016-013**



High jet multiplicity: **ATLAS-CONF-2016-020**

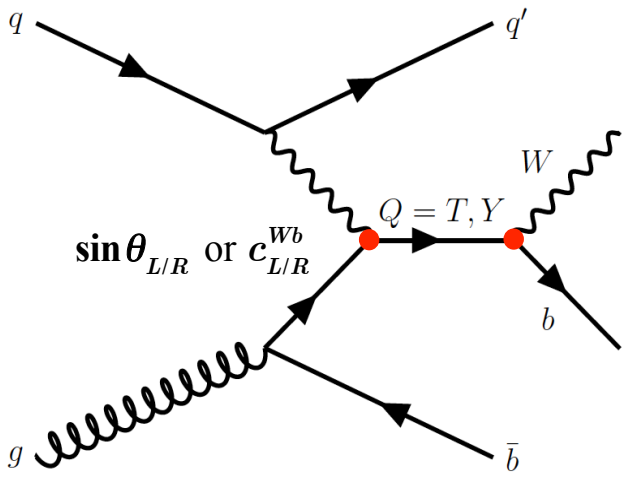


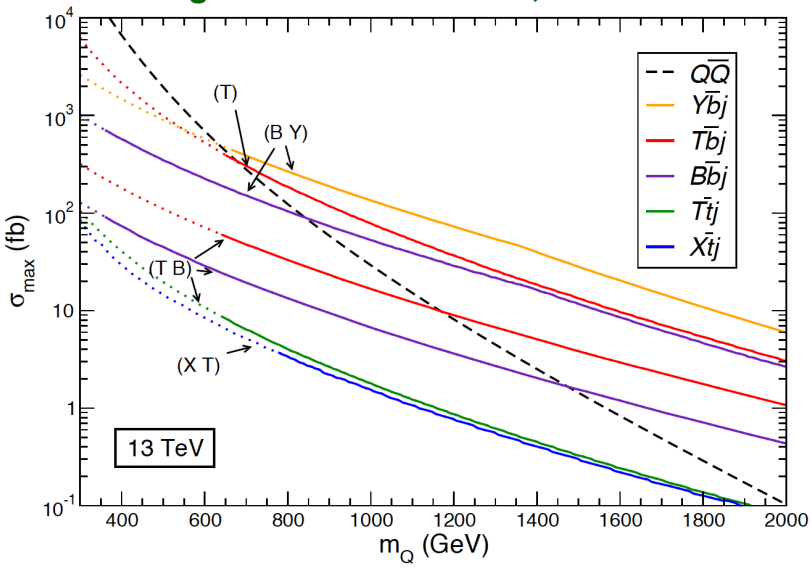
Single Production T,Y → Wb

ATLAS-CONF-2016-072

- Single production is sensitive to high mass, if coupling is sufficiently large

Aguilar-Saavedra et al., 1306.0572





- Coupling QWb

Aguilar-Saavedra et al., 1306.0572

  - mixing term

$$\begin{pmatrix} t \\ T \end{pmatrix}_{L/R} = \begin{pmatrix} \cos\theta_{L/R} & -\sin\theta_{L/R} e^{i\phi} \\ \sin\theta_{L/R} e^{-i\phi} & \cos\theta_{L/R} \end{pmatrix} \begin{pmatrix} t^0 \\ T^0 \end{pmatrix}_{L/R}$$

$$\tan\theta^q_R = \frac{m_q}{m_Q}\tan\theta^q_L \quad \text{(singlets, triplets)}$$

$$\tan\theta^q_L = \frac{m_q}{m_Q}\tan\theta^q_R \quad \text{(doublets)}$$

    - similarly for b-B mixing

  - or, more generally, phenomenological Lagrangian, in effective model with coupling $c^{Wb}_{L/R} = \sqrt{2}\sin\theta_{L/R}$

$$\sigma(Q\bar{b}) \sim (c_L^2 + c_R^2)$$

O. Matsedonskyi et al., 1409.0100

Single Production T,Y → Wb

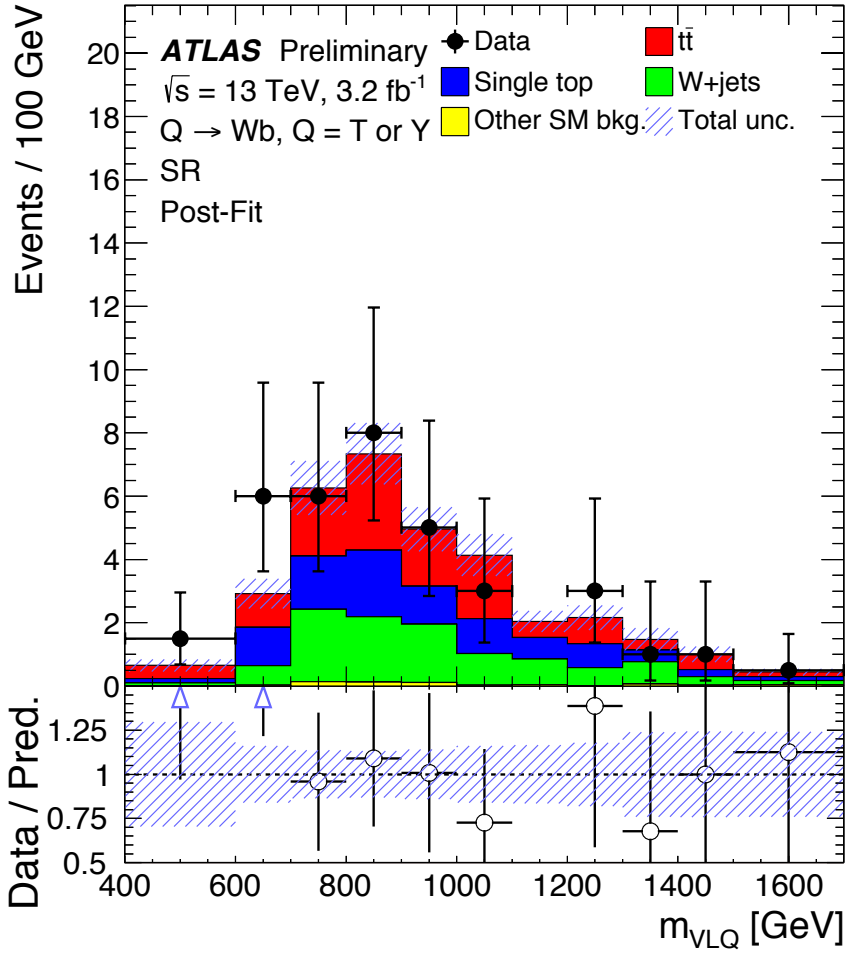
- Signal generated with MadGraph
  - width vary with coupling
- Backgrounds
  - $t\bar{t}$ → Powheg & Pythia

    V + *jets* → Sherpa2.2

    single t → Powheg & Pythia

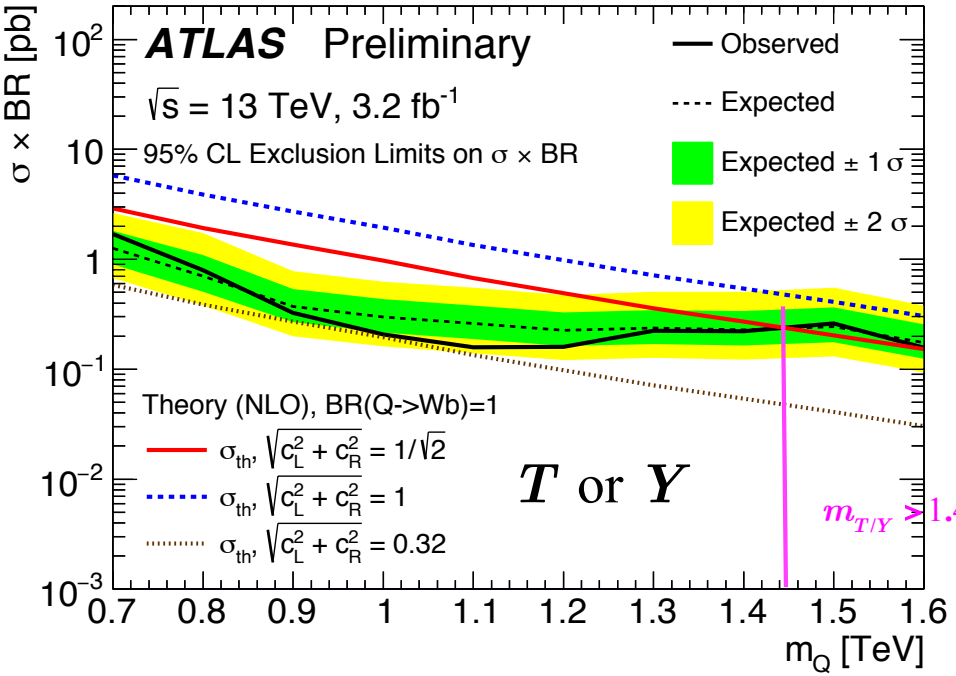
    dibosons → Sherpa

    fake electrons → matrix method
- Event selection
  - exactly one lepton
  - high p_T b-tagged jet $p_T > 350$ GeV
  - a forward jet, $|\eta|>2.5$
  - veto hard central jet with $p_T > 250$ GeV (reduce tt background)
  - large $\Delta\phi$(lepton, leading jet) > 2.5
- Control regions
  - W + jets
    - leading jet not b-tagged, $p_T > 250$ GeV
  - ttbar
    - leading jet $p_T > 200$ GeV
    - at least one hard jet
- Systematic uncertainties
  - dominated by b-tagging efficiency uncertainty, ~ 10%
  - mismodelling of tt (6%) and W+jets at high pT(W) ~ 25%



ATLAS-CONF-2016-072

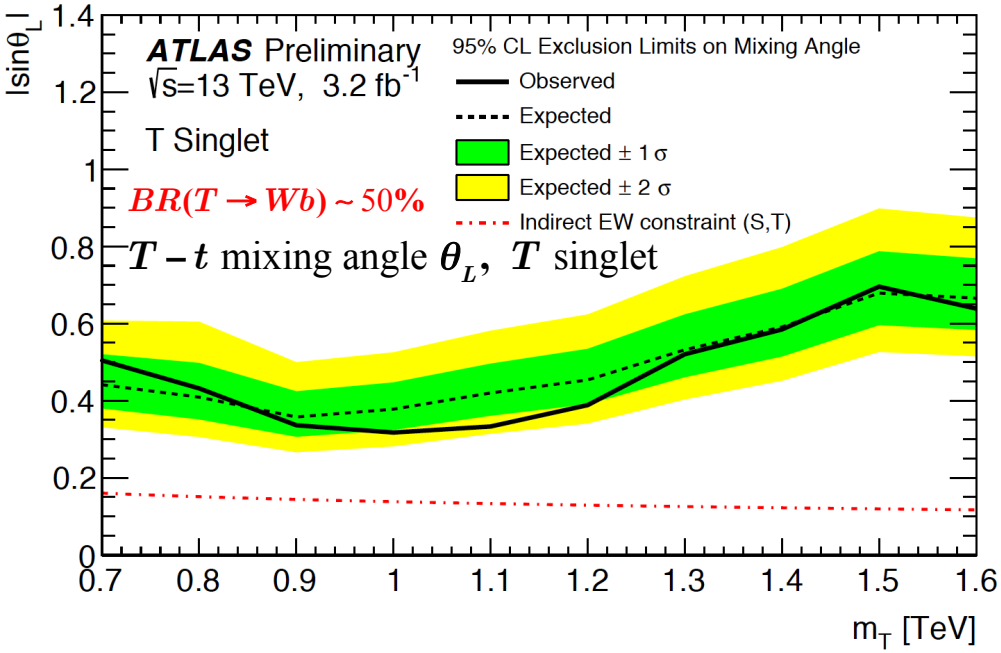
Limit on T, Y from single production

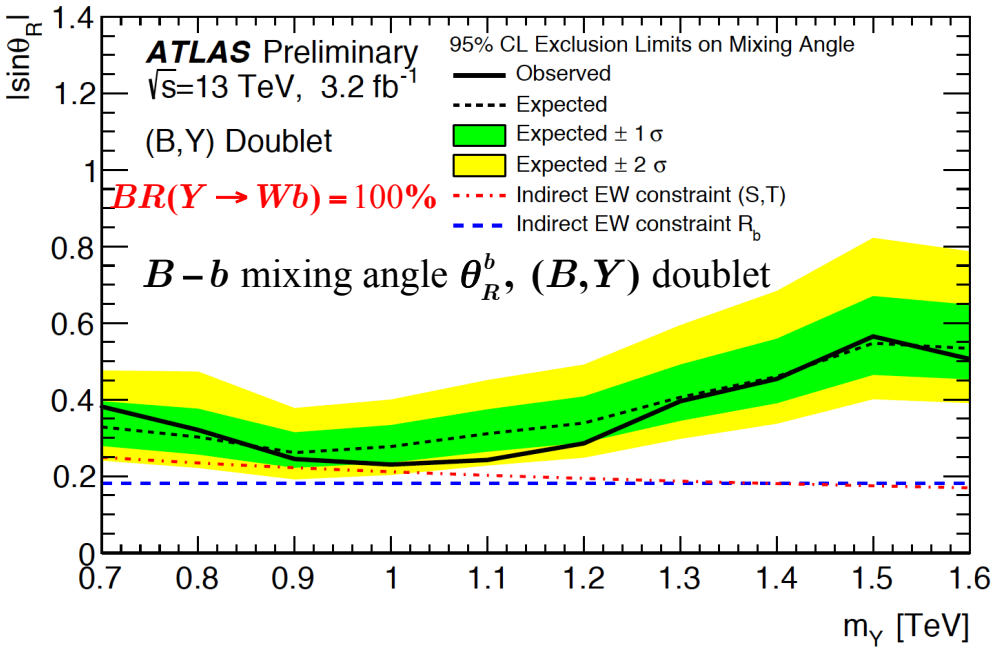


$m_{T/Y} > 1.44$ TeV

ATLAS-CONF-2016-072

	SR	$t\bar{t}$ CR	W+jets CR
$t\bar{t}$	13.7 ± 3.6	154.0 ± 13.1	200.9 ± 36.9
single top	9.6 ± 1.4	27.9 ± 3.8	41.7 ± 6.0
W+jets	10.4 ± 1.9	21.2 ± 3.0	1086.1 ± 54.1
Multijet	0.1 ± 0.1	5.3 ± 5.9	26.5 ± 15.9
Z+jets, diboson	0.6 ± 0.2	3.1 ± 0.6	71.6 ± 5.7
Total	34.3 ± 3.6	211.5 ± 14.9	1426.9 ± 51.0
Data	37	199	1427





Conclusion

Improved limits on vector-like quarks with first 3.2 fb^{-1} at 13 TeV

✸ pair production:

⊙ same-sign leptons

ATLAS-CONF-2016-032

$m(B \text{ singlet}) > 830$ GeV

$m(T \text{ singlet}) > 780$ GeV

$m(T_{5/3}) > 990$ GeV

$|c_{4t}|/\Lambda^2 < 3.5$ TeV^{-2}

$\sigma(4t) < 95/67$ fb (SM, contact kinematics)

$m_{KK} > 1.4$ TeV (2ED/RPP, $R_4 = R_5$)

✸ single production

ATLAS-CONF-2016-072

$m_Y > 1.44$ TeV $\left(\text{for } \sqrt{\left(c_L^{Wb}\right)^2 + \left(c_r^{Wb}\right)^2} = 1/\sqrt{2}\right)$

$\sqrt{\left(c_L^{Wb}\right)^2 + \left(c_r^{Wb}\right)^2} < 0.33$ for Y quark

< 0.45 for T quark

$T-t$ mixing angle dominantly θ_L^t, T singlet

$\sin\theta_L < 0.32 - 0.69$ for $m(T)$ between 1 TeV and 1.5 TeV

$B-b$ mixing angle dominantly θ_R^b, (B,Y) doublet

$\sin\theta_R < 0.23 - 0.56$ for $m(Y)$ between 1 TeV and 1.5 TeV

⊙ lepton + jets

ATLAS-CONF-2016-013
ATLAS-CONF-2016-020

$m(T \text{ singlet}) > 750$ GeV (900 GeV if $BR(T \to Wb) = 1$)

$m(T \text{ doublet}) > 800$ GeV

$|c_{4t}|/\Lambda^2 < 4.8$ TeV^{-2}

$\sigma(4t) < 190/140$ fb (SM/contact kinematics)

$m_{KK} > 1.45$ TeV

More data coming in fast
➔ expect stronger limits
(or discovery!)

Backup

Limit on mixing angles

$$m_{T/Y} > 1.44 \text{ TeV} \left(\text{for } \sqrt{\left(c_L^{Wb}\right)^2 + \left(c_r^{Wb}\right)^2} = 1/\sqrt{2} \right)$$

$$\sqrt{\left(c_L^{Wb}\right)^2 + \left(c_r^{Wb}\right)^2} < 0.33 \text{ for Y quark}$$

$$< 0.45 \text{ for T quark}$$