# Searching for New Physics in Final States with Multiple B-jets with the ATLAS Detector

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# My Research Area at the ATLAS

- New physics searches via final States containing a pair of same-sign leptons: SUSY (EW production of chargino and neutralino), 4tops, Heavy Higgs

- New Physics searches via final States containing top quarks and b quarks: Vector like quark, 4 tops, Heavy Higgs, FCNC

# Motivation

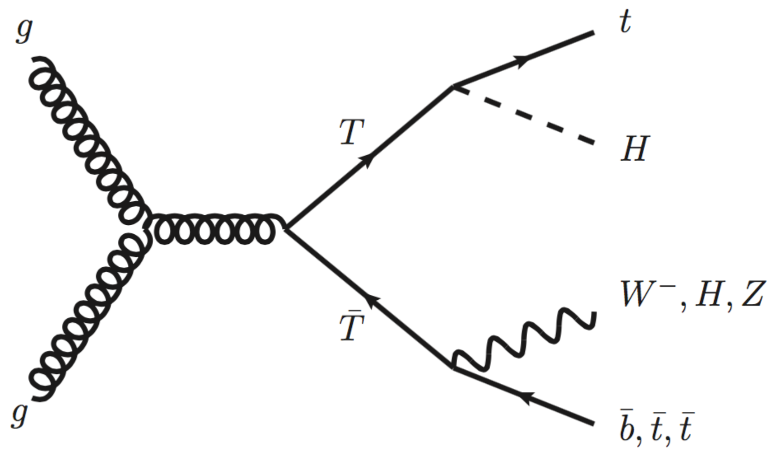
- In the SM, the Higgs boson mass is not stable due to the quadratically divergent corrections at quantum level (hierarchy problem).
- Many new physics models propose solutions to this issue: e.g.
  - the Supersymmetry models cancel the quadratically divergence by introducing contributions from super partners of the SM particles.
  - the Composite Higgs models provide attractive solutions to stabilize the Higgs mass by introducing new strong dynamics. (the light Higgs is a bound state of a strongly interacting sector and a pseudo-Goldstone boson of an enlarged symmetry)
- These motived new physics models typically contain an extended Higgs sector and sometimes vector-like quarks

# Vector-like Quarks

- What are Vector-like quarks
  - VLQ are hypothetical spin-1/2 particles with left-handed and right-handed components that transform in the same way under the SM gauge group.
- Vector-like quarks in many models of New Physics, e.g
  - Universal extra-dimensions
  - Composite Higgs models: excited resonances of the bounded states which form SM particles
  - Little Higgs models: partners of SM fermions in larger group representations which ensure the cancellation of divergent loops
- VLQ masses are not generated by a Yukawa coupling to the Higgs boson, therefore they are not excluded by existing Higgs measurements, e.g. $h \to \gamma\gamma$.
- The VLQ quarks produce rich detector signatures, including both charged-current decays ($T \to Wb$) and neutral current decays ($T \to Zt$ and $T \to Ht$)

# VLQ(TT→Ht+X)

- Final states:
  - 0-lepton, multiple jets and b-jets (sensitive to TT→Zt+X,withZ→νν)
  - 1-lepton (electron or muon), multiple jets and b-jets
- Dominant background: $t\bar{t}$ +jets
- Other background: single-top-quark, *W/Z*+jets, multijet and diboson (*WW*,*WZ*,*ZZ*), *ttV* and *ttH, SM 4top*




**CERN-EP-2018-031, submitted to JHEP**

# Pre-selection

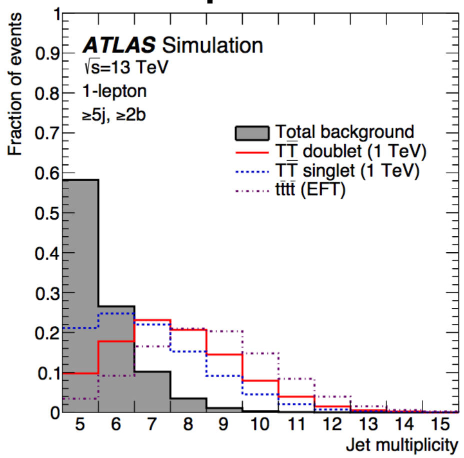
- Event pre-selections

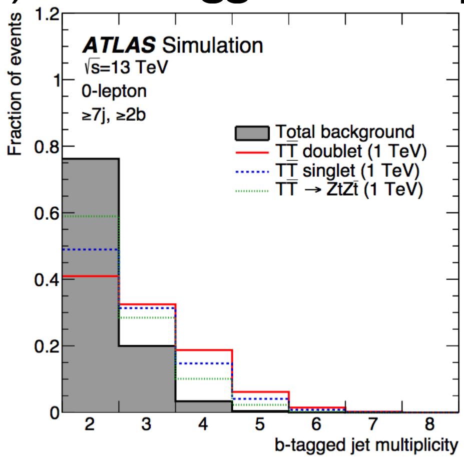
| Preselection requirements | | |
|---|---|---|
| Requirement | 1-lepton channel | 0-lepton channel |
| Trigger | Single-lepton trigger | $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger |
| Leptons | =1 isolated $e$ or $\mu$ | =0 isolated $e$ or $\mu$ |
| Jets | $\geq$5 jets | $\geq$6 jets |
| $b$-tagging | $\geq$2 $b$-tagged jets | $\geq$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 | $\Delta\phi_{\mathrm{min}}^{4j} > 0.4$ |

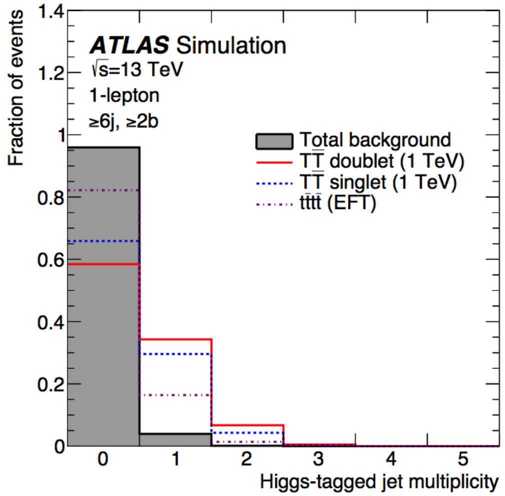
- Small-R (=0.4) jets with $p_T > 25$ GeV and $|eta| < 2.5$
- $\Delta\varphi^{4j}_{min}$ is the minimum azimuthal separation between the $E^{miss}_T$ vector and each of the four highest-$p_T$ jets.

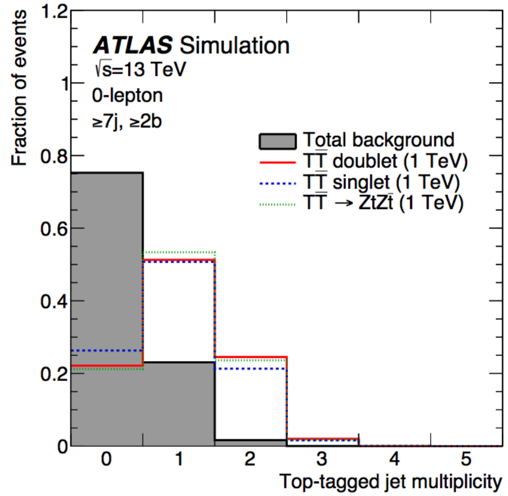
# Category of Events

- Top_tagged_jets: large-R (=1.0) jets reclustered from small-R jets with pT > 300 GeV, |eta| < 2.0, mass> 140 GeV.
- Higgs_tagged_jets: large-R (=1.0) jets reclustered from small-R jets with pT > 200 GeV, |eta| < 2.0, 105 GeV<mass< 140 GeV.
- The pre-selected events are categorised into different regions depending on the jet multiplicity (5 and ≥6 jets in the 1-lepton channel; 6 and ≥7 jets in the 0-lepton channel), *b*-tagged jet multiplicity (3 and ≥4 in the 1-lepton channel; 2, 3 and ≥4 in the 0-lepton channel) and Higgs- and top-tagged jet multiplicity (0, 1 and ≥2).



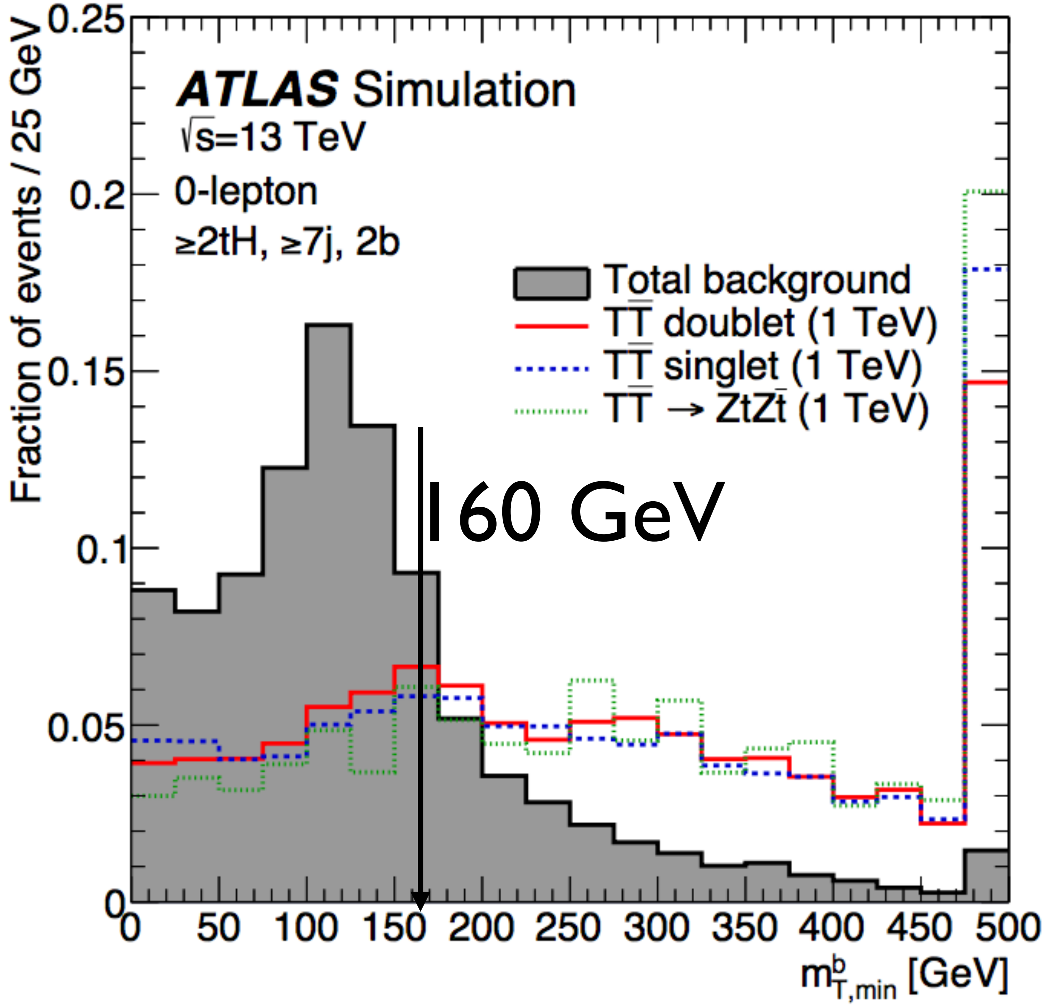



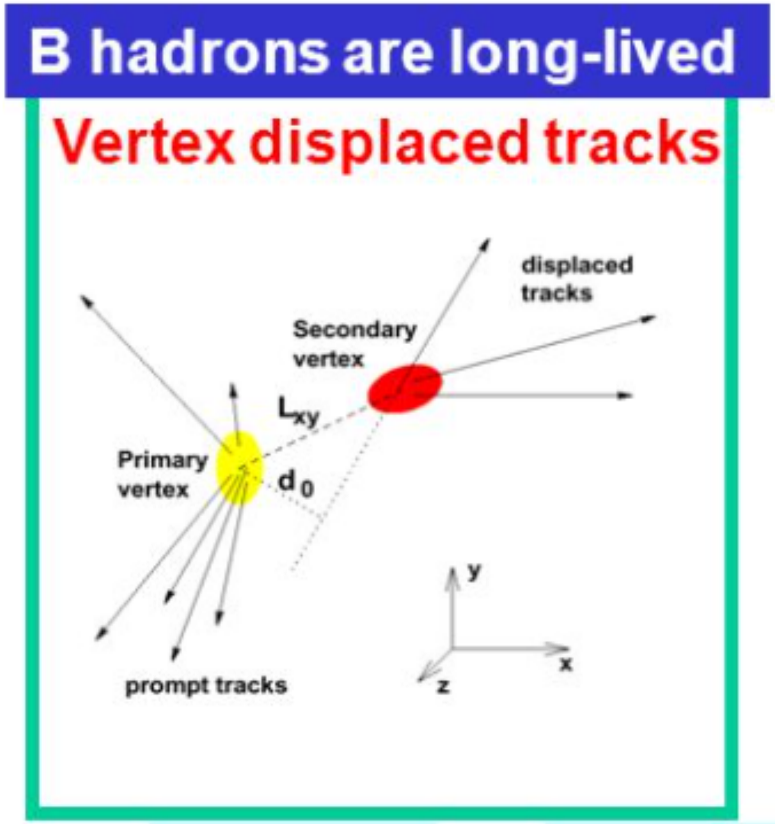



# Category of Events

- Events in the 0-lepton channel are further categorised into two regions according to the value of $m^{b}_{T,min}$, the minimum transverse mass of $E^{miss}_{T}$ and any of the three (or two, in events with exactly two *b*-tagged jets) leading *b*-tagged jets in the event.



# B-tagging




- Use multivariate techniques to combine information about the impact parameters of displaced tracks and the topological properties of secondary and tertiary decay vertices reconstructed within the jet
- A jet is considered *b*-tagged if this value is above the threshold corresponding to an average 77% efficiency to tag a *b*-quark jet, with a light-jet rejection factor of ~134 and a charm-jet rejection factor of ~6.2

# 1-lepton Channel

- A total of 12 search regions and 10 validation regions are considered in the 1-lepton channel.

| 1-lepton channel | | | | |
|---|---|---|---|---|
| **Search regions (≥6 jets)** | | | | |
| $N_t$ | $N_H$ | $b$-tag multiplicity | $m_{eff}$ | Channel name |
| 0 | 0 | 3 | >1 TeV | 0t, 0H, ≥6j, 3b |
| 0 | 0 | ≥4 | >1 TeV | 0t, 0H, ≥6j, ≥4b |
| 1 | 0 | 3 | >1 TeV | 1t, 0H, ≥6j, 3b |
| 1 | 0 | ≥4 | >1 TeV | 1t, 0H, ≥6j, ≥4b |
| 0 | 1 | 3 | >1 TeV | 0t, 1H, ≥6j, 3b |
| 0 | 1 | ≥4 | >1 TeV | 0t, 1H, ≥6j, ≥4b |
| 1 | 1 | 3 | – | 1t, 1H, ≥6j, 3b |
| 1 | 1 | ≥4 | – | 1t, 1H, ≥6j, ≥4b |
| ≥2 | 0 or 1 | 3 | – | ≥2t, 0–1H, ≥6j, 3b |
| ≥2 | 0 or 1 | ≥4 | – | ≥2t, 0–1H, ≥6j, ≥4b |
| ≥0 | ≥2 | 3 | – | ≥0t, ≥2H, ≥6j, 3b |
| ≥0 | ≥2 | ≥4 | – | ≥0t, ≥2H, ≥6j, ≥4b |
| **Validation regions (5 jets)** | | | | |
| $N_t$ | $N_H$ | $b$-tag multiplicity | $m_{eff}$ | Channel name |
| 0 | 0 | 3 | >1 TeV | 0t, 0H, 5j, 3b |
| 0 | 0 | ≥4 | >1 TeV | 0t, 0H, 5j, ≥4b |
| 1 | 0 | 3 | >1 TeV | 1t, 0H, 5j, 3b |
| 1 | 0 | ≥4 | >1 TeV | 1t, 0H, 5j, ≥4b |
| 0 | 1 | 3 | >1 TeV | 0t, 1H, 5j, 3b |
| 0 | 1 | ≥4 | >1 TeV | 0t, 1H, 5j, ≥4b |
| 1 | 1 | 3 | – | 1t, 1H, 5j, 3b |
| ≥2 | 0 or 1 | 3 | – | ≥2t, 0–1H, 5j, 3b |
| ≥0 | ≥2 | 3 | – | ≥0t, ≥2H, 5j, 3b |
| $N_t + N_H \geq 2$ | | ≥4 | – | ≥2tH, 5j, ≥4b |

# 0-lepton Channel

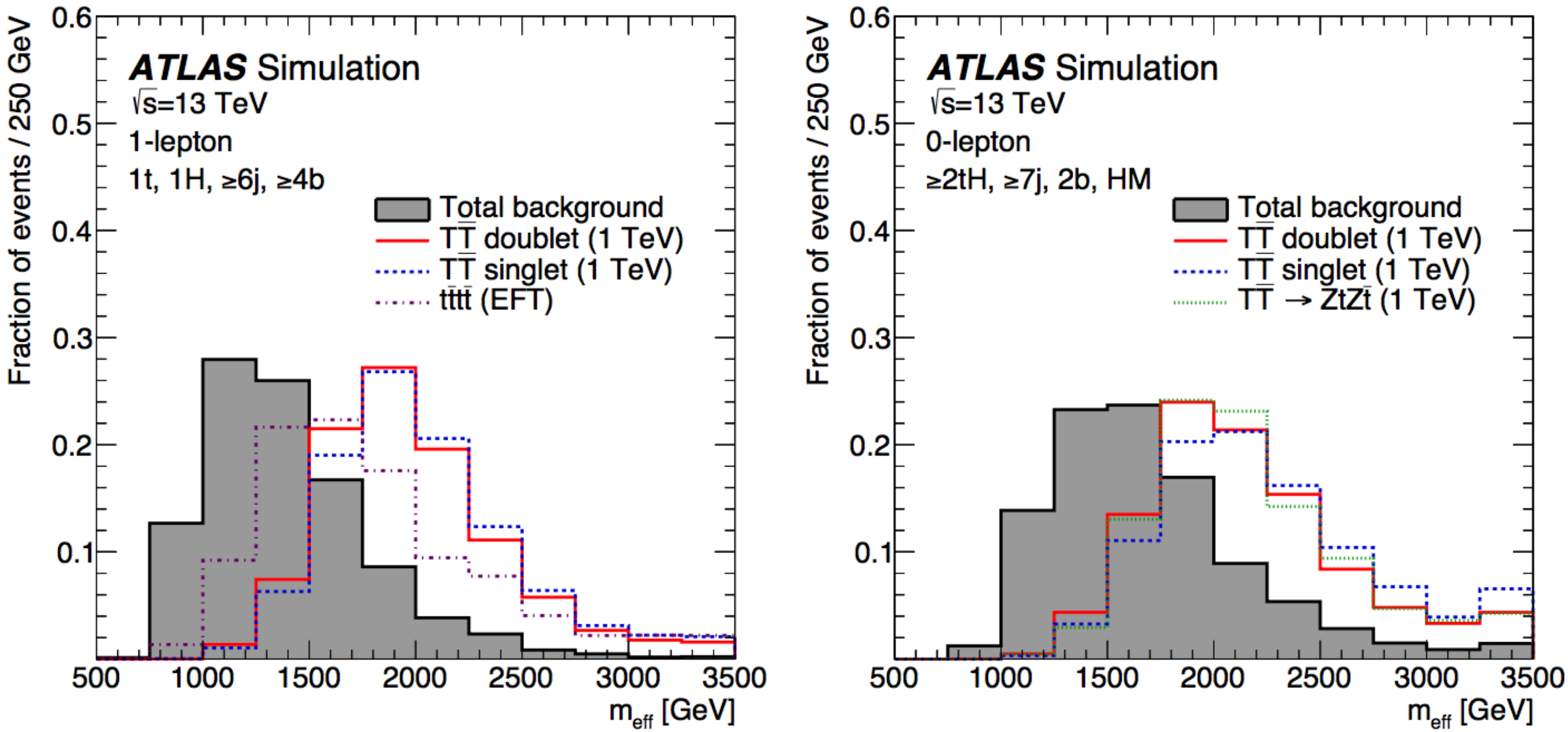
- 22 search regions and 16 validation regions are considered in the 0-lepton channel

| 0-lepton channel | | | | | |
|---|---|---|---|---|---|
| Search regions (≥7 jets) | | | | | |
| $N_t$ | $N_H$ | $b$-tag multiplicity | $m^b_{T,min}$ | $m_{eff}$ | Channel name |
| 0 | 0 | 2 | >160 GeV | >1 TeV | 0t, 0H, ≥7j, 2b, HM |
| 0 | 0 | 3 | <160 GeV | >1 TeV | 0t, 0H, ≥7j, 3b, LM |
| 0 | 0 | 3 | >160 GeV | >1 TeV | 0t, 0H, ≥7j, 3b, HM |
| 0 | 0 | ≥4 | <160 GeV | >1 TeV | 0t, 0H, ≥7j, ≥4b, LM |
| 0 | 0 | ≥4 | >160 GeV | >1 TeV | 0t, 0H, ≥7j, ≥4b, HM |
| 1 | 0 | 2 | >160 GeV | >1 TeV | 1t, 0H, ≥7j, 2b, HM |
| 1 | 0 | 3 | <160 GeV | >1 TeV | 1t, 0H, ≥7j, 3b, LM |
| 1 | 0 | 3 | >160 GeV | >1 TeV | 1t, 0H, ≥7j, 3b, HM |
| 1 | 0 | ≥4 | <160 GeV | >1 TeV | 1t, 0H, ≥7j, ≥4b, LM |
| 1 | 0 | ≥4 | >160 GeV | >1 TeV | 1t, 0H, ≥7j, ≥4b, HM |
| 0 | 1 | 2 | >160 GeV | >1 TeV | 0t, 1H, ≥7j, 2b, HM |
| 0 | 1 | 3 | <160 GeV | >1 TeV | 0t, 1H, ≥7j, 3b, LM |
| 0 | 1 | 3 | >160 GeV | >1 TeV | 0t, 1H, ≥7j, 3b, HM |
| 0 | 1 | ≥4 | <160 GeV | >1 TeV | 0t, 1H, ≥7j, ≥4b, LM |
| 0 | 1 | ≥4 | >160 GeV | >1 TeV | 0t, 1H, ≥7j, ≥4b, HM |
| 1 | 1 | 3 | <160 GeV | >1 TeV | 1t, 1H, ≥7j, 3b, LM |
| 1 | 1 | 3 | >160 GeV | >1 TeV | 1t, 1H, ≥7j, 3b, HM |
| ≥2 | 0 or 1 | 3 | <160 GeV | >1 TeV | ≥2t, 0–1H, ≥7j, 3b, LM |
| ≥2 | 0 or 1 | 3 | >160 GeV | >1 TeV | ≥2t, 0–1H, ≥7j, 3b, HM |
| ≥0 | ≥2 | 3 | – | >1 TeV | ≥0t, ≥2H, ≥7j, 3b |
| $N_t + N_H \geq 2$ | | 2 | >160 GeV | >1 TeV | ≥2tH, ≥7j, 2b, HM |
| $N_t + N_H \geq 2$ | | ≥4 | – | >1 TeV | ≥2tH, ≥7j, ≥4b |

| Validation regions (6 jets) | | | | | |
|---|---|---|---|---|---|
| $N_t$ | $N_H$ | $b$-tag multiplicity | $m^b_{T,min}$ | $m_{eff}$ | Channel name |
| 0 | 0 | 2 | >160 GeV | >1 TeV | 0t, 0H, 6j, 2b, HM |
| 0 | 0 | 3 | <160 GeV | >1 TeV | 0t, 0H, 6j, 3b, LM |
| 0 | 0 | 3 | >160 GeV | >1 TeV | 0t, 0H, 6j, 3b, HM |
| 0 | 0 | ≥4 | <160 GeV | >1 TeV | 0t, 0H, 6j, ≥4b, LM |
| 0 | 0 | ≥4 | >160 GeV | >1 TeV | 0t, 0H, 6j, ≥4b, HM |
| 1 | 0 | 2 | >160 GeV | >1 TeV | 1t, 0H, 6j, 2b, HM |
| 1 | 0 | 3 | <160 GeV | >1 TeV | 1t, 0H, 6j, 3b, LM |
| 1 | 0 | 3 | >160 GeV | >1 TeV | 1t, 0H, 6j, 3b, HM |
| 1 | 0 | ≥4 | – | >1 TeV | 1t, 0H, 6j, ≥4b |
| 0 | 1 | 2 | >160 GeV | >1 TeV | 0t, 1H, 6j, 2b, HM |
| 0 | 1 | 3 | <160 GeV | >1 TeV | 0t, 1H, 6j, 3b, LM |
| 0 | 1 | 3 | >160 GeV | >1 TeV | 0t, 1H, 6j, 3b, HM |
| 0 | 1 | ≥4 | – | >1 TeV | 0t, 1H, 6j, ≥4b |
| $N_t + N_H \geq 2$ | | 2 | >160 GeV | >1 TeV | ≥2tH, 6j, 2b, HM |
| $N_t + N_H \geq 2$ | | 3 | – | >1 TeV | ≥2tH, 6j, 3b |
| $N_t + N_H \geq 2$ | | ≥4 | – | >1 TeV | ≥2tH, 6j, ≥4b |

# Final Discriminant

- Signal discrimination based on shape of effective mass ($m_{eff}$), defined as the scalar sum of the transverse momenta of the lepton, the selected jets and the missing transverse momentum, used in a profile likelihood fit performed across signal regions



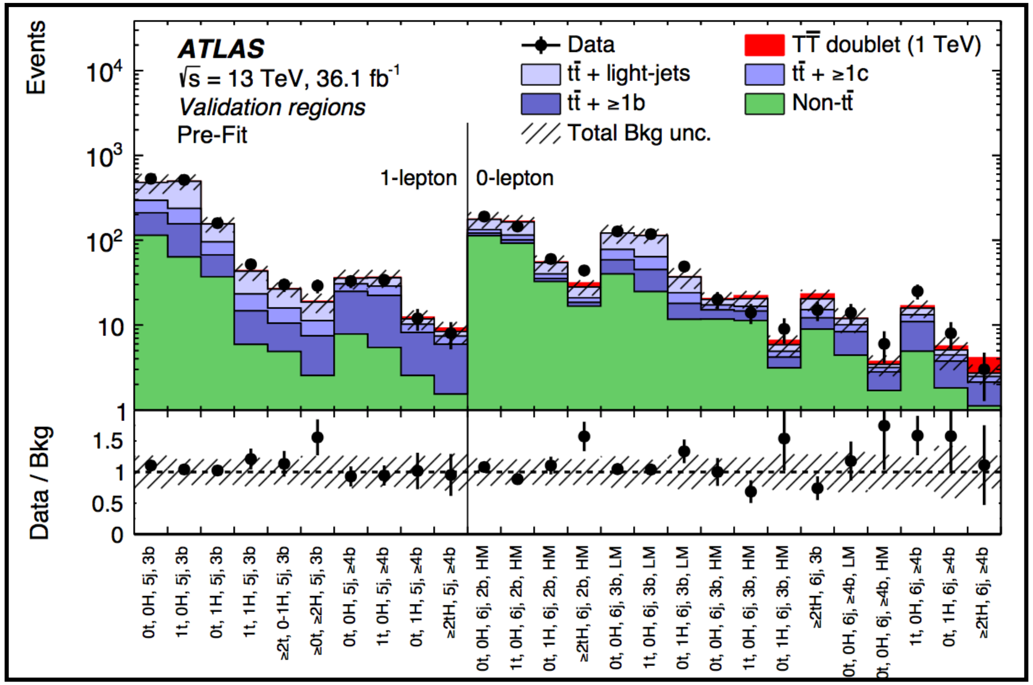
# Systematic Uncertainties

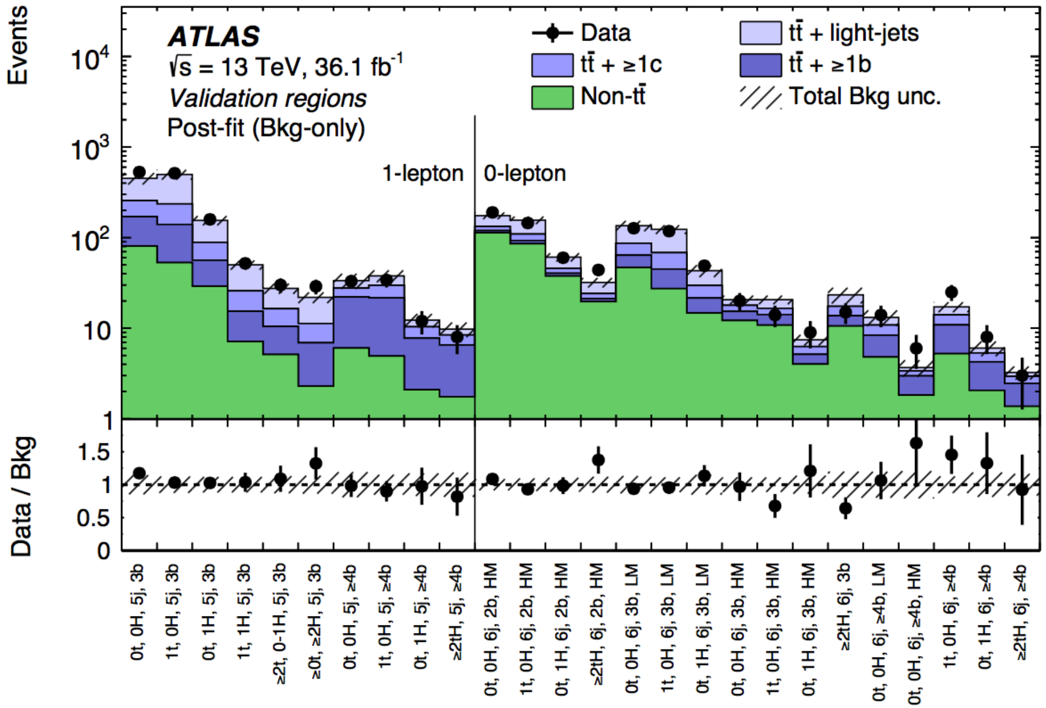
- Systematic uncertainty are considered that affect the normalisation of signal and background and/or the shape of their $m_{\mathrm{eff}}$ distributions.
  - Luminosity
  - Reconstructed objects: trigger, reconstruction, identification, momentum/energy scale/resolution
  - Background modelling: cross section (factorisation and renormalisation scales, PDF, top mass etc), normalisation, generators (ISR/FSR, parton shower+hadronisation etc) etc.

- The leading sources of systematic uncertainty vary depending on the analysis region considered.
  - e.g, the total systematic uncertainty of the background normalisation in the highest-sensitivity search region in the 1-lepton channel (≥0t, ≥2H, ≥6j, ≥4b) is with the largest contributions originating from uncertainties in $tt$+HF modelling and flavour tagging efficiencies ($b$, $c$, and light).
  - the joint fit to data across the 34 search regions considered in total in the 1-lepton and 0-lepton channels allows the overall background uncertainty to be reduced significantly, e.g., in the case of the search region above down to 10% (including the uncertainty in the $tt+\geq 1b$ normalisation).

# Fitting Results in Validation Regions

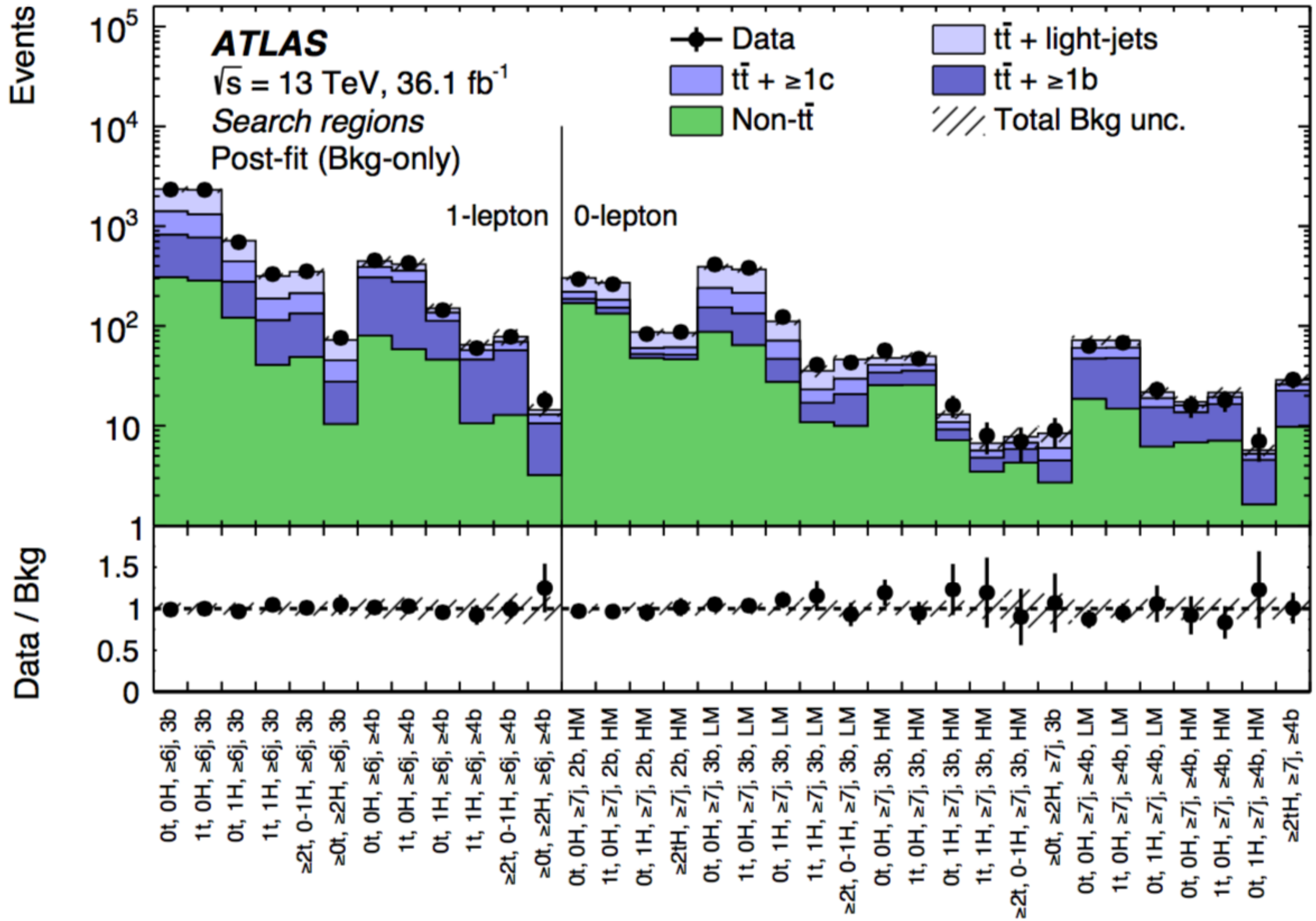
- Comparison between the data and background prediction for the yields in each of the validation regions considered in the 1-lepton and 0-lepton channels before the fit ("Pre-fit") and after the fit ("Post-fit").



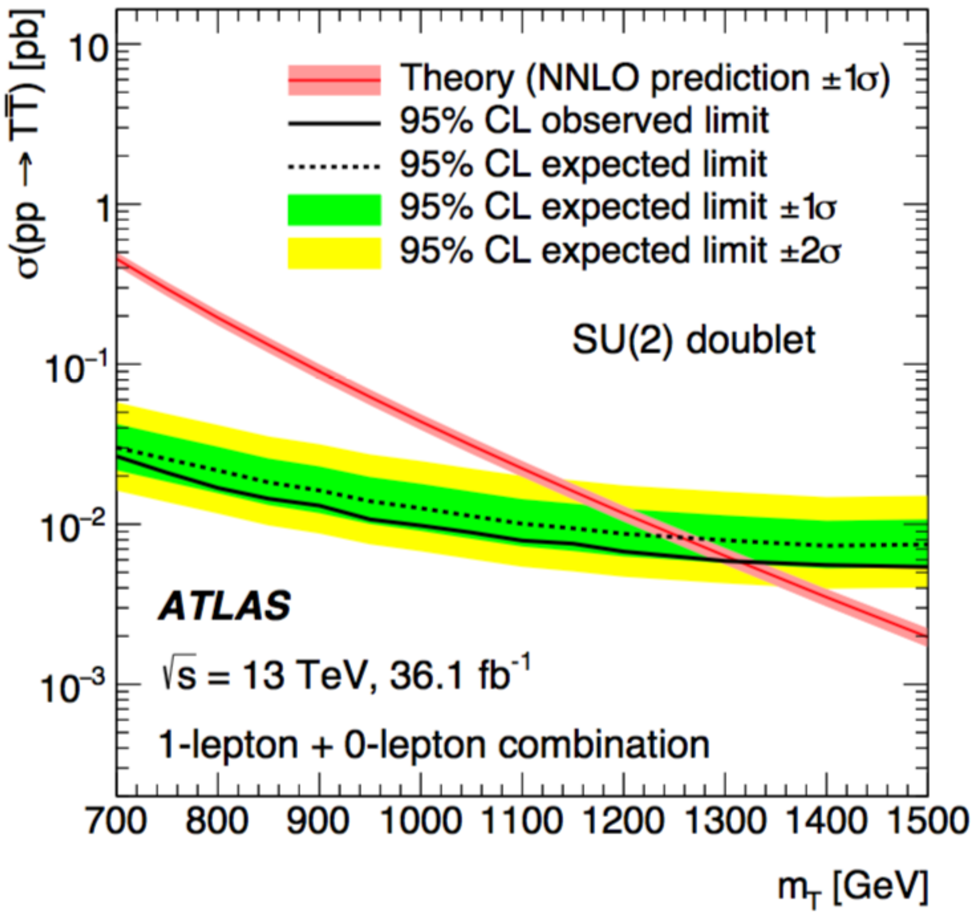



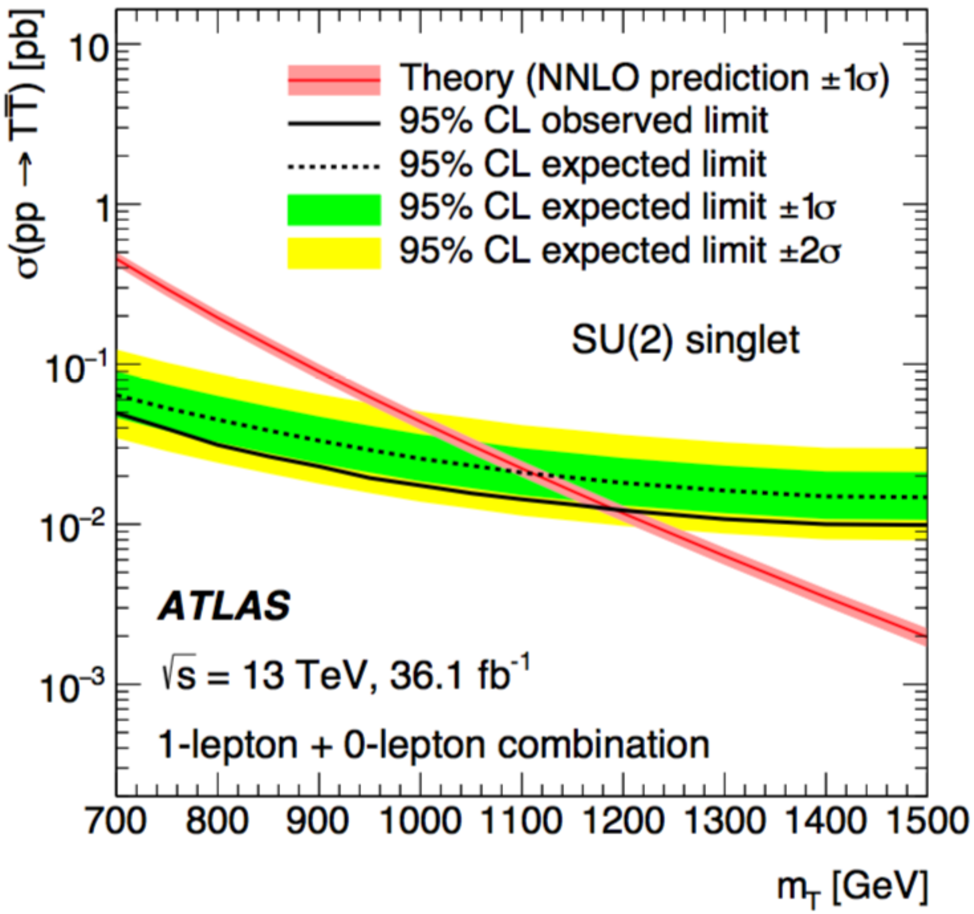
# Fitting Results in Searching Regions

- Comparison between the data and the background prediction for the yields in the search regions considered in the 1-lepton and 0-lepton channels, after the combined fit to data ("Post-fit") under the background-only hypothesis.

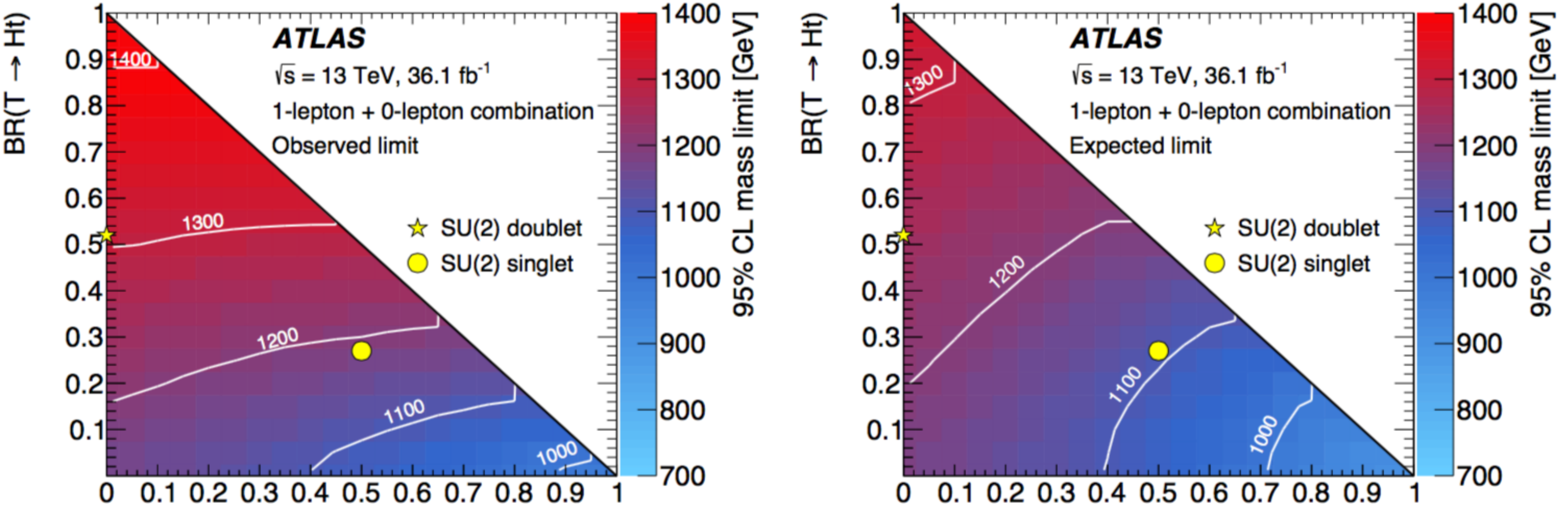


# 95% CL Cross Section Limits



# 95% CL Mass Limits

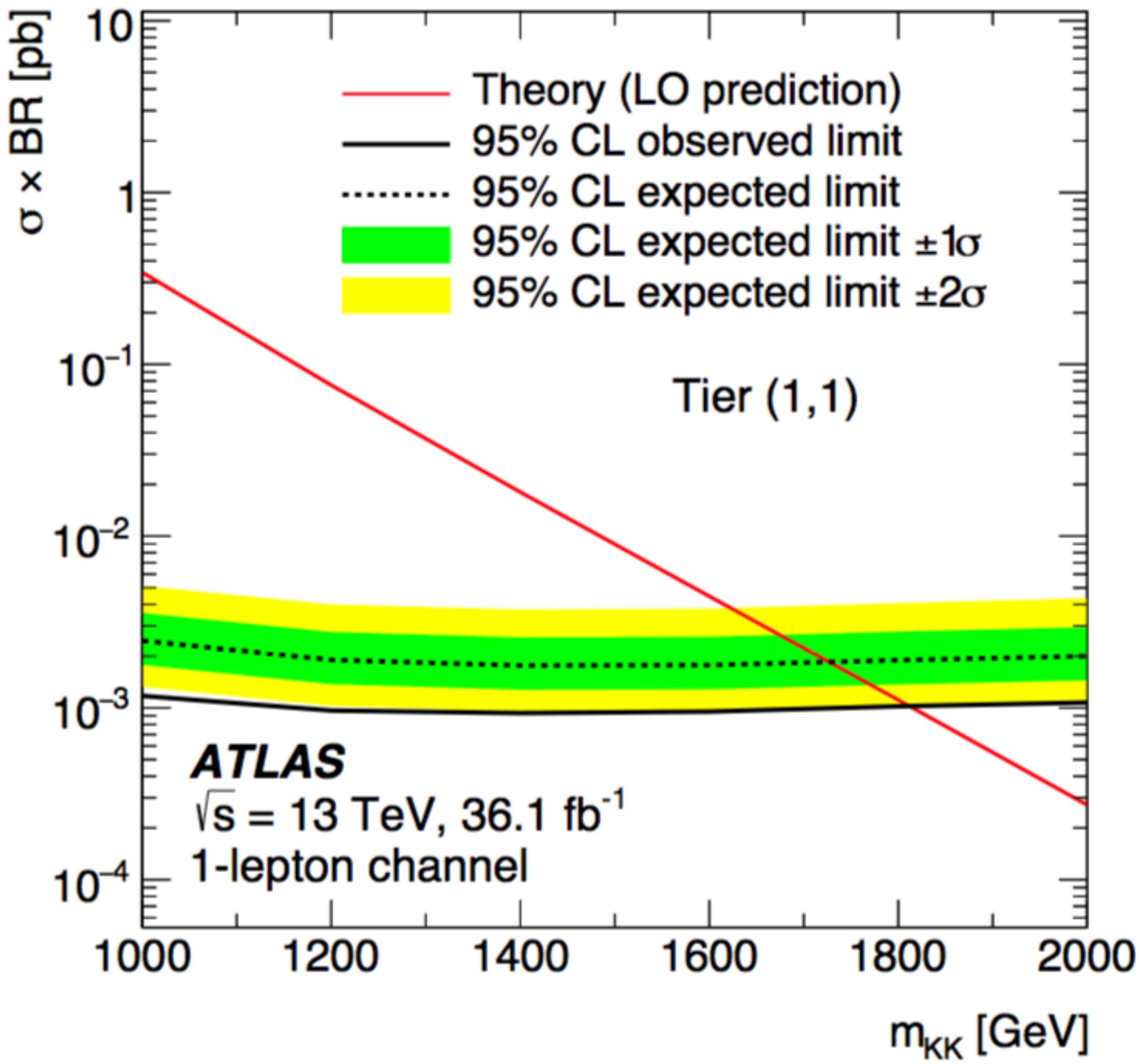



| 95% CL lower limits | quark mass [TeV] | | | |
|---|---|---|---|---|
| Search | $\mathcal{B}(T \to Ht) = 1$ | $\mathcal{B}(T \to Zt) = 1$ | Doublet | Singlet |
| 1-lepton channel | 1.47 (1.30) | 1.12 (0.91) | 1.36 (1.16) | 1.23 (1.02) |
| 0-lepton channel | 1.11 (1.20) | 1.12 (1.17) | 1.12 (1.19) | 0.99 (1.05) |
| **Combination** | **1.43 (1.34)** | **1.17 (1.18)** | **1.31 (1.26)** | **1.19 (1.11)** |

| Previous Run-1 ATLAS $T\bar{T} \to Ht$+X search [25] | | | | |
|---|---|---|---|---|
| 1-lepton channel | 0.95 (0.88) | 0.75 (0.69) | 0.86 (0.82) | 0.76 (0.72) |

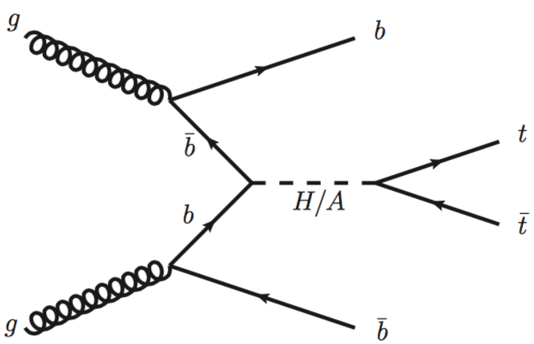
# VLQ (TT→Ht+X)(4)

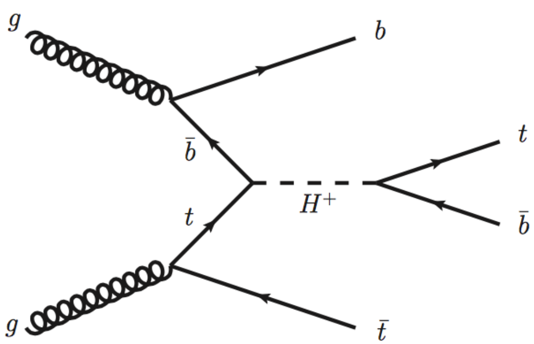
- Limits on four-top-quark production

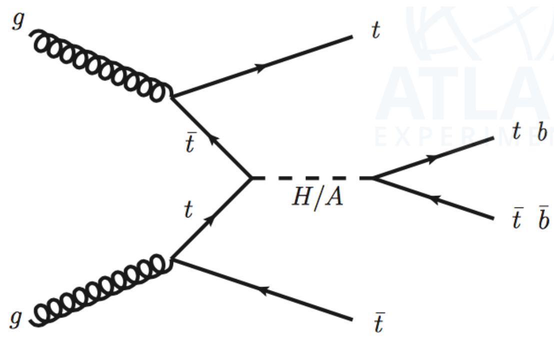


# Other Searches with B Jets: Heavy Higgs

- At the LHC, the major searches for non-SM-like neutral Higgs bosons were in the channels of *Zh*, *ZZ*, *WW*, ττ , hh and charged Higgs bosons in the channels of *cs*, τν, *WZ*, and *tb*
- In the alignment limit of two-Higgs-doublet models : the $H/A \to tt$ decay mode is dominant for $m_{H/A} > 2m_t$ at low tan β. In addition, the $H^+ \to tb$ decay mode is dominant for $m_{H^+} > m_t + m_b$ for any value of tan β.







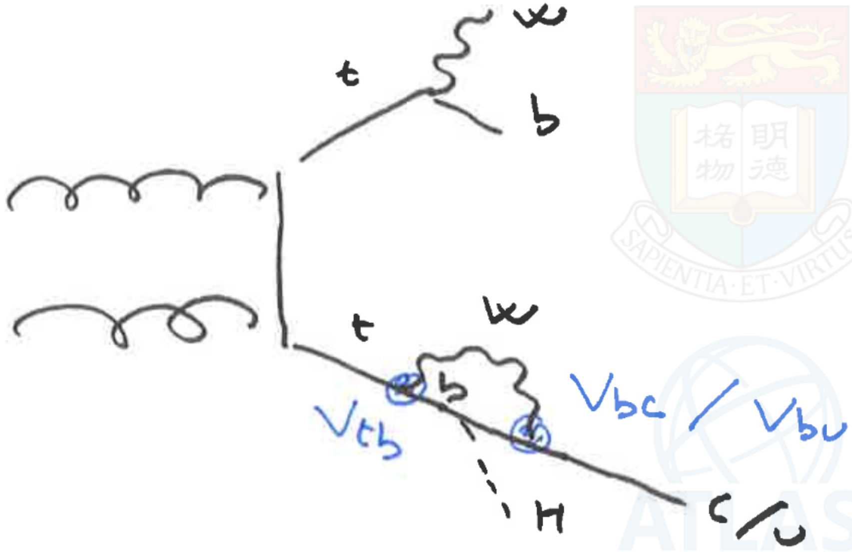
# Other Searches with B Jets: FCNC

Flavour changing neutral current (FCNC) decays t→Hq (q=u,c) are strongly suppressed in the Standard Model (SM)

SM t→Hq decay not expected to be detectable in any foreseeable future experiment

Branching ratio enhanced by many orders of magnitude in many BSM scenarios scenarios with extended Higgs sector or new heavy quarks

FCNC top decay in the SM




| | SM | QS | 2HDM | FC 2HDM | MSSM | RPV SUSY |
|---|---|---|---|---|---|---|
| BR(t→uH) | $2\times10^{-17}$ | $\sim10^{-5}$ | $\sim10^{-5}$ | - | $\sim10^{-5}$ | $\sim10^{-6}$ |
| BR(t→cH) | $3\times10^{-15}$ | $\sim10^{-5}$ | $\sim10^{-3}$ | $\sim10^{-5}$ | $\sim10^{-5}$ | $\sim10^{-6}$ |

# Conclusions

- The B meson is the known particle with relatively long life time, which has been very useful to produce distinguishable signatures in colliders.

- Some experiences of such searches could be helpful for searching long live particles yet to be discovered.

Thank you!

$T \to Wb$ in single lepton final states; ATLAS-CONF-2016-72

$TT$ or $BB$ or $T_{5/3}T_{5/3}$ ($B \to Wt$, $Zb$, $Hb$; $T \to Wb, Zt, Ht$; $T5/3 \to Wt$) or 4 tops in same-sign dilepton or trilepton final states. ATLAS-CONF-2016-032

$TT \to Wb+X$; ATLAS-CONF-2016-102

$TT \to Zt+X$, with $Z \to \nu\nu$. ATLAS-CONF-2016-101

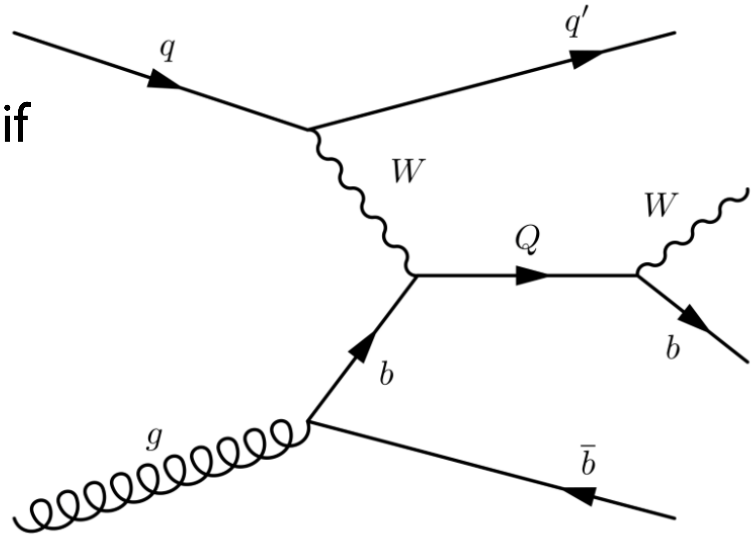
$TT \to Ht+X$ or 4tops or $ttH$, $bbH$, $tbH^{\pm}$; ATLAS-CONF-2016-104

# VLQ Single Production (Q→Wb)

ATLAS-CONF-2016-072

- Single production of heavy vector-like T quarks produced via Wb fusion, pp → Qqb + X, with Q → Wb.
- Final state: one charged lepton(electron or muon) and multiple jets
- Dominant background: $t\bar{t}$ +jets, single top, W+jets

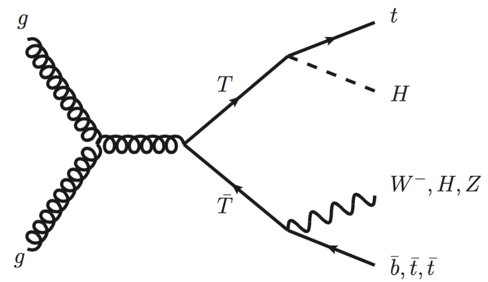
- Event selections:
  - Isolated lepton with pT> 25 GeV
  - At least one jet with pT > 25 GeV and |eta| < 2.5; if there is any forward jet, the pT > 40 GeV
  - At least one b-jet with pT > 350 GeV
  - MET > 120 GeV
  - |Δφ (lepton, leading b-tagged jet)|> 2.5
  - Reject events with a central jet pT> 75 GeV (|η| < 2.5) with ΔR (jet, leading b-tagged jet) <1.2 or >2.7.

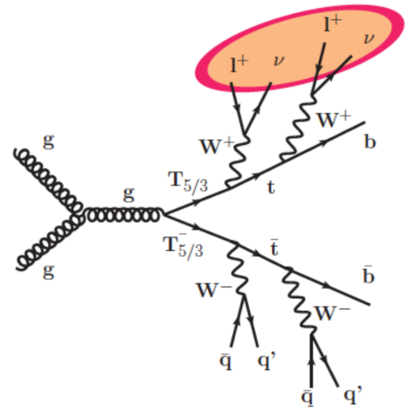


# VLQ (same-sign di-lepton, trilepton)

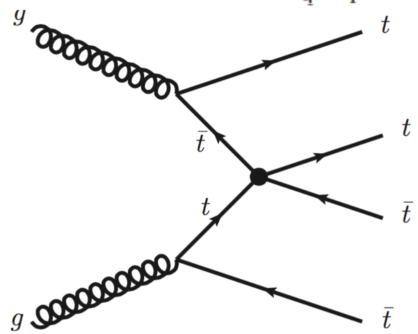
**ATLAS-CONF-2016-032**

- Search for BB, TT, $T_{5/3}T_{5/3}$ (B → Wt, Zb, Hb; T → Wb, Zt, Ht; T5/3 → Wt);
- Final state: same-sign di-lepton (or tri-lepton), multiple jets and b jets
- Dominant background: charge mis-id, fake leptons
  - Event selections:
    - Isolated lepton with pT> 25 GeV
    - At least two jet with pT > 25 GeV and |eta| < 2.5; at least one b-jet.




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



# VLQ (TT→Wb+X)

**ATLAS-CONF-2016-102**

- Search for a TT production, where one T→ W (lν).
- Final state: one lepton(electron or muon), multiple jets and b jets
- Dominant background: $t\bar{t}$ +jets
- Event selections:
  - Isolated lepton (e or mu) with pT> 25 GeV
  - Small-R (=0.4) jets with pT > 25 GeV and |eta| < 2.5, At least one of the small-*R* jets must be *b*-tagged.
  - Large-R (=1.0) jets with pT > 150 GeV, |eta| < 2.0
  - MET > 60 GeV
  - Two orthogonal signal regions are included in the analysis: boosted and resolved, using the scalar sum of all small-*R* jet and lepton momenta and *MET* ($S_T$) and the separation between the lepton and neutrino (*R*(lep, neutrino))
  -

| Region | $S_T$ | $\Delta R(\text{lep}, \nu)$ | Small-$R$ jets | Large-$R$ jets |
|---|---|---|---|---|
| Boosted signal region | > 1200 GeV | < 0.8 | ≥ 3 | ≥ 1 |
| Resolved signal region | > 1200 GeV | < 0.8 | ≥ 4 | = 0 |
| $t\bar{t}$ control region 1 | > 700 GeV | > 1.0 | ≥ 3 | ≥ 1 |
| $t\bar{t}$ control region 2 | 750 – 1200 GeV | < 1.0 | ≥ 3 | ≥ 1 |

# VLQ (Zt+X,withZ→νν)

- Search for TT→Zt+X, where Z→νν and the top decays leptonically.
- Final state: with one lepton, multiple jets and large MET.
- Dominant background: $t\bar{t}$ +jets

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- Event selections:
  - Exactly one isolated lepton (e, mu) with pT> 25 GeV
  - At least four small-R (=0.4) jets with |eta| < 2.5; |Δφ(*j_leading, MET*)| > 0.4 and |Δφ(*j_sub-leading, MET*)| > 0.4
  - Large-radius jets are clustered from signal small-radius jets with *R* = 1.0.
  - To derive the $t\bar{t}$ and *W*+jets processes from data, dedicated control regions are defined (TCR, WCR).

| Variable | SR | TCR | WCR |
|---|---|---|---|
| $E_T^{miss}$ | $> 350$ GeV | $> 300$ GeV | |
| $m_T^W$ | $> 170$ GeV | $m_T^W \in [30, 90]$ GeV | |
| $am_{T2}$ | $> 175$ GeV | $> 100$ GeV | |
| $H_{T,sig}^{miss}$ | $> 12$ | – | |
| small-$R$ jet $p_T$ | $> 120, 80, 50, 25$ GeV | $> 120, 80, 50, 25$ GeV | |
| number of $b$-tagged jets | $\geq 1$ | $\geq 1$ | $= 0$ |
| number of large-$R$ jets | $\geq 2$ | $\geq 2$ | |
| large-$R$ jet mass | $> 80, 60$ GeV | $> 80, 60$ GeV | |
| large-$R$ jet $p_T$ | $> 290, 290$ GeV if $E_T^{miss} < 450$ GeV<br>$> 200, 200$ GeV if $E_T^{miss} > 450$ GeV | $> 200$ GeV | |