Searches for heavy resonances decaying to top quarks with the ATLAS detector

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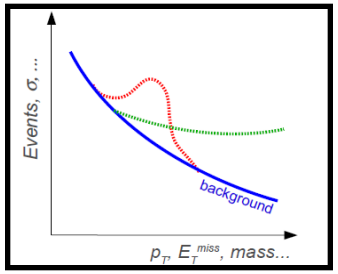
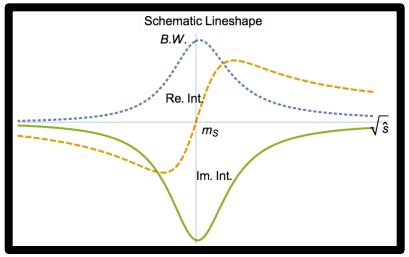
Top quark coupling to Beyond the Standard Model (BSM)

- BSM physics at the TeV scale is a major goal for LHC
- Top quark offers a unique window to search for new physics due to its large mass
  - Could have a fundamental role in EWSB
  - larger coupling to new physics than any other lighter fermions

- Many scenarios for BSM physics (**exotic models**) predict enhanced couplings to top:
  - SM-like W' and Z' appear for e.g. in Little Higgs models, Technicolour, GUT, etc.
  - Randall-Sundrum Kaluza-Klein excitations in extra dimension models
  - Scalar/pseudoscalar H/A in the two-Higgs-doublet models (2HDMs)

- **Typical Search strategy:** Focus on observables such as invariant mass, p_T or E_T
  - Search for deviations from known background (BG)
  - Search for bump (resonant phenomena)
  - Search for excess in tail (non-resonant phenomena)
  - Search for peak–dip structure like for A/H
    - due to interference effects of 2HDM type-II

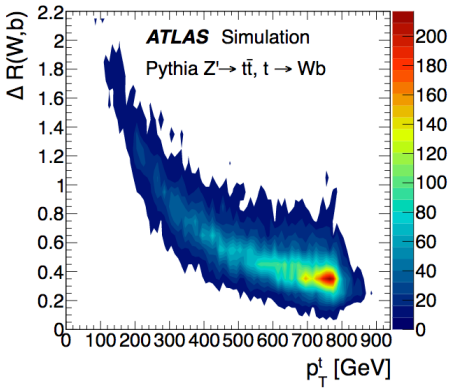




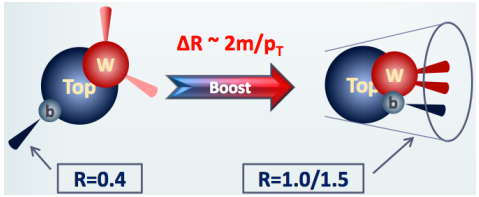
Top quarks in BSM searches

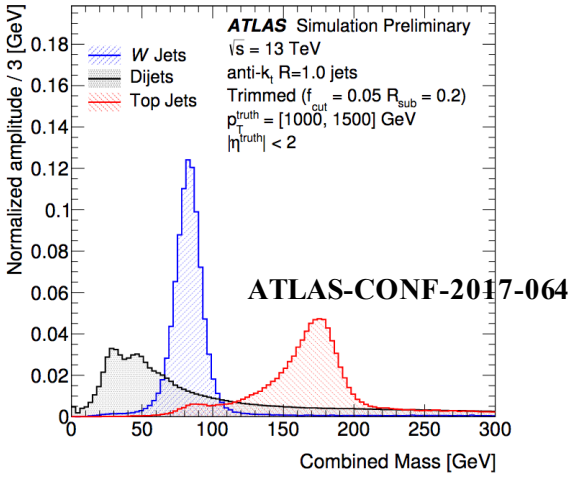
JHEP09 (2013) 076

- Decay of heavy mediators (like Z', W', g_{KK} and G_{KK}) is in the multi-TeV mass range



- Result in highly boosted very massive objects such as Top
  - Decay products of Boosted
    Tops collimated in direction of p_T
  - Separation can be described according to $\Delta R \approx 2m/p_T$





- Standard reconstruction methods are no longer sufficient for boosted top quarks
- Efficient hadronic top tagging;
  - Large-radius jet as top candidate could contain all of top-decay quarks (identify top through the substructure)

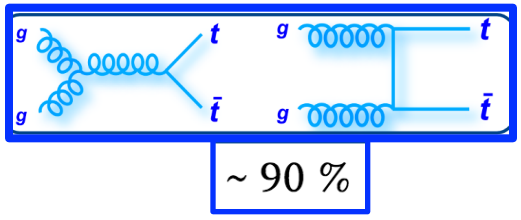
ATLAS has a standard top tagger

N-subjettiness ratio τ_{32} and R = 1.0 jet mass

Status of the heavy resonances searches in ATLAS

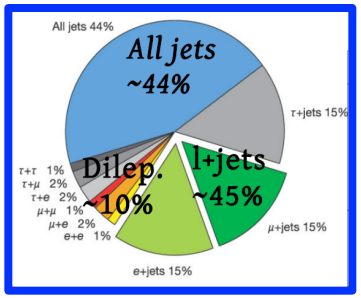
- This talk focuses on **searches** with third generation quarks and shows results of:
  - **Search for $t\bar{t}$ resonance in lepton+jets channel**
    - **arXiv:1804.10823 [hep-ex] (accepted by EPJC)**
  - **Search for $W' \to tb$ decays in hadronic final channel**
    - **Phys. Lett. B 781 (2018) 327**
  - **Search for $W' \to tb$ in semileptonic final channel**
    - **ATL-COM-PHYS-2016-1467 (To be submitted to: Phys. Lett. B.)**
  - **Search for Scalar resonances in lepton+jets channel**
    - **First experimental result including scalar interference**
      - **Rev. Lett. 119 (2017) 191803**

Results using 36 fb^{-1} at $\sqrt{s}$ = 13 TeV



t → Wb (BR ~ 99%)

- **Analysis channel: Final states and analysis channels depend on the decay of the two W bosons.**

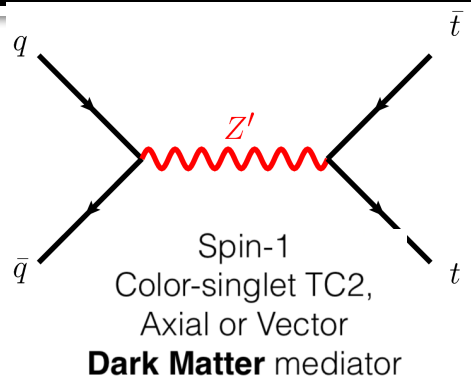


- **Recent ATLAS Exotics results are published herein:**
  - https:// twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

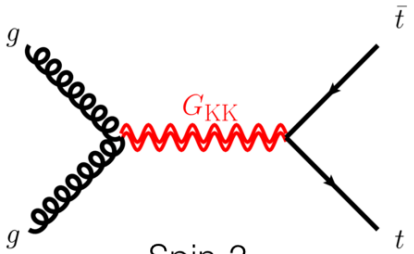
- The LHC is a top-quark factory (10M/year at 13 TeV)
- **ATLAS detector optimized to find top-quarks**
  - Very good electron and muon reconstruction and identification
  - Full azimuthal coverage to measure neutrino transverse component via ETmiss
  - Close tracker layer (IBL) to select displaced vertexes from b-jets

$t\bar{t}$ resonance: benchmark models

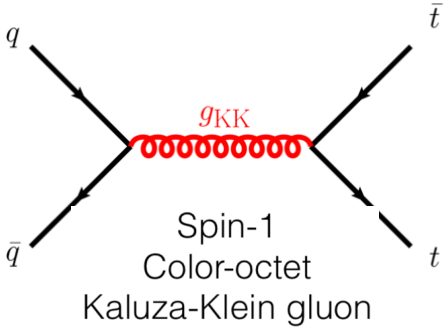
arXiv:1804.10823 [hep-ex] (accepted by EPJC)



Spin-1
Color-singlet TC2,
Axial or Vector
Dark Matter mediator

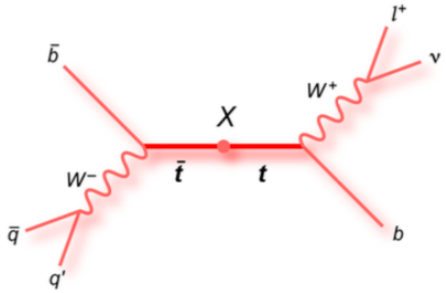


Spin-2
Color-singlet
Kaluza-Klein graviton



Spin-1
Color-octet
Kaluza-Klein gluon

Search in lepton+jets $t\bar{t}$ decay mode



- Lepton ⇒ multijet background suppression
  - trigger more efficient on leptons
- Jets ⇒ keep good statistics level (high branching ratio)

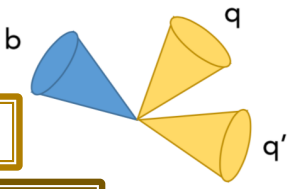
Analysis strategy :

- Build a model independent analysis
  - Select events
  - Reconstruct $t\bar{t}$ invariant mass
  - Scan $m_{t\bar{t}}$ to find an excess/deficit

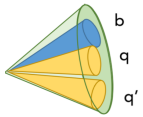
$t\bar{t}$ resonance: lepton+jets

arXiv:1804.10823 (accepted by EPJC)

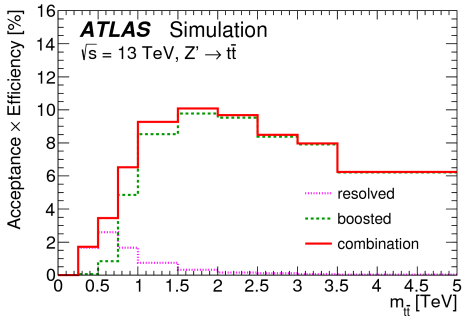
- **Analysis strategy**
- Top quark signature is difficult to reconstruct efficiently → Many objects
  - Adapt the event selection and reconstruction to the final configuration



Boosted Channel



- single lepton trigger with **exactly 1** isolated lepton (e/μ)
- missing E_T > 20 GeV, missing E_T + $m_T(W)$ > 60 GeV
- **1 top-tagged**, large-R calo-jet, p_T > 300 GeV with b-tagged track-jet.
- at least 1 b-tagged, small-R calo-jet
- back-to-back topology



Resolved Channel

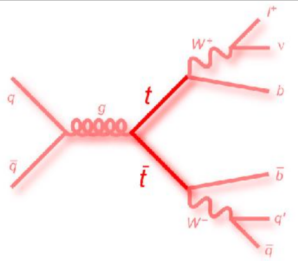
- veto boosted selection
- single lepton trigger with **exactly 1** isolated lepton (e/μ)
- missing E_T > 20 GeV, missing E_T + $m_T(W)$ > 60 GeV
- at least 2 small-R calo-jet
- at least 1 b-tagged track-jet
- minimize $\chi 2$ to find best combination of jets

- Resolved selection mainly relevant at low $m_{t\bar{t}}$
- Boosted selection relevant at high $m_{t\bar{t}}$
  - **The boosted selection helps improving efficiency in high signal mass region**

$t\bar{t}$ resonance: lepton+jets

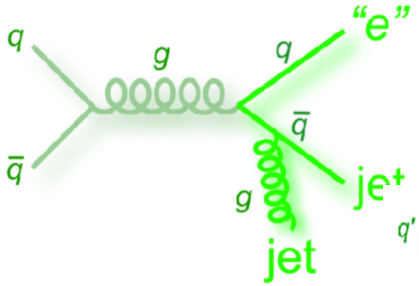
arXiv:1804.10823 (accepted by EPJC)

- **Dominant background is SM $t\bar{t}$** from MC
- **Multijet estimated with data**
  - Matrix method with differences in efficiency for lepton isolation of QCD and non-QCD
- **W+jets estimation**
  - Shape from MC
  - Scaling from data;
    - The normalization is estimated by the data of charge asymmetry (W^++jets vs. W^- +jets)
      - correcting for the relative flavour fractions
- **Other backgrounds : Z+jets, single top, diboson : directly from MC**

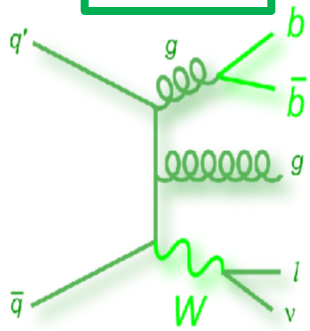


$t\bar{t}$ (dominant)

QCD multi-jets



W+jets



$t\bar{t}$ resonance: lepton+jets

arXiv:1804.10823 (accepted by EPJC)

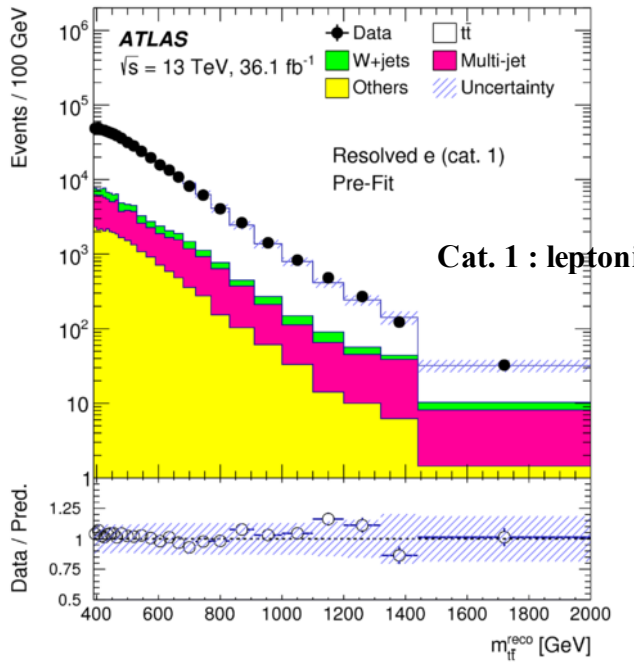
Final discriminant: $t\bar{t}$ invariant mass reconstruction
$p_z(\nu)$: from lepton+E_T^{miss} system with m_W constraint

Resolved: χ^2 algorithm using m_t and m_W, top pair p_T balance as constraint

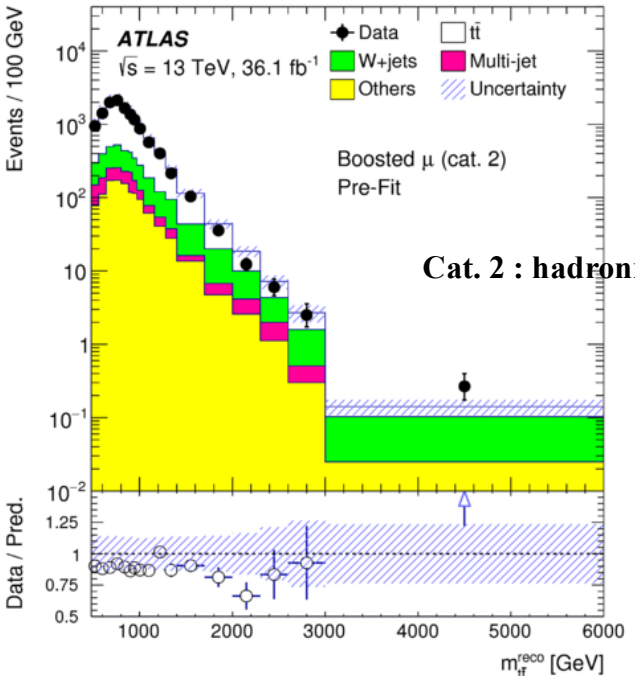
Boosted: take R=1 jet as hadronically decaying top; build the other top from ν, lepton and R=0.4 jet

Categorize $m_{t\bar{t}}$ into 12 channels.

- Resolved or boosted
- Electron or muon
- 3 types of b-tagging matching



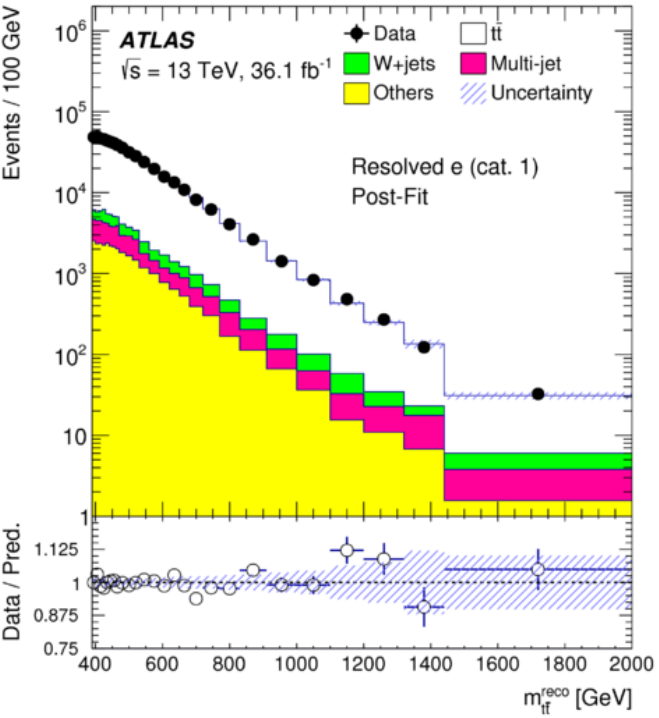
Cat. 1 : leptonic top *b*-tagged



Cat. 2 : hadronic top *b*-tagged

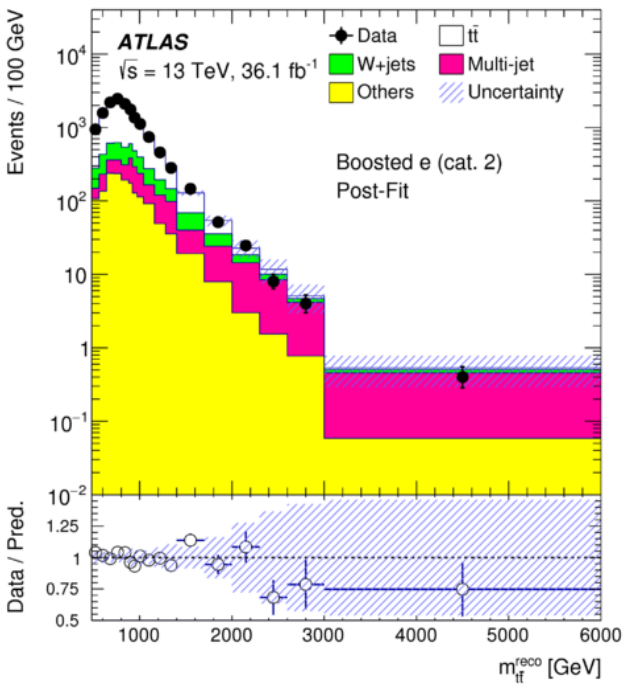
$t\bar{t}$ resonance: lepton+jets

arXiv:1804.10823 (accepted by EPJC)



- Good Data-Simulation agreement, within systematic uncertainties
  - **Perform likelihood fit of $m_{t\bar{t}}$ in all categories**

No evidence for a deviation from the Standard Model

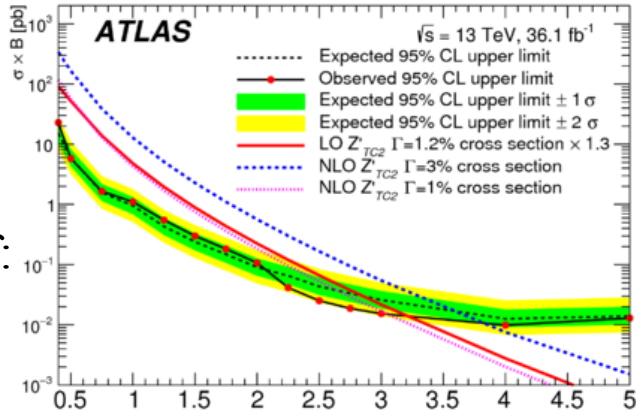


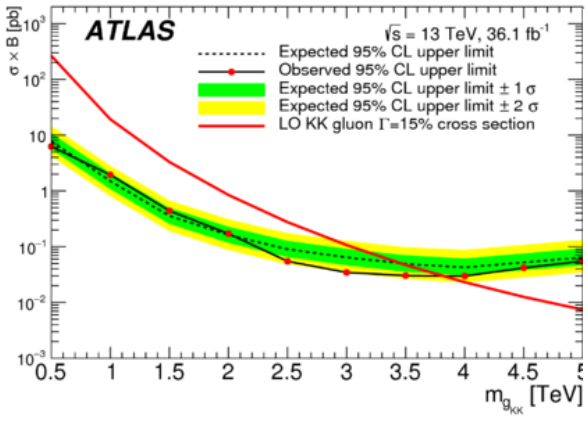
- Statistical and systematic uncertainties are included as nuisance parameters in the fit
- **Main systematics from: $t\bar{t}$ modeling, uncertainties in large-R jet energy and background normalization**

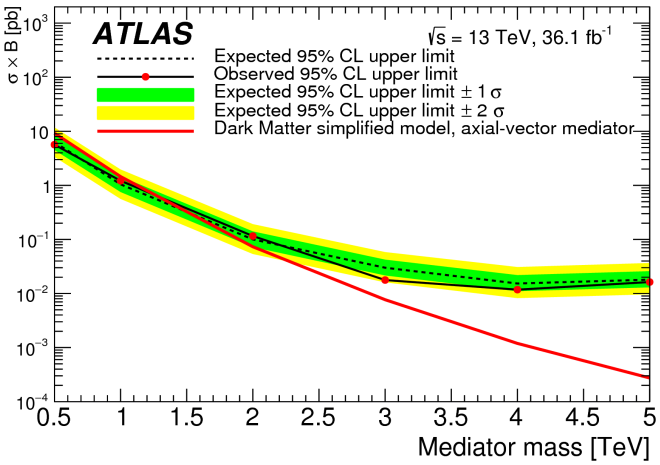
tt resonance: Results

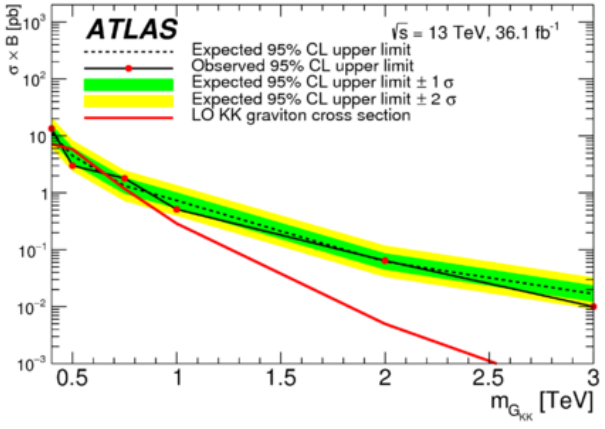
arXiv:1804.10823
(accepted by EPJC)

- **Expected** (**observed**) limits (95 % C.L.) are set for several Benchmark models:
  - $m(Z'_{TC2}) < 3.1$ (**2.6**) TeV, $\Gamma/m = 1.2\%$
  - $m(g_{KK}) < 3.9$ (**3.5**) TeV, $\Gamma/m = 15\%$
  - $m(Z'_{DM}) < 1.25$ (**1.5**) TeV
  - $m(G_{KK})$ region excluded around 500 GeV
- Improvement of Run-1 limit at 8 TeV(JHEP 08 (2015) 148) of:
  - **~1.3 TeV (1.7 TeV) for Z'_{TC2} (g_{KK})**





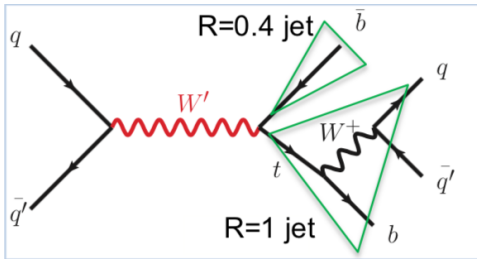




W→tb resonance searches at √s = 13 TeV

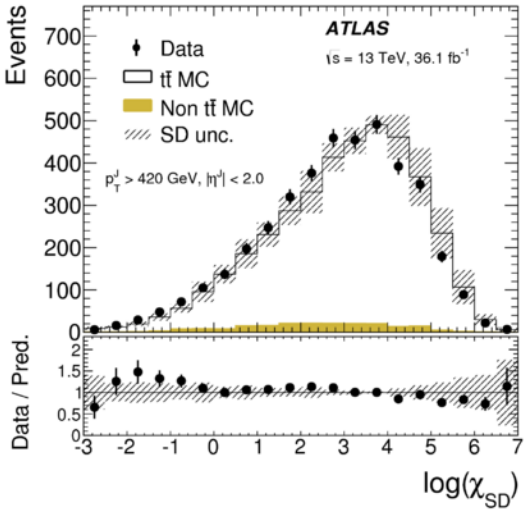
Phys. Lett. B 781 (2018) 327

- Extra dimensions, strong dynamics composite Higgs predict new vector charged-current interactions
- Specially interesting for models in which $m\nu > m$ W′
  - Heavy gauge bosons W′ a mediator of a new charged vector current → has strong coupling to third generation



➢ **Search for leptophobic W′ decaying to tb in all-hadronic decay mode**

- **Top candidate selection**
  - Trigger: 1 small-R jet, p_T>420 GeV
  - Large-R jets: trimmed anti-kt R=1.0 jet, p_T>420 GeV
  - Select **large-R jet** with highest effective mass: → $\mathbf{m_{leading\ small\text{-}R;<R=1.0} + m_{large\text{-}R}}$
  - **Shower deconstruction (SD) algorithm to tag top jets**
    - Likelihood χ_{SD} : signal-or background-like event
    - b-tagging: 77% eff., MVA-based
- **Bottom candidate selection**
  - b-jet candidate: highest p_T small-R jet, ΔR>2.0 from large-R
- **2 signal categories:**
  - 1 and 0 "**b-tag in**" inside or not ΔR=1.0 of top jet



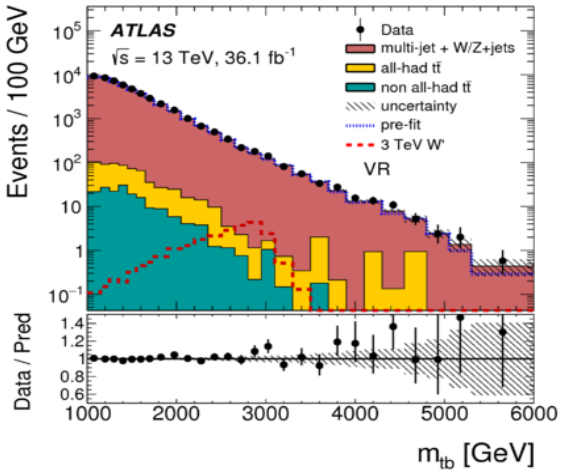
W'→tb resonance searches at √s = 13 TeV

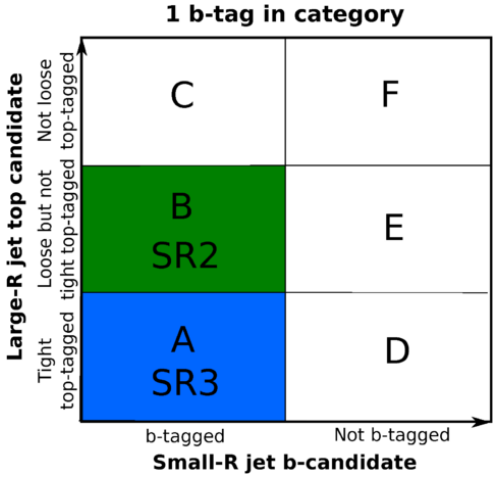
Phys. Lett. B 781 (2018) 327

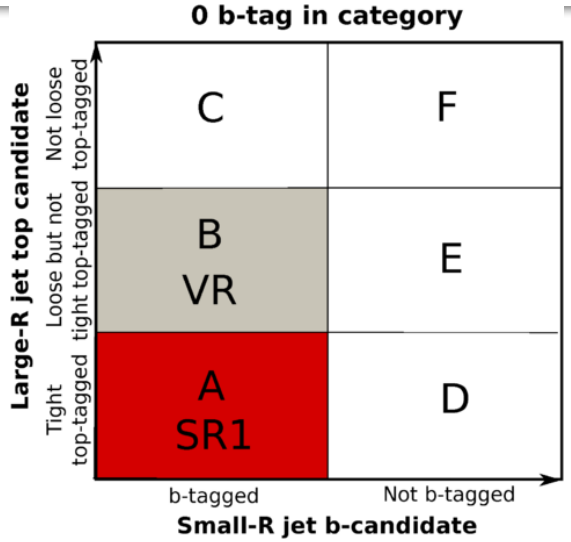
- **Background**: similar as in top-quark pair resonance search
- **Multijet is the dominant one**:
  - Estimate QCD multijet (and W/Z+jets; ~1%) events from $t\bar{t}$ subtracted data in regions C,D,E and F:

$$N_{\mathrm{A}}^{\mathrm{bkg}} = R_{\mathrm{A}}^{\mathrm{corr}} \cdot \frac{(N_{\mathrm{C}}^{\mathrm{data}} - N_{\mathrm{C}}^{t\bar{t}}) \cdot (N_{\mathrm{D}}^{\mathrm{data}} - N_{\mathrm{D}}^{t\bar{t}})}{N_{\mathrm{F}}^{\mathrm{data}} - N_{\mathrm{F}}^{t\bar{t}}}$$

$$N_{\mathrm{B}}^{\mathrm{bkg}} = R_{\mathrm{B}}^{\mathrm{corr}} \cdot \frac{(N_{\mathrm{C}}^{\mathrm{data}} - N_{\mathrm{C}}^{t\bar{t}}) \cdot (N_{\mathrm{E}}^{\mathrm{data}} - N_{\mathrm{E}}^{t\bar{t}})}{N_{\mathrm{F}}^{\mathrm{data}} - N_{\mathrm{F}}^{t\bar{t}}}$$







- **SR (signal region):**
  - fitting and limit setting
- **VR (validation region):**
  - not for fitting nor for limit setting

- Correlation of top and b taggers : correlation factors are derived from QCD background simulation for each SR

W'→tb resonance searches at √s = 13 TeV

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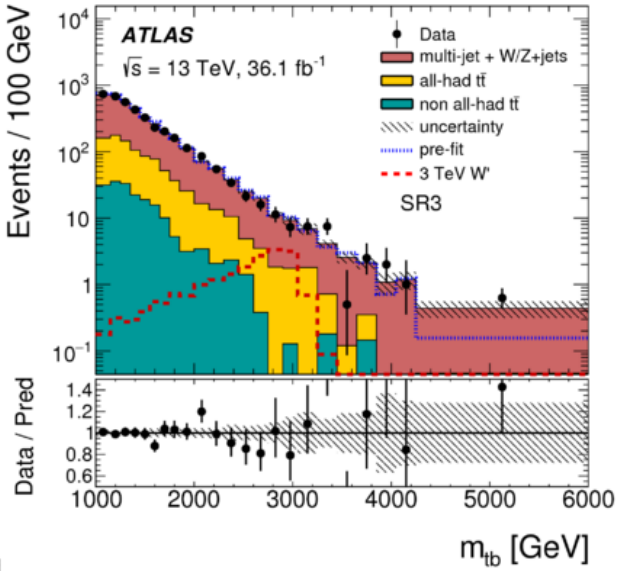
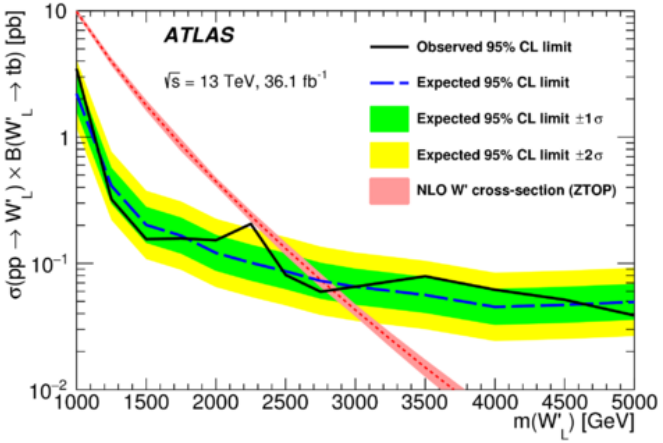
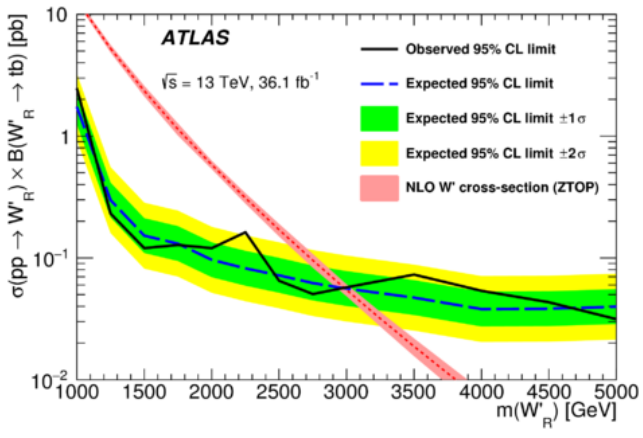
- **Invariant mass of the top and bottom system,**
  - after a binned max-likelihood fit to data
- Simultaneous fit performed in three SRs (VR for validation)

- No significant deviation is observed
- Limits are set excluding W' bosons at 95% CL for:
  - $m(W'_L) < 2.95$ **TeV,**
  - $m(W'_R) < 2.98$ **TeV**







- **Improvement of Run-1 limit at 8 TeV of W'_R below 2 TeV**
  - Eur. Phys. J. C (2015) 75:165

Most significant systematic uncertainties:

Background dominated

- ABCD correlation factors

Signal dominated

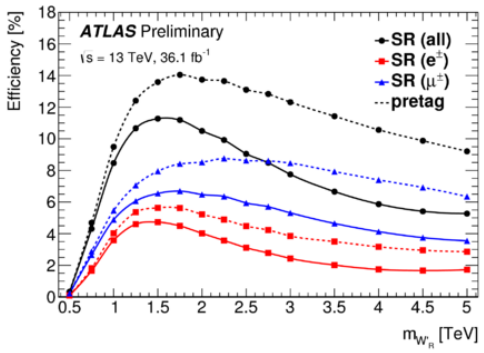
- flavor tagging and top tagging statistically dominated for $m_{tb} > 2$ TeV

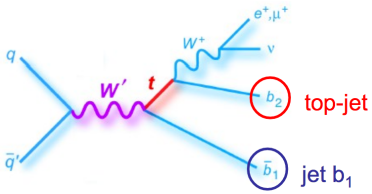
Search for $W' \rightarrow tb$ in semileptonic final channel

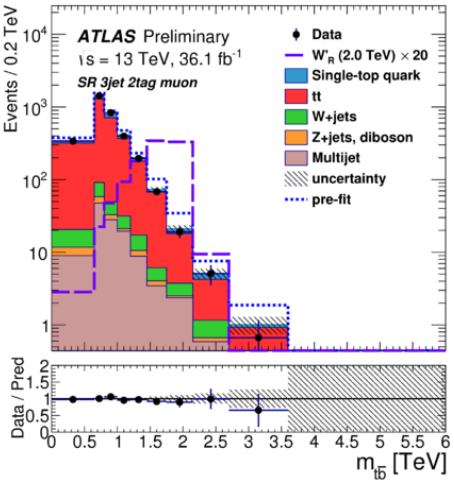
ATL-COM-PHYS-2016-1467 (To be submitted to: Phys. Lett. B.)

- **Signal and control regions definition**

- **Event selection**
  - Exactly **1 lepton** (e, μ) with **p_T>50 GeV**
  - ≥ **2 central jets**: p_T>30 GeV, |η|<2.5
  - E_{miss}+ M_T(W)>60 GeV
  - E_{miss} > 30 (80) GeV for μ/e+jets channel
  - **$p_T(b_1)$ > 200 GeV, p_T(top) > 200 GeV**



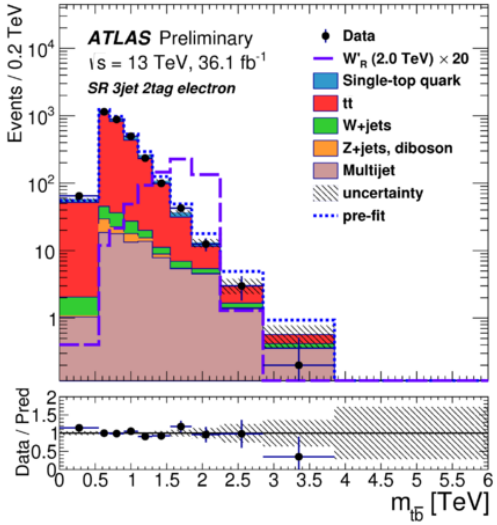




- **Signal regions**
  - **2-jets 1/2 b-tags**
  - **3-jets 1/2 b-tags**

- **Validation region (inclusive)**
  - ≥2 jets pretag: inclusive rich in W+jets

- **Validation regions (orthogonal)**
  - ≥2 jets 0-tag : enriched in W+jets
  - 4-jets 1/2 b-tags: ttbar enriched

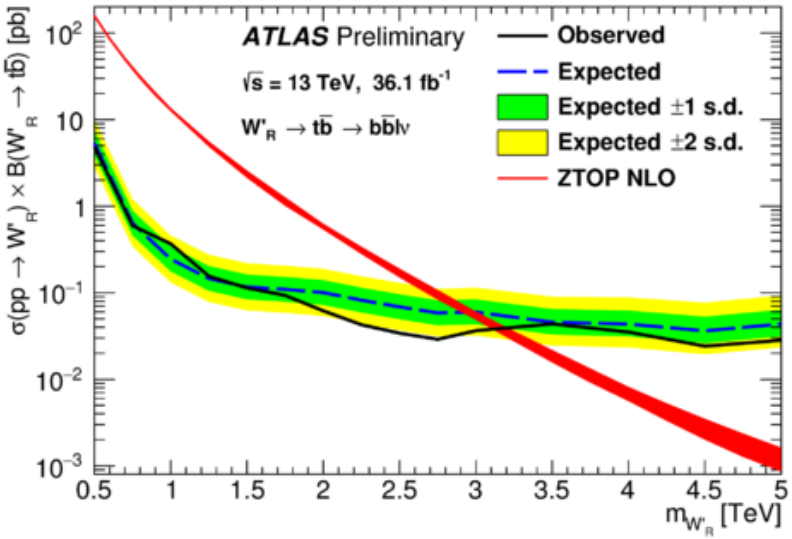


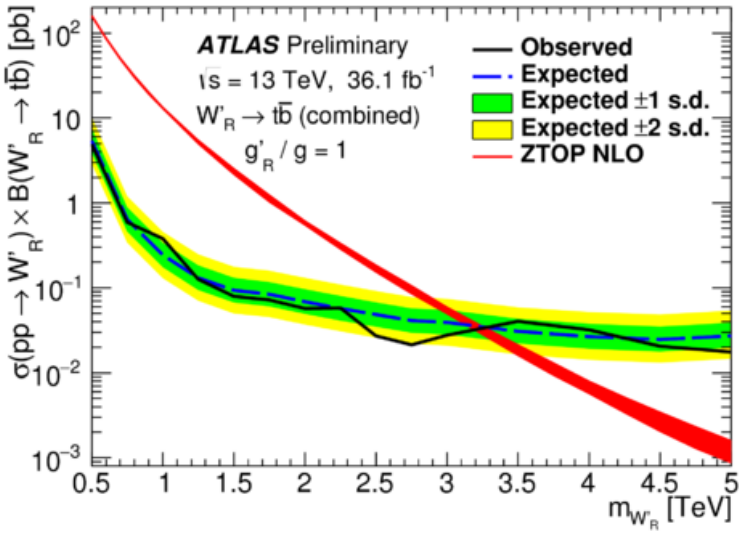
- **Search is carried out in 8 regions (e/μ, 2-jet and 3-jet, and 1-b-tag and 2-b-tags) using the reconstructed invariant mass m_{tb}**

Search for $W' \rightarrow tb$ in semileptonic final channel

ATL-COM-PHYS-2016-1467 (To be submitted to: Phys. Lett. B.)

- **No significant deviation is observed**
  - Limits are set using the m_{tb} distribution in a binned maximum likelihood (ML) approach based on the RooSTATS
- 95% CL limits are set excluding :
  - $m(\mathbf{W'_R}) < \mathbf{3.15\ TeV}$





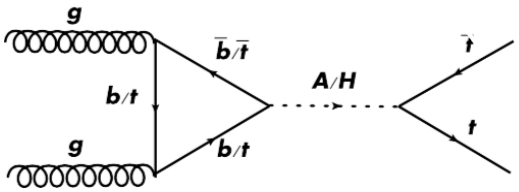
- Combined semi-leptonic and hadronic scenarios
- 95% CL limits are set excluding :
  - $m(\mathbf{W'_R}) < \mathbf{3.25\ TeV}$

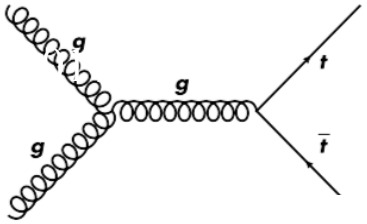
Limit improvement of roughly 35% above 1 TeV

Search for Scalar resonances @8 TeV: Lepton + Jets

Phys. Rev. Lett. 119 (2017) 191803

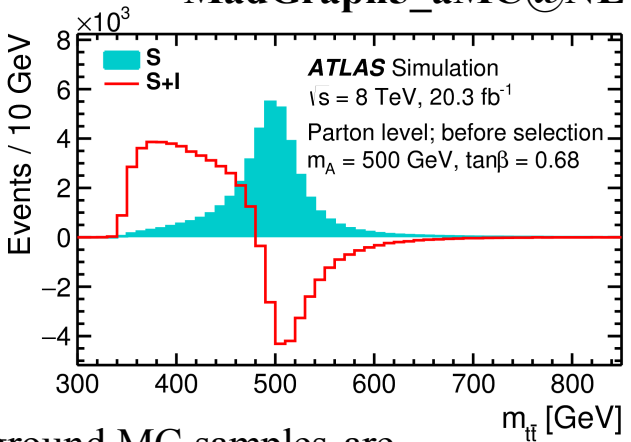
- **Re-interpretation 8 TeV (20 fb^{-1}) $t\bar{t}$ resonances search**
  - 2HDM model predicts Scalar (H) or Pseudoscalar (A) decaying into $t\bar{t}$
  - Large interference (I) with SM gg $\rightarrow t\bar{t}$ production
  - It would require signal (S)+ (I) + background (B) simulation at parton level for each mass point





MadGraph5_aMC@NLO

- Generator modified to produce only S+I
- $m_{t\bar{t}}$ Signal modeling at parton level versus Signal + Interference modeling.
- Validated with S+I+B generation for some parameter space points



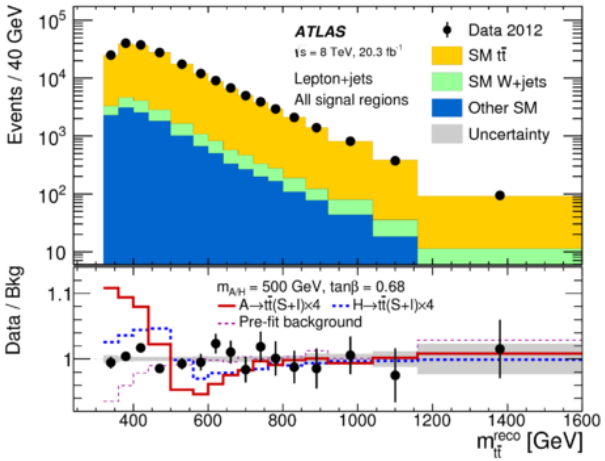
- Difference between this approach and an approach where Background MC samples are subtracted from S + I + B samples is taken as a systematic uncertainty for the signal

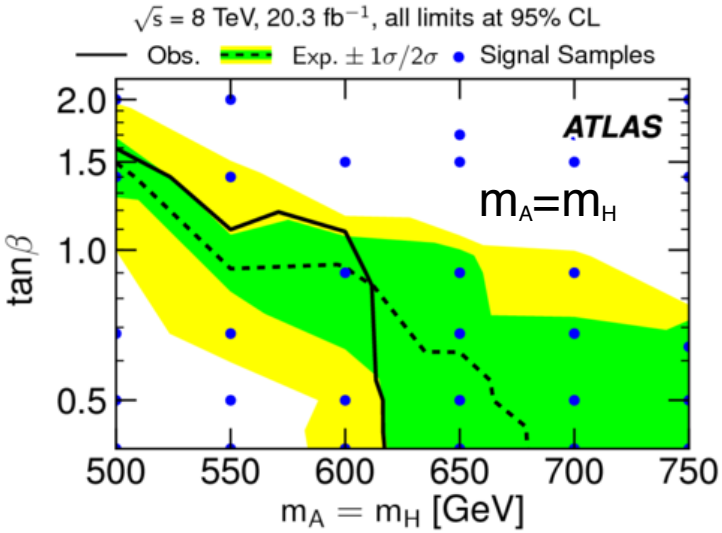
Search for Scalar resonances @8 TeV: Lepton + Jets

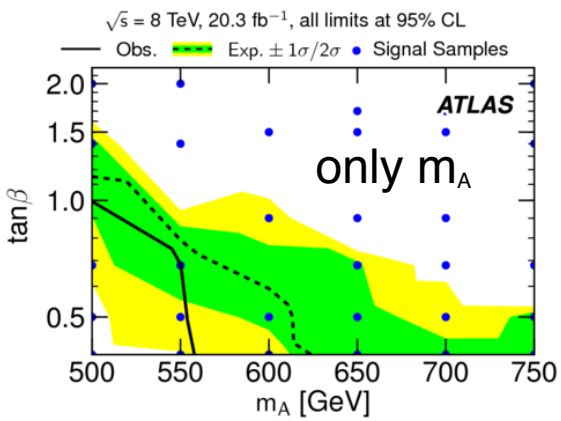
Phys. Rev. Lett. 119 (2017) 191803

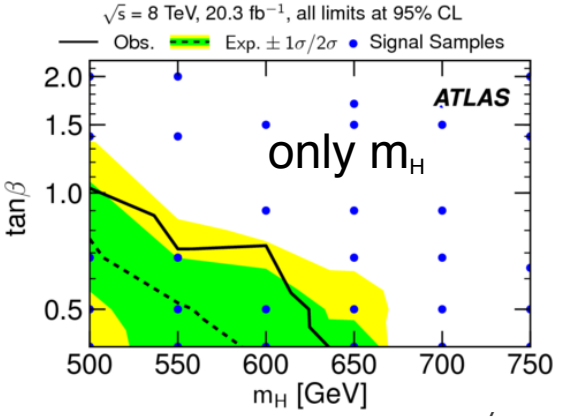
- **Resolved channel; same setup as described previously**
  - Exactly 1 lepton (electron or muon)
  - 4 jets (1 or 2 b-tags)
  - Jet ambiguity solved by minimizing a $\chi 2$
  - over jet combinations
- No sign of scalar/pseudoscalar
- Limit on the signal strength μ versus tan(β) set in 3 scenarios
- **Exclusion limits on the signal for $m_{H/A} > 500$ GeV**

Final discriminant: invariant $t\bar{t}$ mass









Summary

- **No sign of new resonances found so far in:**
  - the lepton plus jets top-quark pair decay channel
  - the all-hadronic and semi-leptonic W' decay channels
  - the inclusion of interference effects in search for scalar

selection of **most recent** analyses

- **13 TeV data exclude:**
  - leptophobic Z′ with $\mathbf{m_{Z'} < 2.6\ TeV}$
  - KK gluons, $\mathbf{m(g_{KK}) < 3.5\ TeV}$
  - Z' (DM axial mediator) with $\mathbf{m_{Z'DM} < 1.5\ TeV}$
  - leptophobic W′ with: $m_{W'L} < \mathbf{2.95\ TeV}$, $m_{W'R} < \mathbf{2.98\ TeV}$
    - $\mathbf{m_{W'R} < 3.25\ TeV}$ **(**Combined semi-leptonic and hadronic scenarios)

- **Significant improvement on mass limits from Run-1 for Run-2 searches**
  - **More data from Run-2 will push further into the TeV scale.**

BACKUP

Jet Definitions

- **Jets clustered using anti-KT algorithm.**

- **Calo-jets :** jets are cluster from three-dimensional topological clusters of energy in the calorimeter.
  - **Small-R** : clustered with anti-KT radius parameter of 0.4, calibrated at EM energy scale.
  - **Large-R**: clustered with anti-KT radius parameter of 1.0, calibrated with local cluster weighting procedure, trimmed ($Rsub = 0.2, fcut = 0.05$)
  - **Reclustered, Large-R**: Small-*R* jets reclustered with anti-KT algorithm with radius 1.0.

- **Track-jets** : tracks (pT > 0.4 GeV) clustered with anti-KT radius parameter of 0.2.

χ^2 details

- To find better jet lepton combination $\Rightarrow$ minimize $\chi 2$

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{th-W}}{\sigma_{th-W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{tl}}{\sigma_{t\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,th} - p_{T,t\ell})}{\sigma_{diffpT}}\right]^2$$

1. term constraint the W jet mass
2. term constraint the top-W mass
3. term constraint the top mass
4. term constraint the p_t balance between leptonic and hadronic side

Some words on Shower Deconstruction (SD)

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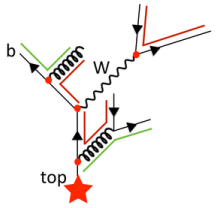
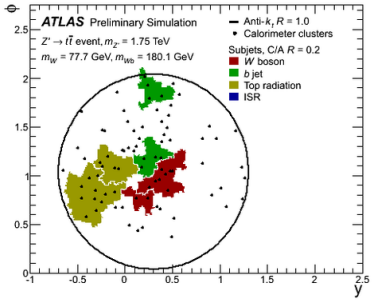
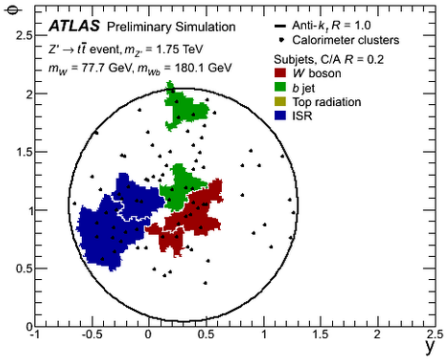
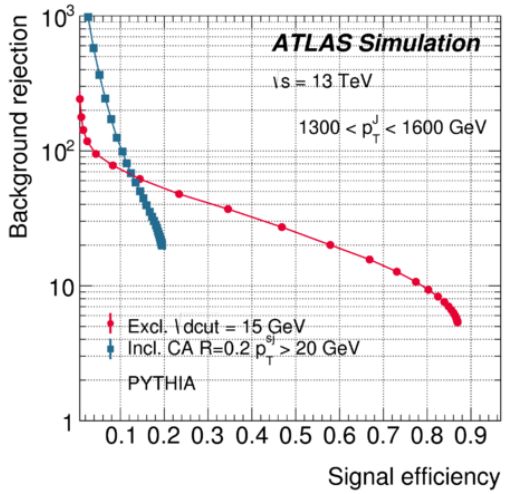
- **Possible shower histories from a top-jet, two among hundreds with high probabilities**

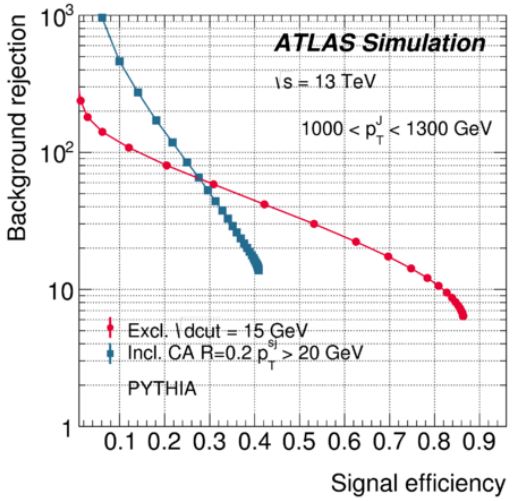


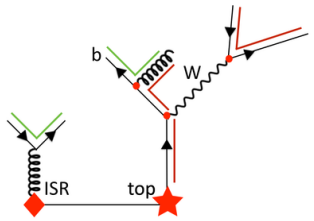


- Improved SD top tagging performance compared to Run-1
  - **Run 1: R=0.2 CA jets not enough to resolve top decay products at high *pt***
  - **Run-2: Exclusive kT sub-jet inside R=1.0 jets (splitting**
  - **scale threshold is 15 GeV)**
- **Better performance at high *pt* than previous version**









ATLAS-CONF-2014-003

W' resonance searches at $\sqrt{s} = 13$ TeV

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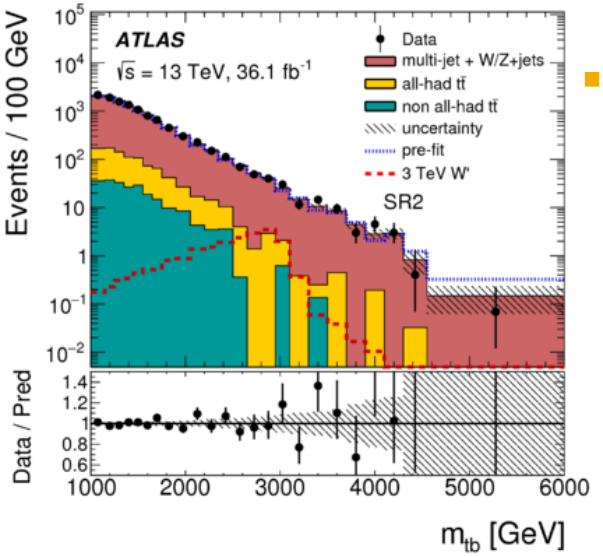
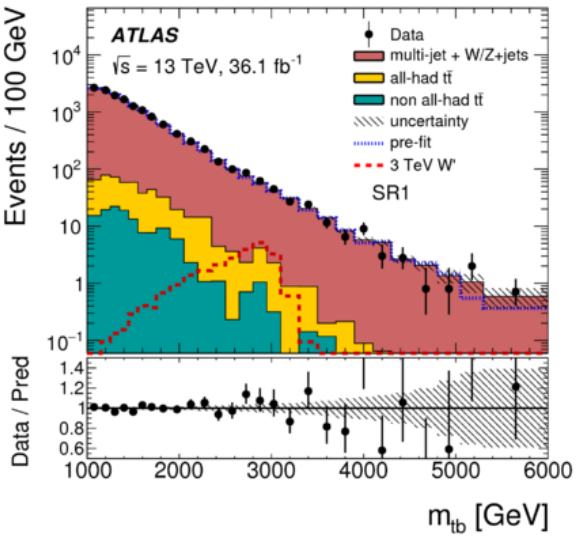
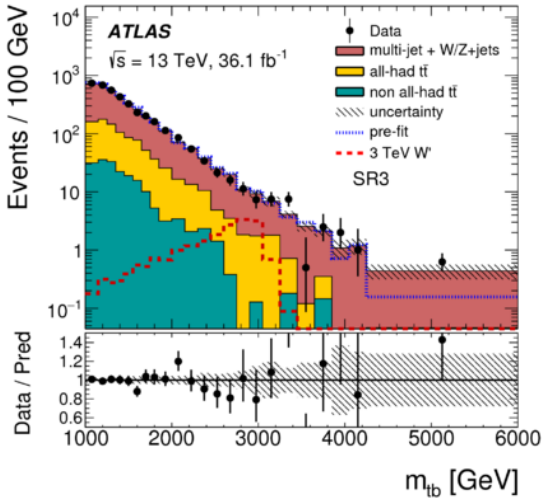
Final discriminant

- **Invariant mass of the top and bottom system,**
  - after a binned max-likelihood fit to data
- **Simultaneous fit performed in**
  - **three signal regions (SR),**
    - **VR used for validation of results**



- Most significant systematic uncertainties:
  - **Background dominated**
    - ABCD correlation factors
  - **Signal dominated**
    - flavor tagging and top tagging statistically dominated for $m_{tb} > 2$ TeV





No excess found, perform limit setting