Boosting sensitivity in searches for Dark Matter and heavy resonances with ATLAS

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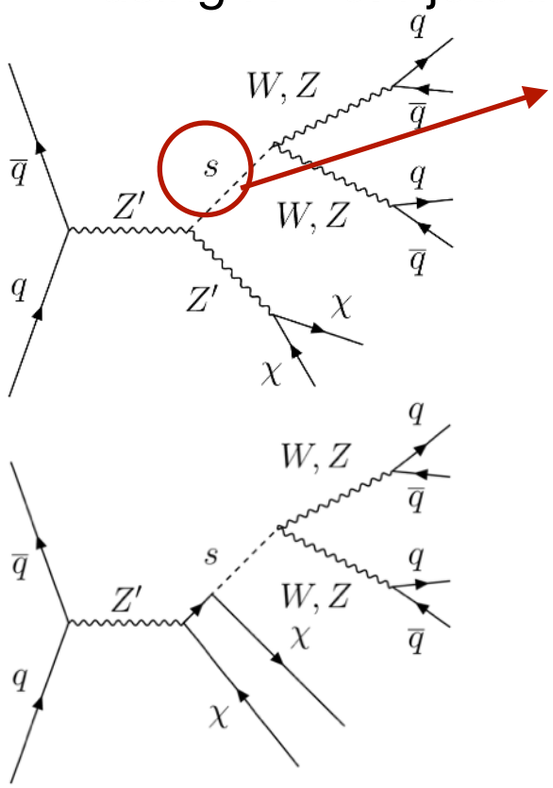
Outline

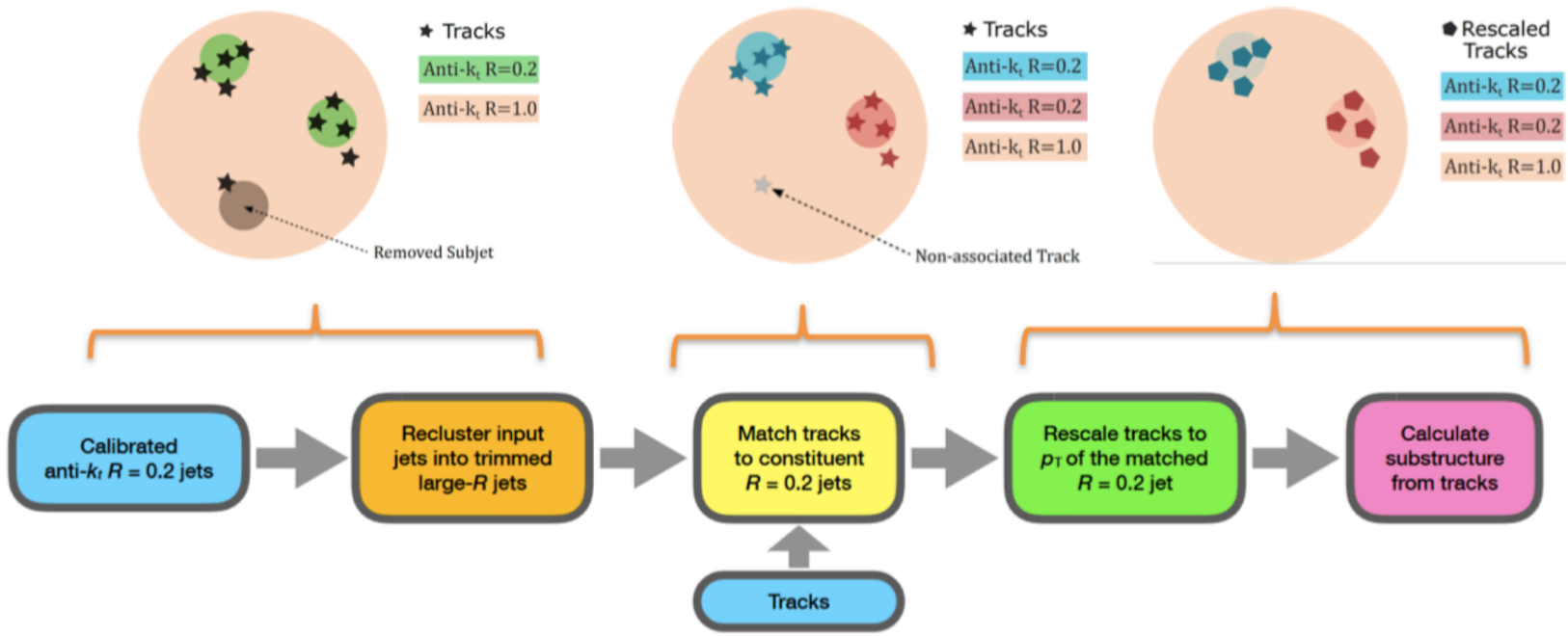
- **Dark matter searches with full Run 2 dataset**:
  - Search for dark matter produced in association with a dark Higgs decaying into $W^{\pm}W^{\pm}$ or ZZ in fully hadronic final states: **Phys. Rev. Lett. 1126 (2021) 121802** [arXiv:2010.06548]
    - Four prompt tagger.
  - Search for Dark Matter produced in association with a SM Higgs boson decaying to b-quarks. [ATLAS-CONF-2021-006]
    - Identifying boosted $H \to b\bar{b}$.
- **Heavy resonances searches with full Run 2 dataset**:
  - Search for $t\bar{t}$ resonances in fully hadronic final states: **JHEP 10 (2020) 61** [arXiv:2005.05138]
    - Tagging boosted tops.
  - Search for pair-production of vector-like quarks with at least one leptonically-decaying Z boson and a third-generation quark: [ATLAS-CONF-2021-024]
    - Multi-class Boosted Object tagger.
  - Search for a single vector-like B quark production and decay via $B \to bH(b\bar{b})$: [ATLAS-CONF-2021-018]
    - Identifying boosted $H \to b\bar{b}$.
  - Search for pair production of scalar leptoquarks decaying into first- or second-generation leptons and top quarks: **Eur. Phys. J. C. 81 (2021) 313** [arXiv:2010.02098]
    - BDT classifier using jet substructure variables.
  - Search for high-mass $W\gamma$ and $Z\gamma$ resonances: [ATLAS-CONF-2021-041]
    - Tagging boosted W/Z bosons.

Search for DM produced in association with a dark Higgs

- Search for DM in the context of a two-mediator-based DM model containing a new U'(1) gauge symmetry which yields an additional spin-1 vector Z' boson via the new scalar boson s.
  - The relevant model parameters are DM particle mass (m_χ), $m_{Z'}$, m_s, g_q ($Z'q\bar{q}$ coupling) and g_χ.
  - W/Z are required to be on-shell: 160 GeV < m_s < 360 GeV and 0.5 TeV < $m_{Z'}$ < 2.5 TeV.
  - Final states characterized by large $E_\mathrm{T}^\mathrm{miss}$ and at least two high-p_T large-R jets.
- Main backgrounds estimated with MC samples: V+jets, $t\bar{t}$, VH
  - Alternative MC samples used to estimate MC modelling systematics.
- **Track-assisted reclustered (TAR) jets used**: based on reclustering R = 0.4 jets with R = 0.8.
  - Using **associated tracks to construct mass and substructure variables**: **tracks rescaled** using R = 0.4 jets information **to account for contributions from neutral particles.**



Dark scalar Higgs



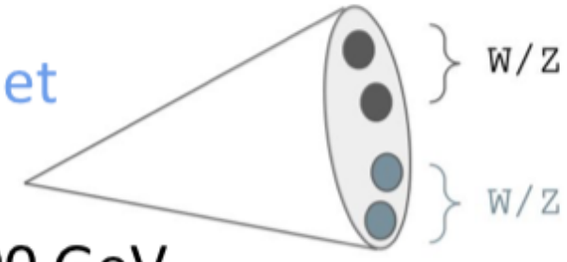
Search for DM produced in association with a dark Higgs

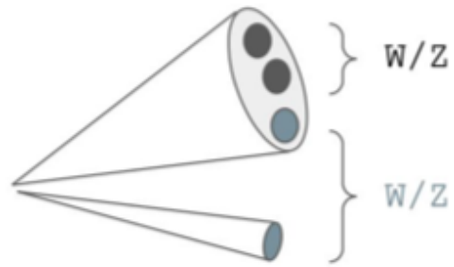
- Two selection categories defined: **Merged** and **Intermediate.**
  - Merged category:
    - **Four-prong jets expected** ($s \to VV \to q\bar{q}q'\bar{q}'$), for signals with $m_s \ll m_{Z'}$.
    - Background reduced by requiring **0.0 < τ_4/τ_2< 0.3 and 0.0 < τ_4/τ_3< 0.6.**

Merged: R=0.8 TAR jet

E_T^{miss} > 500 GeV and

300 GeV < E_T^{miss} < 500 GeV

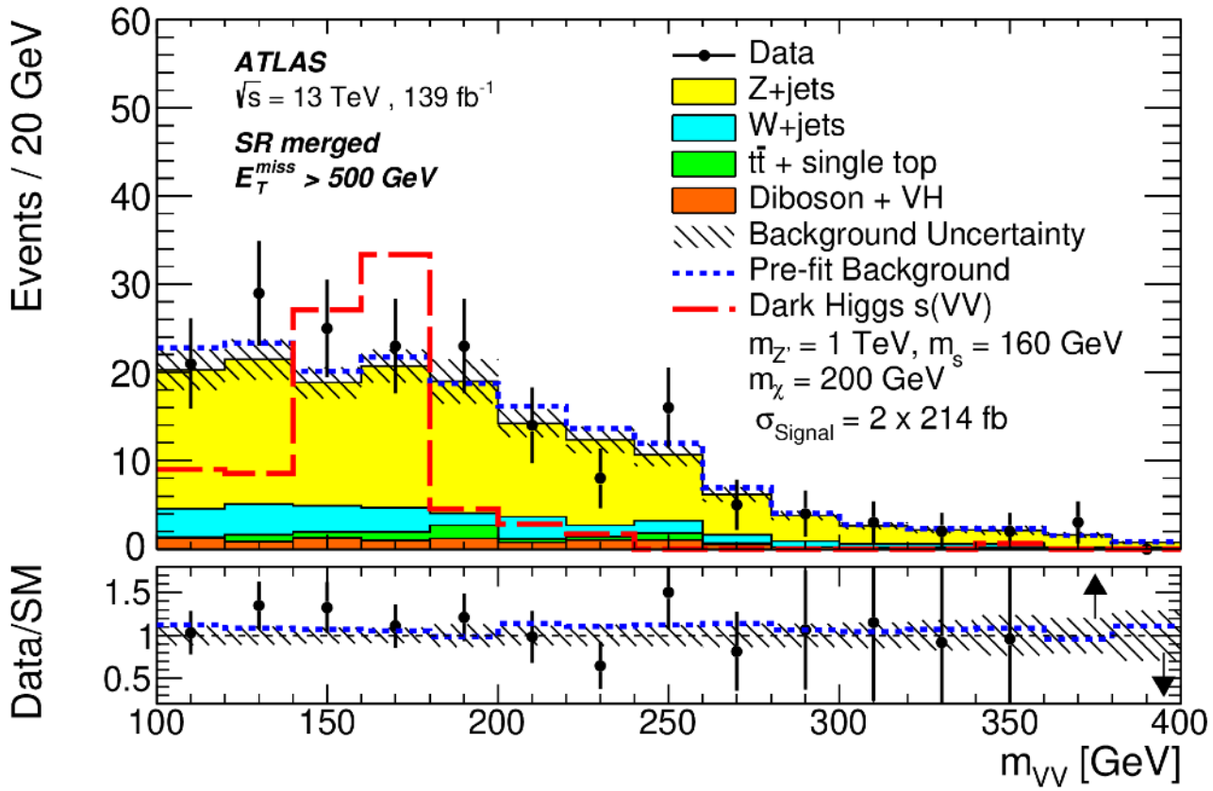


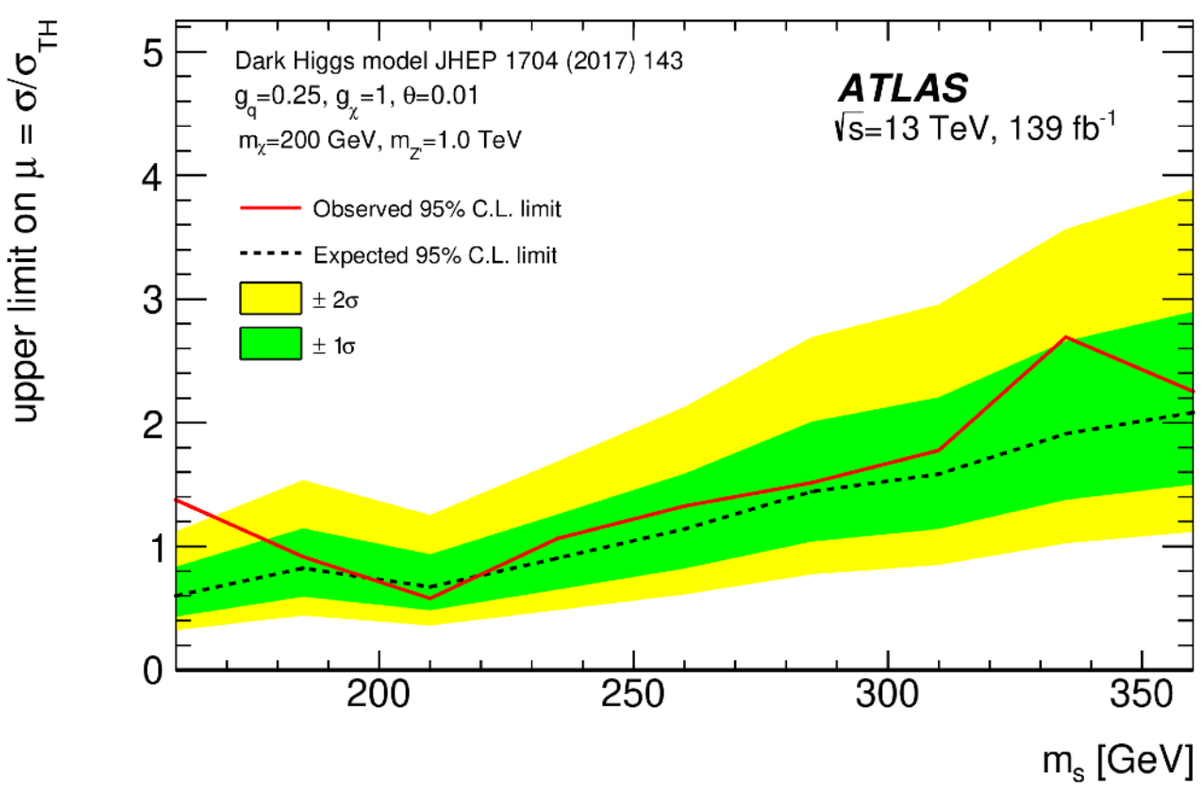


Intermediate: TAR jet + 1-2 R=0.4 jets

E_T^{miss} > 200 GeV

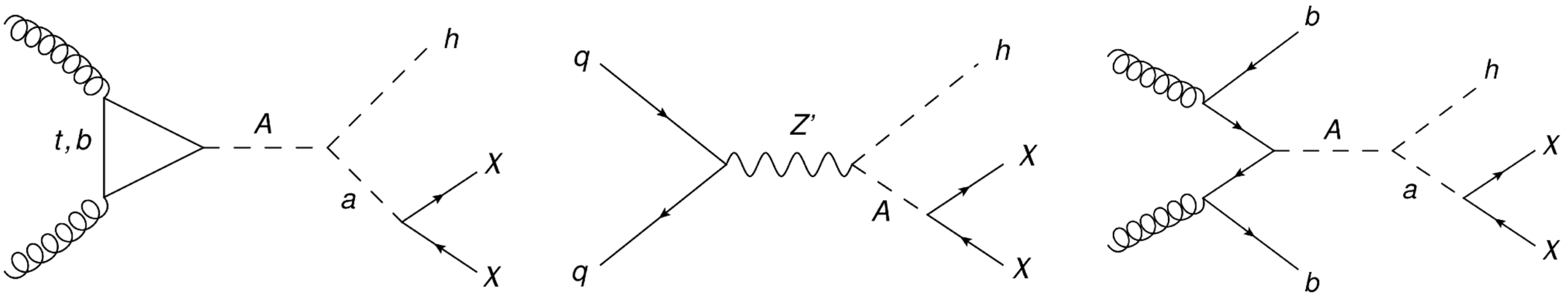
- 1μ- and 2l- CRs defined to correct MC samples.





Search for DM produced in association with a SM Higgs

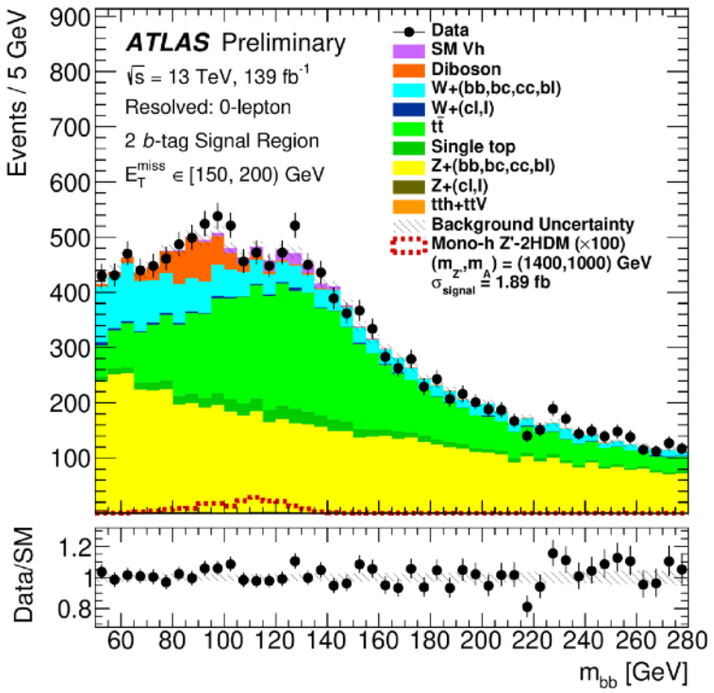
- Search for DM in the context of a two-Higgs-doublet model together with an additional pseudo-scalar a or vector boson (Z'):
  - Z'-2HDM scenario which adds an heavy vector boson. This model is used mainly as a benchmark for high-mass resonances.
  - 2HDM+a scenario which add a new pseudo scalar singlet.
  - **Introduction of the $\geq$ 3b jets category sensitive to bbA production with $\tan\beta$ = 10!**
- $H \to b\bar{b}$ decay mode used in this search.
  - For large $m_{Z'}$ and m_A values boosted final-state Higgs boson is expected if $m_A \ll m_{Z'}$ (Z'-2HDM scenario) or $m_a \ll m_A$ (2HDM-a scenario).
  - **Large-R (R = 1.0) jets used to reconstruct Higgs boson in boosted channel**.
- This analysis benefits from VR track jets to identify boosted Higgs boson candidate.
  - **b-tagged VR track jets ghost-associated to large-R jet** Higgs candidate is required.
  - VR track jets allow to reconstruct b-jets in highly boosted Higgs boson final states:
    $R_{\text{eff}}(p_{\text{T}}) = 30\ \text{GeV}/p_{\text{T}}$ **with 0.02 < $R_{\text{eff}}(p_T)$ < 0.4**
  - Large-R mass from Higgs candidate (m_{h}) used as fitted observable in 0-lepton channel.



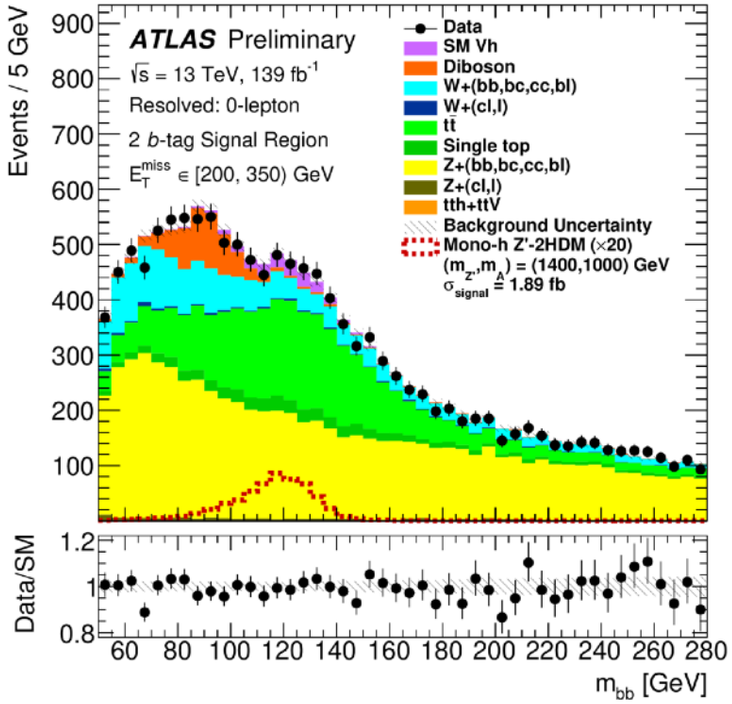
Search for DM produced in association with a SM Higgs

- Good description of the data by SM expectation in resolved and boosted regions.
  - ➡ 95% CL exclusion limits are derived for the studied signal models.

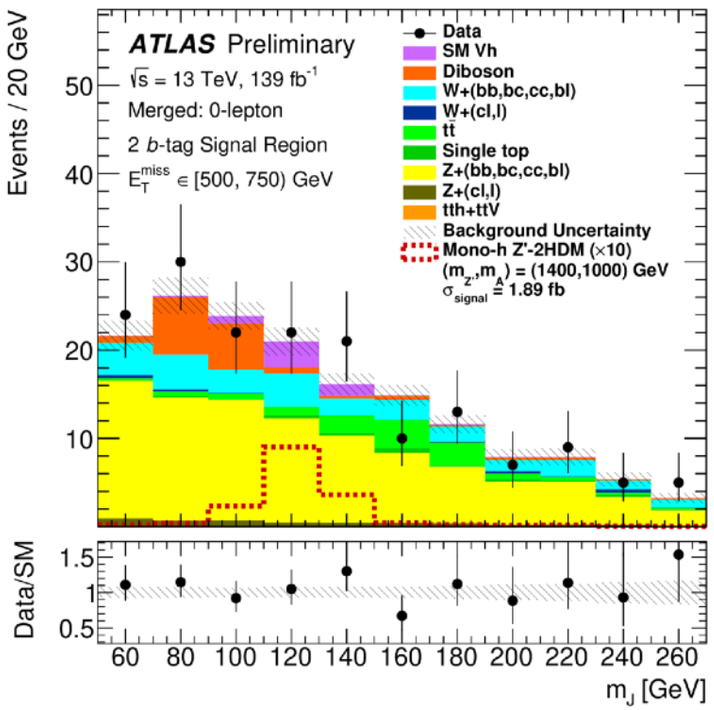
Resolved

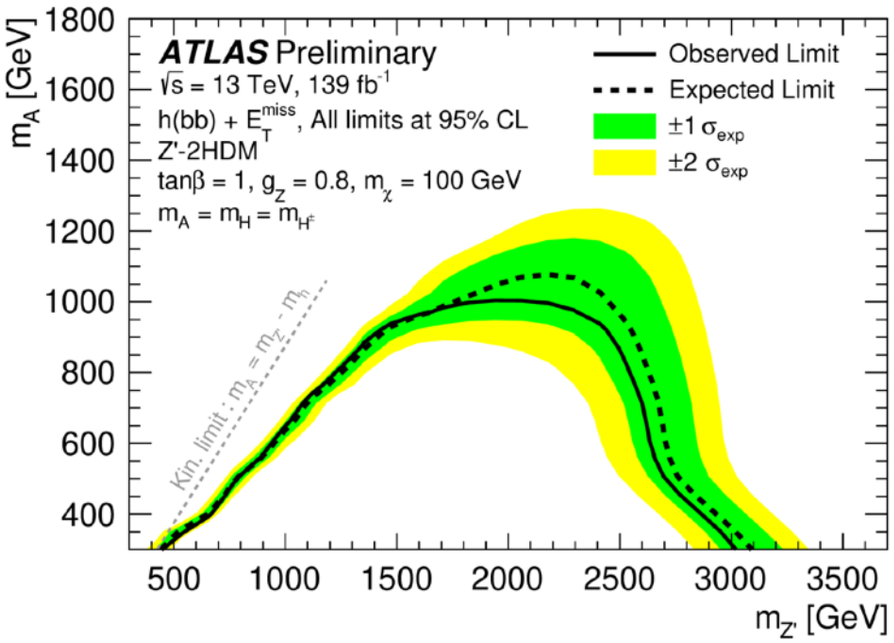


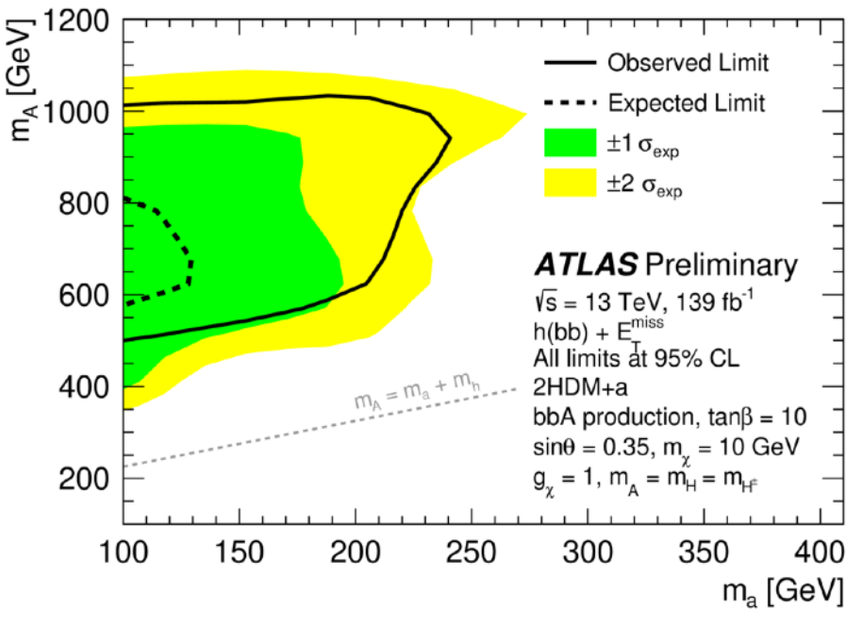
Resolved



Boosted







2D limits derived:

- $(m_{Z'}, m_A)$ for Z'-2HDM scenario.
- (m_a, m_A) for 2HDM+a scenario.

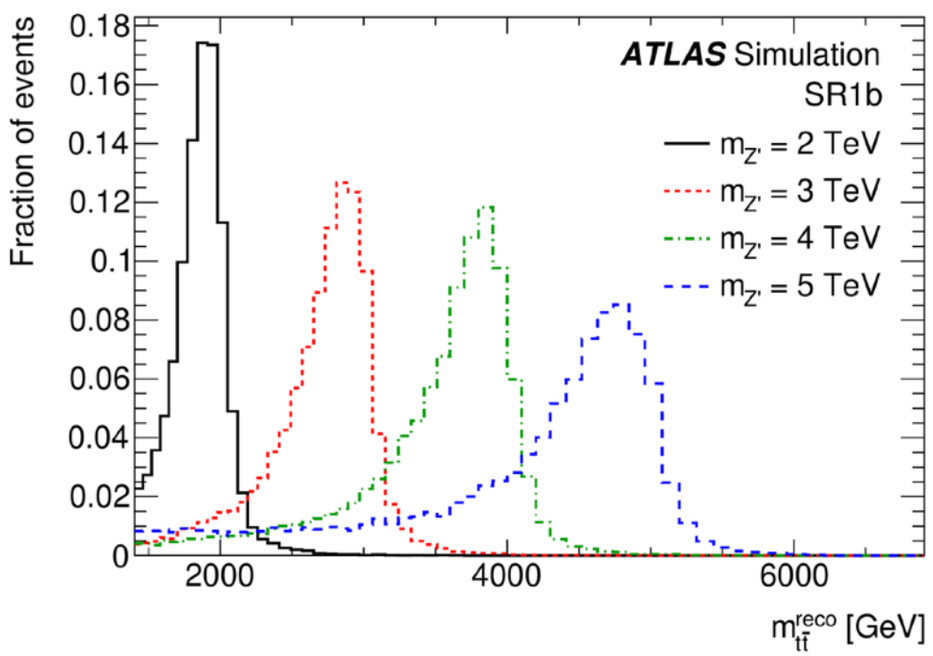
- **VR track jets allow to extend limits:**
  - **up to $m_{Z'} \approx$ 3 TeV for $m_A \approx$ 300 GeV.**
  - **up to $m_A \approx$ 1 TeV for m_a = 100 GeV.**

Search for $t\bar{t}$ resonances in fully hadronic final states

- Search for heavy $t\bar{t}$ resonances in fully hadronic final states.
  - Predicted by topcolor-assisted-technicolor (TC2), two-Higgs-doublet model (2HDM) and Randall-Sundrum (RS) models of warped extra dimensions.
  - Two boosted $t/\bar{t}$ quarks expected in the final state for resonances in the TeV mass range.
- Large-R jets used to collect top decay products (**LCTopo Large-R jets**):
  - They are built from topological clusters that are calibrated to hadronic energy scale with local cluster weighting (LCW) using anti-k_t jet algorithm with R = 1.0.
  - **Trimming procedure applied to remove contributions from pile-up and soft radiation.**
    - ➡ Constituents from R = 0.2, k_t jets with $p_{\mathrm{T}}^{R=0.2}/p_{\mathrm{T}}^{R=1.0} < 0.05$ removed.
  - m_{J} **calculated combining calorimeter energy measurement with tracking information**:

$$m_{\mathrm{J}} = \frac{\sigma_{\mathrm{calo}}^{-2}}{\sigma_{\mathrm{calo}}^{-2}+\sigma_{\mathrm{TA}}^{-2}} \times m^{\mathrm{calo}} + \frac{\sigma_{\mathrm{TA}}^{-2}}{\sigma_{\mathrm{calo}}^{-2}+\sigma_{\mathrm{TA}}^{-2}} \times m^{\mathrm{TA}}$$

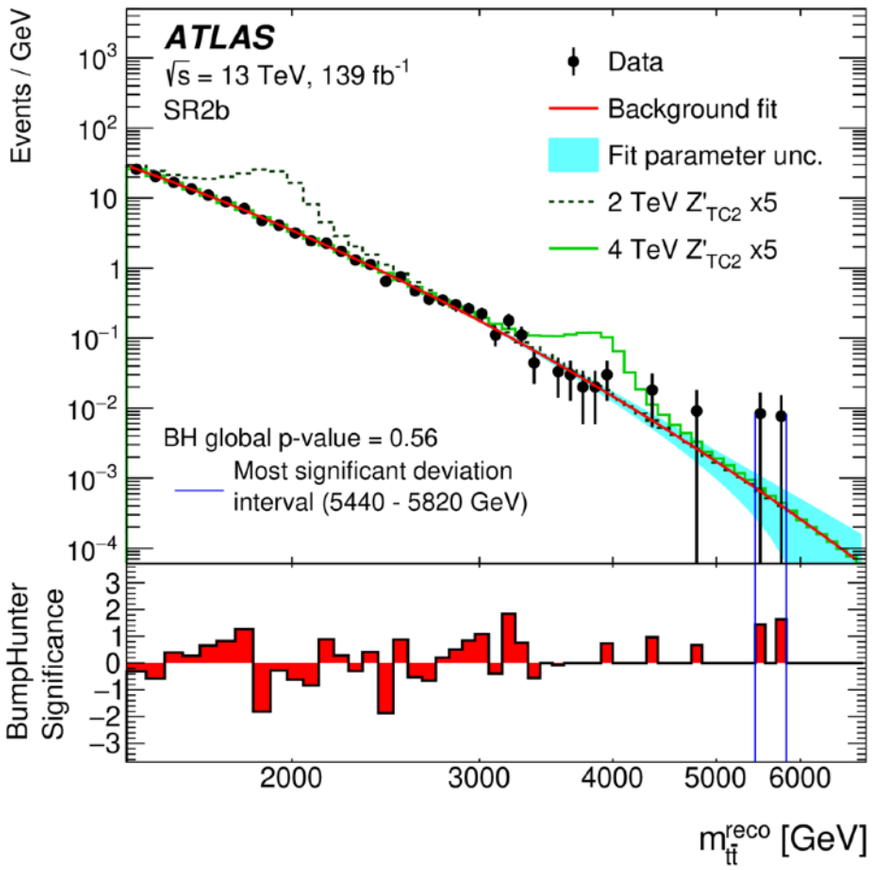
  - JES/JER and JMS/JMR calibrations apply to Large-R jets.



- b-tagged VR track jets to identify b-jets within top candidates.
  - Two SRs depending on number of b-jets jets: SR1b, SR2b
- **DNN-based top tagger applied to suppress multijet background** (flat efficiency 80% WP):
  - Trained with several substructure variables:
    $p_{\mathrm{T}}, m_{\mathrm{J}}, e_3, C_2, D_2, \tau_{21}, \tau_{32}, \sqrt{d_{12}}, \sqrt{d_{23}}, Q_{\mathrm{w}}$ …
  - **Top tagger performance corrected by means of SFs estimated by comparing data and MC in $t\bar{t}$ events.**

Search for $t\bar{t}$ resonances in fully hadronic final states

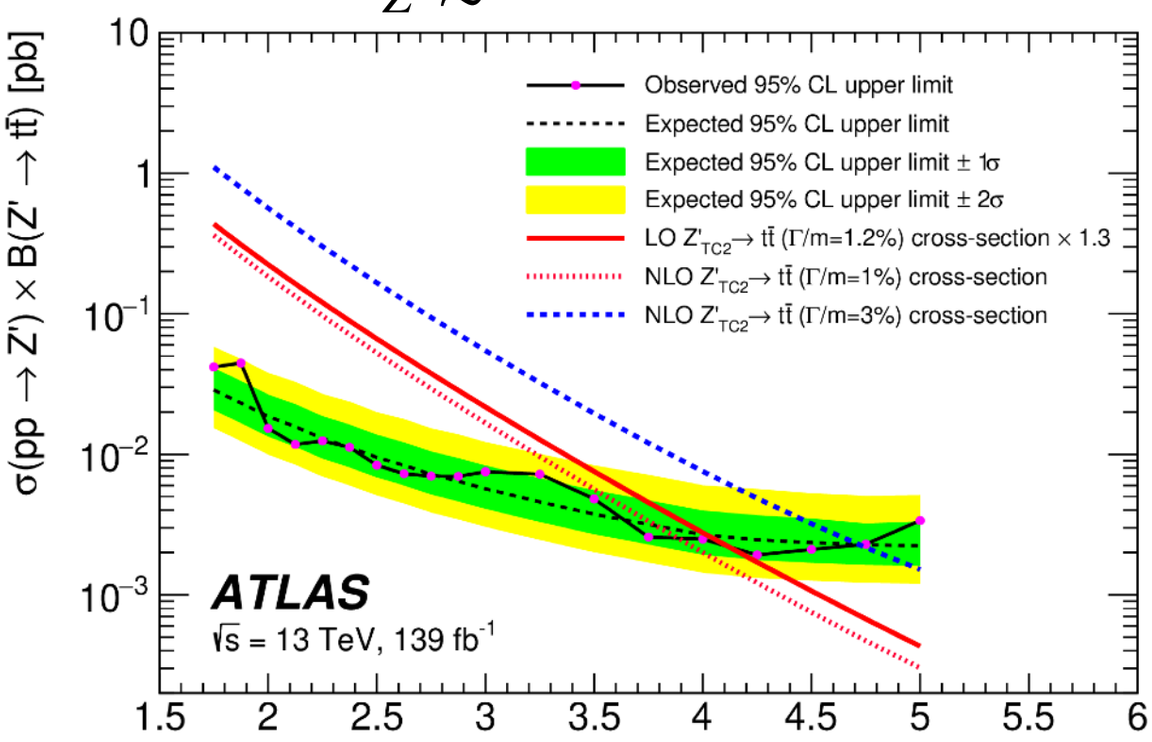
- Background estimated directly from data by performing a fit with a smoothly falling spectrum:
  - Fitting function validated in SRs by using data-driven multijet estimation.

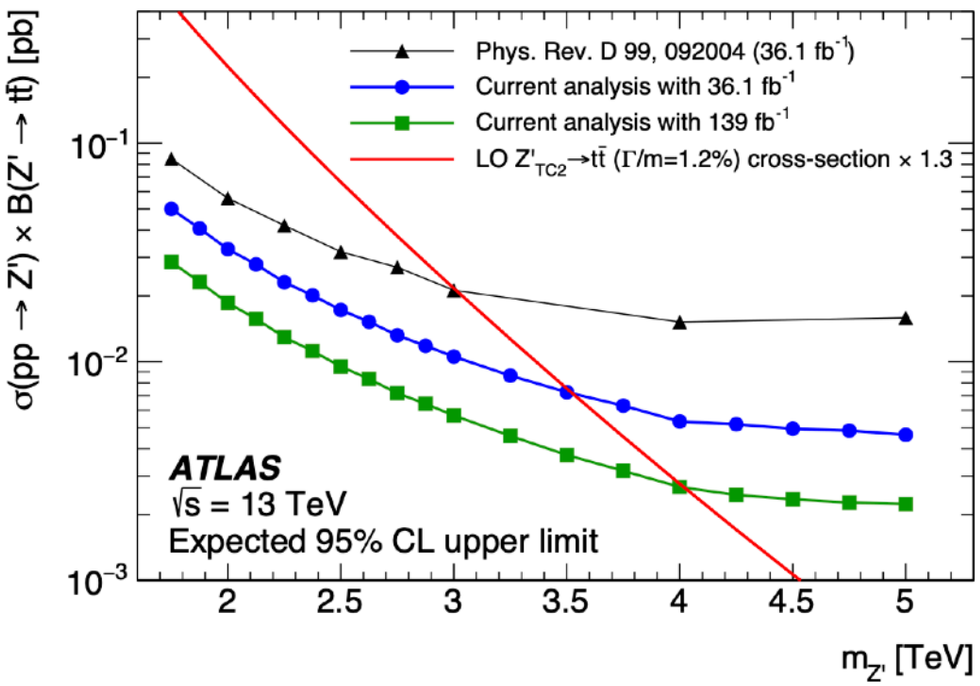


- Since no excess found in SRs, a 95% CL exclusion limits are derived:
- Up to $m_{Z'} \approx 4.7$ excluded depending of Z' decay width

- **Improved analysis techniques such as top and b-tagging highly improves limits compared to previous round of this search.**

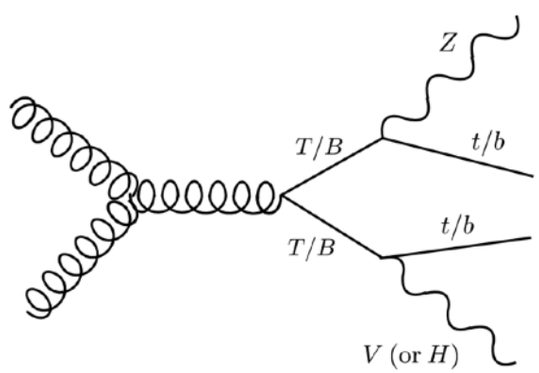
$m_{Z'} \lesssim$ 4.2 TeV excluded



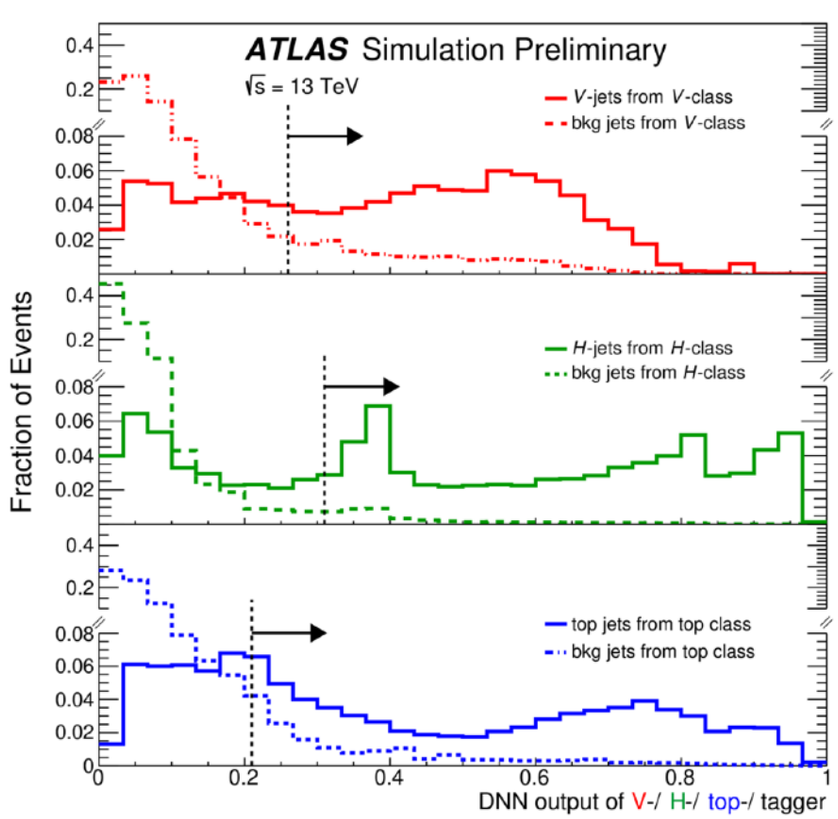


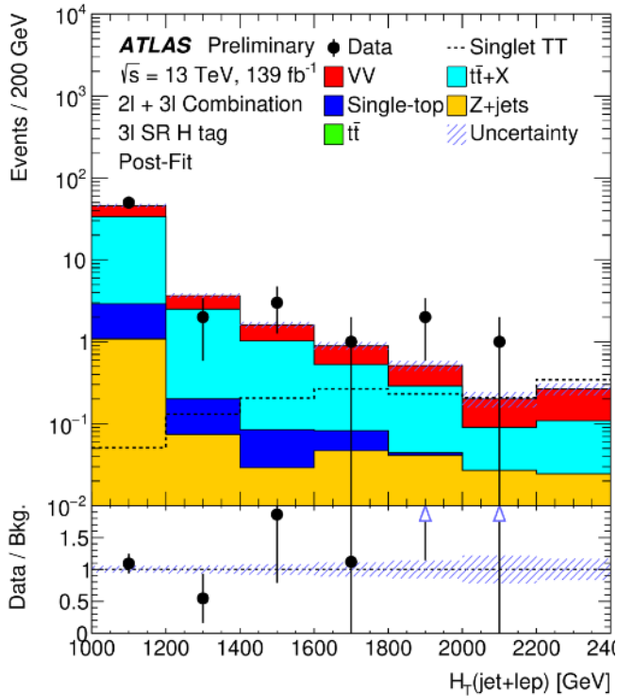
Search for a pair-production of vector like quarks

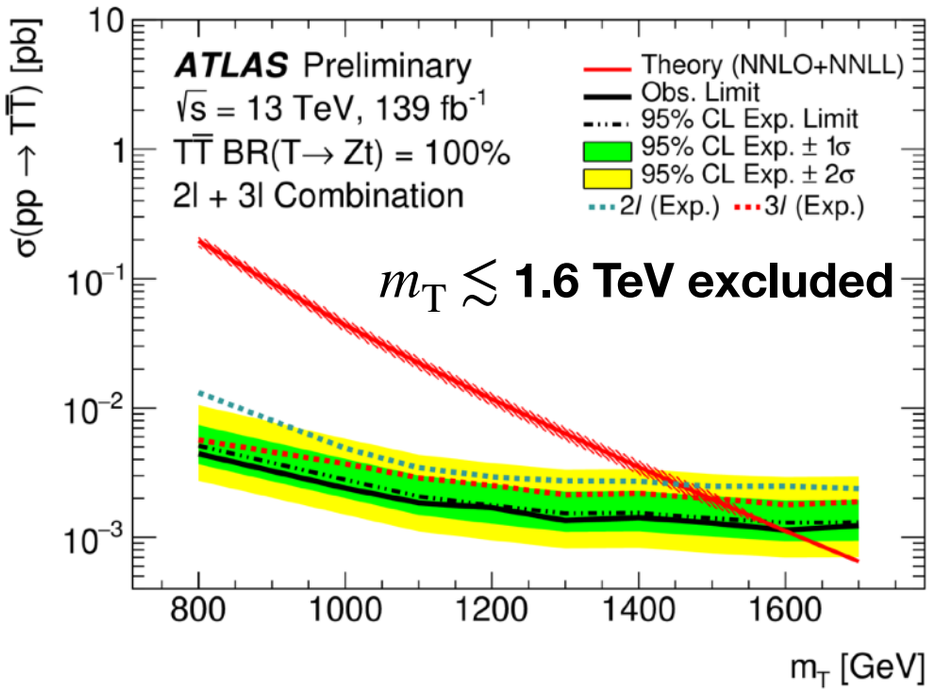
- Existence of VLQ predicted by many BSM theories:
  - Composite Higgs, Little Higgs …
  - spin-1/2 fermions that in some models often assumed to couple preferentially to a top or b quarks.
- This search focus on pair-production of T and B VLQ particles in events with at least two e or μ originated from Z decays.



- **Large-R reclustered (RC) jets used to identify V/H,top**
  - Reclustered jets: small-R jet input to jet clustering.
- **Multi-Class Boosted Objet Tagger (MCBOT)**
  - DNN trained with 18 input variables to identify jet origin:
    - p_{T}, mass, RC constituents, b-tagging score of three leading RC constituents.
  - Simultaneous identification of V/H/top jets
    - In case of ambiguities choose tag with highest score.

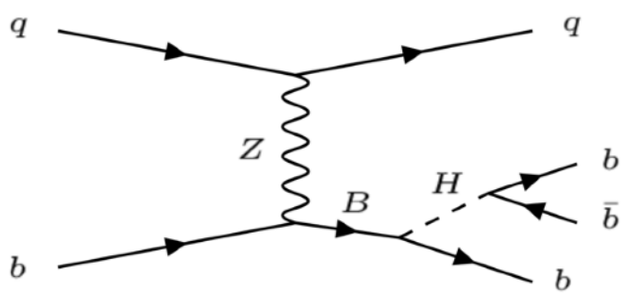




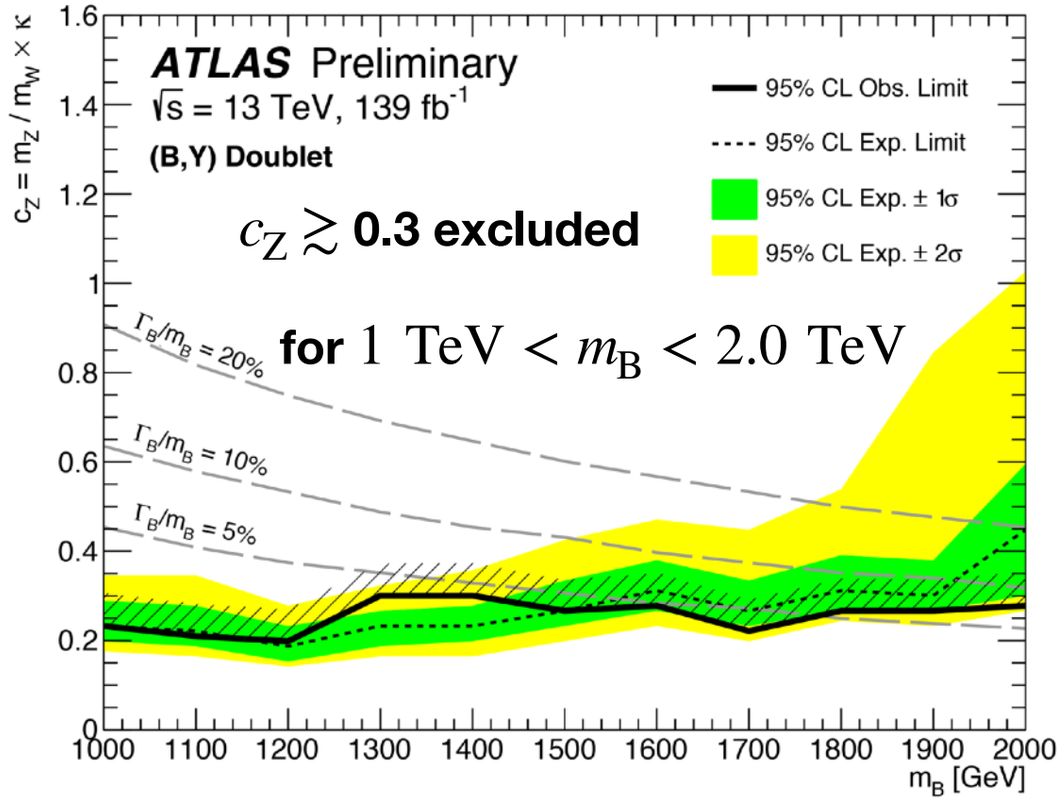


Search for a single vector-like B quark

- This search is focused on single-produced vector-like B-quark decaying to $B \to bH, H \to b\bar{b}$ final state.
  - As a result 95% CL limits derived on coupling constant c_Z appearing in the simplified VLQ model.

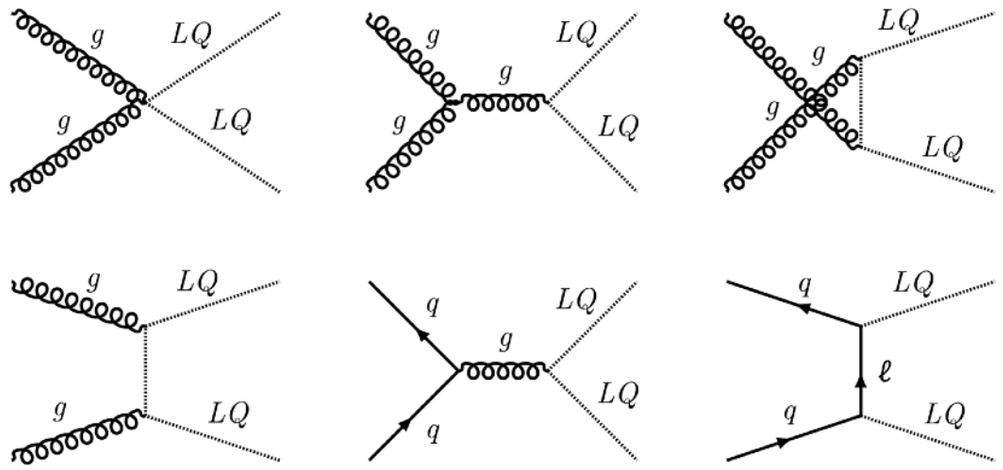


- LCTopo large-R jets to reconstruct boosted Higgs decay products.
  - **Two-pronged energy profile originated from $b\bar{b}$ expected.**
- b-tagging and Higgs tagging techniques applied to reduce multijet background.
  - Data-driven method to estimate remaining multijet contribution.
- **b-tagging algorithm (DL1r)** based on multivariate classification technique is used to **identify small-R jets containing a b-hadron.**
  - Information from track impact parameter, reconstructed muons in jets and topological properties of secondary and tertiary decay vertices are included.
- **VR track jets ghost-associated to large-R are inspected for b-tagging**:
  - At least one b-tagged VR track jet is required within the Higgs candidate.
- No excess was found between the data and the expected background.

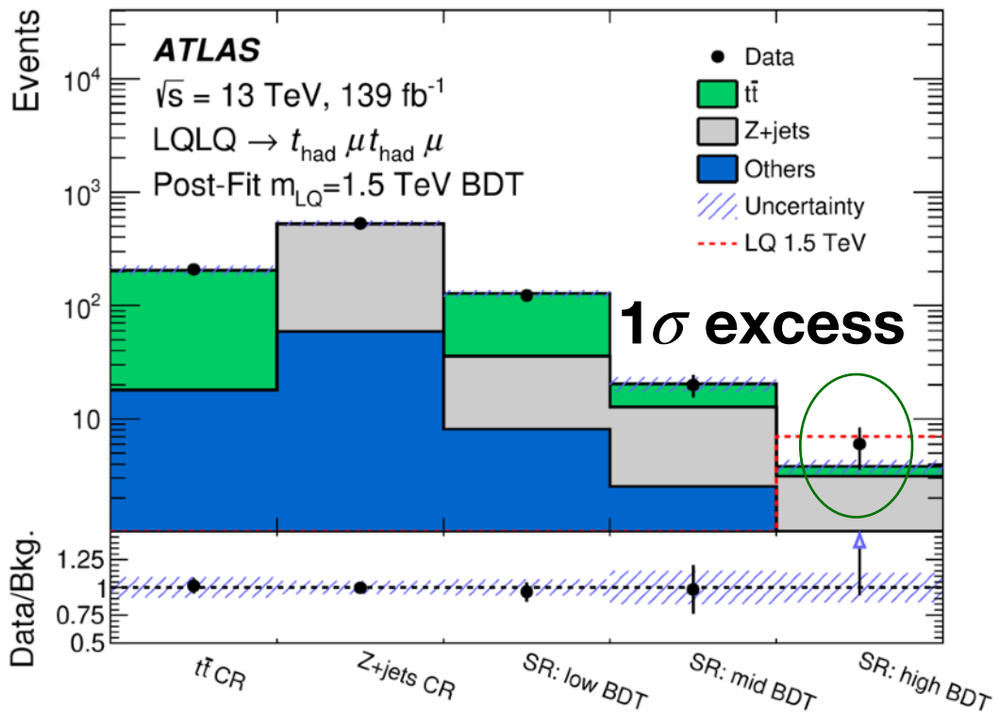


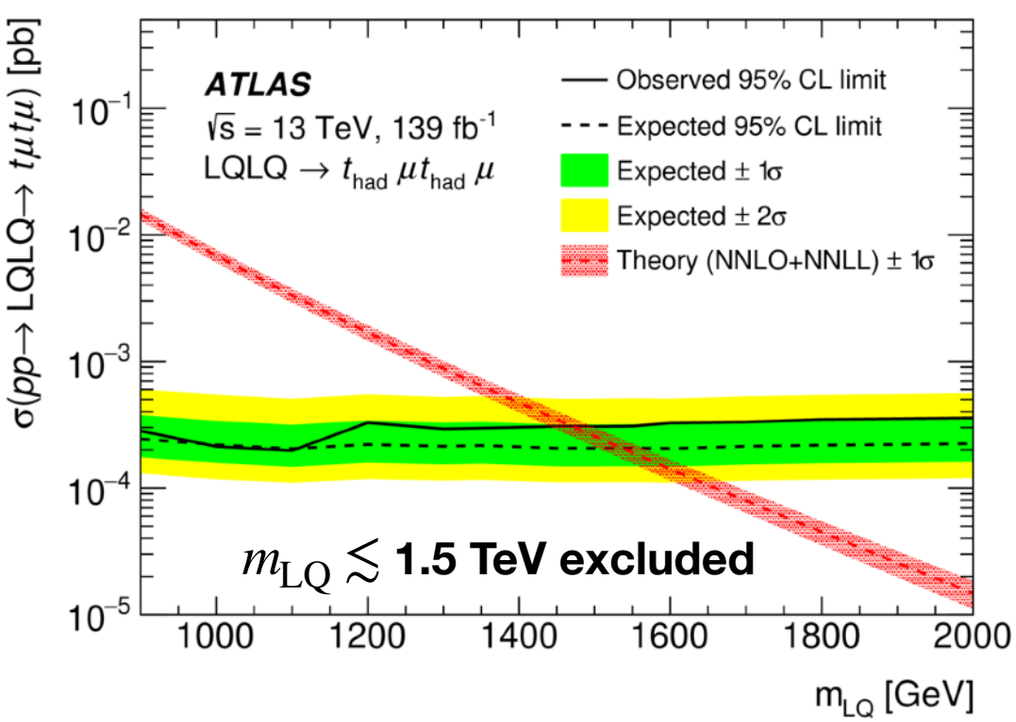
Search for pair production of scalar leptoquarks

- Similarities between quark and lepton SM sectors motivate to hypothesize a fundamental symmetry between the two sectors:
  - GUT, Pati-Salam model on SU(4), RPV SUSY models …
  - New class of bosons carrying both L and B numbers.
- This search targets LQ pair production focused on:
  - **LQ** $\rightarrow e/\mu\ t$**, where top quark decays hadronically**.
  - Final state signature described by pair leptons and a pair of LCTopo large-R jets.



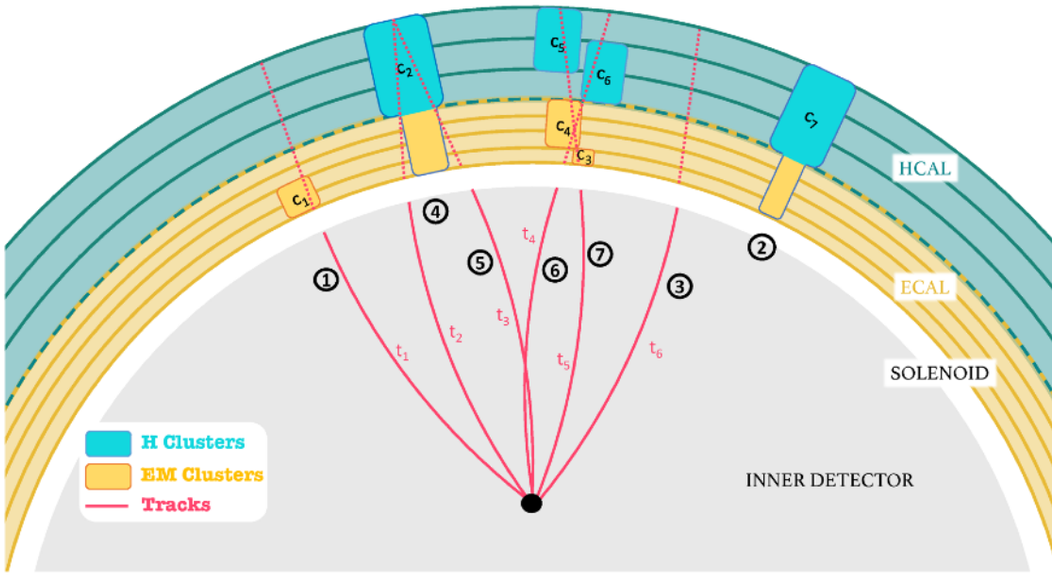
- **BDT approach based on kinematic variables and jet substructure variables** applied to classify events as originating from the signal or background in SR.
  - Best discriminating variables: $m_{l_1 l_2}$, $p_{T,l_1} + p_{T,l_2}$, m_{J_1}, m_{J_2}, $m_{l_1 l_2 J_1 J_2}$.
  - Parametrize BDT to maximize sensitivity in a wide m_{LQ} range.
  - Dedicated CRs defined to control normalization of dominant backgrounds such as $t\bar{t}$ and Z+jets.

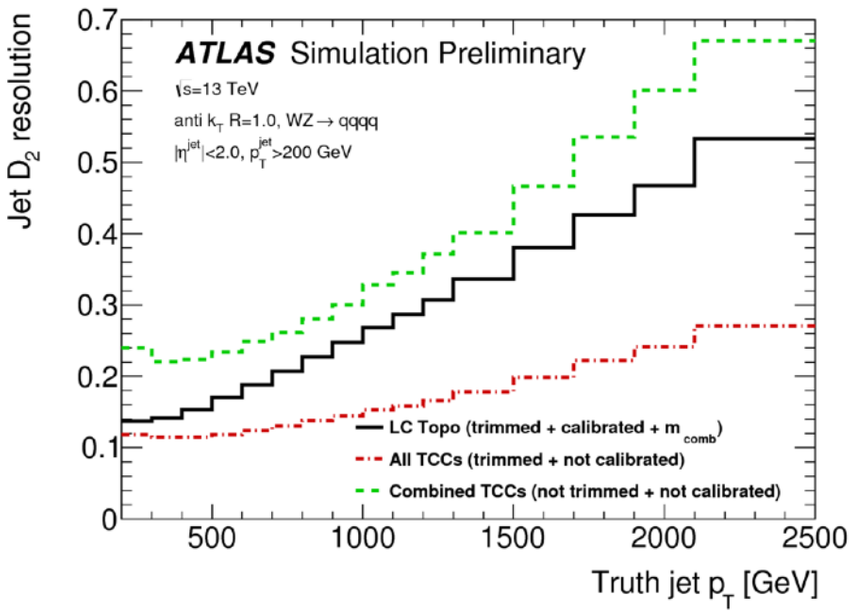


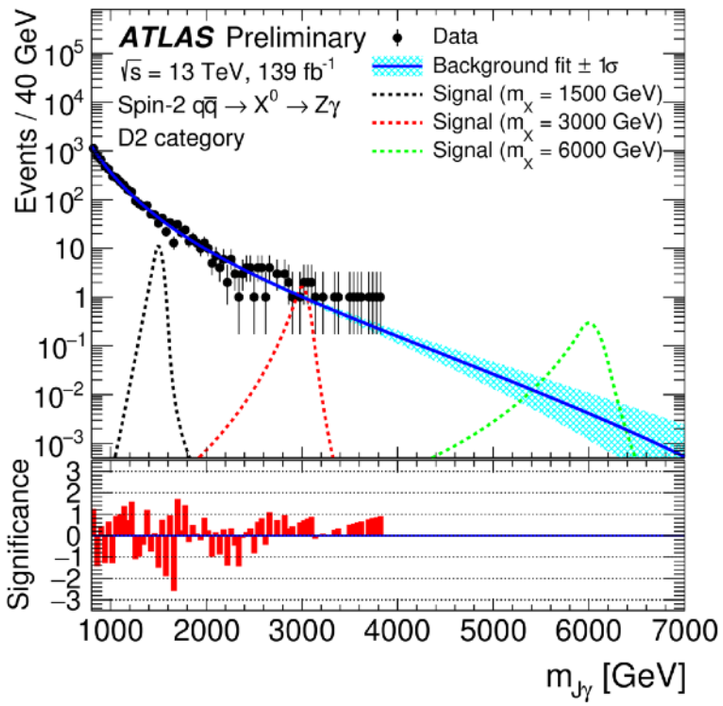


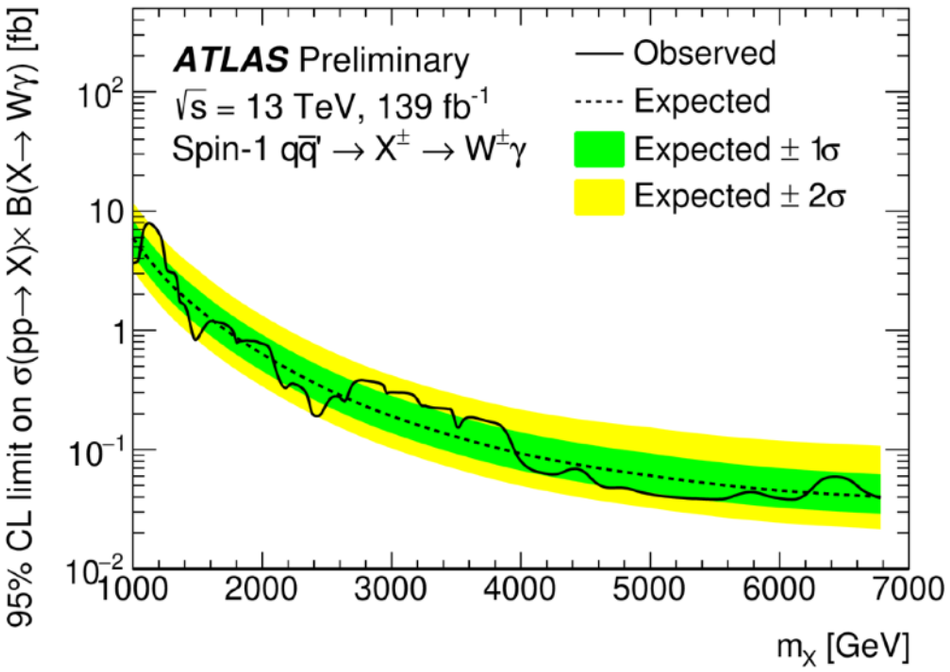
Search for high-mass $W\gamma$ and $Z\gamma$ resonances

- BSM theories predict new $X^{\pm}$ and X^{0} bosons to couple to the SM $W^{\pm}$ and Z bosons and photons.
  - For large $X^{\pm}$ and X^{0}masses, boosted $W^{\pm}/Z$ and a high-p_{T} γ expected in the final state.
- Large-R jets used to reconstruct boosted $W^{\pm}$/Z candidates:
  - Jets built from track-calorimeter clusters (TCCs) which **combines** information from the calorimeter and ID.
  - Thanks to tracking information**, very good reconstruction performance found for jet-substructure variables at high-p_{T}.**
  - D_2 variable used to identify 2-prong structure expected from $W^{\pm}$/Z decays.
  - Mass window cuts applied consistent to m_W and m_Z.









Conclusions

- Several searches for DM particles and heavy resonances have been presented.

- Boosting techniques allows to improve sensitivity to signal models where boosted heavy particles are expected in the final state.

  - Mainly in models where resonances in TeV mass range decay to O(EW)-massive particles, such as, Higgs, W/Z and tops.

  - They allow to extend sensitivity of searches to very massive particles.

  - Improving the performance of boosted top/W/Z and Higgs taggers has allowed to increase sensitivity to smaller signal cross-sections.

    ➡ More improvements will come In the future!