# Heavy Resonances Searches with ATLAS and CMS

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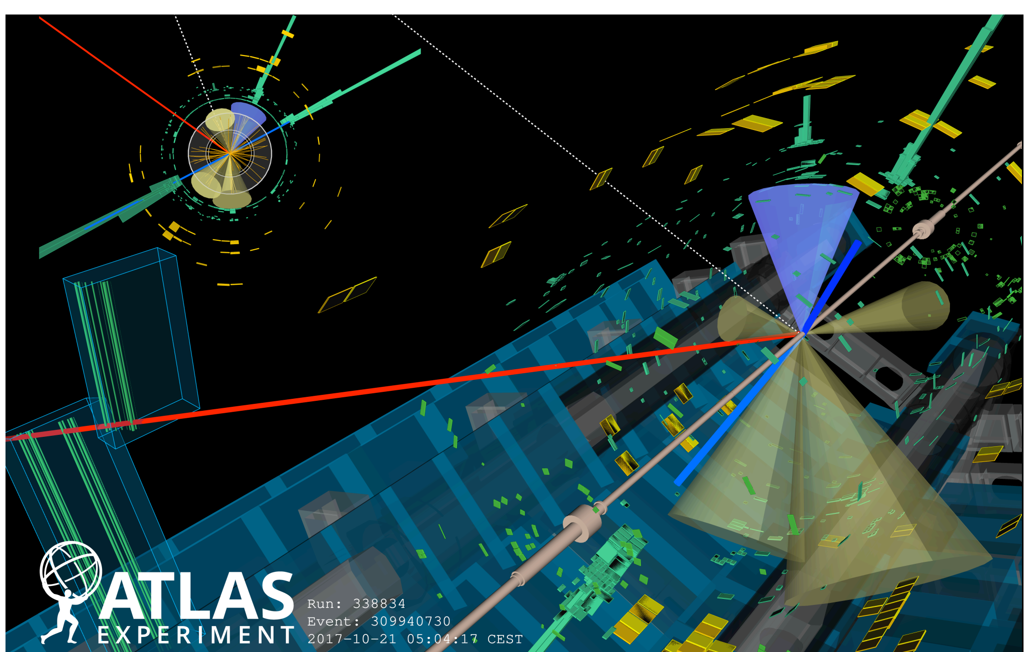
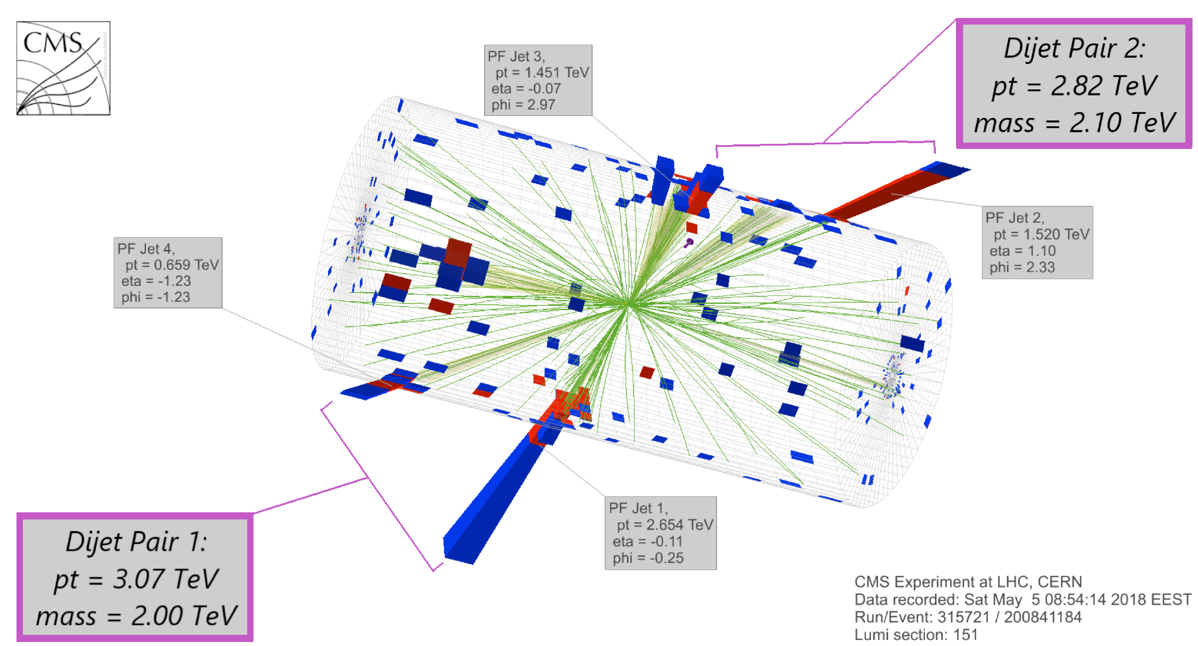
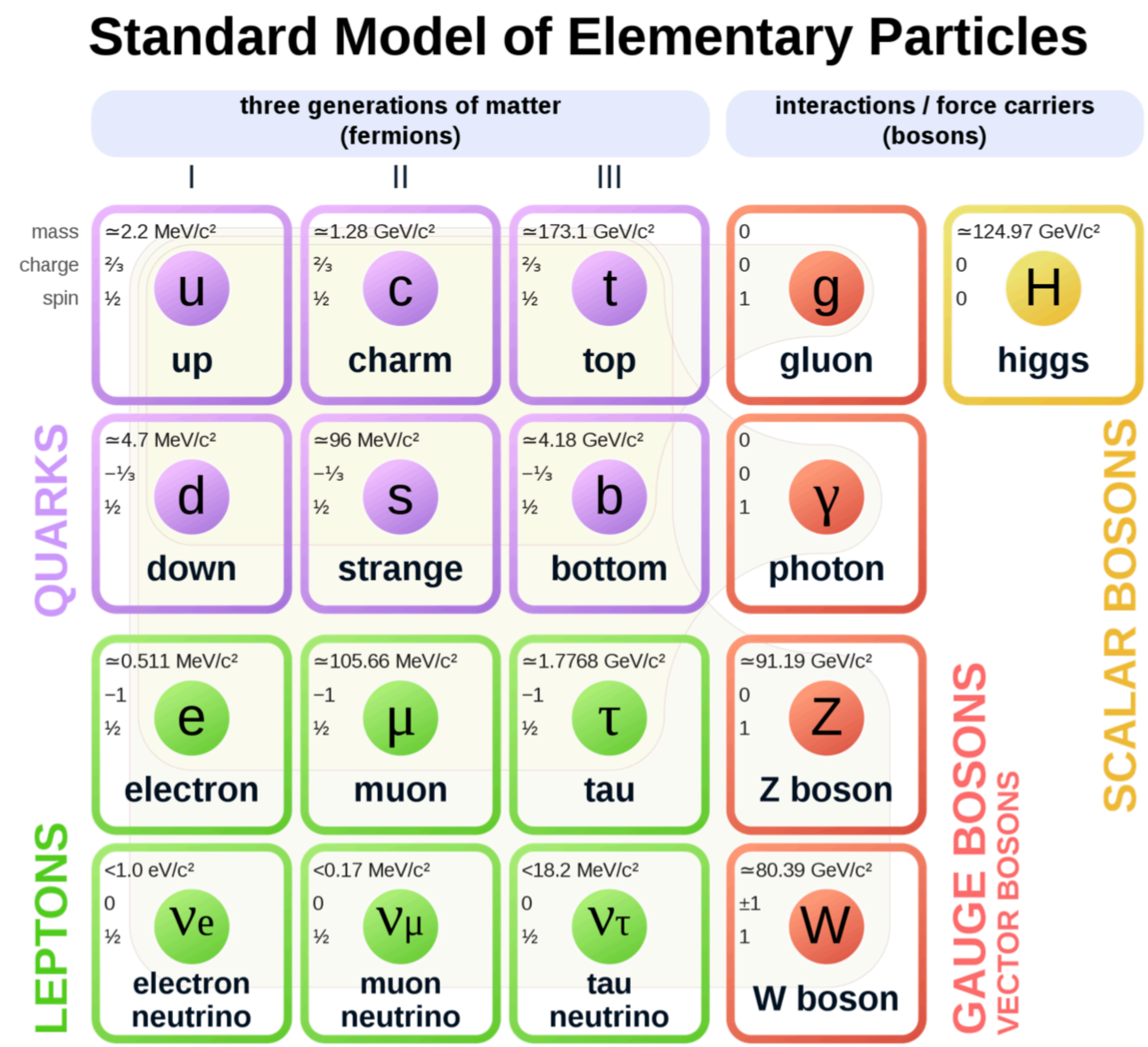


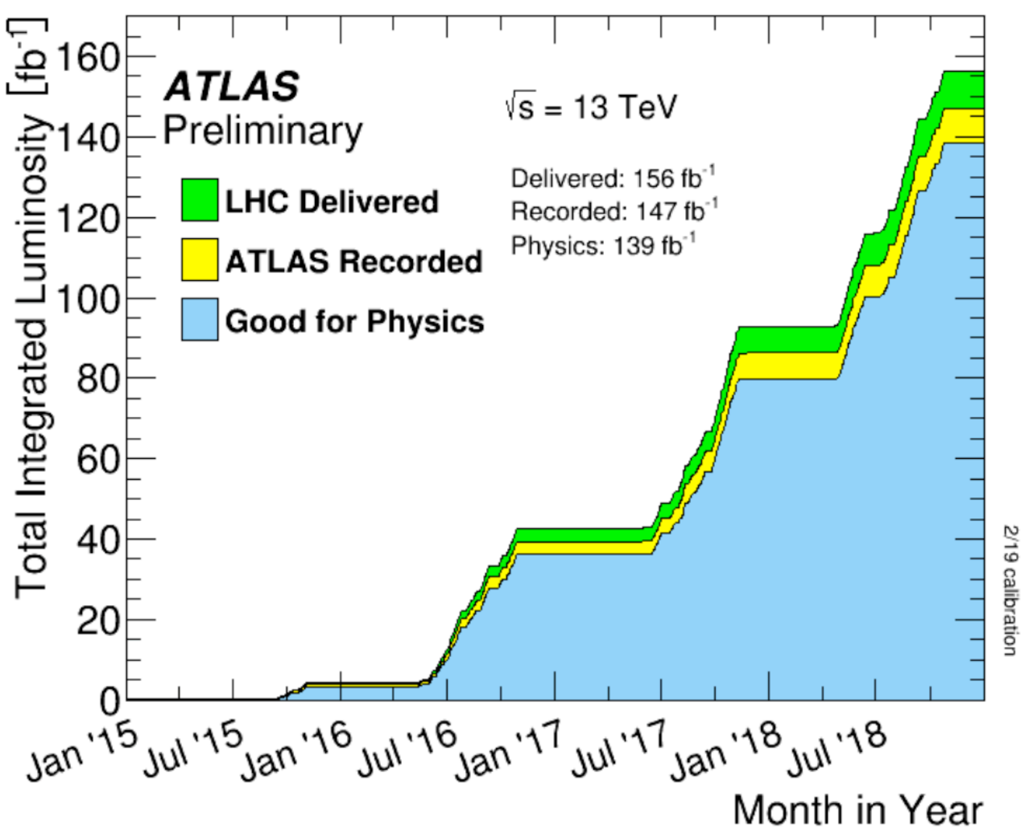



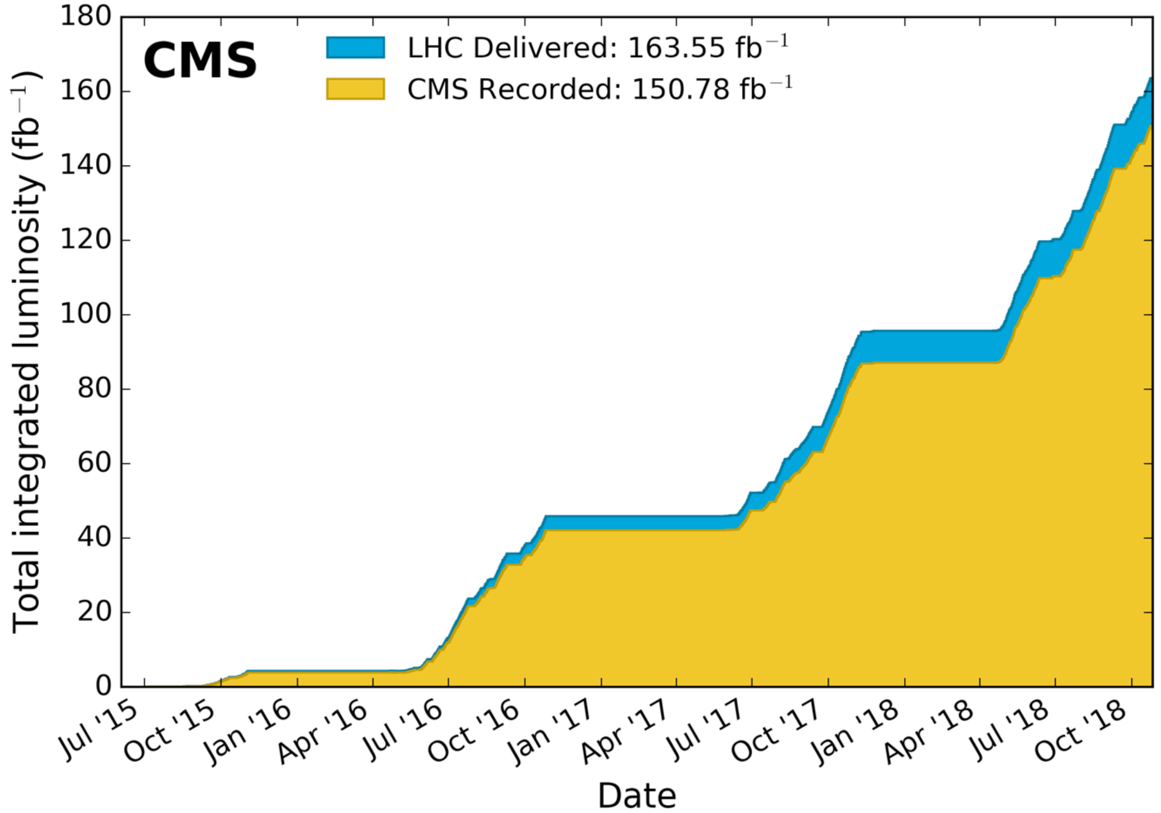
# Introduction

- The **Standard Model (SM)** is a very successful model for describing elementary particles
- It does not answer many questions such as **matter anti-matter asymmetry and the hierarchy problem**
- **Beyond Standard Model (BSM)** theories predict the existence of **heavy resonances** decaying to SM particles
- Present results on recent heavy resonance searches conducted by the **ATLAS and CMS** experiments
- Results interpreted in the context of models such as the Heavy Vector Triplet (HVT), Two-Higgs-Doublet Model (2HDM), Sequential Standard Model (MSSM), Dark Matter models (DM), ..



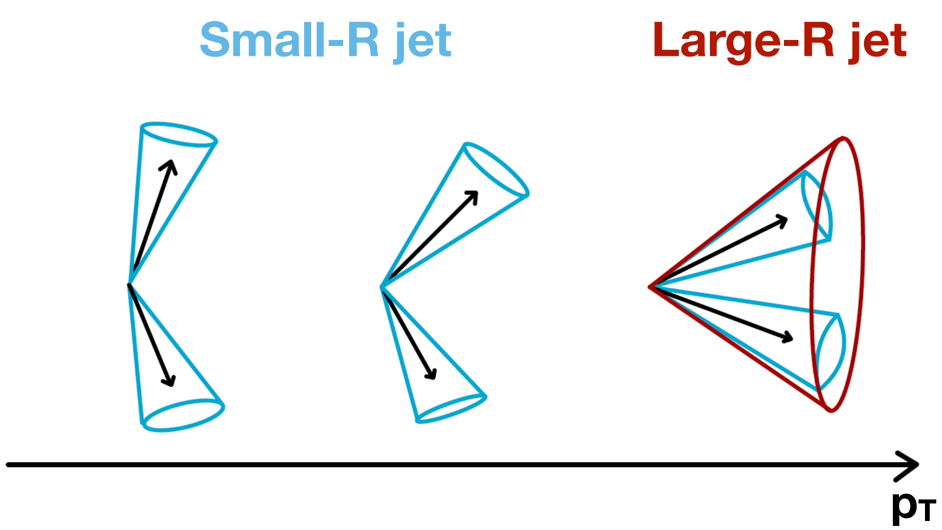
# Results using Run2 data



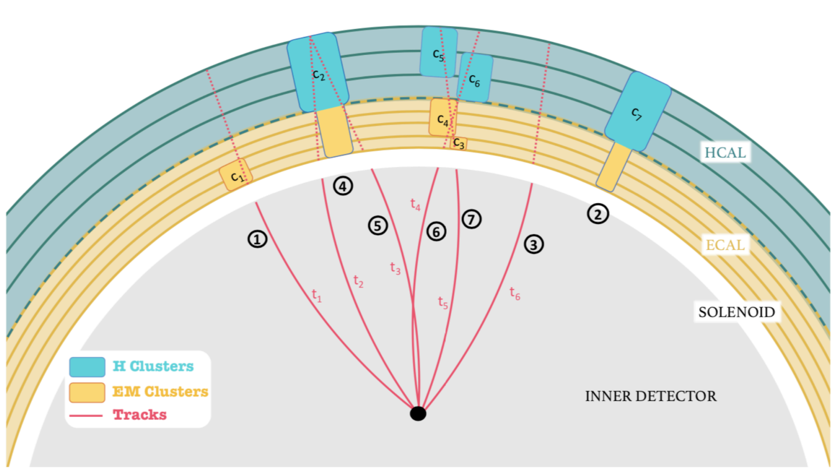




- Heavy resonances mostly decay to particles in the **boosted regime (high masses ⇒ high $p_T$)** decaying to SM particles (leptons and hadrons) in the final state
- **Powerful tools** to identify and reconstruct these particles (such as jets reconstruction, *b*-jets tagging, V-boson tagging)
- Results presented from ATLAS and CMS based on the full Run 2 dataset
- **A lot of recent results to cover! but not all will be shown today**

# Jet definition and techniques




- High $p_T$ massive particles (*V* boson, Higgs, top-quark) are used in heavy resonance searches
- The hadronic decay of these particles are reconstructed using anti-$k_T$ algorithm
  - **Small-R jets** (resolved) with R=0.4
  - **Large-R jets** (boosted) with R=0.8/1.0
- Topological calorimeter clusters and matched tracks are used (better performance at high $p_T$)
- Analyses mostly use Track-CaloClusters (TCCs) and Particle-flow (PFlow) jets
- Jet grooming applied to remove contamination (pile-up, soft radiation) from the reconstructed jets

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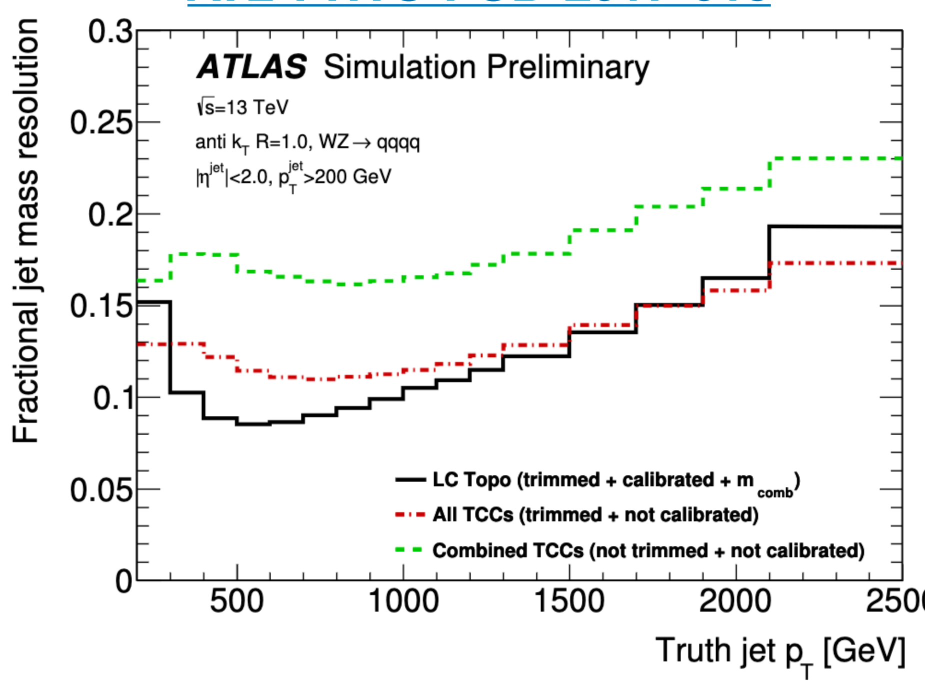
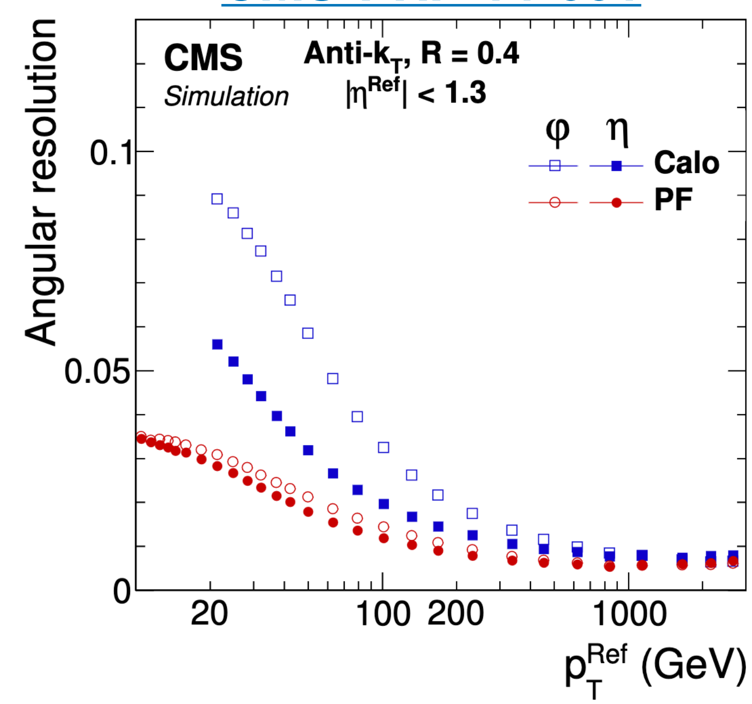
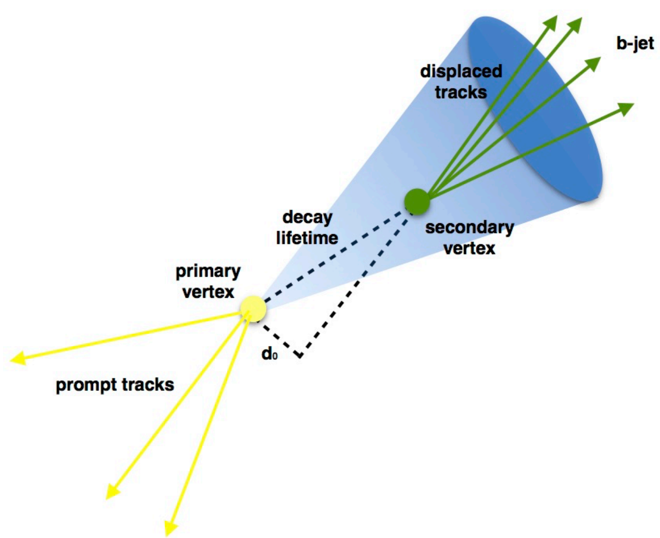



CMS-PRF-14-001

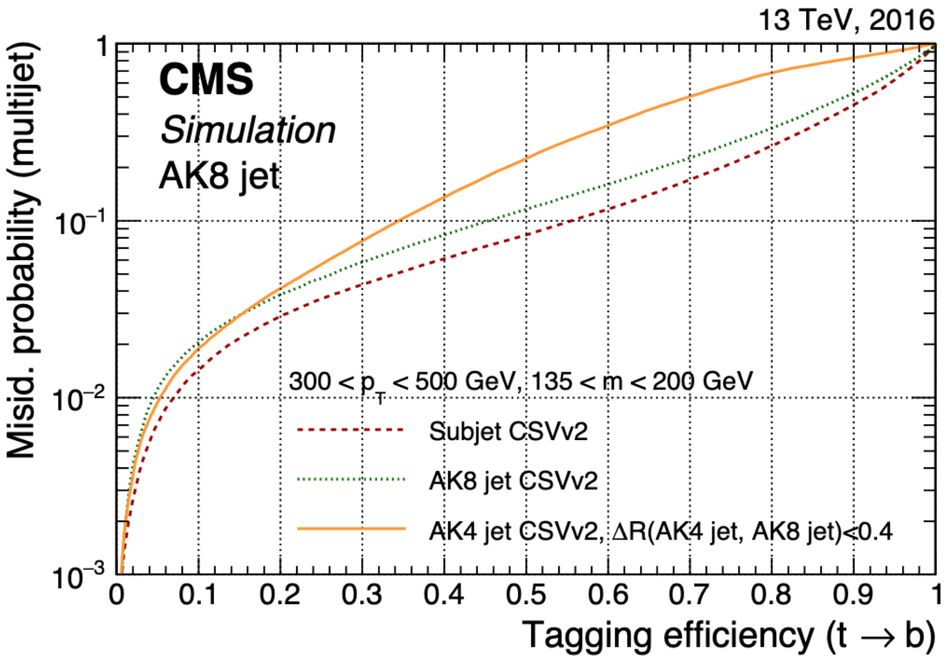


# *b*-jets tagging




- Identification of heavy-flavour decays is a crucial ingredient to the tagging of boosted *V*- and Higgs bosons as well as top-quarks
- **B-tagging tools** essential to identify *b*-quarks and study processes with *b*-jets in the final state
- Tools based on the properties of *b*-hadrons originated inside the jet
  - High-level taggers developed and applied to jets (**resolved**) and variable radius track jets matched to large-R jets (**boosted**)
  - Dedicated algorithms to identify *b*-jets in boosted topologies

CMS-BTV-16-002

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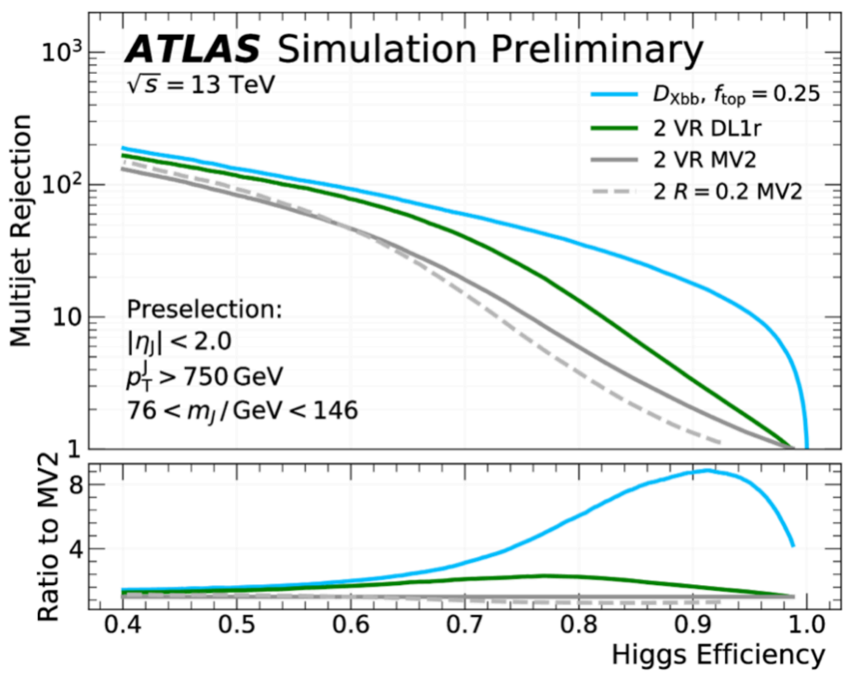
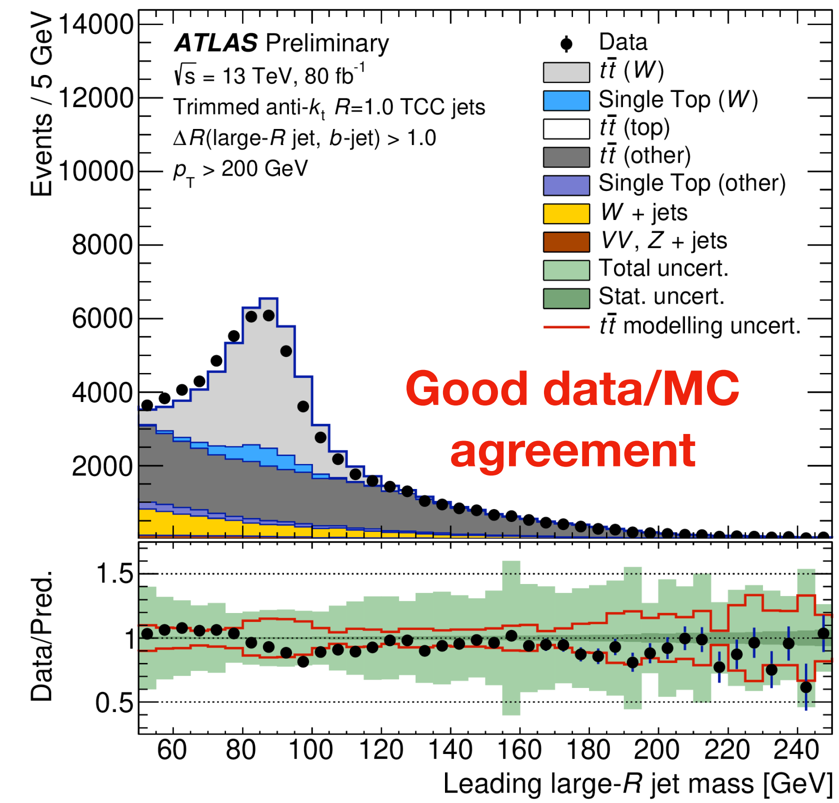



- Such as the Xbb tagger used by ATLAS to distinguish boosted $H \rightarrow bb$ from QCD jets and t-quarks, applied on the Large-R jet

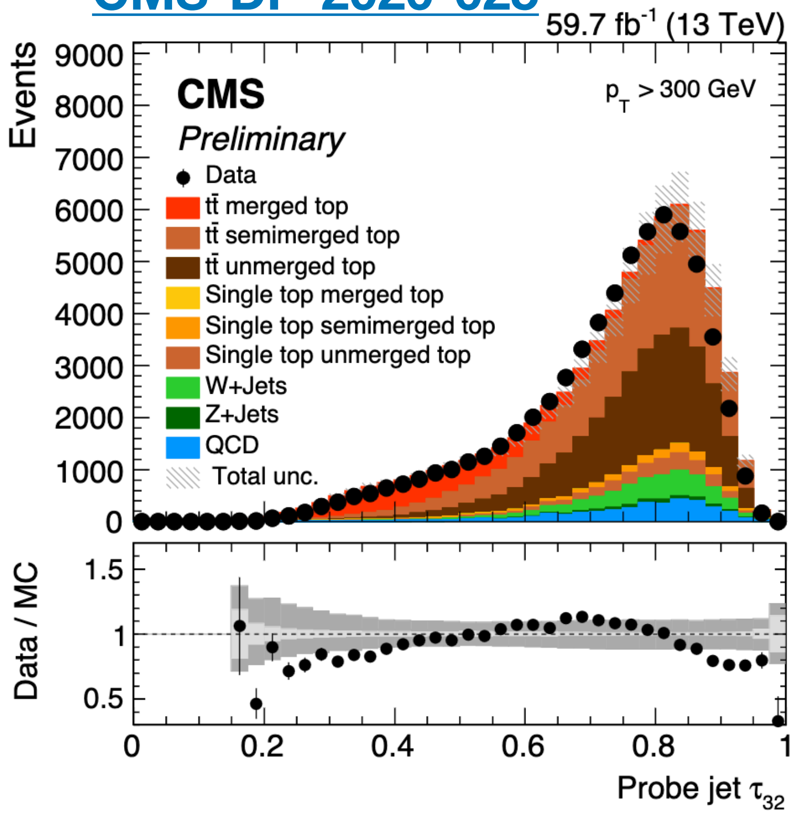
# Boosted $V$-boson and $t$-quark tagging



- W/Z bosons and top-quark taggers are used to identify hadronically decaying particles based on large-R jets
- They are either cut-based ($V$-taggers in **ATLAS**) or deep neural-network-based ($W$ tagger in **CMS and** top-quark taggers)
- Dedicated scale factors on the signal efficiency
  - Derived by comparing the performance between data and Monte-Carlo simulation




CMS-DP-2020-025

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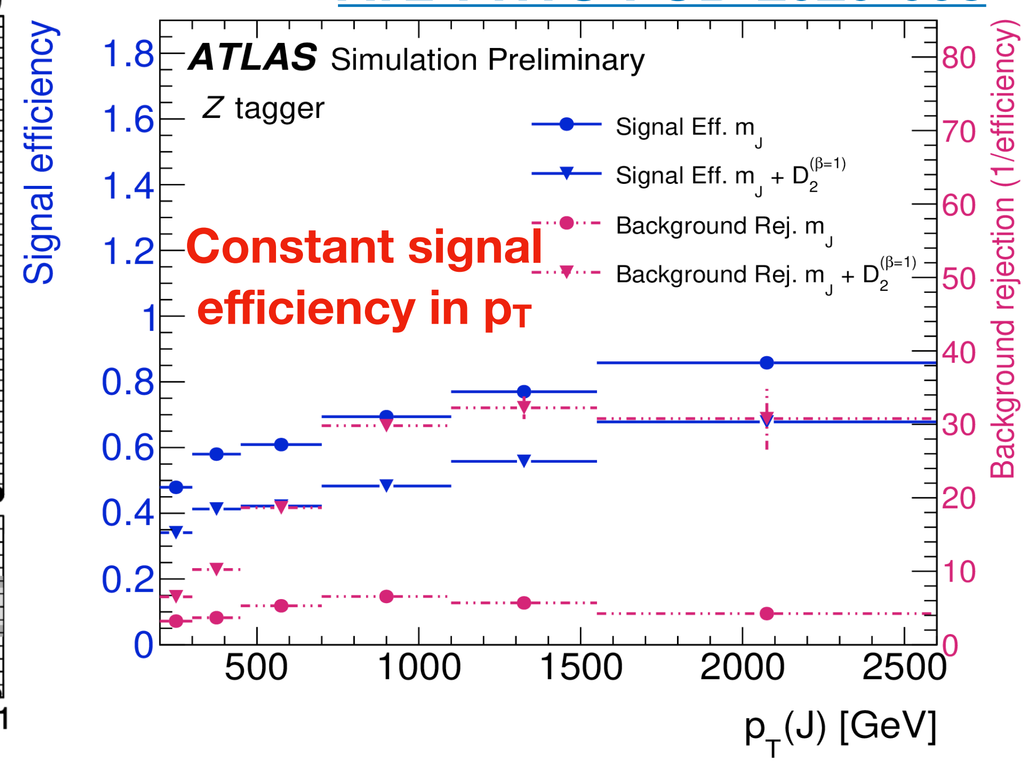


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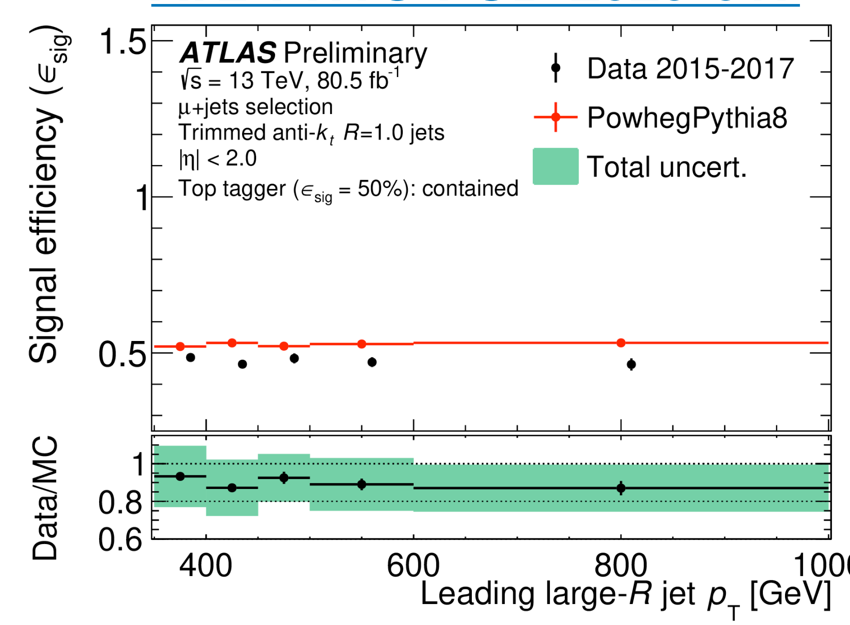
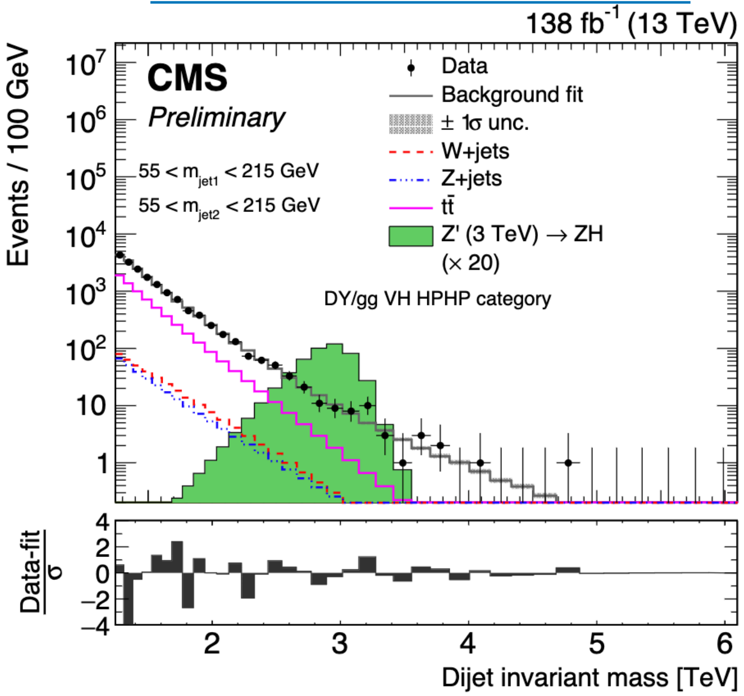
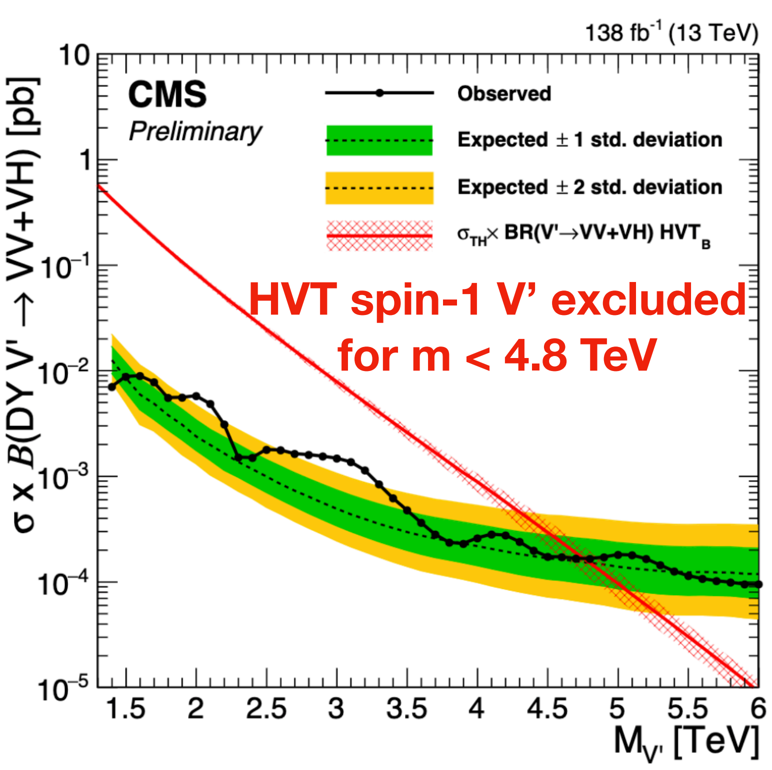


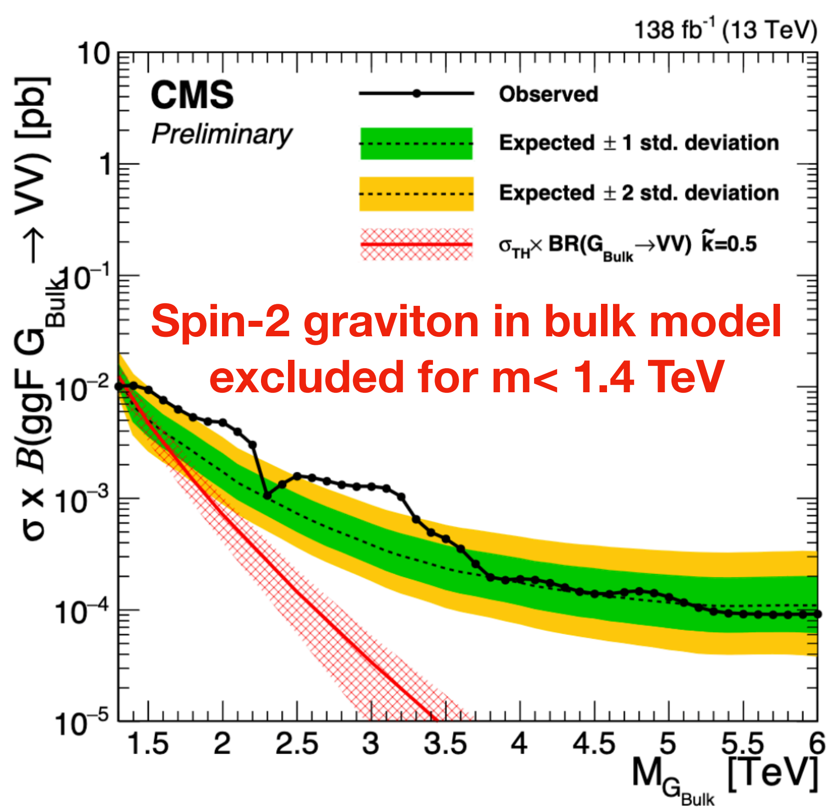
# Fully hadronic X → VV/ VH

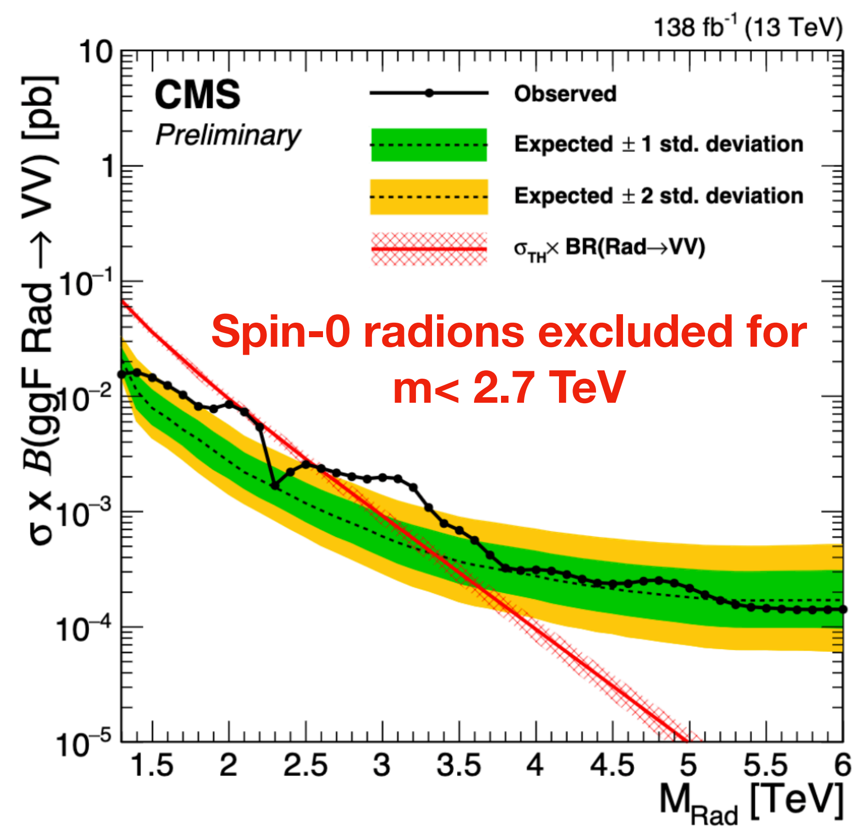
[CMS-PAS-B2G-20-009](CMS-PAS-B2G-20-009)




- Search for new heavy resonances decaying to pairs of bosons (WW, WZ, or WH) in the all-jets final state
- Final state events with either two Large-R jets for DY/gg production and two additional small-R jet for VBF production
- **A 3D maximum likelihood fit to $m_{jj}$, $m_{j1}$ and $m_{j2}$**
- Largest deviation of 3.6σ (local) and 2.3σ (global) at 2.1 and 2.9 TeV
- VBF production constrained with an upper **cross section limit of 0.1fb**
- Several models were considered to set mass exclusion limits



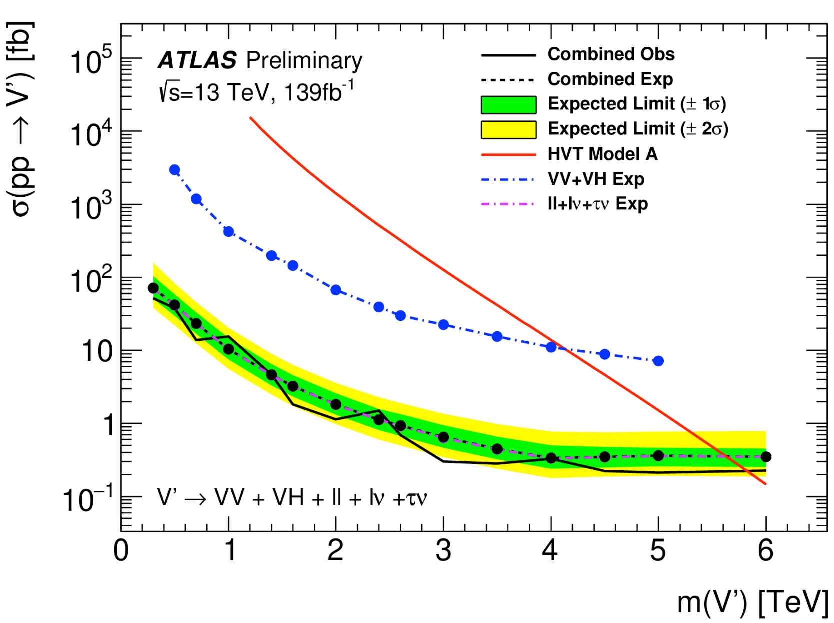



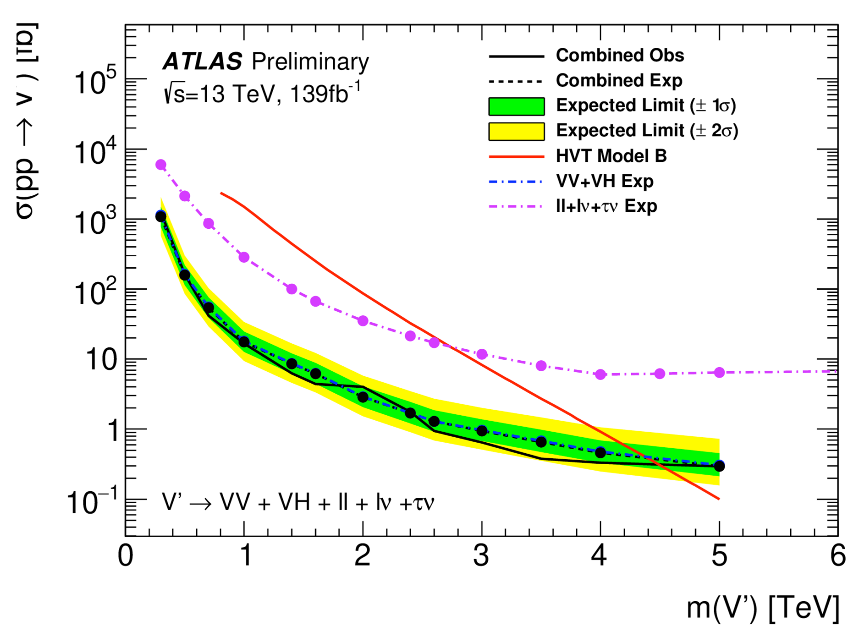
# V’ → bosons/leptons combination

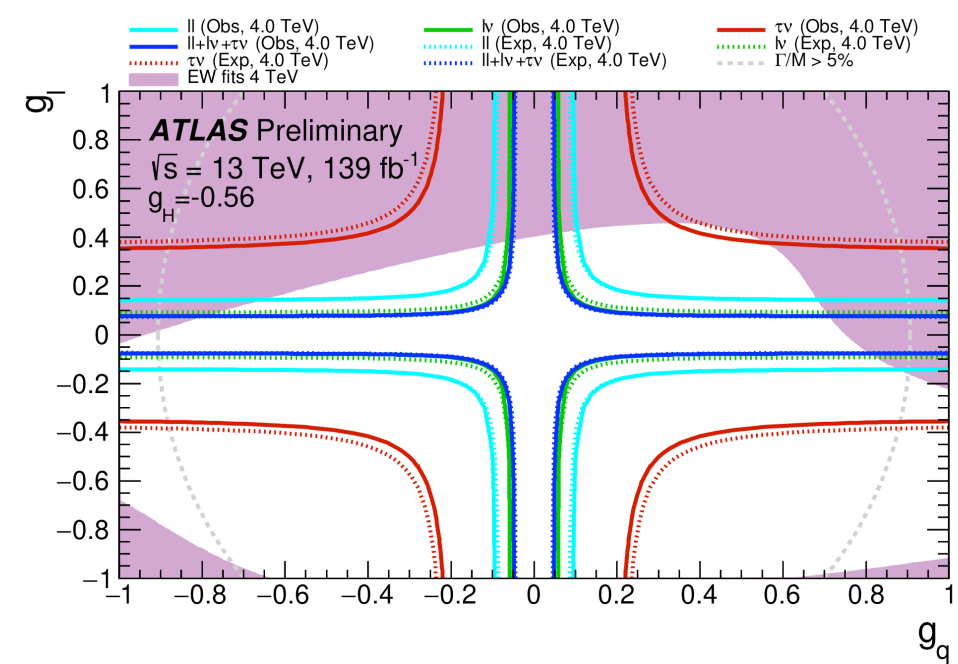
- A search for a **new heavy resonance *V’*** $\rightarrow VV/VH/\ell\nu/\ell\ell$
- The combined measurements strengthen the constraints on physics beyond the SM
- Investigate model predicting a **spin-1 heavy vector-boson triplet (HVT)**
- Cross-section limits are set as a function of the resonance mass using an asymptotic approximation
- The 95% CL in the weakly coupled **HVT model A is 5.8 TeV** and the corresponding limit in the strongly coupled **HVT model B is 4.5 TeV**
- Set stringent **constraints on couplings** of the heavy vector-boson triplet to quarks, leptons, and the Higgs boson

ATLAS-CONF-2022-028

| Analysis | leptons | $E_{T_{miss}}$ | jets | b-tags | Discr. |
|---|---|---|---|---|---|
| $WW/WZ \rightarrow qqqq$ | 0 | Veto | ≥2J | - | $m_{VV}$ |
| $WZ \rightarrow \nu\nu qq$ | 0 | Yes | ≥1J | 0 | $m_{VV}$ |
| $WZ \rightarrow \ell\nu qq$ | 1e, 1$\mu$ | Yes | ≥2j, ≥1J | 0, 1, 2 | $m_{VV}$ |
| $WZ \rightarrow \ell\ell qq$ | 2e, 2$\mu$ | - | ≥2j, ≥1J | 0 | $m_{VV}$ |
| $WZ \rightarrow \ell\nu\ell\ell$ | 3 ⊂ (e, $\mu$) | Yes | - | 0 | $m_{VV}$ |
| $WH \rightarrow qqbb$ | 0 | Veto | ≥2J | 1, 2 | $m_{VH}$ |
| $ZH \rightarrow \nu\nu bb$ | 0 | Yes | ≥2j, ≥1J | 1, 2 | $m_{VH}$ |
| $WH \rightarrow \ell\nu bb$ | 1e, 1$\mu$ | Yes | ≥2j, ≥1J | 1, 2 | $m_{VH}$ |
| $ZH \rightarrow \ell\ell bb$ | 2e, 2$\mu$ | Veto | ≥2j, ≥1J | 1, 2 | $m_{VH}$ |
| $\ell\nu$ | 1e, 1$\mu$ | Yes | - | - | $m_T$ |
| $\tau\nu$ | 1$\tau$ | Yes | - | - | $m_T$ |
| $\ell\ell$ | ≥2e, ≥2$\mu$ | - | - | - | $m_{\ell\ell}$ |

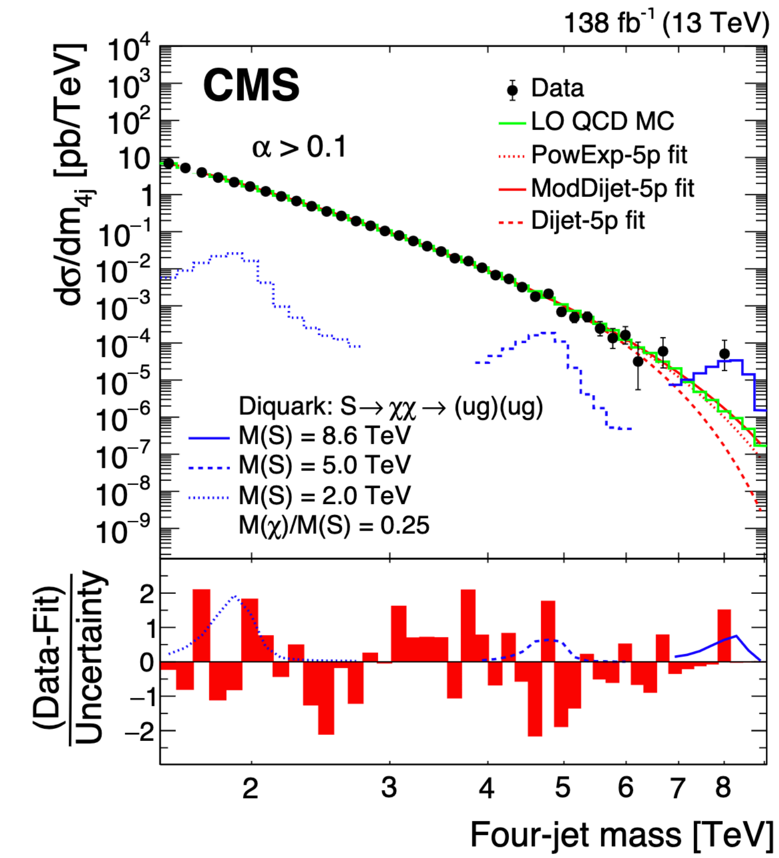


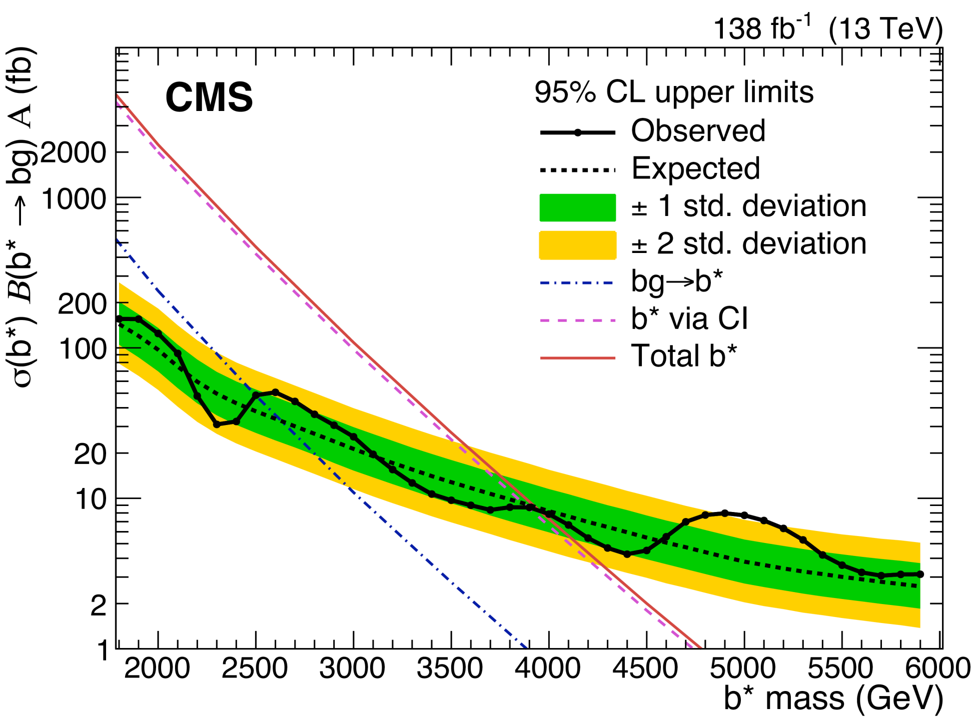



# Dijet and multijet resonances

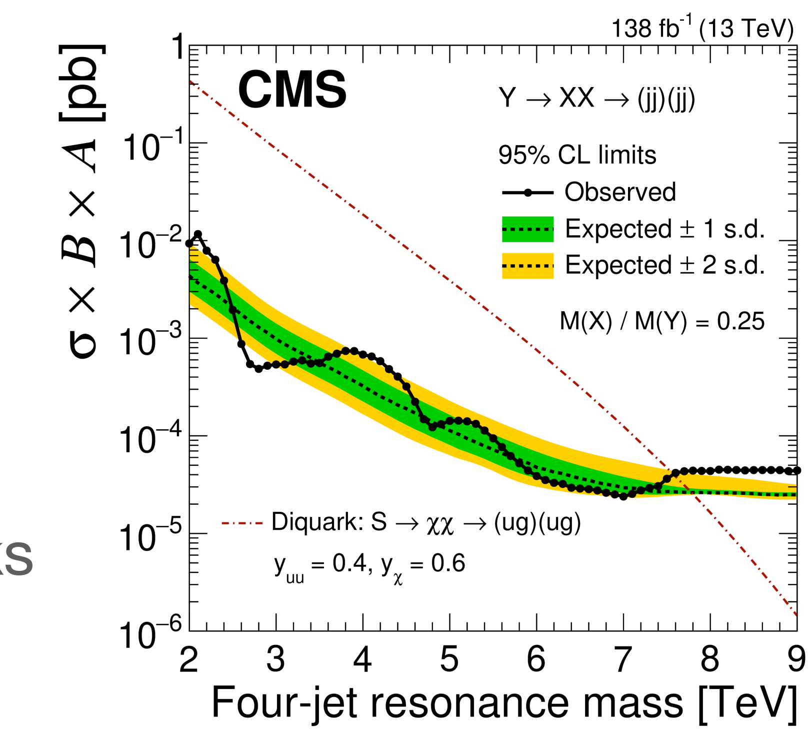
CMS-EXO-20-008 CMS-EXO-21-010




- Search for resonances decaying to jets: X → jj and X → YY → (jj) (jj)
- Using the invariant mass of the jet pairs to **set limits** by fitting a smooth background parameterisation
- Limits set for **dijet final states with *b*-quarks** to exclude models of Z' bosons in the HVT Model A and SSM with masses from **1.8 to 2.4 TeV** and b*-quarks model from **1.8 to 4.0 TeV**



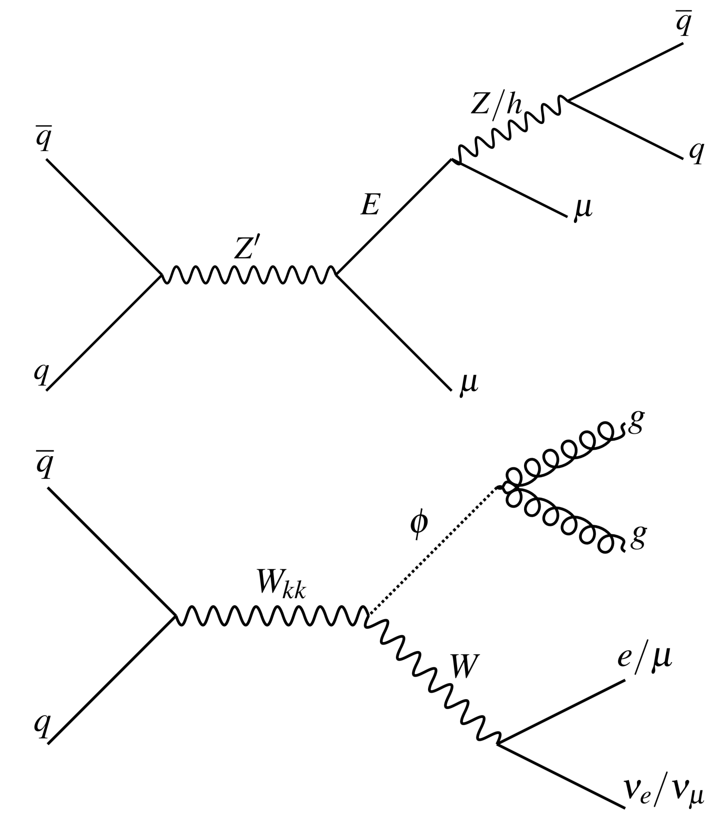

- Limits set for **production cross section of pairs of dijets** as function of $m_{jjjj}$ for model of scalar diquarks decaying to vector-like quarks

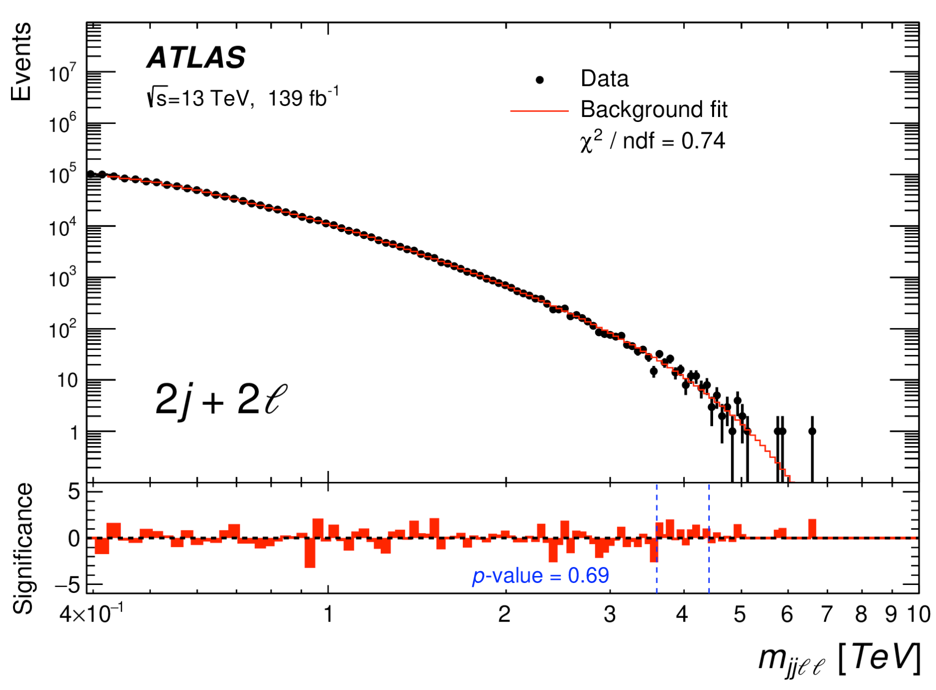


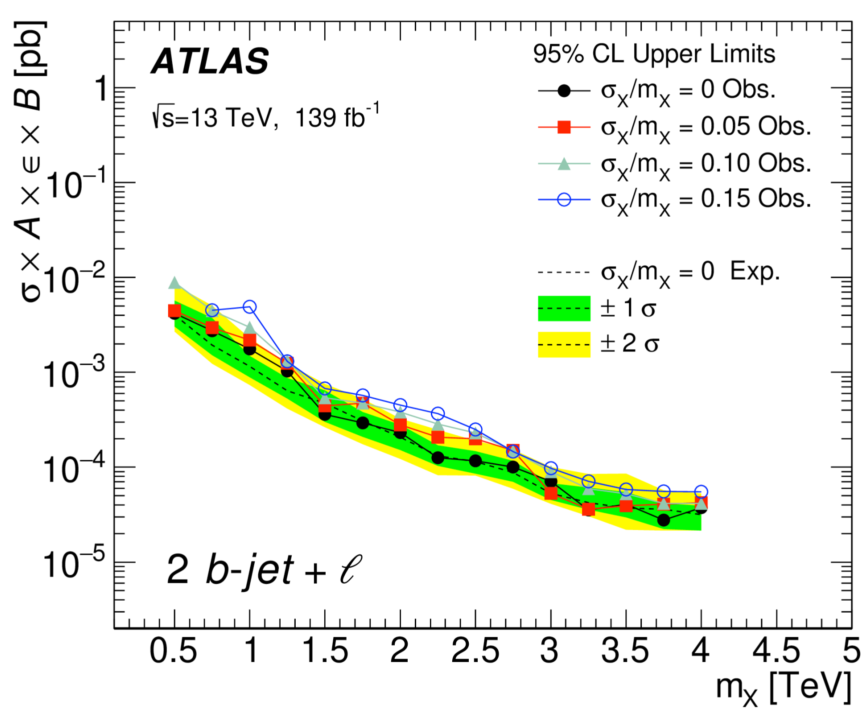
# Search with multi-body invariant mass

ATLAS-CONF-2022-048

- Search for resonances with at least one isolated charged lepton
- Access low-mass regions with lepton triggers (difficult in dijet events)
- A new resonant state X (→jet, lepton, photon) and **three- and four-body invariant mass distributions**
- No significant excess above the smoothly falling background
- Model independent limits using $m_X$ at 95% CL set on the cross section times the branching ratio
- Limits set on other contributions from models such as the Sequential Standard Model (SSM) and a simplified DM model



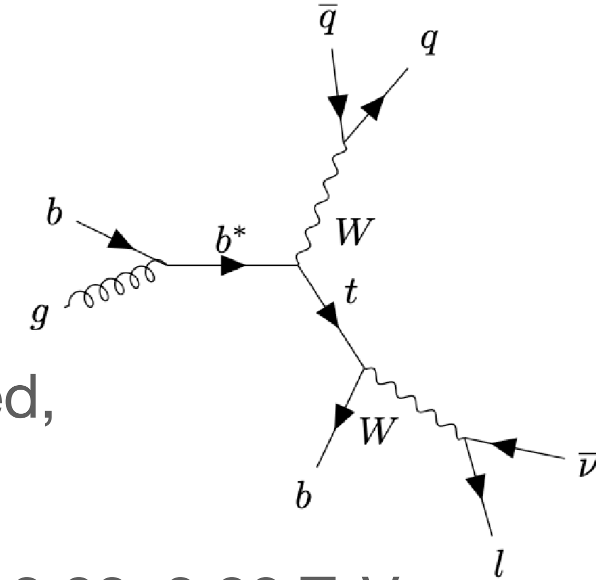



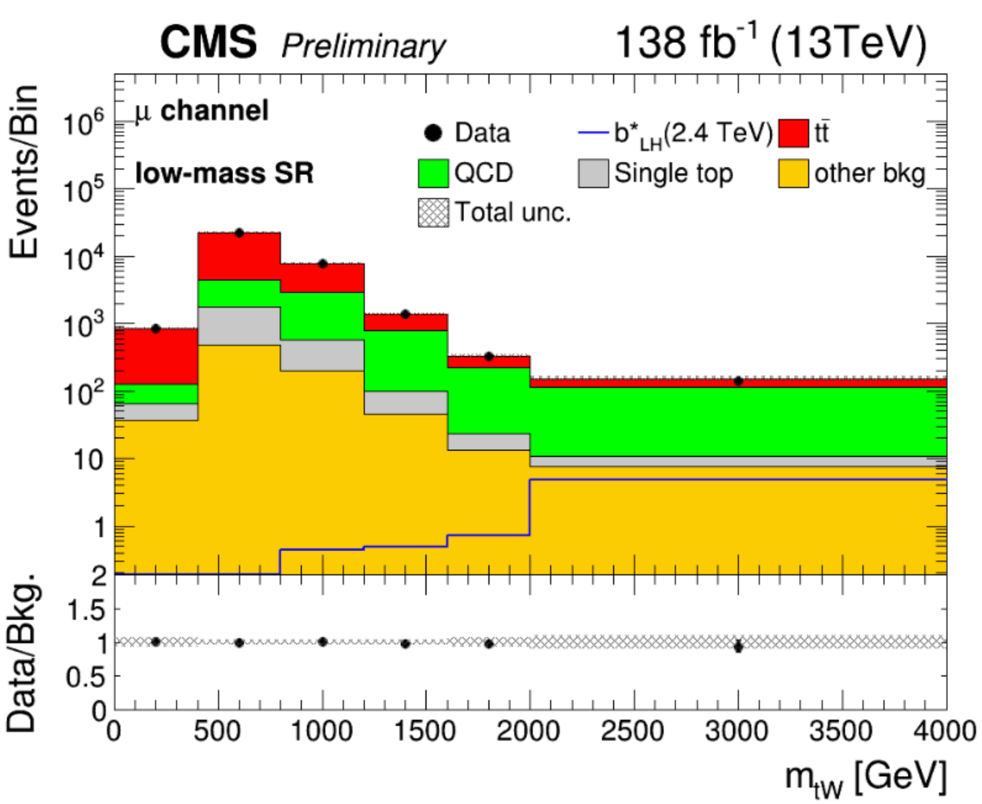
# $b^* \to tW \to$ leptons+jets

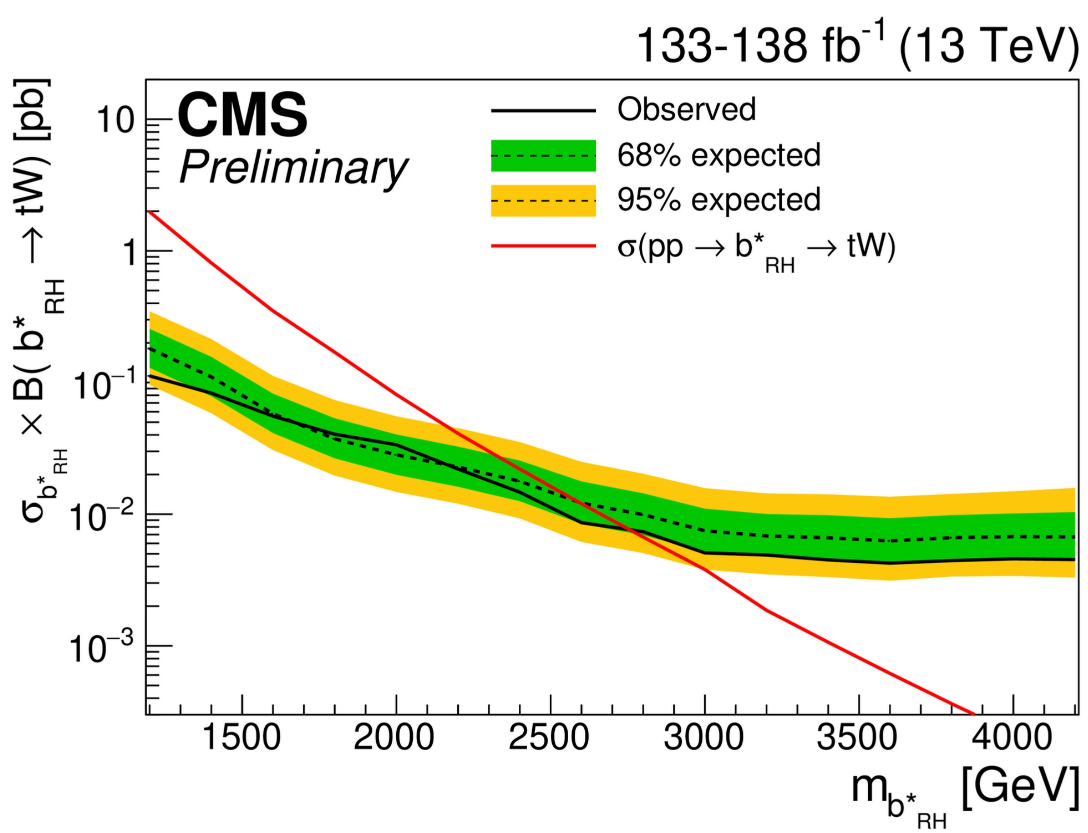
CMS-PAS-B2G-21-005

- Searches for heavy resonances decaying into a *t*-quark and *W*-boson
- Two different searches with the hadronic and leptonic decay channels of the *W*-boson (from the resonant decay)
- Maximum Likelihood fit using $m_{tW}$ distributions
- Limits set on excited *b*-quark (*b*)* hypotheses with left- handed, right-handed, and vector-like chiralities respectively:



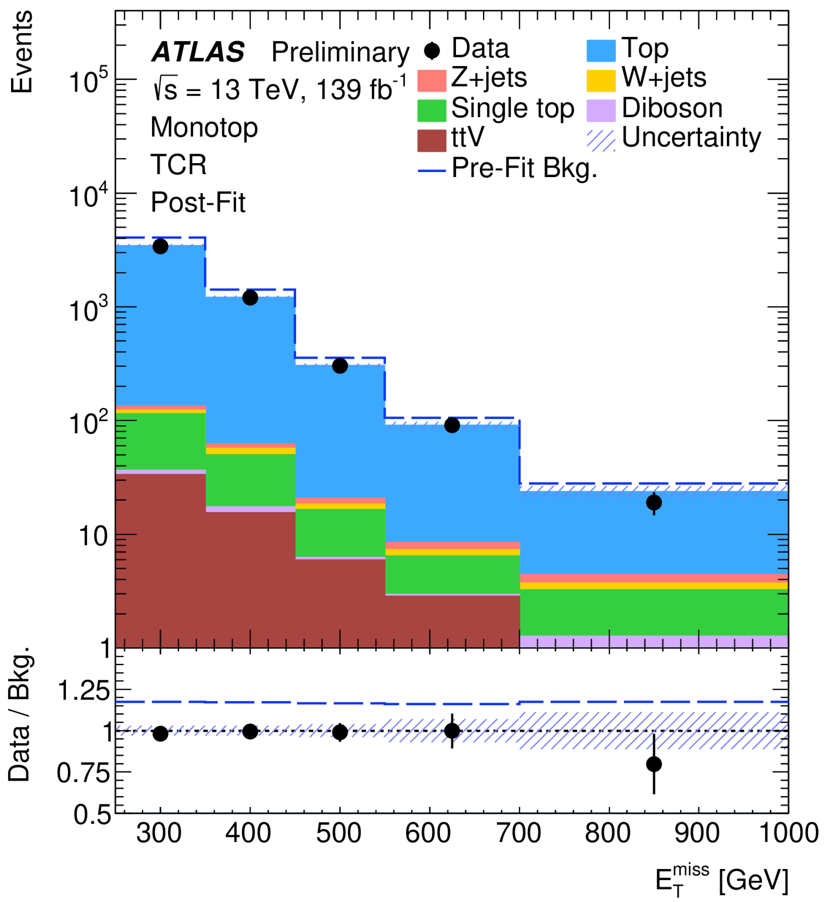

- $t \to b\,W(\to qq')$ and $W \to qq'/\ell\nu$ channel: excluded for masses below 2.95, 3.03, 3.22 TeV
- $t \to b\,W(\to \ell\nu)$ and $W \to qq'$ channel: excluded for masses below 2.4, 2.8, 3.1 TeV



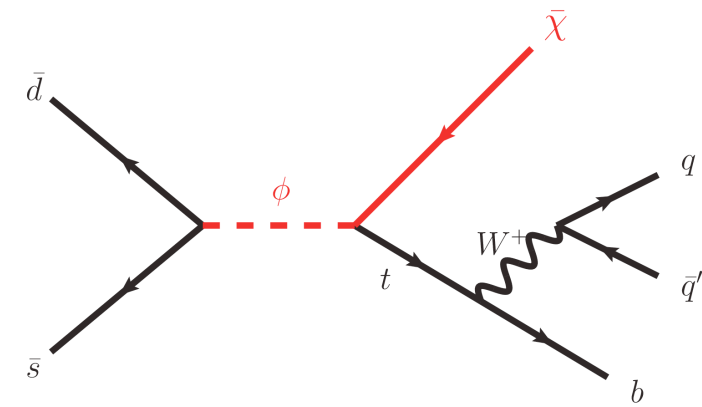



# Mono-top search

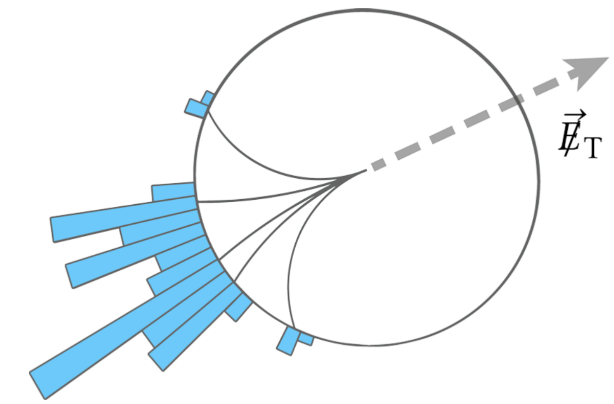
ATLAS-CONF-2022-036

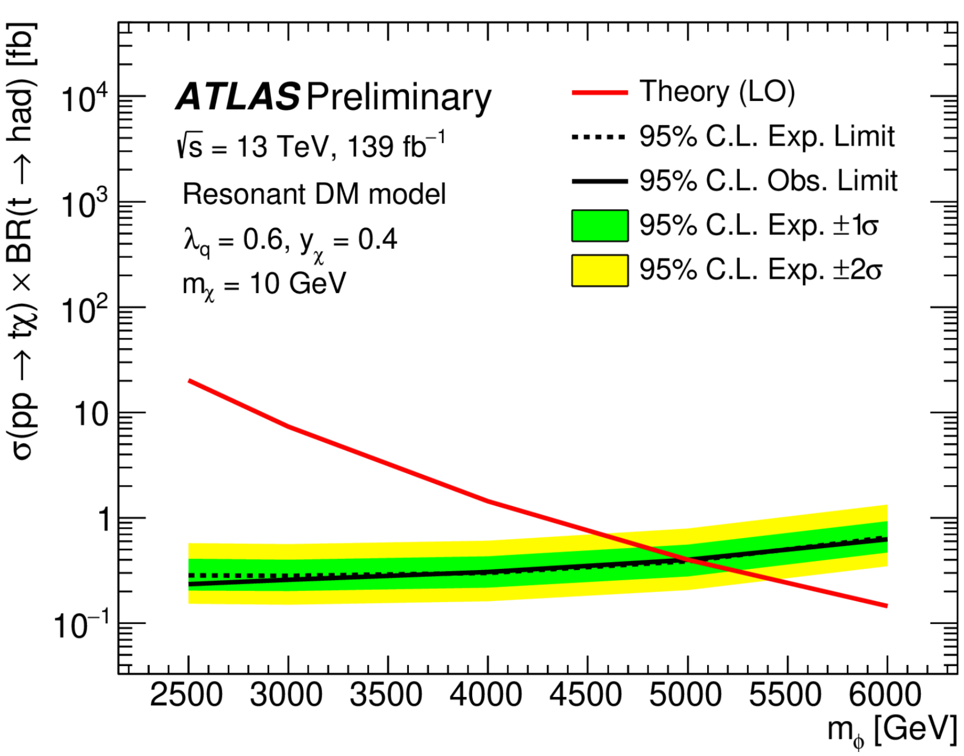



- Search for a heavy scalar resonance ϕ decaying into an invisible particle X and a top quark




- Final states with **large** amount of missing transverse energy ($E_T^{miss}$)
- $E_T^{miss}$ is reconstructed from the negative vector sum of calibrated leptons, small-R jets and a soft term from all tracks associated with the primary vertex



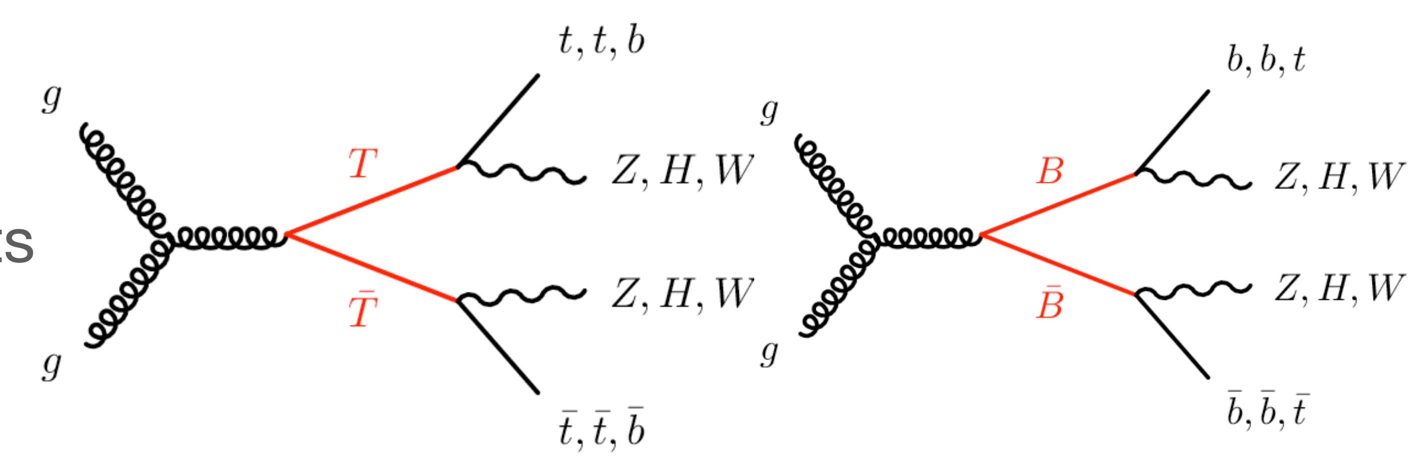



- Considering vector-like T-quark models and simplified models for Dark Matter (DM)
- Limits set as function of $m_\phi$, at 95% CL on the production of vector-like T-quark
- Large improvement on the limits of DM resonant production

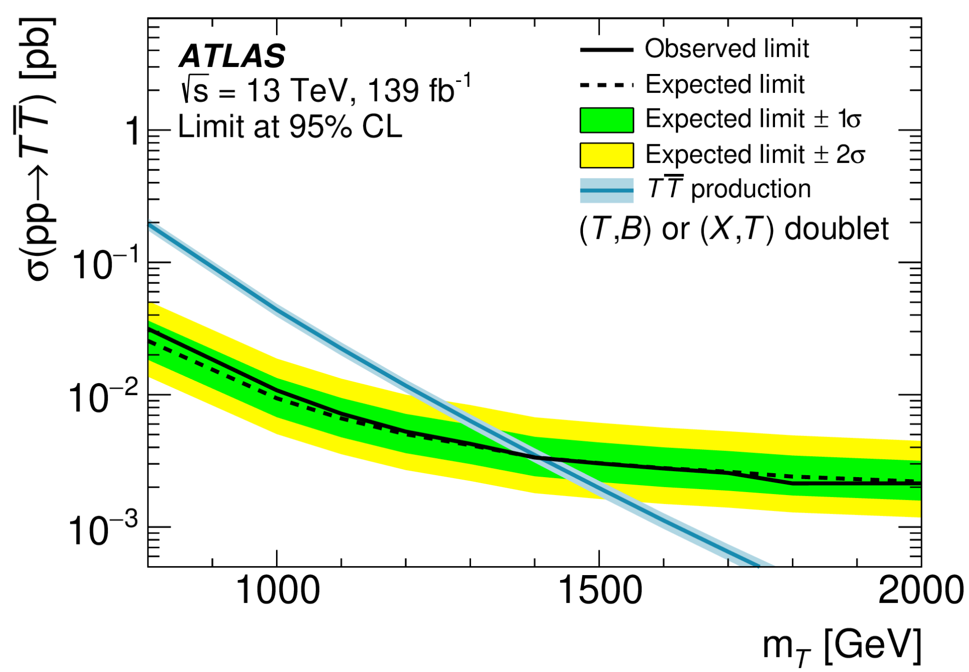
# Vector like T- and B-quarks

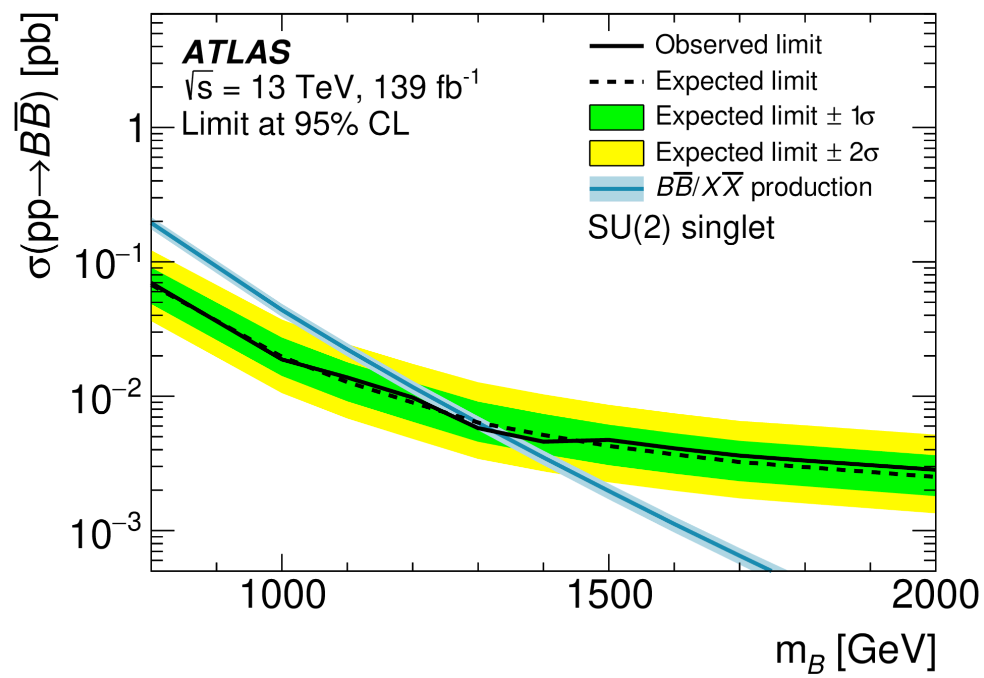
CERN-EP-2022-201

- Vector-like quarks (VLQ) decay to SM bosons and third generation quarks
- Search for production of a T- and B-quarks vector like pairs, considering one lepton, jets and large $E_T^{miss}$ in the final state
- Signature with at least 4 jets and at least one *b*-tagged jet




- No significant deviations from the SM expectation were observed

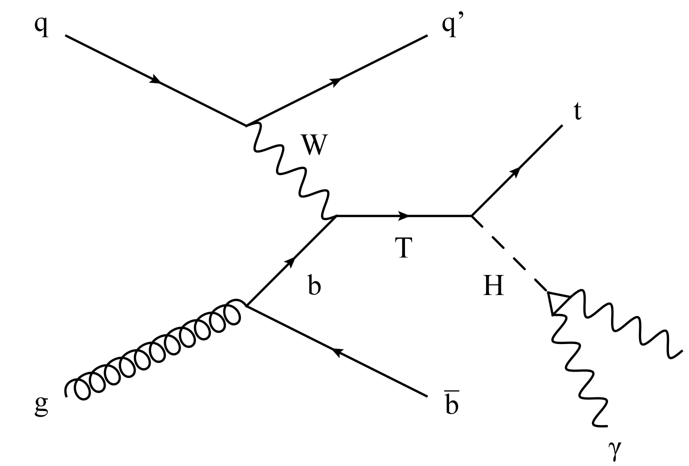


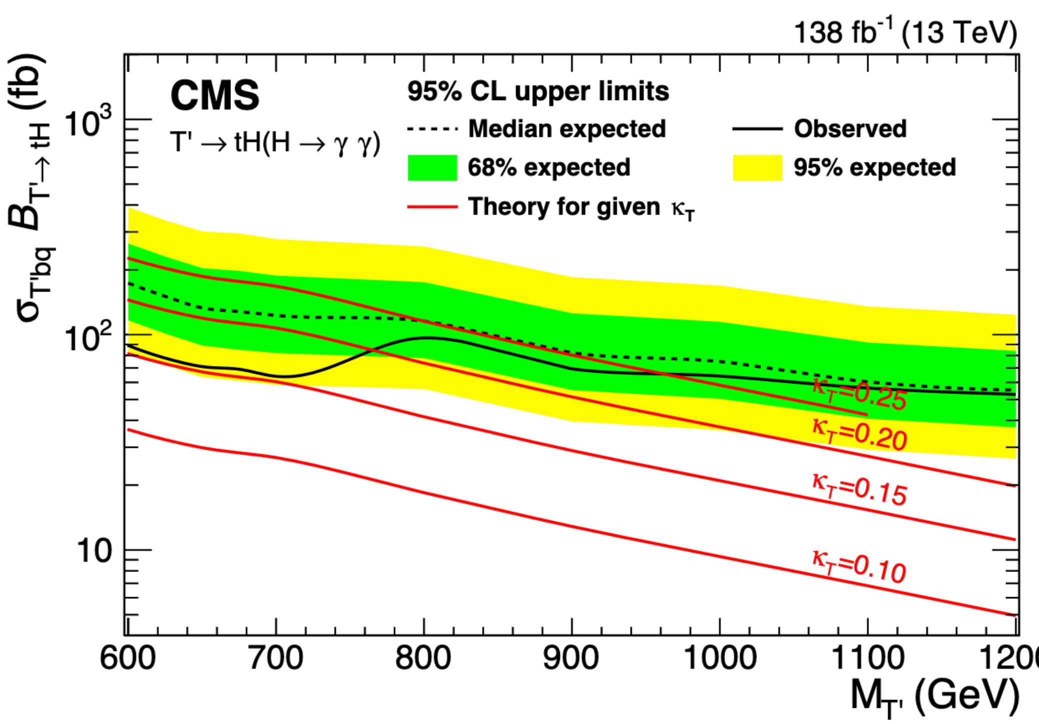

- **Strongest limits** at $m_{T/B}$ = 1.59 TeV for degenerate masses and weak-isospin doublet model for branching ratios
- **Upper and lower cross section limits set as function of the mass of the T- and B-quarks**

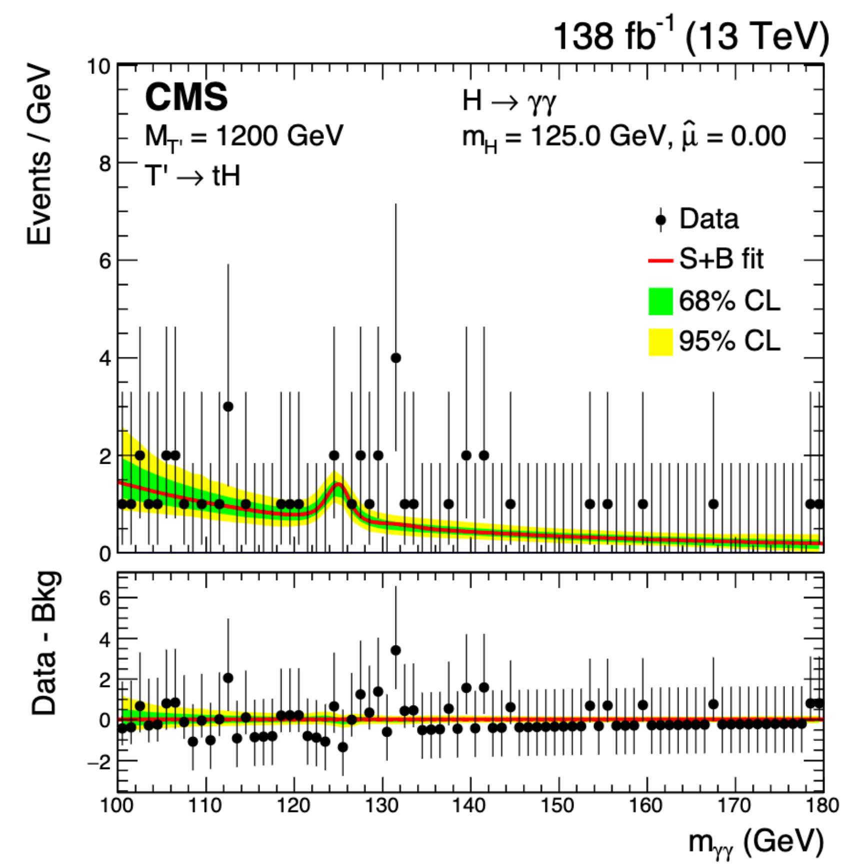
# Vector-like quark T’→$t$ H→$t$ γγ

CMS-B2G-21-007




- **First search for a vector-like quark T’ → $t\ H$ with $H$ → γγ**, considering both hadronic and leptonic decays of $t$-quark
- Based on a model of the electroweak production of T’ in a narrow width approximation Γ with $\Gamma/M_{T'}$ ~1%
- Use BDTs for better discrimination of signal and background
- Maximum likelihood fit of $m_{\gamma\gamma}$ distribution for $M_{T'}$ = 600, 900,1200 GeV
- T′ production with **mass up to 960 GeV is excluded at 95% CL** assuming a coupling strength **$K_T$ = 0.25 and $\Gamma/M_{T'}$ < 5%**

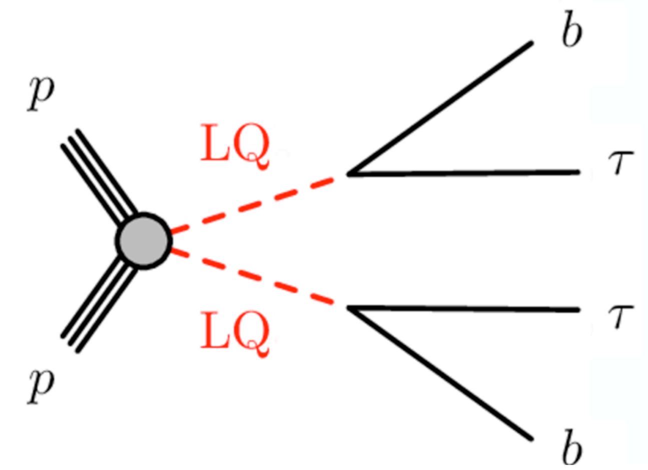


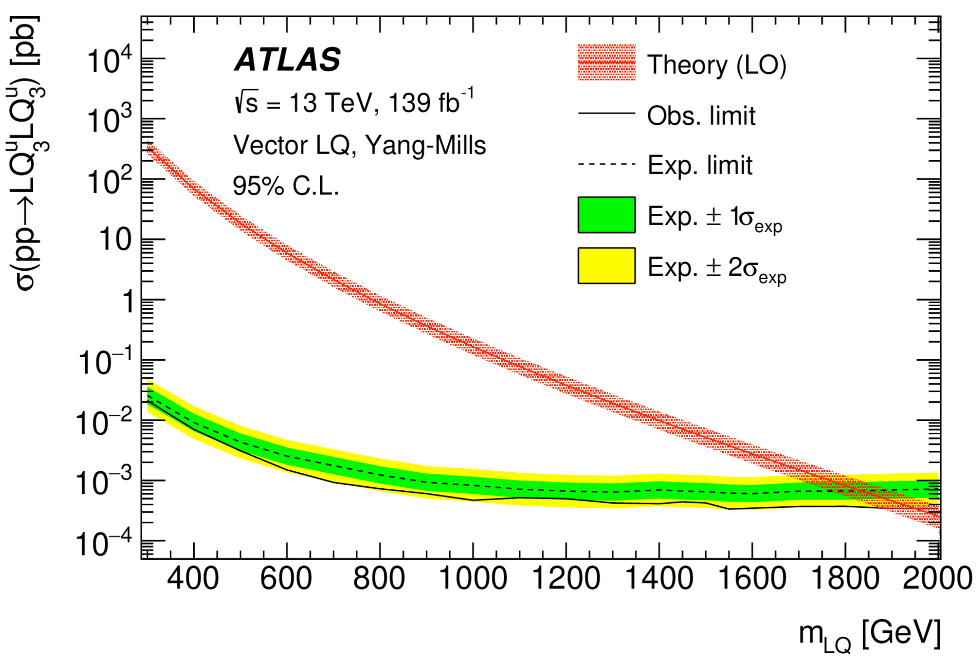



# Leptoquarks

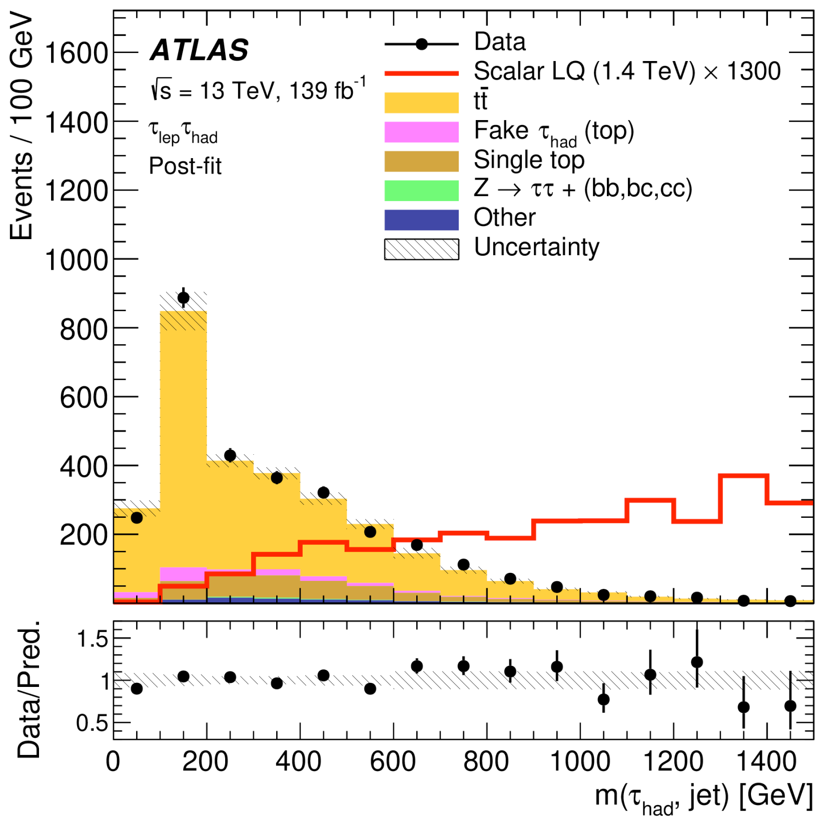
CERN-EP-2022-267

- Search for Leptoquarks (LQ) pair production, decaying to *b*-quarks and $\tau$-leptons (two $\tau_{lep}\tau_{had}$ and $\tau_{had}\tau_{had}$ channels)
- LQ describe the similarities of the lepton and quark and a potential explanation for lepton flavour anomalies



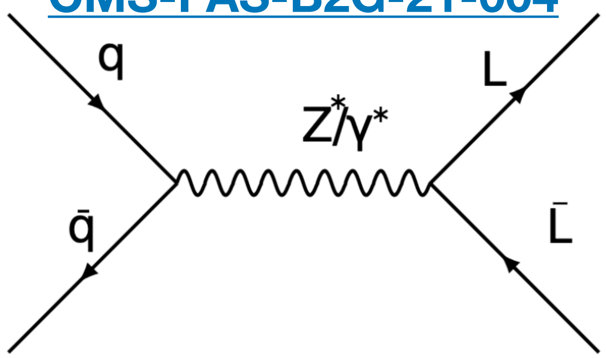

- Parameterised neural networks to extract the signal for an optimised sensitivity in the full mass range
- Maximum binned likelihood fit is performed
- Investigating different hypothesis: scalar and vector LQ pairs



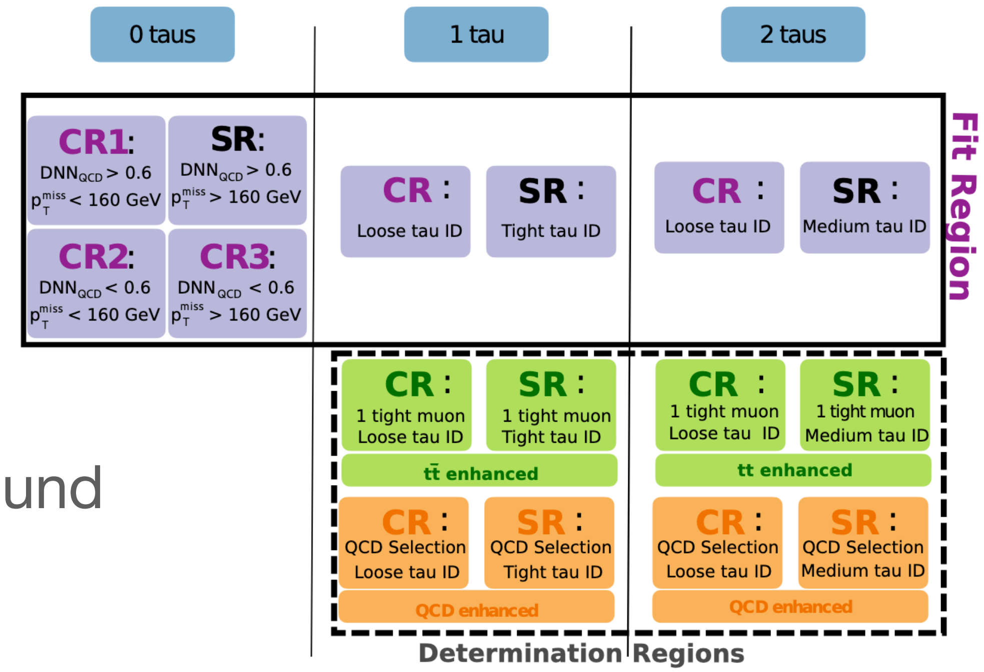

- **Upper limits on the production cross-section** at 95% CL as function of mass LQ were set
- Limits on the mass set for the different LQ hypotheses

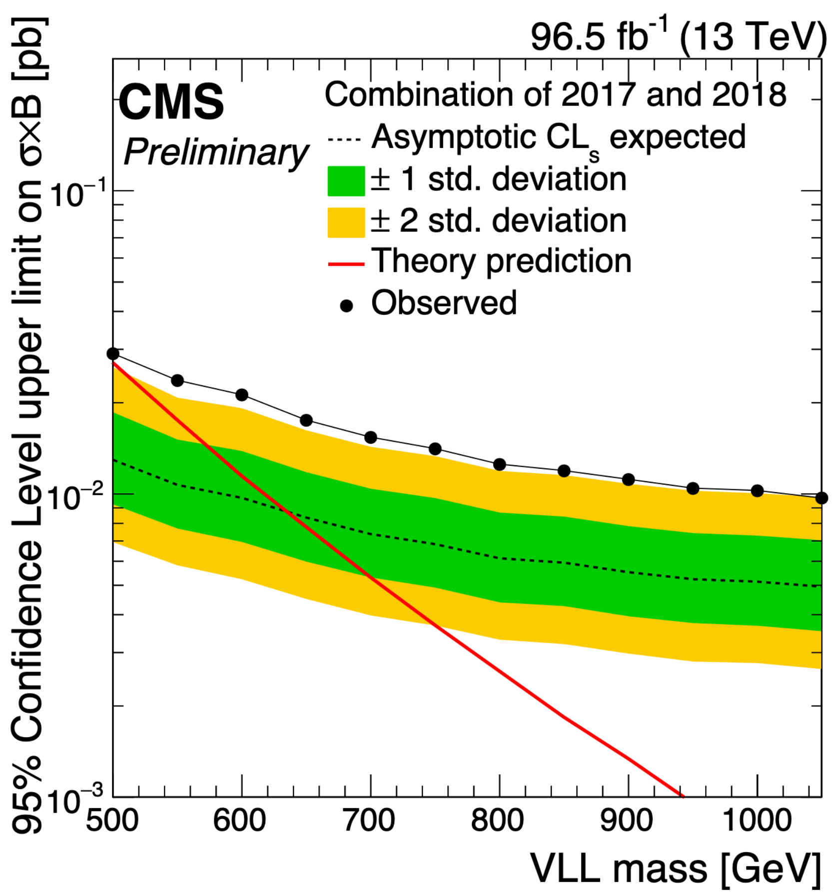
# Vector-like leptons

[CMS-PAS-B2G-21-004](CMS-PAS-B2G-21-004)




- **First search for pair production of vector-like leptons** (VLL)
- VLL decaying to third generation SM particles (through leptoquark interactions) as an interpretation for **flavour anomalies observed in *B*-hadron decays**
- Considering 4*b*-quarks and $\tau$-leptons in the final state
- Categorisation based on the number of $\tau$ in the event



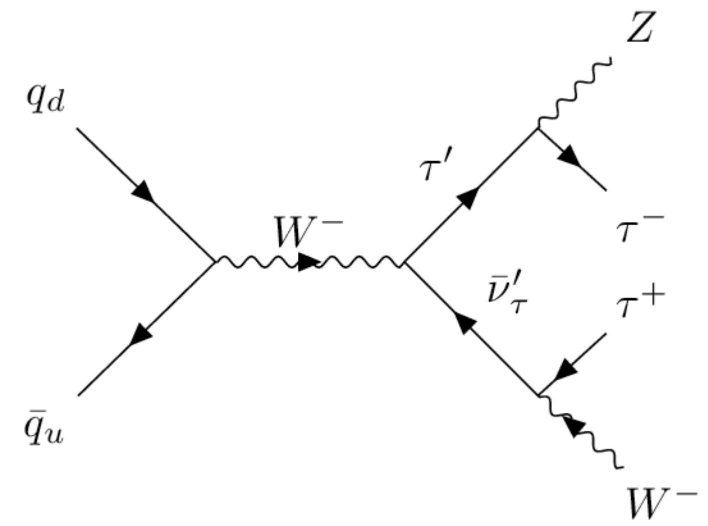

- QCD and tt enhanced control regions to constraint background and dedicated classifiers to separate from signal
- A maximum likelihood fit is performed across all $\tau$-categories
- Limits on the cross sections were set between 10 and 30 fb depending on the VLL mass hypothesis
- The largest excess found at the level of 2.8σ, for a VLL mass of 600 GeV

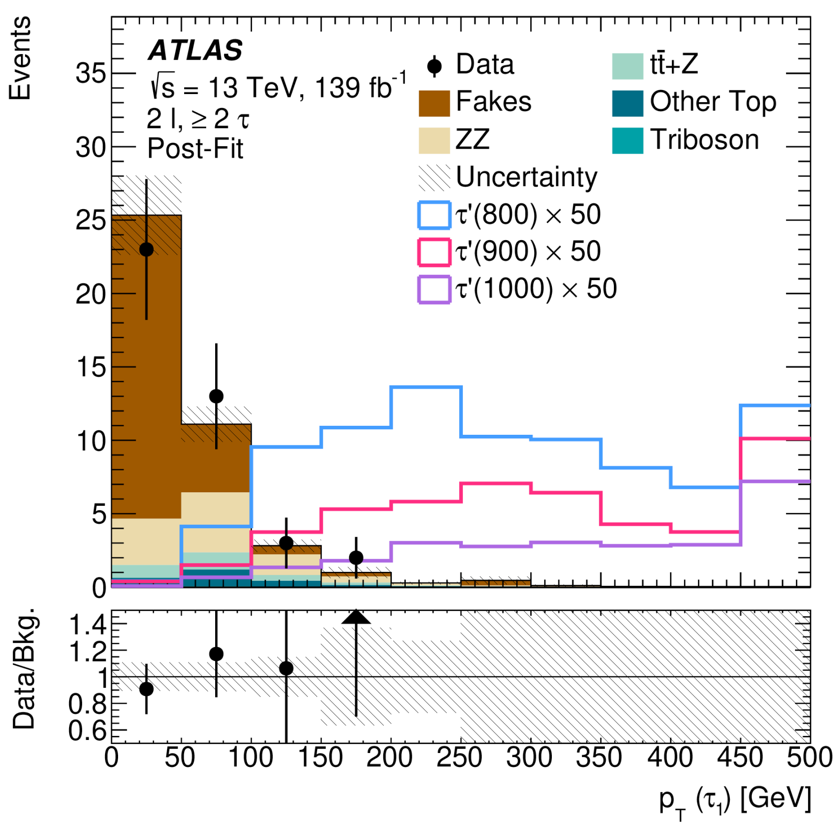
# Vector-like taus

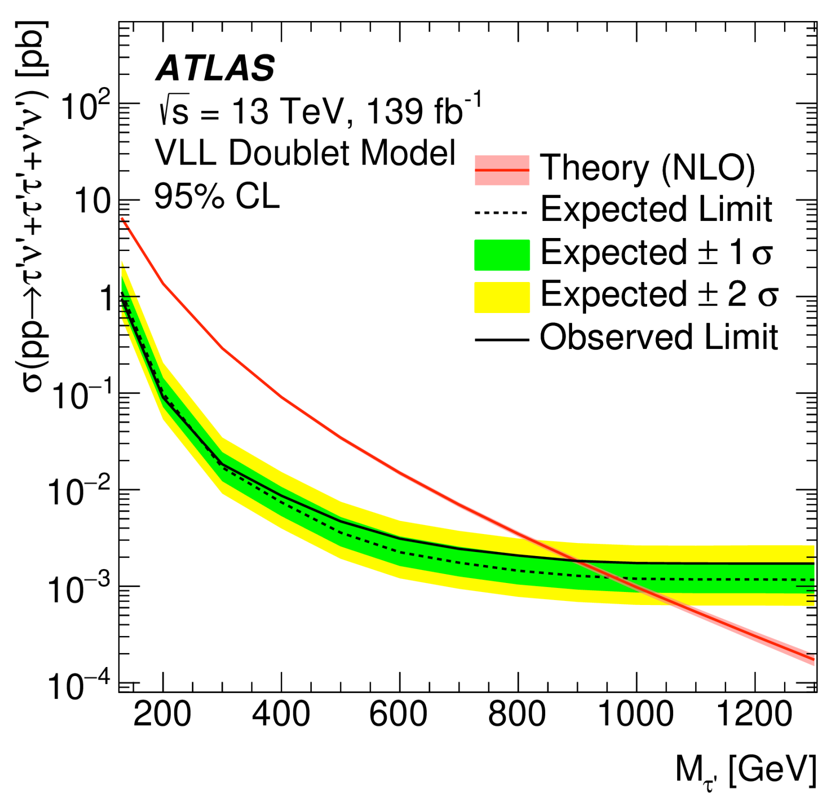


EXOT-2020-07

- Search for vector-like $\tau$-leptons decaying to multileptons
- With **hadronic $\tau$-leptons in the final state**
- MVA analysis using Boosted Decision Tree (BDT) classifier for best signal and background separation
- Binned maximum likelihood fit to the BDT score template
- Target models of doublet vector-like lepton and vector-like leptons coupling to third-generation SM leptons



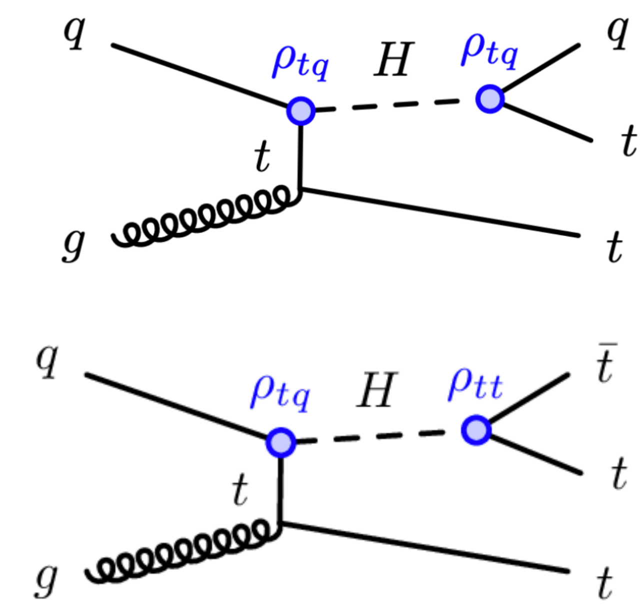



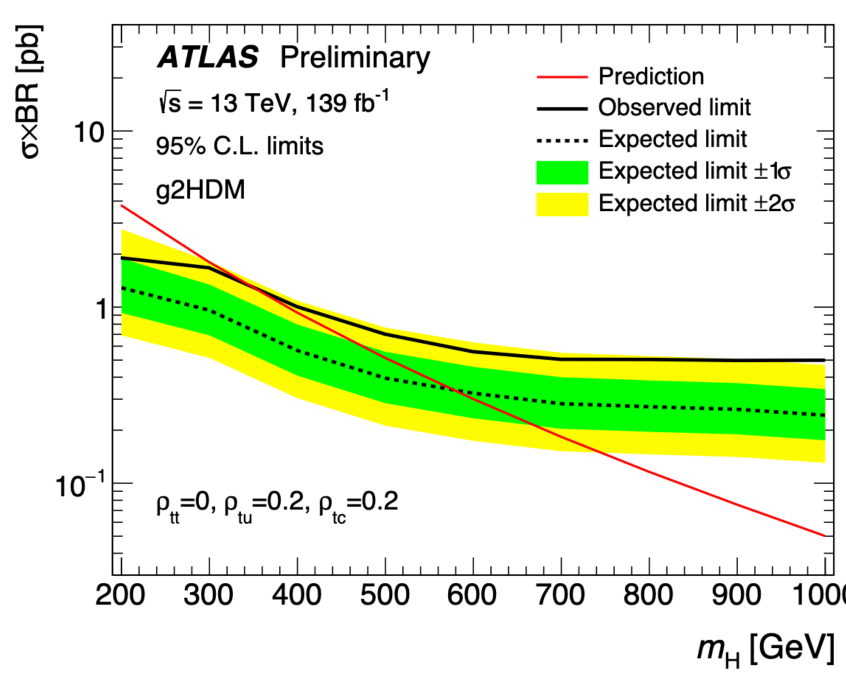

- No excess observed beyond the Standard Model expectation
- Upper limit on the production cross section was calculated
- **Upper exclusion mass limit set at 970 GeV at 95% CL**

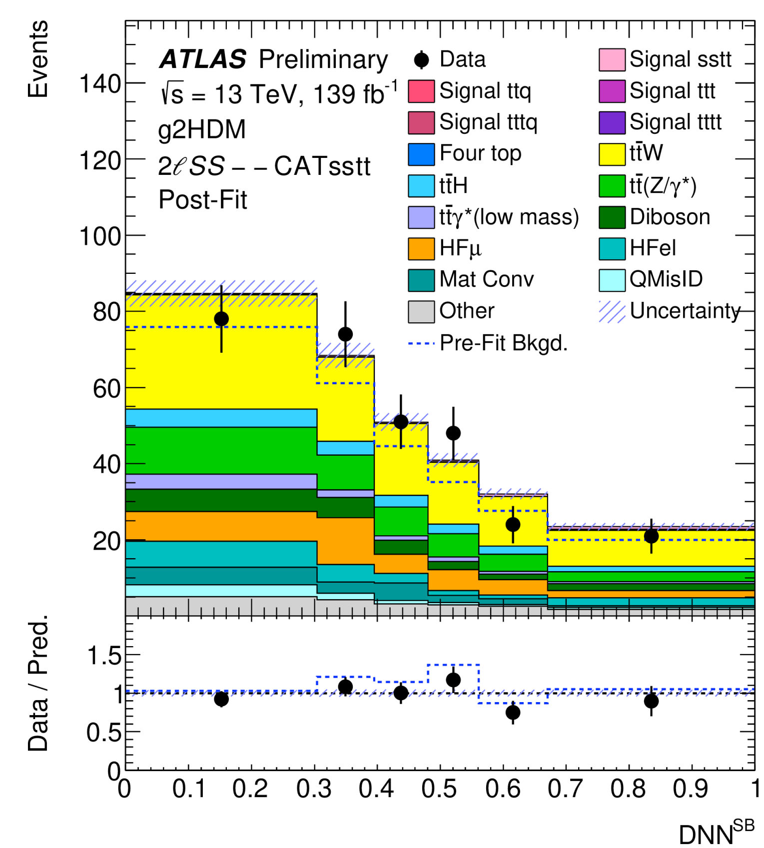
# Heavy Higgs boson

ATLAS-CONF-2022-039

- **Heavy Higgs boson search with multi-leptons and *b*-jets in the final state**
- **First BSM search for three top-quark production**
- Results are interpreted in the two Higgs doublet model (g2HDM) with flavour violation
- Only coupling involving top-quarks are considered ($\rho_{tt}$ , $\rho_{tc}$, $\rho_{tu}$ )
- A multi-output deep neural network (DNN) classifier used to improve the sensitivity
- A maximum-likelihood fit is performed DNN discriminant
- A mild excess observed over the SM expectation at $m_H$ = 1000 GeV for a local significance of 2.81$\sigma$
- Limits on $m_H$ were set for different coupling choices



# Conclusion

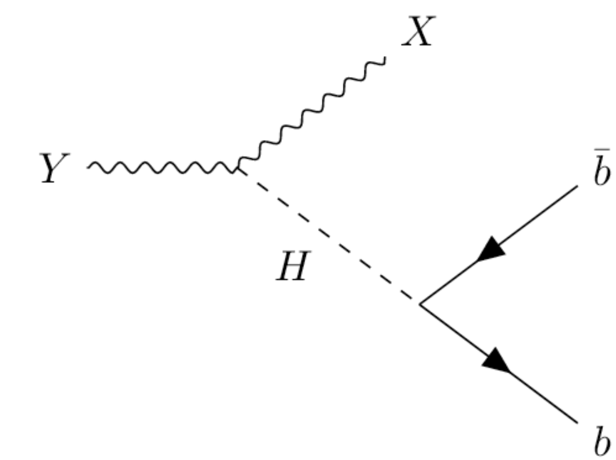
- Many BSM models predict the production of heavy resonances decaying to SM particles
- Summary of recent ATLAS and CMS heavy resonance searches
- Enhancement seen with Run2 analyses due to more statistics, use improved tools for particle identification and reconstruction, combination of analyses
- Still ongoing analysis with full Run2 data. More results coming !
- More progress expected with Run3 → increased luminosity (x2 more data)
    - Limits of the searches can be extended to much higher masses
    - Benefit from the increased collision energy, more analysed data and the further optimised identification algorithms

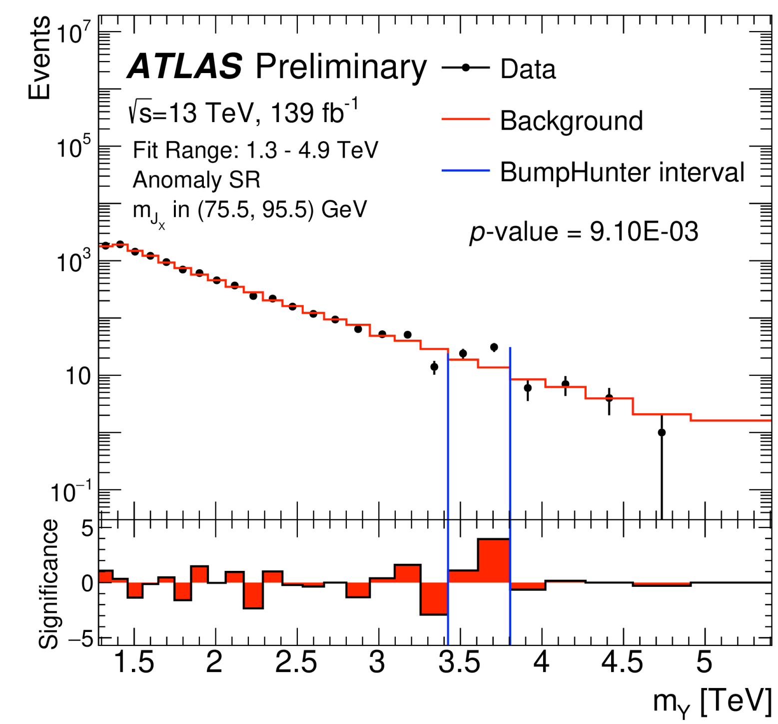
# Back-up

# Y resonance decay to XH

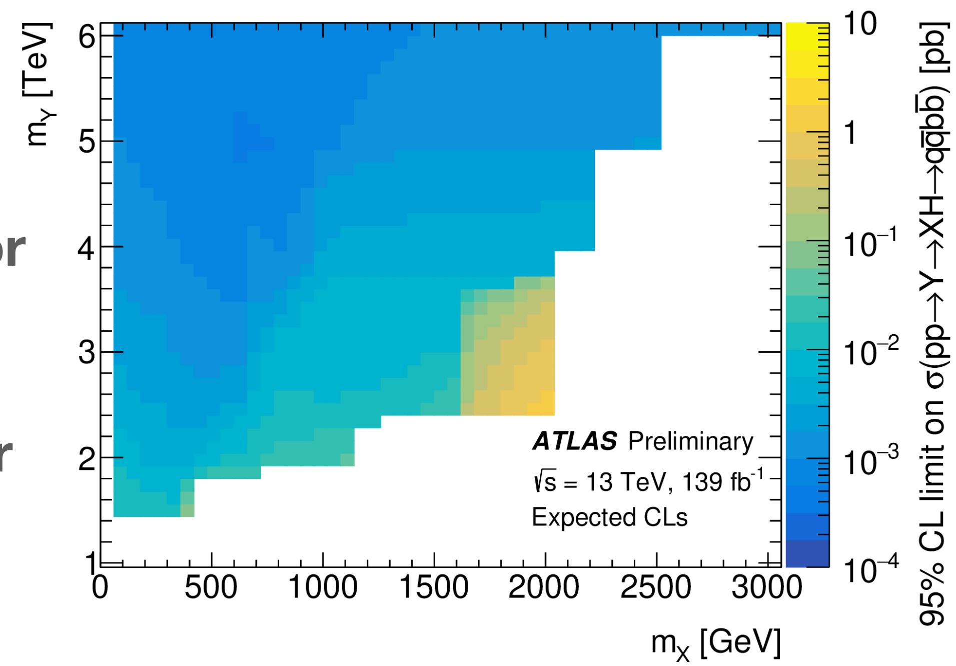
ATLAS-CONF-2022-045

- Search a heavy resonance $Y$ decaying to SM $H$ and a new particle $X$ in a high $Y$ mass regime
- **Fully hadronic final state with $H \rightarrow$ *bb***
- Considering both resolved and boosted topologies and using **Xbb tagger** to increase sensitivity
- Use newly developed $X \rightarrow bb$ tagging tool
- Use a deep neural network for a data-driven estimation of the backgrounds applied to non-tagged events in the H mass sideband
- Limits on cross-section were set at 95% CL in the 2D $m_X$-$m_Y$ plane



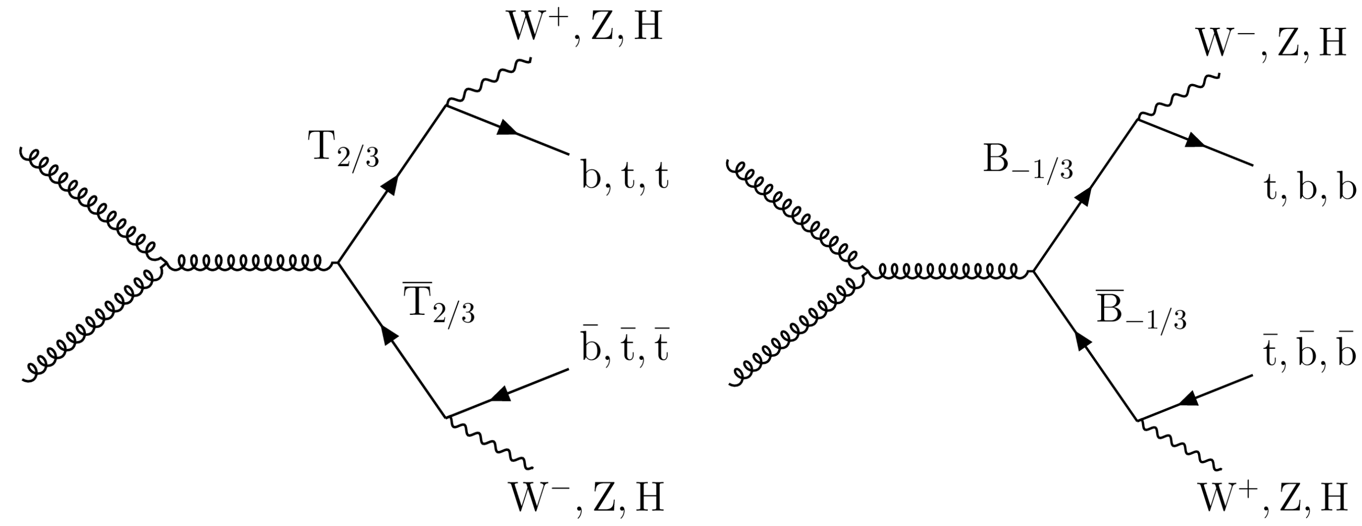

- **Lowest limit found to be 0.342 fb for $m_Y$ = 5000 GeV and $m_X$= 600 GeV**
- **highest limit found to be 1.22 pb for $m_Y$ = 2500 GeV and $m_X$= 2000 GeV**



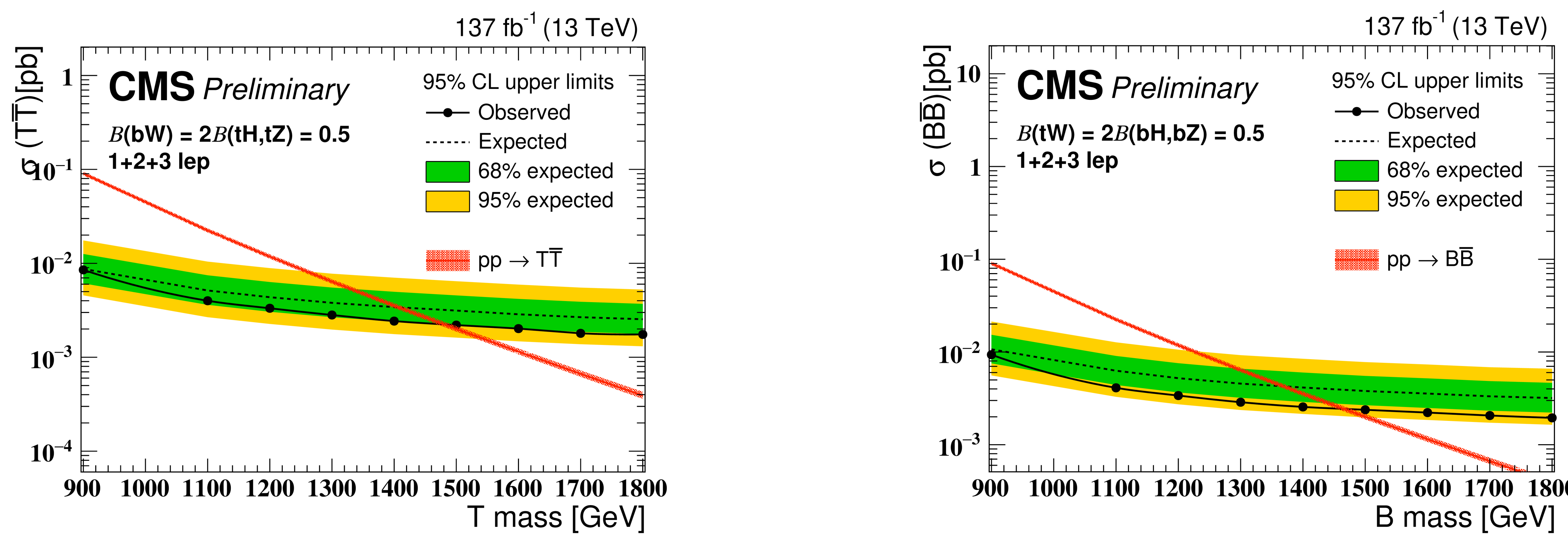
# Vector like T- and B-quarks

[CMS-PAS-B2G-20-011](CMS-PAS-B2G-20-011)

- Vector-like quarks (VLQ) decay to SM bosons and third generation quarks
- Search for production of a pair of vector-like T- or B-quarks, considering only leptonic channels
- The **strongest limits** set on the production of pair of T- and B-quarks (in the tH, bW and tW) decay channels)



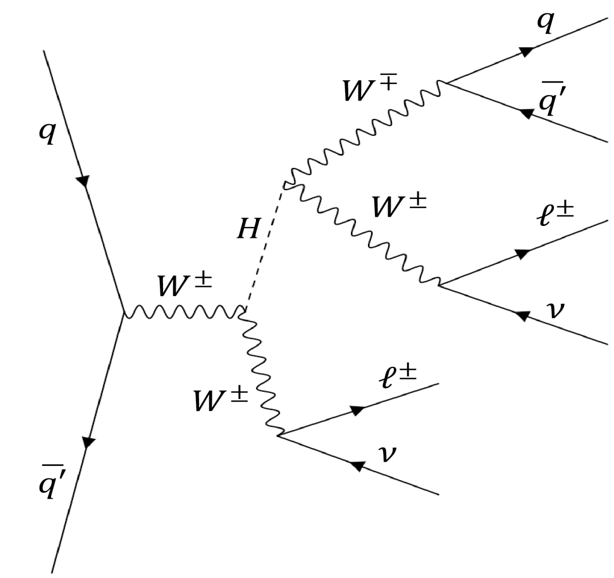

- **Excluding T-quark masses up to 1.54 TeV and B-quark masses up to 1.56 TeV**
- **Maximal sensitivity** corresponds to decay modes that include multiple top quarks

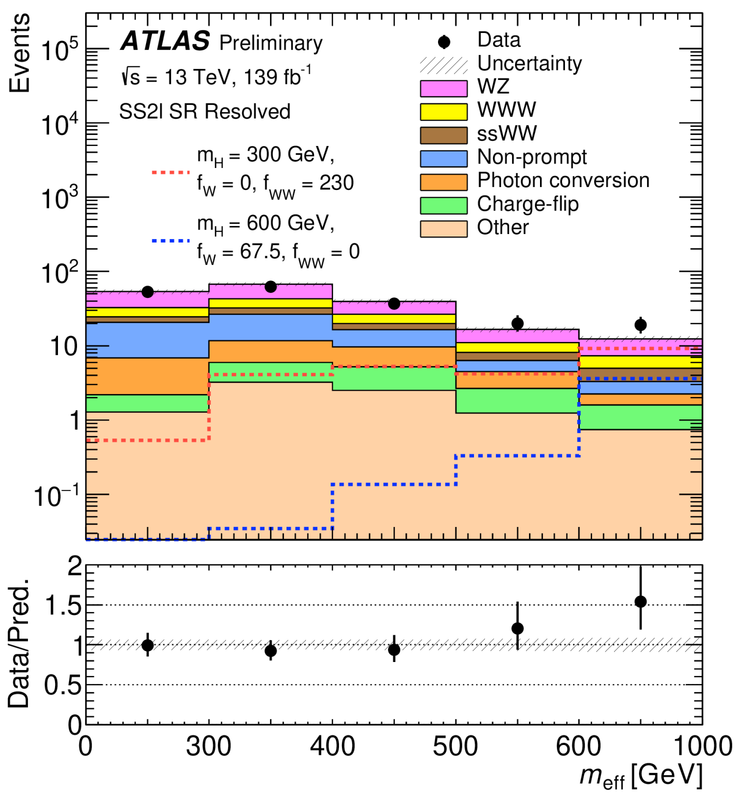


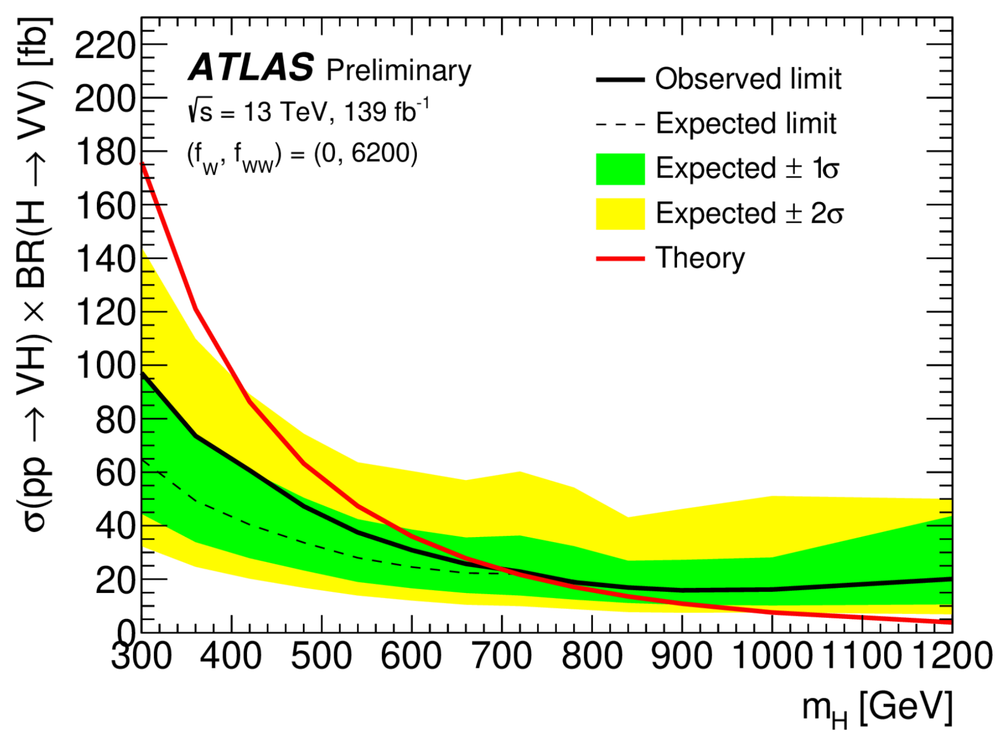
# Heavy Higgs boson

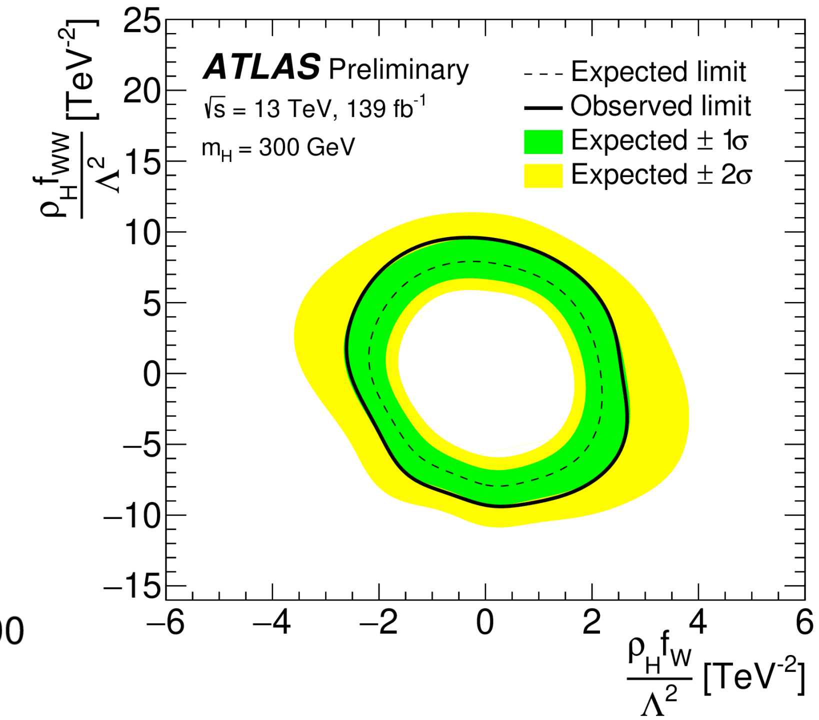
ATLAS-CONF-2022-033

- Search for a **heavy Higgs boson produced in association with a V-boson and decaying to a pair of *W*-bosons**
- Considering events with two leptons of the same sign in the final state
- EFT interpretation using dim-4 and dim-6 operators to set limits on coupling strengths
- Cross section limits were set at 95% CL as function of $m_H$
- Heavy Higgs bosons are **excluded** at 95% CL for mass up to **700 GeV and 900 GeV** with fixed anomalous couplings to vector bosons $f_W$ and $f_{WW}$



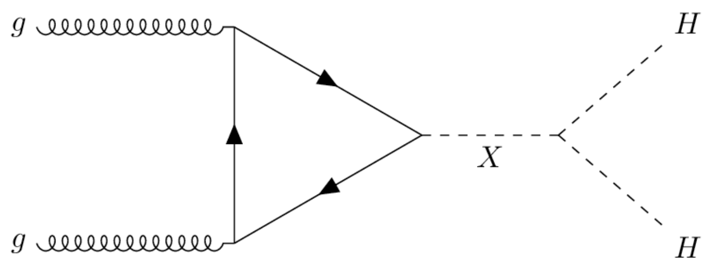



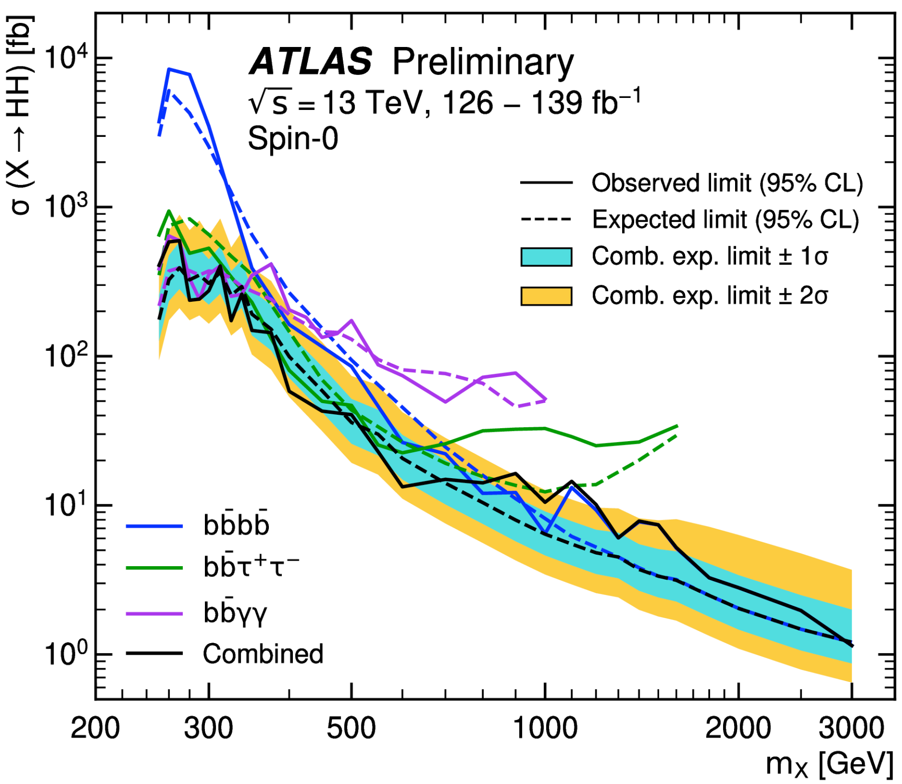
# DiHiggs (HH) searches

ATLAS-CONF-2021-052

- Search for resonant production of SM-like Higgs bosons in the *bbɣɣ*, *bbττ* and *bbbb* final states




- *bbbb and bbττ* are two of the largest SM $HH$ decay branching fractions
- Target models predicting heavy spin-0 particles
- No significant excess above the SM expectations was found
- **Limits** on the cross sections set at 95% CL depending on $m_X$ between **1.1 and 595 fb** (observed) within a $m_X$ range of 251GeV - 3TeV
- The largest excess seen at **$m_X$ = 1.1 TeV** for a **local (global) significance of 3.2$\sigma$ (2.1$\sigma$)**




| Mass [GeV] | 375.0 | 400.0 | 450.0 | 500.0 | 550.0 | 600.0 | 700.0 | 800.0 | 900.0 | 1000.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| Exp. $b\bar{b}\gamma\gamma$ | 241 | 190 | 146 | 130 | 95.2 | 81.1 | 76.5 | 65.8 | 45.8 | 50.1 |
| Exp. $b\bar{b}\tau\tau$ | 222 | 147 | 69.4 | 43.6 | 33.6 | 26.5 | 19.1 | 15.6 | 13.6 | 12.3 |
| Exp. $b\bar{b}b\bar{b}$ | | 267 | | 94.3 | | 45.4 | 24.6 | 15.9 | 11.1 | 8.16 |
| Exp. combined | 152 | 99.5 | 58.7 | 35.9 | 30 | 20.7 | 14.1 | 10.4 | 7.97 | 6.41 |
| Obs. $b\bar{b}\gamma\gamma$ | 415 | 205 | 134 | 173 | 87.6 | 74.1 | 49.3 | 72.2 | 77.1 | 51.8 |
| Obs. $b\bar{b}\tau\tau$ | 132 | 80.5 | 49.9 | 46.8 | 25.4 | 22.5 | 25.9 | 31.6 | 32.4 | 32.7 |
| Obs. $b\bar{b}b\bar{b}$ | | 163 | | 85.3 | | 26.4 | 22.1 | 12 | 12.2 | 6.45 |
| Obs. combined | 144 | 58.2 | 42.8 | 40.5 | 22.9 | 13.3 | 14.9 | 14.1 | 16.4 | 10.5 |