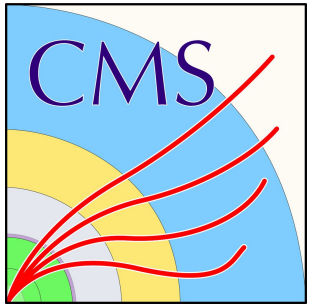
Search for heavy resonances at the LHC

PANIC 2021 conference

Dominik Duda

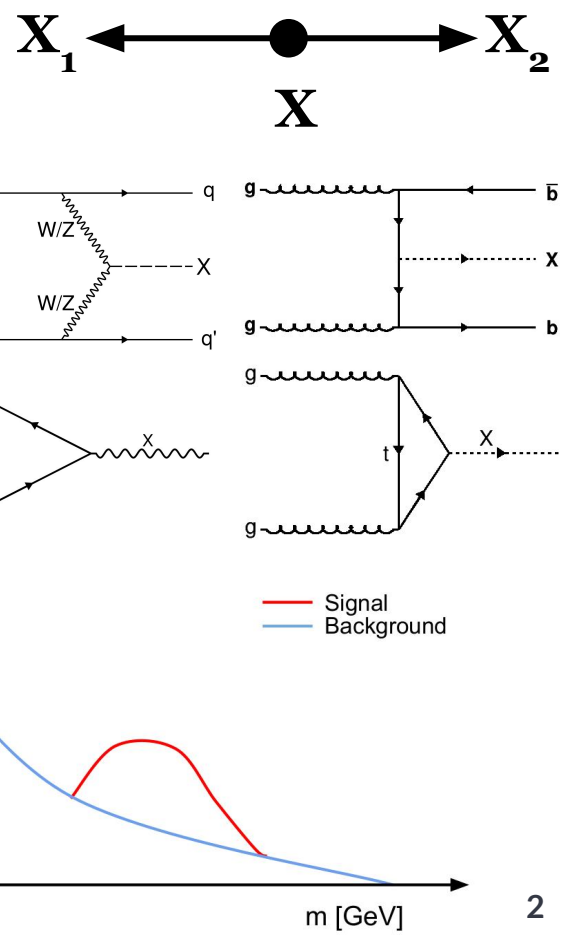
8th September 2021



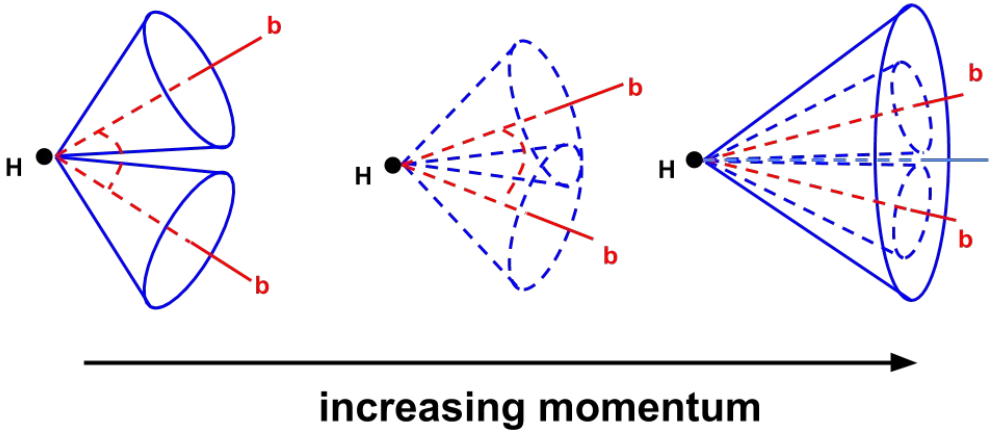
Searches for heavy resonances:

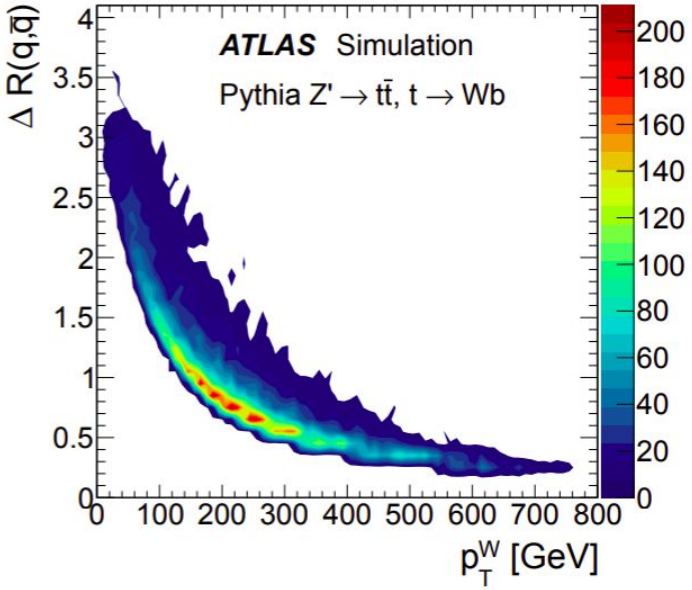
- **Focus: Searches for a (heavy) resonance X decaying into X_1 and X_2 (with X_1/X_2 = γ, Z, W, H, A, h, q, ℓ, …)**
  - Searches are performed for different production modes
  - Targeting diverse sets of final states:
    - Multi-lepton
    - Di-photon
    - Di-tau
    - Lepton + jets
    - b-jets
    - multi-jets

- Most analyses are designed to perform (quasi) **model-independent searches for a bump in a smoothly falling mass spectrum**
  - **Interpretations in generic frameworks:**
    - **Extended Higgs sector:**
      - Two Higgs Doublet Model (2HDM)
    - **Other generic frameworks:**
      - Heavy Vector Triplet (HVT) models
      - RS Extra-dimensional models



Boosted topologies:



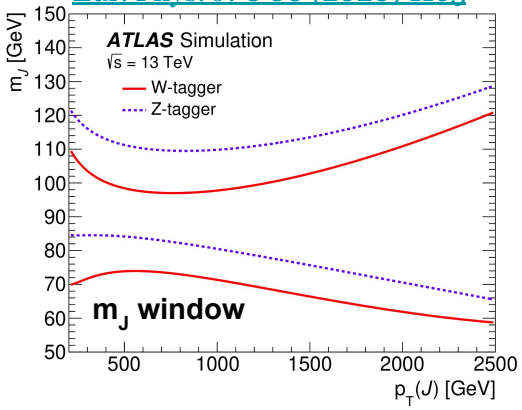


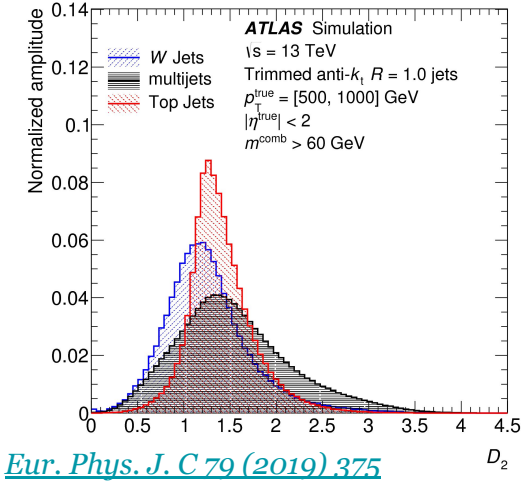
- **Decay products of boosted particles tend to be collimated**
- For p_T^W > 200 GeV and p_T^{Higgs} > 300 GeV decay products tend to have an angular separation smaller than 0.8
  - Partonic structure of decays can no longer be sufficiently described by R=0.4 jets
    - Use R=1.0 jets instead

$$\Delta R \approx \frac{2m}{p_T}$$

Reconstruction of boosted bosons in ATLAS:

Eur. Phys. J. C 80 (2020) 1165

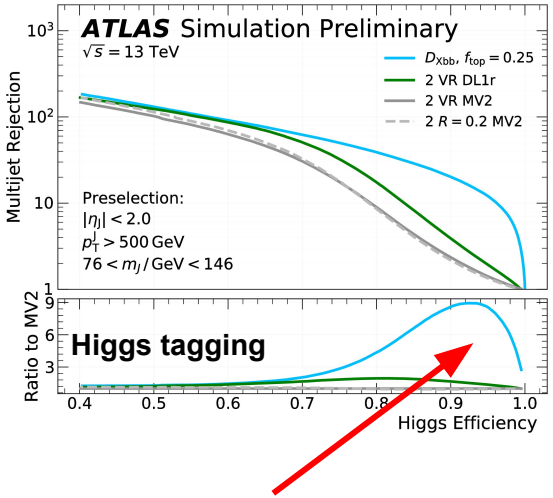




Eur. Phys. J. C 79 (2019) 375

- **Use trimmed R = 1.0 jets:**
  - **W/Z tagging:**
    - m_J window requirement
    - $D_2^{(\beta=1)}$ requirement
    - (N^{trks} requirement)
  - **Higgs tagging:**
    - VR track jets
    - m_J window requirement
    - **DNN (p_T, η, DL1r scores)**

ATL-PHYS-PUB-2020-019



New D_{Xbb} tagger significantly improves our ability to identify Higgs jets

$$D_2^{(\beta)} = \frac{e_3^{(\beta)}}{(e_2^{(\beta)})^3}$$

$$e_2^{(\beta)} = \frac{1}{p_{TJ}^2} \sum_{1 \le i < j \le n_J} p_{Ti} p_{Tj} R_{ij}^{\beta} \ ,$$

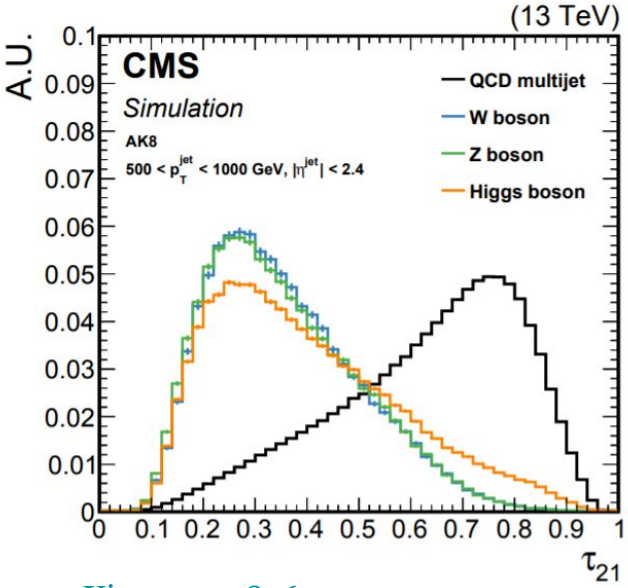
$$e_3^{(\beta)} = \frac{1}{p_{TJ}^3} \sum_{1 \le i < j < k \le n_J} p_{Ti} p_{Tj} p_{Tk} R_{ij}^{\beta} R_{ik}^{\beta} R_{jk}^{\beta}$$

Reconstruction of boosted bosons in CMS:

- **Use groomed (via SoftDrop) R = 0.8 jets:**
  - **W/Z/H tagging:**
    - **Cut based:** Requirements on m_J window and ratio of N-subjettiness τ_{21}
    - **DeepAK8:** Multiclass classifier for the identification of hadronically decaying particles with five main categories (W/Z/H/t/others) using four-vectors and other properties of pflow objects

- **N-subjettiness:**

$$\tau_N = \frac{1}{d_0} \sum_i p_{T,i} \min \left[\Delta R_{1,i}, \Delta R_{2,i}, \ldots, \Delta R_{N,i} \right]$$



arXiv:2004.08262

Some Recent searches for heavy resonances by ATLAS and CMS

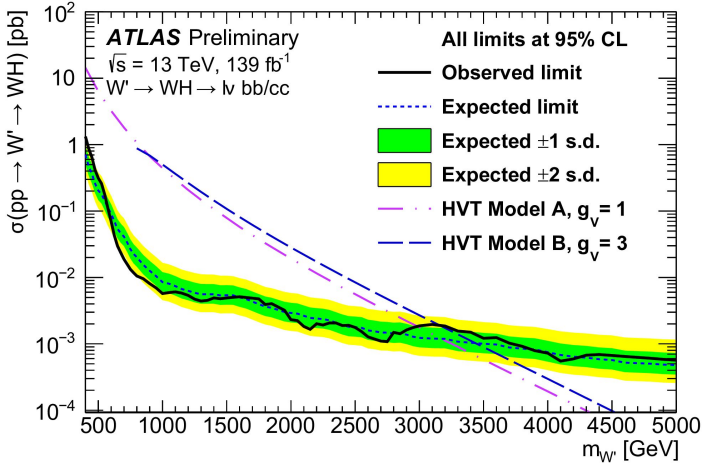
- **Searches for di-boson resonances:**
  - X → Wh by ATLAS and CMS (ATLAS-CONF-2021-026, CMS-PAS-B2G-19-002)
  - X → Wγ and X → Zγ by ATLAS and CMS (ATLAS-CONF-2021-041, arXiv::2106.10509)
- **Searches for di-quark resonances:**
  - X → tb by ATLAS and CMS (ATLAS-CONF-2021-043, *Phys. Lett. B 820 (2021) 136535*)
  - X → bb by ATLAS and CMS (CMS-PAS-EXO-20-008, arXiv:2108.09059)
- **Searches for vector-like quarks:**
  - Search for vector-like *B*-quarks by ATLAS (ATLAS-CONF-2021-018)
  - Search for vector-like *T*-quarks by ATLAS and CMS (ATLAS-CONF-2021-040, CMS-PAS-B2G-19-004)
  - Search for vector-like quark pairs by ATLAS (ATLAS-CONF-2021-024)
  - Search for a W' decaying to a vector-like quark and a t- or b-quark by CMS (CMS-PAS-B2G-20-002)
- **Others:**
  - Search for resonances decaying to triple W-boson by CMS: (B2G-20-001, B2G-21-002)
  - Search for an excited b-quark decaying via b* → tW by CMS: (CMS-PAS-B2G-20-010)
  - Search for a right-handed W boson and heavy neutrino by CMS: (CMS-PAS-EXO-20-002)
  - Search for heavy leptons by ATLAS: (ATLAS-CONF-2021-023)

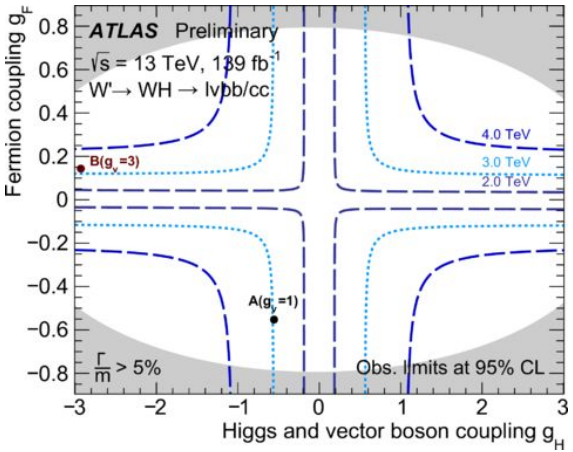
For information on hh resonance searches please have a look at the presentation by Tiesheng

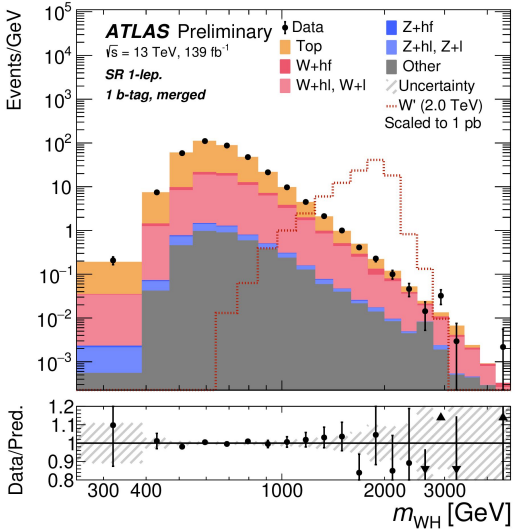
Searches for di-boson resonances

Search for resonances in X → Wh decays:

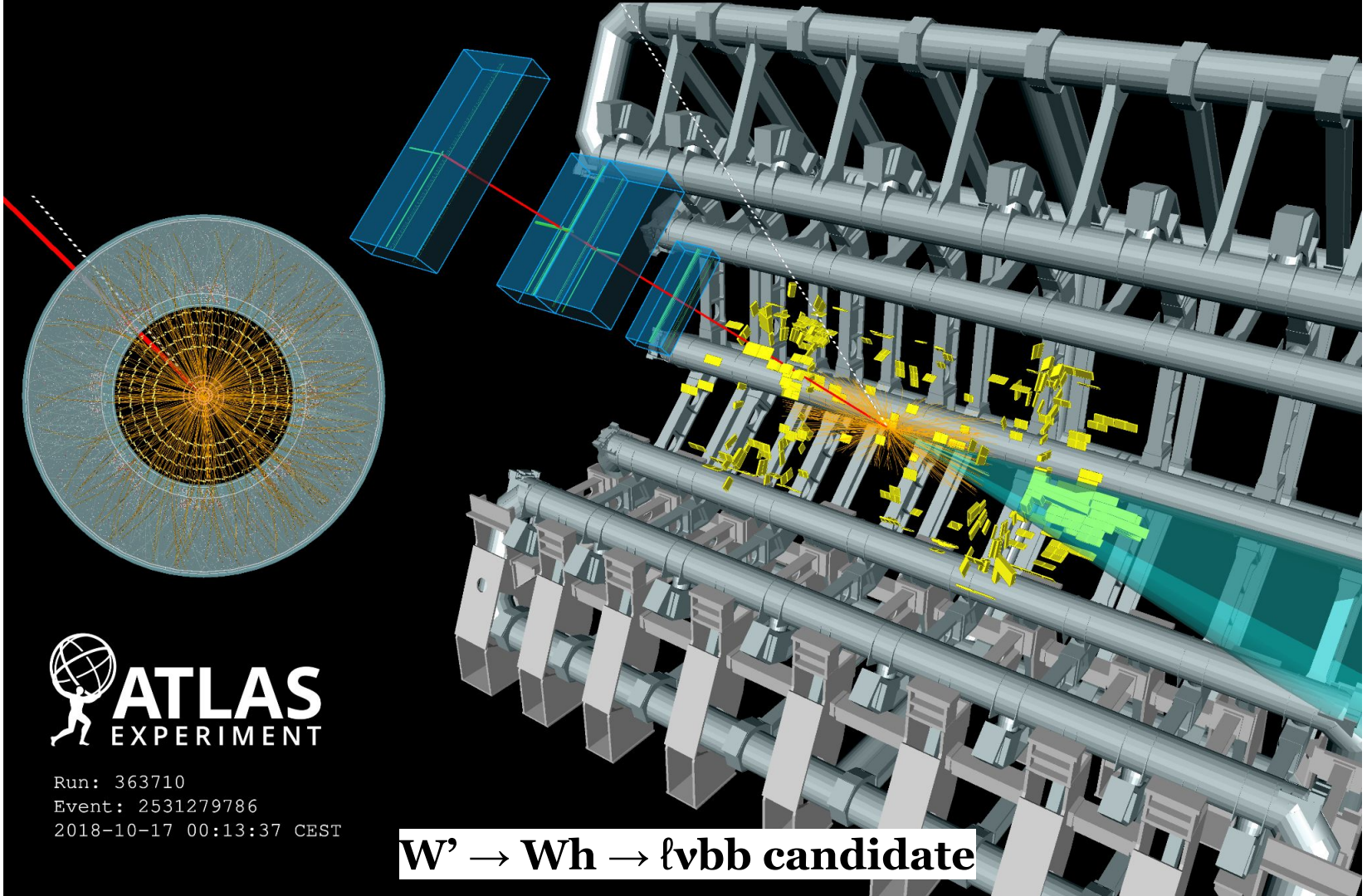
- **Probe resolved and merged ℓνbb (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Search for bumps in $m_{\ell\nu bb}$ spectra
  - Simultaneous fit of all 4 event categories: (resolved, merged) × (1-tag, 2-tag)
- **Dominant uncertainties:**
  - Modelling of backgrounds (top bkg. ME +PS)
  - Large-R jets (mass resolution)







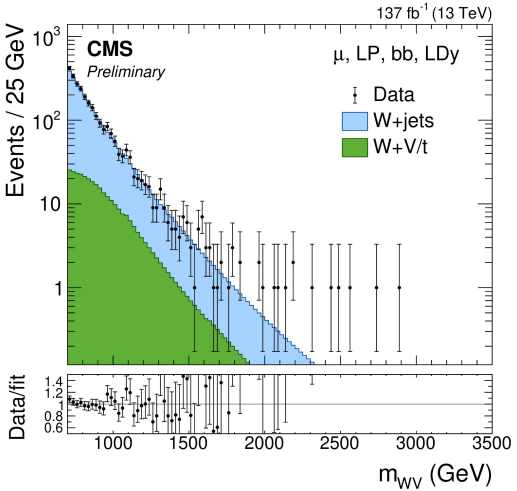
ATLAS-CONF-2021-026

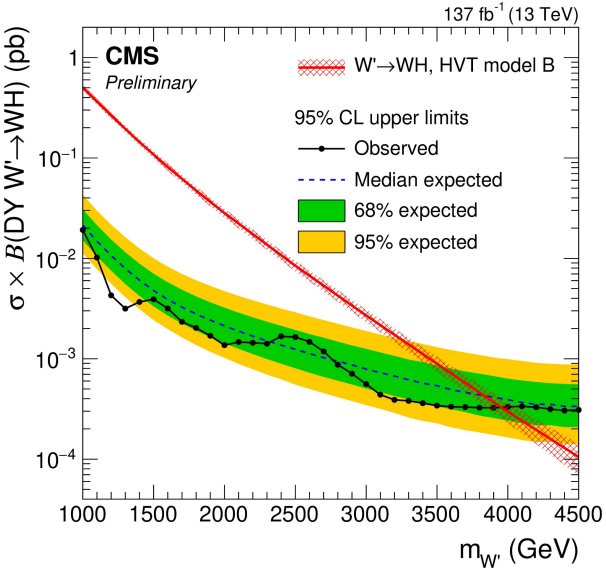

ATLAS
EXPERIMENT
Run: 363710
Event: 2531279786
2018-10-17 00:13:37 CEST
W' → Wh → ℓνbb candidate

Search for resonances in X → WW, WZ and Wh decays:

- **Probe merged ℓνqq (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Search for bumps in $m_{\ell\nu qq}$ spectra
  - Simultaneous 2-dimensional fit of the (m_{qq} , $m_{\ell\nu qq}$) distribution in 24 categories
    - (μ, e) × (HP, LP) × (VBF, bb-tagged, others) × (LDy, HDy)
      - High and low purity (HP & LP) regions based on τ_N **cut**
      - Use low and high rapidity regions (LDy and Hdy)
  - 2d probability density functions are build for signal and bkg.

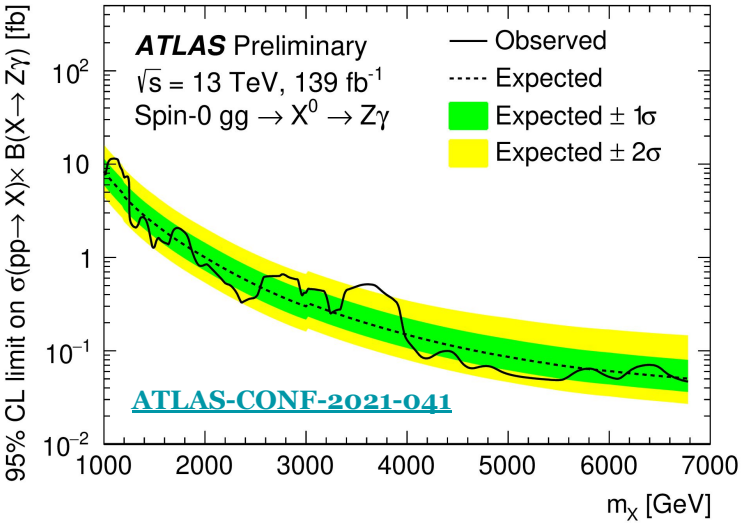
- **Dominant syst. unc. :**
  - V-tagging
  - Double-b tagging
  - Bkg modelling

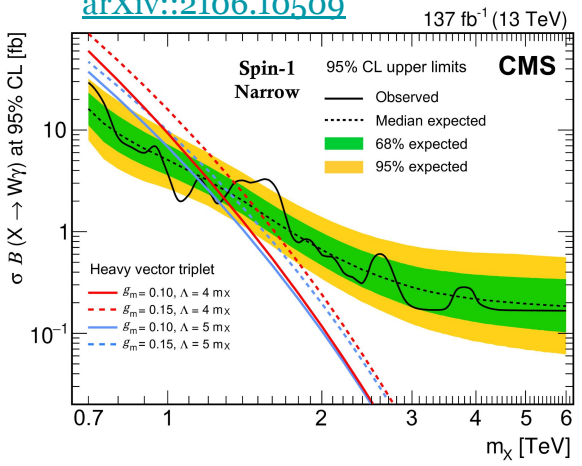


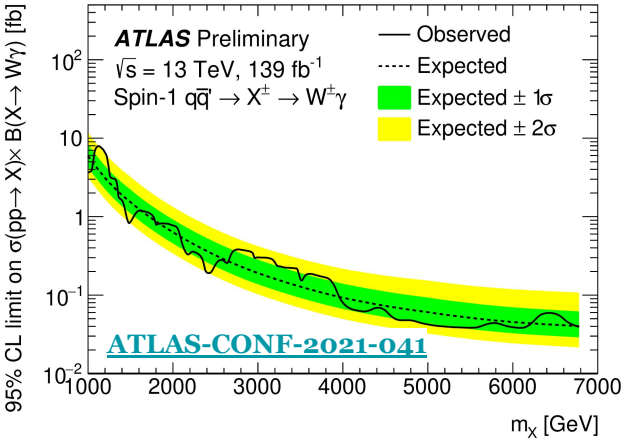


CMS-PAS-B2G-19-002

Searches for Vγ diboson resonances







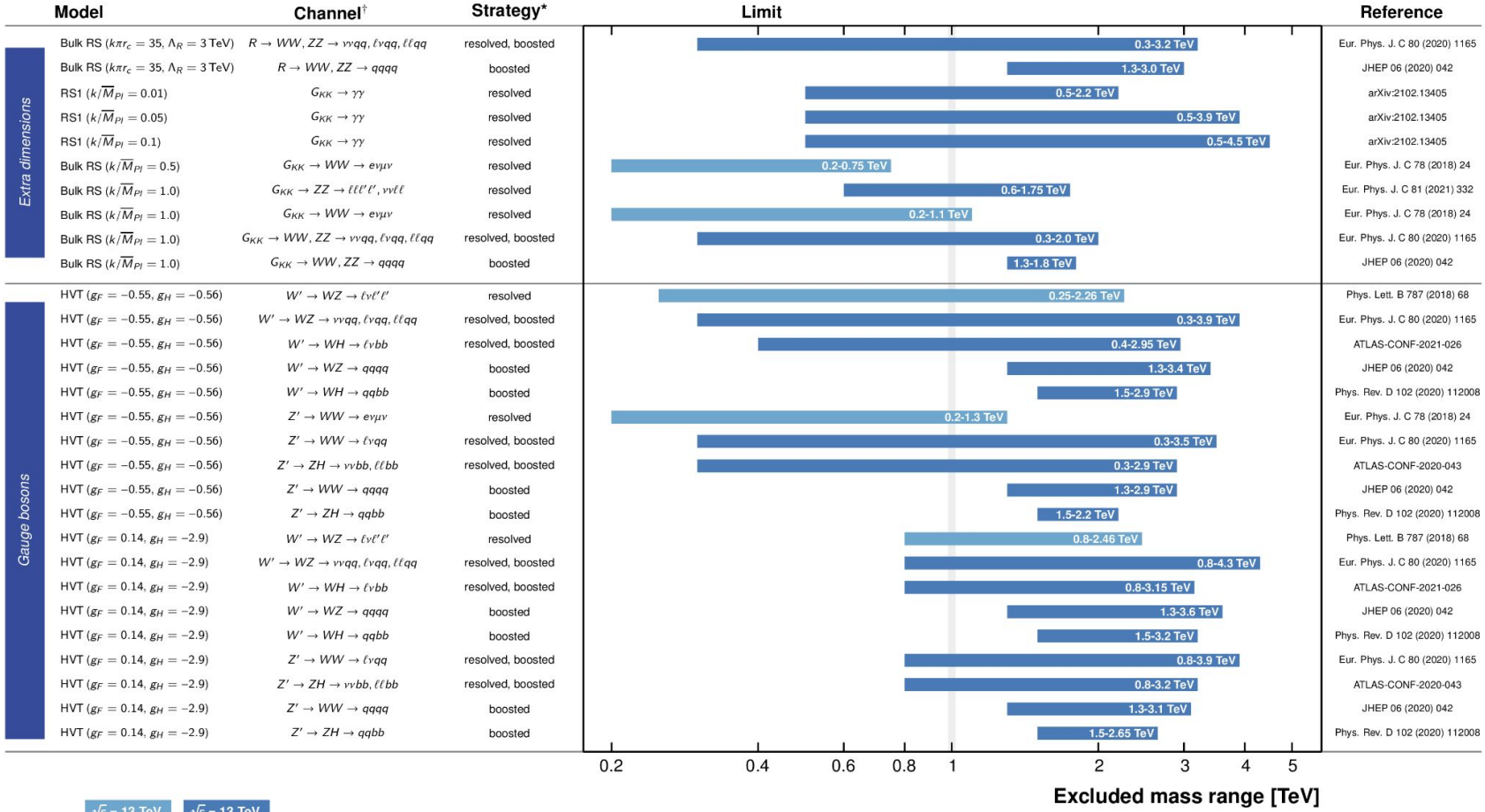
- Search for resonances in (merged) qqγ final states performed by ATLAS and CMS
  - Probe for particles with spin 0, 1 or 2 hypothesis
  - Include searches for X → Wγ *and* X → Zγ *resonances*

ATLAS Diboson Searches - 95% CL Exclusion Limits

Status: June 2021

ATLAS Preliminary

$\mathcal{L}$ = (36.1 – 139) fb^{-1} $\sqrt{s}$ = 13 TeV



$\sqrt{s}$ = 13 TeV $\mathcal{L}$ = 36.1 fb^{-1}

$\sqrt{s}$ = 13 TeV $\mathcal{L}$ = 139 fb^{-1}

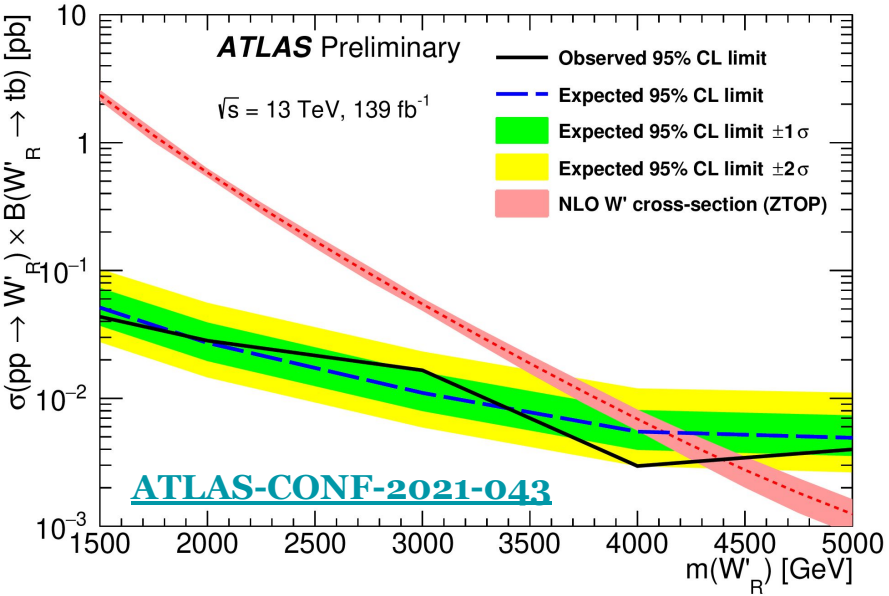
*small-radius (large-radius) jets are used in resolved (boosted) events

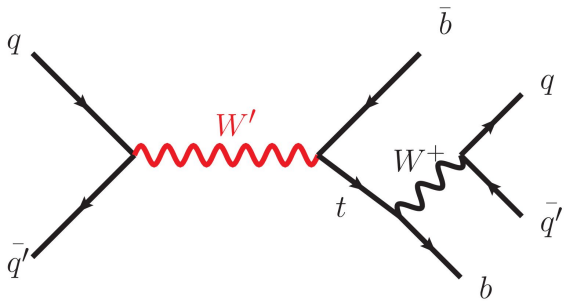
†with $\ell = \mu, e$

ATL-PHYS-PUB-2021-018

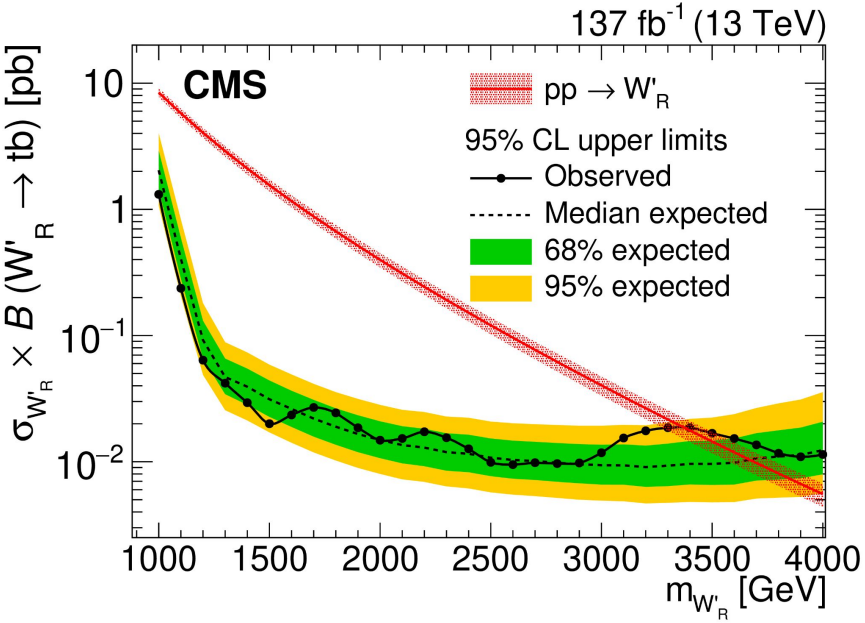
Searches for di-quark resonances

Searches for X → tb resonances by ATLAS and CMS



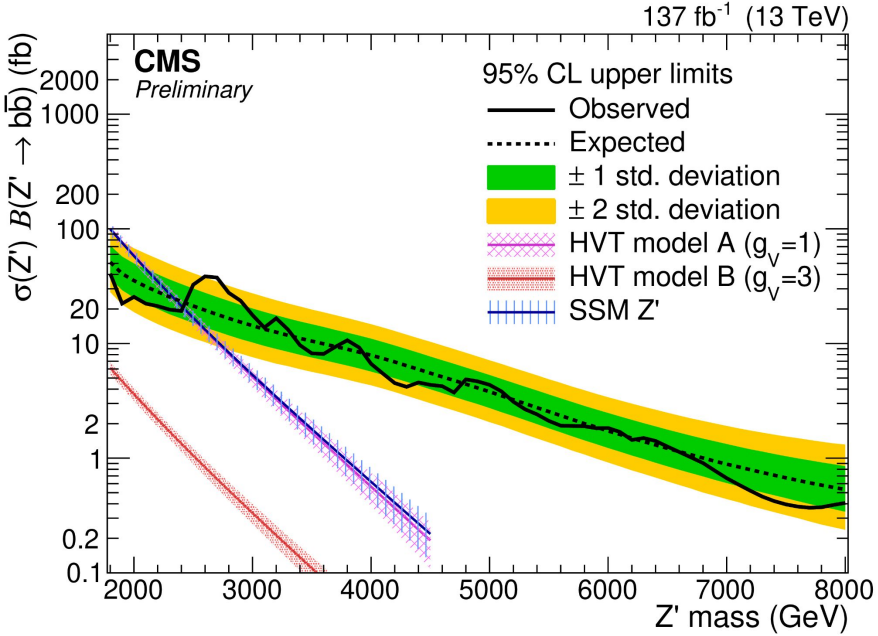


- Search for a heavy charged vector boson
  - Decay: **W'→ tb**
  - Signature: **fully hadronic**
  - Predicted by: **left-right symmetric models**



Phys. Lett. B 820 (2021) 136535

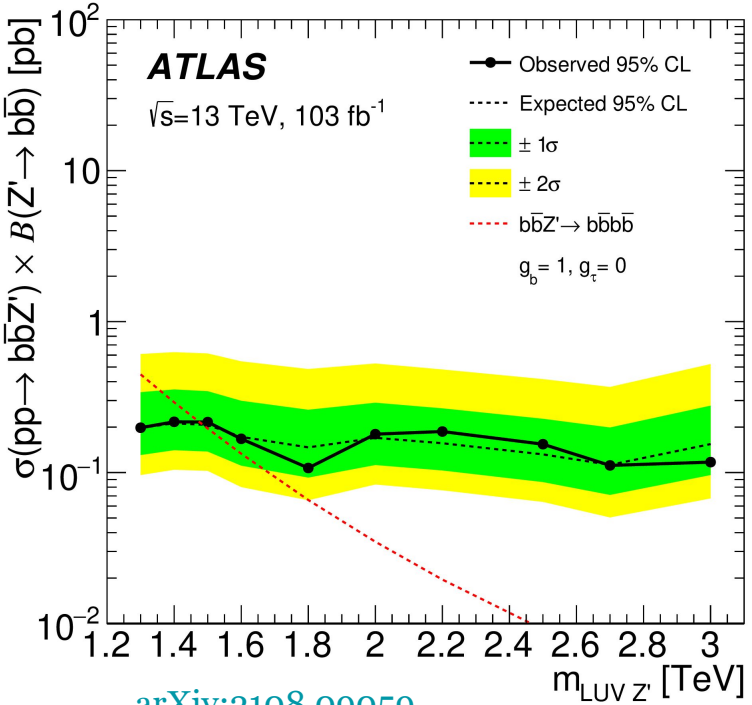
Searches for X → bb resonances by ATLAS and CMS



- Search for a heavy vector boson
  - Decay: **Z' → bb**
  - Predicted by: **Compositeness models, extra-dimensional models etc.**

CMS-PAS-EXO-20-008

- Search for a heavy vector boson
  - Production mode **bbZ'**
  - Decay: **Z'→ bb**

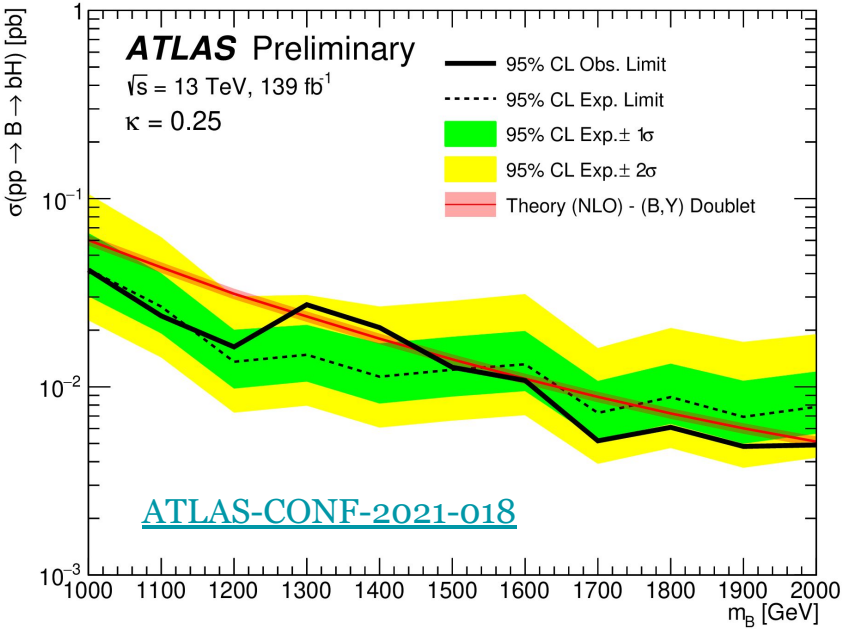


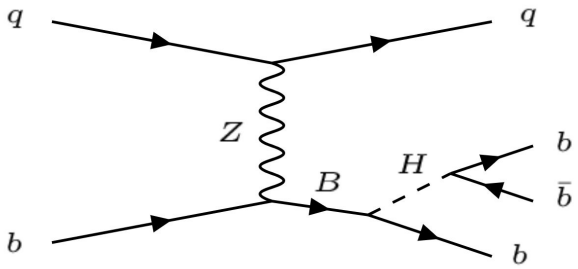
arXiv:2108.09059

Searches for vector-like quarks

Searches for vector-like quarks by ATLAS and CMS

- **Vector-like quarks (VLQ):**
  - Hypothetical spin ½ particles
  - Left and right handed components have the same electroweak quantum numbers
  - Predicted by e.g. **Little Higgs** or **Composite Higgs models**

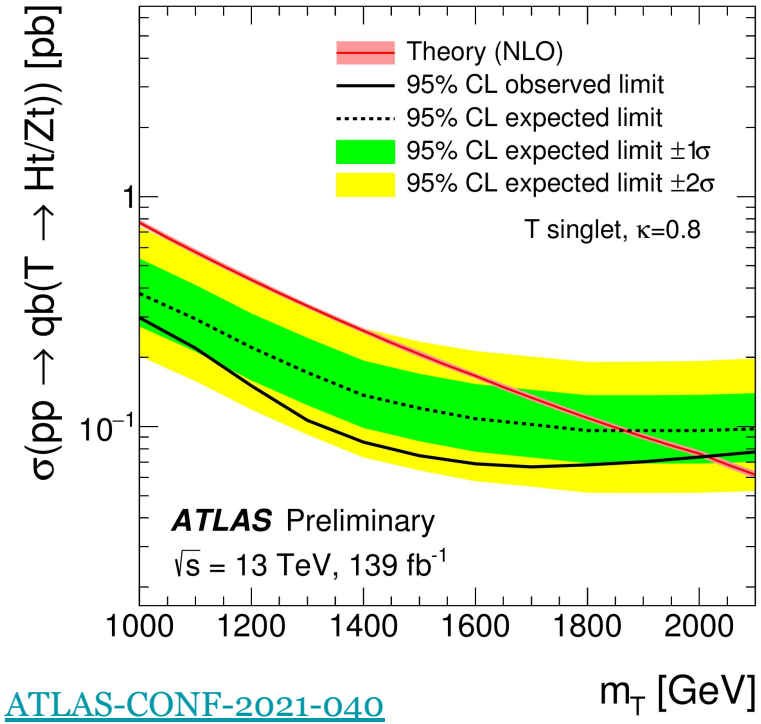




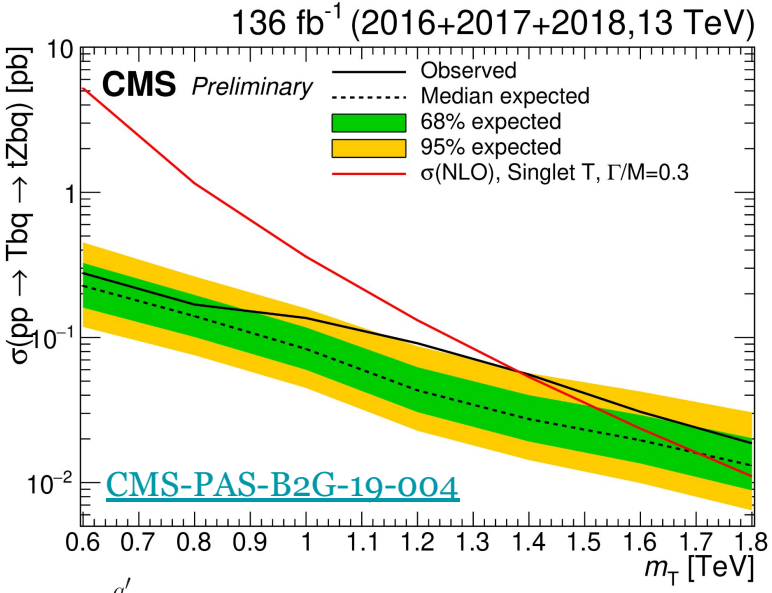
- Search for single vector-like *B*-quark production
  - Signature**: Large-R jet + b-jet + light-flavour jet**

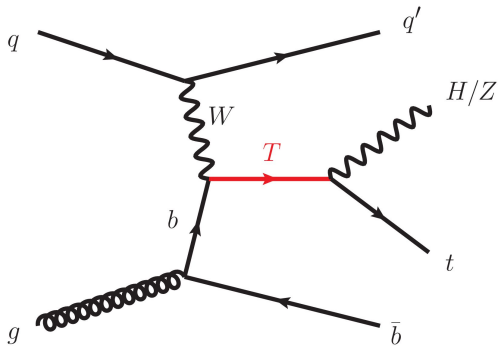
Searches for single vector-like quarks

- ATLAS search in final states with a **single lepton + multiple jets**



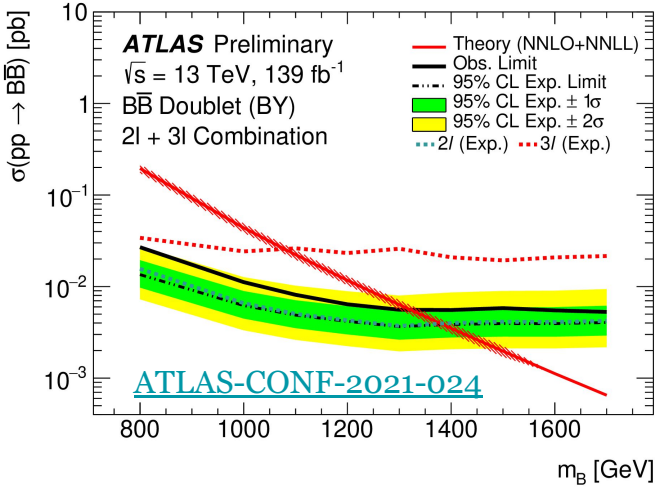
ATLAS-CONF-2021-040



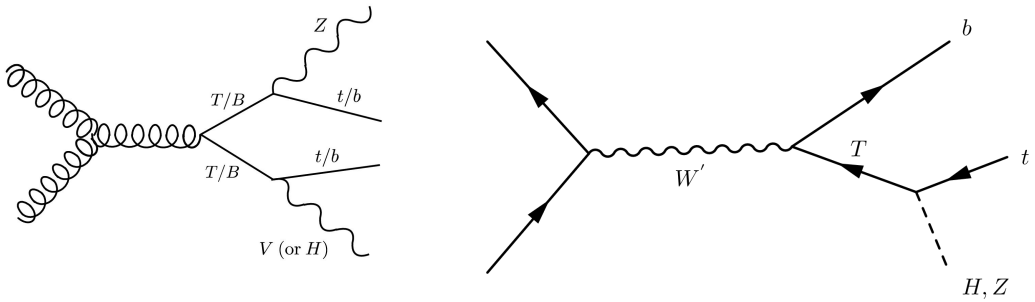


- CMS search in final states with **multiple jets and E_T^{miss}**

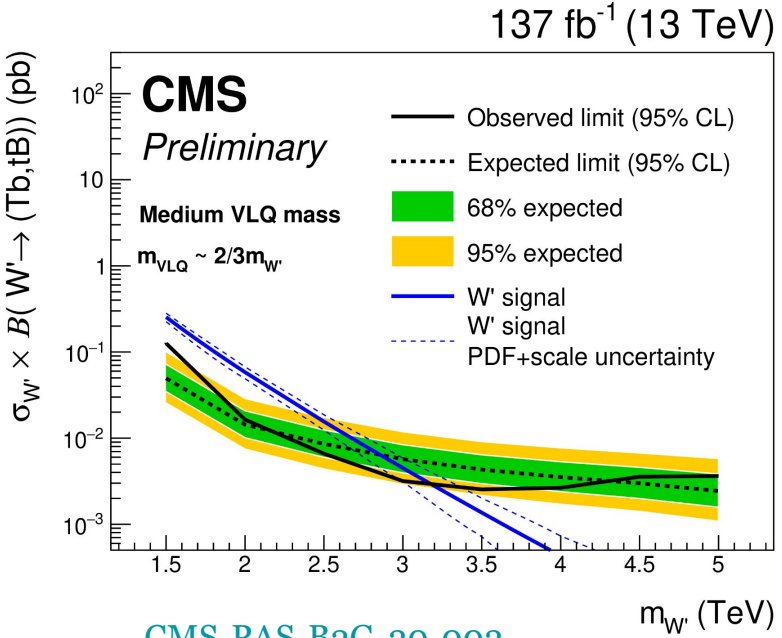
Searches for vector-like quarks by ATLAS and CMS



- **Search for pairs of vector-like quarks**
  - Signature: **2 leptons** + b-jets + large-R jet



- **Search for a W' decaying to a vector-like quark and a top or bottom quark:**
  - Signature: 2 large-R jets + b-jet

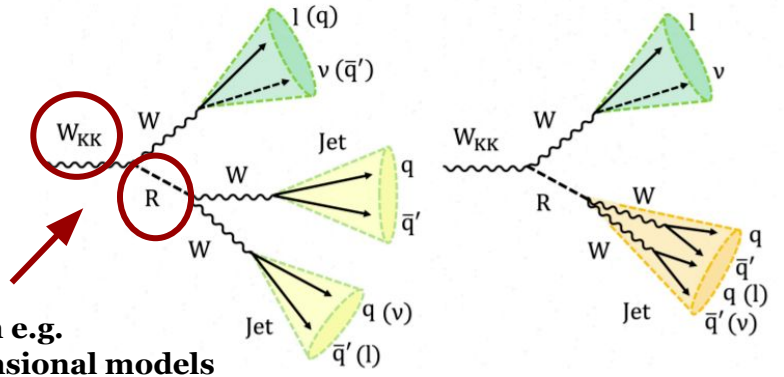


Other resonance searches

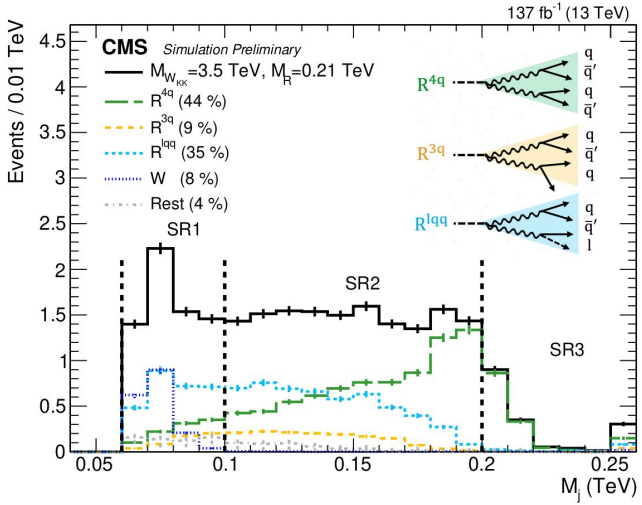
- **Triboson cascades**
- **Excited quarks**
- **Heavy leptons**

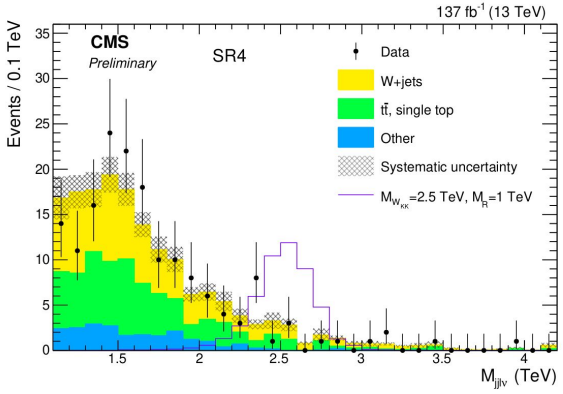
Search for resonances decaying to triple W-boson final states:

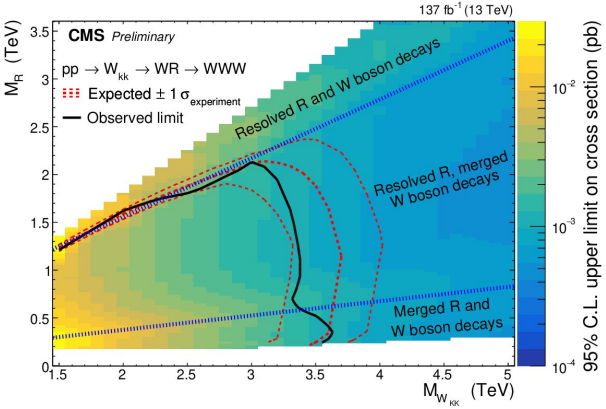
- **Search for cascade decays leading to merged ℓνqqqq (ℓ = μ, e) final states**
  - Study events with one or two Large-R jets
- **Analysis strategy:**
  - Probe for bumps in $m_{j\ell\nu}$ and $m_{jj\ell\nu}$ spectra
- **Dominant systematic uncertainties:**
  - Multi-prong jet tagging
  - Background modelling



Predicted in e.g. extra-dimensional models



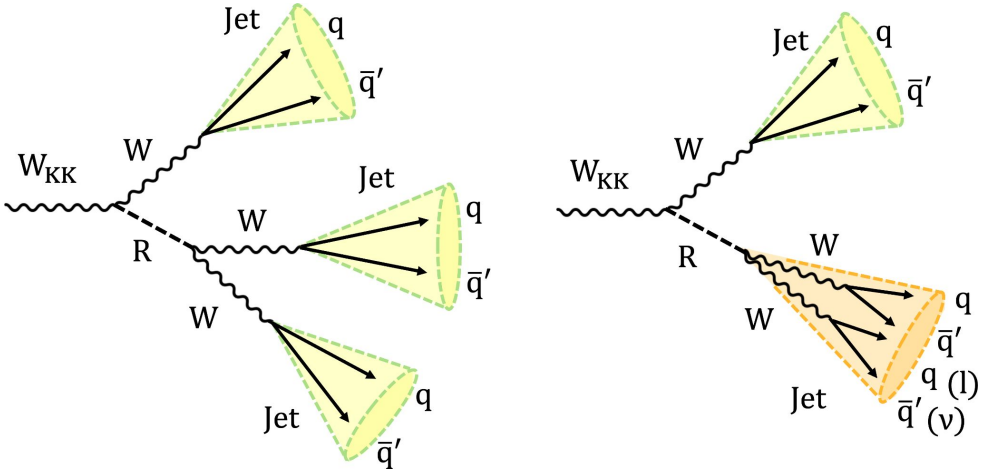




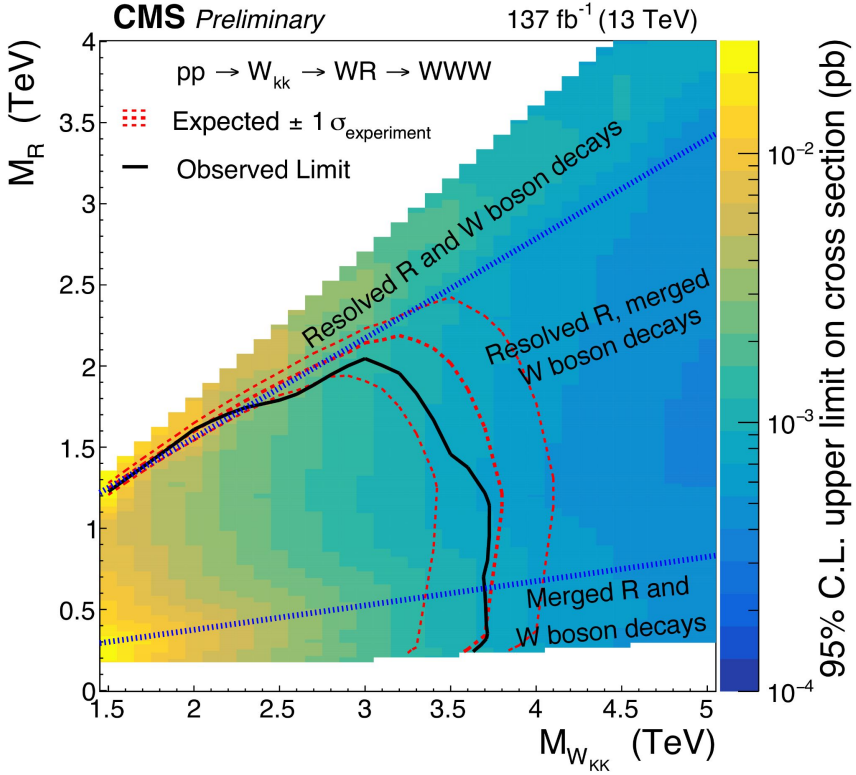
CMS-PAS-B2G-20-001

Search for resonances decaying to triple W-boson final states:

- **Search for cascade decays leading to merged qqqqqq final states**
  - Study events with two or three Large-R jets

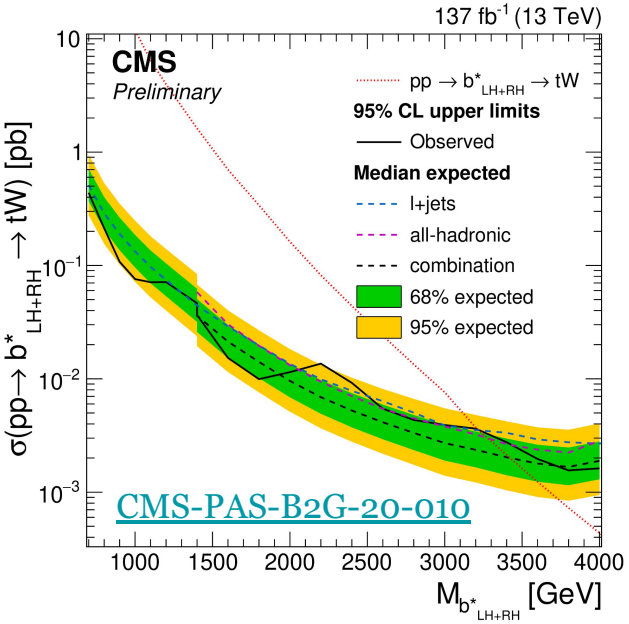


Expected and observed upper limits at 95% CL on the product cross section of the signal from combining the all-hadronic and single-lepton searches.



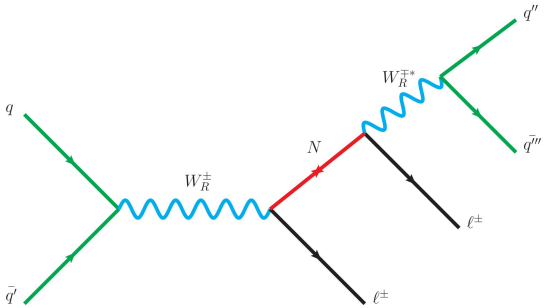
CMS-PAS-B2G-21-002

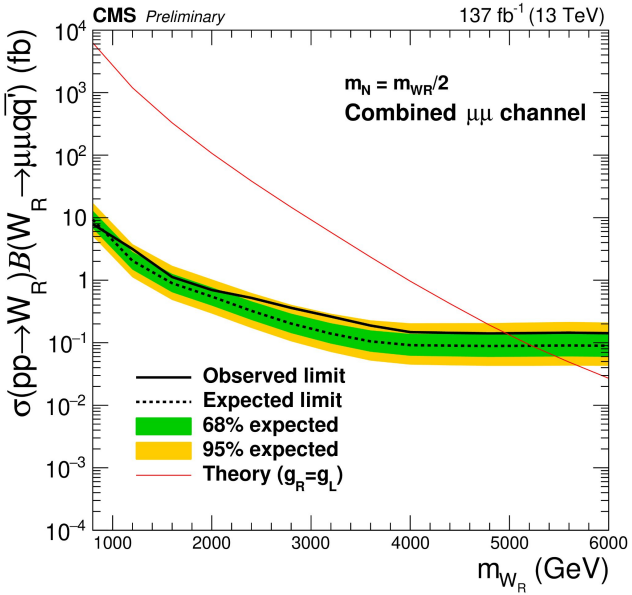
Searches for excited quarks and right handed W bosons



- Search for an excited b-quark
  - Decay: **b* → tW**
  - Signature: **single lepton + large-R jet**
  - Predicted by: **Compositeness models**

- Search for a right-handed W boson and heavy neutrino
  - Signature: **same sign ℓℓjj & ℓJ (strongly boosted neutrinos)**
  - Predicted by: **Left-right symmetric models**



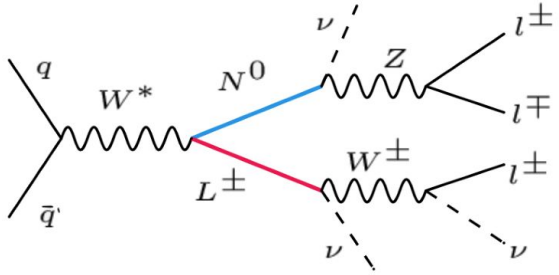


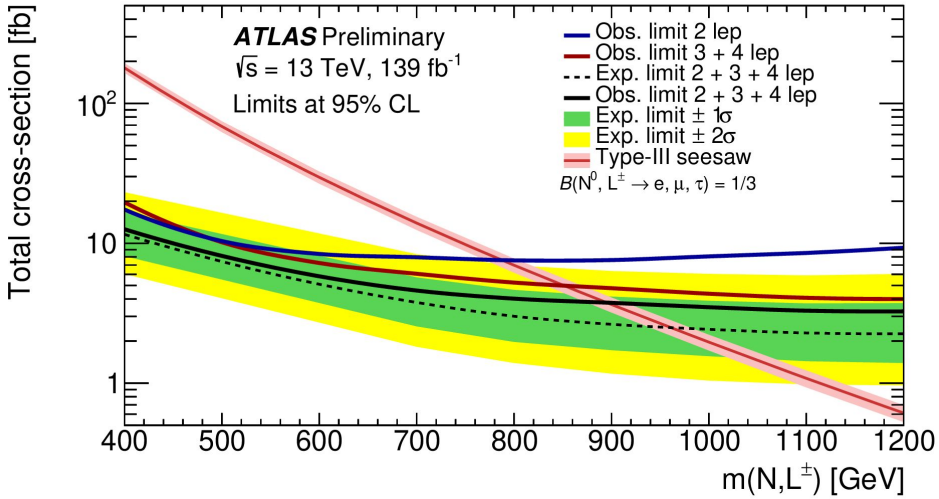
CMS-PAS-EXO-20-002

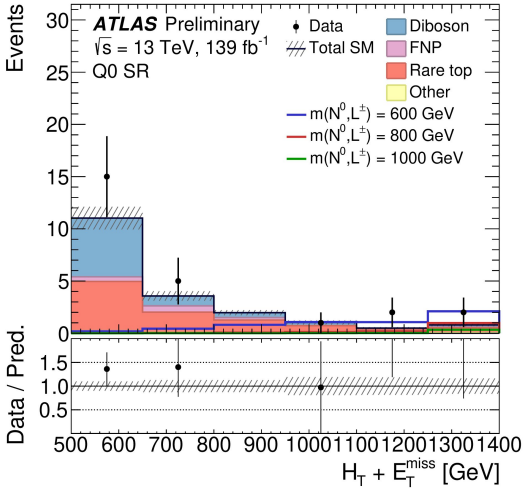
Searches for heavy leptons

ATLAS-CONF-2021-023

- Searches for heavy charged and neutral leptons ($L^{\pm}$ and N^0)
  - **Signature:**
    - **Three charged leptons + E_T^{miss}**
    - **Four charged leptons + 2 jets**
  - **Analysis strategy:**
    - Define various signal regions based on **N^{lep}, N^{jets} and $m_{\ell\ell}$**
    - Simultaneous fits to the mT and ($H_T + E_T^{miss}$) distributions for the three- and four-lepton channels in all signal regions





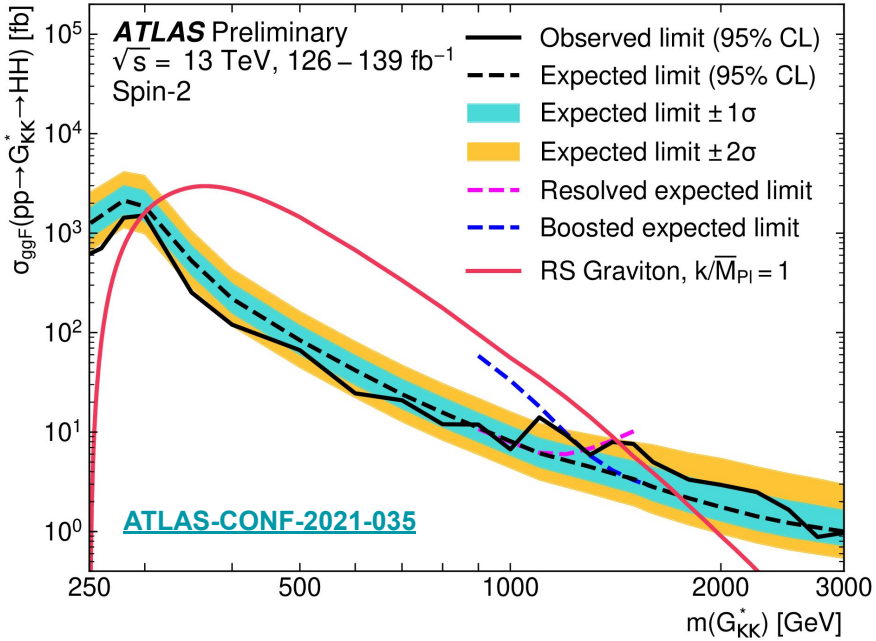


Concluding remarks:

- **Many interesting searches for new (heavy) resonances are ongoing within ATLAS and CMS**
  - Presented only a few highlights of available results.
    - Additional results can be found via the **ATLAS** and **CMS** publication pages
  - No significant hint for physics beyond the SM has been observed so far
  - Many results based on the full Run-2 data set are expected in the next month/years

Back-up

Search for X → hh resonances (ATLAS)

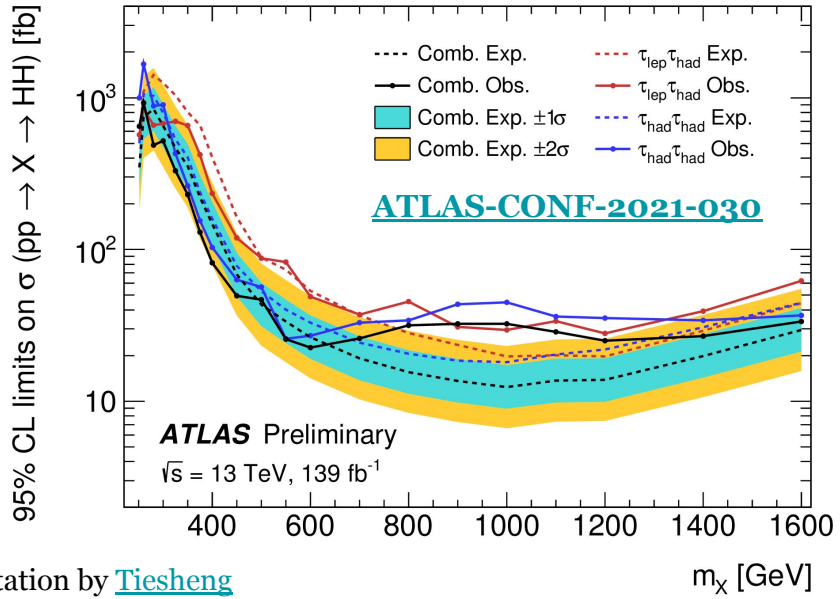


Search for resonances decaying via:

- $X \rightarrow hh \rightarrow bbbb$
- Signature: **4 small-R jets** or **2 large-R jets**

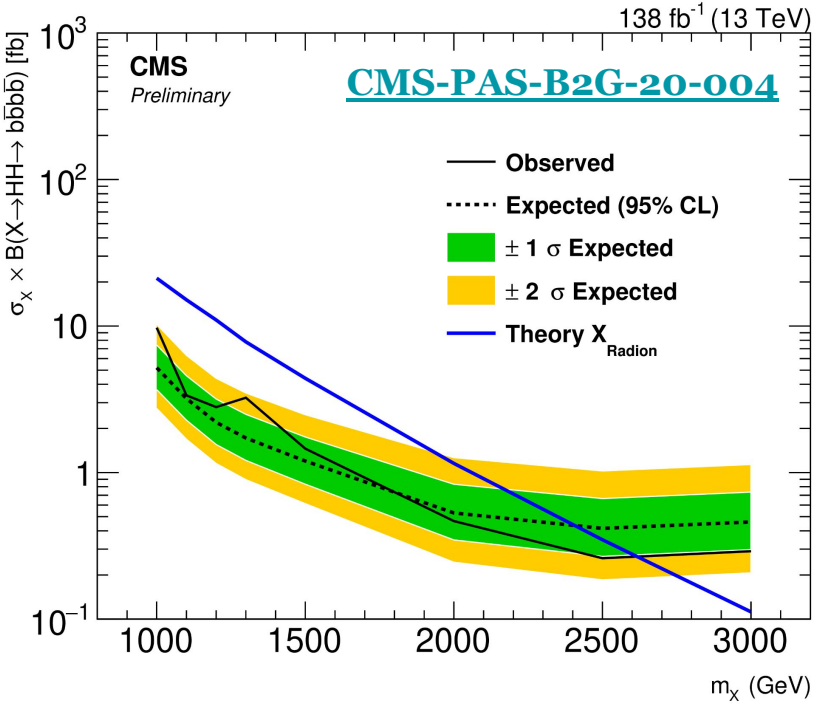
Search for resonances decaying via:

- $X \rightarrow hh \rightarrow bbe\tau_h$
- $X \rightarrow hh \rightarrow bb\mu\tau_h$
- $X \rightarrow hh \rightarrow bb\tau_h\tau_h$
- Signature: **1 (0) Leptons + 3 (4) small-R jets**



More information on hh resonance searches can be found in the presentation by Tiesheng

Search for X → hh resonances (CMS)

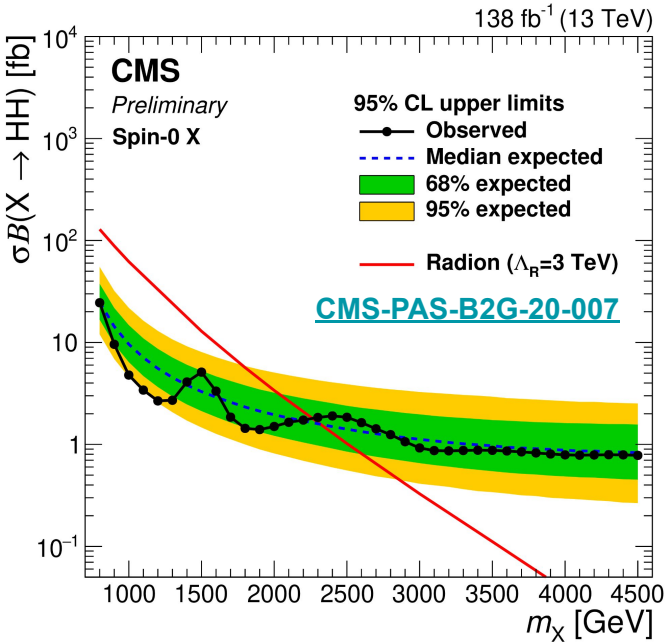


Search for resonances decaying via:

- X → hh → bbbb
- Signature: **2 large-R jets**

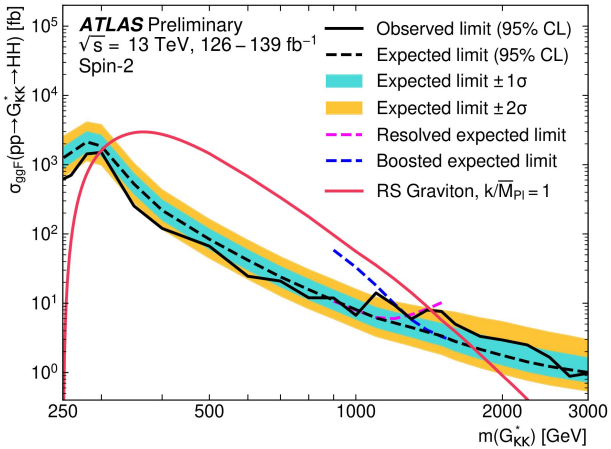
Search for resonances decaying via:

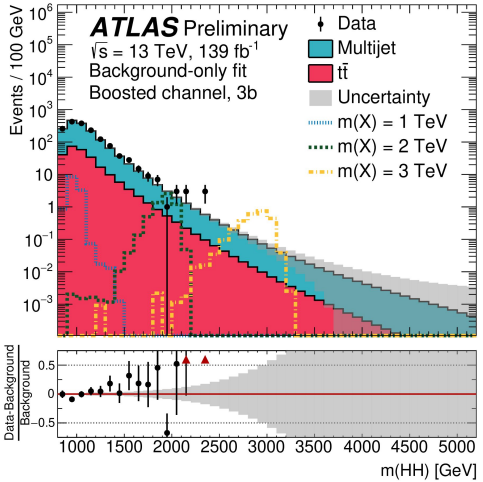
- X → hh→ bbWW* → bbℓνqq
- X → hh → bbWW*→ bbℓνℓν
- X → hh → bbττ → bbℓννℓνν
- Signature: **Leptons + E_T^{miss}+1 large-R jets**

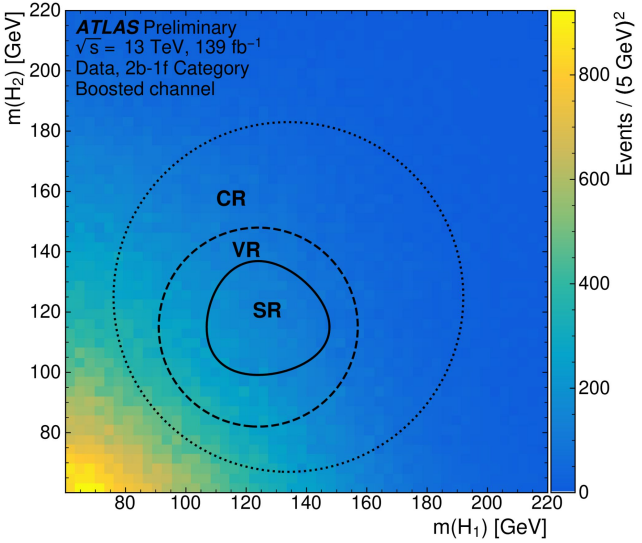


Search for resonances in X → hh→ bbbb decays:

- **Search for resolved and merged bbbb final states**
- **Analysis strategy:**
  - Resolved/Boosted events are classified into the SR/VR/CR based on their m_{H1} and m_{H2} values
  - Probe for bumps in m_{bbbb} spectra
  - Train neural network for background estimation
    - **Extrapolate background distribution from CRs to SR**
- **Dominant systematic uncertainties:**
  - Background m_{HH} shape
  - Jet momentum/mass resolution







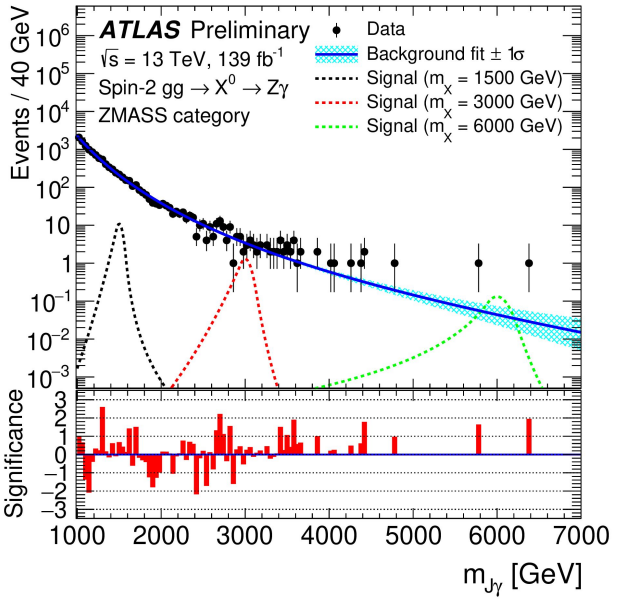
ATLAS-CONF-2021-035

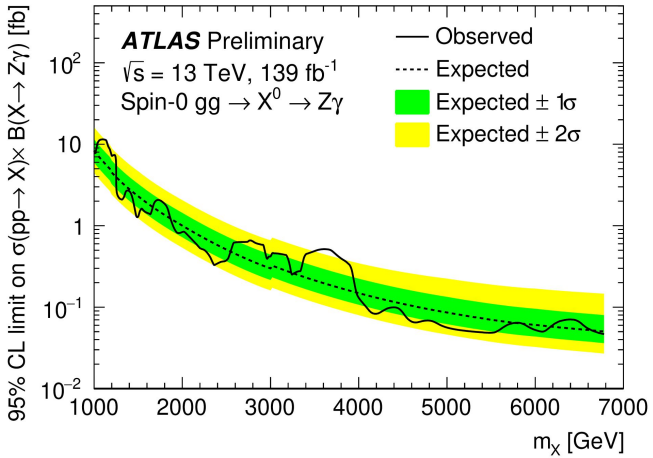
Search for high-mass *Wγ* and *Zγ* resonances:

- **Search for resonances in (merged) qqγ final states**
  - Probe for particles with spin 0, 1 or 2 hypothesis
- **Analysis strategy:**
  - Split events in several non-overlapping signal regions
  - Use parametric fit function to describe background:

$$\mathcal{B}(m_{J\gamma}; \boldsymbol{p}) = (1-x)^{p_1} x^{p_2+p_3 \log(x)} \quad \text{with:} \quad x = m_{J\gamma}/\sqrt{s}$$

  - The signal is modeled with a double-sided crystal ball function





- **Dominant systematic uncertainties:**
  - Jet mass/energy scale
  - Jet energy resolution

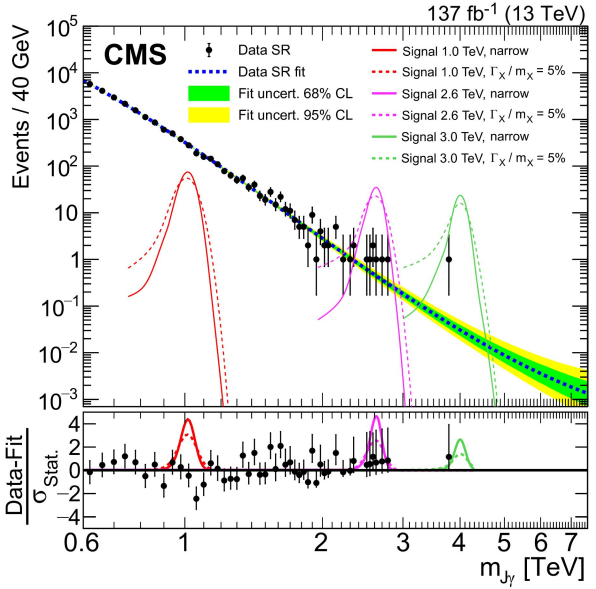
ATLAS-CONF-2021-041

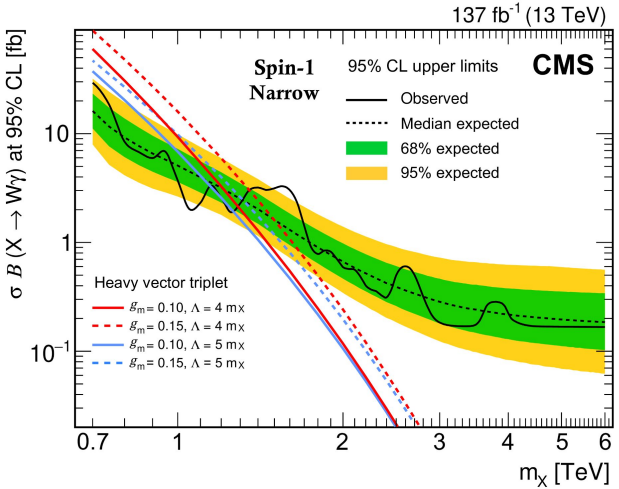
Search for resonances in X → Wγ decays:

- **Search for resonances in (merged) qqγ final states**
  - Probe for particles with spin 0 or 1 hypothesis
- **Analysis strategy:**
  - Use parametric fit function to describe background:

$$\frac{dN}{dm} = p_0(m/\sqrt{s})^{p_1+p_2\log(m/\sqrt{s})+p_3\log^2(m/\sqrt{s})}$$

  - The signal is modeled with the sum of a Crystal Ball function and Gaussian functions



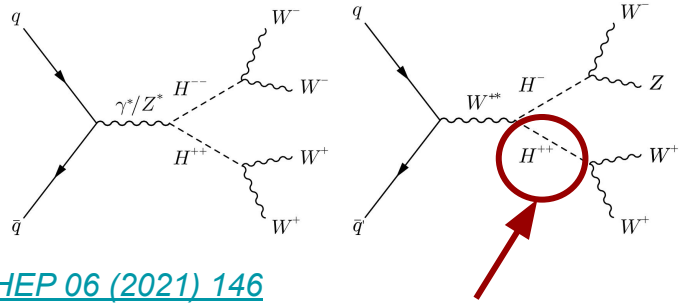


- **Dominant systematic uncertainties:**
  - W-tagging
  - Photon reconstruction and identification

arXiv::2106.10509

Search for doubly and singly charged Higgs bosons:

- **Probe multi-lepton final states ($2\ell^{SC}$, 3ℓ, 4ℓ)**
- **Analysis strategy:**
  - Define signal regions (angular distances, invariant masses)
  - Probe for excess of observed signal region yields
  - Simultaneous fit of the three signal regions
- **Dominant systematic uncertainties:**
  - Non-prompt lepton estimation
  - MC statistics



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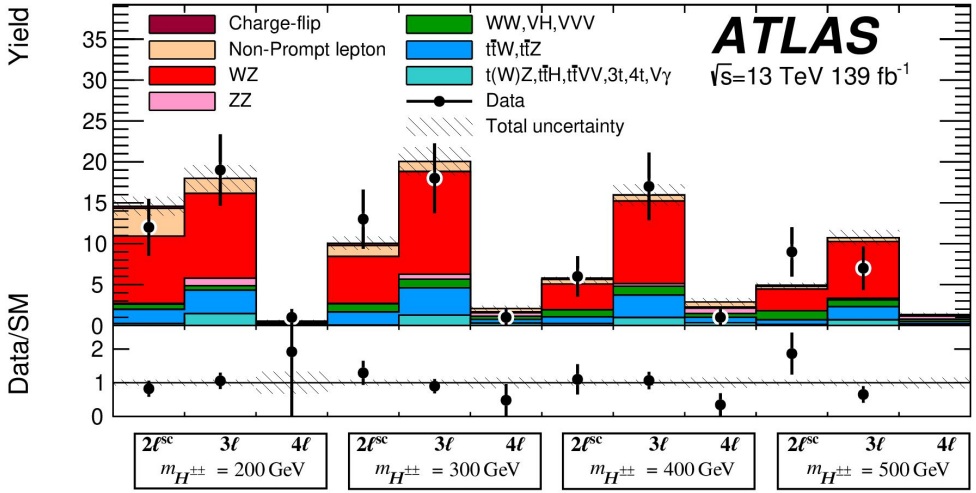
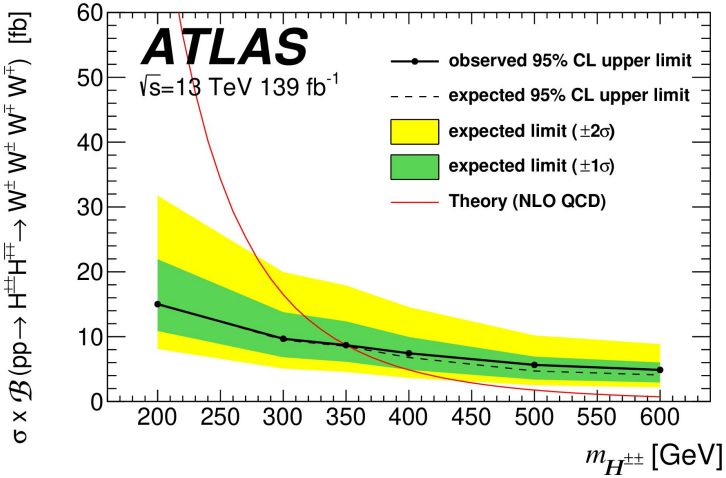
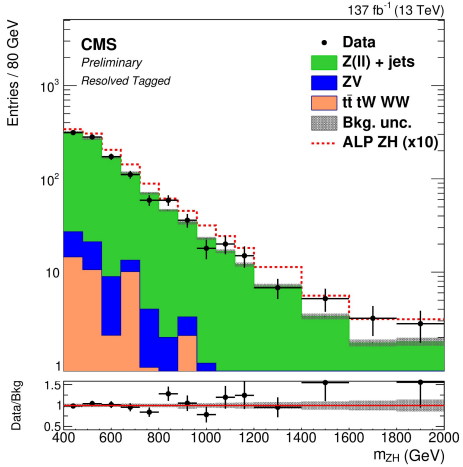
Predicted in Higgs triplet models (needed for e.g. type-II seesaw mechanism)

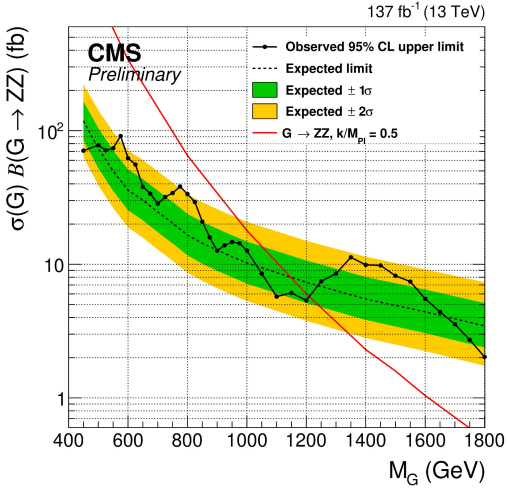


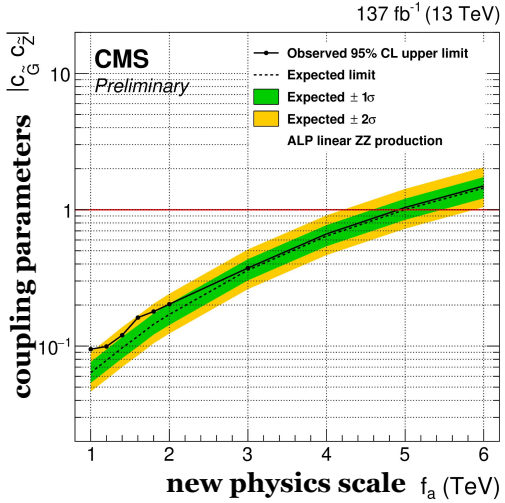


Search for new particles in X → ZZ, ZH, ZW events:

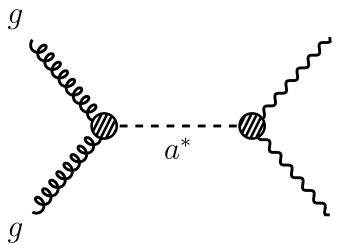
- **Probe resolved and merged ℓℓjj (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Search for bumps in $m_{\ell\ell jj}$ spectra (or excesses in the tails)
    - To probe for new physics in resonant and non-resonant ZZ, ZH, ZW production
  - Simultaneous fit of all 8 event categories:
    - (μμ, ee) × (resolved, merged) × (tagged, untagged)







- **Dominant uncertainties:**
  - Large-R jet mass resolution
  - Z/W-tagging
  - b-tagging

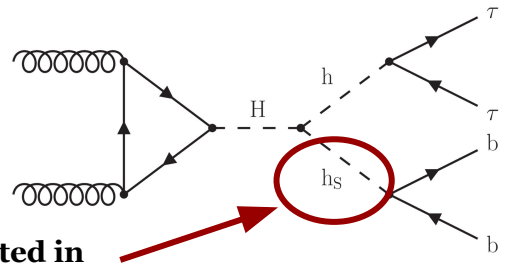


nonresonant ALP-mediated scattering

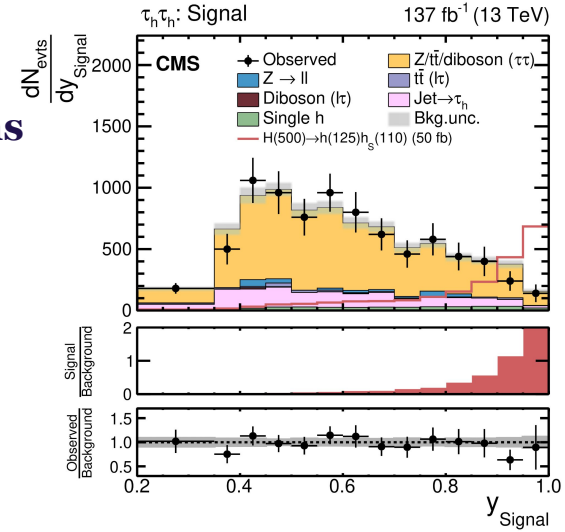
[CMS-PAS-B2G-20-013]

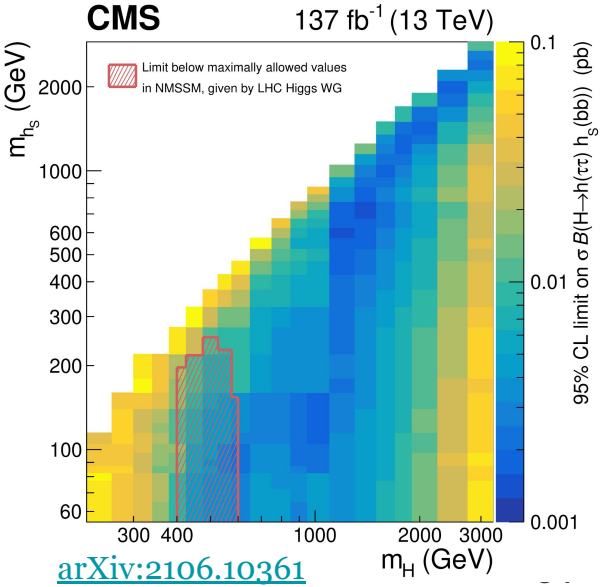
Search for resonances in $H \rightarrow hh_S \rightarrow bb\tau\tau$ decays:

- **Search for resolved bbeτ_h, bb$\mu\tau_h$ and bb$\tau_h\tau_h$ final states**
- **Analysis strategy:**
  - Event categorisation based on neural networks (with five output nodes):
    - Events with true τ-pairs
    - Events with quark/gluon jets misidentified as τ_h
    - Top quark pair events
    - Remaining backgrounds
    - Signal events
  - **Fit all max(y_i) distributions**
    - 15 event categories
- **Dominant systematic uncertainties:**
  - Background modelling



Predicted in e.g. NMSSM

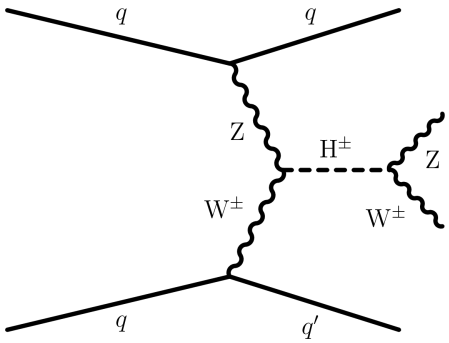


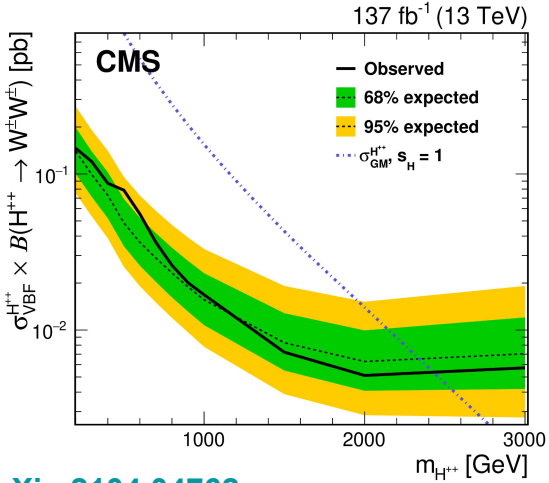


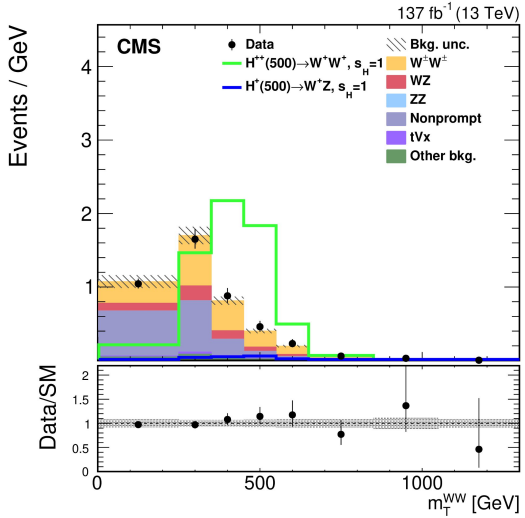
arXiv:2106.10361

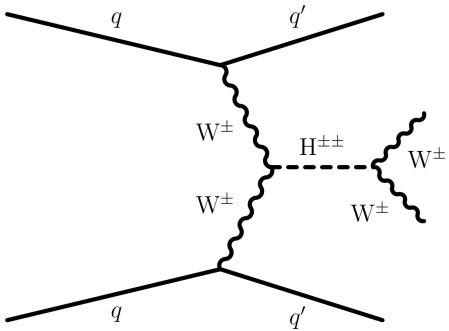
Search for fermiophobic charged Higgs bosons:

- **Search for same-sign ℓνℓνjj and ℓνℓℓjj (ℓ = μ, e) final states**
- **Analysis strategy:**
  - Estimate non-prompt lepton bkg. from data (crucial for ℓνℓν channel)
  - Probe m_T and $m_{\ell\nu\ell\ell}$ distributions for bumps
- **Dominant systematic uncertainties:**
  - Lepton reconstruction/identification
  - Background modelling ($W^{\pm}W^{\pm}$ and WZ)









Predicted in e.g. Higgs triplet models

arXiv:2104.04762