Istituto Nazionale di Fisica Nucleare

Search for new resonances coupling to third generation quarks at CMS

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on behalf of CMS Collaboration

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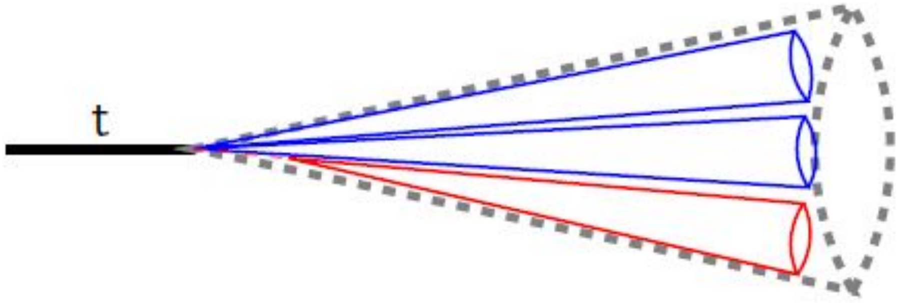
Introduction



Searching for new very heavy particles

- Their decay products are boosted
  - Subsequent decays are collimated, e.g. top quarks
    - Can be captured in a jet with a large solid angle
    - Big efforts in developing dedicated reconstruction algorithm
- Peculiar signature of investigated decay helps the discrimination with Standard Model processes

Third generation: a highway to New Physics

- Considering final states with 3rd generation quarks is an optimal choice
  - Potential preferred fermions to couple for Beyond Standard Model particles
  - Enhance experimental discrimination power against Standard Model backgrounds

Studies performed with full RunII dataset (from 2016 to 2018, L = 137 fb^{-1})

Hadronic jets @CMS

Conic composite object with a definite angular opening constructed performing a definite algorithm → a jet!

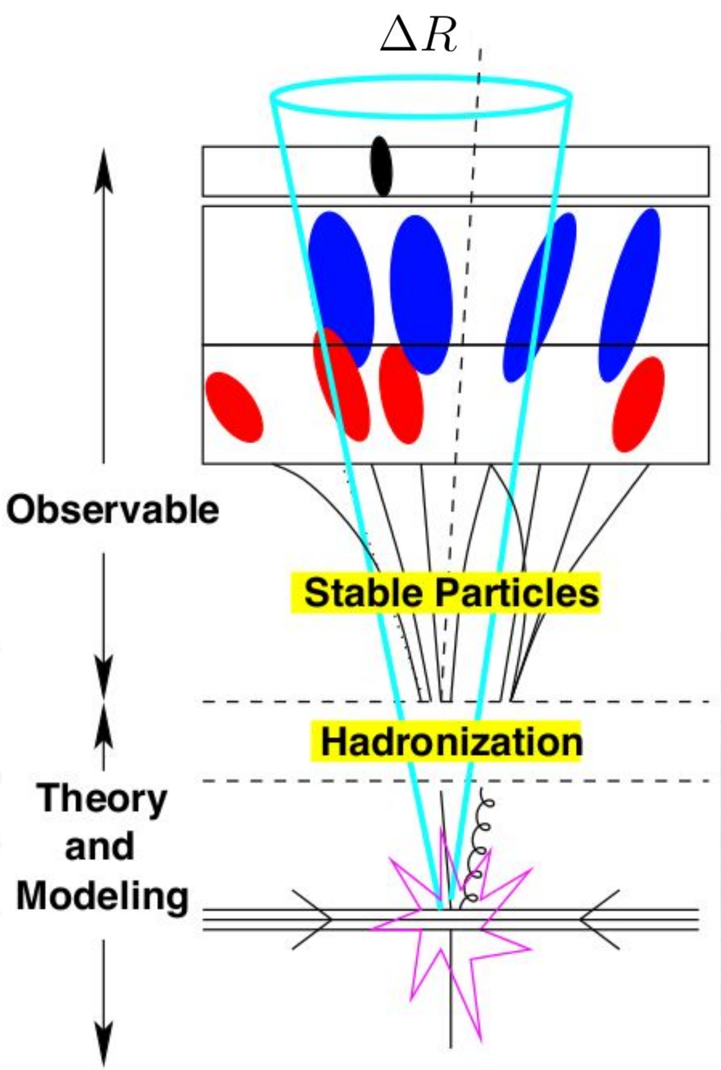
The usual way to proceed
anti-k_T algorithm

- ΔR = 0.4 → AK4 jets (heavy object resolved decay topology)
  - b/c/(uds)-tagging with DNN (i.e., DeepFlavour)
- ΔR = 0.8 → AK8 jets (heavy object boosted decay topology)
  - Pileup-induced constituents removed with dedicated algorithm
  - Mass and substructure crucial to assign mother particle flavour (tagging)
- Different topology, different reconstruction strategy

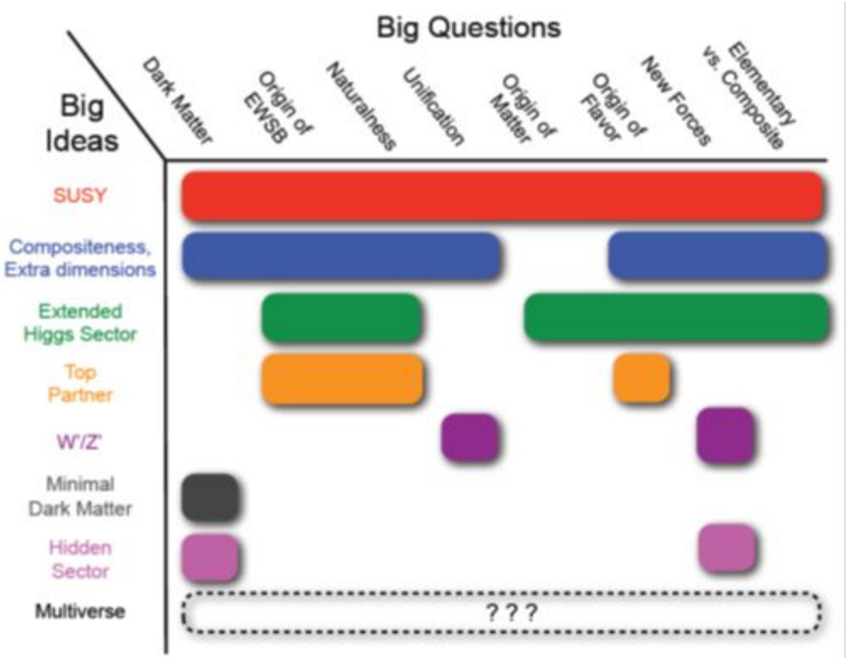
A one-shot approach
HOTVR (Heavy Object Tagger with Variable R)

- Based on an p_T-adaptive definition of the angular opening
- Addresses the need to have a unique algorithm to study both resolved and boosted and intermediate topology at same time

Measure of solid angle in CMS coordinate system



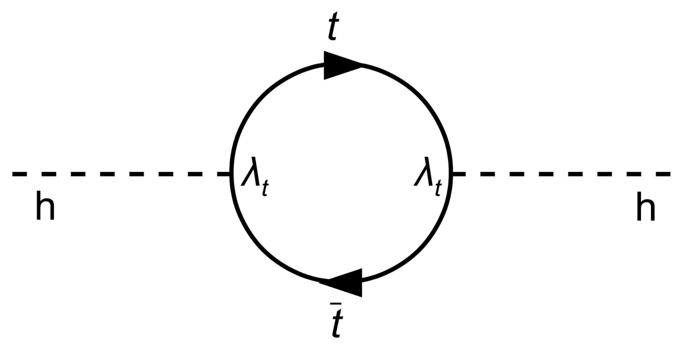
Beyond the Standard Model



Different scenarios having a look Beyond Standard Model (BSM)

- Expansions of SM guage symmetry group
  - New extra dimensions
  - Compositeness (more fundamental particles)

  considered here
- SM fermions acquire excited states (e.g., b*)
- New bosonic resonances compare: W', Z'
  - Can be accompanied with a new composite fermionic sector
    - Vector-like quarks (VLQs) → transform as vectors under EW symmetry group
      Mass terms permitted in BSM Lagrangian
      Not excluded by Higgs sector experiments
    - Heavy bosons decay in VLQs
- New models address the hierarchy problem
  - New Physics preferentially couples with 3rd generation quarks
    Top quark plays a key role in Higgs mass corrections



b* → tW
Overview

Hadronic production of an excited state of b quark

- m_{b*} > 1 TeV
- Three different scenarios for b* couplings tested:
  - LH, RH, Vector-like

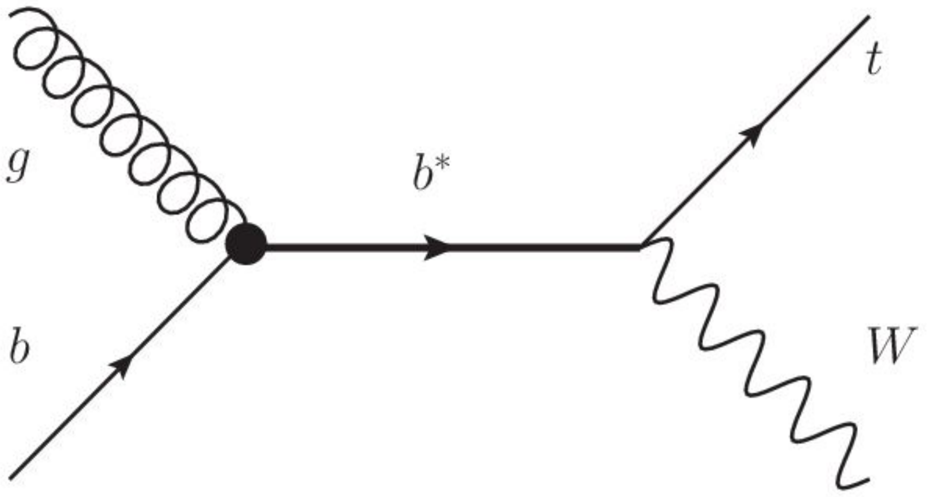
Decay to top quark and W boson

- b* → tW (also B'_{VLQ} → tW in full hadronic scenario)

Two different scenarios investigated combination performed!

- **Full hadronic** (*CERN-EP-2021-044*)
  t and W hadronic decays (m_{b*} > 1.2 TeV)
  - t → Wb → qqb → one 3-prong large jet
  - W → qq → one 2-prong large jet
- **Semileptonic** (*CMS-B2G-020-010*)
  t (W) hadronic (leptonic) decay (0.7 TeV < m_{b*} < 4.2 TeV)
  - t → Wb → qqb → one 3-prong large jet
  - W → $l\nu_l$ → charged lepton + missing energy

$$\mathcal{L} = \frac{g_s}{2\Lambda} G_{\mu\nu}\bar{b}\sigma^{\mu\nu}\left(\kappa_L^b P_L + \kappa_R^b P_R\right) b^* + \text{h.c.}$$



$$\mathcal{L} = \frac{g_2}{\sqrt{2}} W^+_\mu \bar{t}\gamma^\mu \left(g_L P_L + g_R P_R\right) b^* + \text{h.c.}$$

b* → tW full hadronic
Selection and tagging of AK8 jets

Event preselection

Two leading AK8 jets:

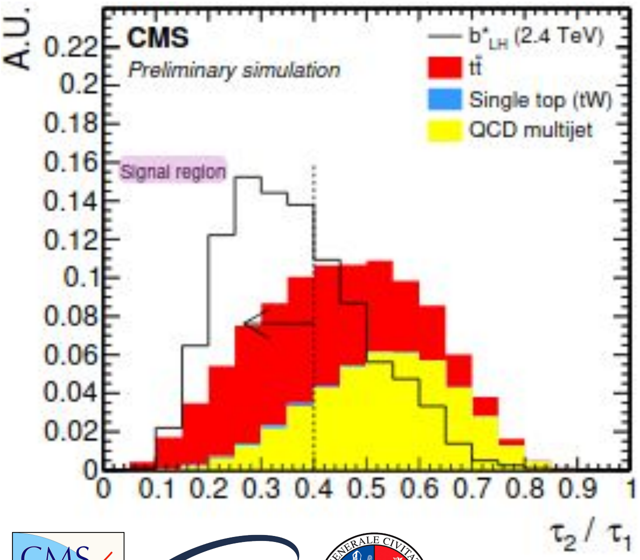
- high transverse momentum (p_T > 400 GeV) and angularly separated ($|\Delta\varphi| > \pi/2$, $|\Delta y| < 1.6$)

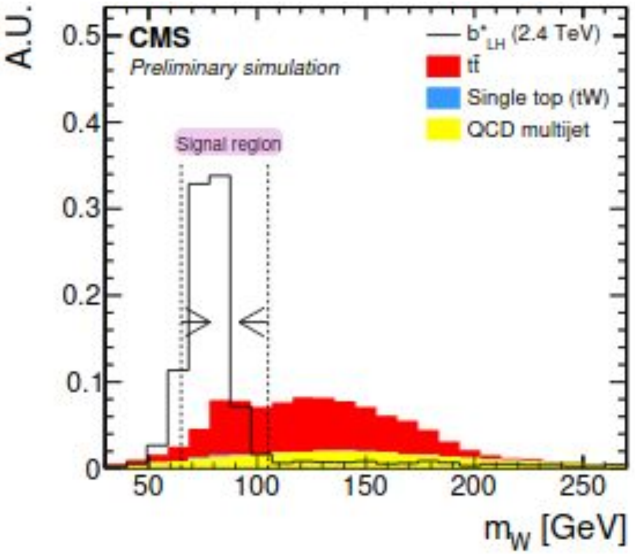
W tagging

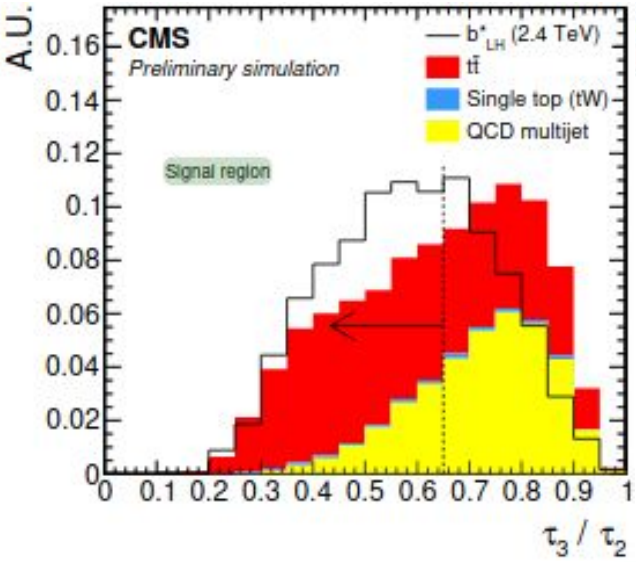
- 2-prong structure (estimated with τ_{21})
- 65 GeV < m_{SD} < 105 GeV

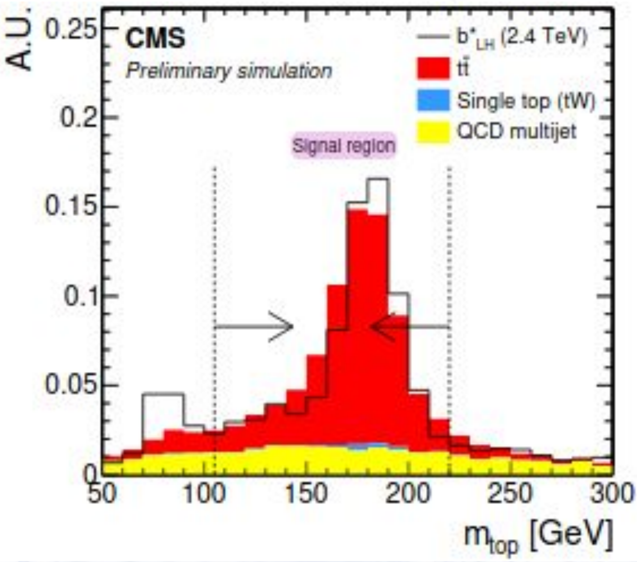
Top tagging

- 3-prong structure (estimated with τ_{32})
- 105 GeV < m_{SD} < 220 GeV
- at least one b-tagged subjet





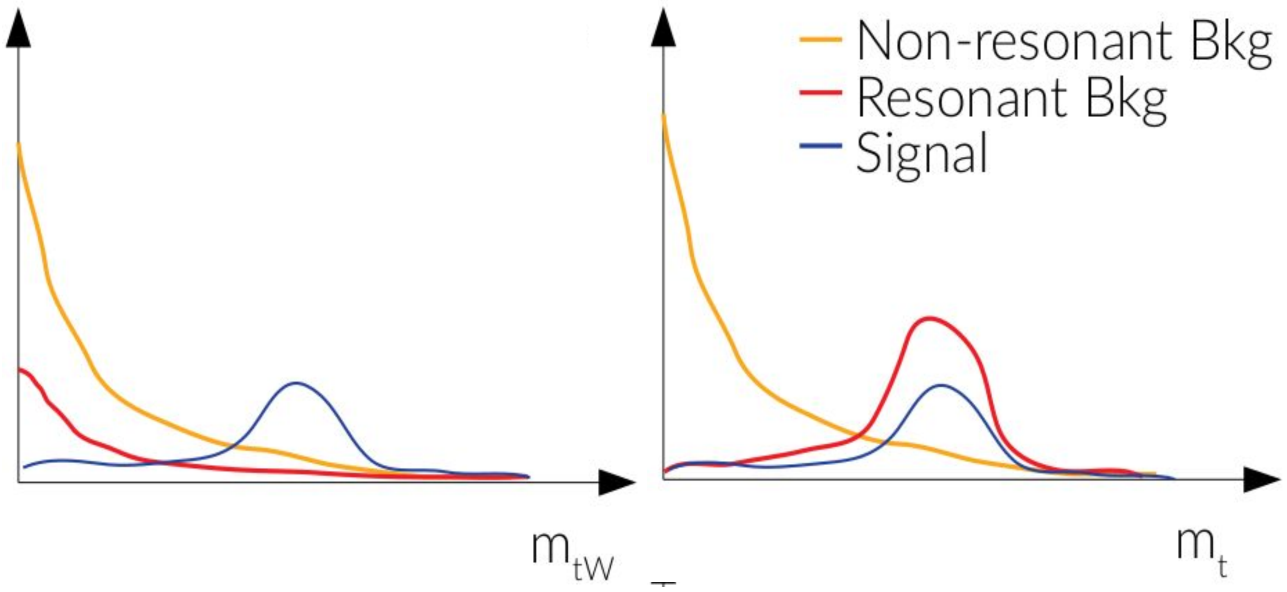




b* → tW full hadronic
Analysis method

Analysis performed in (m_t, m_{tW}) space - 2D fit

- ttbar simultaneously constrained using only top-tagged jets in (m_t, m_{tt}) (ttbar measurement region)



Event selection

- One of the two jets must be W tagged
- m_{tW} > 1200 GeV, m_t > 50 GeV

Event classification based on top tagging

- "fail" or "pass"
  "pass" events constitute signal region

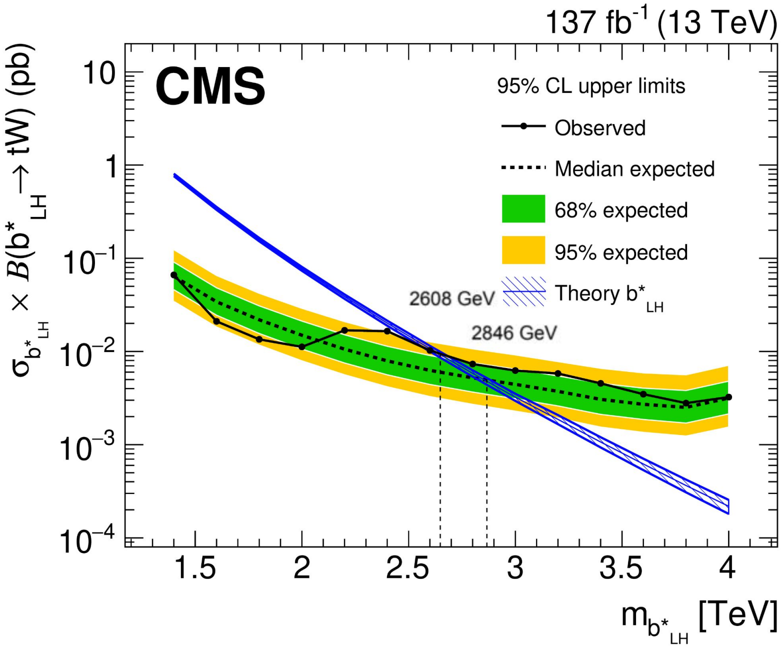
Background estimation

- Resonance-like: template fit
  ttbar and single top tW-channel
- Combinatorial: data-driven method
  QCD multijets, W+jets

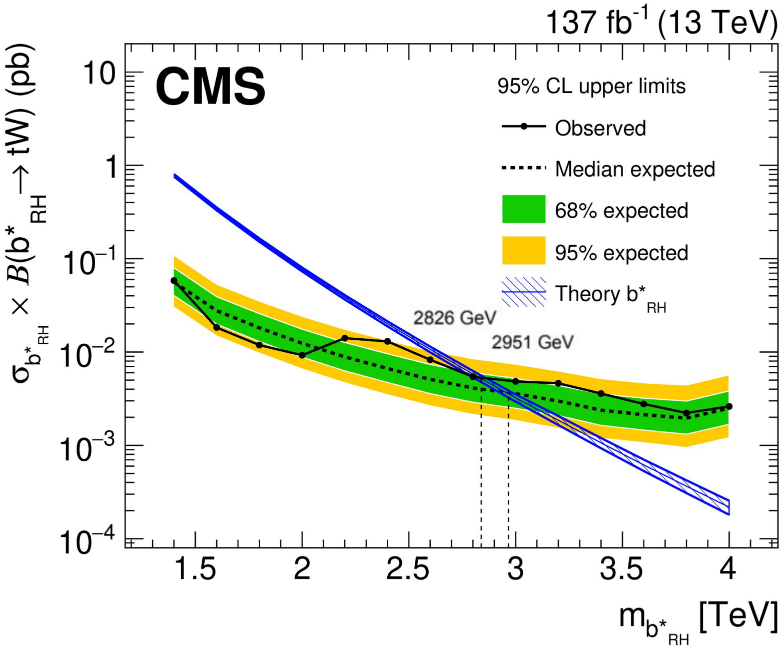
b* → tW full hadronic

Results

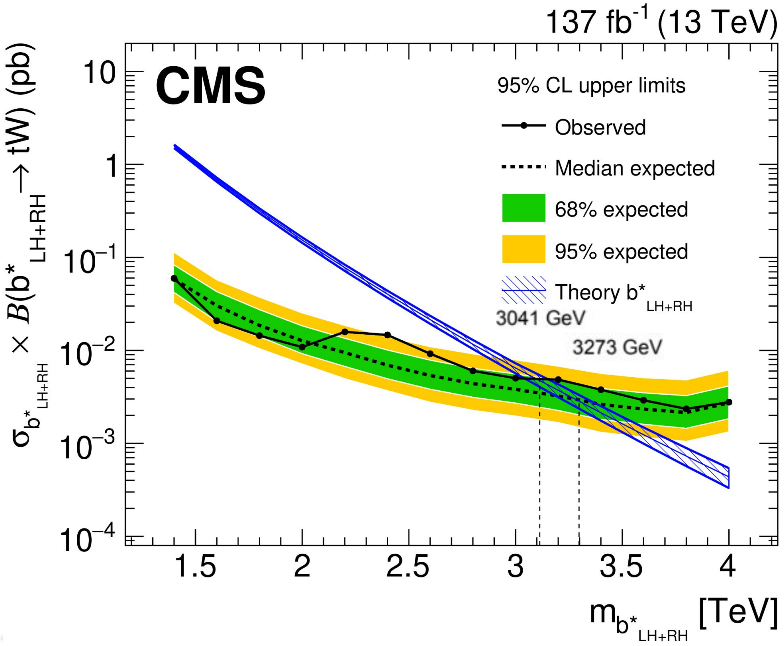
Limits imposed on b* mass doubles exclusions of previous analyses in same channel



LH



RH



Vector-like

An order of magnitude more sensitive than cross-section limits imposed in b* → jj channel

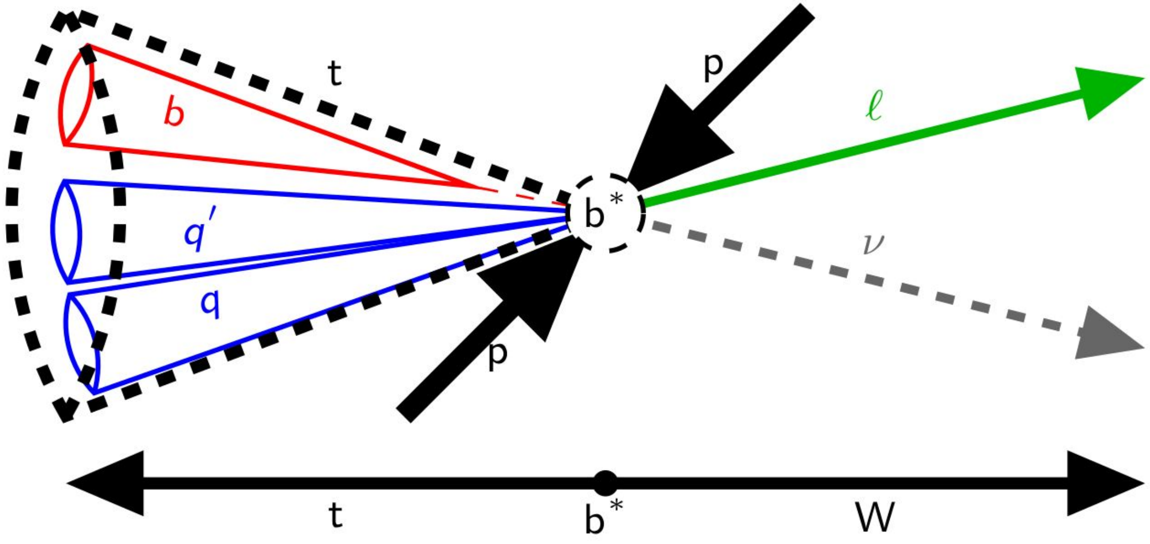
B’ corresponding cross-section upper limits are 22% more sensitive at $m_{B'}$ = 1.4 TeV

b* → tW semileptonic
Selection and top/W reconstruction

Event preselection
- One isolated charged lepton with $p_T > 50$ GeV, $|\eta| < 2.4$
- Missing transverse momentum > 50 GeV, angular distance with lepton $|\Delta\varphi| < \pi/2$
- One top-tagged HOTVR jet with pT > 200 GeV, $|\eta| < 2.5$
- Hadronic activity $H_T > 200$ GeV, overall transverse momentum $S_T > 400$ GeV

Leptonic W reconstruction
- ν identified as unique source of missing p_T
- ν 4-momentum reconstructed imposing $m_{l\nu} = m_{W,PDG}$
  - If multiple solutions, select one which minimizes $|p_{\nu,z} - p_{l,z}|$
- $W^\mu = l^\mu + \nu^\mu$

Top tagging
- The unique top-tagged HOTVR jet
- 3-prong structure (estimated with τ_{32})



tW system identified as a **b* candidate**

$b^* \to tW$ semileptonic
Analysis method

Statistical analysis performed with reconstructed m_{tW}

Exploit the back-to-back topology to measure how signal-like a b* candidate is

$$\chi^2 = \left(\frac{\Delta\phi_{t,W} - \pi}{\sigma_{\Delta\phi_{t,W}}}\right)^2 + \left(\frac{A_{p_T}}{\sigma_{p_T}}\right)^2$$

tW system χ^2 estimator

asymmetry

$$A_{p_T} = \frac{p_T^t - p_T^W}{p_T^t + p_T^W}$$

Event categorization based on b-tagged AK4 jets (bjets)

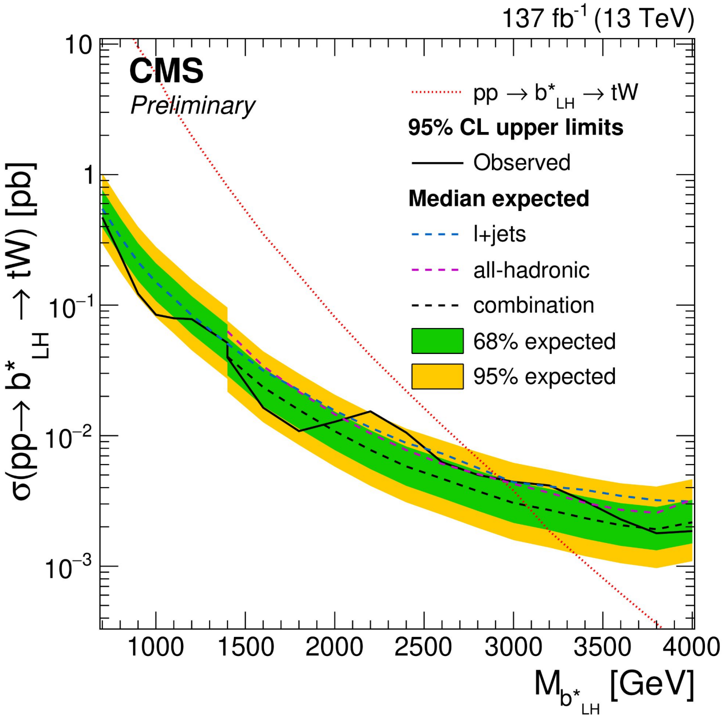
- 0 bjets → fake top backgrounds **(0b region)**
  W/Z + jets, diboson production
- 1 bjet → signal enhanced **(signal region)**
  $\chi^2 < 20$ and $\Delta R(l, \text{bjet}) > 2.0$ to boost sensitivity
- 2 or more bjets → ttbar production **(2b region)**

Background estimation

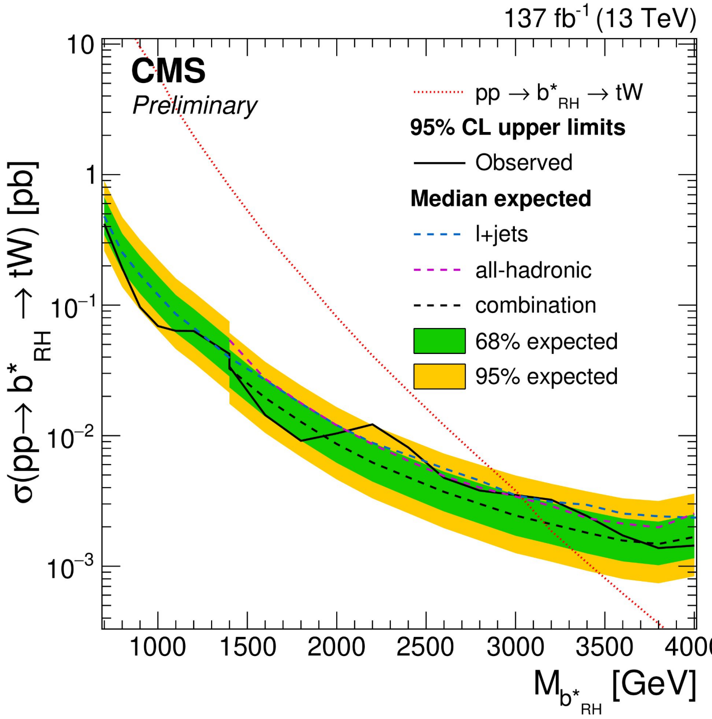
- Fake top: semi-data-driven method
- ttbar, single top and tW: template fit to constrain them in signal region

b* → tW
Combination and results

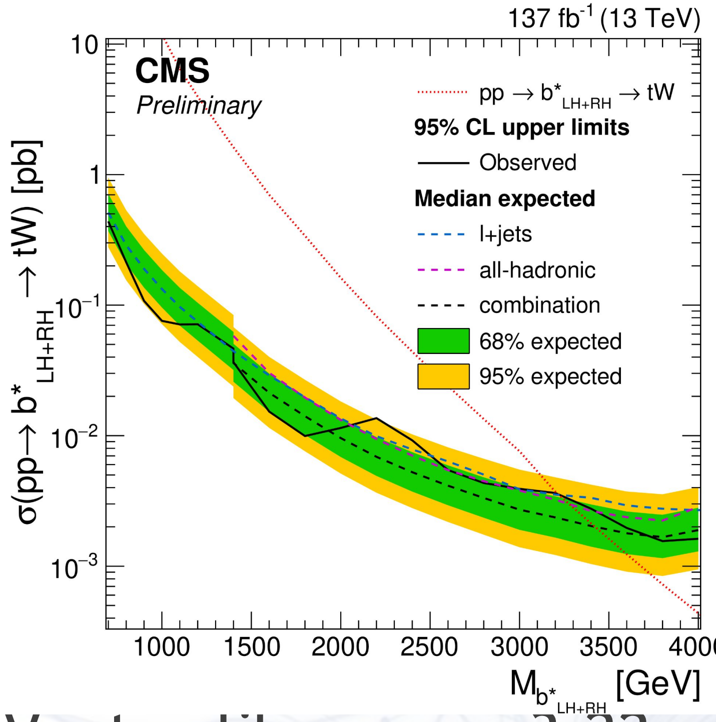
Combination full hadronic and semileptonic performed with a simultaneous fit to data with m_{tW} in all the regions defined in the two analysis



LH: m_{b*} > 2.95 TeV



RH: m_{b*} > 3.03 TeV



Vector-like: m_{b*} > 3.22 TeV

Strongest constraints on m_{b*} to date

W’ $\rightarrow$ tb full hadronic
Phys. Lett. B 820 (2021) 136535 - Overview

Hadronic production of a new hypothetic vector boson W’

- W replica, but heavier and different coupling to fermions
- Two scenarios for interaction with fermions tested:
  - **W’$_L$** : Coupling only with LH fermions (interference with SM)
  - **W’$_R$** : Coupling only with RH fermions
- 1 TeV < $m_{W'}$ < 4 TeV

Decay to top-bottom quark pair

- W’ $\rightarrow$ tb
  Preferred decay wrt other fermionic pairs

Full hadronic final state

bottom hadronization and top hadronic decay

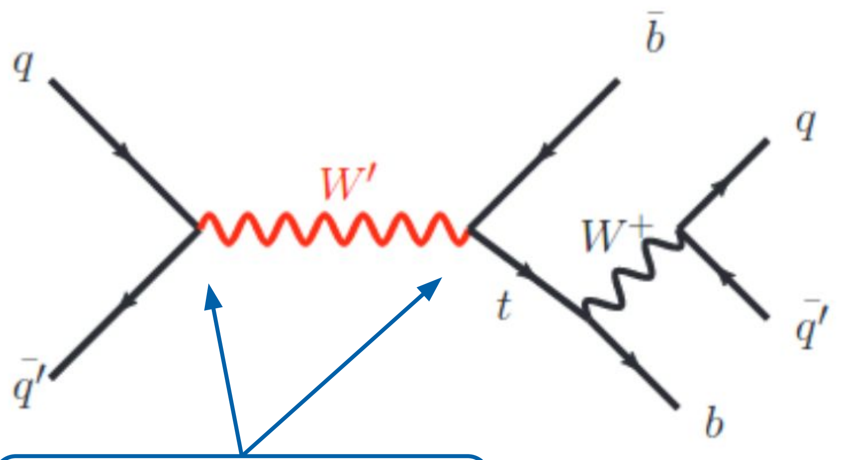
- t $\rightarrow$ Wb $\rightarrow$ qqb $\rightarrow$ one 3-prong large jet

Simplest extension to SM with W’

$$SU(2)_1 \times SU(2)_2 \times U(1)$$

Simmetry breaking

W_{SM} W’



$$L = \frac{W'_\mu}{\sqrt{2}}[q'_i(C^R_{q_{ij}}P_R + C^L_{q_{ij}}P_L)\gamma^\mu q_j + \bar{\nu}_i(C^R_{l_{ij}}P_R + C^L_{l_{ij}}P_L)\gamma^\mu l_j]$$

Most general interaction Lagrangian

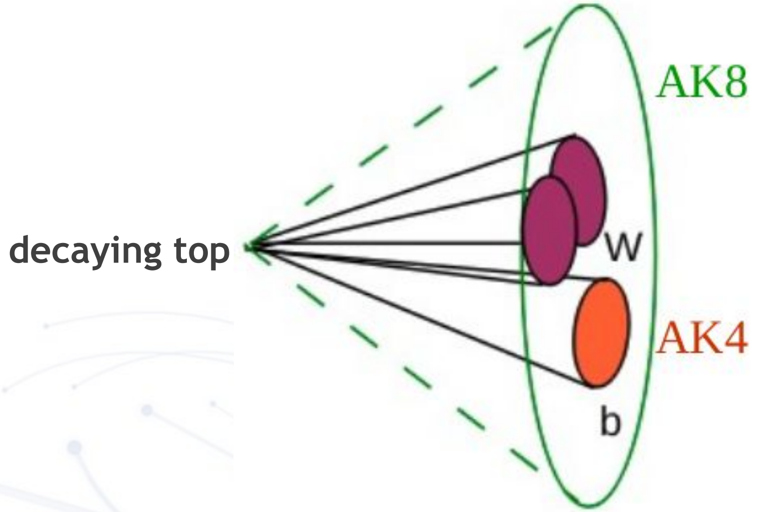
W’ → tb full hadronic
Selection and jet tagging

Event preselection

- Veto on events with isolated leptons
- At least one AK4 jet and one AK8 jet with p_T > 550 GeV both, not overlapping

Tagging W’ candidate products

- AK8 top-tagged with the highest score (DeepAK8)
  - 105 GeV < m_{SD} < 210 GeV to enhance signal sensitivity
- AK4 b-tagged (DeepFlavour) with the highest p_T
  - $|\Delta\varphi| > \pi/2$ and $|\Delta R| > 1.2$ between top AK8 and b AK4
  - Surrounding AK8 m_{SD} < 60 GeV
    Vetoes b AK4 coming from top → ttbar rejection



tb system as W’ candidate

- $m_{W'} = m_{tb}$ as quantity sensitive to signal detection

W' → tb full hadronic
Analysis method

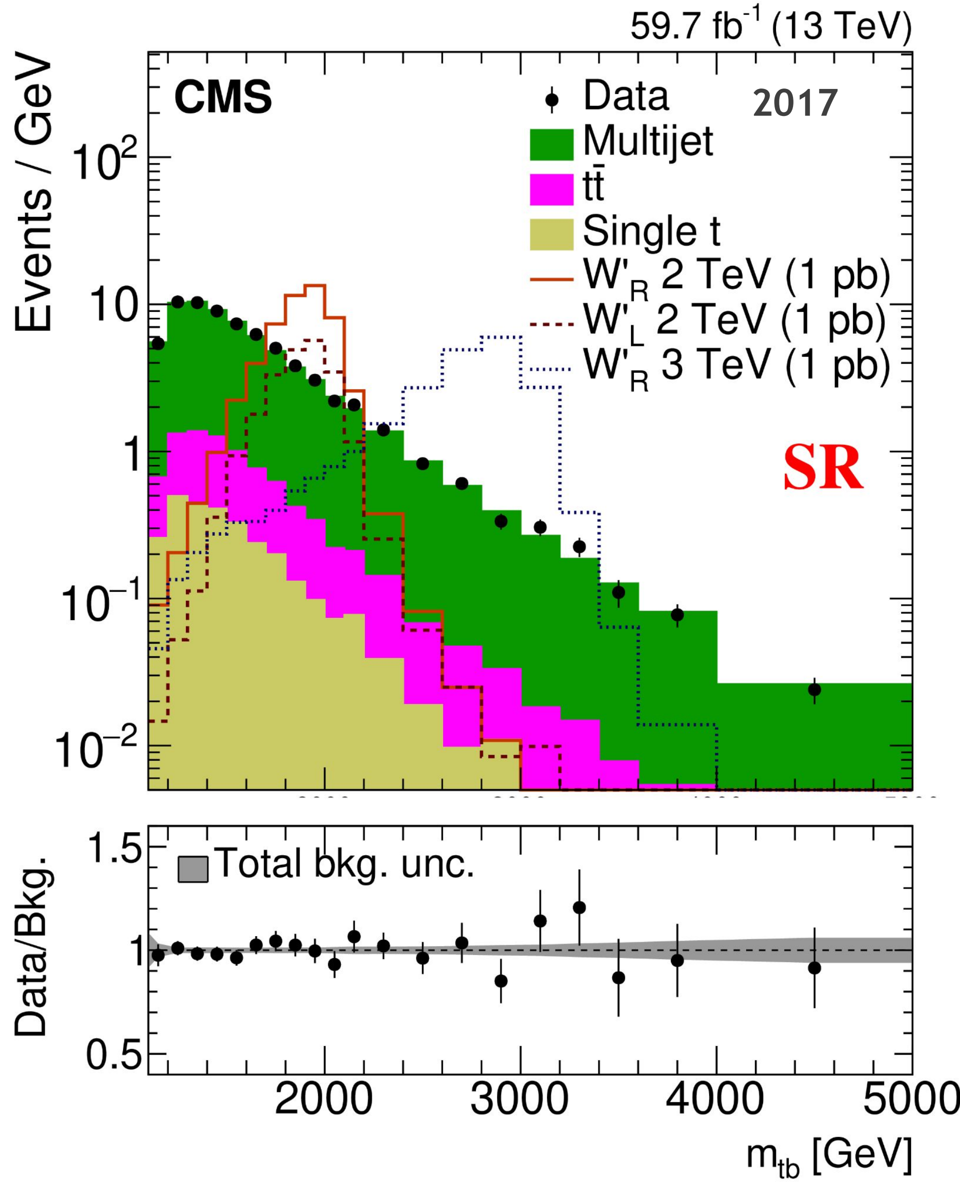
Statistical analysis performed with reconstructed m_{tb}

Background estimation

- QCD multijets: data-driven method
- ttbar, single top: template fit to constrain them in signal region

Event categorization based on jet tagging and top-jet mass

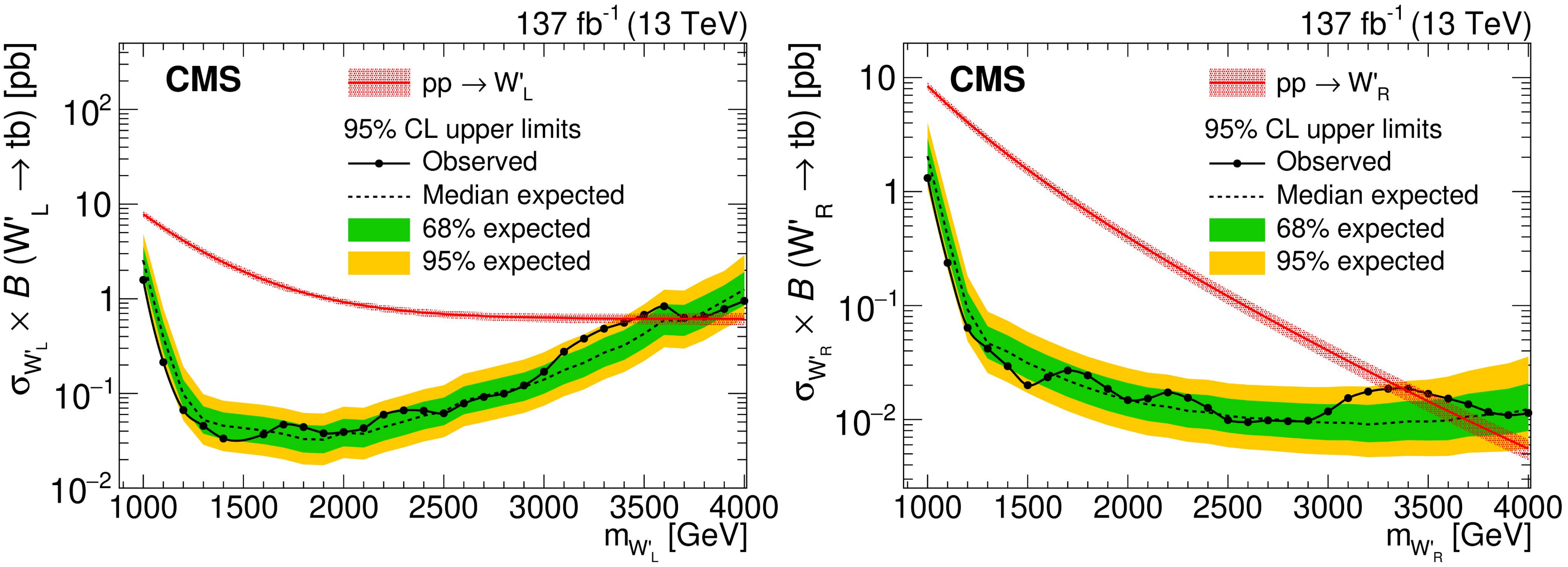
- All tagging requests passed → **Signal Region**
- Failing one or more tagging requests → **Control Regions**
  - AK8 surrounding b AK4 not top-tagged → QCD multijet
  - AK8 surrounding b AK4 top-tagged → ttbar production



W' → tb full hadronic

Results

Previous observed limits: $m(W'_{L,R}) > 2$ TeV



LH: $m(W'_L) > 3.6$ TeV

RH: $m(W'_R) > 3.7$ TeV

W'_L cross-section saturation at high $m_{W'}$ due to interference with SM single top production
Sensitivity loss due to tagging inefficiency scaling with energy

Conclusions

Searching for heavy new particles nowadays

- 3rd generation quarks as portal to New Physics
- Different new models and processes investigated
  - Compositeness
  - Heavy bosons → VLQs and SM quarks
- Tagging techniques based on jet substructure enhance sensitivity to new processes

For the future

- Enhancing sensitivity with further development of tagging algorithms exploiting jet substructure
- New results expected from the combined 2016, 2017 and 2018 dataset

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Thank you for your attention!

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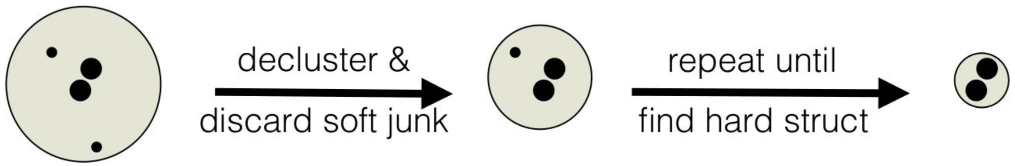
backup

Tagging AK8 jets

Exploit AK8 jet substructure to assign mother particle flavour (aka tagging)

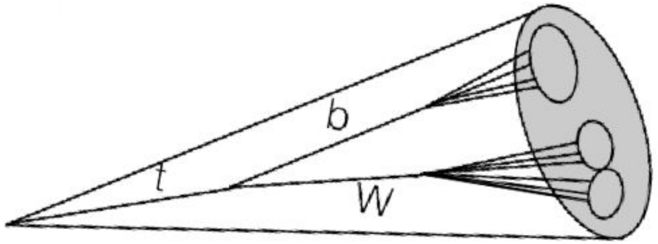
- Jet mass grooming techniques to improve the mass estimates of jets



Soft Drop (SD) technique → defines m_{SD}

More reliable estimates can be used to identify jet origin (i.e., a resonance)

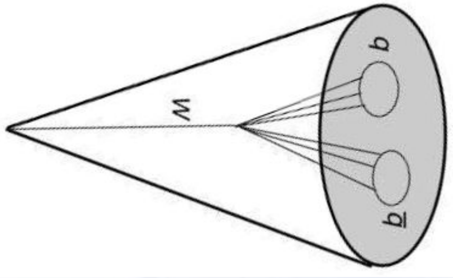
- Metrics for degree of compositeness of a jet based on spatial distribution
  - N-subjettiness τ_N : compatibility with N AK4-subjets pattern
    Ratios $\tau_{NN'}$: evaluate most probable pattern between N and N’
- *b*-tagging subjets inside an interesting jet: top/Higgs decay signature



top hadronic decay

Tagging techniques based on combination of these information

- Top tagging: 3-prong structure, m_{SD} compatible with m_{top} , one b-subjet
- W/Z tagging: 2-prong structure, m_{SD} compatible with $m_{W/Z}$
- Machine Learning algorithms exploiting AK8 substructure (i.e., DeepAK8)



W hadronic decay

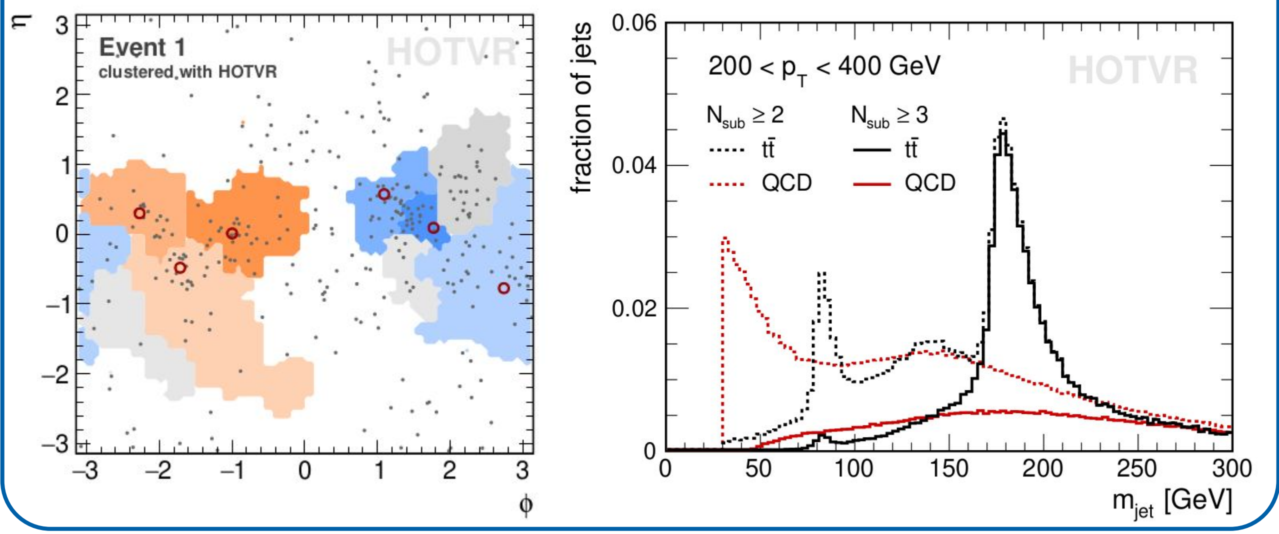
HOTVR algorithm
Reconstruct and tag for every occasion

Jet clustering, subjet finding and soft radiaton rejection in one shot

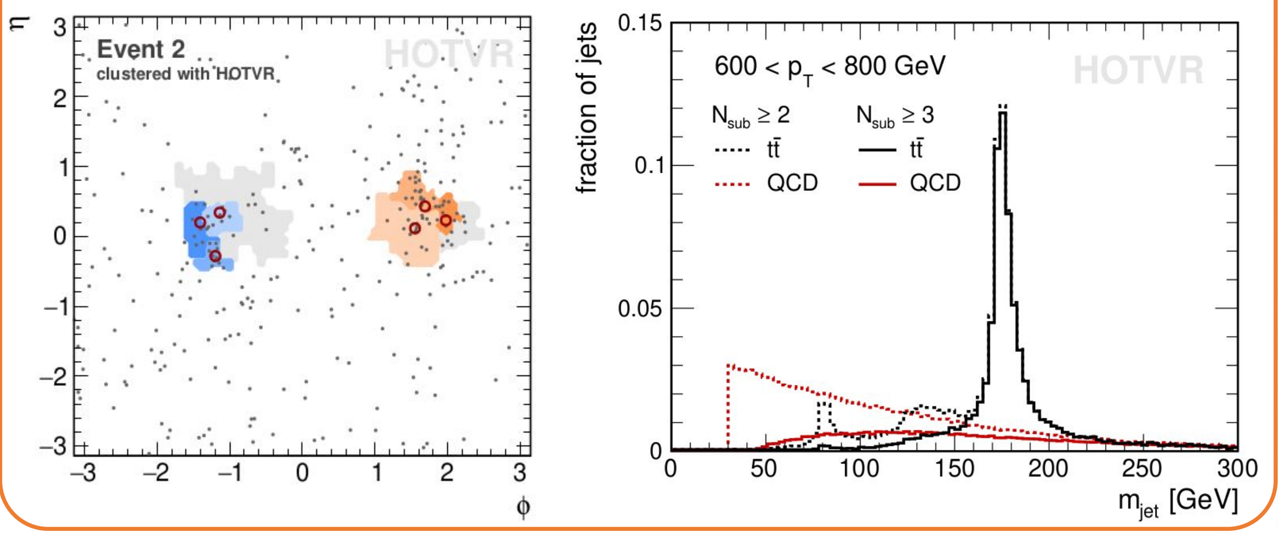
- Adaptive jet angular opening depending on total p_T: $R_{\text{eff}}(p_T) = \frac{\rho}{p_T}$
- Avoid clustering subjets coming from soft radiation (jet grooming)
  - Mass and p_T thresholds on subjet pairs
- Tagging jets exploiting substructure information

No need to separate events on decay topology!

ttbar events - resolved topology

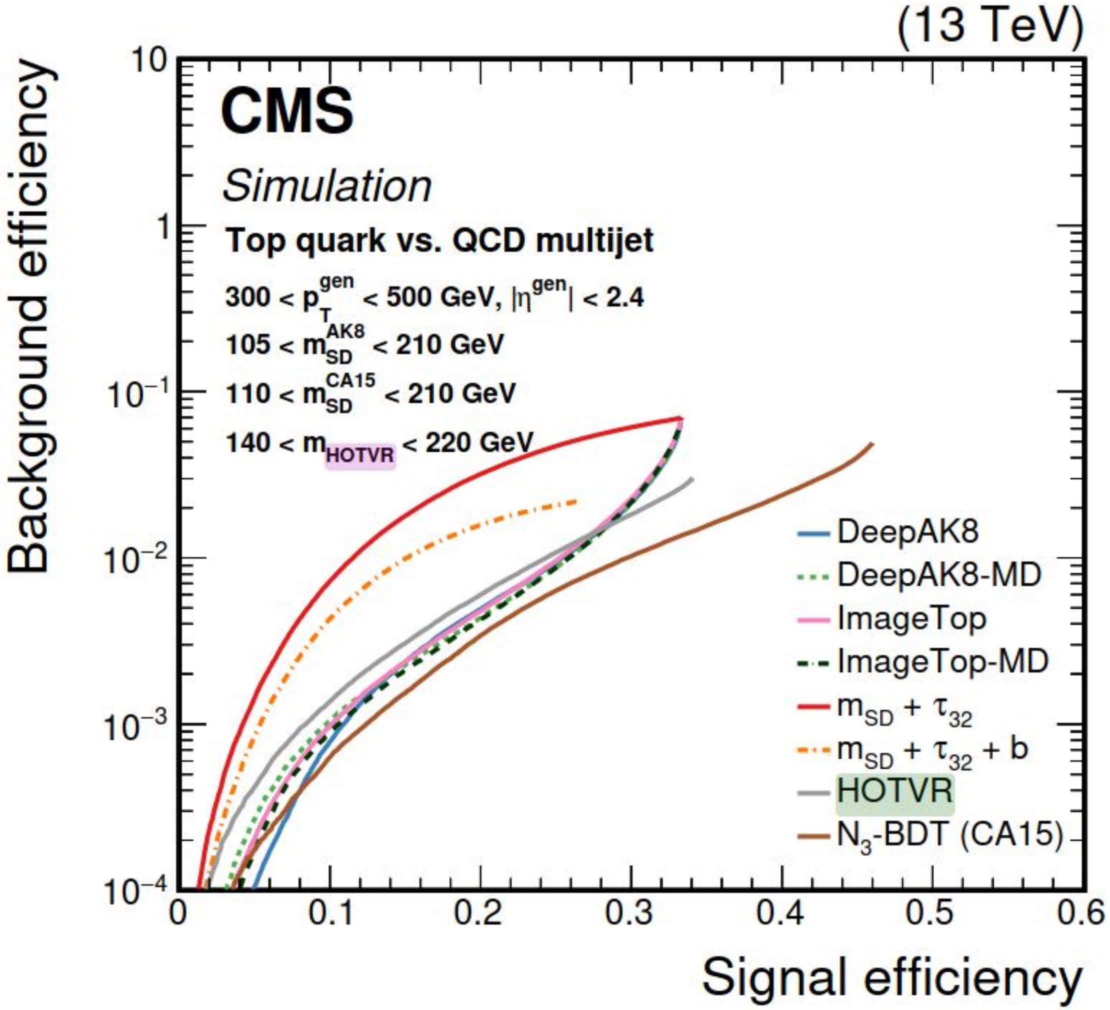


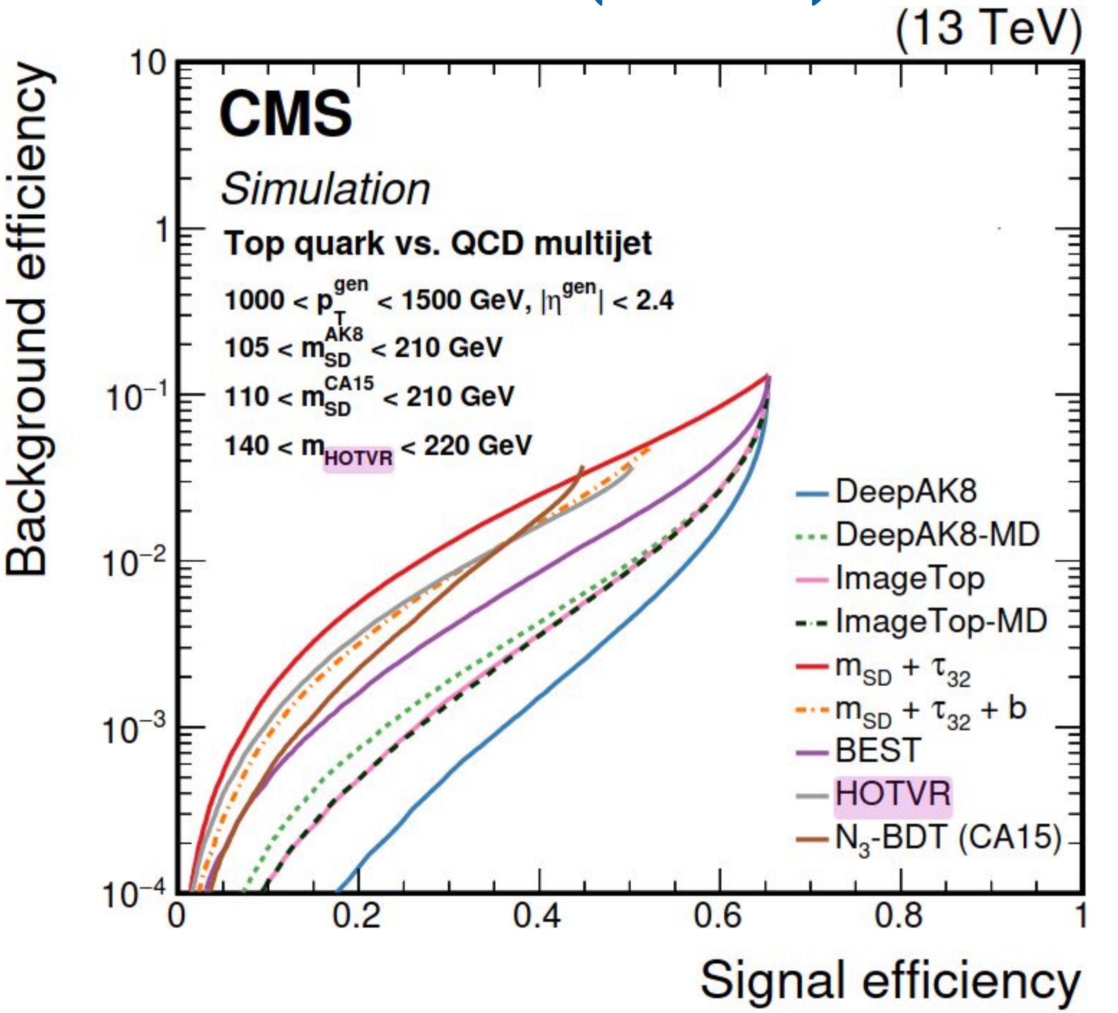
ttbar events - boosted topology



HOTVR algorithm

Performances wrt other techniques - *JINST 15 (2020) P06005*





DeepAK8, ImageTop, BEST, are Machine-Learning- and AK8- based; N_3-BDT is Machine-Learning- and Cambridge-Aachen- based

b* → tW full hadronic

Data-driven background estimation: 2D Alphabet method

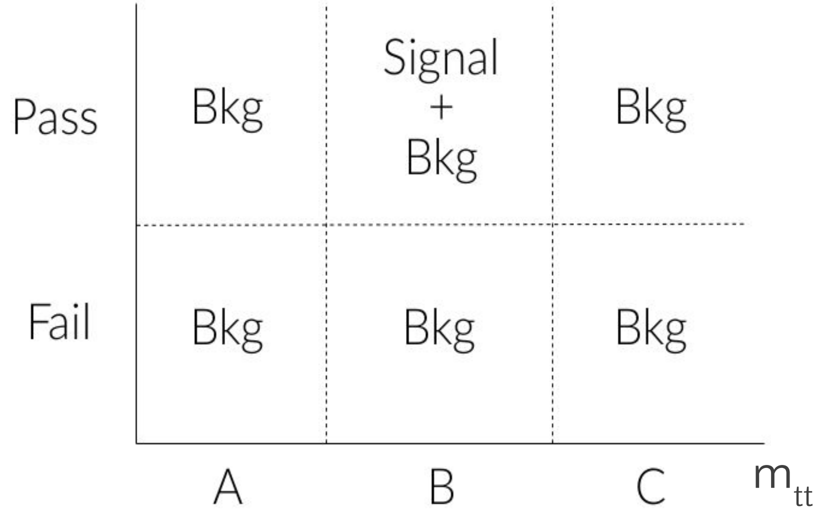
Estimating background contribution in SR through a transfer function $f(m_t, m_{tW})$: $n_{fail} \rightarrow n_{pass}$

Defining $R_{P/F} = n_{pass}/n_{fail}$ for MC simulations and data

$$n_{QCD}^{pass} = n_{QCD}^{fail} \cdot R_{P/F}^{MC} \cdot \left(\frac{R_{P/F}^{data}}{R_{P/F}^{MC}}\right) = n_{QCD}^{fail} \cdot \underbrace{R_{P/F}^{MC} \cdot R_{ratio}}_{f(m_t,\, m_{tW})}$$

R_{ratio} parametrized surface obtained after a simultaneous fit to data in "pass" and "fail" regions

Applied also in ttbar measurement region for taking account of combinatorial background



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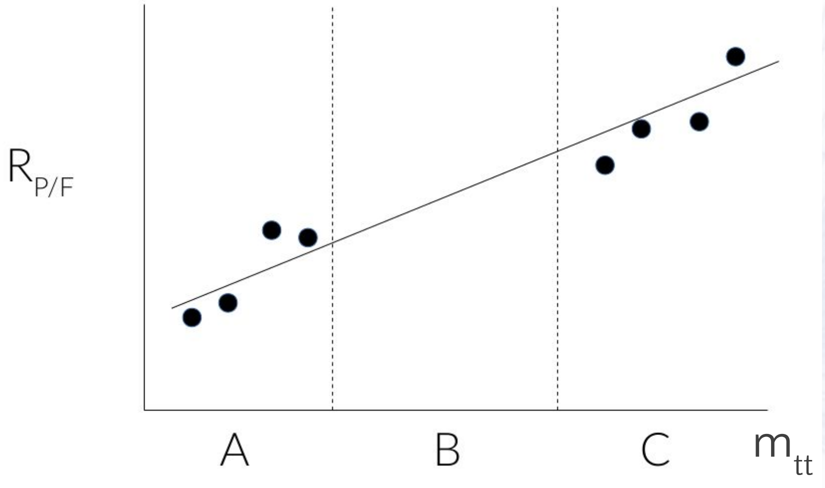


b* → tW semileptonic
Semi-data-driven background estimation: α method

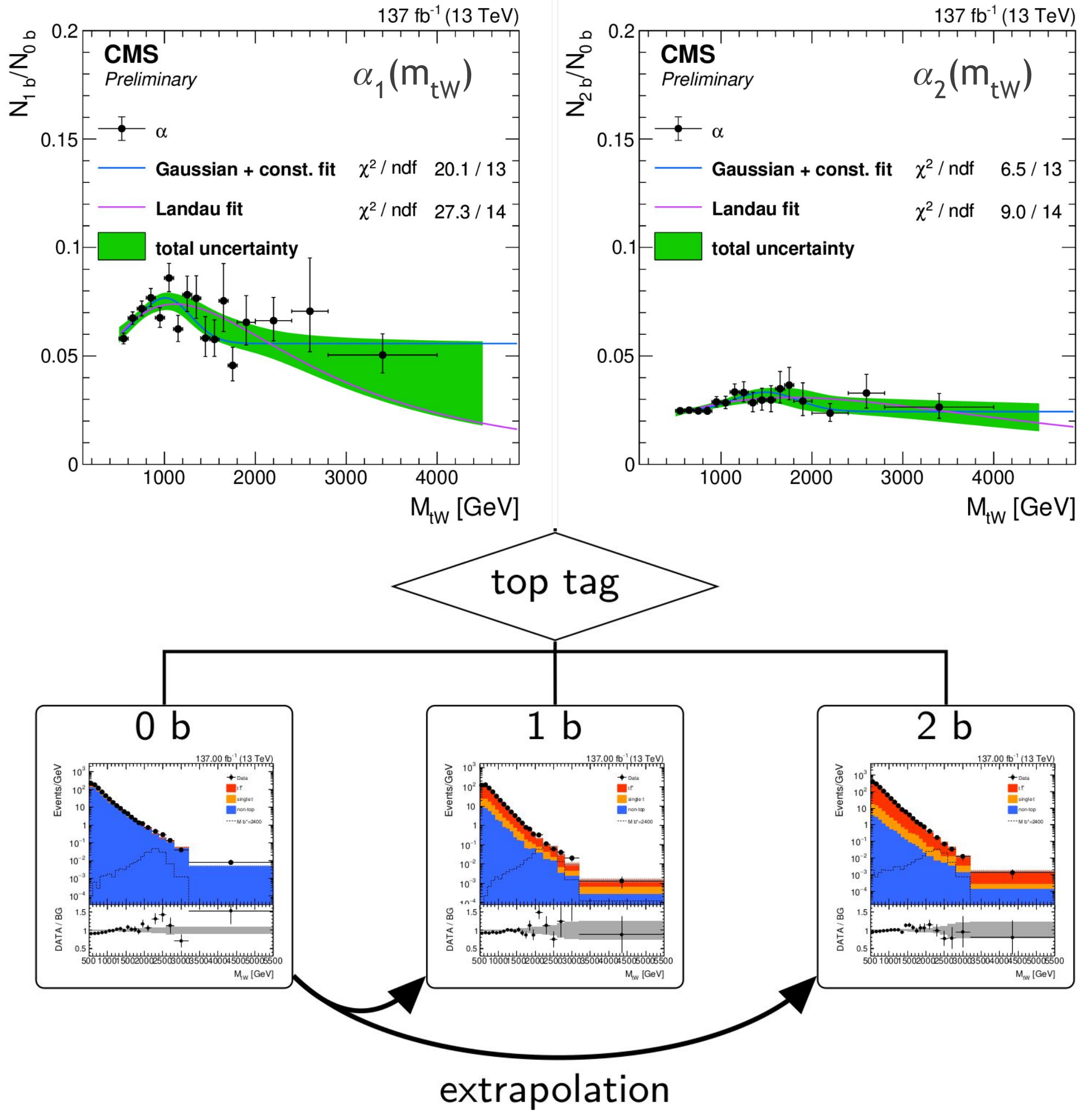
1) **From W/Z+jets and diboson production:**
   - N_{0b} → number of events in 0b region
   - N_{1b} → number of events in signal region
   - N_{2b} → number of events in 2b region

2) **For each *i*-th bin:**

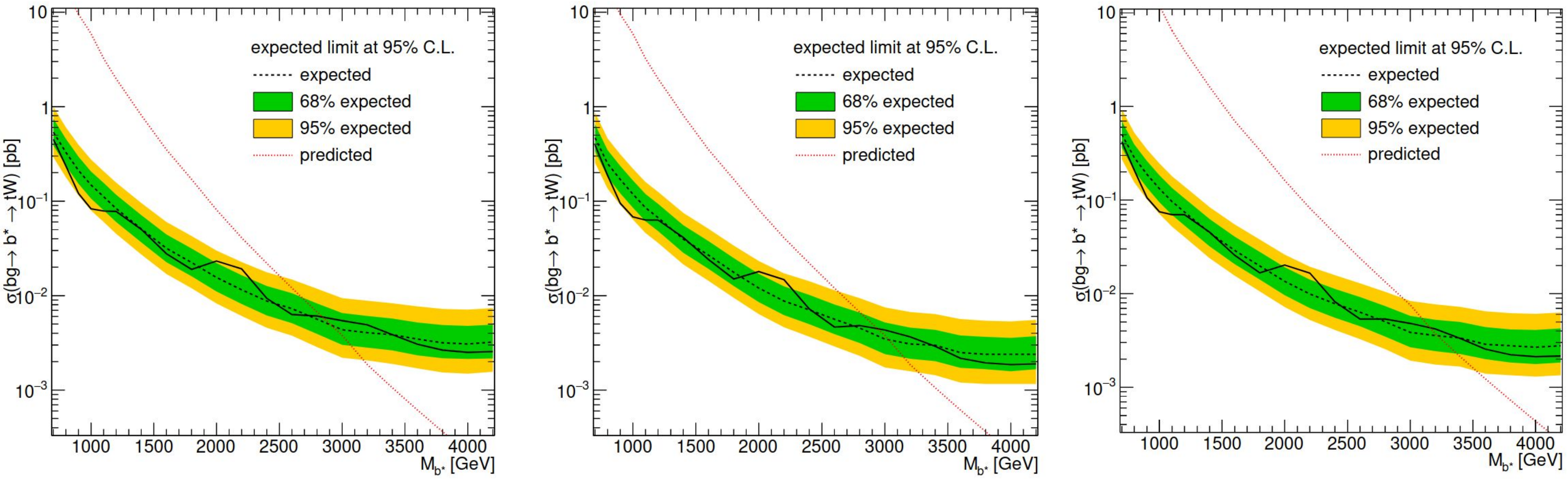
$$\alpha_{1,i} = N_{1b,i} / N_{0b,i} \qquad \alpha_{2,i} = N_{2b,i} / N_{0b,i}$$

3) **Fit $\alpha_{1,i}$ and $\alpha_{2,i}$ as functions of m_{tW}**
   - Gaussian distribution with a constant offset
   - Landau fit to estimate systematic uncertainty

4) **Apply fitted $\alpha_{1,i}$ ($\alpha_{2,i}$) to 0b events in data to extract fake top contribution in 1b (2b) region**



b* → tW semileptonic
Results



LH: m_{b*} > 2.8 TeV

RH: m_{b*} > 2.9 TeV

Vector-like: m_{b*} > 3.2 TeV

W' → tb full hadronic
Data-driven background extraction pass-to-fail ratio method

1) **From data, using m_{tb} distributions**
   - $N_{fail,C}$ → number of events in CR1'
   - $N_{pass,C}$ → number of events in CR1

2) **For each *i*-th bin:**

$$R_{f/p}(m_{tb}) = N_{fail,C} / N_{pass,C}$$

3) **Fit $R_{f/p}$ as function of m_{tW}**
   - Second-order polynomial fit
   - Validated inverting AK8 top-tagging

4) **Apply fitted $R_{f/p}$ (m_{tb}) to SR' events in data to estimate QCD multijet contribution in SR**