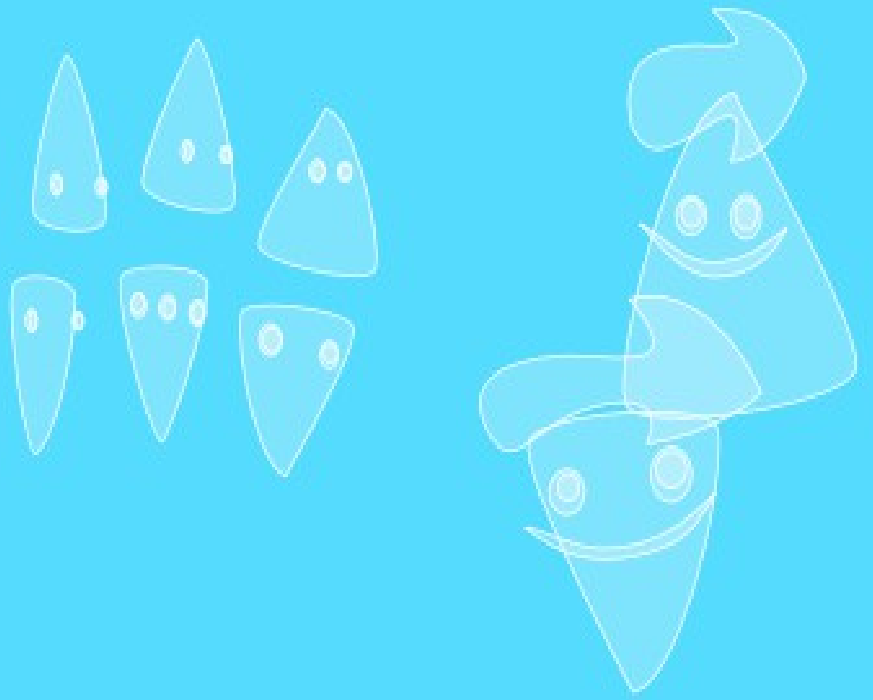
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft DFG

Universität Hamburg

top/bottom partners and new phenomena with **top/bottom pairs** in **ATLAS** and **CMS**

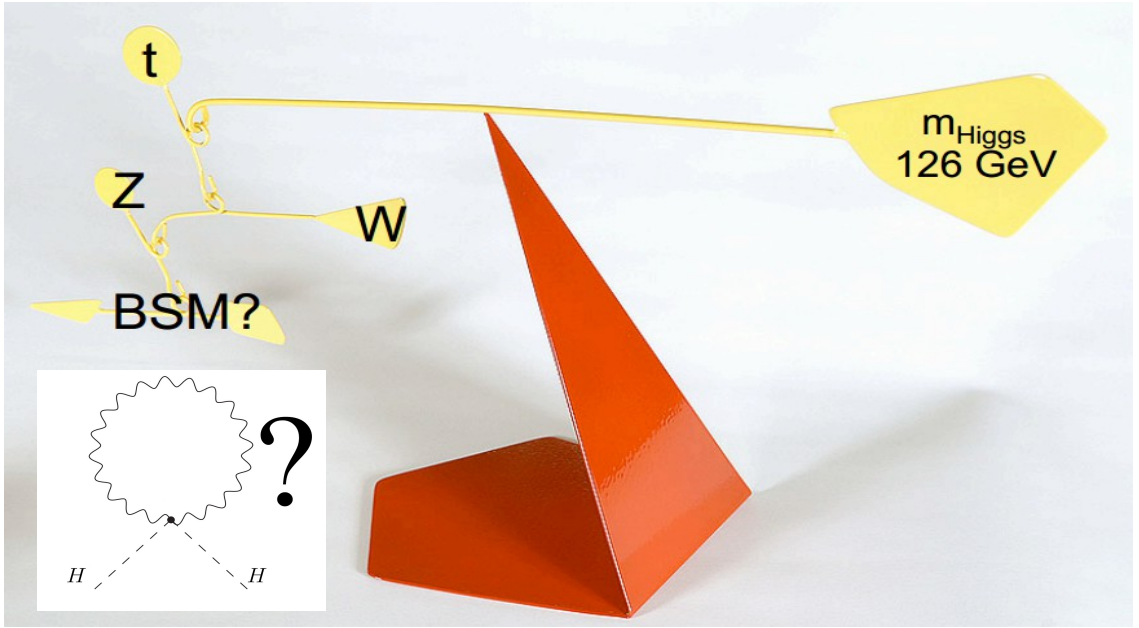


Ivan Marchesini, EPS-HEP 2015, Vienna
on behalf of the ATLAS and CMS collaborations

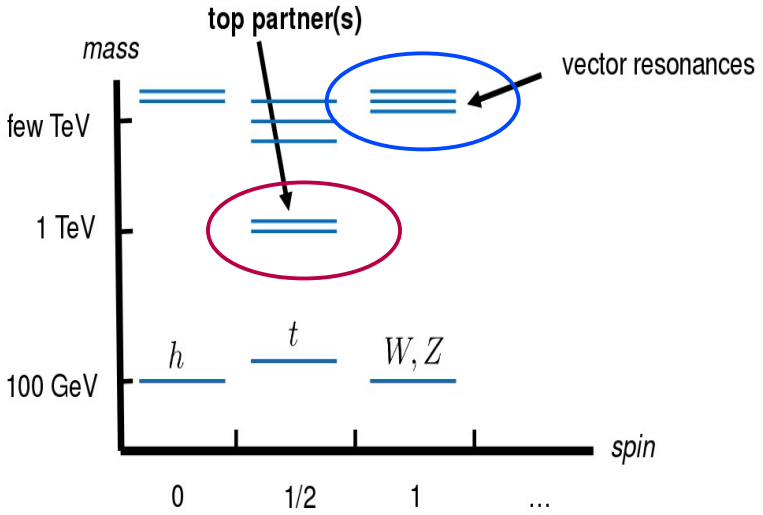
Introduction

- Many theories predict a special role of the top quark and **new particles coupling preferentially to the third generation**:
  - e.g. cure the **little Hierarchy problem**, additional loops

- Focus on **non-Susy searches** with third generation quarks:
  - challenging final states: **cutting edge reconstruction tools**



From F. Blekman's talk, HCP, 2013



E. Salvioni, MC4BSM, 2015

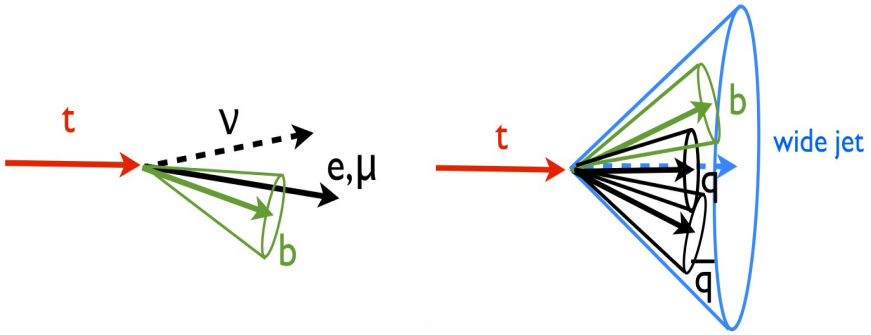
- Areas covered:
  - **vector-like quarks**:
    typically predicted to be < 2 TeV (fine-tuning solution/naturalness arguments)

  - **heavy resonances**:
    new LHC energy opens up larger mass regions
    - **Z'**→tt
    - **W'**→tb

Boosted regime

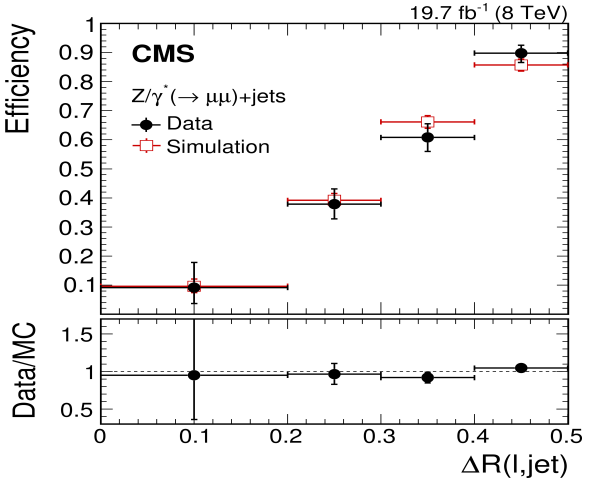
[ATLAS: JHEP 1309 (2013) 076, CMS: arXiv:1506.03062]

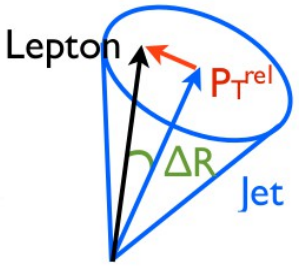
Classical selection methods fail:



➔non-isolated leptons
➔hadronic decay products from heavy particles **merged into large fat-jets**

Leptons: simple cone isolation fails, e.g. exploit **p_T,rel** observable





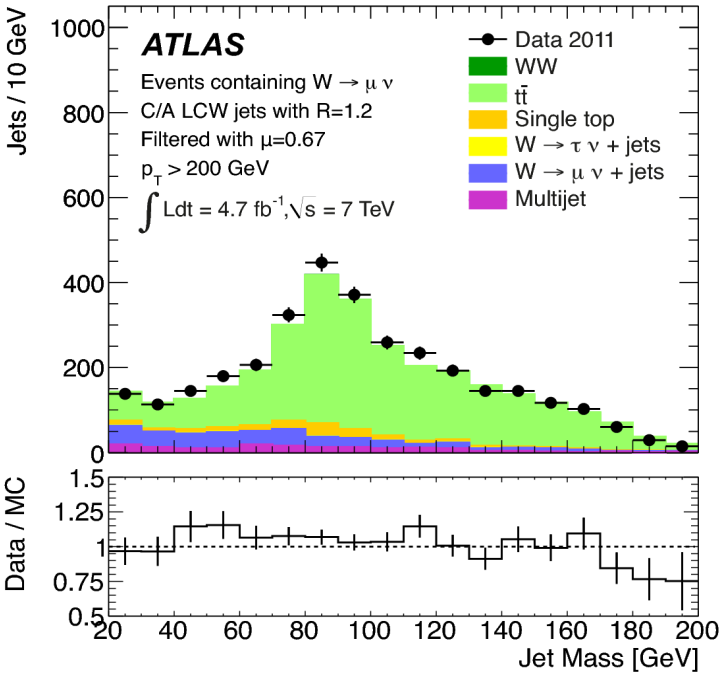
Jet mass: fundamental observable to identify merged jets

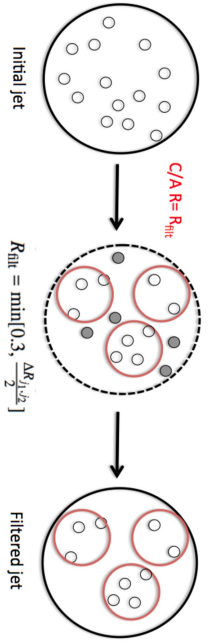
➔ **grooming** (pruning, trimming, filtering, ...): remove soft/large angle radiation, protect from pile-up

Sophisticated tools (back-up):

- **top-tagging**, **subjet b-tagging**, n-subjettiness, W-tagging

filtering, merged W candidates



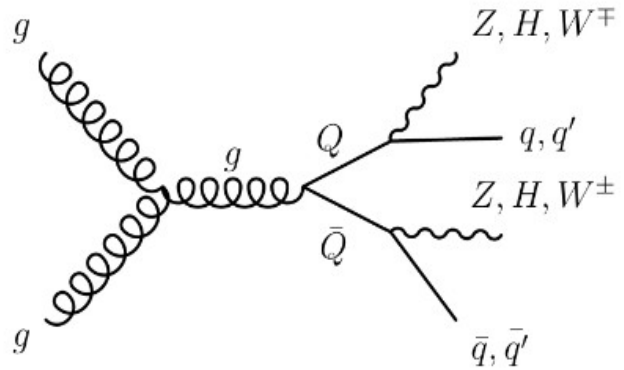


Vector-like quarks

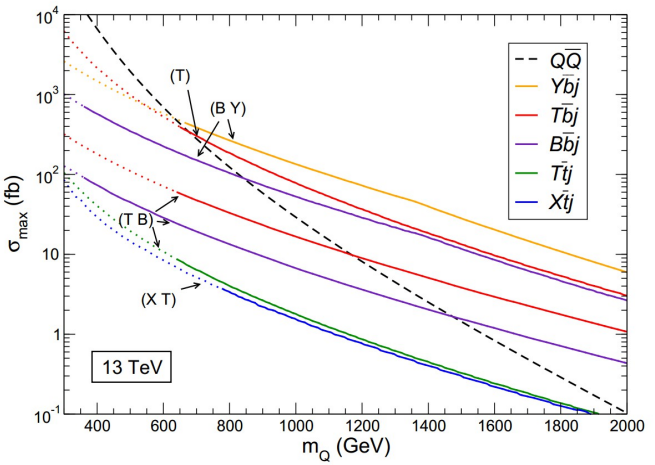
Vector-like quarks

- Why?
  - naturally solve the **hierarchy problem** and are predicted by several theories (little Higgs models, composite Higgs models, extra dimensions)
  - modest impact on SM Higgs production and decay modes: **not ruled out**

- Run 1 focus on **pair-production**
  - driven only by QCD: **model independent**



arxiv:1306.0572



- **Single-production**:
  - dominant for large VLQ masses: focus in Run II
  - model dependent

- Focus on **third generation couplings**: coupling to light quarks possible, but heavily constrained

$T(+2/3)$	$W^+b,\ Ht,\ Zt$
$B(-1/3)$	$W^-t,\ Hb,\ Zb$
	this talk
$X(+5/3)$	W^+t
$Y(-4/3)$	W^-b

TT searches at CMS

[B2G-12-013, Phys. Lett. B 729 (2014) 149, B2G-12-017, JHEP 06 (2015) 080, B2G-14-003]

Single lepton, TT→bWbW→μ+ν+4jets, e+ν+4jets:

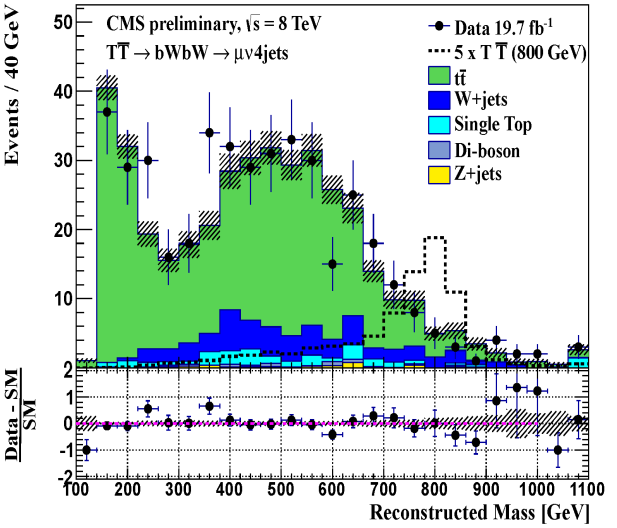
- **W-tagging** for boosted W hadronic decays
- **Kinematic fit** to reconstruct T mass:

$$m(\text{lep } \nu) = M_W$$

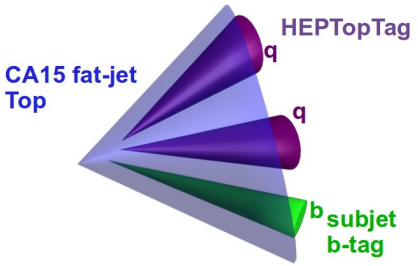
$$m(qq) = M_W$$

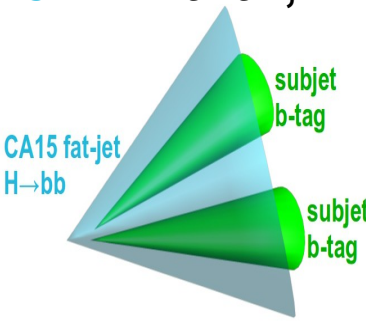
$$m(\text{lep } \nu\, b) = m\,(qqb)$$

- bW decay mode, obs (exp) limit: **912 (851) GeV**

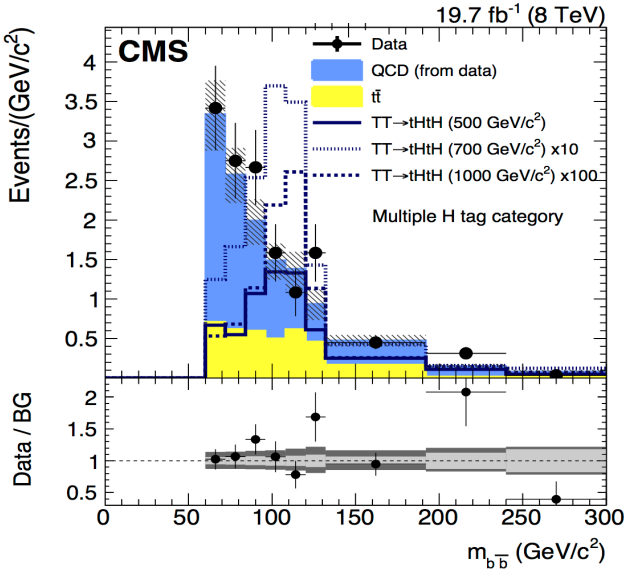


Hadronic with substructure: TT→tHtH, H→bb





- likelihood of two observables: H_T **and** M_{higgs}
- substructure allows similar sensitivity as leptonic signatures: mass limit of **745 (773) GeV**, for 100% BR



CMS strategy: explore and **optimize for all final states**. Searches not shown: inclusive with leptons, hadronic with substructure targeting bW decays, tH decays with H→γγ

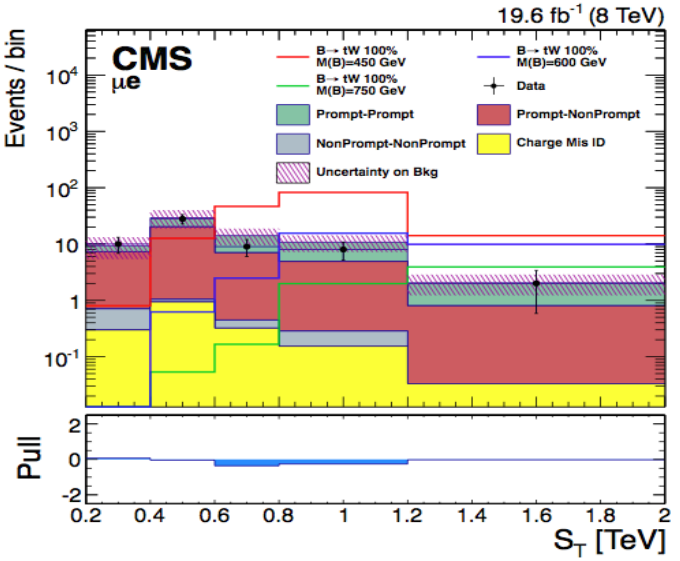
BB searches at CMS

[B2G-13-006, on arXiv soon]

Same-sign di-lepton:

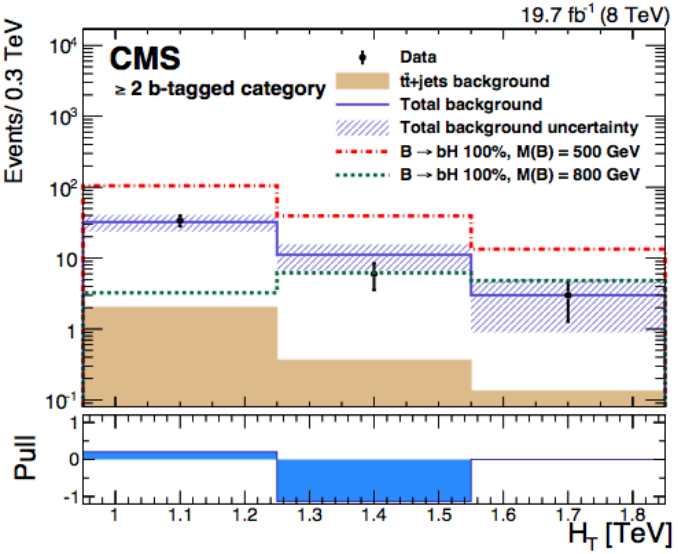
- lepton pairs from different combinations: **BB→tWtW, BB→bHtW, BB→bHbH, H→WW**
- 4 jets and S_T > 200 GeV, E_T^{miss}> 30 GeV, with:

  $S_T = \Sigma\, p_T(\text{jets}) + p_T(\text{leptons}) + E_T^{miss}$
- control regions for fake leptons backgrounds: relaxed isolation criteria
- tW decay mode: obs (exp) limit of **798 (800) GeV**



Hadronic with substructure: BB→bHbH, H→bb

- strong Higgs-tagging: **subjet b-tagging + n-subjettiness**
- driving sensitivity to bH decays, where leptonic seaches are weak. Obs (exp) limit: **846 (811) GeV**



Combination of all searches shown for the first time. Also including three searches not shown:

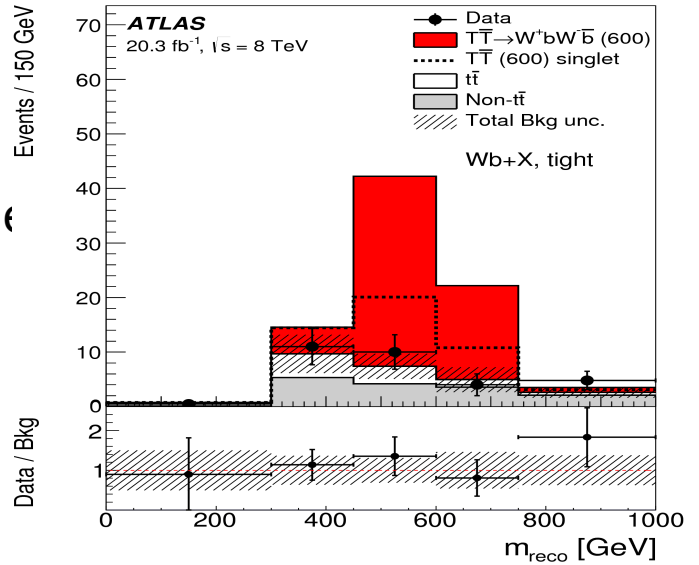
- single lepton with boosted **V-tagging** (V=H/Z/W)
- di-lepton, reconstruct mass B from **Z(→l^+l^-)+b-jet**
- **multi-lepton**, with several exclusive channels

VLQ searches at ATLAS

[arXiv:1505.04306]

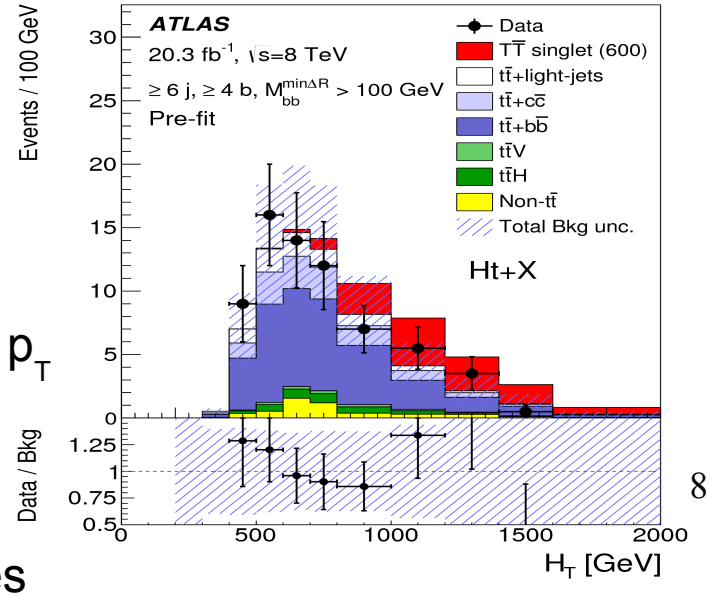
TT→ Wb + X

- **single lepton** (e, μ), ≥1 b-tag, ≥4 jets
- $m_T(W) + E_T^{miss} > 60$ GeV, $E_T^{miss} > 20$ GeV
- **hadronic W**: boosted (p_T>400 GeV) + resolved (single jets with small angle)
- m_{reco} (T) from hadronic W + b-jet
- bW decay mode, obs (exp) limit: **760 (800) GeV**



TT→ tH + X and BB→bH + X

- large jet and **b-jet multiplicity**
- **event categories**: n jets (5, ≥6)/n b-tags(2, 3, ≥4)
- Higgs-candidate from b-jets with min ∞R
- two channels based on $\mathbf{m_{bb}^{min\Delta R}}$ (> or < 100 GeV)
- limits from $\mathbf{H_T} = \Sigma\, p_T(\text{jets}) + p_T(\text{leptons}) + E_T^{miss}$
- **BB→bH + X**: **same analysis**, only minor change on p_T leading b-jets (more boosted)
- mass limit of **950 (885) GeV**, for 100% BR T→tH



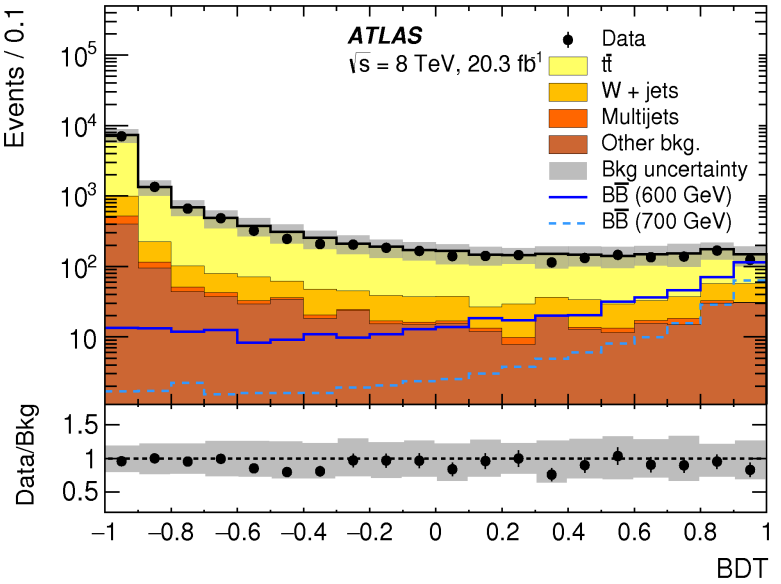
ATLAS strategy: **inclusive**, **signature-based** searches

VLQ searches at ATLAS

[Phys. Rev. D 91, 112011 (2015), JHEP 11 (2014) 104, arXiv:1504.04605]

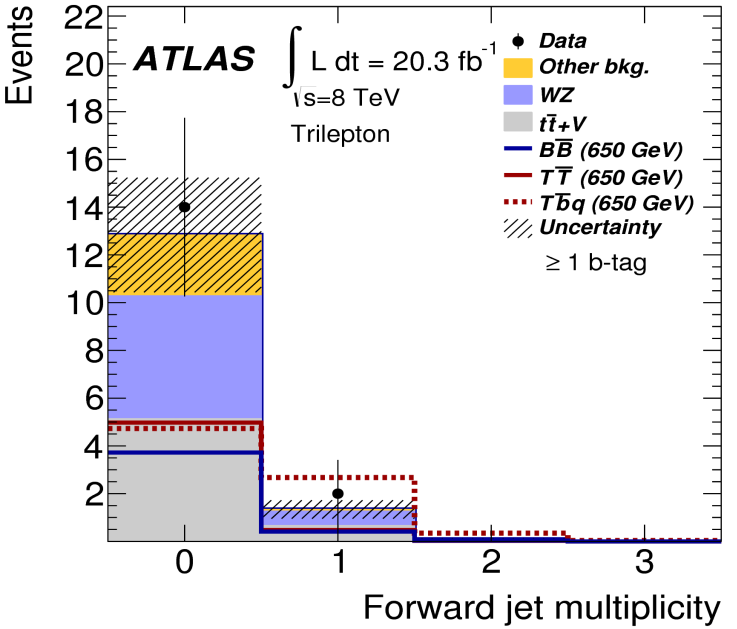
Multi-variate, single lepton, BB→tW + X

- 1 lepton (e, μ), E_T^{miss}, jets
- **categories**: N jets, N hadronic W/Z, N b-jets, H_T
- **BDT** with 12 variables, most discriminating:
  - H_T, ΔR (lep, b-jet 1), M_T(W lep)
- BDT cross-checked with cut-based analysis
- bW decay mode, obs (exp) limit: **810 (760) GeV**



Multi-lepton analysis

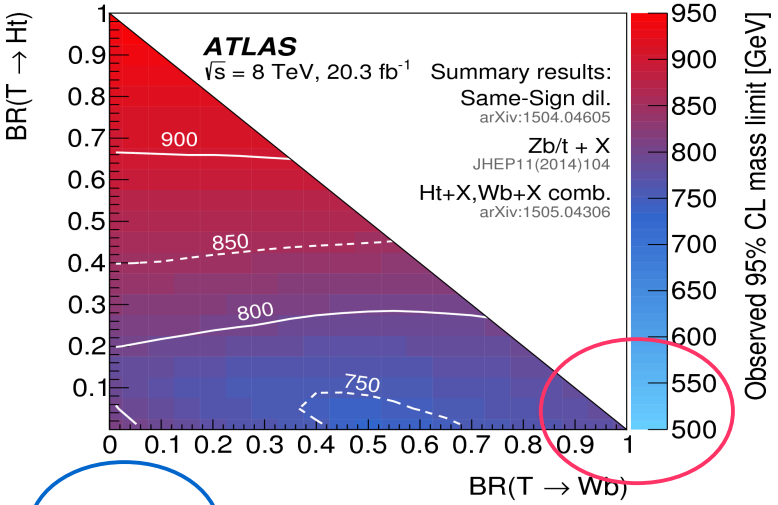
- targets also **single VLQ production**: **forward jet requirement**
- **di-lepton**: targets Z decays, T→Zt, B→Zb, observable **m(Zb)**
- **tri-lepton**: targets multi-boson final states (W, Z, H), observable **H_T**

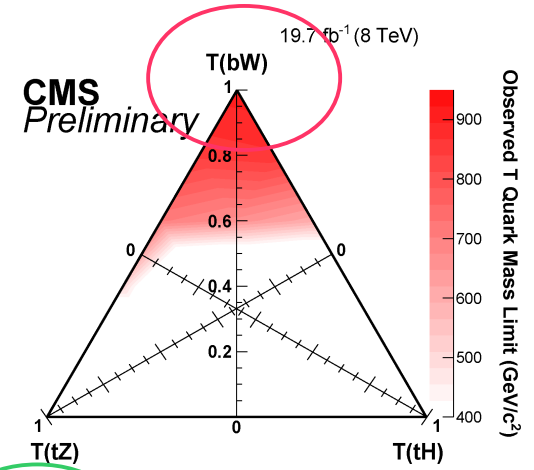


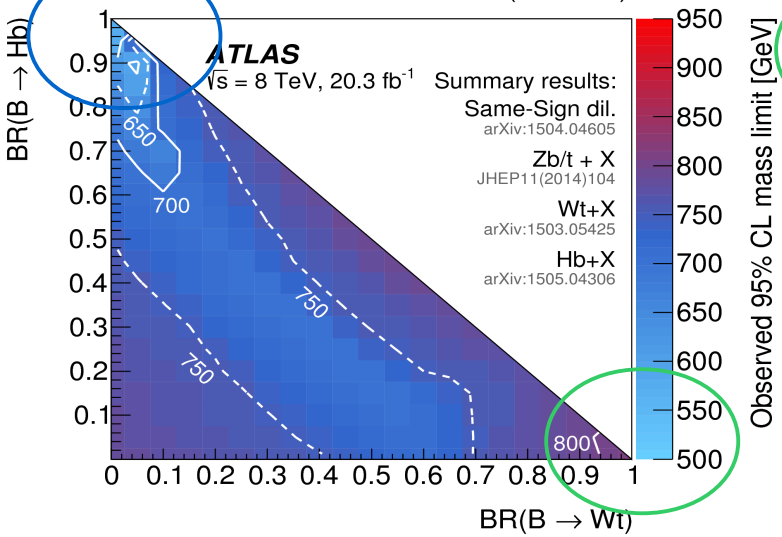
Same-sign di-lepton + b-jets: cut and count experiment, event categories based on H_T, N b-jets, E_T^{miss}. **~2σ eccess** in categories with large H_T

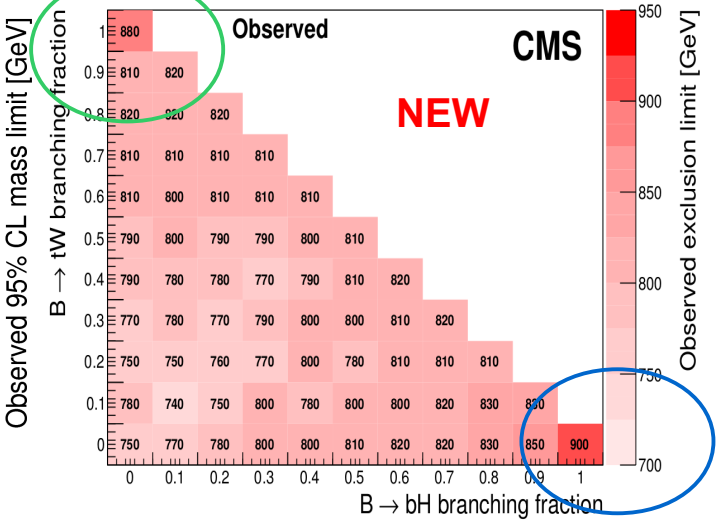
Summary of Run 1

[ATLAS: arXiv:1505.04306, CMS: B2G-13-006 (arXiv soon), B2G-12-013, Phys. Lett. B 729 (2014) 149, B2G-12-017, JHEP 06 (2015) 080, B2G-14-003]









ATLAS:
expected: 715-885 GeV
observed: 730-950 GeV

CMS	exp (GeV)	obs (GeV)
bW	851	912
tH	773	745
tZ	813	782

ATLAS:
expected: 615-800 GeV
observed: 575-813 GeV

CMS	exp (GeV)	obs (GeV)
tW	890	880
bH	810	900
bZ	740	750

- ATLAS. Plots contain individual limits from most restrictive searches
- CMS. B: combination. T: combination of searches published soon, here shown: tighter limit for bW corner

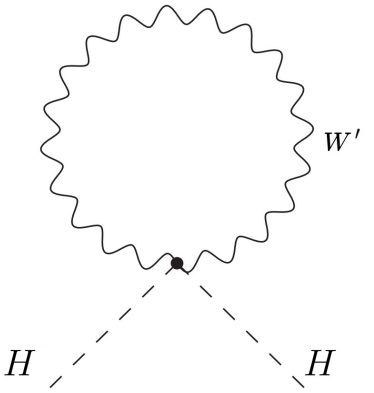
tt and tb resonances

Introduction

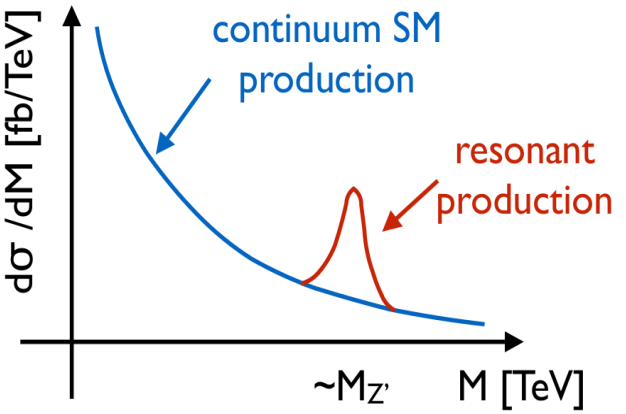
- **W'→tb resonances**:
  - another way to cancel fine-tuning
  - signal modeling:

$$\mathcal{L} = \frac{V_{f_i f_j}}{2\sqrt{2}} g_w \bar{f}_i \gamma_\mu \left(a^{\mathrm{R}}_{f_i f_j} (1+\gamma^5) + a^{\mathrm{L}}_{f_i f_j} (1-\gamma^5) \right) \mathrm{W}'^{\mu} f_j + \mathrm{h.c.}$$

  - left-coupling component: non-zero **interference with SM**



- **ttbar resonances**:
  - appear as a deviation from the SM in M_{tt} spectrum
  - predicted by **several models**, searches can be interpreted in any of these:
    - extended gauge sectors
    - top-colour condensates
    - warped extra dimensions
    - Kaluza-Klein excitations



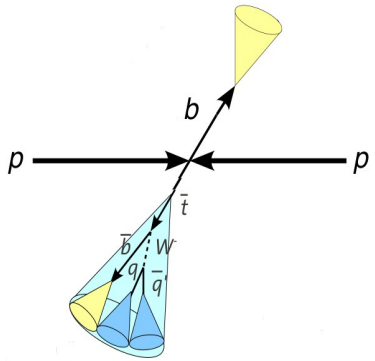
W' resonances at CMS

[JHEP 05 (2014) 108, B2G-12-009]

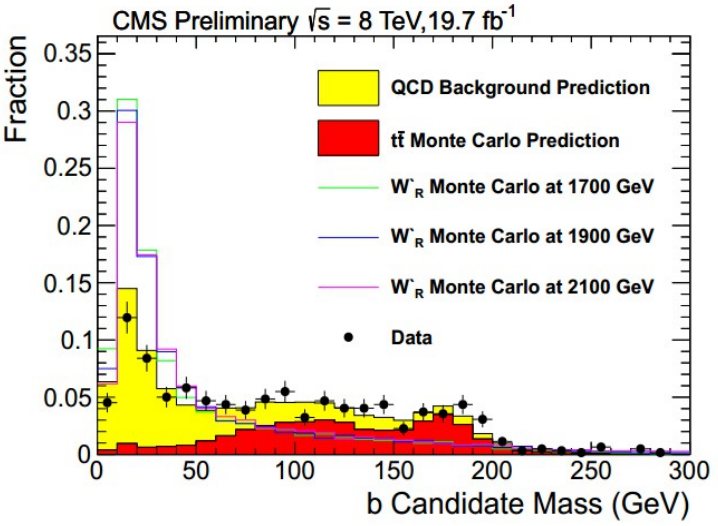
Lepton+jets:

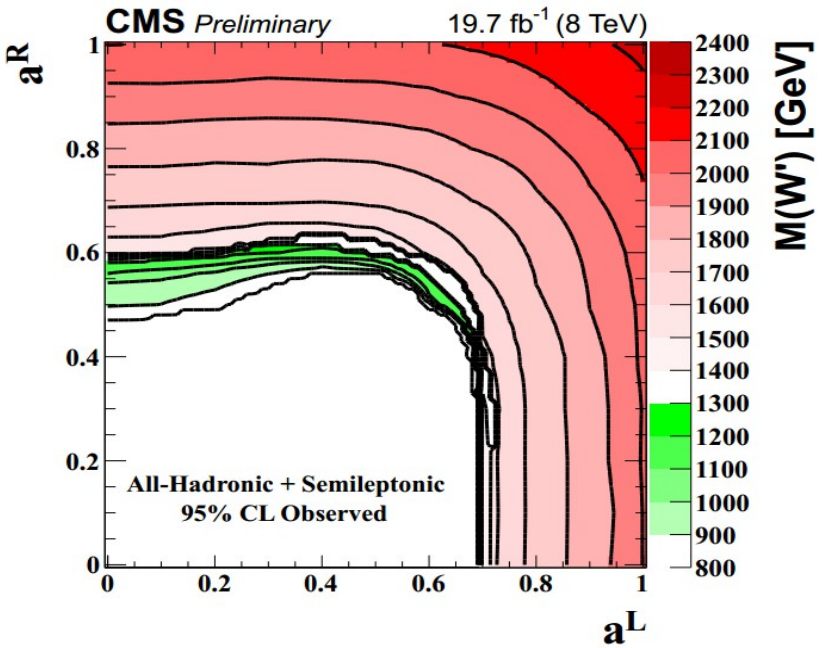
- resolved: single lepton (e, μ), 2 jets, 1 b-tag
- W' candidate from top candidate and leading jet

Boosted all hadronic:



- b-candidate: b-tag + mass < 70 GeV
- top-decay: CMSTopTagger+ n-subjettiness + subjet b-tagging
- **substructure**: similar sensitivity as cleaner semi-leptonic final state





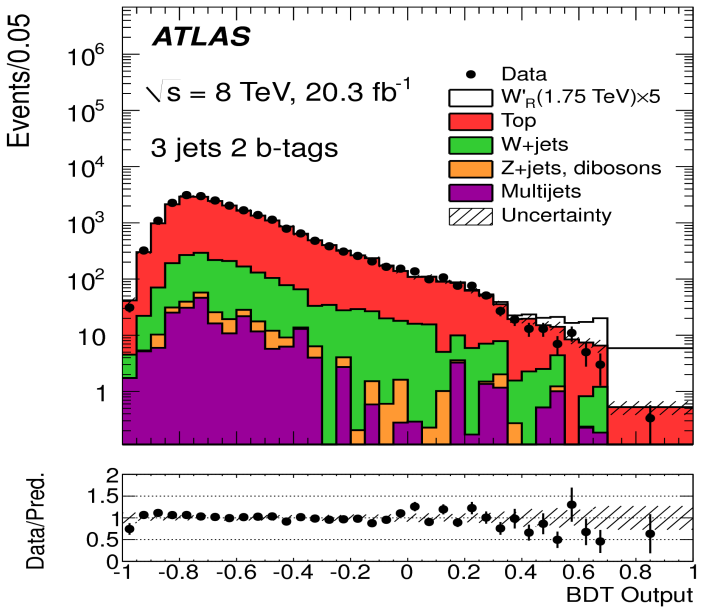
W'$_R$ mass limit of 2.15 TeV. Limits provided also for mixed couplings

W' resonances at ATLAS

[Eur. Phys. J. C (2015) 75:165, Physics Letters B 743 (2015) 235-255]

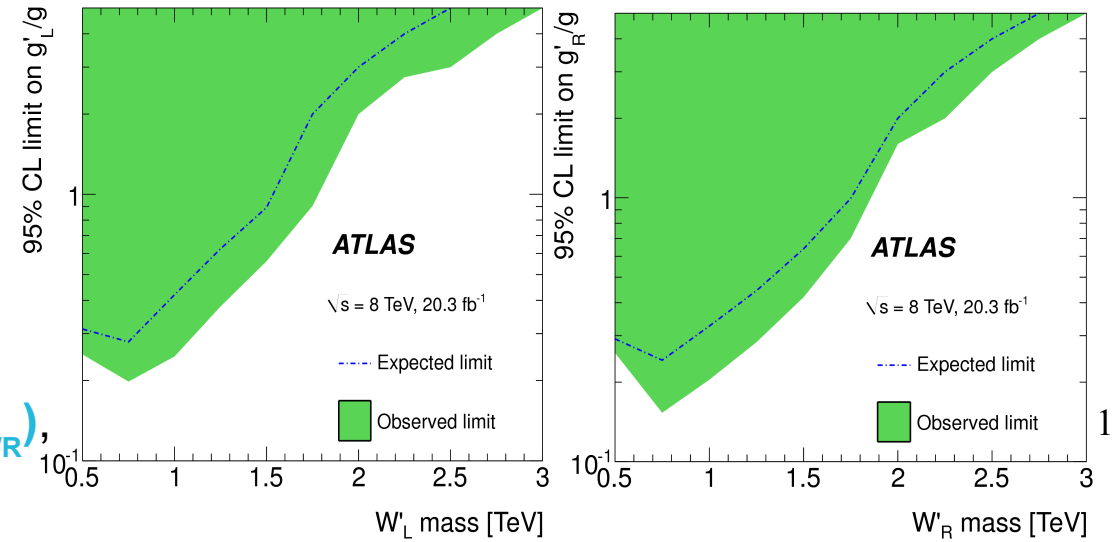
- **All hadronic**:
  - **substructure**: 1 top-tagged jet
  - 1 or 2 b-tags, the second close to the top-tagged jet: accounts for b coming from the top decay

- **Lepton+jets**:
  - 1 lepton (e, μ), 2 or 3 jets, 2 b-tags
  - $m_T(W) + E_T^{miss} > 60$ GeV
  - object assignment to reconstruct W' and top candidates
  - **BDT** of several variables, most discriminating:
    - **mass$_{W'}$**
    - **mass$_{top}$**



- W'$_R$ mass limit of 1.92 TeV

- Different way to express limits for other couplings: **g'$_{L/R}$/g vs m(W'$_{L/R}$)**, where g is the SM SU(2)$_L$ coupling



ttbar resonances at CMS

[arXiv:1506.03062]

Resolved

- conventional analysis: 4 jets, 1 b-tag, isolated lepton (μ or e), E_T^{miss}
- ttbar system reconstructed from χ^2 **assignment**

Di-leptonic

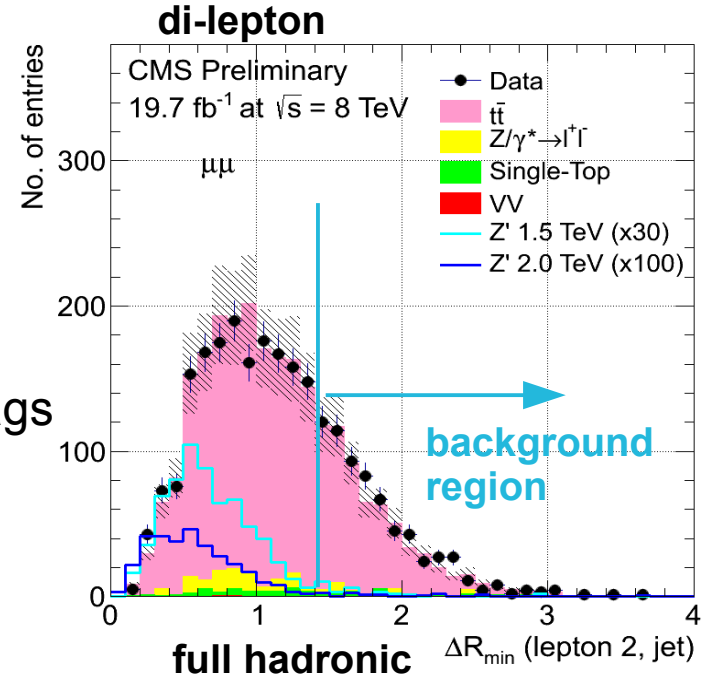
- two (non-)isolated leptons (ee, $\mu\mu$, $e\mu$), 1 or 2 b-tags
- background region: ΔR_{min}**(lept 2, jet) > 1.5**

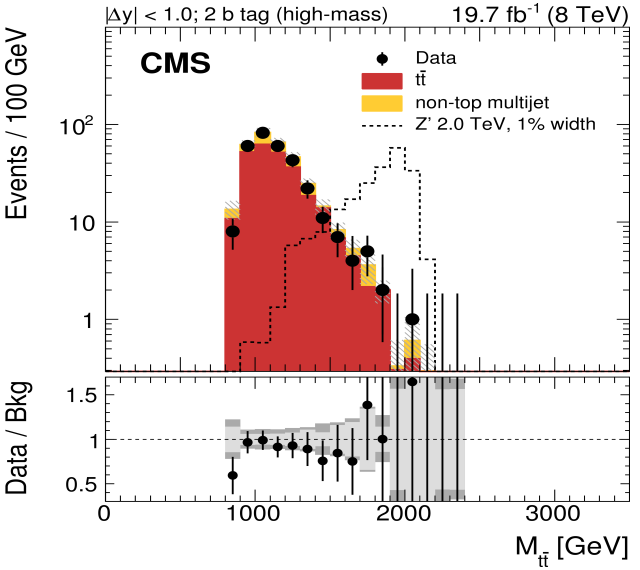
Semi-leptonic:

- leptonic decay: (non-)isolated lepton, e or μ
- hadronic decay:
  - boosted: events with 1 CMS-**top-tag**
  - χ^2 **assignment** for (partially) resolved decays

Full hadronic:

- large use of **substructure:**
  - **HepTopTagger** (200-400 GeV) **and CMSTopTagger** (>400 GeV)
  - **n-subjettiness + subjet b-tagging**
- pure, QCD-depleted signal regions

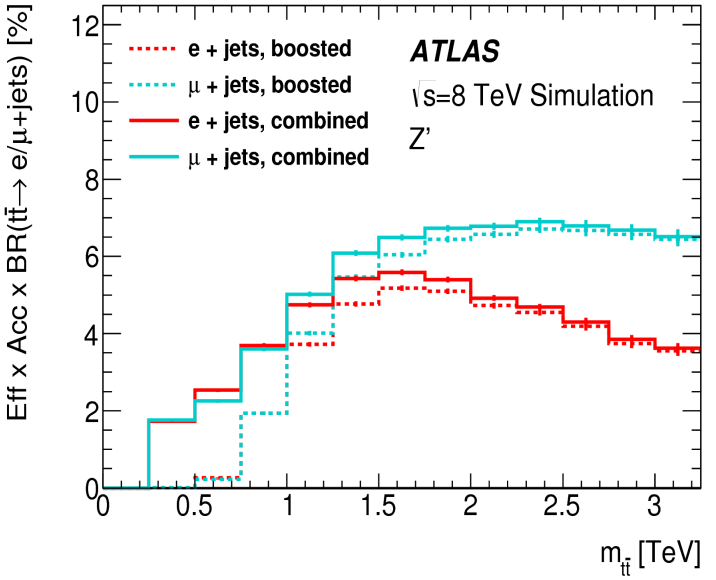


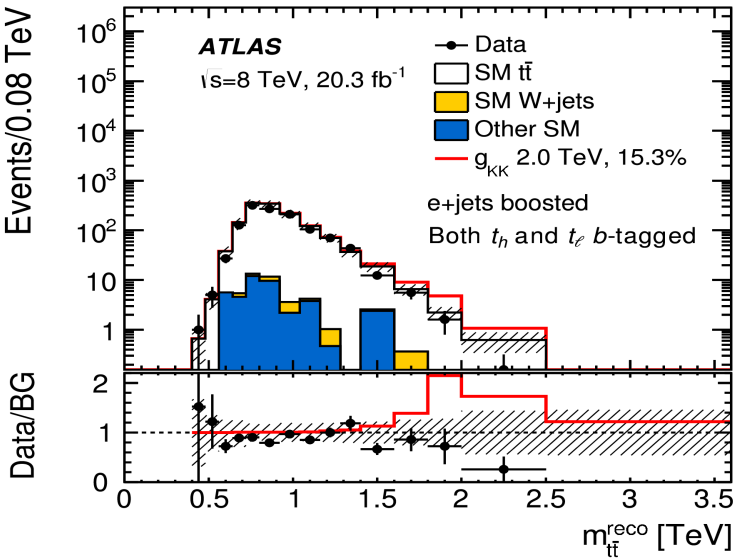


ttbar resonances at ATLAS

[arXiv:1505.07018]

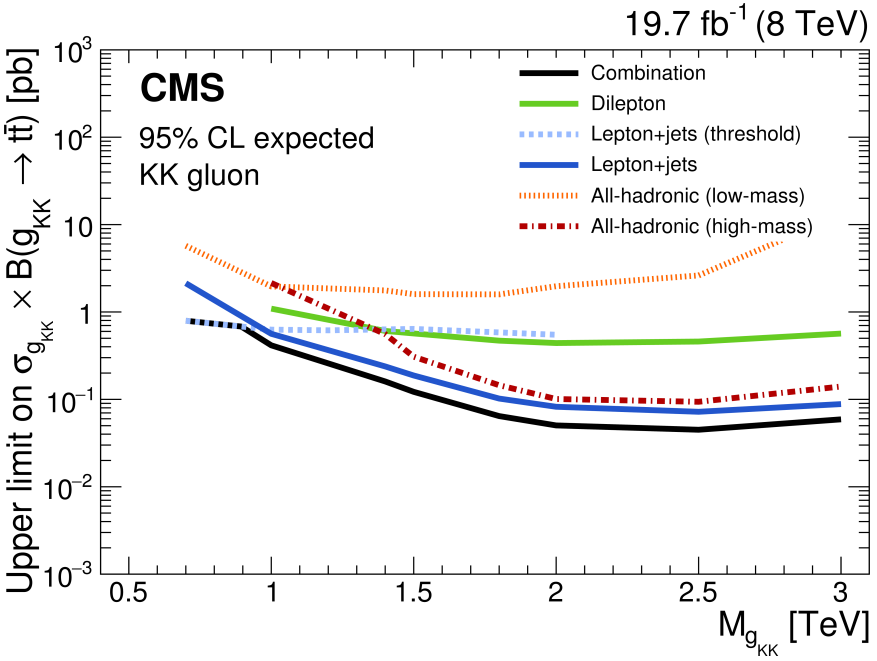
- New ATLAS **semi-leptonic** analysis
  - both boosted and resolved topologies
- Lepton (*e* or μ) isolation cone: **$\Delta R < 10$ GeV / E_T**
  - increases acceptance in the boosted regime
- **Resolved** selection:
  - multiple small jets and χ^2 **assignment**
- **Boosted** selection:
  - one large jet, pT > 300 (*e*)/380 (μ) GeV
  - m_{jet} > 100 GeV + **substructure**
- **12 event categories**:
  - b-tag: leptonic side/hadronic side/both
  - resolved/boosted
  - lepton flavor

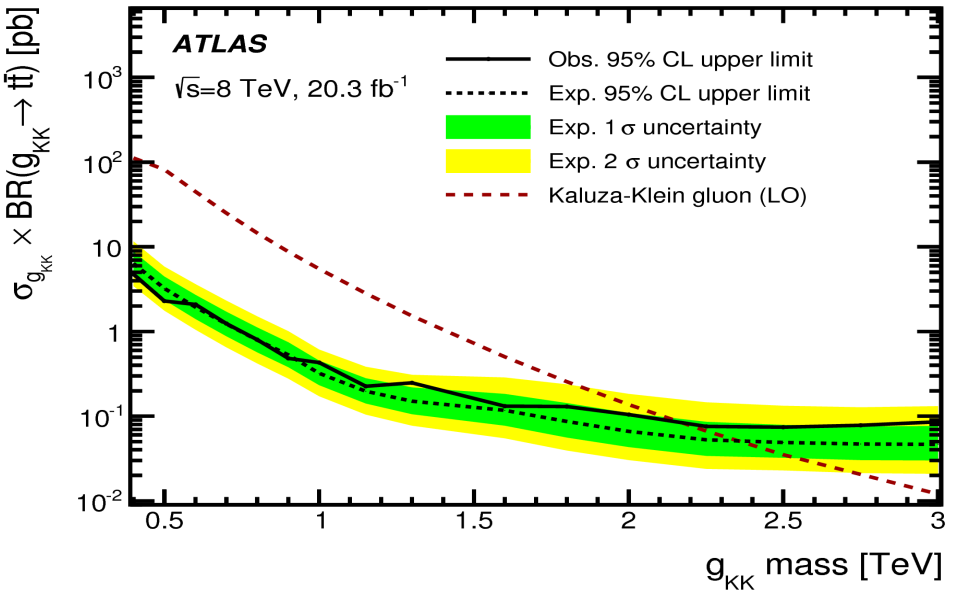




ttbar resonances: limits

[CMS: arXiv:1506.03062, ATLAS: arXiv:1505.07018]





- CMS: different channels contribute to sensitivity in different mass regions
- Mass exclusions depend on the considered model. E.g. for a Kaluza-Klein gluon:
  - CMS excludes masses < 2.8 TeV
  - ATLAS excludes masses < 2.2 TeV

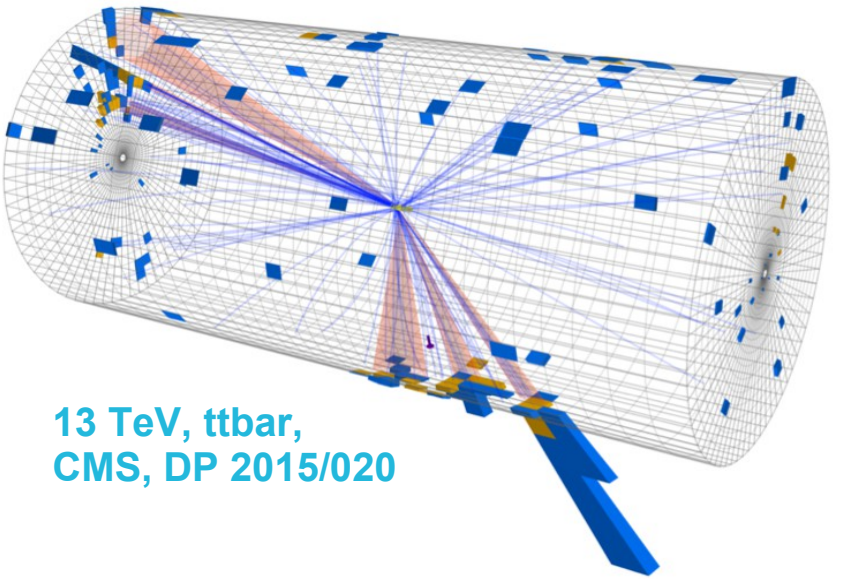
Run 2 outlook

- **Experimental challenges**:
  - efforts to further optimize analysis tools, such as substructure
  - **triggers** targeting single VLQ searches including **substructure**

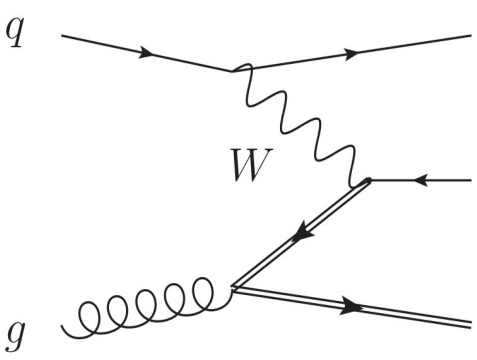
- **Rich phenomenology**, will further expand in Run 2: single VLQ, **Z'→Tt**

- **Single VLQ-model dependence**: communication theory/ATLAS/CMS, to identify **benchmarks** and help **future interpretations of the results**. E.g. effective operators approach:

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

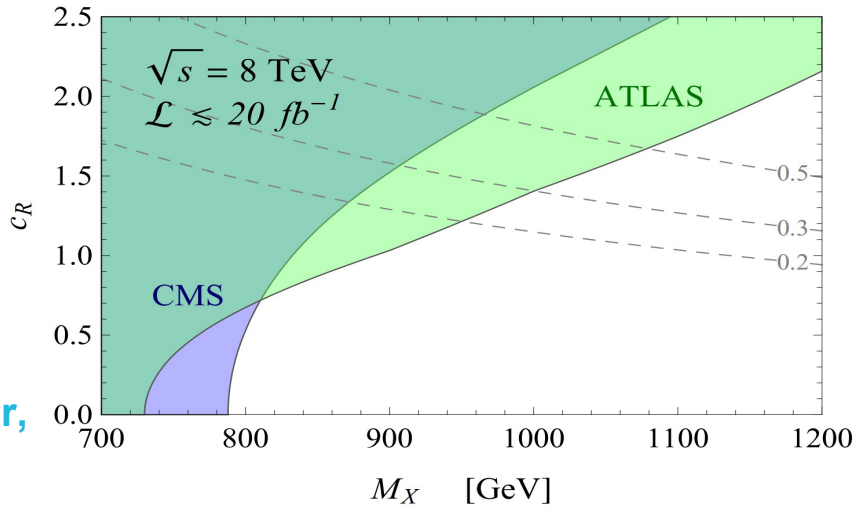


13 TeV, ttbar, CMS, DP 2015/020



$$\sigma_{\text{sing}}(X\bar{t}) = c_R^2\,\sigma_{W+\bar{t}}(M_X)$$

Matsedonskyi, Panico, Wulzer, arXiv:1409.0100



Additional Slides

Vector-like quarks

- Vector-like heavy quarks:
  - **spin 1/2, colored**
  - left and right components transform in the same way under $SU(3)_c \times SU(2)_L \times U(1)_Y$

- Why are they called “vector”-like?

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \qquad j_R^\mu = 0$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu(1-\gamma^5)f'$$

$$V - A$$

SM chiral quarks

$$j_L^\mu = \bar{f}_L \gamma^\mu f'_L \qquad j_R^\mu = \bar{f}_R \gamma^\mu f'_R$$

$$j^\mu = j_L^\mu + j_R^\mu = \bar{f}\gamma^\mu f'$$

$$V$$

VLQs

- Mass term independent from symmetry breaking mechanism:

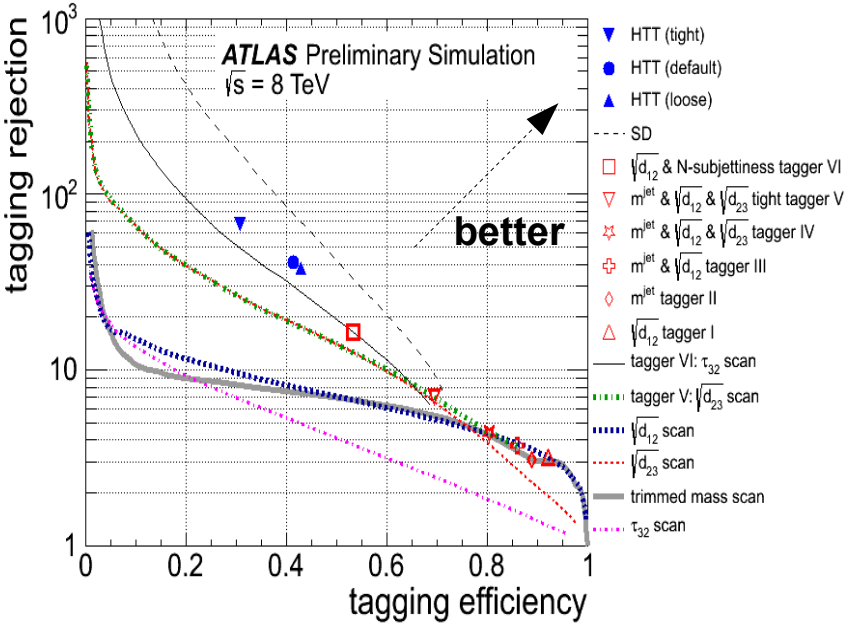
$$L_{mass} = -M(\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

- Appealing:
  - naturally solve the **hierarchy problem** and are predicted by several theories (little Higgs models, composite Higgs models, extra dimensions)
  - modest impact on SM Higgs production and decay modes, **not ruled out**

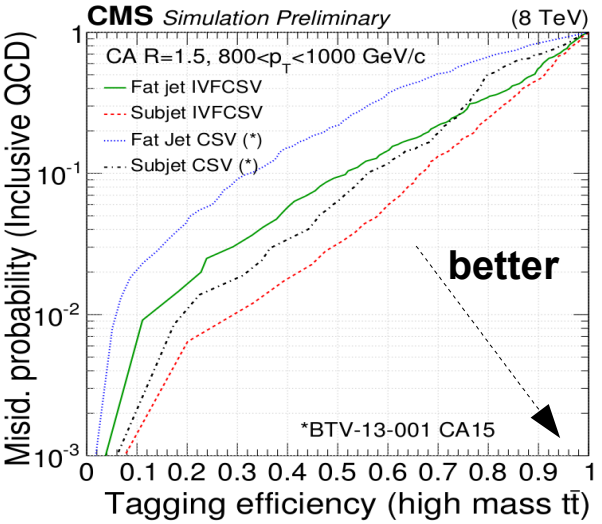
Substructure tools

[ATLAS: ATLAS-CONF-2014-003, CMS: CMS DP-2014/031]

- **Top/Higgs/W/Z-tagging**:
  - jets mass + substructure requirements (2 or 3-body structure of the fat-jet)
  - sophisticated top-tagging algorithms: HepTopTagger, CMSTopTagger
  - large optimization efforts in both collaborations, several tools tested:
    - n-subjettiness
    - shower deconstruction
    - ...



- **Boosted b-tagging**:
  - largely orthogonal from substructure
  - b-tagging sequence applied to individual subjets (CMS) or smaller-size track jets (ATLAS)
  - combined to top-tagging: up to **factor 10 gain in QCD rejection**, keeping 70% efficiency

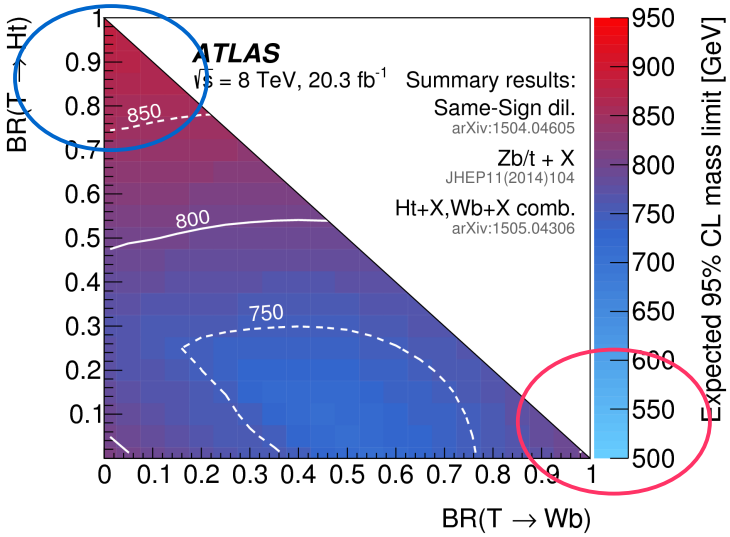


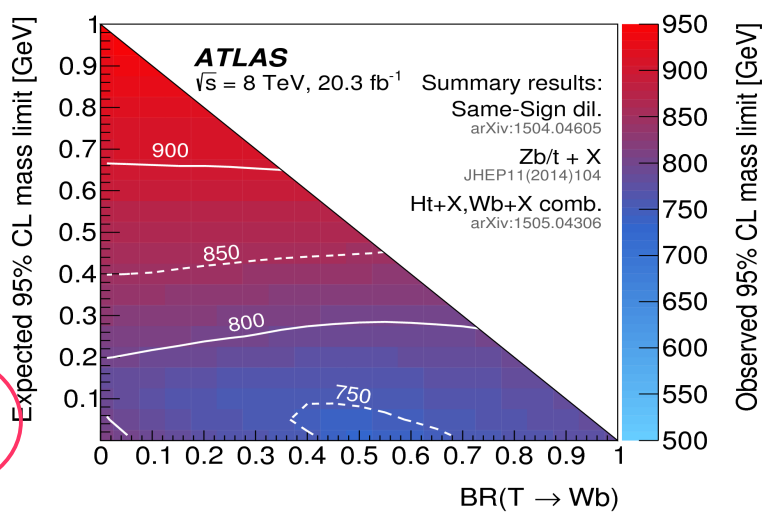
Run 1 subjet b-tagging

Run 2 subjet b-tagging

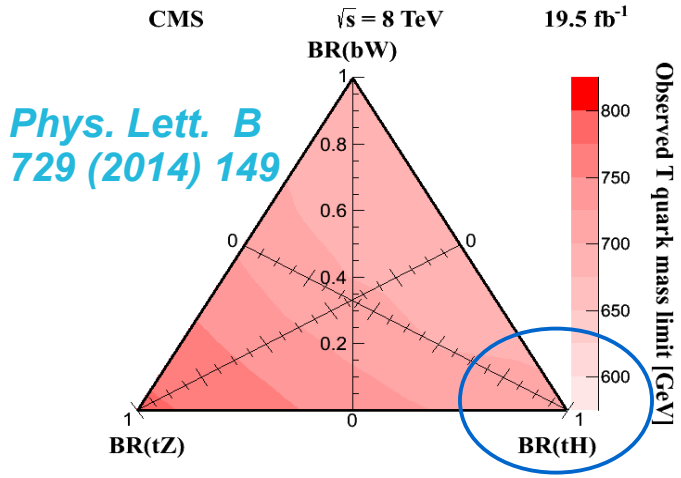
Summary of Run 1: TT

[ATLAS: arXiv:1505.04306, CMS: B2G-12-013, Phys. Lett. B 729 (2014) 149, B2G-12-017, JHEP 06 (2015) 080, B2G-14-003]

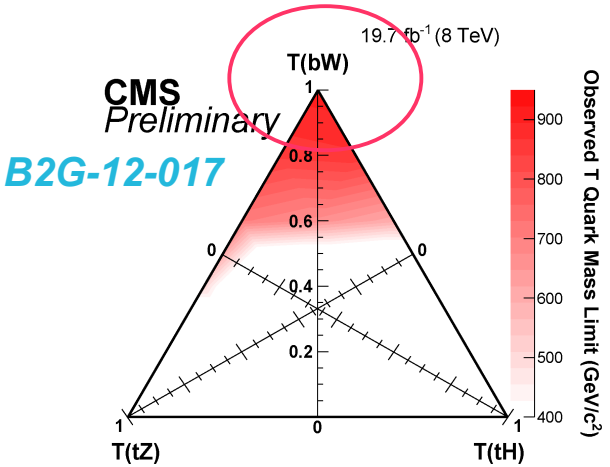




expected: 715-885 GeV
observed: 730-950 GeV



Phys. Lett. B 729 (2014) 149



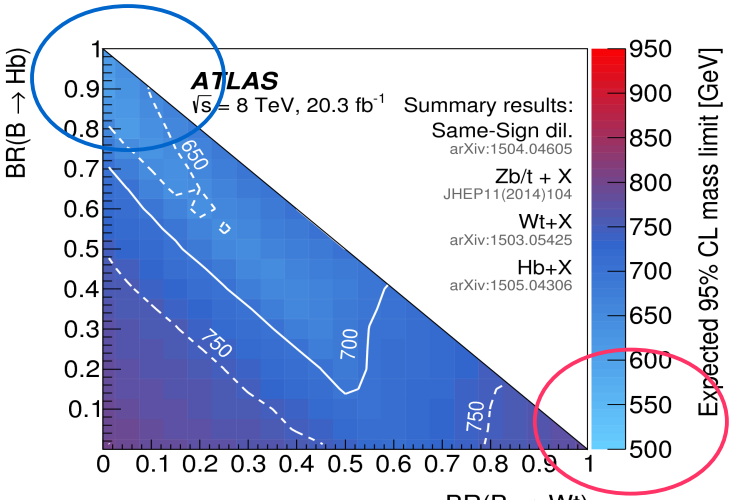
B2G-12-017

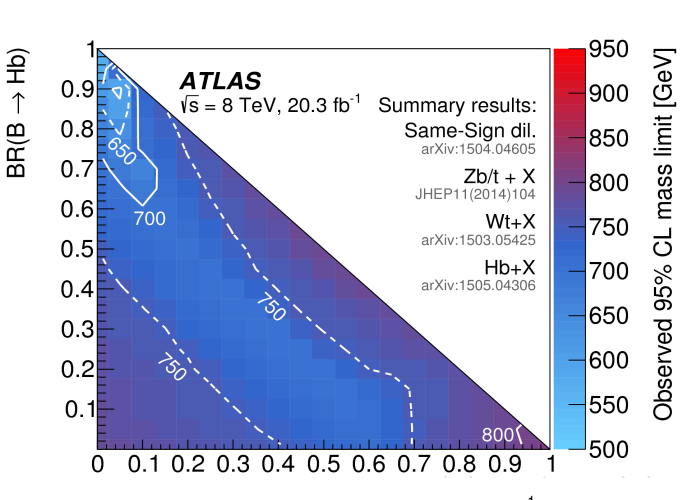
decay	exp (GeV)	obs (GeV)
bW	851	912
tH	773	745
tZ	813	782

- ATLAS: plot contains individual limits from most restrictive searches
- CMS: combination of searches published soon. Shown: tighter limit for bW corner and inclusive analysis

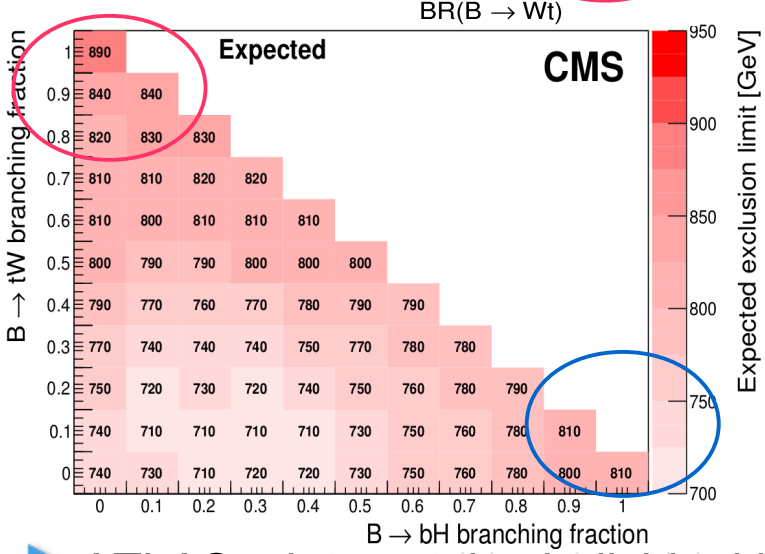
Summary of Run 1: BB

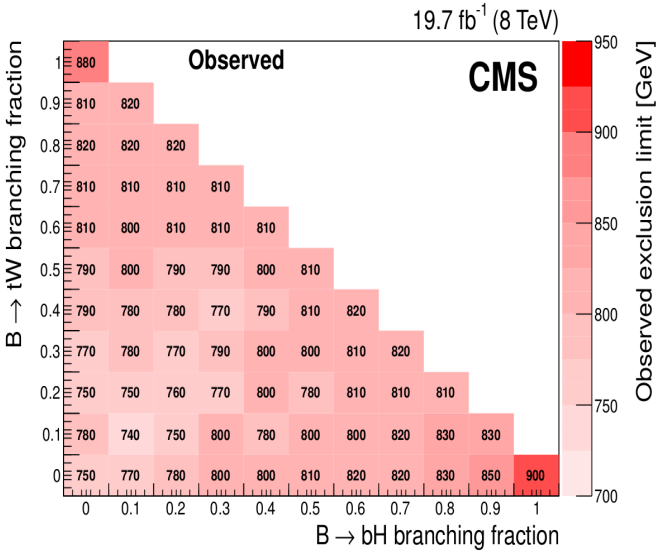
[ATLAS: arXiv:1505.04306, CMS: B2G-13-006 (on arXiv soon)]





expected: 615-800 GeV
observed: 575-813 GeV





decay	exp (GeV)	obs (GeV)
tW	890	880
bH	810	900
bZ	740	750

- ATLAS: plot contains individual limits from most restrictive searches
- CMS: combination of searches