Oxford Physics

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Search for vector-like quarks with top quarks at the LHC

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Top2015, Ischia
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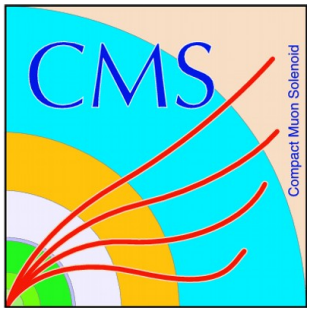


Vector-like quarks

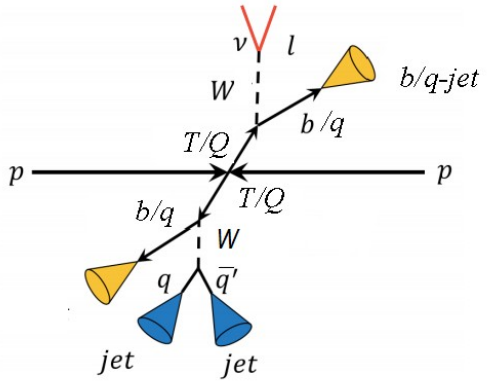
- Quark-like fermions for which left-handed and right-handed fields transform in the same way under SM gauge groups
  - Mass term gauge invariant
    - Doesn't need Higgs to acquire mass
    - Does not modify EWK observables significantly

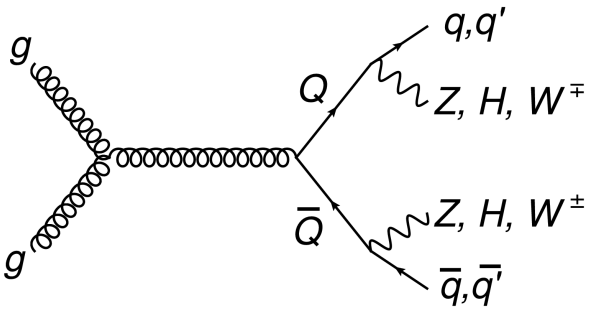
$$L = m\bar{\psi}\psi$$

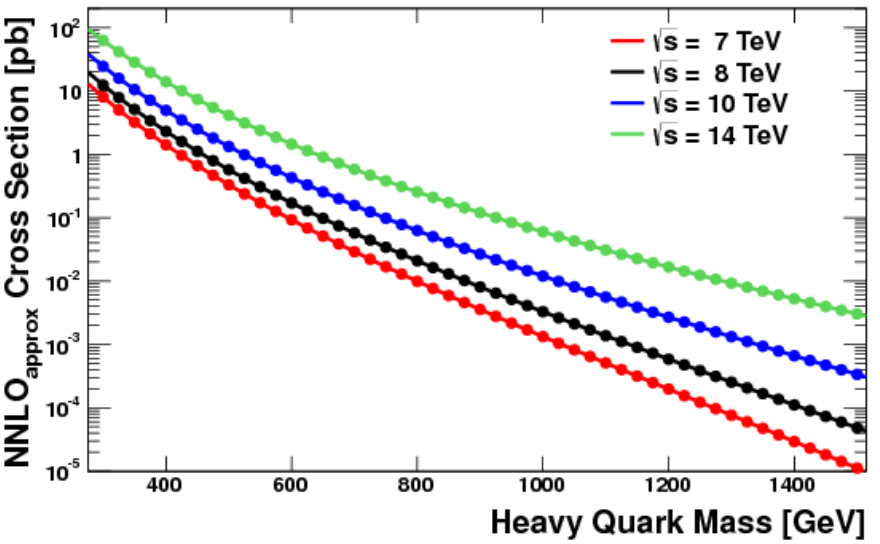
  - Arise in many models of BSM physics, e.g.,
    - Extra dimensions
    - Composite Higgs
    - Little Higgs
    - Non-minimal SUSY
  - Could include quarks with unusual charges, e.g., $T_{5/3}$, $B_{4/3}$
  - See theory presentations, especially M Peskin and A Deandrea
- Attractive generic signature of BSM physics

Experimental signatures

- Usually assume pair production – important for inclusive searches
  - Single production may become important at higher masses
- Primarily search via coupling to 3rd generation
  - T → bW, tZ, tH
  - B → tW, bZ, bH
- Other modes possible:
  - Q → qW
  - BSM charges possible, e.g., U(1)': B→Z'b→bbb (Fox, Tucker-Smith, arXiv:1509.00499)







HATHOR, from additional CMS material for PLB 729, 149 (2014)

t → Wb
W → ℓ ν, jets(s)
Z → ℓ ℓ, jet(s)
H → bb, γγ

- High-p_T isolated leptons
- Significant jet activity
- Multiple b jets

Spoiler

- No significant excess observed yet
- Reported here:
  - Recent 8 TeV results, mostly with a final state t
  - Developing techniques: jet substructure, multivariate optimization
- Eagerly await analysis of 13 TeV data
- Outline
  - Single lepton signatures
  - Same-sign dilepton signatures
  - Non-leptonic signatures
  - Limits

N_{lep}			ATLAS	CMS
1	lepton+jets	B	PRD 91, 112011 (2015) JHEP 08, 105 (2015)	arXiv:1507.07129
		T	JHEP 08, 105 (2015)	arXiv:1509.04177 PLB 729, 149 (2014)
		$T_{5/3}$	PRD 91, 112011 (2015)	
		Q	arXiv:1509.04261	PAS B2G-12-017
2	Same-sign dilepton	B	arXiv:1504.04605	arXiv:1507.07129
		T	arXiv:1504.04605	PLB 729, 149 (2014)
		$T_{5/3}$	arXiv:1504.04605	PRL 112, 171801 (2014)
	Opp-sign dileptons	B	JHEP 11, 104 (2014)	arXiv:1507.07129
		T	JHEP 11, 104 (2014)	PLB 729, 149 (2014)
		T'		PAS B2G-12-025
≥3	multilepton	B	JHEP 11, 104 (2014) arXiv:1504.04605	arXiv:1507.07129
		T	JHEP 11, 104 (2014) arXiv:1504.04605	PRL 112, 171801 (2014)
0	all-hadronic	B		arXiv:1507.07129
		T		arXiv:1509.04177 JHEP 06, 80 (2015)
	Diphoton	T		arXiv:1509.04177
≥1	Single production		JHEP 11, 104 (2014) EXOT-2014-13	

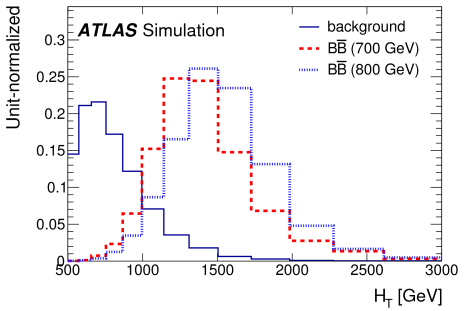
Single lepton signatures

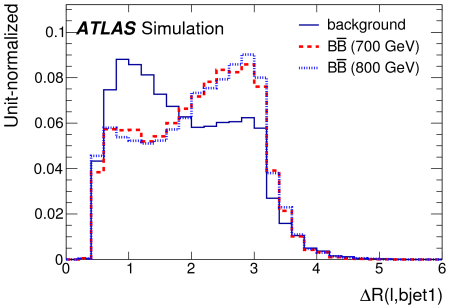
ATLAS BB → tW+X

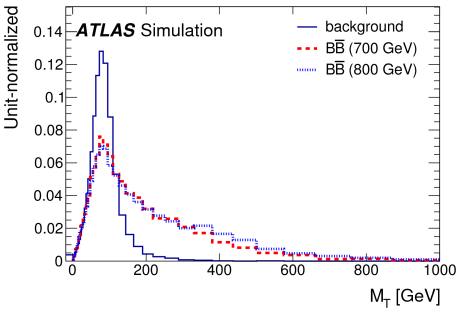
- Single e/μ with p_T > 25 GeV
- 12 discriminating variables

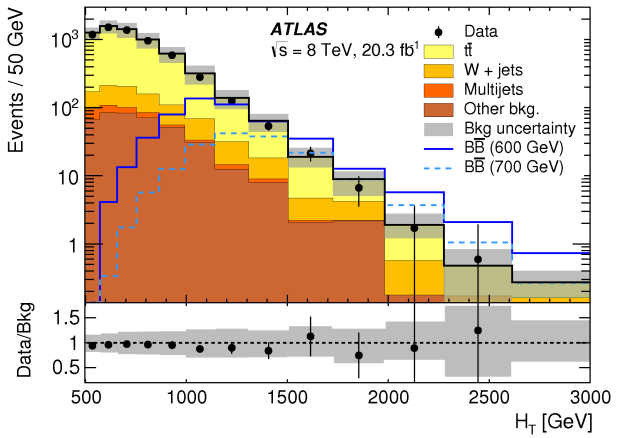
W/Z dijets → N_V
p_T > 120 GeV
60 < m_{jj} < 110 GeV

E_T^{miss} > 20 GeV
$E_T^{miss}+M_T$ > 60 GeV
$N_{jets} \geq 6$
$N_b \geq 1$
$N_V \geq 1$
H_T > 500 GeV

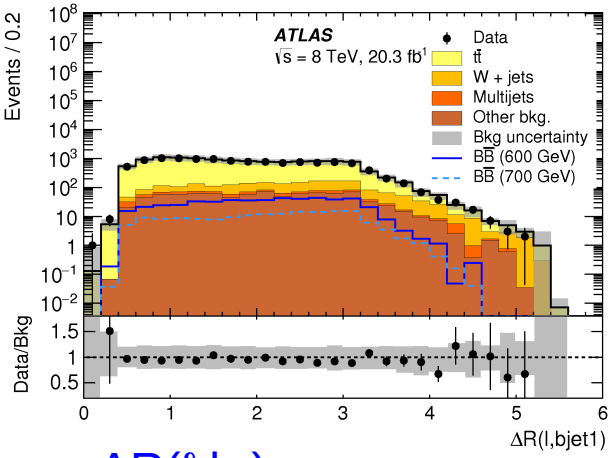




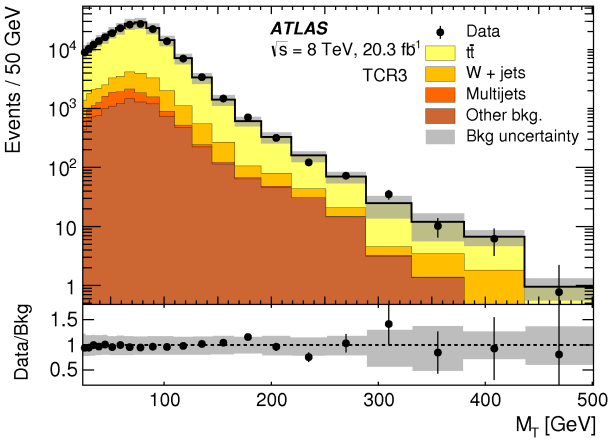




$H_T(\ell+jets+E_T^{miss})$



$\Delta R(\ell,b_1)$

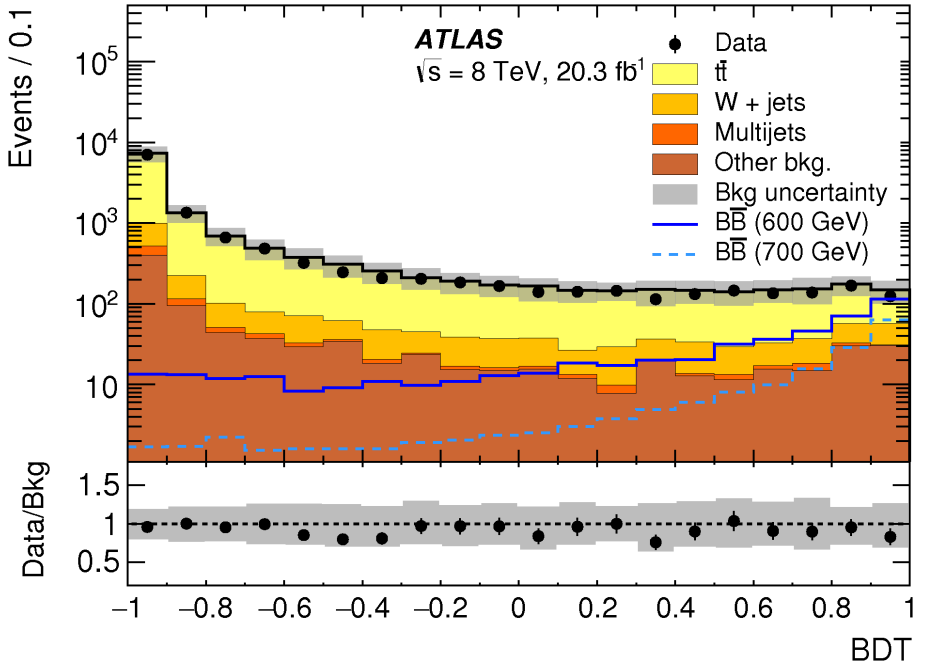


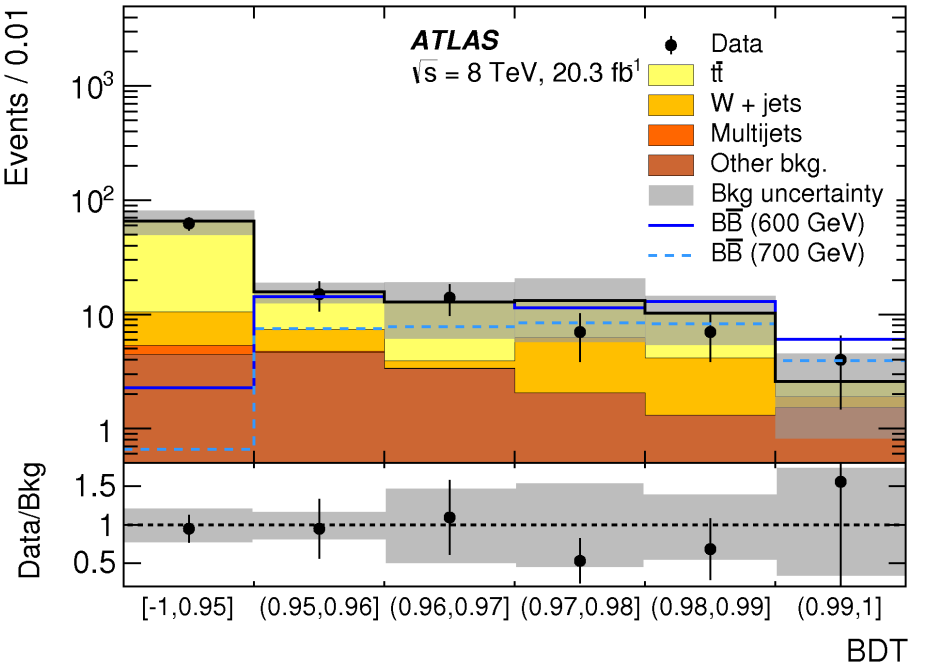
M_T

PRD 91, 112011 (2015)

ATLAS BB → tW+X

- Boosted decision tree (BDT): combine 12 observables into one discriminant





➔ No evidence of signal

➔ Can also be interpreted as limit on $T_{5/3}$

PRD 91, 112011 (2015)

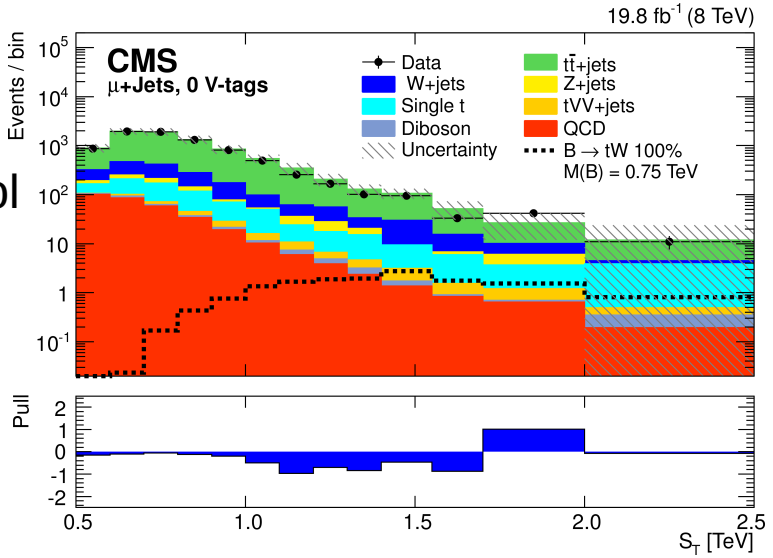
CMS BB → tW+X

arXiv:1507.07129

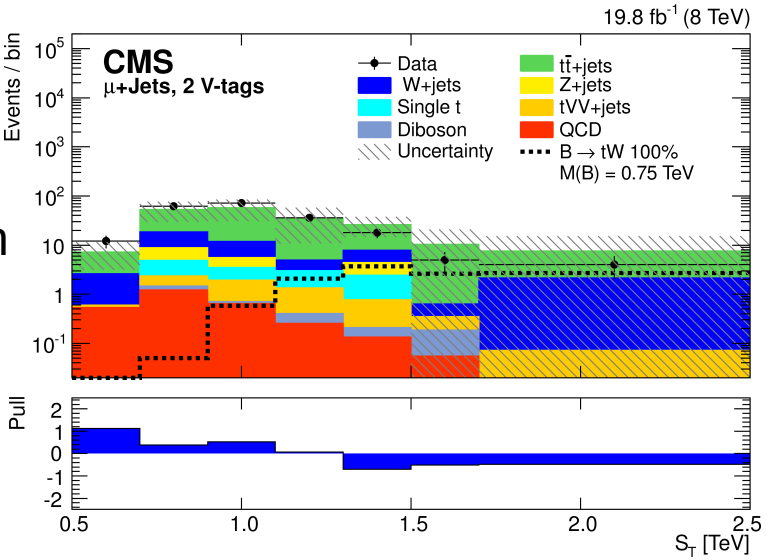
- Single e/μ, p_T > 30 GeV

$N_{jets} \geq 4$
p_T > 200/60/40/30 GeV
$N_b \geq 1$
Centrality C > 0.4
E_T^{miss} > 20 GeV

Control region

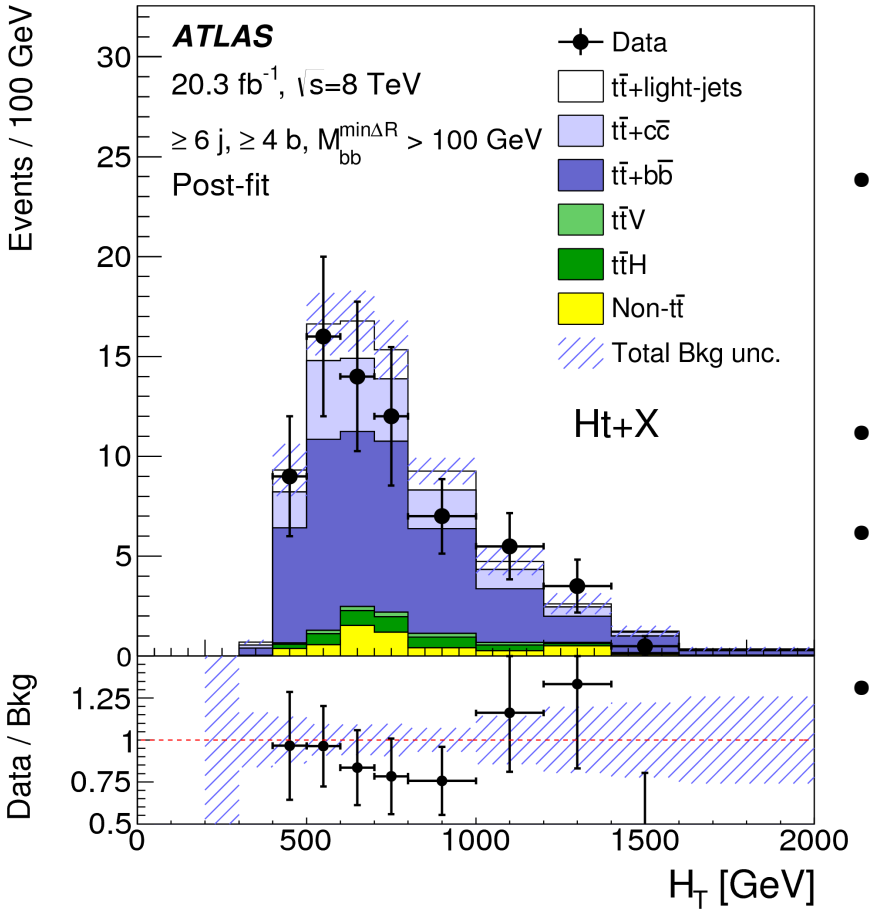


Best signal region



- Primary discriminant: $S_T(\ell+jets+E_T^{miss})$
- Data consistent with backgrounds in signal and control regions

ATLAS TT → tH+X, H → bb



Single e/μ, p_T > 25 GeV
E_T^{miss} > 20 GeV
$E_T^{miss}+M_T$ > 60 GeV

- H candidate:
  - 2 b-tagged jets with minimum ΔR
  - m_{bb} > 100 GeV
- Primary discriminant: $H_T(\ell+jets+E_T^{miss})$
- Use lower N_{jets} and N_b regions to constrain backgrounds
- Best region for signal:
  - $N_{jets} \geq 6$
  - $N_b \geq 4$
- Also set limits on tttt for various models

JHEP 08, 105 (2015)

CMS TT → bW+X

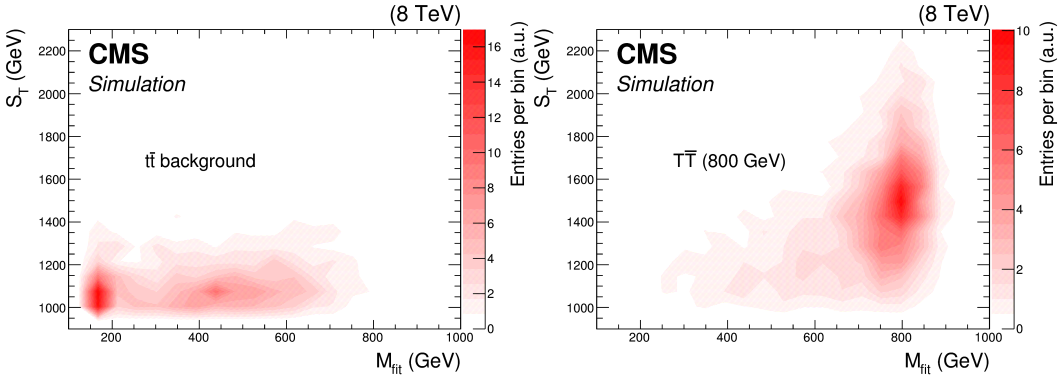
arXiv:1509.04177

- Use substructure to tag high-p_T W's
- Constrain W and M_{fit}-mass combinations to resolve T pair

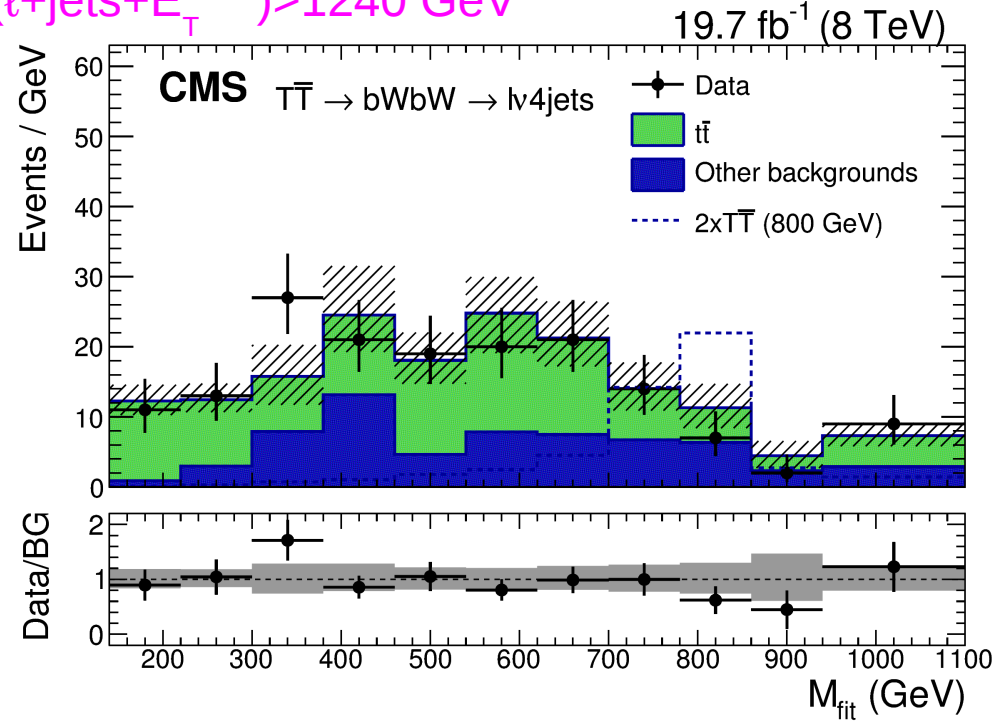
Single e/μ, p_T > 30/45 GeV
$N_{jets} \geq 4$
p_T > 120/90/50/30 GeV
N_W = 0 or 1
N_b = 1 or 2
E_T^{miss} > 30 GeV

Dijet or single-jet W → N_W
Single-jet W tag:
- Pruned Cambridge-Aachen, R=0.8
- p_T > 200 GeV, 60 < m_{jet} < 110 GeV
- Mass drop μ≡m_1/m_{jet} < 0.4

- Similar analysis used for QQ → qW+X



$S_T(\ell+jets+E_T^{miss})$>1240 GeV



ATLAS QQ → qW+X

Single e/μ, p_T > 25 GeV
E_T^{miss} > 20 GeV
$E_T^{miss}+M_T$ > 60 GeV
W_{lep}: p_T > 125 GeV
$N_{jets} \geq 4$, $N_b = 0$

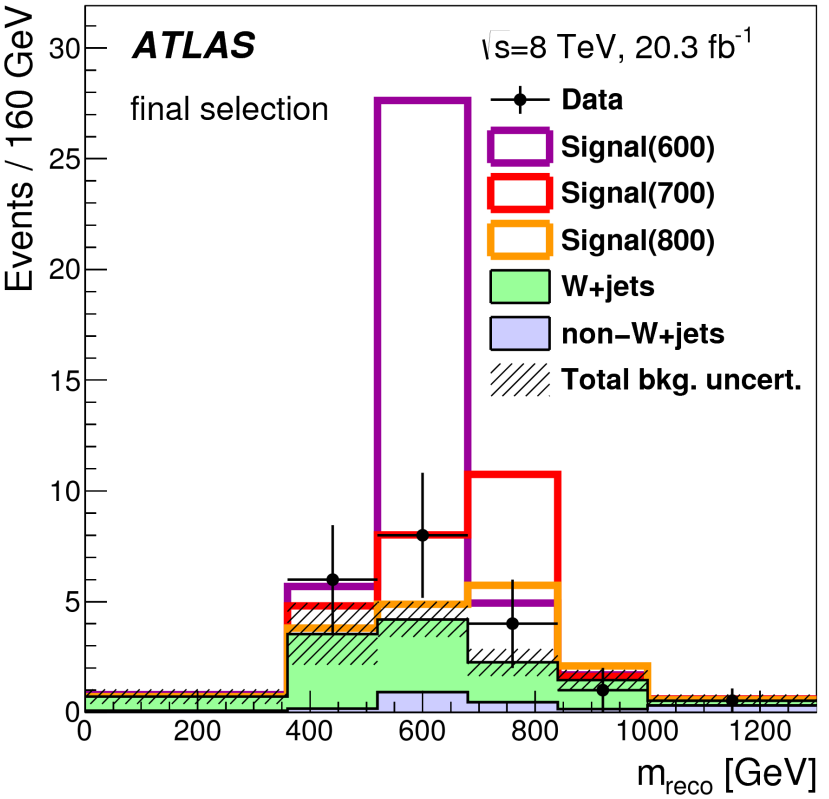
arXiv:1509.04261

- Search for generic VLQ decaying to qW
  - Use splitting scale y_{12} in dijet W

$$y_{12} \equiv \frac{min(p_{T1}, p_{T2})^2 \Delta R_{12}^2}{m_{12}^2}$$

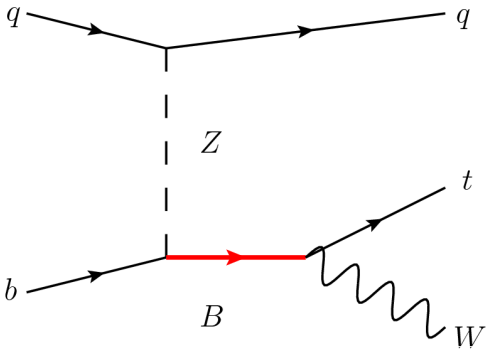
Dijet W:
$\Delta R_{12} < 1$
p_T > 200 GeV
$65 < m_{jj} < 100$ GeV
$y_{12} > 0.25$

- Pair jets with W's:
  - $p_T(q_1)$ > 160 GeV
  - $p_T(q_2)$ > 120 GeV
- Resolve qW combinations
  - Δm < 120 GeV
  - Back-to-back topology
- $H_T(\ell+E_T^{miss}+4jets)$ > 1100 GeV
- Primary discriminant: resolved mass



ATLAS Single B → tW

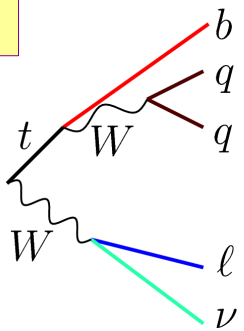
ATLAS EXOT-2014-13

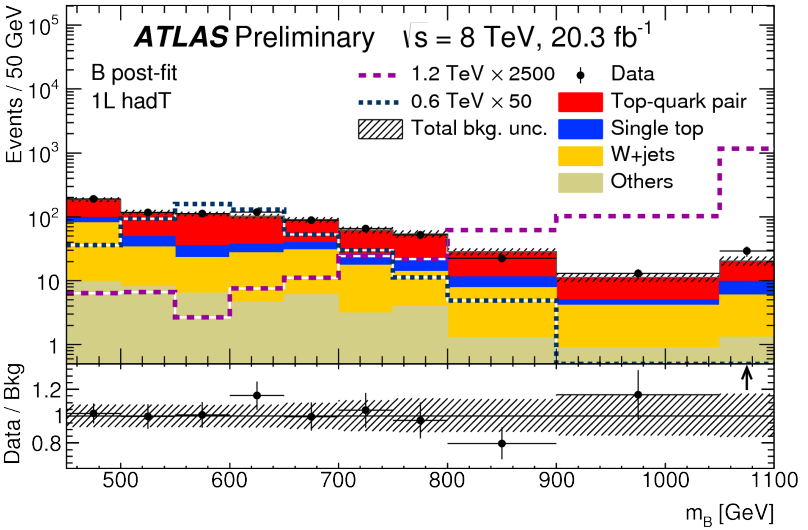


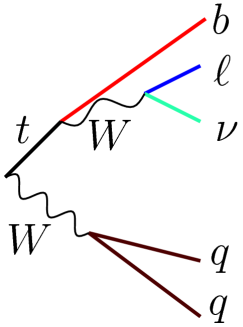
Single e/μ, p_T > 25 GeV
E_T^{miss} > 20 GeV
$E_T^{miss}+M_T$ > 60 GeV
N_{jets} = 2 or 3 (R=0.4)
N_b = 1

- Expect single B produced in association with a (tagged) forward jet
- Rudimentary W/t tag:
  - ≥ 1 trimmed wide jet (anti-k_T, R=1)
  - may overlap narrow jets
  - p_T > 200 GeV, m > 50 GeV
- Visible B mass:
  ℓ + E_T^{miss} + narrow jets

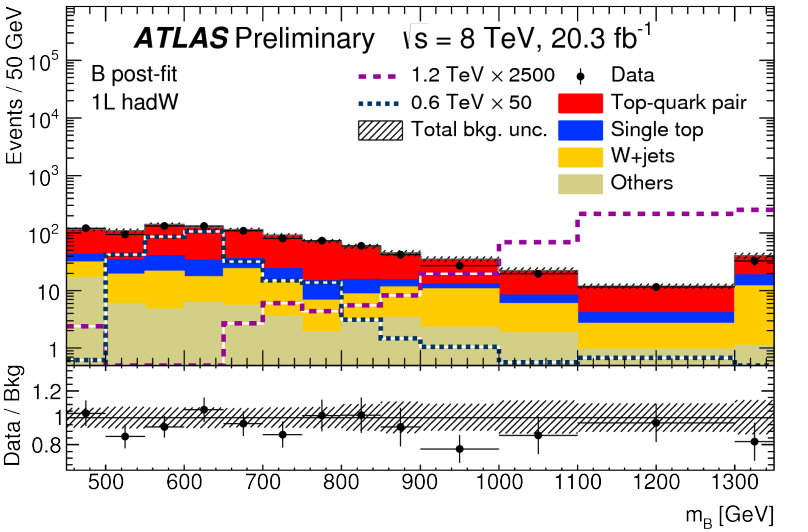
1L hadT



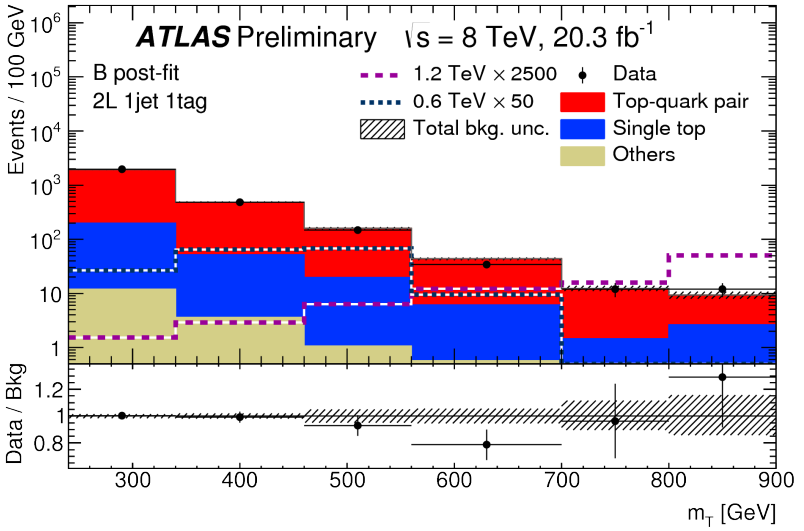




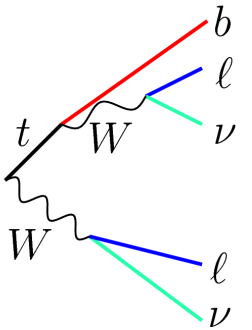
1L hadW

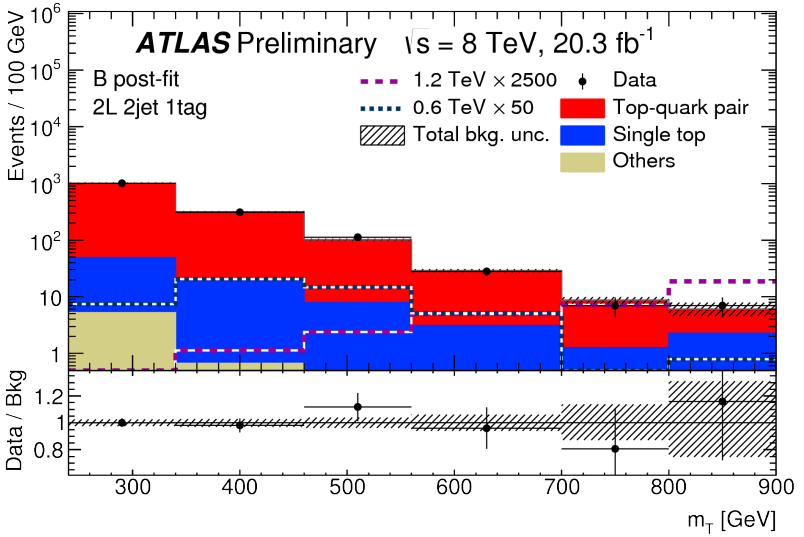


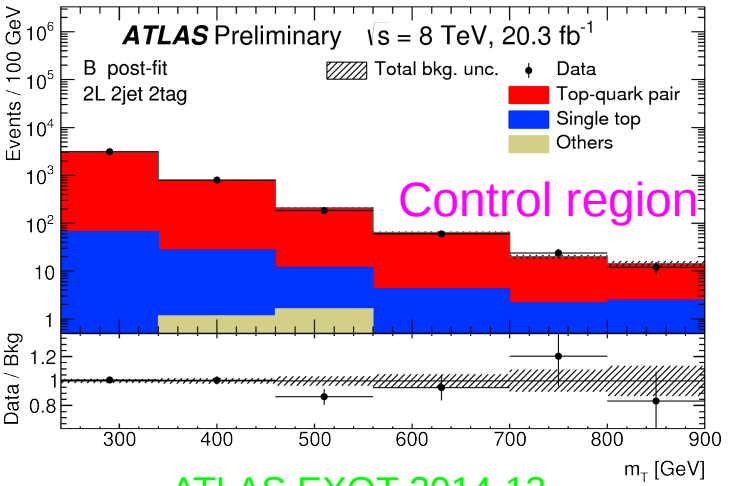
ATLAS Single B → tW



- Opposite sign eμ pair
  - No additional E_T^{miss} requirements
- 1 central b-tagged leading jet near lepton (Δφ<0.9)
- 1 forward jet: 1.5<|η| <4.5
  - Not b-tagged if |η| <2.5
- Use m_T of eμ, E_T^{miss}, and leading jet





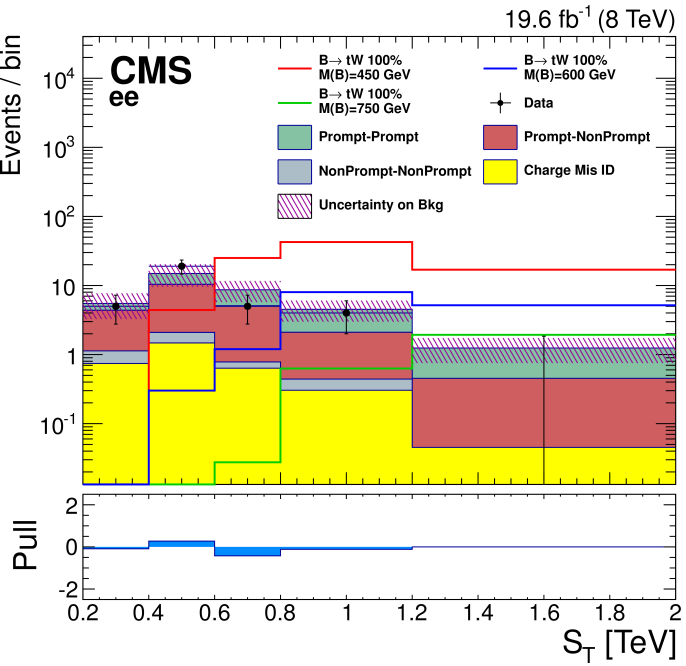


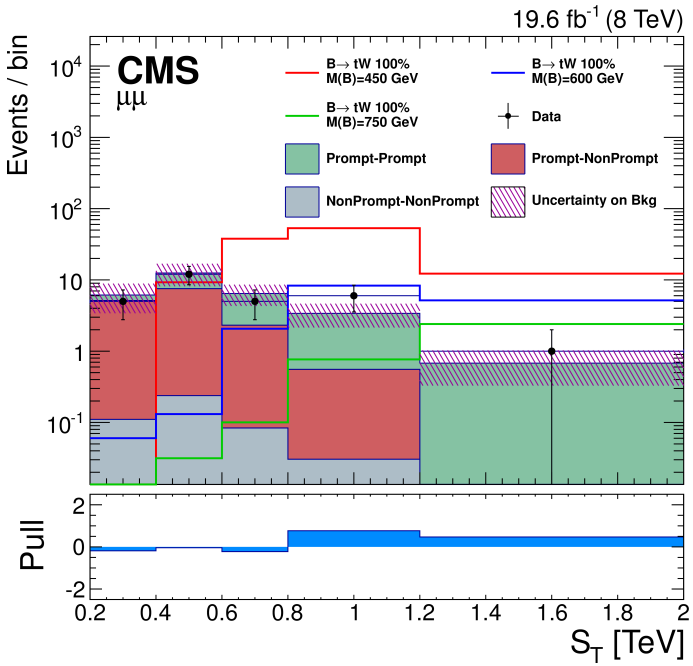
ATLAS EXOT-2014-13

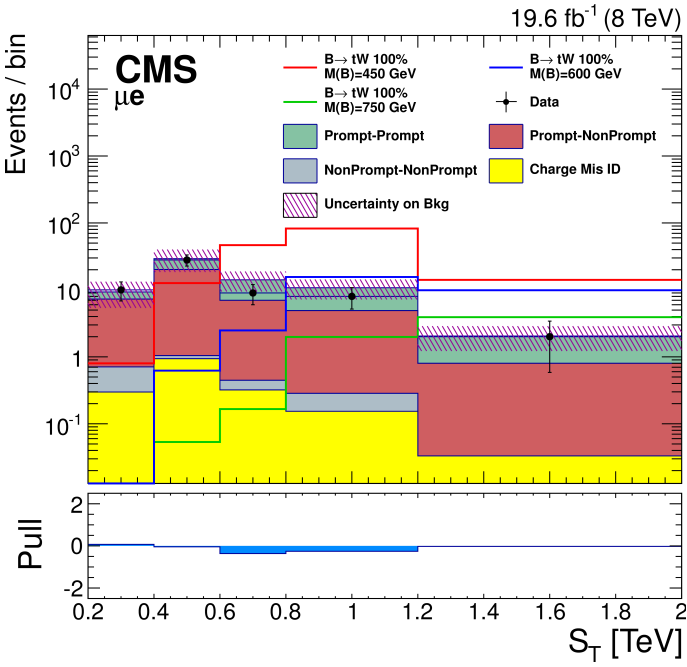
Same-sign dilepton signatures

CMS BB → tW+X → $\ell^{\pm}\ell^{\pm}$ + jets

- Take advantage of pair production
  - e.g., BB → WWWWbb







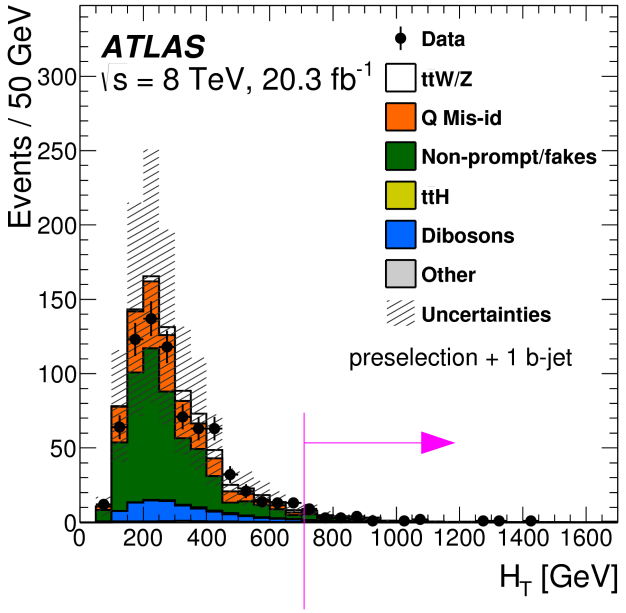
arXiv:1507.07129

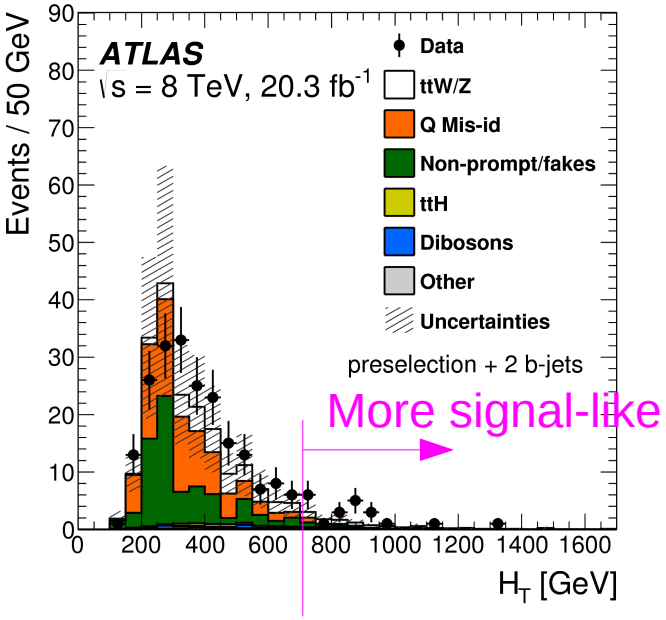
ATLAS $\ell^{\pm}\ell^{\pm}$ + jets

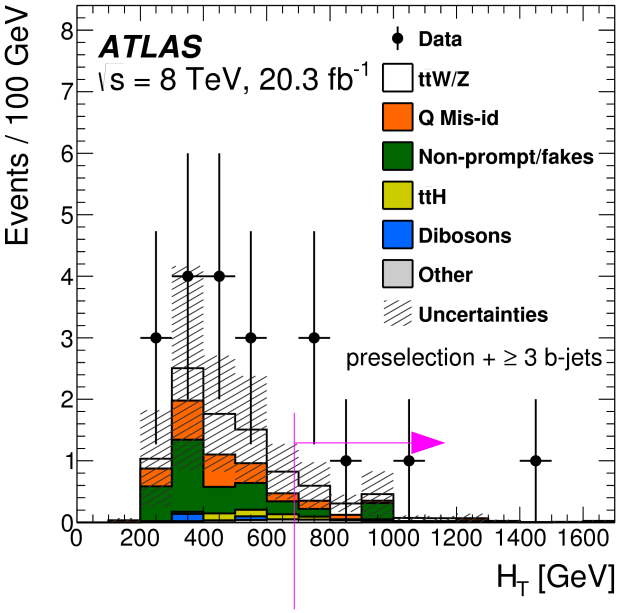
Lepton p_T > 25 GeV
E_T^{miss} > 40 GeV
m_{ee} > 15 GeV, not Z
$H_T(\ell+jets)$ > 400 GeV

- Same-sign ee or μμ

More signal-like







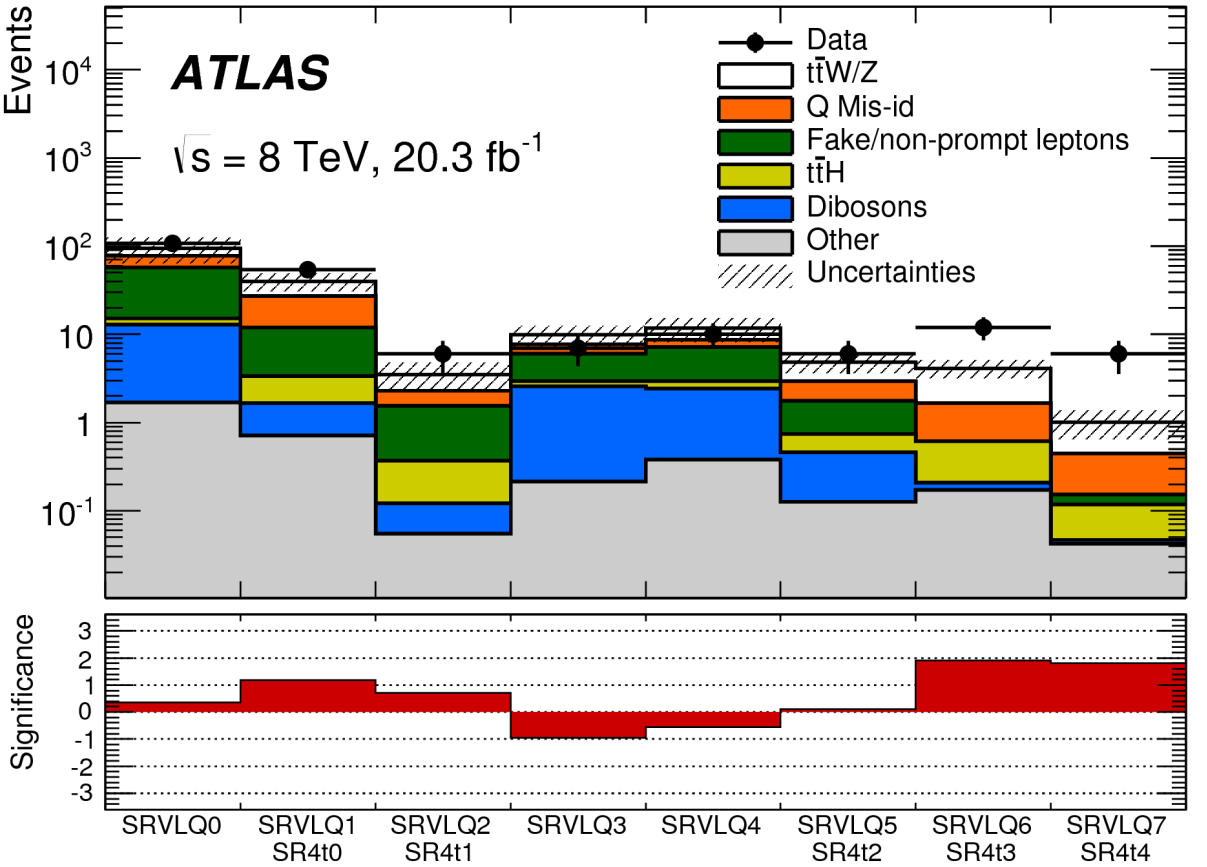
arXiv:1504.04605

- Define 8 signal regions for different VLQ's

ATLAS $\ell^{\pm}\ell^{\pm}$ + jets

arXiv:1504.04605

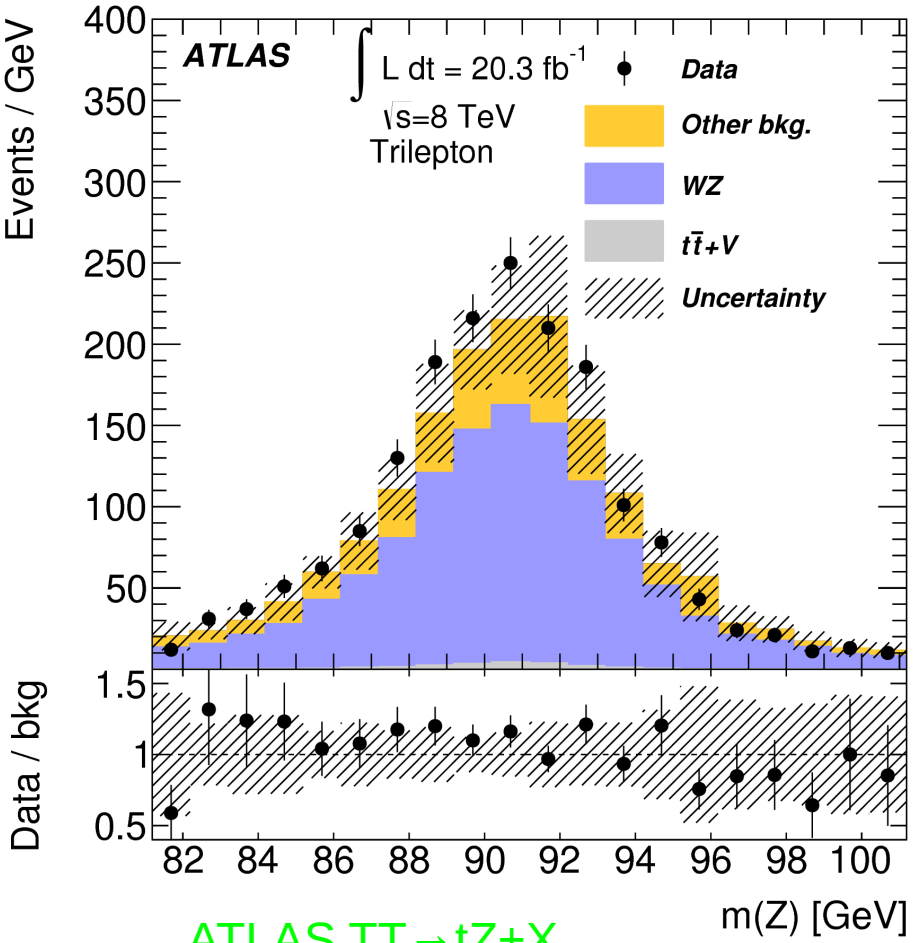
SR#	H_T [GeV]	N_b	E_T^{miss} [GeV]
0	(400,700)	1	>40
1		2	
2		≥3	
3	>700	1	(40,100)
4		1	>100
5		2	(40,100)
6		2	>100
7		≥3	>40



- Small excess (~1-2σ) in two signal regions

Multilepton signatures

- Not enough time to cover here (somewhat older results)
- Sometimes it's nice to remember what a real particle looks like



ATLAS TT→tZ+X
JHEP 11, 104 (2014)

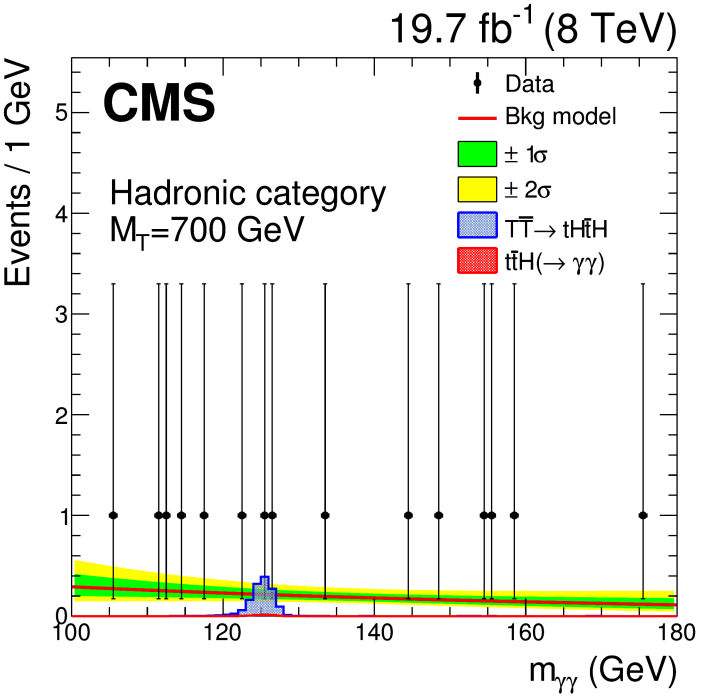
Non-leptonic signatures (CMS)

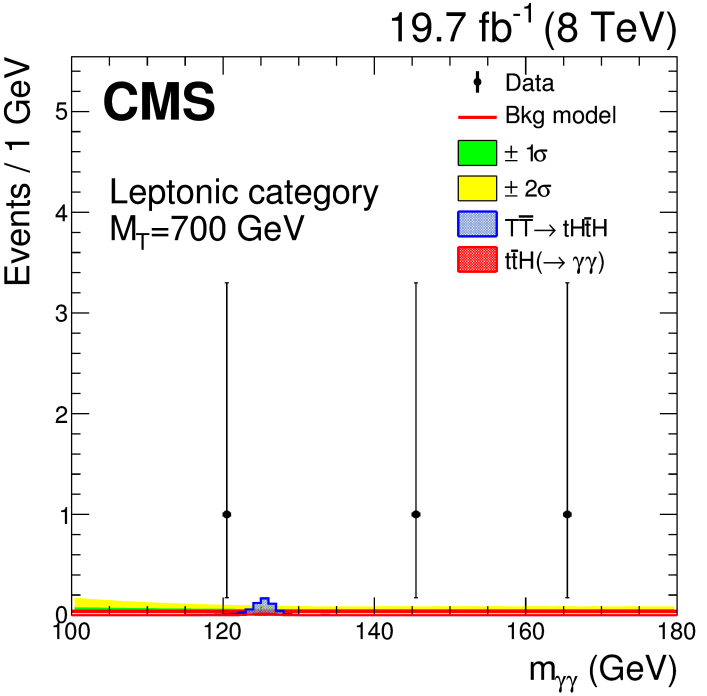
TT → tH+X, H → γγ

- Start with diphoton events
- Reconstruct narrow H resonance

Leptonic top:
$N_{lep} \geq 1$
$N_{jets} \geq 2$
$S_T > 770$ GeV
$p_T(\gamma_1) > ½\ m_{\gamma\gamma}$
$p_T(\gamma_2) > 25$ GeV

Hadronic top:
$N_{lep} = 0$
$N_{jets} \geq 2$
$N_b \geq 1$
$S_T > 1000$ GeV
$p_T(\gamma_1) > ¾\ m_{\gamma\gamma}$
$p_T(\gamma_2) > 35$ GeV





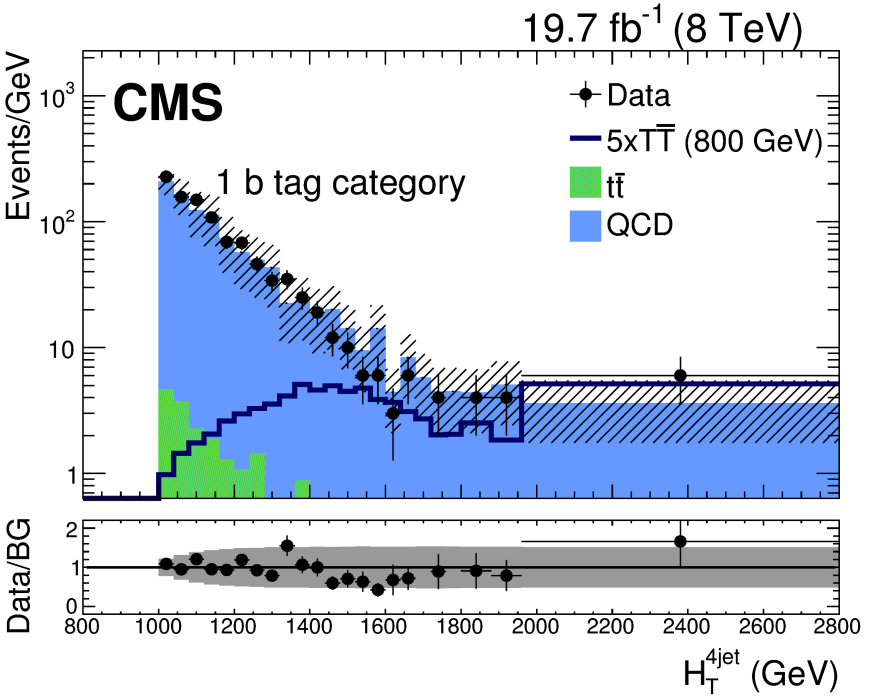
arXiv:1509.04177

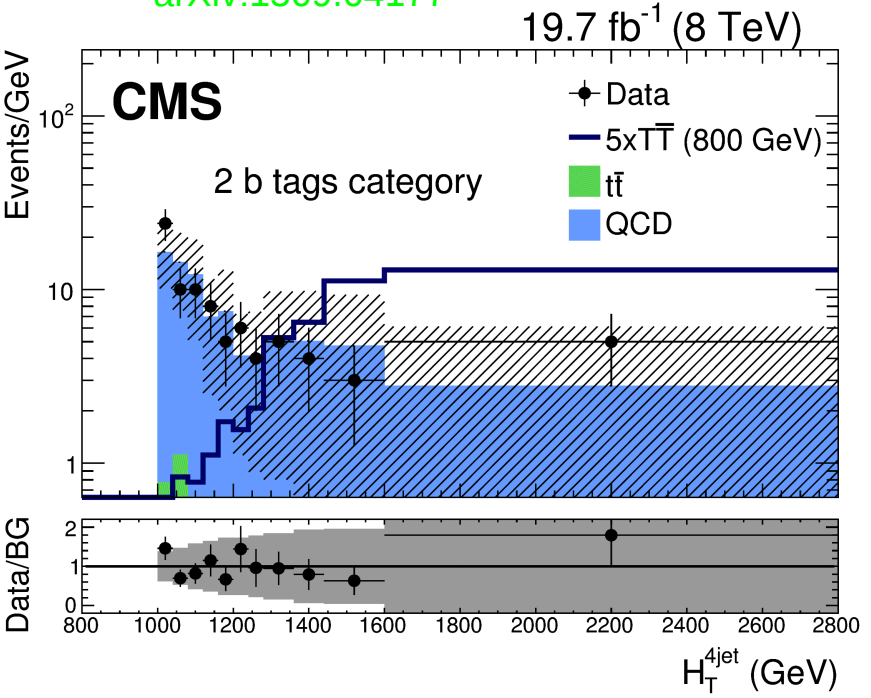
Hadronic TT → bW+X

- 2 single-jet W's, 2 b's → H_T(4 jets)
- Resolve opposite T's with mass difference
  - T mass > 200 GeV, back-to-back

Single-jet W tag:
- Pruned Cambridge-Aachen, R=0.8
- p_T > 150 GeV, 60 < m_{jet} < 100 GeV
- Mass drop $\mu \equiv m_1/m_{jet}$ < 0.4

arXiv:1509.04177





- CMS has also used substructure techniques in all-hadronic B → bH → bbb

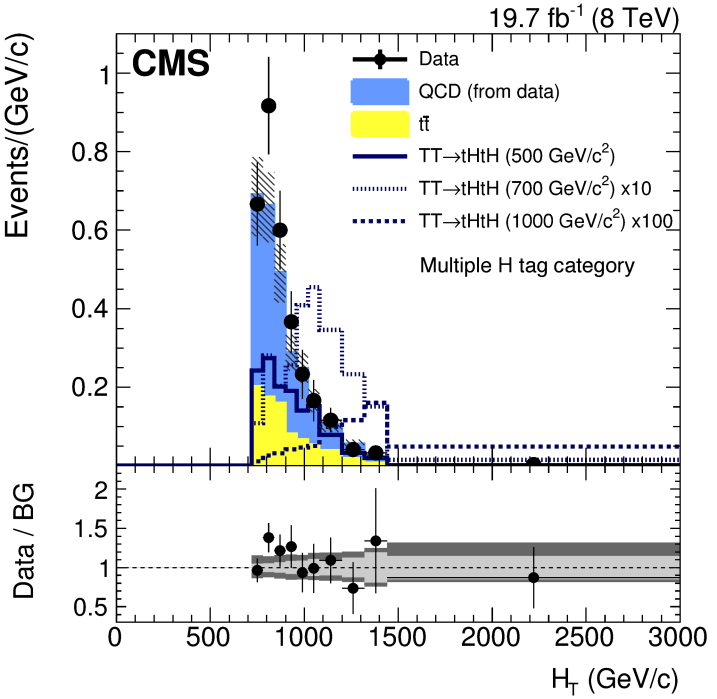
Hadronic TT → tH+X

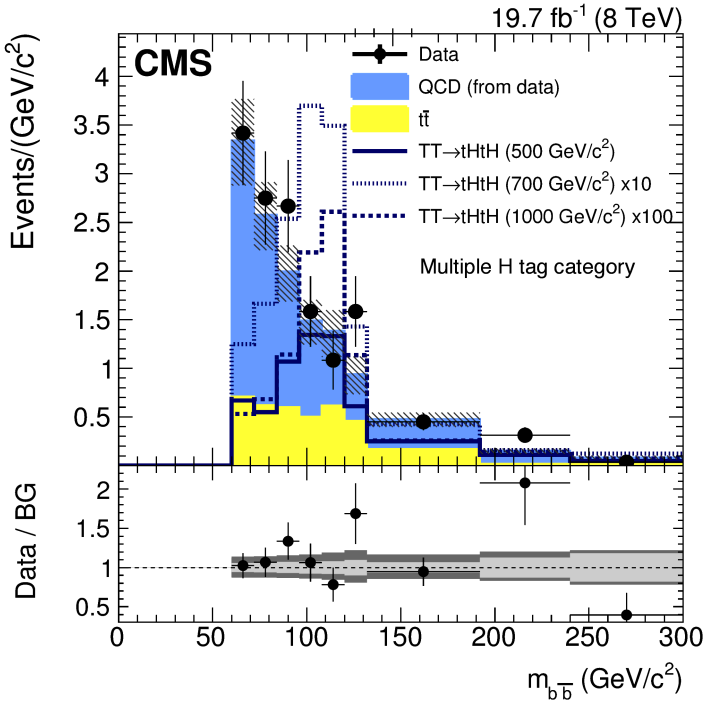
- Use top and Higgs jet tagging
  - CA, R=1.5, filtered for subjets
- Combined discriminant: H_T(subjets), m_{bb}

$N_t \geq 1$, $p_T > 200$ GeV
$N_H \geq 1$, $p_T > 150$ GeV
H_T(subjets) > 720 GeV

Top tagging
- HepTopTagger
- 3 subjets
- W pair
- $N_b \geq 1$

Higgs tagging
- $N_b = 2$
- $m_{bb} > 60$ GeV





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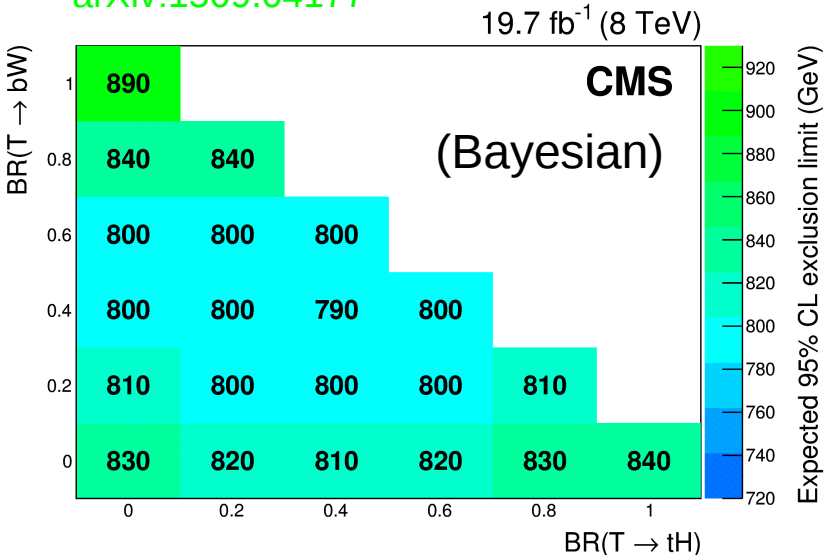
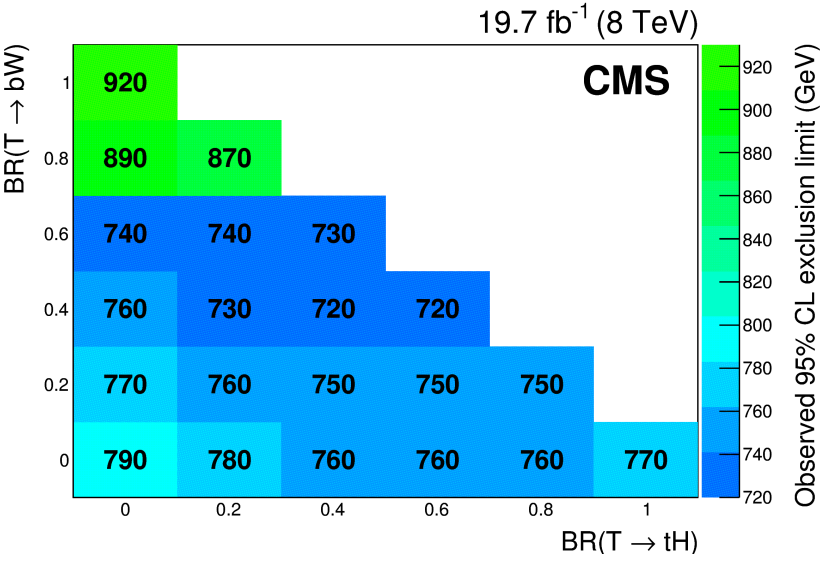
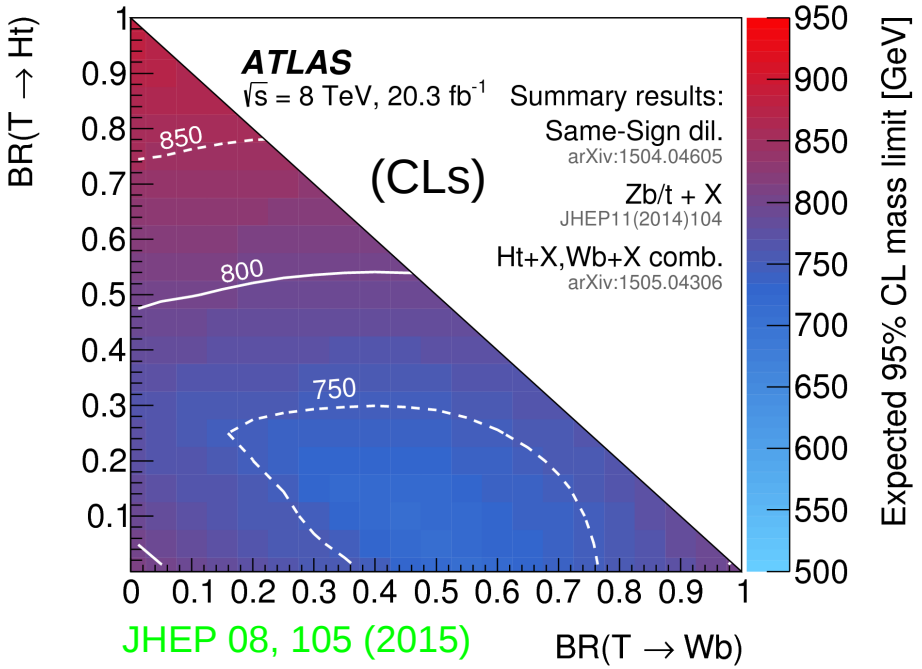
Limits

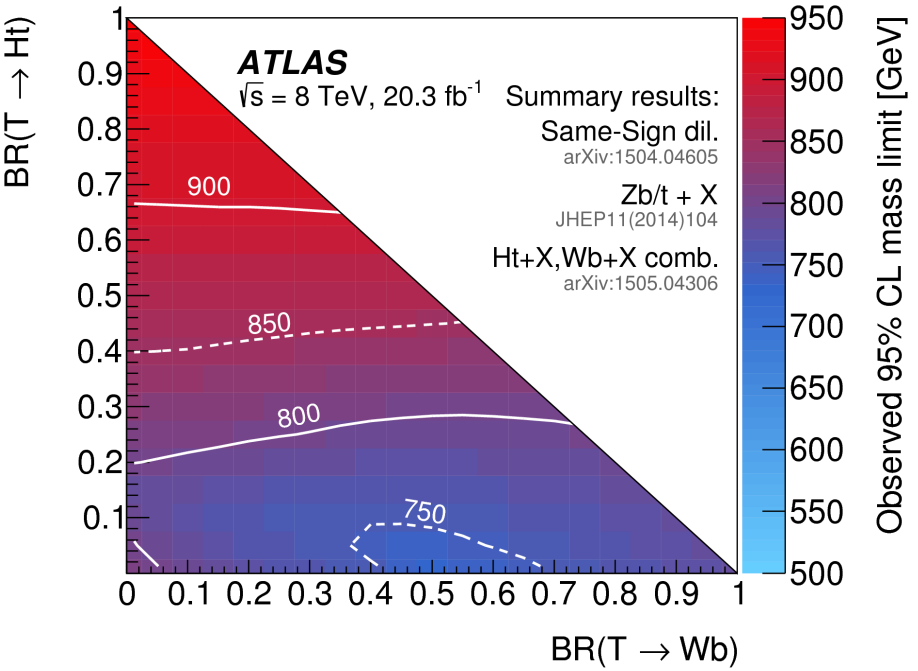
VLT summary

arXiv:1509.04177





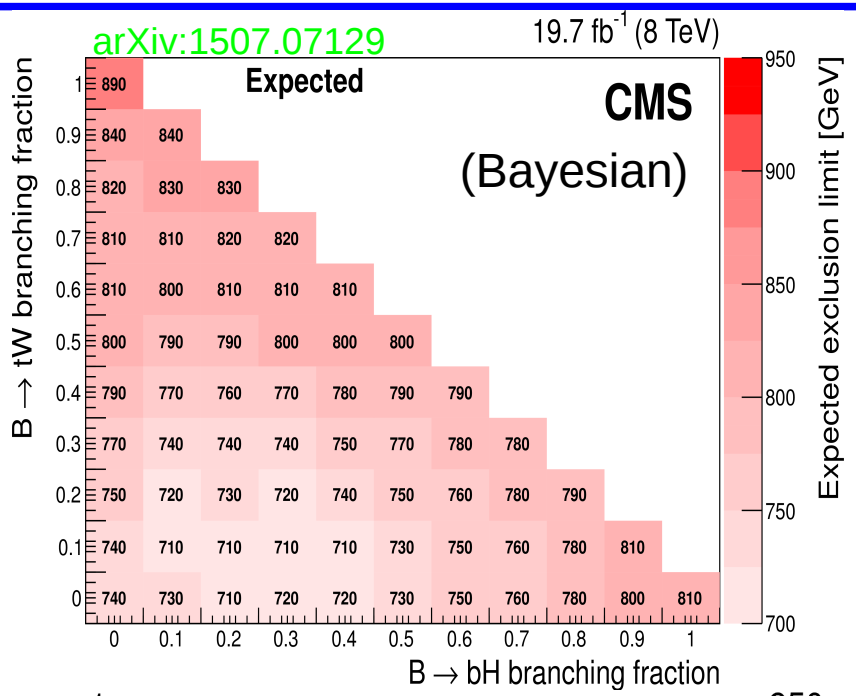


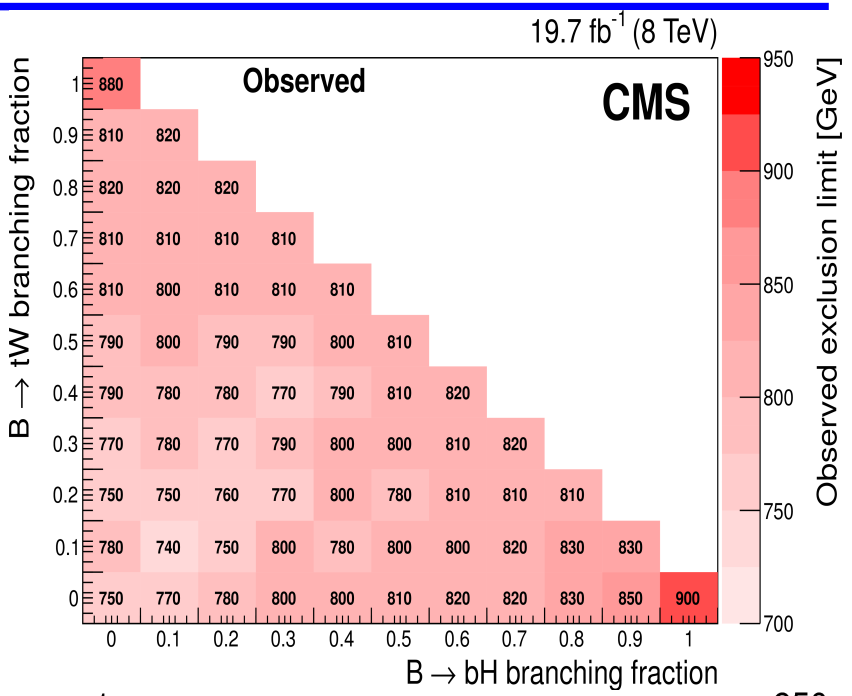


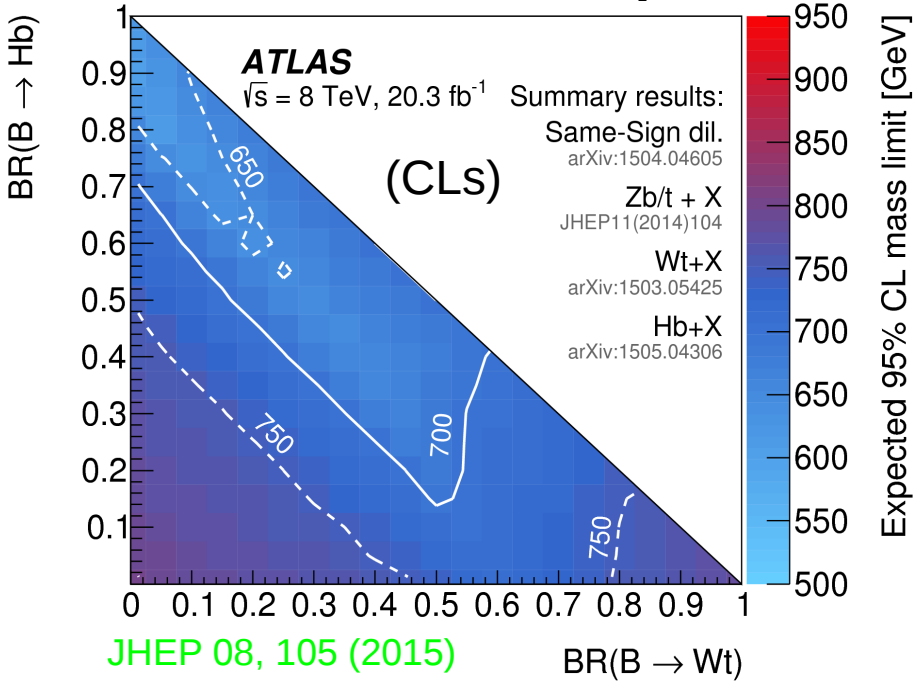
JHEP 08, 105 (2015)

VLB summary

arXiv:1507.07129







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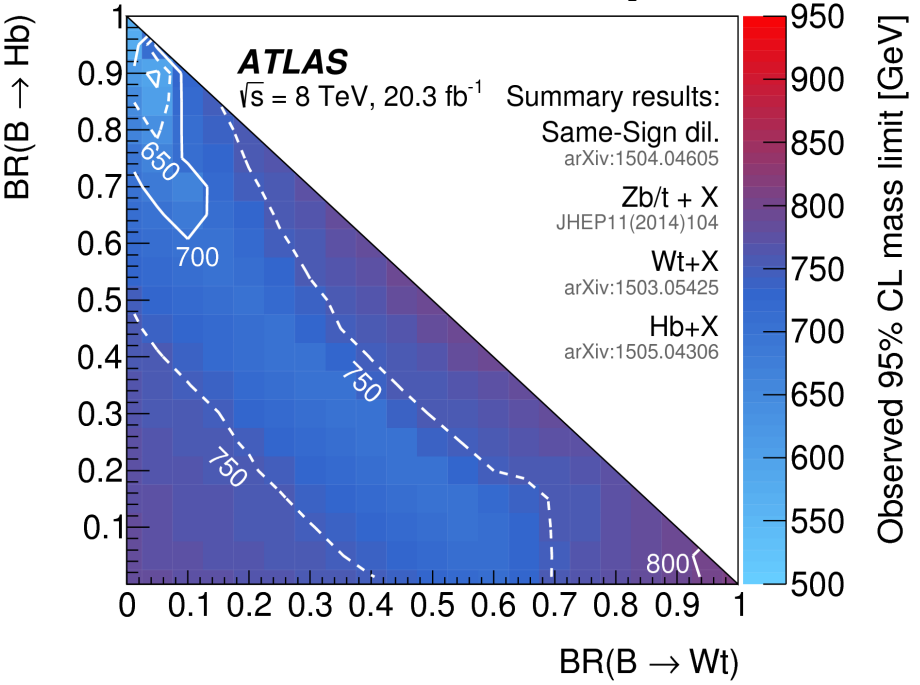
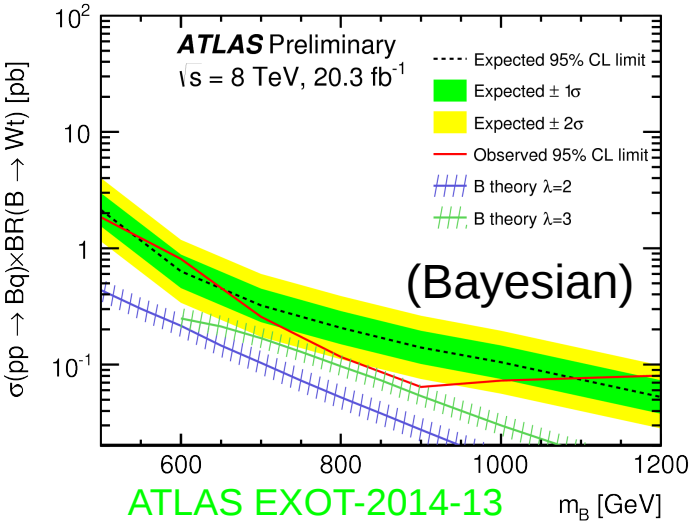
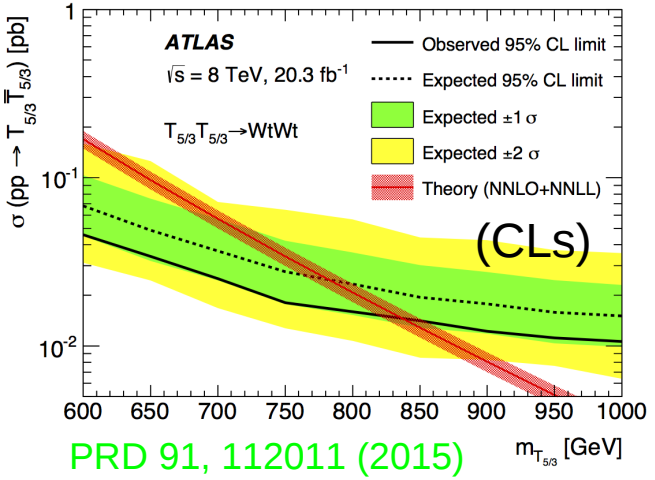


Other Limits

Single B



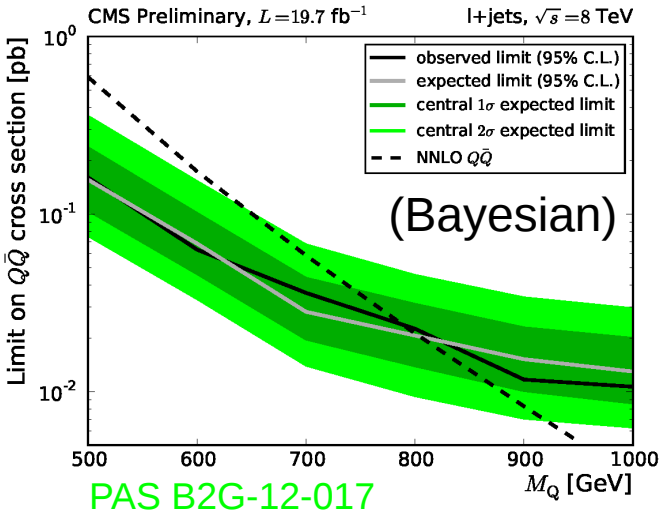
ATLAS EXOT-2014-13



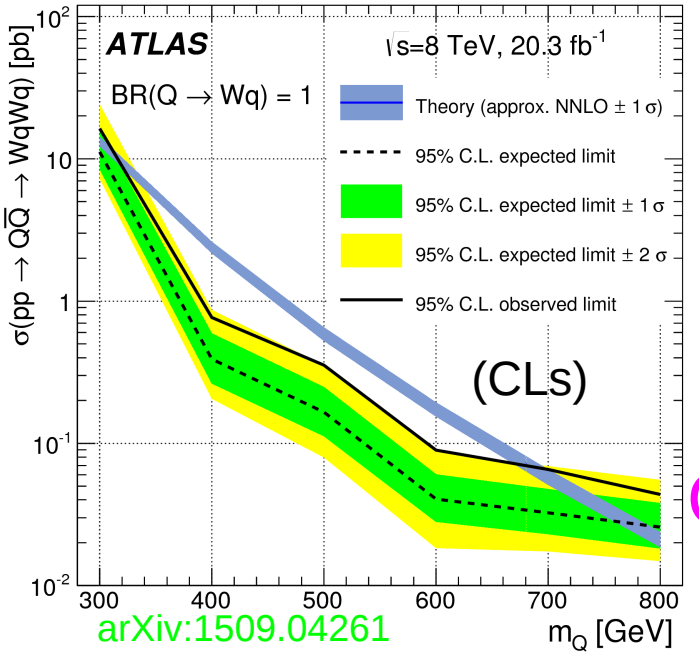
PRD 91, 112011 (2015)

$T_{5/3}$

Q



PAS B2G-12-017



arXiv:1509.04261

$Q/B_{4/3}$

Summary

- Vector-like quarks remain a promising signature for new physics
- No significant signals in 8 TeV LHC data
  - Mass limits pushing above 750 GeV (95% CL) irrespective of model
  - Most stringent single $T_{5/3}$ limit at 840 GeV (95% CL)
  - Q limits with BR(Q→qW)=1: 690 GeV (ATLAS), 788 GeV (CMS preliminary)
  - Not quite “Don't know a number, but if you want one, 2 TeV” (M Peskin)
- Experiments pursuing/increasing use of a number of techniques to increase sensitivity
  - Boosted jet substructure
  - Multivariate optimization
  - Probes of electroweak single production
- Eagerly await analysis of 13 TeV data

Backup

Observables (broad outline)

	ATLAS	CMS
Luminosity	20.3 fb^{-1}	19.7 fb^{-1}
Trigger	e/μ	e/μ, all-hadronic
Isolated electrons	E_T > 25 GeV ΔR > 0.4 from jets	p_T > 30 GeV
Isolated muons	p_T > 25 GeV ΔR > 0.4 from jets	p_T > 30 GeV
Taus (hadronic)		HPS (hadron+strip) algorithm p_T > 20 GeV ΔR > 0.1 from leptons
Jets	Anti-k_T, R=0.4 p_T > 25 GeV	Anti-k_T, R=0.5 p_T > 30 GeV
E_T^{miss}	Calorimeter	Particle flow

Systematic uncertainties

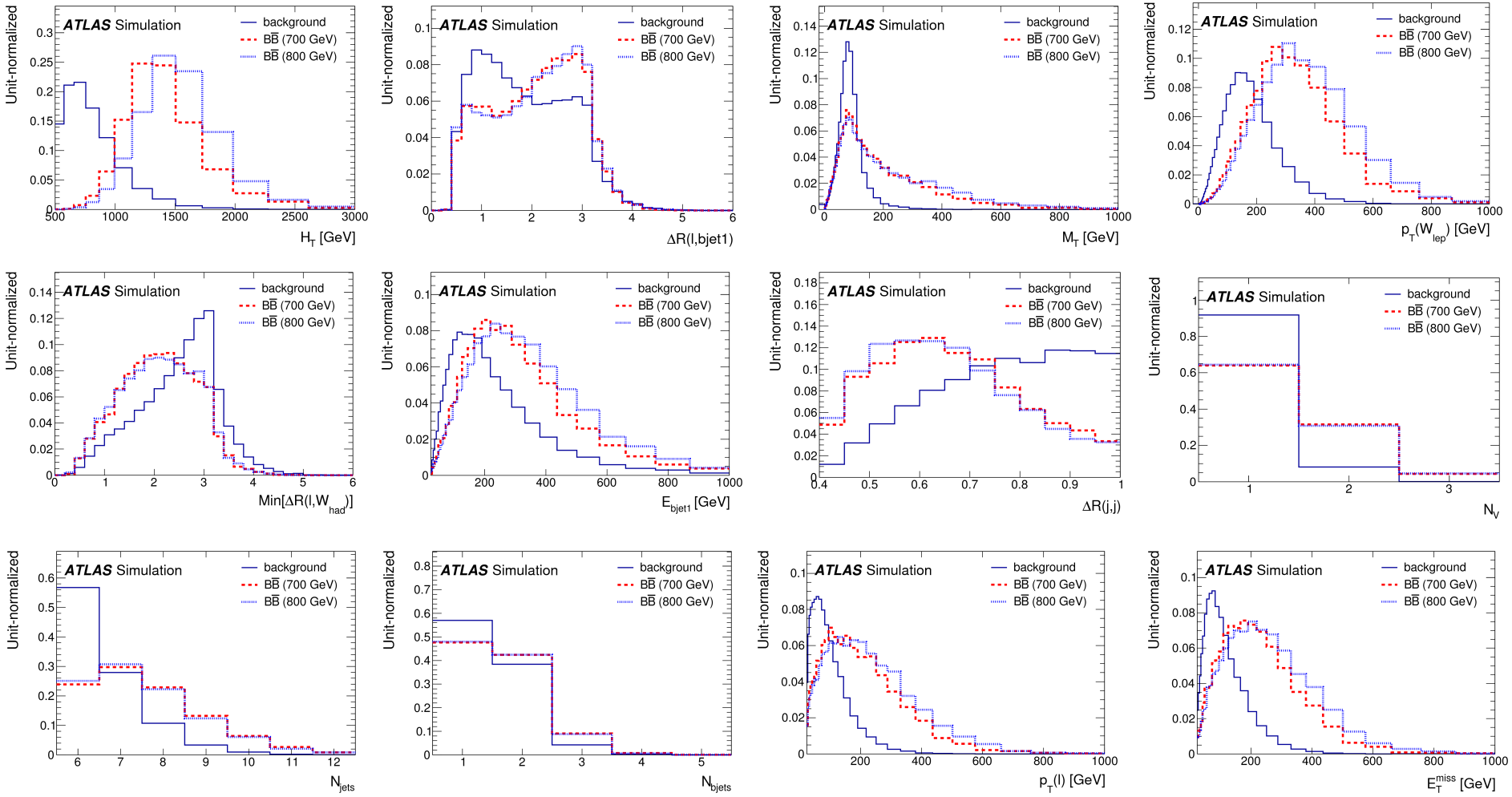
- Jet energy scale/resolution
- PDF's
- Integrated luminosity
- Background rates and distributions
  - tt + jets, ttV, single t
  - Single/double/triple W/Z production
  - QCD multijet

- Lepton/jet reconstruction efficiency
- b(c)-tagging efficiency
- E_T^{miss} resolution
- Pileup
- Factorization/renormalization scale

➔ Uncertainty on background determination to compare with data

Discriminating VLQ's

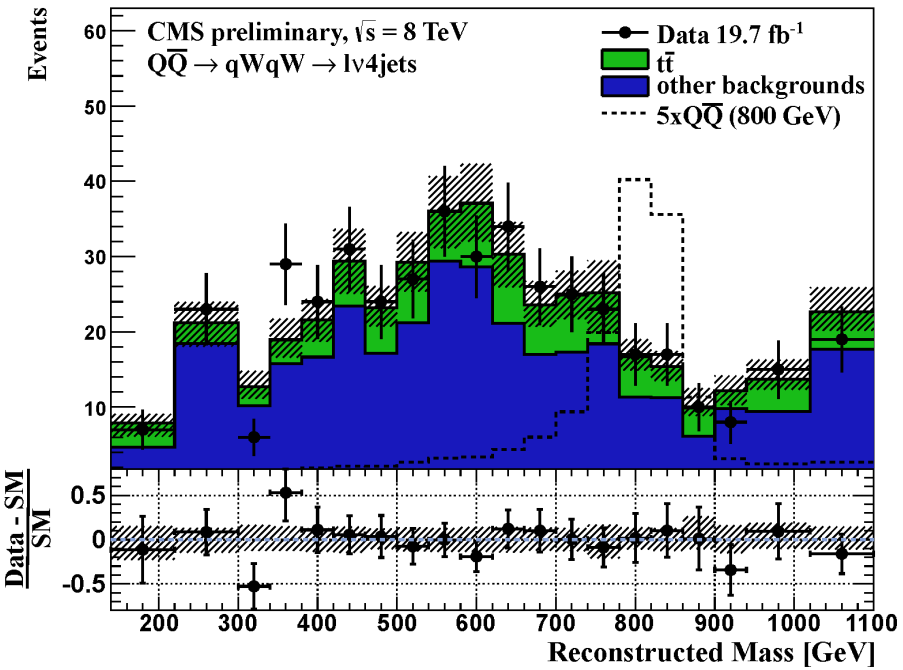
ATLAS B → tW → ℓ + jets



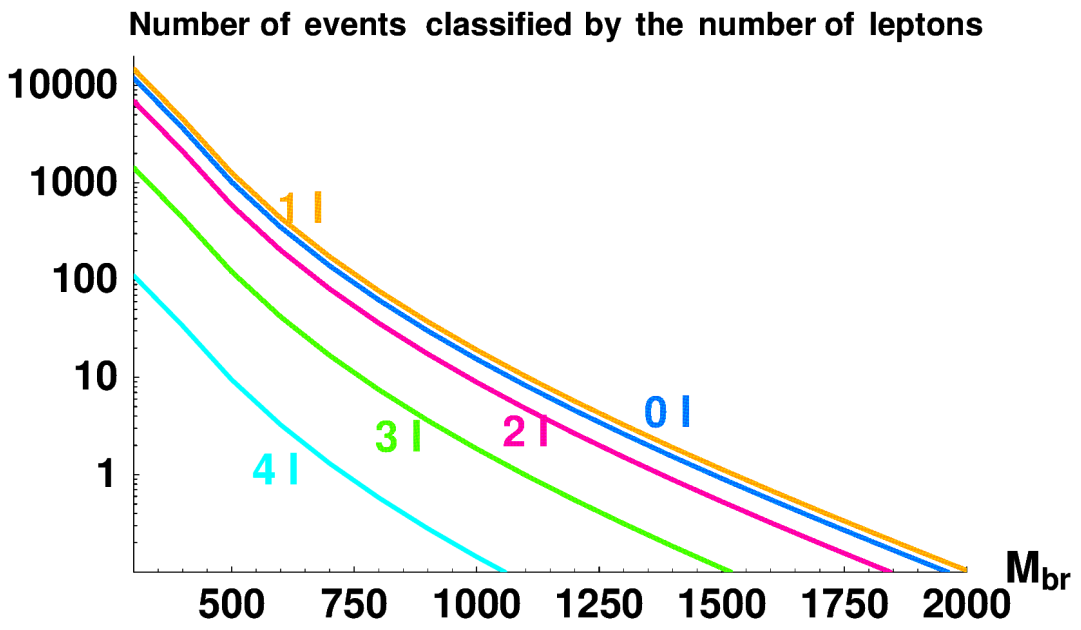
CMS QQ → qW+X

- Same analysis technique as TT → bW+X
  - Looser b tag operating points + Quark-Gluon Likelihood Discrimination Tagger (QGT)
  - ➔ Select light quark jets
- $S_T(\ell+E_T^{miss}+4jets) > 1000$ GeV

CMS PAS B2G-12-017



Multilepton signatures



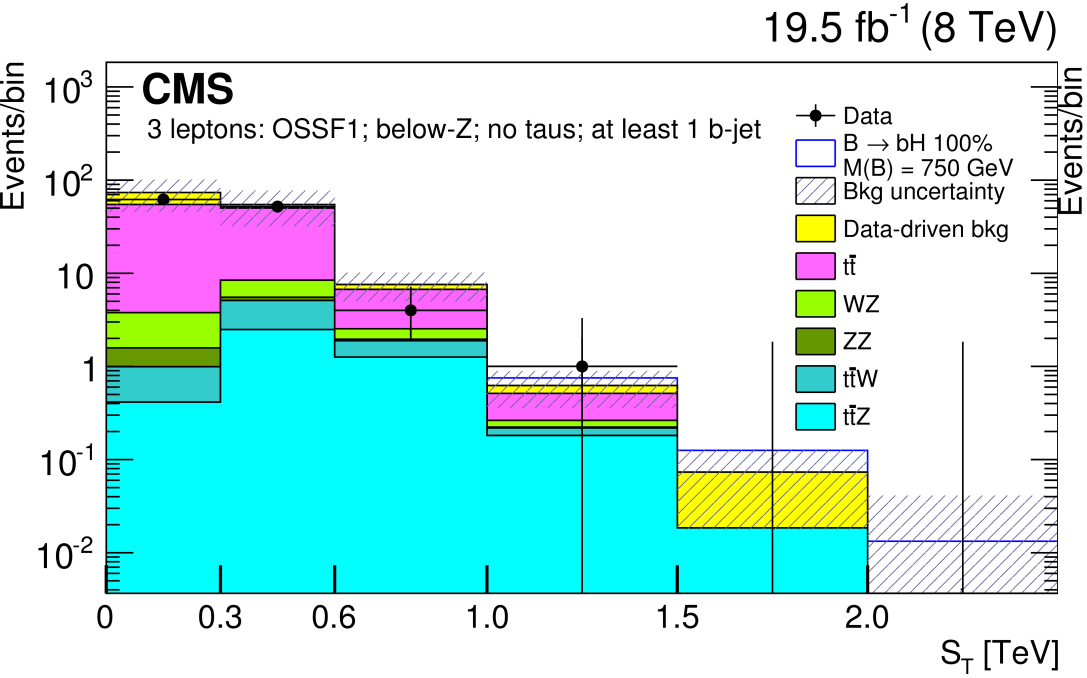
- 1 and 2 leptons capture most of the rate
- 3 leptons ~O(10) lower, but purer
- 2007 plot of rate vs number of leptons
  - m_H=300 GeV!

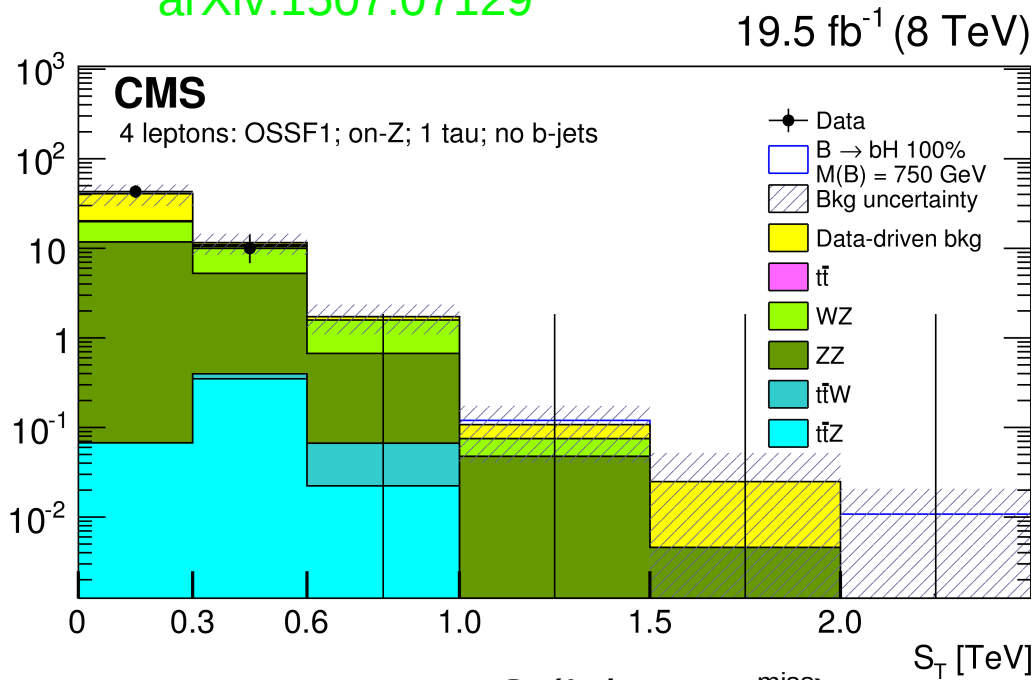
Dennis, Karagöz, Servant, Tseng, hep-ph/0701158

CMS BB → tW/bZ+X → ℓℓℓ + X

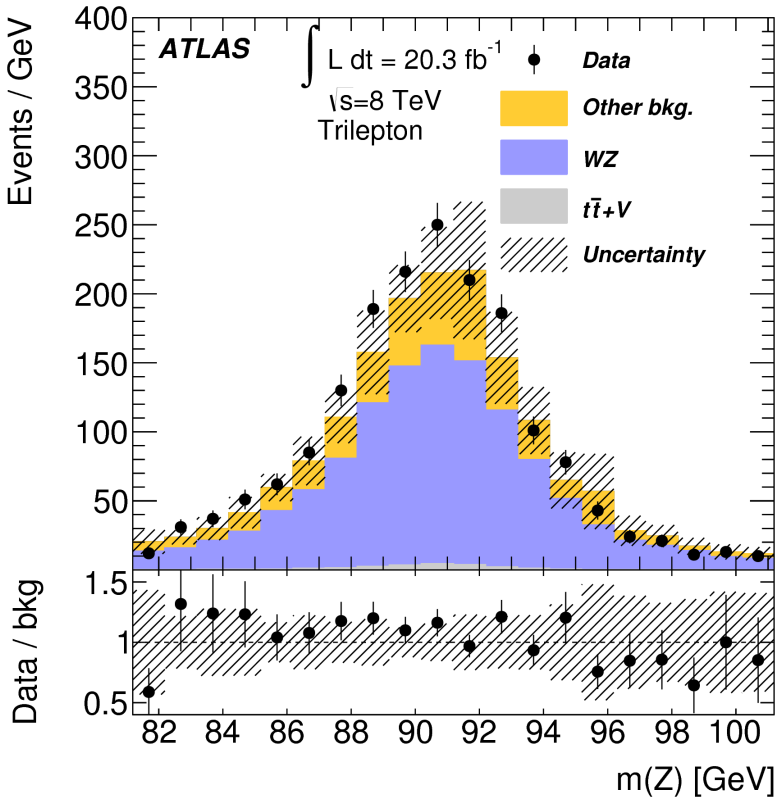
- Most sensitive to tW and bZ decay modes
- Uses e, μ, and hadronic τ with p_T > 20/10 GeV
- Selected event categories:

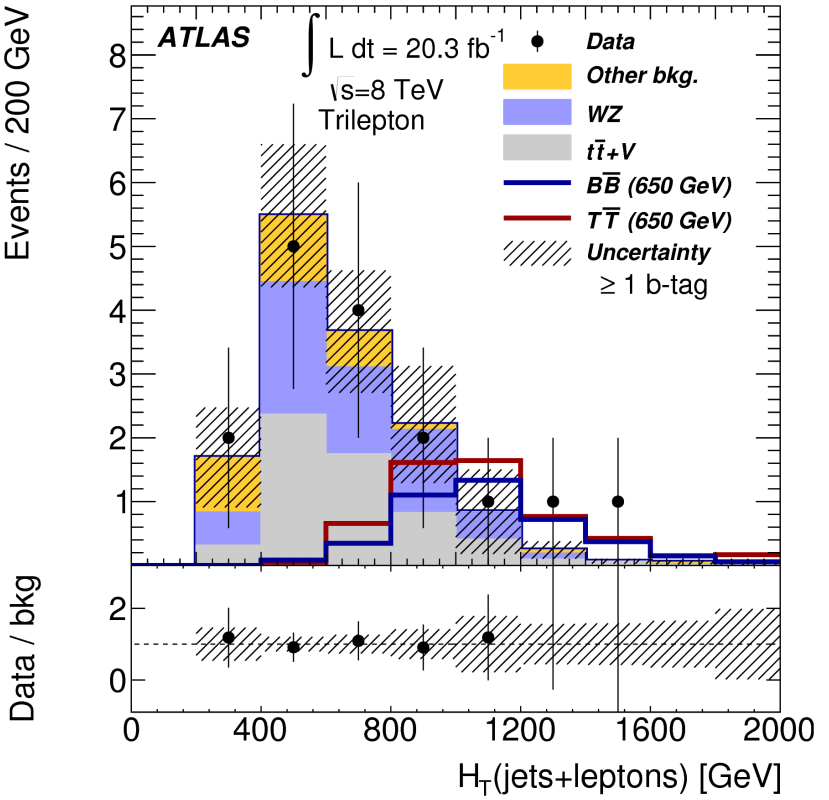
arXiv:1507.07129





ATLAS TT → tZ+X → ℓℓℓ + X





- $p_T(Z) > 150$ GeV, $N_{jets} \geq 2$, $N_b \geq 1$

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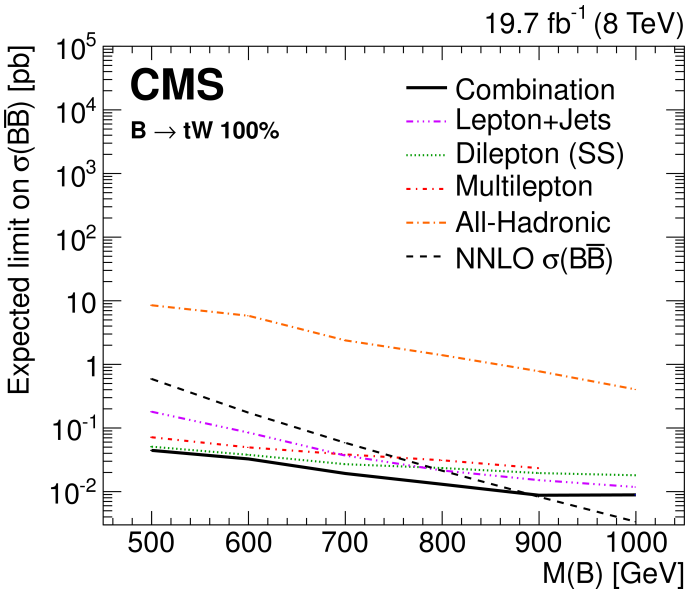
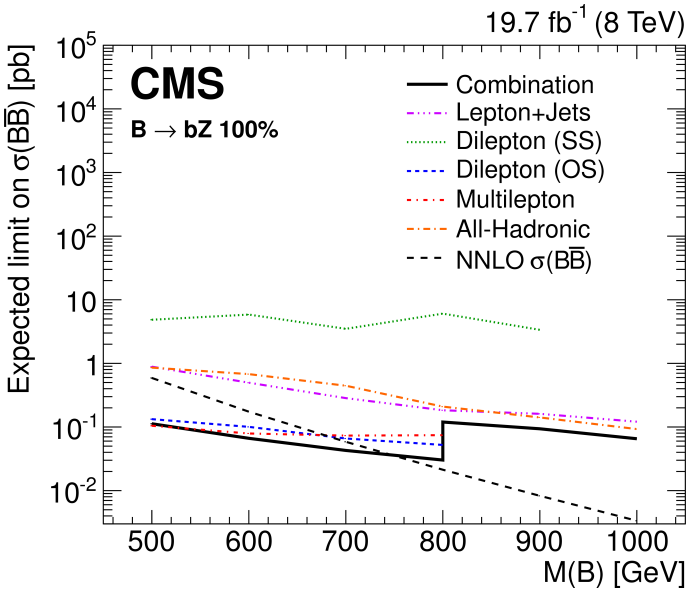
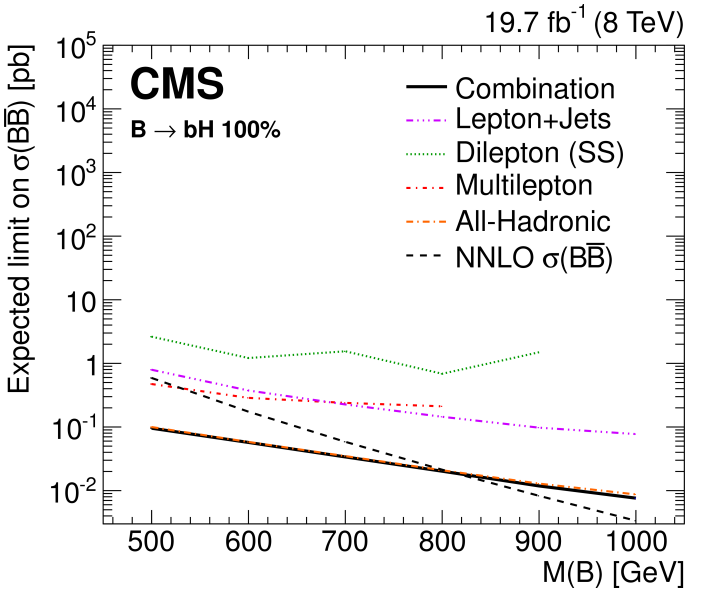
- Also included search for single T production by requiring ≥ 1 forward jet

Limit contributions: CMS B







Limit contributions: CMS T