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Searches for new heavy quarks

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On behalf of the ATLAS and CMS Collaborations

ATLAS EXPERIMENT

ICREA

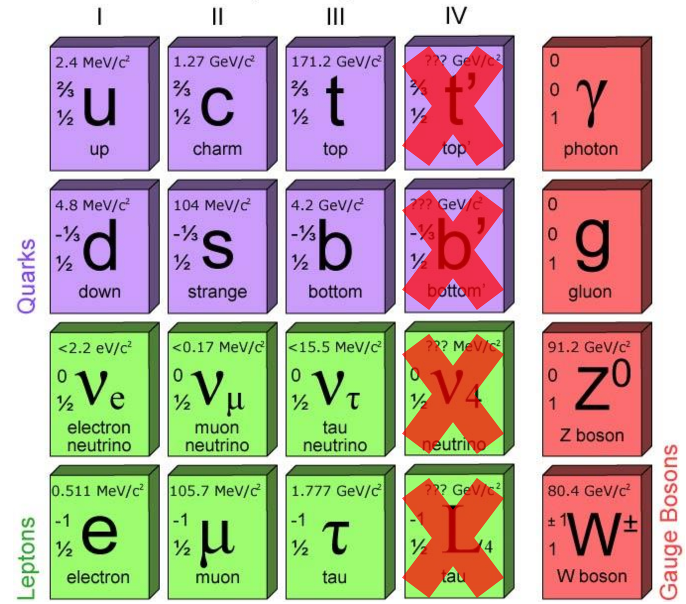
IFAE Institut de Física d'Altes Energies

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

CMS Compact Muon Solenoid

Introduction



The LHC represents an extremely powerful instrument to search for new heavy quarks:

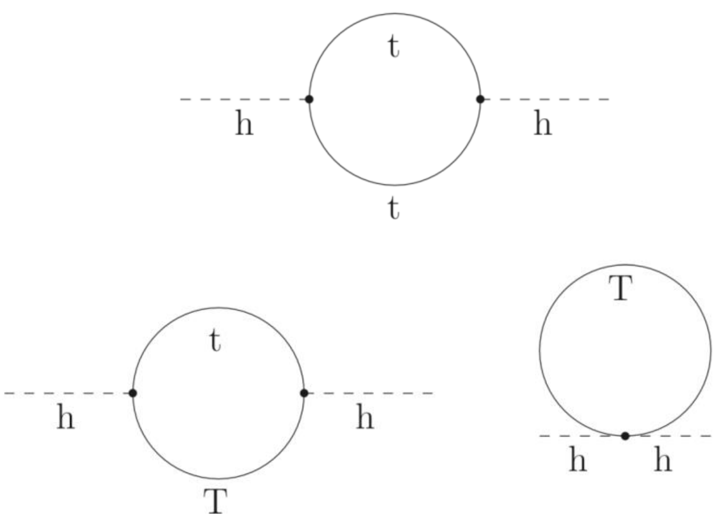
- **Direct searches** in a plethora of kinematic regions and final state signatures.
- Broad program of **precise measurements** of SM processes and parameters.

  ➔ Higgs boson cross section measurements exclude chiral 4th generation of quarks.

A more compelling possibility: **Vector-Like Quarks** (VLQs) ➔ Focus of this talk

- Present in many BSM extensions: e.g. Composite Higgs, extra dimensions.
- Colored spin-1/2 fermions whose left and right components transform the same under $SU(2)_L$.
- Can mix with their SM counterparts and regulate the Higgs mass-squared divergence.

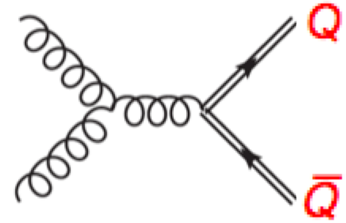
  ➔ attractive solution to the Hierarchy Problem.

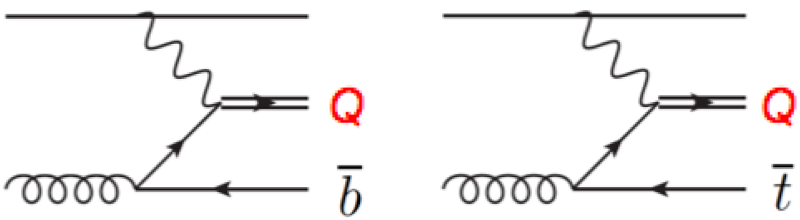


Vector-Like Quarks: Production and Decay

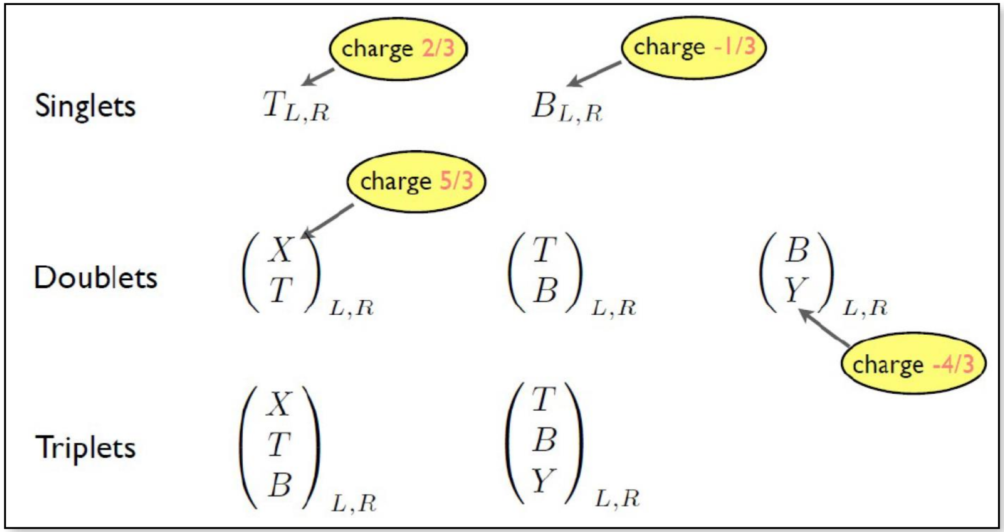
Production:

- Pair production: via QCD, "universal" production mode (just depends on m_Q).
  ➔ Focus of Run 1 searches
- Single production: via EW interaction, depends on coupling strength, but potentially important at high m_Q.

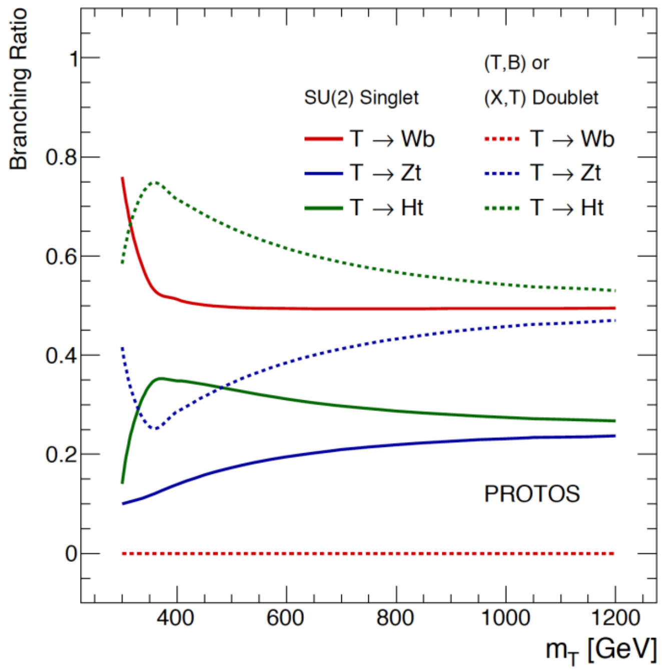




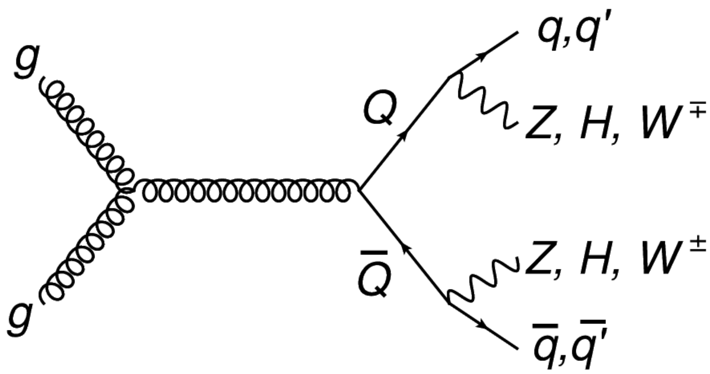
Decay: Q→Wq, Zq, Hq, all with sizable BR



VLQs assumed to mix preferentially with 3rd generation quarks.



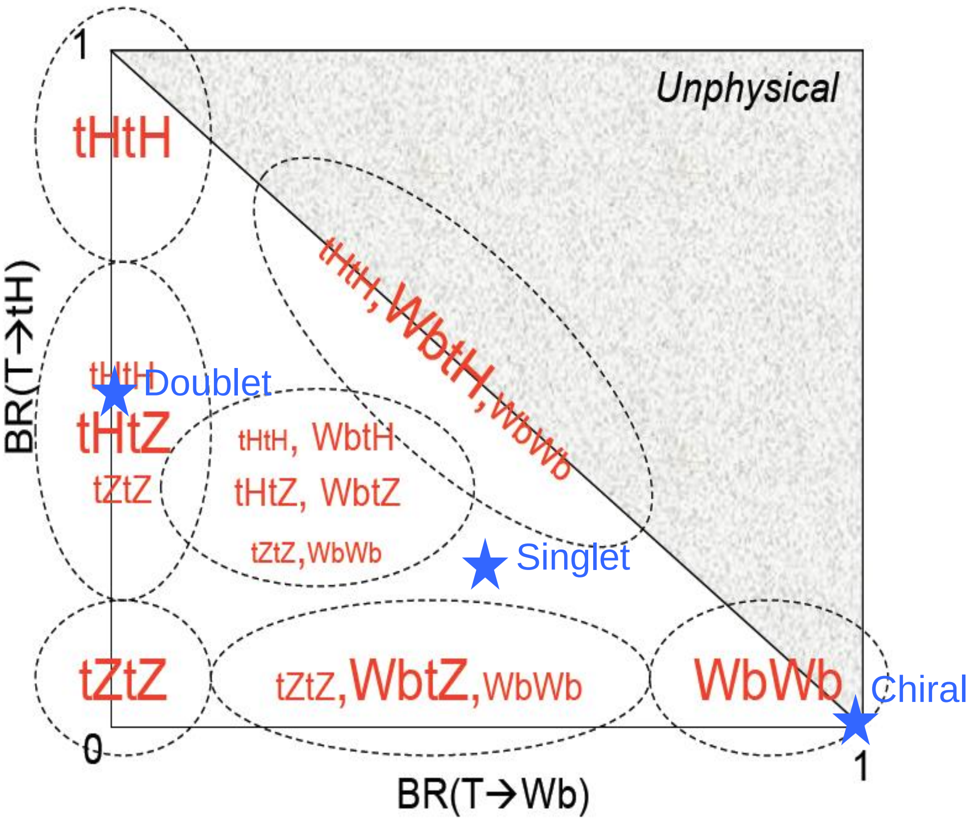
Pair Production Strategy



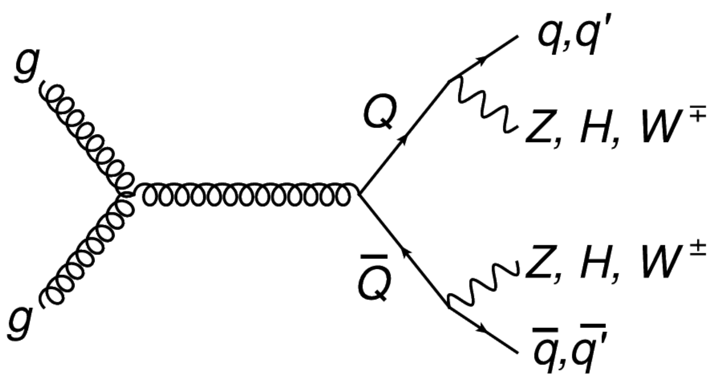
- Very rich phenomenology, depending on VLQ mass and quantum numbers.
- Goal is to probe full BR plane in as model independent possible way.

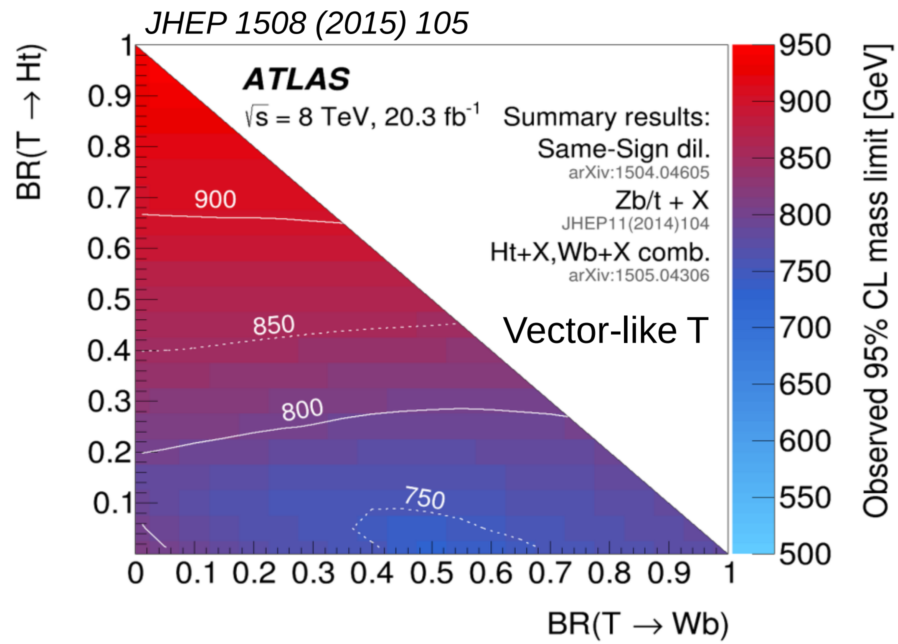
  ➔ Searches specialized on particular heavy quark decay modes, but also able to probe part of the plane.

  ➔ Multiple searches required, ideally overlapping on the plane.



Pair Production Strategy





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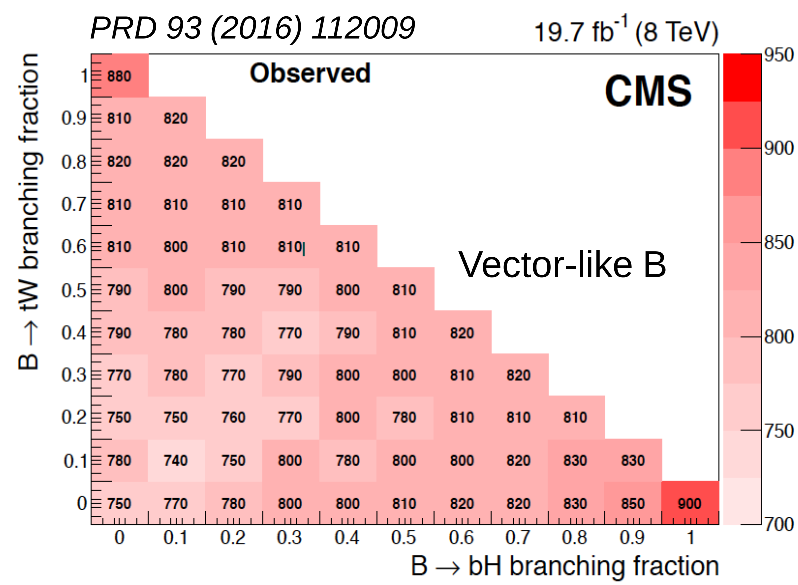
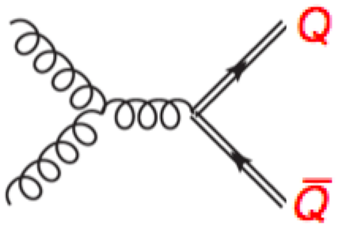


Run 1 excludes T-quark (B-quark) masses below ~720 (740) GeV for any combination of BRs

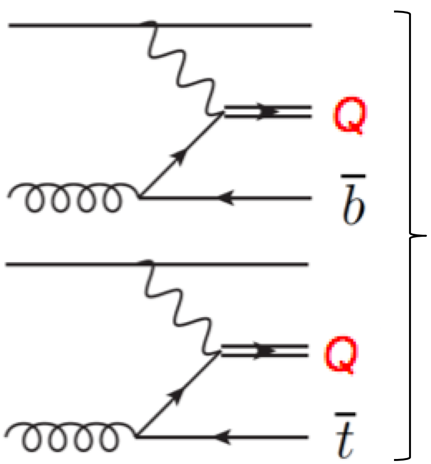
Run 2 Status and Plans

Plan for Run 2 Analyses

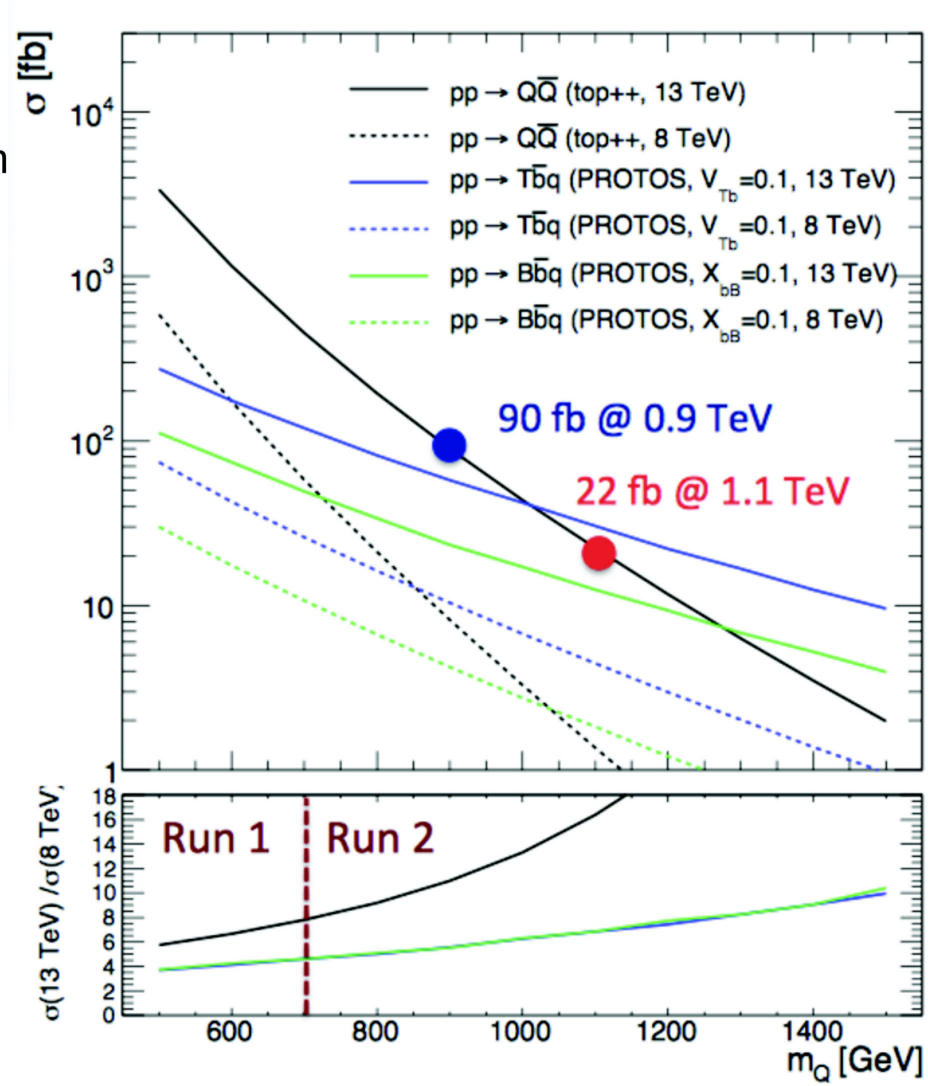
- **Capitalize on Run 1 experience**
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
    - Continue to exploit pair production above 1 TeV
    - Add single production above 1 TeV



Pair production
model independent,
relevant at low mass



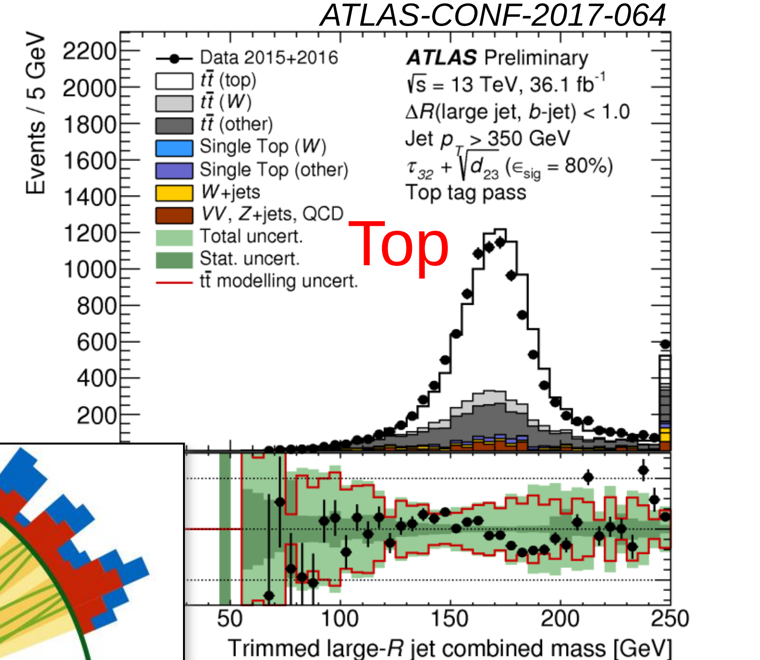
Single production
model dep. coupling,
PDF-favored at high mass

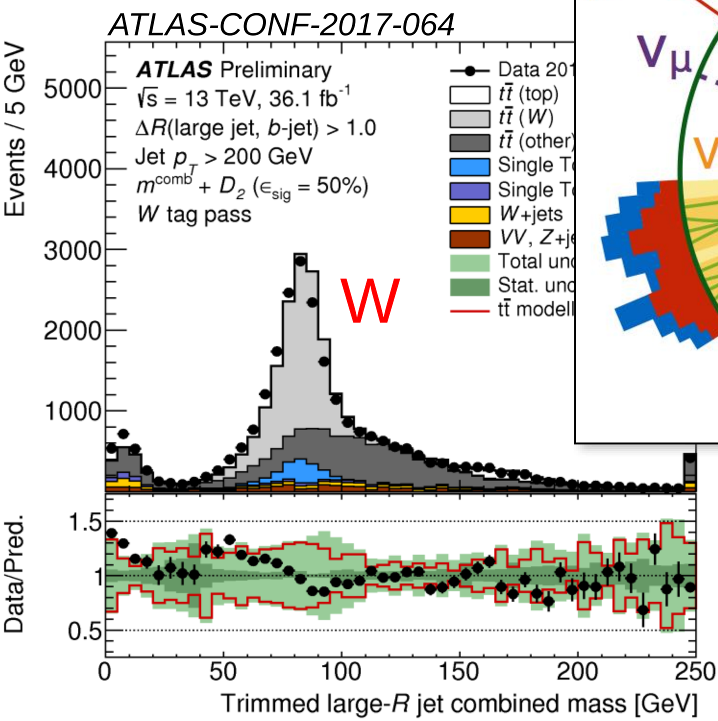


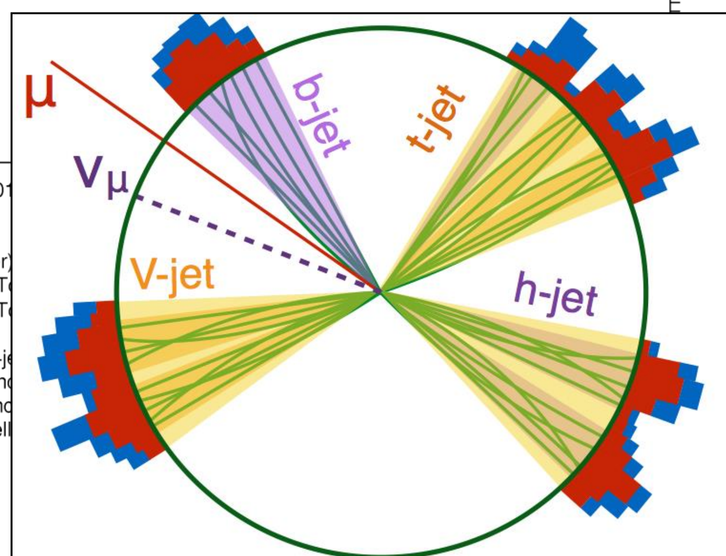
Plan for Run 2 Analyses

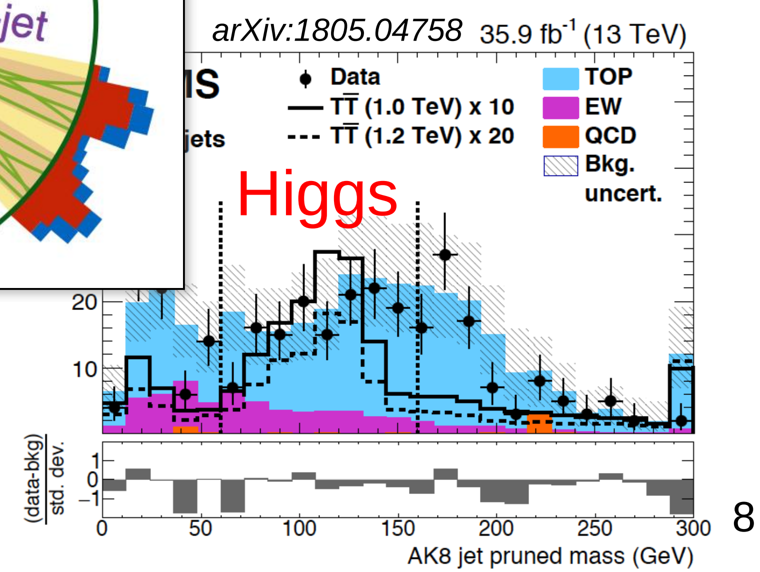
- **Capitalize on Run 1 experience**
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
  - Optimize strategy at high mass

SM resonances are often boosted!









Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- **Plan according to integrated luminosity**

Less sophisticated

2015: 3.9 fb^{-1} recorded

First results exceeding Run 1 sensitivity!

2016: ~36 fb^{-1} recorded

Exceed design inst. lumi of ~10^{34} $cm^{-2}s^{-1}$.

Record daily delivered luminosity of ~0.6 fb^{-1}.

Results shown today:
up to 36 fb^{-1}

2017: ~47 fb^{-1} recorded

Record inst. lumi of ~2.1×10^{34} $cm^{-2}s^{-1}$.

2018: Ongoing (started on April 17, 2018).

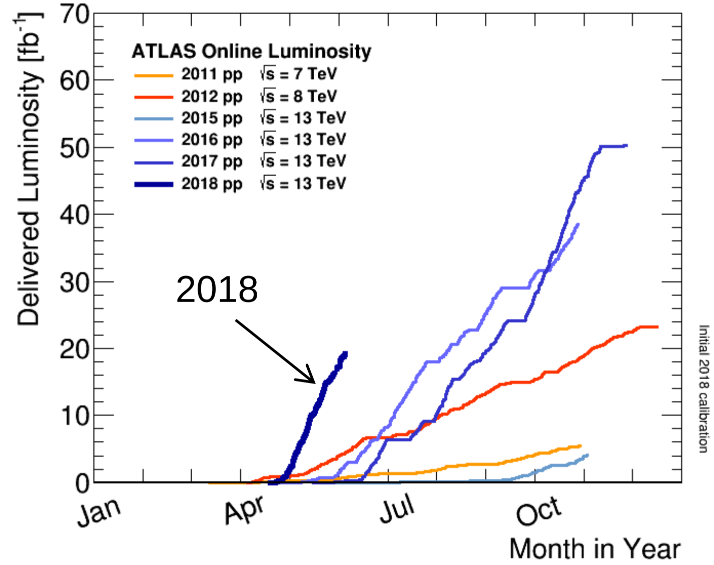
Inst. lumi regularly at ~2×10^{34} $cm^{-2}s^{-1}$.

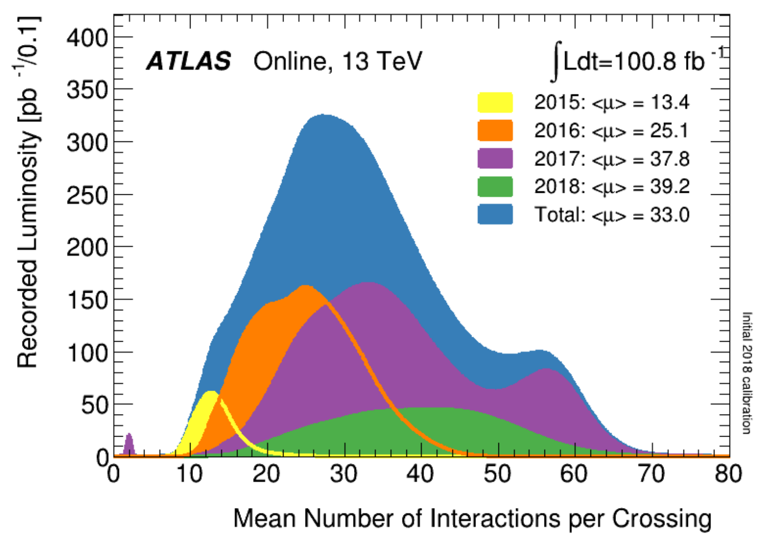
Expect 60 fb^{-1} delivered in 2018.

More sophisticated

Full Run 2: ~130 fb^{-1}

Outstanding performance!

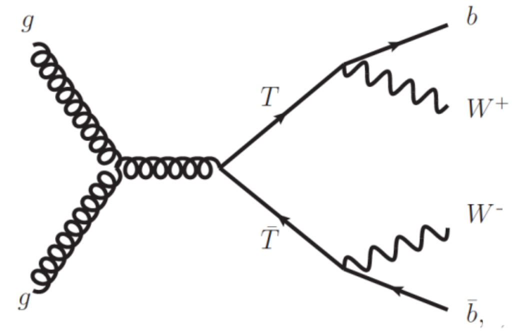




Pair Production: TT→Wb+X

~36 fb^{-1}

- Search targeting high BR($T \to W^+b$), but also sensitive to other decay modes.
- Most sensitive searches exploit the lepton+jets final state.
- Strategy:
  - Presel: 1 lepton, high E_T^{miss}, ≥4 jets/≥1 b-tags.
  - Reconstruct boosted hadronic W boson.
  - Tight cuts: high H_T (*), additional cuts to exploit boosted topology for W bosons.
  - Analyze reconstructed T-quark mass spectrum.



(*) $H_T = \sum p_T^{\text{jets}} + p_T^{\text{lep}} + E_T^{\text{miss}}$

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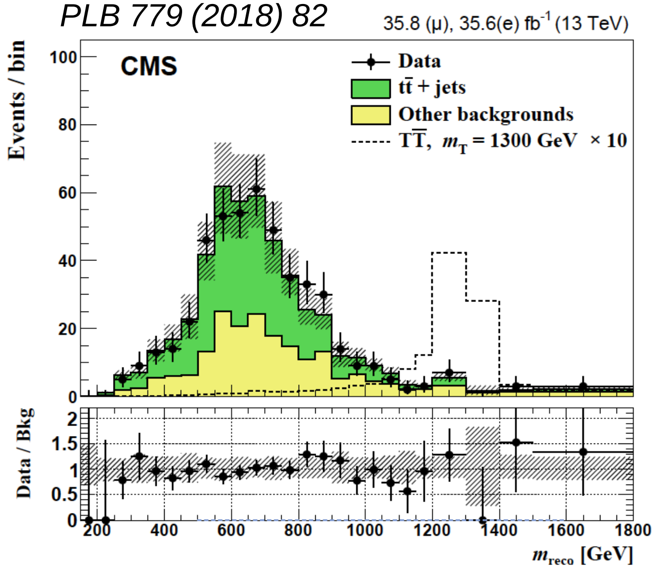
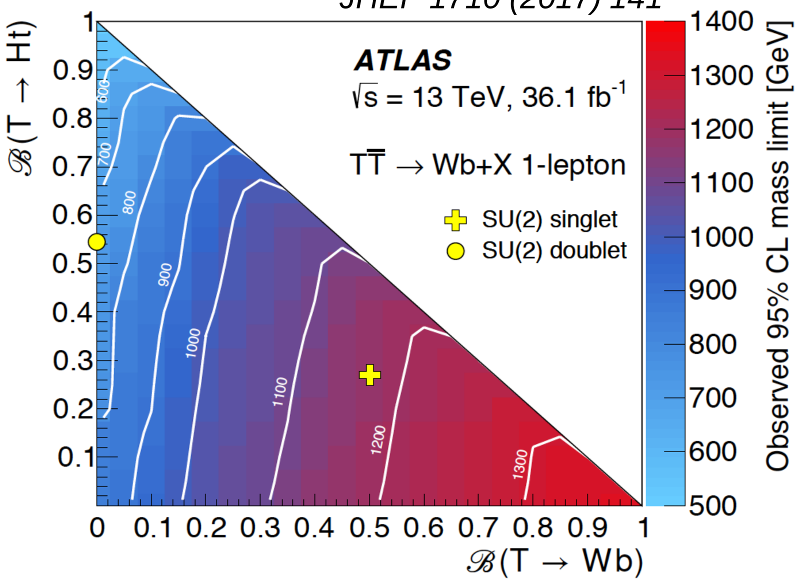


BR(T→Wb)=1: m_T>**1.28** (1.30) TeV

Limits also apply to $Y_{-4/3}$.

JHEP 1710 (2017) 141



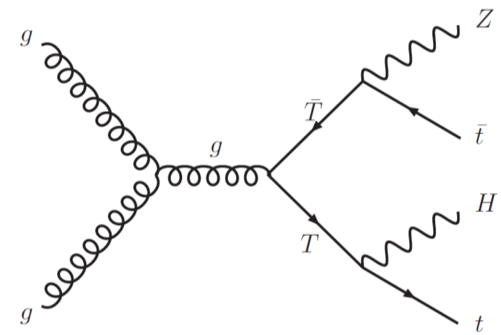
BR(T→Wb)=1: m_T>**1.35** (1.31) TeV

Singlet: m_T>**1.17** (1.08) TeV

Pair Production: TT→Zt+X

~36 fb^{-1}

- Most sensitive searches exploit Z→ll decays, giving OS dileptons or trilepton final states (coming soon).
- Search targeting high BR(T→Zt), with Z→νν.
- Strategy:
  - Presel: 1 lepton, E_T^{miss}>300 GeV, ≥4 jets, ≥1 b-tag.
  - Signal region defined through tight cuts to suppress tt background (on $m_{T,W}$, am_{T2}, ≥2 large-R jets, etc).
  - Control regions used to normalize tt and W+jets bkgs in signal region. Background prediction checked in dedicated validation regions.



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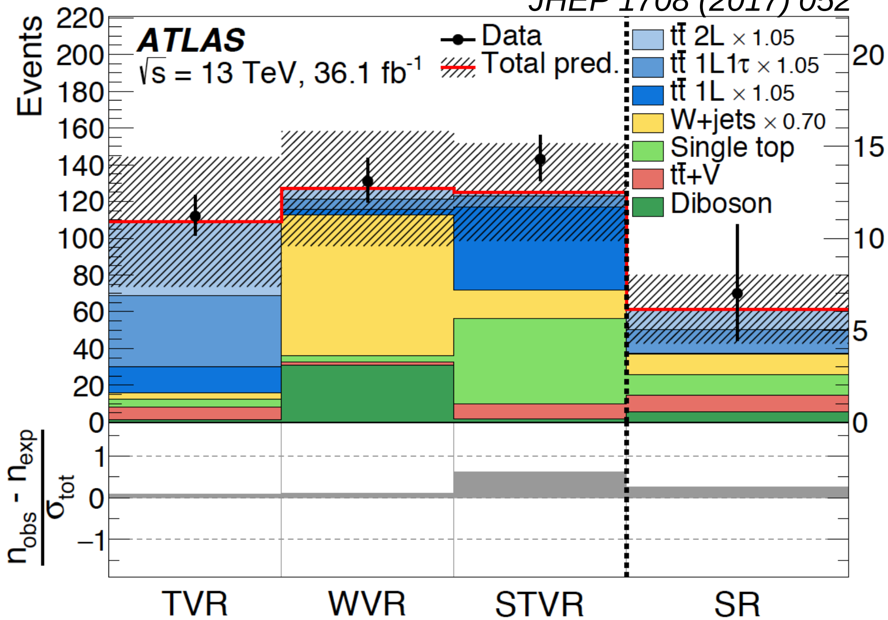
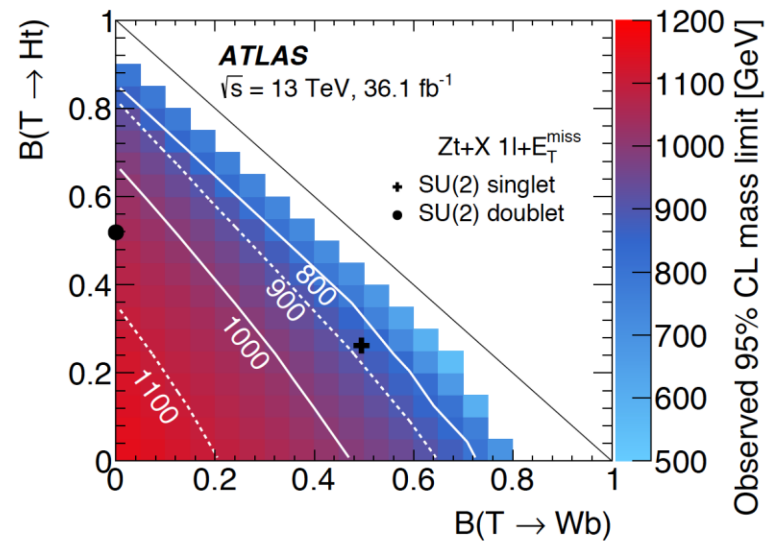




95% CL obs (exp) limits:

BR(T→Zt)=1: m_T>**1.16** (1.17) TeV

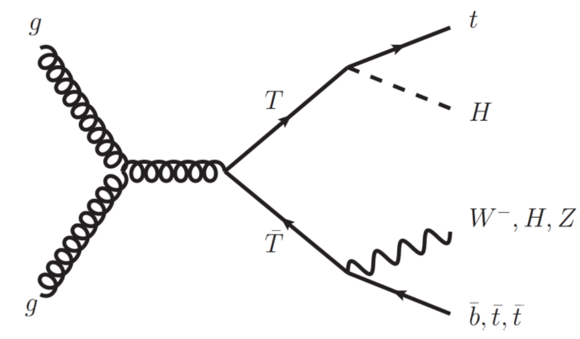
Doublet: m_T>**1.05** (1.06) TeV

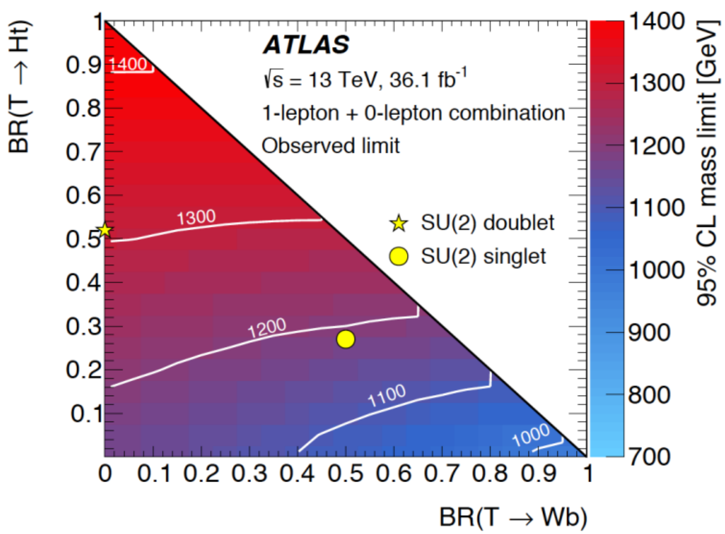
Singlet: m_T>**0.87** (0.89) TeV

Pair Production: TT→Ht+X

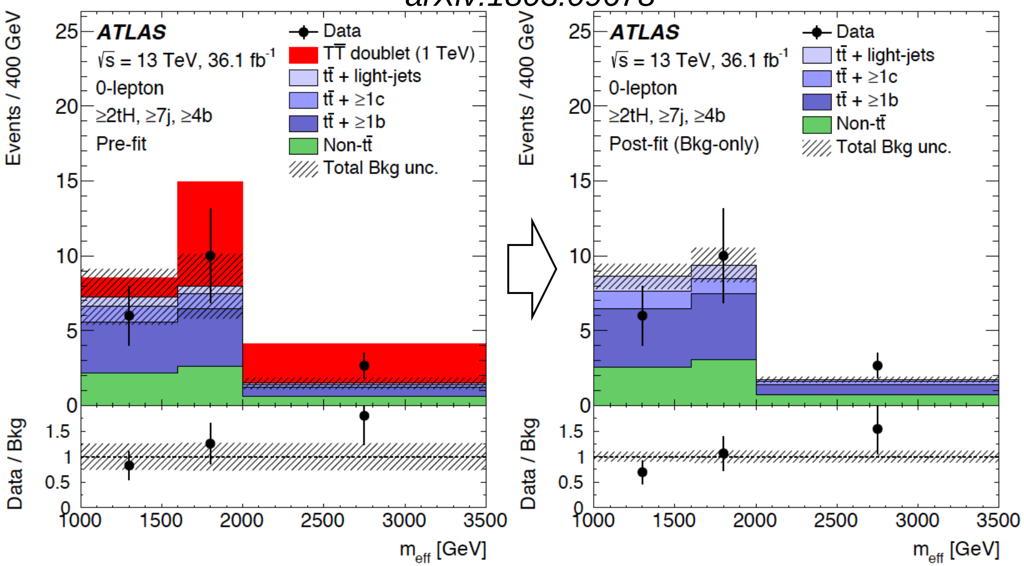
~36 fb^{-1}

- Search targeting high BR(T→Ht), with H→bb, but designed as broad-band search.
- Strategy:
  - Consider lepton+jets and high-E_T^{miss}+jets channels.
  - Top and Higgs tagging via mass cut on large-R jets.
  - Categorize events according to b-tag, top-tag and Higgs-tag multiplicities (a total of 34 regions).
  - Analyze effective mass spectrum.
  - Signal-depleted regions used to constrain in-situ bkg uncert. through likelihood fit to data.





arXiv:1803.09678



95% CL obs (exp) limits:

BR(T→Ht)=1: m_T>**1.43** (1.34) TeV

Doublet: m_T>**1.31** (1.26) TeV

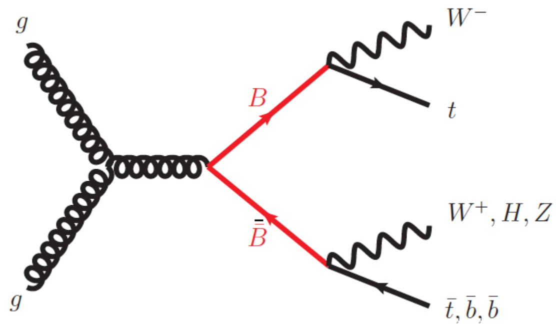
BR(T→Zt)=1: m_T>**1.17** (1.18) TeV

Singlet: m_T>**1.19** (1.11) TeV

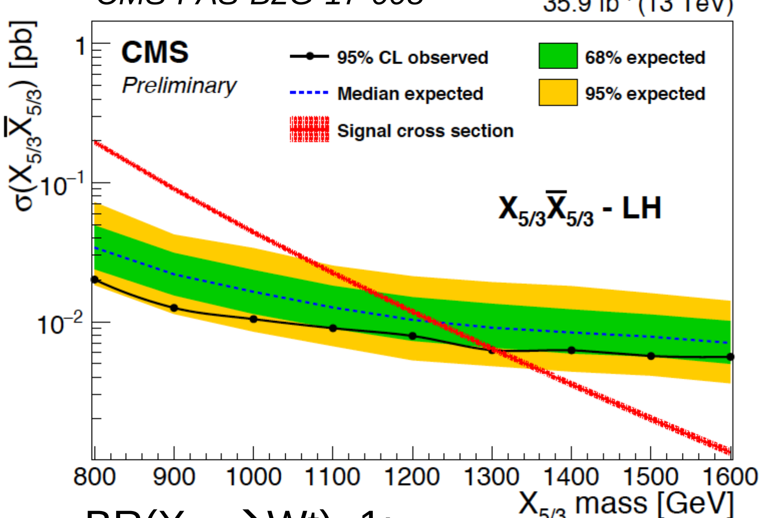
Pair Production: BB, $X_{5/3}X_{5/3}$ → WtWt

~36 fb^{-1}

- Searches targeting B→W^-t or $X_{5/3}$→W^+t.
- Consider SS dilepton+jets and lepton+jets signatures, both with comparable sensitivity.
- Strategy (lepton+jets):
  - Presel: 1 lepton, high E_T^{miss}, ≥4 jets/≥1 b-tags.
  - Multiple event categories depending on the presence of boosted hadronic W bosons.
  - Analyze B-quark mass or BDT output (ATLAS), or min[M(l,b)] (CMS) spectra.



CMS-PAS-B2G-17-008

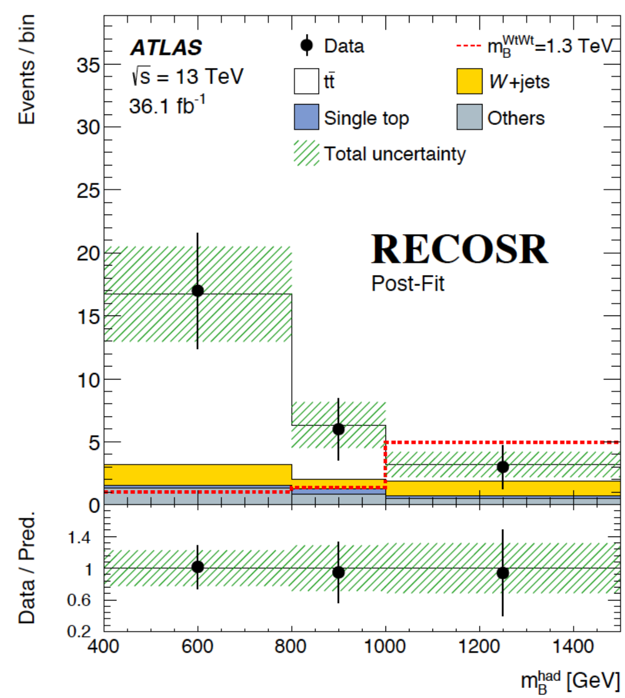


BR($X_{5/3}$→Wt)=1:

Left-Handed: m_T>**1.30** (1.33) TeV

Right-Handed: m_T>**1.28** (1.30) TeV

arXiv:1806.01762

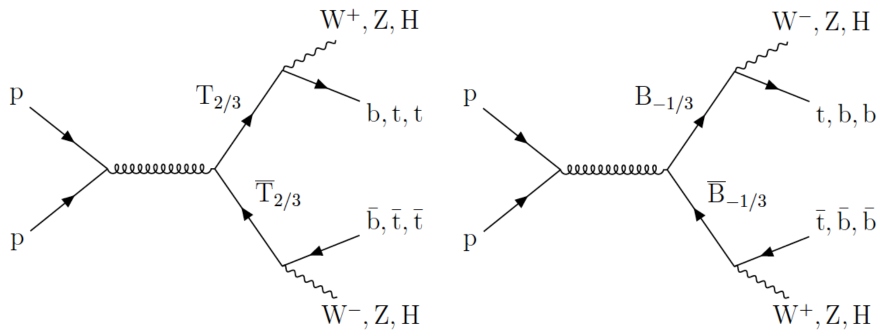


BR(B, $X_{5/3}$→Wt)=1: m_T>**1.35** (1.33) TeV

Singlet: m_T>**1.17** (1.14) TeV

Pair Production: Inclusive Search

~36 fb^{-1}



- Inclusive search for TT and BB production focused on final states with leptons.
- Three channels considered:

1-lepton:

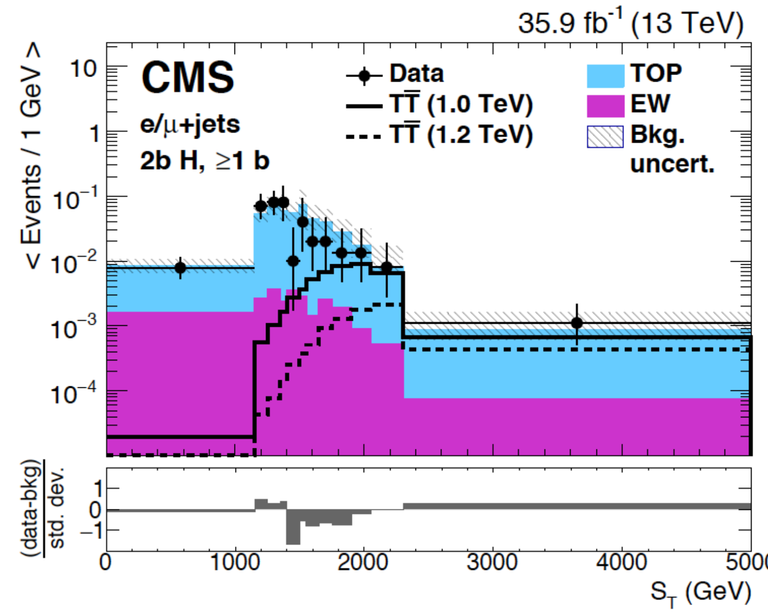
- W and Higgs tagging based on large-R jets via jet substructure variables and b-tagging requirements.
- 16 event categories based on W, H and b-tag multiplicities.
- Analyze S_T distribution.

Same-sign 2-leptons:

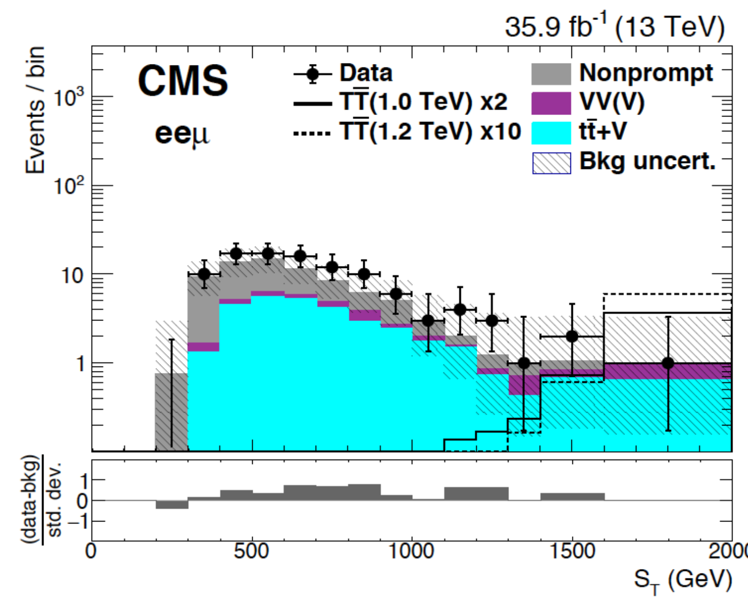
- Counting experiment.

3-leptons:

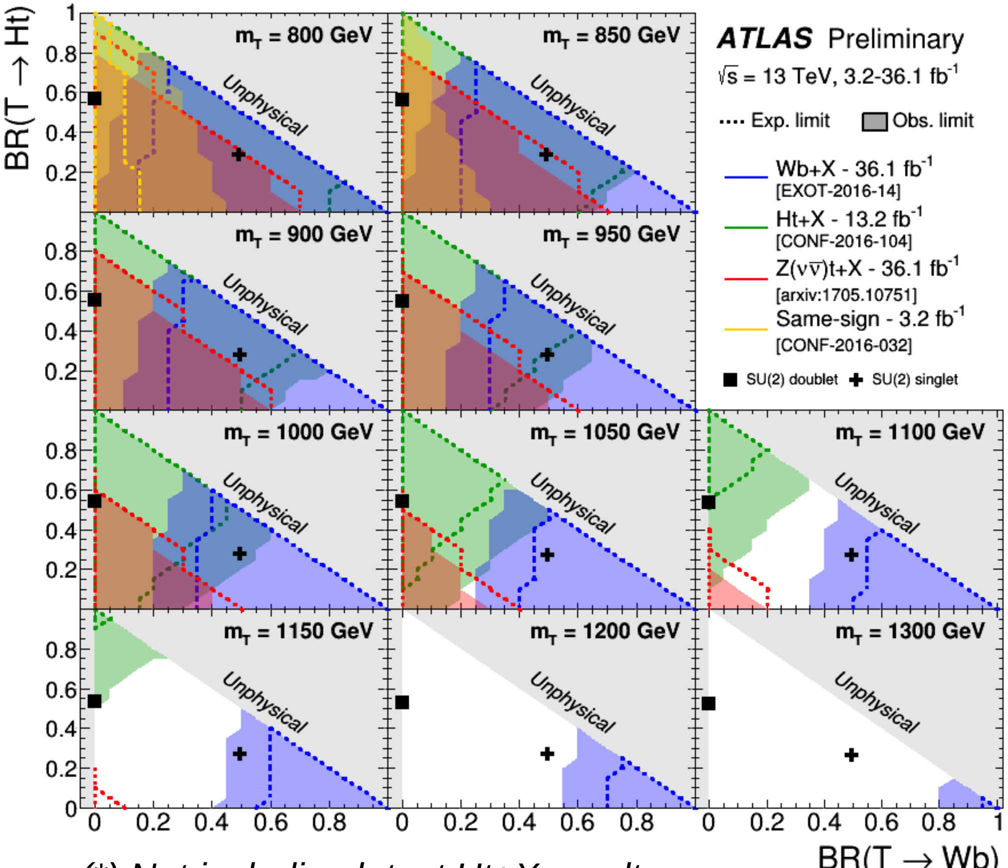
- Analyze S_T distribution.



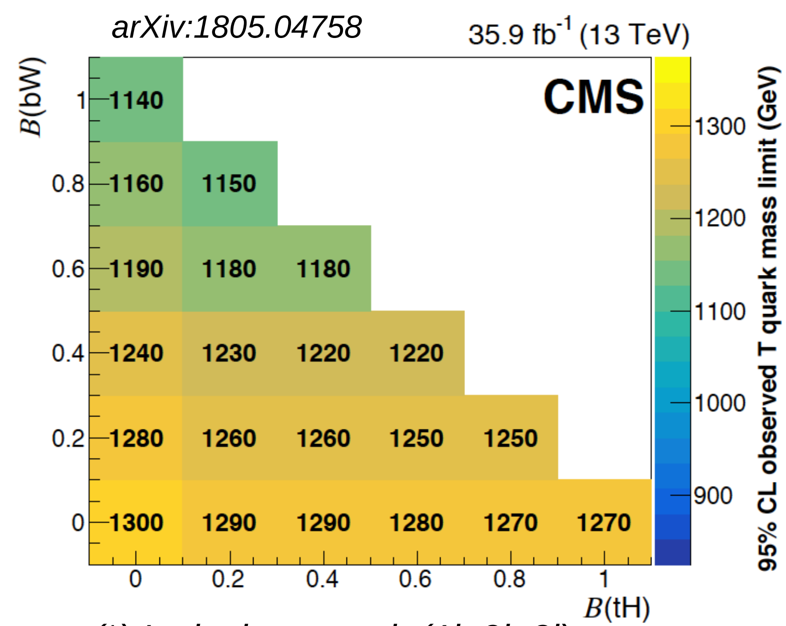
arXiv:1805.04758



Pair Production Summary: Vector-Like Top



(*) Not including latest Ht+X results



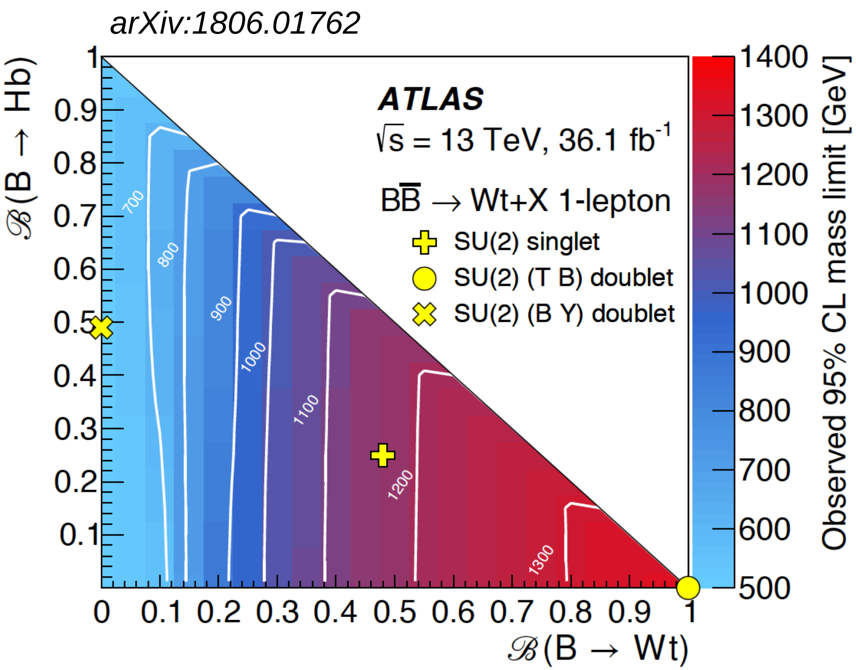
(*) Inclusive search (1l, 2l, 3l)

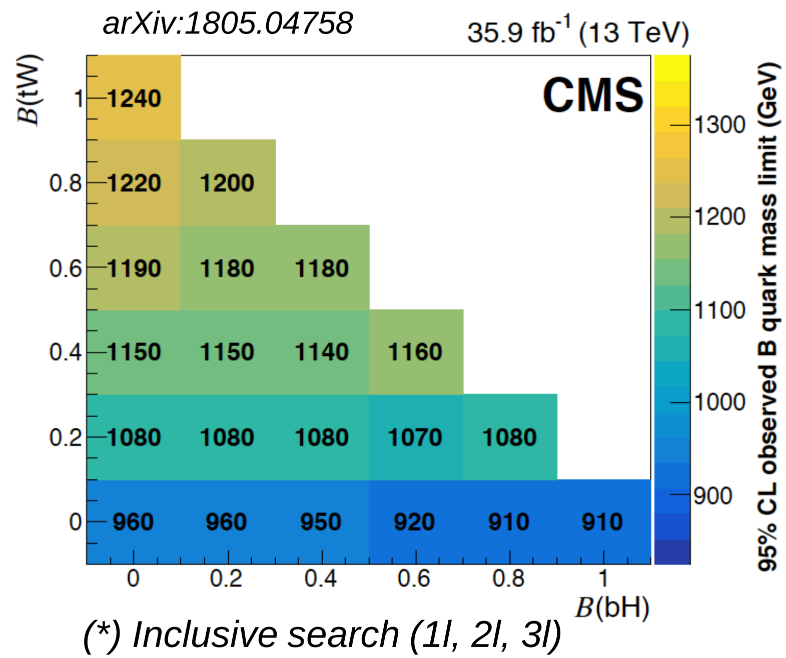
VLT masses below ~1.14 TeV excluded for any possible combination of BRs

Most restrictive single bounds to date

Vector-like T BR Hypothesis	ATLAS: 95% CL Limit on m_T (TeV) obs (exp)	CMS: 95% CL Limit on m_T (TeV) obs (exp)
100% Wb (chiral, Y)	**1.35** (1.31)	**1.28** (1.30)
T singlet	**1.19** (1.11)	**1.20** (1.16)
T in (T, B) doublet	**1.31** (1.26)	**1.28** (1.24)

Pair Production Summary: Vector-Like Bottom





(*) Inclusive search (1l, 2l, 3l)

(*) Several new results imminent

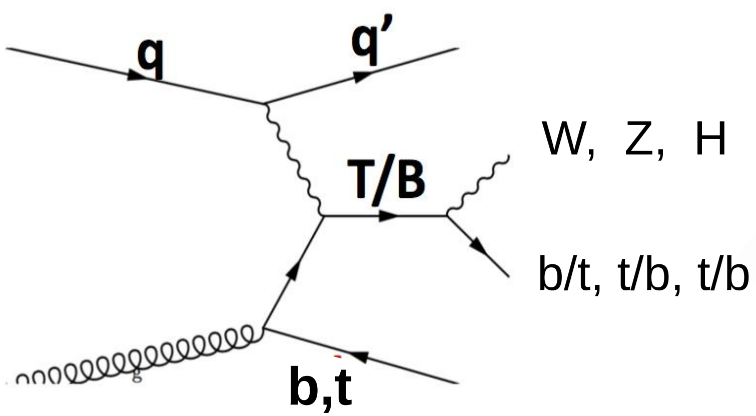
VLB masses below ~0.91 TeV excluded for any possible combination of BRs

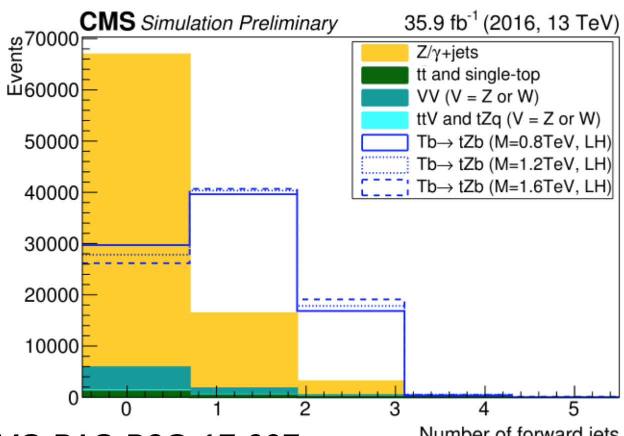
Most restrictive single bounds to date

Vector-like B BR Hypothesis	ATLAS: 95% CL Limit on m_B (TeV) obs (exp)	CMS: 95% CL Limit on m_B (TeV) obs (exp)
100% Wt (chiral, X)	**1.35** (1.33)	**1.24** (1.24)
B singlet	**1.17** (1.14)	**1.17** (1.13)
B in (B, Y) doublet	**0.76** (0.76) [Run 1]	**0.94** (0.92)

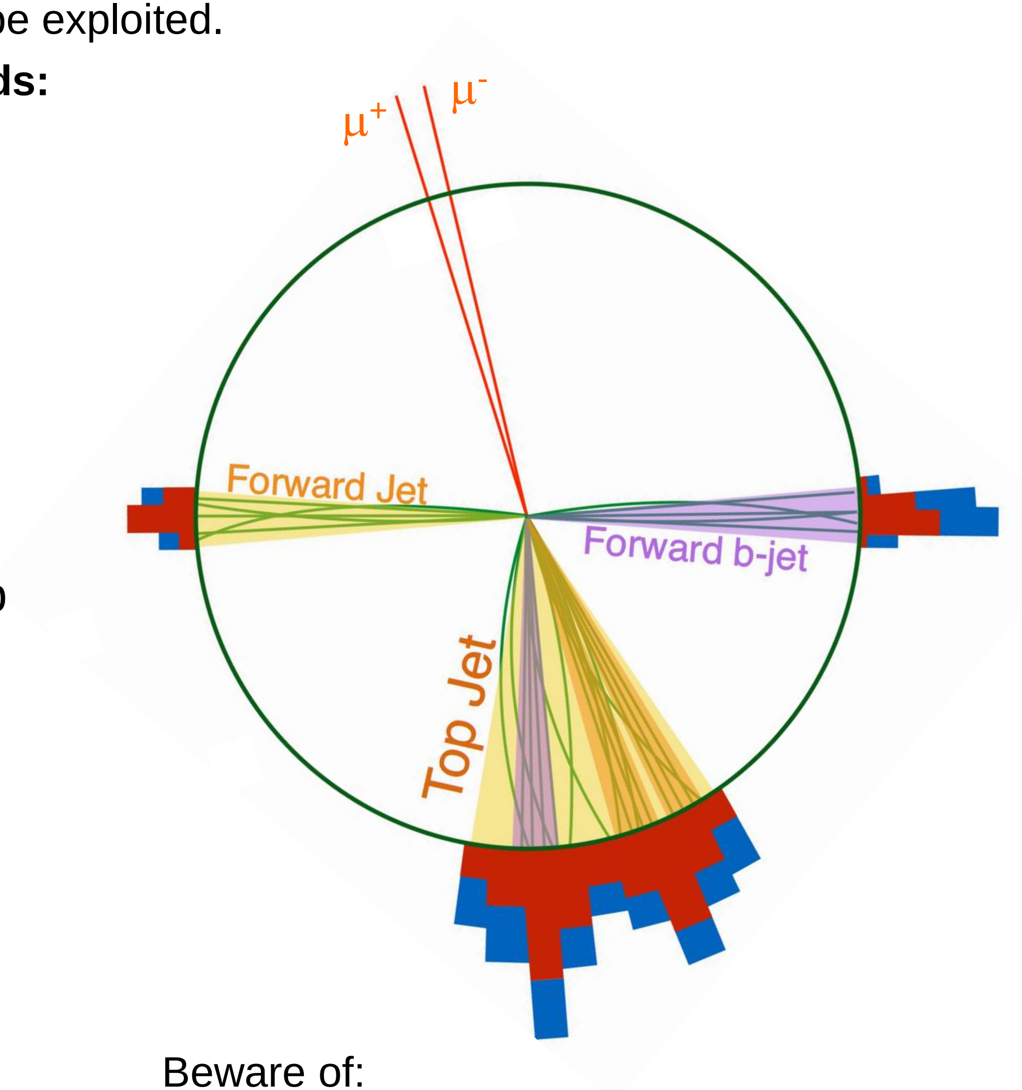
Single Production Strategy

- Many channels (w/ and w/o leptons) to be exploited.
- **Powerful handles against backgrounds:**
  - Forward jet tagging
  - Boosted techniques
  - VLQ mass reconstruction





CMS-PAS-B2G-17-007



Beware of:

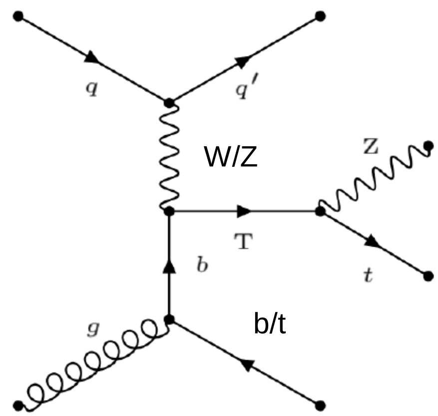
- Signal/background interference
- Helicity propagation in decay

Single Production: T(→Zt)+X

~36 fb^{-1}

Strategy:

- Presel: Z(→ll)+jets, ≥1 b-tags, small ΔR(ll).
- Top-tagging and W-tagging on AK8 jets.
- 10 event categories depending on lepton flavor, top kinematics (fully-merged/semi- merged/resolved) and presence of forward jets.
- Use heavy quark mass built from reconstructed Z-boson and top candidates.
- Main background: Z+jets. Estimated using dedicated control regions.



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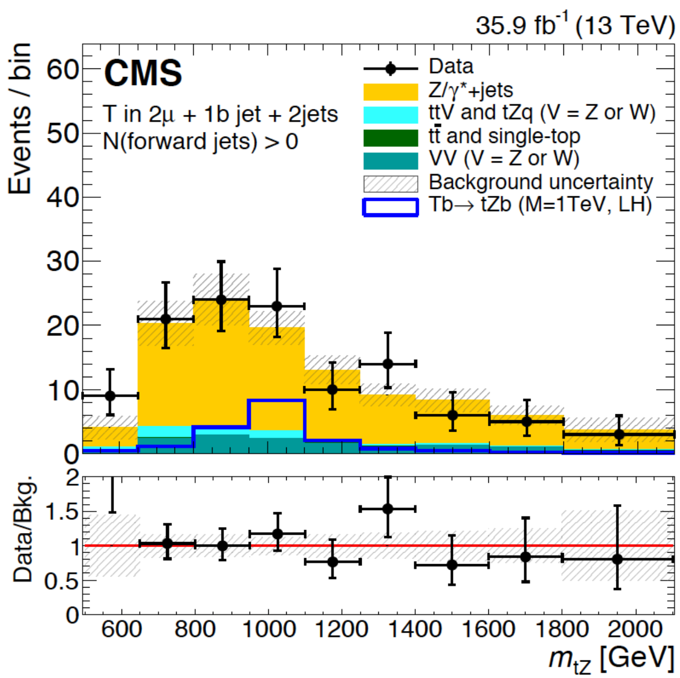
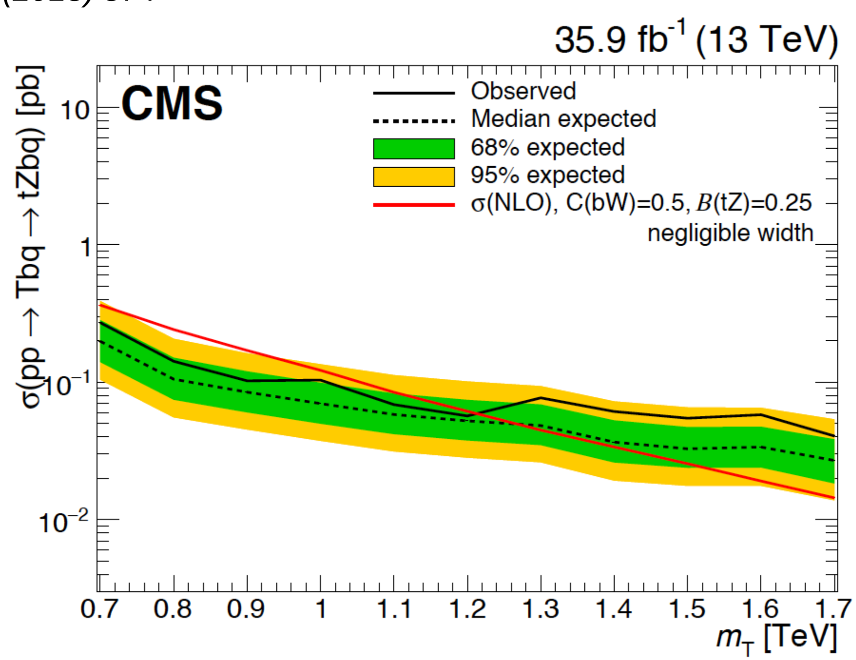


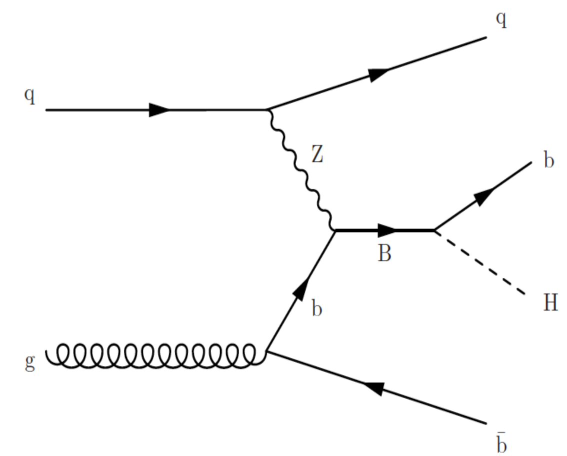


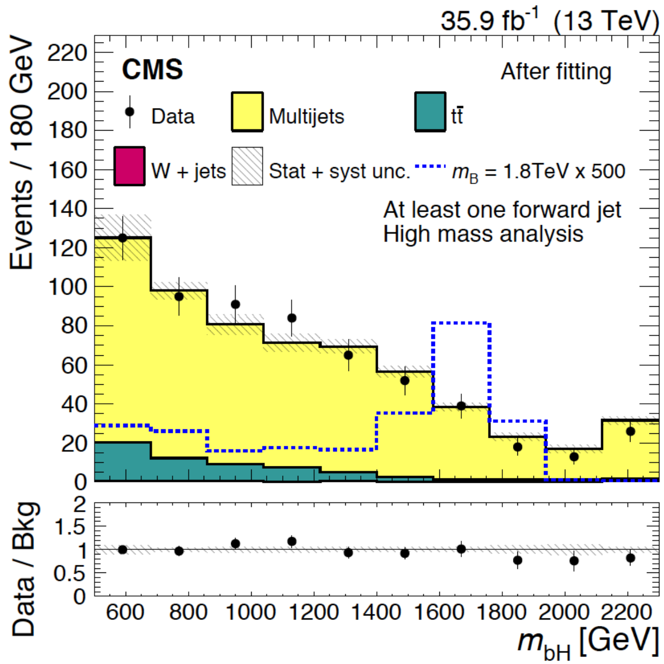
Single Production: B(→Hb)+X

~36 fb^{-1}

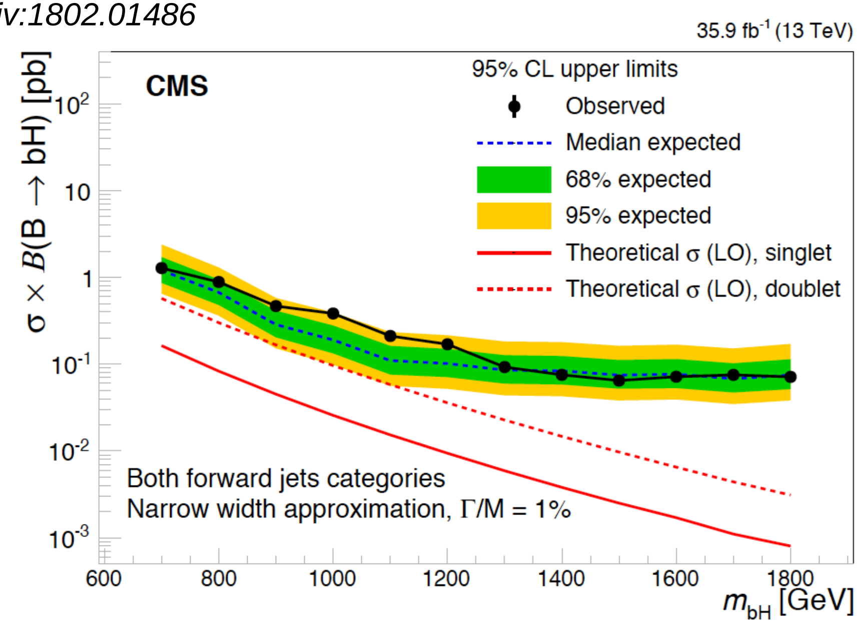
Strategy:

- Trigger based on scalar sum of jet p_T.
- Presel: ≥3 small-R jets/≥1 b-tag, ≥1 large-R jet tagged as Higgs boson. Additional kinematic cuts to suppress multijet background.
- Higgs tagging based on large-R jets via jet substructure variables and b-tagging requirements.
- Events categorized according to forward jet multiplicity.
- Main background: tt and multijet. Multijet estimated using data-driven techniques.





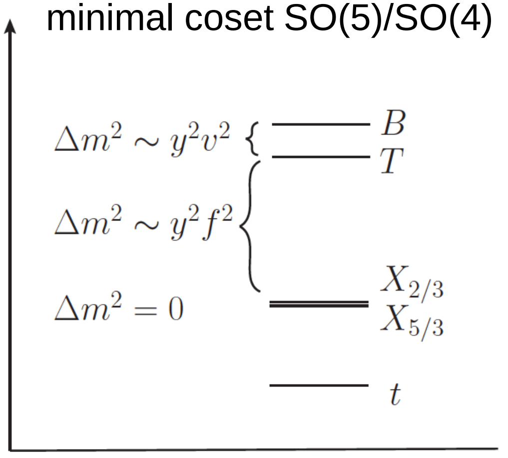
arXiv:1802.01486

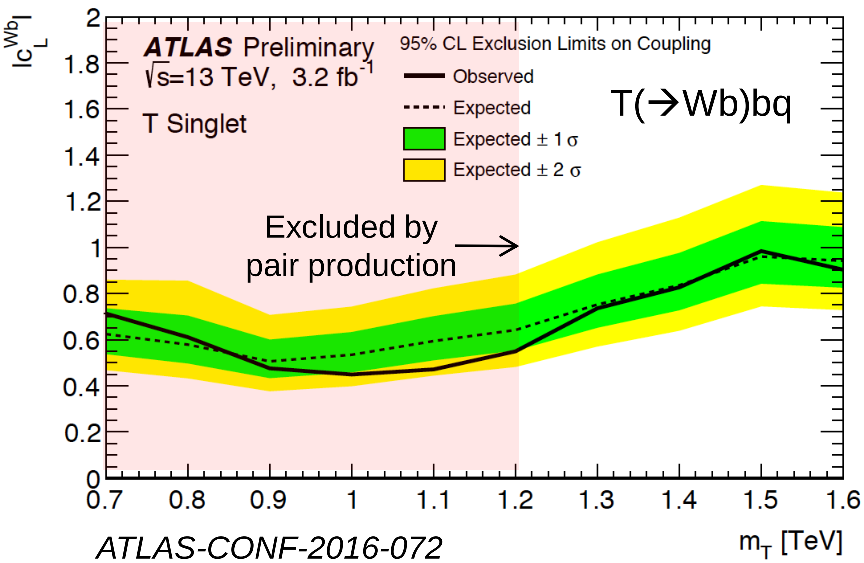


Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**
  - Increased use of simplified models
  - Combination of pair and single production
  - Take into account effect of extra resonances in some cases

Typical spectrum in minimal coset SO(5)/SO(4)





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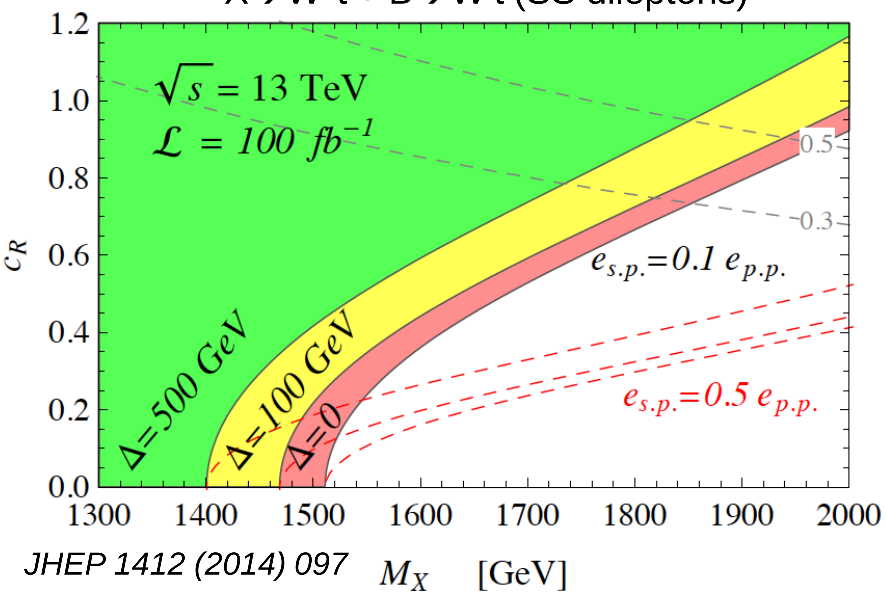
X→W⁺t + B→W⁻t (SS dileptons)



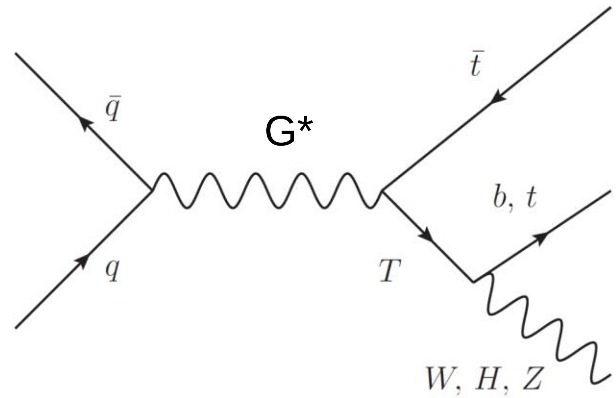
JHEP 1412 (2014) 097

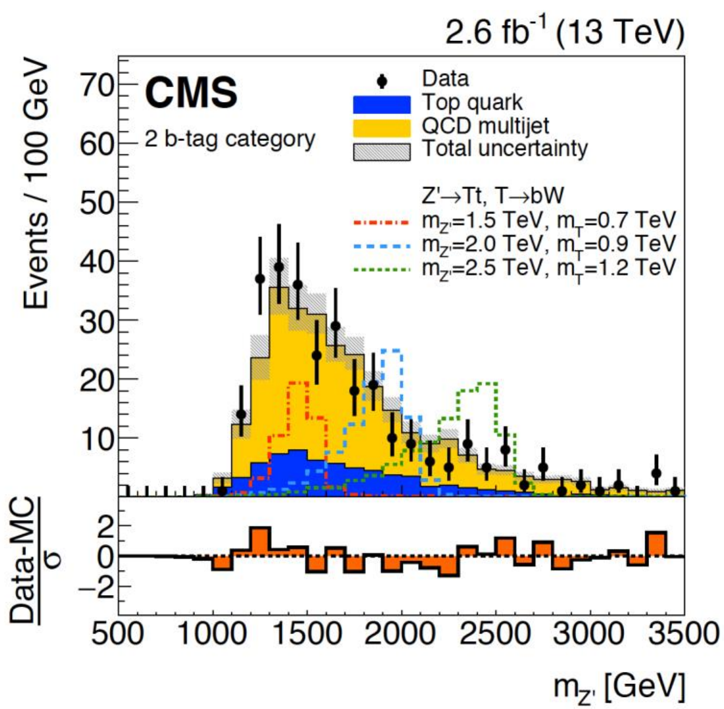
Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard production

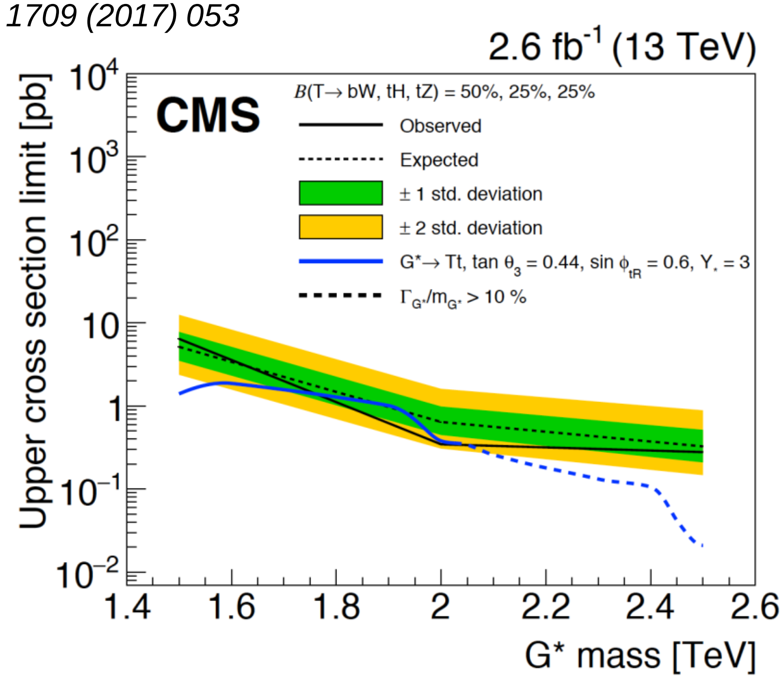
    E.g. via heavy gluon: $G^* \rightarrow TT$ ($m_{G^*} \geq 2m_T$),

    $G^* \rightarrow Tt$ ($m_T + m_t < m_{G^*} < 2m_T$)





JHEP 1709 (2017) 053

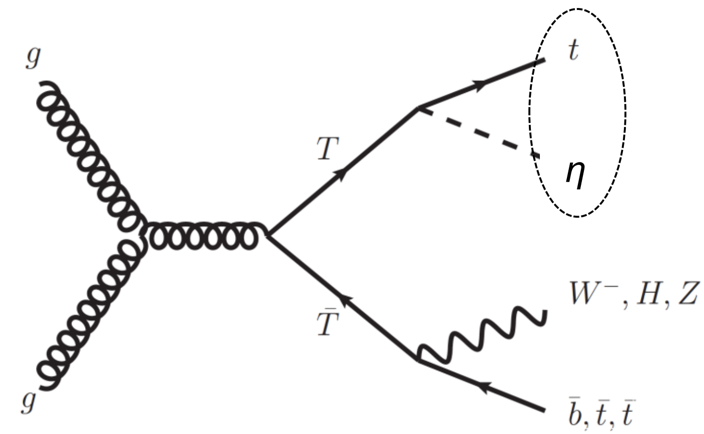


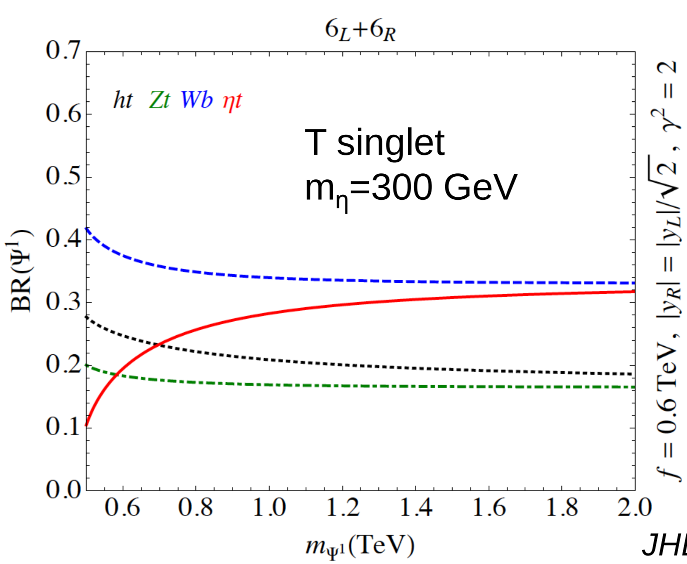
Plan for Run 2 Analyses

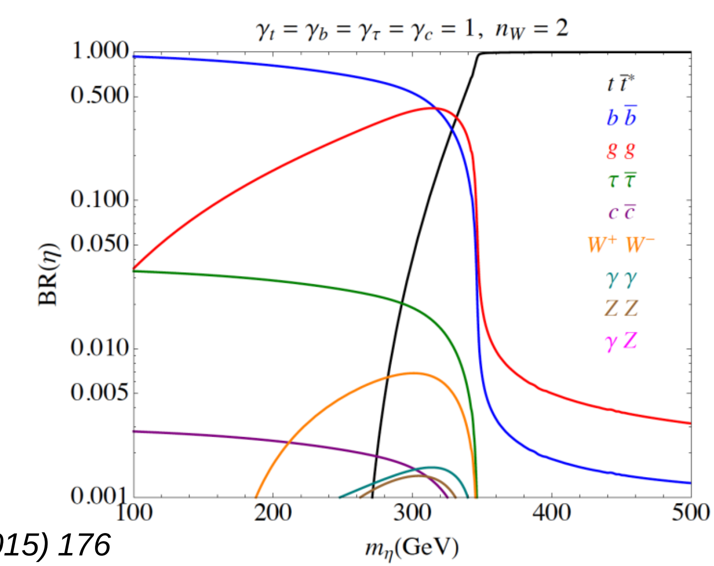
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard decays

    BR(Q→Wq)+BR(Q→Zq)+BR(Q→Hq)<1

    Example: Q→q+η, η CP-odd scalar
    - If exotic BRs dominant, signal may be picked by existing searches.
    - For comparable BRs, it becomes difficult as signal split into challenging channels. But also promising channels: TT→W$^+$bttt!





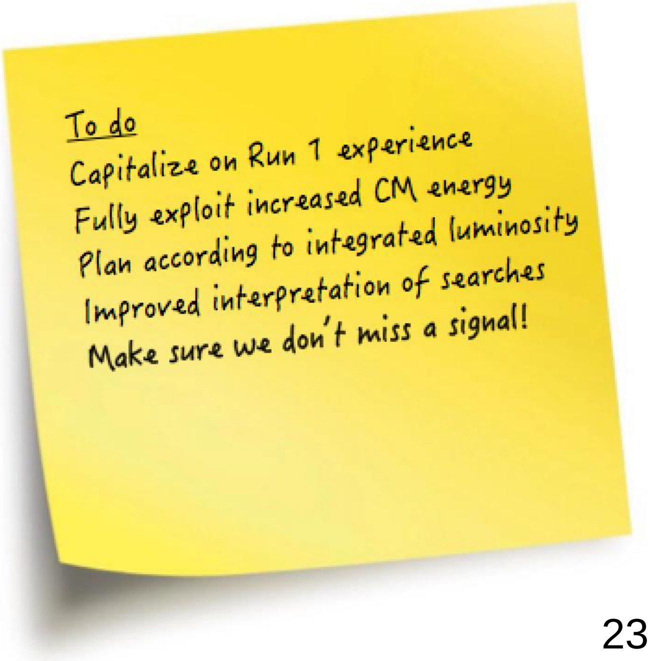


JHEP 1509 (2015) 176

Summary and Outlook

- **Run 2 program of searches for vector-like quarks in full swing**
  - First round of publications with up to 36 fb^{-1} of data at $\sqrt{s}$=13 TeV becoming available.
  - Pair production searches significantly extend the Run 1 sensitivity, excluding VLQ masses up to 1.3 TeV (depending on scenario).
  - Broad program of single production searches being developed.
  - Starting to target non-standard production/decay modes.

- More sophisticated searches being developed with the full Run 2 dataset, capitalizing on the experience gained and improvements in object reconstruction algorithms.



Exciting times ahead!

Extra

Recent VLQ Searches

For more information see:

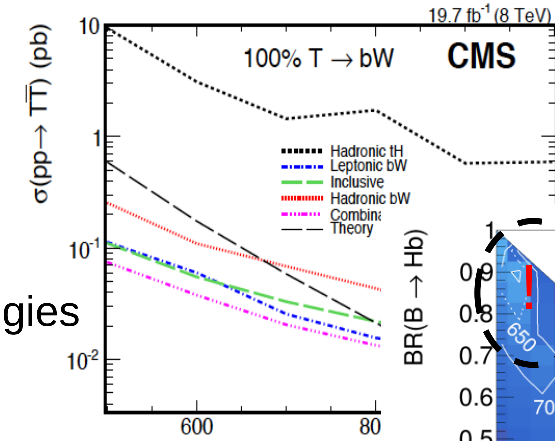
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

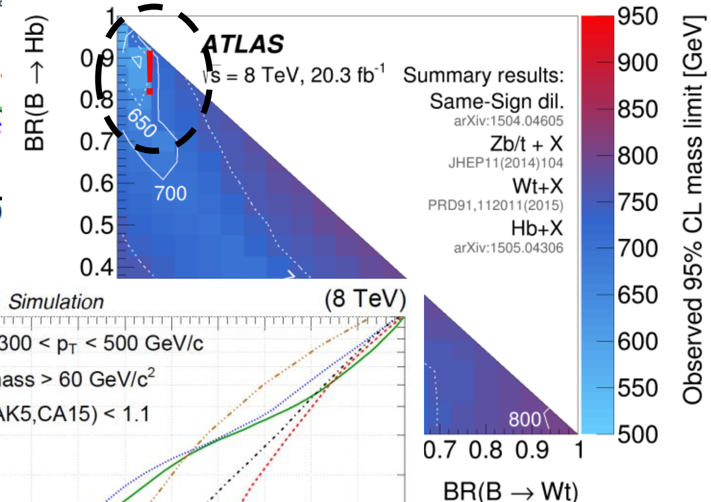
http://cms-results.web.cern.ch/cms-results/public-results/publications/B2G/index.html
http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/B2G/index.html

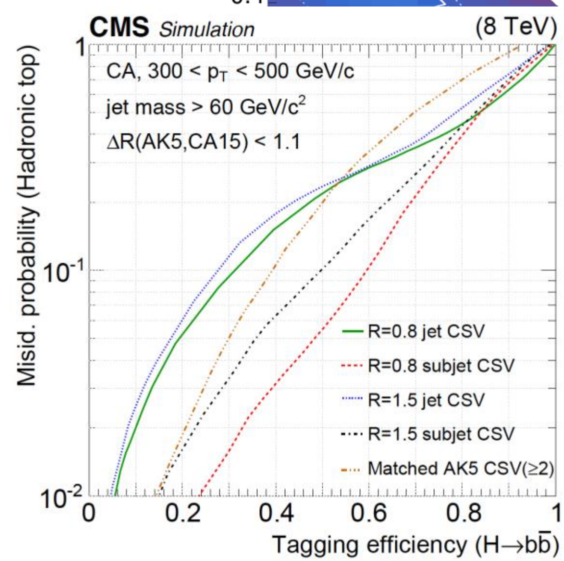
Plan for Run 2 Analyses

- **Capitalize on Run 1 experience**
  - Most sensitive channels
  - Complementary channels
  - Missing channels
  - Most powerful experimental strategies
  - Improved background estimation techniques
  - Reducing the impact of systematic uncertainties
  - …

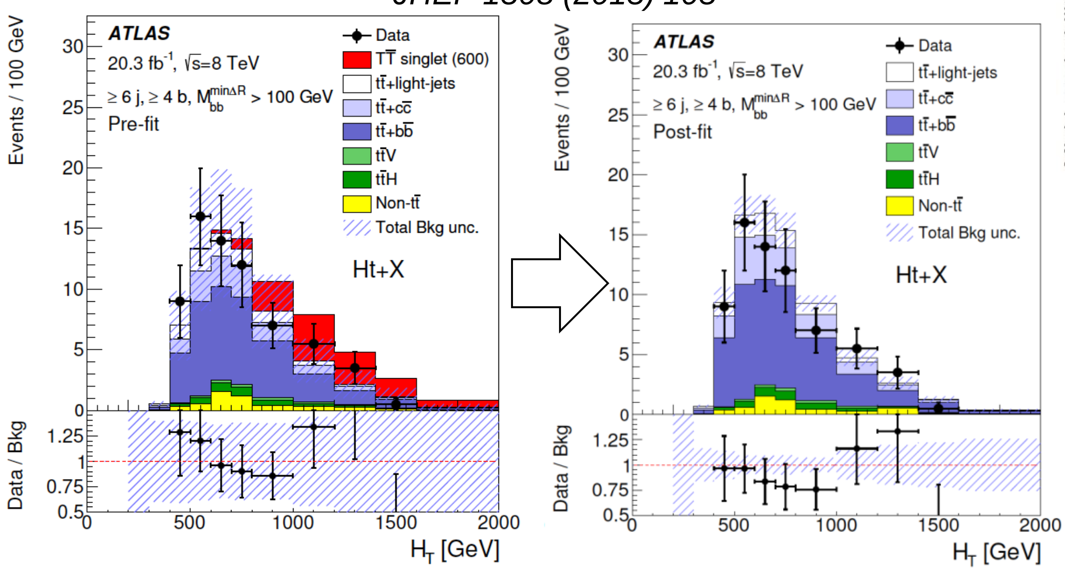
PRD 93 (2016) 012003







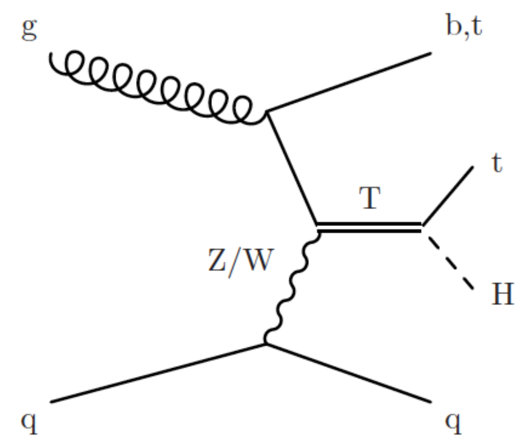
JHEP 1508 (2015) 105



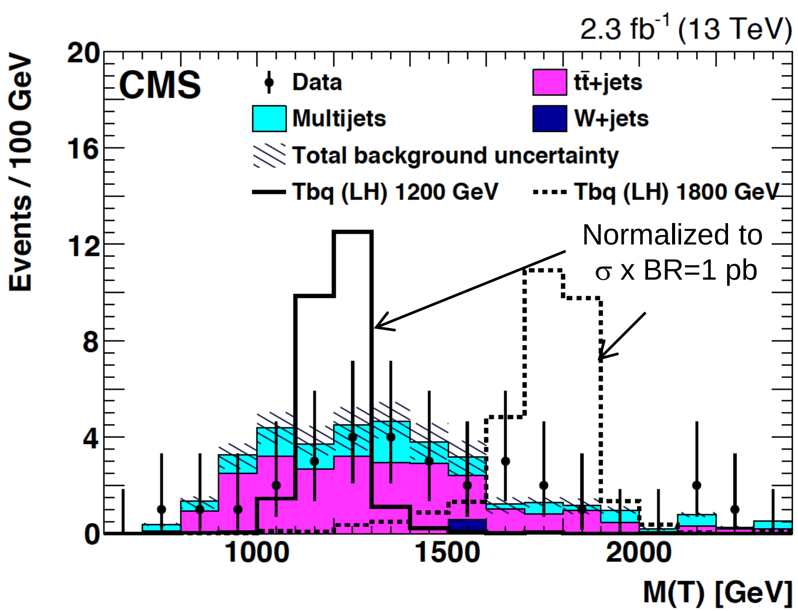
Single Production: T(→Ht)+X

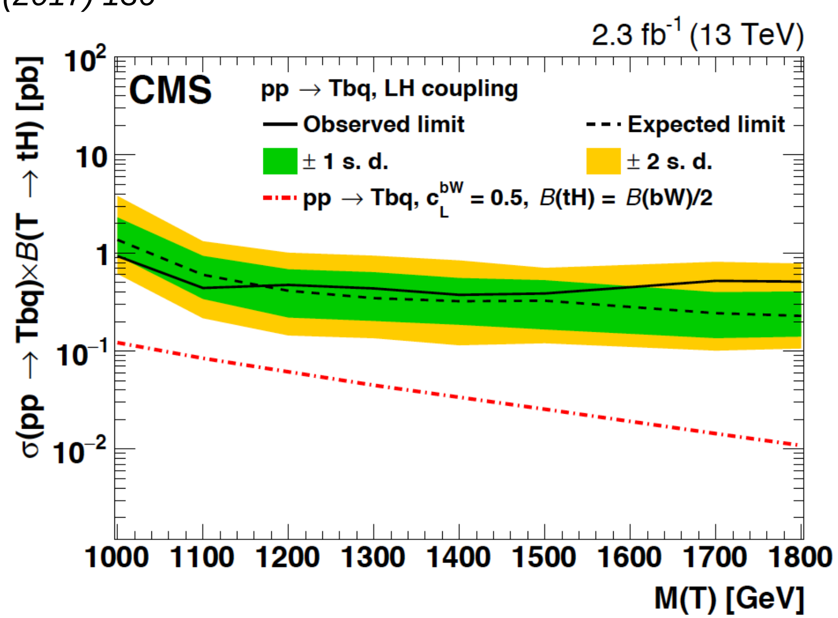
~2 fb^{-1}

- Searches performed in lepton+jets and all-hadronic final states, with comparable sensitivity.
- Basic strategy (all-hadronic):
  - Trigger based on scalar sum of jet p_T.
  - Presel: ≥4 small-R jets, ≥1 large-R jets, H_T>1100 GeV.
  - Top and Higgs tagging based on large-R jets via jet substructure variables and b-tagging requirements.
  - Main background: tt and multijet. Multijet estimated using data-driven techniques.



JHEP 1704 (2017) 136





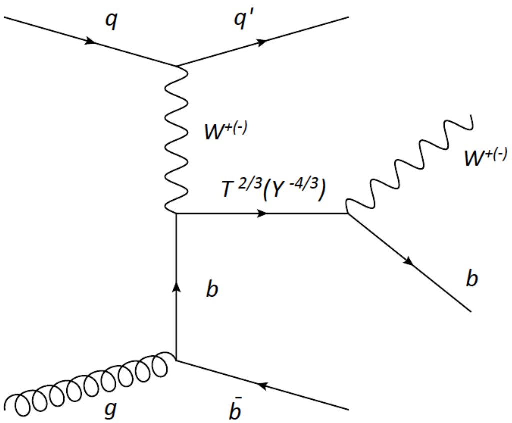
See also: PLB 771 (2017) 80

Single Production: T(→Wb)+X

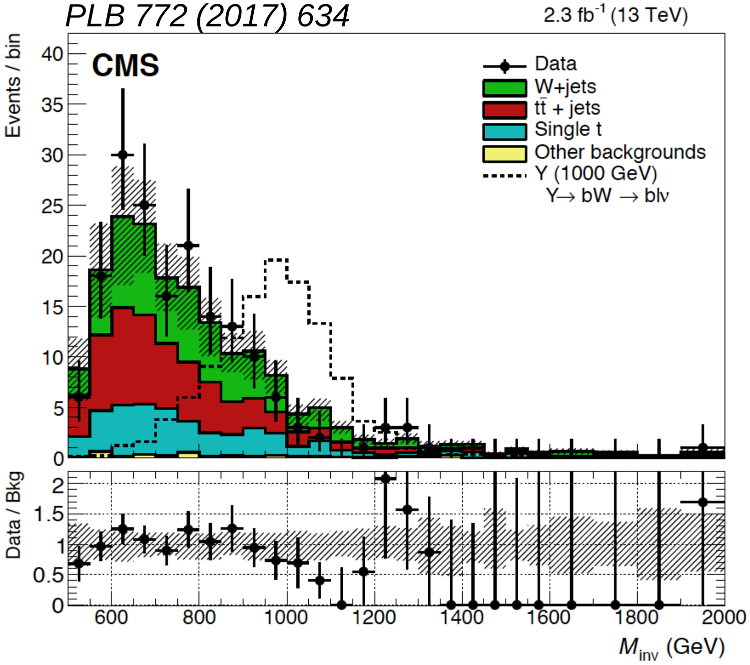
~2-3 fb^{-1}

Basic strategy:

- Presel: 1 lepton, high E_T^{miss}, ≥1 hard central jet b-tagged, 1 forward jet.
- Additional tight kinematic requirements.
- Kinematic reconstruction of leptonic W candidate and pairing with b-tagged central jet to estimate heavy quark mass.
- Main backgrounds: tt and W+jets. Estimated using dedicated control regions.



PLB 772 (2017) 634



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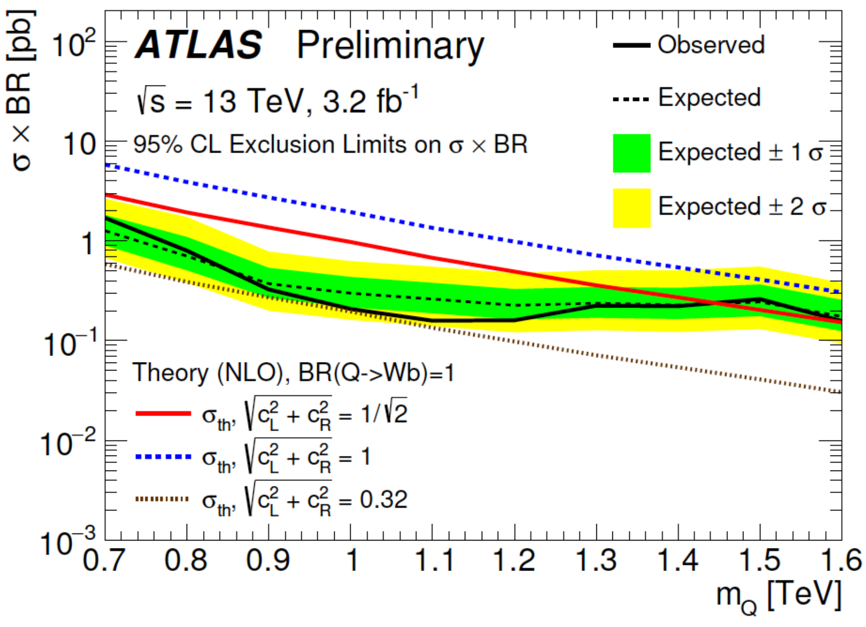

Comparable limits between ATLAS and CMS

Plan for Run 2 Analyses

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**

  So far:
  - Renormalizable extension of the SM including mixing term between SM quarks and VLQs (e.g. arXiv:1306.0572).
  - Phenomenological (non-renormalizable) Lagrangian parameterized with coupling terms.

Simplified model

$$\mathcal{L} = \frac{g_w}{2}\left[c_R^{XV}\,\overline{X}_R \not{V} t_R + c_L^{XV}\,\overline{X}_L \not{V} t_L\right] + \frac{g_w}{2}\left[c_L^{XV}\,\overline{X}_L \not{V} b_L + c_R^{XV}\,\overline{X}_R \not{V} b_R\right] + \left[c_R^{Xh}\,h\,\overline{X}_L t_R + c_L^{Xh}\,h\,\overline{X}_R t_L\right] + \left[c_L^{Xh}\,h\,\overline{X}_R b_L + c_R^{Xh}\,h\,\overline{X}_L b_R\right] + \text{h.c.}\,,$$

		couplings			
partner (MG name)	Q	$W^\pm$	Z	h	$W^\pm W^\pm$
$T_{2/3}$ (T23)	2/3	c_L^{TW}, c_R^{TW}	c_L^{TZ}, c_R^{TZ}	c_L^{Th}, c_R^{Th}	—
$B_{1/3}$ (B13)	-1/3	c_L^{BW}, c_R^{TW}	c_L^{BZ}, c_R^{BZ}	c_L^{Bh}, c_R^{Bh}	—
$X_{5/3}$ (X53)	5/3	c_L^{XW}, c_R^{XW}	—	—	—
$Y_{4/3}$ (Y43)	-4/3	c_L^{YW}, c_R^{YW}	—	—	—
$V_{8/3}$ (V83)	8/3	—	—	—	c_L^{VW}, c_R^{VW}

JHEP 1304 (2013) 004

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