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# Vector-like quarks at the LHC

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# Outline

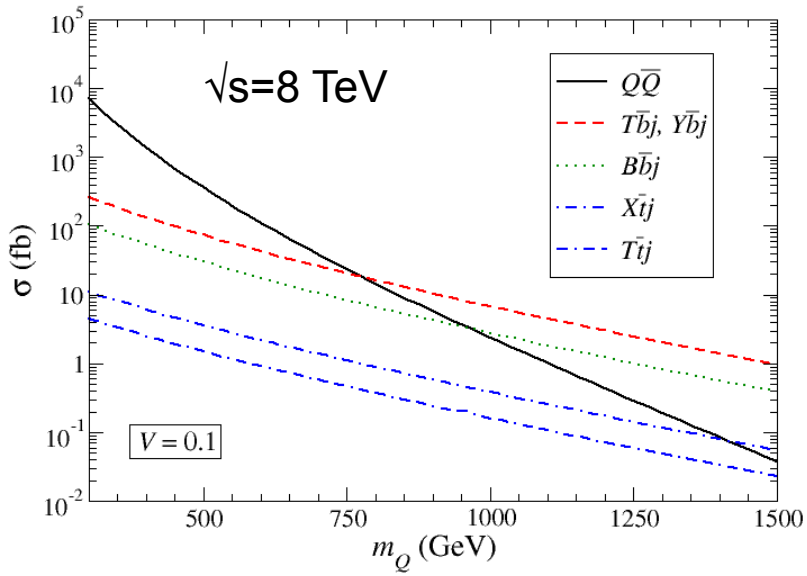
- Introduction
- Overview of Run 1 LHC results
- Status and plans for LHC Run 2
- Summary and outlook

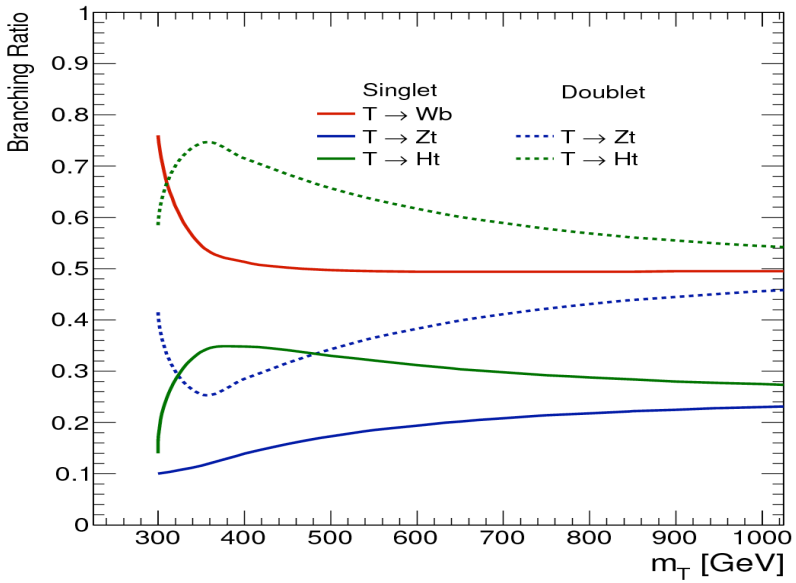
# Vector-Like Quarks: Production and Decay

- Top/bottom partners are vector-like quarks (left and right components transform the same under $SU(2)_L$). VLQs present in many BSM scenarios.
- Production:
  - Pair production via QCD: "universal" mode (just depends on $m_Q$).
    ➔ Focus of Run 1 searches
  - Single production via EW: potentially important at high $m_Q$ (depends on coupling strength).
    ➔ Important to consider in Run 2
- Decay: Q→Wq, Zq, Hq all with sizable BR

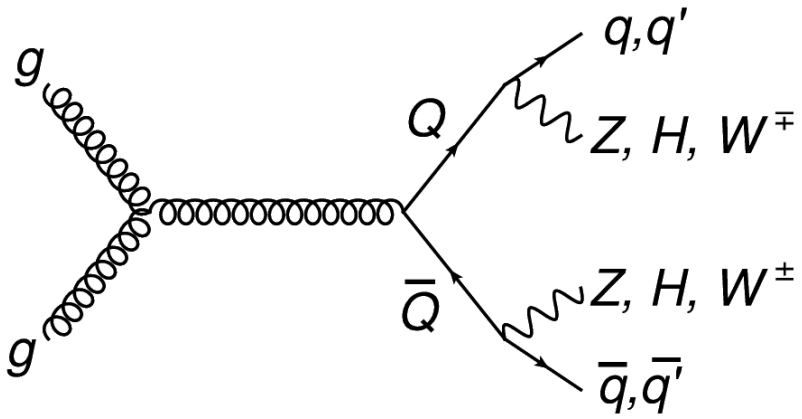
*JHEP 11, 030 (2009)* *(triplets not included)*

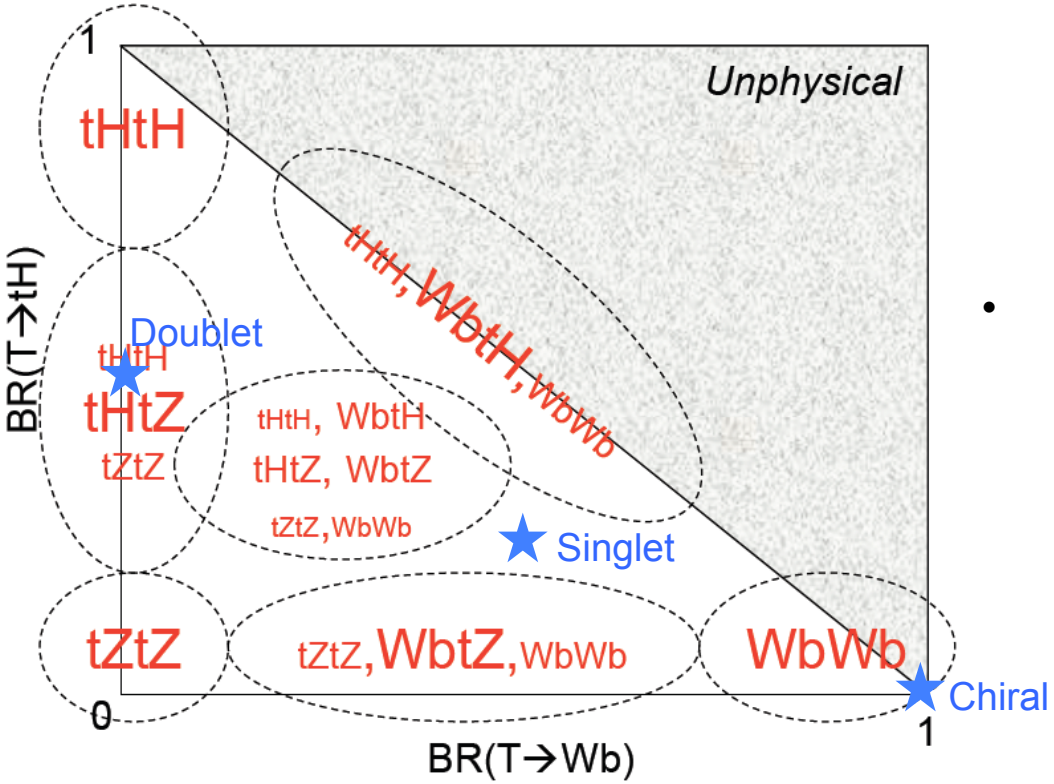
| | Label | Charge | Decay mode |
|---|---|---|---|
| T singlet | $T_S$ | +2/3 | T→$W^+$b, Zt, Ht |
| B singlet | $B_S$ | -1/3 | B→$W^-$t, Zb, Hb |
| (T,B) doublet | $TB_d$ | (+2/3, -1/3) | T→Zt, Ht<br>B→$W^-$t |
| (X,T) doublet | $XT_d$ | (+5/3, +2/3) | X→$W^+$t<br>T→Zt, Ht |
| (B,Y) doublet | $BY_d$ | (-1/3, -4/3) | B→Zb, Hb<br>Y→$W^-$b |



# Strategies




- Very rich phenomenology, depending on the heavy quark 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.
- Run 1 searches considered one heavy quark at a time, assuming other resonances do not contribute to the signature. Single production typically neglected.

  ➔ Something to improve upon for Run 2.

# Signatures

- There are many signatures that could be exploited, and which are ultimately needed both to enhance discovery potential and model discrimination. Just looking at pair-production:

| | | *SU(2) singlet* | | *SU(2) doublet* | | |
|---|---|---|---|---|---|---|
| | | $T_S$ | $B_S$ | $TB_d$ | $XT_d$ | $BY_d$ |
| 4 leptons | 4l (2Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$ | $B\bar{B}$ |
| | 4l (1Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$ | $B\bar{B}$ |
| | 4l (0Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$,$X\bar{X}$ | $B\bar{B}$ |
| 3 leptons | 3l (1Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$ | |
| | 3l (0Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$,$X\bar{X}$ | |
| OS dileptons | $l^+l^-$ (1Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$ | $B\bar{B}$ |
| | $l^+l^-$ (0Z) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$,$X\bar{X}$ | $B\bar{B}$,$Y\bar{Y}$ |
| SS dileptons | $l^\pm l^\pm$ | | $B\bar{B}$ | $B\bar{B}$ | $X\bar{X}$ | |
| lepton+jets | $l^\pm$ (4j) | $T\bar{T}$ | | $T\bar{T}$ | $T\bar{T}$ | $Y\bar{Y}$ |
| | $l^\pm$ (≥6j) | $T\bar{T}$ | $B\bar{B}$ | $T\bar{T}$,$B\bar{B}$ | $T\bar{T}$,$X\bar{X}$ | |

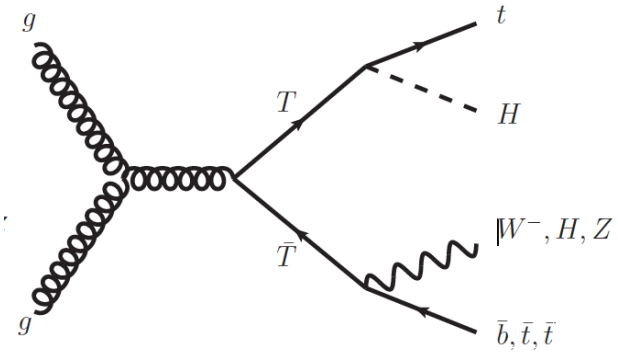
And not even including all-hadronic final state and Higgs tagging!

- Of course, some of them are more challenging and/or powerful than others…

# Overview of Run 1 Results

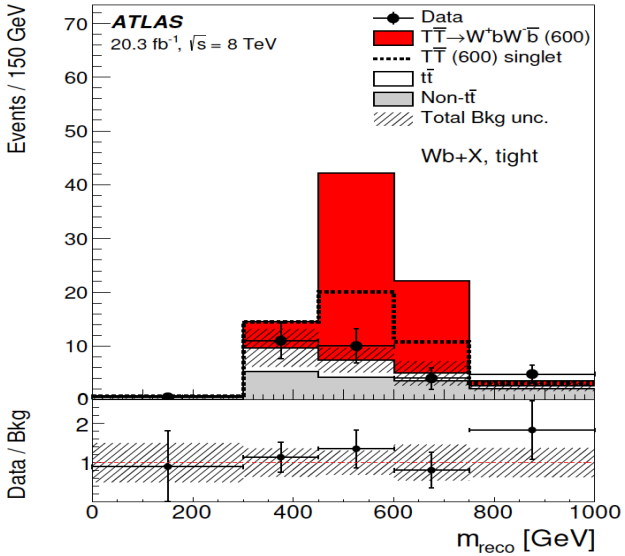
# Vector-Like Top: 1-lepton Searches

- Searches targeting high BR($T_{2/3}$→$W^+b$), but also sensitive to other decay modes.
- Most sensitive searches exploit lepton+jets final state. Also searches on all-hadronic mode but lower sensitivity.
- Basic 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.
  - Uses reconstruct heavy quark mass.
  - All BRs tested. Best exclusion for BR(T→Wb)=1.

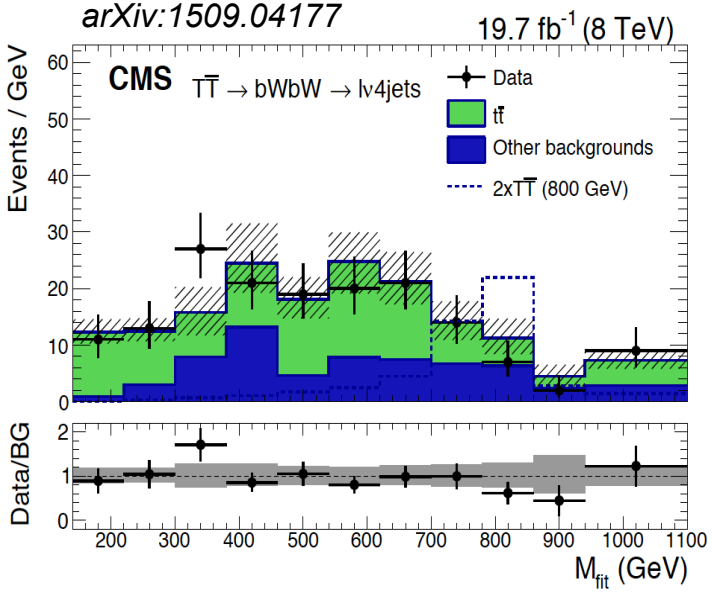



(*) $H_T = \sum p_T^{jets} + p_T^{lep} + E_T^{miss}$

*arXiv:1505.04306*




*arXiv:1509.04177*




**95% CL obs (exp) limits [100% WbWb]:**

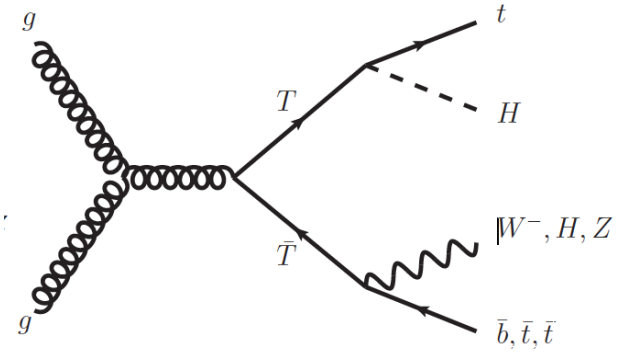
ATLAS: $m_T$>**770** (795) GeV

CMS: $m_T$>**912** (851) GeV

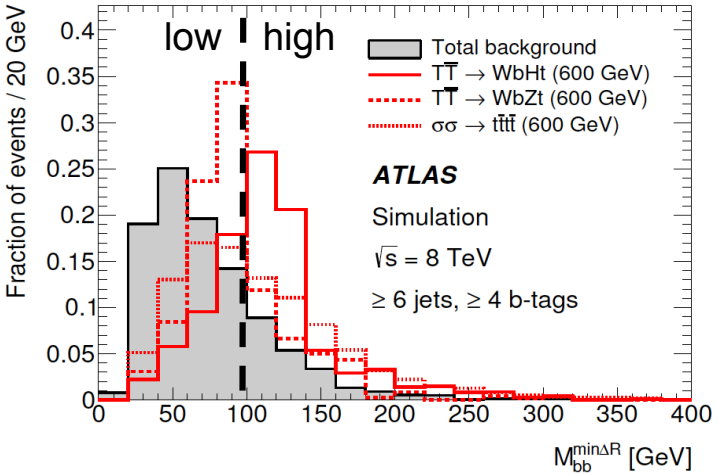
Limits also apply to $Y_{-4/3}$, since BR($Y_{-4/3}$→$W^-b$)=1.

# Vector-Like Top: 1-lepton Searches

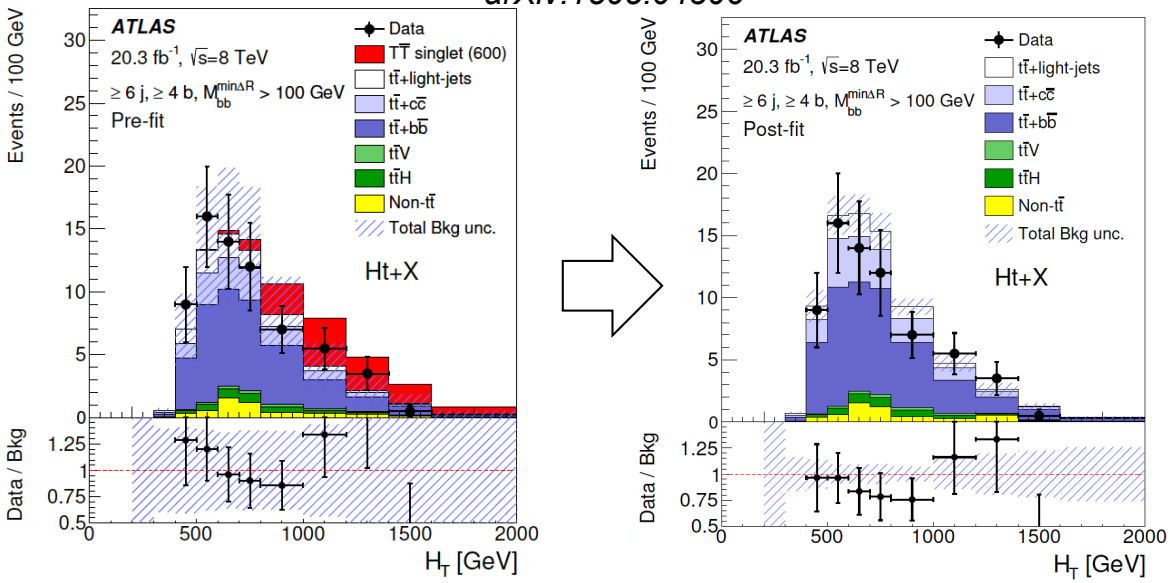
- Search targeting high BR($T_{2/3}$→Ht), but designed as broad-band search sensitive to multiple decay modes:
  TT→HtHt, HtWb, HtZt, ZtZt, ZtWb
- Basic strategy:
  - Presel: 1 lepton, high $E_T^{miss}$, ≥5 jets/≥2 b-tags.
  - Analyze $H_T$ spectrum across 8 regions:
    (5 jets, ≥6 jets) x (2 b-tags, 3 b-tags, ≥4 b-tags)
    ≥6 jets/≥3 b-tags regions split in low/high $M_{bb}$
  - Signal-depleted regions used to constrain in-situ bkg uncert. through likelihood fit to data.
- All BRs tested. Best exclusion for BR(T→Ht)=1.




*arXiv:1505.04306*




*arXiv:1505.04306*




**95% CL obs (exp) limits:**

BR(T→Ht)=1: $m_T$>**950** (885) GeV

Doublet: $m_T$>**855** (820) GeV

Singlet: $m_T$>**765** (720) GeV

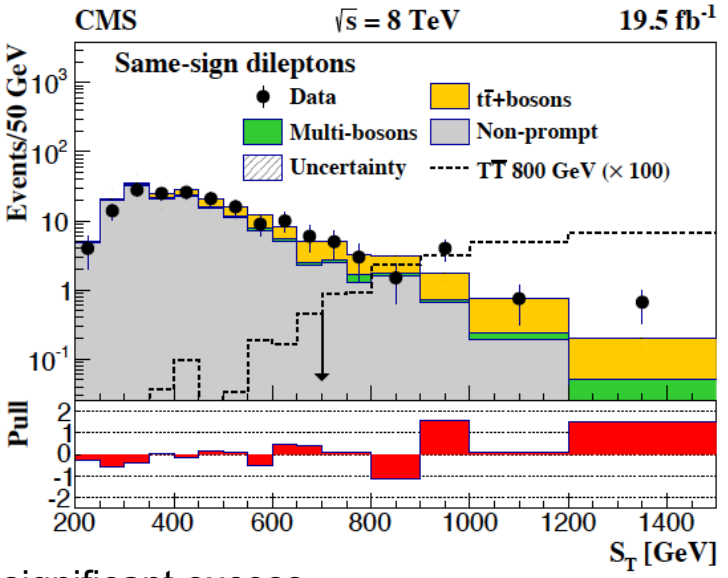
# Vector-Like Top: Multilepton Searches

- Inclusive multilepton searches. Consider multiple search channels that are eventually combined.
- CMS search:

| | *OS1* | *OS2* | *SS* | Multileptons |
|---|---|---|---|---|
| $H_T$ (GeV) | $>300$ | $>500$ | $>500$ | $>500$ |
| $S_T$ (GeV) | $>900$ | $>1000$ | $>700$ | $>700$ |
| Number of jets | 2 or 3 | $\geq 5$ | $\geq 3$ | $\geq 3$ |
| b tags | $\geq 1$ | $\geq 2$ | $\geq 1$ | $\geq 1$ |
| $E_T^{miss}$ (GeV) | $>30$ | $>30$ | $>30$ | $>30$ |
| $M_{b\ell}$ (GeV) | $>170$ | — | — | — |
| $M_{\ell\ell}$ (GeV) | $>20$ | $>20$ | $>20$ | $>20$ |
| Z boson veto | yes | no | no | no |

| | *OS1* | *OS2* | *SS* | Multileptons |
|---|---|---|---|---|
| Total background | $17.4 \pm 3.7$ | $84 \pm 12$ | $16.5 \pm 4.8$ | $3.7 \pm 1.3$ |
| Data | 20 | 86 | 18 | 2 |

*arXiv:1311.7667*

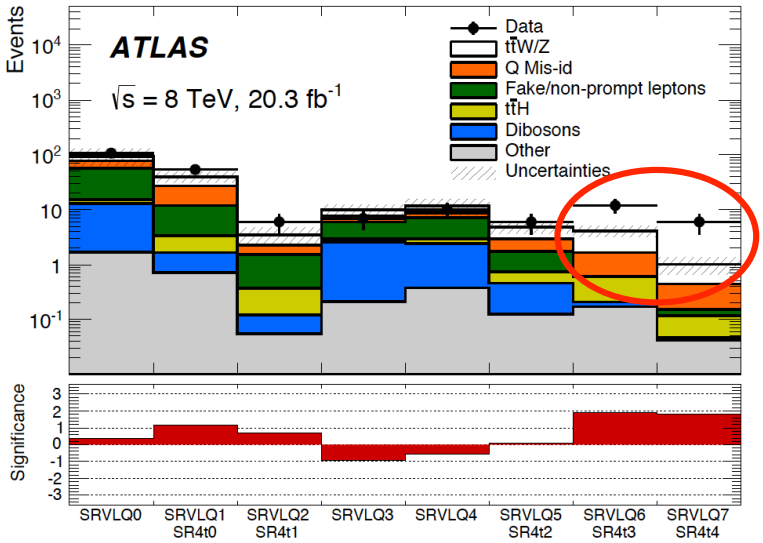



➔ No significant excess

- ATLAS search:

| Definition | | | |
|---|---|---|---|
| $e^{\pm}e^{\pm} + e^{\pm}\mu^{\pm} + \mu^{\pm}\mu^{\pm} + eee + ee\mu + e\mu\mu + \mu\mu\mu$, $N_j \geq 2$ | | | |
| $400 < H_T < 700$ GeV | $N_b = 1$ | $E_T^{miss} > 40$ GeV | SRVLQ0 |
| | $N_b = 2$ | | SRVLQ1 |
| | $N_b \geq 3$ | | SRVLQ2 |
| $H_T \geq 700$ GeV | $N_b = 1$ | $40 < E_T^{miss} < 100$ GeV | SRVLQ3 |
| | | $E_T^{miss} \geq 100$ GeV | SRVLQ4 |
| | $N_b = 2$ | $40 < E_T^{miss} < 100$ GeV | SRVLQ5 |
| | | $E_T^{miss} \geq 100$ GeV | SRVLQ6 |
| | $N_b \geq 3$ | $E_T^{miss} > 40$ GeV | SRVLQ7 |

*arXiv:1504.04605*




Apparent excess in VLQ6 and VLQ7 SRs ➔

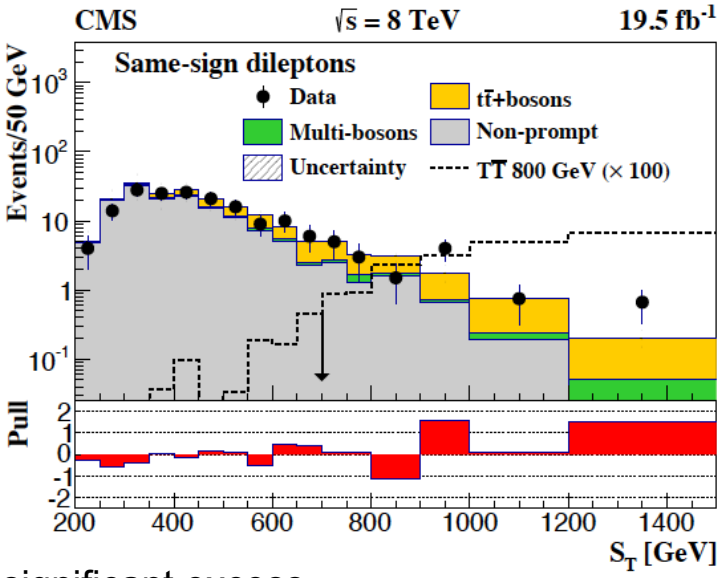
# Vector-Like Top: Multilepton Searches

- Inclusive multilepton searches. Consider multiple search channels that are eventually combined.
- CMS search:

| | *OS1* | *OS2* | *SS* | Multileptons |
|---|---|---|---|---|
| $H_T$ (GeV) | $>300$ | $>500$ | $>500$ | $>500$ |
| $S_T$ (GeV) | $>900$ | $>1000$ | $>700$ | $>700$ |
| Number of jets | 2 or 3 | $\geq 5$ | $\geq 3$ | $\geq 3$ |
| b tags | $\geq 1$ | $\geq 2$ | $\geq 1$ | $\geq 1$ |
| $E_T^{miss}$ (GeV) | $>30$ | $>30$ | $>30$ | $>30$ |
| $M_{b\ell}$ (GeV) | $>170$ | — | — | — |
| $M_{\ell\ell}$ (GeV) | $>20$ | $>20$ | $>20$ | $>20$ |
| Z boson veto | yes | no | no | no |

| | *OS1* | *OS2* | *SS* | Multileptons |
|---|---|---|---|---|
| Total background | $17.4 \pm 3.7$ | $84 \pm 12$ | $16.5 \pm 4.8$ | $3.7 \pm 1.3$ |
| Data | 20 | 86 | 18 | 2 |

*arXiv:1311.7667*

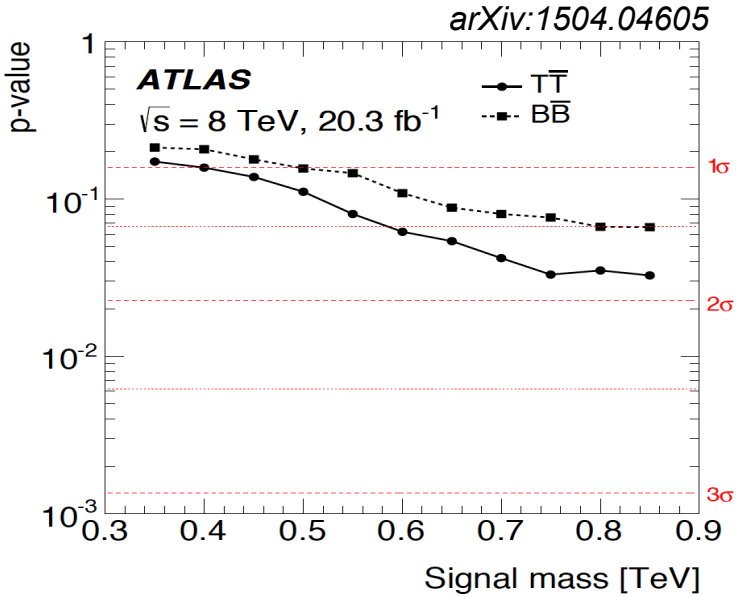



➔ No significant excess

- ATLAS search:

| | SRVLQ5/SR4t2 | SRVLQ6/SR4t3 | SRVLQ7/SR4t4 |
|---|---|---|---|
| $t\bar{t}W/Z$ | $1.87 \pm 0.09 \pm 0.80$ | $2.46 \pm 0.11 \pm 1.06$ | $0.57 \pm 0.05 \pm 0.25$ |
| $t\bar{t}H$ | $0.31 \pm 0.04 \pm 0.05$ | $0.44 \pm 0.04 \pm 0.06$ | $0.08 \pm 0.02 \pm 0.02$ |
| Dibosons | $0.33 \pm 0.14 \pm 0.10$ | $0.04 \pm 0.12 \pm 0.03$ | $0.00 \pm 0.12 \pm 0.00$ |
| Fake/Non-prompt | $1.03 \pm 0.97 \pm 0.60$ | $0.00 \pm 1.02 \pm 0.28$ | $0.04 \pm 0.83 \pm 0.24$ |
| Q mis-Id | $1.17 \pm 0.16 \pm 0.38$ | $1.09 \pm 0.14 \pm 0.34$ | $0.30 \pm 0.09 \pm 0.10$ |
| Other bkg. | $0.16 \pm 0.08 \pm 0.02$ | $0.23 \pm 0.08 \pm 0.05$ | $0.14 \pm 0.08 \pm 0.08$ |
| Total bkg. | $4.9 \pm 1.0 \pm 1.0$ | $4.3 \pm 1.1 \pm 1.1$ | $1.1 \pm 0.9 \pm 0.4$ |
| Data | 6 | 12 | 6 |
| $p$-value | 0.46 | 0.029 | 0.036 |
| | | $1.9\sigma$ | $1.8\sigma$ |

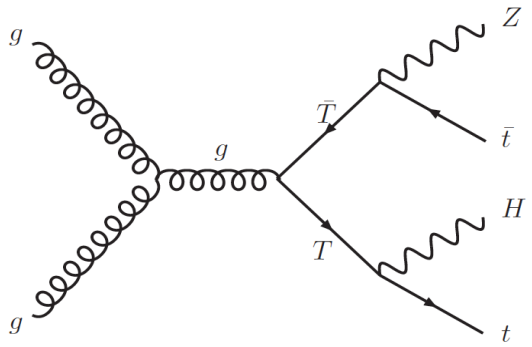
*arXiv:1504.04605*



# Vector-Like Top: Multilepton Searches

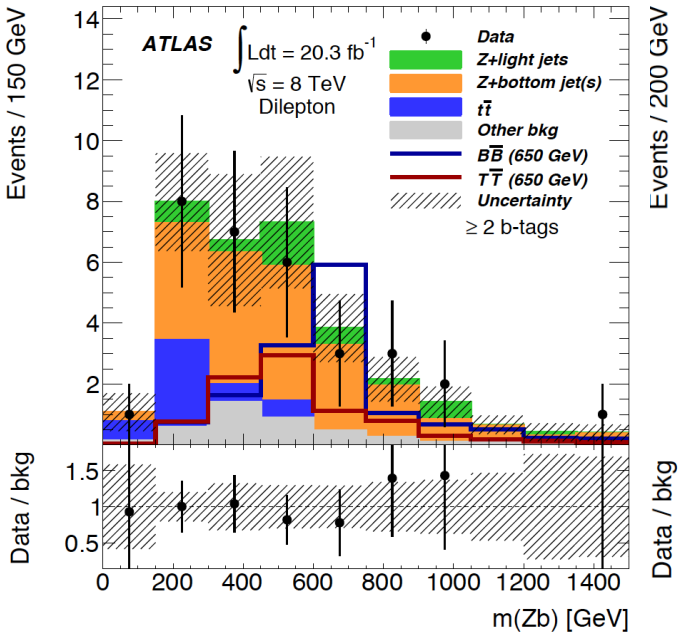
- Dedicated search probing TT→Zt+X (*).
- Multiple search channels that are eventually combined.

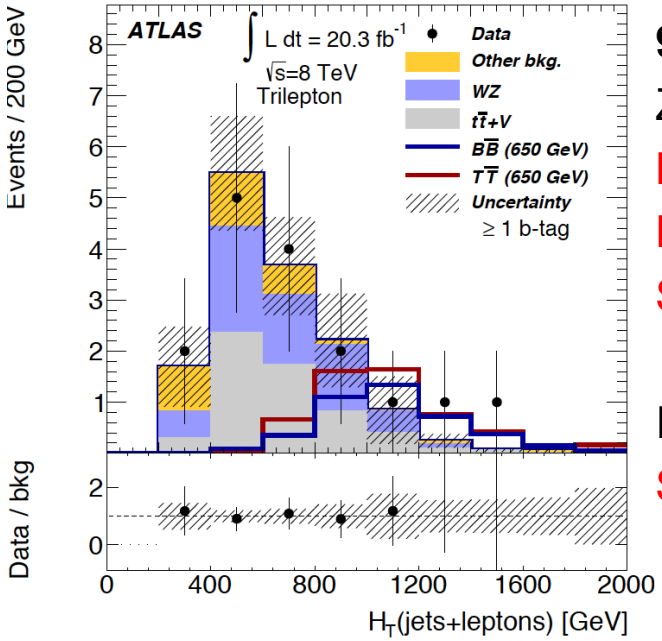
| Event selection | | | |
|---|---|---|---|
| $Z$ boson candidate preselection<br>$\geq 2$ central jets<br>$p_{\mathrm{T}}(Z) \geq 150$ GeV | | | |
| **Dilepton channel** | | **Trilepton channel** | |
| $= 2$ leptons | | $\geq 3$ leptons | |
| $\geq 2$ $b$-tagged jets | | $\geq 1$ $b$-tagged jet | |
| **Pair production** | **Single production** | **Pair production** | **Single production** |
| $H_{\mathrm{T}}(\mathrm{jets}) \geq 600$ GeV | $\geq 1$ fwd. jet | – | $\geq 1$ fwd. jet |
| **Final discriminant** | | | |
| $m(Zb)$ | | $H_{\mathrm{T}}$(jets+leptons) | |




(*) Not orthogonal to inclusive multilepton search.

*arXiv:1409.5500*




**95% CL obs (exp) limits:**

Zt+X search:

BR(T→Zt)=1: $m_T$>**810** (810) GeV

Doublet: $m_T$>**735** (720) GeV

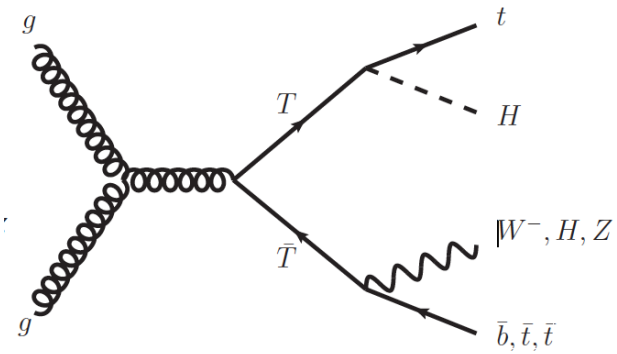
Singlet: $m_T$>**655** (625) GeV

Inclusive multilepton search

Singlet: $m_T$>**590** (660) GeV

# Vector-Like Top: All-Hadronic Searches

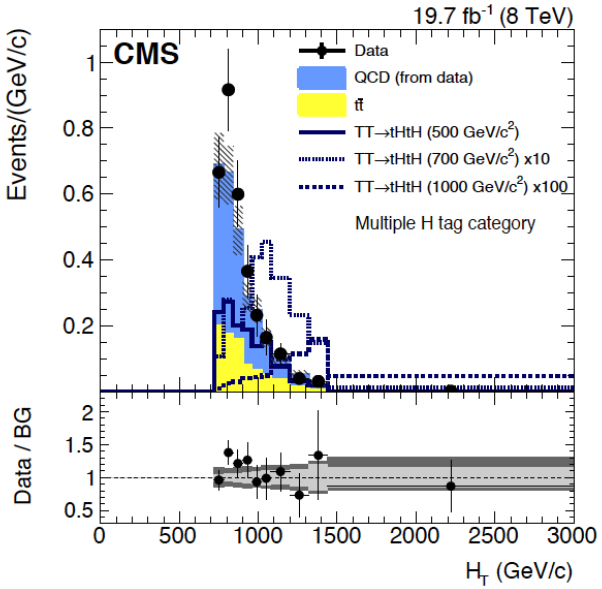
- CMS performed several VLQ searches in the all-hadronic final state using jet substructure techniques.

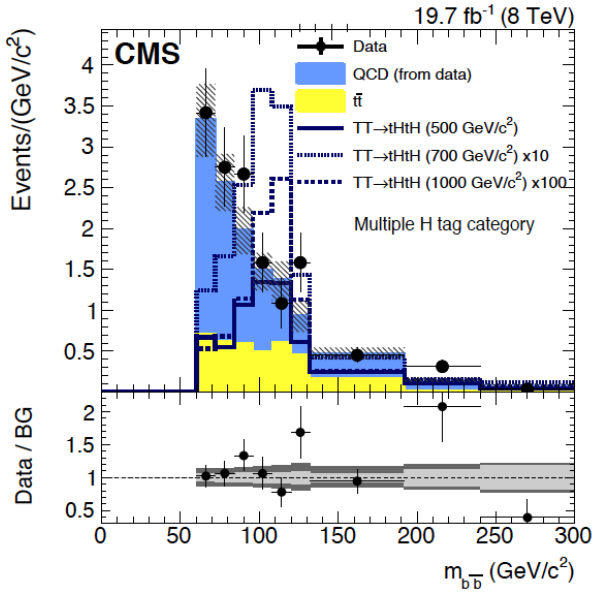



**TT→Ht+X, H→bb**

- CA R=1.5 jets used as input to HepTopTagger and Higgs tagging (based on subjet b-tagging)
- ≥1 HTT candidate ($p_T$>200 GeV).
- ≥1 Higgs candidate ($p_T$>150 GeV), $m_j$>60 GeV
- Categorize events depending on number of Higgs candidates (=1 and ≥2).
- Uses likelihood discriminant based on $H_T$ and Higgs invariant mass.

*arXiv:1503.01952*



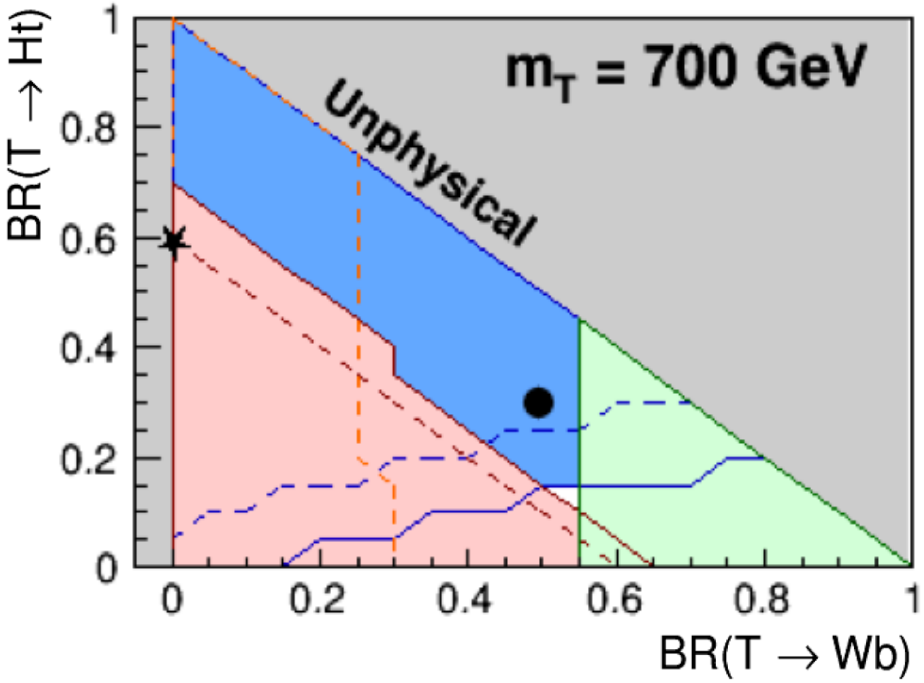

**95% CL obs (exp) limits [100% HtHt]:**

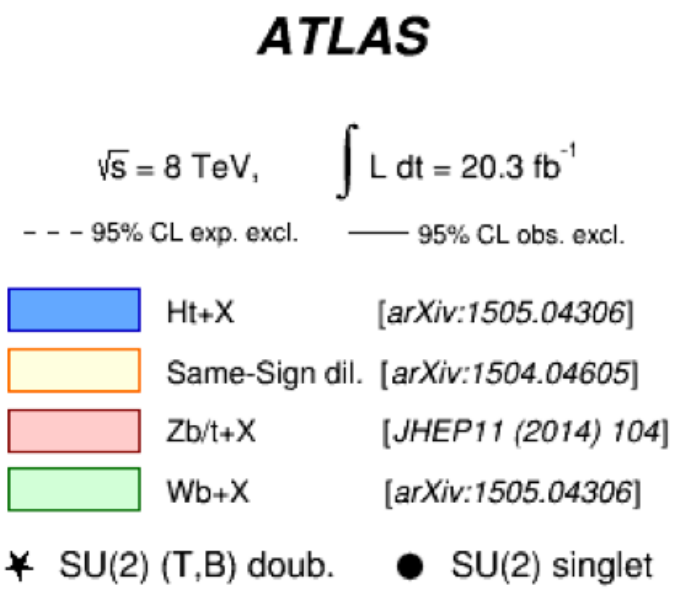
$m_T$>**900** (810) GeV

Competitive with inclusive CMS search, which combines 1-lepton and multilepton searches

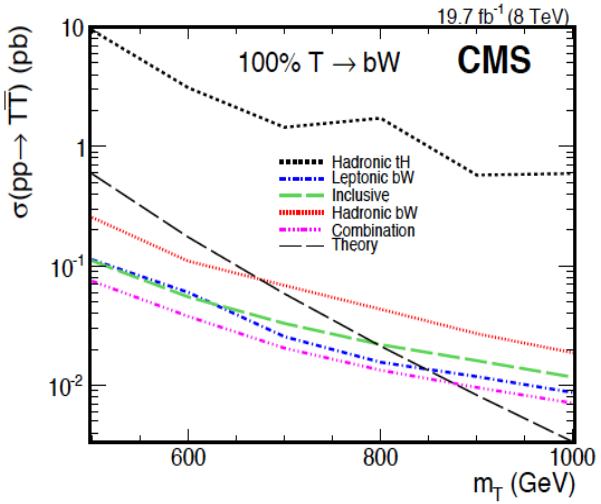
*arXiv:1311.7667*

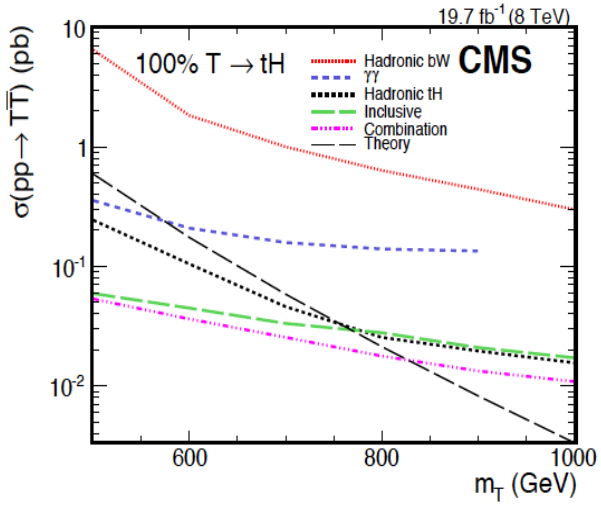
# Vector-Like Top: Complementarity

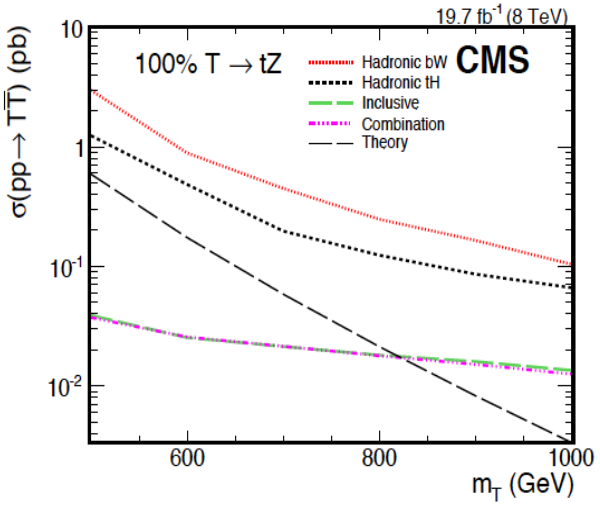



*arXiv:1509.04177*

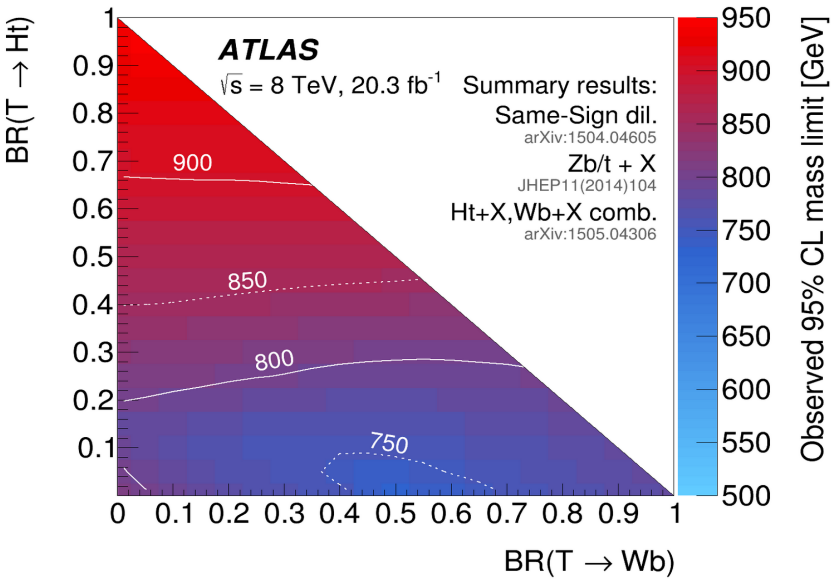


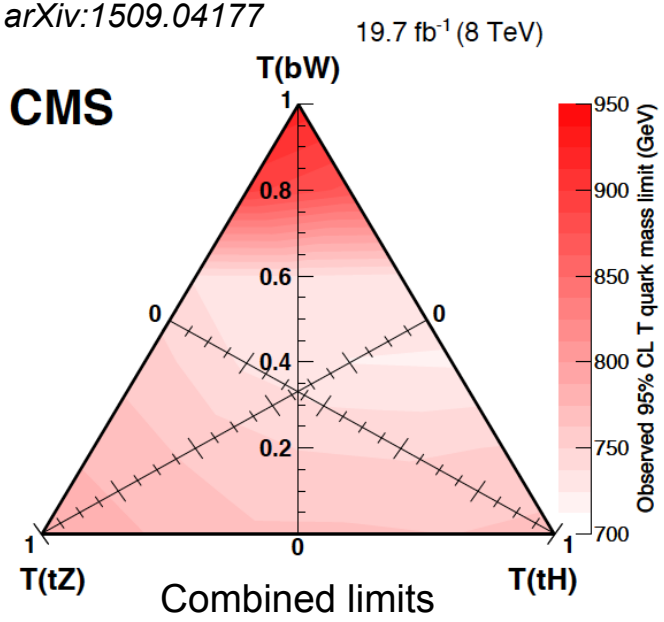
# Vector-Like Top Summary

*arXiv:1505.04306*




(*) Not a combination. Only most restrictive individual bounds shown.

*arXiv:1509.04177*

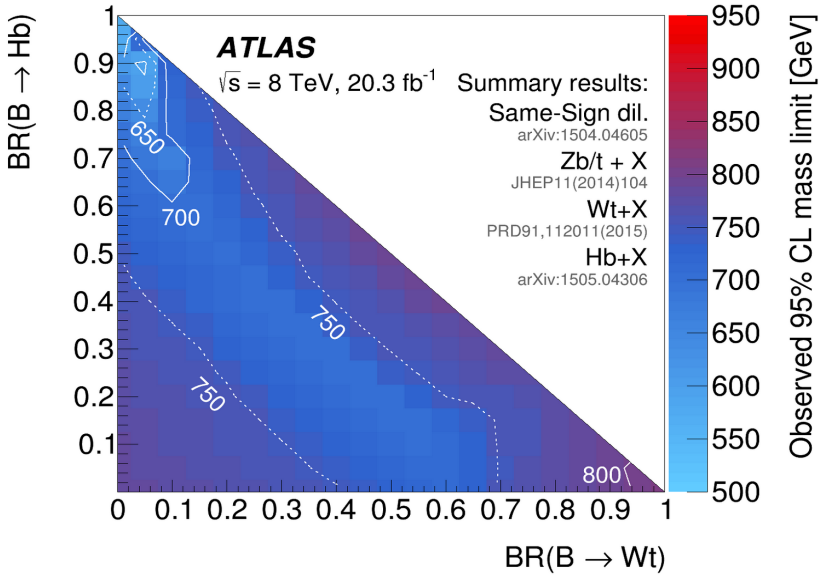



Vector-like top masses below ~720 GeV excluded for any possible combination of BRs.

| | ATLAS (*) | CMS |
|---|---|---|
| **Vector-like T BR Hypothesis** | **95% CL Limit on $m_T$ (GeV) obs (exp)** | **95% CL Limit on $m_T$ (GeV) obs (exp)** |
| 100% Wb (chiral, Y) | **770** (795) | **920** (890) |
| 100% Zt | **810** (810) | **790** (830) |
| 100% Ht | **950** (885) | **770** (840) |
| T singlet | **800** (755) | **740** (800) |
| T in (T, B) doublet | **855** (820) | **760** (820) |

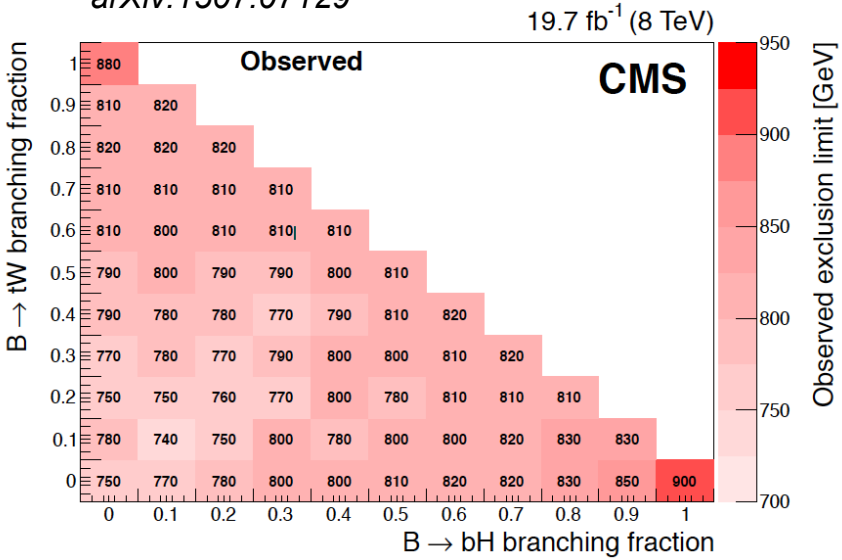
# Vector-Like Bottom Summary

*arXiv:1505.04306*




(*) Not a combination. Only most restrictive individual bounds shown.

*arXiv:1507.07129*




Combined limits

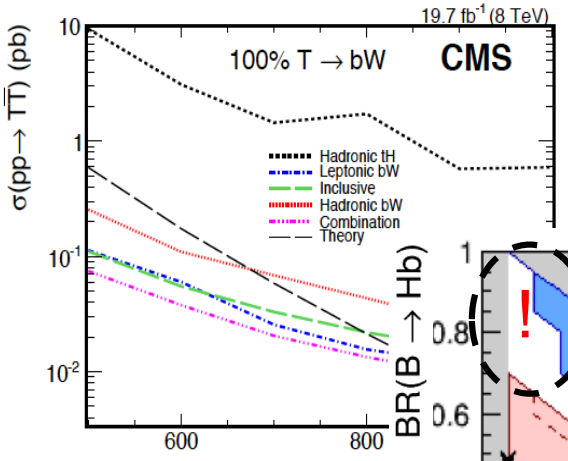
Vector-like bottom masses below ~740 GeV excluded for any possible combination of BRs.

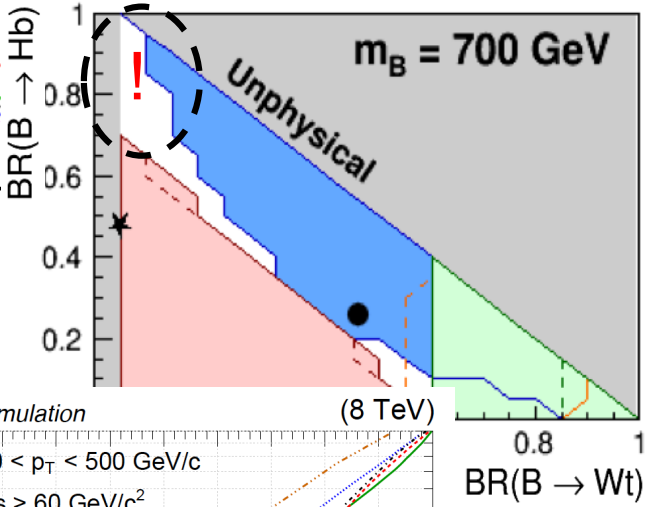
| | ATLAS (*) | CMS |
|---|---|---|
| **Vector-like B BR Hypothesis** | **95% CL Limit on $m_B$ (GeV) obs (exp)** | **95% CL Limit on $m_B$ (GeV) obs (exp)** |
| 100% Wt (chiral, X) | **730** (790) | **880** (890) |
| 100% Zb | **790** (800) | **750** (740) |
| 100% Hb | **700** (625) | **900** (810) |
| B singlet | **685** (670) | **780** (760) |
| B in (B, Y) doublet | **755** (755) | **810** (800) |

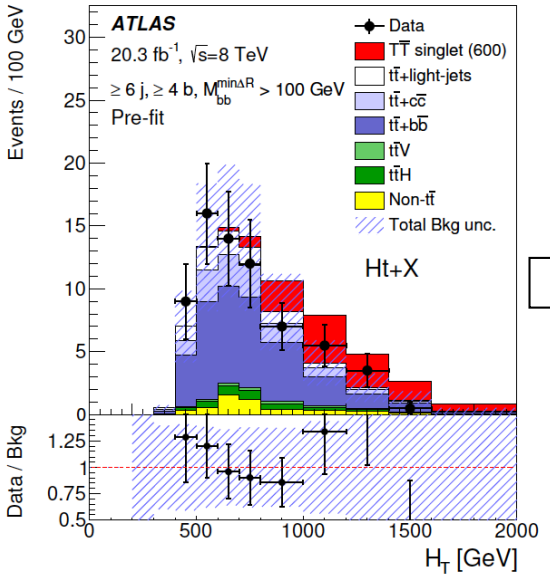
# Run 2 Status and Plans

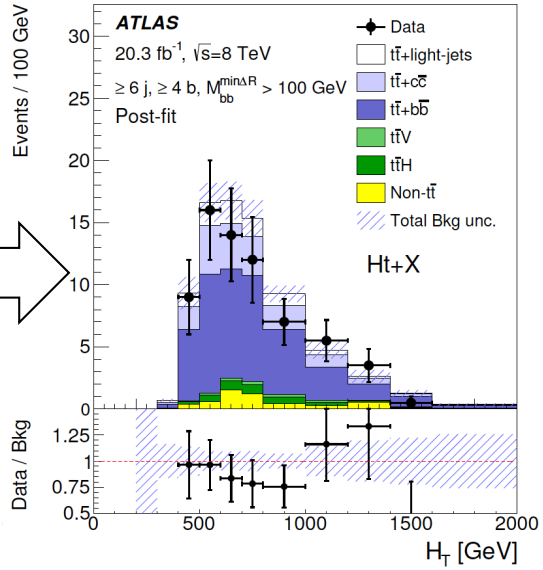
# Basic Plan for Run 2

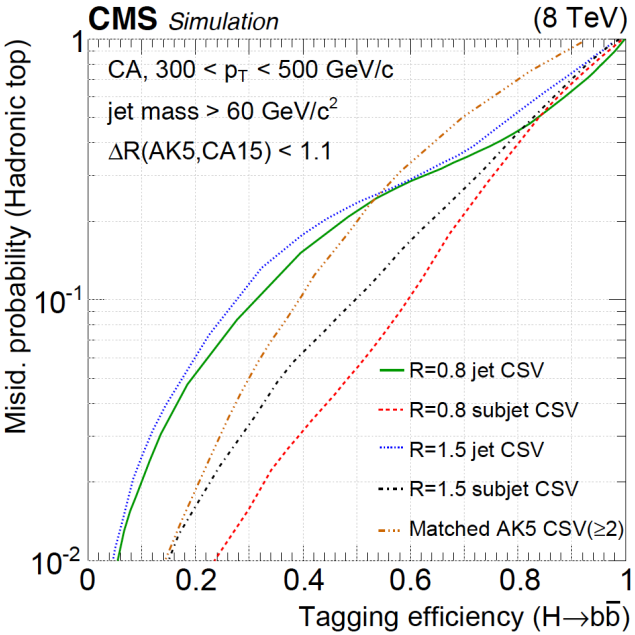
- **Capitalize on Run 1 experience**
  - Most sensitive channels
  - Complementary channels
  - Missing channels
  - Most powerful experimental strategies
  - Improved background estimation techniques
  - Reducing the impact of systematic uncertainties
  - …



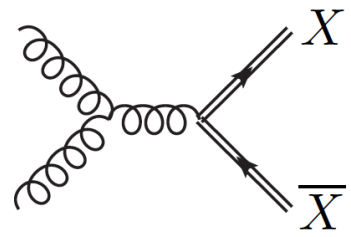



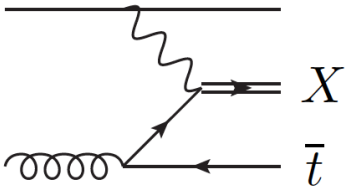



# Basic Plan for Run 2

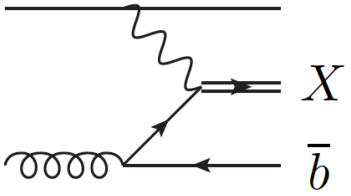
- Capitalize on Run 1 experience
- **Fully exploit increased CM energy**
  - Large increase in production cross section at high masses
  - Continue to exploit pair production above 1 TeV
  - Add single production above 1 TeV
  - Optimize strategy at high mass



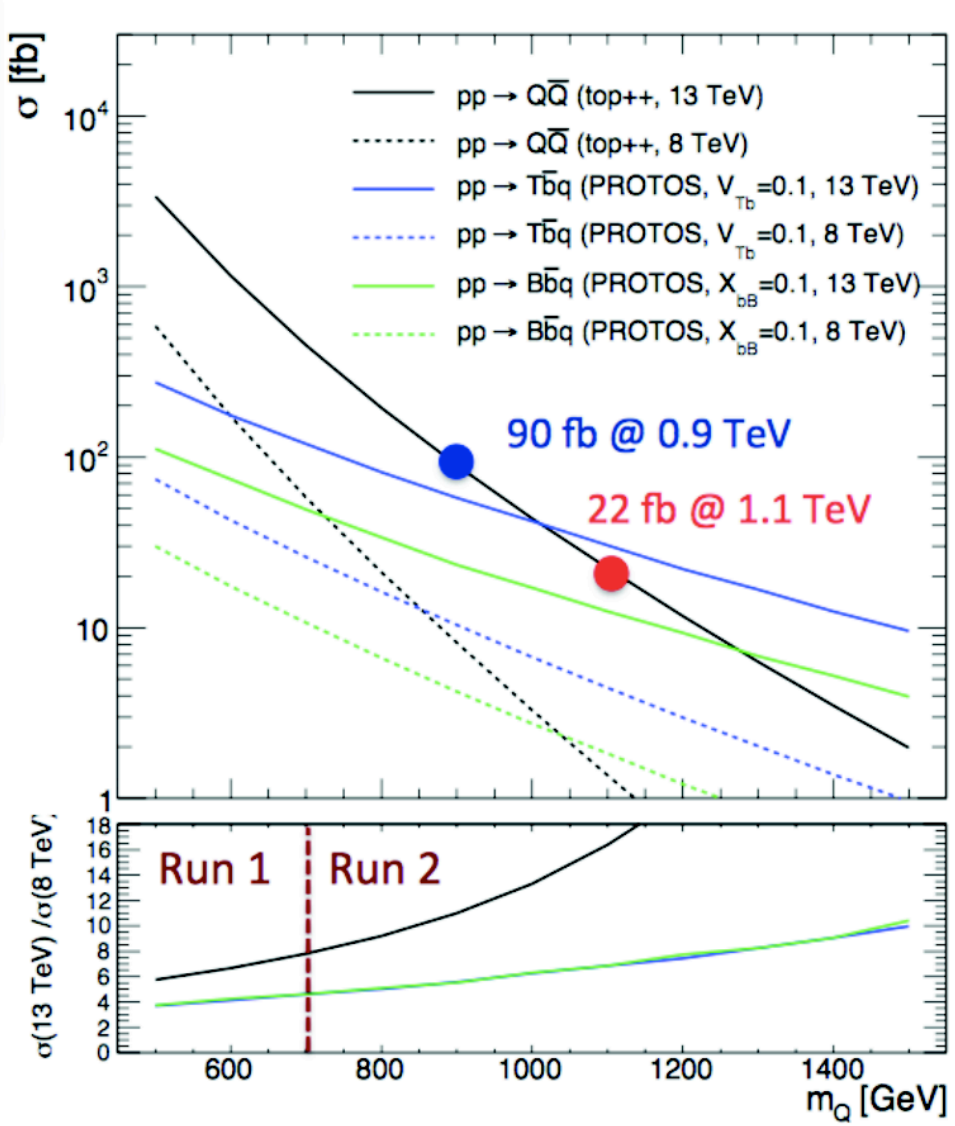

QCD **pair prod.**
model indep.,
relevant at low mass




**single prod.** with **t**
model dep. coupling
pdf-favoured at high mass




**single prod.** with **b**
favoured by small b mass
**dominant** when allowed



# Basic Plan for Run 2

- 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
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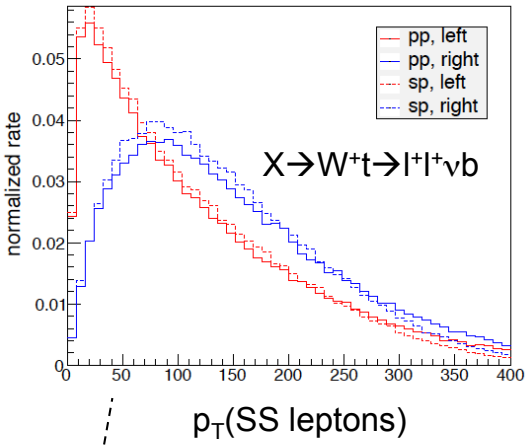
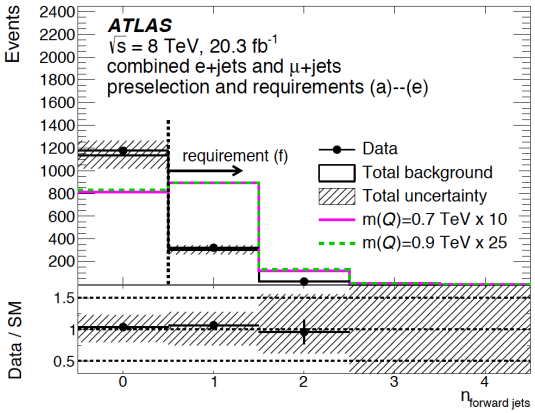
  - Optimize strategy at high mass

*arXiv:1409.0100*

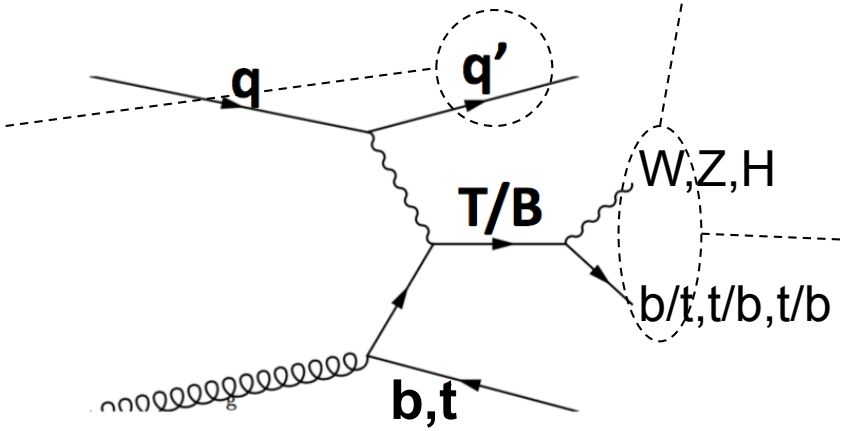



$p_T$(SS leptons)

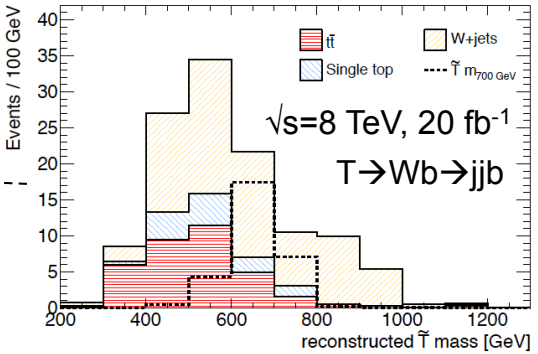
*arXiv:1602.05606*




Forward jet:
$p_T$>35 GeV, 2.4<|η|<4.5



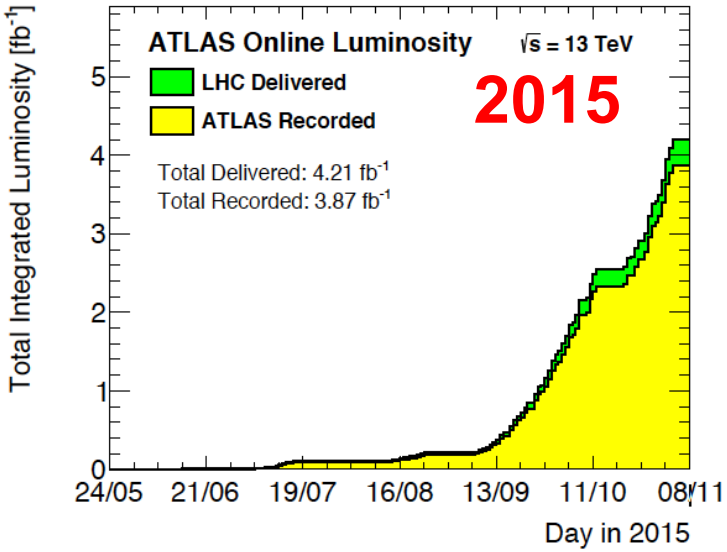

*arXiv:1403.7490*




- Forward jet tagging critical.
- Many channels, with and without leptons.
- Boosted techniques for all-hadronic modes crucial.
- Must ensure proper helicity propagation in decay.

# Basic Plan for Run 2

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- **Plan according to integrated luminosity**
  - **2015**: 3.9 $fb^{-1}$ recorded
    - High-priority to checking Run 1 excesses.
    - For the most part Run 1-style analyses with early data.
    - ***First results already exceeding Run 1 sensitivity*!**

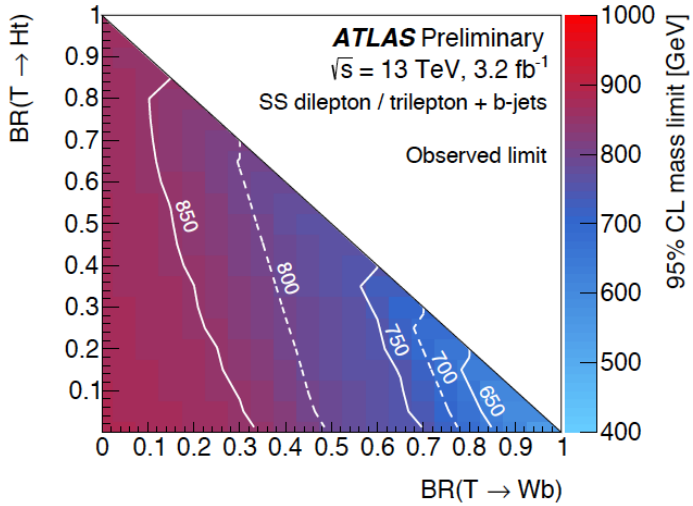


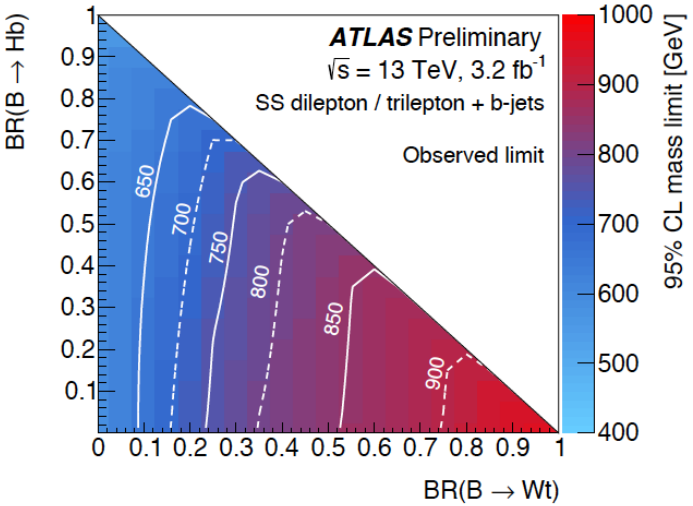
# Early Run 2 Results: Multileptons

~3 fb$^{-1}$

- Early Run 2 analysis using the same strategy and signal regions as Run 1 analysis to check excess.

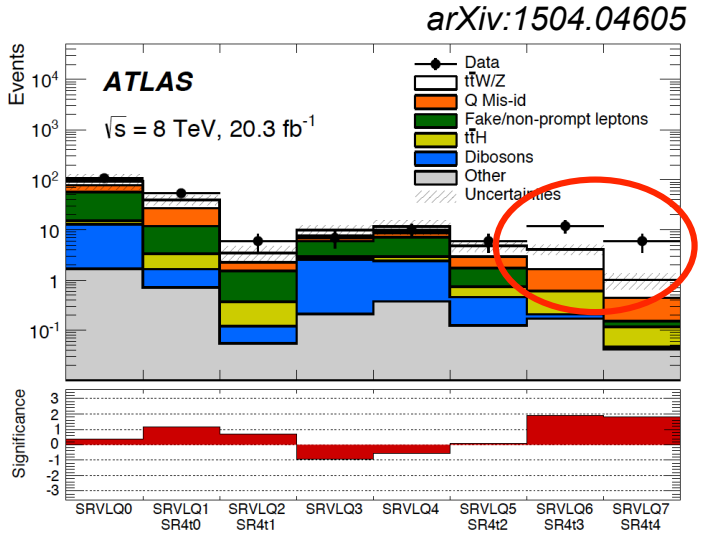
➔ Excess not confirmed!



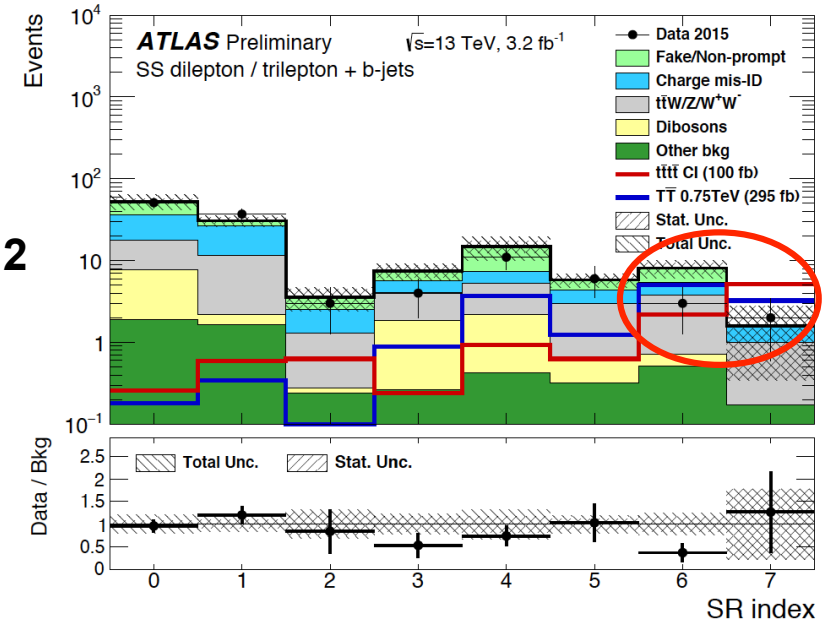

**Run 1**

*arXiv:1504.04605*



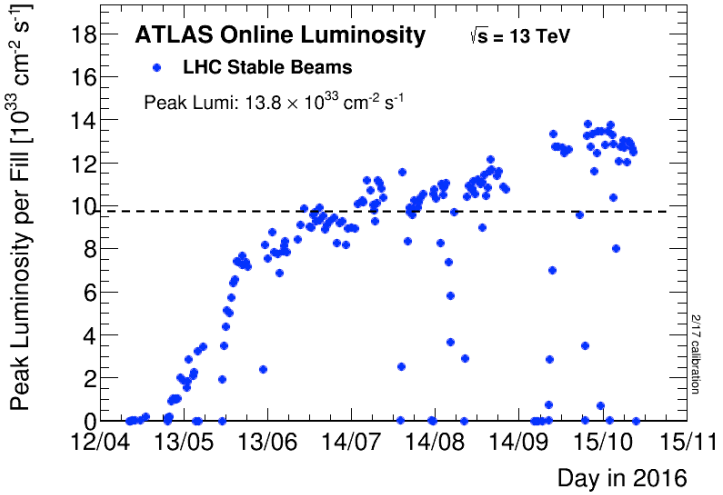

**Run 2**

*ATLAS-CONF-2016-032*

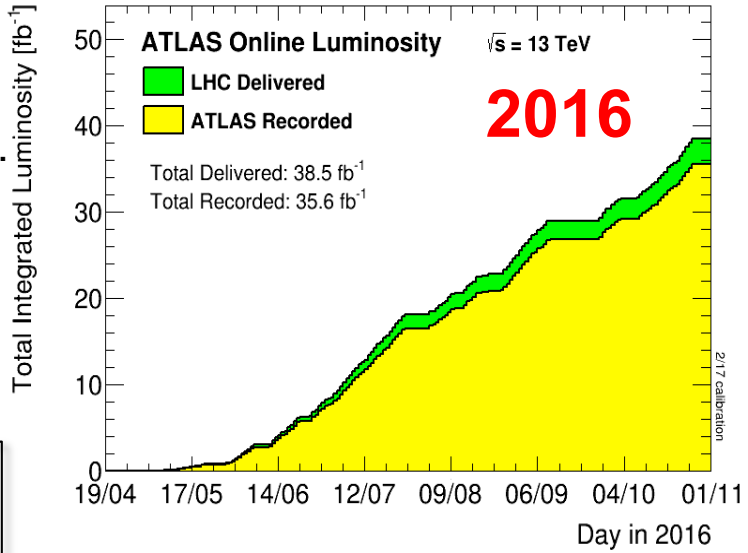


# Basic Plan for Run 2

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- **Plan according to integrated luminosity**
  - **2015**: 3.9 fb$^{-1}$ recorded
    - High-priority to checking Run 1 excesses.
    - For the most part Run 1-style analyses with early data.
    - ***First results already exceeding Run 1 sensitivity***!




  - **2016**: 35.6 fb$^{-1}$ recorded
    - Exceed design luminosity of ~$10^{34}$ cm$^{-2}$s$^{-1}$.
    - Record daily delivered luminosity of ~0.6 fb$^{-1}$.
    - ***Significant discovery potential!***

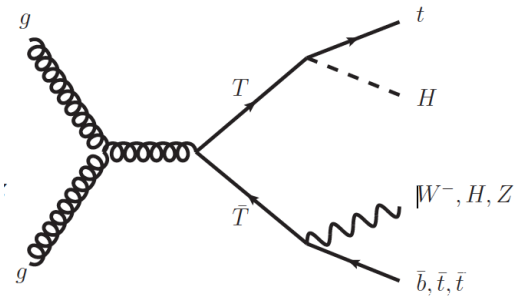



Publication results with 2015+2016 dataset (~36 fb$^{-1}$) becoming available.
Here most results shown use a partial dataset.

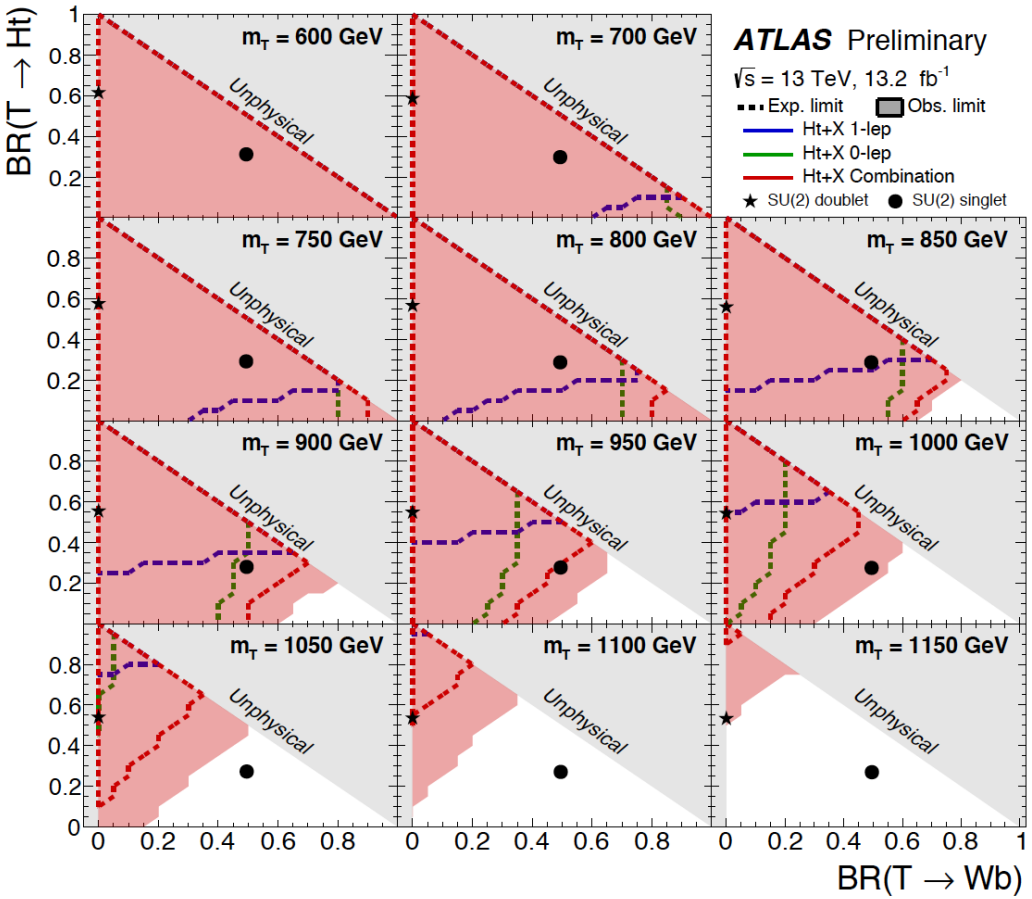
# $T\bar{T}\rightarrow Ht+X$

~13 fb$^{-1}$

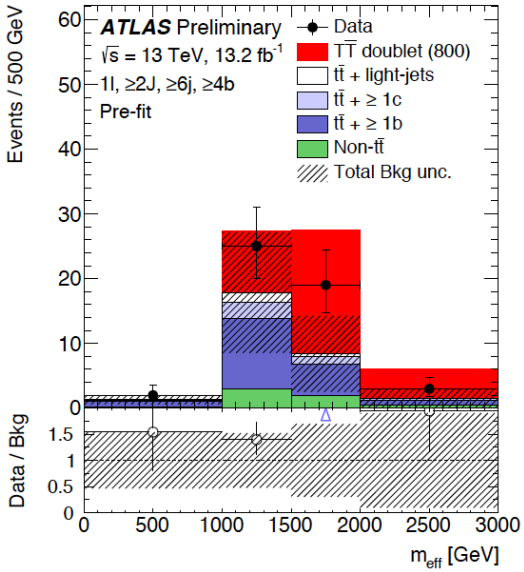
- Re-optimized Run 1 search for $T\bar{T}\rightarrow Ht+X$.
- Considers 1-lepton and 0-lepton+high-$E_T^{miss}$ channels.
- Basically same strategy, now adding splitting in mass-tagged jet multiplicity (re-clustered R=0.4 jets within R=1.0, $p_{T,J}$>300 GeV, $m_J$>100 GeV) ➔ 20 analysis regions.




*ATLAS-CONF-2016-104*




One of the highest-sensitivity regions




**95% CL obs (exp) limits:**

BR(T→Ht)=1: $m_T$>**1200** (1160) GeV

Doublet: $m_T$>**1160** (1110) GeV

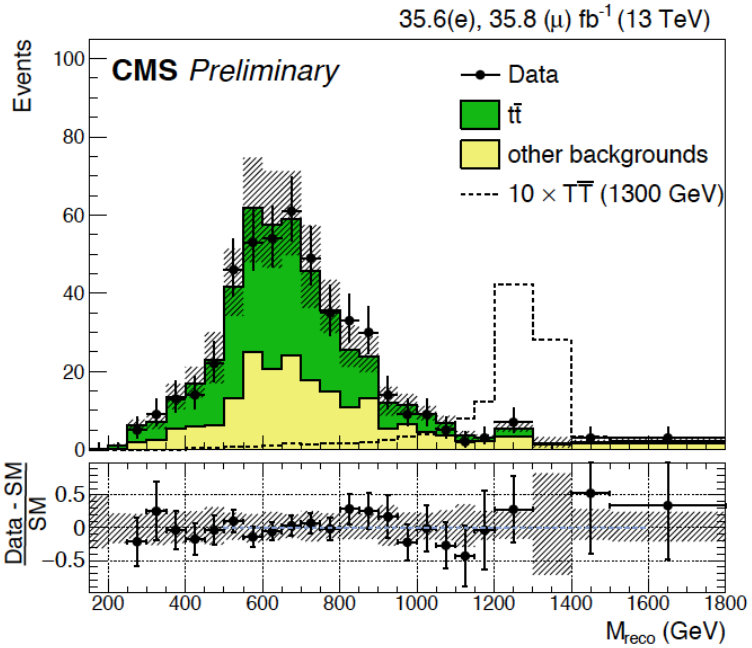
BR(T→Zt)=1: $m_T$>**1100** (1040) GeV

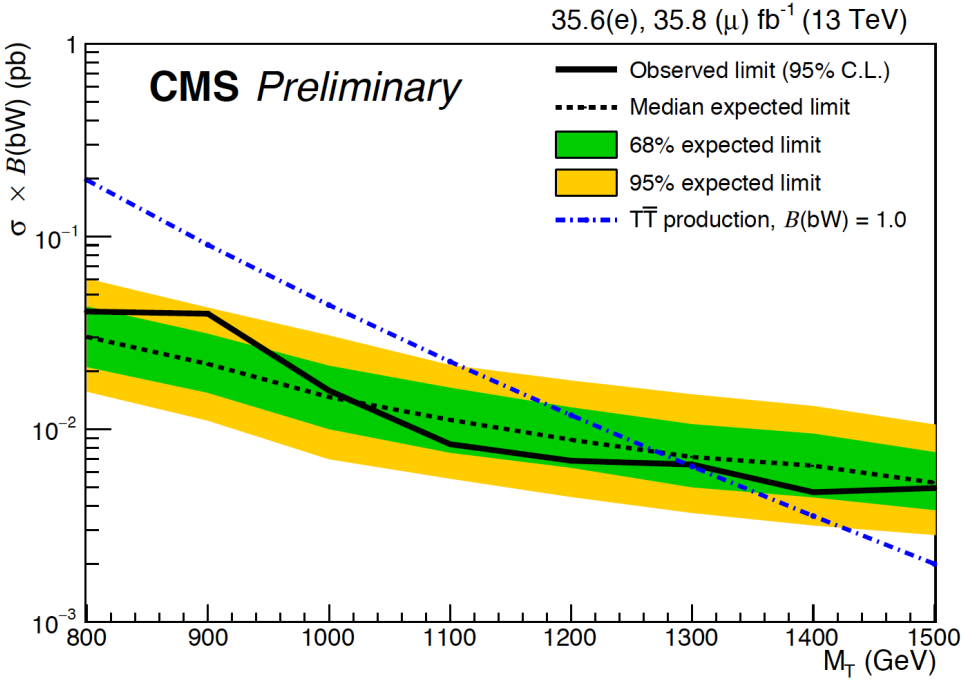
Singlet: $m_T$>**1020** (960) GeV

# $T\bar{T}\rightarrow Wb+X$

~36 fb$^{-1}$

- Focus on $T\bar{T}\rightarrow WbWb$ in the lepton+jets final state.
- Basic strategy (CMS analysis):
  - Presel: 1 lepton, ≥4 AK4 jets or 3 AK4 jets and 1 AK8 jet ($p_T$>200 GeV).
  - AK8 jet is "W-tagged" via mass cut.
  - Tight kinematic cuts, in particular $S_T$>1000 GeV.
  - Events categorized according to b-tagging.
  - Kinematic fit to reconstruct T-quark mass.




**95% CL obs (exp) limits:**

CMS (36 fb$^{-1}$): *CMS-PAS-B2G-17-003*

BR(T→Wb)=1: $m_T$>**1295** (1275) GeV

Limits also apply to $Y_{-4/3}$, as BR($Y_{-4/3}\rightarrow W^-b$)=1

ATLAS (14.7 fb$^{-1}$): *ATLAS-CONF-2016-102*

BR(T→Wb)=1: $m_T$>**1090** (980) GeV

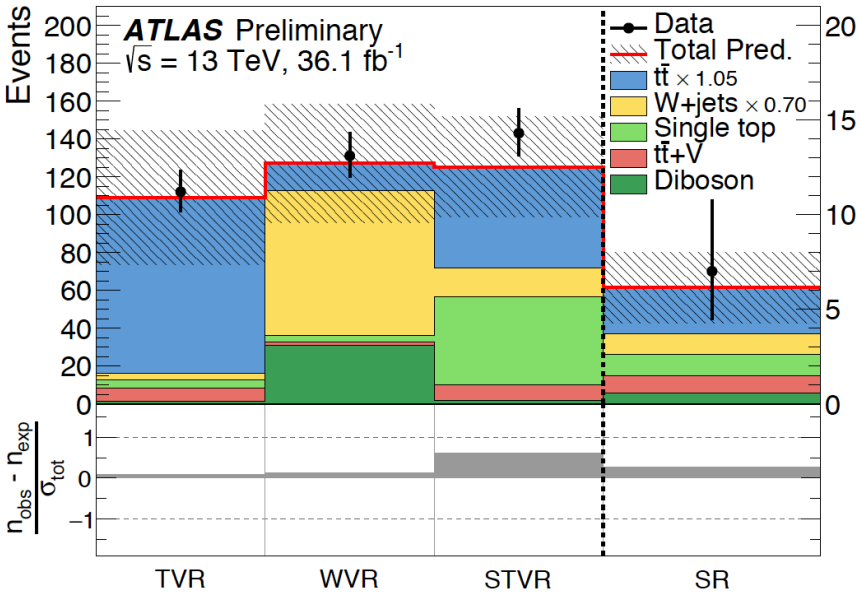
Singlet: $m_T$>**810** (870) GeV

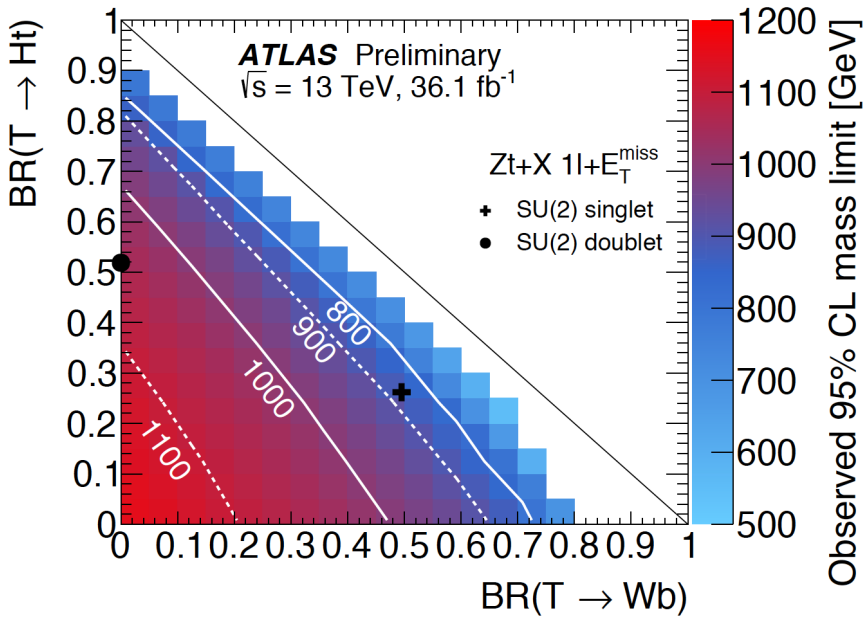
# $T\bar{T}\rightarrow Zt+X$

~36 fb$^{-1}$

- Search targeting $TT\rightarrow Zt+X$, $Z\rightarrow\nu\nu$.
- Basic strategy:
  - Presel: 1 lepton, $E_T^{miss}$>300 GeV, ≥4 jets, ≥1 b-tag.
  - Signal region defined through tight cuts to suppress $t\bar{t}$ background (on $m_{T,W}$, $am_{T2}$, ≥2 large-R jets, etc).
  - Control regions used to normalize $t\bar{t}$ and W+jets bkgs in signal region.
  - Background prediction checked in dedicated validation regions.

*ATLAS-CONF-2017-015*




**95% CL obs (exp) limits:**

BR(T→Zt)=1: $m_T$>**1.16** (1.17) TeV

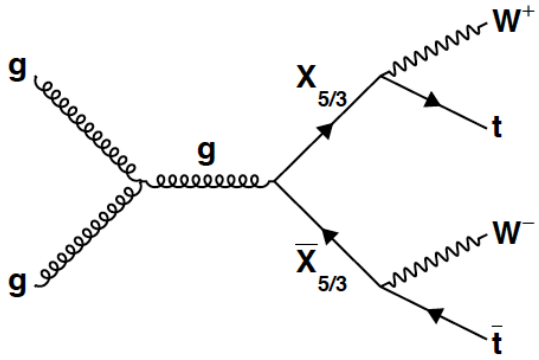
Doublet: $m_T$>**1.05** (1.06) TeV

Singlet: $m_T$>**870** (980) GeV

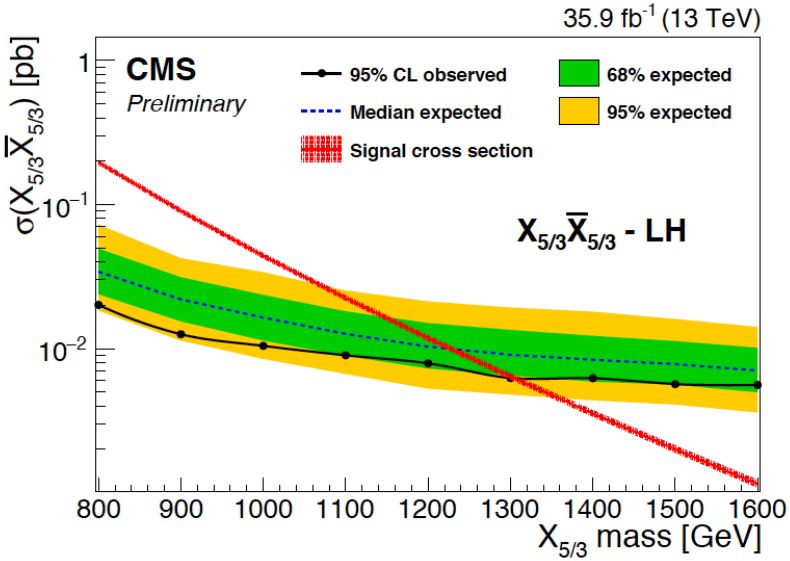
# $X_{5/3}\bar{X}_{5/3}\rightarrow tWtW$

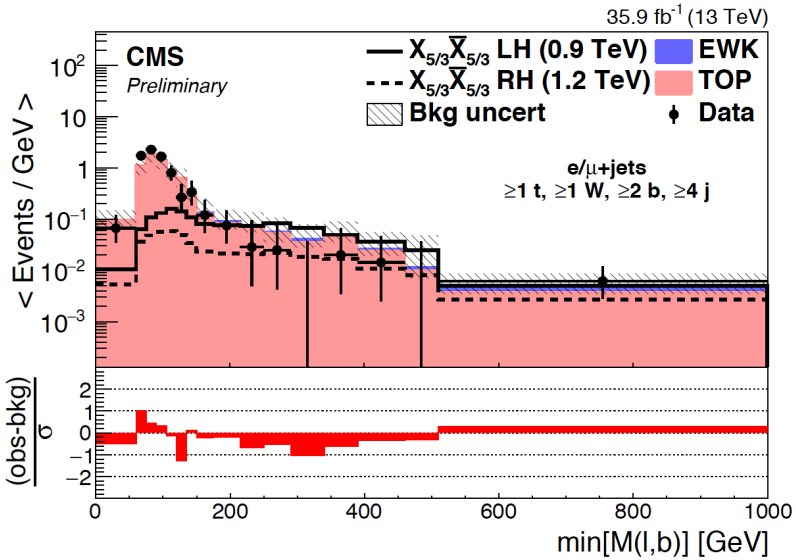
~36 fb$^{-1}$

- Searches targeting pair production of $X_{5/3}$, with $X_{5/3}\rightarrow tW^+\rightarrow W^+W^+b$.
- Consider SS dilepton (+additional jets or leptons) and lepton+jets signatures, both with comparable sensitivity.
- Basic strategy (lepton+jets):
  - Presel: 1 lepton ($p_T$>80 GeV), $E_T^{miss}$>100 GeV, ≥4 jets $p_{Tj1,j2}$>450,150 GeV, ≥1 b-tags.
  - Events separated into 16 categories depending on lepton flavor (e, μ), b-tags (1, ≥2), W-tags (0, ≥1), and top-tags (0, ≥1).
  - Analyze min[M(l,b)] spectrum in all regions.




*CMS-PAS-B2G-16-019*
*CMS-PAS-B2G-17-008*




**95% CL obs (exp) limits:**

RH: $m_T$>**1.32** (1.23) TeV

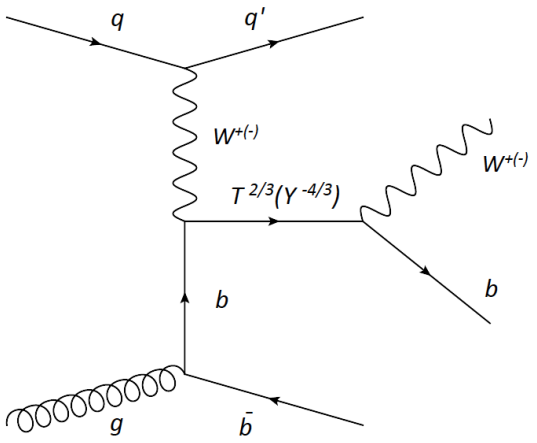
LH: $m_T$>**1.30** (1.23) TeV

# Single T(→Wb)+X

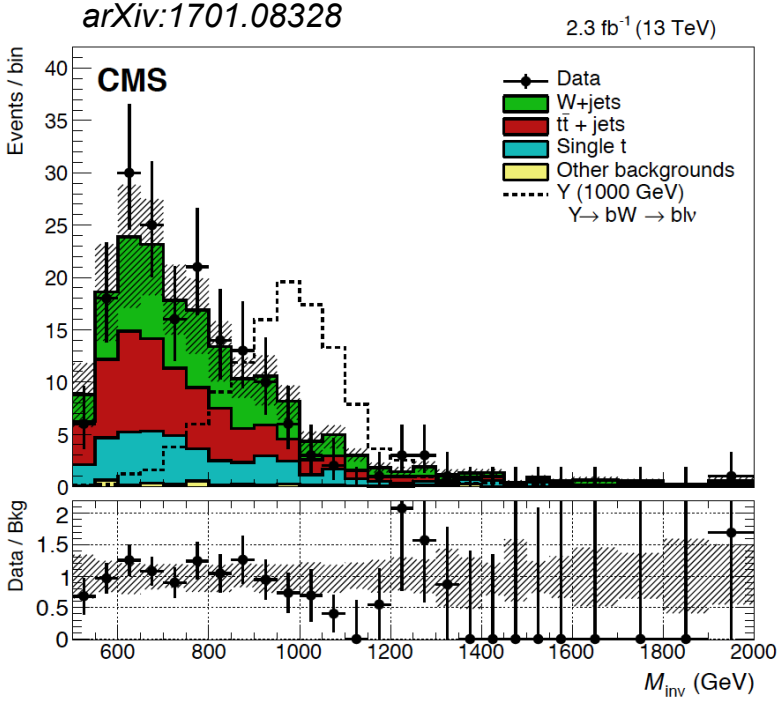
~2-3 fb$^{-1}$

Basic strategy:

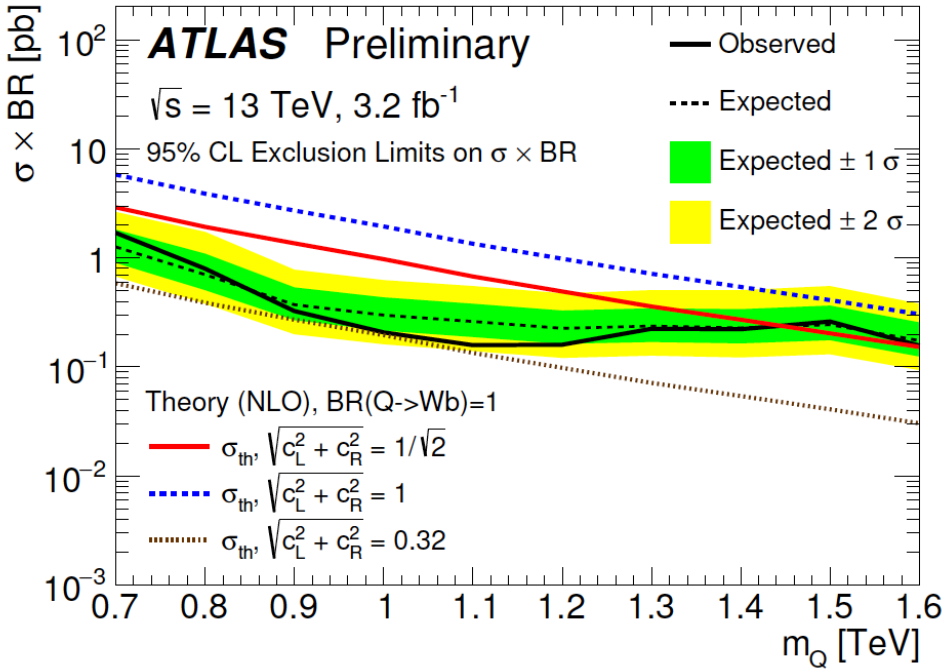
- Presel: 1 lepton, high $E_T^{miss}$, ≥1 hard central jet b-tagged, 1 forward jet.
- Additional tight kinematic requirements.
- Kinematic reconstruction of leptonic W candidate and pairing with b-tagged central jet to estimate heavy quark mass.
- Main backgrounds: $t\bar{t}$ and W+jets. Estimated using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




arXiv:1701.08328




ATLAS-CONF-2016-072

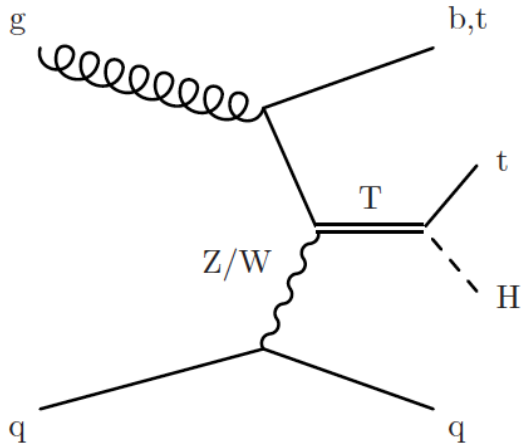



Comparable limits between ATLAS and CMS

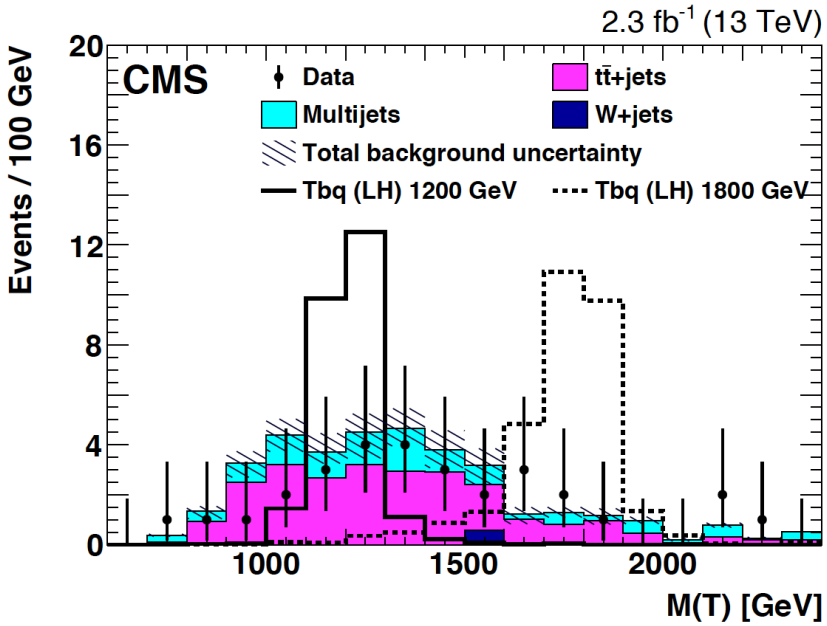
# Single T(→Ht)+X

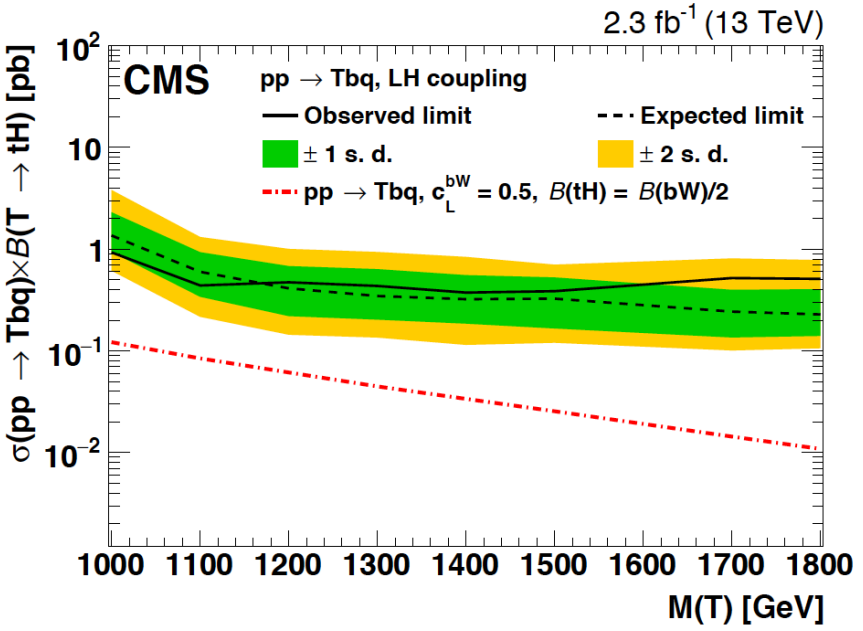
~2 fb$^{-1}$

- 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 AK4 jets ($p_T$>30 GeV), ≥1 AK8 jets ($p_T$>300 GeV), $H_T$>1100 GeV.
  - Top and Higgs tagging on AK8 jets using a combination of jet substructure variables and b-tagging requirements.
  - Main background: $t\bar{t}$ and multijet. Multijet estimated using data-driven techniques.




*arXiv:1612.00999*
*arXiv:1612.05336*



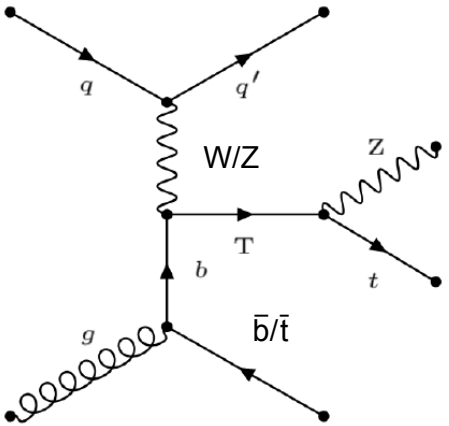



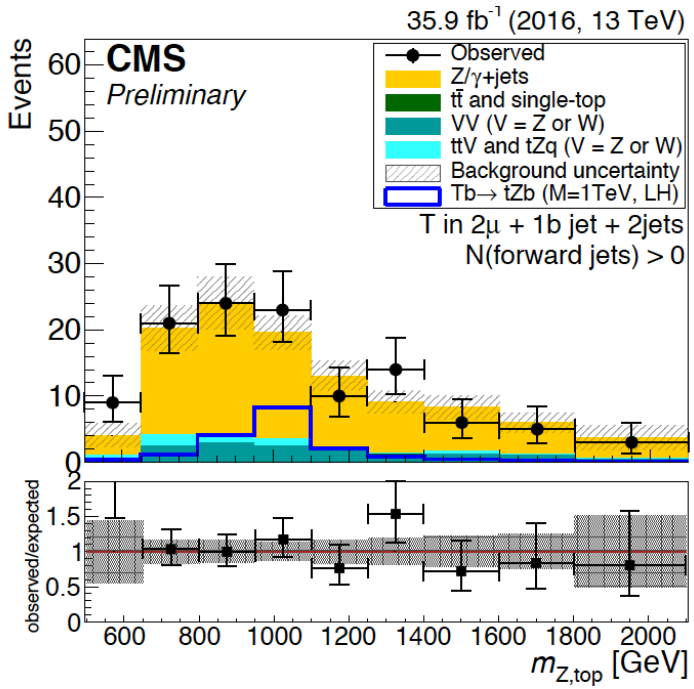
# Single T(→Zt)+X

~36 fb$^{-1}$

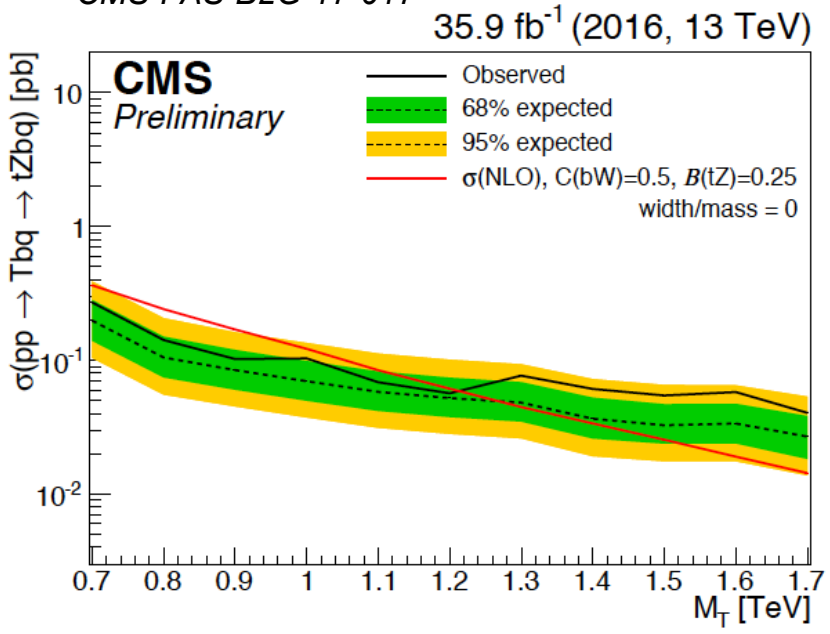
Basic strategy:

- Presel: Z(→ll)+jets, ≥1 b-tags, small ΔR(ll)
- Top-tagging and W-tagging on AK8 jets.
- Events separated into 10 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 and top candidates.
- Main background: Z+jets. Estimated using dedicated control regions.



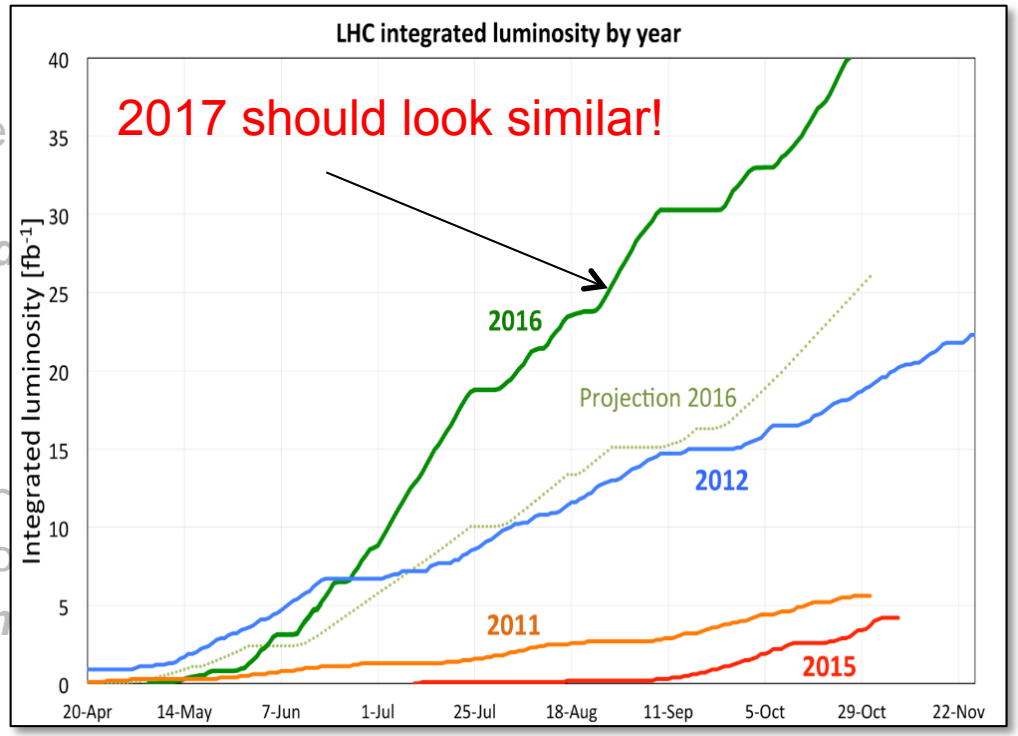




CMS-PAS-B2G-17-017



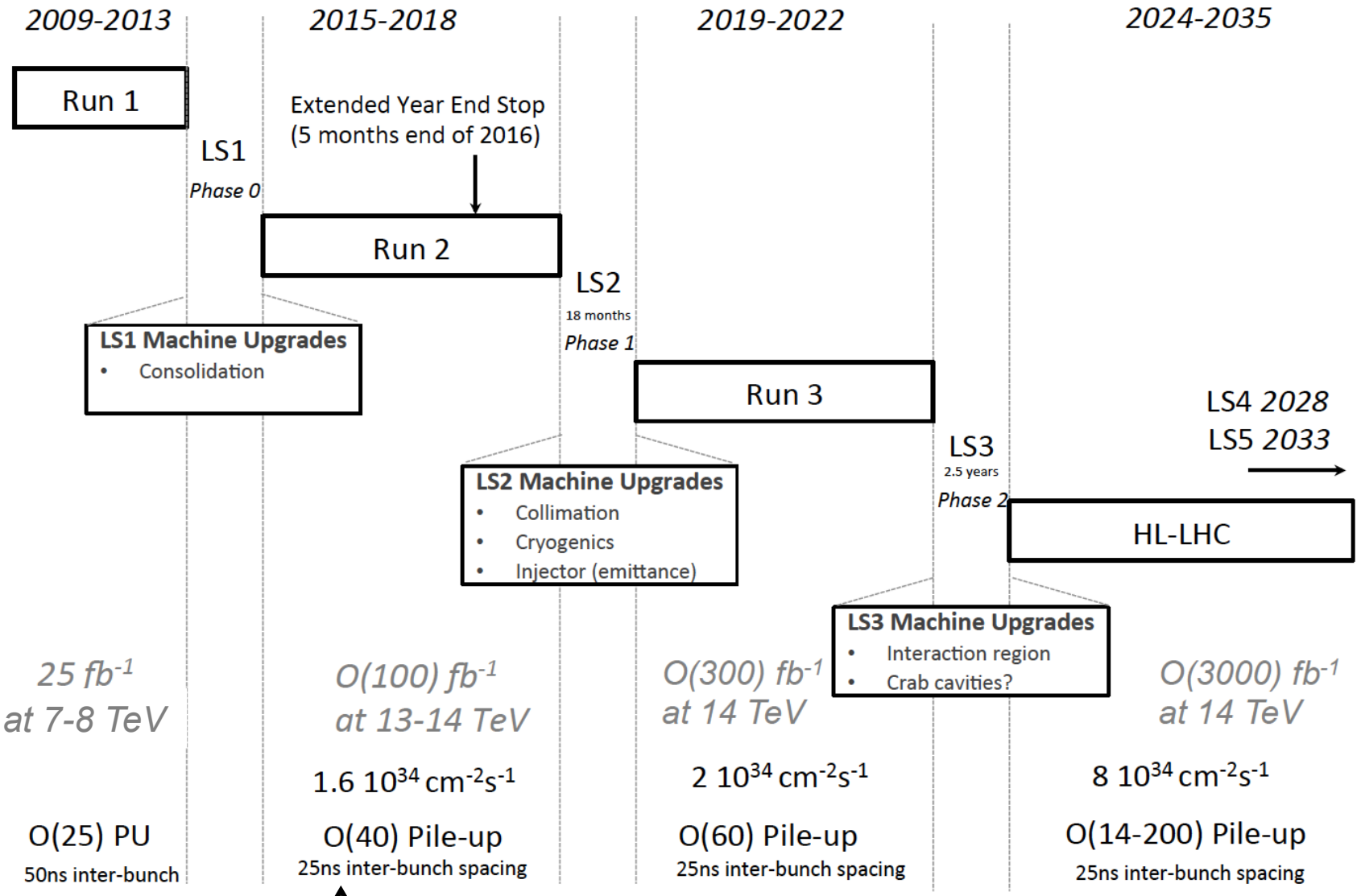
# Basic Plan for Run 2

- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- **Plan according to integrated luminosity**
  - **2015**: 3.9 $fb^{-1}$ recorded
    - High-priority to checking Run
    - For the most part Run 1-style early data.
    - ***First results already exceed sensitivity*!**
  - **2016**: 35.6 $fb^{-1}$ recorded
    - Exceed design luminosity of ~
    - Record daily delivered lumino
    - ***Significant discovery poten***
  - **2017 and beyond**:
    - Beam commissioning ongoing. Will start run at the end of May.
    - Expect 45 $fb^{-1}$ delivered in 2017.
    - Expect ~120 $fb^{-1}$ by end of Run 2 (2015-2018)!



# The LHC Run 2 and Beyond

Eventually will multiply by x100 the 2016 dataset!




We are at the beginning of a ~20 year program!

# Basic Plan for Run 2

- 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.

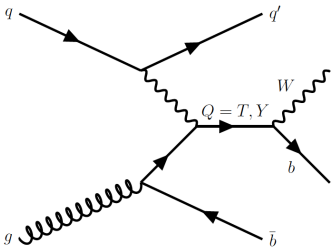
## Simplified model

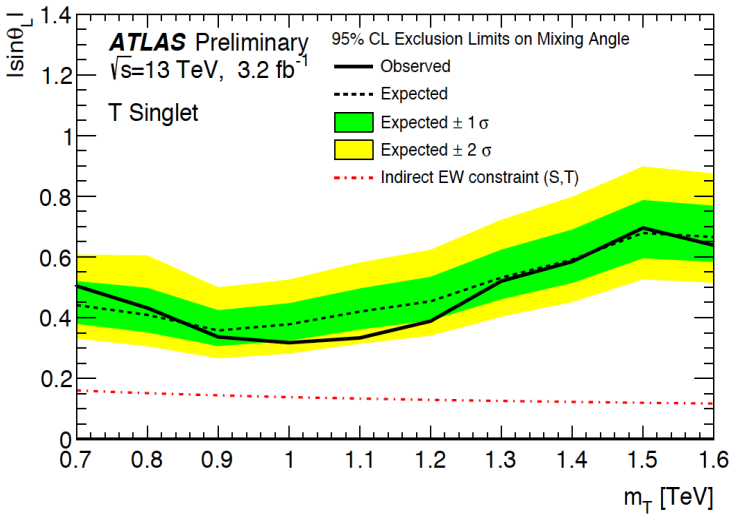
$$\mathcal{L} = \frac{g_w}{2}\left[c_R^{XV}\,\overline{X}_R \not{V} t_R + c_L^{XV}\,\overline{X}_L \not{V} t_L\right] + \frac{g_w}{2}\left[c_L^{XV}\,\overline{X}_L \not{V} b_L + c_R^{XV}\,\overline{X}_R \not{V} b_R\right] + \left[c_R^{Xh}\,h\,\overline{X}_L t_R + c_L^{Xh}\,h\,\overline{X}_R t_L\right]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

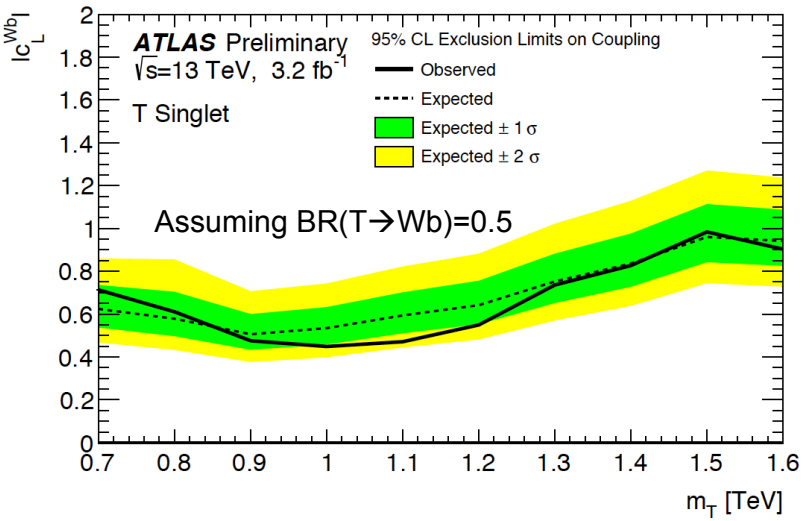
| | | couplings | | | |
|---|---|---|---|---|---|
| partner (MG name) | $Q$ | $W^\pm$ | $Z$ | $h$ | $W^\pm W^\pm$ |
| $T_{2/3}$ (T23) | 2/3 | $c_L^{TW},\ c_R^{TW}$ | $c_L^{TZ},\ c_R^{TZ}$ | $c_L^{Th},\ c_R^{Th}$ | — |
| $B_{1/3}$ (B13) | -1/3 | $c_L^{BW},\ c_R^{TW}$ | $c_L^{BZ},\ c_R^{BZ}$ | $c_L^{Bh},\ c_R^{Bh}$ | — |
| $X_{5/3}$ (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 | — | — | — | $c_L^{VW},\ c_R^{VW}$ |

*arXiv:1211.5663*

*ATLAS-CONF-2016-072*



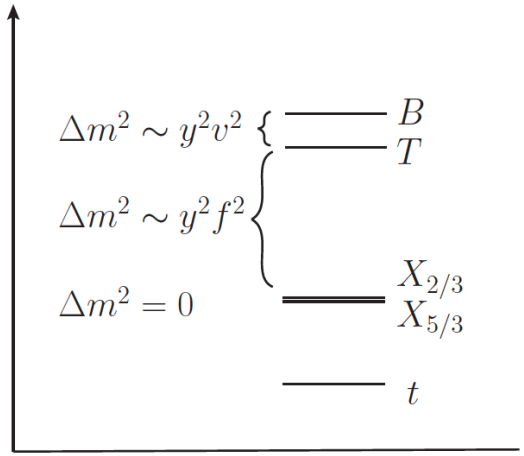



# Basic Plan for Run 2

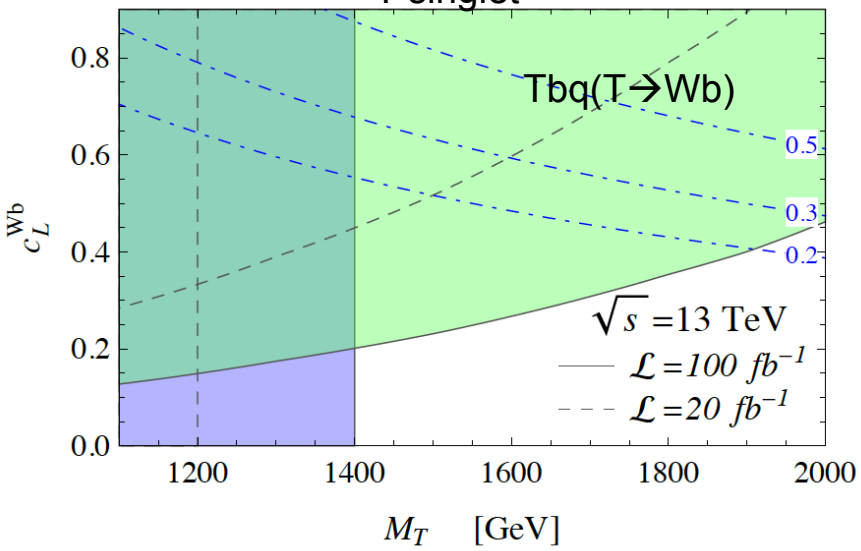
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- **Improved interpretation of searches**
  - Increased use of simplified models
  - Combination of pair and single production
  - Take into account effect of extra resonances in some cases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

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

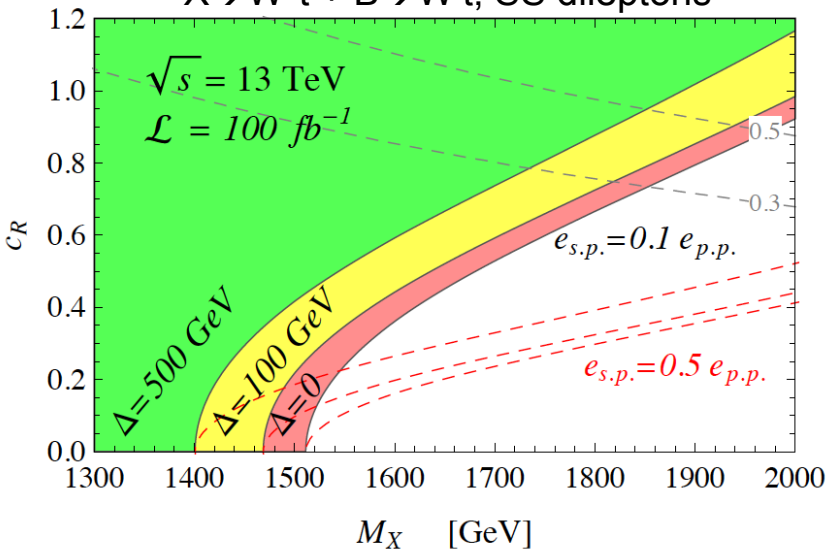



*arXiv:1409.0100*

T singlet



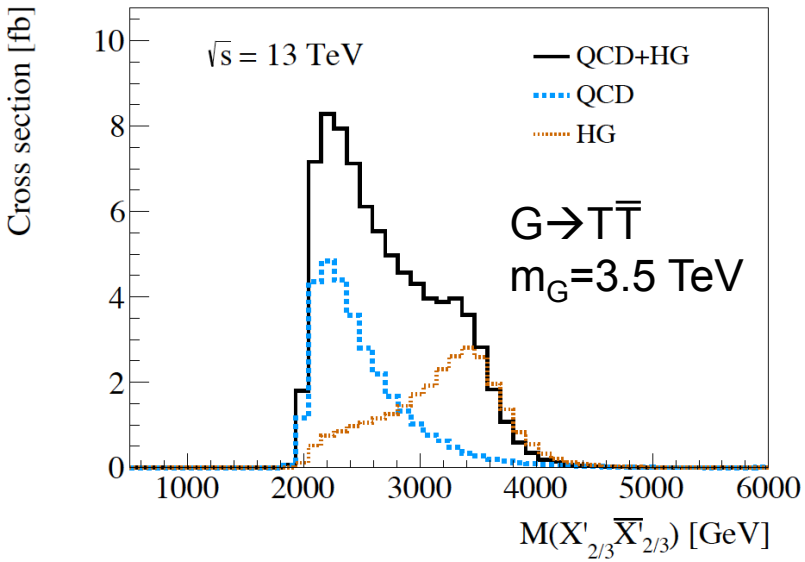

X→W⁺t + B→W⁻t, SS dileptons



# Basic Plan for Run 2

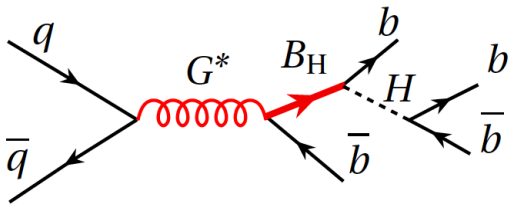
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard production
    - Heavy gluon:
      $G \rightarrow Q\bar{Q}$, $m_G \geq 2m_Q$
      $G \rightarrow Q\bar{q}$, $m_Q + m_q < m_G < 2m_Q$

*arXiv:1507.05628*



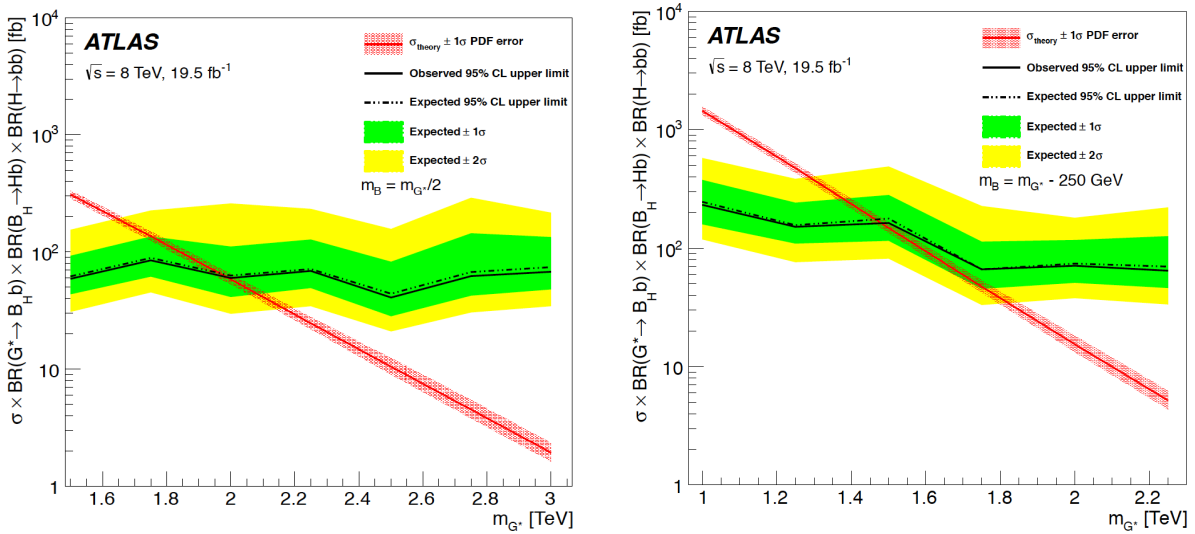

Most searches not examining $M(Q\bar{Q})$ distribution

Dedicated Run 1 search:




(proposed in *arXiv:1305.1940*)

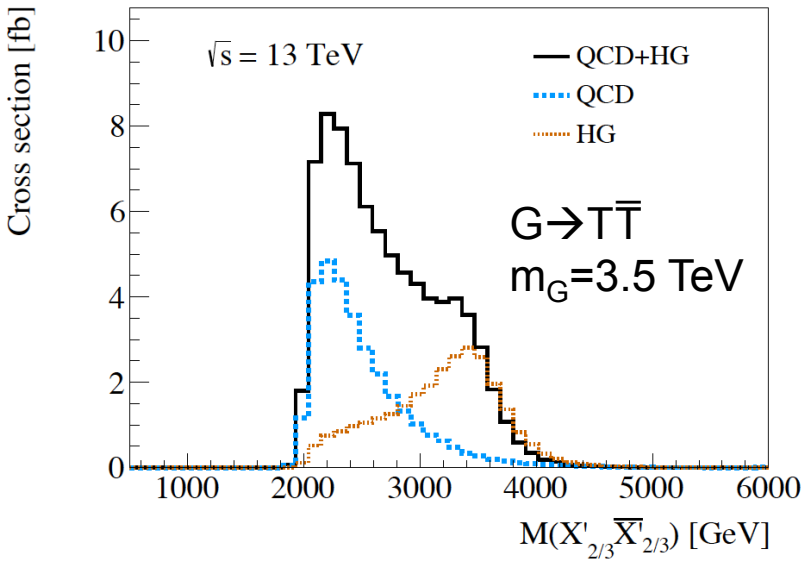
*arXiv:1602:06034*



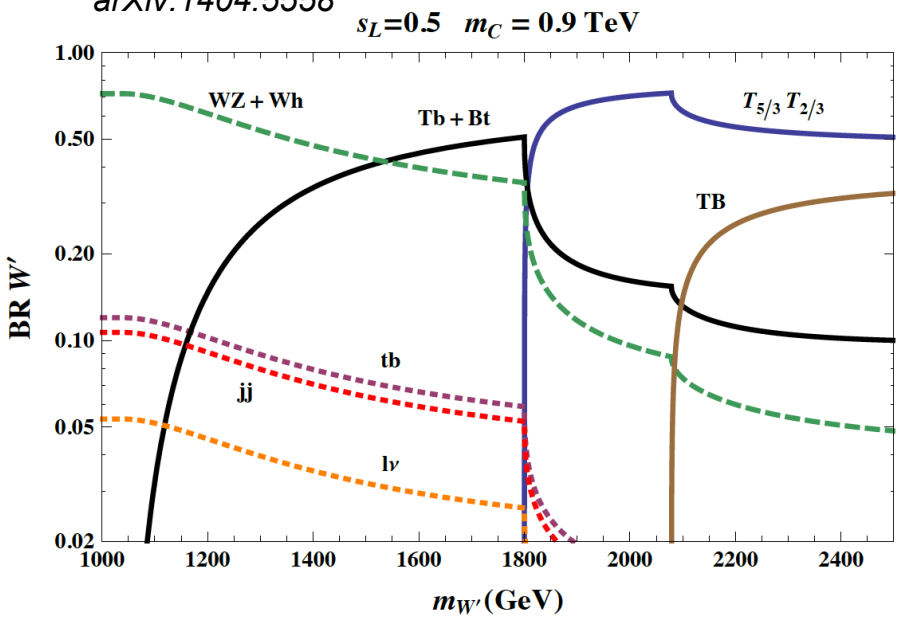
# Basic Plan for Run 2

- 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
    - Heavy gluon:
      $G \rightarrow Q\bar{Q}$, $m_G \geq 2m_Q$
      $G \rightarrow Q\bar{q}$, $m_Q + m_q < m_G < 2m_Q$
    - Heavy W'/Z':
      W'→Tb, Bt, XT, depending on custodian mass and mixing
    - …

*arXiv:1507.05628*




*arXiv:1404.5558*

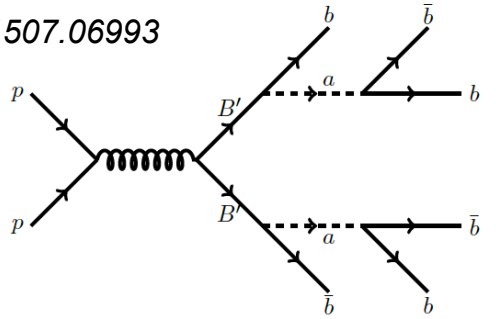


# Basic Plan for Run 2

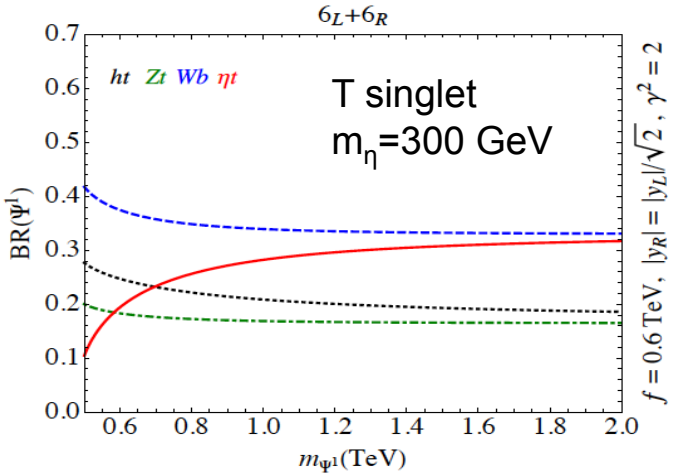
- Capitalize on Run 1 experience
- Fully exploit increased CM energy
- Plan according to integrated luminosity
- Improved interpretation of searches
- **Make sure we don't miss a signal!**
  - Non-standard production
  - Non-standard decays
    - BR(Q→Wq)+BR(Q→Zq)+BR(Q→Hq)<1
    - Examples:
      - Q→q+inv
      - Q→q+η, η CP-odd scalar
      - …
    - If exotic BRs dominant, signal may be picked by existing searches (e.g. direct sbottom searches for $B\bar{B}\rightarrow b\bar{b}+E_T^{miss}$).
    - For comparable BRs, it becomes difficult as signal split into challenging channels (e.g. $T\bar{T}\rightarrow W^+b\bar{t}gg$).

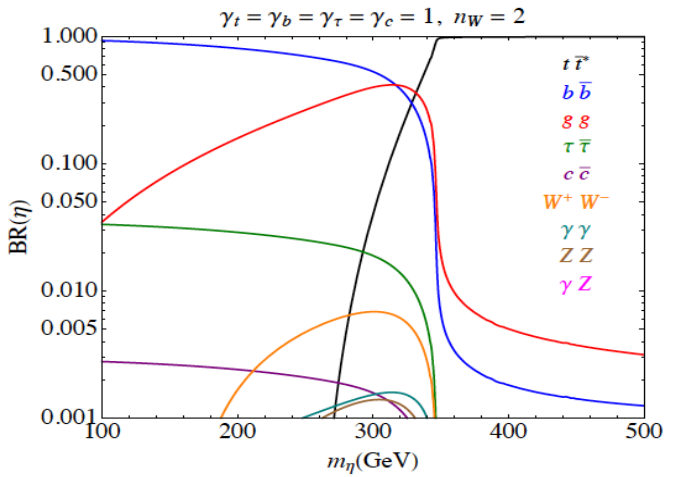
      But also promising channels: $T\bar{T}\rightarrow W^+b\bar{t}t\bar{t}$!

*arXiv:1507.06993*




*arXiv:1506.05110*



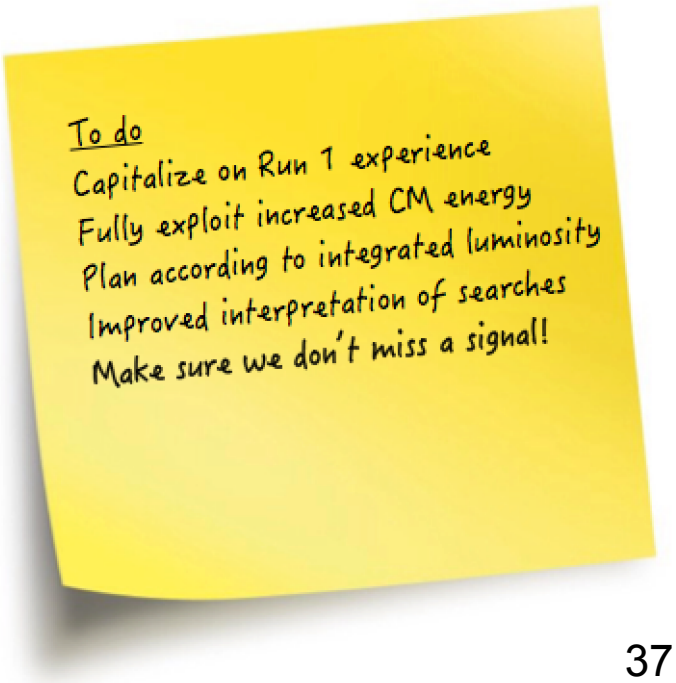
# Summary and Outlook

- Broad program of searches for pair production of VLQs during LHC Run 1.
  - VLQs with mass below ~800 GeV excluded in minimal scenarios.
  - Serves as a stepping stone for more incisive tests during Run 2.

- **Run 2 program in full swing, covering pair and single production.**
  - First results at $\sqrt{s}$=13 TeV significantly extend Run 1 sensitivity.
    Publications with 36 $fb^{-1}$ of data upcoming, including combinations.
  - With 100 $fb^{-1}$ should be able to probe VLQ masses up to 1.4 TeV via pair production and even beyond via single production, depending of the electroweak couplings.
  - Should also target bosonic resonances!

- We basically have a plan…

Exciting times ahead!



# Backup

# Vector-Like Bottom: 1-lepton Searches

- Searches targeting high BR($B_{-1/3} \rightarrow W^{-}t$), but also sensitive to other decay modes.
- Basic strategy:

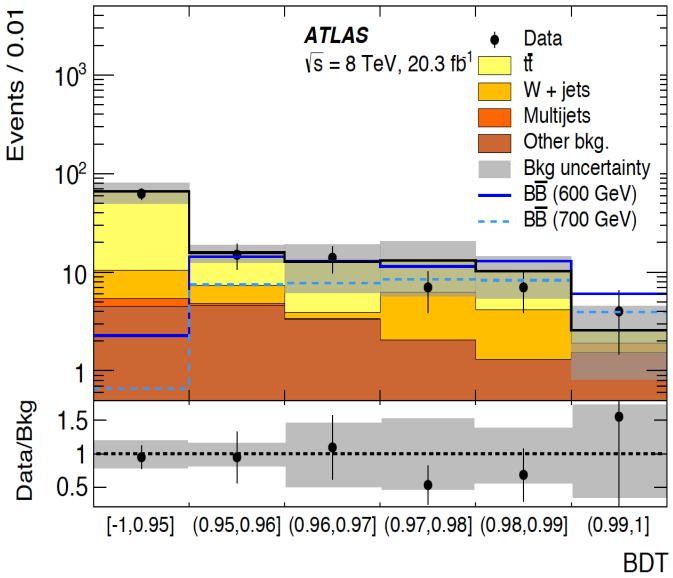
**ATLAS**

- Preselection: 1 lepton, ≥6 jets w/ $p_T$>25 GeV ≥1 b-tags, $H_T$>500 GeV
- ≥1 hadronic W/Z candidate
  - Dijet pair with $\Delta R_{jj}$<1.0, $p_{T,jj}$>200 GeV, 60<$m_{jj}$<110 GeV
- Uses BDT as final discriminant variable.

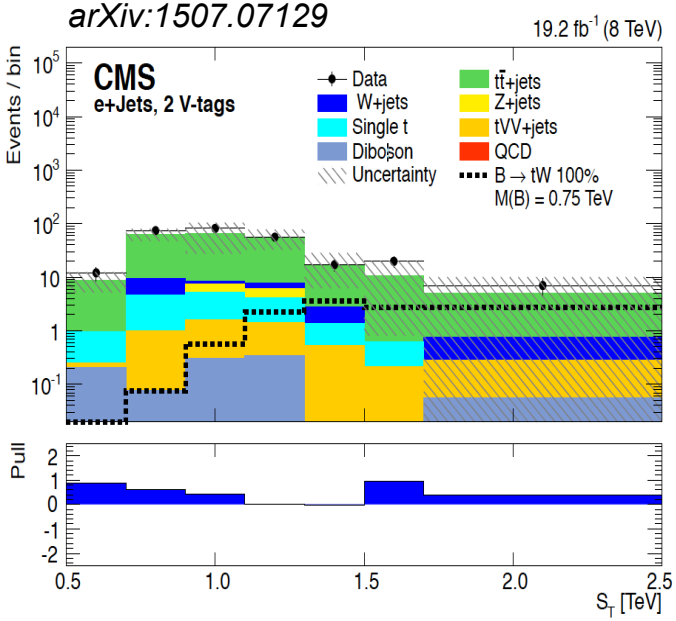
**CMS**

- Preselection: 1 lepton, ≥4 jets w/ $p_T$>200,60,40,30 GeV, ≥1 b-tags
- Categorize events in 0, 1, ≥2 tagged W/Z candidates
  - CA R=0.8 jets, $p_T$>200 GeV, pruned/mass drop, 50<$m_j$<150 GeV
- Uses $S_T$ as final discriminant variable.

*arXiv:1503.05425*




*arXiv:1507.07129*




95% CL obs (exp) limits [100% WtWt]:

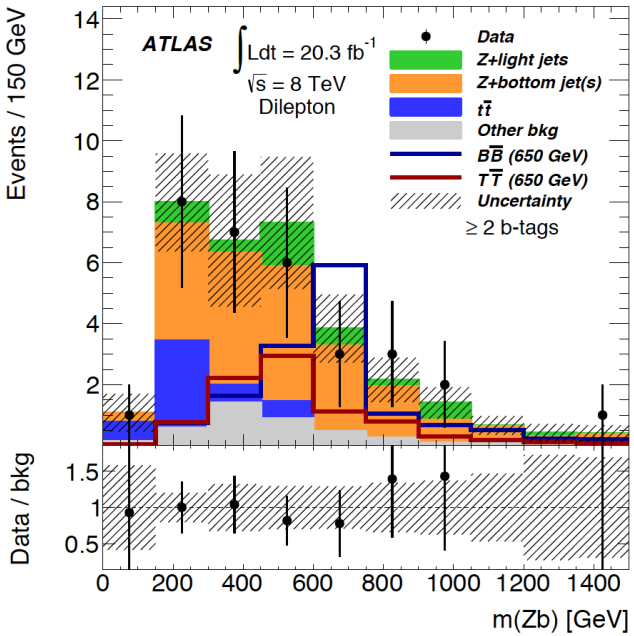
ATLAS: $m_B$>**810** (760) GeV

CMS: $m_B$>(~800) GeV

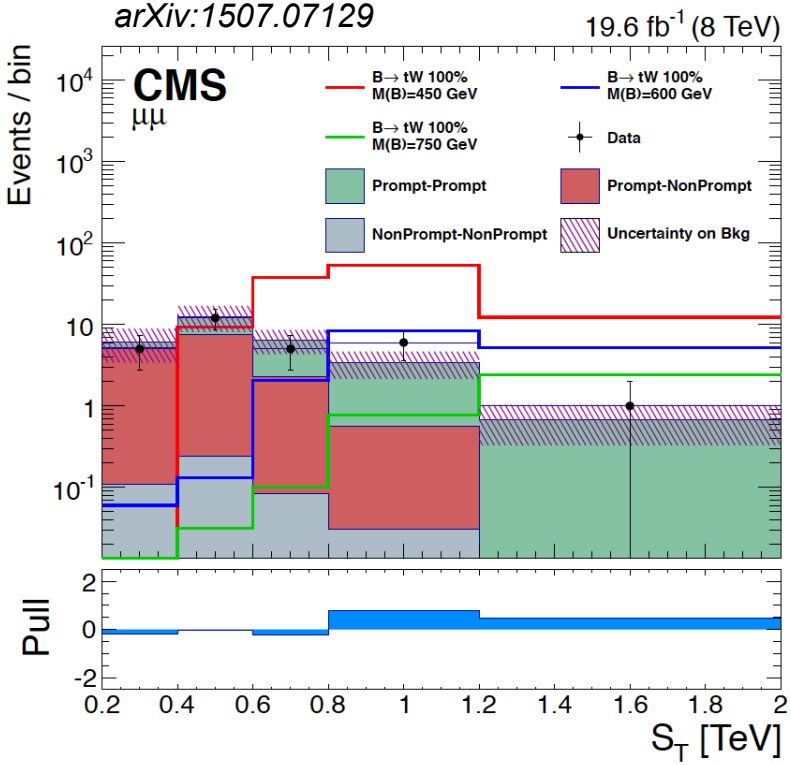
# Vector-Like Bottom: Multilepton Searches

- ATLAS: same multilepton searches used for vector-like top interpreted in the context of vector-like bottom (sometimes even better optimized for the latter, e.g. Zb+X).
- CMS: several analysis channels
  - SS 2l, ≥4 jets, $E_T^{miss}$>30 GeV; uses $S_T$
  - OS 2l, Z candidate, ≥1 b-jet, $p_{T,Z}$>150 GeV; uses M(Zb)
  - Multileptons: ≥3 leptons (incl τ), several categories depending on number of leptons and flavor; uses $S_T$

*arXiv:1409.5500*




*arXiv:1507.07129*




95% CL obs (exp) limits:

ATLAS:

BR(B→Wt)=1: $m_B$>**730** (790) GeV [Multilepton]

BR(B→Zb)=1: $m_B$>**790** (800) GeV [Zb+X]

CMS multilepton combination:

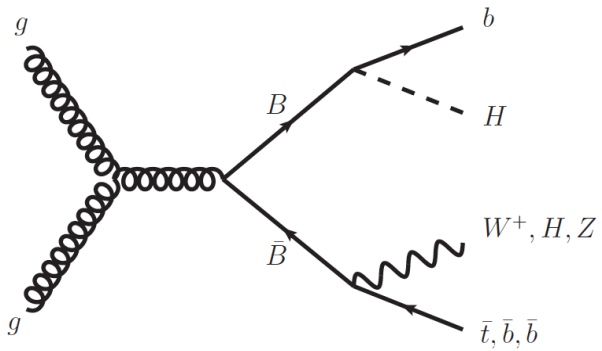
BR(B→Wt)=1: $m_B$>(~800) GeV

BR(B→Zb)=1: $m_B$>(740) GeV

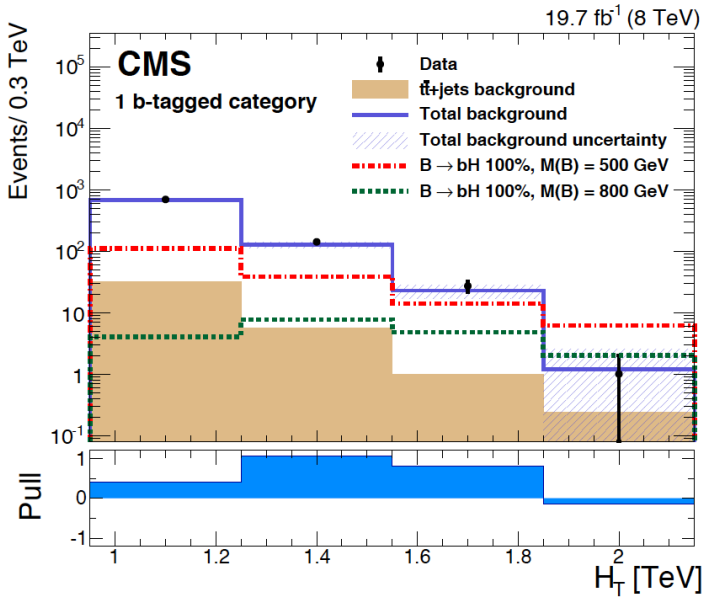
# Vector-Like Bottom: All-Hadronic Searches

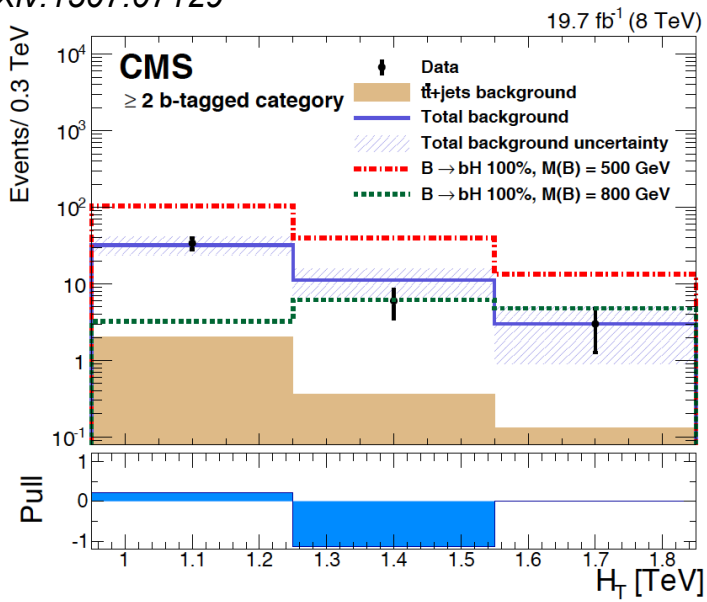
**BB→Hb+X, H→bb**

- Search targeting high BR(B→Hb), with H→bb.
- Strategy:
  - ≥1 Higgs-tagged jet
    - CA R=0.8, $p_T$>300 GeV, pruned, 90<$m_j$<140 GeV
    - 2-prong-like ($\tau_2/\tau_1$<0.5), 2 b-tagged subjets
  - $H_T$>950 GeV (from AKT5 jets with $p_T$>50 GeV)
  - ≥1 additional b-tagged AKT5 jet
  - Events categorized into =1 and ≥2 additional b-tagged jets
  - Uses $H_T$ as final discriminant



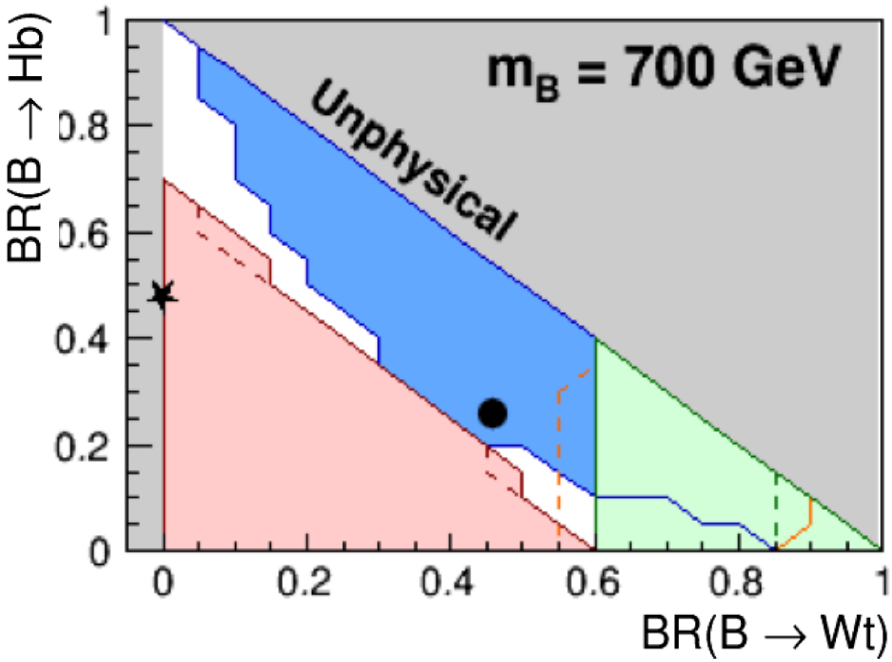

*arXiv:1507.07129*

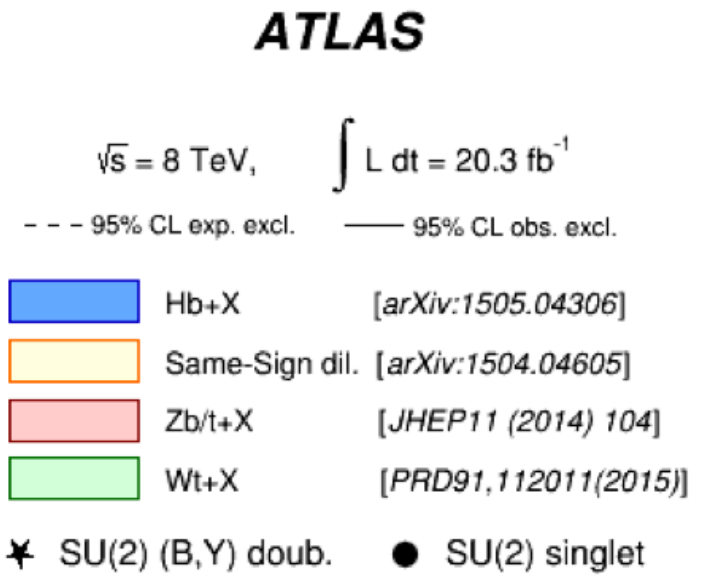


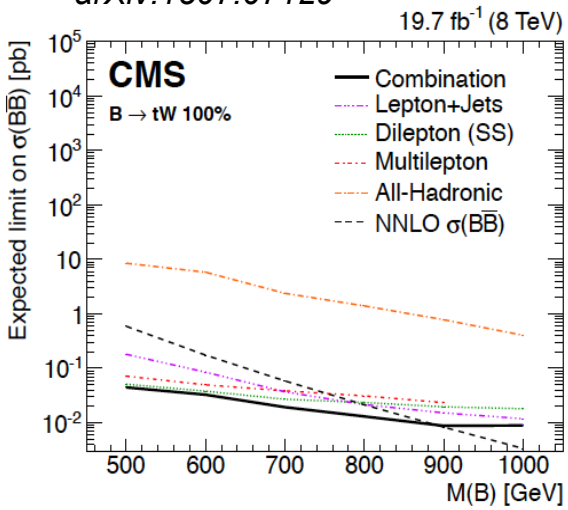

95% CL obs (exp) limits [100% HbHb]:
$m_B$>**900** (810) GeV

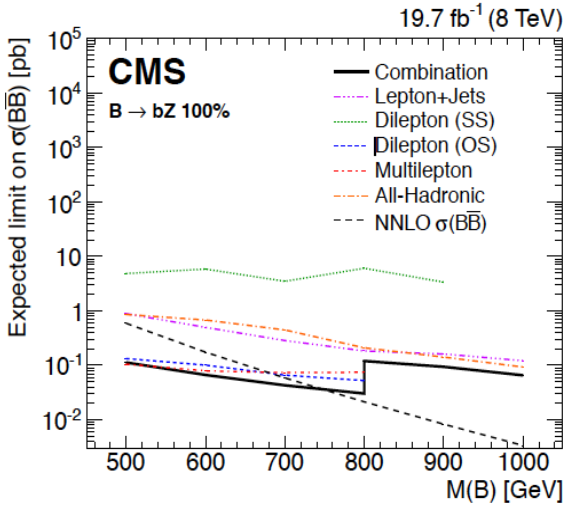
# Vector-Like Bottom: Complementarity

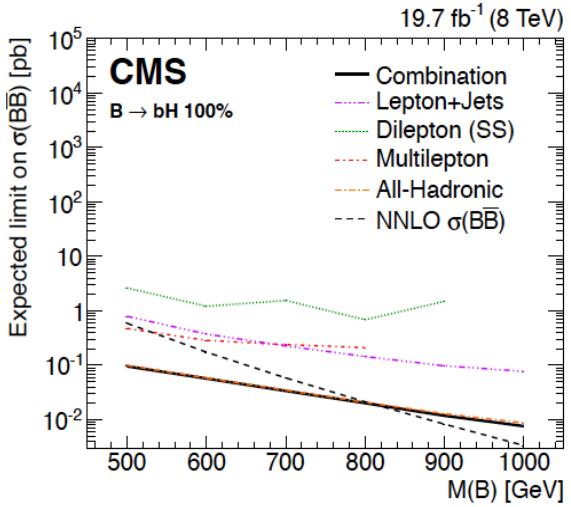



*arXiv:1507.07129*

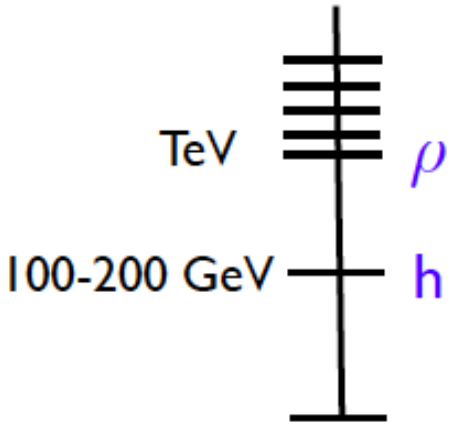


# Composite Higgs Paradigm

- Models where the Higgs boson is a composite state give a natural solution to the hierarchy problem.
- The Higgs boson can be light if it is a PNGB emerging from the breaking of a global symmetry (e.g. SO(5)→SO(4)).
- Partial compositeness:
  - SM fermions mix linearly with composite fermions.
  - Fermion mass generation needs separate composite partner for each SM fermion.




- Basic phenomenology:
  - Indirect effects:
    - deviations in top couplings to EW gauge bosons, and in precision EW observables.
    - deviations in Higgs couplings to fermions and vector bosons.
  - Direct effects:
    - New heavy gauge bosons (since vector boson scattering not fully unitarized by the composite Higgs).
    - Partially composite top quark can be strongly coupled to the composite sector ➔ anomalous four-top-quark production.
    - New fermionic resonances ➔ searches for top/bottom partners.

Pair production

- ATLAS: Zt+X (1lep+MET) 36/fb, Wb+X 13/fb, Ht+X (l+jets) 13/fb, multilep 3.2/fb
- CMS: Wb+X 36/fb, X5/3 (l+jets) 36/fb, X5/3 (2l SS) 36/fb, Ht+X (l+jets) 3.2/fb

Single production

- ATLAS: T->Wb 3.2/fb
- CMS: T->Zt (Z->ll) 36/fb, T->Wb 3/fb, T->Zt/b (Z->ll) 3/fb, T->Ht (l+jets and allhad) 2.3/fb

Heavy resonances:

- CMS: Z'->Tt, T->Wb 3/fb
- CMS: Z'->Tt, T->Zt 36/fb