Experimental results on VLQ searches

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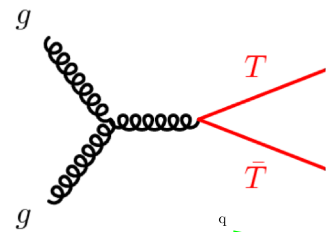
Outline

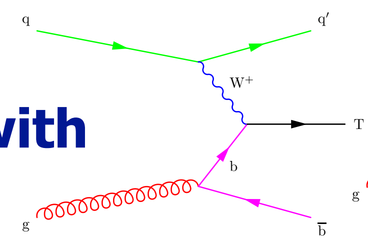
- VLQ production and decays
- Experimental apparatus and reconstruction tools
- Analysis Strategy
- Search with VLQ in decays
- Results from Pair Production
- Results from Single Production
- Last minute addition…
- Prospect (Run 3 and beyond)
- Conclusion

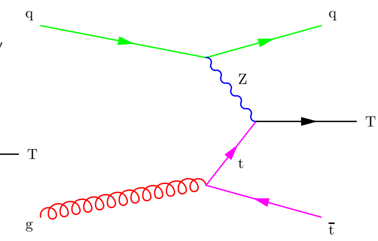
NB: Main focus here is VLQ coupling to 3rd quark generation mainly. Only one analysis looking for coupling to $1^{st}/2^{nd}$ quark generation.

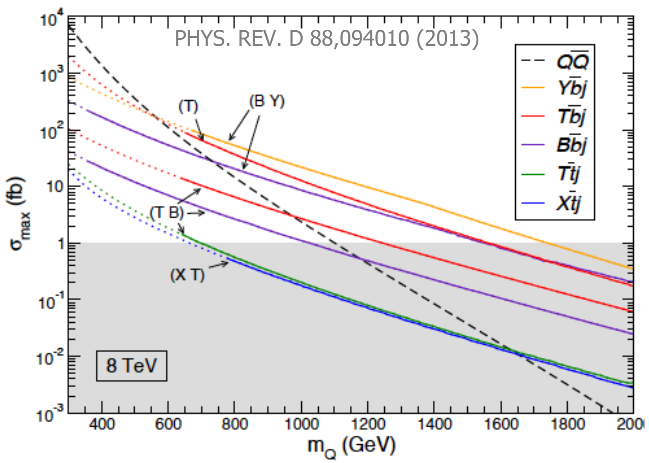
Production

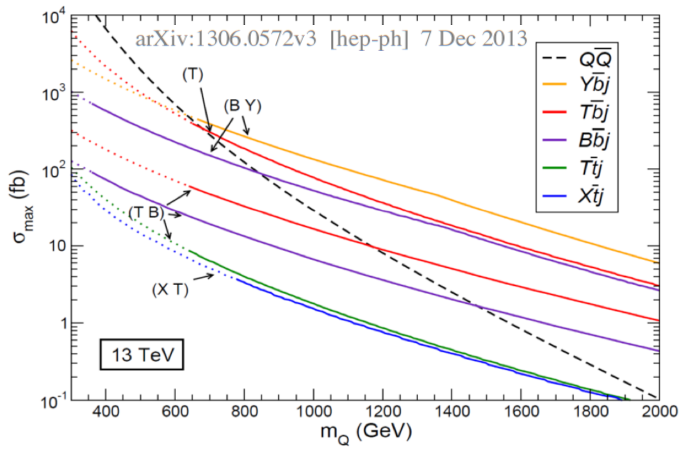
Pair-production:
Strong mechanism, the cross section depends only on the VLQ mass
Single production:
Electroweak mechanism, the cross section depends on VLQ mass and on its couplings with SM particles







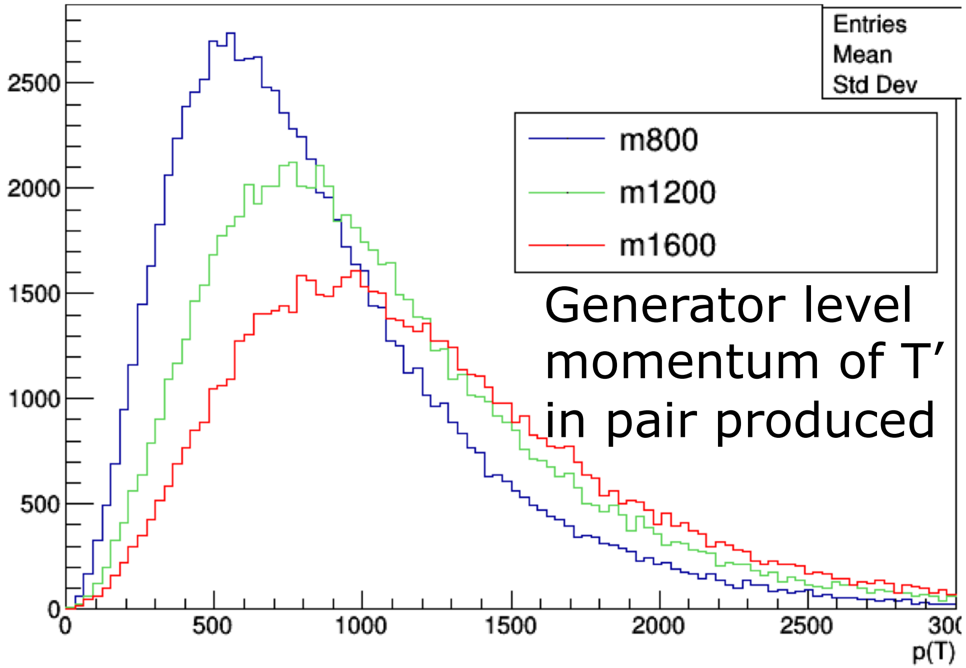




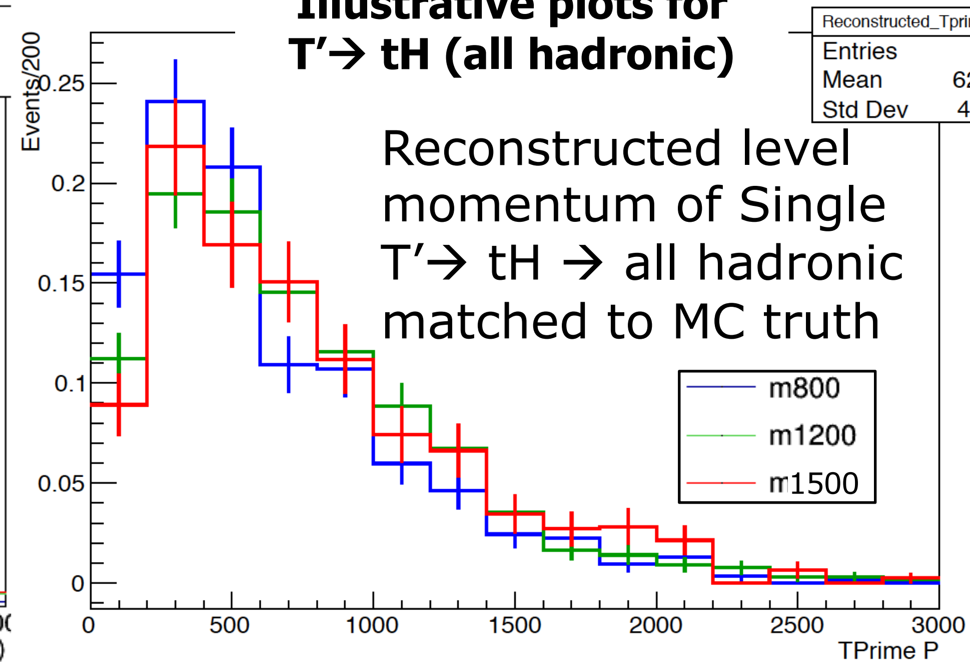
Plots above are for given benchmarks couplings but still giving an idea of what is happening…

Pair production cross section falling very rapidly and single production dominates as soon as 800 GeV for T and Y.

Pair Produced=Momentum



Illustrative plots for T'→ tH (all hadronic)



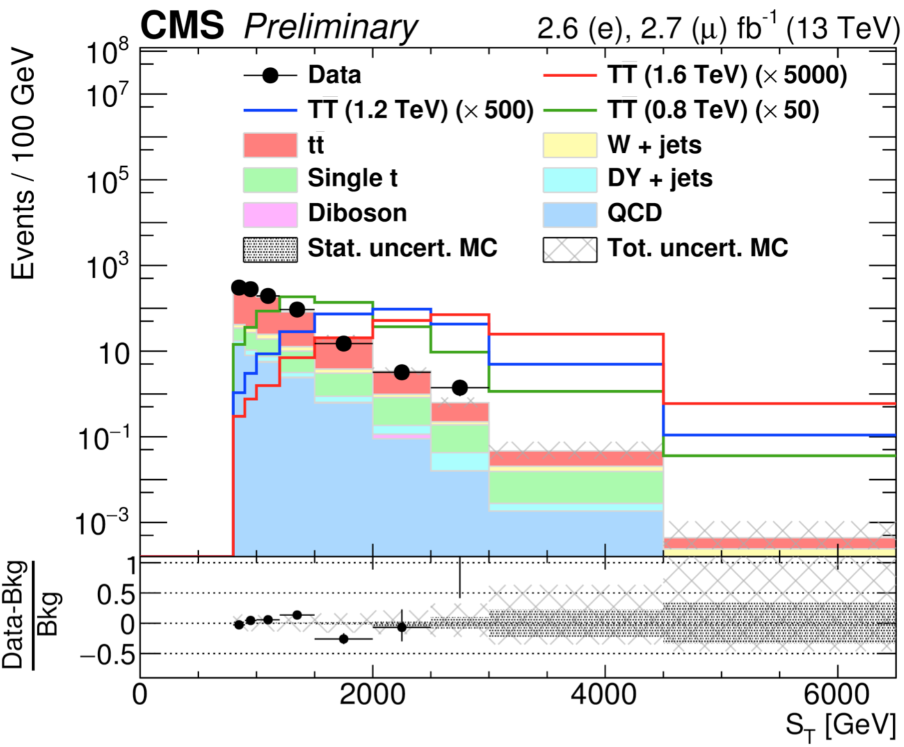
In pair production, the momentum of the produced VLQ is ~M/2, so it is increasing with mass while cross section is going down

Coming from threshold artifact linked from spin ½ (low cross section but more energy available for production)

In single production mode, the momentum does not change much with mass.

Pair Produced=Momentum

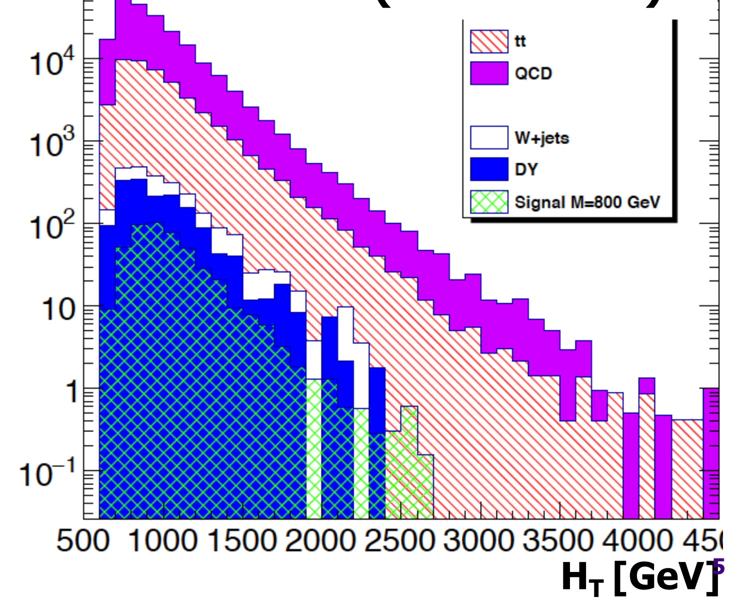
CMS PAS B2G 16 011



Typical background distribution in variable like scalar sum of pt of reconstructed object

→ Very quickly can be in configuration of "background" free analysis, so stronger limit can be set

Illustrative plots for T'→ tH (all hadronic)



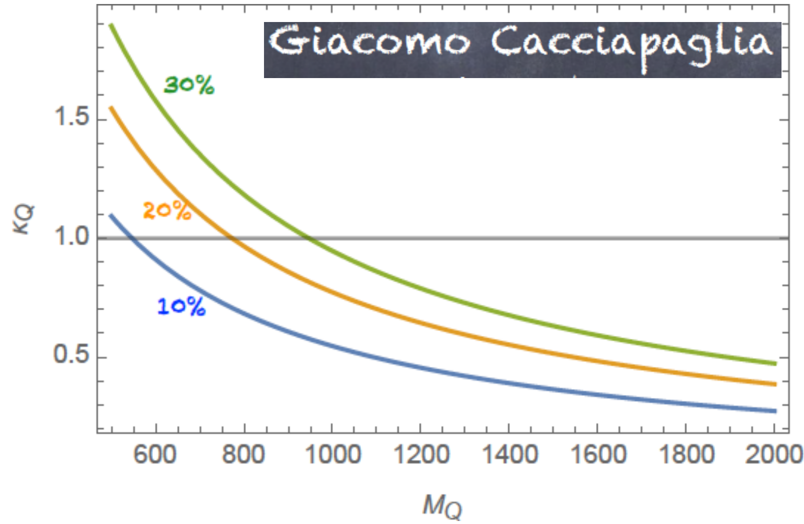
Single VLQ will tend to remain in the bulk of the background distribution
➔ Important to have dedicated analysis for single VLQ

Question of Width?

Single VLQ only EW contributions and sensitive to both the VLQ mass and its mixing parameters

→ Mixing parameters entering the width of VLQ

→ Model dependent



Currently all pair analysis only doing narrow width while acceptance/analysis selection could be not optimal for large width (as 30%)

➔ Single VLQ and pair VLQ search are complementary

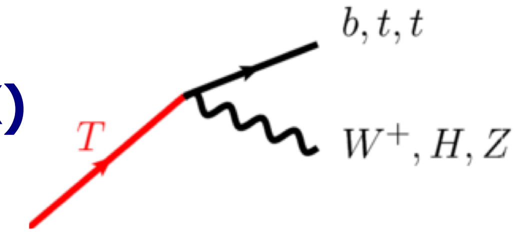
VLQ Decay

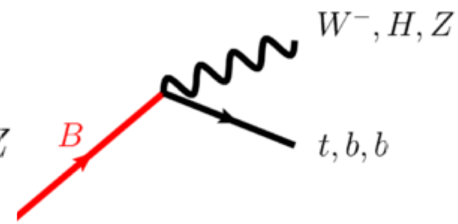
Heavy Vector like Quark

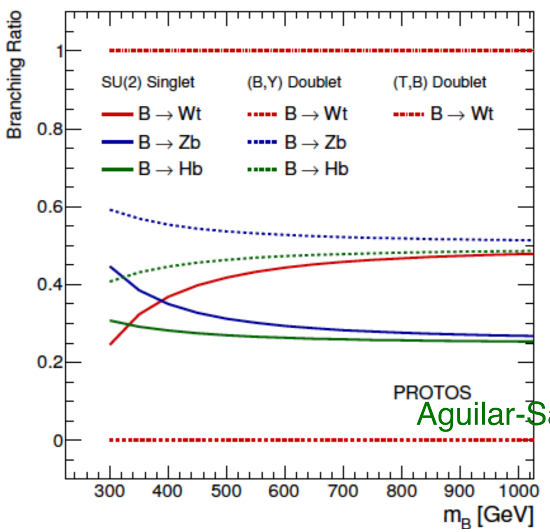
	$T \quad B$	$\binom{X}{T}\ \binom{T}{B}\ \binom{B}{Y}$	$\begin{pmatrix}X\\T\\B\end{pmatrix}\ \begin{pmatrix}T\\B\\Y\end{pmatrix}$
$SU(2)_L$ multiplet	1	2	3
Charge	2/3 -1/3	$\binom{5/3}{2/3}\ \binom{2/3}{-1/3}\ \binom{-1/3}{-4/3}$	$\begin{pmatrix}5/3\\2/3\\-1/3\end{pmatrix}\ \begin{pmatrix}2/3\\-1/3\\-4/3\end{pmatrix}$

VLQ	W-decay	Z-decay	h-decay
T	Wb	Zt	ht
B	Wt	Zb	hb
$T_{5/3}$	Wt	-	-
$Y_{-4/3}$	Wb	-	-

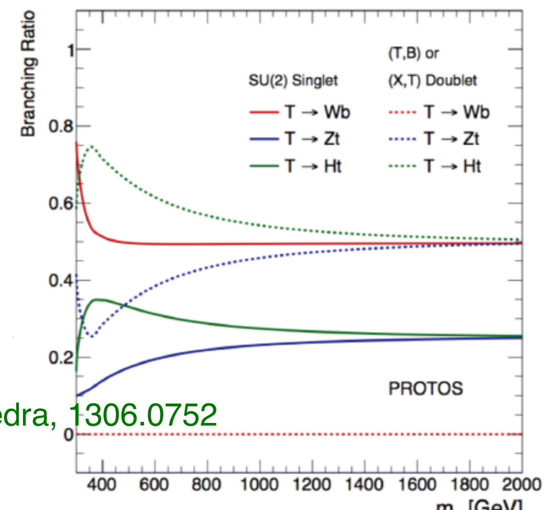
Can decay:
(equivalent for Y/X)







Aguilar-Saavedra, 1306.0752



no mixing between $B^{-1/3}$ and b for $(T,B)_R$ doublet in these plots ($\theta_R^d = 0$)

Current Focus

Pair production is leading in terms of publication as it is mainly high energy search (low background) and model independent.
BUT all searches are done in NWA approximation → Width <~5%
Larger width would be more difficult to identify (integration over larger region so background increase).

Single Production searches requests usually more time (trickier background to take into account) but also give access to model parameter so interpretation can be wider.

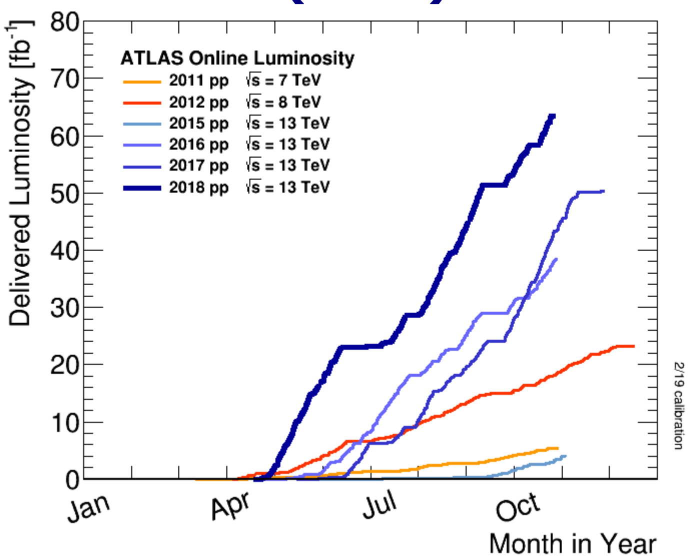
Experimental Apparatus and Tools

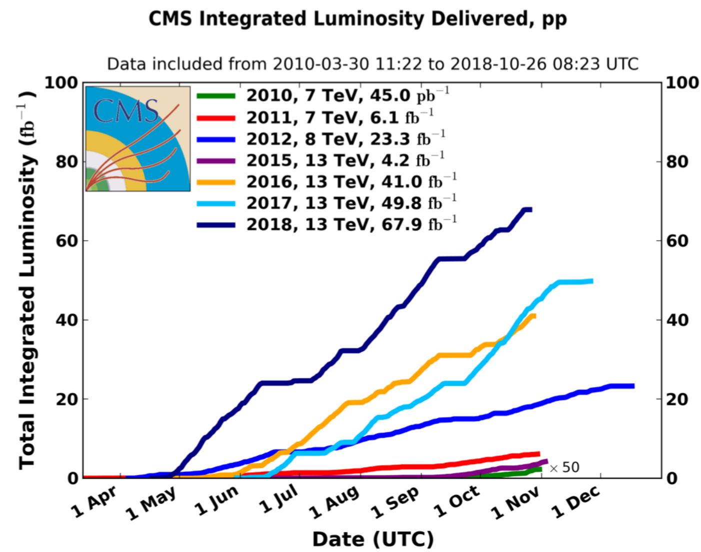
LHC has delivered pp collision to Atlas and CMS at various beam center of mass of energy since 2009.

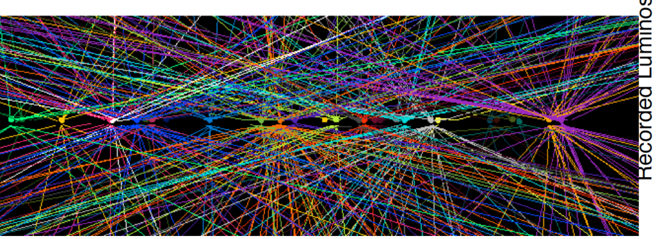
Groups of similar year:

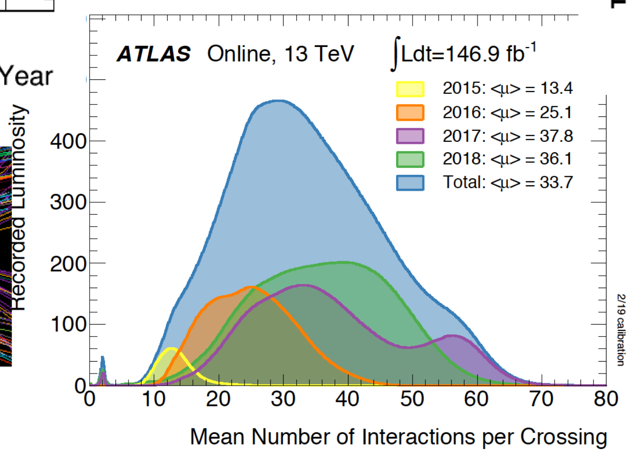
Run1 = (2010)+2011+2012 → 7/8 TeV

Run2 = (2015)+2016+2017+2018 → 13 TeV









= low pT jets (<30 GeV) but mainly present in forward region and without tracker acceptance → difficult

Generalist Detector

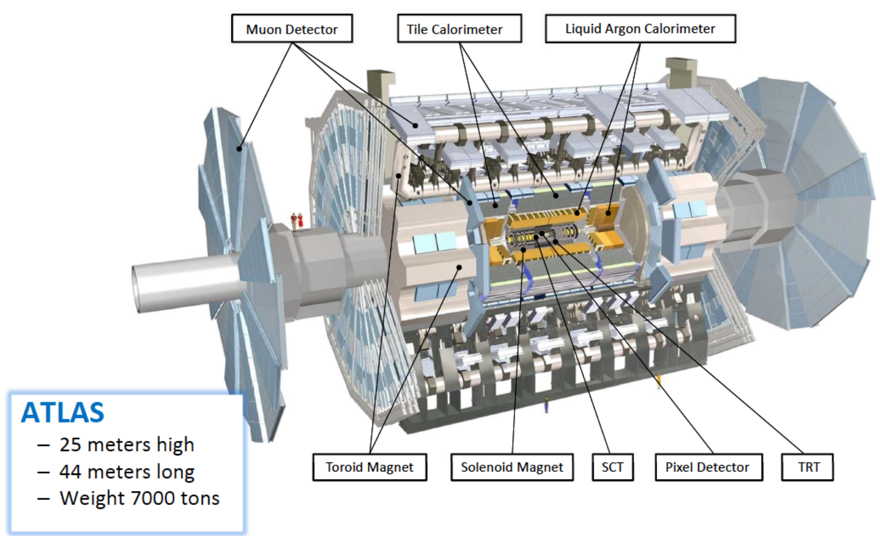
General-purpose detector: investigate largest possible physics range

Hermetic, many layers, and highly granular

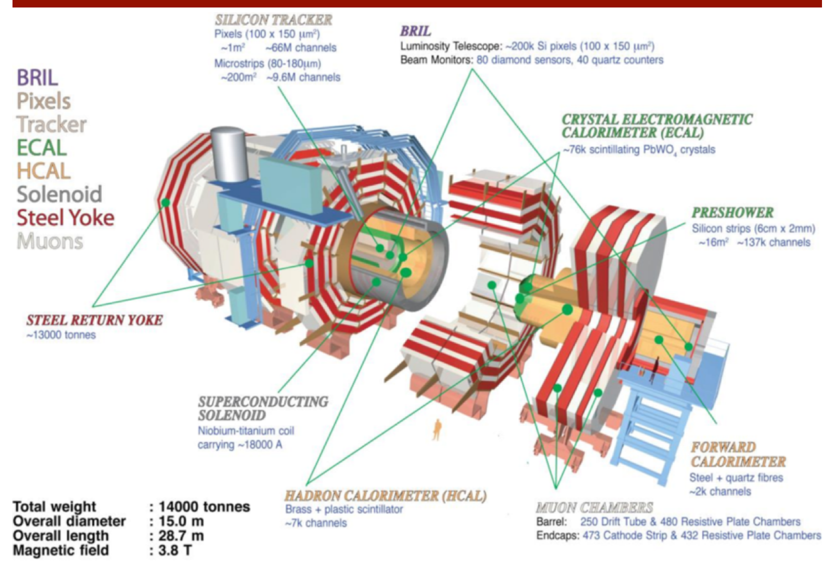
Designed to precisely reconstruct and identify decays of produced particles

Tracking acceptance ~2.5 in eta → Above no real tracking to point to vertex etc ➔ With PU, forward region is difficult to understand

The ATLAS Detector

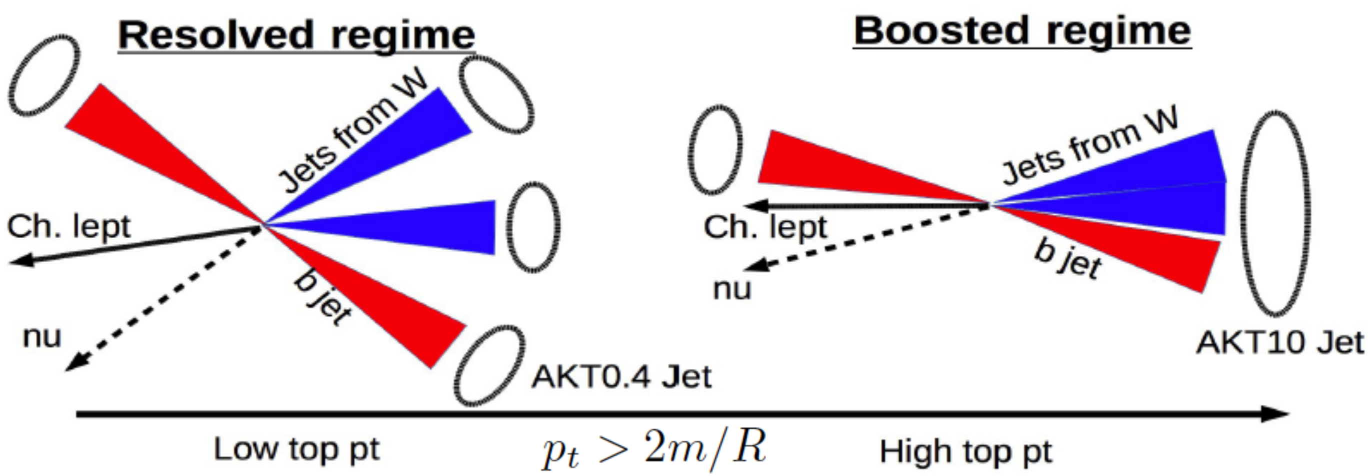


The CMS Detector



Tools

I.e. ttbar pair production:



Higher boost is given, more collimated are the decay:

Adjust reconstruction/identification variable:

Lepton isolation: with a cone size depending on pT:

i.e. Atlas: $I = \sum_R p_T^{trk}$ with $R = \min\left(\frac{10GeV}{p_T}, 0.2\ \ (0.3)\right)$ **electron/muon**

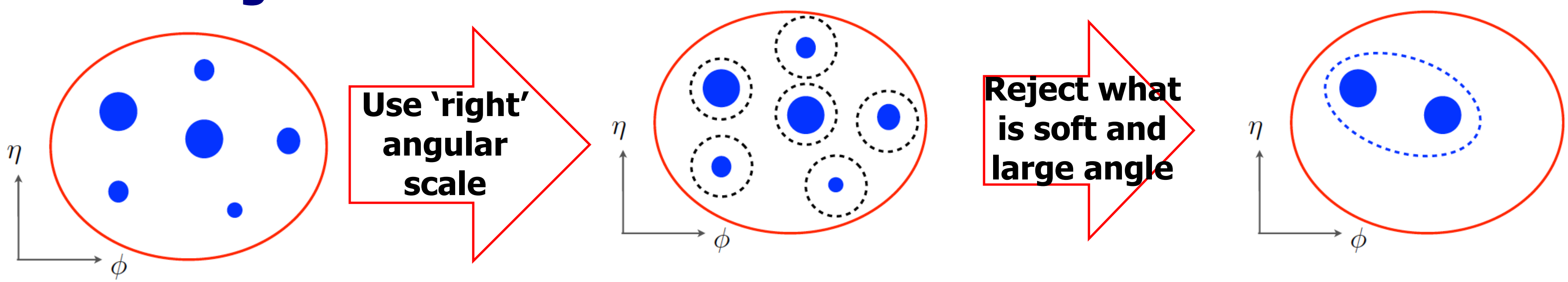
Using larger cone size for jets to get all decay in

→ Look at jet sub-structure to identify

Jets sub-structure

Exploit jet substructure: grooming and tagging

Grooming:

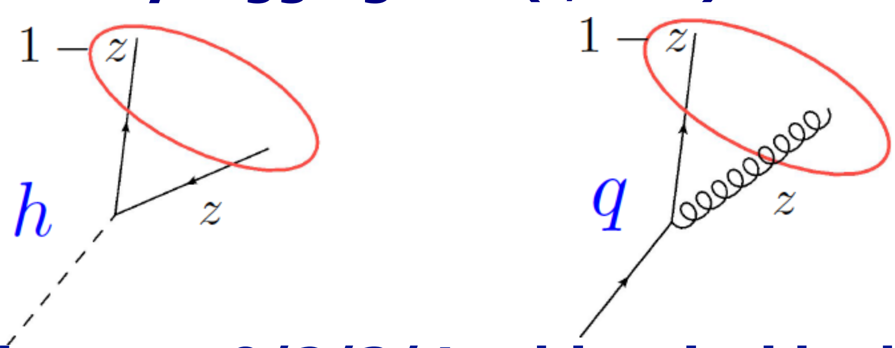


Tagging:

identify the features of hard decays and cut on them

core-idea for 2-body tagging: min(z, 1 - z) > zcut

symmetric sharing of the energy



asymmetric sharing of the energy

discriminate between0/2/3/4 subjets inside the wide jet
→N-subjettiness

Jets Multiple Taggers

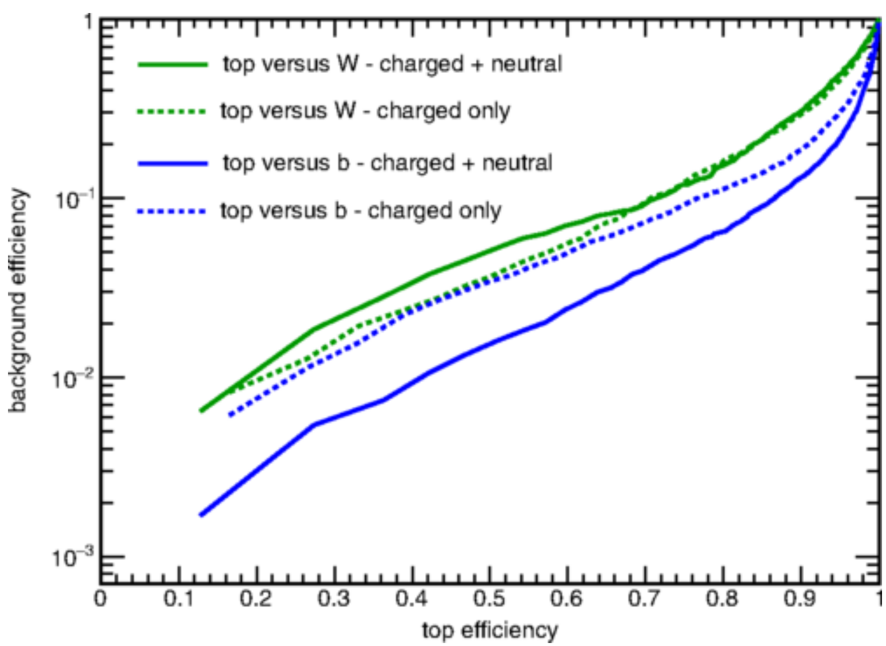
[Phys. Rev. D 94, 094027]

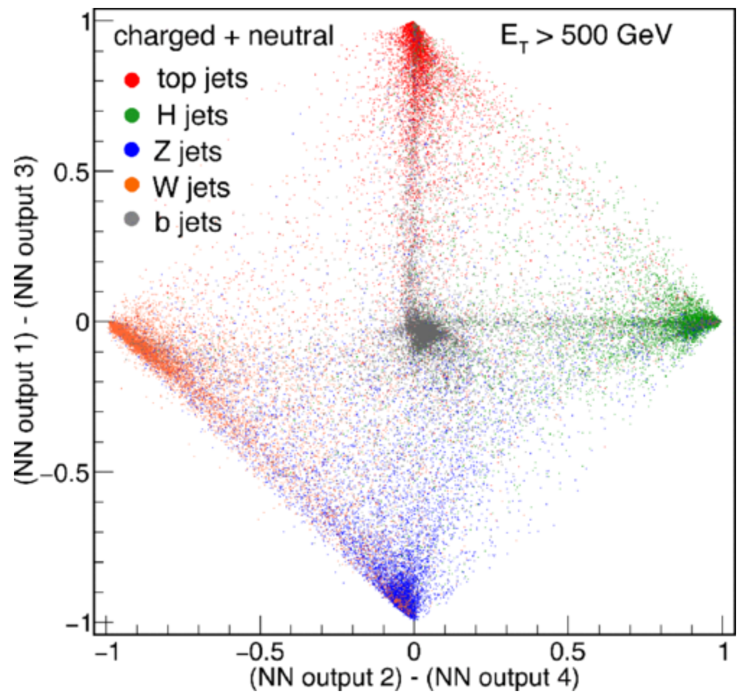
BEST algorithm = Boosted Event Shape Tagger

Using machine learning to classify a wide jet into W, Z, H, top, b or light quark jet

Main ideas:

- **Move to the rest frame of the assumed particle**
- **Use several variables to build a neural network discriminant**

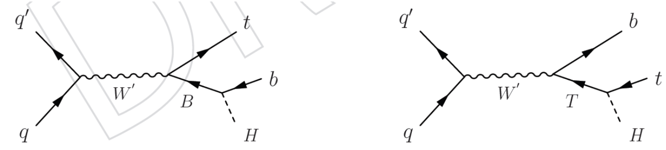




→ Use in case multiple wide jets in final state

Searches using VLQ

W’



[JHEP 03 (2019) 127]

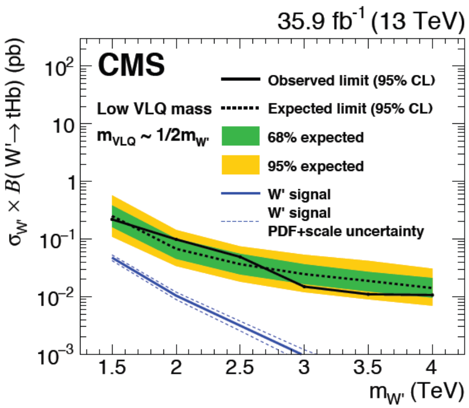
All hadronic final state for W’ search >1.5 TeV and tbH as final state

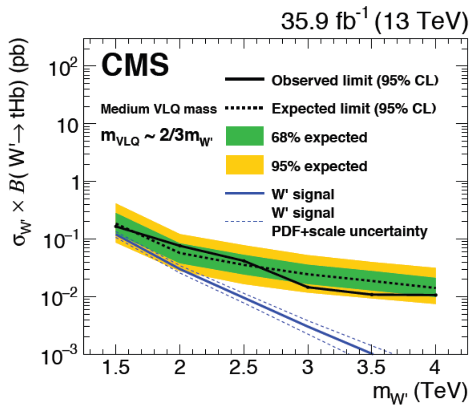
2ak8 jet: Higgs-tag + 1 top-tag

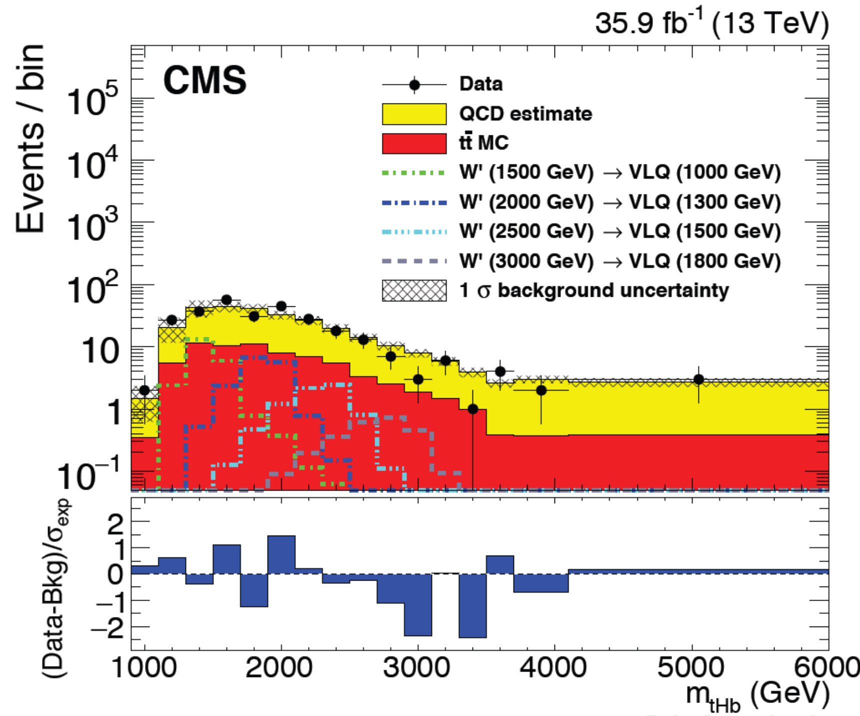
1ak4 b-tag jet

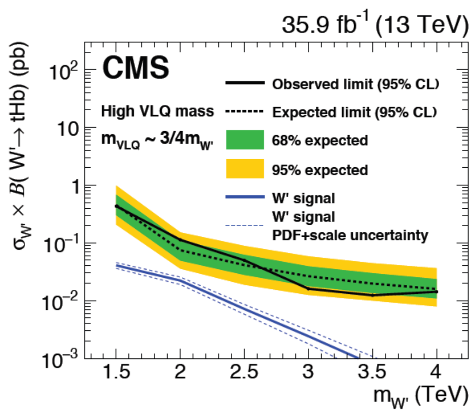
BR(B→bH)=BR(T→tH)=0.5

Main variable is M(W’)

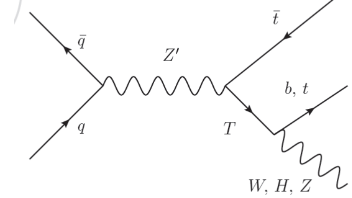








Z′



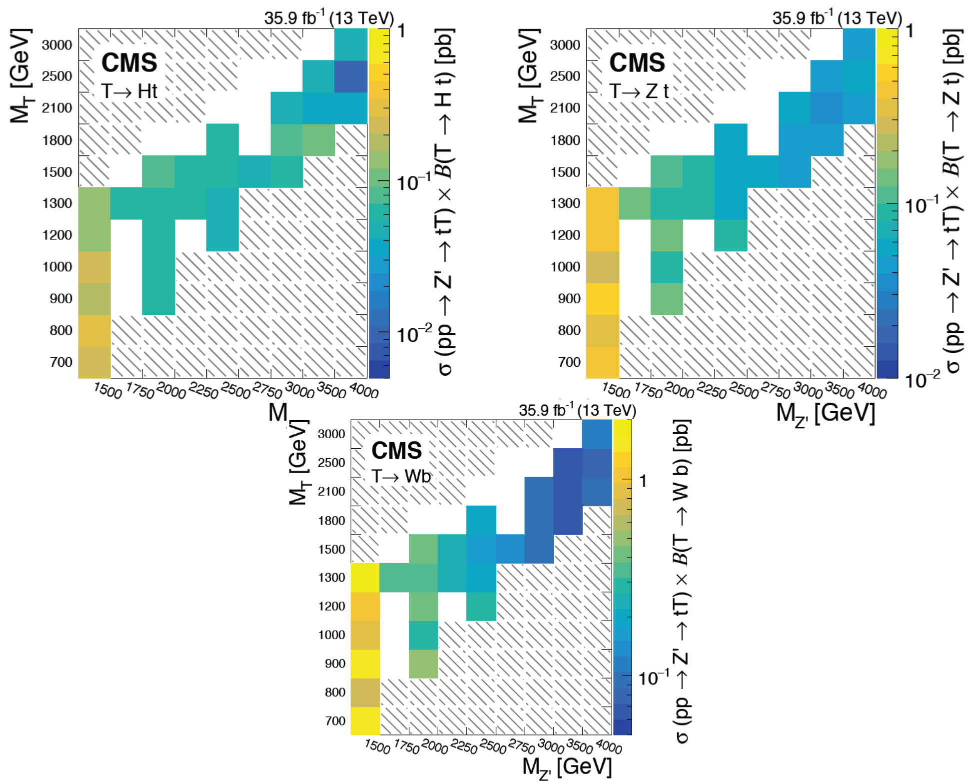
EPJC 10052-019-6688-5

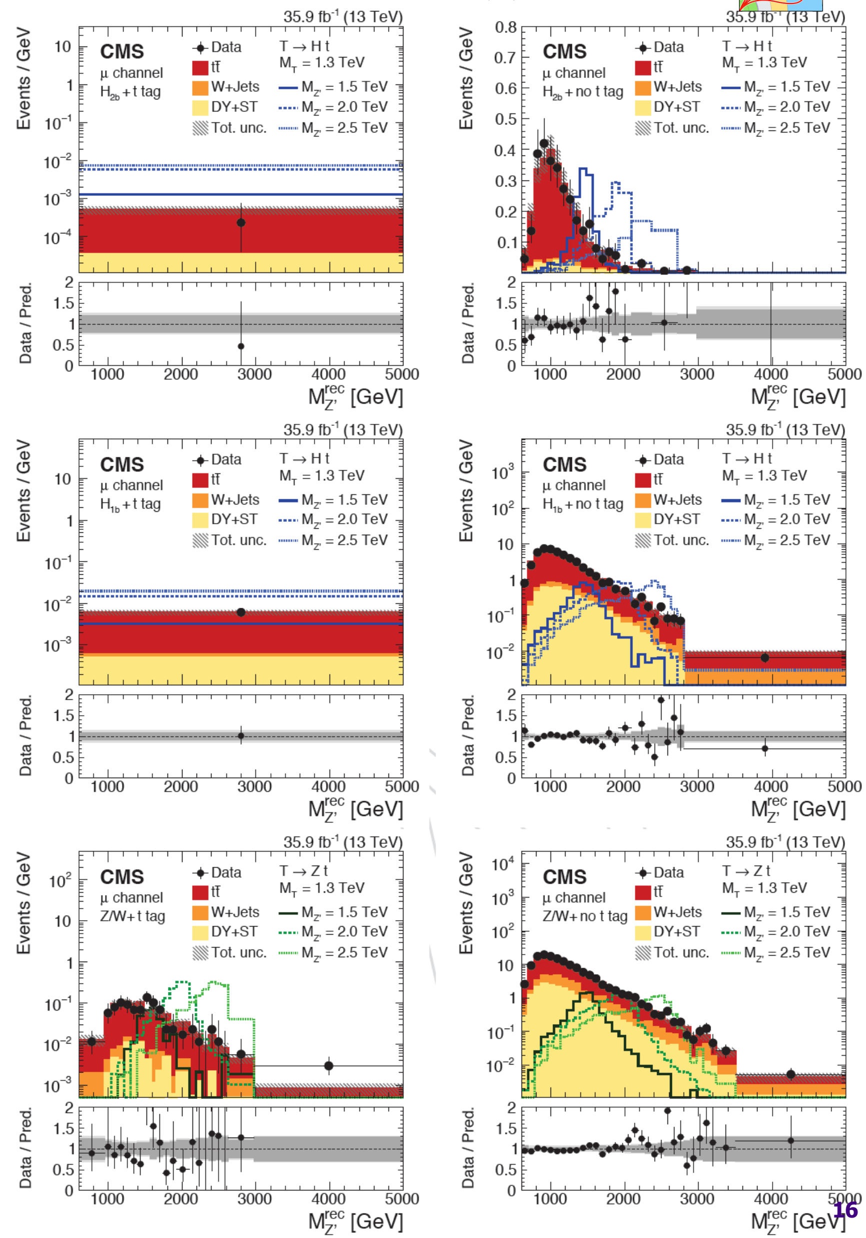
L+jets final state for Z′ search >1.5 TeV and optimized for T′→ tH/tZ

1 lepton + 1ak8 jet: W/Z-tag or Higgs-tag + ≥0 top-tag

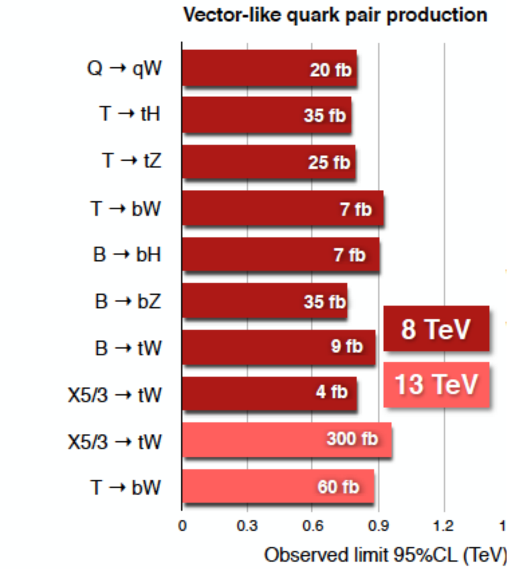
M(T′) starting at 1.3TeV (above pair production exclusion)

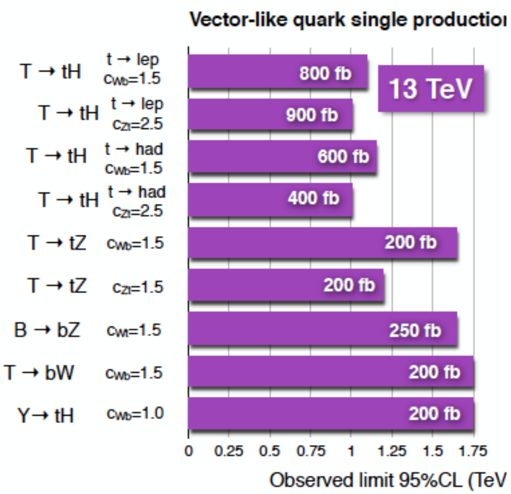
Main variable is M^{rec}(Z′)





VLQ Searches





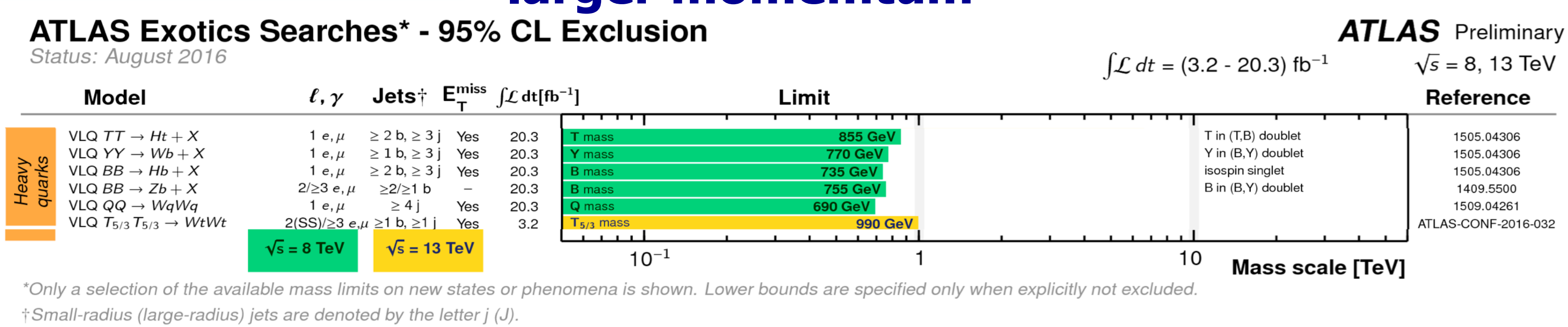
Run 1 + 2015

Atlas and CMS got two different approaches:

- **Atlas has dedicated analysis for some single VLQ channel and includes single VLQ production as additional signal while developing pair VLQ analysis**
- **CMS has dedicated analysis for single VLQ but in single VLQ, no consideration of pair production is done (and vice et versa)**

Second interesting point: pair VLQ is getting up to two order of magnitude lower in cross section than the single VLQ

→ Limit more stringent in pair than in single due to larger momemtum



Run 2 Analysis

- **Atlas is retuning an analysis for VLQ → Wb with width/coupling consideration**
- **CMS is following existing ones (T→tZ) with large width consideration (10%/20%/30%).**

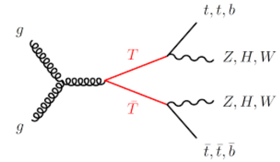
- **Both analysis are scaling cross section to NLO but do not take potential effect of NLO on forward jet**

- **For T/B: Chirality is not presenting major differences in the final state quantities used by the analysis, so the tuning of the criteria is done over one chirality and applied to both.**
  For X: Chirality effect is seen.

Pair Production

Different methodology is used so results from Atlas and CMS are difficult to compare nevertheless, try to present them side a side

All Hadronic

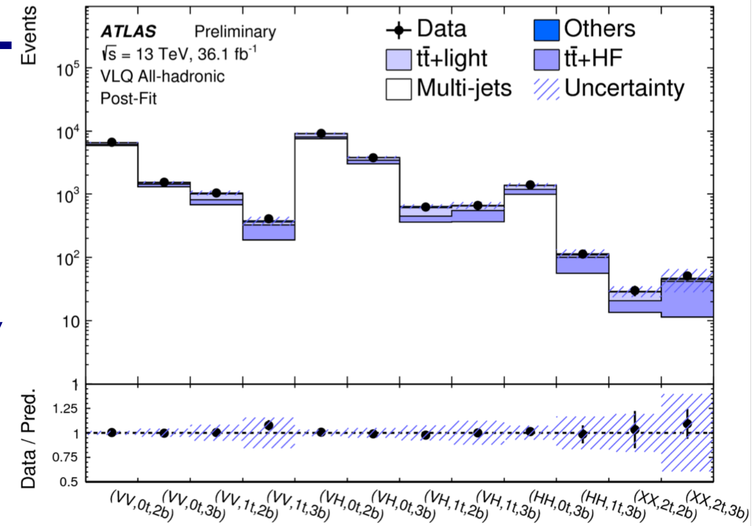


IP2I

ATLAS EXPERIMENT [Phys. Rev. D 98 (2018) 092005](https://doi.org/10.1103/PhysRevD.98.092005)

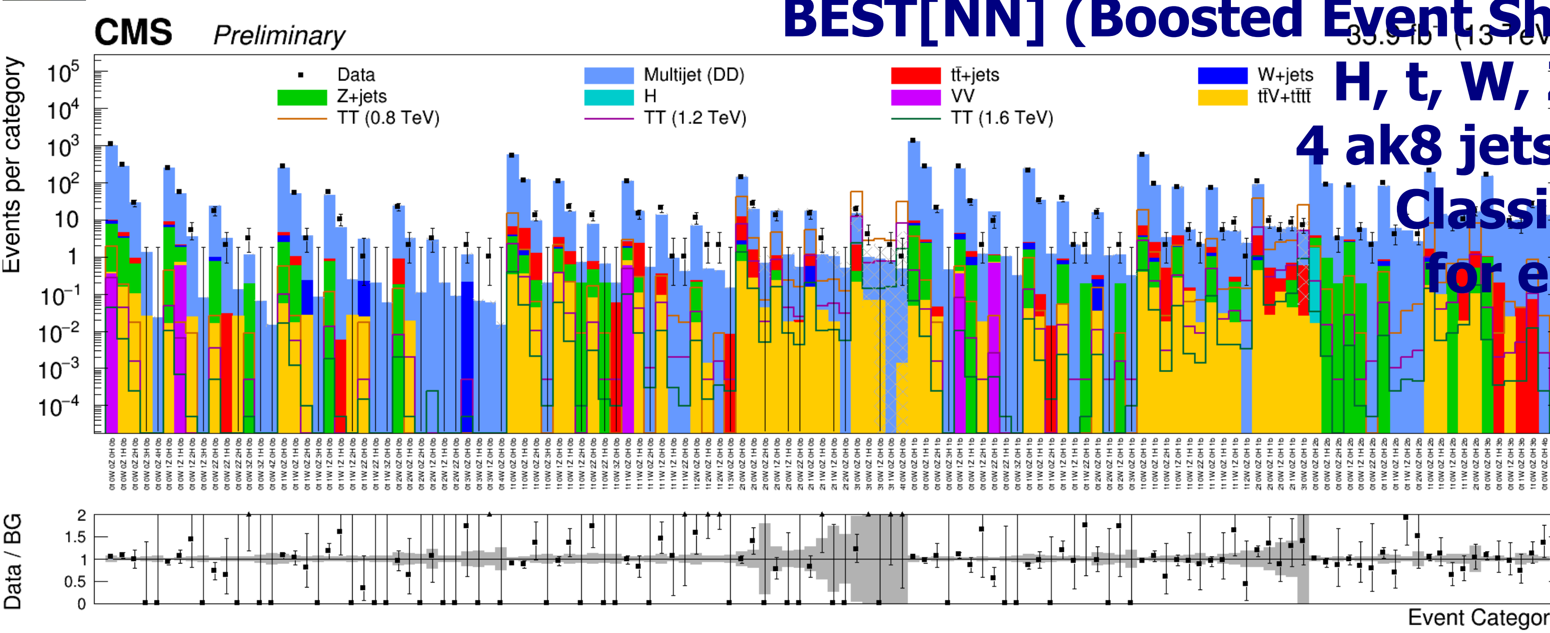
≥4 Small-R jets combined into variable-size [0.4,1.2] large-R jets p_T>150 GeV
NN used to identify V-boson, H, t and bkg jets

Classification done as VV,VH,HH with 0, 1 or 2 top-tag and 2 or 3b tag



[CMS-PAS-B2G-18-005](http://cds.cern.ch/record/2668187)

Simultaneously identify 6 jets category: BEST[NN] (Boosted Event Shape Tagger): H, t, W, Z, b and light
4 ak8 jets p_T>400 GeV
Classification done for each potential final state



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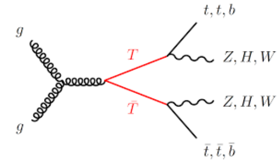

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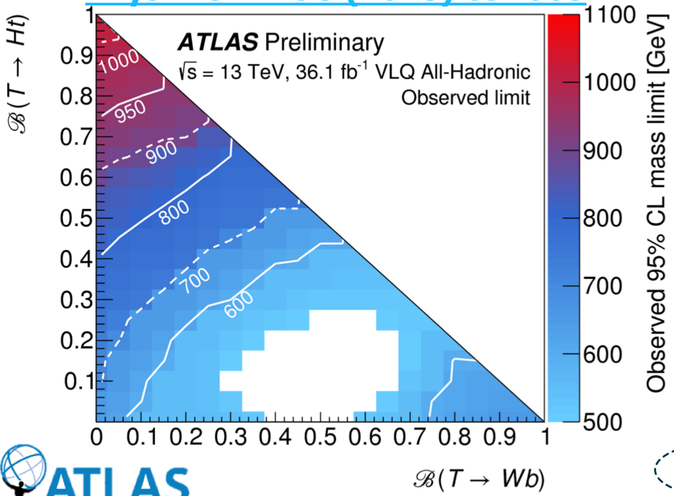
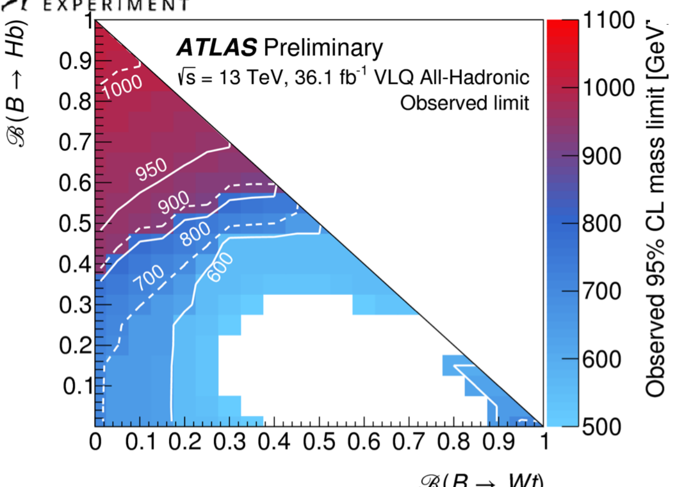
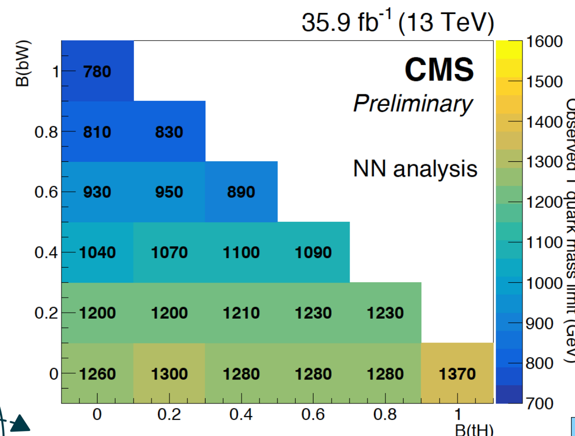
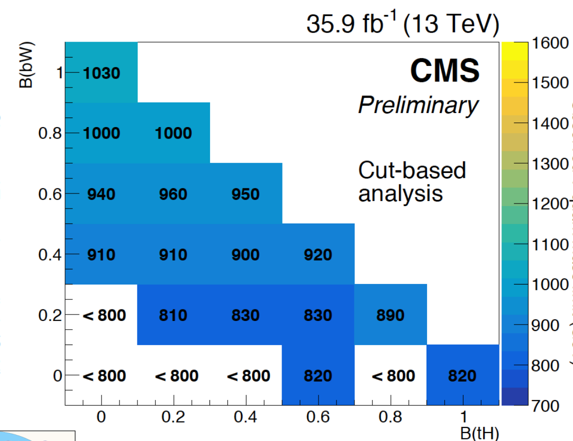
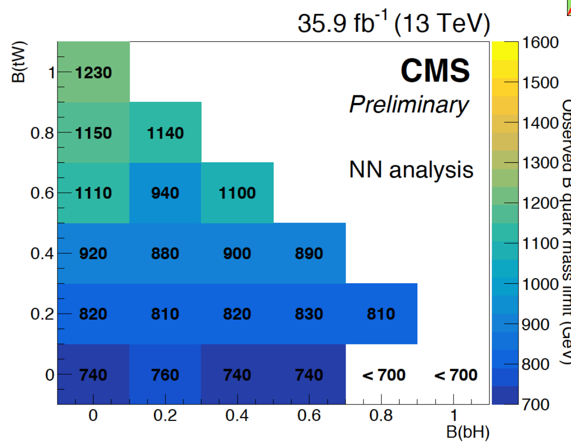


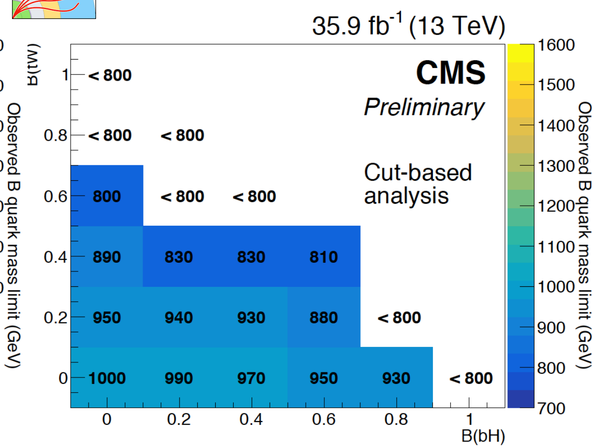






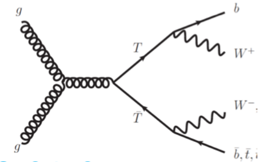
[CMS-PAS-B2G-18-005](http://cds.cern.ch/record/2629621)





CMS is having a Cut based analysis which is complementary to the NN one. For VLQ T, Atlas results are compare to CMS cut based one. NN-CMS has stronger limit even in the mixing area.
For VLQ B case, the CMS and Atlas results appear to be complementary to each other.

Lepton + jets: → WbWb



ATLAS EXPERIMENT JHEP 05 (2019) 164

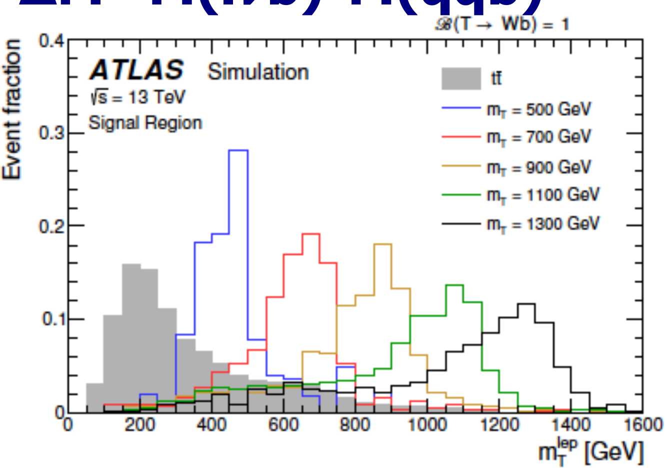
10.1016/j.physletb.2018.01.077 CMS

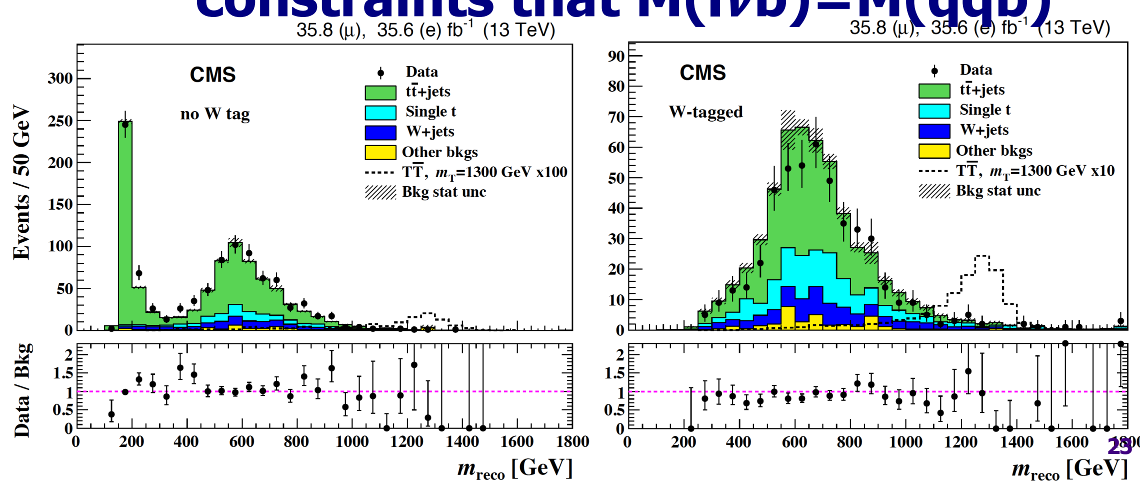
ATLAS	CMS
Neutrino P4 obtained by W-mass constraint.	**Kinematics fit →reconstruct VLQ mass**
Look at m_T^{lep} (VLQ mass in lept.)	**Excess in VLQ mass and Scalar E_T**
Only boosted channel (W-tag)	**Resolved (ak4) +boosted (W-tag)**

Events Selection:

ATLAS	CMS
One electron/muon + Ptmiss	**One electron/muon + Ptmiss**
≥ 3 ak4 jets, ≥ 1 W-tag	**4 ak4 jets or 1 ak8, W-tagged jets + 2 ak4 jets**
≥ 1 b-tagged	**2 loose b-tag jets**
ΔR(l, ν) < 0.7 and	
ST > 1800 GeV	**ST > 1000 GeV**
Jets assignment via ΔM=M(lνb)-M(qqb)	**Use kinematics fit with main constraints that M(lνb)=M(qqb)**

$$S_T \equiv \sum_{\substack{\text{jets},l,\\ E_{T\text{miss}}}} |p_T|$$





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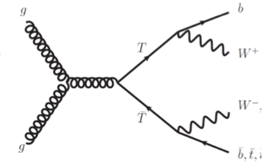
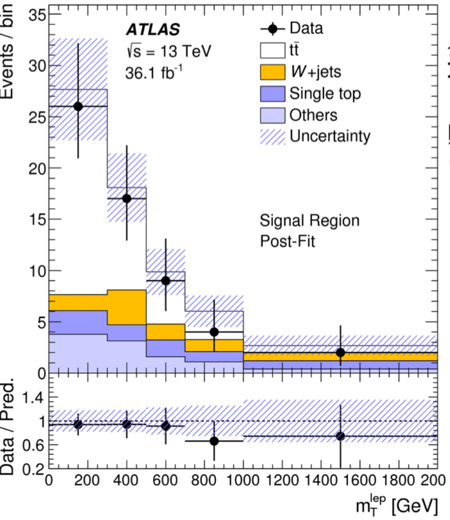
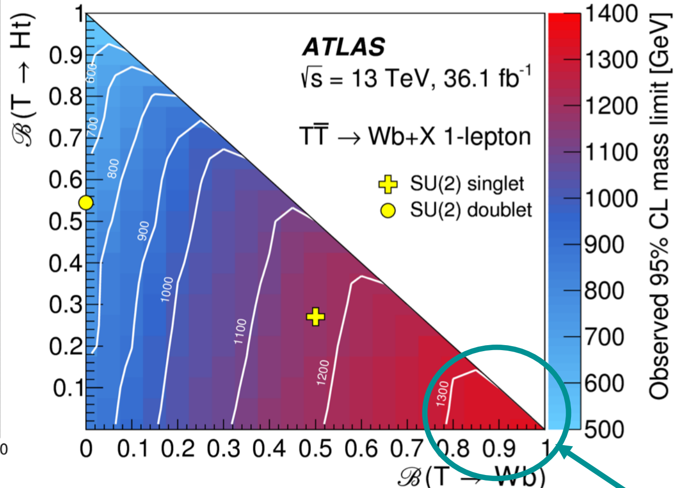


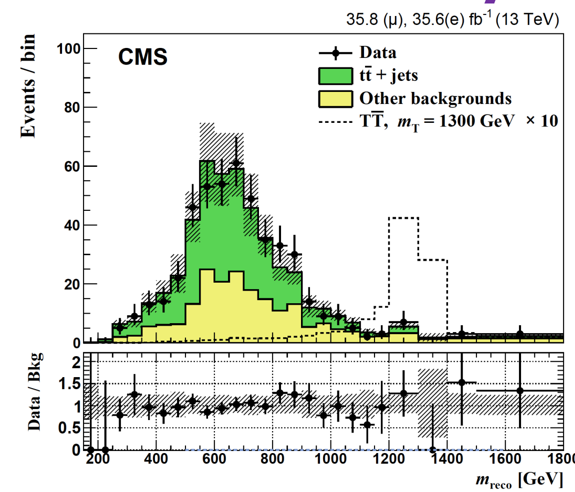
ATLAS EXPERIMENT [JHEP 05 (2019) 164]

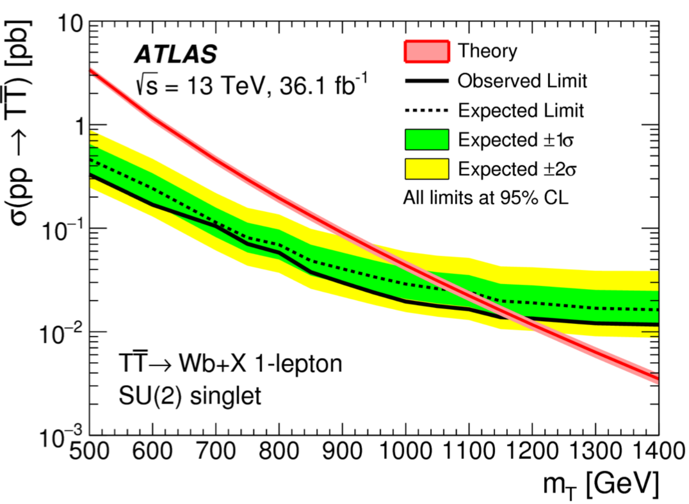
[10.1016/j.physletb.2018.01.077]

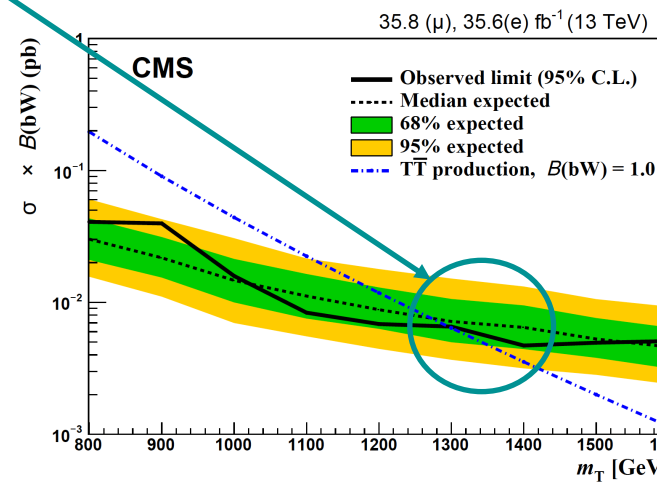
Kinematics fit
→No BR variation only BR=1





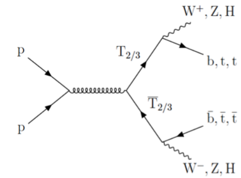


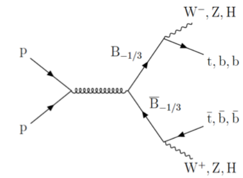




Similar results when comparing BR=1

Lepton +X





ATLAS EXPERIMENT

Focus on multilepton channel:

VLQ→ t+H: JHEP 07 (2018) 089

2 topologies: 0-lepton and 1-lepton
ETmiss > 200 GeV if 0-leptons
≥ 2 b-tagged jets
Signal regions based on lepton/jets multiplicity, H, top and b-tag multiplicities
Analyse m_{eff} (=scalar sum of object pT)

VLQ→ t+Z (→$\nu\nu$): JHEP 08 (2017) 052

1-lepton+ ETmiss > 300 GeV
Signal region requires ≥ 2 large-R jet
Counting experiment

JHEP 12 (2018) 112010

Signal Region based on lepton multiplicity (≥ 2), jet multiplicity, b-tag multiplicities, HT and ETmiss

CMS

1-lepton: JHEP 08(2018)

1-lepton+Ptmiss>75 GeV
≥ 3 ak4 and ≥ 2 ak8 jets
W and Higgs tagging via jet substructure variables and b-tagging requirements
16 event categories based on W, H and b-tag multiplicities
Analyze ST or min(M(l,b)) distribution

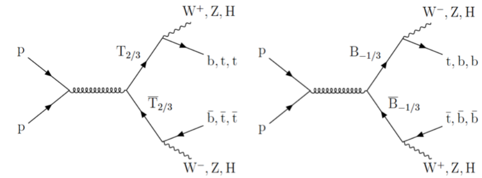
Same-sign 2-leptons:

HT_{lep} > 1.2 TeV
Counting experiment

3-leptons:

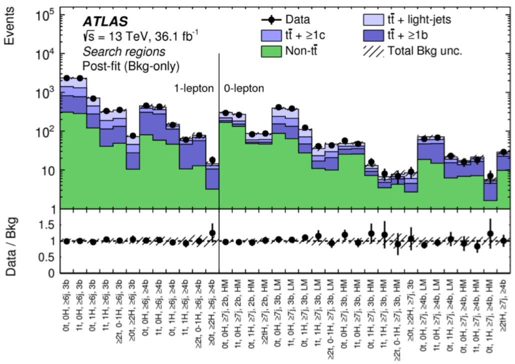
3-leptons + Ptmiss>10 GeV +≥ 3 ak4 and ≥1 b-tag
Analyze ST distribution

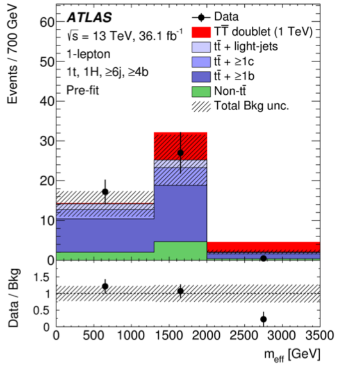
Lepton +X



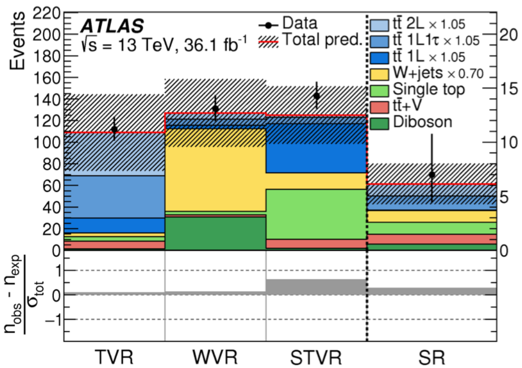
ATLAS EXPERIMENT

JHEP 07 (2018)

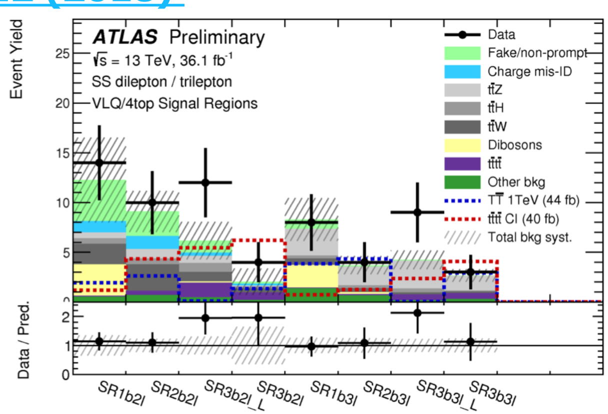




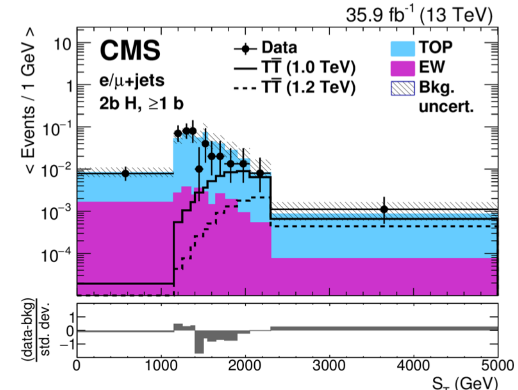
JHEP 08 (2017)

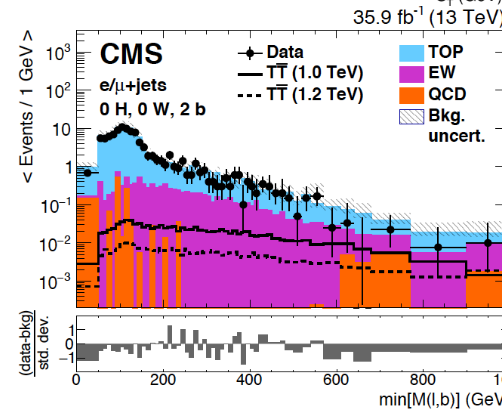


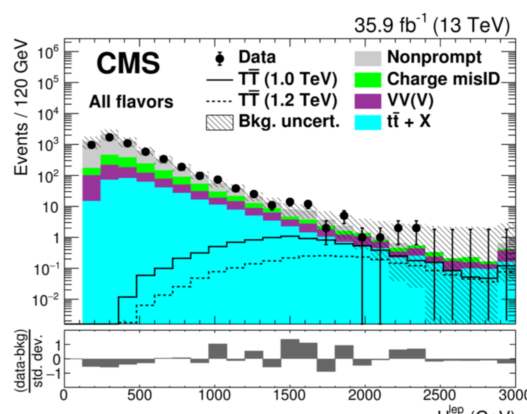
JHEP 12 (2018)

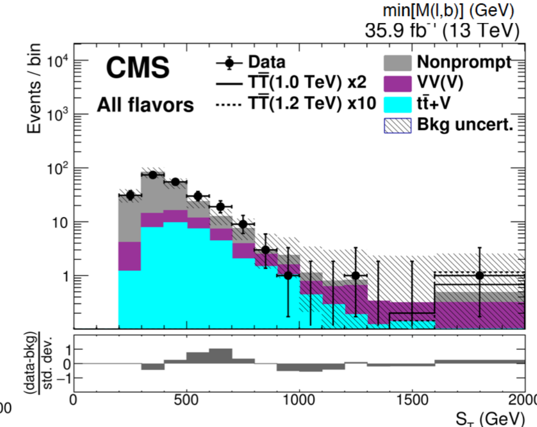


JHEP 08(2018)

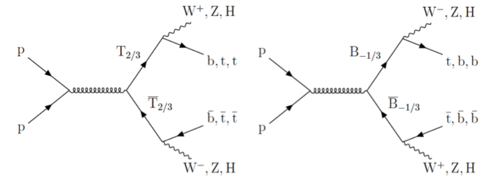








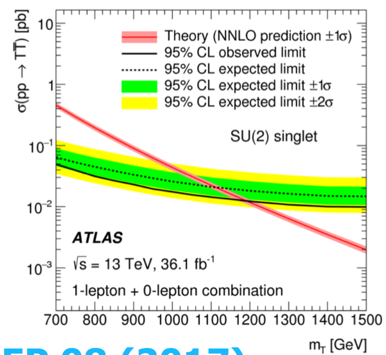
Lepton +X

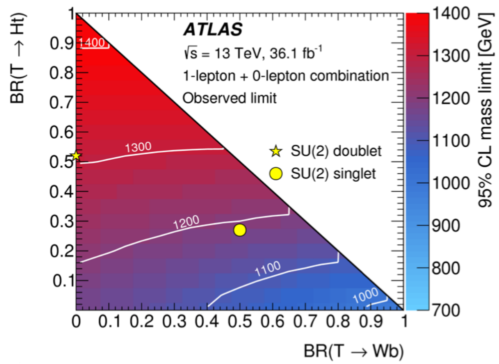


IP2I

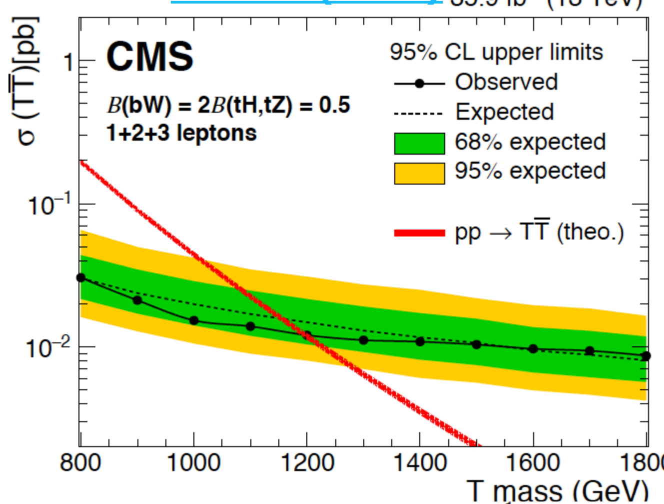
ATLAS EXPERIMENT

JHEP 07 (2018)

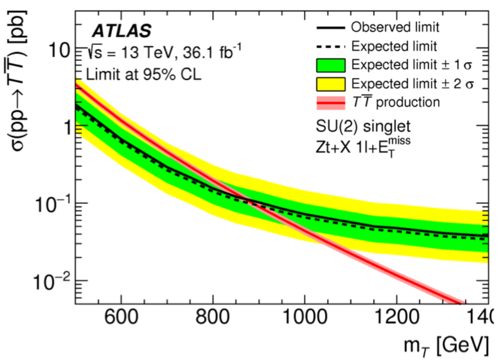


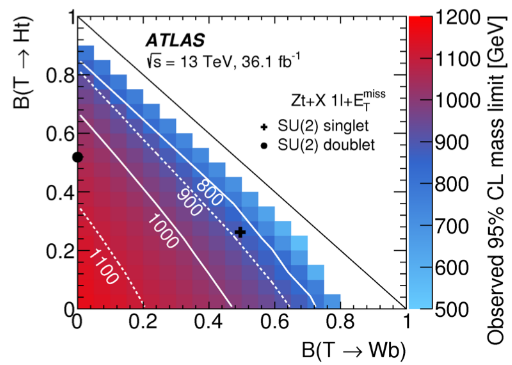


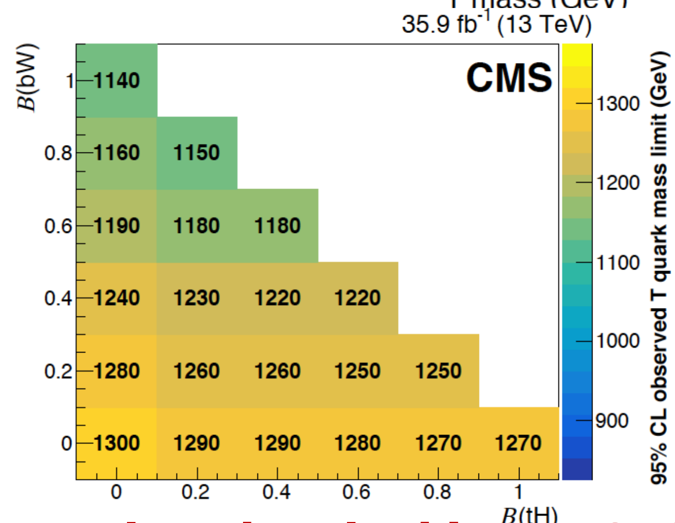
JHEP 08(2018)



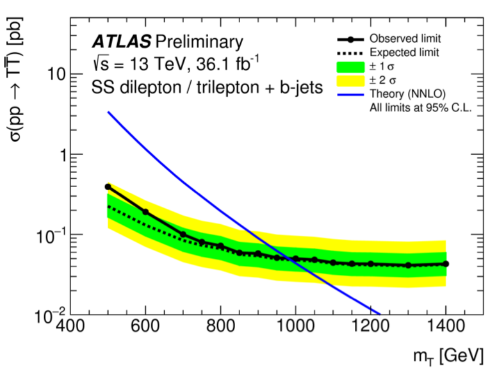
JHEP 08 (2017)

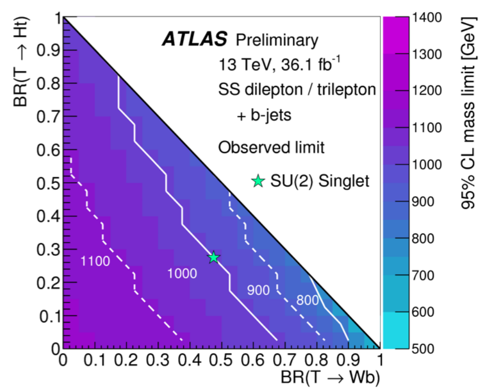






JHEP 12 (2018)





Similar results when looking at SU(2) singlet

Stringent limit for Atlas for BR(tH)=1

Stringent limit for CMS for BR(bW)=1

Dilepton search

Opposite-sign 2-leptons: Select events with $Z\to\ell\ell$

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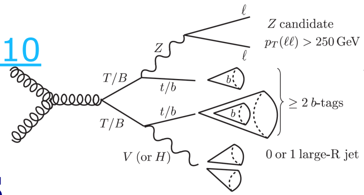
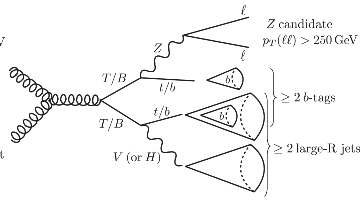
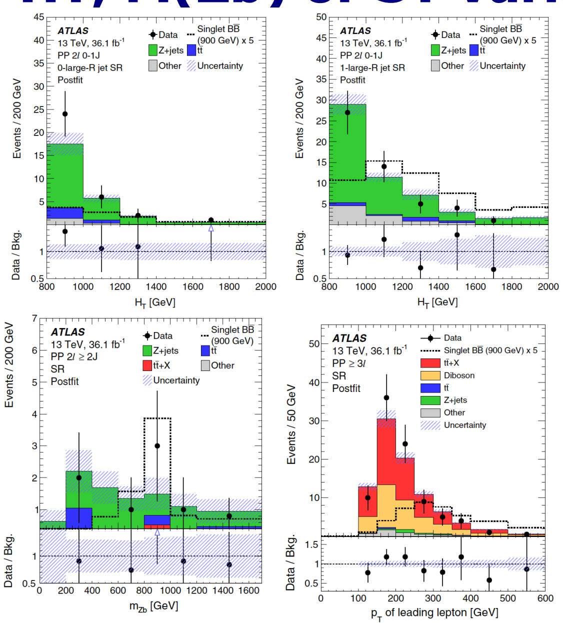
EPJC 79 (2019)

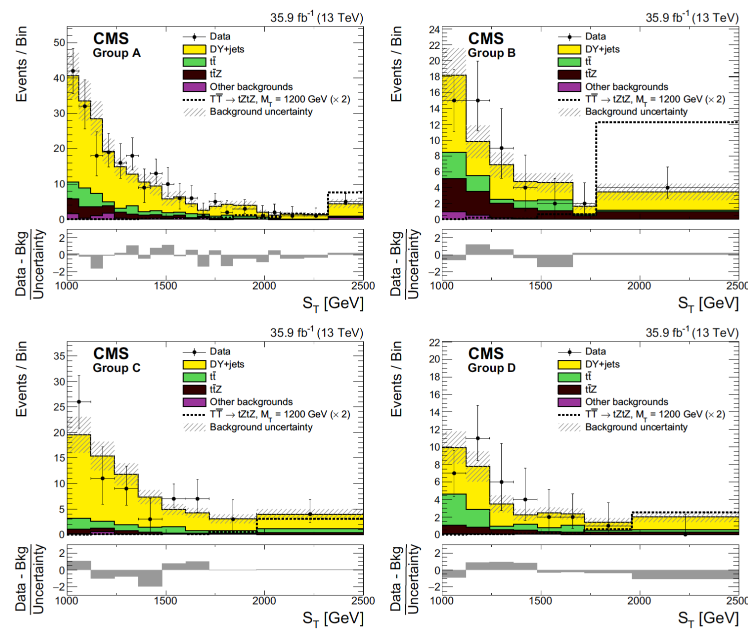




- ≥ 2 leptons
- ≥ 1 b-tagged jets
- 0-1-2 large-R jets
- Categories based on lepton multiplicity, b-tag multiplicity and large-R jet multiplicity
- Depending on categories look at HT, M(Zb) or ST variable

- 2 leptons making a Z-candidate
- ≥ 3 ak4 jets
- ≥ 1 b-tagged jets
- Categories based on b-tag multiplicity + ak8 jets tagging type
- ST variable is looked at





Dilepton search

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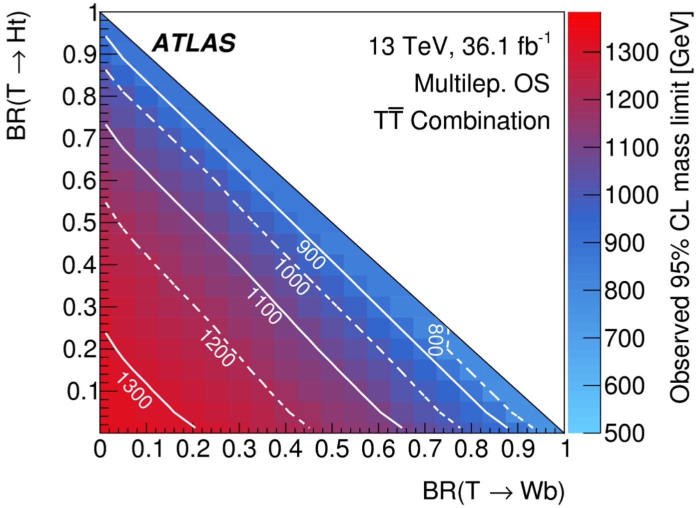
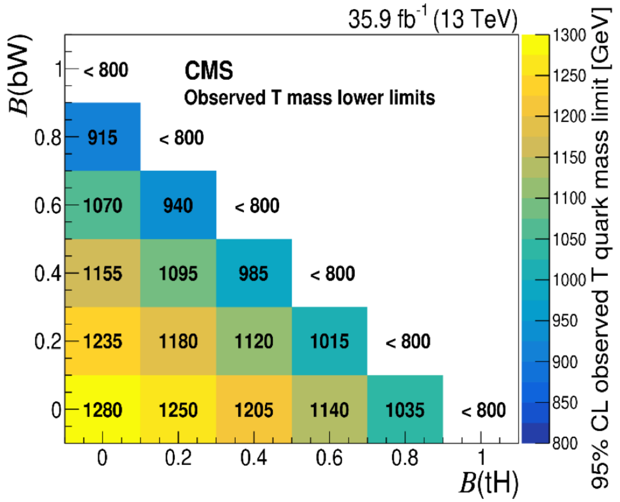
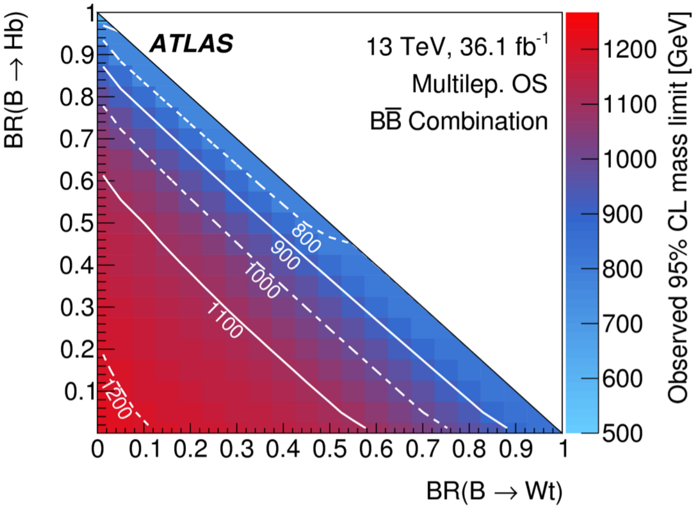
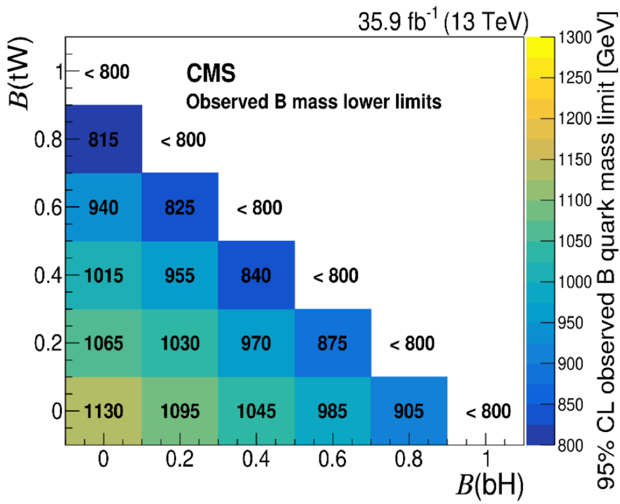
EPJC 79 (2019)





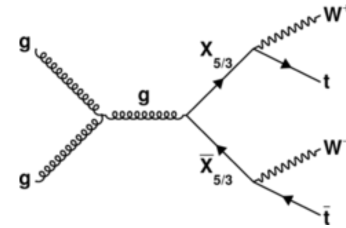


Slightly stringent limits for Atlas but Atlas contains 3 lepton channel



Pair $X^{5/3}$/B

In multilepton



l+jets:

JHEP 12(2018) 039

1 lepton, ≥ 4 jets (≥ 1 b-tagged), ≥ 1 large-R jet, ST > 1.2 TeV
Signal region based on mainly W-tag
Main variable: M(Wt) or BDT output

JHEP 03 (2019) 082

e/μ + Met + ≥ 4 jets
W and Top tagging
16 event categories based on W, t-tagged and b-tag multiplicities.
Main variable: min(M(lb))

SS dilepton + trilepton:

Signal Region based on lepton multiplicity (≥ 2), jet multiplicity, b-tag multiplicities, HT and ETmiss
Counting experiment

SS dilepton:

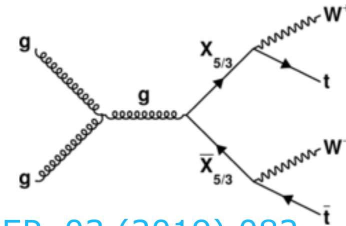
ee/μμ/eμ (same sign), HTlep, Nb Constituants
Counting experiment

(+combination)

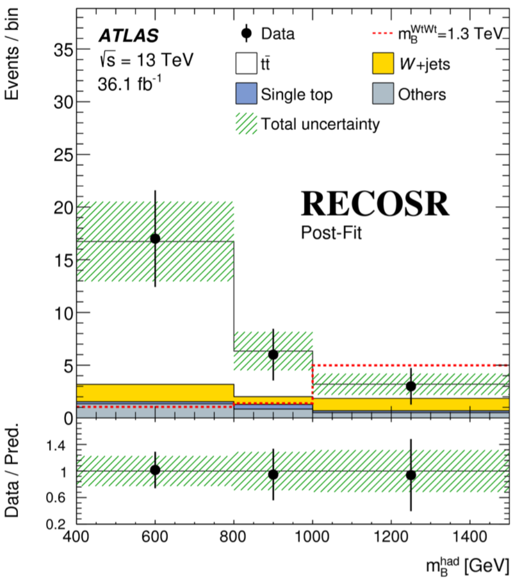
Pair $X^{5/3}$/B

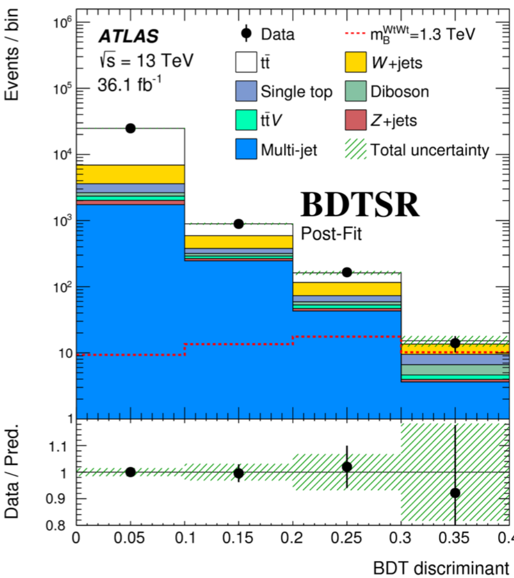
In multilepton

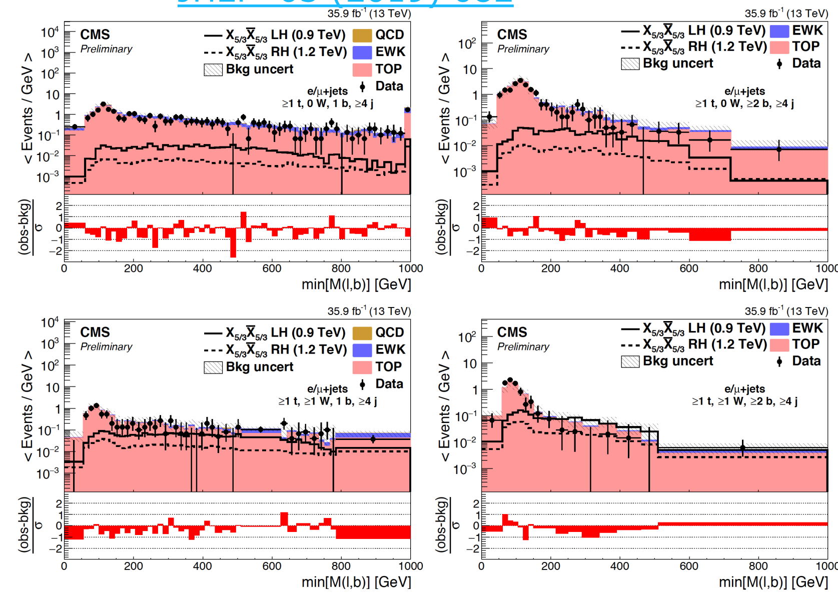
ATLAS EXPERIMENT JHEP 12(2018) 039

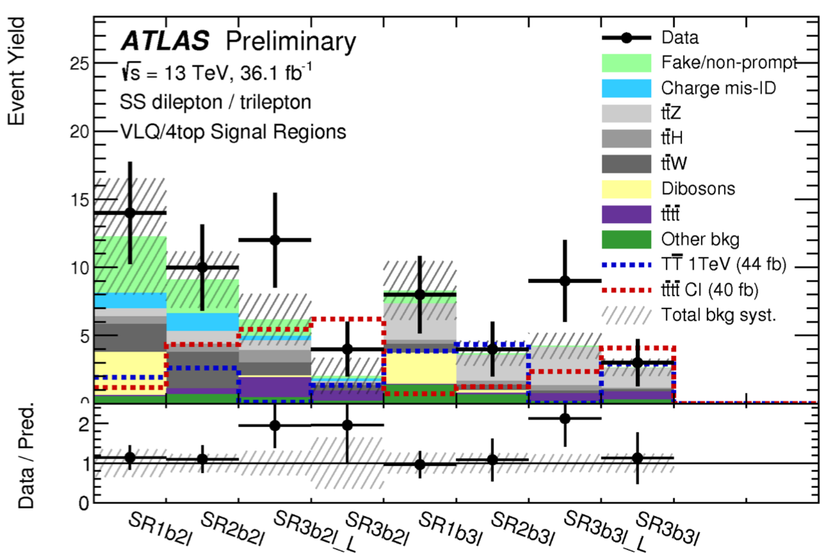


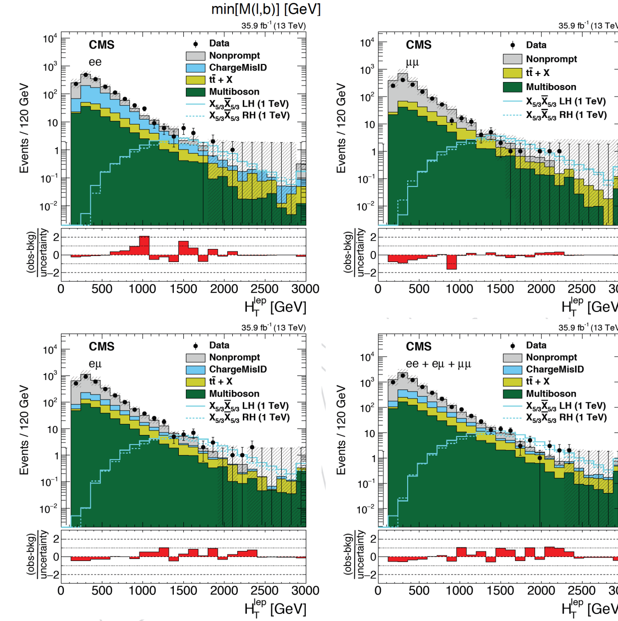
JHEP 03 (2019) 082







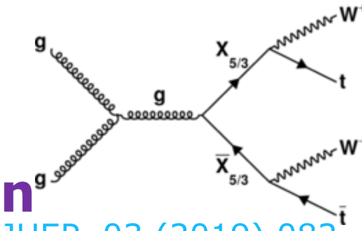




Pair $X^{5/3}$/B

ATLAS EXPERIMENT JHEP 12(2018) 039

In l+jets and SS dilepton



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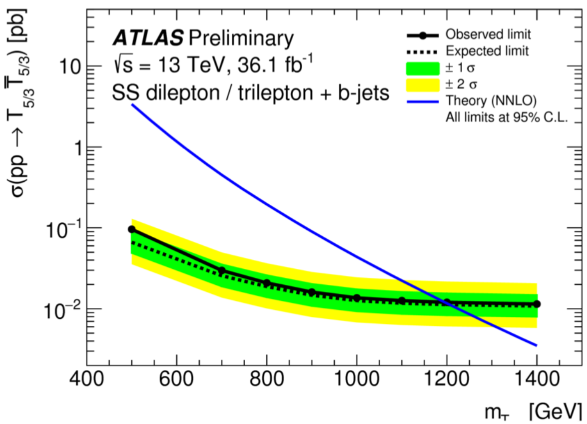
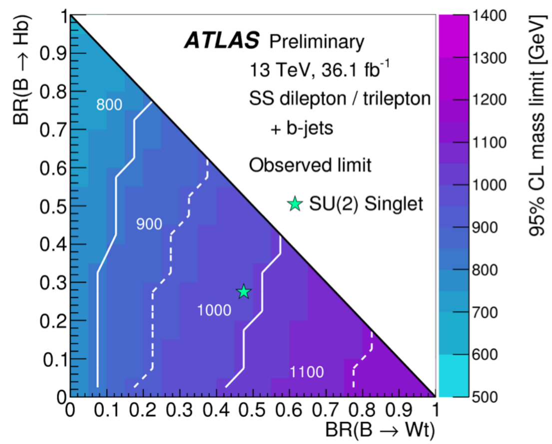
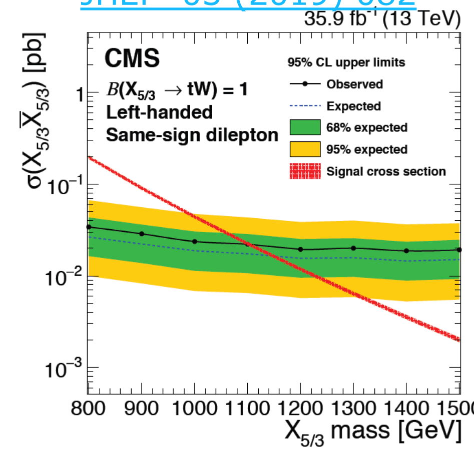
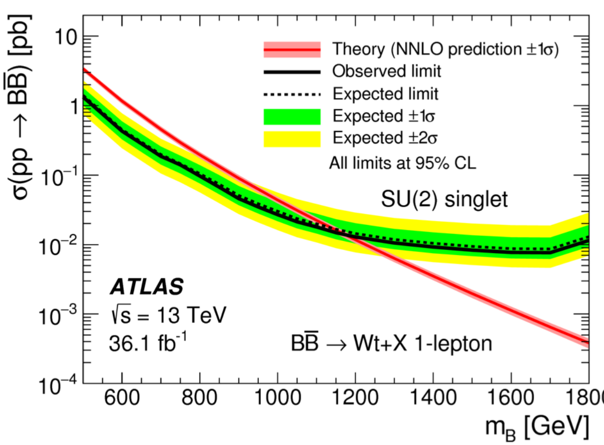
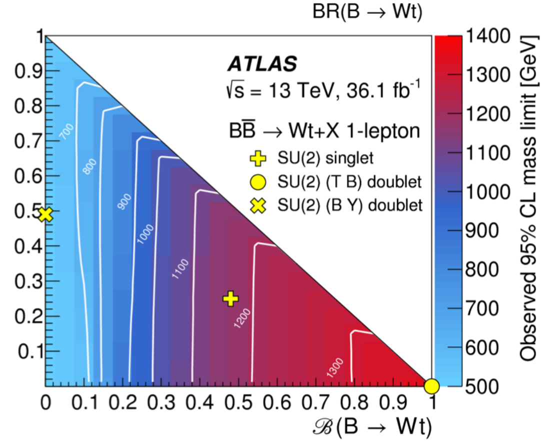
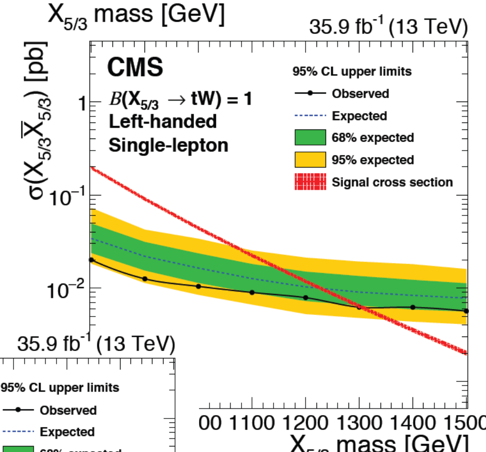


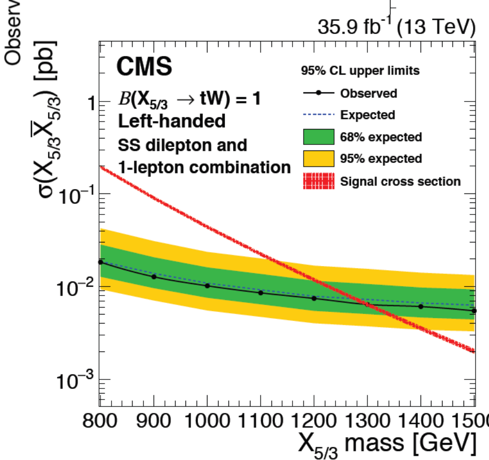












Slightly stringent limits for Atlas
Atlas SS contains 3 lepton channel

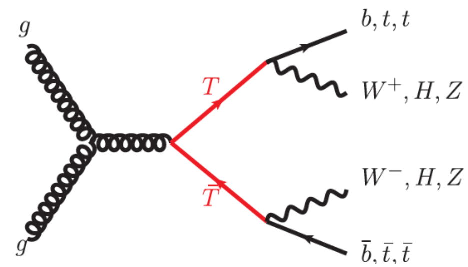
Atlas Combination

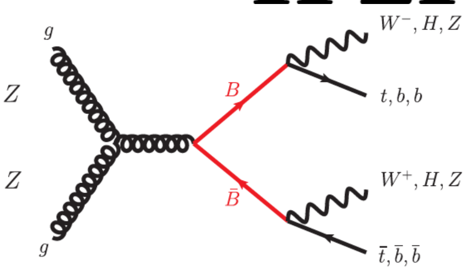
2016 data for pair VLQ

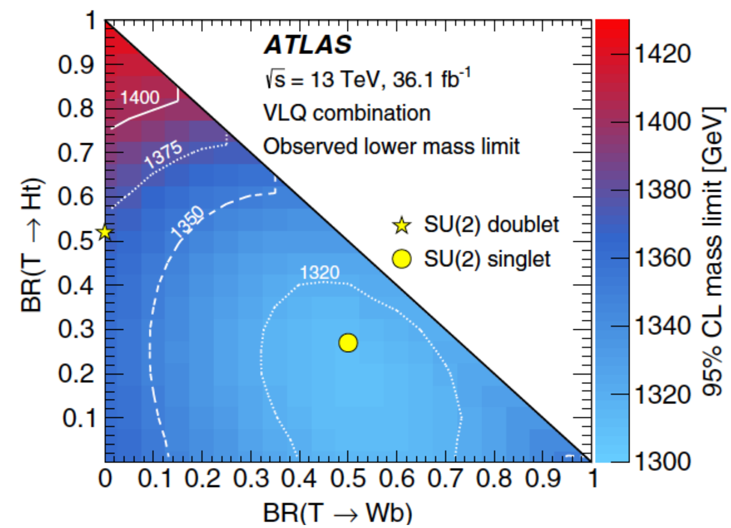
Phys. Rev. Lett 121 (2018) 211801

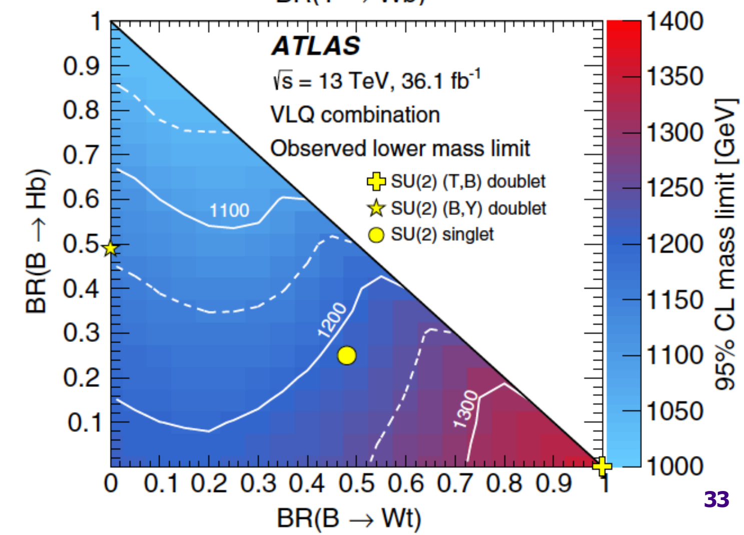
TABLE I. The most sensitive decay channel for each analysis entering the combination. A "$\cdots$" indicates that the analysis was not used for that signal process.

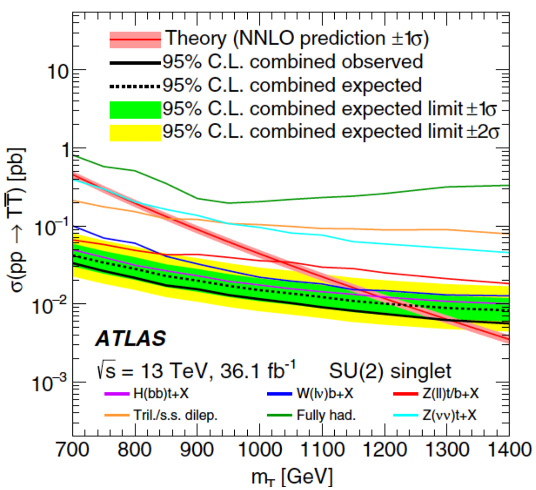
Analysis	$T\bar{T}$ decay	$B\bar{B}$ decay
$H(bb)t+X$ [16]	$HtH\bar{t}$	$\cdots$
$W(\ell\nu)b+X$ [17]	$WbW\bar{b}$	$\cdots$
$W(\ell\nu)t+X$ [18]	$\cdots$	$WtW\bar{t}$
$Z(\nu\nu)t+X$ [19]	$ZtZ\bar{t}$	$\cdots$
$Z(\ell\ell)t/b+X$ [20]	$ZtZ\bar{t}$	$ZbZ\bar{b}$
Tril./s.s. dilepton [21]	$HtH\bar{t}$	$WtW\bar{t}$
Fully hadronic [22]	$HtH\bar{t}$	$HbH\bar{b}$

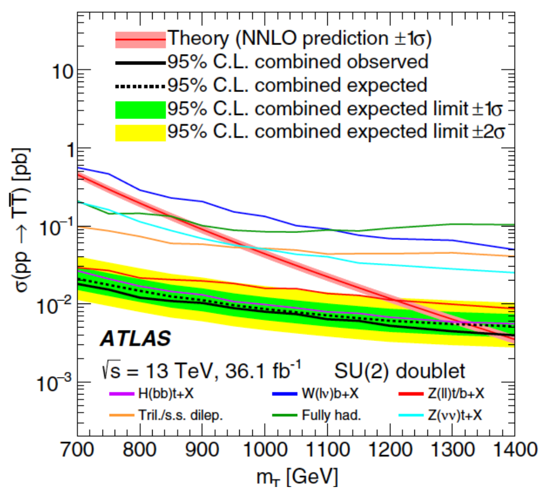








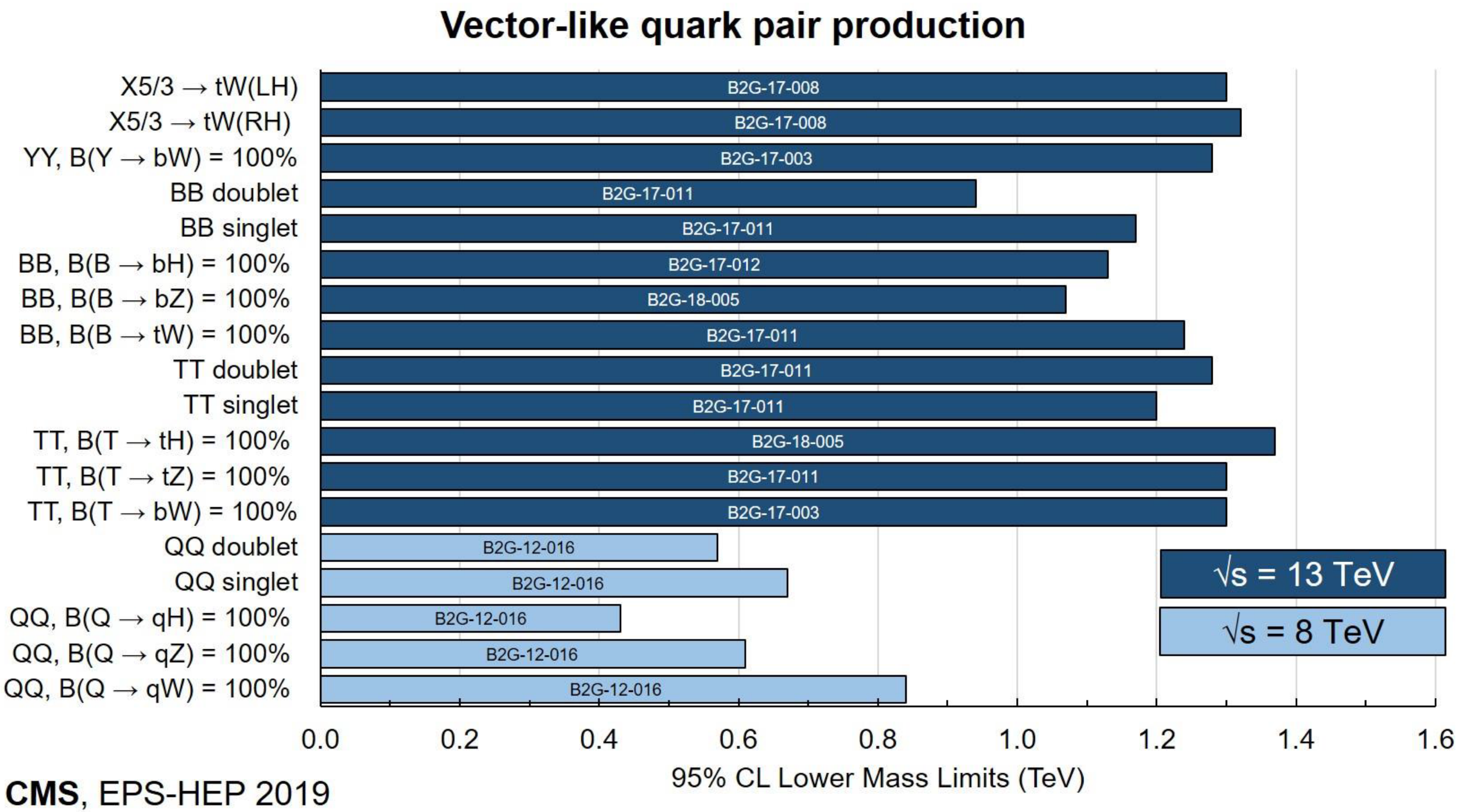




CMS: no current plan to do combination

→ Run2 statistics first

CMS Summary



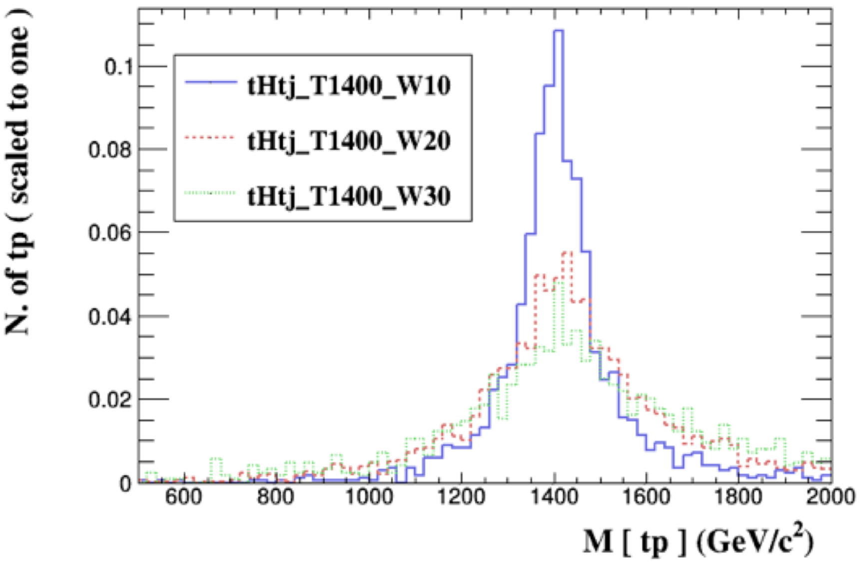
CMS has light VLQ searches at 8 TeV (revive for 13 TeV)

Single Production

Single VLQ

- **Interpretation as singlet/doublet**
- **Studies made with narrow width approximation + MC produced for various width: 10%, 20%, 30%**
- **Analysis performed in various regimes: resolved, semi-resolved, boosted**
- **Using full VLQ mass reconstruction in all channels**
- **Categorization as function of presence of a forward jet**

LHE level for T'→ tH



Single T → Zt

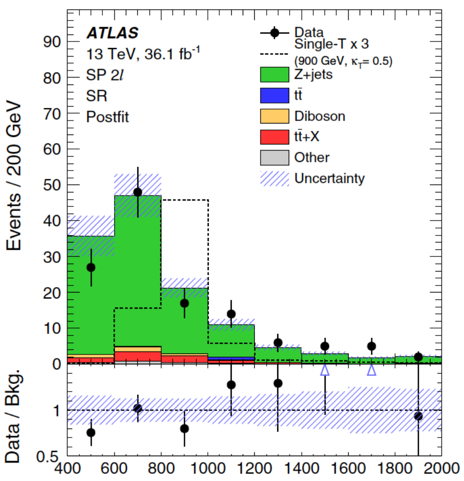
[Phys. Rev. D98 (2018) 112010] [10.1016/j.physletb.2018.04.036]

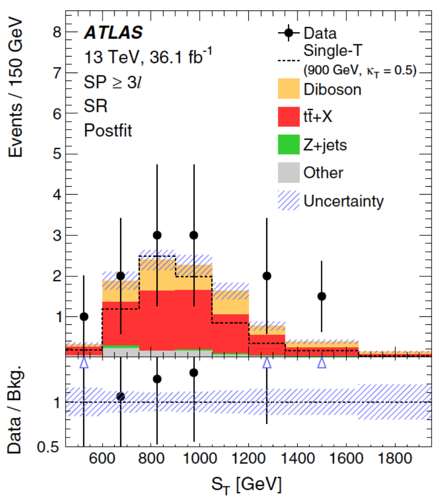
Opposite-sign 2-leptons: Select events with $Z \rightarrow \ell\ell$

≥ 1 forward ak4 jet
≥ 1 b-tag jet
≥ 1 top-tag jet
→ Boosted only
Main Variable: mass(Zt)

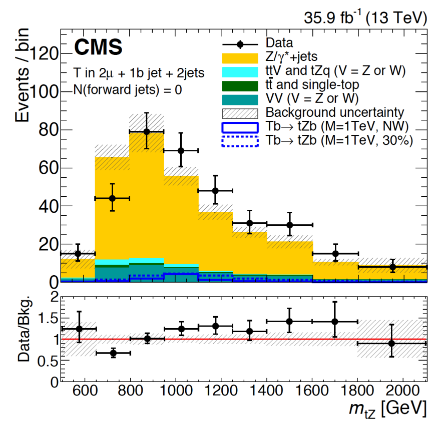
3 leptons analysis

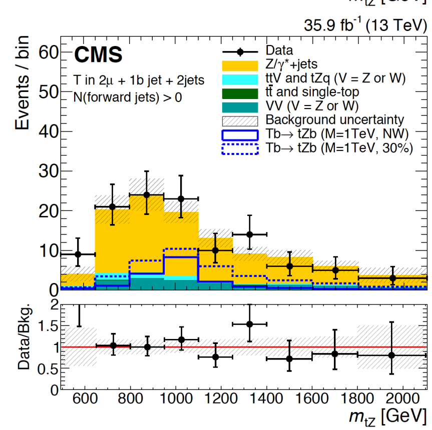
Remove top-tag criteria
Main Variable: ST

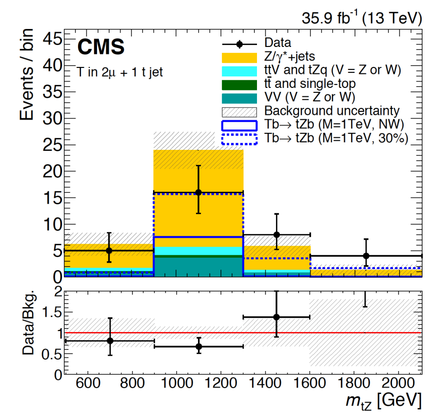




≥ 0 forward ak4 jet (2.5<|η|<4.5)
≥ 1 b-tag jet
Resolve+semi-Resolved+Boosted
Categories: Nb forward jets, W/top-tagging
Main Variable: mass(Zt)





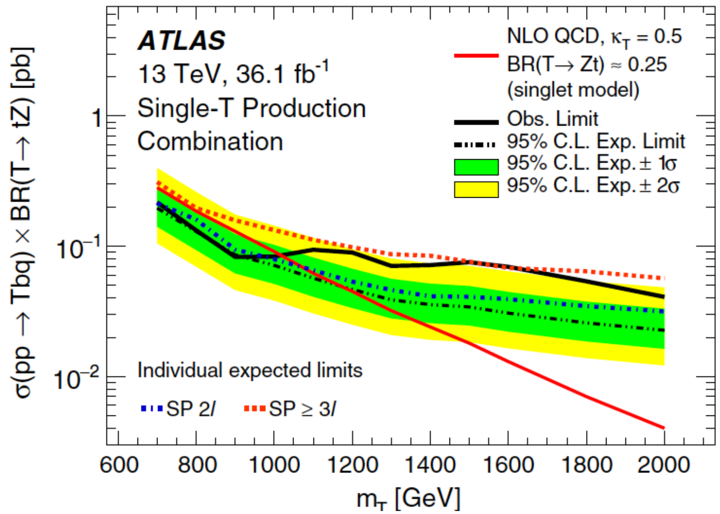


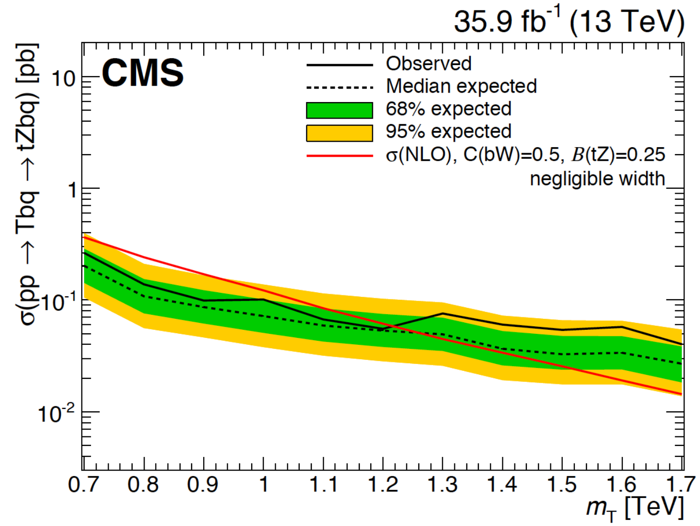
Single T → Zt

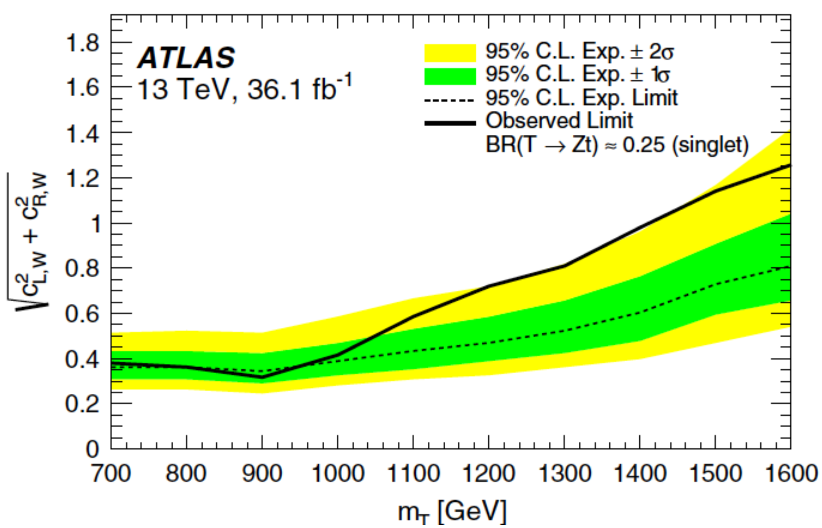
Phys. Rev. D98 (2018) 112010

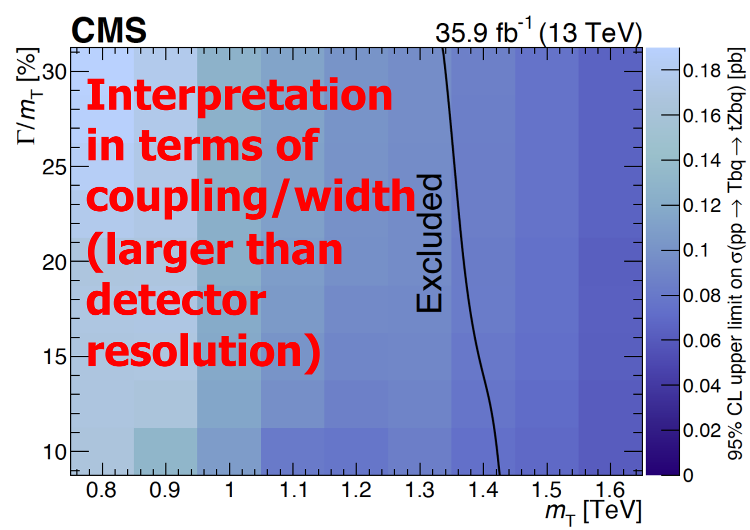
10.1016/j.physletb.2018.04.036

Opposite-sign 2-leptons: Select events with Z→ℓℓ









Slightly stringent limits for CMS. Atlas contains 3 lepton channel, stringent limits for CMS if consider 2l only

Atlas Single T → Zt (Z→νν)

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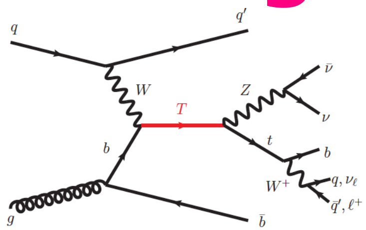
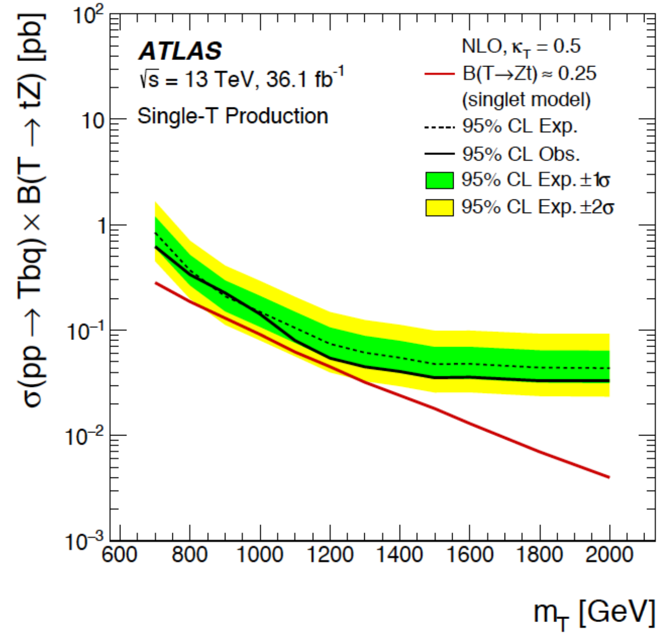
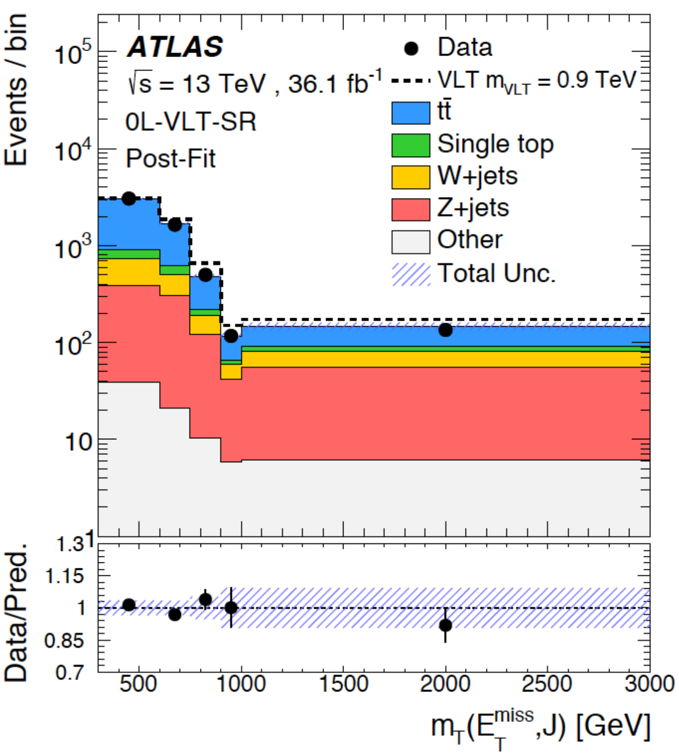
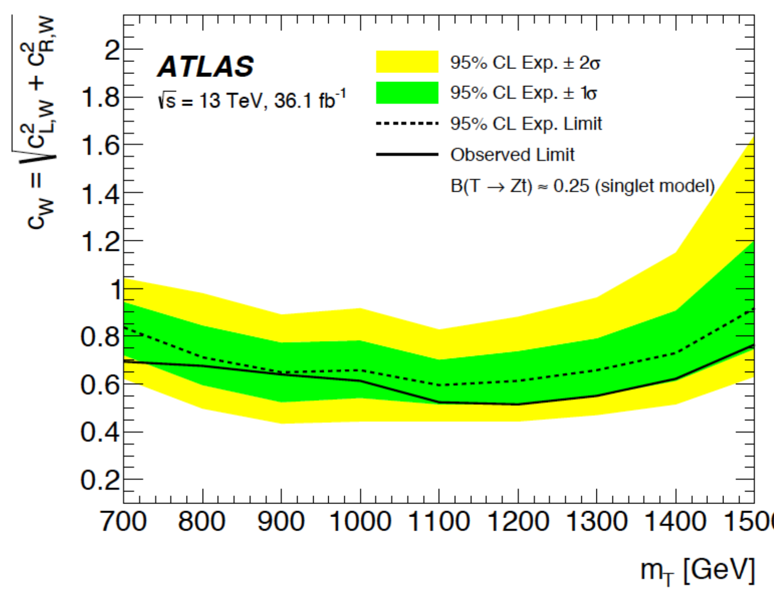


Etmiss > 200 GeV
= 1 b-tag jet
≥ 1 top-tag jet
≥ 1 forward ak4 jet
→ Boosted only
Main Variable: m_T(ETmiss + top)







Atlas: Single $Y^{4/3}$/T → Wb

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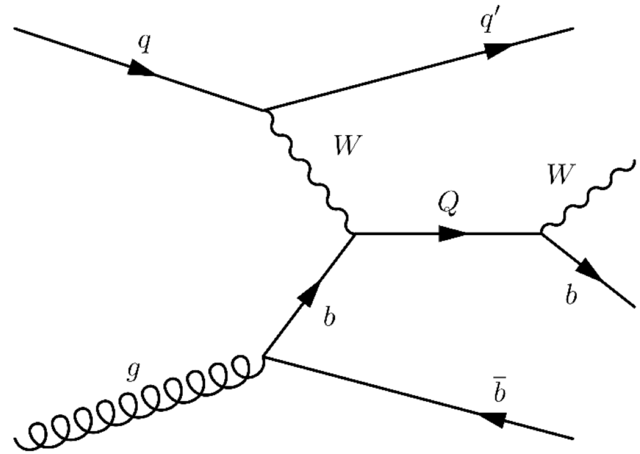
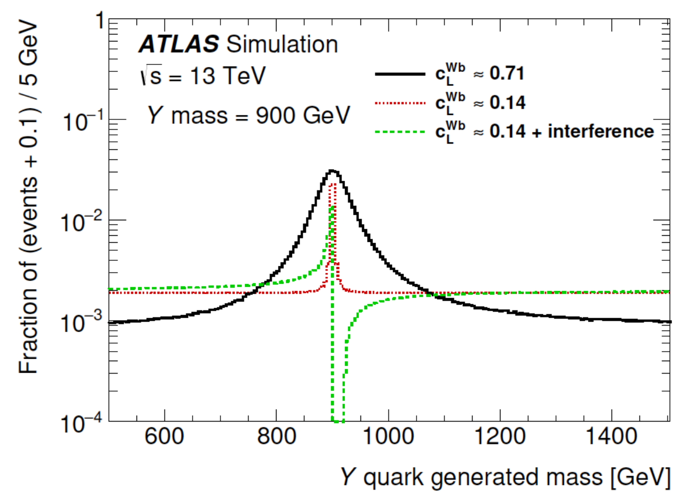
- **Leading order feynman**
- **Interpretation as (B,Y) doublet or T singlet**
- **Studies made with narrow width approximation, smearing performed to study larger width**
- **Interference with SM background taken into account +NLO effects**
- **Search performed in lvb final state with mass reconstruction (pz is minimal from real solution, if non real, then varies E_T to get real solution)**
- **Main background are W+jets and tt which are estimated from MC with cross check in control region**
- **Non prompt lepton from Matrix Method**



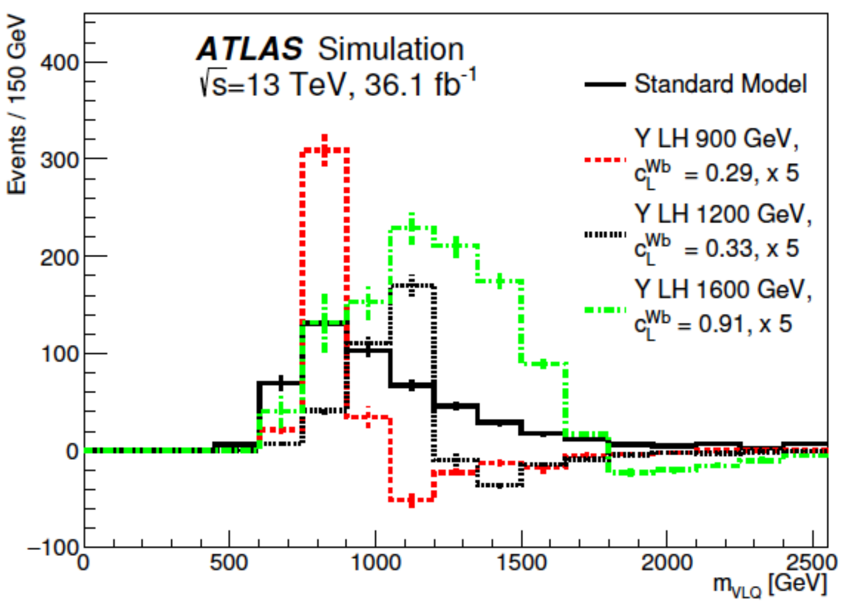


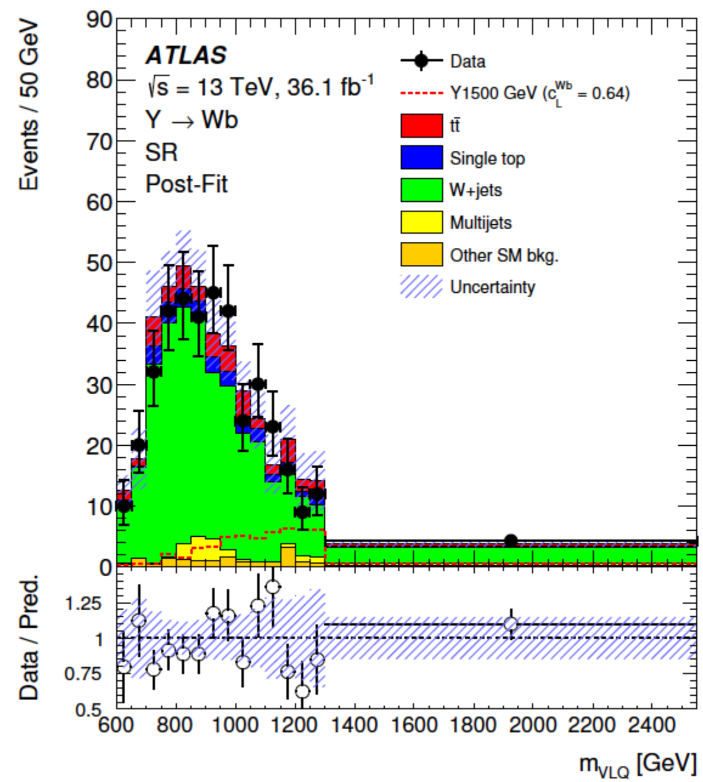
**Width ~ 50 GeV (?)
So below detector resolution (?)**

Atlas: Single $Y^{4/3}/T \rightarrow Wb$

Selection: JHEP 05 (2019) 164

- **1 isolated e/μ with pt >28 GeV**
- **≥ 1 b-jet with pt> 350 GeV**
- **Etmiss > 120 GeV**
- **Δφ (lepton,leading b-tagged jet)|> 2.5**
- **≥ 1 forward ak4 jet pt>40 GeV (2.5<|η|<4.5)**
- **Veto if 1 ak4 jet pt>75 GeV, |η|<2.5 and ΔR (jet, leading b-tagged jet)< 1.2 or ΔR (jet, leading b-tagged jet) > 2.7**





Atlas: Single $Y^{4/3}$/T → Wb

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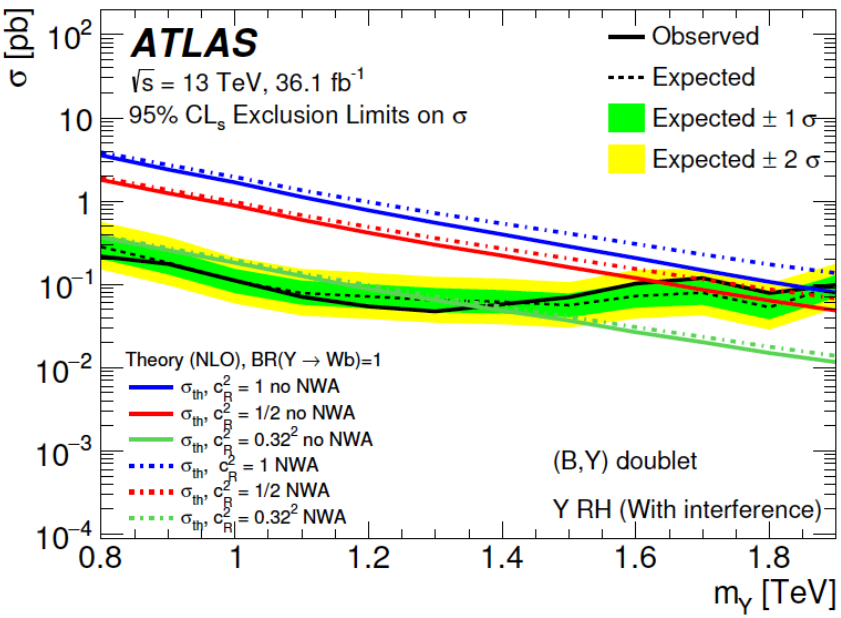
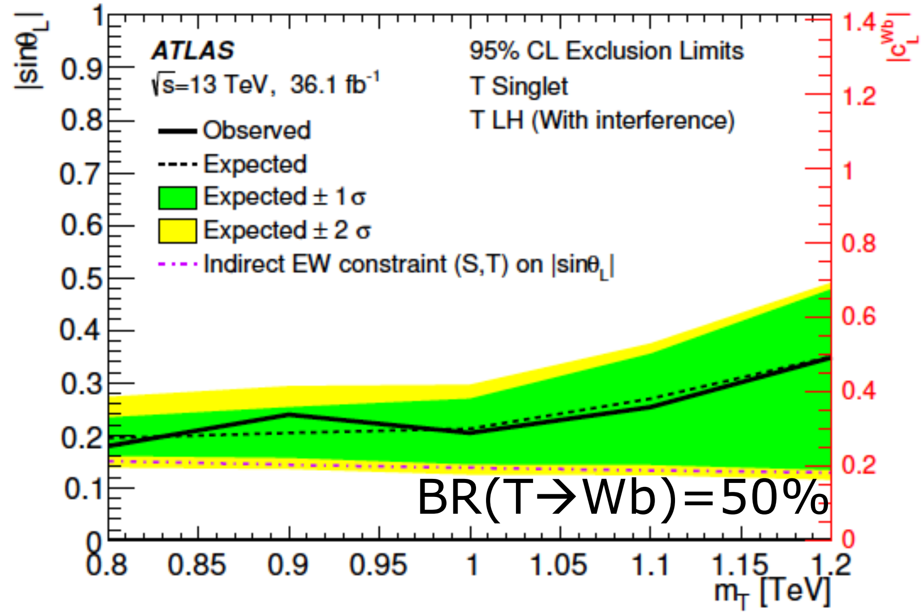
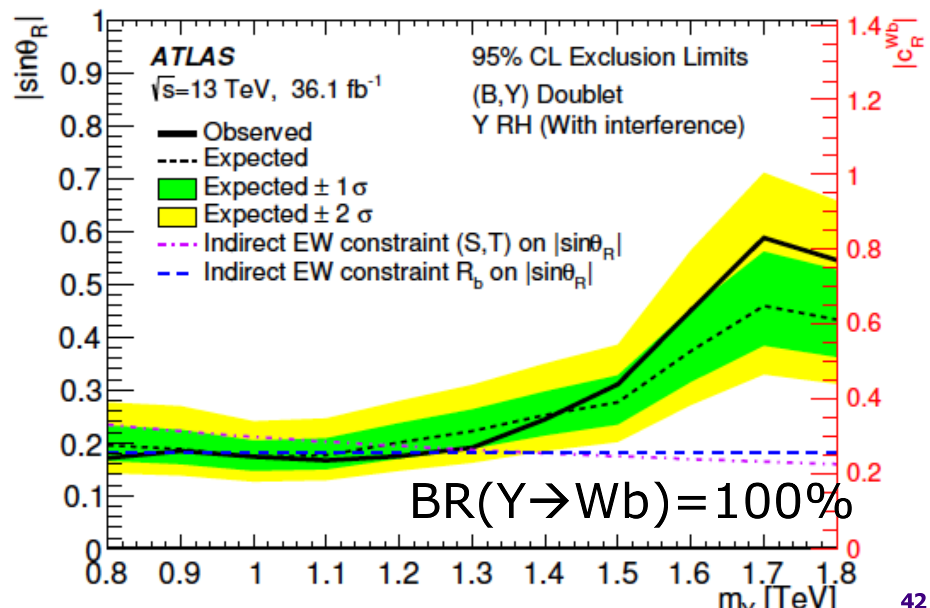
Limits:





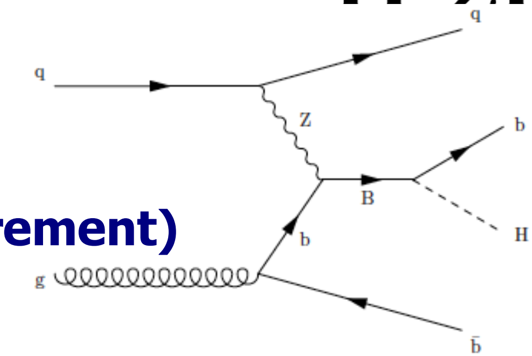


Interpretation in terms of coupling/width
Width consideration still below detector resolution

➔ Exclusion of large part of narrow width approximation

CMS: Single B→ bH

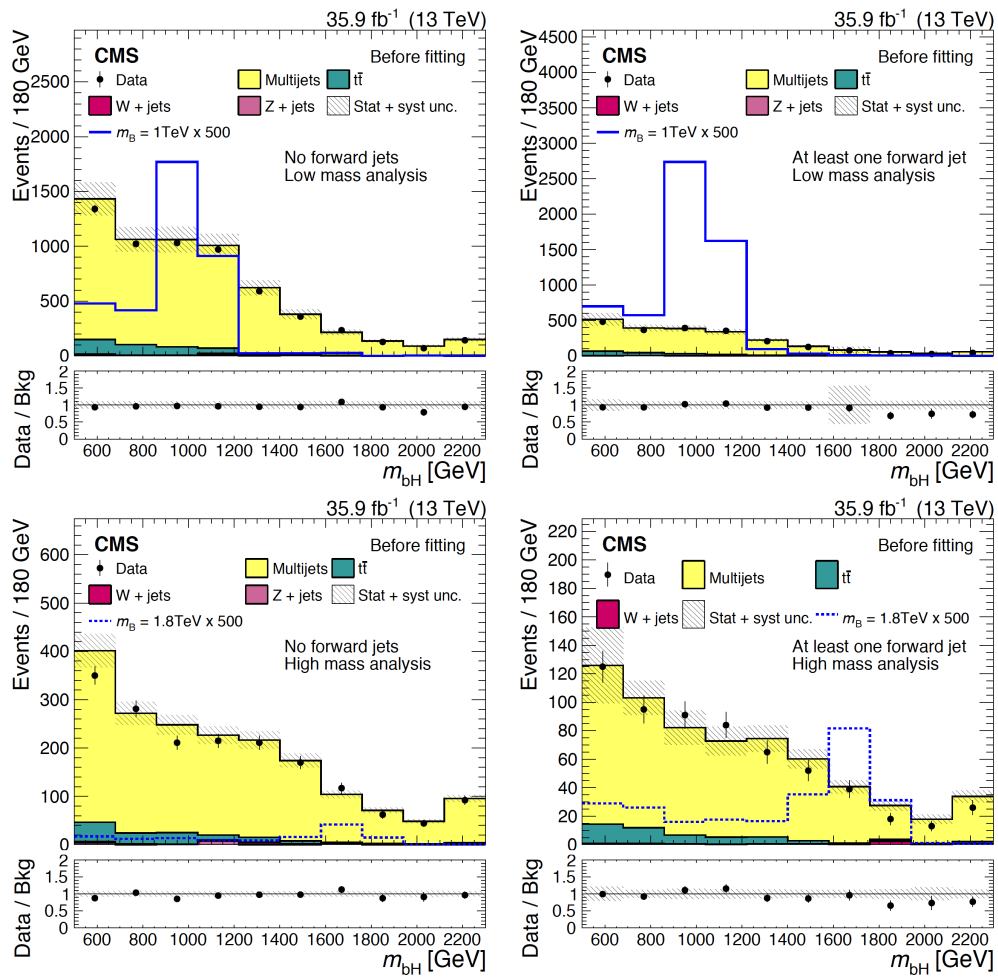
10.1007/JHEP06(2018)031



- **All hadronic final state**
- **Use boosted Higgs (→ bb) with b-tagging**
- **Analysis split in 2: low/high mass regime (Ht requirement)**
- **Split in no/at least one forward jet**

Events Selection:

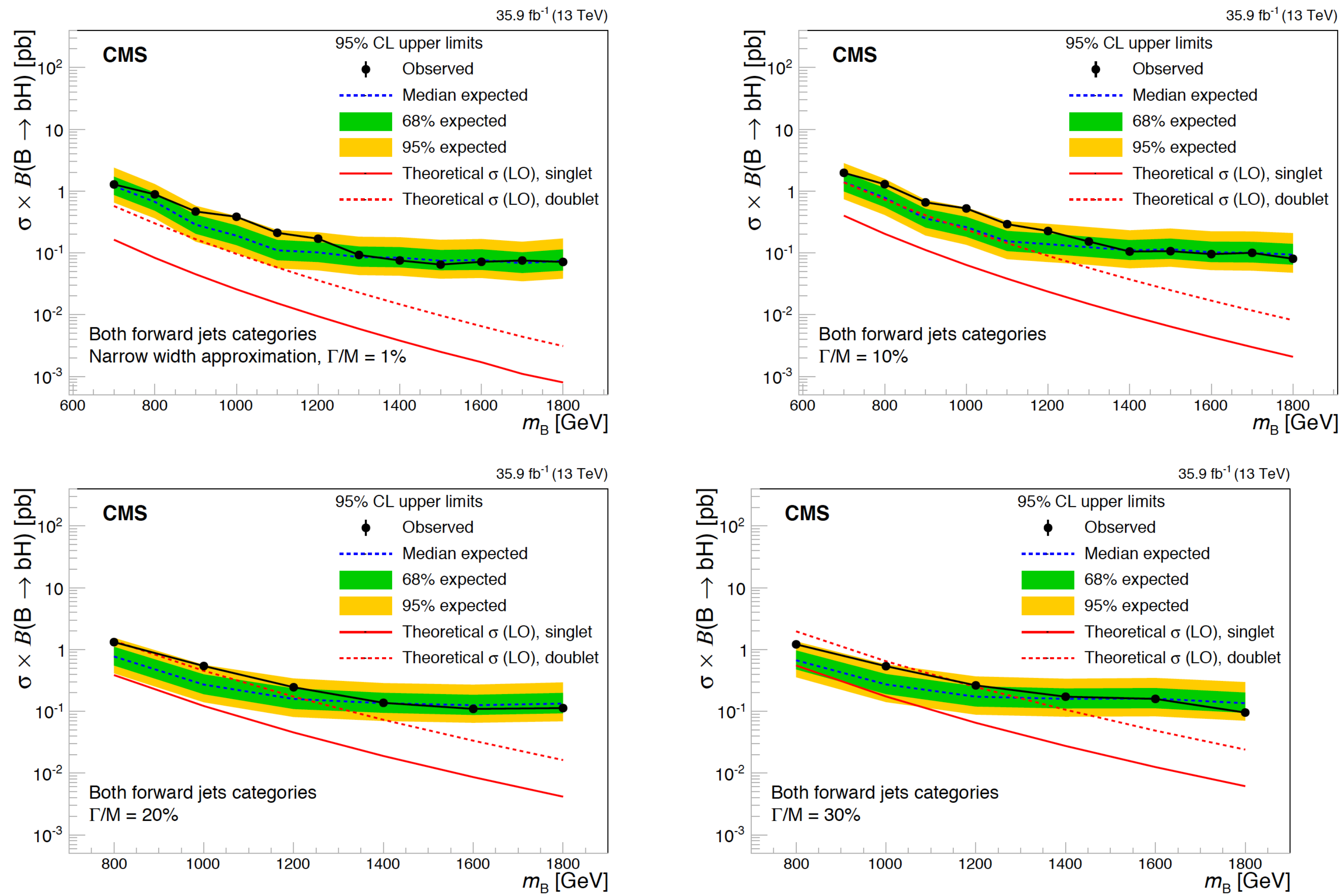
- **≥ 3 ak4 jets**
- **≥ 1 b-tag jets**
- **≥ 1 ak8 Higgs tag**
- **HT>900 / 1250 GeV (low/high)**



CMS: Single B→ bH

10.1007/JHEP06(2018)031

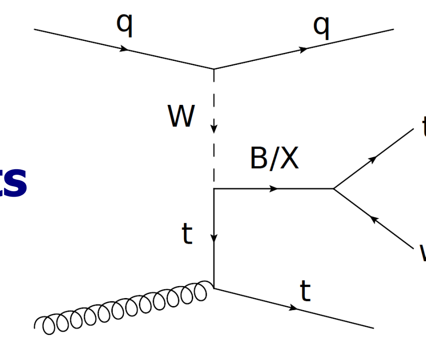
Studies as function of width



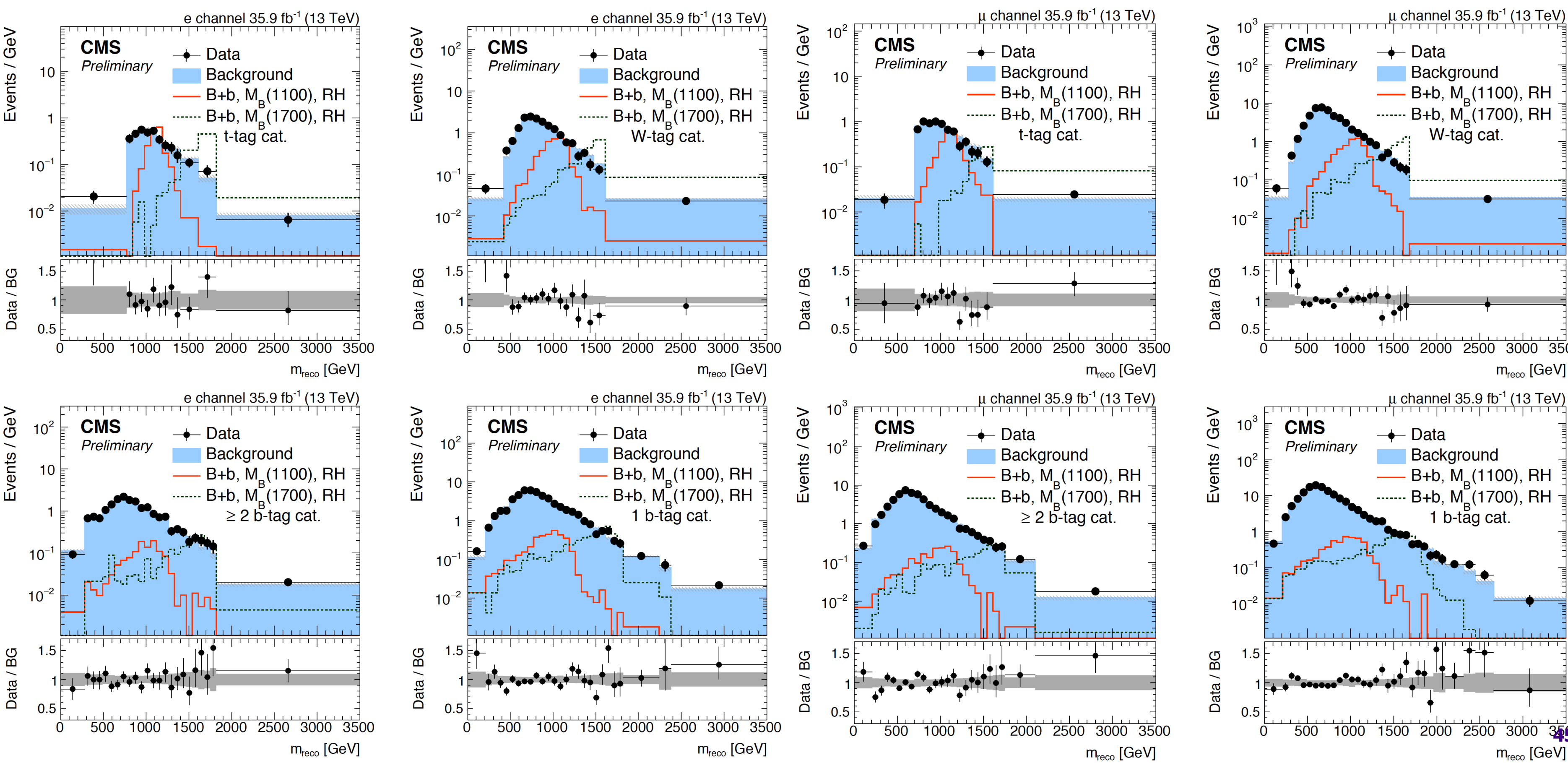
Exclusion reached for doublet case and 20/30% widths

CMS: Single $X^{5/3}$/B→ Wt

EPJC 10052-019-6556-3



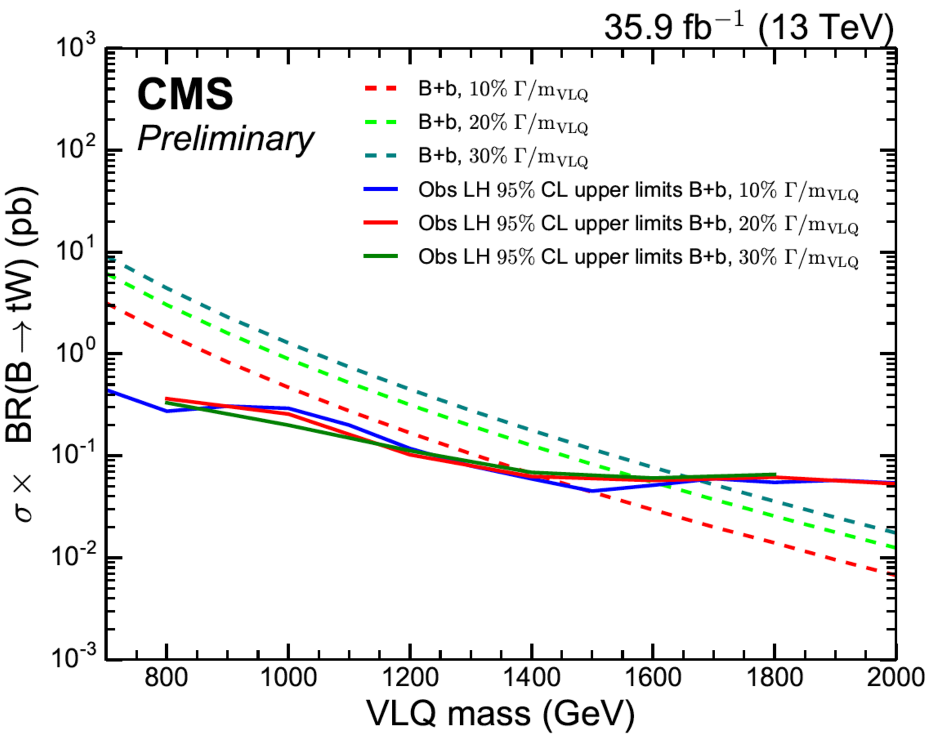
- l+jets as final state
- Boosted and resolved case are considered
- Analysis split in categories based on kind of boosted jets
- Best jet association determine via chi2
- Simultaneous fit of 0/≥1 forward jet

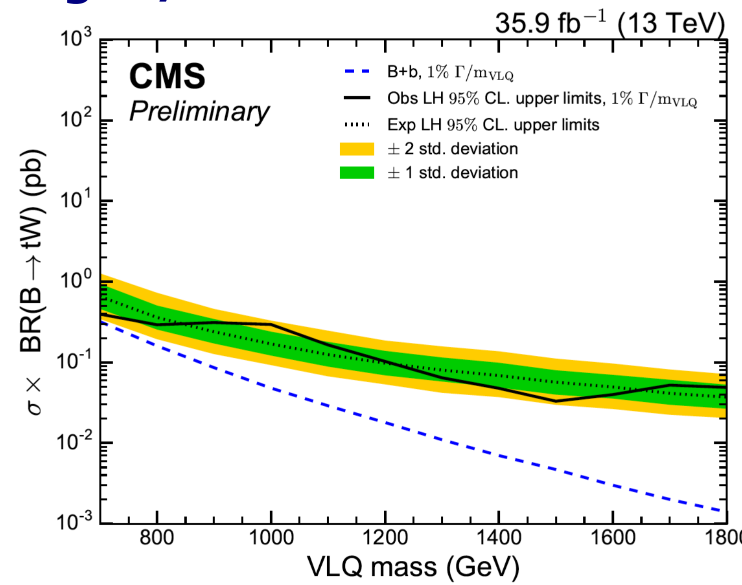


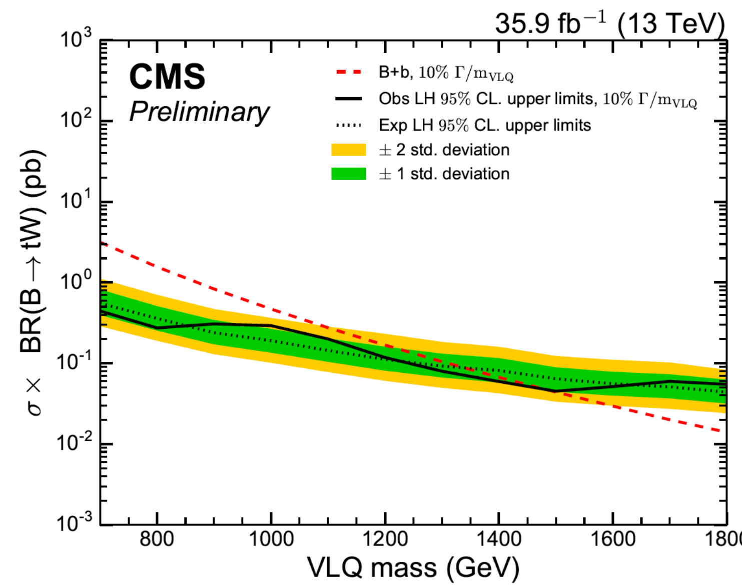
CMS: Single $X^{5/3}$/B→ Wt

EPJC 10052-019-6556-3

Limits set for $X^{5/3}$ and B, for each chirality, singlet/doublet model and for the various width studied.







Most of the masses <1.4 TeV are excluded for width >10%

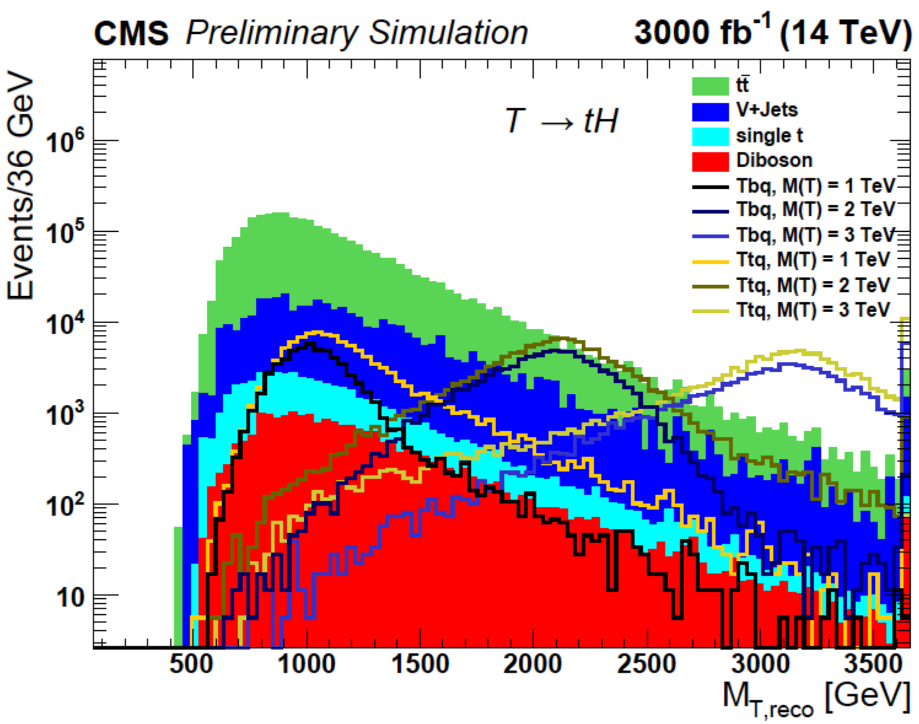
CMS on going analysis

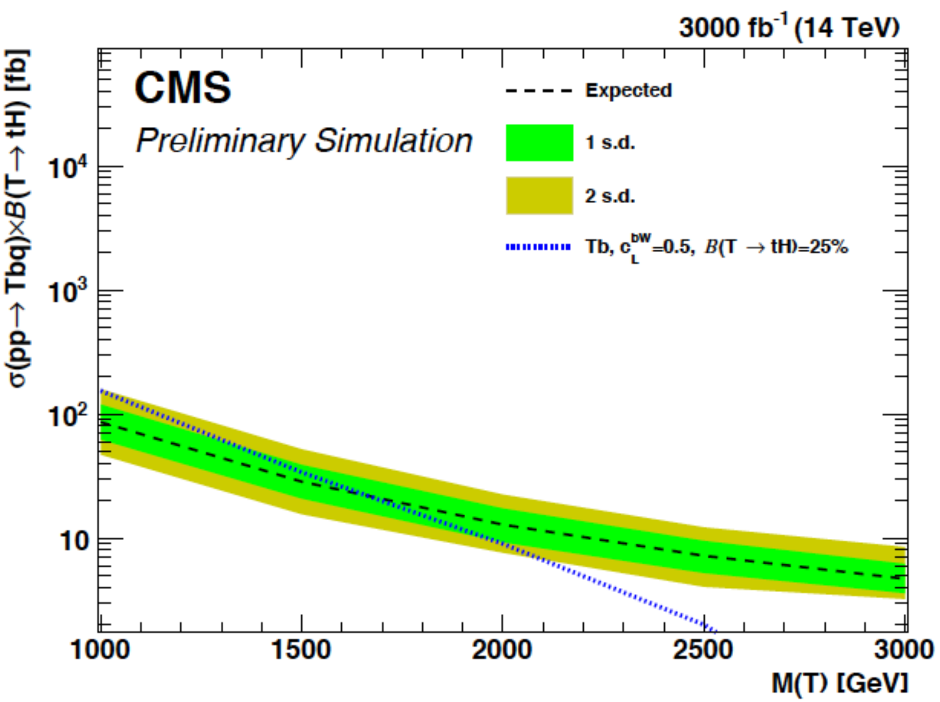
- Single T→ tH/tZ all hadronic Run2
- Single T→ tH (→WW) in l+jets Run 2
- Single T→ tZ (→$\nu\nu$) Run 2
- Single T/Y$^{-4/3}$→ Wb in l+jets Run 2
- Single B/X$^{5/3}$→ Wt in SS dilepton Run 2
- Pair production BB all hadronic Run 2
- Pair production TT all hadronic Run 2
- Pair production TT/BB l+jets Run 2
- Pair production BB in Di-lepton Run 2
- Pair production Light VLQ Run 2

Future of VLQ Searches

CMS: Single T→t+H at HL-LHC

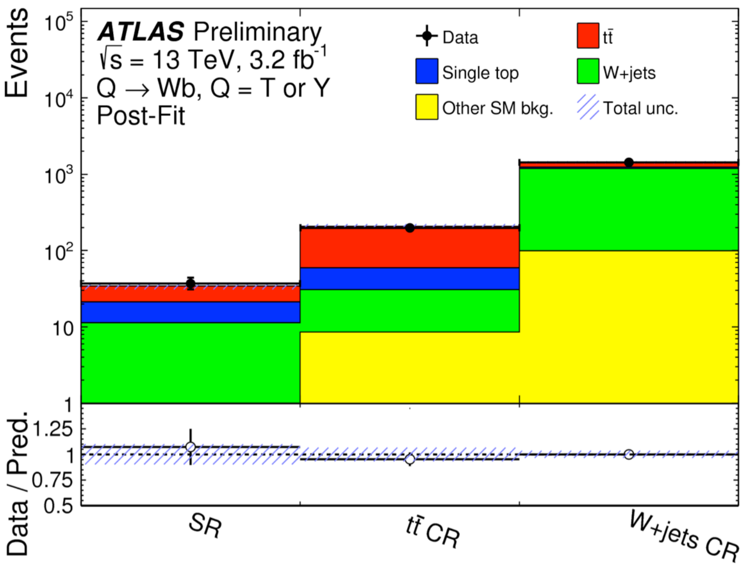
l+jet:
=1 lepton
ETmiss
2 ak4 central, at least one b-tag
1 Higgs-tag Ak8 jet
T mass reconstruction via chi2





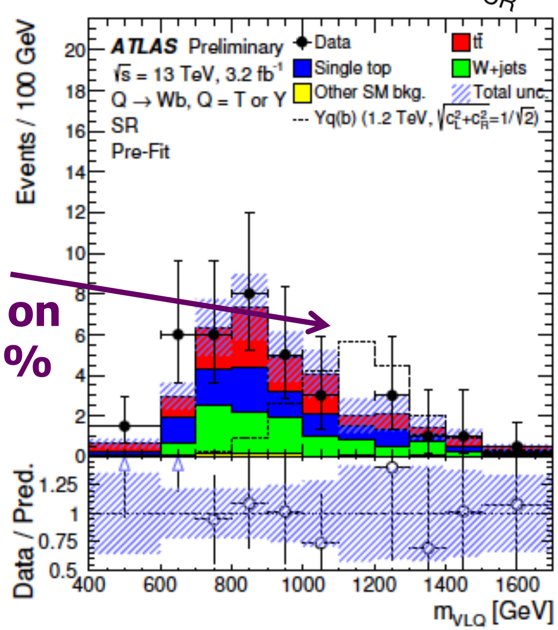
Atlas: Single $Y^{4/3}/T \rightarrow Wb$

Simultaneous fit in SR and CR

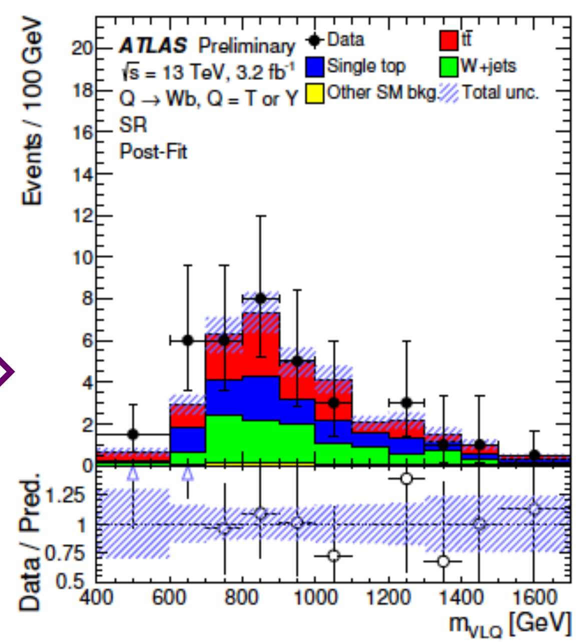


	SR	$t\bar{t}$ CR	W+jets CR
$t\bar{t}$	13.4 ± 3.4	149.8 ± 14.8	195.5 ± 38.0
single top	9.8 ± 1.5	28.5 ± 4.0	42.0 ± 7.5
W+jets	10.7 ± 2.0	22.0 ± 4.4	1093.4 ± 59.1
Multijet	0.01 ± 0.3	5.4 ± 6.4	27.0 ± 16.3
Z+jets, diboson	0.6 ± 0.2	3.2 ± 0.6	72.2 ± 5.8
Total	34.5 ± 3.6	208.9 ± 15.6	1430.1 ± 52.1
Data	37	199	1427

Mass resolution on signal > 5%



Fit



ATLAS CONF 2016-072

Conclusion

Atlas and CMS are producing a lot of results on VLQ

Pair production is preferred so far but single production is coming up to speed (modulo models fixes)

Results obtained by Atlas and CMS are pretty similar all the time

A lot of new results should come with Run2 data analysis!