Experimental results on single VLQ searches

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Outline:

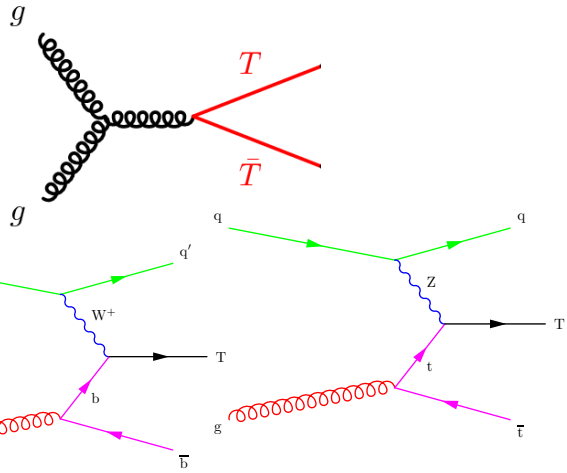
- **VLQ production and decays**
- **Tools**
- **Searches: T', $Y^{4/3}$, B, $X^{5/3}$**
- **Conclusion**

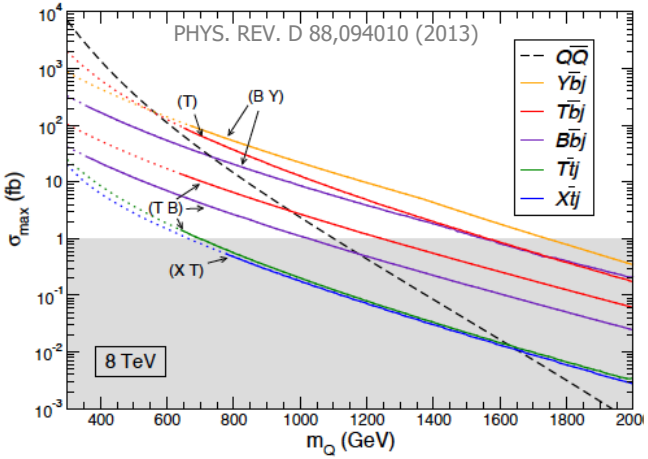
NB: Main focus here is VLQ coupling to 3rd quark generation mainly.

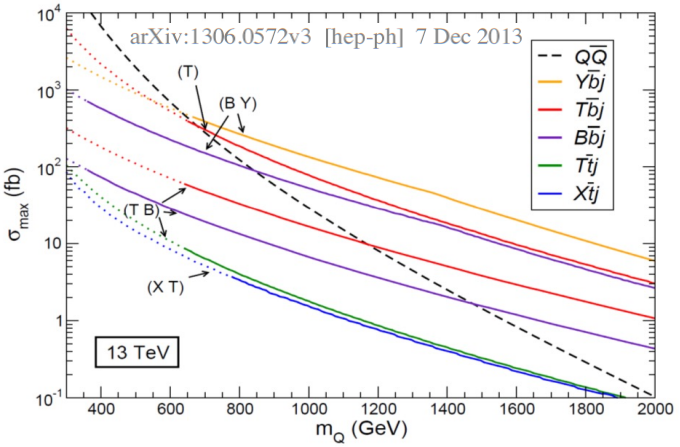
Production

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



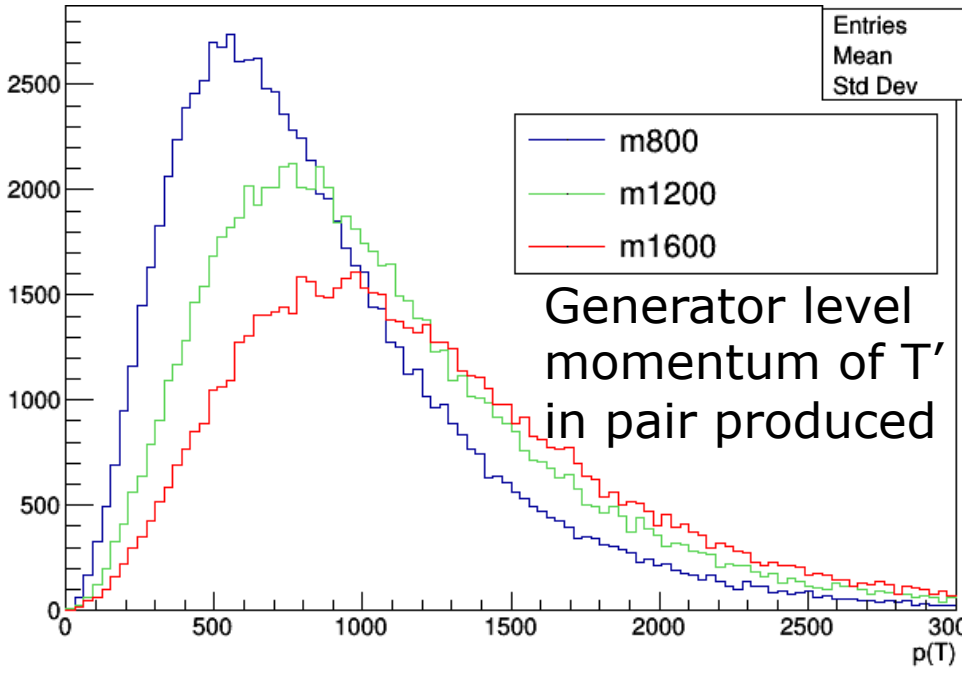




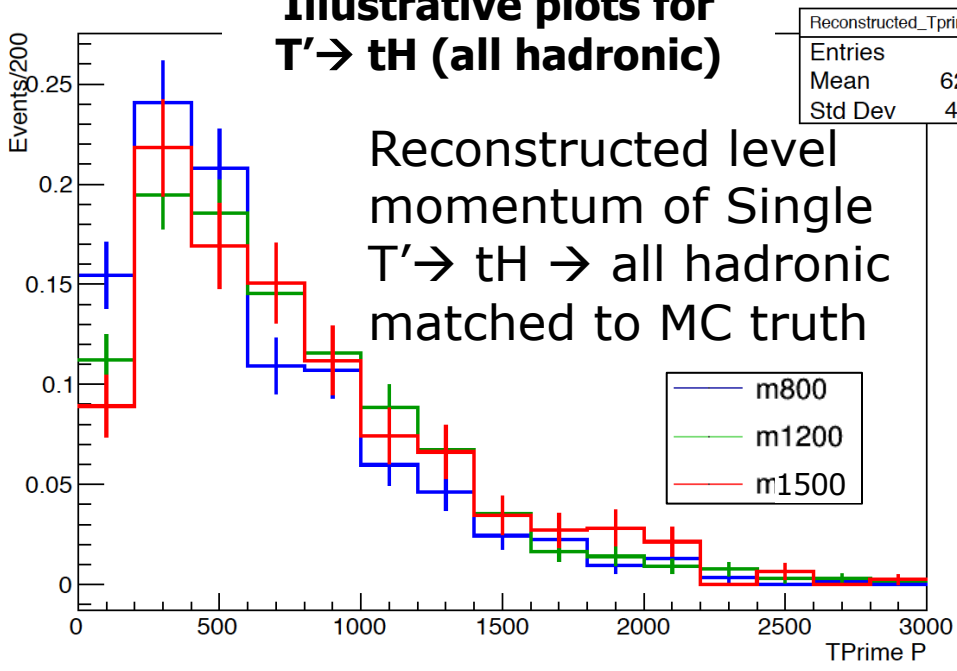
Plots above are for given benchmarks couplings but still giving an idea of what is happening…

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)

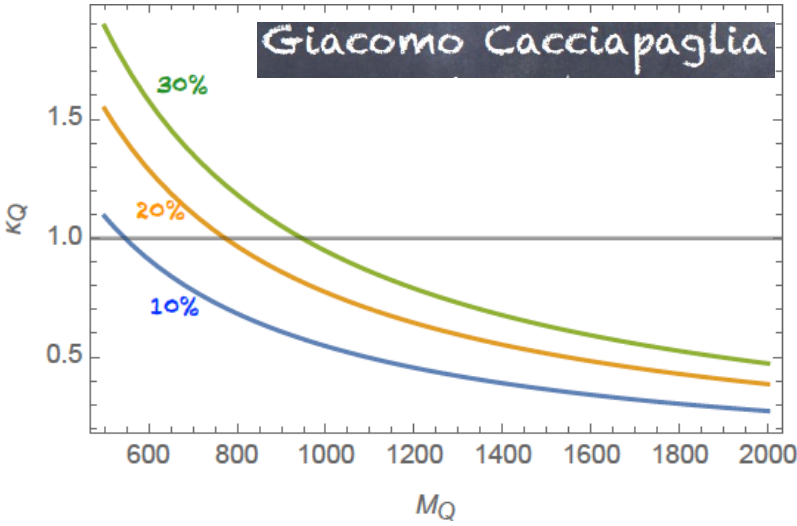
In single production mode, the momentum does not change much with mass.

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

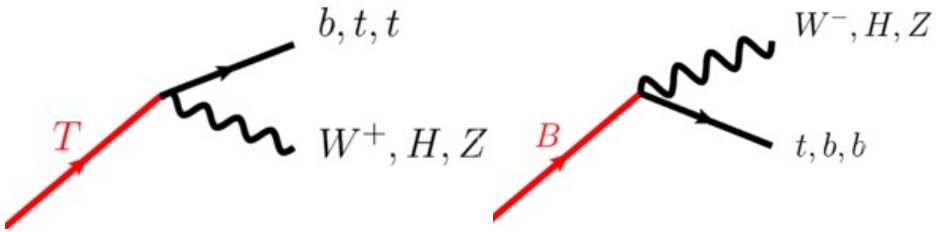
IP2I

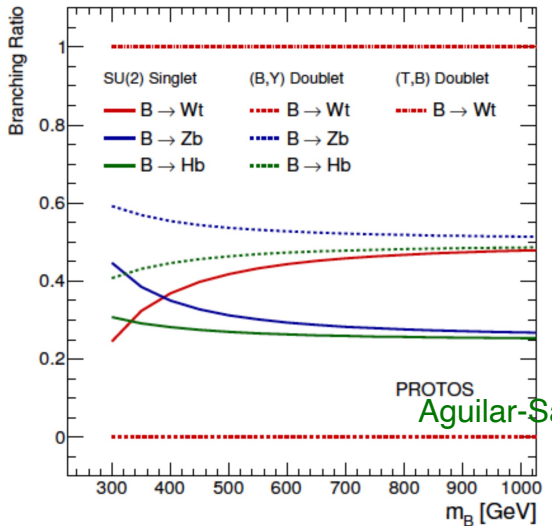
Heavy Vector like Quark

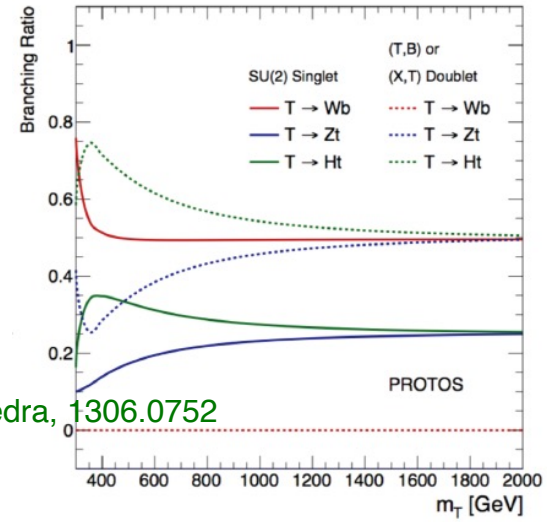
	T B	$\begin{pmatrix}X\\T\end{pmatrix}$ $\begin{pmatrix}T\\B\end{pmatrix}$ $\begin{pmatrix}B\\Y\end{pmatrix}$	$\begin{pmatrix}X\\T\\B\end{pmatrix}$ $\begin{pmatrix}T\\B\\Y\end{pmatrix}$
$SU(2)_L$ multiplet	1	2	3
Charge	2/3 -1/3	$\begin{pmatrix}5/3\\2/3\end{pmatrix}$ $\begin{pmatrix}2/3\\-1/3\end{pmatrix}$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

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)





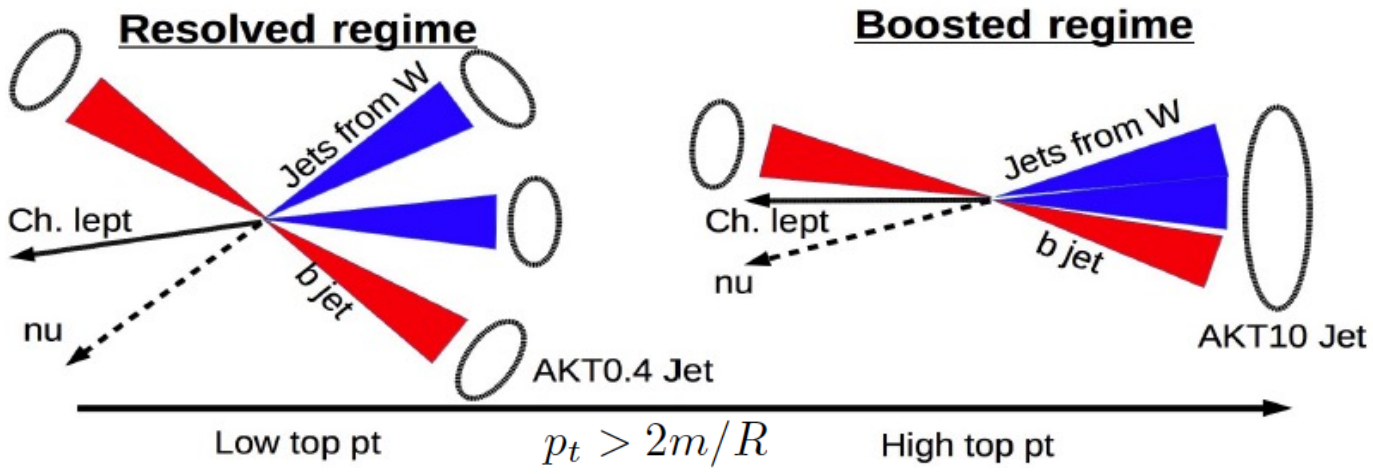


Aguilar-Saavedra, 1306.0752

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

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**

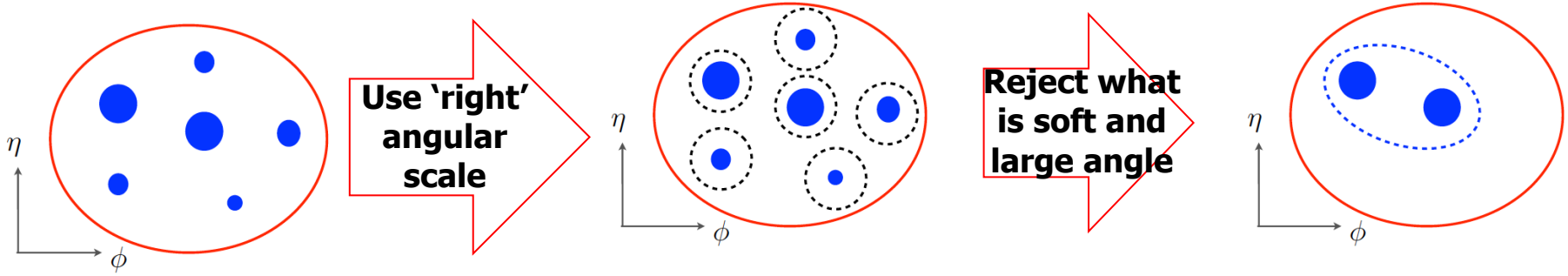
Using larger cone size for jets to get all decay in

→ Look at jet sub-structure to identify

Jets sub-structure

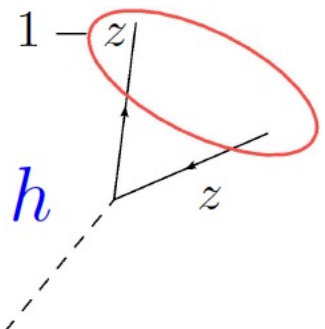
Exploit jet substructure: grooming and tagging

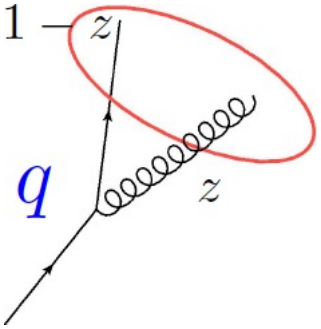
Grooming:



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

Run 2 Analysis

- Atlas is retuning an analysis for VLQ → Wb with width/coupling consideration + T→tH with MC varying κ_Q parameter
- CMS is following existing ones (T→tZ/tH) 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.

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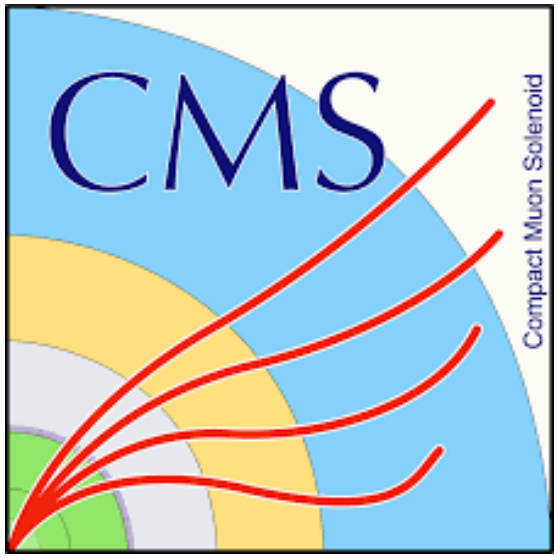
Single Production



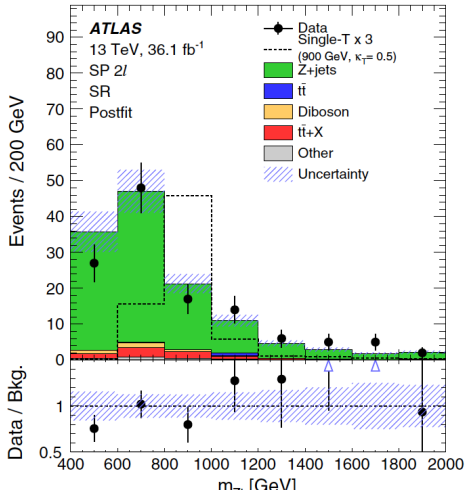
Single T → Zt

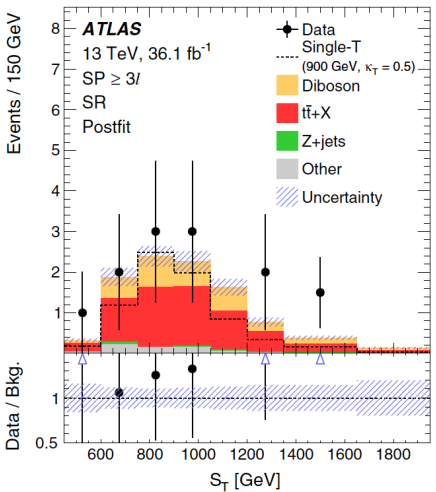
IP2I

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

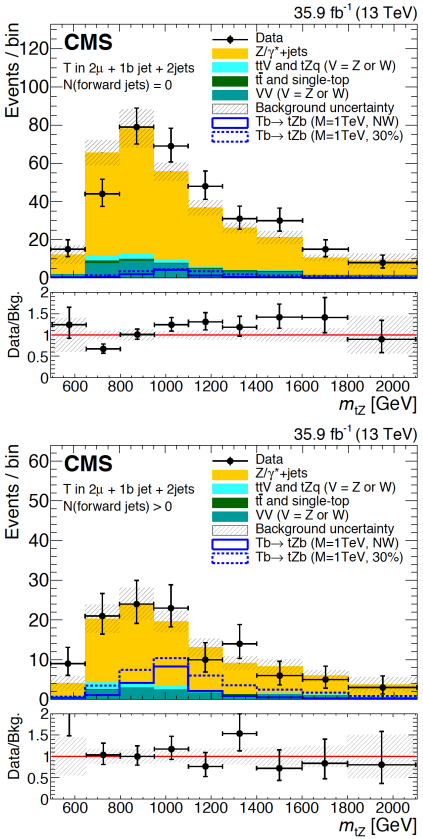
Opposite-sign 2-leptons: Select events with Z→ℓℓ

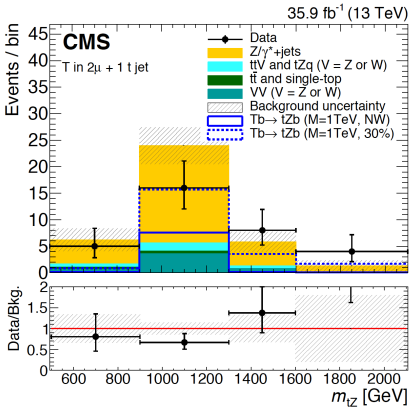
≥ 1 forward ak4 jet
≥ 1 b-tag jet
≥ 1 top-tag jet
→ Boosted only
Main Variable: mass(Zt)
3 leptons analysis
Remove top-tag criteria
Main Variable: ST





≥ 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)





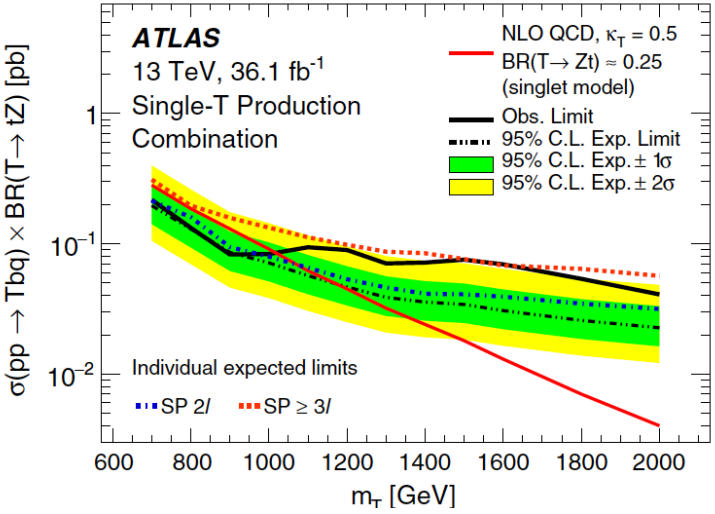
Single T → Zt

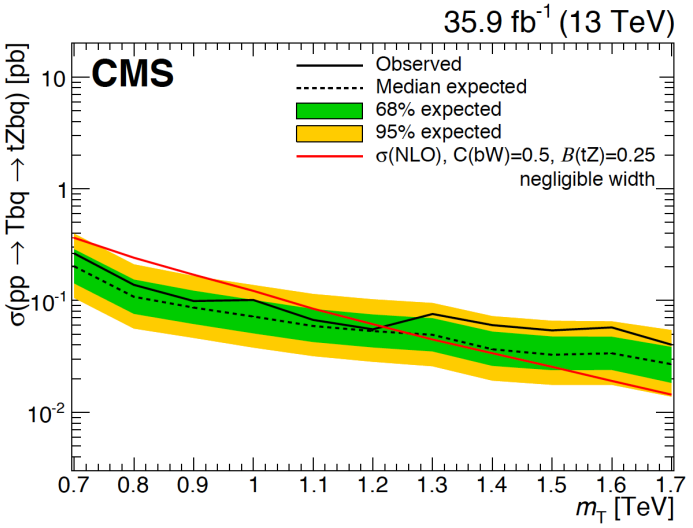
IP2I

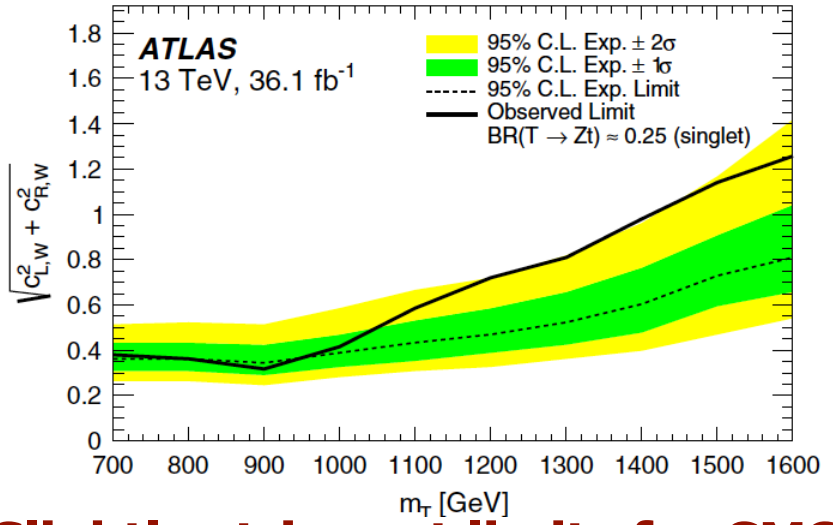
Phys. Rev. D98 (2018) 112010

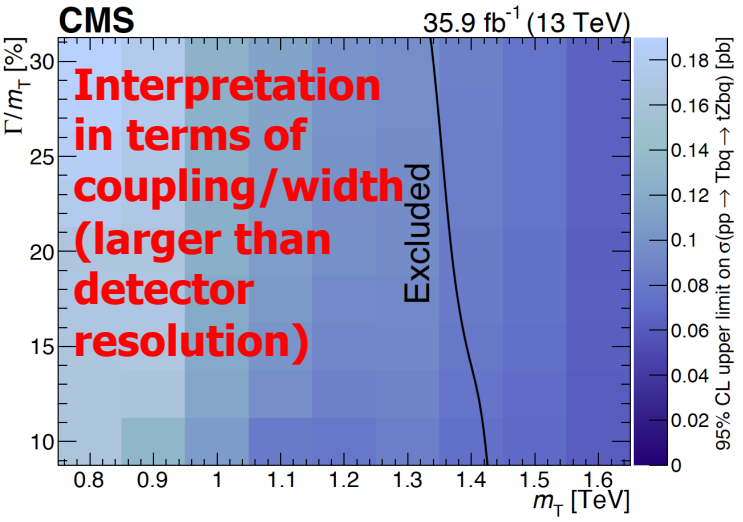
10.1016/j.physletb.2018.04.036

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



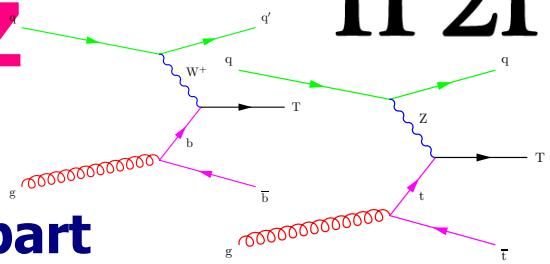






Slightly stringent limits for CMS. Atlas contains 3 lepton channel, stringent limits for CMS if consider 2l only

CMS: Single T→ tH/Z



JHEP 01 (2020) 036

Single VLQ T → t+H/Z all hadronic analysis:
Split in resolved (below 1 TeV) and fully boosted part

Fully Boosted: 2 ak8 jets: 1 top-tag, 1 H/Z-tag, one forward jet, ST
Work in categories depending on b-tag of ak8 jets
Main variable looked at (X=H/Z):

$$\widetilde{m}_{\mathrm{T}} = \sqrt{(P_{\mathrm{t}} + P_{\mathrm{X}})^2} - \sqrt{P_{\mathrm{t}}^2} - \sqrt{P_{\mathrm{X}}^2} + m_{\mathrm{t}} + m_{\mathrm{X}} = m_{\mathrm{tX}}^{j} - (m_{\mathrm{t}}^{j} - m_{\mathrm{t}}) - (m_{\mathrm{X}}^{j} - m_{\mathrm{X}})\,.$$

Resolved: ≥6 jets in the final state, 3 b-tag (tight for signal area), jets are coupled via a chi2 method to make a H/Z-candidate, W/top-candidate. No Forward jets required. No correlation between top-H/Z candidate.
Work in 3 categories depending on b-tagging on 3 jets: 2 Medium (1% fake rate)+1Loose (10% fake rate), 3 Medium or 3 Tight b-tag (0.1% fake rate).
Main variable looked at: M(5J) = M(top+H/Z)

CMS: Single T→ tH/Z

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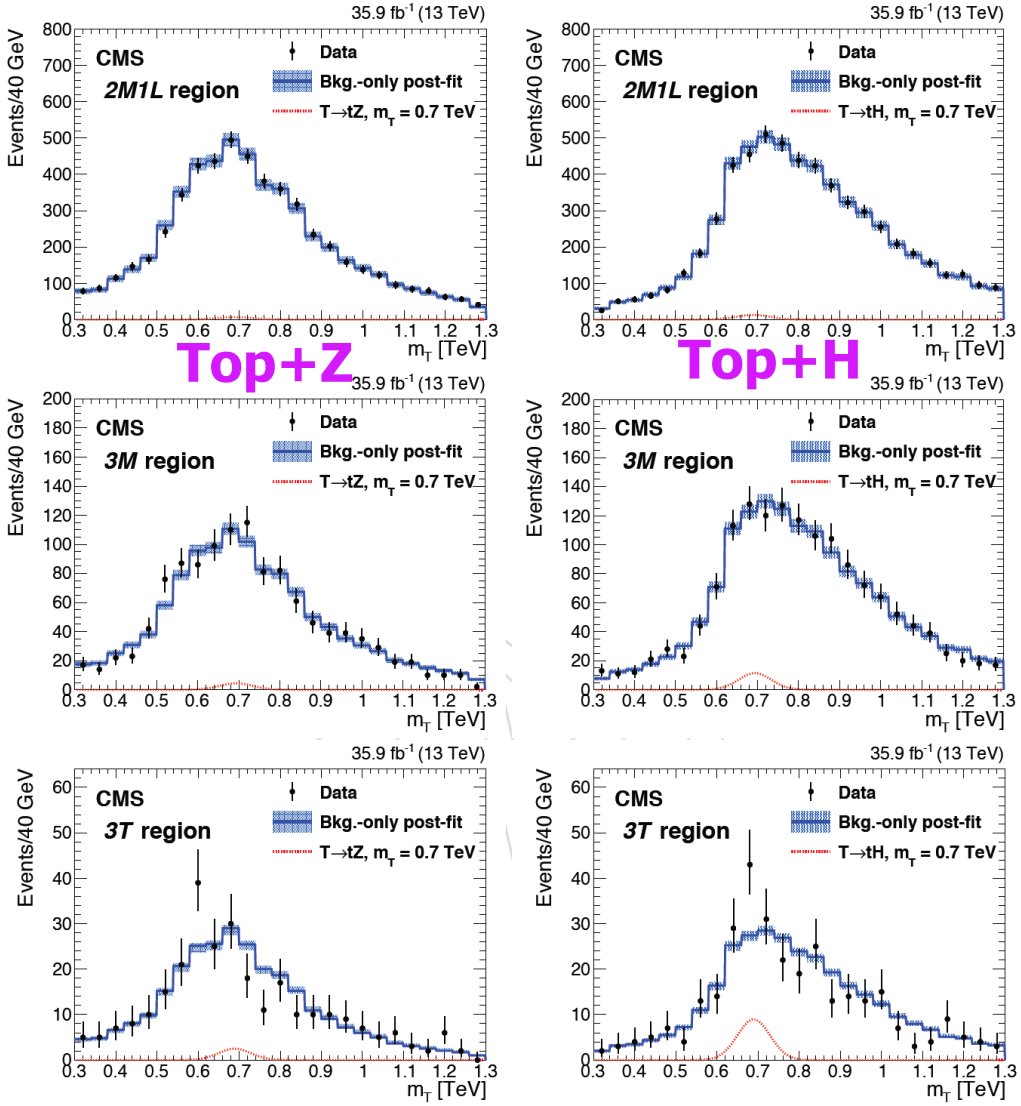
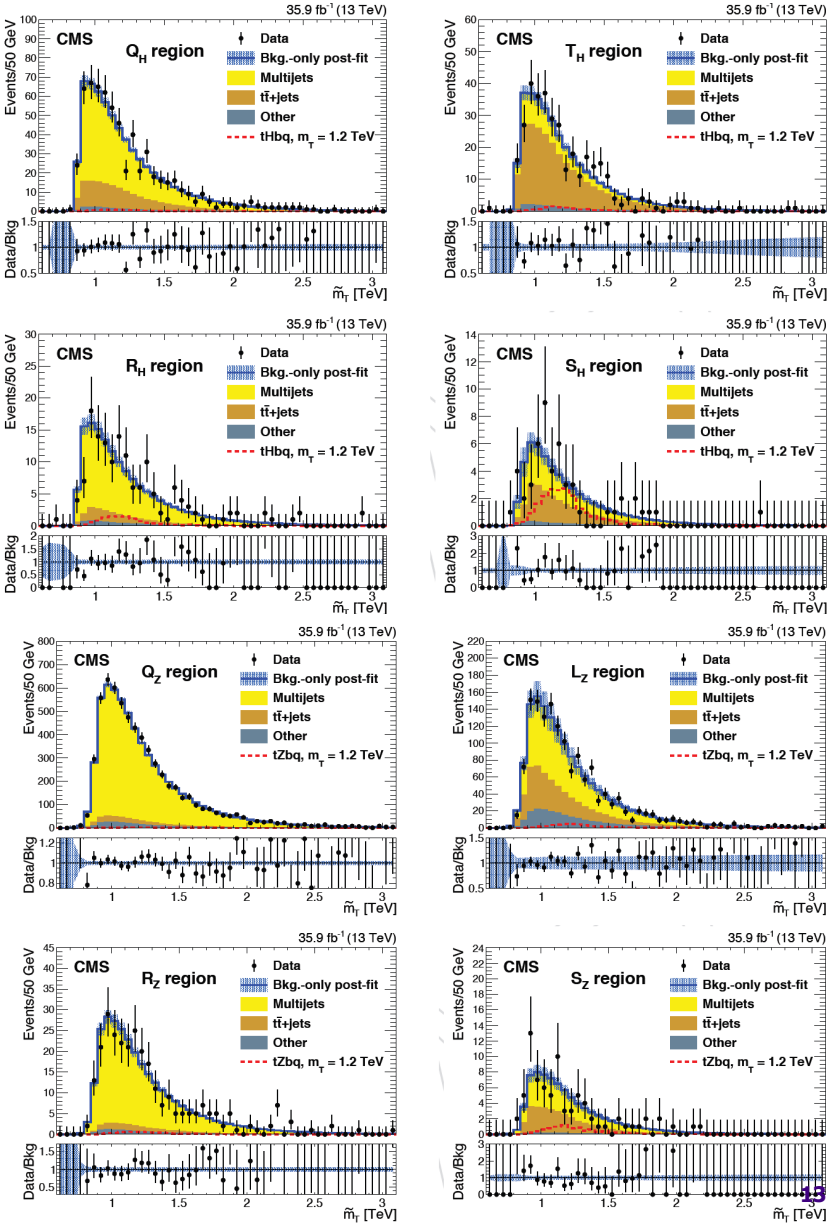
Post-Fit background only





CMS: Single T→ tH/Z

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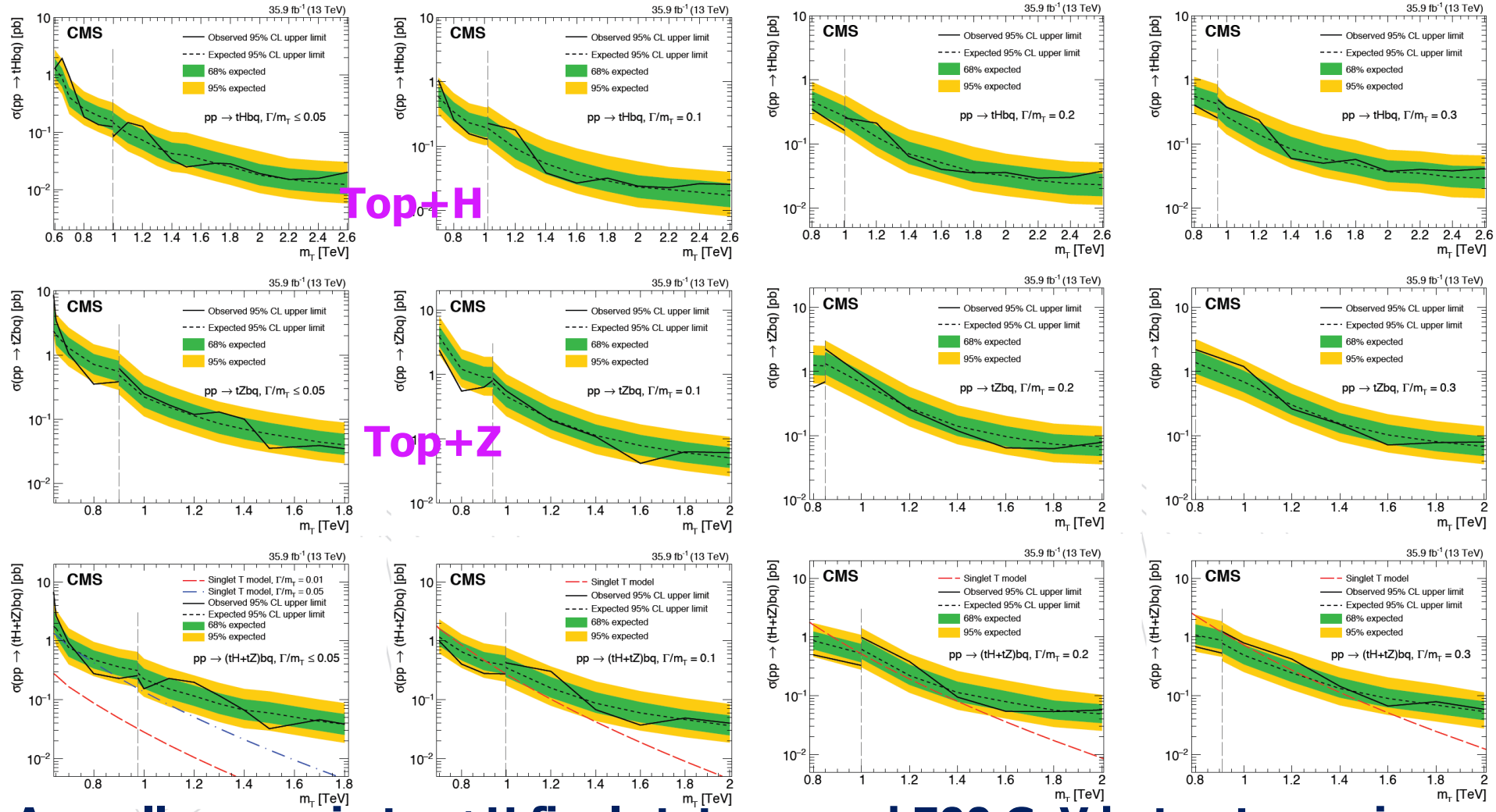


A small excess in top+H final state around 700 GeV but not seen in top+Z, all large width tends to be excluded at low mass, no exclusion at high mass but getting closed

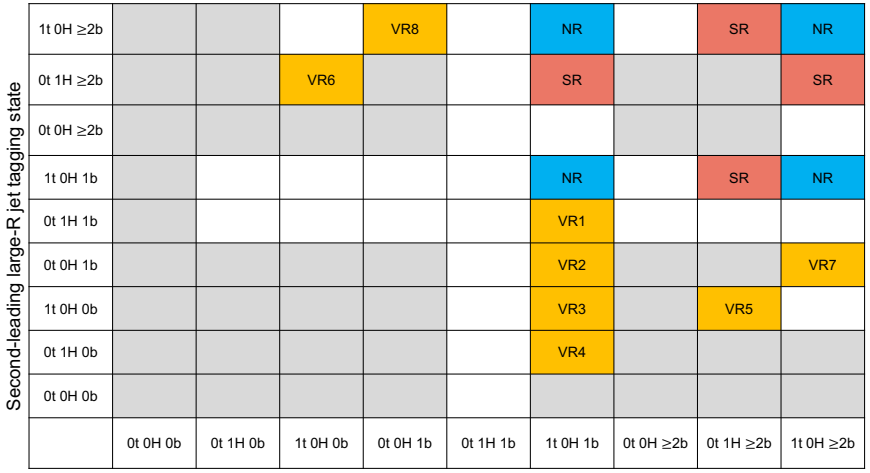
Atlas: Single T→ top+H

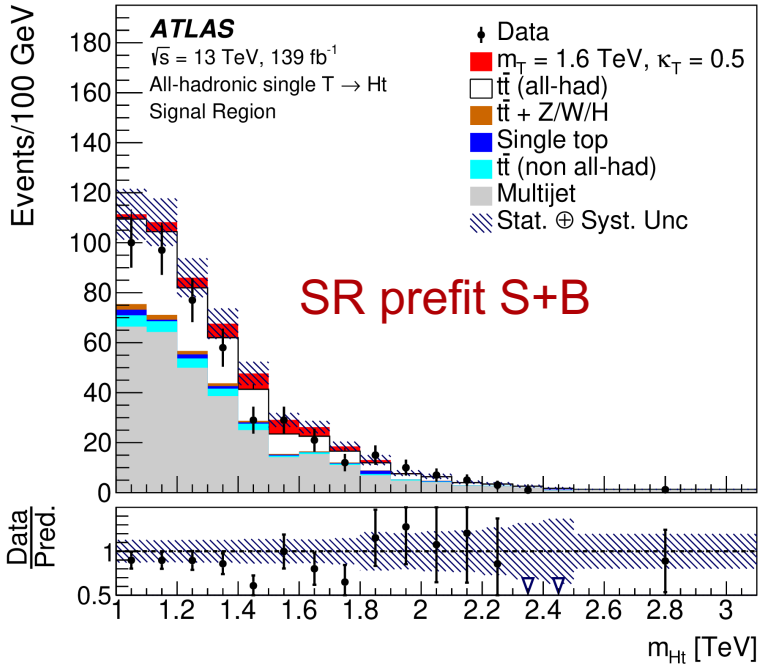
arXiv:2201.07045

Top and Higgs boosted
→ 2 wide jets

Classification 81 categories based on:
"H, t, other" & "0b, 1b, 2b" jets
→ Signal Region (red), Validation Region (Yellow), Normalisation Region for ttbar (blue)

→ Search over m(jj)
→ QCD (from grey regions) & tt, data-driven pred.

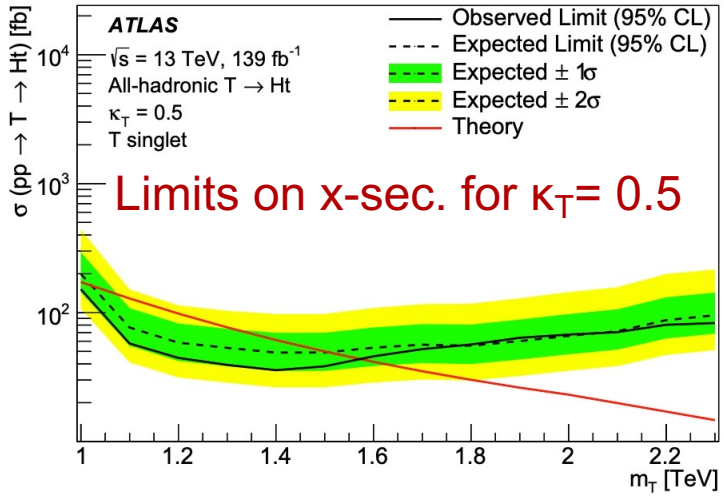


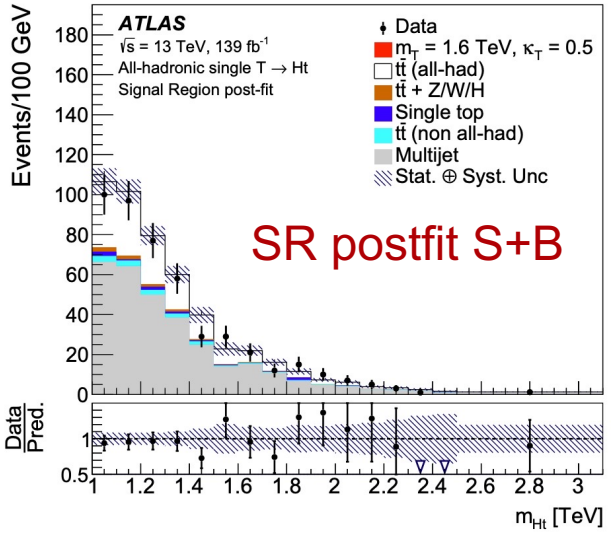


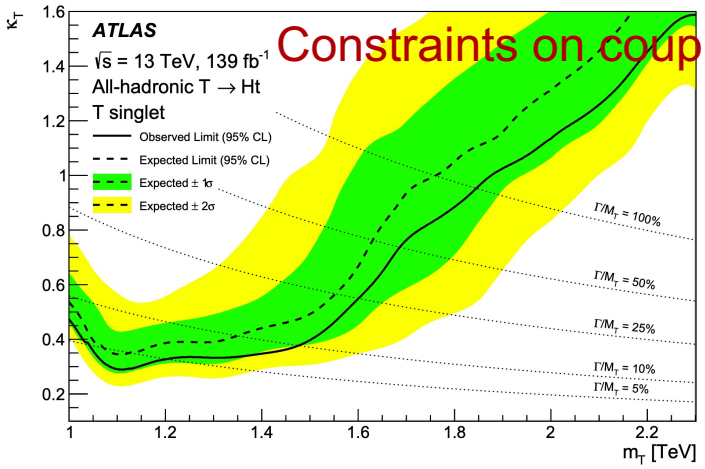
Atlas: Single T→ top+H

arXiv:2201.07045

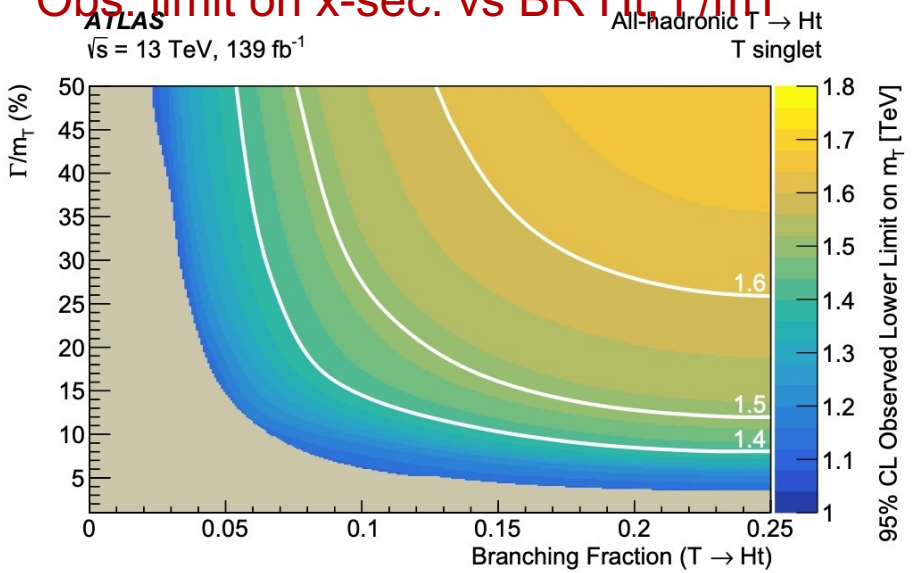
MC produced with κ_T variation
→ Direct studies of width







Obs. limit on x-sec. vs BR Ht, Γ/mT



Exclusion of masses [1,1.6] TeV with 20% width

Atlas Single T → Zt (Z→νν)

IP2I

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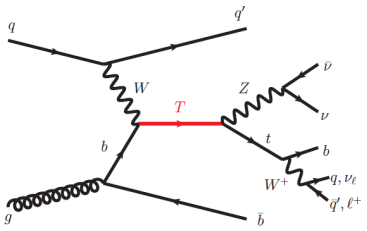
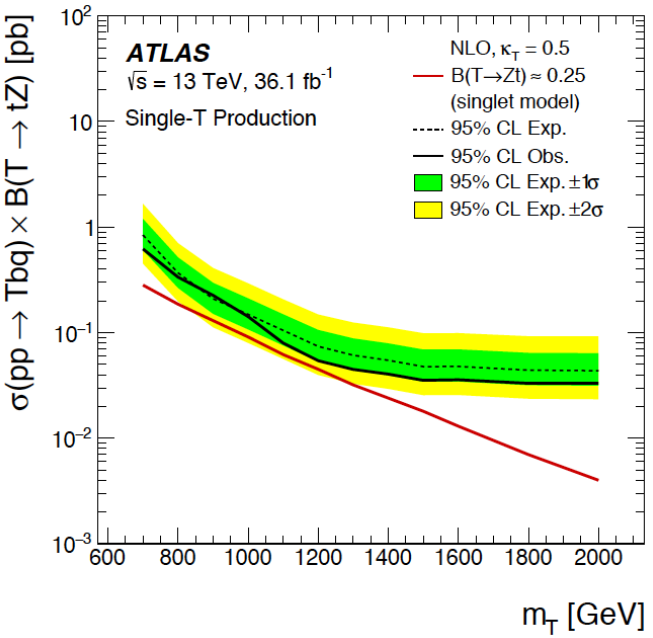
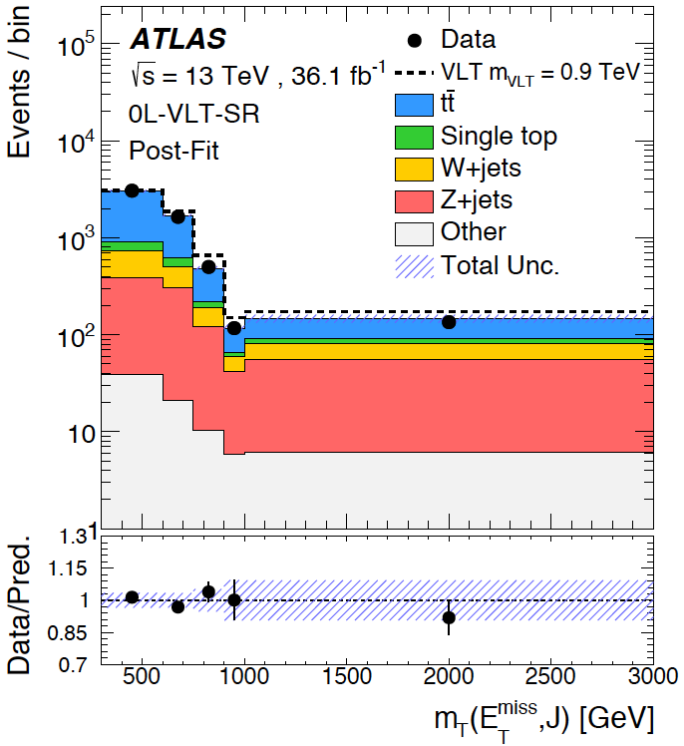
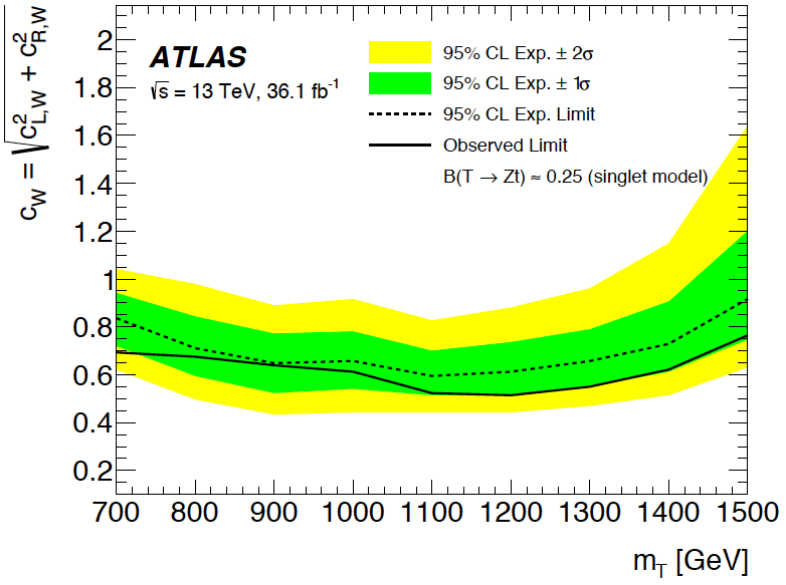
Etmiss > 200 GeV
= 1 b-tag jet
≥ 1 top-tag jet
≥ 1 forward ak4 jet
→Boosted only
Main Variable: m_T(ETmiss + top)









CMS: Single T → Zt (Z→$\nu\nu$)

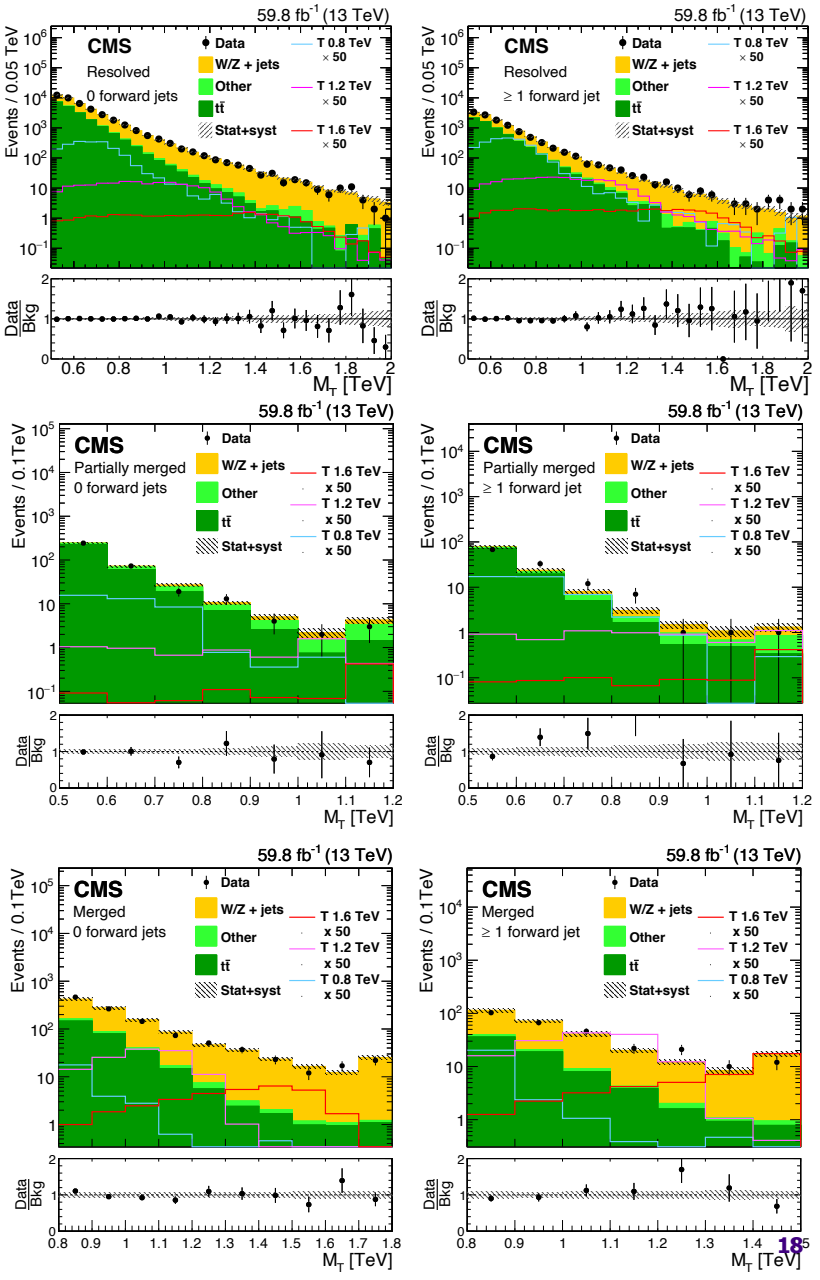
IP2I

B2G-19-004

3 regimes: resolved, partially-merged, merged

Etmiss > 200 GeV,
= 1 b-tag jet
≥ 1 top-tag jet or W-tag jet or 2 ak4 jets
Categories based on forward ak4 jet

Main Variable: m_T(ETmiss + top)

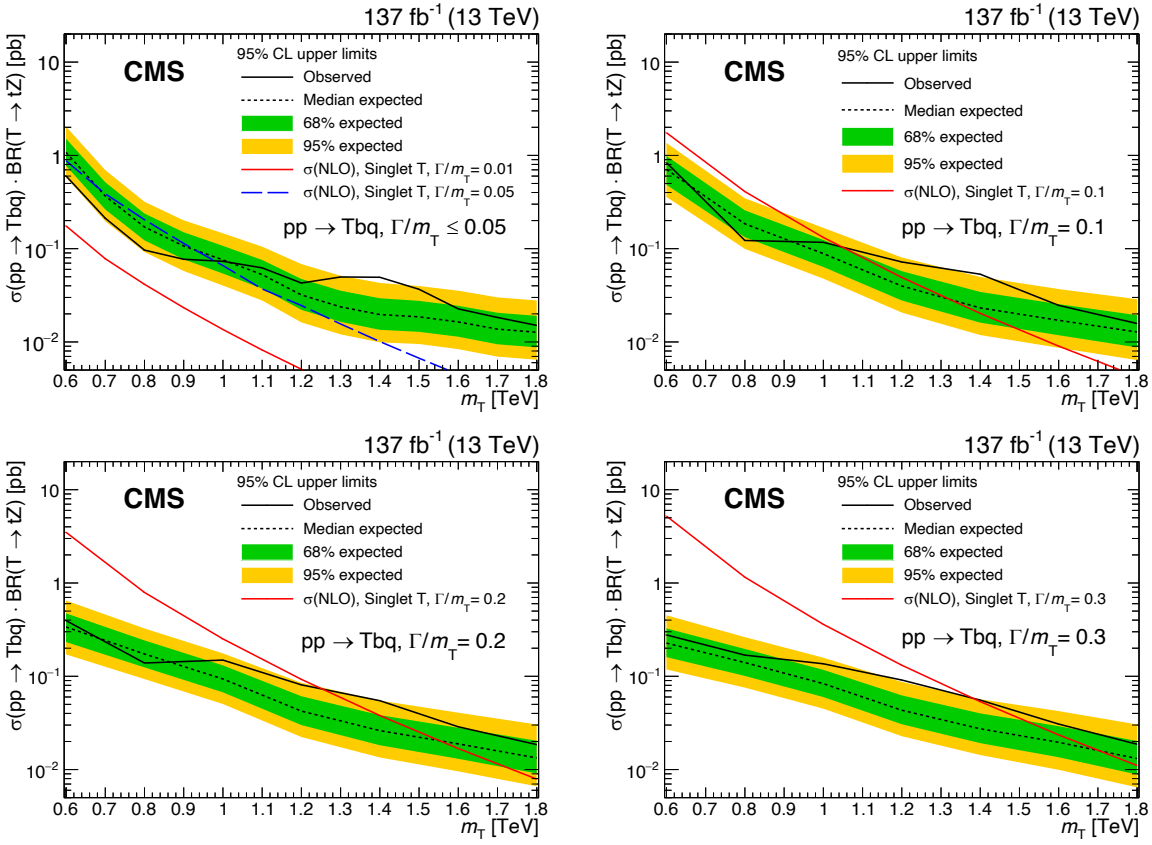


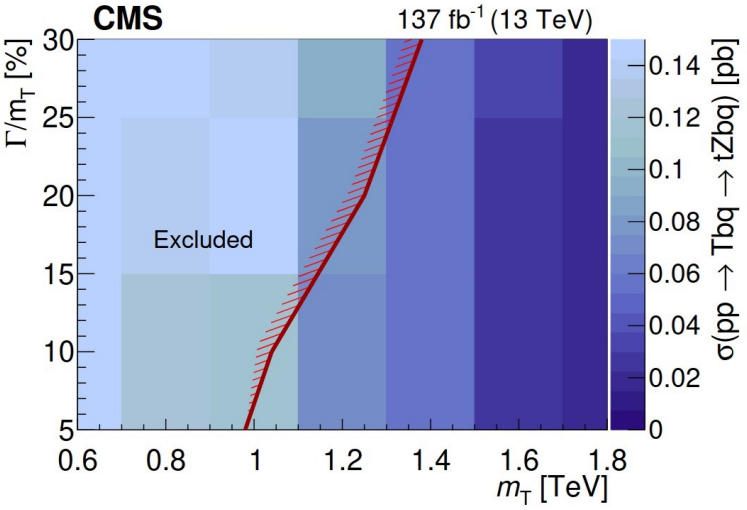
CMS: Single T → Zt (Z→νν)

IP2I

Limits per width consideration:

B2G-19-004



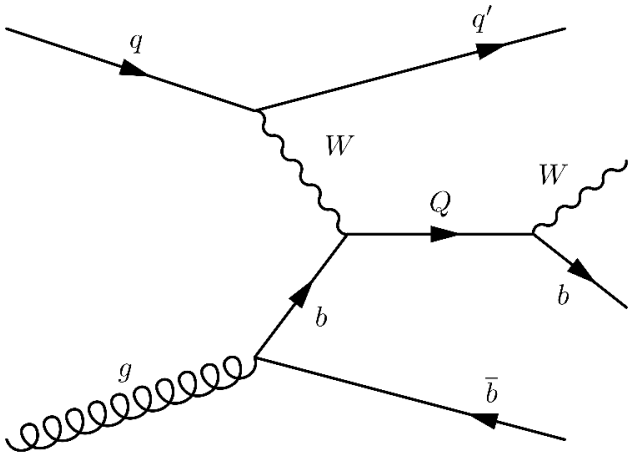


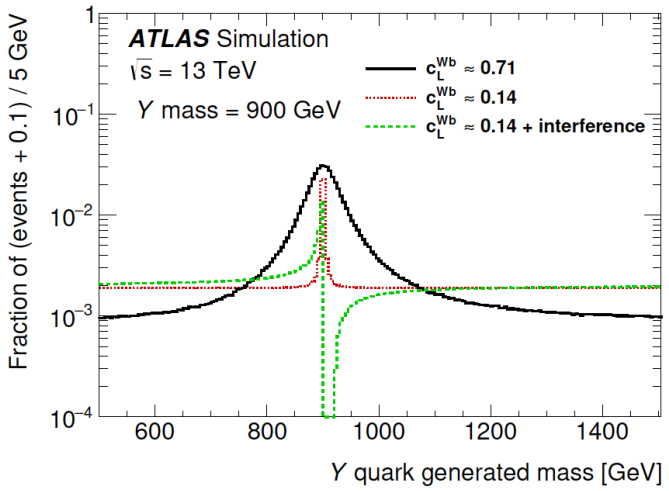
T' mass<1TeV are excluded what ever is the width considered.
For large width, exclusion up to 1.4 TeV

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

JHEP 05 (2019) 164

- **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**





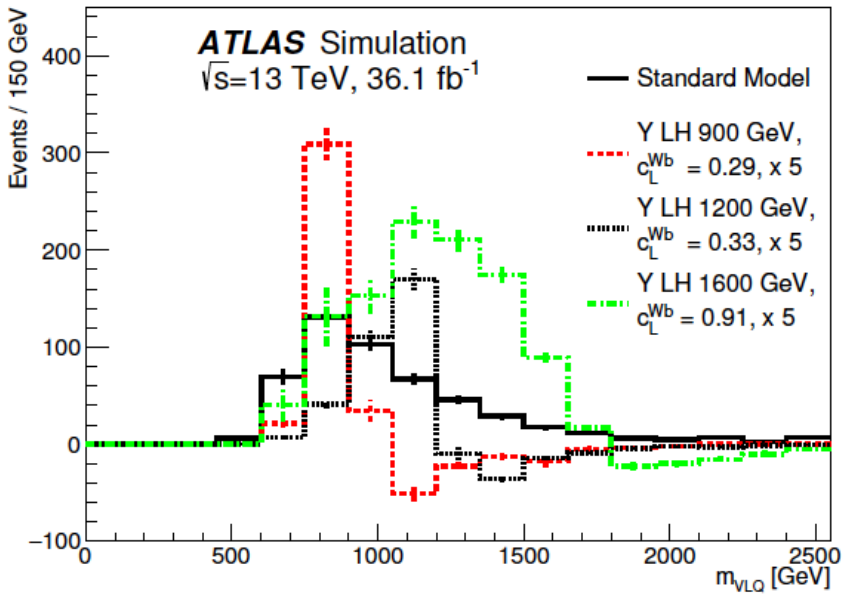
Width ~ 50 GeV (?)
So below detector resolution (?)

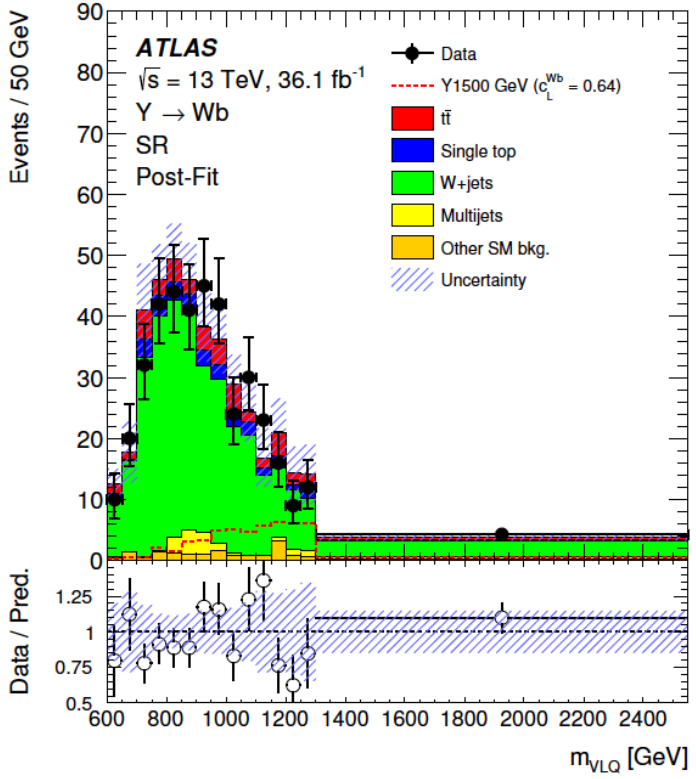
Atlas: Single $Y^{4/3}/T \rightarrow Wb$

IP2I

Selection: JHEP 05 (2019) 164

- **1 isolated e/μ**
- **≥ 1 b-jet with pt> 350 GeV**
- **Etmiss > 120 GeV**
- **Δφ (lepton,leading b-tagged jet)|> 2.5**
- **≥ 1 forward ak4 jet (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 $Y^{4/3}/T \rightarrow Wb$

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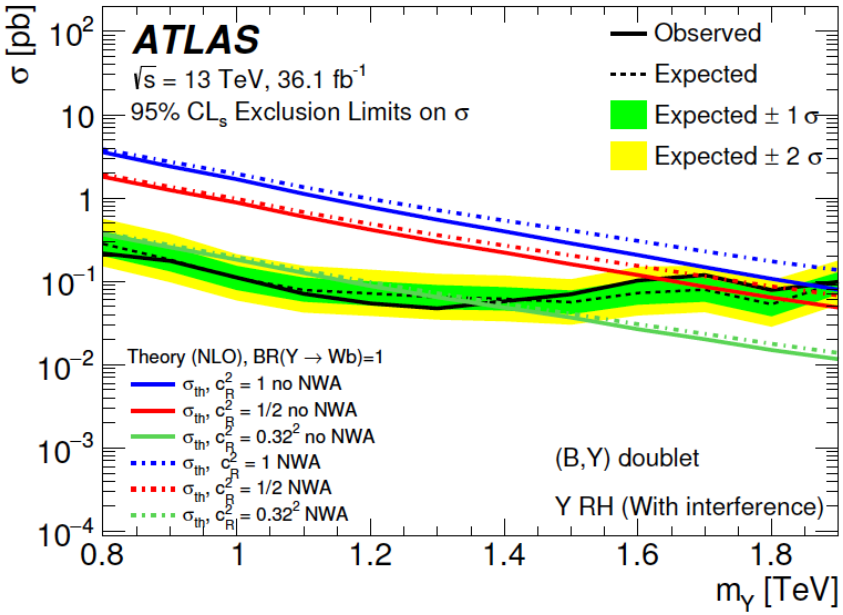
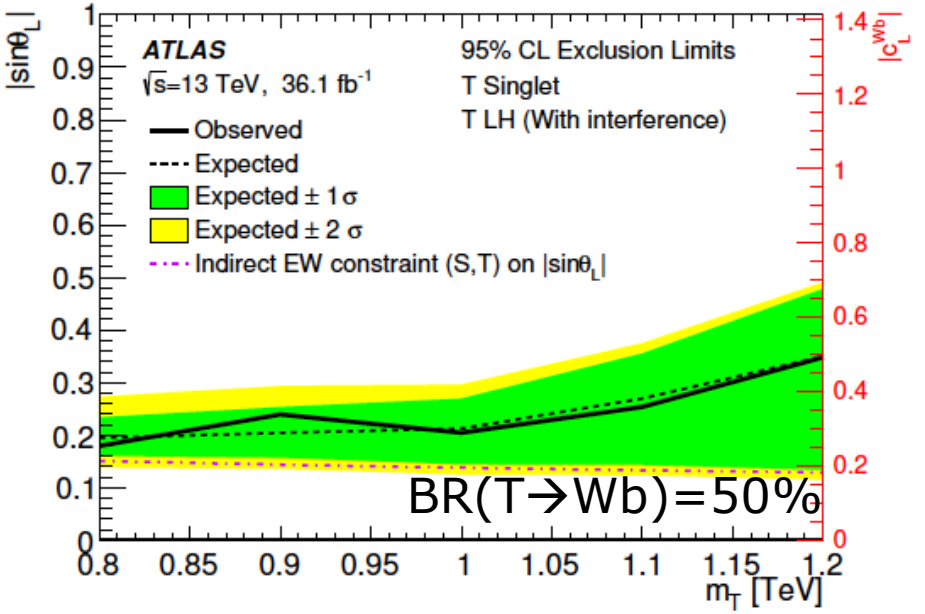
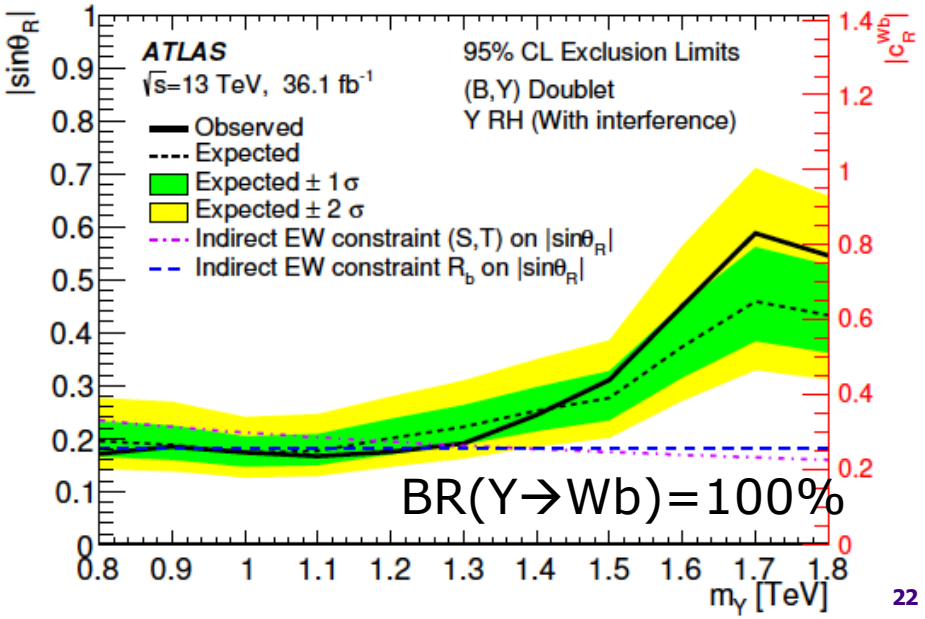
Limits:



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

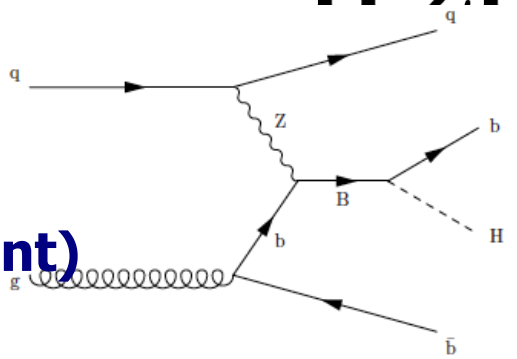
➔ Exclusion of large part of narrow width approximation





CMS: Single B→ bH

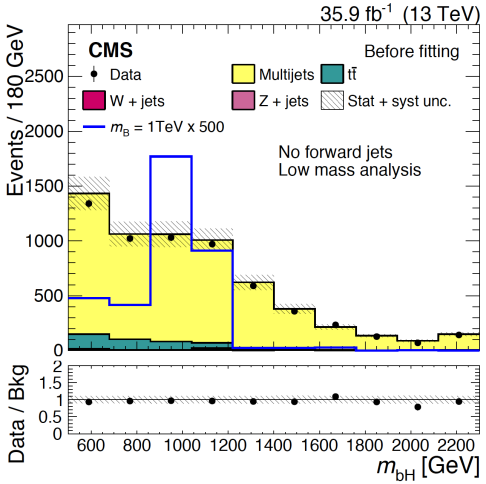
10.1007/JHEP06(2018)031

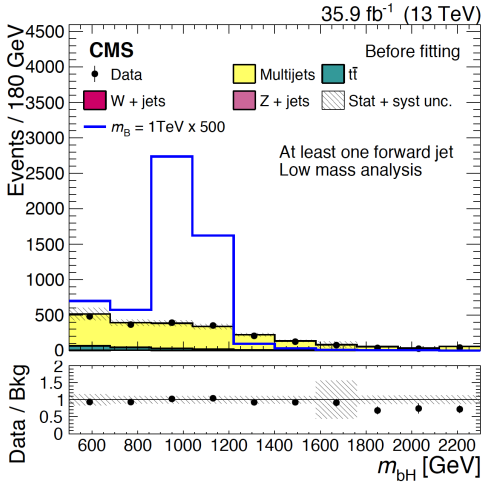


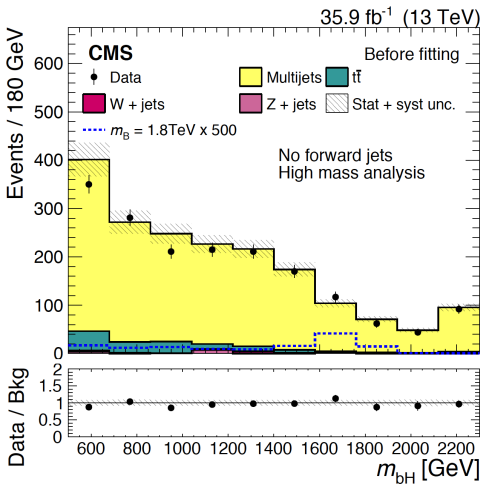
- **All hadronic final state**
- **Use boosted Higgs (→ bb) with b-tagging**
- **Categories: low/high mass regime (Ht requirement)**
- **Split in no/at least one forward jet**

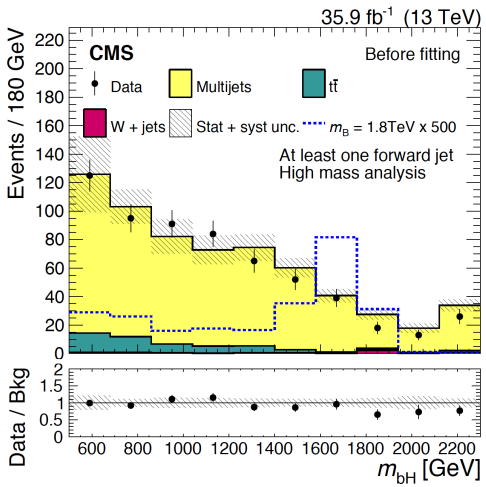
Events Selection:

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





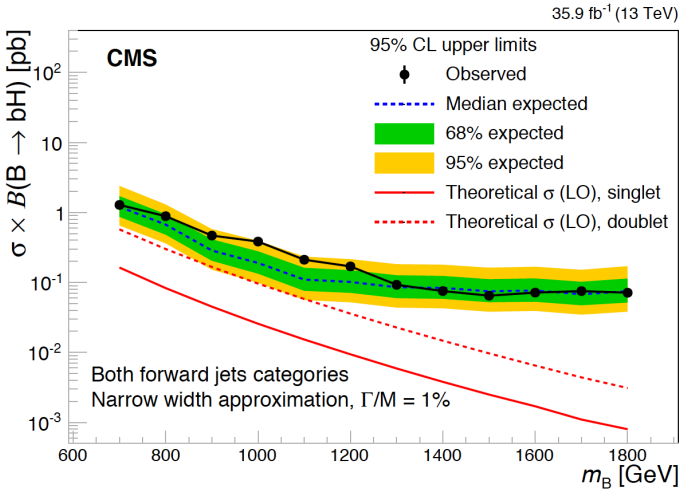


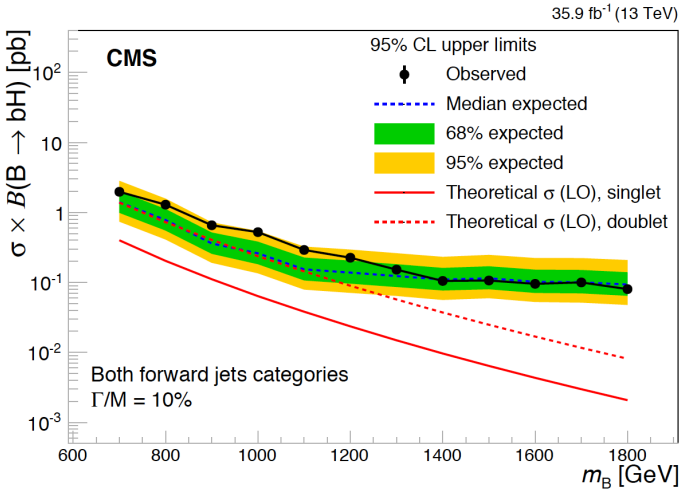


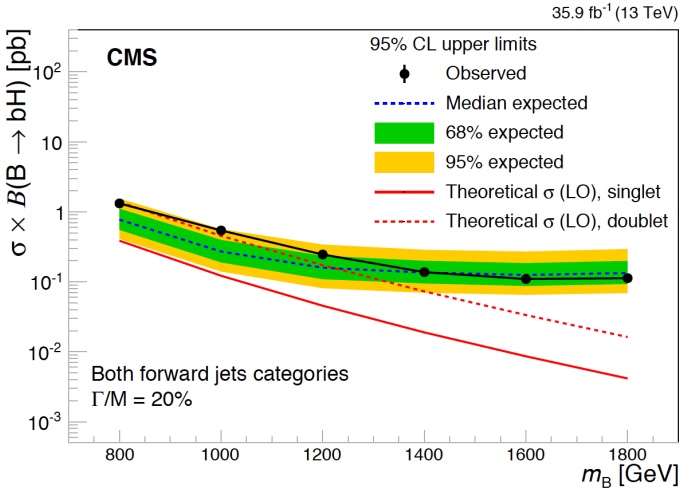
CMS: Single B→ bH

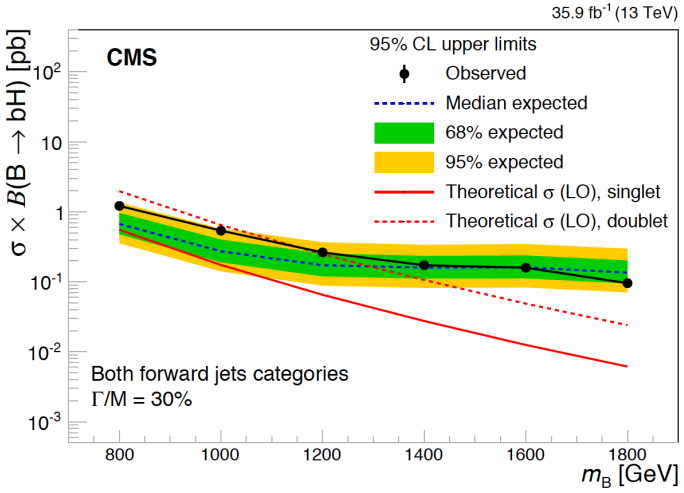
10.1007/JHEP06(2018)031

Studies as function of width







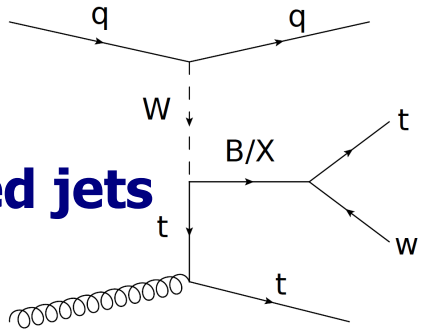


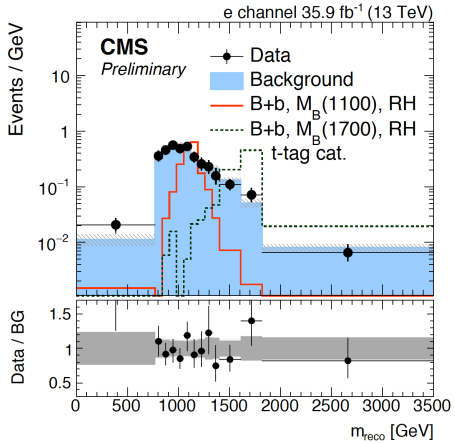
Exclusion reached for doublet case and 20/30% widths

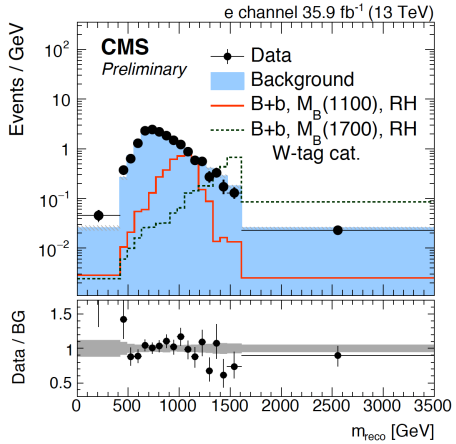
CMS: Single $X^{5/3}/B \rightarrow Wt$

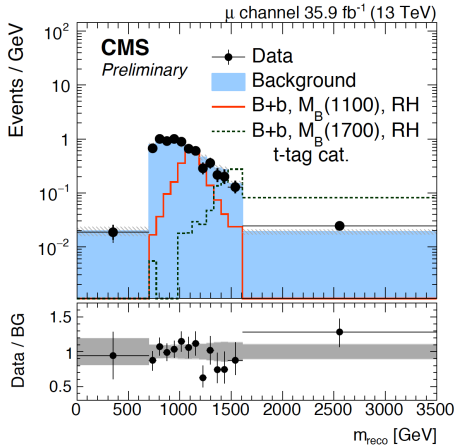
EPJC 10052-019-6556-3

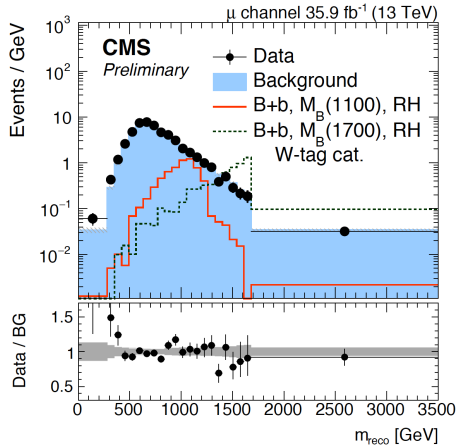
- l+jets as final state
- Boosted and resolved case are considered
- Analysis split in categories based on kind of boosted jets
- Best jet association determine via chi2
- Simultaneous fit of 0/≥1 forward jet

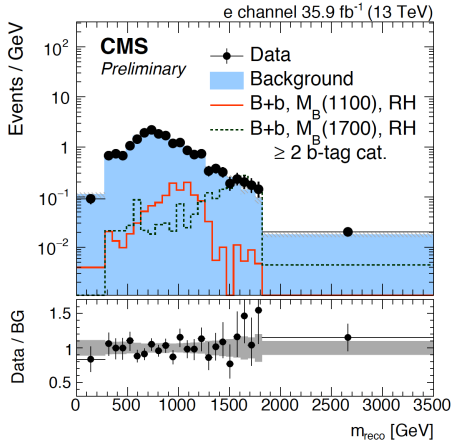


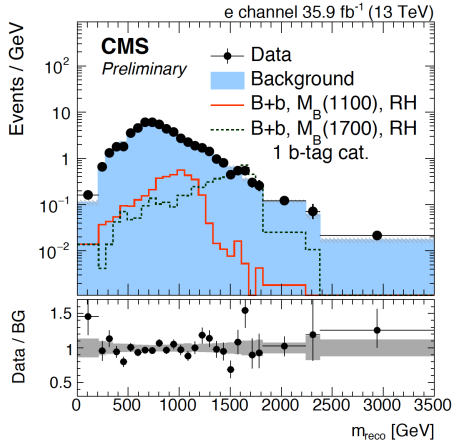


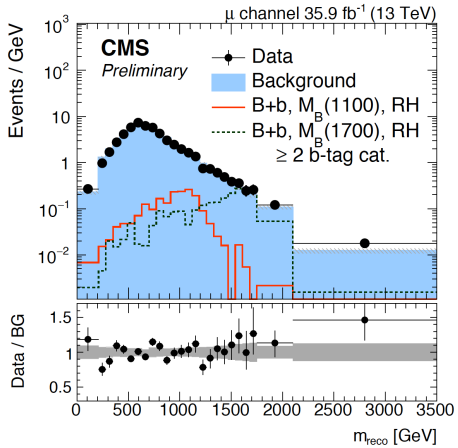


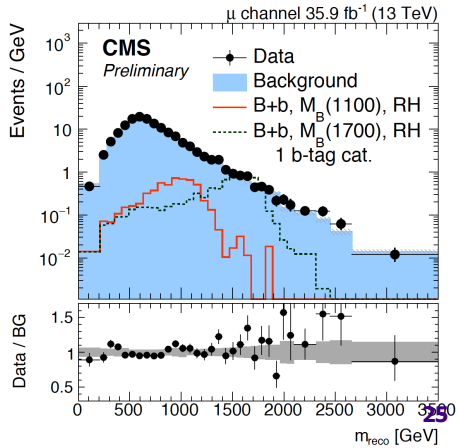












CMS: Single $X^{5/3}$/B→ Wt

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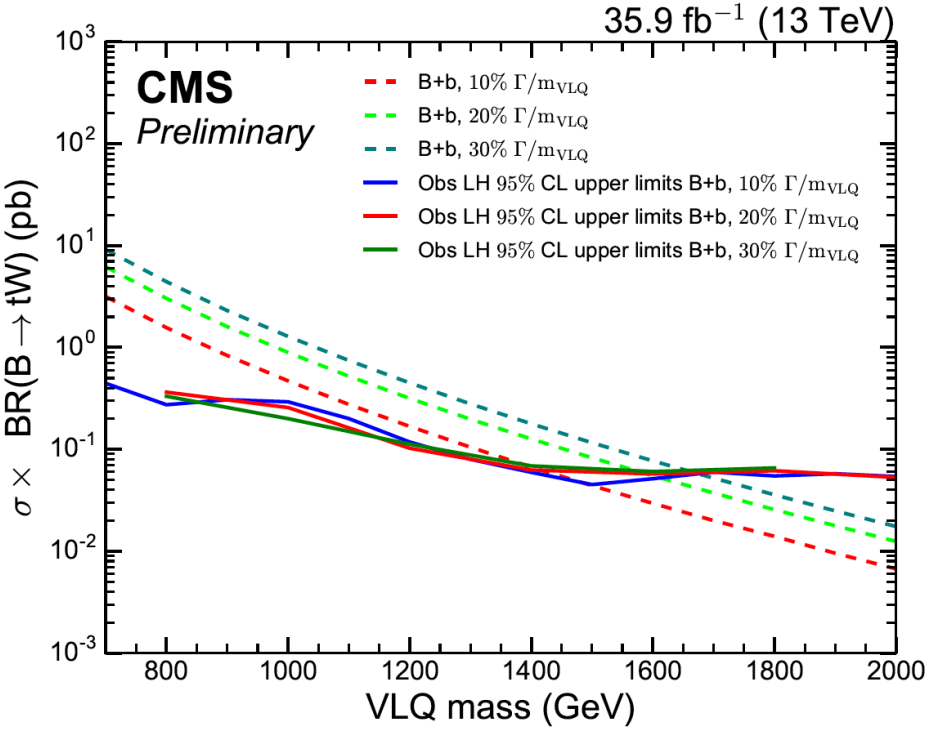
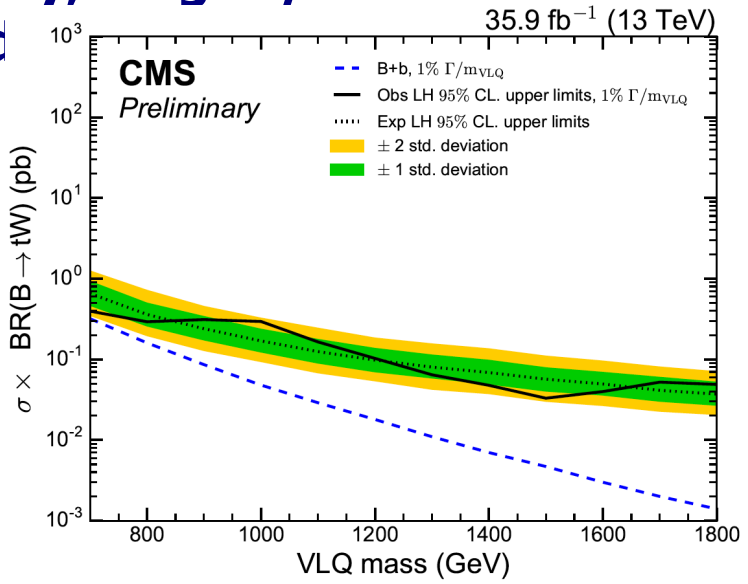
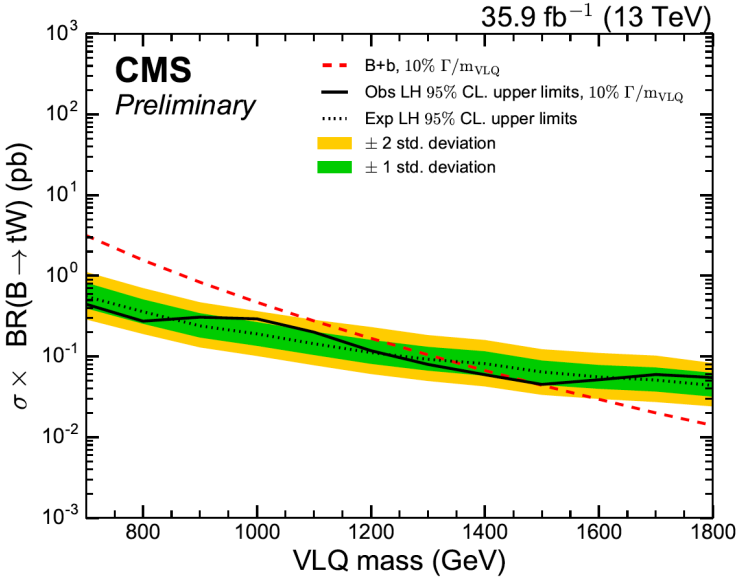
EPJC 10052-019-6556-3

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





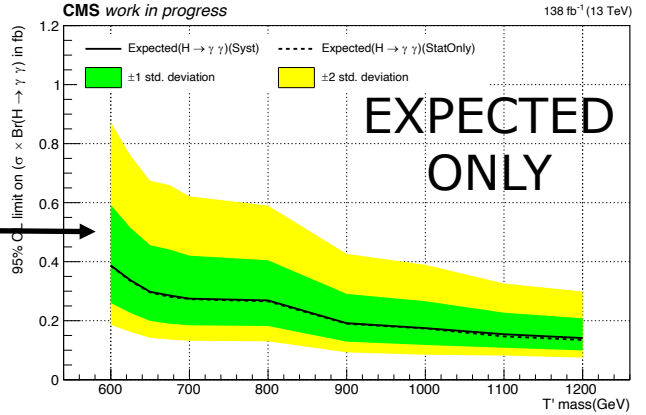


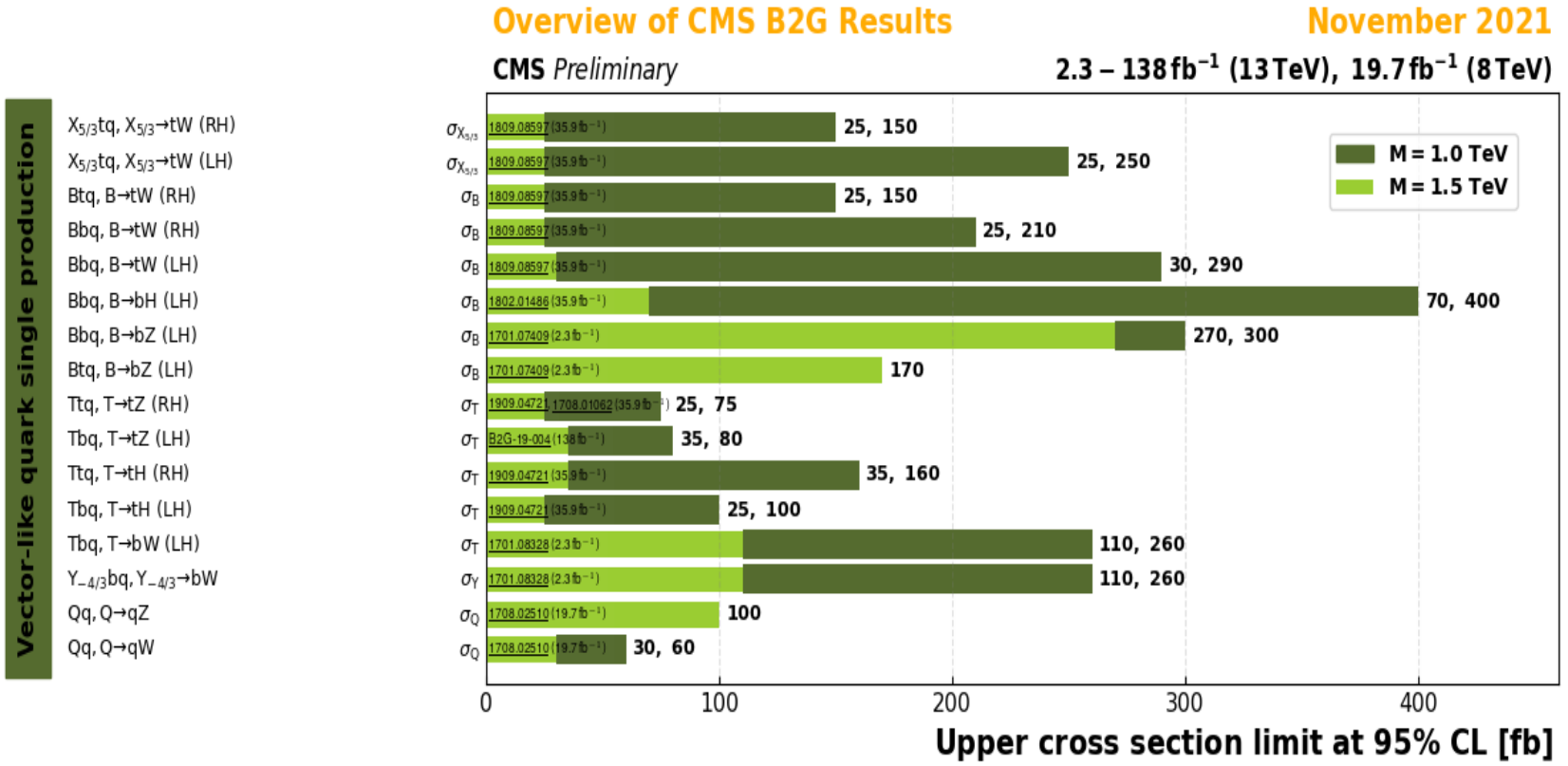
Most of the masses <1.4 TeV are excluded for width >10%

CMS on going analysis

- Single T→ tH (→WW) in l+jets Run 2
- Single T→ tH (→bb) in l+jets Run 2
- Single T→ tH (→$\gamma\gamma$) Run 2
- Single T/$Y^{-4/3}$→ Wb in l+jets Run 2
- Single B/$X^{5/3}$→ Wt in SS dilepton Run 2

Hopefully in a few weeks





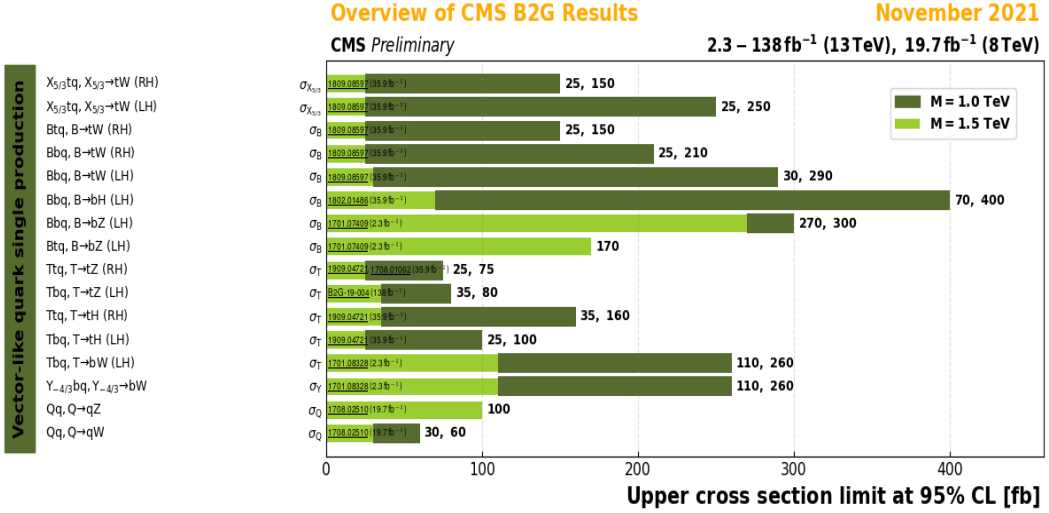
Conclusion

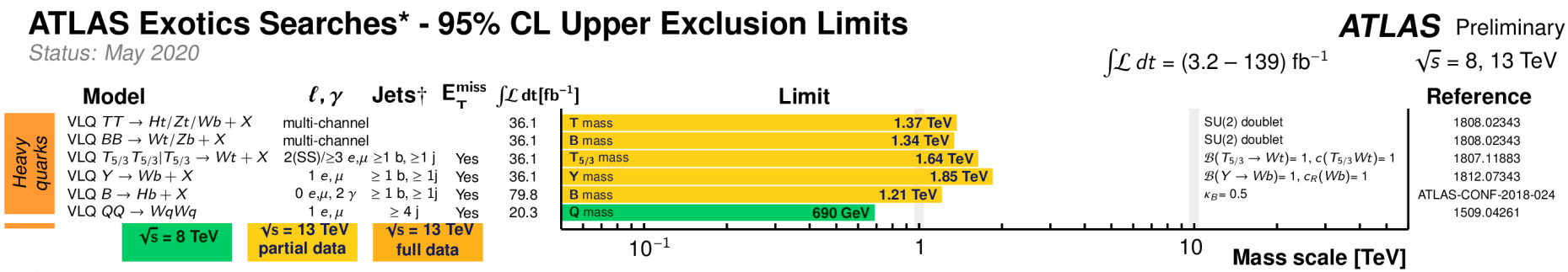
Atlas and CMS are producing a lot of results on VLQ

Results obtained by Atlas and CMS are pretty similar

Both experiments look at width exclusion (parameter κ_T)

A lot of new results should come with Run2+Run3 data analysis!



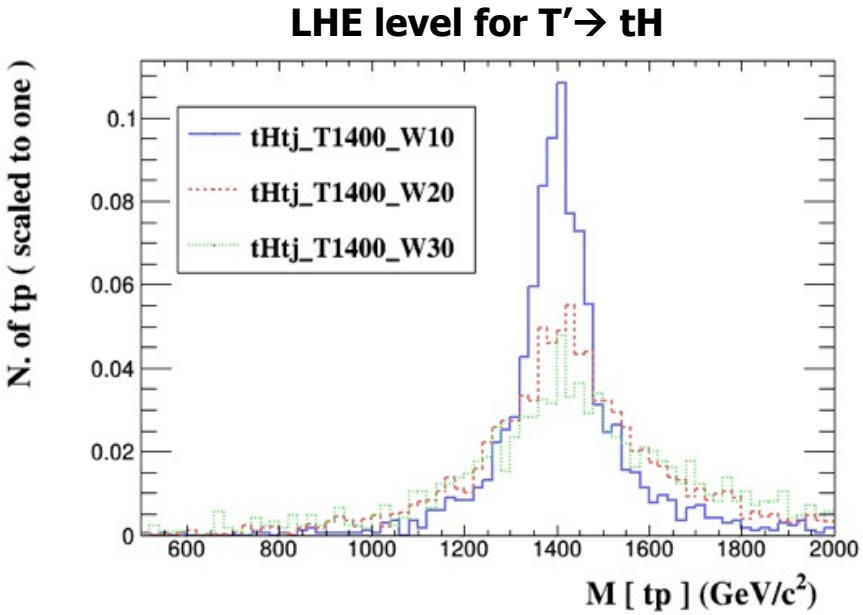


*Only a selection of the available mass limits on new states or phenomena is shown.

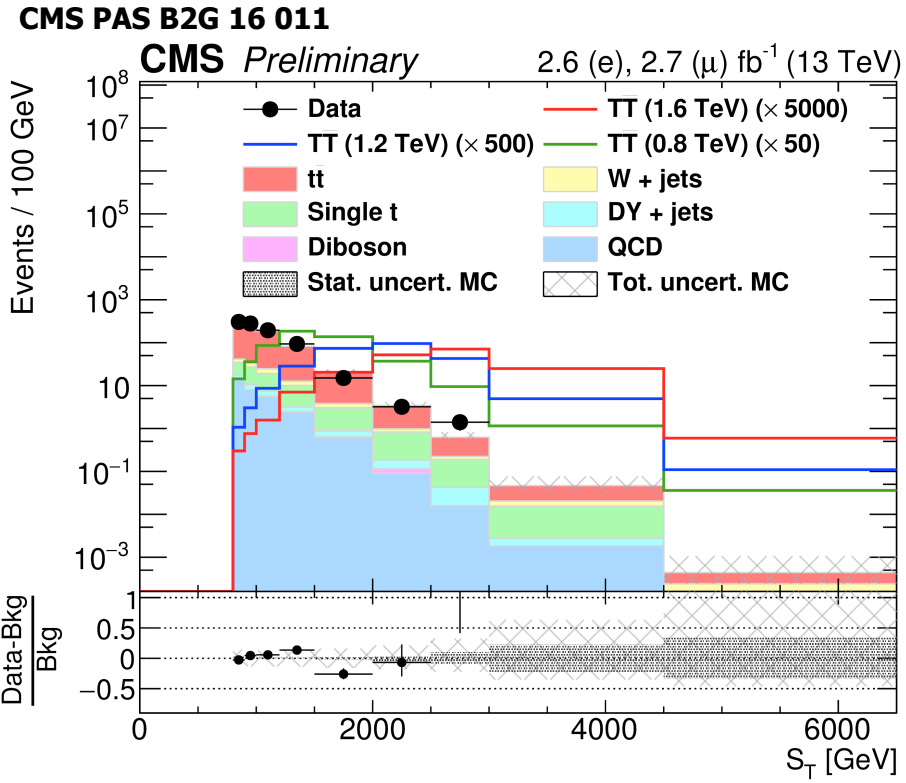
BackUp

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



Pair Produced=Momentum

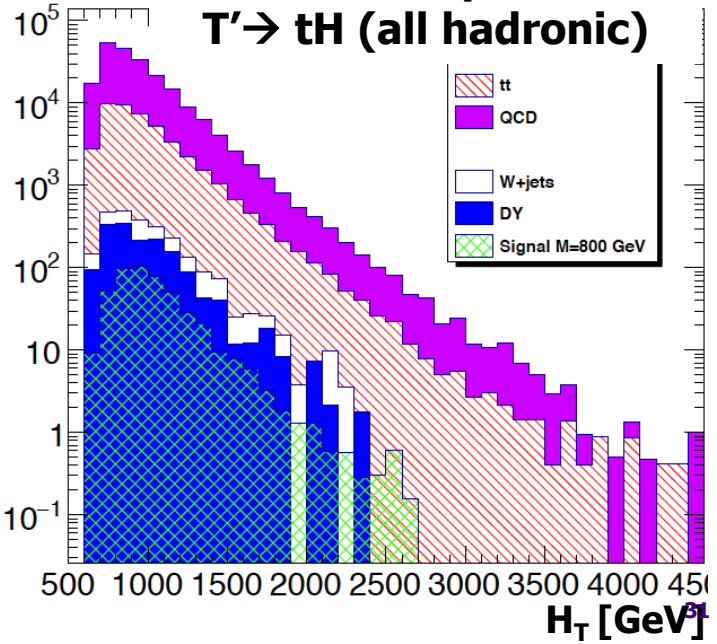


Typical background distribution in variable like scalar sum of pt of reconstructed object

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

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

Illustrative plots for T'→ tH (all hadronic)



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.

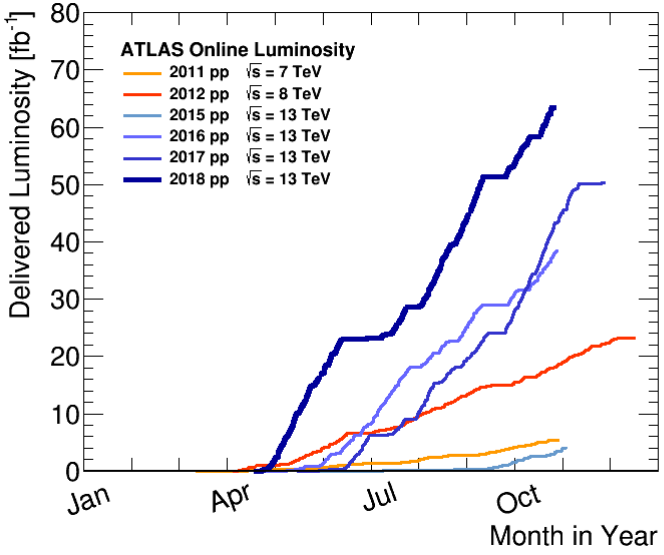
Experimental Apparatus and Tools

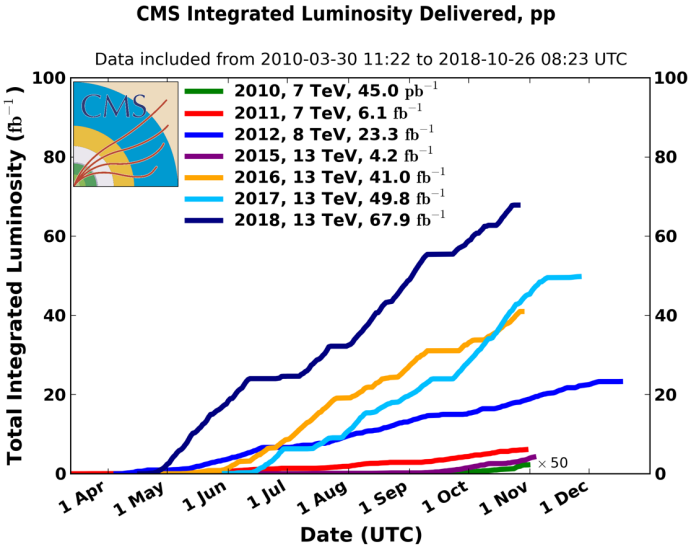
LHC has delivered pp collision to Atlas and CMS at various beam center of mass of energy since 2009.

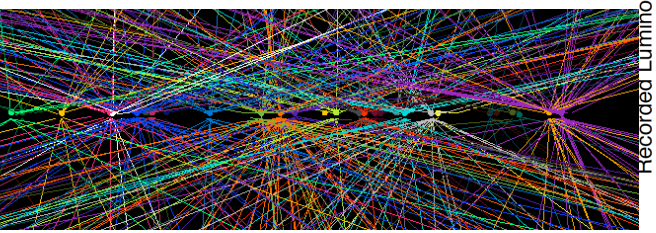
Groups of similar year:

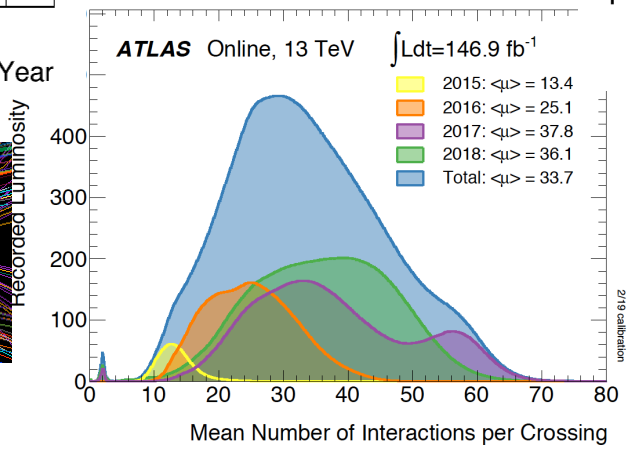
Run1 = (2010)+2011+2012 → 7/8 TeV

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

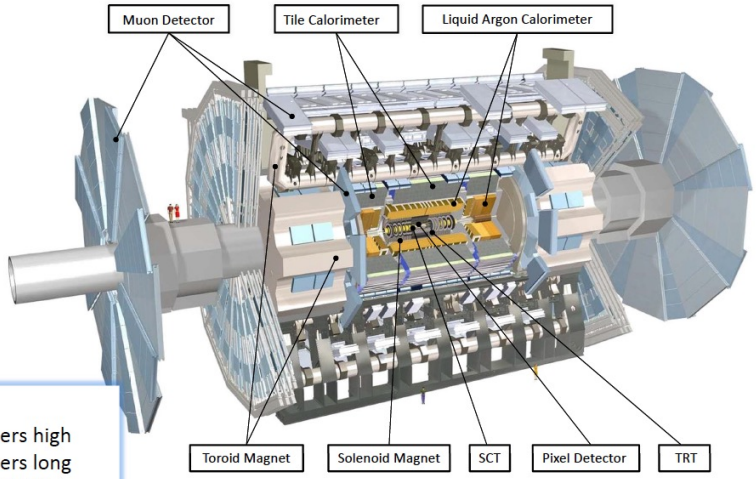
General-purpose detector: investigate largest possible physics range

Hermetic, many layers, and highly granular

Designed to precisely reconstruct and identify decays of produced particles

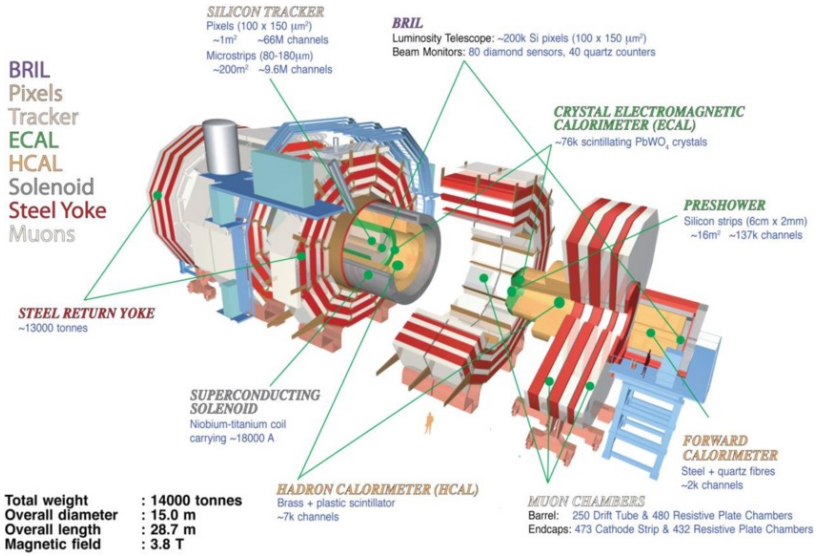
Tracking acceptance ~2.5 in eta → Above no real tracking to point to vertex etc ➔ With PU, forward region is difficult to understand

The ATLAS Detector



ATLAS
- 25 meters high
- 44 meters long
- Weight 7000 tons

The CMS Detector



Jets Multiple Taggers

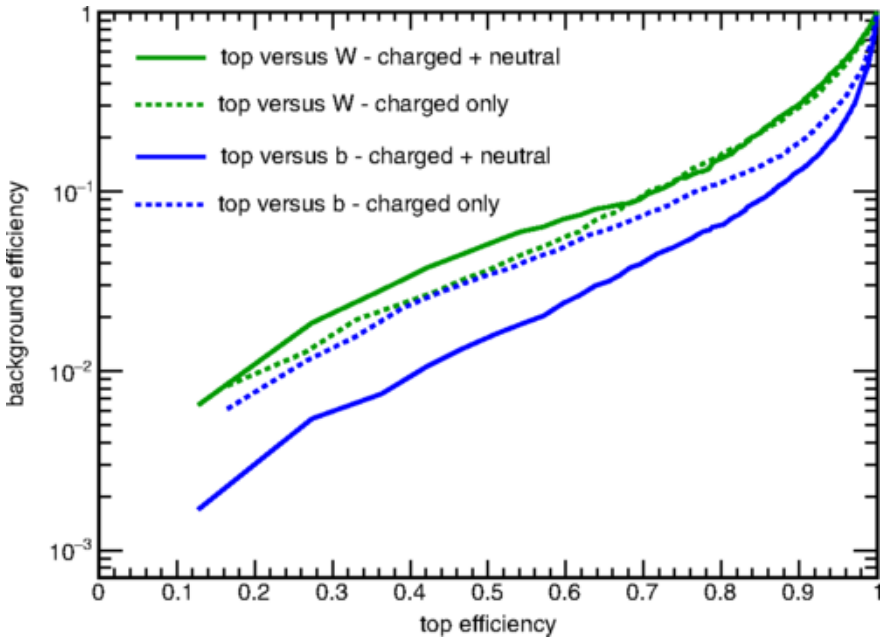
Phys. Rev. D 94, 094027

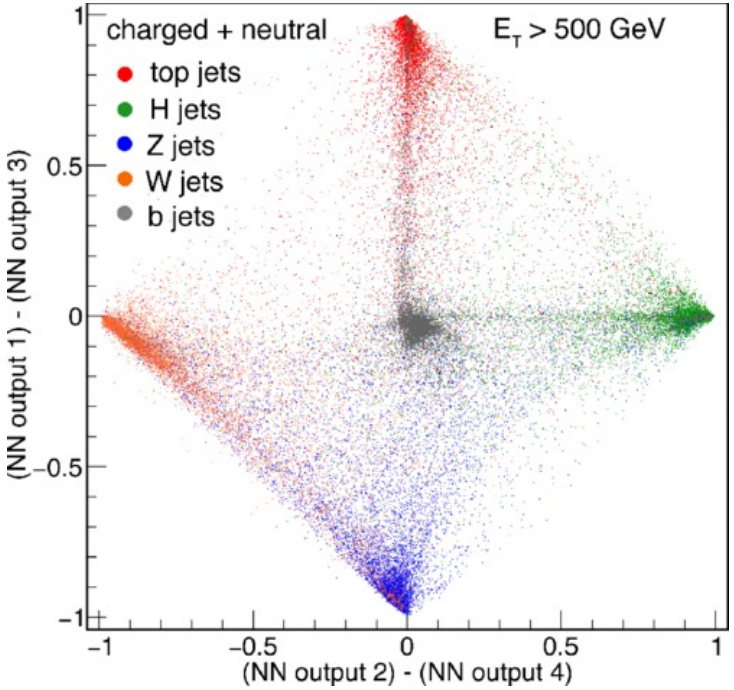
BEST algorithm = Boosted Event Shape Tagger

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

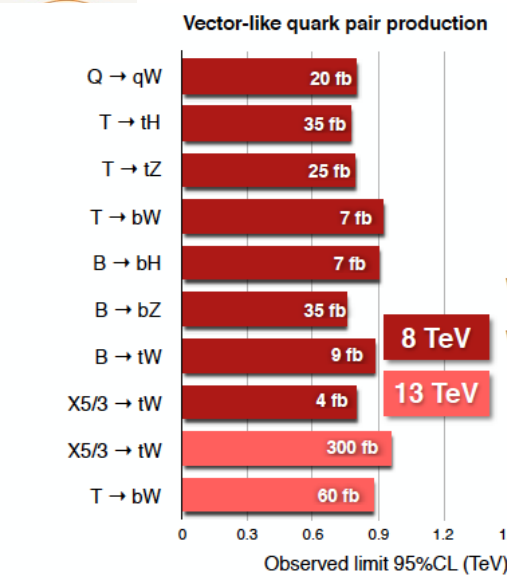
Main ideas:

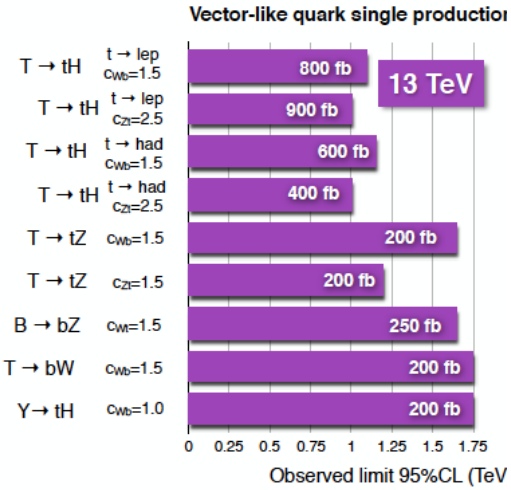
- **Move to the rest frame of the assumed particle**
- **Use several variables to build a neural network discriminant**





→ Use in case multiple wide jets in final state





Run 1 + 2015

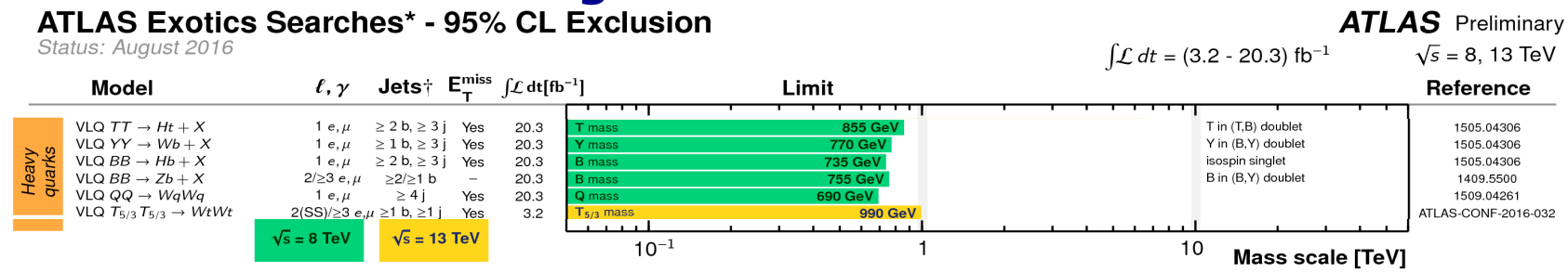
IP2I

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



*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).