Recent BSM Highlights from ATLAS and CMS

Vector-like-Quarks/Leptoquarks/New vector bosons

Hector de la Torre Perez
Northern Illinois University
On behalf of the ATLAS and CMS Collaborations

ATLAS EXPERIMENT

Northern Illinois University

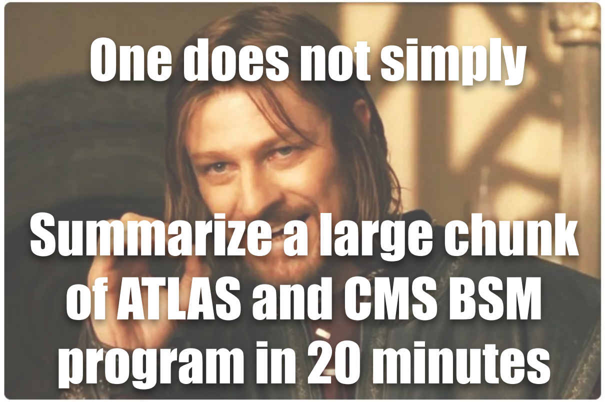
What to expect today

Both ATLAS and CMS have an extensive BSM program. More than 50 searches in 2023/2024 that could fit within this talk scope !

Today I'll try to :

- Give you a brief snapshot of the experimental status at the LHC of three specific areas of BSM physics that we are looking into:
  - **Vector-like-quark**, **Leptoquarks** and 'generic' **W'/Z' searches**
- Describe few recent analyses (6 of them) in those areas with some detail
  - All of them with run 2 data (139 fb^{-1} at $\sqrt{s}$=13 TeV)

There are heavy recency and personal bias in my choices of analyses to describe but decisions had to be made. I didn't want to just give you a list of results in rapid fire! If you want to discuss specific analyses that I didn't cover on these areas please talk to me during the conference !



Sean Bean in Lord of the Rings (Credit: New Line)

H. de la Torre, Northern Illinois University

Vector-like-quarks (VLQ) *The one-slide version*

"Quarks": Colored, fractionally charged, spin ½ particles
"Vector-like": Left and right chiralities have the same weak isospin

VLQs: $(\bar{Q}\gamma^{\mu}Q')$ ⟷ SM quarks: $(\bar{q}\gamma^{\mu}(1-\gamma^{5})q')$

A chiral 4th generation has strong constraints from Higgs measurements and EW precision data but VLQ can have bare mass terms, loosening those constraints

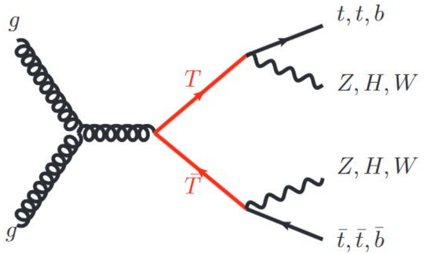
Can help canceling the divergent top correction to the Higgs boson without fine tuning (Hierarchy problem)

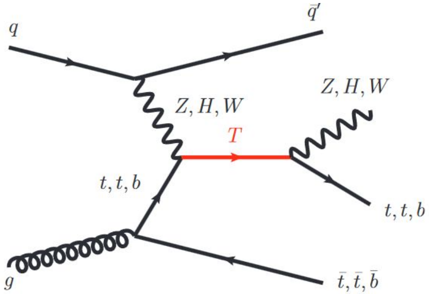
Q[e]	VLQs: singlets	VLQs: doublets			VLQs: triplets	
5/3		X			X	
2/3	(T)	T	T		T	T
−1/3	(B)		B	B	B	B
−4/3				Y		Y

Couple with SM quarks and appear in Little/Composite Higgs models, GUTS, Topcolor among others

How do we look for VLQ at the LHC?

In many models, VLQ couple preferentially to third generation, and can decay through many different channels, involving W,Z or H boson. Wealth of final states generally involving tops and b's, but with lots of options for the boson decays





Pair production:

- Dominant for light VLQ (<1TeV)
- More 'model independent' (QCD production)
- Historically more explored

Single production:

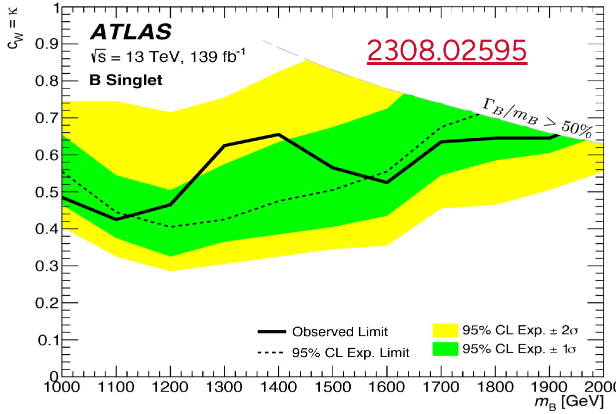
- Can be dominant for high masses
- Depends on mass and coupling
- More complicated signal modelling

The story so far

ATLAS: 8 full Run 2 analyses
CMS: 7 full Run 2 analyses

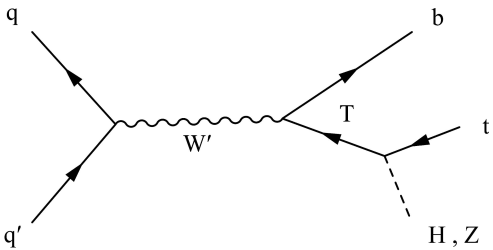
Full list in backup

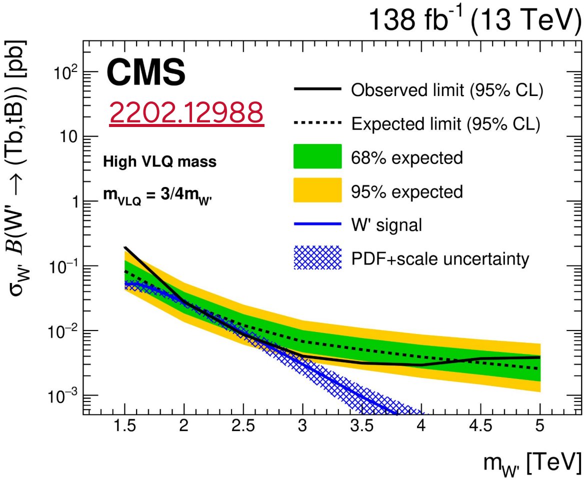
Huge effort by both collaborations on covering all of the possible final states and both single and pair production analyses! Mainly focused on 3rd generation couplings and interpretations based on minimal models. Good coverage of final states with mass limits between 1.5 and 2 TeV, considering a wide range of couplings/widths.



ATLAS: Generally considering larger widths, more coupling/mass coverage. Up to 50% in many recent searches

CMS: Has considered models with BSM couplings (W′,Z′ decaying into VLQ)

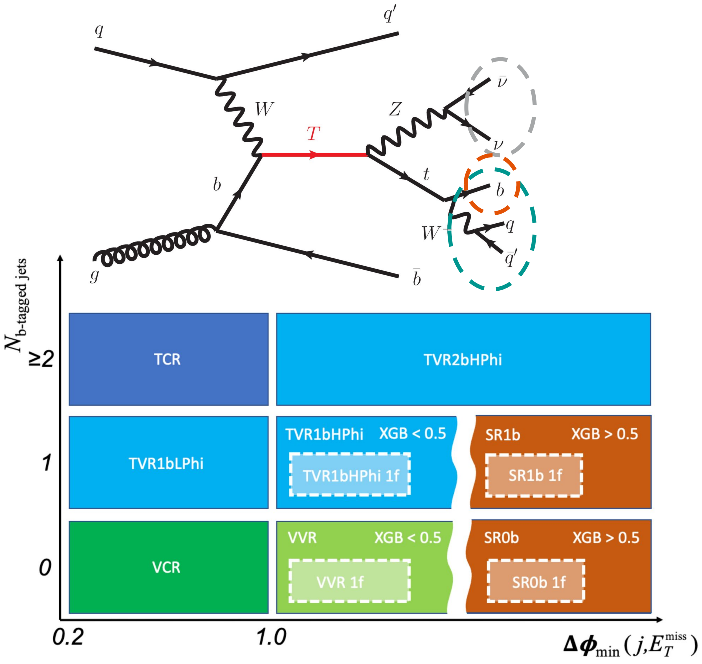




Just a small selection of the many results from the last year..

ATLAS Monotop search 2402.16561

Search on single-top final states with interpretations in DM and VLQ production



Top-tagging: technique used to identify large-R jets coming from top-quarks: **Deep Neural network (DNN) using substructure information**

Selection

- One **top-tagged large-R jet (p_T > 350 GeV)**
- additional **b-tagged jets**
- missing transverse energy (> 250 GeV)

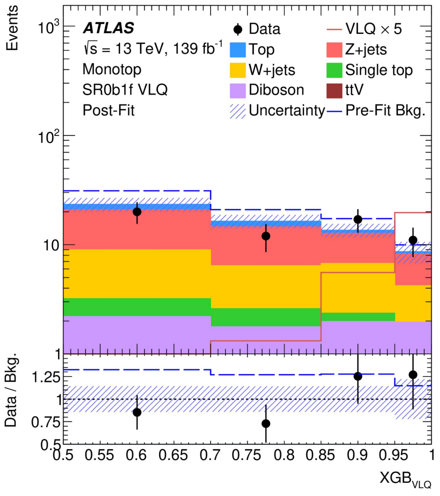
XGBoost (XGB): Boosted Decision Tree (BDT)

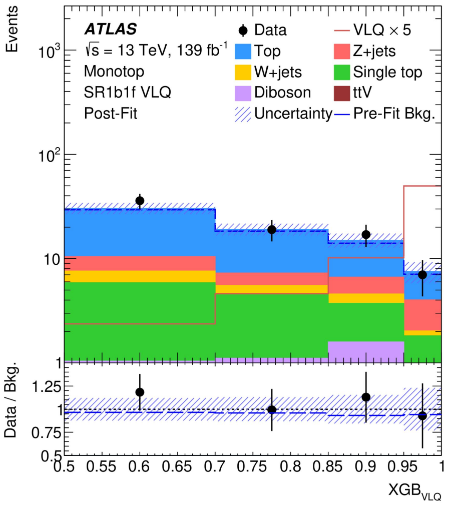
- To separate signal and background (tt and Z+jets dominant)
- 13 variables as input -> MET and b-jet higher importance

B-tagging :technique used to identify jets originated from b-quarks: **DNN using tracking and vertexing information**

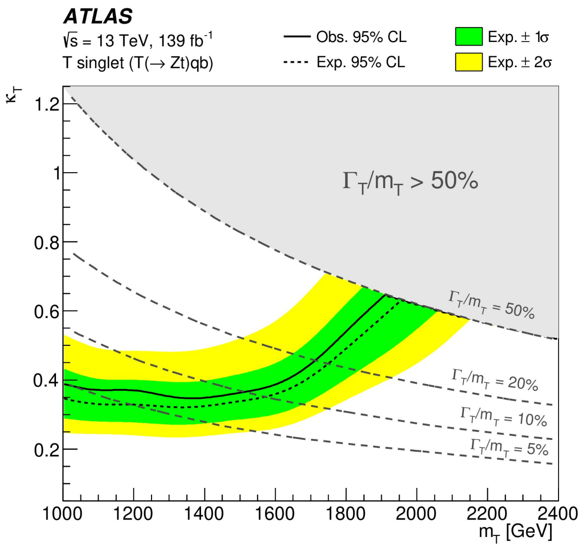
H. de la Torre, Northern Illinois University

ATLAS Monotop search 2402.16561





Interpreted in the context of a **singlet T VLQ** with different values of the coupling. Mass limit improved ~400 GeV with respect to previous results !



Simultaneous fit in signal all SR and CR

- **XGB score** in SR, Event yields in CR
- All templates are MC based

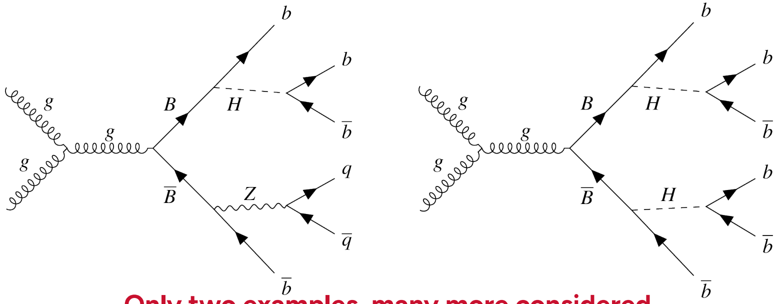
Good agreement with the SM prediction

H. de la Torre, Northern Illinois University

Bottom VLQ CMS search

2402.13808
pair production

Many different decay modes under the same roof, Considering B→Hb, B→Zb and B→Wt. Fully hadronic decays for all combinations except $Z \to l^+l^-$ which is also considered



Only two examples, many more considered

Categories with **large number of jets** and a large amount of H_T (> 1350 GeV)

Jet multiplicity	Leptonic category	Fully hadronic category
3	bHbZ, bZbZ	—
4	bHbZ, bZbZ	bHbH, bHbZ, bZbZ
5	—	bHbH, bHbZ, bZbZ, bHtW, bZtW
6	—	bHbH, bHbZ, bZbZ, bHtW, bZtW

B-tagging is used to define the signal regions and to reconstruct the H and Z candidates

- Resolved (with two b-tagged jets)
- merged (with one bb tagged large-R jet)
- **Leptonic category is the exception**

B candidates reconstructed using a χ^2 method to select the right combination of jets to use.

$$\chi^2_{\text{mod}} = \frac{(\Delta m_{\text{VLQ}} - \overline{\Delta m_{\text{VLQ}}})^2}{\sigma^2_{\Delta m_{\text{VLQ}}}} + \frac{(m_1 - \overline{m_1})^2}{\sigma^2_{m_1}} + \frac{(m_2 - \overline{m_2})^2}{\sigma^2_{m_2}},$$

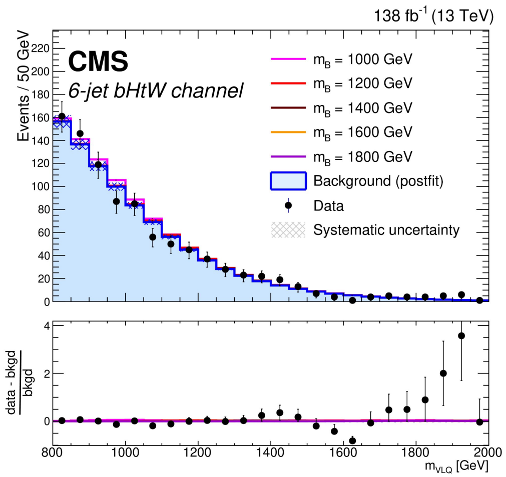
H. de la Torre, Northern Illinois University

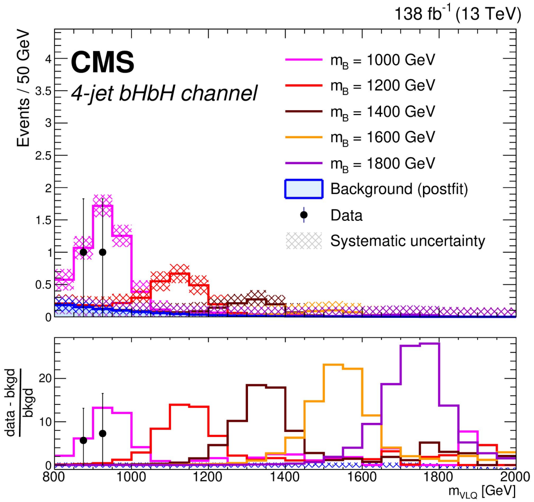
Bottom VLQ CMS search

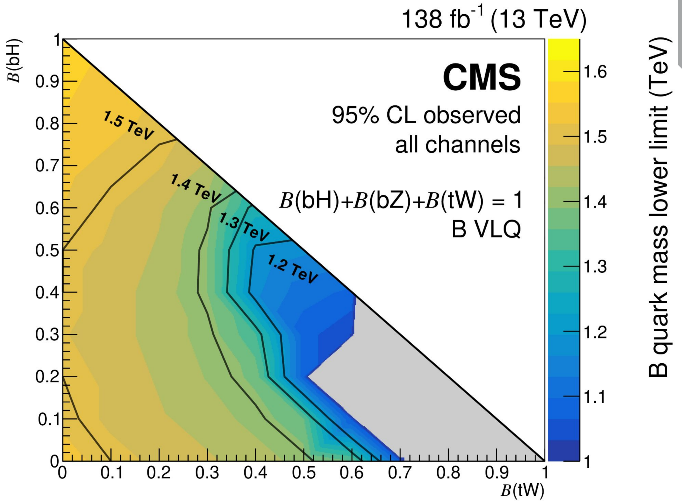
2402.13808
pair production

A fully data-driven approach is used to estimate the background in each category.

- Template fit in the pre-selection regions (before b-tagging requirements)
- Normalization correction from a low M_{VLQ} region





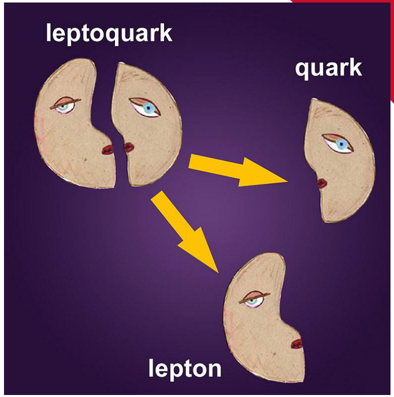


No statistically significant excess is found in any of the regions after fitting M_{VLQ}, and limits are set for different values of the branching ratios.

H. de la Torre, Northern Illinois University

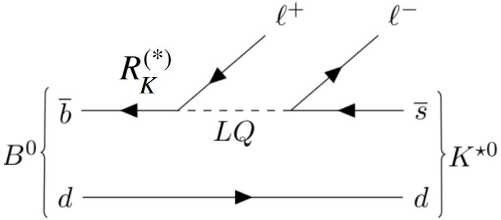
Leptoquarks (LQ)

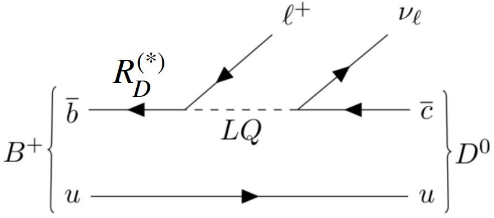
The one-slide version

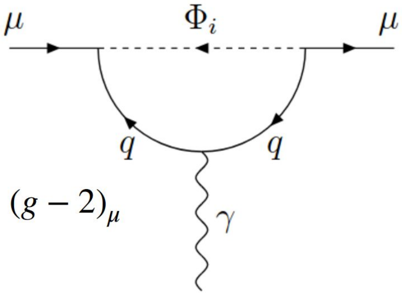


From fermilab today / October 2009

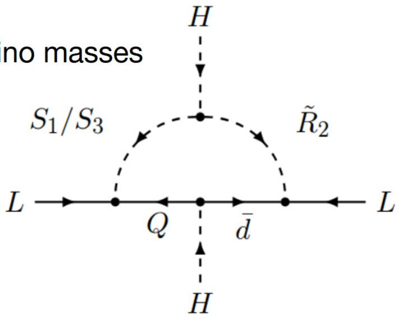
Scalar or **vector** particles that carry **color, charge, baryon and lepton numbers.** By allowing direct couplings between lepton and quarks, they are useful to explain many SM problems !







Neutrino masses



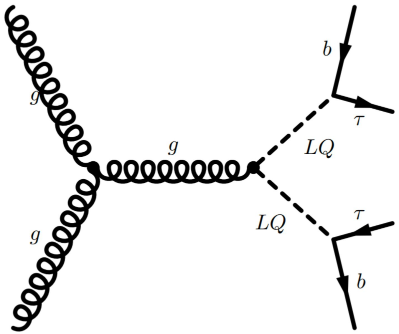
Two types of LQ in models

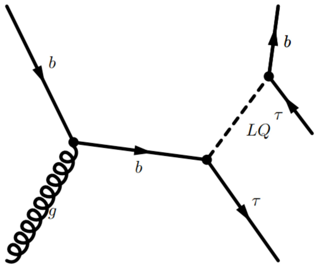
- $LQ_{1,2,3}$: Mix with only one generation
- LQ_{mix}: Allow for **cross-generation**

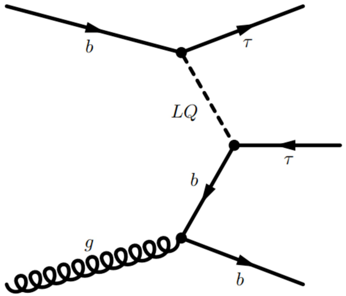
Lepton Flavor Universality violation (LFUV) scenarios !

How do we look for LQ

Similar situation of VLQs Both pair and single production scenarios are possible. Most papers focused on LQ^3, with final states containing ***τ***, ***ν***, b-quarks and top-quarks







Pair production:

- Dominant for light LQ (<1TeV)
- More 'model independent' (QCD production)
- Historically more explored

Single production:

- Can be dominant for high masses
- Depends on mass and coupling
- More complicated signal modelling

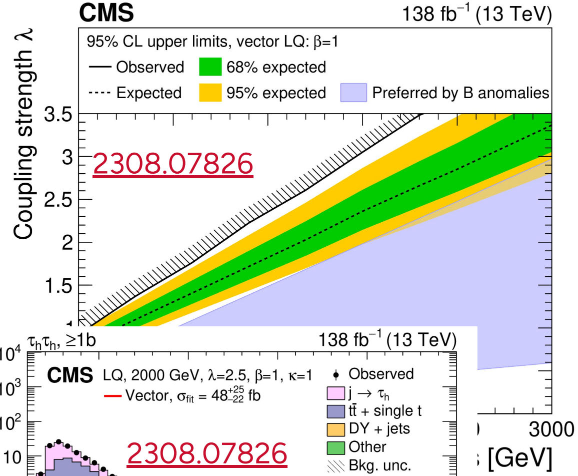
Note that both 'up-type' LQ (Q=⅔) and 'down type' LQ (Q=-⅓) are possible and they lead to different final states

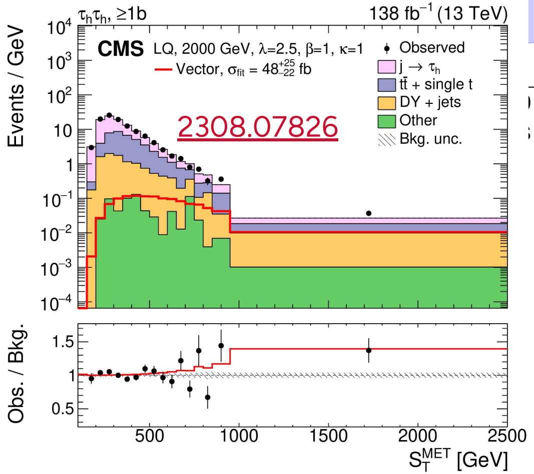
The story so far

ATLAS: 14 full run 2 analyses
CMS: 8 full run 2 analyses

Full list in backup

Number of papers exploded synchronously with the interest in flavor anomalies, initial focus on 3rd generation LQ and pair production but a fair amount of papers allowing for cross-generational couplings are also available

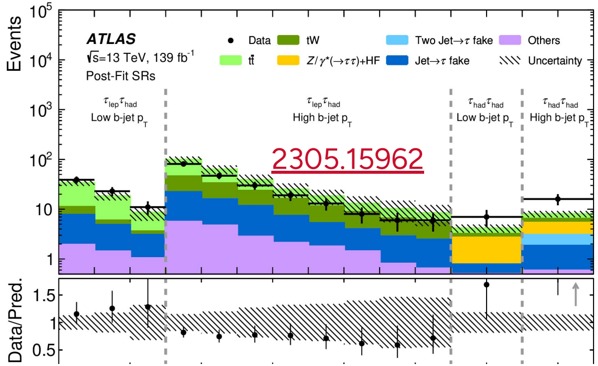


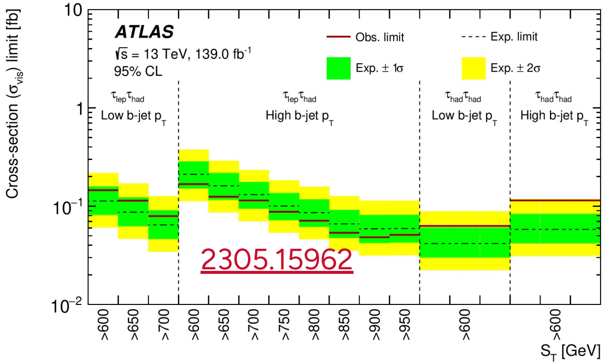


Masses up to 1.8 TeV excluded from pair production. Some interesting recent results on single production analyses

CMS: Small excess for a 3rd generation vector LQ in a bτ decay. Dominated by events in 'low' sensitivity region and not present in 'high' sensitivity ones

ATLAS: Hints of similar behavior in the equivalent ATLAS search. However, much better compatible with SM prediction

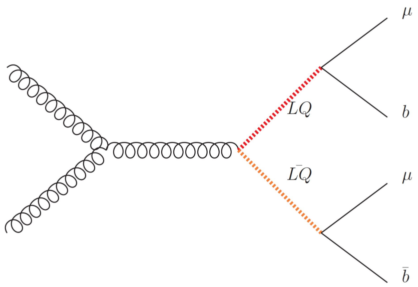




H. de la Torre, Northern Illinois University

CMS Pair production search LQLQ→$\mu b \mu b$

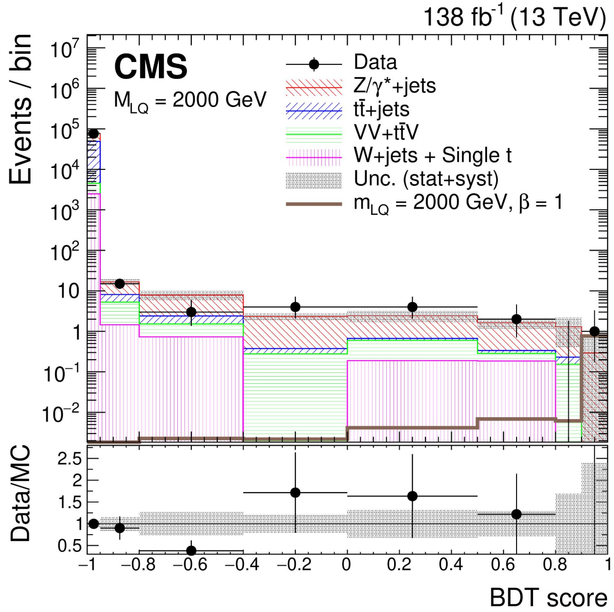
2402.08668



Straightforward preselection

- Exactly two isolated and well separated muons (p_T > 35 GeV)
- two jets (p_T > 50 GeV) with at least one of them b-tagged.
- Additional requirements on $m_{\mu\mu}$ and $S_T^{\mu j \mu j}$ (Scalar p_T sum)

BDTs are trained at preselection level (One per signal hypothesis). **Eleven variables** are used as input to the BDT



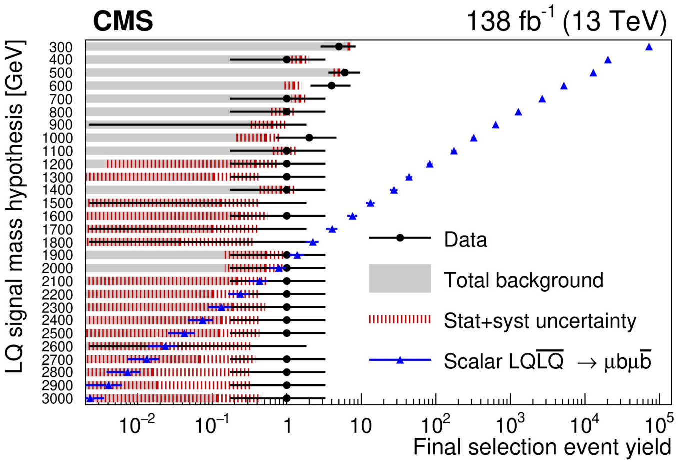
One-bin signal regions defined using the BDT

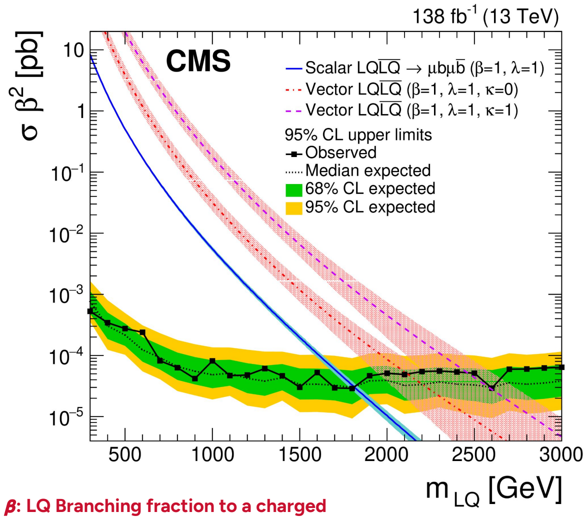
- Score cut chosen to optimize discovery potential.
- Background estimated using MC simulation
- Normalization corrected using two dedicated CR
  - **Z+jets/tt+jets** and **VV/ttV**
  - Built using dedicated $m_{\mu\mu}$ selections

CMS Pair production search LQLQ→*μbμb*

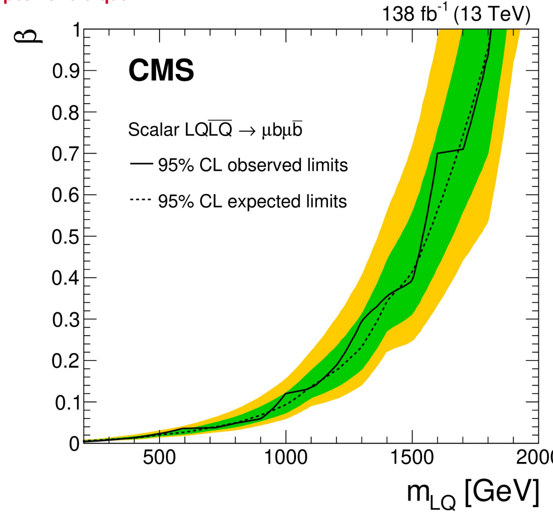
[2402.08668](2402.08668)

Background expected yields and data compared in the different regions for each signal mass hypothesis.





***β*: LQ Branching fraction to a charged lepton and a quark**



Limits obtained for both scalar and vector LQ, with mass limit depending on the model. Exclude m_{LQ} < 2 TeV for any minimal coupling model with *β* = 1 which is the strongest limit to date

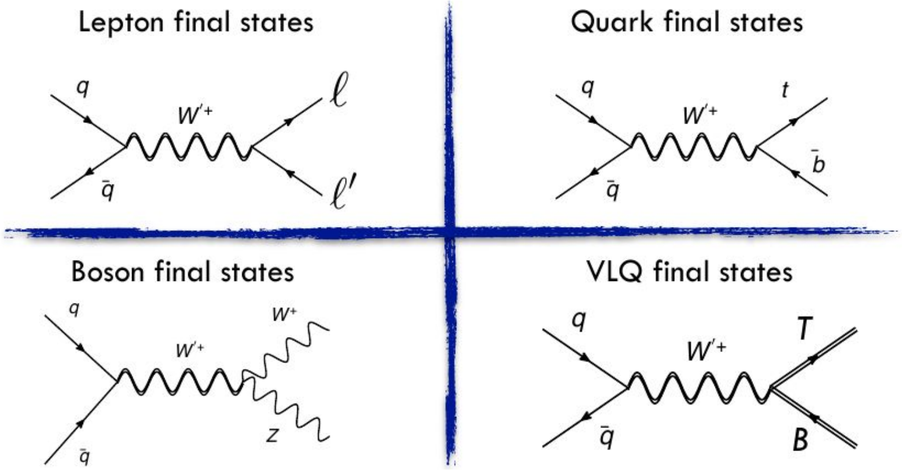
An aside on combinations

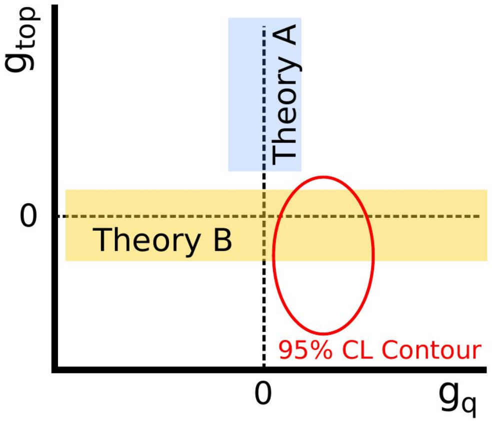
Two of the analyses I have yet to talk about are combinations of several analysis. What do I mean by combination?

Statistical combination of **several analyses with a common underlying model** or production mechanism

Realistic models have a varied phenomenology

- Access to discovery via **small compatible excesses**
- Additional axes in **N-dimensional parameter space**

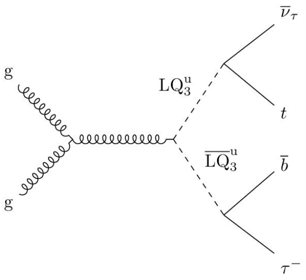


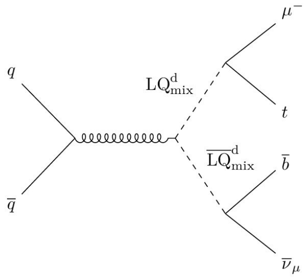


H. de la Torre, Northern Illinois University

ATLAS Leptoquark combination 2401.11928

pair production with b-jets



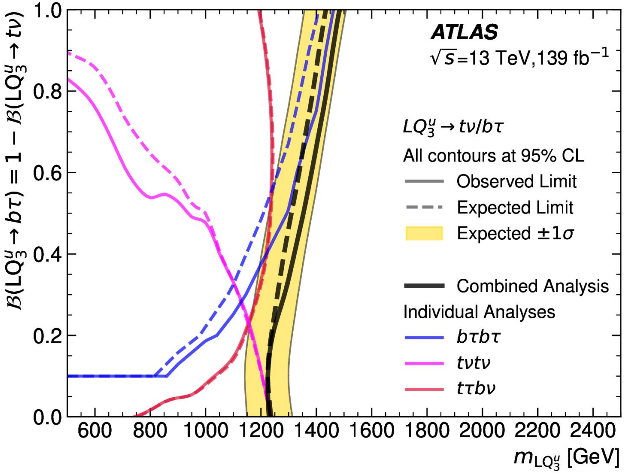


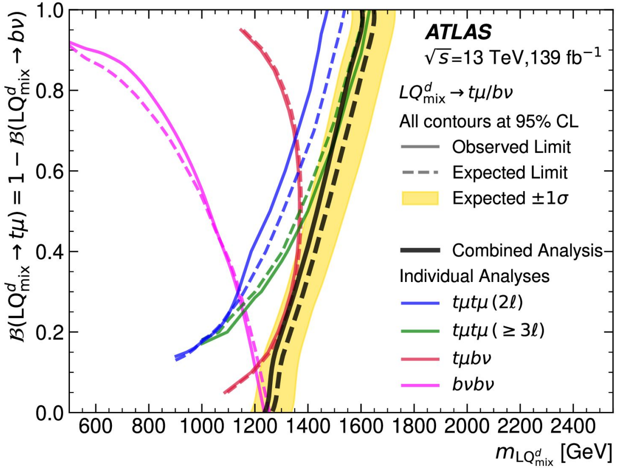
$t\nu b\tau$
$b\tau b\tau$
$t\tau t\tau$
$t\nu t\nu$
$b\nu b\nu$

$b\ell b\ell$
$t\ell t\ell$ (2ℓ)
$t\ell t\ell$ ($> 3\ell$)
$t\nu b\ell$

All relevant SR and CR are used in a combined likelihood fit

Only some examples, All possible decays of the leptoquarks into quarks of the third generation and charged or neutral leptons of any generation investigated. Full set of limits in backup





H. de la Torre, Northern Illinois University

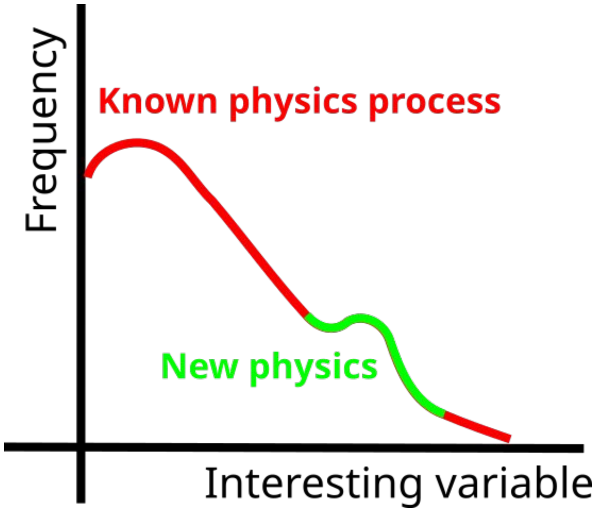
New vector bosons

Large category of models that predict new W′/Z′ bosons with different properties. Sometimes they appear as DM mediators and sometimes they couple strongly to specific generations (3rd for example), among many other possibilities

Both collaborations have looked for W′ and Z′ **in many different final states** and are exploring new ones with some regularity

Typical benchmark models for general searches
Sequential Standard Model (SSM) or Heavy Vector Triplet (HVT)

Often searches in the invariant mass of the expected decay (dijet, tt, bb, tb , e^+e^- , etc…). Very good coverage at high mass, Low mass still has uncovered phase-space !



ATLAS Spin 1 resonance combination 2402.10607

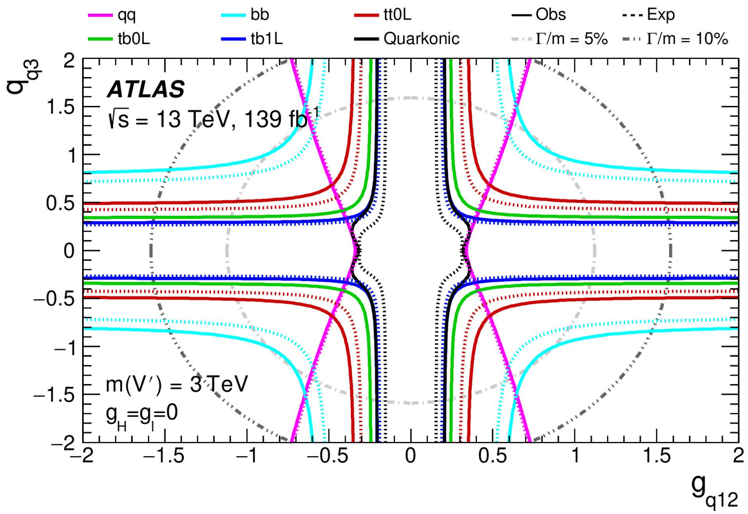
18 different searches combined in a single framework ! Interpreted in the context of HVT, using the multidimensional coupling space to different fermions/bosons to obtain contours in several 2D planes

Most analyses are orthogonal by construction, but some additional requirements were implemented to ensure it when necessary

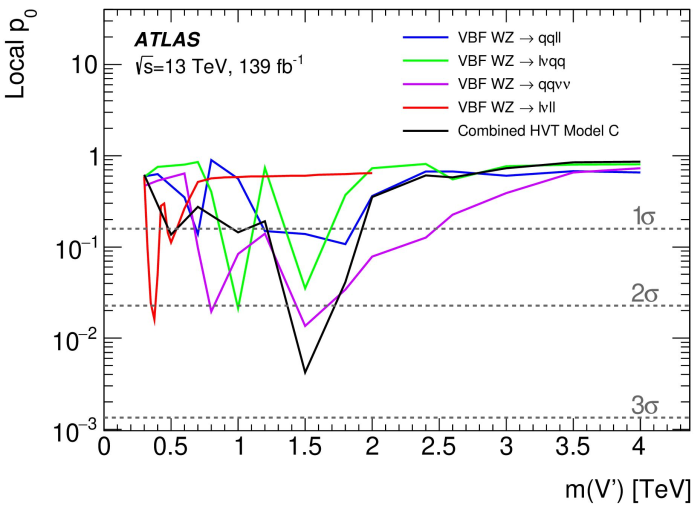
	Analysis	Leptons	$E_{\mathrm{T}}^{\mathrm{miss}}$	Jets	b-tags	Top-tags	VBF
Bosonic decays	$WW/WZ \to qqqq$	0	Veto	≥2J	-	-	-
	$WW/WZ \to \ell\nu qq$	$1e$, 1μ	Yes	≥2j, ≥1J	0, 1, 2	-	Yes
	$WZ \to qq\nu\nu$	0	Yes	≥1J	0	-	Yes
	$WZ \to qq\ell\ell$	$2e$, 2μ	-	≥2j, ≥1J	0	-	Yes
	$WZ \to \ell\nu\ell\ell$	$3 \subset (e, \mu)$	Yes	-	0	-	Yes
	$WH/ZH \to qqbb$	0	Veto	≥2J	1, 2	-	-
	$ZH \to \nu\nu bb$	0	Yes	≥2j, ≥1J	1, 2	-	-
	$WH \to \ell\nu bb$	$1e$, 1μ	Yes	≥2j, ≥1J	1, 2	-	-
	$ZH \to \ell\ell bb$	$2e$, 2μ	Veto	≥2j, ≥1J	1, 2	-	-
Leptonic decays	$\ell\nu$	$1e$, 1μ	Yes	-	-	-	-
	$\tau\nu$	1τ	Yes	-	-	-	-
	$\ell\ell$	$\geq 2e$, $\geq 2\mu$	-	-	-	-	-
	$\tau\tau$	0, $1e$, 1μ	Yes	-	0, ≥1	-	-
Quarks decays	tt0L	0	-	2J	1, 2	2	-
	tb0L	0	-	≥(1j+1J)	≥1	1	-
	tb1L	$1e$, 1μ	Yes	2j, 3j	1, 2	-	-
	qq	0	-	2j	0	-	-
	bb	0	-	2j	1, 2	-	-

ATLAS Spin 1 resonance combination 2402.10607

Couplings to quarks, lepton and the Higgs boson (possible to also separate the third generation quark coupling) used to build several 2D planes. Also interpreted for few interesting HVT benchmarks (Specific coupling values)



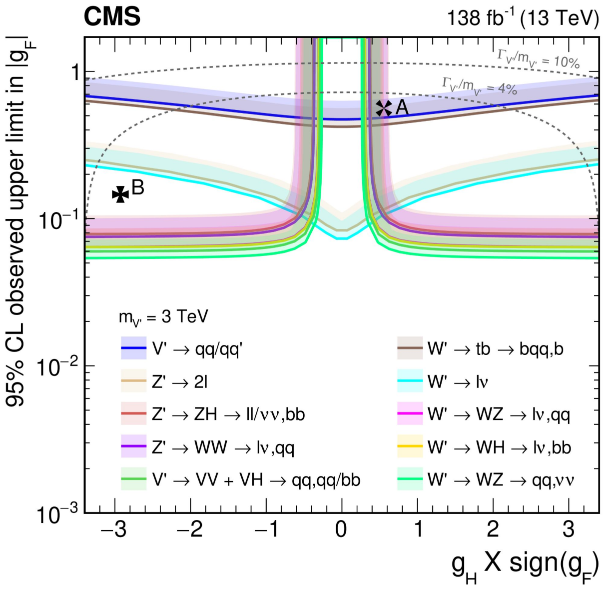
Only one example, more can be found in backup. Improvement with respect to individual channels across the board

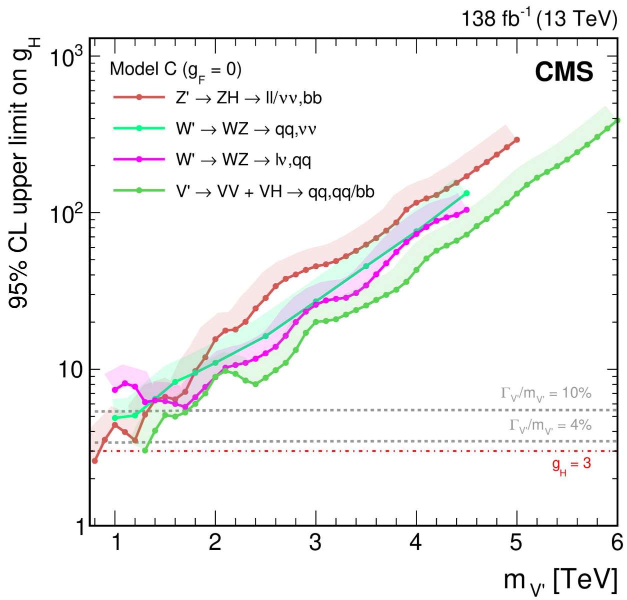


Combination of small excesses around 1.5 for VBF searches increased significance when combined. HVT model C corresponds to g_H=1.0 and g_f=0.0. No fermion couplings !

CMS review on resonances decaying to hX 2403.16926

Not a full statistical combination, but a comparison of previous searches using a common interpretation within the HVT model space (Among other interpretations).





Similar multidimensional approach as the ATLAS combination! Shows clearly that model C phase-space (VBF dominated) is mostly unconstrained by LHC data

Summary

- **Described the overall status of three of the more active BSM areas in ATLAS and CMS**
  - Vector-like-quark, **Leptoquarks** and 'generic' **W'/Z' searches**
- **Showed some recent highlights in those areas**
  - **ATLAS: Monotop search (VLQ interpretation only)** 2402.16561 ***Submitted to JHEP***
  - **ATLAS Leptoquark combination** 2401.11928 ***Submitted to Phys. Lett. B***
  - **ATLAS Spin 1 resonance combination** 2402.10607 ***JHEP 04 (2024) 118***
  - **CMS: Pair production VLB search** 2402.13808 ***Submitted Phys. Rev. D***
  - **CMS: Pair production LQLQ→$\mu b \mu b$ search** 2402.08668 ***Accepted Phys. Rev. D***
  - **CMS: Review on hV and VV resonances** 2403.16926
- **… And flashed glimpses of few more**
  - Even then, I've only covered a small piece of the BSM program
- **Lots of analyses performed during Run 2, with sadly, no hints of new physics**
  - Many ideas being explored to extract as much as possible from the ongoing Run 3 in both collaborations and leave **no stone unturned** !

THANK YOU FOR YOUR ATTENTION

BACKUP

22

The full list of VLQ analyses

Full Run 2 only

ATLAS

- 2402.16561 → Monotop (Single production)
- 2401.17165 → Pair production Wb + X
- 2308.02595→ B->bH(bb)
- 2307.07584 → Single production opposite sign multilepton
- 2305.03401→ Single production Ht/Zt +X (1 lepton channel)
- 2212.05263→ Pair production T->Zt (1 lepton + MET)
- 2210.15413 → Pair production opposite sign multilepton
- 2201.07045→ Single production all-hadronic

CMS

- 2402.13808→ Pair production B to dileptonic/hadronic
- 2302.12802→Single production T ->tH(γγ)
- 2209.07327→ Pair production (leptonic)
- 2202.12988 →W'->Tb/Bt (all-hadronic)
- 2201.02227→ Single production T->Zt (jets + MET)
- 2008.09835→ Pair production BB (all-hadronic)
- 2405.05071→ Single production T->Ht/Zt (all-hadronic)

H. de la Torre, Northern Illinois University

The full list of LQ analyses

Full Run 2 only

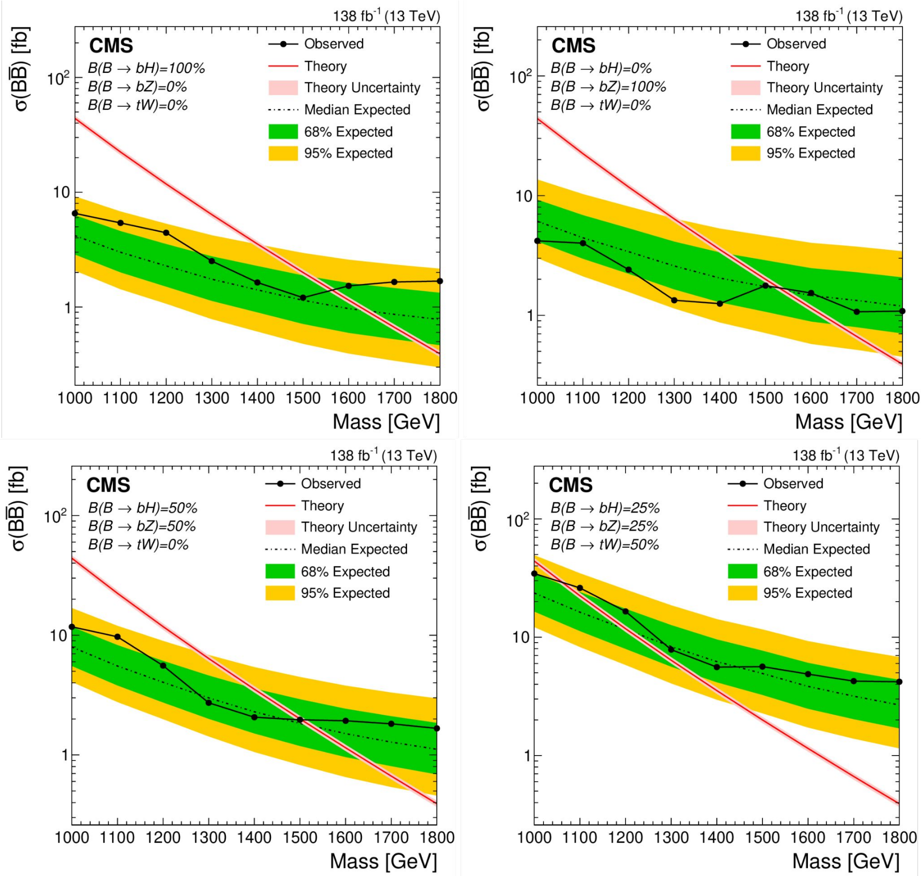
ATLAS

- 2403.06742 LFV in top production/decay
- 2401.11928 Pair production (b-jets combination)
- 2306.17642 Pair production ($t\ell t\ell$ multilepton)
- 2305.15962 Single production (bττ)
- 2303.09444 Single production (ττ + jets)
- 2303.01294 Pair production ($b\tau b\tau$)
- 2210.04517 Pair production (t/b + ℓ final states)
- 2108.07665 Pair production (all τ final states)
- 2101.12527 Pair production (bb+MET)
- 2101.11582 Pair production (tτtτ)
- 2010.02098 Pair production ($t\ell t\ell$ hadronic tops)
- 2006.05872 Pair production first and second gen.
- 2004.14060 Pair production (t/b + MET)

CMS

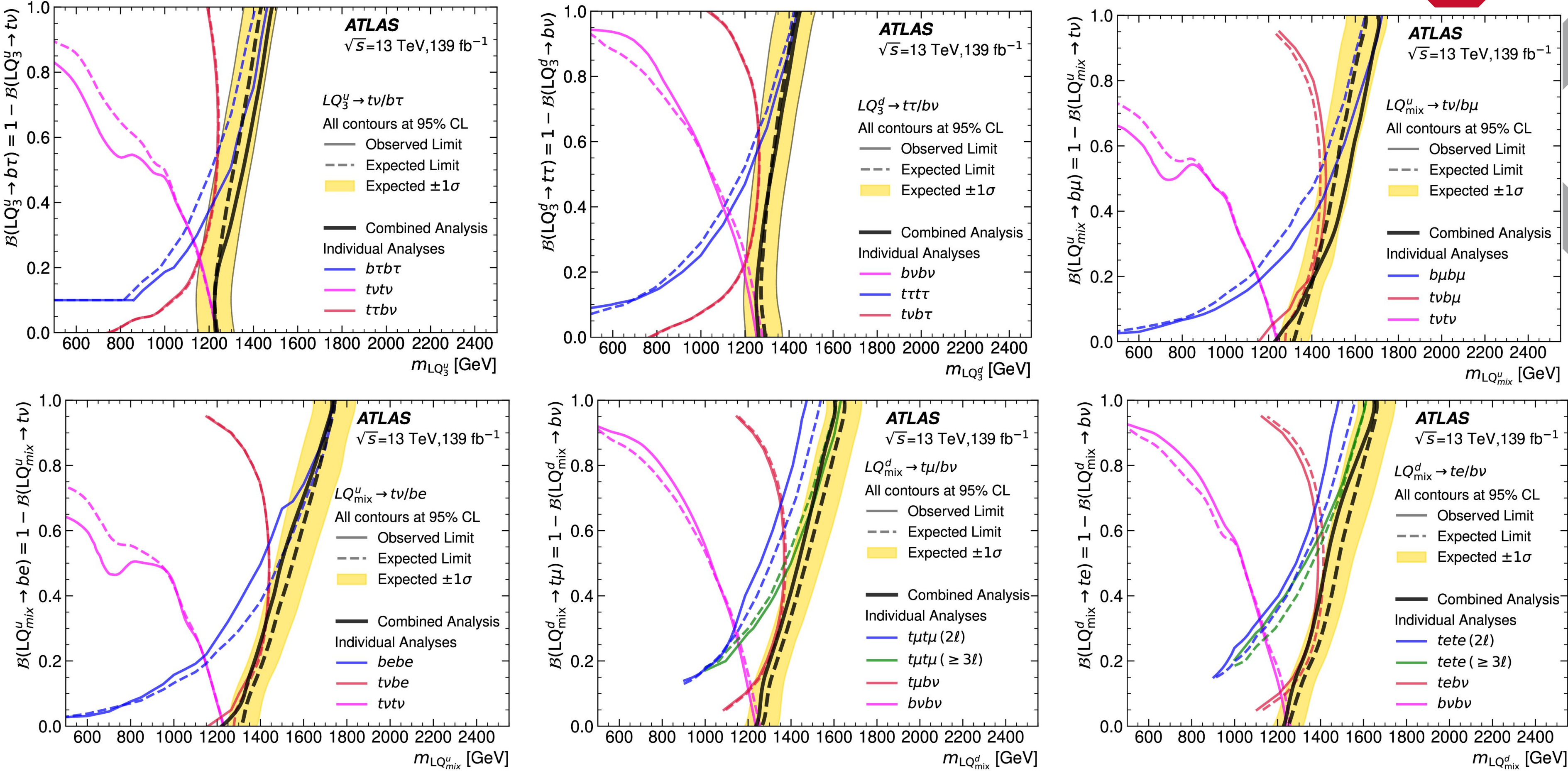
- 2402.08668 Pair production (muons and bottom quarks)
- 2308.07826 Third generation LQ->τb (all modes)
- 2308.06143 Single production $LQ_{\tau b}$ (tau initiated production)
- 2212.12604 Non-resonant LQ (τ + MET)
- 2208.02717 Non-resonant LQ (ττ final state)
- 2202.08676 Third generation (Multilepton inclusive search)
- 2107.13021 Single LQ first generation (MET + jets)
- 2012.04178 Single and pair third generation (t/b+$\tau\nu$ final states)

More VLQ limits from CMS 2402.13808

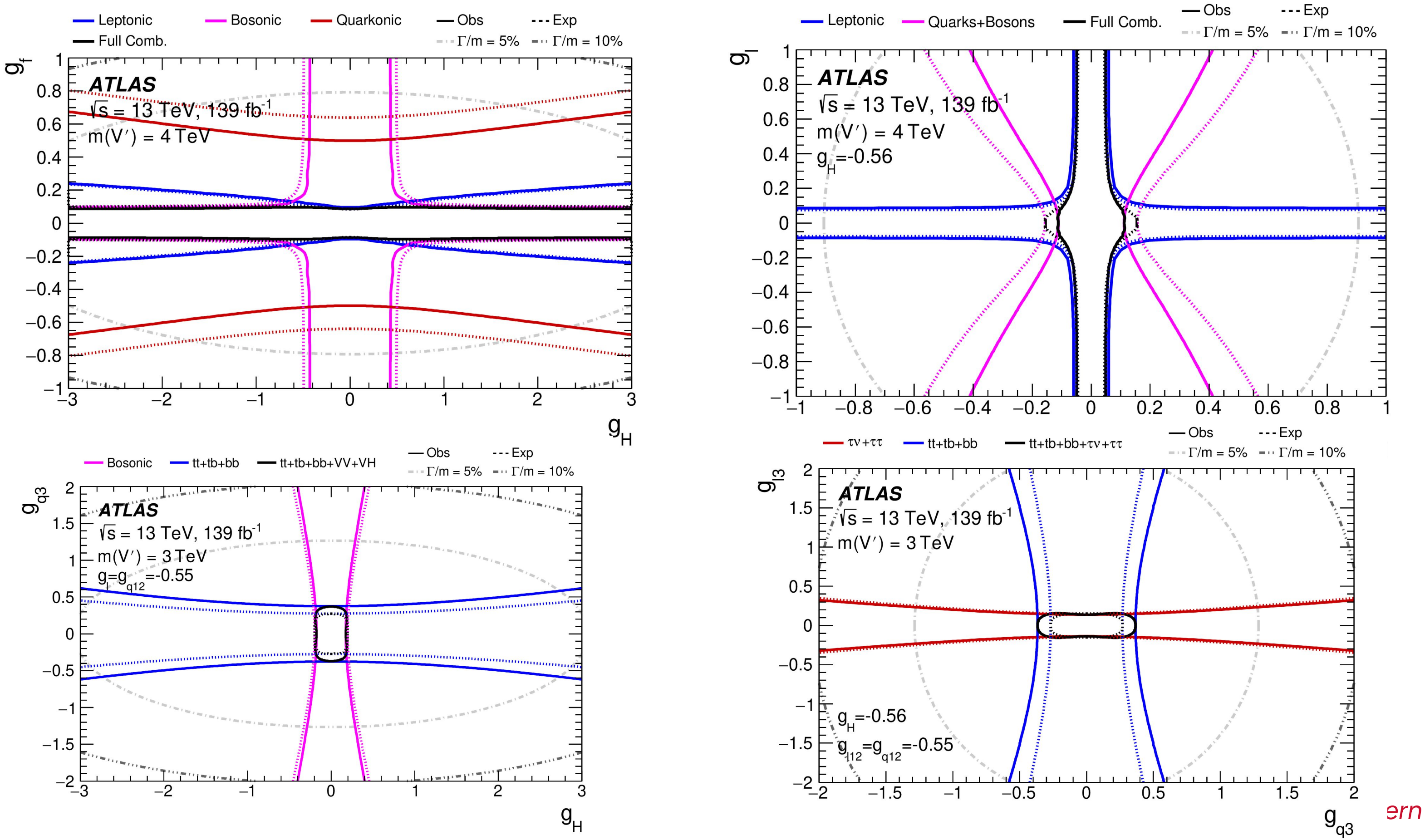


ATLAS Leptoquark combination

2401.11928

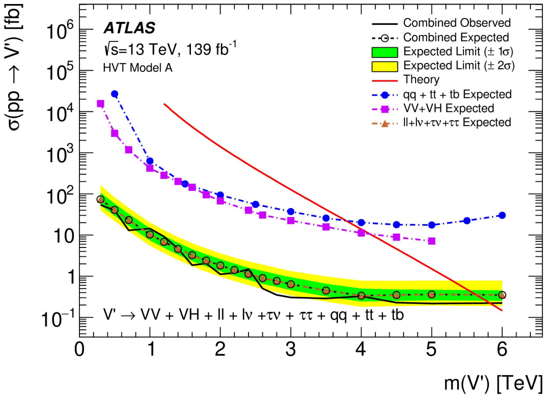


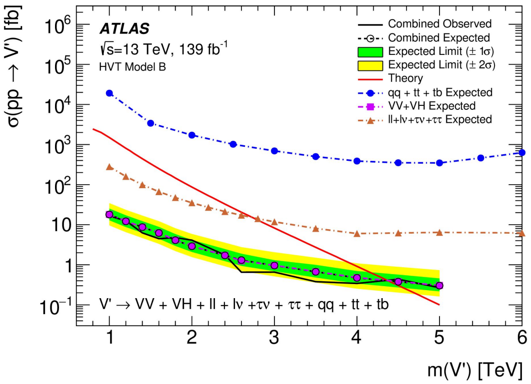
ATLAS Spin 1 resonance combination 2402.10607

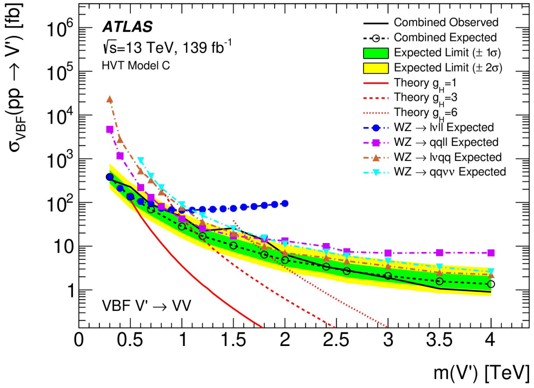


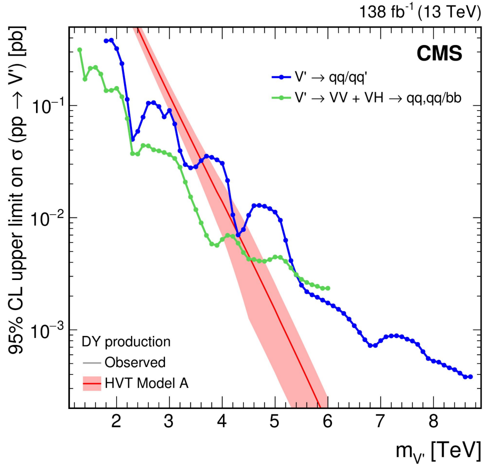
HVT result comparisons

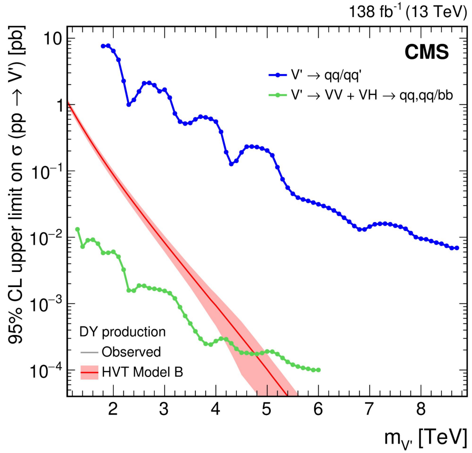
2402.10607 2403.16926

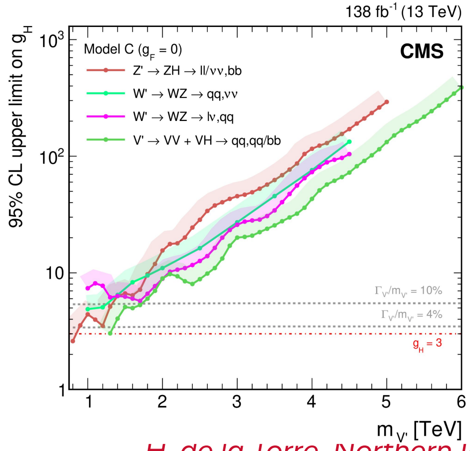






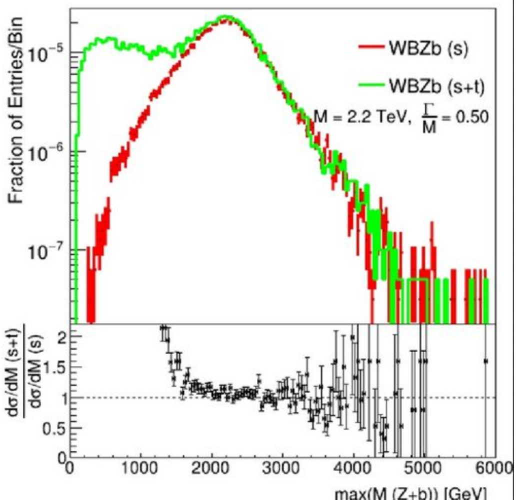


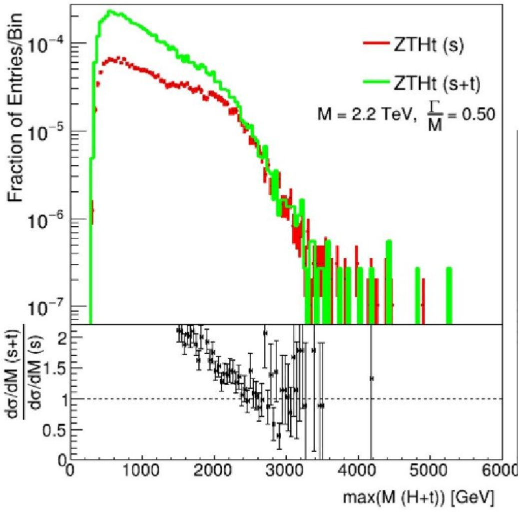




Single VLQ modelling

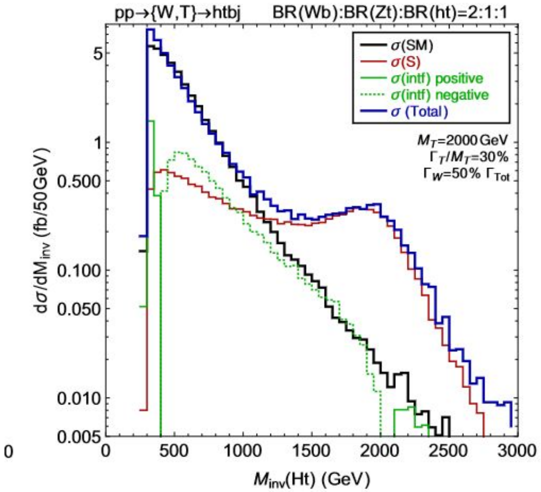
2202.02640 Roy, Avik and Andeen, Timothy





Non resonant production contributions very large for several production modes when considering large widths/couplings !

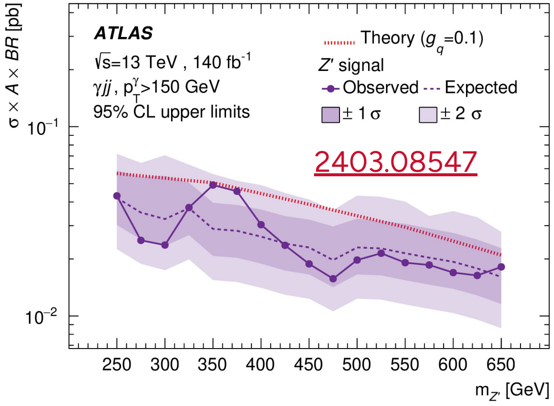
2105.08745 Deandrea, Aldo et al

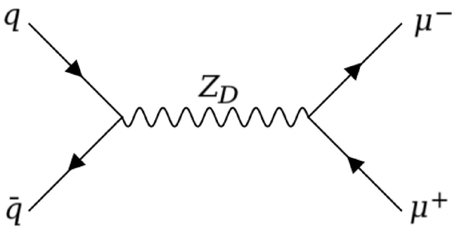


Interference with the standard model can be important in certain productions modes and shape effects need to be taken into account

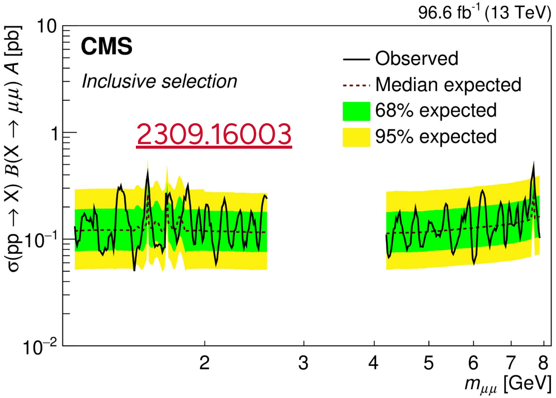
Low mass resonance searches

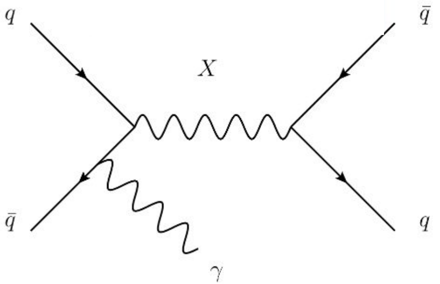
New techniques being implemented in recent years to cover corners of the phase space and final states that we don't have such a good handle in. Low mass for example requires special care due to trigger limitations.





CMS: Dimuon resonances using a dedicated dimuon stream with partial event information



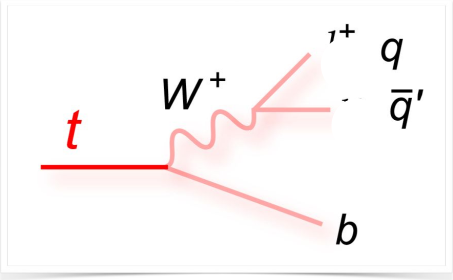


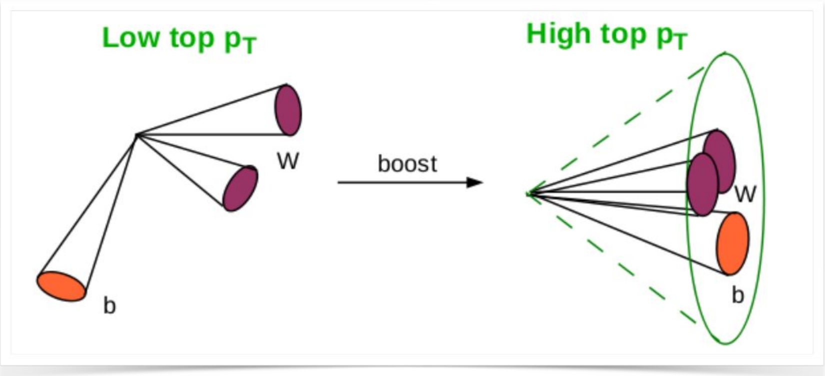
ATLAS: Low mass dijet resonance below jet trigger threshold by exploiting photon/jet initial state radiation

Jets and Jet tagging

Large-R jets are a useful tool for boosted scenarios

Same jet algorithms as standard jets (but larger size) are used to reconstruct complex hadronic structure, such as boosted hadronic top-quarks





Top-tagging

Series of techniques used to identify large-R jets coming from top-quarks

H. de la Torre, Northern Illinois University

Substructure information

In ATLAS (Substructure based) 1808.07858

Observable	Variable	Used for
Calibrated jet kinematics	$p_{\mathrm{T}}, m^{\mathrm{comb}}$	top, W
Energy correlation ratios	e_3, C_2, D_2	top, W
N-subjettiness	$\tau_1, \tau_2, \tau_{21}$	top, W
	τ_3, τ_{32}	top
Fox–Wolfram moment	R_2^{FW}	W
Splitting measures	z_{cut}	W
	$\sqrt{d_{12}}$	top, W
	$\sqrt{d_{23}}$	top
Planar flow	$\mathcal{P}$	W
Angularity	a_3	W
Aplanarity	A	W
KtDR	$KtDR$	W
Qw	Q_w	top

In CMS (Particle flow based)

2004.08262

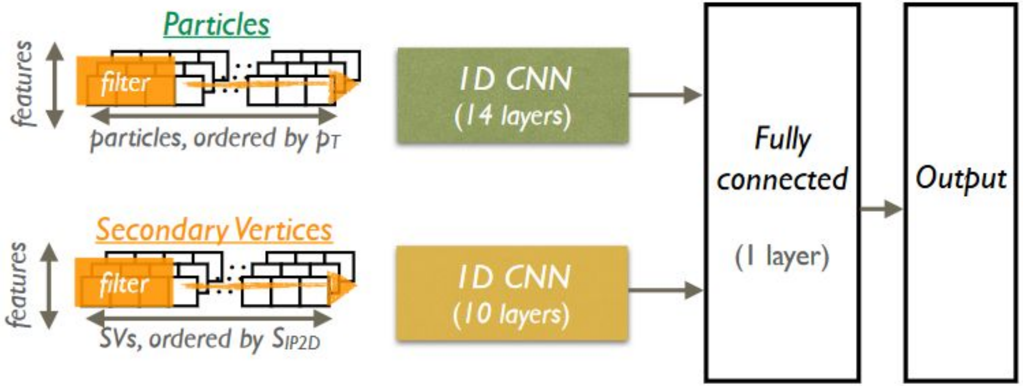
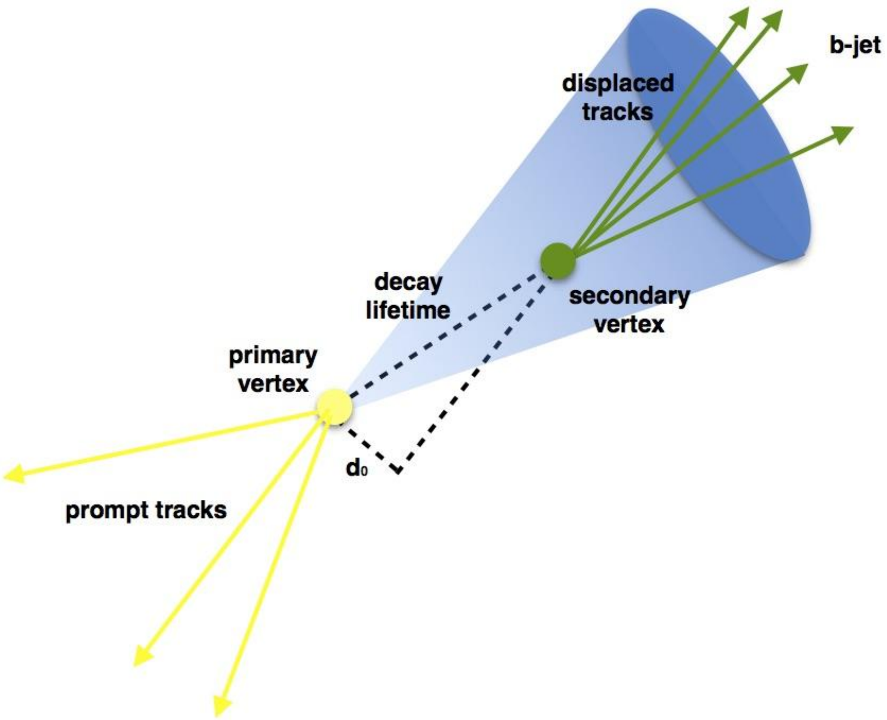


Figure 9. The network architecture of DeepAK8.

Flavor tagging



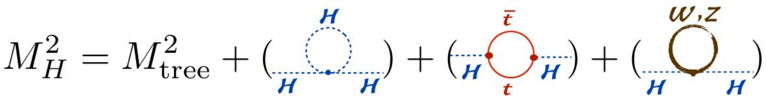
Both collaborations use different flavor of ML methods to identify jets originating from b-quarks using variables and objects related to displaced tracks and displaced vertices

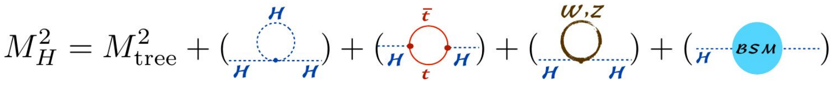
CMS:1712.07158
ATLAS: 2211.16345

Higgs mass and fine tuning

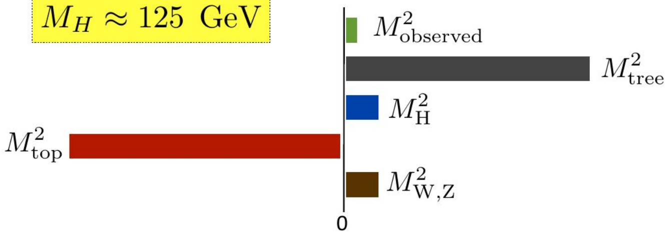
$$\delta M^2 \propto \frac{a}{16\pi^2} g^2 \Lambda^2$$

$$\Lambda_{\text{Planck}} \sim 10^{19}\ \text{GeV}$$

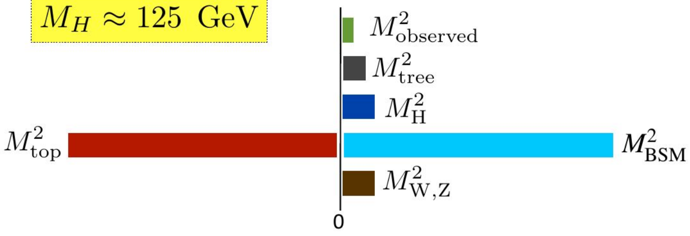




$M_H \approx 125$ GeV



$M_H \approx 125$ GeV



Ultra-fine tuning!

Reasonable fine tuning!