Exotic results from ATLAS and CMS, with emphasis on models with sensitivity to LFV

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Introduction

- There is growing evidence for some form of anomaly in the lepton flavour sector
  - In particular, muons and electrons are increasingly appearing to behave differently
  - Some evidence also for tau differences, but they are experimentally more challenging

- In short, there is increasing evidence for some form of **Lepton Flavour Violation** (LFV)

- Many extensions to the Standard Model (SM) have been proposed to explain this
  - A large number of them foresee the existence of new very heavy particles
  - The LHC is the world's highest-energy collider, and may be sensitive to these new particles
  - There is a diverse search program at ATLAS and CMS looking for such particles

- Note: I will be providing a high-level overview of results, but may have missed a few
  - Apologies if I missed your favourite result in my lists!

A simplified view of the experimental program

- LHC-resonant: look for **new resonances** indicating the existence of a new particle
- LHC-non-resonant: look for **spectrum/tail excesses** indicating higher-energy deviations
- **LHC-inaccessible**: no direct search is possible, constrain using indirect measurements
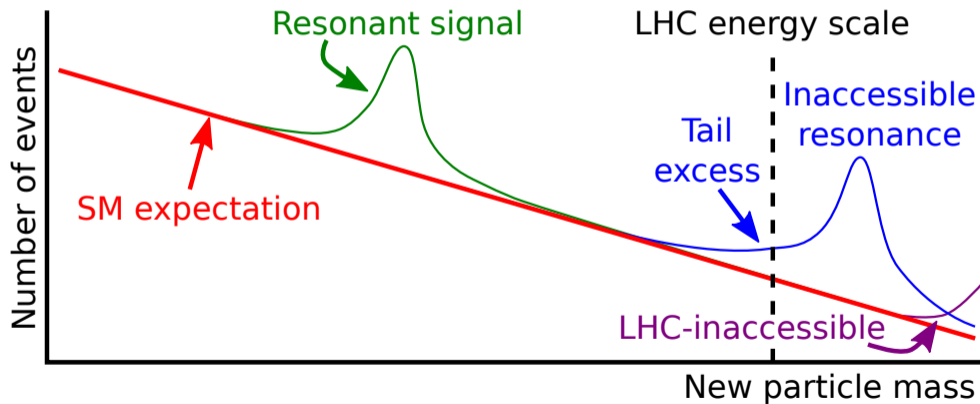
Experimentally, what is the x-axis? Depends on the model under study!

Different models of new physics under study (not exhaustive!)

- **Vector-Like Leptons (VLLs)**
  - Color-singlet fermions, left- and right-handed components act similarly under SM gauge sym.
- **Vector-Like Quarks (VLQs)**
  - Color-triplet fermions, left- and right-handed components act similarly under SM gauge sym.
  - Charge varies: $\frac{5}{3}$ (q^u, W^+), $\frac{2}{3}$ ($q^u, Z/H \,||\, q^d, W^+$), $-\frac{1}{3}$ ($q^d, Z/H \,||\, q^u, W^-$), $-\frac{4}{3}$ (q^d, W^-)
- **Lepto-Quarks (LQs)**
  - Color-triplet bosons that carry both lepton number and baryon number
  - LQ spin varies between models: scalar LQs (sLQs) and vector LQs (vLQs)
  - Charge also varies: $\frac{5}{3}$ ($q^u, \bar{\ell}$), $\frac{2}{3}$ ($q^u, \nu \,||\, q^d, \bar{\ell}$), $-\frac{1}{3}$ ($q^d, \nu \,||\, q^u, \ell$), and $-\frac{4}{3}$ (q^d, ℓ)
- **Heavy Vector Bosons**
  - More massive counterparts to the SM W and Z bosons, with generally same behaviour
  - A lepton-flavour-violating heavy Z boson could also help to explain flavour anomalies
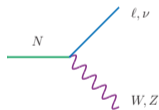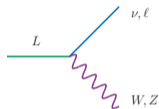- **Generic di-lepton contact interactions**
  - Many models predict heavy and/or wide new particles, often beyond LHC scale
  - In this regime, tail excesses and contact interactions may provide first explanations
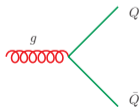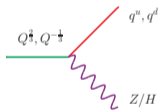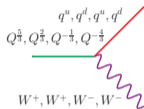
Example Feynman diagrams for these new particles under consideration

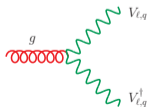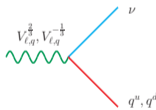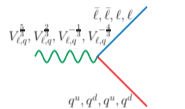Colour scheme: New physics   leptons   quarks/gluons   massive SM bosons

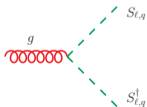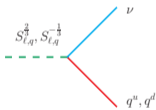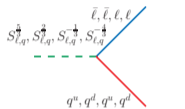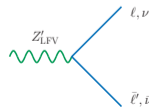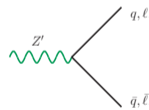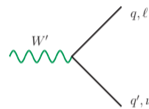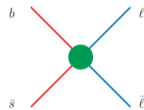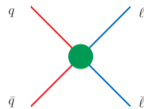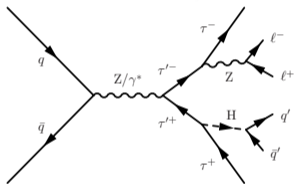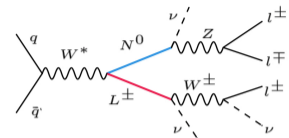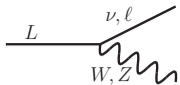- Large variety of final states, typically with multiple leptons
  - Typically also involve a jet pair with a W/Z/H mass constraint
- Currently only a couple results aimed at VLL models
  - ATLAS: 1st and 2nd generation, but only L+N production
  - CMS: L+L and L+N production, but only 3rd generation

VLL	Generation		
	1st	2nd	3rd
L+L	✓✗	✓✗	✗✓
L+N	✓✗	✓✗	✗✓
N+N	✗✗	✗✗	✗✗
L	✗✗	✗✗	✗✗
N	✗✗	✗✗	✗✗
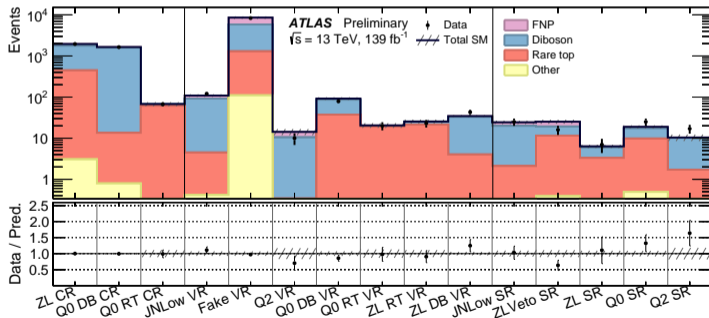
Vector-Like Lepton (VLL) sensitivity
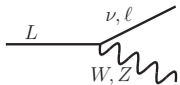
- Current limits from these two VLL searches shown below
  - ATLAS: 1st and 2nd generation, but only L+N production
  - CMS: L+L and L+N production, but only 3rd generation
- Many currently-unexplored final states
  - In particular, no associated production (single-L or -N) so far
- Lots of potential to increase VLL sensitivity
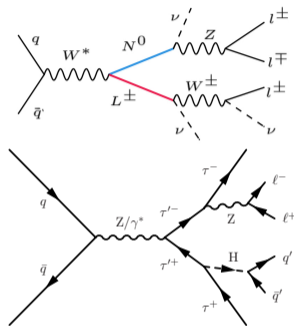
VLL	Generation		
	1st	2nd	3rd
L+L	✓✗	✓✗	✗✓
L+N	✓✗	✓✗	✗✓
N+N	✗✗	✗✗	✗✗
L	✗✗	✗✗	✗✗
N	✗✗	✗✗	✗✗
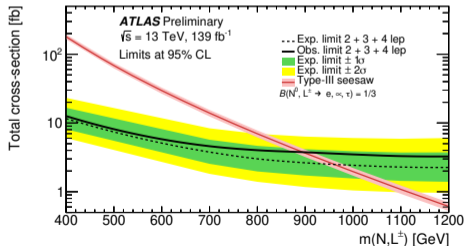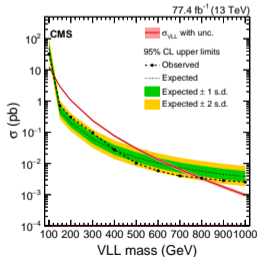
- Searches typically include multiple bosons and 3rd gen quarks
  - Extremely active final states, with a lot of event activity
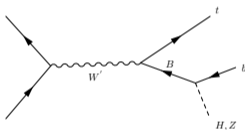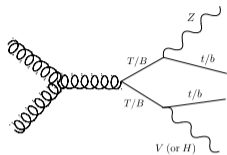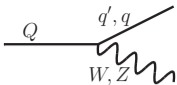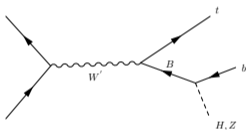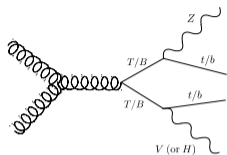- Final states depend on VLQ charge: $X_{5/3}$, $T_{2/3}$, $B_{-1/3}$, $Y_{-4/3}$
  - $\frac{5}{3} = Wt$, $\frac{2}{3} = (Zt, Ht, Wb)$, $-\frac{1}{3} = (Zb, Hb, Wt)$, $-\frac{4}{3} = Wb$

- Usually semi-leptonic or fully-hadronic searches (due to statistics)
- Heavy use of jet taggers: b-hadron, $W/Z \rightarrow qq$, $H \rightarrow bb$, and $t \rightarrow qqb$
  - Sometimes together, in fully-hadronic channels

Prod & decay	VLQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1×, Wx	✓✗	✗✗	✓✓	✓✗
2×, Wx	✓✓	✓✓	✓✓	✗✓
1×, Zx	—	✗✓	✗✗	—
2×, Zx	—	✓✓	✓✓	—
1×, Hx	—	✗✓	✓✓	—
2×, Hx	—	✓✓	✗✓	—

ATLAS Simulation Preliminary
$\sqrt{s} = 13$ TeV

V-jets from V-class
bkg jets from V-class

H-jets from H-class
bkg jets from H-class

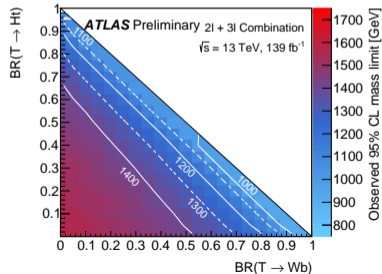top jets from top class
bkg jets from top class

Fraction of Events
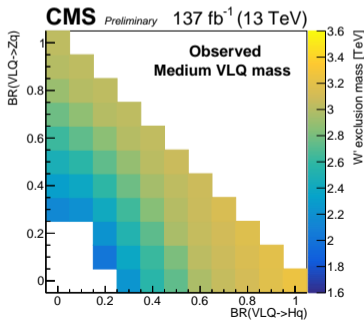
DNN output of V-/ H-/ top-/ tagger

Vector-Like Quark (VLQ) sensitivity

- Interpreting results as VLQ limits requires BR assumptions
  - Typically shown as 2D plane with respect to two relevant BRs
- Large range of parameter space to study
  - Beyond branching ratios, also different VLQ charges
- Some final states not yet covered - more work to be done!

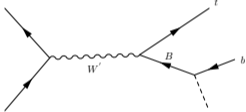| Prod & decay	VLQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1×, Wx	✓✗	✗✗	✓✗	✓✗
2×, Wx	✓✓	✓✓	✓✓	✗✓
1×, Zx	—	✗✓	✗✗	—
2×, Zx	—	✓✓	✓✓	—
1×, Hx	—	✗✓	✓✓	—
2×, Hx	—	✓✓	✗✓	—

Vector-Like Quark (VLQ) summary

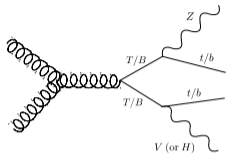| Prod & decay	VLQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1×, Wx	✓✗	✗✗	✓✓	✓✗
2×, Wx	✓✓	✓✓	✓✓	✗✓
1×, Zx	—	✗✓	✗✗	—
2×, Zx	—	✓✓	✓✓	—
1×, Hx	—	✗✓	✗✓	—
2×, Hx	—	✓✓	✓✗	—

$S_{\ell,q}$ (or $V_{\ell,q}$)

Lepto-Quark (LQ) searches

- In the simplest form, final states are two leptons and two jets
  - The leptons may be neutrinos, so E_T^{miss} is also common
- 3rd generation can change this signature: τ and top decays
  - Sometimes large-R jets used for tops, but not full top taggers
  - Contrasts with VLQ: di-lepton suppresses QCD background
- 1st and 2nd gen inclusive searches, 3rd gen dedicated searches
  - Tau fakes are key: Swiss CMS group leads improvements [1,2]

Gen & decay	LQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1st, qe	✓✓	✓✓	✓✓	✓✓
2nd, $q\mu$	✓✓	✓✓	✓✓	✓✓
3rd, $t\tau$	✗✗	—	✓✓	—
3rd, $b\tau$	—	✓✓	✓✓	✗✗
3rd, $t\nu$	—	✓✓	✓✓	—
3rd, $b\nu$	—	—	✓✓	—

Recent CMS results on both single- and double-production of LQs

- Also first combinations!
- Both scalar and vector LQs
  - Vector: increased LQ production cross-section
  - Result: more sensitive to vector LQ models

Gen & decay	LQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1st, qe	✓✓	✓✓	✓✓	✓✓
2nd, $q\mu$	✓✓	✓✓	✓✓	✓✓
3rd, $t\tau$	✗✗	—	✓✓	—
3rd, $b\tau$	—	✓✓	✓✓	✗✗
3rd, $t\nu$	—	✓✓	—	—
3rd, $b\nu$	—	—	✓✓	—

$S_{\ell,q}$ (or $V_{\ell,q}$)

- ATLAS has just released overlaid LQ interpretation results
  - Includes SUSY (re-)interpretations: complementary searches!
  - Final states for scalar LQs and SUSY stop/sbottom overlap
  - stop & sbottom $\approx$ LQ$_{2/3}$ & LQ$_{-1/3}$, for massless neutralinos
- Lots of potential for (re-)interpretation and cooperation

Gen & decay	LQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1st, qe	✓✓	✓✓	✓✓	✓✓
2nd, $q\mu$	✓✓	✓✓	✓✓	✓✓
3rd, $t\tau$	✗✗	—	✓✓	—
3rd, $b\tau$	—	✓✓	✓✓	✗✗
3rd, $t\nu$	—	✓✓	✓✓	—
3rd, $b\nu$	—	—	✓✓	—

$pp \rightarrow LQ_3^d LQ_3^d$, all contours at 95 % confidence level — June 2021

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 139 fb^{-1}

— observed
⋯ expected

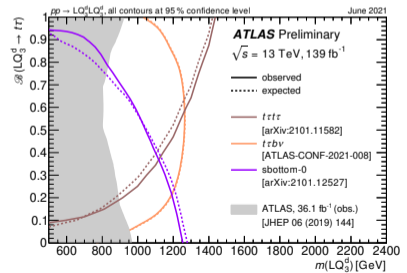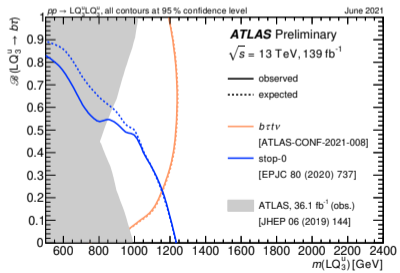$b\tau t\nu$ [ATLAS-CONF-2021-008]
stop-0 [EPJC 80 (2020) 737]
ATLAS, 36.1 fb^{-1} (obs.) [JHEP 06 (2019) 144]

$pp \rightarrow LQ_3^d LQ_3^d$, all contours at 95 % confidence level — June 2021

ATLAS Preliminary
$\sqrt{s} = 13$ TeV, 139 fb^{-1}

— observed
⋯ expected

$t\tau\tau$ [arXiv:2101.11582]
$t\tau b\nu$ [ATLAS-CONF-2021-008]
sbottom-0 [arXiv:2101.12527]
ATLAS, 36.1 fb^{-1} (obs.) [JHEP 06 (2019) 144]

Lepto-Quark (LQ) summary

Massive vector bosons: W' and Z'

- Huge number of searches for different W' and Z' final states
  - Include leptonic and hadronic decays, but also bosonic decays
- Will focus here on those that are "most interesting" for LFV
  - In particular 3rd generation quarks, $W' \to tb$ and $Z' \to t\bar{t}$
  - Heavy use of b-tagging and top-tagging at highest energies
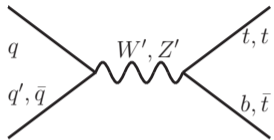
Gen &	Vector boson			
decay	W'_L	W'_R	Z'	Z_{FV}
$\ell(\nu\ell\ell')$	✓✓	✓✓	✓✓	✗✗
$\tau(\nu\tau\ell)$	✓✓	✗✓	✓✗	✓✗
qq	✓✓	✗✗	✓✓	—
$b(c\bar{b}s)$	✗✗	✗✗	✓✓	✗✗
$t(b\bar{t}c)$	✗✓	✓✓	✓✓	✗✗

Also VV/VH/etc decays
(not the focus of this talk)
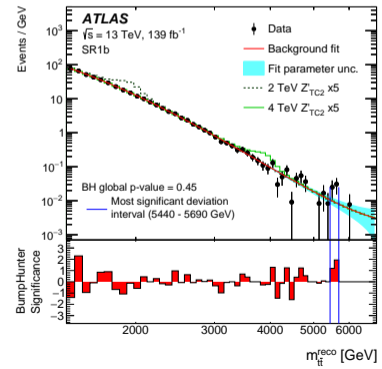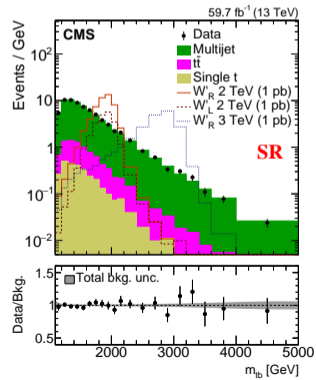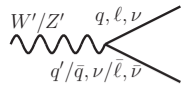
W' and Z' sensitivity
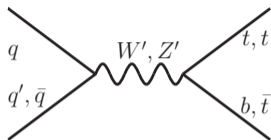
- Set limits on both left- and right-handed W' bosons
- Z' more thoroughly covered than W'
  - Below left table doesn't give the full picture, more on this soon

Gen & decay	Vector boson			
	W'_L	W'_R	Z'	Z_{FV}
$\ell(\nu\ell\ell')$	✓✓	✓✓	✓✓	✗✗
$\tau(\nu\tau\ell)$	✓✓	✗✓	✓✗	✓✗
qq	✓✓	✗✗	✓✓	—
$b(c\bar{b}s)$	✗✗	✗✗	✓✓	✗✗
$t(b\bar{t}c)$	✗✓	✓✓	✓✓	✗✗

Also VV/VH/etc decays
(not the focus of this talk)

- Search for direct lepton flavour violation in Z decays
  - $Z \to e\tau$ and $Z \to \mu\tau$, no evidence for such couplings

Gen &	Vector boson			
decay	W'_L	W'_R	Z'	Z_{FV}
$\ell(\nu\ell\ell')$	✓✓	✓✓	✓✓	✗✗
$\tau(\nu\tau\ell)$	✓✓	✗✓	✓✗	✓✗
qq	✓✓	✗✗	✓✓	—
$b(c\bar{b}s)$	✗✗	✗✗	✓✓	✗✗
$t(b\bar{t}c)$	✗✓	✗✗	✓✓	✗✗

Also VV/VH/etc decays
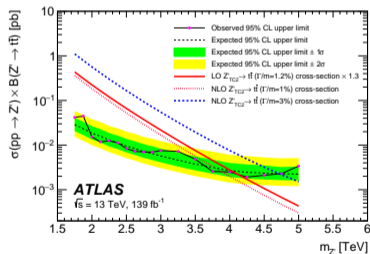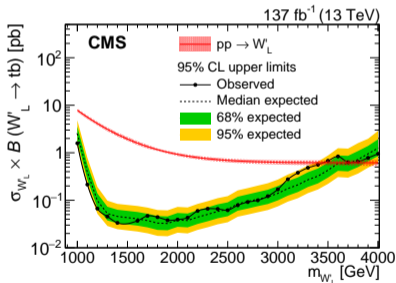(not the focus of this talk)
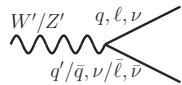
Massive vector boson summary
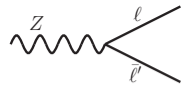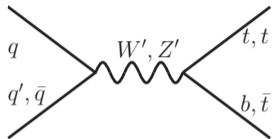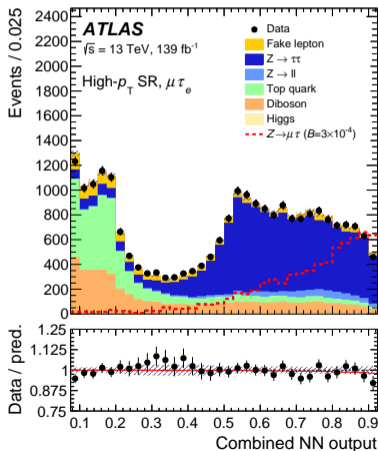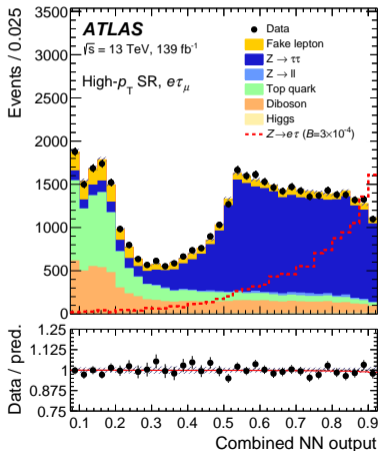
ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

ATLAS Preliminary

Status: March 2021

L dt = (3.6 – 139) fb⁻¹   √s = 8, 13 TeV

Model	ℓ, γ	Jets†	E_T^miss	L dt[fb⁻¹]	Limit		Reference
SSM Z′ → ℓℓ	2 e, μ	–	–	139	Z′ mass	5.1 TeV	1903.06248
SSM Z′ → ττ	2 τ	–	–	139	Z′ mass	2.42 TeV	1709.07242
Leptophobic Z′ → bb	–	2 b	–	36.1	Z′ mass	2.1 TeV	1805.09299
Leptophobic Z′ → tt	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z′ mass	4.1 TeV	2005.05138
SSM W′ → ℓν	1 e, μ	–	Yes	139	W′ mass	6.0 TeV	1906.05609
SSM W′ → τν	1 τ	–	Yes	36.1	W′ mass	3.7 TeV	1801.06992
HVT W′ → WZ → ℓνqq model B	1 e, μ	2 j / 1 J	Yes	139	W′ mass	4.3 TeV	2004.14636
HVT Z′ → ZH model B	0-2 e, μ	1-2 b	Yes	139	Z′ mass	3.2 TeV	ATLAS-CONF-2020-043
HVT W′ → WH model B	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	W′ mass	3.2 TeV	2007.05293
LRSM W_R → tb	multi-channel			36.1	W_R mass	3.25 TeV	1807.10473
LRSM W_R → μN_R	2 μ	1 J	–	80	W_R mass	5.0 TeV	1904.12679

*Only a selection of the available mass limits on new states or phenomena is shown.
†Small-radius (large-radius) jets are denoted by the letter j (J).

Mass scale [TeV]

CMS Preliminary

35.9 - 77.3 fb⁻¹ (13 TeV)

Z'_SSM→tt̄, B(Z'→tt̄)=100%, Γ/M_{Z'}=1%	M_{Z'} B2G-17-017 (all final states)	3.8
Z'_SSM→tt̄, B(Z'→tt̄)=100%, Γ/M_{Z'}=10%	M_{Z'} B2G-17-017 (all final states)	5.2
Z'_SSM→tt̄, B(Z'→tt̄)=100%, Γ/M_{Z'}=30%	M_{Z'} B2G-17-017 (all final states)	6.6
G_{KK}→tt̄, Kaluza-Klein G_{KK}	M_{KK} B2G-17-017 (all final states)	4.5
W'_R→tb→bbℓν, M_{W'}<M_{v_R}, right-handed W	M_{W'} B2G-17-010 (bb(v))	3.6
Z'_SSM→tt̄ (tZt, tH t)→ℓν + jets, B(t→tZ)=B(t'→tH)=50%	M_{Z'} B2G-17-015 (ℓν + jets)	2.3
W'→(tB, B'Γ)→tHb→bqqbb̄, B(W'→bT)=100%	M_{W'} B2G-18-001 (bqqbbb)	1.6

Selection of observed exclusion limits at 95% CL (theory uncertainties are not included).

mass scale [TeV]

EPS-HEP 2019

CMS preliminary

36-140 fb⁻¹ (13 TeV)

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

mass scale [TeV]

Moriond 2021

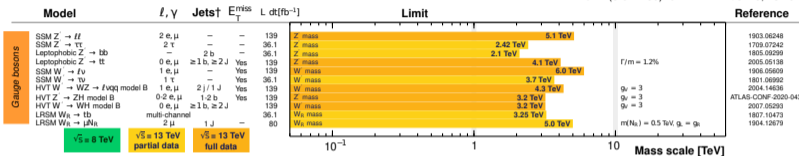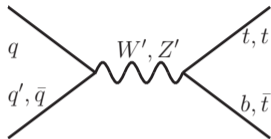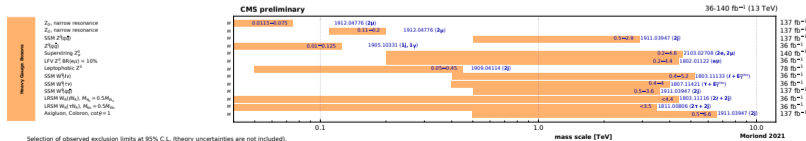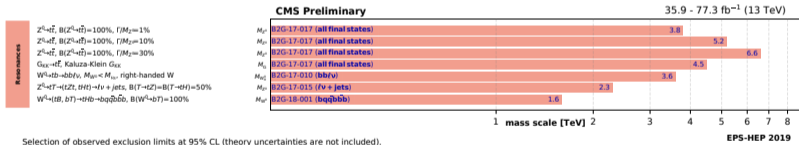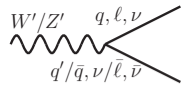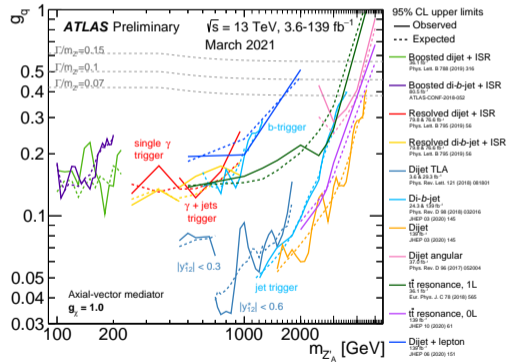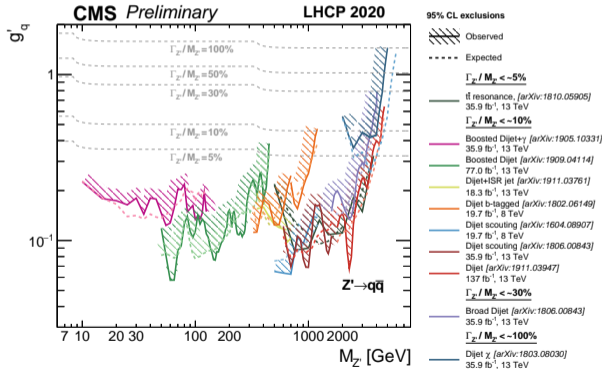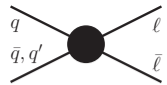| Gen & decay	Vector boson			
	W'_L	W'_R	Z'	Z_{FV}
$\ell(\nu\ell\ell')$	✓✓	✓✓	✓✓	✗✗
$\tau(\nu\tau\ell)$	✓✓	✗✓	✓✗	✓✗
qq	✓✓	✗✗	✓✓	—
$b(c\bar{b}s)$	✗✗	✗✗	✗✗	✗✗
$t(b\bar{t}c)$	✗✓	✓✓	✓✓	✗✗

Also VV/VH/etc decays
(not the focus of this talk)

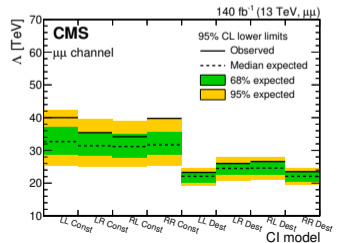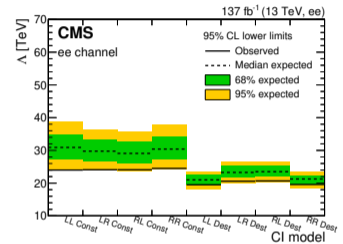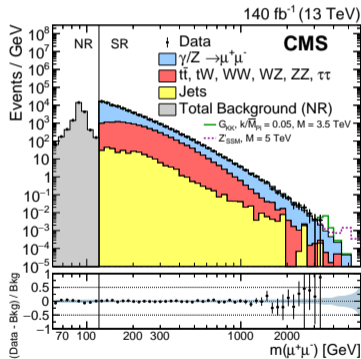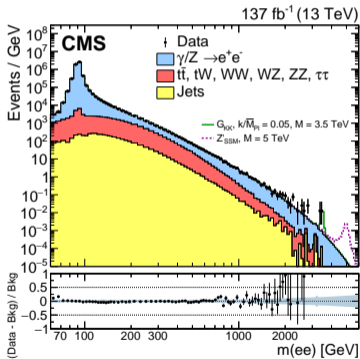W'/Z' — q, ℓ, ν / $q'/\bar{q}, \nu/\bar{\ell}, \bar{\nu}$

- The search for Z' in particular is very diverse: major focus of the DM search programme
  - Studied in many different hadronic final states, including $t\bar{t}$ and $b\bar{b}$, by ATLAS and CMS

- CMS searches for dilepton contact interactions show possible deviations
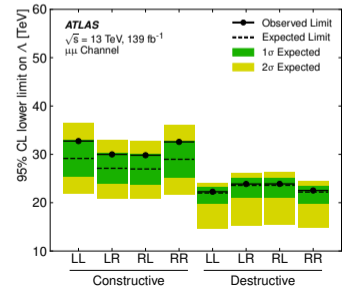 - Appear to be different for *ee* and $\mu\mu$, as you may expect for a LFV-related phenomenon
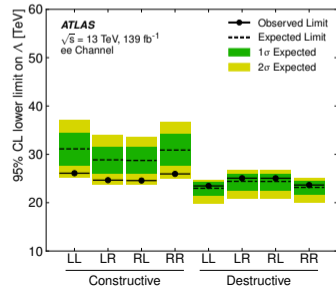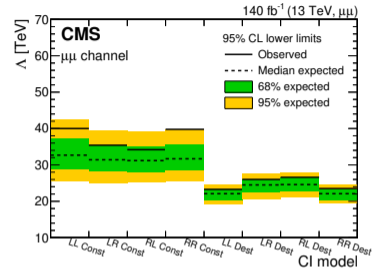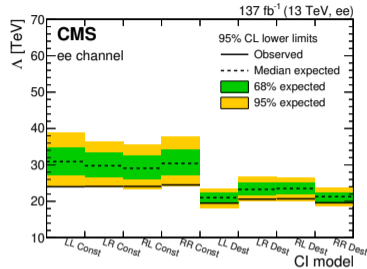
Di-lepton contact interactions

- It turns out that these trends roughly match what ATLAS has seen

- Nothing definitive, but interesting to watch
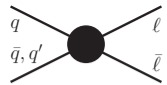
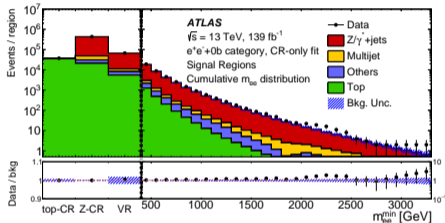- Very recent ATLAS result: cumulative $\ell\ell$ mass distributions show ee excess, $\mu\mu$ deficit
  - Potential difference in 0-b-tag (top) and 1-b-tag (bottom) categories
  - Largest deviation: ee 1-b-tag category at $m_{ee}^{min} = 1.7$ TeV, with 2.6σ local and 1.5σ global

Supersymmetric models
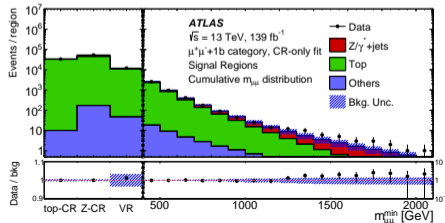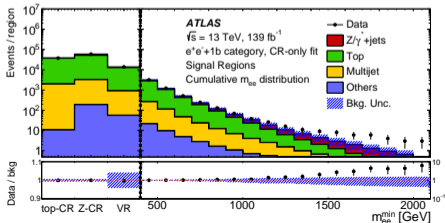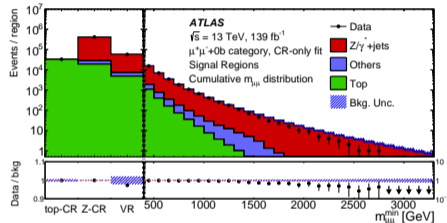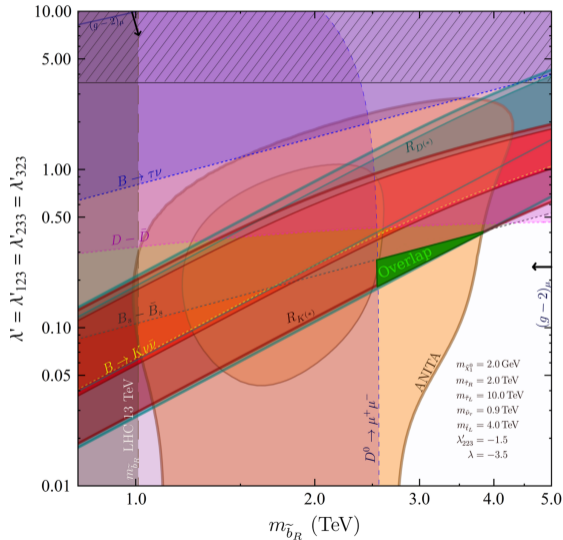
- We have now looked at a huge variety of "simplified models" of new physics that could be related to the flavour anomalies

- Important to remember to also consider UV-complete theories, such as SUSY

- **Overlap can explain many anomalies**
  - R_D and R_{D*}
  - R_K and R_{K*}
  - Muon $g - 2$
  - Excess of ultra-high-energy cosmic rays

- When searching for new physics, we must consider many options!

Summary

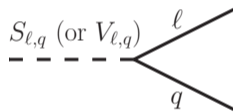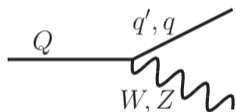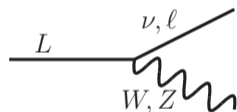- As we've seen, ATLAS and CMS are studying a wide variety of possible new models
  - VLLs, VLQs, LQs, heavy vector bosons, contact interactions, and more
- However, there are still many areas where we can improve our search programme
  - Summary tables give a first indication; not the full picture, and doesn't show dataset used
  - May be missing models, final states, or event reconstruction strategies – feedback welcome!
- We will be watching the anomalies evolve; hopefully ATLAS and CMS will find something!

VLL	Generation		
	1st	2nd	3rd
L+L	✓✗	✓✗	✗✓
L+N	✓✗	✓✗	✗✓
N+N	✗✗	✗✗	✗✗
L	✗✗	✗✗	✗✗
N	✗✗	✗✗	✗✗

Prod & decay	VLQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1×, Wx	✓✗	✗✗	✗✓	✓✗
2×, Wx	✓✓	✓✓	✓✓	✗✓
1×, Zx	—	✗✓	✗✗	—
2×, Zx	—	✓✓	✓✓	—
1×, Hx	—	✗✓	✓✓	—
2×, Hx	—	✓✓	✗✓	—

Gen & decay	LQ charge			
	$\frac{5}{3}$	$\frac{2}{3}$	$-\frac{1}{3}$	$-\frac{4}{3}$
1st, qe	✓✓	✓✓	✓✓	✓✓
2nd, $q\mu$	✓✓	✓✓	✓✓	✓✓
3rd, $t\tau$	✗✗	—	✓✓	—
3rd, $b\tau$	—	✓✓	—	✗✗
3rd, $t\nu$	—	✓✓	—	—
3rd, $b\nu$	—	—	✓✓	—

Gen & decay	Vector boson			
	W'_L	W'_R	Z'	Z_{FV}
$\ell(\nu\ell\ell')$	✓✓	✓✓	✓✓	✗✗
$\tau(\nu\tau\ell)$	✓✓	✗✓	✗✓	✓✗
qq	✓✓	✗✗	✓✗	—
$b(c\bar{b}s)$	✗✗	✗✗	✓✓	✗✗
$t(b\bar{t}c)$	✗✓	✓✓	✓✓	✗✗
Also VV/VH/etc decays				

Backup Material
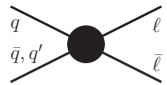
- Largest deviation:
  - *ee* 1-b-tag category
  - $m_{ee}^{\min} = 1.7$ TeV
  - 2.6σ local
  - 1.5σ global