High-p_T implications of (muon) anomalies

Experimental perspective

Aurelio Juste
(ICREA / IFAE)

ICREA

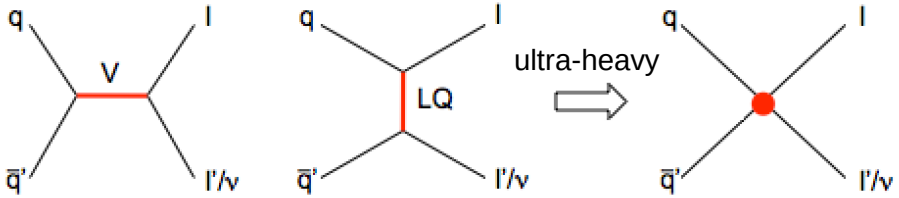
IFAE Institut de Física d'Altes Energies
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

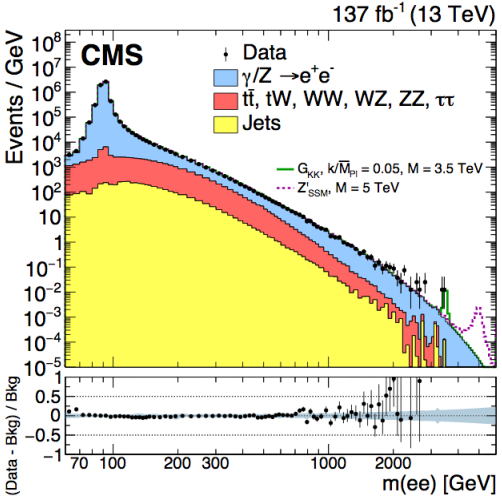
High-p_T tails

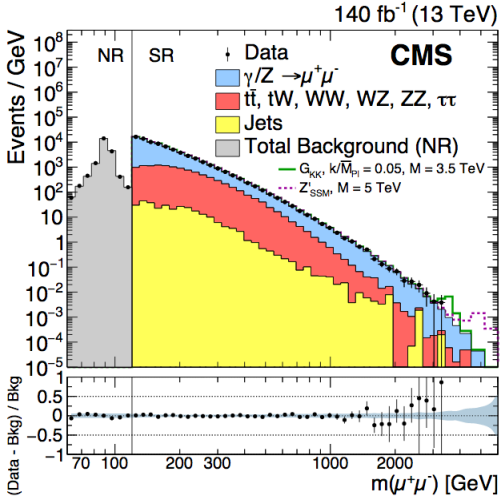
Non-resonant dileptons: current program

Anomaly scorecard

- R(K) R(K*)
- R(D) R(D*)
- a_μ
- Other



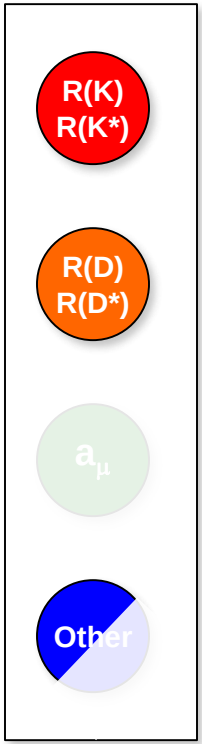




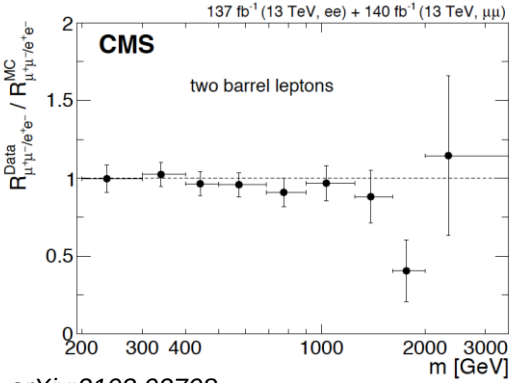
arXiv:2103.02708

Non-resonant dileptons: current program

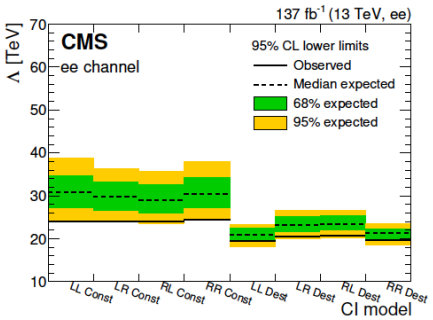
Anomaly scorecard

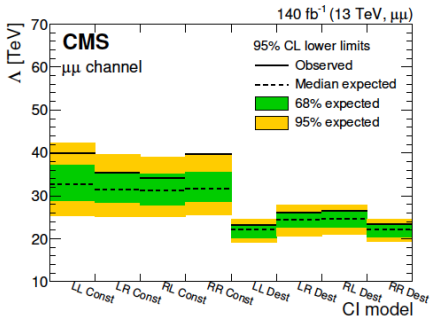


- Non-resonant inclusive ee, μμ searches published.
  - Slight excess in ee channel.
- Unfolded spectra and LFUV ratio test recently performed by CMS.

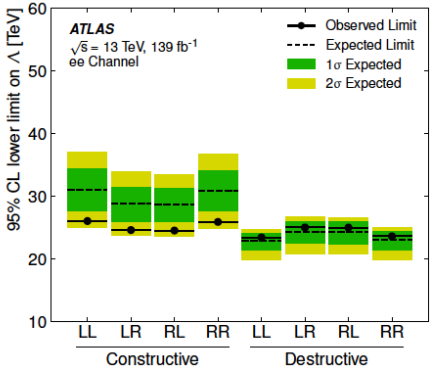


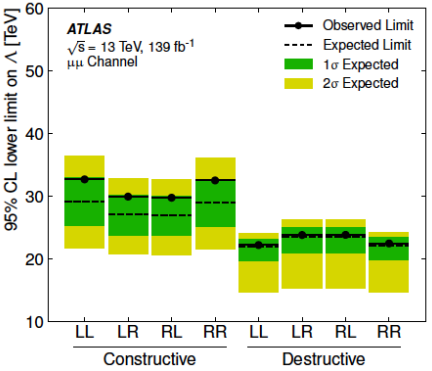
arXiv:2103.02708





arXiv:2103.02708





arXiv:2006.12946

Non-resonant dileptons: current program

Anomaly scorecard

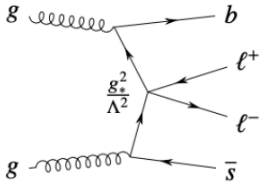
R(K) R(K*)

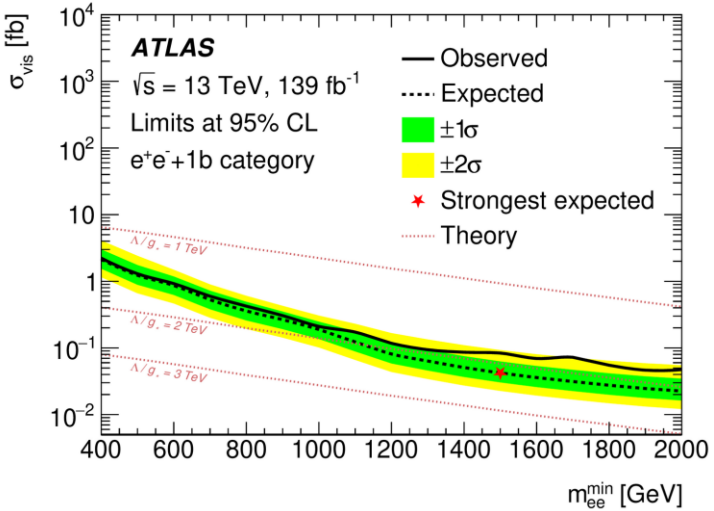
R(D) R(D*)

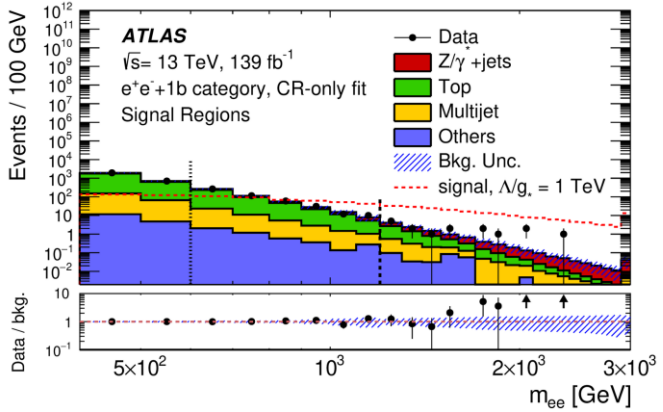
a_μ

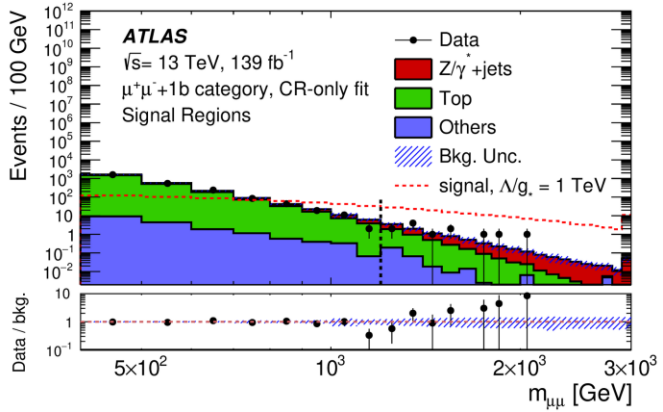
Other

- First search for bsll CI recently completed:









arXiv:2105.13847

Non-resonant dileptons: opportunities

Anomaly scorecard

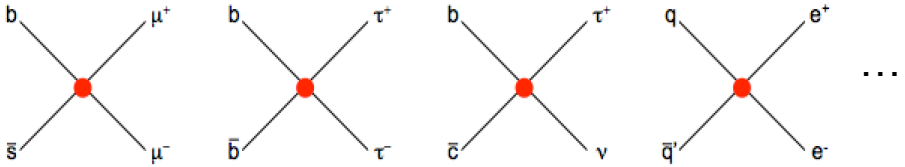
R(K) R(K*)

R(D) R(D*)

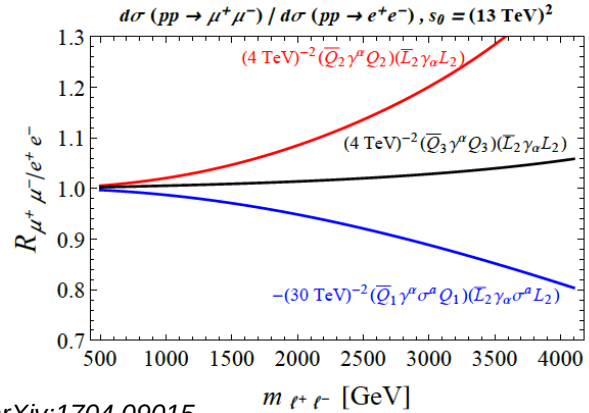
a_μ

Other

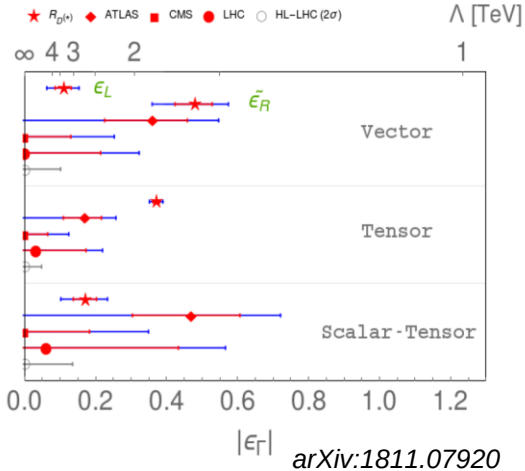
- Develop broad program of non-resonant dilepton searches (ee, μμ, ττ, eν, μν, τν), both in inclusive and exclusive (e.g. ≥1b) final states.



- Unfolded dilepton mass spectra and LFU ratio tests.



arXiv:1704.09015



arXiv:1811.07920

Leptoquarks

Leptoquarks

Anomaly scorecard

R(K) R(K*)

R(D) R(D*)

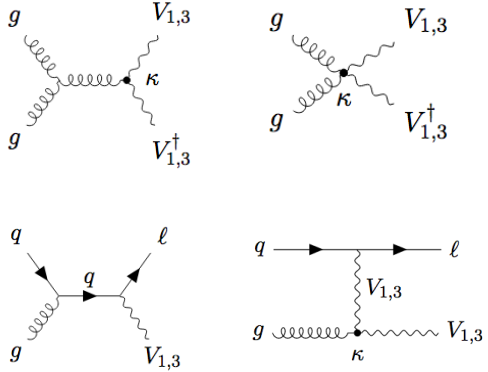
a_μ

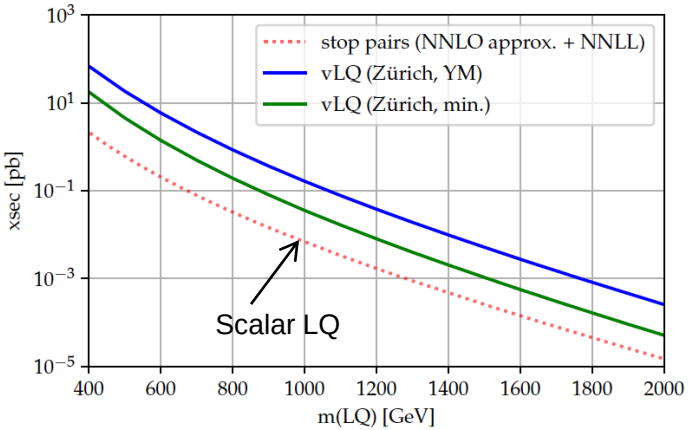
Other

- Resonant production in pairs or singly.
  Enhanced cross section if of gauge origin in the case of vector LQs.
- Single-particle explanation: V_1 (V_3 also possible).
- Dominant decay if only explaining R(K), R(K*) :
  $V_1^{+2/3} \rightarrow b\mu, t\nu$

  $V_3^{-1/3} \rightarrow b\nu$
  $V_3^{+2/3} \rightarrow b\mu, t\nu$
  $V_3^{+5/3} \rightarrow t\mu$

  If also explaining R(D), R(D*), couplings to τ dominate.





Need a broad program!

Leptoquarks

Anomaly scorecard

R(K) R(K*)

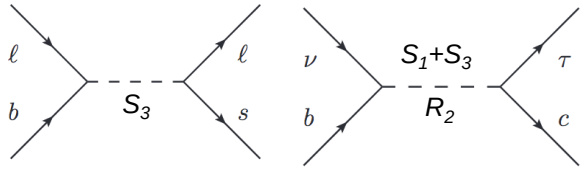
R(D) R(D*)

a_μ

Other

- Resonant production in pairs or singly.
  Enhanced cross section if of gauge origin in the case of vector LQs.

- Most successful scalar LQ models involve at least two LQs:
  - S_1 and S_3 *(e.g. arXiv:1703.09226)*
  - R_2 and S_3 *(e.g. arXiv:1806.05689)*



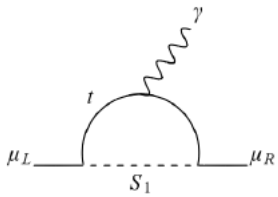
- Decay modes directly related to the B anomalies:

  $S_1^{-1/3} \rightarrow b\nu, c\tau \rightarrow$ R(D), R(D*) $\leftarrow$ $R_2^{+2/3} \rightarrow b\tau, c\nu$; $R_2^{+5/3} \rightarrow t\tau, c\tau$

  $S_3^{+2/3} \rightarrow t\nu$

  $S_3^{-1/3} \rightarrow b\nu, t\mu$

  $S_3^{-4/3} \rightarrow b\mu \rightarrow$ R(K), R(K*)



However, other decay modes may actually dominate (e.g. $S_3^{-4/3} \rightarrow b\tau^-$) if similar hierarchies as in SM quark Yukawas hold ($\lambda_{b\tau} > \lambda_{b\mu}$).

Need a broad program!

Leptoquarks: current program

Anomaly scorecard

R(K) R(K*)

R(D) R(D*)

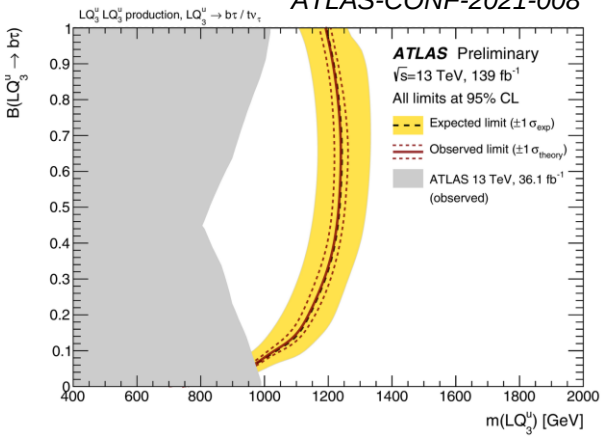
a_μ

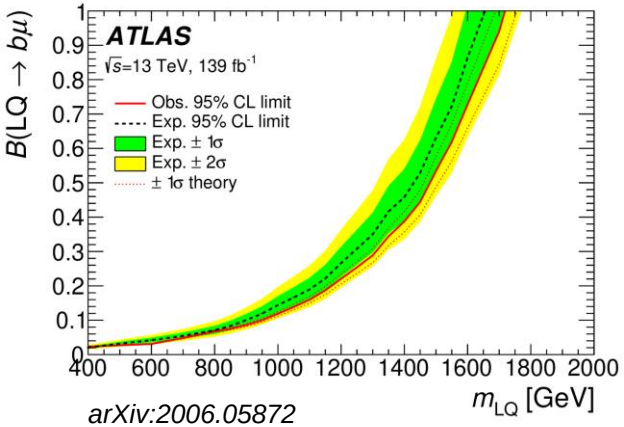
Other

- Broad program of searches for pair-production.
- Mass exclusions:
- LQ_S: ~1.0-1.7 TeV depending on search/benchmark
- LQ_V: ~ LQ_S limit + 0.4 TeV

	u, d, s	c	b	t
νν	X		X	X
νl			X	
ll	X	X	X	X
ντ			X	
ττ			X	X

ATLAS-CONF-2021-008





arXiv:2006.05872

Leptoquarks: current program

Anomaly scorecard

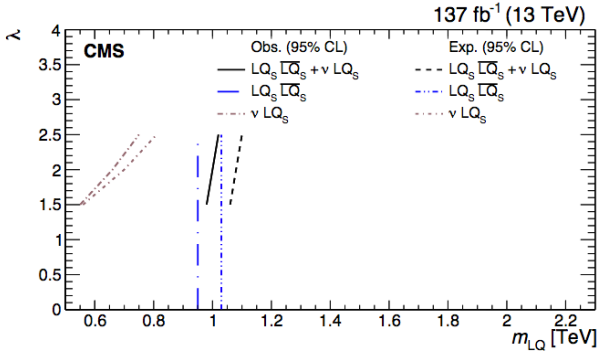
R(K) R(K*)

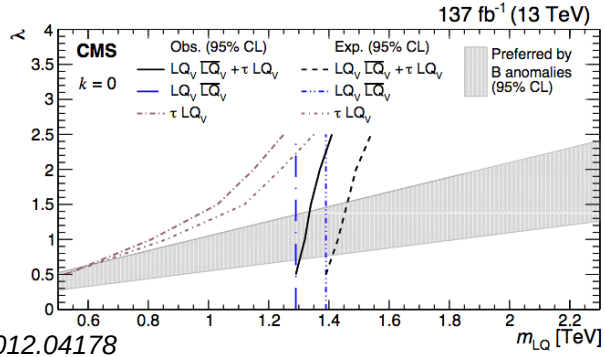
R(D) R(D*)

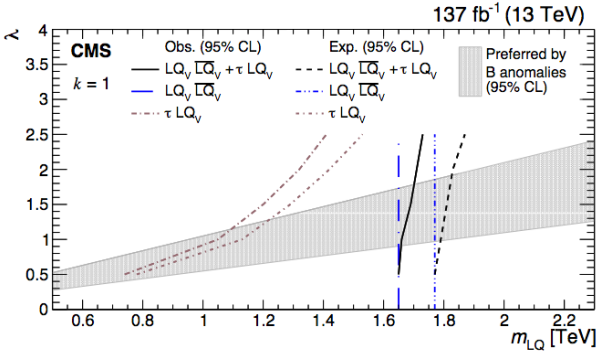
a_μ

Other

- Growing program of single LQ searches:
  l+LQ(→bl) (l=e,μ,τ), τ+LQ(→bν), ν+LQ(→bτ), ν+LQ(→cτ)
- First combinations of pair and single production.







arXiv:2012.04178

Leptoquarks: opportunities

Anomaly scorecard

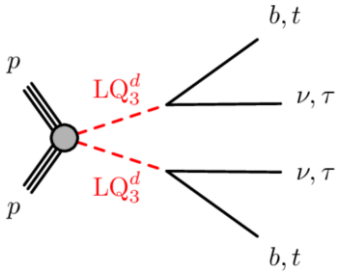
R(K) R(K*)

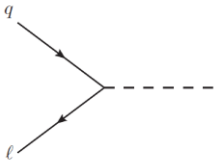
R(D) R(D*)

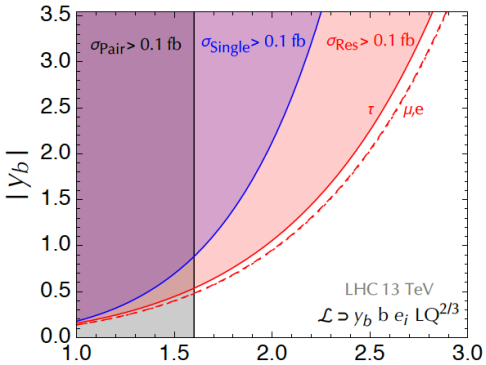
a_μ

Other

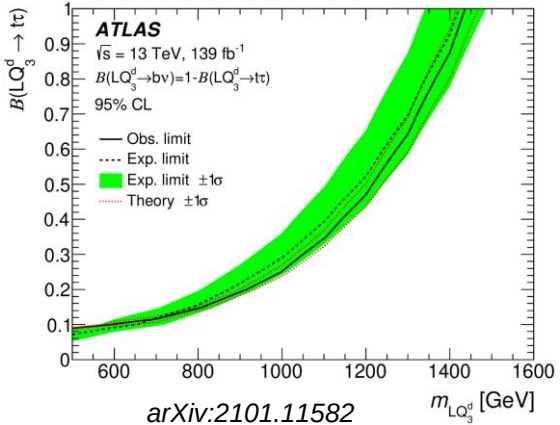
- Pair production:
  - More sophisticated analyses
  - Combinations!
- Single production:
  - Same as for pair production.
  - Explore single resonant production



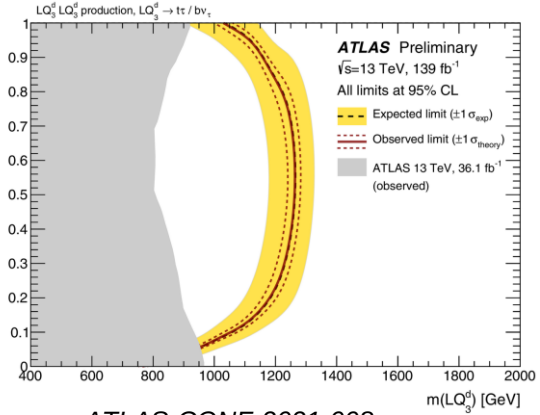




arXiv:2012.02092



arXiv:2101.11582



ATLAS-CONF-2021-008

Heavy resonances

Heavy vector particles: current program

Anomaly scorecard

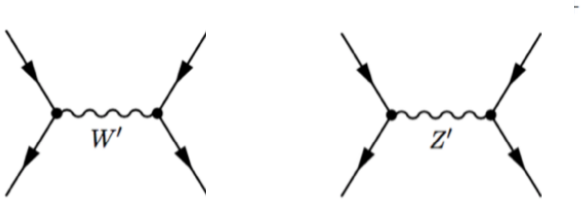
R(K) R(K*)

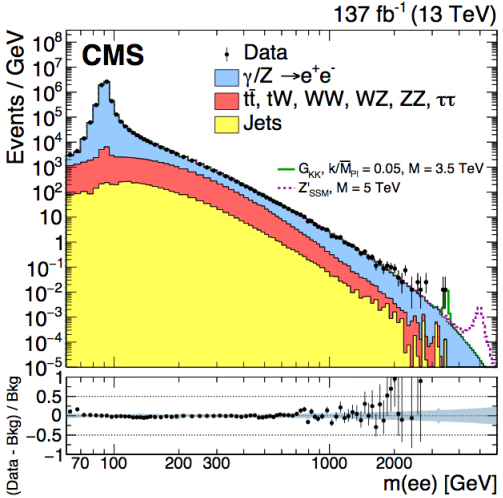
R(D) R(D*)

a_μ

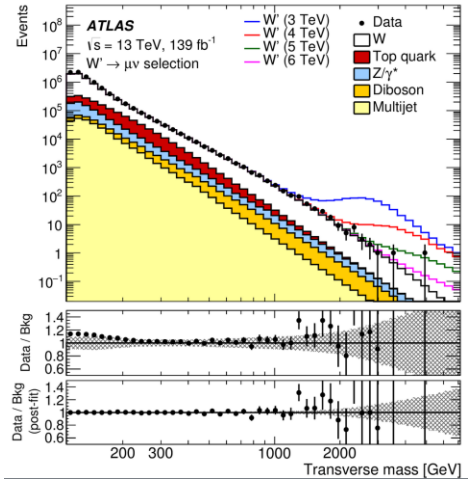
Other

- Broad program of inclusive searches for dilepton, dijet, and tt/tb resonances

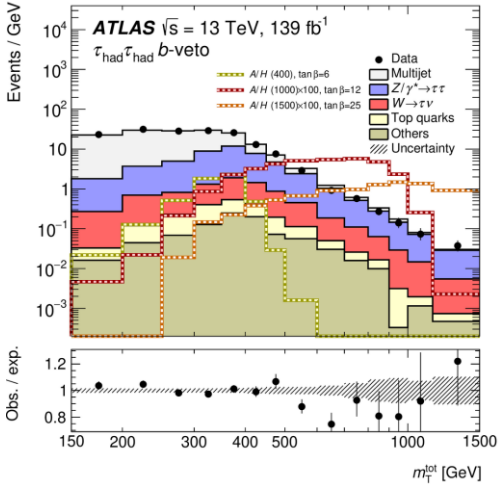




arXiv:2103.02708



arXiv:1906.05609



arXiv:2002.12223

Heavy vector particles: current program

Anomaly scorecard

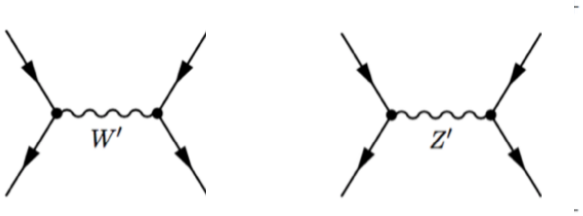
R(K) R(K*)

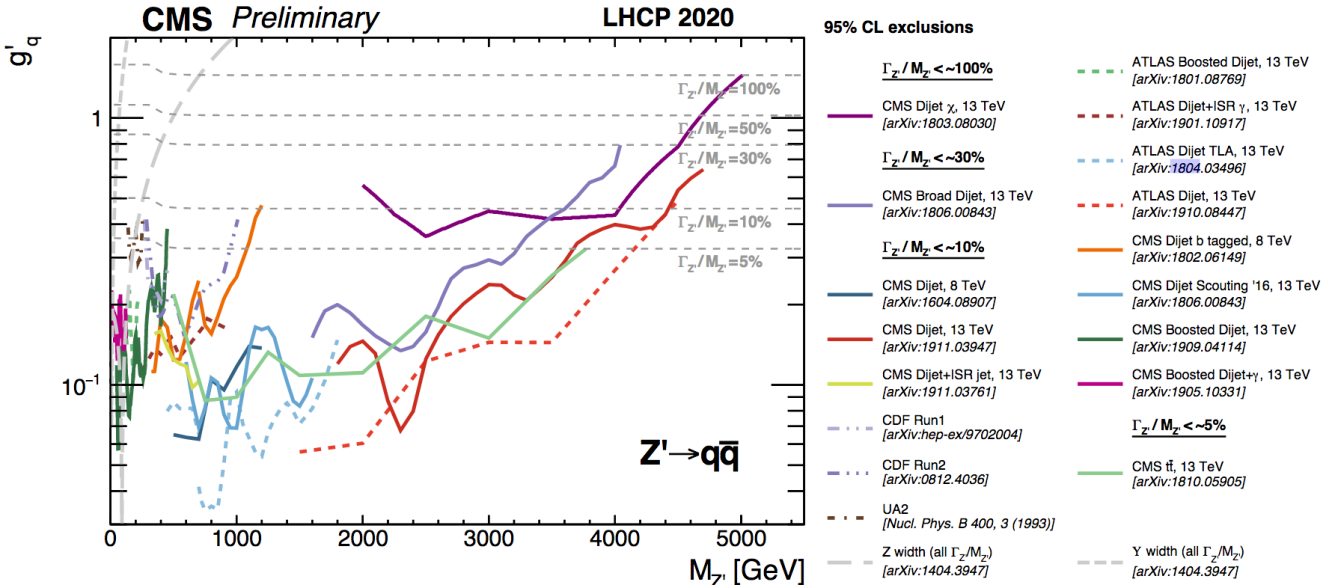
R(D) R(D*)

a_μ

Other

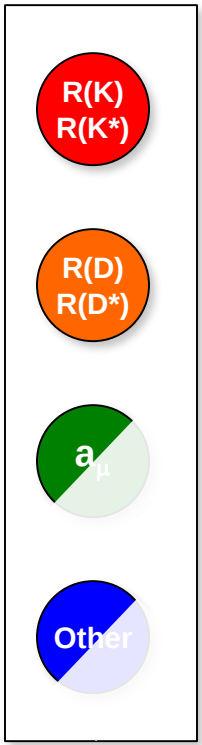
- Broad program of inclusive searches for dilepton, dijet, and tt/tb resonances



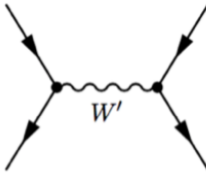


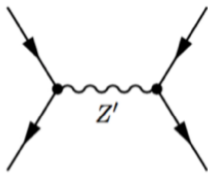
Heavy vector particles: current program

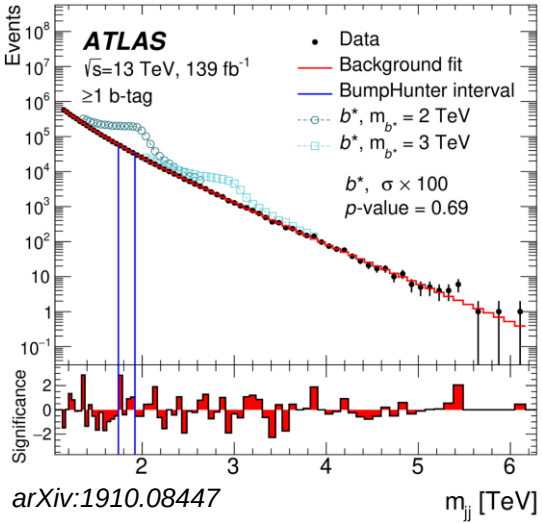
Anomaly scorecard



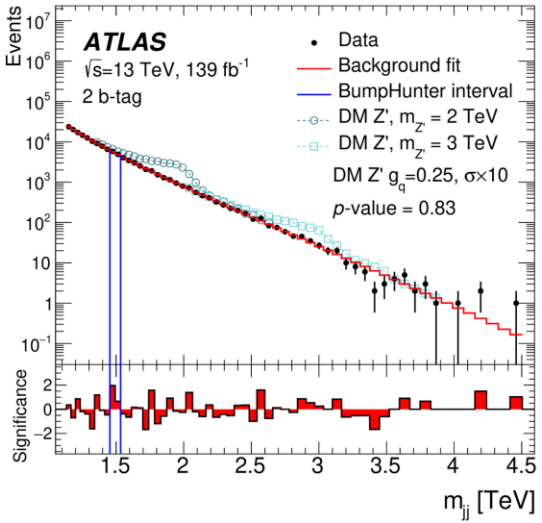
- Broad program of inclusive searches for dilepton, dijet, and tt/tb resonances







arXiv:1910.08447



Heavy vector particles: current program

Anomaly scorecard

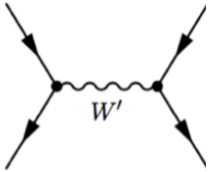
R(K) R(K*)

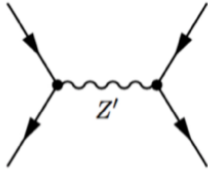
R(D) R(D*)

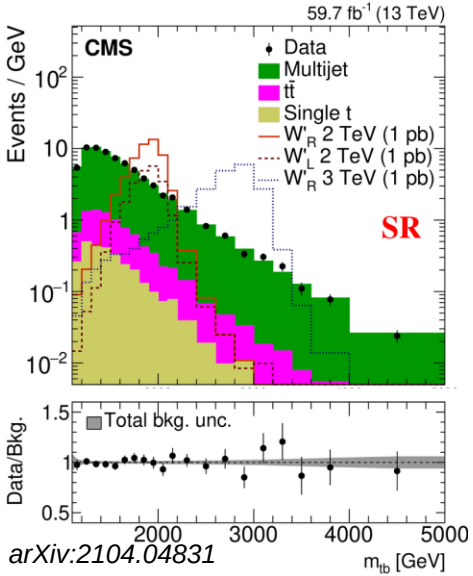
a_μ

Other

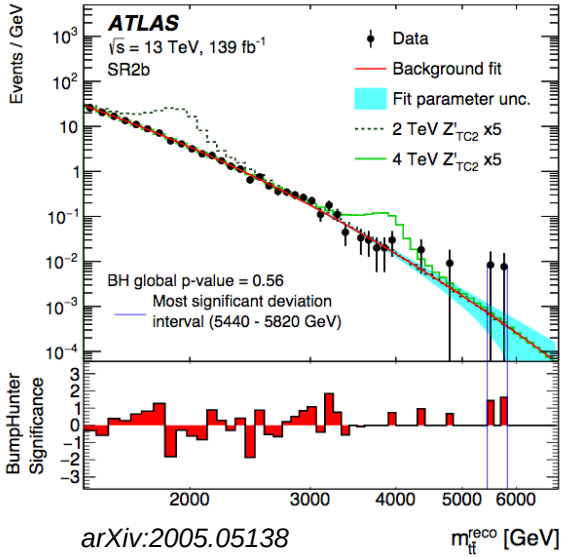
- Broad program of inclusive searches for dilepton, dijet, and tt/tb resonances







arXiv:2104.04831



arXiv:2005.05138

Heavy vector particles: opportunities

Anomaly scorecard

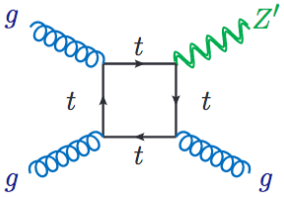
R(K) R(K*)

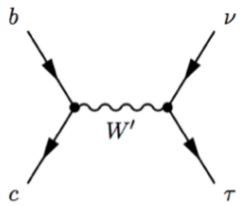
R(D) R(D*)

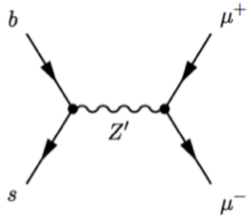
a_μ

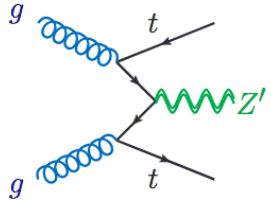
Other

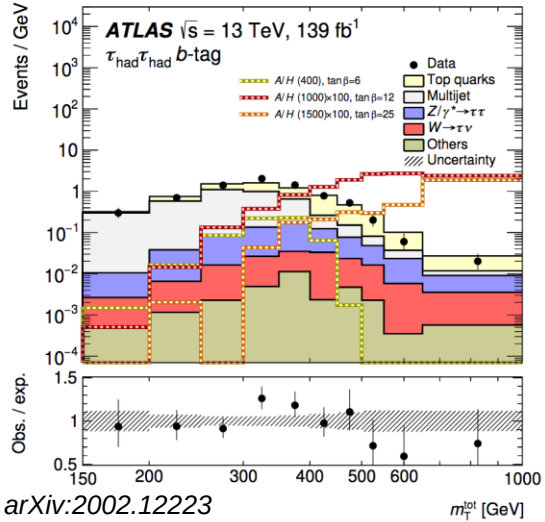
- Extend program to exclusive final states!



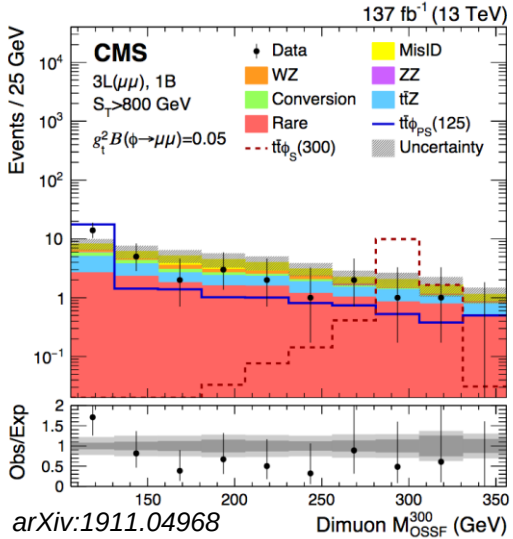








arXiv:2002.12223



arXiv:1911.04968

Heavy vector particles: opportunities

Anomaly scorecard

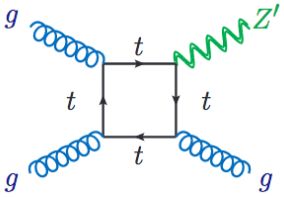
R(K) R(K*)

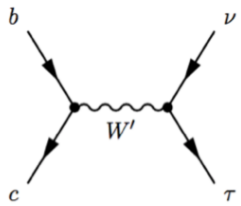
R(D) R(D*)

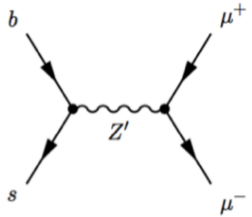
a_μ

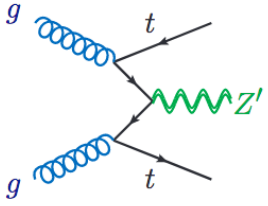
Other

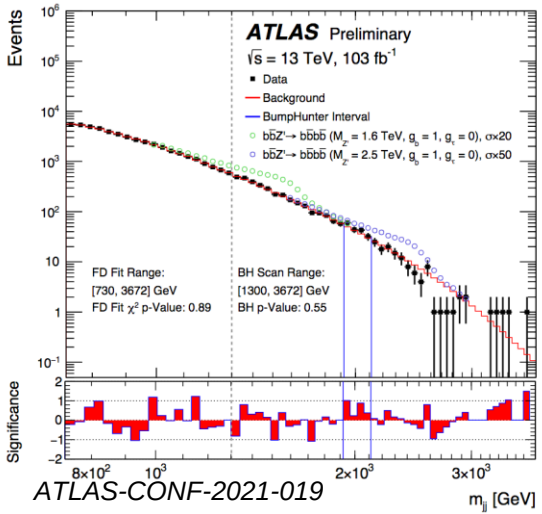
- Extend program to exclusive final states!



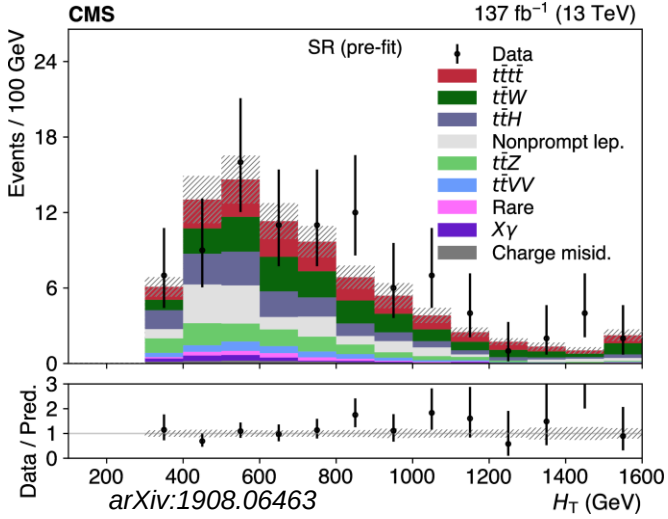








ATLAS-CONF-2021-019



arXiv:1908.06463

Light resonances

Light resonances: current program

Anomaly scorecard

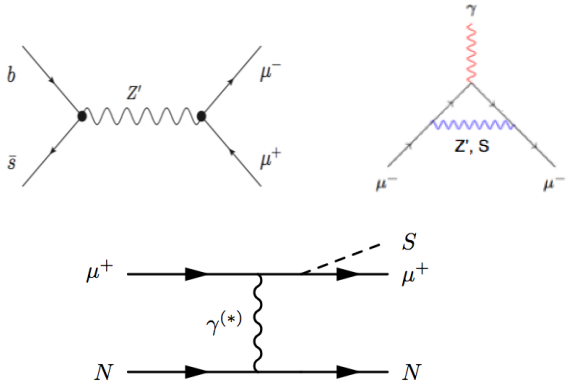
R(K) R(K*)

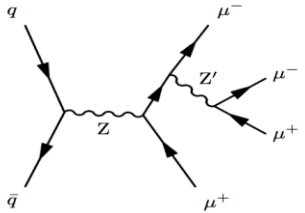
R(D) R(D*)

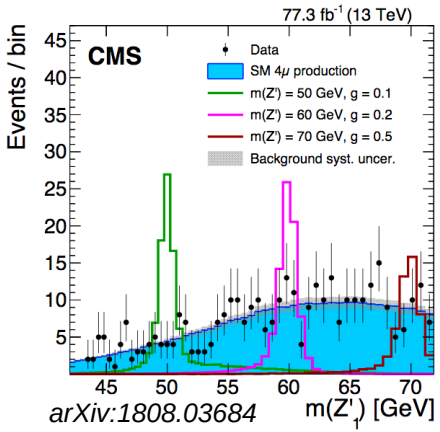
a_μ

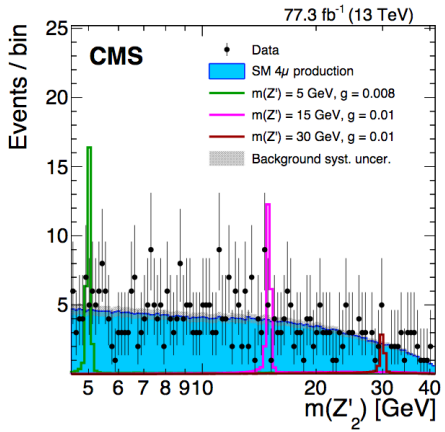
Other

- Leptophilic light vectors and (pseudo-)scalars are challenging at a hadron collider.
- For light Z'/S (<1 GeV) can use fixed target experiments (light particles can be long-lived!).
- For ~5 GeV< $M_{Z'}$< M_Z perform searches in Z→4μ.

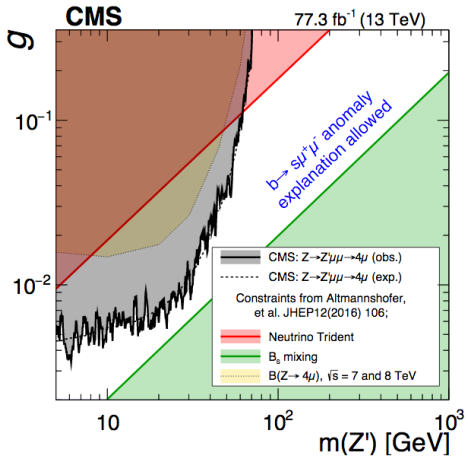








arXiv:1808.03684



Light resonances: opportunities

Anomaly scorecard

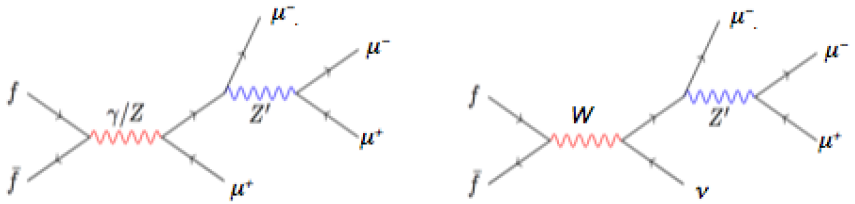
R(K) R(K*)

R(D) R(D*)

a_μ

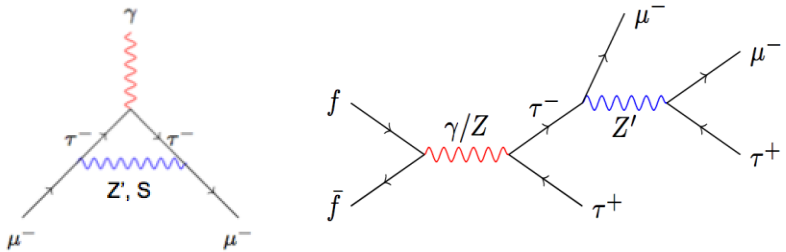
Other

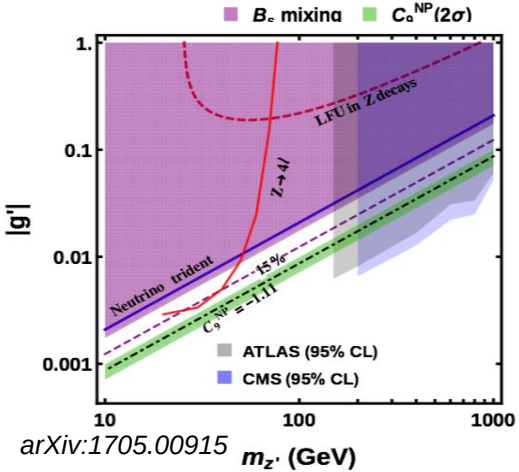
- Searches for $Z^{(*)} \rightarrow 4\mu$ and $W^{(*)} \rightarrow 3\mu + E_T^{miss}$ to go above M_Z.



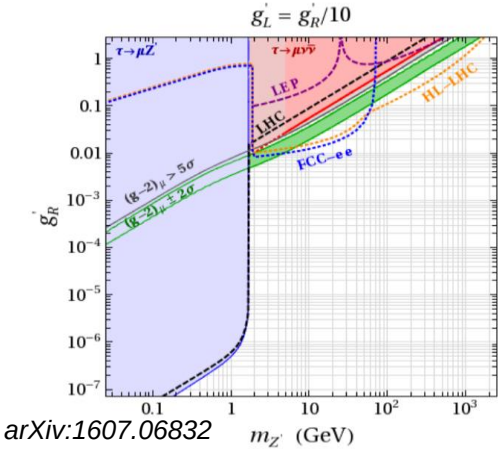
- Another explanation of a_μ involves flavor-violating vectors or scalars.

  ➔ New dedicated multilepton search ($2\mu SS + 2\tau SS$) at higher masses.





arXiv:1705.00915



arXiv:1607.06832

Light resonances: opportunities

Anomaly scorecard

R(K) R(K*)

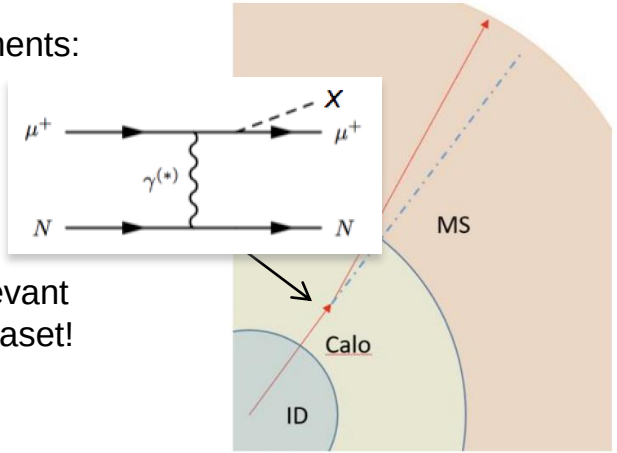
R(D) R(D*)

a_μ

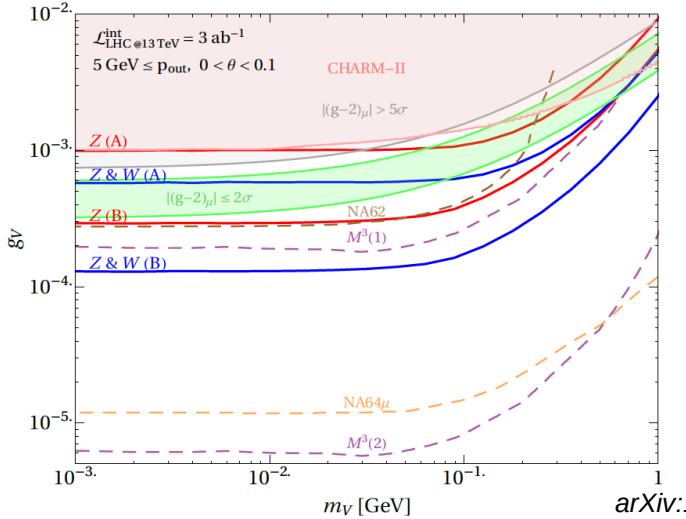
Other

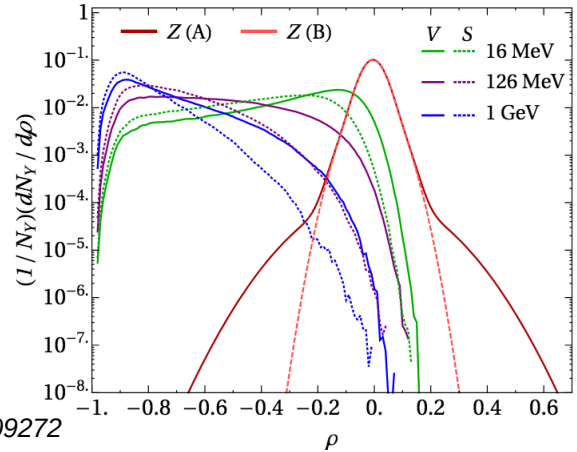
- ATLAS/CMS can be used as muon beam fixed-target experiments:

$$p_{\mathrm{MS}} + E_{\mathrm{cal}} - p_{\mathrm{ID}} < 0 \longrightarrow \rho \equiv \frac{p_{\mathrm{ME}} - p_{\mathrm{ID}}}{p_{\mathrm{ID}}} \approx \frac{p_{\mathrm{out}} - p_{\mathrm{in}}}{p_{\mathrm{in}}}$$



- Expected HL-LHC sensitivity with Z and W events probes relevant region of parameter space. Already interesting with Run 2 dataset!





arXiv:1906.09272

Vector-like leptons

Vector-like leptons

Anomaly scorecard

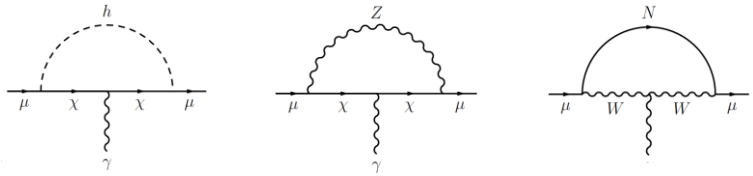
R(K) R(K*)

R(D) R(D*)

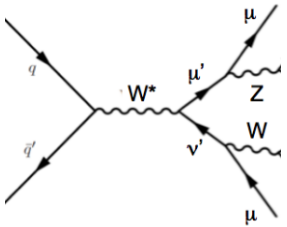
a_μ

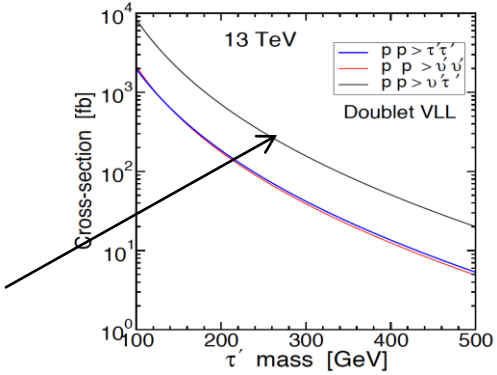
Other

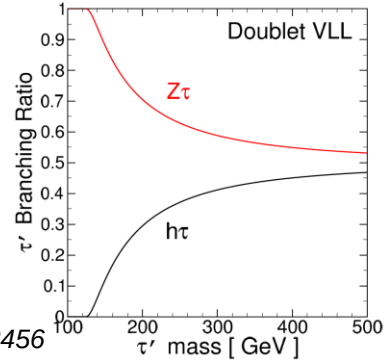
- Mixing between the muonphilic vector-like leptons and the muon gives the main contribution to a_μ.

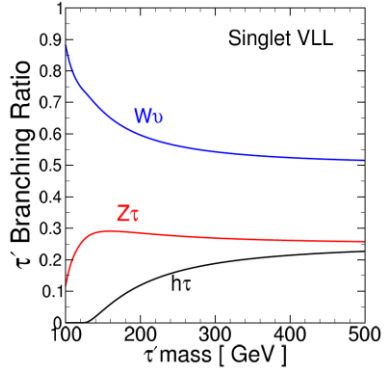


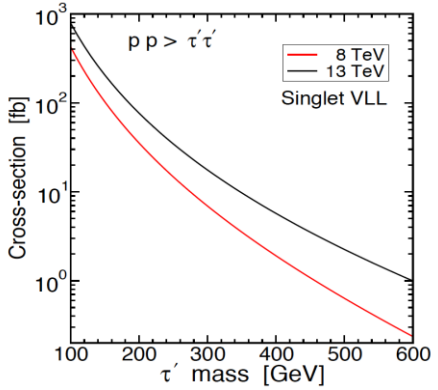
- DY pair production dominant.
- CC (l'→Wν, ν'→Wl) and/or NC decays (l'→Z/Hl), depending on the $SU(2)_L$ representation.











arXiv:1510.03456

arXiv:1510.03456

Vector-like leptons: current program

Anomaly scorecard

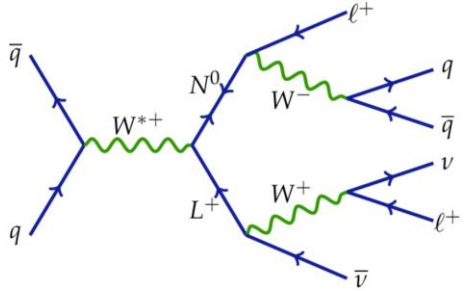
R(K) R(K*)

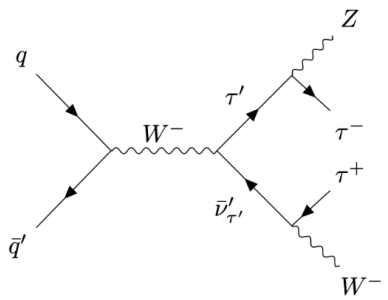
R(D) R(D*)

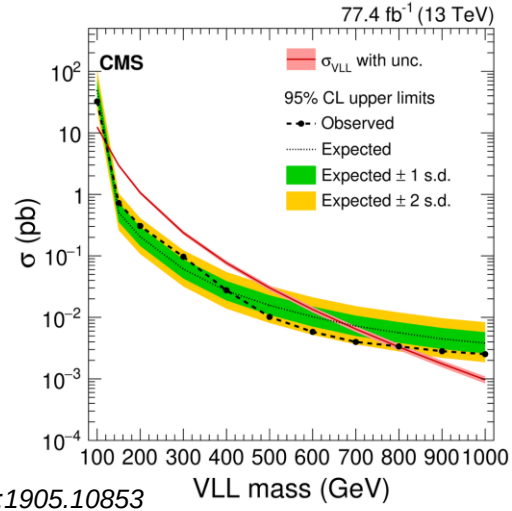
a_μ

Other

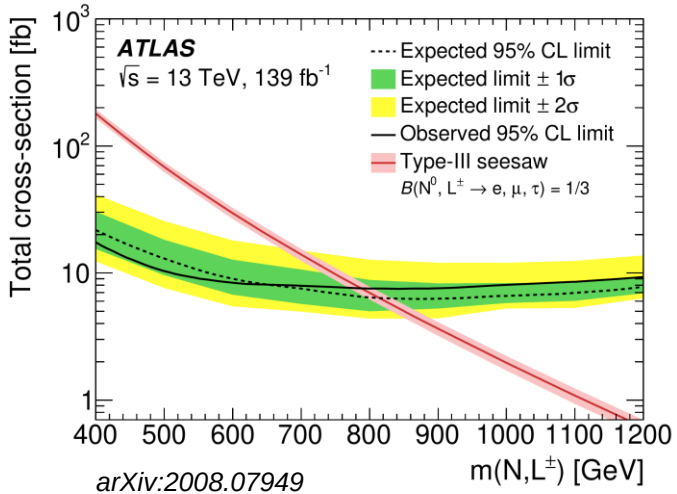
- Most advanced searches target multilepton final states (2l, 3l, 4l), but are not optimized for muonphilic vector-like leptons:
  - Type-III seesaw heavy-lepton multiplet (flavor democratic scenario)
  - Vector-like taus in the doublet scenario







arXiv:1905.10853



arXiv:2008.07949

Vector-like leptons: opportunities

Anomaly scorecard

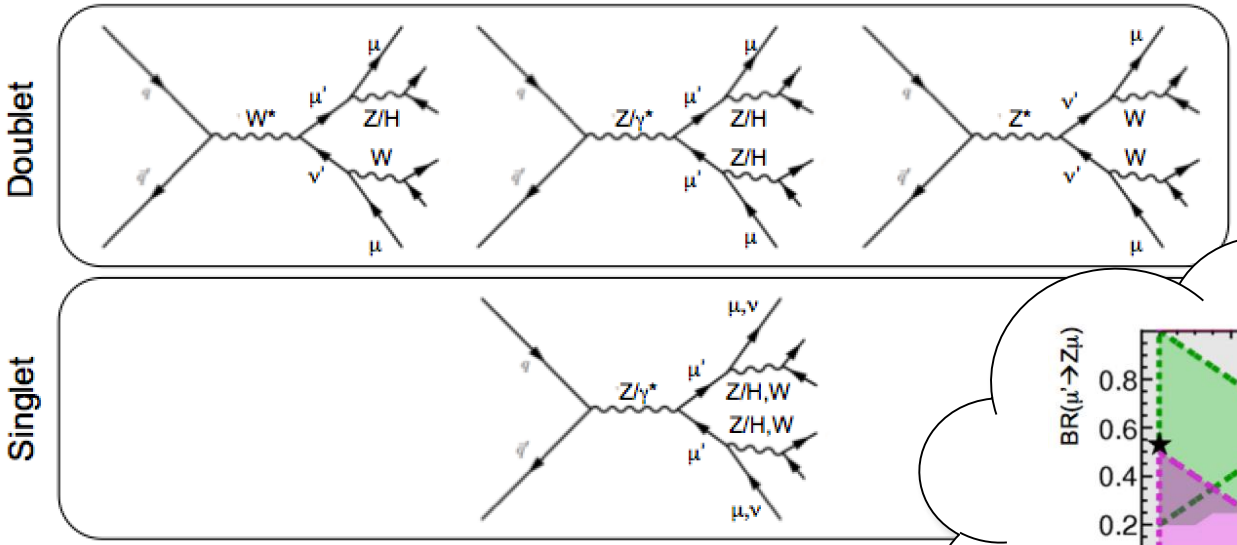
R(K) R(K*)

R(D) R(D*)

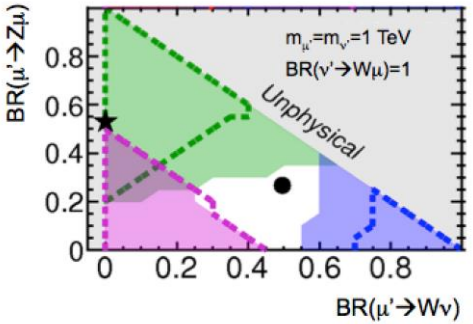
a_μ

Other

- Develop optimized searches for the three different vector-like lepton flavors separately. Given the small production cross section, must optimally exploit broad range of possible signatures (including hadronic W/Z/H decays!):



Program should reach similar level of sophistication as for vector-like quarks!



Beyond simplified models

From simplified to UV-complete models

Anomaly scorecard

R(K) R(K*)

R(D) R(D*)

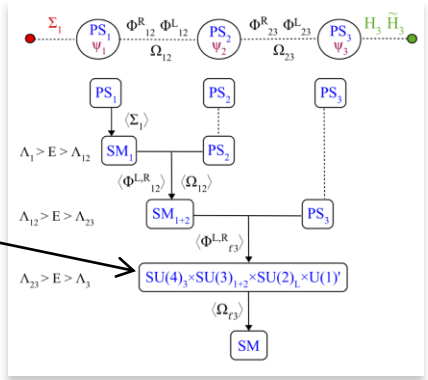
a_μ

Other

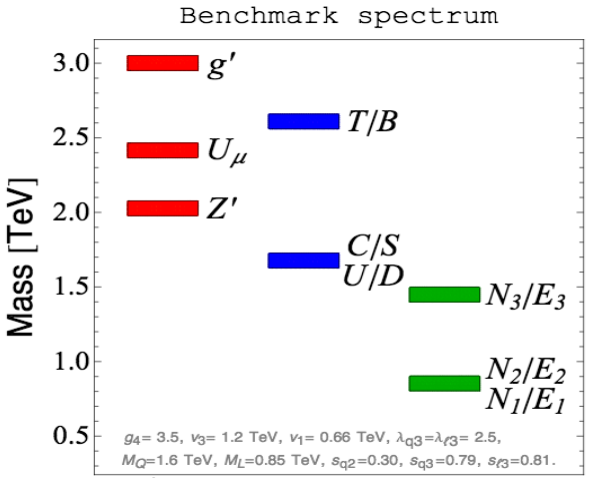
- Most studies carried out in the context of simplified models.
- Nature could potentially be more exciting! Are we ready for it?

- Example: “4321” renormalizable (i.e. “UV complete”) model.
  - Can accommodate B-physics anomalies (via a vector LQ).
  - Consistent with all available constraints.

PS^3 model



arXiv:1712.01368



arXiv:1808.00942

Three heavy gauge bosons:

- Color octet (g’)
- Vector LQ (U_μ)
- Color singlet (Z’)

Three families of vector-like fermions:

- VLQ doublets: U/D, C/S, T/B
- VLL doublets: N_1/E_1, N_2/E_2, N_3/E_3

But very different signatures than typically assumed!

From simplified to UV-complete models

Anomaly scorecard

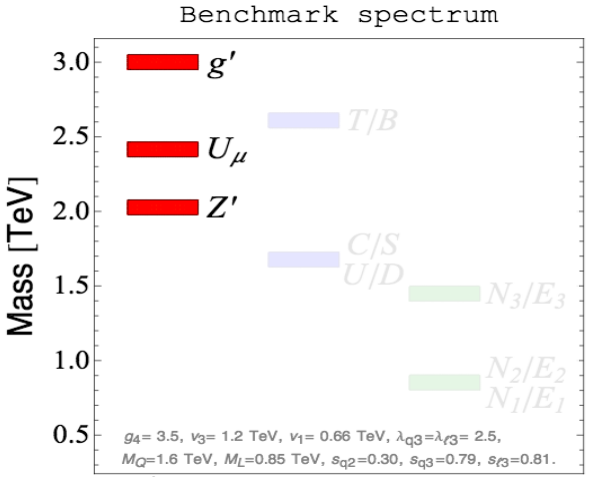
R(K) R(K*)

R(D) R(D*)

a_μ

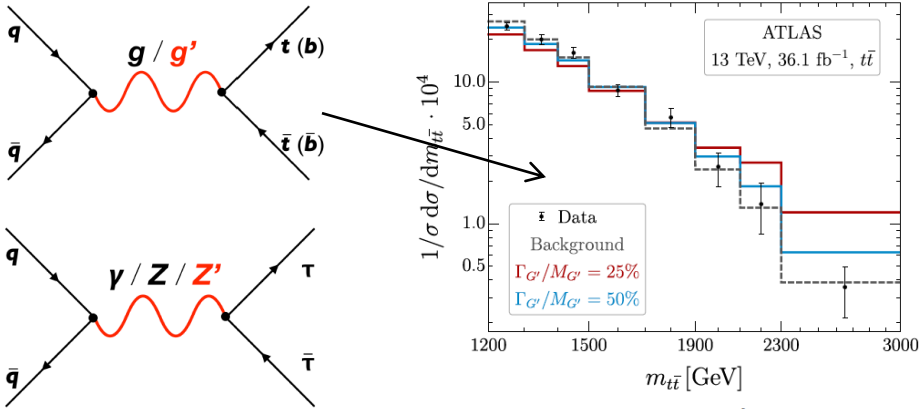
Other

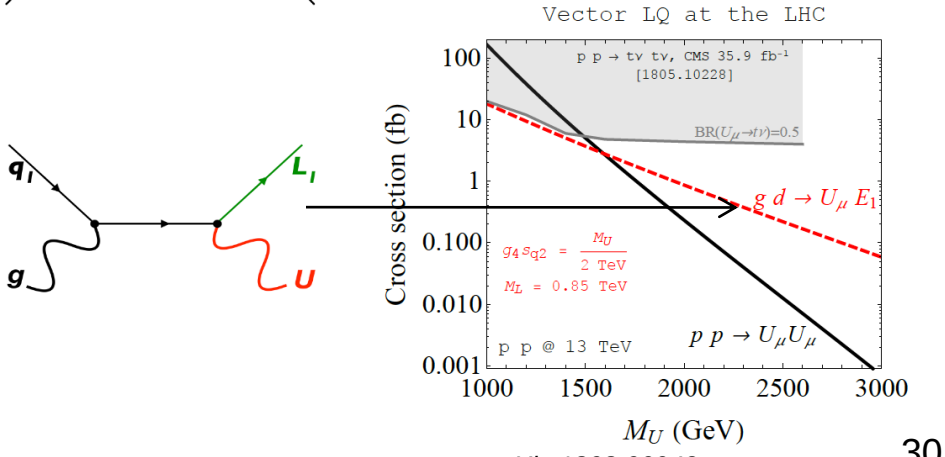
- The g'/Z' and U typically decay into 3rd generation fermions, but also into vector-like fermions.
- Problem: all vector bosons have sizable width!
- At high mass the U is dominantly produced in association with a VLL.



arXiv:1808.00942

arXiv:1901.10480





arXiv:1808.00942

From simplified to UV-complete models

Anomaly scorecard

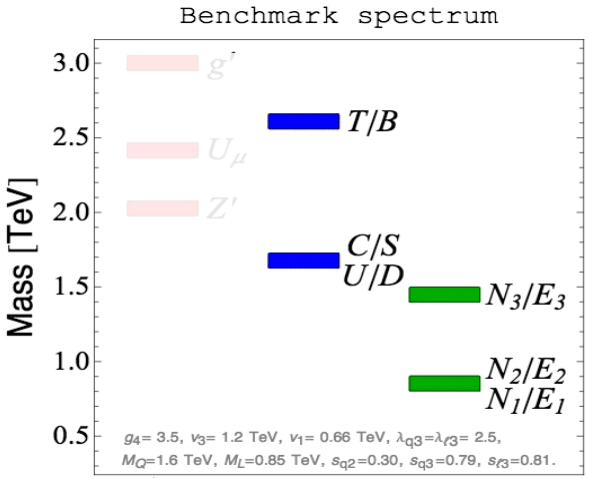
R(K) R(K*)

R(D) R(D*)

a_μ

Other

- Only the 3rd generation VLQs and VLLs decay as usually assumed (e.g. T→Wb, Zt, Ht).
- The 1st and 2nd generation VLQs and VLLs mainly decay into 3-body final state via off-shell g', U_μ, and/or Z'.



arXiv:1808.00942

From simplified to UV-complete models

Anomaly scorecard

R(K) R(K*)

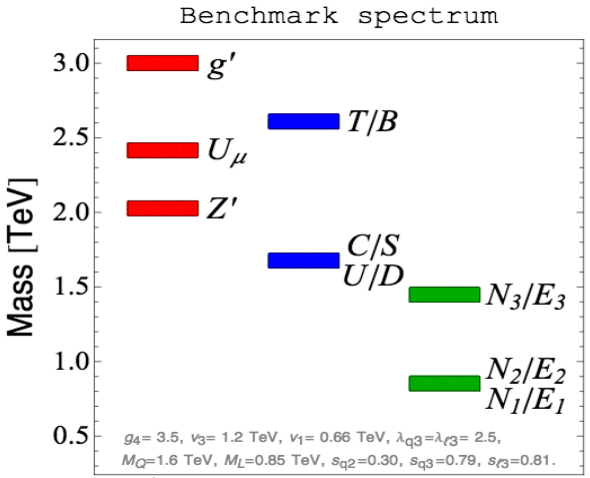
R(D) R(D*)

a_μ

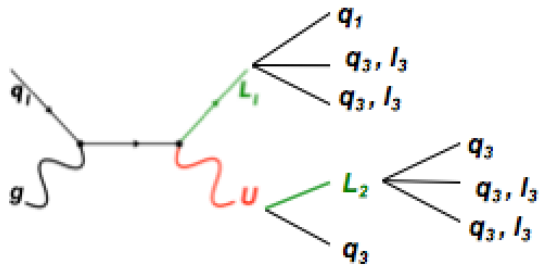
Other

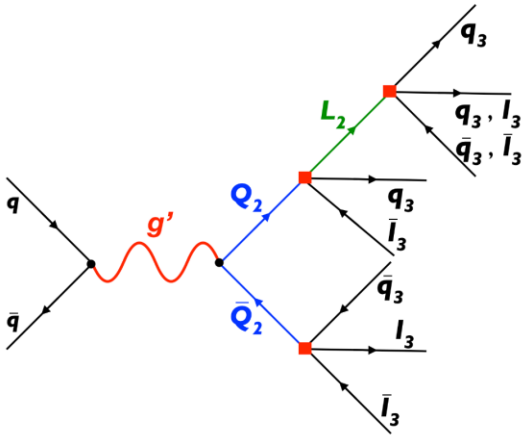
- Only the 3rd generation VLQs and VLLs decay as usually assumed (e.g. T→Wb, Zt, Ht).
- The 1st and 2nd generation VLQs and VLLs mainly decay into 3-body final state via off-shell g', U_μ, and/or Z'.

➔Complex cascades giving heavy-flavored multilepton+multijet final states!



arXiv:1808.00942





No dedicated searches yet!

$q_3 = t, b$
$l_3 = \nu_\tau, \tau$