Lepton Flavour Violation Searches @ ATLAS & CMS

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03/04/2024 39th Rencontres de Moriond QCD

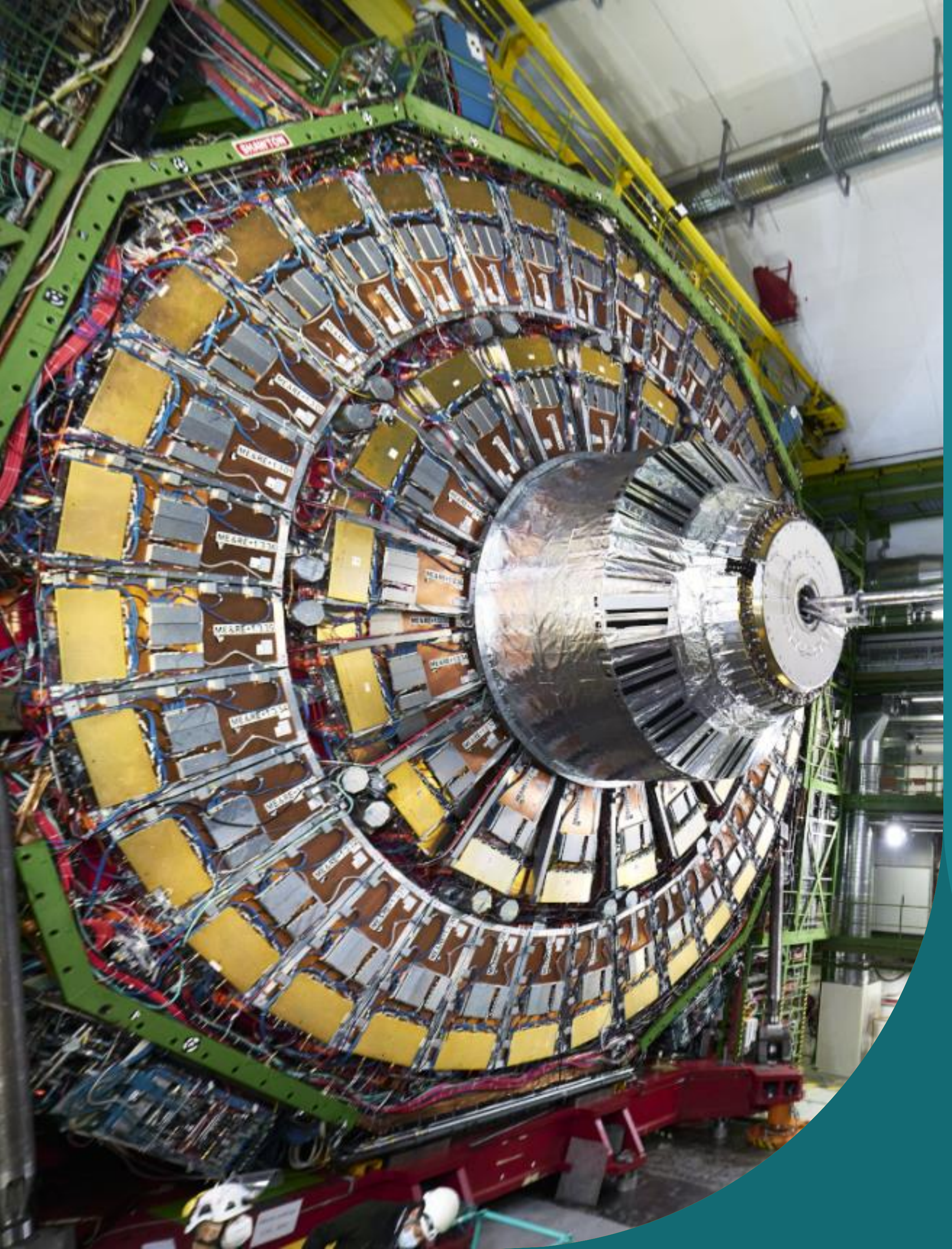
Lepton Flavour Violation

Lepton flavour 'accidentally' conserved in SM with massless νs, but not protected by a symmetry

- ν oscillations = evidence of Neutral Lepton Flavour Violation (nLFV)
- Charged-LFV (cLFV) in SM heavily suppressed by GIM
- Observation of cLFV, or enhanced nLFV would be a sign of BSM!

Lepton flavour universality also not a protected SM symmetry

- Many BSM models that predict LFV also predict LFUV



Contents

Leptoquark (LQ) Searches

- Scalar/Vector $LQLQ \rightarrow b\mu b\mu$ @ CMS
- LQ 3rd Gen Combo @ ATLAS

Heavy Neutral Lepton (N) Searches

- T-channel N, to $ee/e\mu$ @ ATLAS

B Physics

- LFUV in B_c^+ test @ CMS
- $R(K)$ Measurement @ CMS
- LFV $\tau \rightarrow 3\mu$ @ CMS

All Run-2 results @ 13 TeV pp

All NEW! since Last Moriond!

Other Results to check out

ATLAS LFUV in Ws (see backup!)
arXiv:2403.02133

ATLAS t cLFV $\mu\tau$ (see backup!)
arXiv:2403.06742

CMS t cLFV $3l$ (see backup!)
arXiv: 2312.03199

CMS LLP N, to ll'j (see backup!)
arXiv:2312.07484

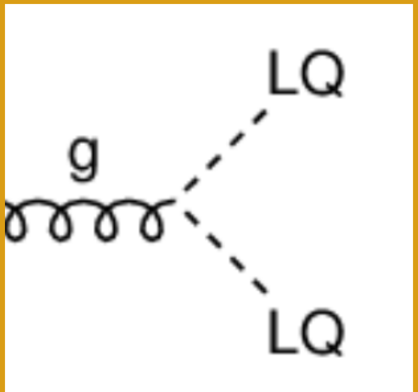
CMS LQ via $\tau - q$ scattering:
arxXv:2308.06143

CMS High Mass Z', to $\mu\mu + bjets$:
arXiv:2307.08708

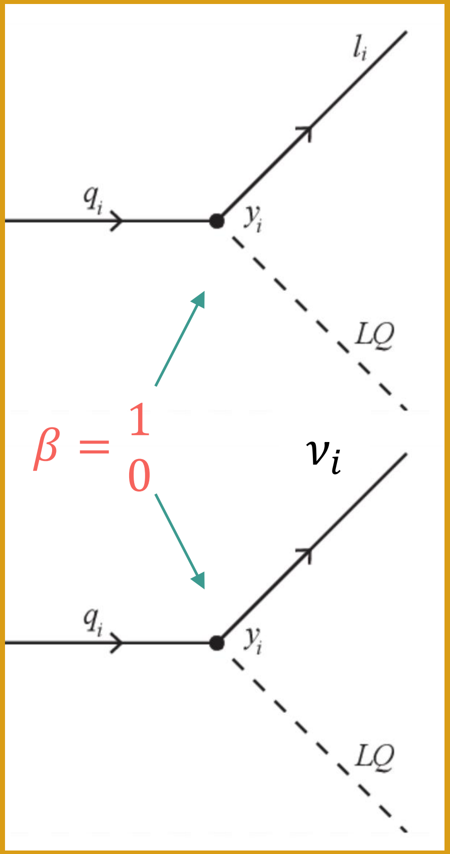
ATLAS LFV High Mass Z':
arXiv:2307.08567

ATLAS $LQLQ \rightarrow tlbv$:
arXiv.2306.17642

Leptoquarks



Yang-Mills scenario adds gluon coupling.
(Else minimal-coupling)

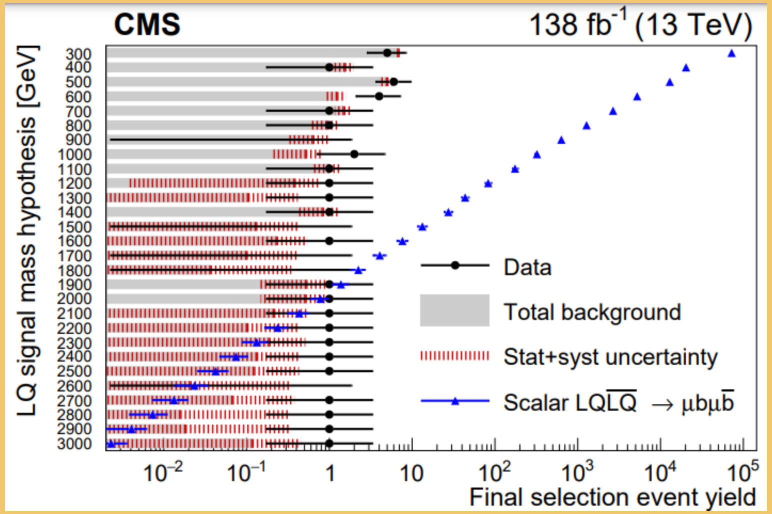


Suppose deeper quark-lepton connection e.g. in GUTs.

Manifests via a LQ that couples to lepton+quark can enhance LFUV processes

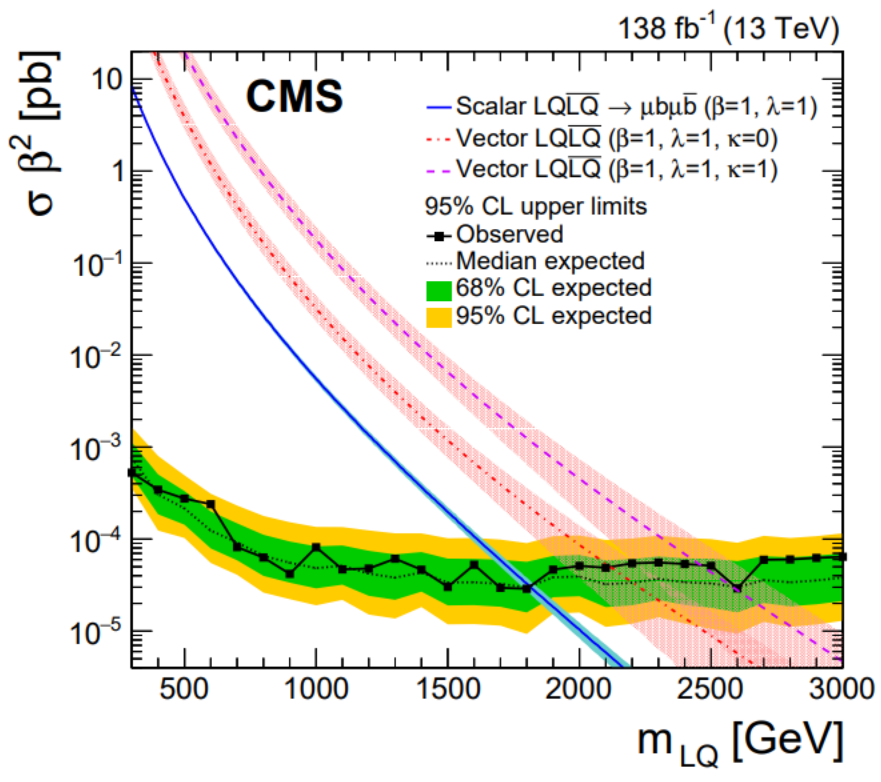
Scalar/Vector $LQLQ \rightarrow b\mu b\mu$ @ CMS

02/24 arXiv:2402.08668 $138 fb^{-1}$



- Full Run-2 search.
- Main drell-yan, $t\bar{t}$ bgs estimated from MC normalised in dedicated regions "Control Region estimate".
- SRs defined for each $m(LQ)$ hypothesis via cut on a dedicated BDT score.
- No significant excess seen, most stringent limits to date!

$m(LQ)$ upper bounds [TeV] @95%CL	Scalar LQ		Vector LQ ($\beta = 1$)	
	$\beta = 1$	$\beta = 0.5$	Minimal Coupling	Yang-Mills
ATLAS [arXiv.org:2210.04517]	1.5	1.3	1.5	1.8
CMS (this)	1.81	1.54	2.12	2.46



LQ 3rd Gen. Pair-prod. Combination @ ATLAS

01/24 arXiv:2401.11928 up to $140 fb^{-1}$

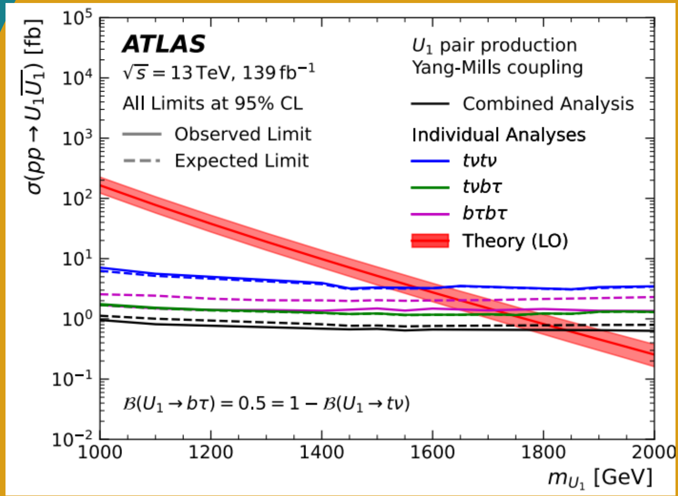
Statistical combination of 9 ATLAS searches (6 LQ searches and 3 SUSY searches) (refs in backup)

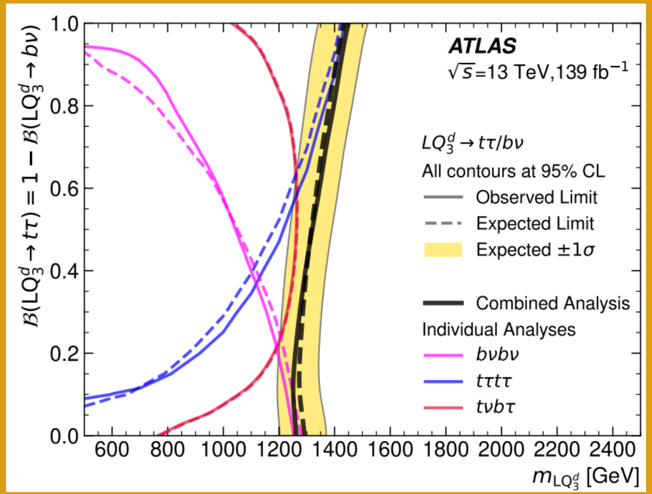
Interpretations;

- Scalar/Vector LQs decaying to 3rd gen $q + l$ ($LQ_3^{u/d}$) or 3rd gen q + 1st /2nd gen l ($LQ_{mix}^{u/d}$).
- Limits on $m(LQ)$ and (B) branching fraction to $l^{\pm}$.

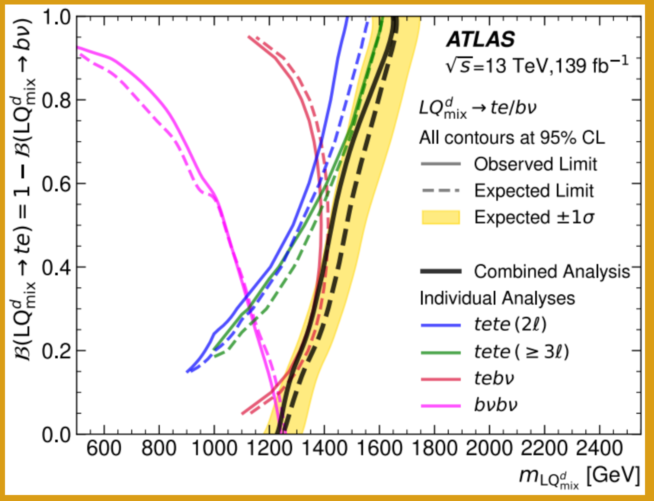
Most stringent results to date for majority of the models.

Search		Interpretation						Signal Region		
		Scalar				Vector				
Final State	Citation	LQ_3^u	LQ_3^d	LQ_{mix}^u	LQ_{mix}^d	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau_{had}}$	N_{bjets}
$t\nu b\tau$	[54]	✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$	[55]	✓	–	–	–	✓	–	$\{0, 1\}$	$\{1, 2\}$	$\{1, 2\}$
$t\tau t\tau$	[57]	–	✓	–	–	–	✓	$\{1, 2, 3\}$	≥ 1	≥ 1
$t\nu b\ell$	[40]	–	–	✓	✓	–	–	1	–	≥ 1
$b\ell b\ell$	[58]	–	–	✓	–	–	–	2	–	$\{0, 1, 2\}$
$t\ell t\ell$ (2ℓ))	[59]	–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)	[61]	–	–	–	✓	–	–	$\{3, 4\}$	–	≥ 2
$t\nu t\nu$	[62]	✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$	[64]	–	✓	–	✓	–	–	0	–	≥ 2

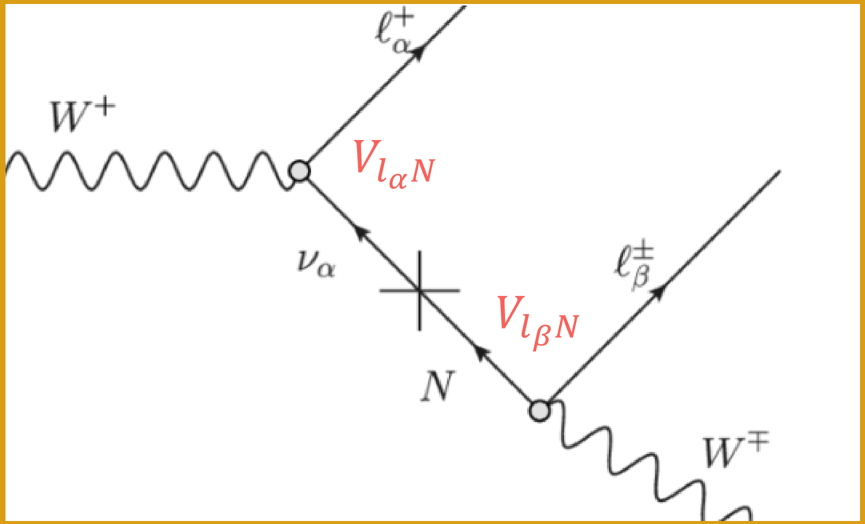




	$\mathcal{B} = 0.0$		$\mathcal{B} = 0.5$		$\mathcal{B} = 1.0$	
	95% CL Limit [GeV]		95% CL Limit [GeV]		95% CL Limit [GeV]	
	Observed	Expected	Observed	Expected	Observed	Expected
$LQ_3^u \to t\nu/b\tau$	1240	1240^{+70}_{-90}	1340	1300^{+70}_{-80}	1480	1440^{+70}_{-80}
$LQ_3^d \to t\tau/b\nu$	1260	1260^{+80}_{-80}	1360	1340^{+60}_{-70}	1520	1470^{+70}_{-70}
$LQ_{mix}^u \to t\nu/b\mu$	1230	1310^{+70}_{-70}	1570	1510^{+70}_{-70}	1710	1650^{+90}_{-90}
$LQ_{mix}^u \to t\nu/be$	1230	1310^{+70}_{-70}	1510	1550^{+80}_{-80}	1730	1740^{+90}_{-100}
$LQ_{mix}^d \to t\mu/b\nu$	1240	1260^{+70}_{-80}	1430	1470^{+70}_{-70}	1600	1650^{+80}_{-80}
$LQ_{mix}^d \to te/b\nu$	1230	1250^{+70}_{-70}	1450	1500^{+70}_{-70}	1650	1660^{+90}_{-90}
$U_1^{YM} \to t\nu/b\tau$	-	-	1840	1810^{+80}_{-90}	-	-
$U_1^{MC} \to t\nu/b\tau$	-	-	1580	1560^{+70}_{-70}	-	-
$U_1^{YM} \to t\nu/b\mu$	-	-	1980	1930^{+50}_{-60}	-	-
$U_1^{MC} \to t\nu/b\mu$	-	-	1710	1660^{+50}_{-50}	-	-
$U_1^{YM} \to t\nu/be$	-	-	1900	1930^{+50}_{-70}	-	-
$U_1^{MC} \to t\nu/be$	-	-	1620	1650^{+50}_{-60}	-	-
$\tilde{U}_1^{YM} \to t\tau$	-	-	-	-	1810	1810^{+80}_{-70}
$\tilde{U}_1^{MC} \to t\tau$	-	-	-	-	1540	1530^{+90}_{-60}



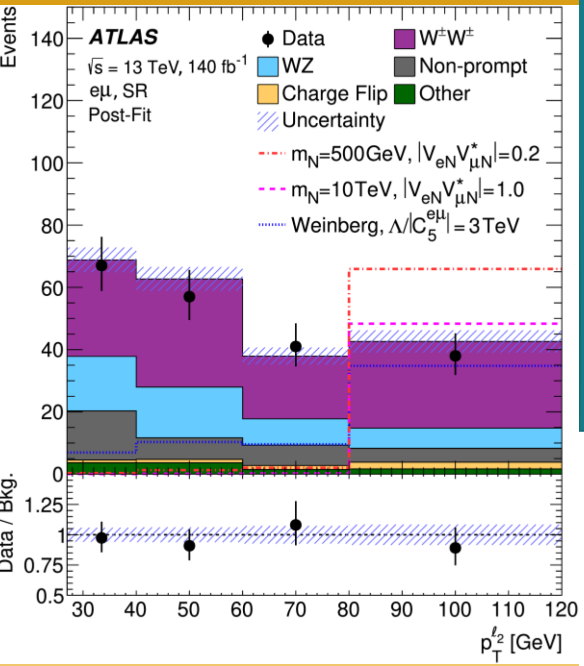
Heavy Neutral Leptons

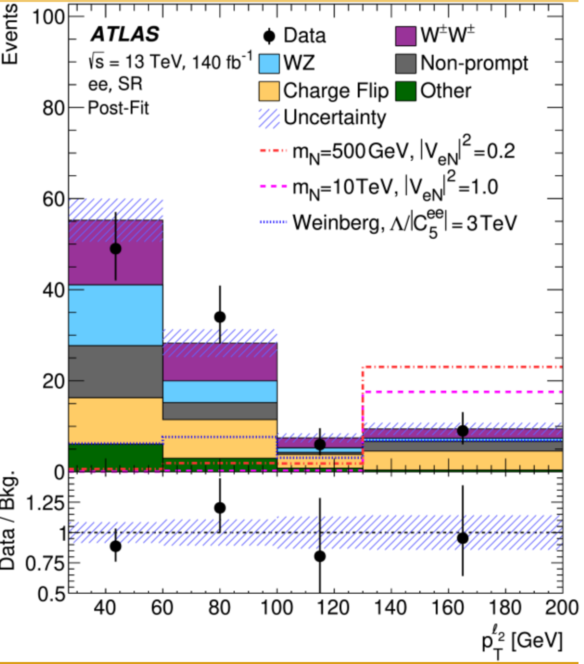


How to explain observed tiny ν masses?
See-Saw mechanism:

- Get light SM νs and heavy BSM νs (Ns)

No reason to assume N decays conserve lepton flavour!

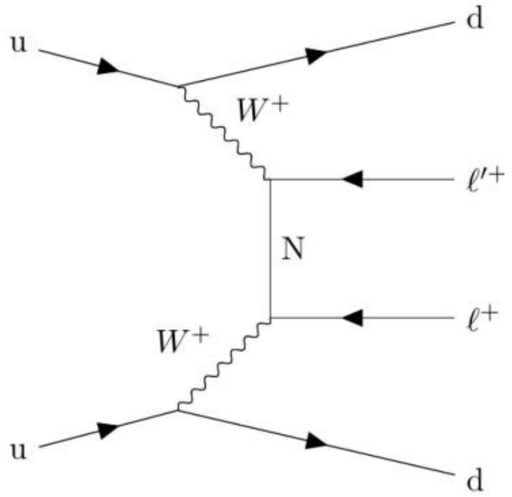




T-channel N, to $ee/e\mu$ @ ATLAS /1 $140fb^{-1}$ arXiv:2403.15016

NEW!

- FIRST Search for Majorana Ns in $0\nu\beta\beta$-like W scattering process: $l^{\pm}l^{\pm}jj$ in ee and **(LFV!)** $\boldsymbol{e\mu}$ channels, complement existing & similar $\mu\mu$ channel [arXiv:2305.14931].
- Cut-based event selection, binned fit in 2nd highest lepton p_T.
- Dominant VBF $W^{\pm}W^{\pm}/WZ$ bgs Control regions.
- Data-driven fake lepton and electron charge mis-ID (Charge Flip) bgs.

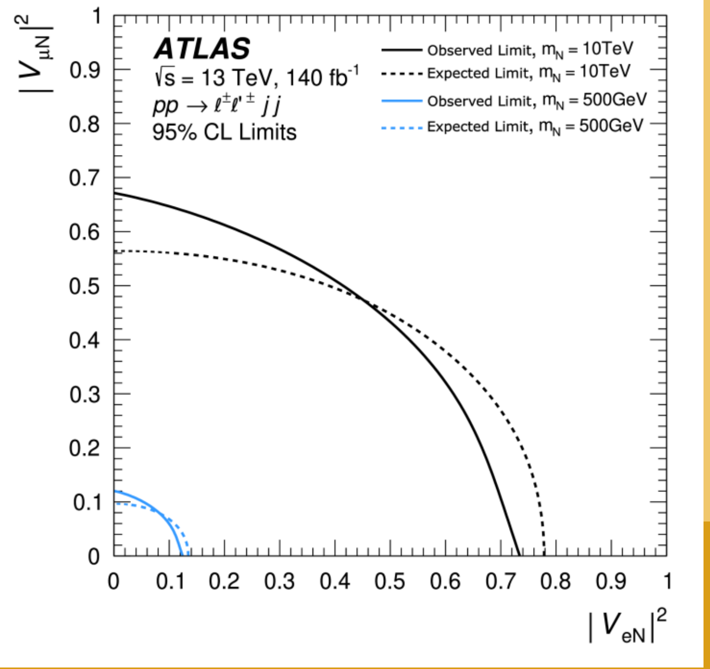


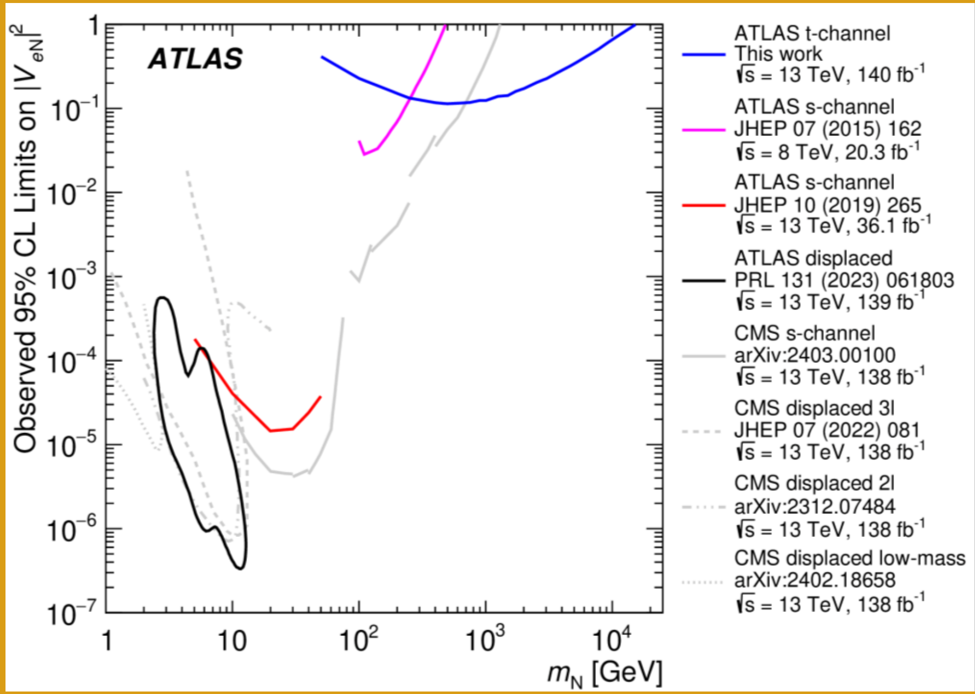
T-channel N, to $ee/e\mu$ @ ATLAS /2

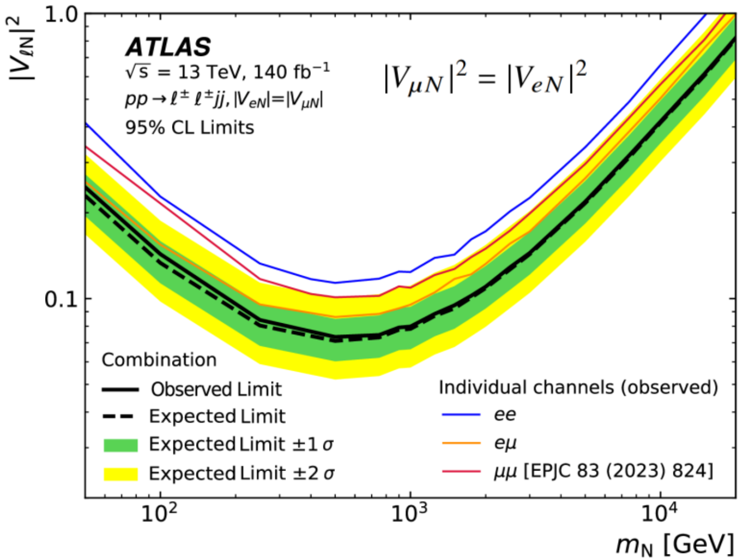
$140 fb^{-1}$ arXiv:2403.15016

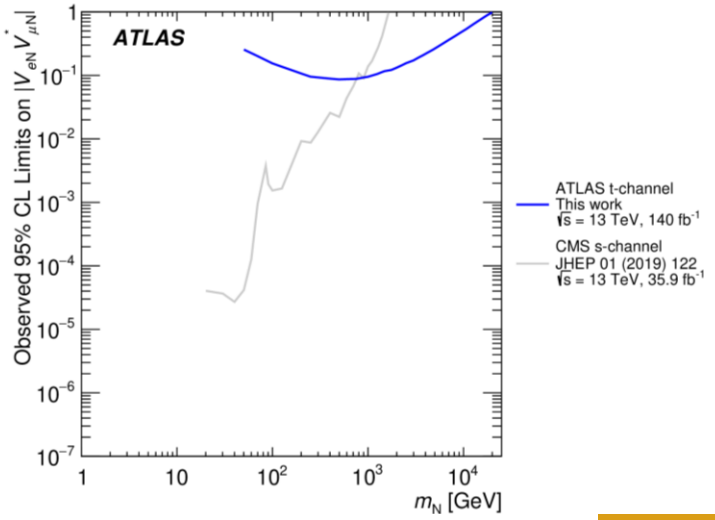
NEW!

- No significant excess, limits set on N couplings and masses. Best sensitivity in the $e\mu$ channel.
- Also, statistical combination of 3 channels performed to constrain e and μ couplings simultaneously!



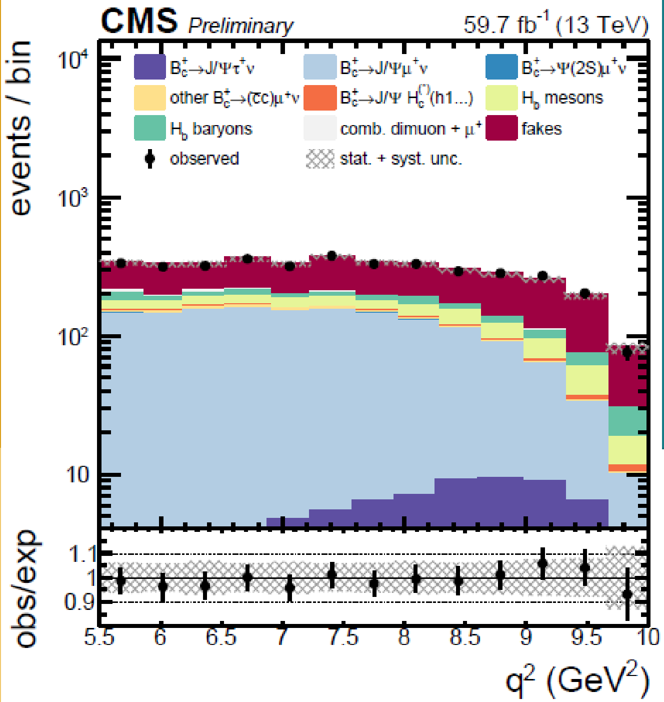


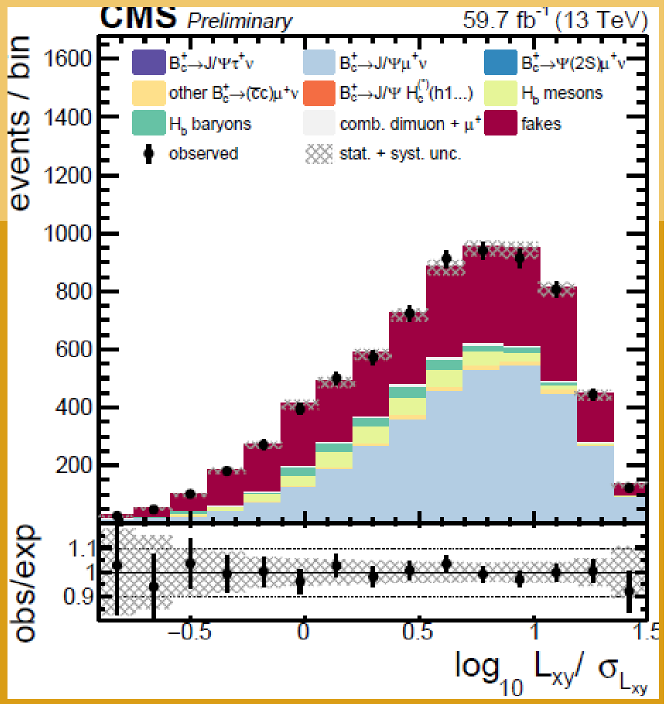




B-physics

Testing LFV & **LFUV**, to compliment other experiments





LFUV in B_c^+ @ CMS

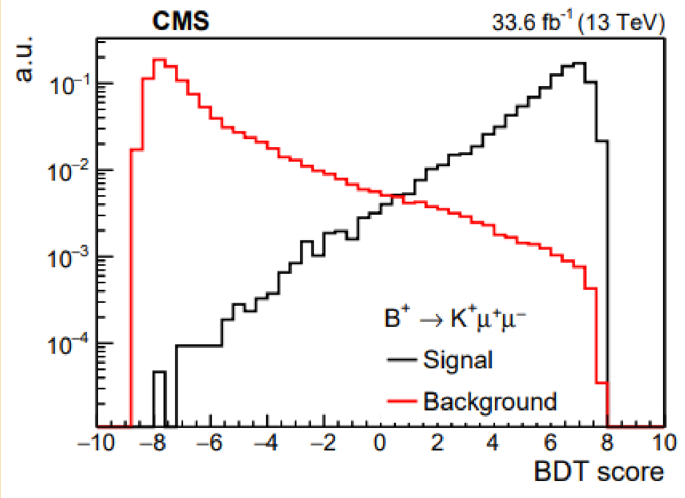
2018 data $57fb^{-1}$ **CMS PAS BPH-22-012**

- $$R(J/\psi) = \frac{Br(B_c^+ \to (J/\psi \to \mu^+\mu^-)\tau^+\nu_\tau)}{Br(B_c^+ \to (J/\psi \to \mu^+\mu^-)\mu^+\nu_\mu)}$$
- Follows LHCb measurement with 2σ above SM.
- 3μ final state ($\tau \to \mu$ decay) use kinematics to distinguish each decay chain.
- Main bg from π/K faking μ: data-driven template, float in fit
  - Reduce using NN is- μ -isolated classifier.
- Fit q^2 and impact parameter together.
- 0.3 sigma from SM prediction (0.2582)

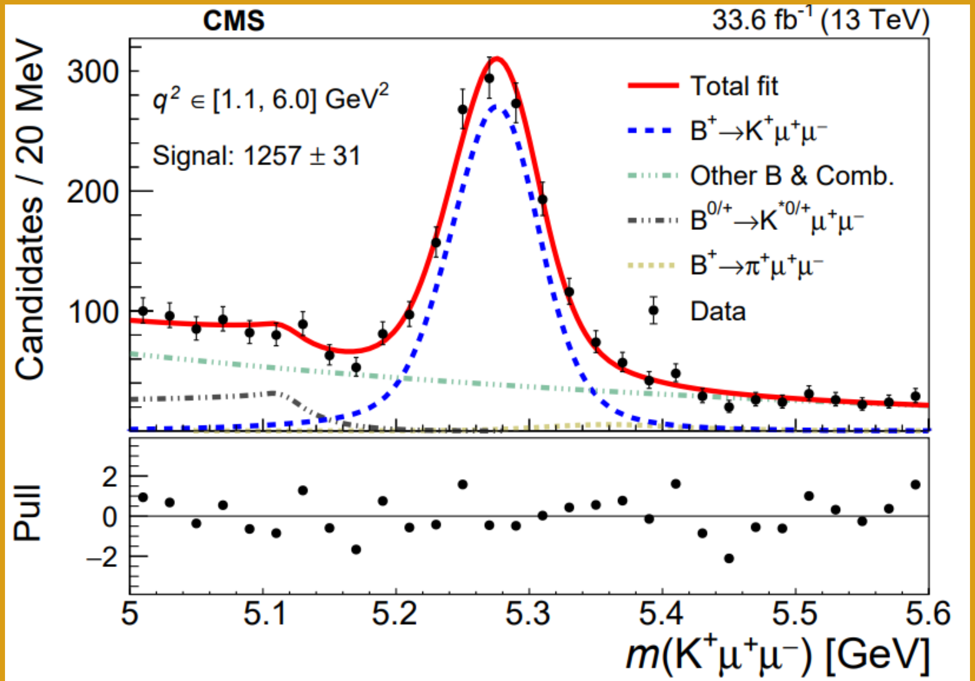
$$R(J/\psi) = 0.17^{+0.18}_{-0.17}\,(\text{stat.})^{+0.21}_{-0.22}\,(\text{syst.})^{+0.19}_{-0.18}\,(\text{theo.}) \quad = 0.17 \pm 0.33$$

First ever CMS $R(K)$ Measurement /1

01/24 arXiv:2401.07090
2018 special data stream

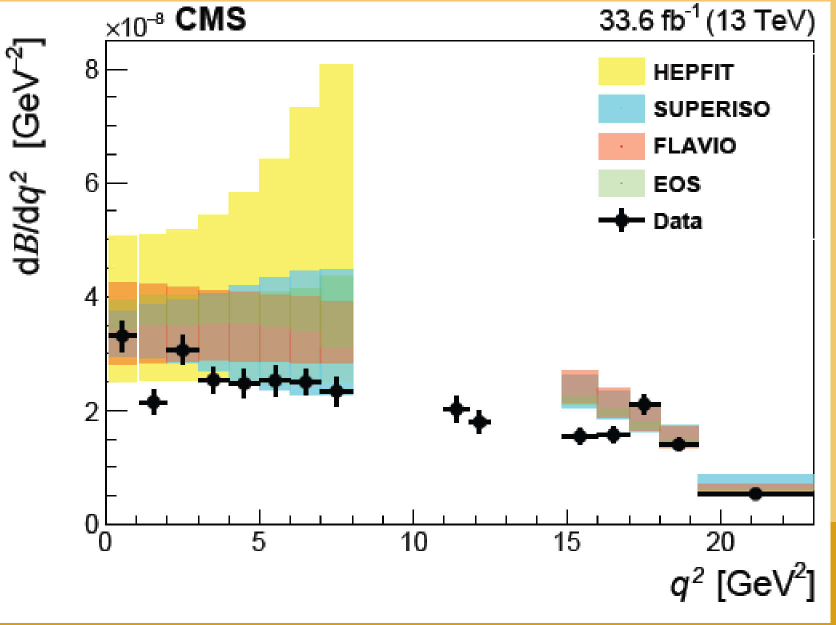


- $R(K) = \frac{Br(B^\pm \to K^\pm \mu^+\mu^-)}{Br(B^\pm \to K^\pm e^+e^-)} \Big/ \frac{Br(B^\pm \to K^\pm (J/\psi \to \mu^+\mu^-))}{Br(B^\pm \to K^\pm (J/\psi \to e^+e^-))}$, 1 in SM
  - Use $1.1 < q^2 < 6.0$ GeV², same as LHCb, Belle
- Special tag+probe trigger -> 10 billion unbiased b-hadron decays.
- Use bespoke low-p_T electron reconstruction, retraining usual Pflow electron ID BDTs to get to $\boldsymbol{p_T(e) > 1}$ **GeV**!
- Cut on BDT signal/bg classifiers + fit $m(B)$ distribution.



First ever CMS $R(K)$ Measurement /2

01/24 arXiv:2401.07090
2018 special data stream



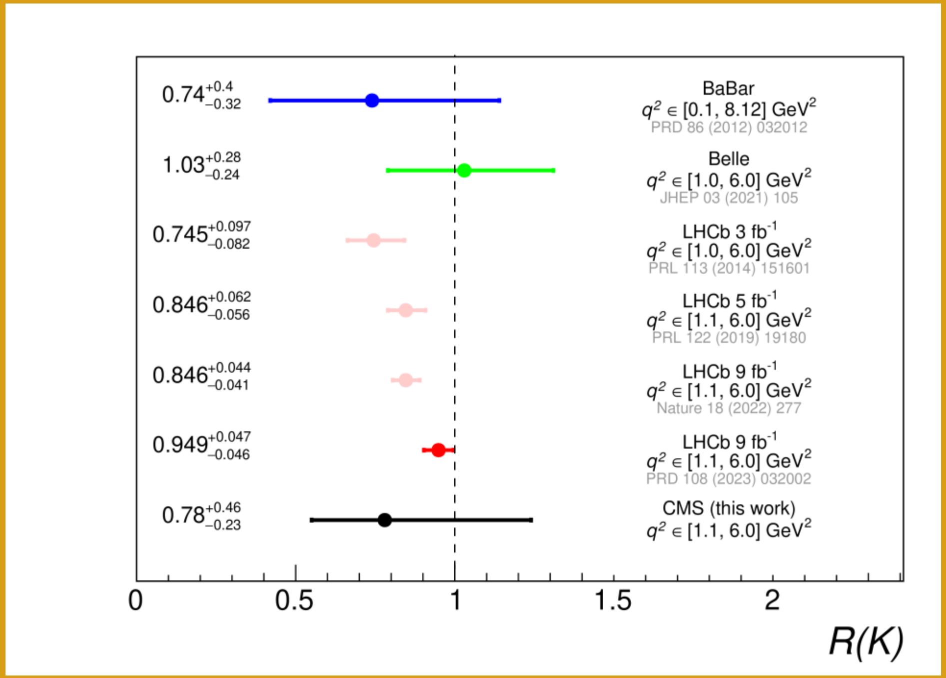
- Dominant uncertainties: Stats. Then Bkg parametrisation.
- Results:
  - $Br(B^{\pm} \to K^{\pm}\mu^{+}\mu^{-})$ consistent with world average.

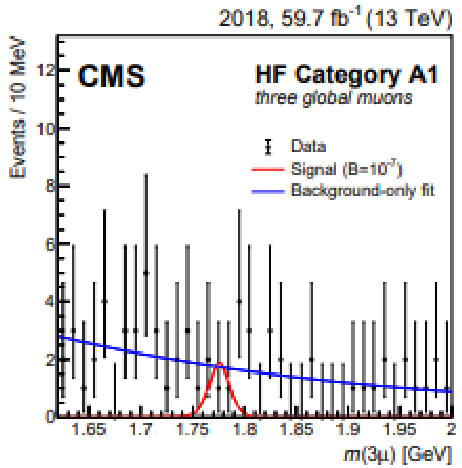
    Differential = fairly low, consistent with LHCb

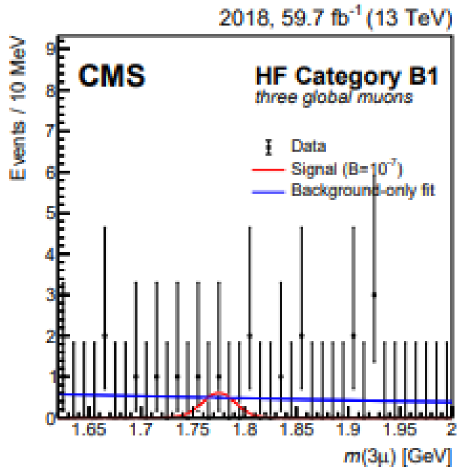
$$\mathcal{B}(\mathrm{B}^{+} \to \mathrm{K}^{+}\mu^{+}\mu^{-})[1.1, 6.0]\,\mathrm{GeV}^2$$
$$= (12.42 \pm 0.54\,(\mathrm{stat}) \pm 0.11\,(\mathrm{MC\ stat}) \pm 0.40\,(\mathrm{syst})) \times 10^{-8}$$
$$= (12.42 \pm 0.68) \times 10^{-8}$$

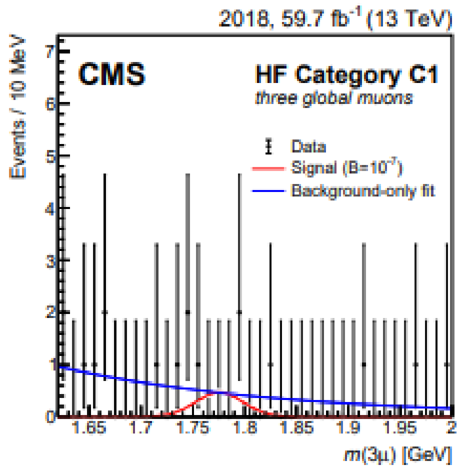
  - $R(K)$ 1 sigma from SM value, consistent.

$$R(\mathrm{K}) = 0.78^{+0.46}_{-0.23}\,(\mathrm{stat})^{+0.09}_{-0.05}\,(\mathrm{syst}) = 0.78^{+0.47}_{-0.23}$$



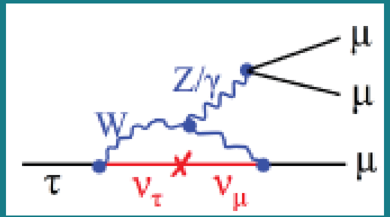






LFV $\tau \rightarrow 3\mu$ Search @ CMS /1

12/23 arXiv:2312.02371 $97.7 fb^{-1}$



SM $B(\tau \rightarrow 3\mu) \sim 10^{-55}$ via ν mixing, search for BSM enhancement.

2017-18 data; combine with 2016 analysis (arXiv:2007.05658) @ $33.2 fb^{-1}$.

Strategy: 3 signal+sideband (ABC) categories based on $m(\mu\mu\mu)$ resolution: $\frac{\sigma_m}{m}$
+ BDT classifier score bins

Two kinds of processes considered…

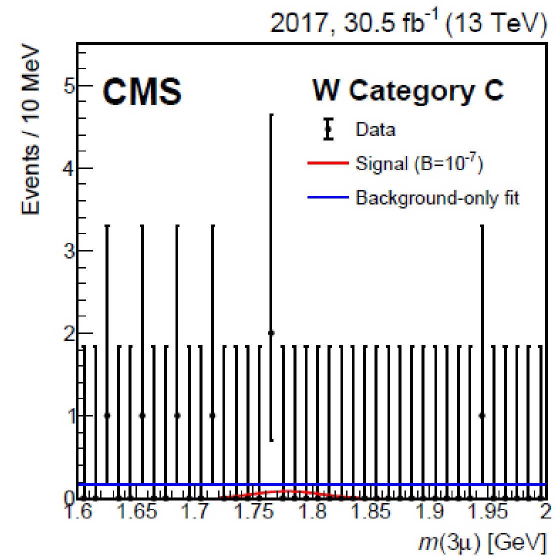
Heavy Flavour decays ($D_s^+ \rightarrow \tau^+\nu_\tau$ & $B \rightarrow \tau + X$)

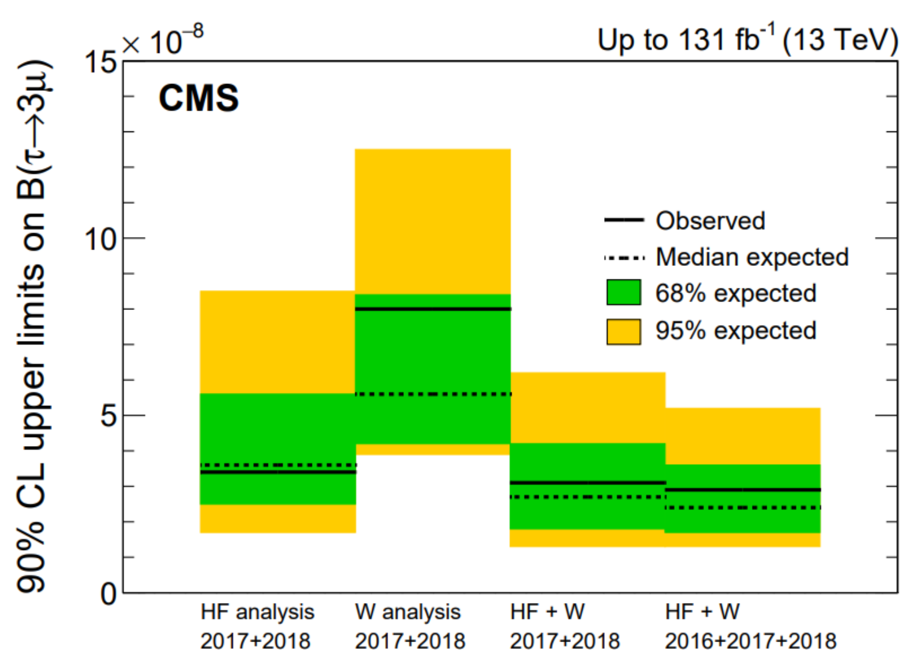
- Bigger signal @ low-p_T μ, higher bg.
- Normalise signal yield to $D_s^+ \rightarrow \pi^+\phi \rightarrow \pi^+\mu^+\mu^-$ yield reduce dependence on σ sections and trigger/selection efficiencies.

LFV $\tau \to 3\mu$ Search @ CMS /2

12/23 arXiv:2312.02371 $97.7 fb^{-1}$

- W decays ($W^+ \to \tau^+ \nu_\tau$)
  - Smaller signal @ high-p_T μ, p_T^{miss} reduces bg.
- Simultaneous fit of $m(\mu\mu\mu)$ distribution in all channels
  - Statistical uncertainties dominates.
- Measure @ 90% CL
  - $\mathrm{B}(\tau \to 3\mu) < 2.9 \times 10^{-8}$
  - Best hadron collider result to date!
    Comparable to Belle II ($\mathrm{B}(\tau \to 3\mu) < 1.9 \times 10^{-8}$)
    P. Horak's talk





No new physics but greatly improved exclusion of BSM models.

More Top cLFV in J.S. Wilson's talk
W LFUV in O. Majersky's talk
HNLs in C. Collard's talk

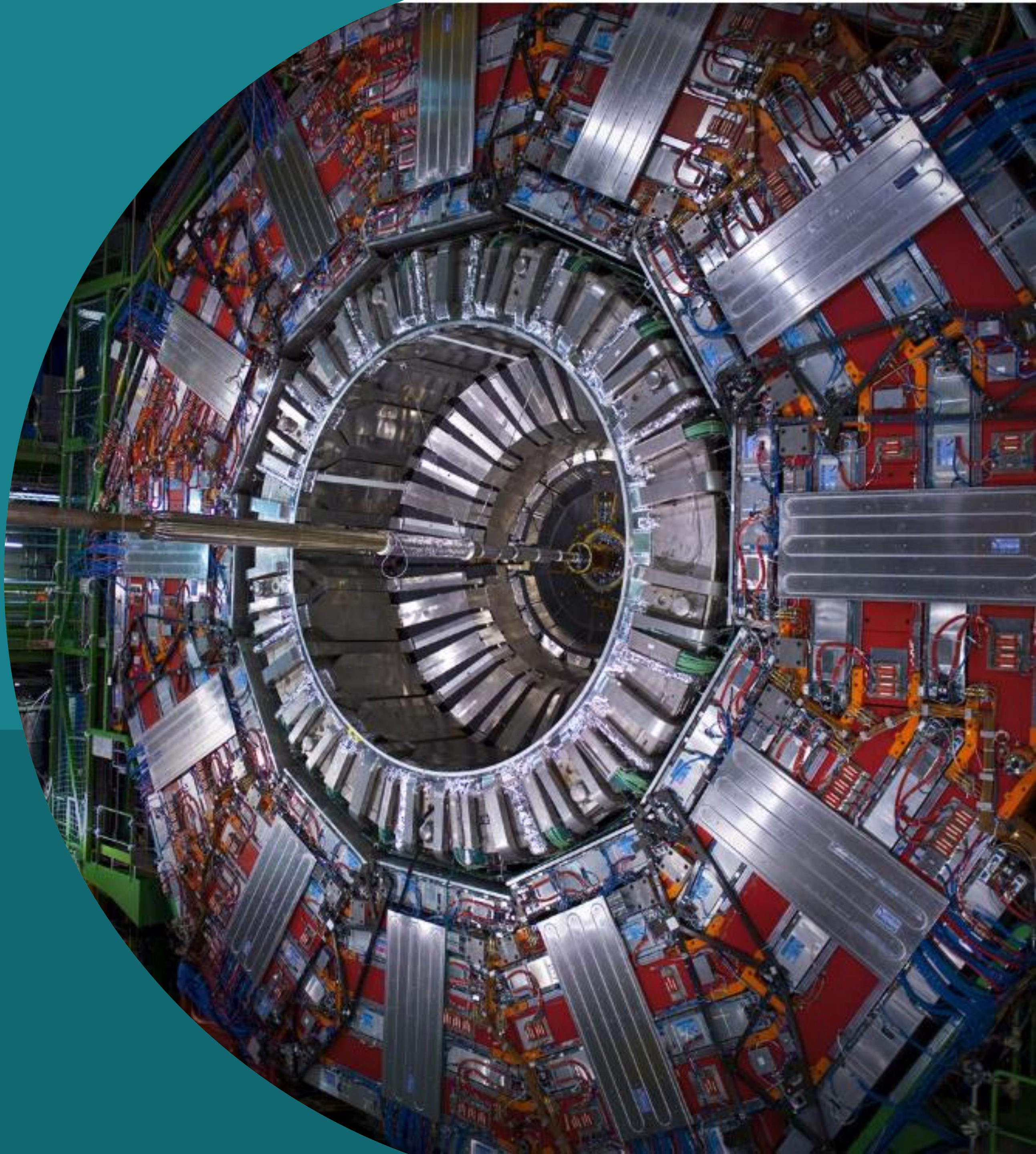
& Checkout other results from the Intro/Backup

Let's see what Run-3 brings…!

Thank You!

More details in the backup!

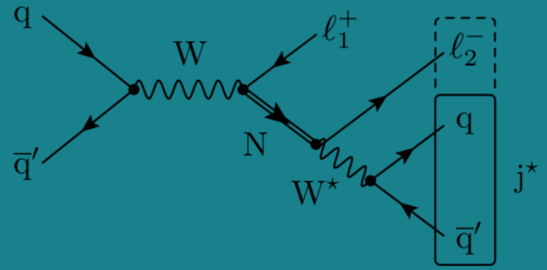
Further Qs? holly.ann.pacey@cern.ch

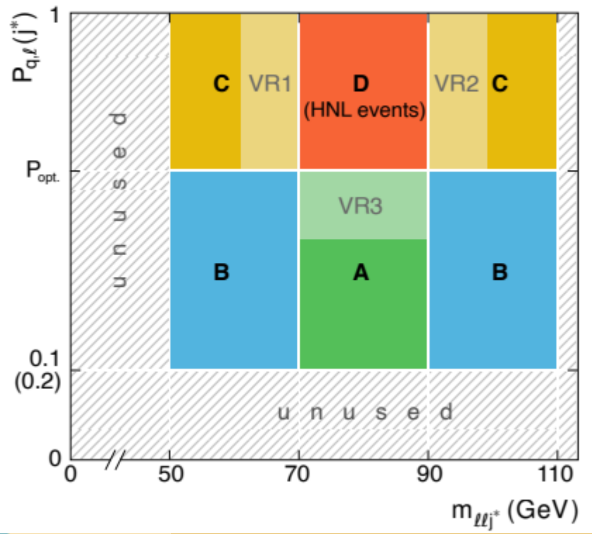


BACKUP

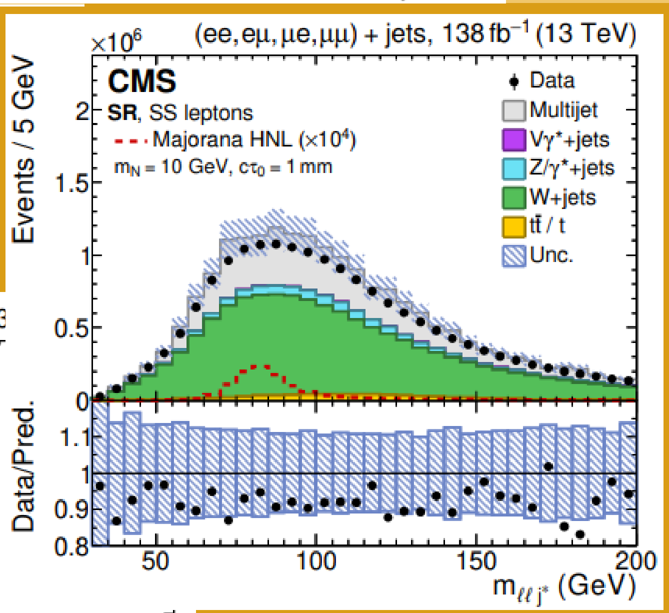
S-channel Long-lived N, to ll'j @ CMS /1

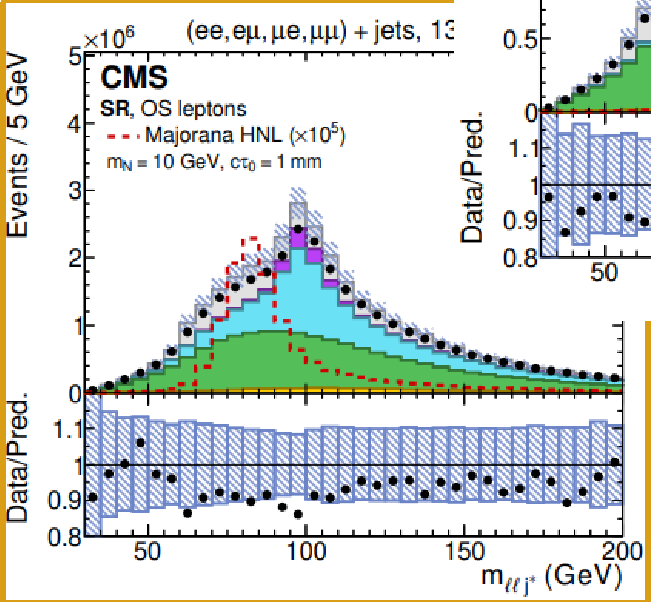
12/23 arXiv:2312.07484 $139 fb^{-1}$





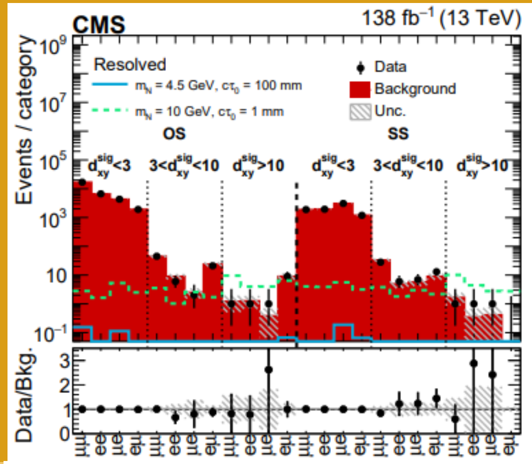
- Full Run-2 search for
  - 1 prompt l to trigger on, 1 displaced l, with a loosened ID/Reco,
  - ≥ 1 displaced jet (j^*). For $m(N) < \sim 8$ GeV, jets collimated into 1.
- N = Dirac ($l^{\pm}l^{\mp}$) or Majorana ($l^{\pm}l^{\mp}$ or $l^{\pm}l^{\pm}$). All flavour couplings: $e, \mu, \tau(\rightarrow l)$. Probe $c\tau^0 \leq 10^4 mm$. Same/opposite charge & same/different flavour categories used.
- Multiclass DNN tagger to ID the j*
  - Parametrized on displacement.
  - Uses Adversarial training to avoid large performance differences between data/MC.
- $m(llj^*) \sim m(W)$ crucial variable: 70-90 GeV for SR, sidebands for ABCD data-driven bg estimate.

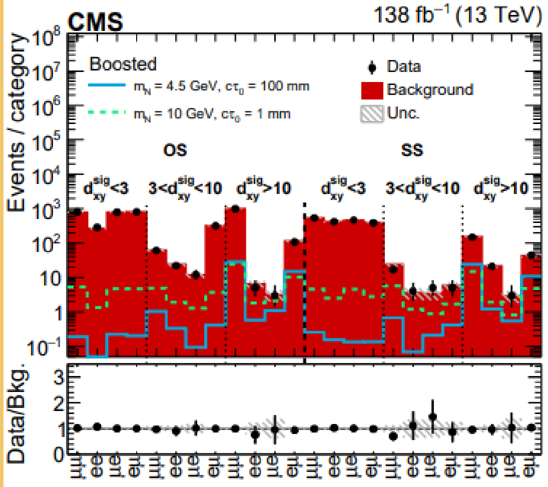


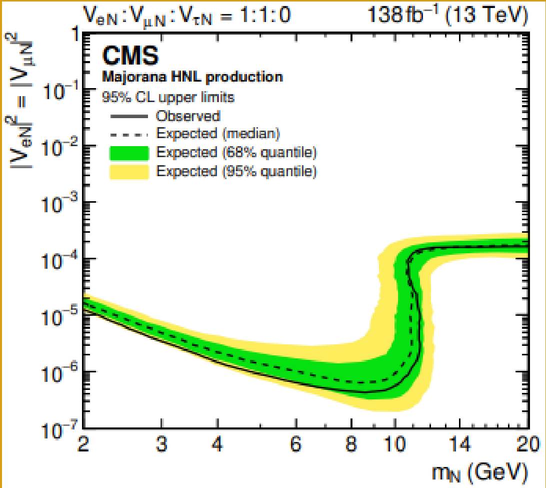


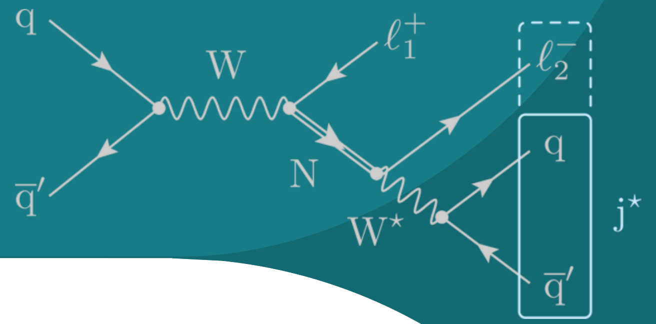
S-channel Long-lived N, to ll'j @ CMS /2

12/23 arXiv:2312.07484 l $139 fb^{-1}$



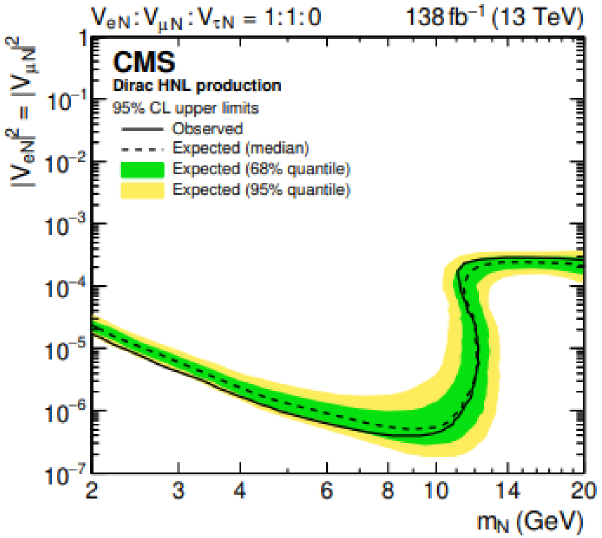


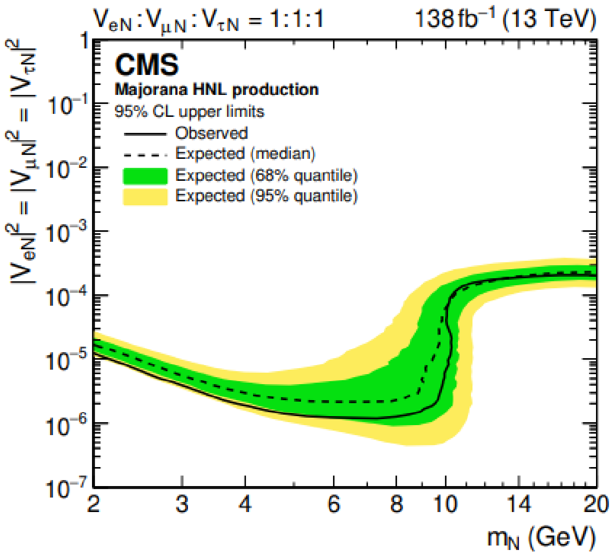


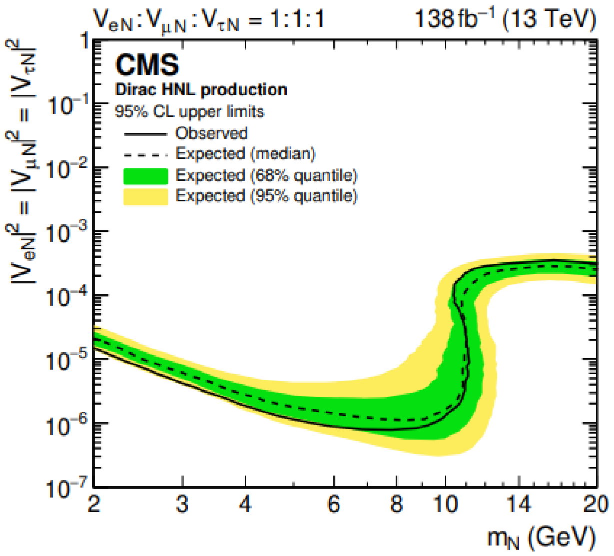


No significant deviation from the SM,

- many limits for 1, 2 or 3 couplings switched on & equal, for Majorana and Dirac.
- Comparable to previous ATLAS/CMS searches for single couplings, but first result for simultaneous coupling to all three..



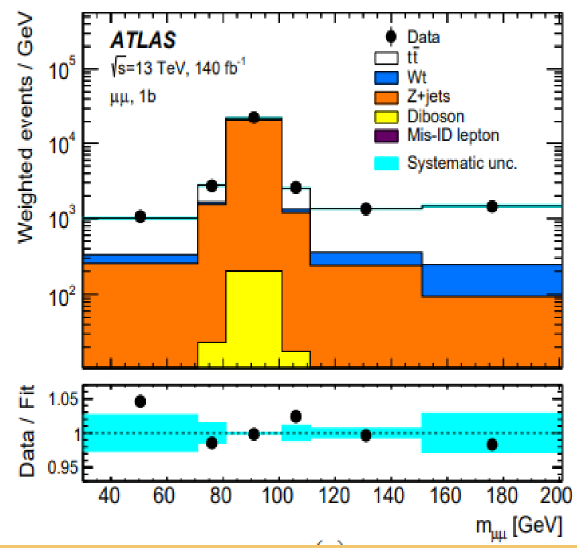


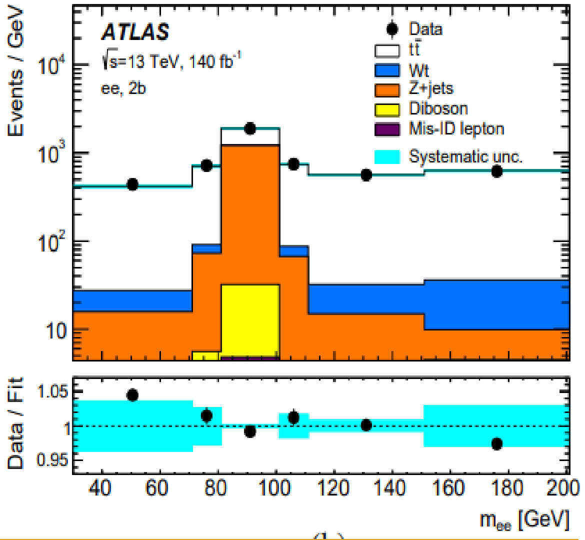


LFUV test: $R_W^{\mu/e} = \frac{B(W\to\mu\nu)}{B(W\to e\nu)}$ measurement @ ATLAS

NEW!

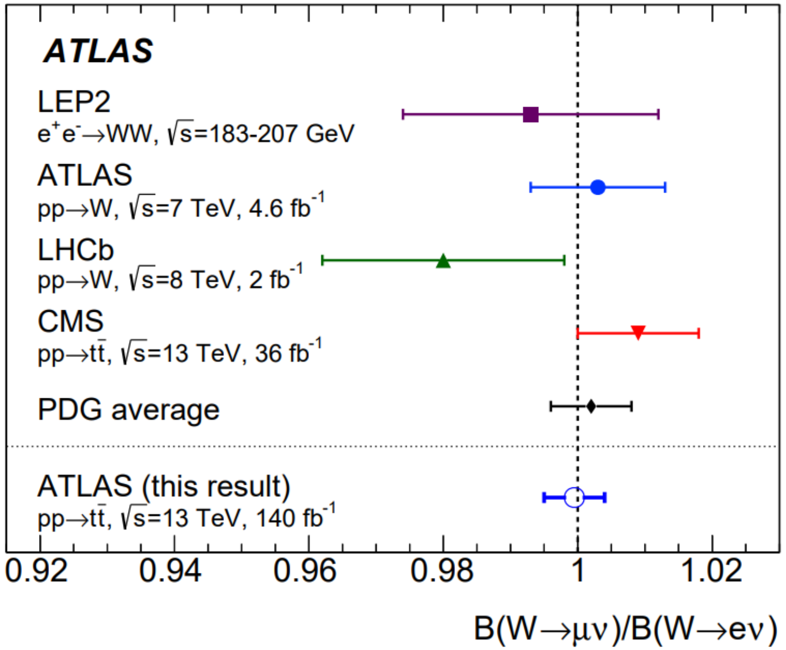
03/24 [arXiv:2403.02133] $140 fb^{-1}$





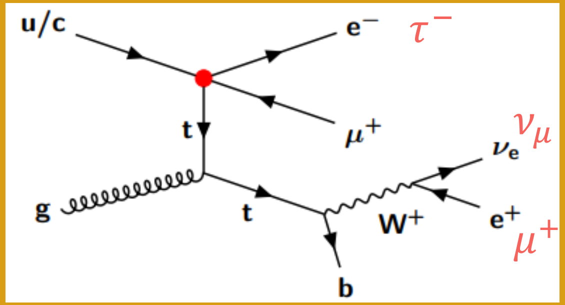
- First full Run-2 LFU test in Ws using leptonic $t\bar{t}$ decays.
- Tricks to reduces systematics:
  - Weight $\mu(p_T, \eta)$ to give similar kinematic acceptance in ee v $\mu\mu$ channels, reduces modelling uncertainties.
  - Normalise using Z ratio to reduce lepton ID uncertainties: measure $R_{WZ}^{\mu/e} = R_W^{\mu/e} / \sqrt{R_Z^{\mu\mu/ee}}$, then get final $R_W^{\mu/e}$ result from $R_{WZ}^{\mu/e}$ and precise LEP/SLF $R_Z^{\mu\mu/ee}$ value.

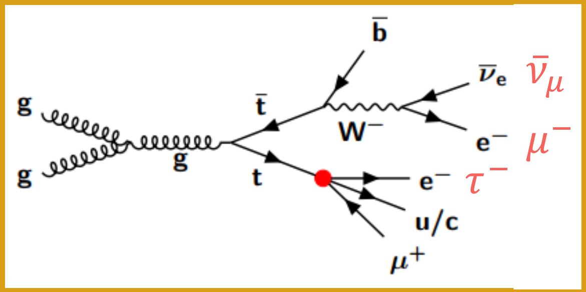
Fit in $m(ee)$ and $m(\mu\mu)$ in 1 or 2 b-jet channels.

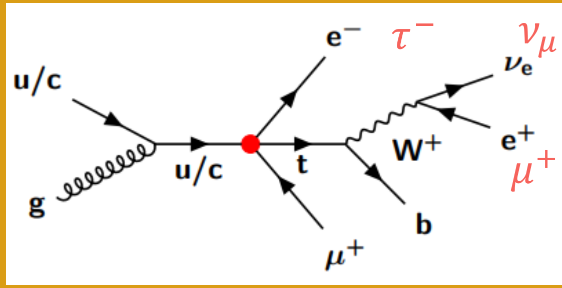


$$R_W^{\mu/e} = 0.9995 \pm 0.0022\,(\text{stat}) \pm 0.0036\,(\text{syst}) \pm 0.0014\,(\text{ext})$$

cLFV in Top physics







Search for cLFV single top and ttbar processes
-> interpret in EFT framework, dim-6 Operators
-> constrain Wilson coefficients $C_\alpha^{(6)}$

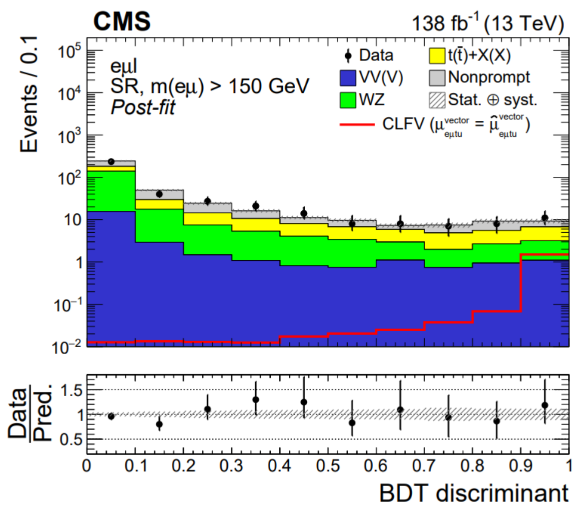
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}}^{(4)} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} O_a^{(6)} + O\left(\frac{1}{\Lambda^4}\right),$$

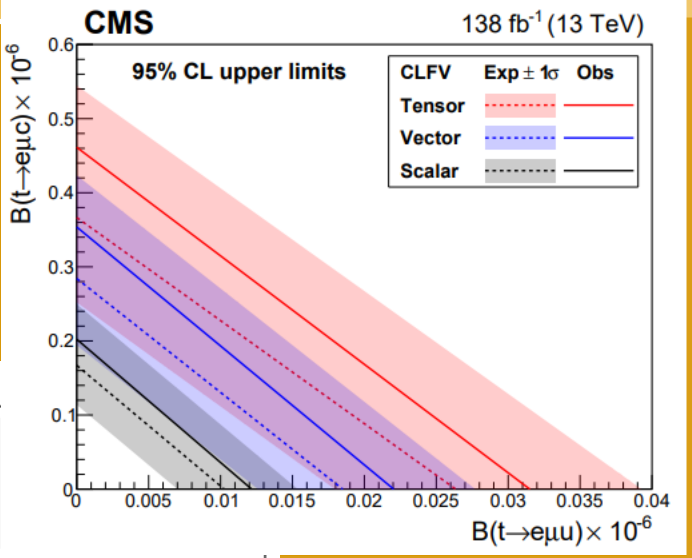
CMS and ATLAS focused on different 4-point couplings
-> constrain different Operators

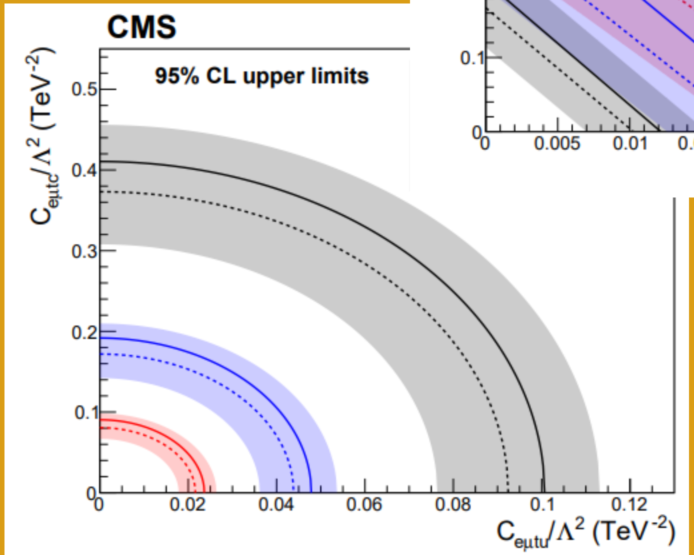
top cLFV with 3leptons @ CMS

12/23 arXiv: 2312.03199 $139 fb^{-1}$

- 2016-18 data, $\boldsymbol{\mu e t (u/c)}$ vertex
- Backgrounds: Real leptons: MC.
  Fake/non-prompt leptons: data-driven estimate.
- Signal selection: BDTs to discriminate signal & background, fit BDT scores
- Most stringent limits to date on BRs for these processes!
  By ~1 order of magnitude.



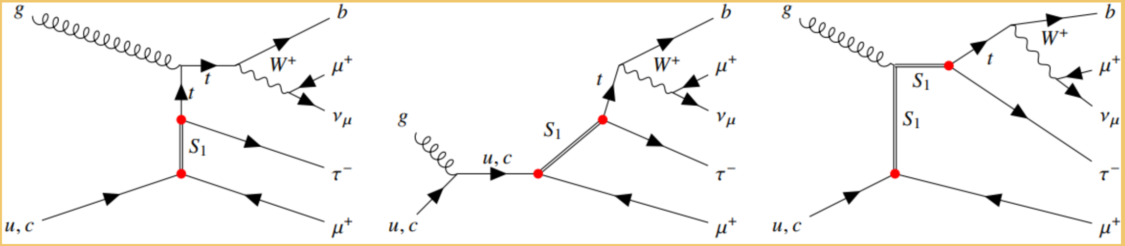




top cLFV decays to $\mu\tau$ @ ATLAS

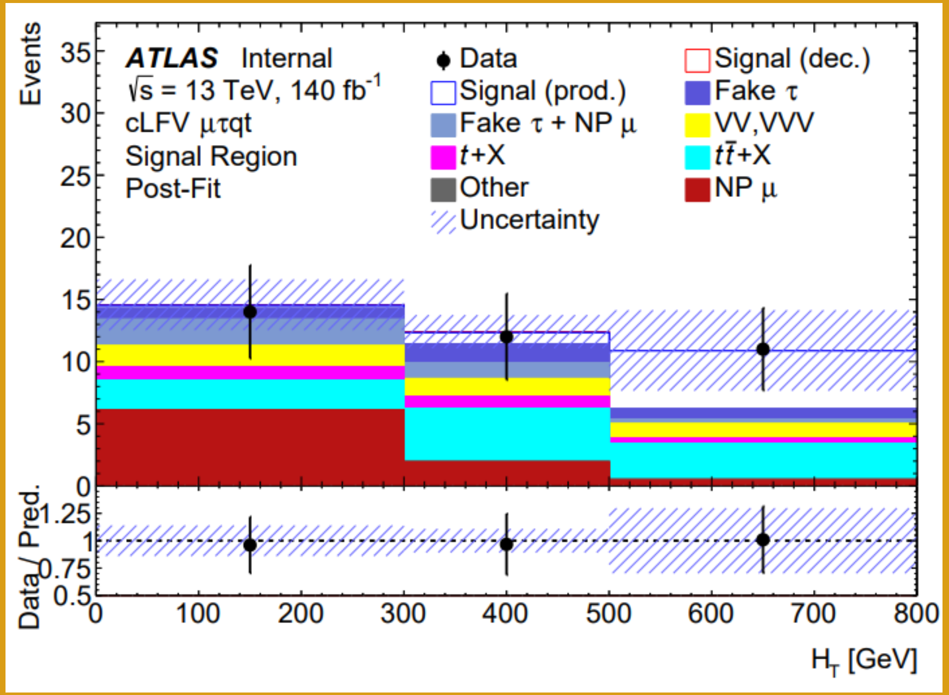
03/24 arXiv:2403.06742 $140 fb^{-1}$

NEW!



$$\lambda_{ki} \in \begin{pmatrix} \lambda_{t\tau} & \lambda_{c\tau} & \lambda_{u\tau} \\ \lambda_{t\mu} & \lambda_{c\mu} & \lambda_{u\mu} \\ \lambda_{te} & \lambda_{ce} & \lambda_{ue} \end{pmatrix} \equiv \lambda^{LQ} \begin{pmatrix} 10 & 1 & 0.1 \\ 1 & 0.1 & 0.01 \\ 0.1 & 0.01 & 0.001 \end{pmatrix}$$

- 2015-18 data, processes as before but use $\boldsymbol{\mu\tau t(u/c)}$ vertex, highly unconstrained!
- Bonus interpretation in scalar LQ model! Simplified with flavour-hierarchy of couplings.
- Cut-based signal region, fit $H_T = \sum p_T(leps, jets)$ distribution.
- Dominant bgs from:
  - $t\bar{t}$ with non-prompt μs inside heavy flavour jets – estimate via template fit from dedicated region,
  - fake τs – data-driven scale-factor method.
- Data agree with SM to within 1.6sigma.



top cLFV decays to $\mu\tau$ @ ATLAS

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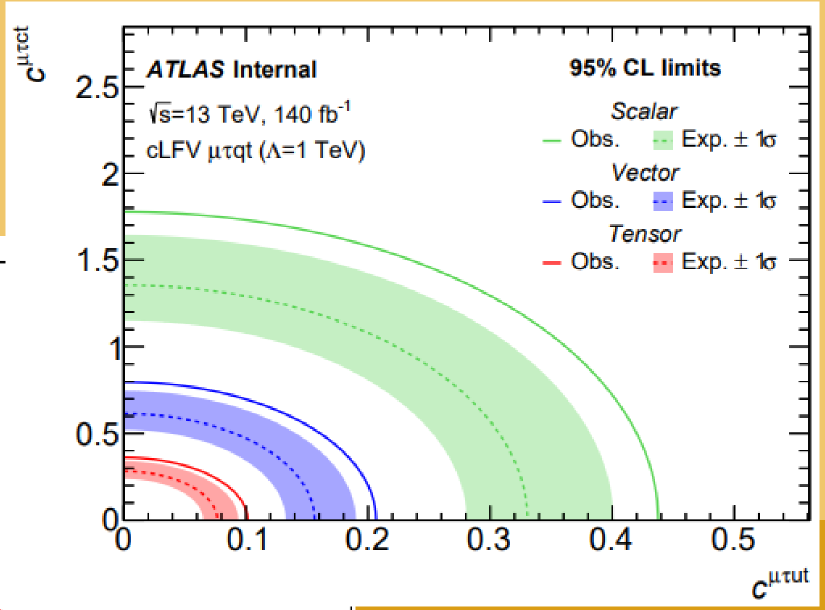
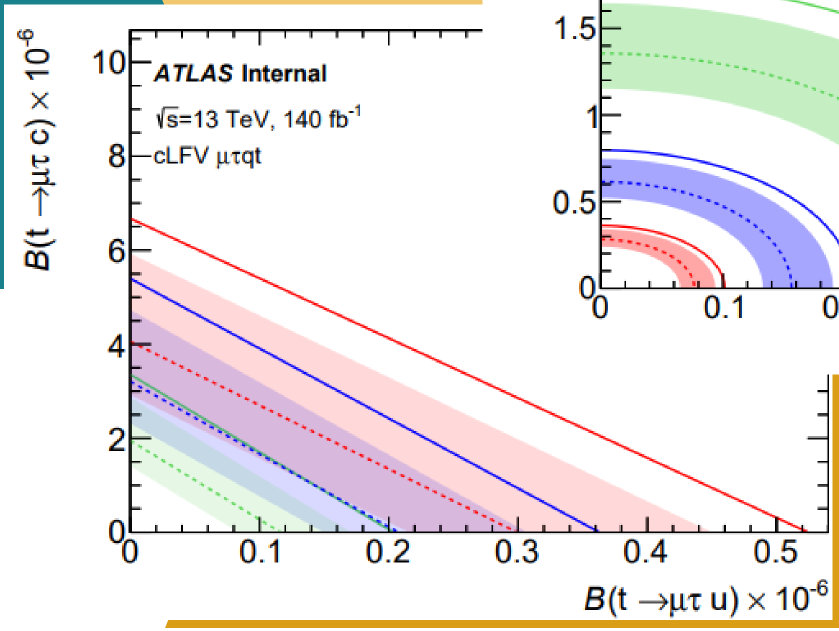
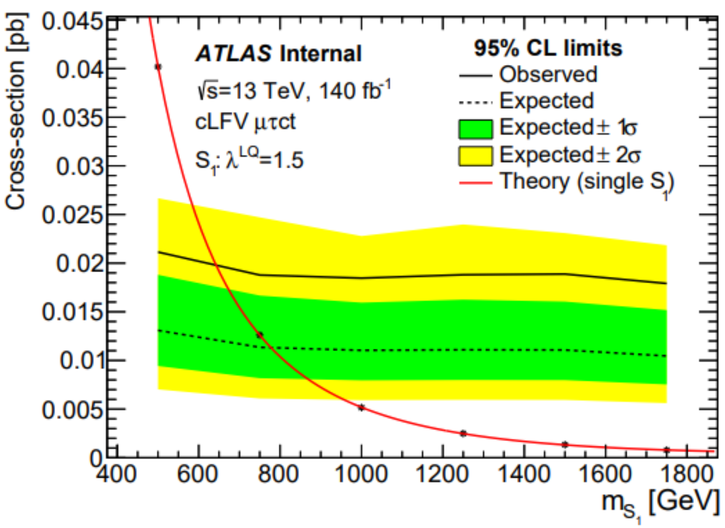
NEW!

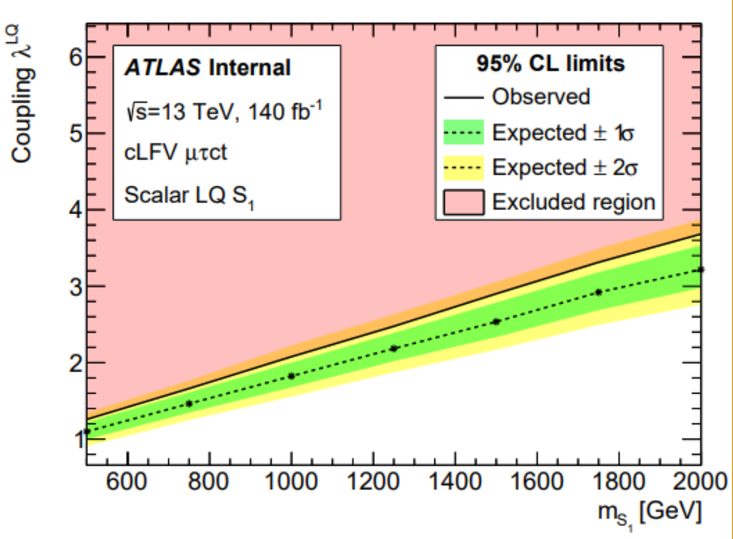




- Wilson coefficient limits improve $\times\, 7.2 - \times\, 41$ compared to previous reinterpretation (JHEP 04 (2019) 014, Chala M., et al).
- First limits for this LQ model!
- Also set 95% CL Br limit:

$$\mathcal{B}(t \to \mu\tau q) < 8.7 \times 10^{-7}$$





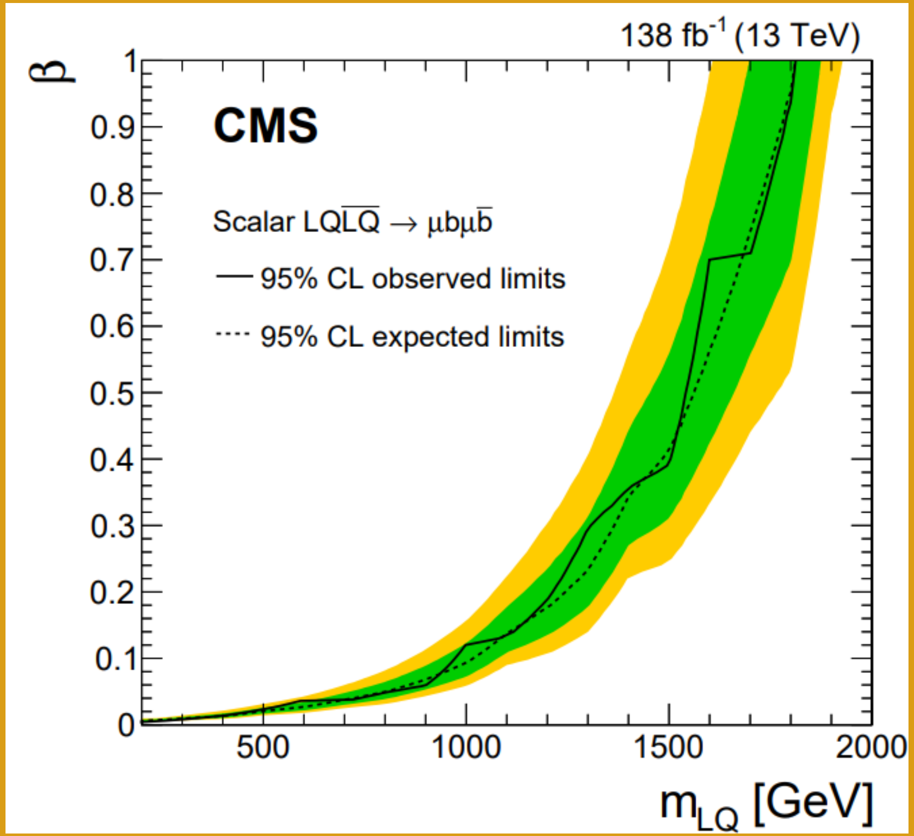
LQ 3G Combo. more results…

- Phys. Rev. D 104 (2021) 112005
- Eur. Phys. J. C 83 (2023) 1075
- JHEP 06 (2021) 179
- JHEP 06 (2023) 188
- JHEP 10 (2020) 112
- Eur. Phys. J. C 81 (2021) 313
- ATLAS-CONF-2022-052
- Eur. Phys. J. C 80 (2020) 737
- JHEP 05 (2021) 093

Search		Interpretation						Signal Region		
		Scalar				Vector				
Final State	Citation	LQ_3^u	LQ_3^d	LQ_{mix}^u	LQ_{mix}^d	$U_1^{YM/MC}$	$\tilde{U}_1^{YM/MC}$	N_ℓ	$N_{\tau_{had}}$	$N_{b\text{jets}}$
$t\nu b\tau$	[54]	✓	✓	–	–	✓	–	0	1	≥ 2
$b\tau b\tau$	[55]	✓	–	–	–	✓	–	$\{0,1\}$	$\{1,2\}$	$\{1,2\}$
$t\tau t\tau$	[57]	–	✓	–	–	–	✓	$\{1,2,3\}$	≥ 1	≥ 1
$t\nu b\ell$	[40]	–	–	✓	✓	–	–	1	–	≥ 1
$b\ell b\ell$	[58]	–	–	✓	–	–	–	2	–	$\{0,1,2\}$
$t\ell t\ell$ (2ℓ)	[59]	–	–	–	✓	–	–	2	–	–
$t\ell t\ell$ ($\geq 3\ell$)	[61]	–	–	–	✓	–	–	$\{3,4\}$	–	≥ 2
$t\nu t\nu$	[62]	✓	–	✓	–	✓	–	0	0	≥ 2
$b\nu b\nu$	[64]	–	✓	–	✓	–	–	0	–	≥ 2

Correlate detector systs. where possible and keep bg modelling systs uncorrelated (different phase space etc.)

Only case of non-negligible overlap between signal regions was removed, without much detriment to the limits.



Scalar/Vector

$LQLQ \to b\mu b\mu$ @ CMS