FLAVORFUL PHYSICS HIGHLIGHTS FROM ATLAS & CMS

Greg Landsberg

Physics of Flavourful Universe 22.09.2021

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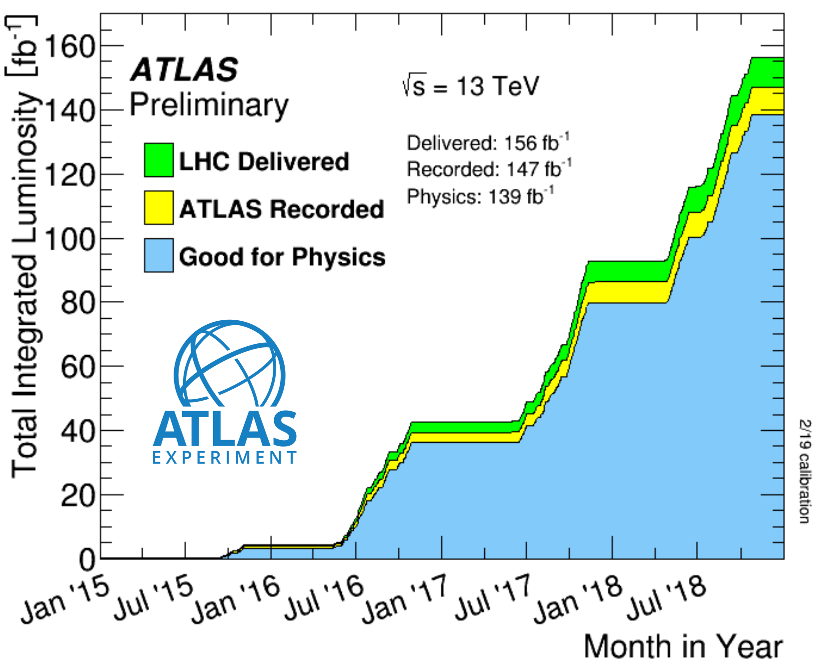
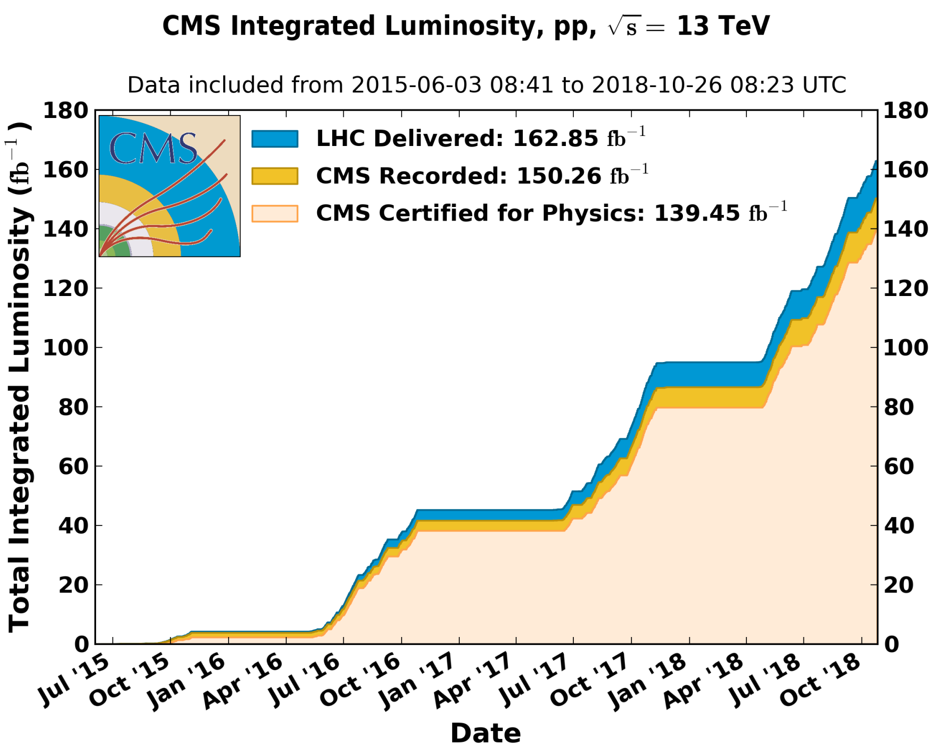
The LHC Legacy

LHC Run 2: Big Success

- 160 fb^{-1} has been delivered by the LHC in Run 2 (2015–2018), at a c.o.m. of 13 TeV, exceeding the original integrated luminosity projections
- About 140 fb^{-1} of physics-quality data recorded by each ATLAS & CMS
- Thank you, LHC, for a spectacular Run 2 and look forward to Run 3!





Three Machines in One!

The LHC Legacy

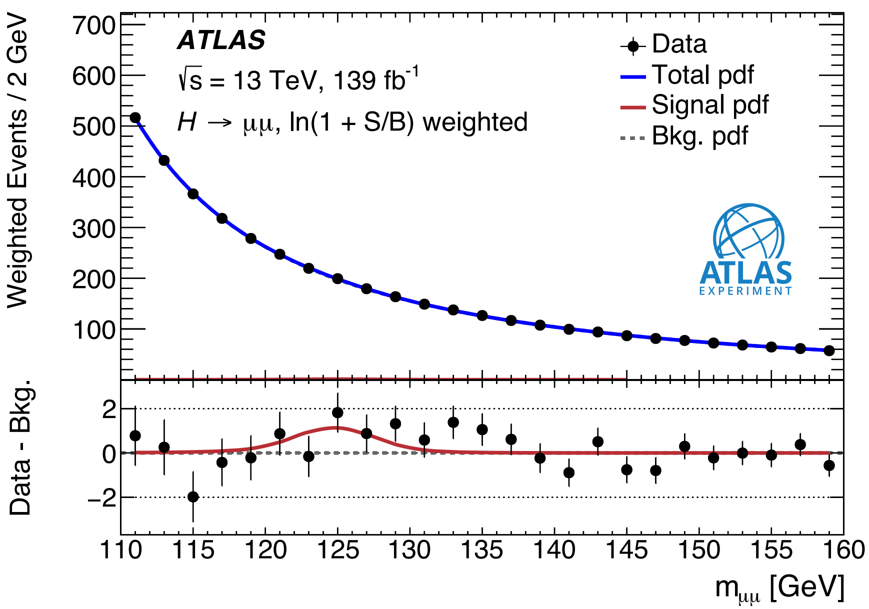
- The LHC has figuratively replaced three machines in one go:
  - ★ Tevatron (Higgs, BSM searches, top physics, and precision EW measurements)
  - ★ BaBar/Belle B factories (flavor physics)
  - ★ RHIC (heavy-ion physics)
- The LHC experiments in general, and ATLAS/CMS in particular, are very successful in all these three areas
- Would not be possible without theoretical and phenomenological breakthroughs of the past decade:
  - ★ Higher-order calculations ("NLO revolution"), modern Monte Carlo generators, reduced and better estimated PDF uncertainties
- Since it's impossible to cover all the aspects of this impressive program in one talk, I'll present a few highlights of recent ATLAS and CMS results related to the physics of flavor, which is the main subject of this workshop
  - ★ The choice of topics clearly reflects my personal bias, in what have been the most relevant and interesting results of the past year or so

First Evidence of LFU Violation

- At the LHC, LFU no longer holds: coupling of the Higgs boson to leptons is not flavor-universal!
- This was first proved recently via an evidence for H(μμ) decays - the first clear sign of LFU violation
- Extremely important measurement, as it allows to see if there is any non-Higgs mass term that would undoubtedly require BSM physics and would manifest itself in the mass to Yukawa coupling ratio for relatively light fermions, such as muons
- Tour de force analyses in both ATLAS and CMS
- State-of-the art muon identification and momentum corrections to achieve best possible mass resolution
- Categorization according to the production mode and/or resolution and the use of multivariate techniques to reduce the dominant Drell-Yan background
- Full Run 2 data set to maximize the sensitivity

ATLAS Search for H(μμ)

- 20 exclusive categories, probing ggF(+jets), VBF, VH, and ttH production
- Mass resolution (Gaussian core) between 2.6 and 3.2 GeV achieved, depending on the category
- Measured signal strength: $\mu = 1.2 \pm 0.6$
- Observed (expected) significance of 2.0 (1.7)σ



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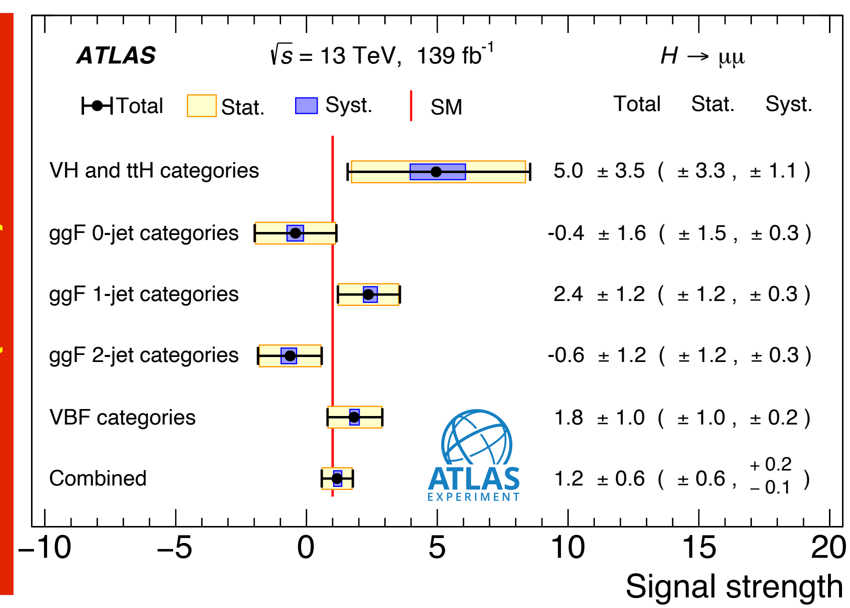
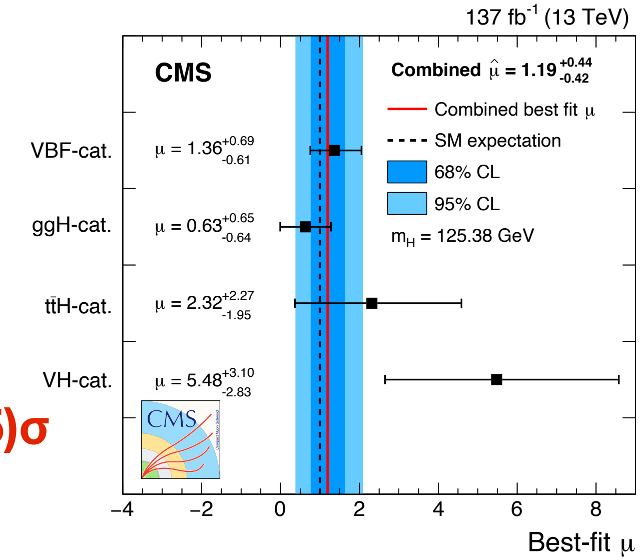


CMS: First Evidence for H(μμ)

- Split by categories: VBF (13 MVA output bins), ggF (5 bins), ttH (3 hadronic & 2 leptonic bins), and WH/ZH (3/2 bins)
- Fit to the dimuon mass distributions in all categories, except for VBF, where the MVA output is fit directly
- Observed (expected) signal significance: 3.0 (2.5)σ



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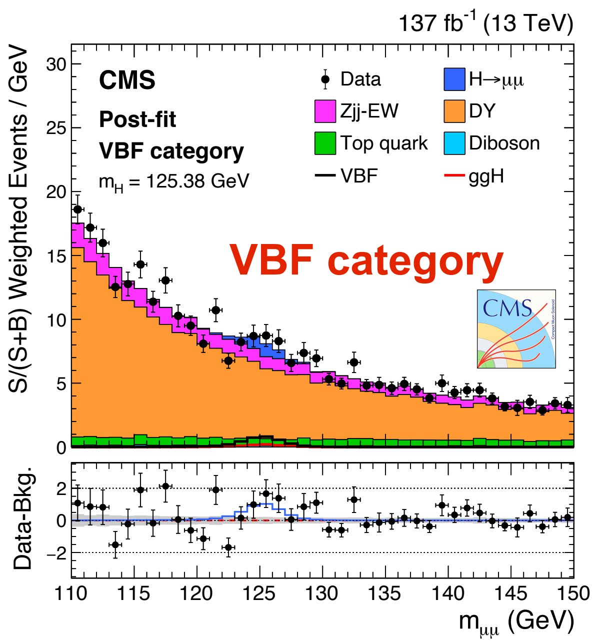
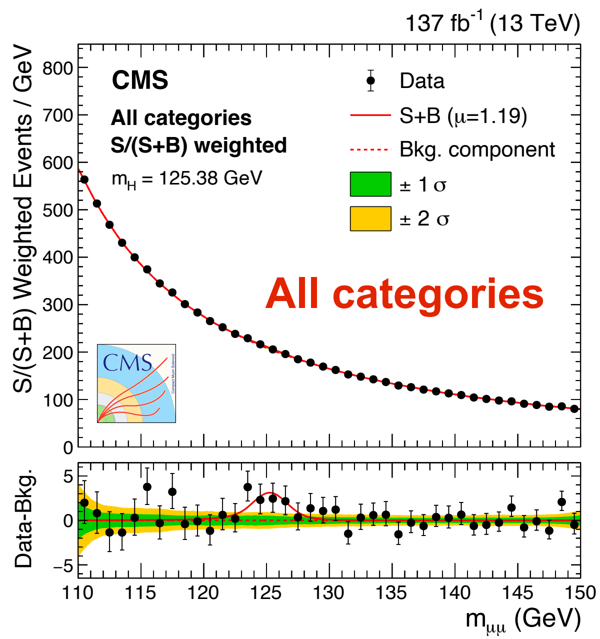
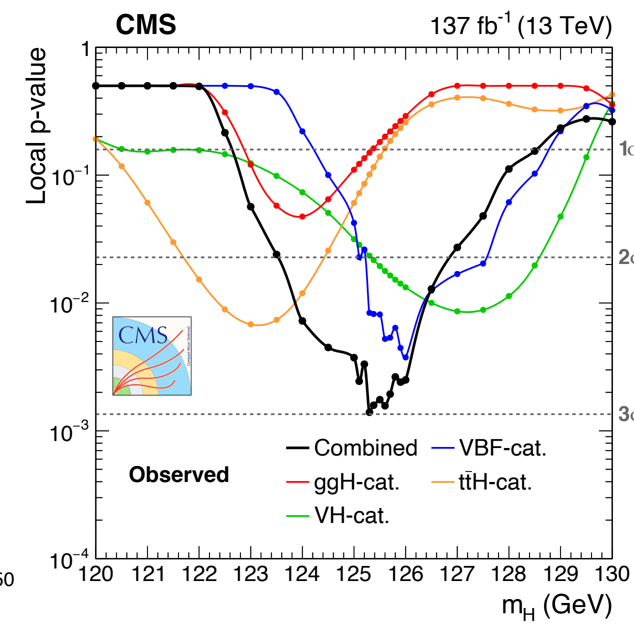


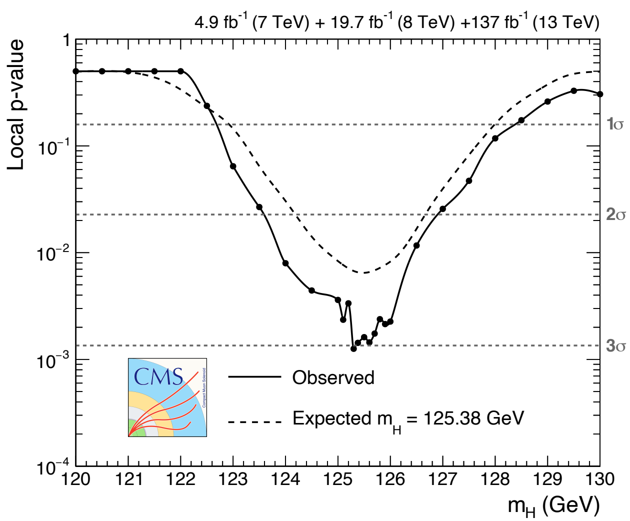




CMS Combination

- **Results are combined with the 7 and 8 TeV analyses, which yields:**
  - ★ **Signal strength: $\mu = 1.19^{+0.40}_{-0.39}\ ^{+0.15}_{-0.14}$**
  - ★ **Observed (expected) significance: 3.0 (2.5)σ**

Production category	Observed (expected) signif.
VBF	2.40 (1.77)
ggH	0.99 (1.56)
$t\bar{t}H$	1.20 (0.54)
VH	2.02 (0.42)
Combined $\sqrt{s} = 13$ TeV	2.95 (2.46)
Combined $\sqrt{s} = 7,\ 8,\ 13$ TeV	2.98 (2.48)



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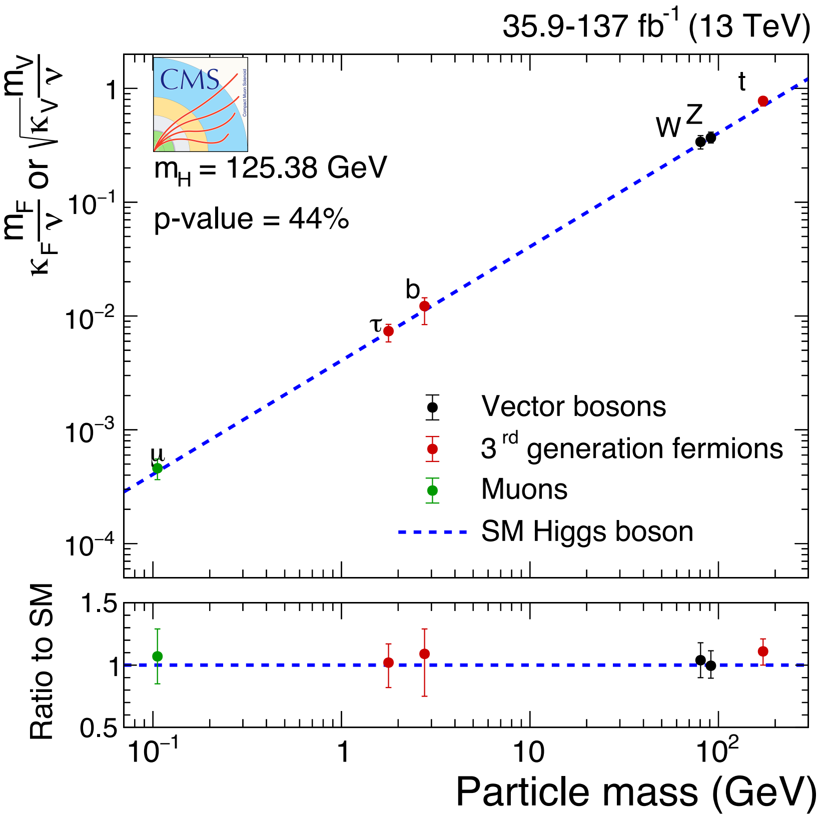


LHC Combination

- The official LHC combination of these exciting results is under way
- However, given that the results are dominated by statistical uncertainties, a naive combination provides a reliable preview of what to expect once the official numbers will become available:

$\mu(H \rightarrow \mu\mu) = 1.19 \pm 0.35$ Unofficial combination

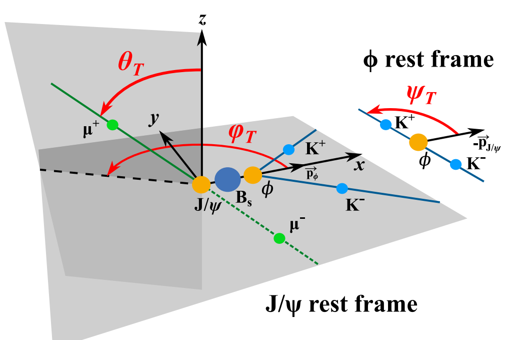
Observed (expected) significance: 3.6 (3.0)σ

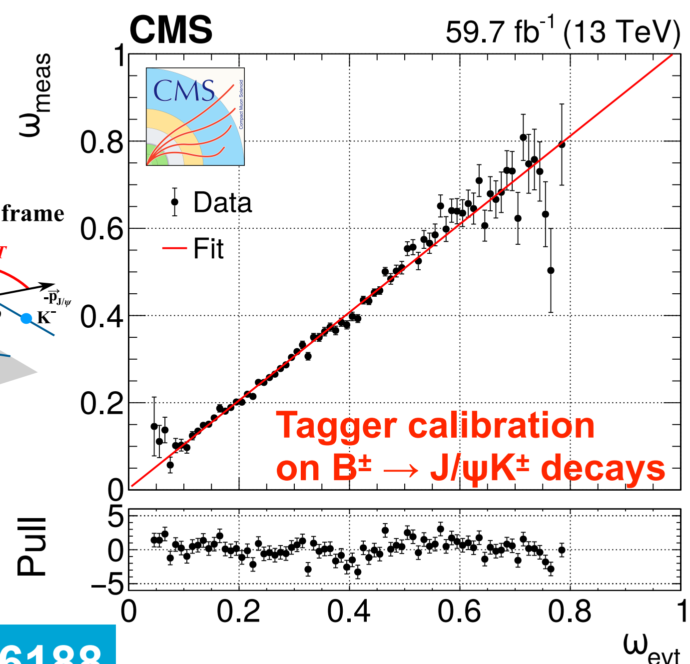
- Couplings to second-generation fermions appear to be consistent with the SM Higgs Yukawa couplings within a ~30% precision

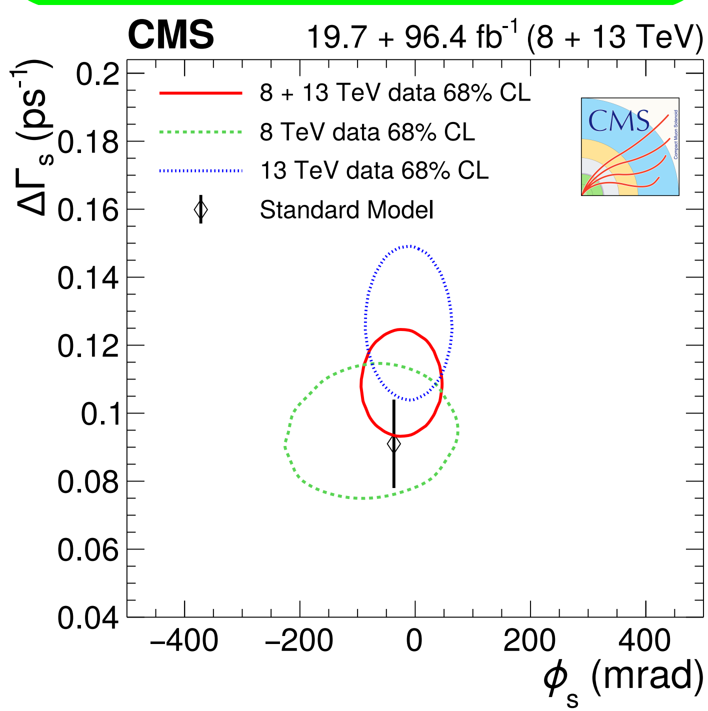
CPV in $B_s \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

- **New CMS CPV parameter measurement using advanced opposite-side DNN muon tagger and a 3μ trigger that together enhance the tagging power εD^2 to ~10% (x10 compared to Run 1)**
  - ★ **Based on 2017+2018 data (trigger not available in 2016)**
  - ★ **Full time-dependent angular analysis (3 angles)**
  - ★ **Significantly improved precision on the CPV parameters, such as ϕ_s, compared to Run 1 result**

Parameter	Fit value	Stat. uncer.	Syst. uncer.
ϕ_s [mrad]	-11	± 50	± 10
$\Delta\Gamma_s$ [ps^{-1}]	0.114	± 0.014	± 0.007
Δm_s [$\hbar$ ps^{-1}]	17.51	$^{+0.10}_{-0.09}$	± 0.03
$\lvert\lambda\rvert$	0.972	± 0.026	± 0.008
Γ_s [ps^{-1}]	0.6531	± 0.0042	± 0.0024
$\lvert A_0\rvert^2$	0.5350	± 0.0047	± 0.0048
$\lvert A_\perp\rvert^2$	0.2337	± 0.0063	± 0.0044
$\lvert A_S\rvert^2$	0.022	$^{+0.008}_{-0.007}$	± 0.016
$\delta_\parallel$ [rad]	3.18	± 0.12	± 0.03
$\delta_\perp$ [rad]	2.77	± 0.16	± 0.04
$\delta_{S\perp}$ [rad]	0.221	$^{+0.083}_{-0.070}$	± 0.048





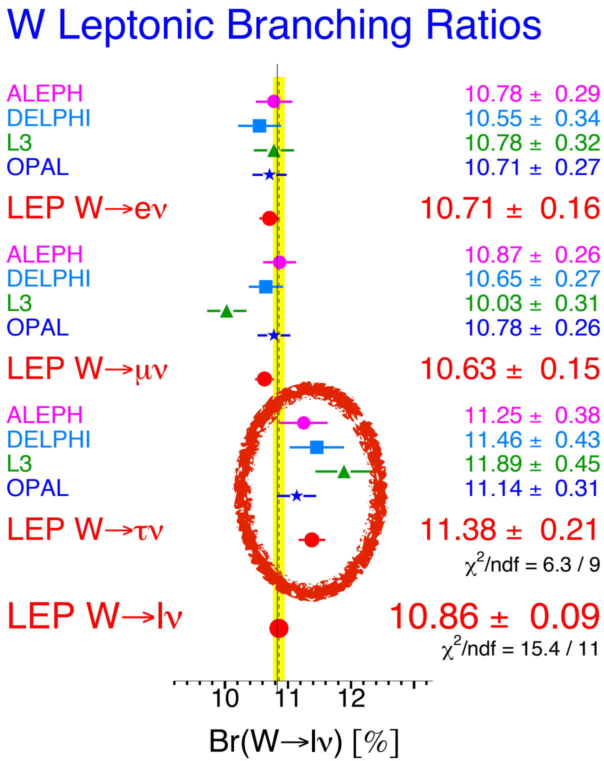


PLB 816 (2021) 136188

Lepton Universality & W Boson

- **Long-standing puzzle from LEP era:**
  - ★ The W(τν) branching fraction is measured consistently higher in all four experiments w.r.t. the W(eν) or W(μν) branching fractions
  - ★ Combined result: $R_{\tau/\mu} = 1.070 \pm 0.026$, 2.7σ from unity
  - ★ Possible hint of lepton non-universality or statistical fluctuation?

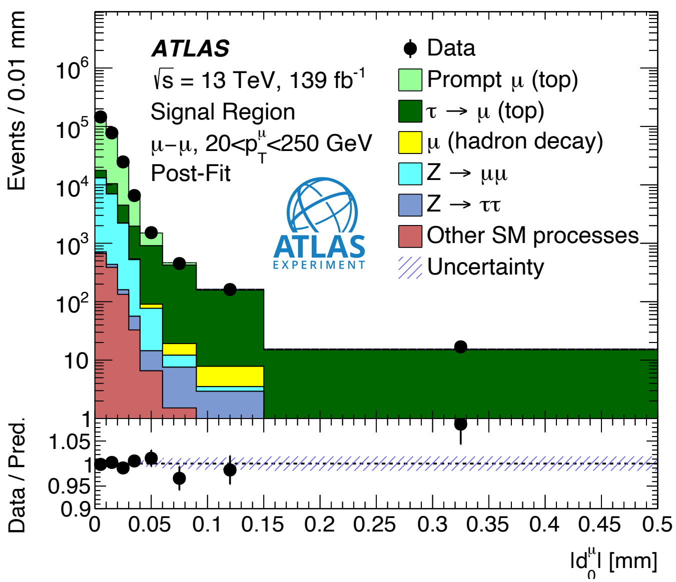
	Lepton non–universality		
Experiment	$\mathcal{B}(W \to e\overline{\nu}_e)$ [%]	$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$ [%]	$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$ [%]
ALEPH	10.78 ± 0.29	10.87 ± 0.26	11.25 ± 0.38
DELPHI	10.55 ± 0.34	10.65 ± 0.27	11.46 ± 0.43
L3	10.78 ± 0.32	10.03 ± 0.31	11.89 ± 0.45
OPAL	10.71 ± 0.27	10.78 ± 0.26	11.14 ± 0.31
LEP	10.71 ± 0.16	10.63 ± 0.15	11.38 ± 0.21
χ^2/dof	6.3/9		



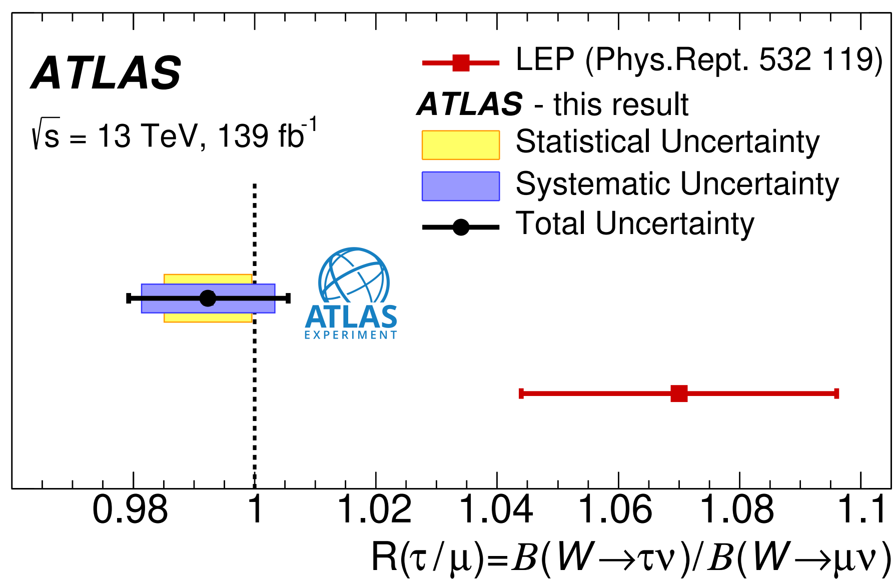
ADLO, Phys. Rep. 532 (2013) 119

ATLAS Test of LFU

- Large samples of muonic W decays in tt events, either prompt or via a τ lepton, made it possible for a precision test of the LEP result
- Tag one top quark leptonic (e/μ) decay and look on the other side, utilizing the probe muon p_T and impact parameter to distinguish prompt and non-prompt events
- Main backgrounds Z(μμ) w/ lost μ and and non-W probe μ events
- Fit impact parameter spectra in different $p_T(\mu)$ bins
- Result: **$R_{\tau/\mu}$ = 0.992 ± 0.013**, in good agreement w/ LFU



Nature Phys. 17 (2021) 813

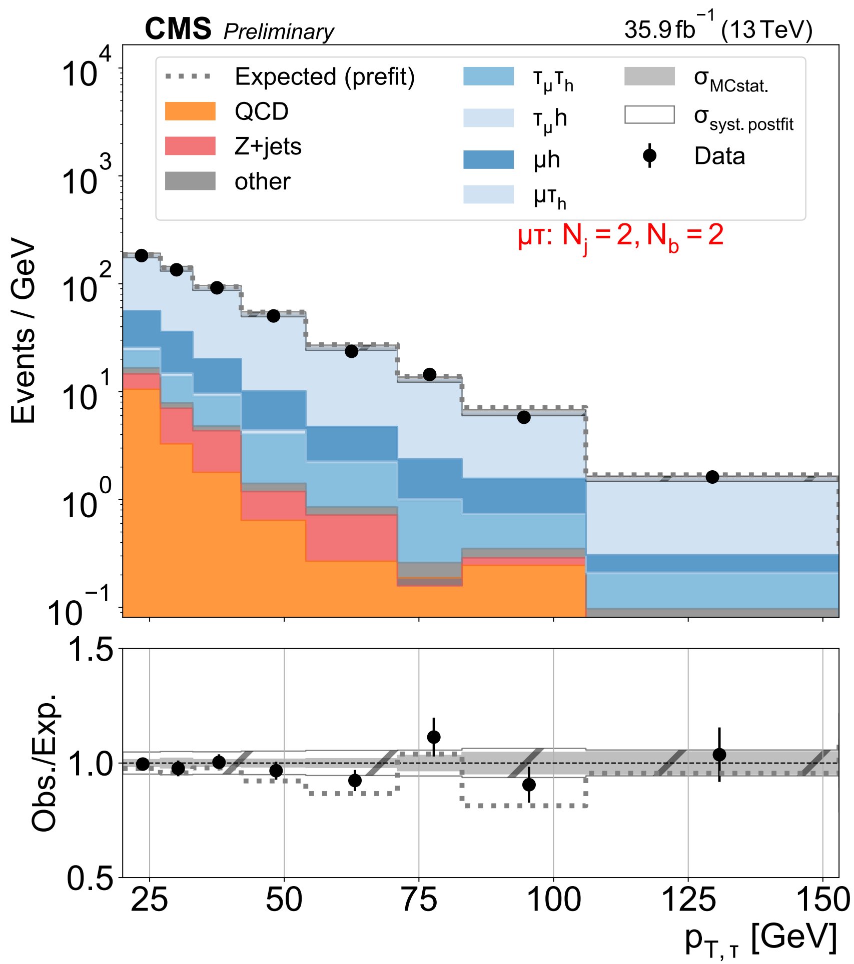


CMS Test of LFU

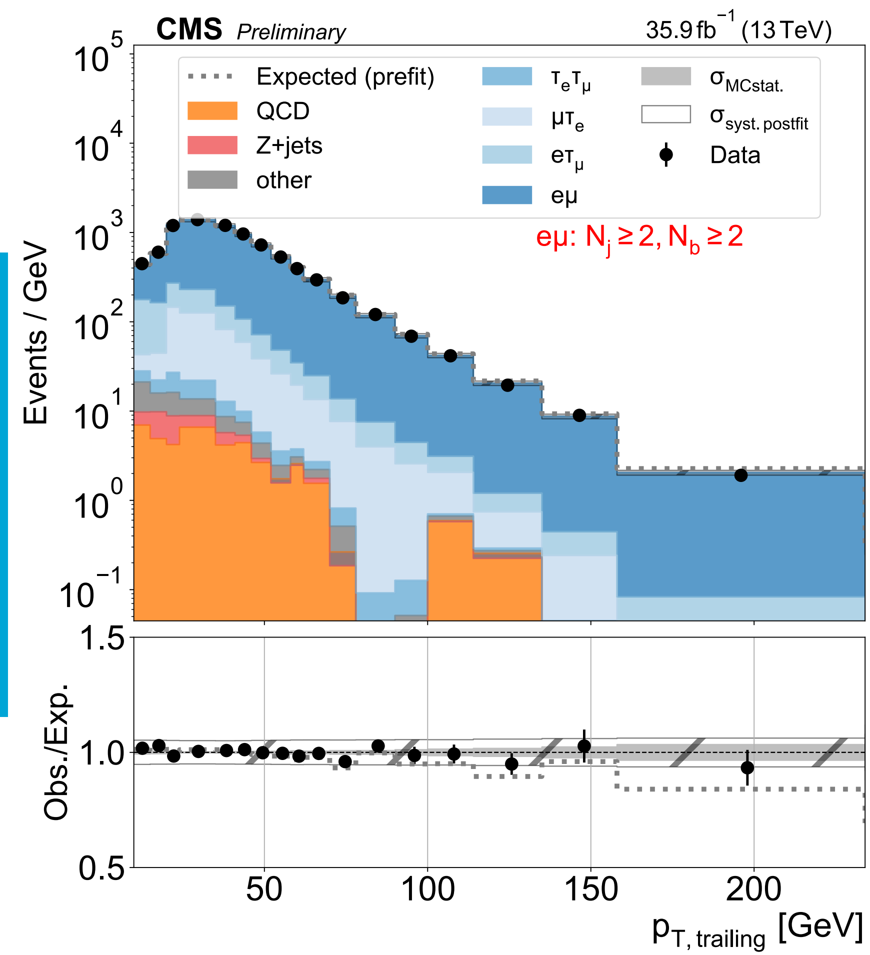
- Inclusive analysis targeting simultaneous extraction of $\beta = \{\beta_e, \beta_\mu, \beta_\tau, \beta_h\}$ W boson branching fractions, using both leptonic and hadronic τ lepton decays
  - ★ Search includes W+jets, WW, tW, and tt production
  - ★ Categorizes events in multiple classes depending on the leptonic and jet content and uses global fit to simultaneously extract the branching fractions
  - ★ Uses kinematic information in dilepton events to separate leptons coming directly from the W boson decay from those coming from the intermediate τ lepton decays
  - ★ Unlike the ATLAS analysis, does not use the lepton displacement to separate direct and τ lepton mediated decays

CMS: Examples of the Fits

- Fits to $p_T(\tau)$ distribution in the $\mu\tau$ category with 2 b jets and to the trailing lepton p_T in the $e\mu$ category with ≥ 2 b jets



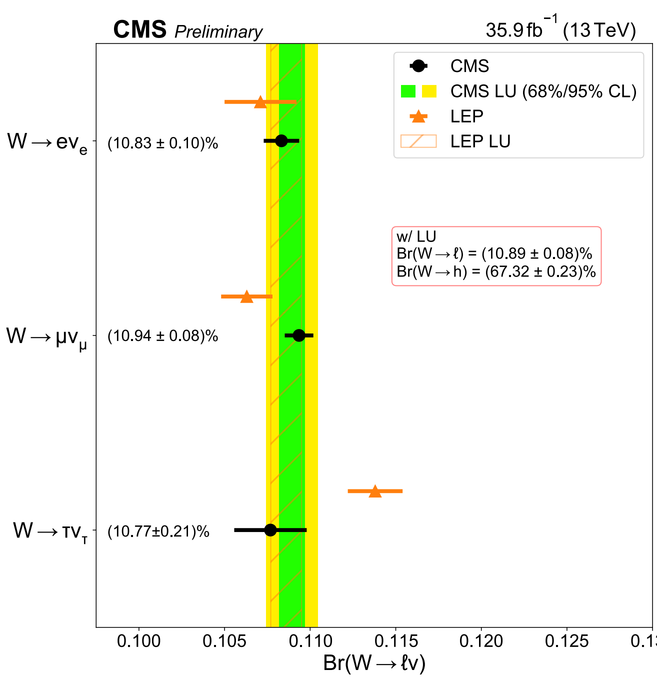
CMS PAS SMP-18-011

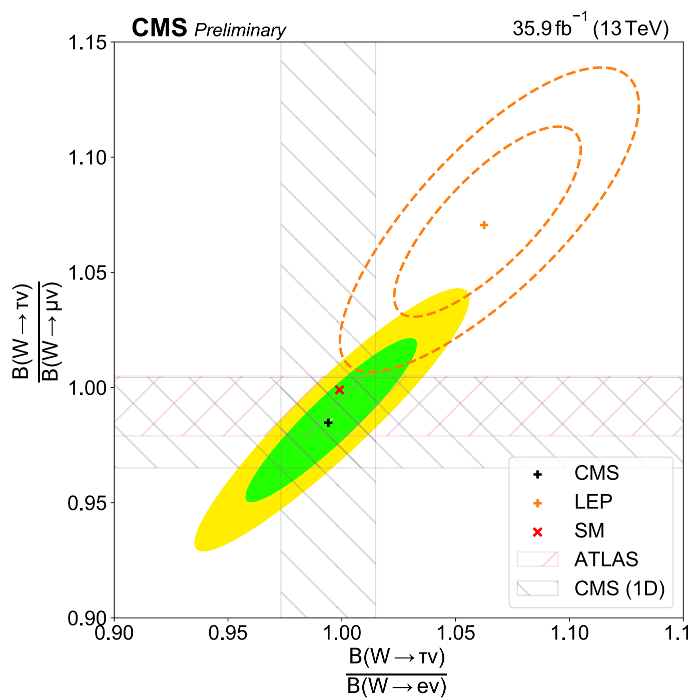


CMS Results

- Results consistent with both LU and ATLAS results, and are complementary to ATLAS via the inclusion of the electron channel
- Sensitivity to hadronic decays allow to test the CKM matrix unitarity and extract the poorly measured $|V_{cs}|$ element with the precision rivaling the world average

	CMS	LEP	ATLAS
$R_{\mu/e} = \mathcal{B}(W \to \mu\overline{\nu}_\mu)/\mathcal{B}(W \to e\overline{\nu}_e)$	1.009 ± 0.009	0.993 ± 0.019	–
$R_{\tau/e} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to e\overline{\nu}_e)$	0.994 ± 0.021	1.063 ± 0.027	–
$R_{\tau/\mu} = \mathcal{B}(W \to \tau\overline{\nu}_\tau)/\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–





CKM matrix unitarity:

$$\sum_{ij}|V_{ij}|^2 = 1.989 \pm 0.021$$

Extraction of $|V_{cs}|$:

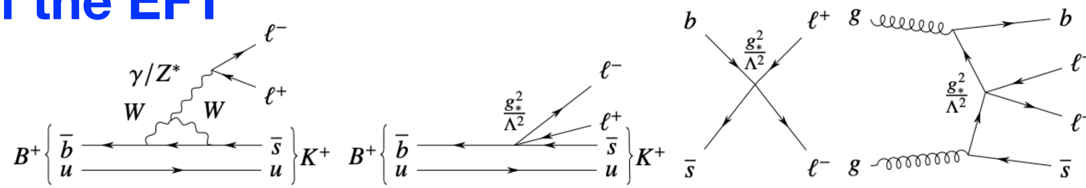
$$|V_{cs}| = 0.969 \pm 0.011$$

World average (from D meson decays):

$$|V_{cs}| = 0.987 \pm 0.011$$

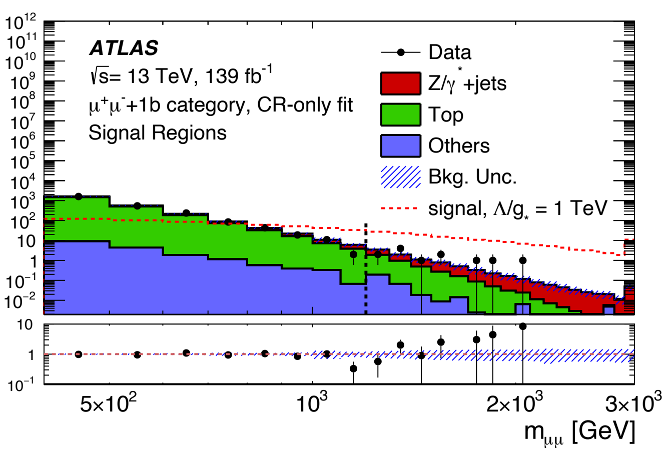
ATLAS LFU in Dilepton + b Jets

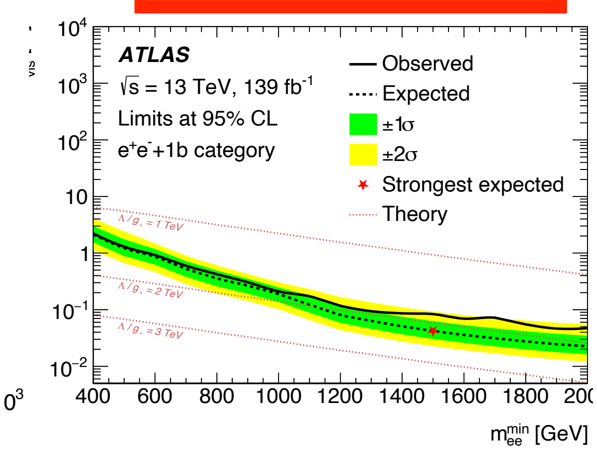
- Flavor anomalies in b → s$\ell\ell$ transitions can be also probed with high-p_T physics, in the context of the EFT

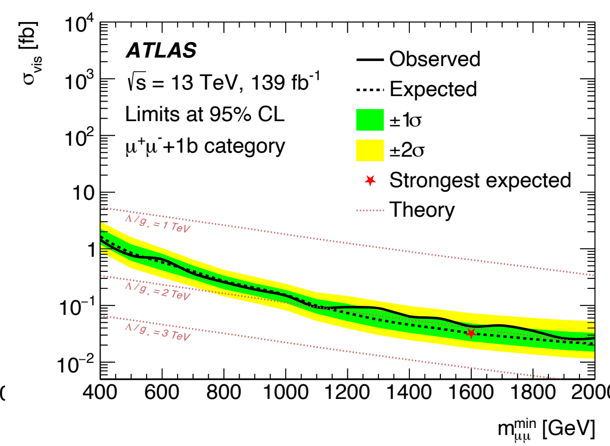


- Same operators will give rise to signatures with dileptons and jets in the final state
- New ATLAS analysis requires a pair of OS electrons and muons and either 0 or 1 b-tagged jet
- The dilepton mass distribution is then analyzed in the EFT or model-independent contexts to set limits on new physics contributions

arXiv:2105.13847



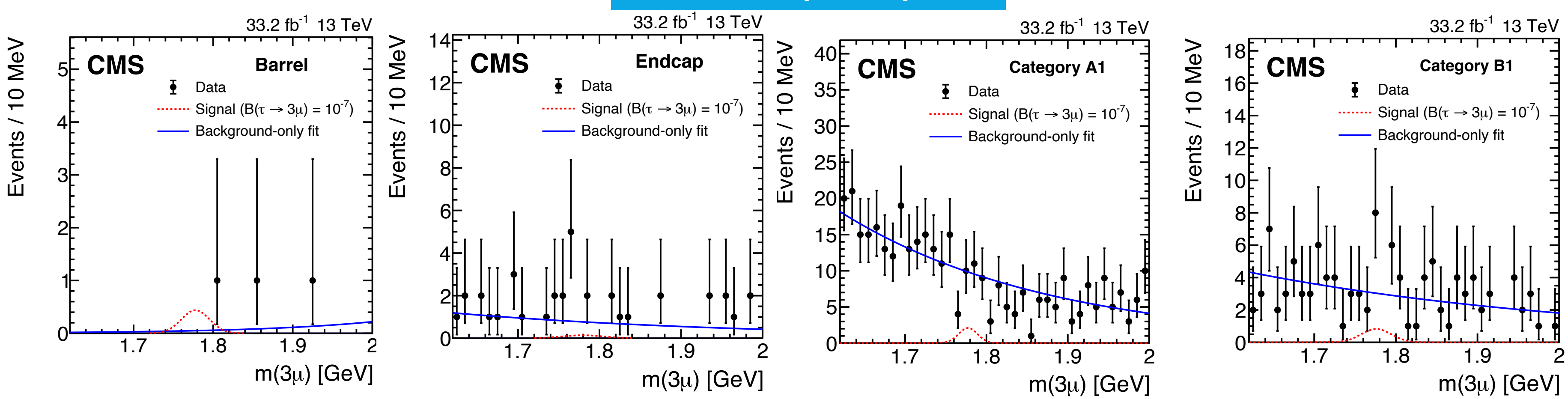




CMS Search for LFV $\tau \to 3\mu$ Decay

- The best limit was set a decade ago by Belle: $B(\tau \to 3\mu) < 2.1\times10^{-8}$ @90% CL
  - ★ At the LHC, ATLAS set a limit of 38×10^{-8} using $W(\tau\nu)$ decays
  - ★ LHCb set a limit of 4.6×10^{-8} using τ leptons from $B/D_{(s)}$ meson decays (HF channel)
- A new analysis from CMS combines the W and HF channels to maximize the sensitivity
  - ★ The HF channel has $D_s \to \phi\pi \to \mu\mu\pi$ as the normalization mode; W channel is normalized through the inclusive W cross section measurement
- Set the limit at 8.0×10^{-8} (6.8×10^{-8} expected) @90% CL. in the combination of the two channels, dominated by the HF channel (2:1)
- Finalizing the full Run 2 data analyses with an even more optimized selection, expected to approach Belle sensitivity

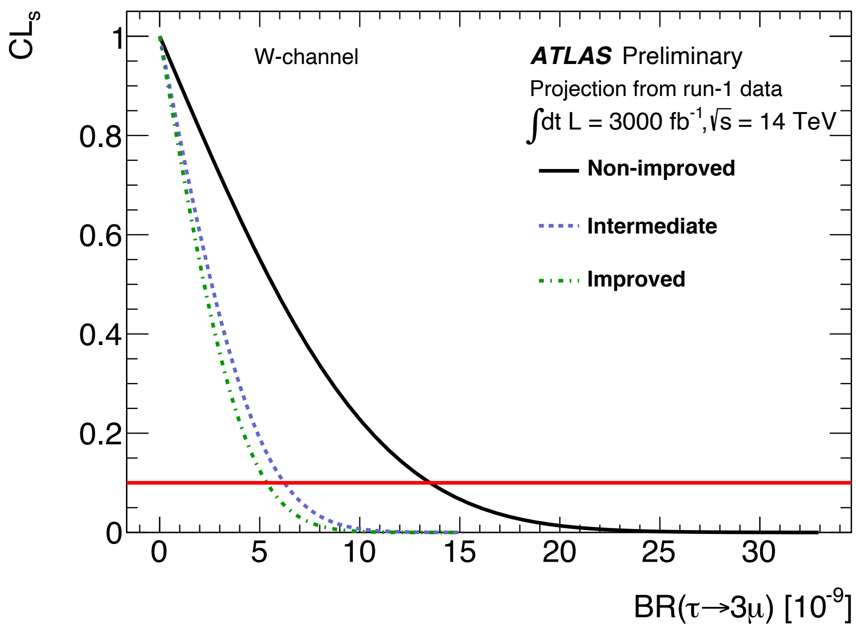
W channel — JHEP 01 (2021) 163 — **HF channel**



HL LHC Projections

- ATLAS compiled the HL LHC projections based on their present analysis (likely to be quite conservative!)
  - ★ Sensitivity ~10^{-9} @ 90% CL is likely to be achieved

Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\text{bkg}}^{\text{exp}}$	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
Run 1 result	2.31	0.19	276
Non-improved	2.31	50.71	13.52
Intermediate	5.01	50.71	6.23
Improved	5.01	40.06	5.36



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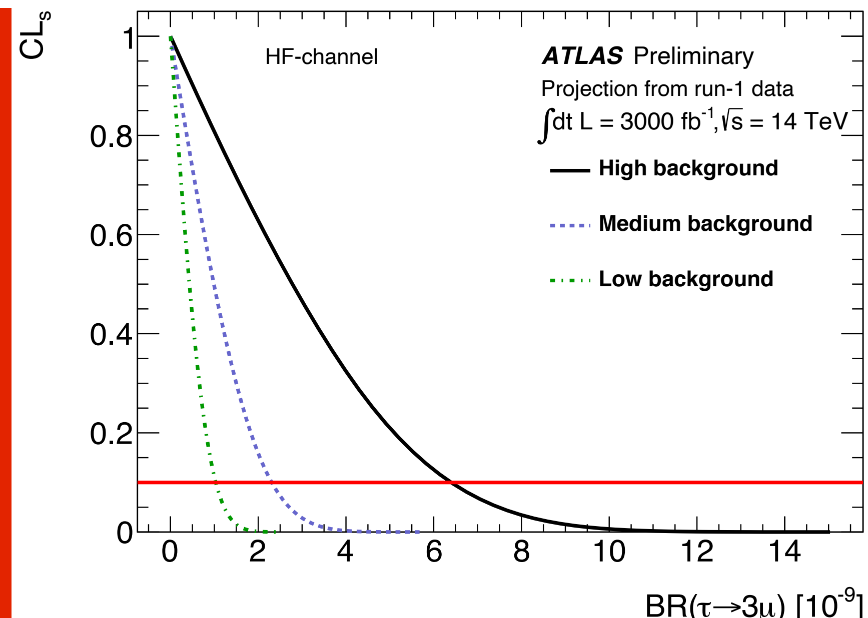


More Searches for LFV

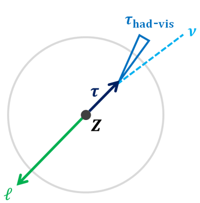
- A related topic is searches for lepton flavor violation in various sectors
  - ★ Particularly topical given possible flavor anomalies reported in the $b \to s\ell^+\ell^-$ and $b \to c\ell^-\nu$ transitions
- By now each ATLAS and CMS has 2.5 orders of magnitude more ($\sim 10^{10}$) Z bosons produced than all four LEP experiments ($\sim 2 \times 10^7$)
  - ★ Explore LFV in Z boson decays with unprecedented precision, particularly for the LFV couplings involving third-generation leptons
  - ★ Previous best limits on the τe and $\tau\mu$ decays were set by LEP at 9.8×10^{-6} and 1.2×10^{-5} @95% CL, respectively (for unpolarized τ leptons)
- Challenging new ATLAS search for $Z \to \tau e$ and $\tau\mu$ using the hadronic τ decay channel

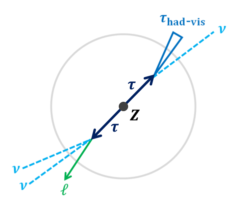
ATLAS Z Boson LFV Search

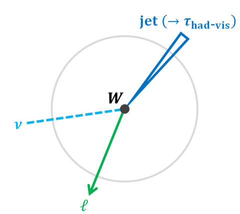
- Explore signatures with an isolated energetic lepton (e or μ), a τ-like jet (single- or three-prong), and relatively small M_T < 35 GeV, but rather large $M_{vis}(\tau\ell)$ > 60 GeV
- Main backgrounds come from $Z(\tau_h\tau_\ell)$ and $W(\ell\nu)$+jet
  - ★ Partially suppressed by the above requirements; further reduced via an NN

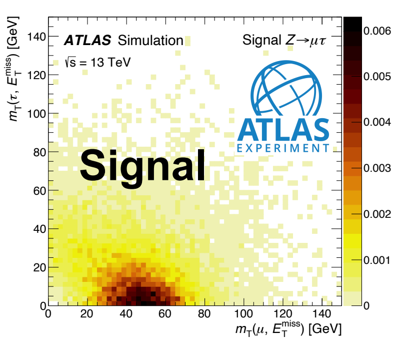
B(Z → τe) < 8.1 (8.1) × 10^{-6},
B(Z → τμ) < 9.6 (6.1) × 10^{-6} [combined w/ Run1] @ 95%CL
Better than LEP limits (both in the unpolarized τ scenario)!

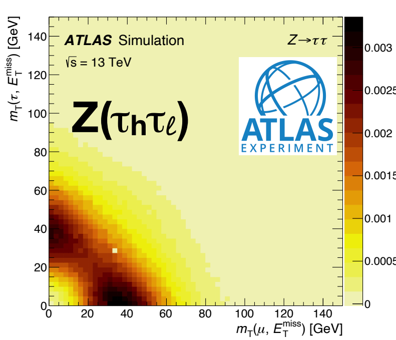
Nature Phys. 17 (2021) 819

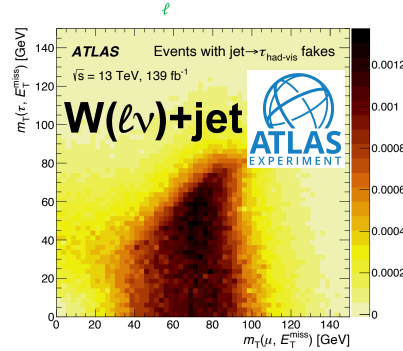


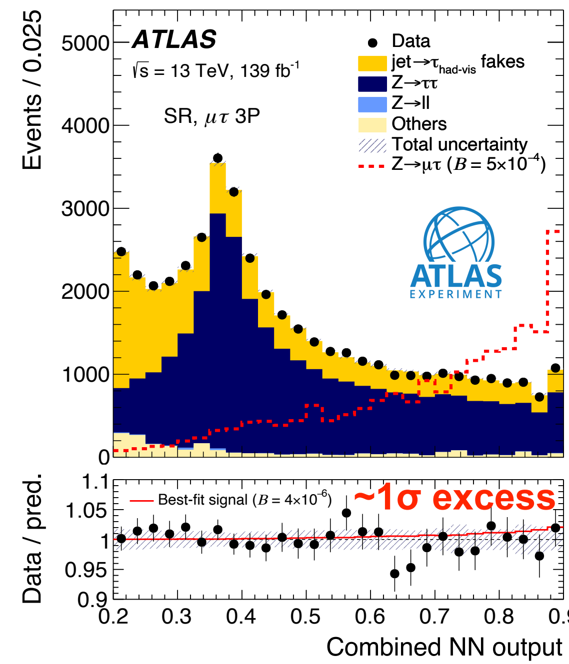






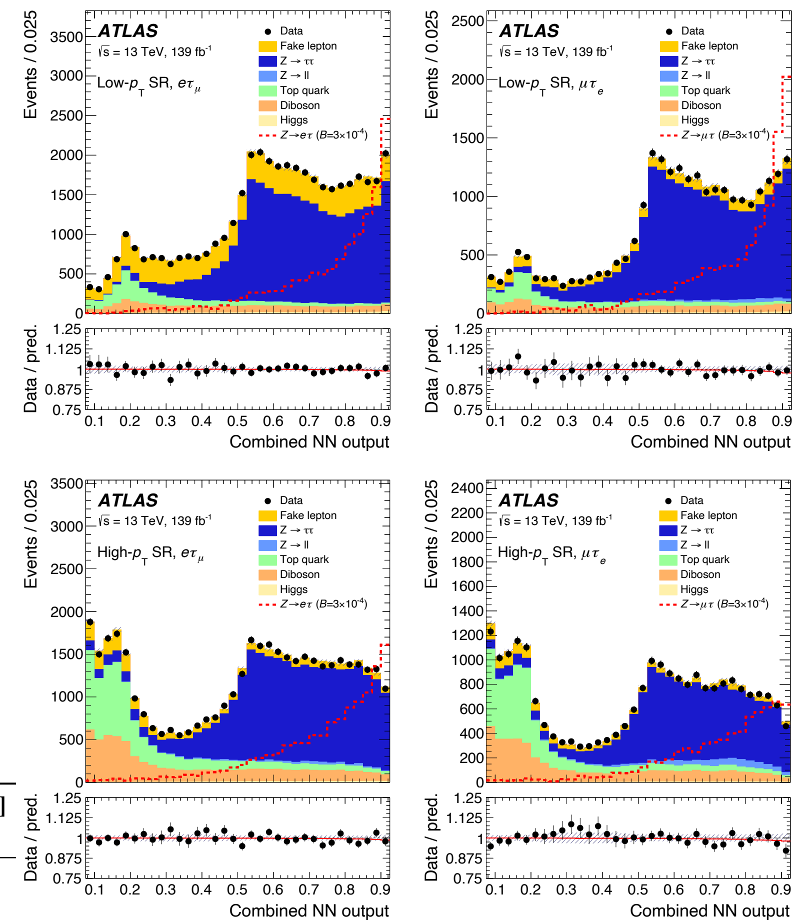






...adding Leptonic Tau Decay

- **First search at the LHC for $Z(\ell\tau_{\ell'})$ in the $e\tau_\mu$ and $\mu\tau_e$ channels**
  - ★ **Channels are further split into a high- and low-$p_T(\ell)$ signal regions**
  - ★ **The main irreducible $Z(\tau_\ell\tau_\ell)$ background is suppressed via a NN based on lepton kinematic variables**
- **The search improves significantly the sensitivity obtained in the τ_h channel and provides the most stringent limits on these LFV Z boson decay to date**



arXiv:2105.12491

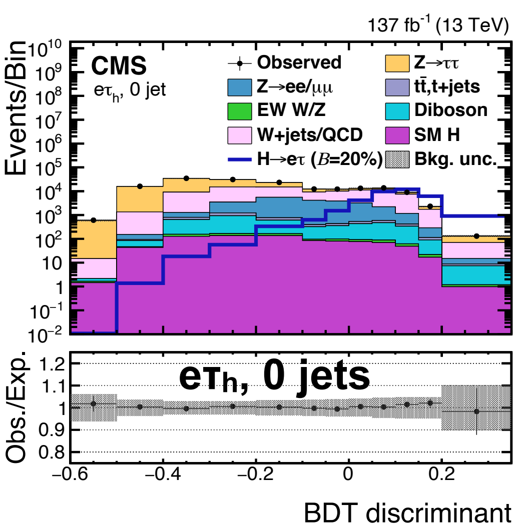
Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z\to\ell\tau)$ [$\times10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ [9]	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ [9]	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ [9]	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)

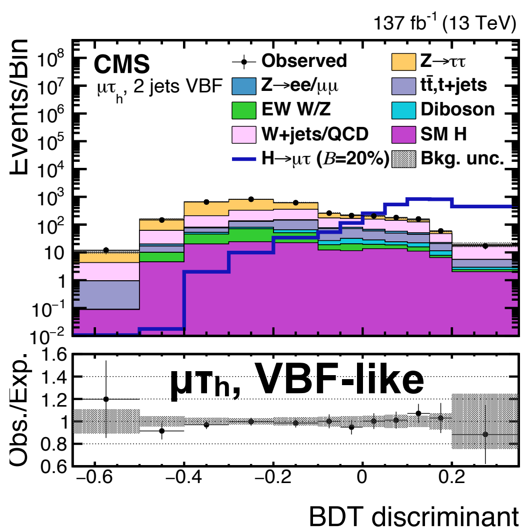
LFV in Higgs Decays

- Higgs is the only know fundamental particle with non-universal lepton flavor couplings
- Interesting to look for LFV decays in this sector, which is predicted in a variety of new physics models
- Both ATLAS and CMS have conducted a number of such searches since LHC Run 1
- The latest search from CMS is based on the entire Run 2 data set and looks for H(eτ) and H(μτ) decays
  - ★ B(H → eμ) is constrained below ~10^{-8} from μ→eγ, while the other two decay modes are only constrained to <10% by rare decays

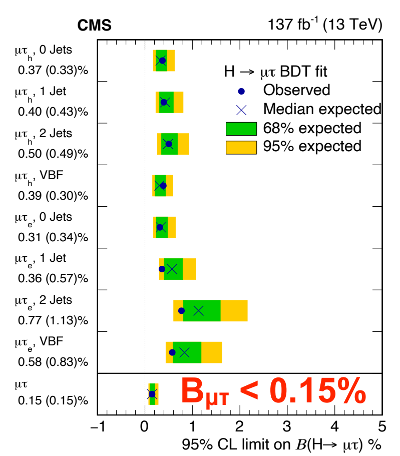
CMS H(e/μ+τ) Search

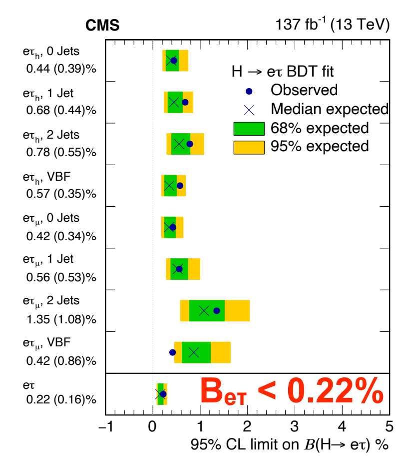
- Search proceeds in 6 different channels, depending on the τ lepton decay mode (τ_e, τ_μ, τ_h)
- Production mode is categorized according to the number of jets (0, 1, 2), and the 2-jet category is split into the VBF-like and the other
- Signal is enhanced via a BTD that uses kinematic properties of the leptons and τ_h, the collinear, visible, and transverse masses
- The dominant Z(ττ) background is estimated using the "embedding" technique based on Z(μμ) events in data with the muon footprints being replaced with simulated τ decays





[PRD 104 (2021) 032013]

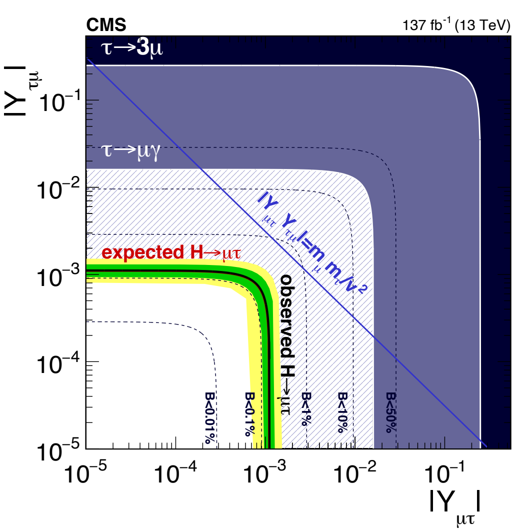


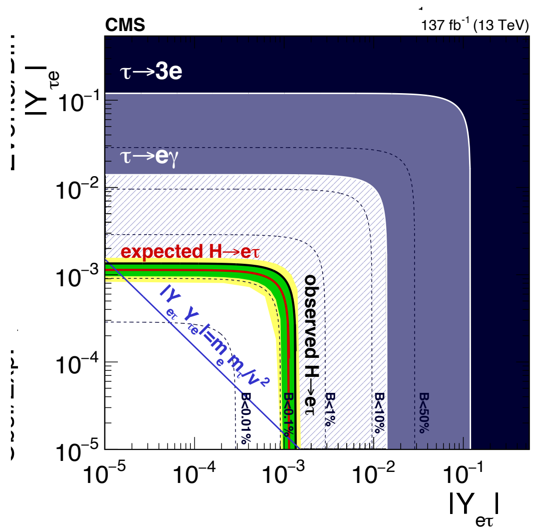


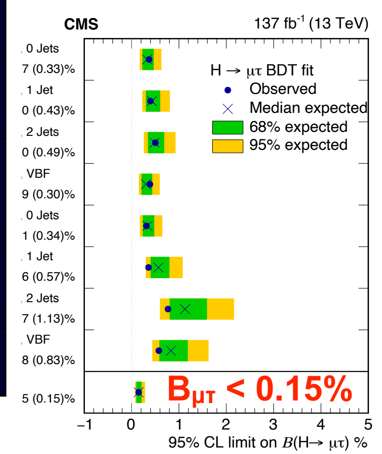
CMS H(e/μ+τ) Search

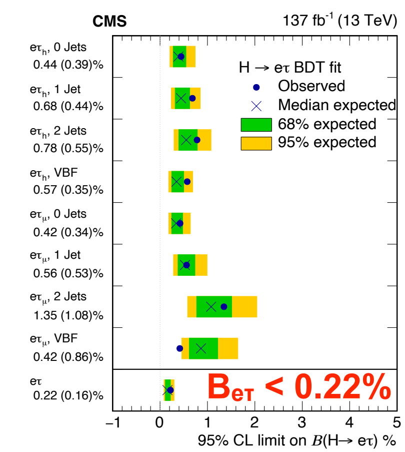
- Search proceeds in 6 different channels, depending on the τ lepton decay mode (τ_e, τ_μ, τ_h)
- Production mode is categorized according to the number of jets (0, 1, 2), and the 2-jet category is split into the VBF-like and the other
- Signal is enhanced via a BTD that uses kinematic properties of the leptons and τ_h, the collinear, visible, and transverse masses
- The dominant Z(ττ) background is estimated using the "embedding" technique based on Z(μμ) events in data with the muon footprints being replaced with simulated τ decays

PRD 104 (2021) 032013









ATLAS LFV in Top Quark Decays

- One could look for charged LFV in top quark decays $t \to \ell\ell'q$ (ℓ = e, μ, τ; q = u, c)
  - ★ Can be described via dim-6 EFT
  - ★ Indirect limits on $B(t \to e\mu u/c) \sim 4 \times 10^{-3}$
- Use top quark pair production with one top quark decaying into $bW \to b\ell\nu$ and the other via LFV, leading to a clean trilepton final state
- Main backgrounds come from non-prompt leptons, WZ, ZZ
  - ★ Use BDT built with the kinematic variables and various invariant masses to suppress the background

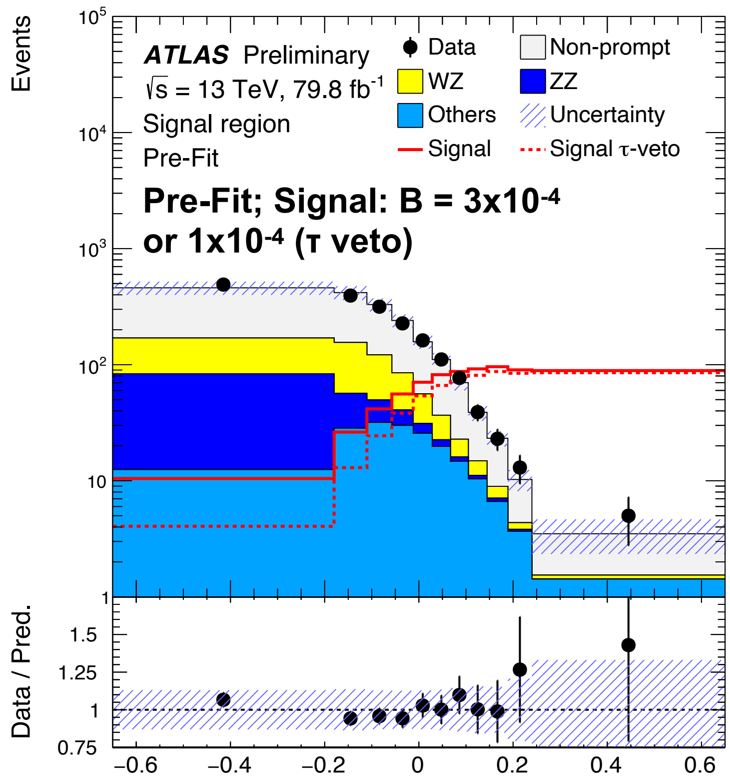
LFV in Top Quark Decays

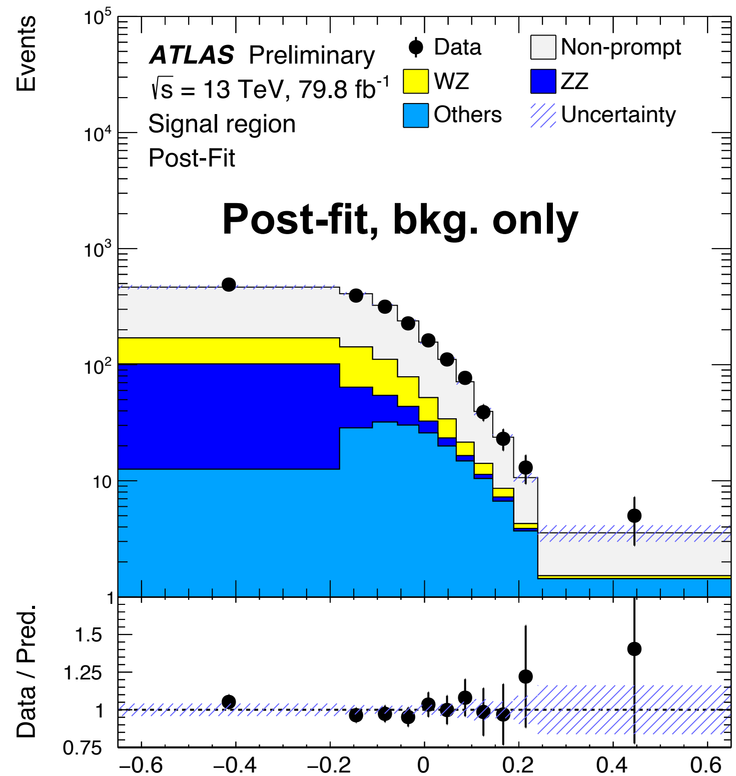
- **Results are the first direct limits on this decay, and improve by 3 orders of magnitude on the indirect B(t →eμq) limit**

$$\mathcal{B}(t \to \ell\ell' q) < 1.36^{+0.61}_{-0.37} \times 10^{-5} \quad \text{(expected)}$$
$$\mathcal{B}(t \to \ell\ell' q) < 1.86 \times 10^{-5} \quad \text{(observed)}$$

$$\mathcal{B}(t \to e\mu q) < 4.8^{+2.1}_{-1.4} \times 10^{-6} \quad \text{(no } \tau \text{ in cLFV vertex, expected),}$$
$$\mathcal{B}(t \to e\mu q) < 6.6 \times 10^{-6} \quad \text{(no } \tau \text{ in cLFV vertex, observed).}$$

ATLAS CONF-2018-044

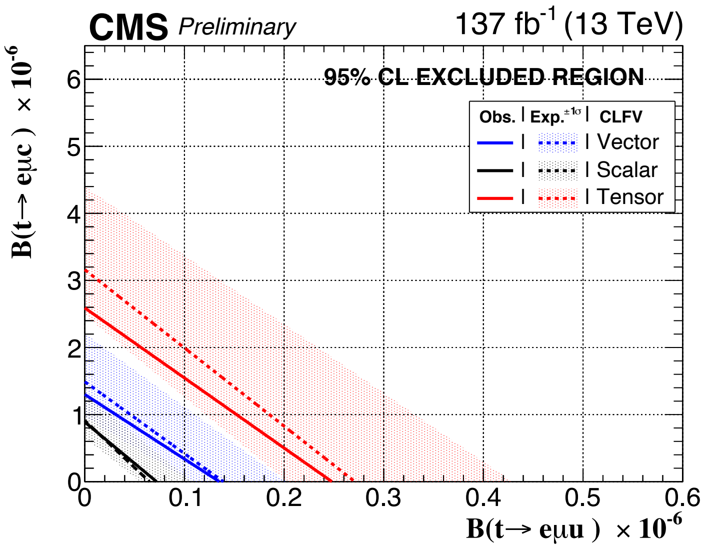


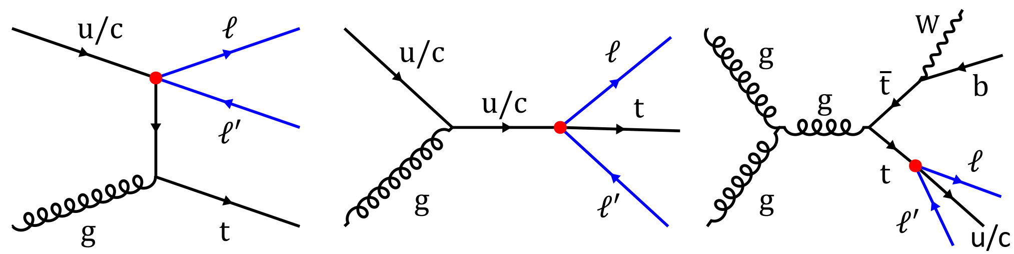


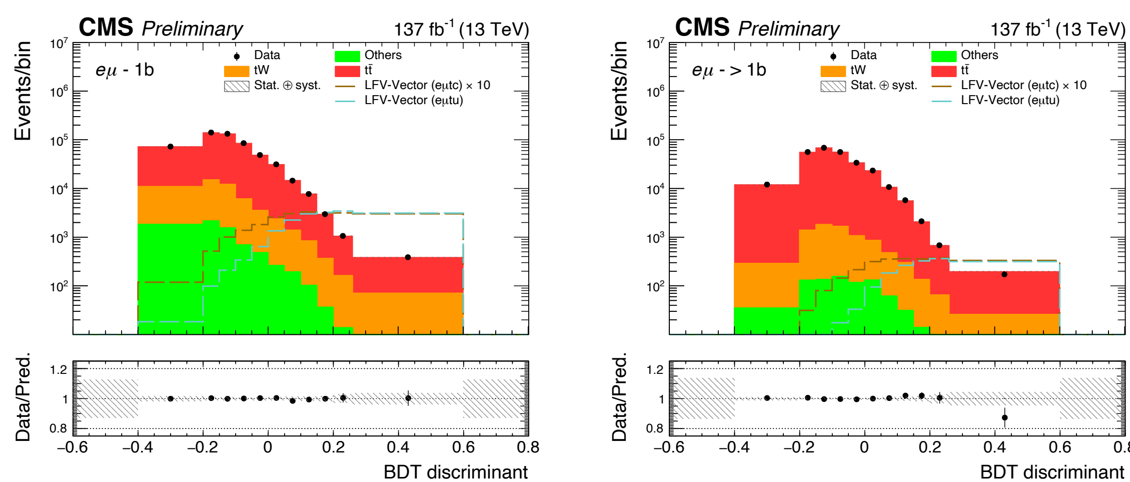
CMS LFV t → eμq Result

- CMS has a recent result in the t → eμu/c channel, using both the effects of this LFV vertex on production and decay
  - ★ Relies mainly on hadronic decays of the second top quark and on single t production
  - ★ Uses BDT and b-tag categories for optimal signal extraction
- Considers somewhat different EFT formalisms with operators corresponding to scalar, vector, and tensor couplings
- Substantially improves on ATLAS limits reaching sub ~10^{-7} sensitivity on the branching fraction

CMS PAS TOP-19-006



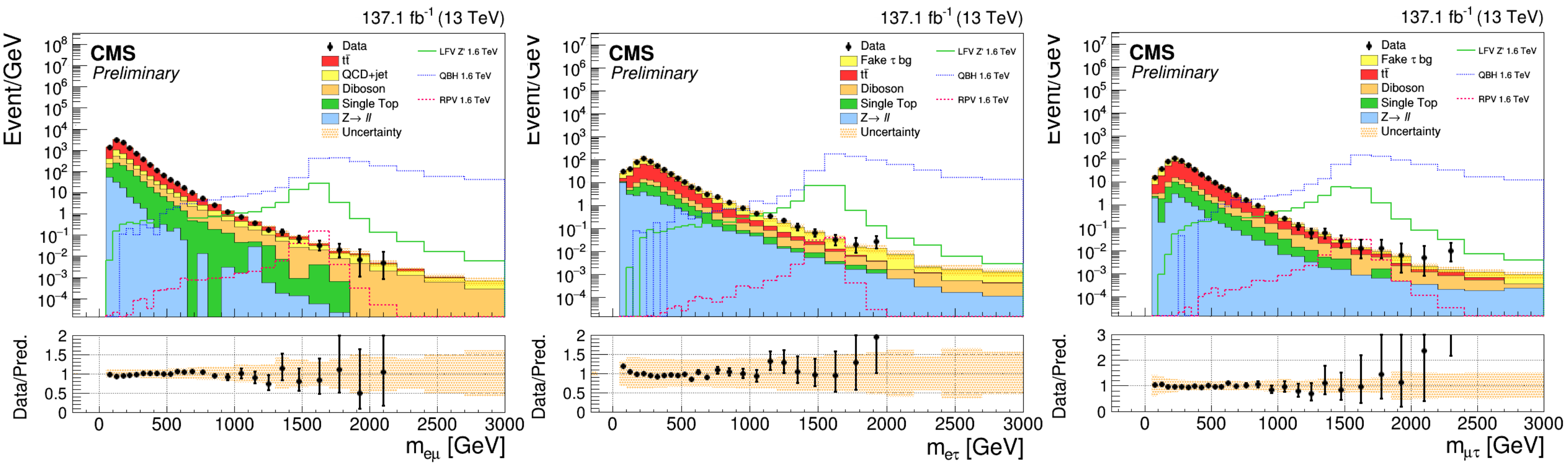




Search for LFV Resonances

- One could look for generic high-mass objects decaying via LFV channels: eμ, μτ, eτ
- Classical examples are R-parity violating SUSY, LFV Z', quantum black holes
- Recent CMS analysis based full Run 2 data
- Standard background estimation techniques: irreducible from MC simulation, reducible from control data samples

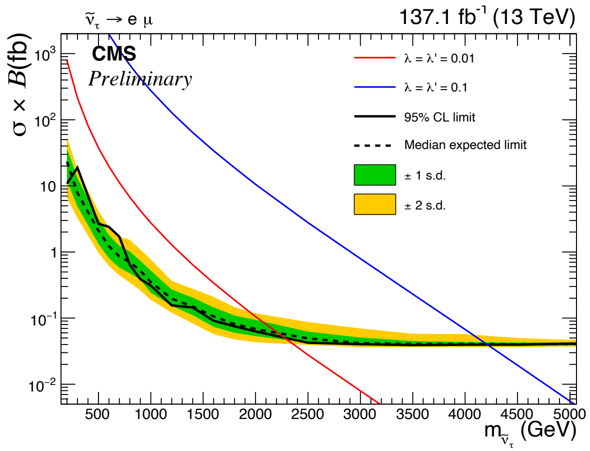
CMS PAS EXO-19-014

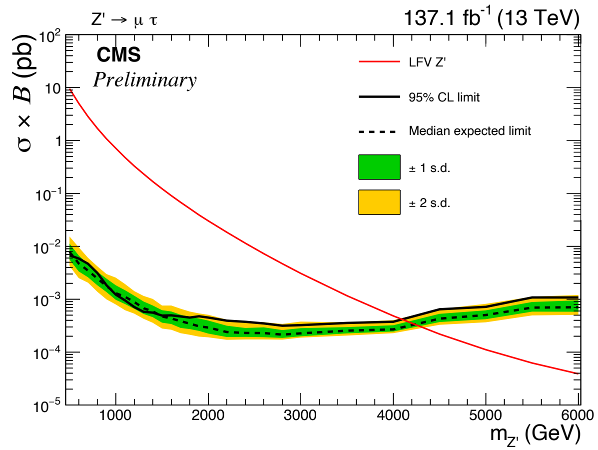


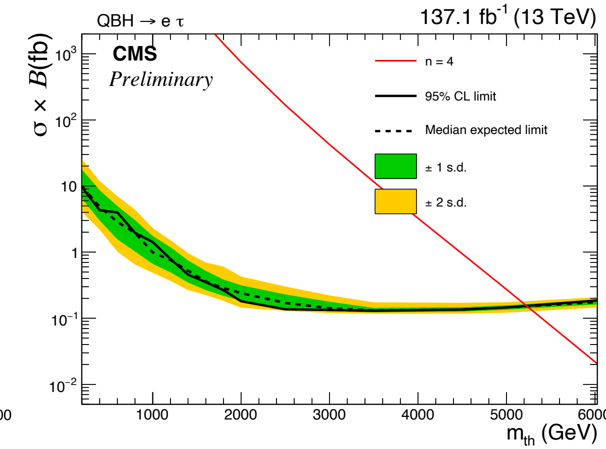
LFV Resonance Limits

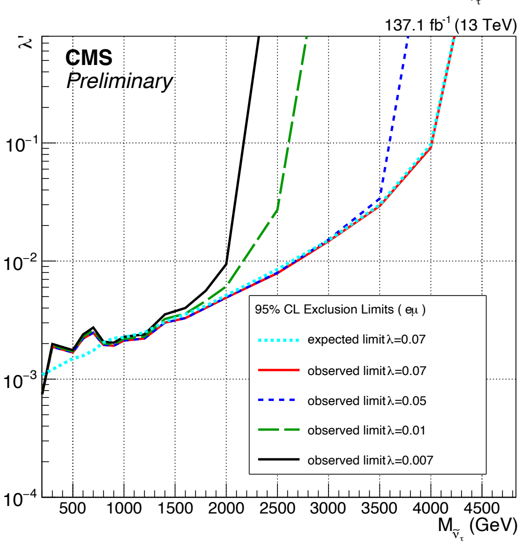
- Set stringent limits on tau sneutrino, LFV Z', QBH, as well as model-independent limits

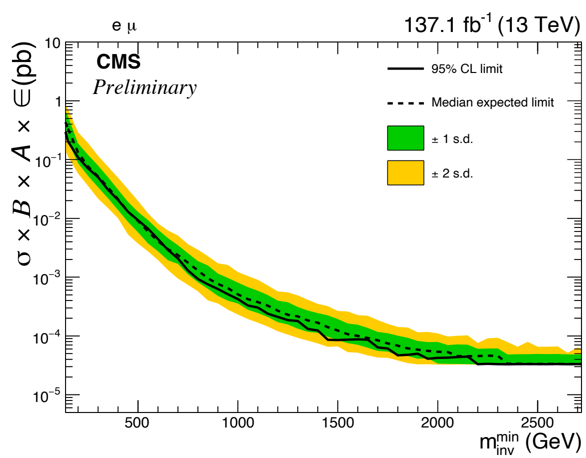
CMS PAS EXO-19-014

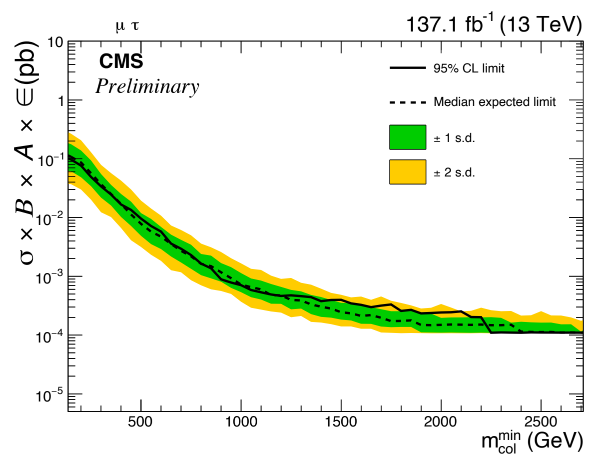










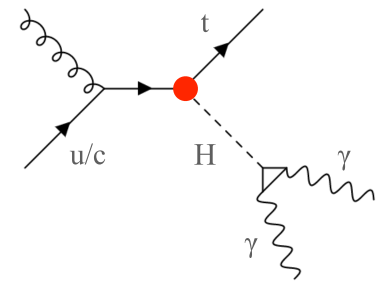


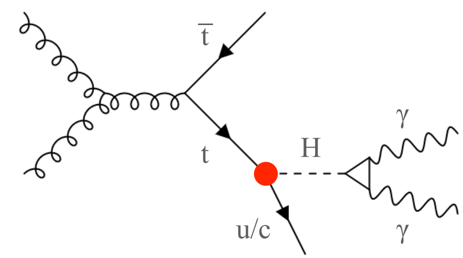
FCNC with Top Quarks

- LFV and FCNC processes are often interconnected
- Looking for FCNC in the quark sector is an interesting way of searching for new physics that may also lead to LFV and/or LFU violation
- Top quark is a great laboratory to search for this process
  - ★ Decays before hadronizaton, so theoretical calculations are simpler and cleaner
  - ★ Has a large Yukawa coupling to the Higgs boson
  - ★ Third-generation FCNC operators are generally less constrained than first- and second-generation ones

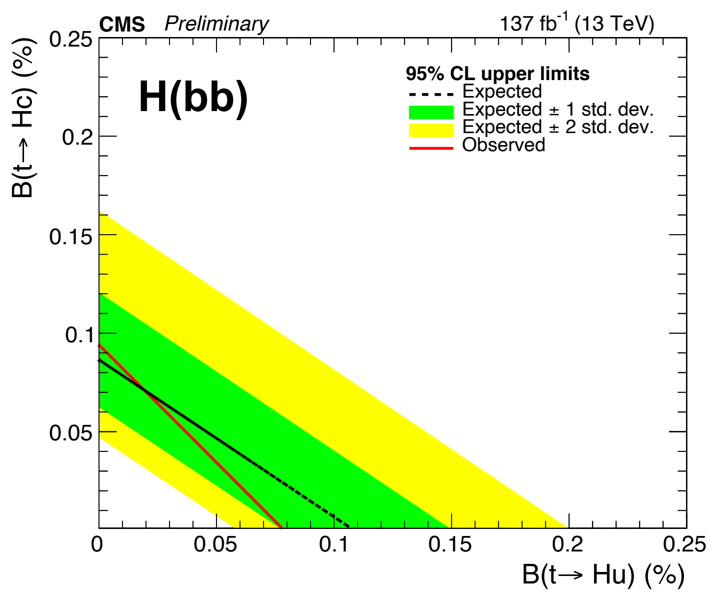
FCNC in Decays to H Bosons

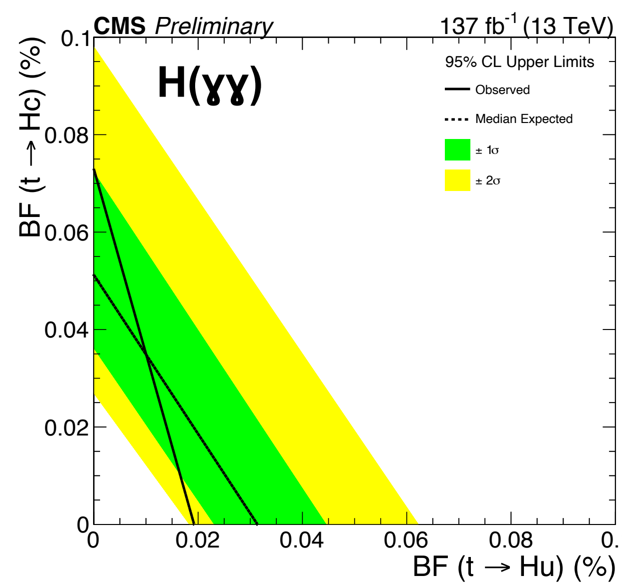
- Promising channels to look are t → Hu, t → Hc
  - ★ Extremely small in the SM (GIM-suppressed, Br ~ $10^{-15...-17}$); can be significantly enhanced in 2HDMs allowing possible detection at the LHC
- Can look for utH/ctH vertices in both single and pair production of top quarks
- Use the Higgs boson decay product invariant mass as the sensitive variable





CMS PAS TOP-19-002

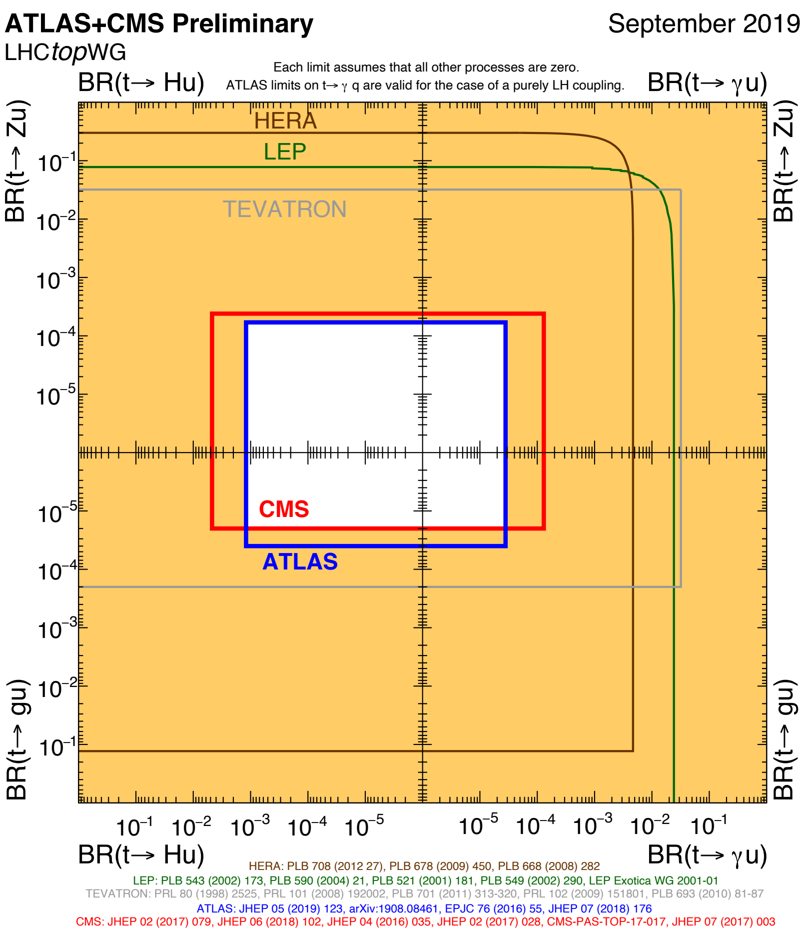




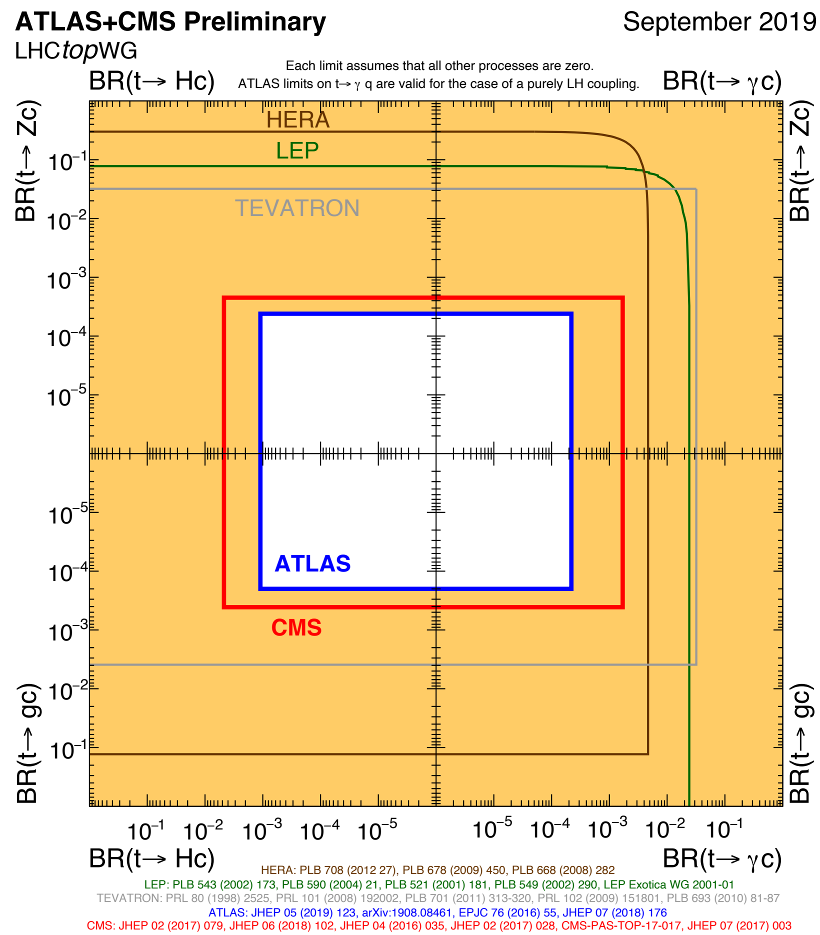
CMS PAS TOP-20-007

FCNC with Gauge Bosons

- **One could also look for FCNC couplings to Z bosons, gluons, or photons**
- **No recent results, but nice summary plots from older ATLAS and CMS measurements reaching 10^{-4}-10^{-5} precision in the B(t → Vu/c)**

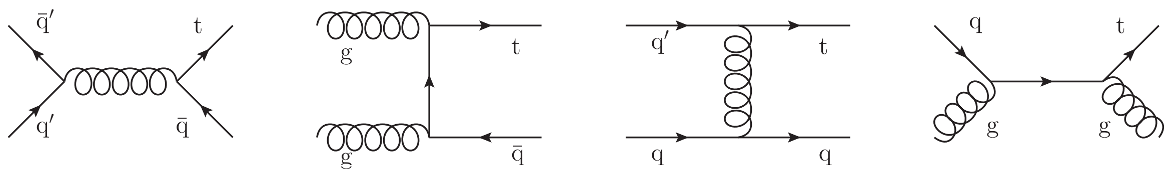


ATLAS-PHYS-PUB-2019-038

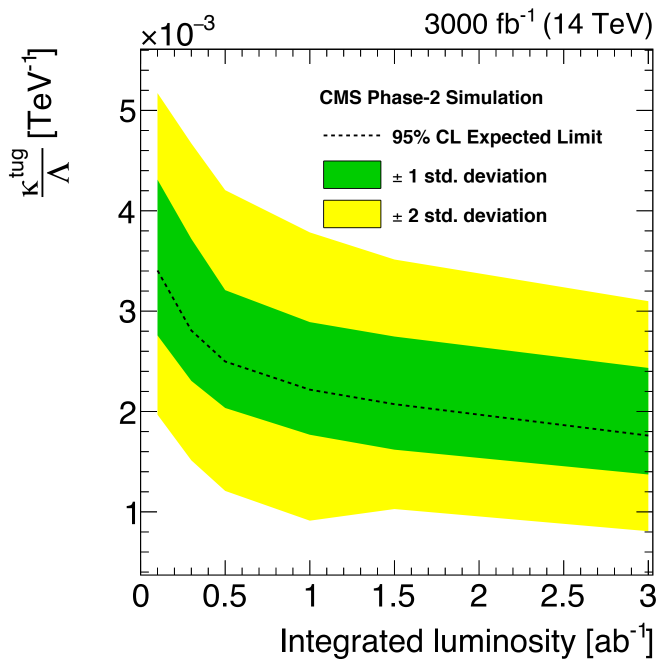


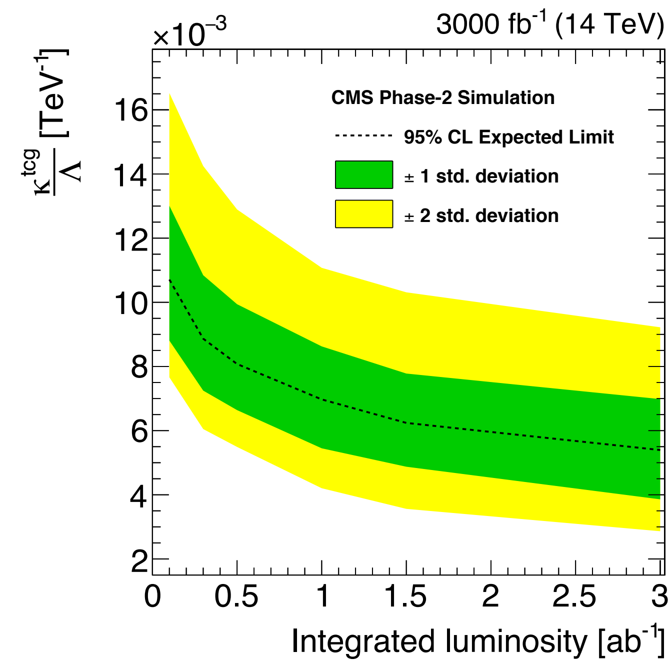
Projections for Run 3 and Beyond

- Projections for the sensitivity to the gtu and gtc couplings as a function of integrated luminosity, using semileptonic top quark decays



CMS PAS FTR-18-004





Modern Take: EFT

- More recently, EFT interpretations became a more systematic way of testing various LFV/FCNC operators
- Has an advantage of a global analysis sensitive to a number of such operators simultaneously
- One can use EFT to focus on specific operators, e.g., 4-fermion ones violating charged LFU or the FCNC ones
- The latter ones are as follows:

$$c_{t\varphi}^{[I](3a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{u\varphi}^{(3a)}\}, \qquad c_{uA}^{[I](3a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{c_W C_{uB}^{(3a)} + s_W C_{uW}^{(3a)}\},$$

$$c_{t\varphi}^{[I](a3)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{u\varphi}^{(a3)}\}, \qquad c_{uA}^{[I](a3)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{c_W C_{uB}^{(a3)} + s_W C_{uW}^{(a3)}\},$$

$$c_{\varphi q}^{-[I](3+a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{\varphi q}^{1(3a)} - C_{\varphi q}^{3(3a)}\}, \qquad c_{uZ}^{[I](3a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{-s_W C_{uB}^{(3a)} + c_W C_{uW}^{(3a)}\},$$

$$c_{\varphi u}^{[I](3+a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{\varphi u}^{(3a)}\}, \qquad c_{uZ}^{[I](a3)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{-s_W C_{uB}^{(a3)} + c_W C_{uW}^{(a3)}\},$$

$$c_{uG}^{[I](3a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{uG}^{(3a)}\}, \; c_{uG}^{[I](a3)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{uG}^{(a3)}\}$$

$$c_{lq}^{-[I](\ell,3+a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lq}^{-(\ell\ell 3a)}\}, \qquad c_{lequ}^{S[I](\ell,3a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lequ}^{1(\ell\ell 3a)}\},$$

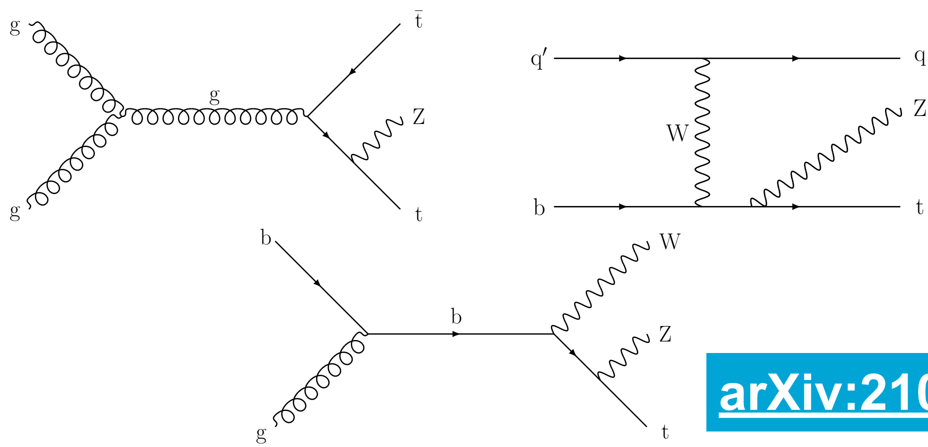
$$c_{eq}^{[I](\ell,3+a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{eq}^{(\ell\ell 3a)}\}, \qquad c_{lequ}^{S[I](\ell,a3)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lequ}^{1(\ell\ell a3)}\},$$

$$c_{lu}^{[I](\ell,3+a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lu}^{(\ell\ell 3a)}\}, \qquad c_{lequ}^{T[I](\ell,3a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lequ}^{3(\ell\ell 3a)}\},$$

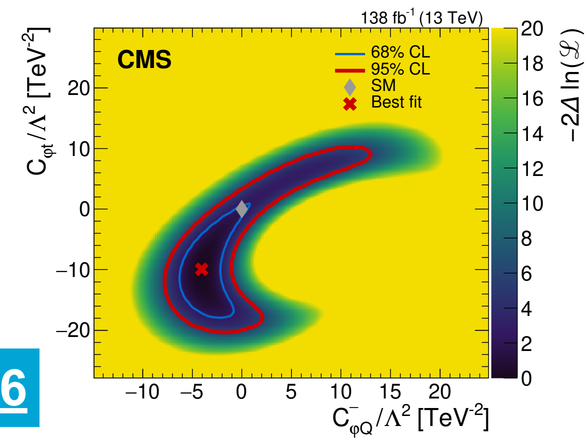
$$c_{eu}^{[I](\ell,3+a)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{eu}^{(\ell\ell 3a)}\}, \qquad c_{lequ}^{T[I](\ell,a3)} \equiv {}^{[\mathrm{Im}]}_{\mathrm{Re}}\{C_{lequ}^{3(\ell\ell a3)}\}.$$

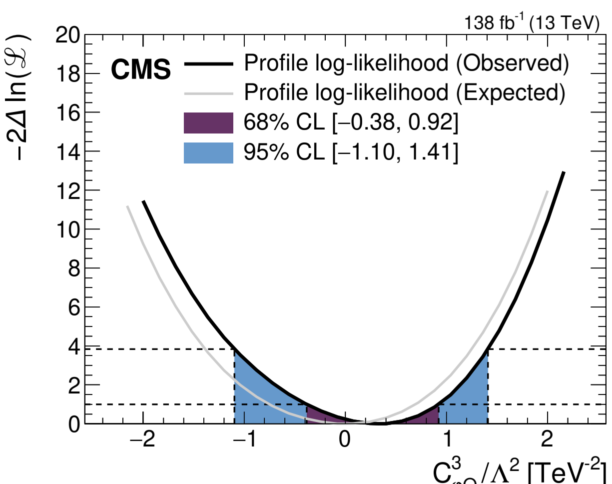
CMS EFT Contraints in tZ Production

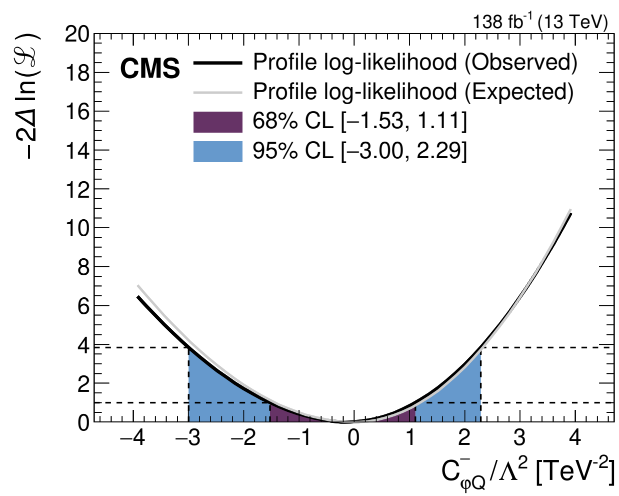
- Recent CMS paper focused on (t)tZ production in multilepton final states, reinterpreted in the EFT framework
- Set limits on some of the FCNC operators discussed above

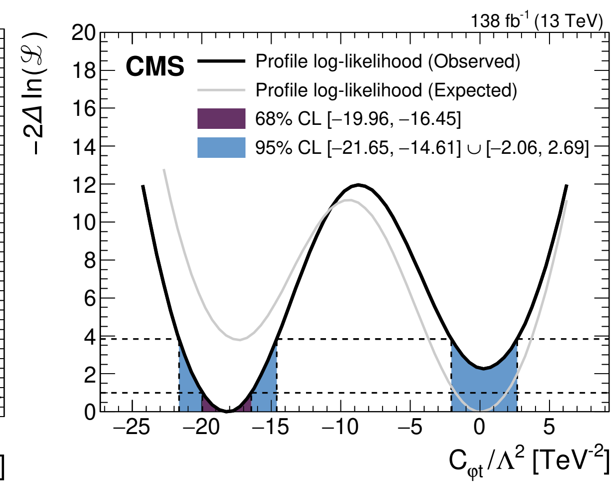


[arXiv:2107.13896](https://arxiv.org/abs/2107.13896)





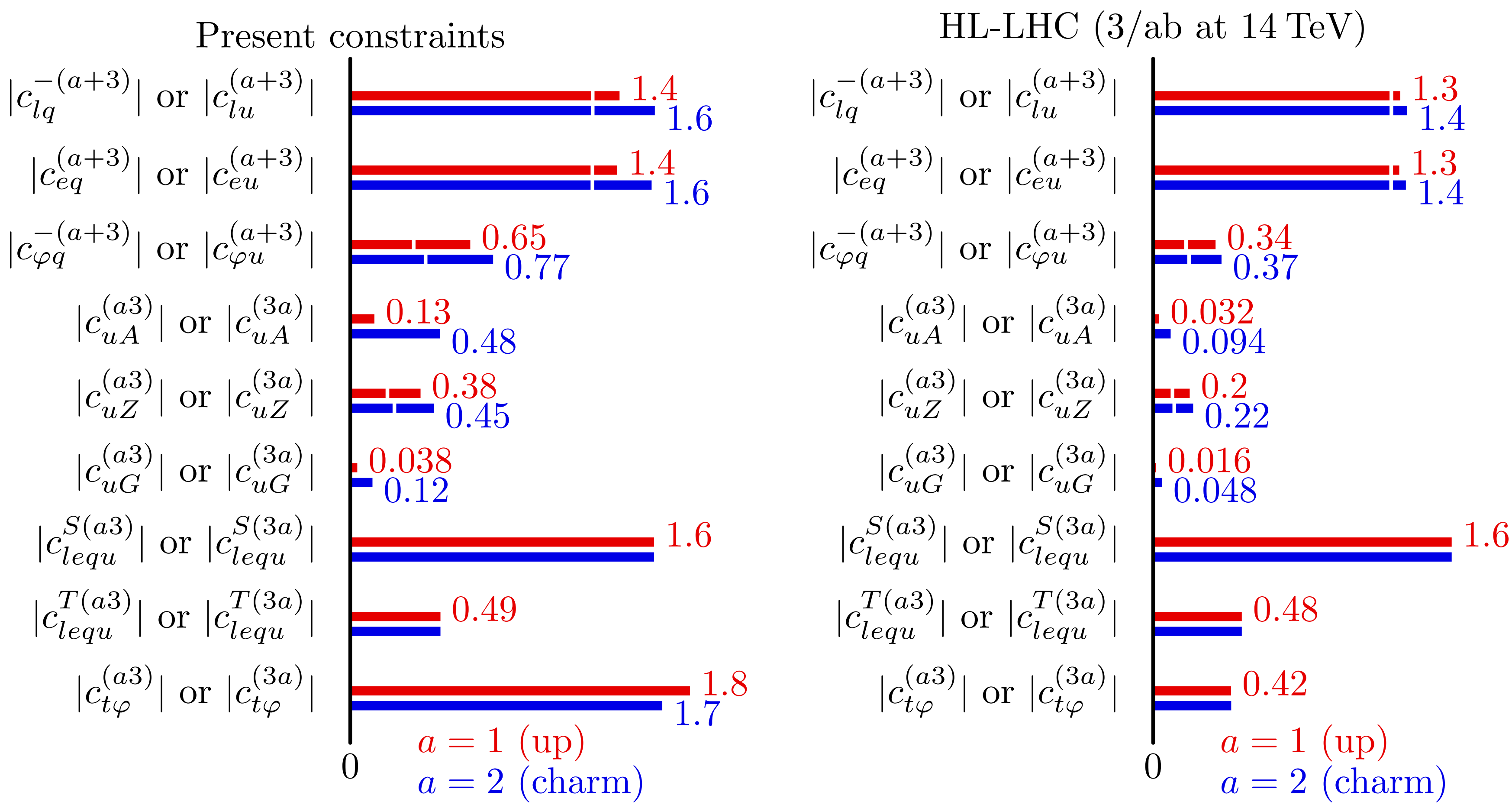




HL LHC Projections

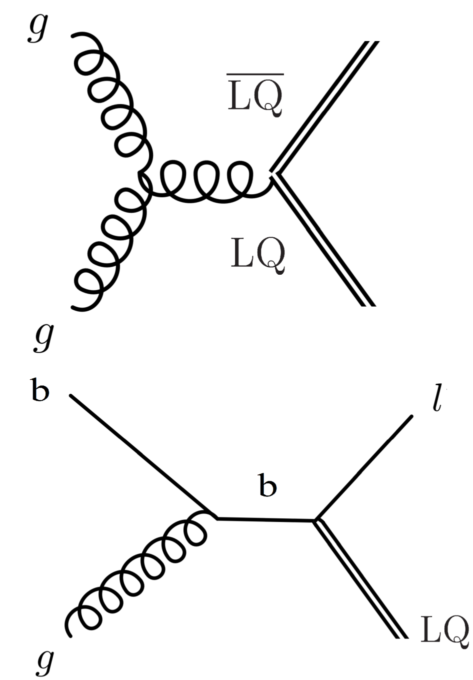
- **Projections for HL LHC running:**

A. Cerri et al., arXiv:1812.07638



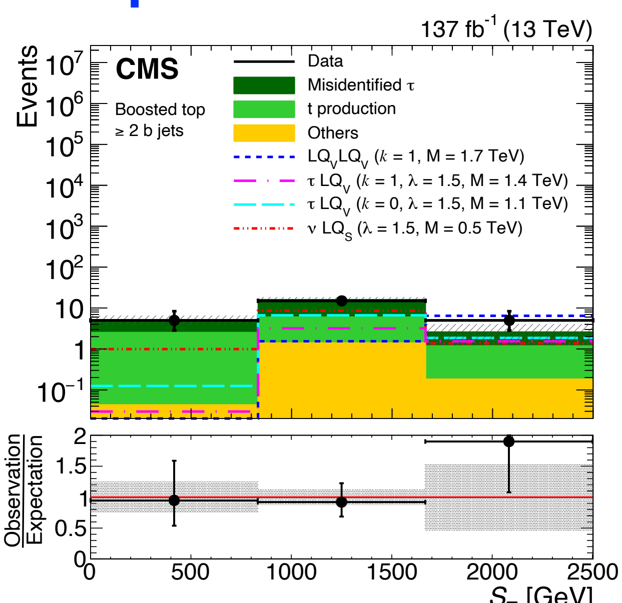
Leptoquark Searches

- Leptoquarks (LQs) remain one of the favorite theoretical models capable of explaining both tree-level anomalies seen in $b \to c\ell\nu$ decays and loop-level anomalies seen in $b \to s\ell\ell$ transitions
- Typically require LQs with cross-generational coupling, often with enhanced couplings to the third-generation fermions
  - ★ Motivates searches in the tτ, bτ, tν, bν LQ decay channels
  - ★ Can explore both single and pair production (the latter is independent of the LQ-ℓ-q coupling λ

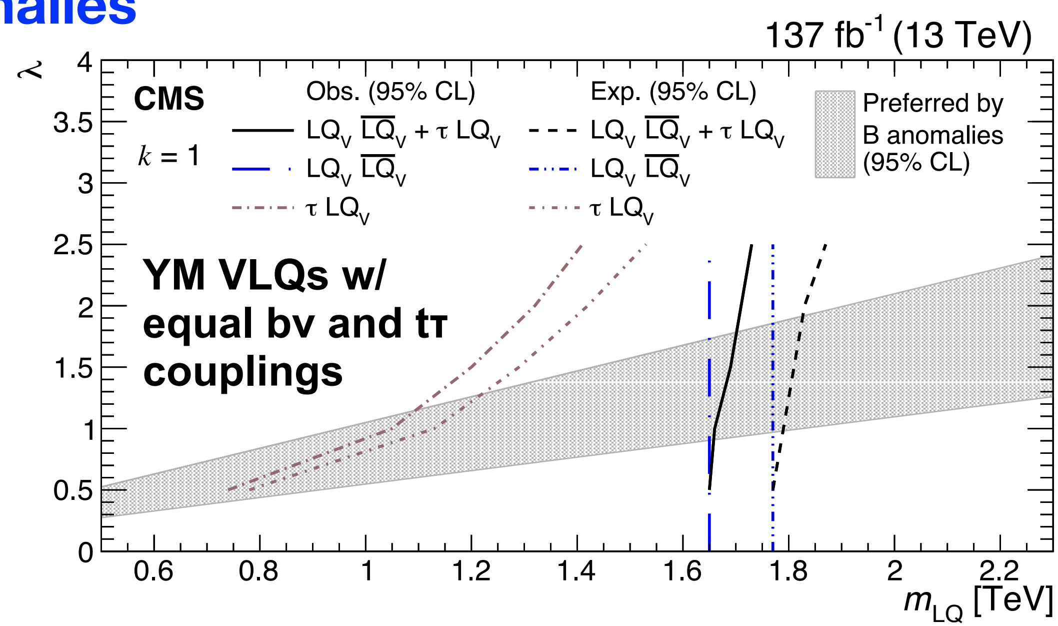


CMS Search for LQ3

- New CMS search combining single and pair production, using the ττν(b) channel, including dedicated analysis for the case when the top quark is produced with a large Lorentz boost
- All-hadronic analysis, which considers both the τ_h and hadronic top quark decays
- Using S_T as a sensitive variable for S/B separation
- Probes interesting range of parameter space for the possible explanation of flavor anomalies



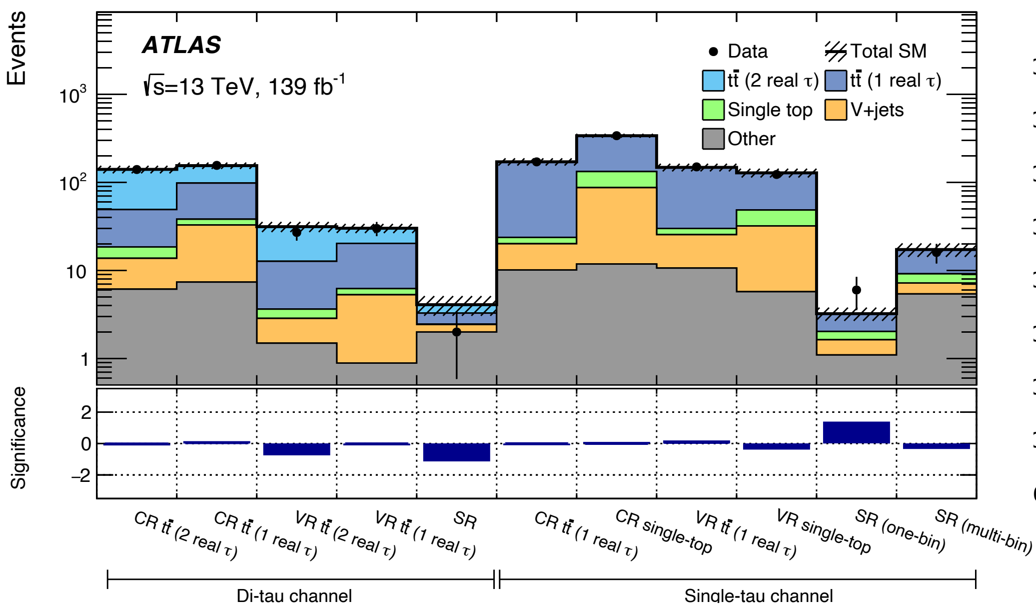
PLB 819 (2021) 136446

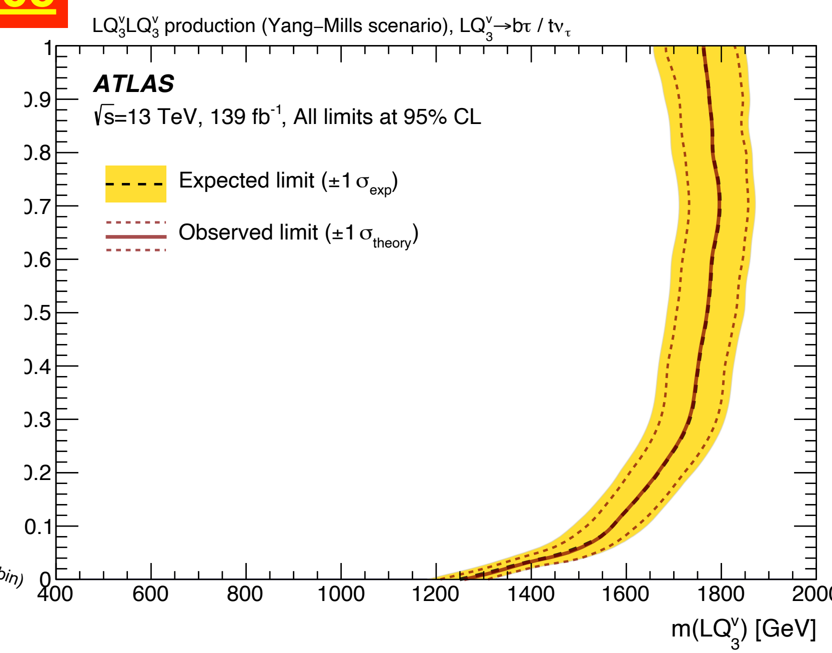


ATLAS Search for LQ3

- Analogous ATLAS analysis focuses on the final states with τ leptons and b jets and sets limits on Yang-Mills vector LQs decaying to bτ or $t\nu_\tau$
- Require either a pair of τ_h leptons or a single τ_h lepton and at least 2 b jets
- Limits also reach 1.8 TeV in this analysis

arXiv:2108.07665





Cross-Generational Couplings

- ATLAS has recently done a search for LQs that have cross-generational couplings, e.g., ce, bμ
- Only pair production is considered and the final states with a pair of OSSF leptons and b- or c-tagged jets are analyzed
- Limits are set as a function of the LQ mass and B(LQ → qℓ) for q = b, c and ℓ = e, μ

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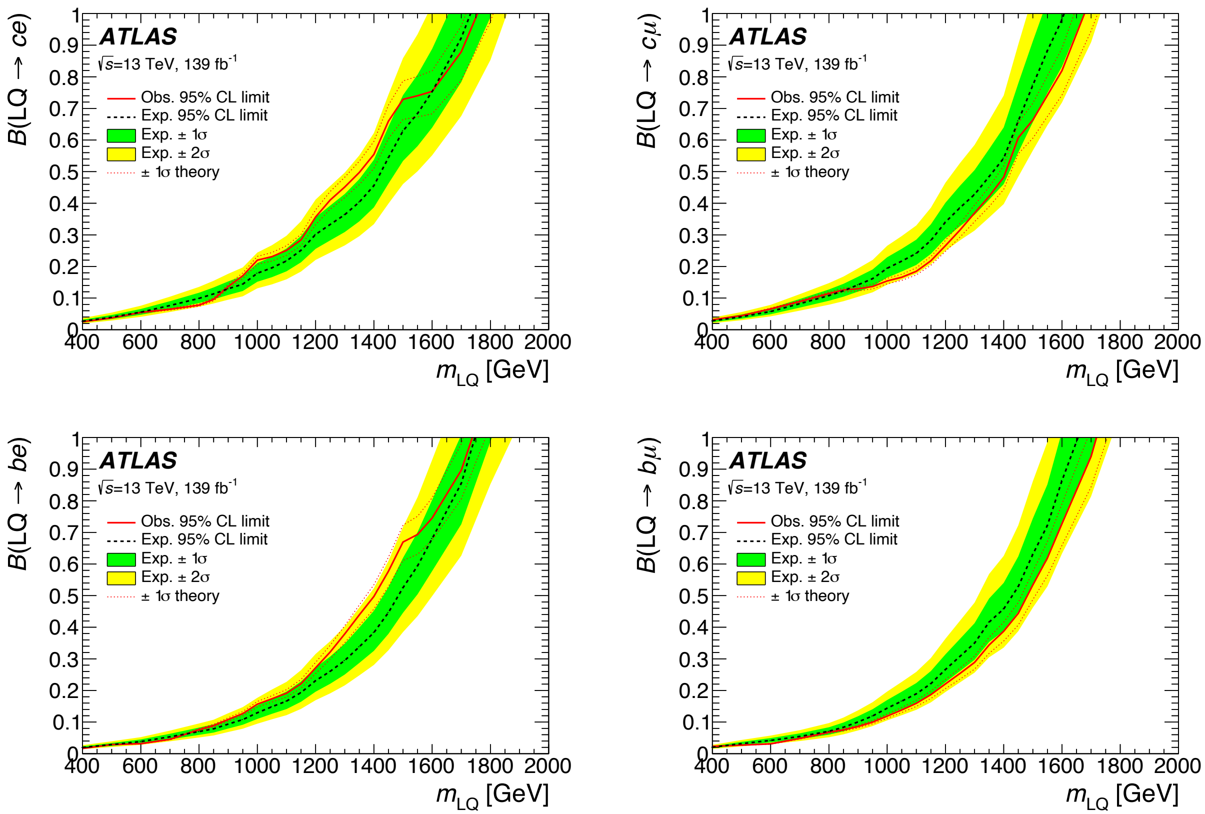

More Flavorful Stuff

- There are also dedicated analyses probing flavor anomalies ongoing
  - ★ R(K), R(D*), R(J/ψ), ...
- Unfortunately, we don't have approved results on these topics yet, but they will be coming very soon, so stay tuned!
- In CMS, much of this program was made available through the 2018 data parking campaign; in ATLAS - via special triggering
- We also plan to enhance our flavor analysis capabilities in Run 3 via dedicated triggers and data streams

Summary

- With the LHC doubling time getting similar to a lifetime of a Ph.D. student in a collaboration, we see a gradual shift to more sophisticated analyses that take >1 year to complete
  - ★ Those include dedicated techniques, dedicated triggers, and sophisticated models and analysis methods
- ATLAS and CMS produced a wealth of results in all areas of particle physics, including heavy-ion and flavor physics, thus demonstrating the power of general-purpose experiments
- I showed just a very few selected recent examples, related to the physics of flavor, despite the major setback related to the COVID-19 closures and limitations
- They highlight new milestones in particle physics and pave road for future exciting results
- Good to see you all in person in 2021 *(even if not on that beach)*!

Thank You!