# BSM SEARCHES IN CMS

Greg Landsberg

06.12.2022

Kruger 2022: Discovery Physics at the LHC

# Disclaimer

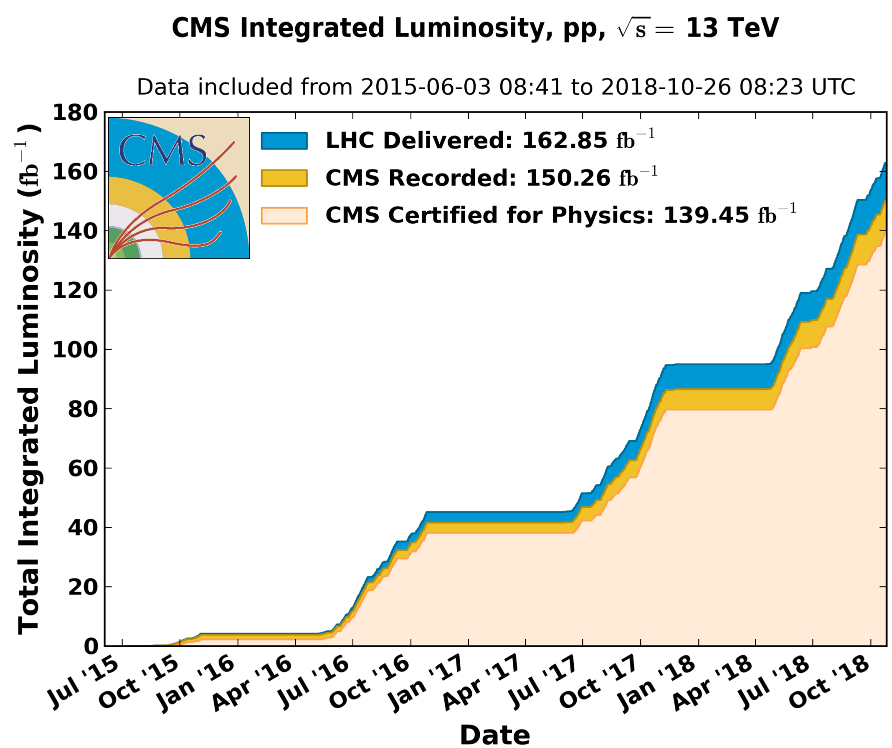
- Given the audience of this conference, I don't want this talk to turn into a shopping list of searches done at the LHC in general and in CMS in particular
  - ★ Even if I wanted to, I'd not fit in anywhere close to 50 minutes!
- Instead, I'll focus on things, which I believe may be more interesting to the broad experimental and theoretical community attending this conference
- I'll talk about new ideas, new search tools, and - of course! - about some new and not so new excesses we have seen in the LHC data
- You can find many more search results on public Web pages of the ATLAS, CMS, and LHCb experiments, as well as in the talks by Eric Chabert (this afternoon), Mohamed Zaazoua (tomorrow morning), and Ethan Lewis Simpson, Phuti Rapheeha, Andrea Coccaro, Anza-Tshilidzi Mulaudzi (tomorrow afternoon)

# Outline

- Looking for Unknown
- New Tools for the New Paradigm
- Towards Low Masses and Small Couplings
- Towards Long Lifetimes
- Flavor Anomaly Inspired Searches
- Run 2 Excesses
- Conclusions

# LHC Run 2: Big Success

- Up to 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; about 6 $fb^{-1}$ has been recorded by the LHCb
- Thank you, LHC, for a spectacular Run 2 and looking forward to even more exciting Run 3!



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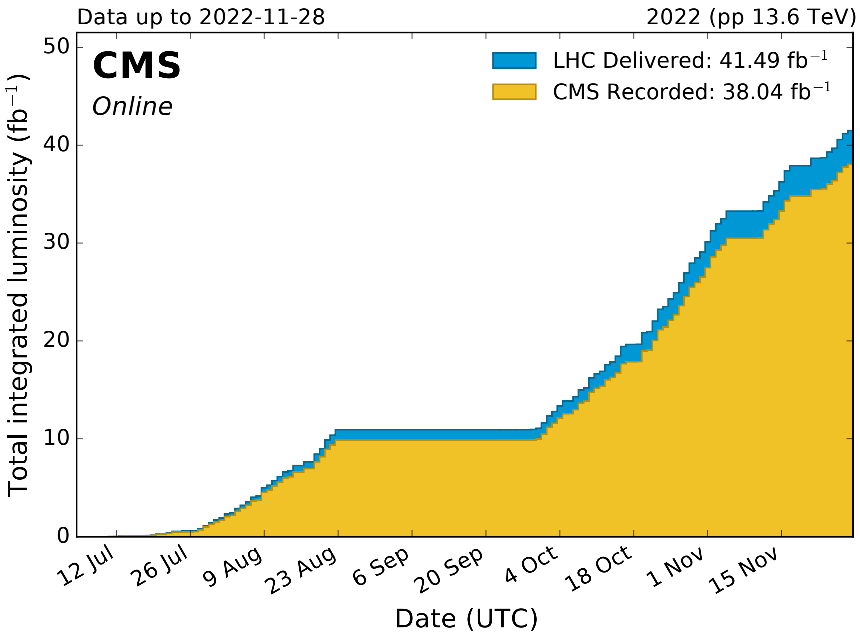


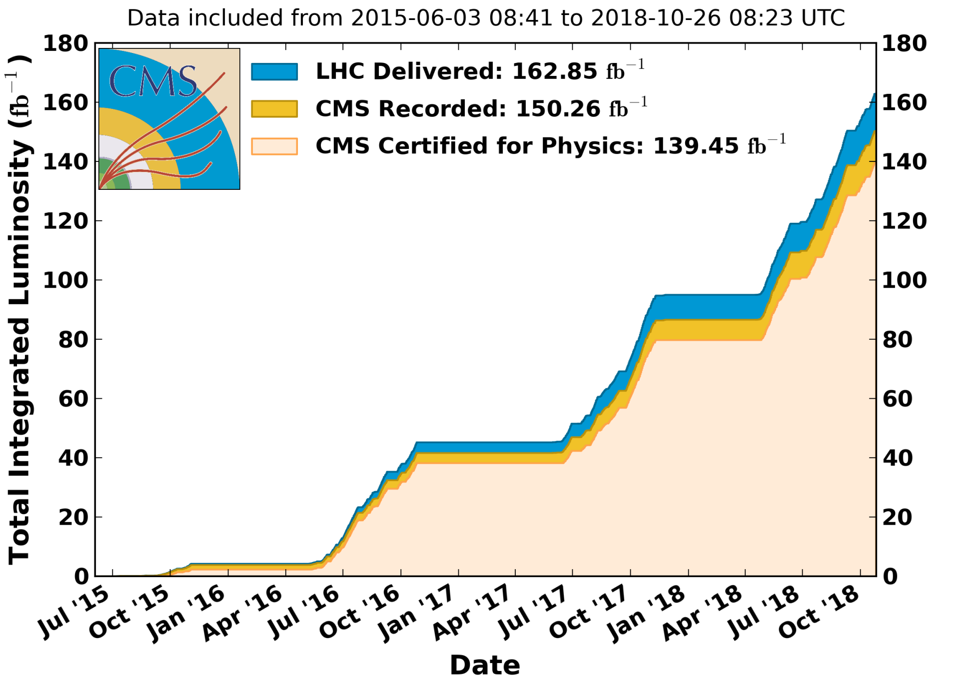

# Looking for Unknown

- The LHC has been successfully operating for over 13 years, transforming the entire landscape of searches for new physics
- Despite a number of tantalizing hints seen by ATLAS, CMS, and LHCb over the years, apart from the observation of the Higgs boson and a number of QCD states, none of them raised to the discovery level yet; many are now gone
- So, why are we still looking for new physics at the LHC and where should we look for it if we continue?

# The Why

- Why are we still covering something like a territory of Brazil with the Brazilian flag exclusion plots?
  - ★ Many things are missing from the standard model (SM), hinting that it is likely incomplete
    - Physics issues: no gravity; no dark matter; no connection between the three generations of quarks and leptons; no quantitative explanation of the matter-antimatter asymmetry in the universe; no neutrino oscillations
    - Math issues: naturalness, which became a real problem since the discovery of the Higgs boson; "arbitrary" fermion masses; strong CP problem
  - ★ Most of viable SM extensions that cure some of the above problems require new particles, dimensions, symmetries
  - ★ Many lead to the phenomenology within the reach of the LHC, although there is no guarantee anymore
  - ★ Many exclusions, while appear strong, are based on simplifying assumptions, which are often arbitrary (e.g., Br = 1) - read the fine print!

# The Why


Read the fine print!

# The Where

- Given that the LHC has reached its ultimate energy, looking for heavy particles is a game of a diminishing return - it will take many years to discover something in this regime, if we haven't seen a hint so far
  - ★ No more low-hanging fruit!

- The focus shifts to much more complicated signatures, which haven't been exploited thus far, as well as significantly more sophisticated analyses than we pursued during the earlier years
- Doubling time has doubled since Run 2; it is now about three years
  - ★ Compatible with a "lifetime" of a graduate student in an LHC experiment, allowing for a well-designed and sophisticated analysis rather than a "luminosity chase"

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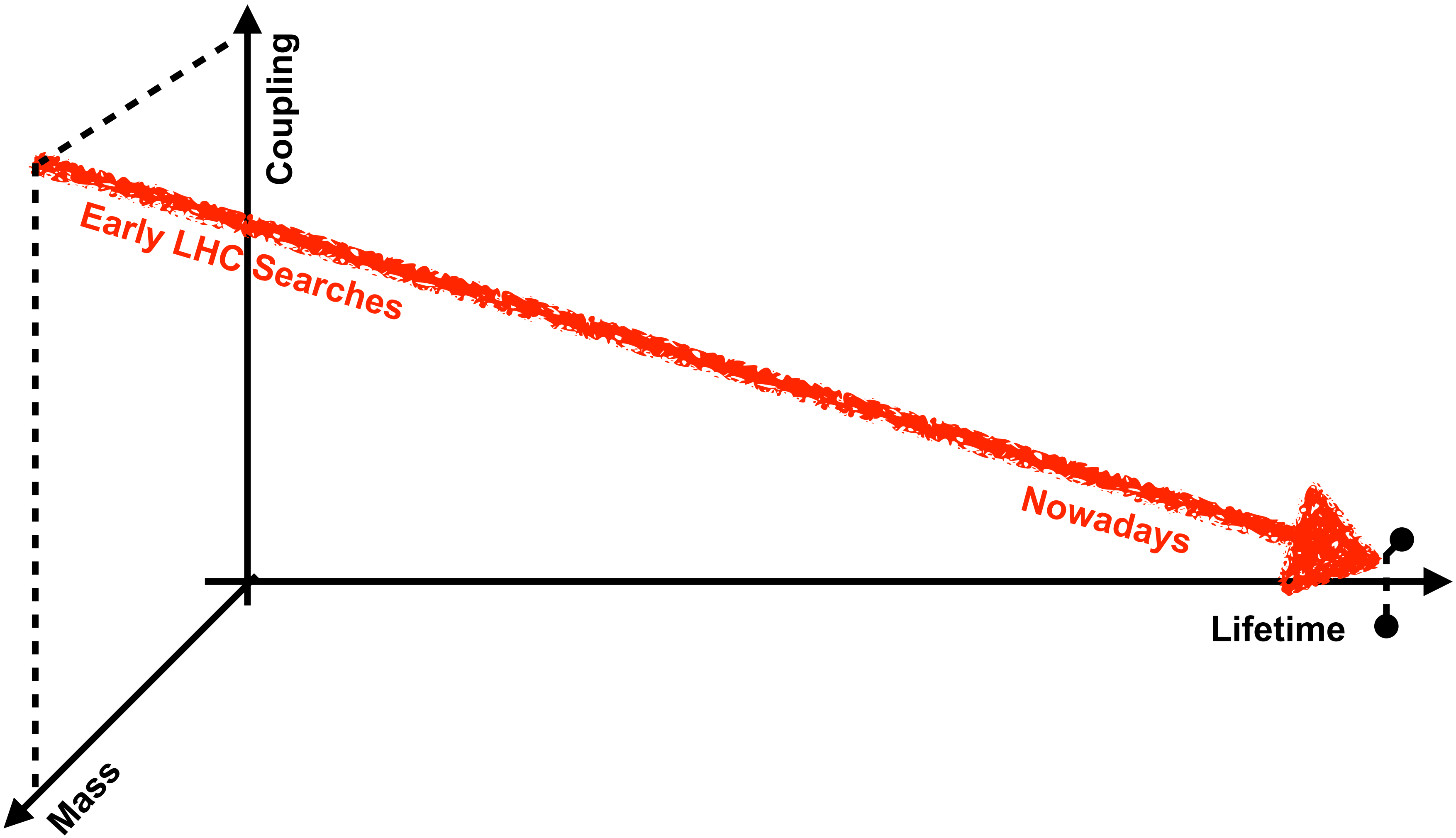
# Stairway to Hell

- The paradigm shift

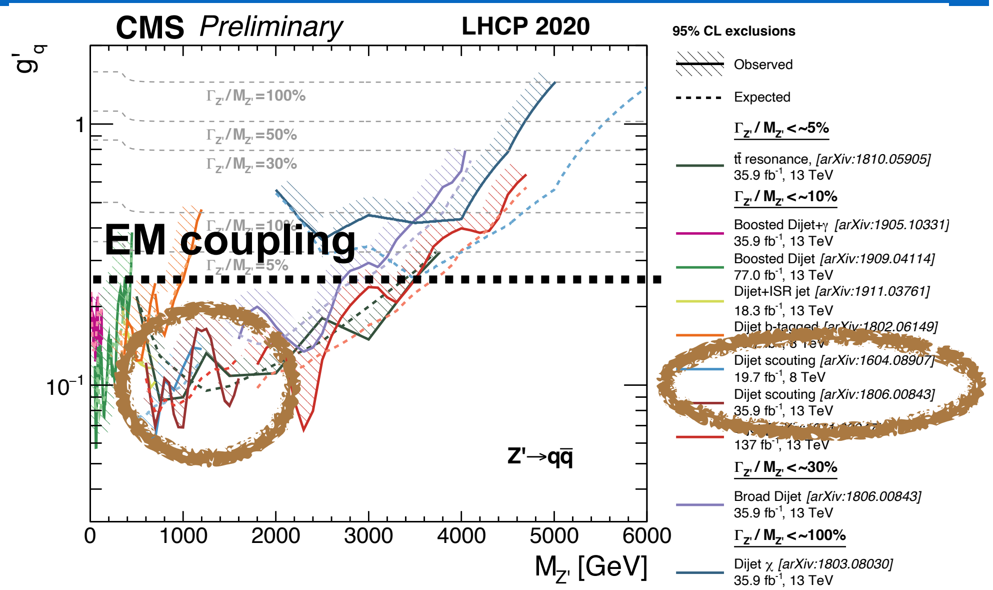


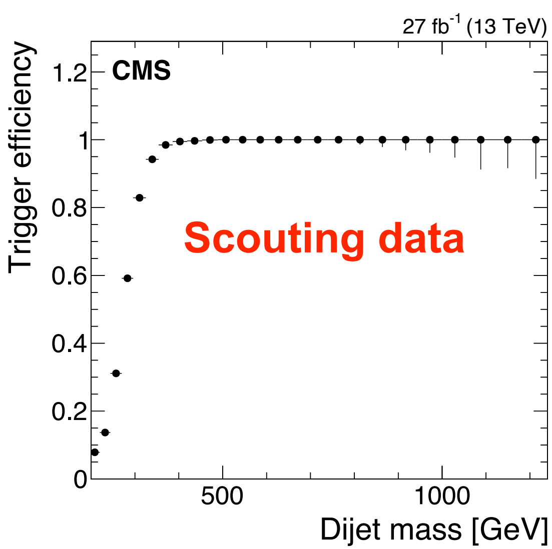
# New Tools for the New Paradigm

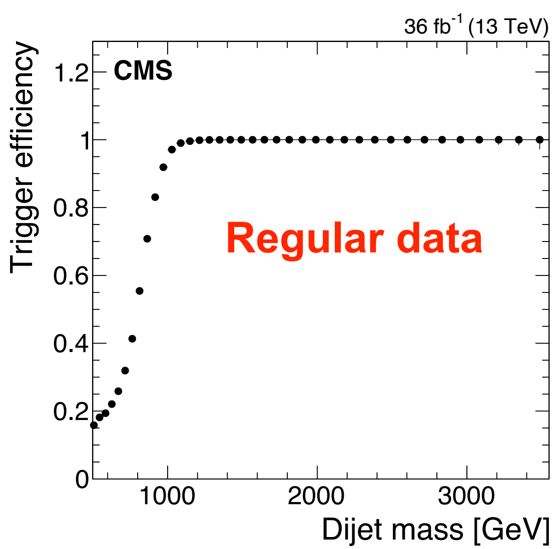
- Use of new triggers not available earlier in the LHC running
  - ★ A variety of triggers optimized for long-lived particles - ATLAS, CMS, LHCb
  - ★ Trigger-level analysis (TLA), aka data scouting - ATLAS and CMS, and triggerless design with real-time alignment and calibration (LHCb)
    - ✤ Extensive use of GPU in the trigger (CMS, LHCb)
  - ★ ISR-based triggers with jet substructure and mass-decorrelated subjet taggers (ATLAS, CMS)
- Data parking (ATLAS, CMS)
- Novel approaches with machine learning (ML) techniques including weakly supervised and unsupervised ML
- Clever use of existing detectors beyond their original design goals
- In what follows I'll illustrate these concepts using a mix of older analyses, where the techniques were established, and some new results

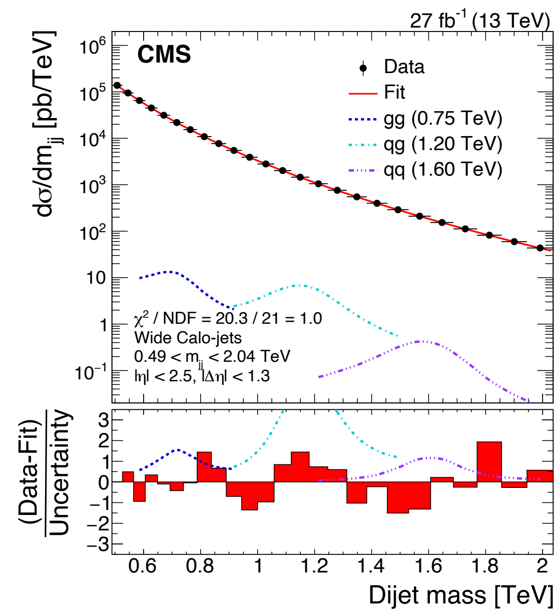
# Toward Small Masses: Scouting

- Scouting analyses are based only on the high-level trigger (HLT) objects resulting in a very compact event size and vastly increased rate per bandwidth for the scouting data stream
    - ★ Avoids the use of (large) trigger prescales



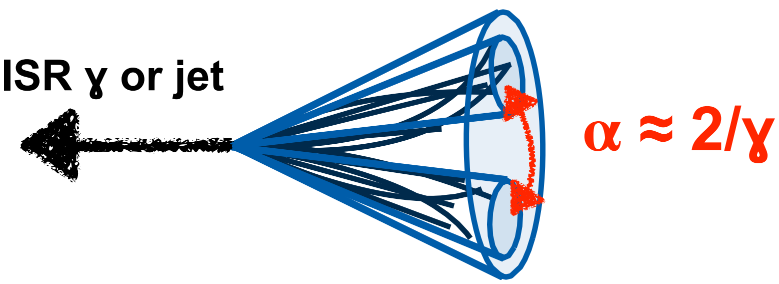



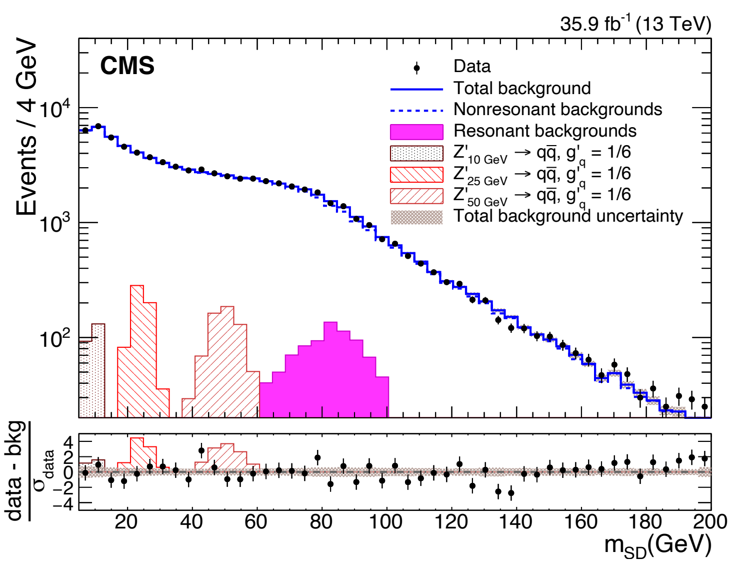




CMS, JHEP 08 (2018) 130

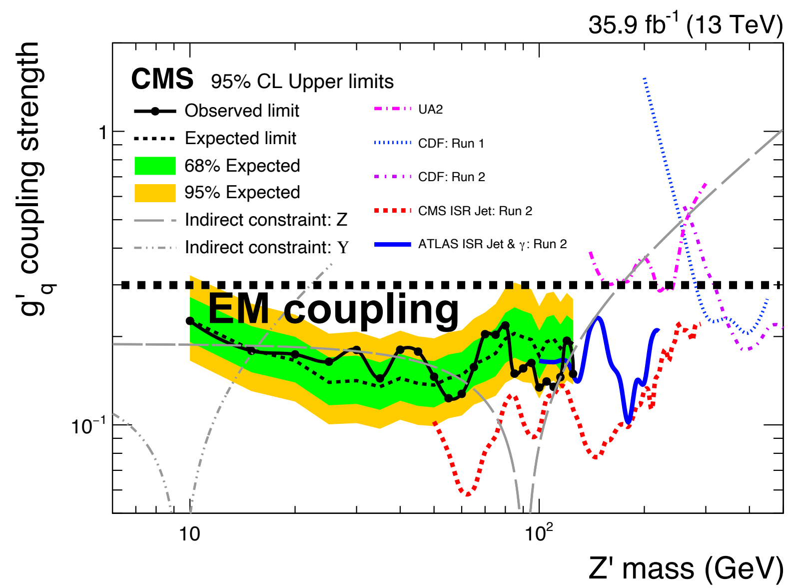
# Toward Small Masses: ISR

- Use high-$p_T$ single-photon or single jet triggers to record the events, require a substructure in the recoiling AK8 jet, and search for narrow resonances in the recoiling jet trimmed mass spectrum
- Allows to go as low as 10 GeV in the resonance mass!




CMS, PRL 123 (2019) 231803



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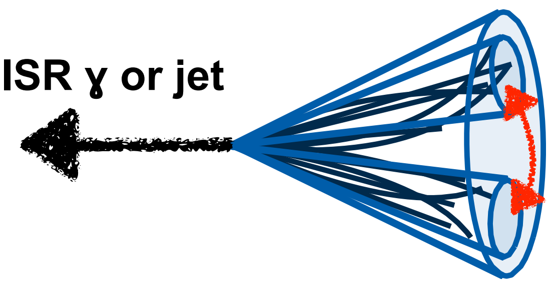
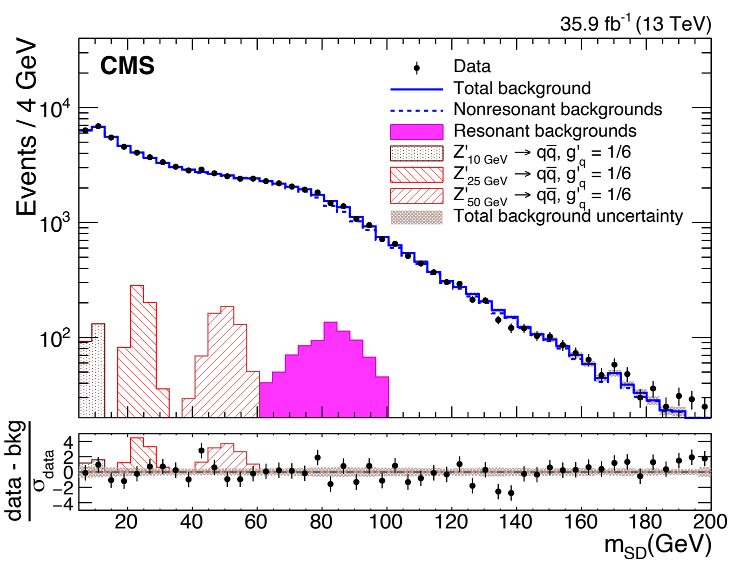



$p_T$(ISR) ~ 100 GeV
m(X) ~ 25 GeV
γ ~ 4, α ~ 0.5 - a single jet

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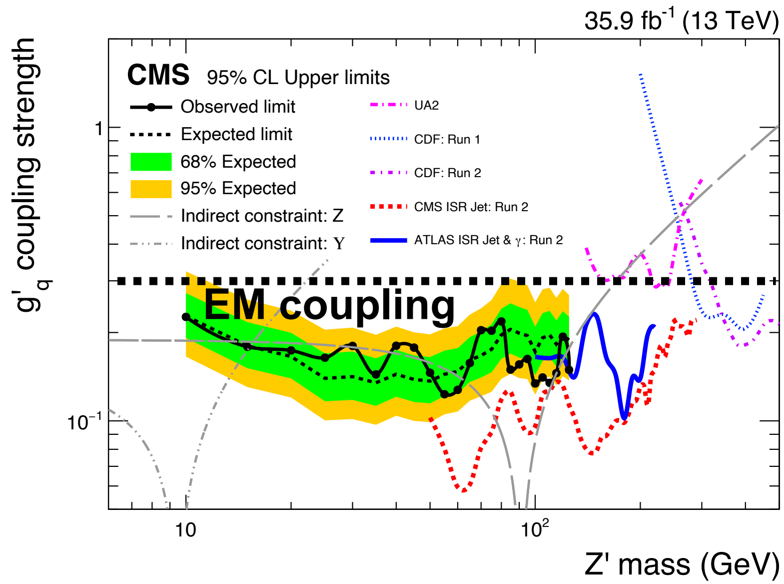

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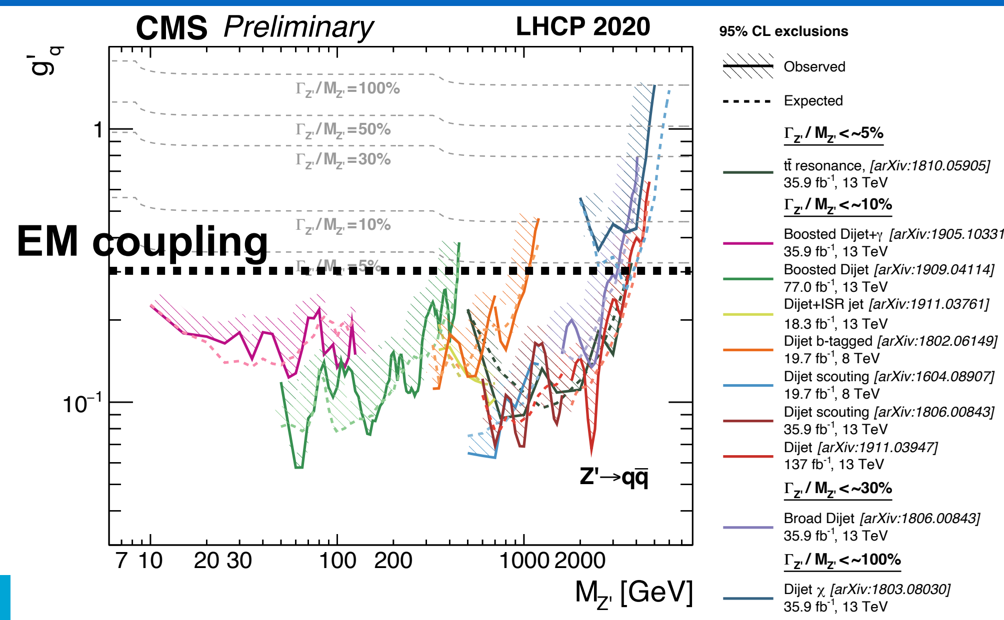


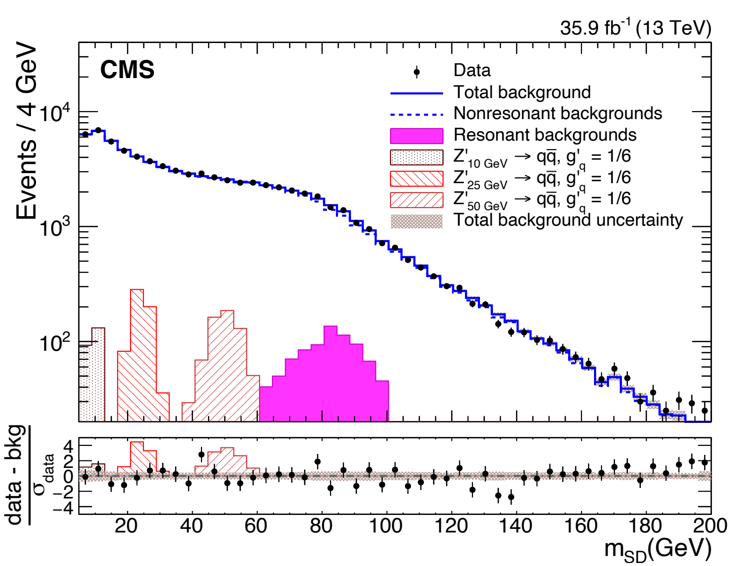


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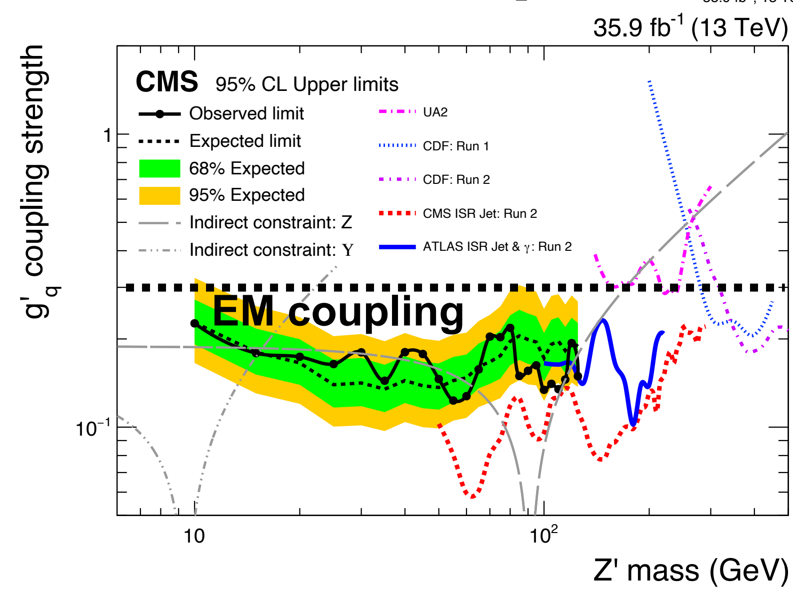
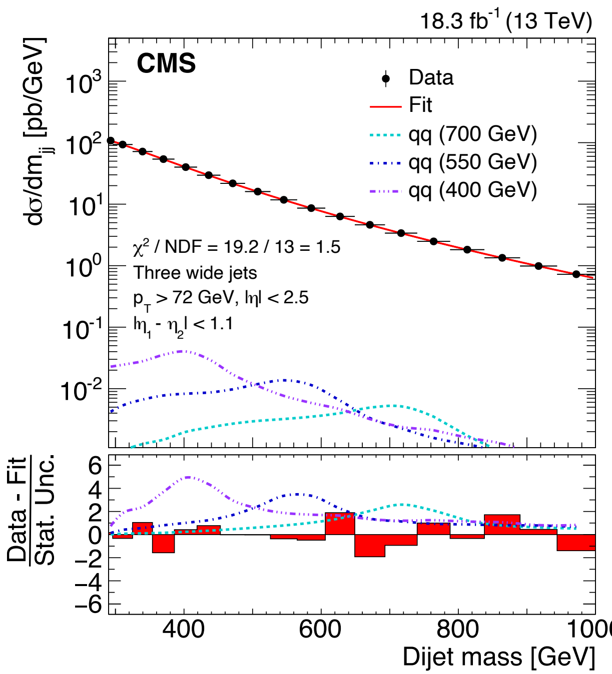
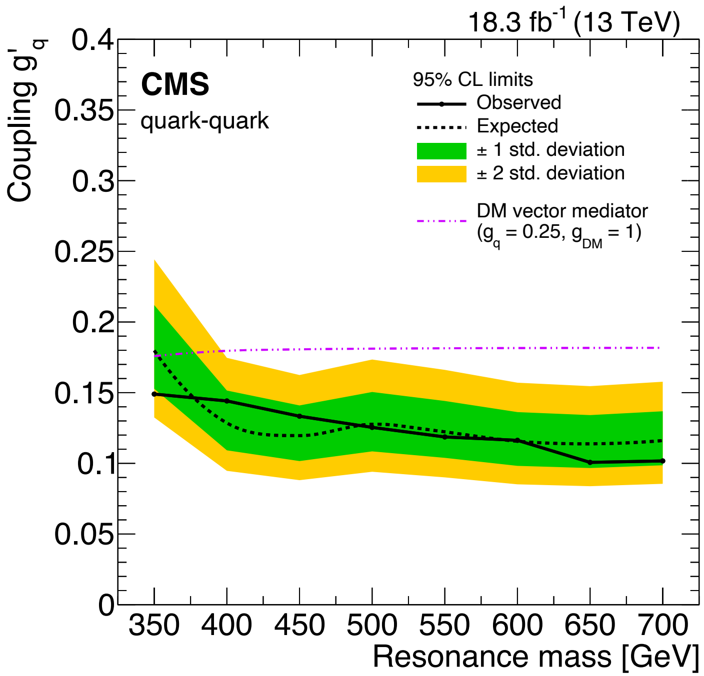


# Toward Low Masses: ISR+Scouting

- One could also combine the two techniques, adding extra sensitivity
  - ★ The idea behind a CMS search for dijet resonances in three-jet events collected by a low-$H_T$ scouting trigger (4 kHz @ $10^{34}$ $cm^{-2}s^{-1}$) available for ~half of 2016 data taking (18 $fb^{-1}$)
  - ★ Use large-R (1.1) jets offline to improve resolution and acceptance
  - ★ Limits set in the 350-700 GeV range as low as 1/3 of EM coupling



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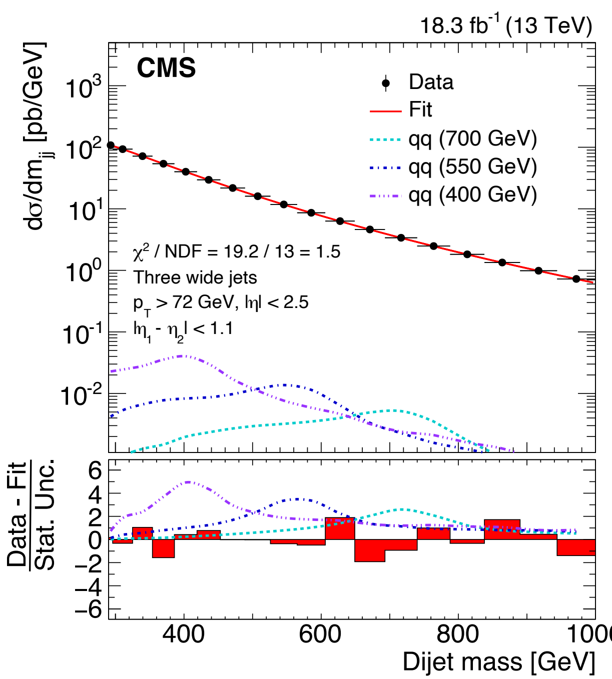
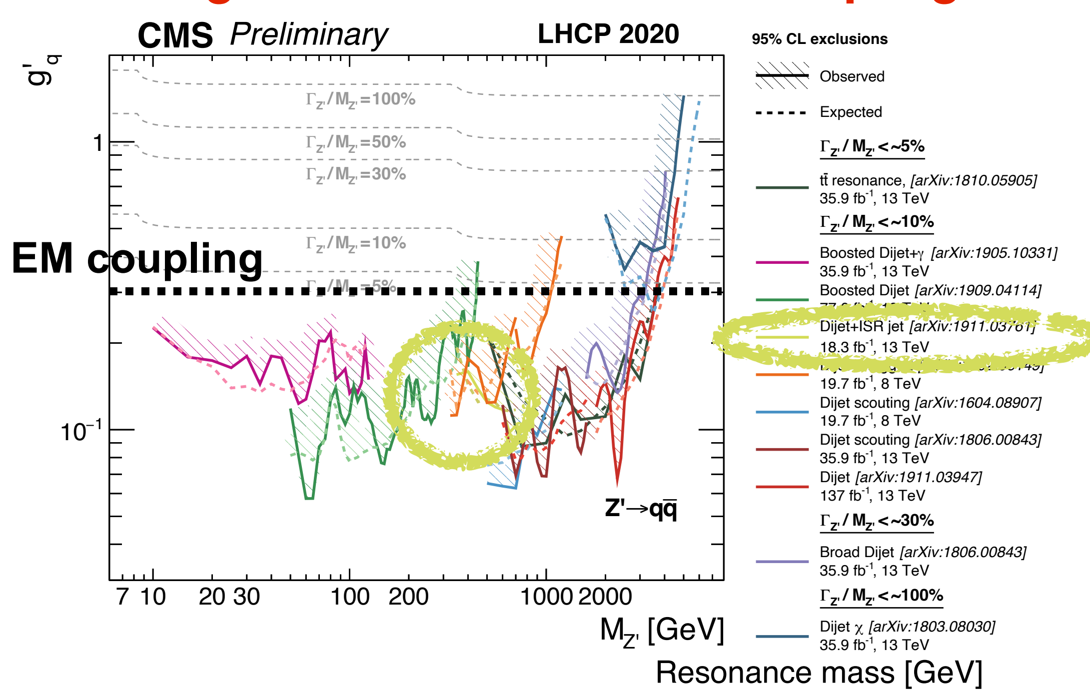
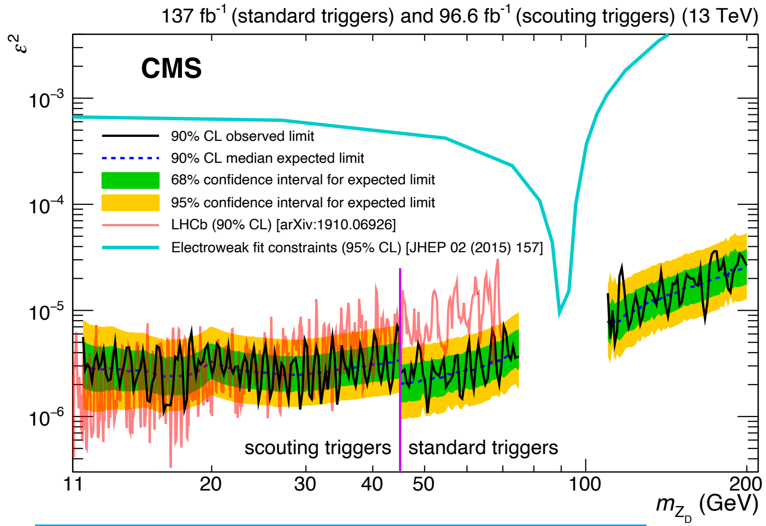


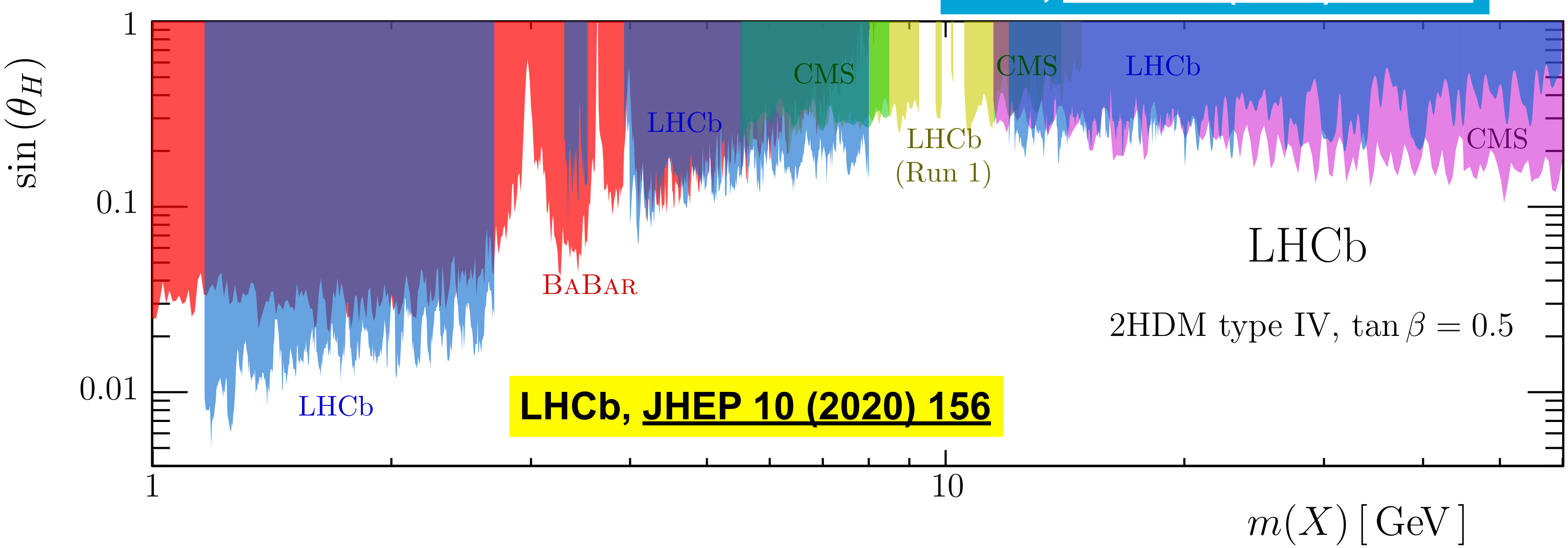



# Low-Mass Dimuon Resonances

- LHCb search based on regular dimuon triggers, as well as a CMS search based on the dimuon regular and scouting triggers
- Nice complementarity between the two sets of results, interpreted as dark Z boson or in the context of 2HDM + complex singlet model w/ H-a mixing



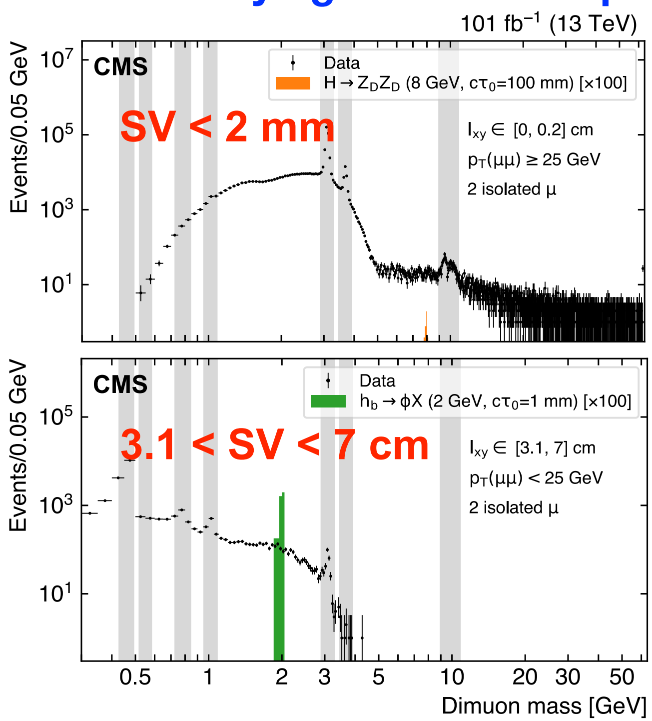

CMS, PRL 124 (2020) 131802



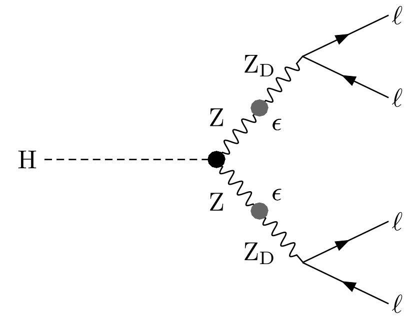

LHCb, JHEP 10 (2020) 156

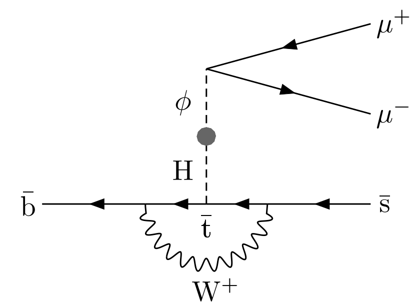
# Scouting and LLPs

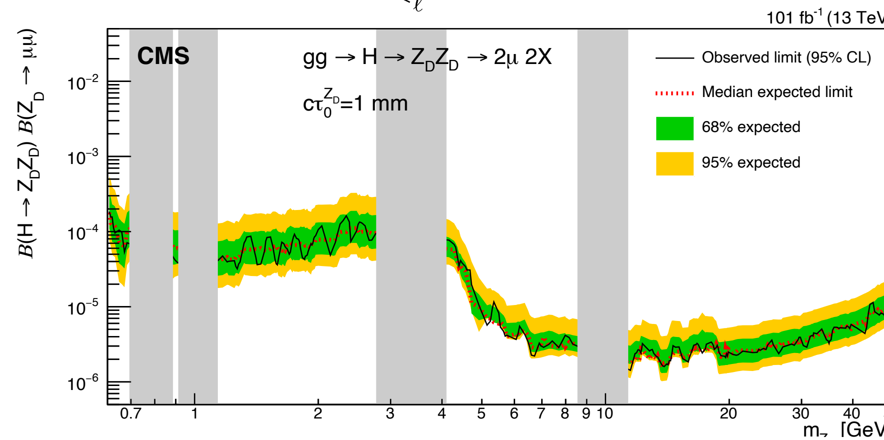
- Search for long-lived particles decaying to a pair of muons, using displaced dimuon vertices at the HLT
- Uses the same dimuon scouting triggers (they do not require muons to be prompt)
- Requiring displaced vertices drastically reduces SM backgrounds, making the search quite sensitive to variety of models with LLPs decaying to a dimuon pair

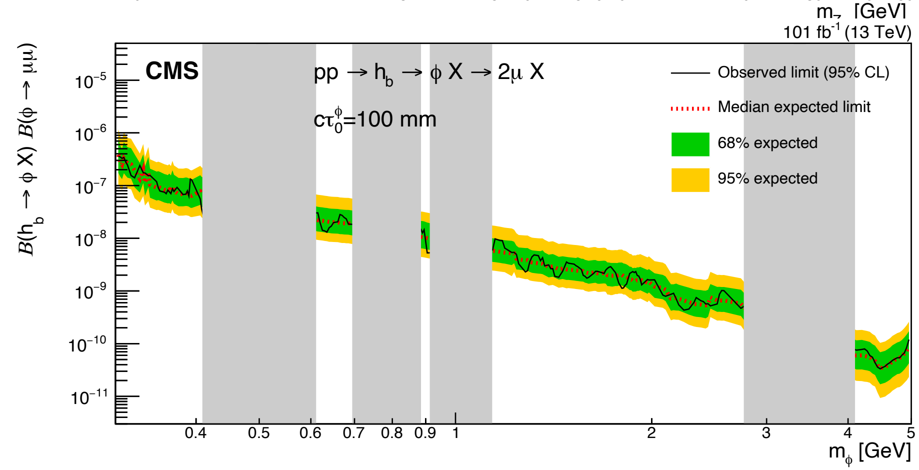



CMS, JHEP 04 (2022) 062



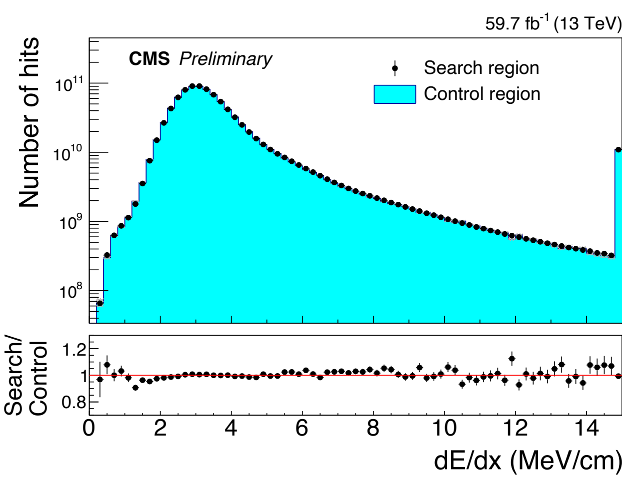



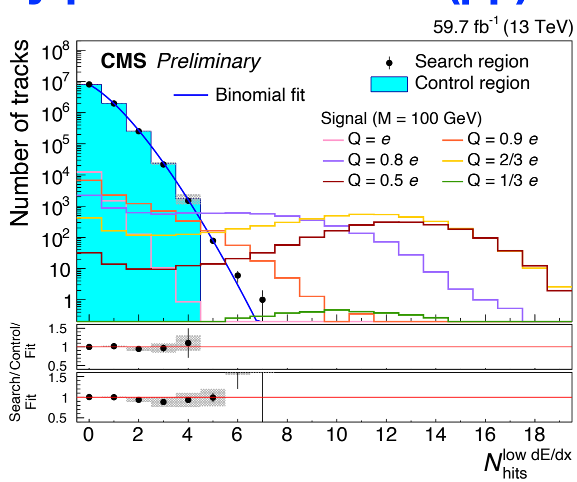
# Fractionally Charged Particles

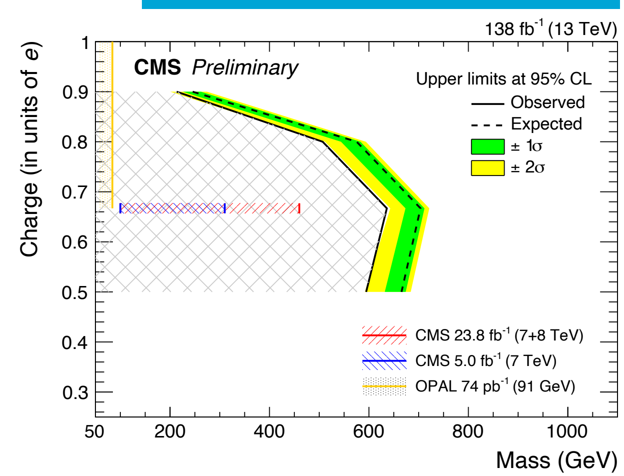


- Small couplings could lead to small charges
- While dedicated small experiments MilliQan, FORMOSA are being proposed for dedicated searches for fractionally charged particles (FCPs) possibly produced at the LHC, even the present detectors have strong capabilities in this domain thanks to their redundancy and robust design
- CMS silicon tracker has an excellent signal-to-noise ratio, which allows to use dE/dx ~ $q^2$ signal to search for FCPs
- Search focused on Drell-Yan production of FCP pairs
- Count the number of hits on a track with dE/dx less than a layer-dependent threshold; signal region has 1 or 2 tracks w/ large number of low-dE/dx hits
- Background can be reliably predicted from Z(μμ) events

CMS PAS-EXO-19-006



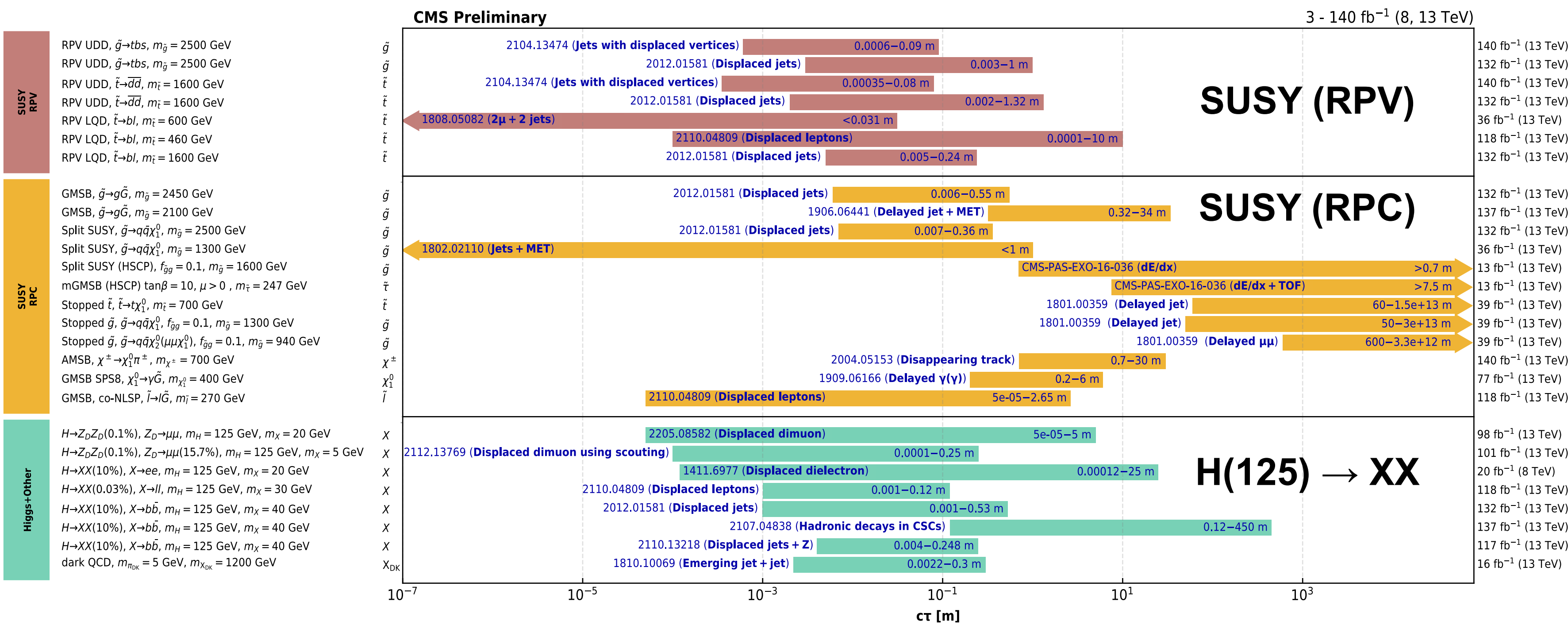



# Toward Long Lifetimes

- Plethora of models and experimental results
- Will highlight just a few in this talk

**Overview of CMS long-lived particle searches**

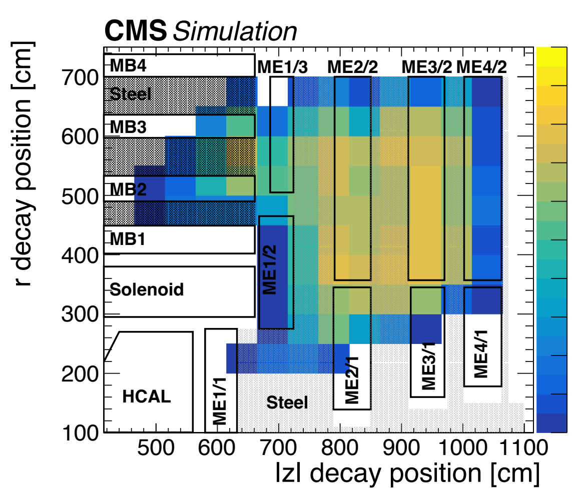


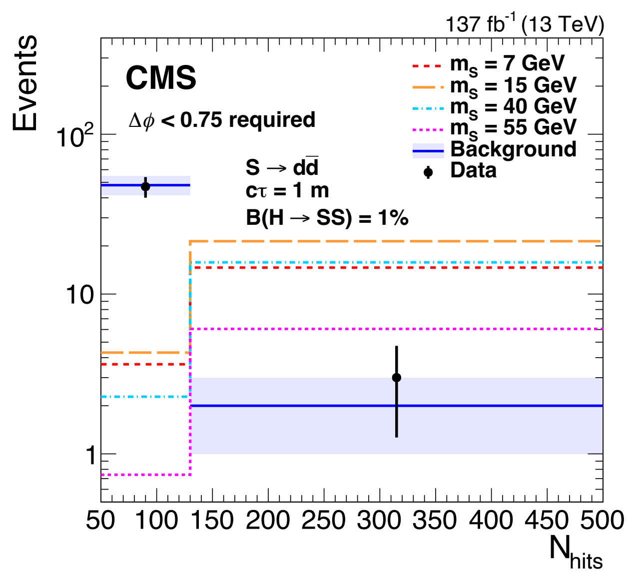

Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included). The y-axis tick labels indicate the studied long-lived particle.

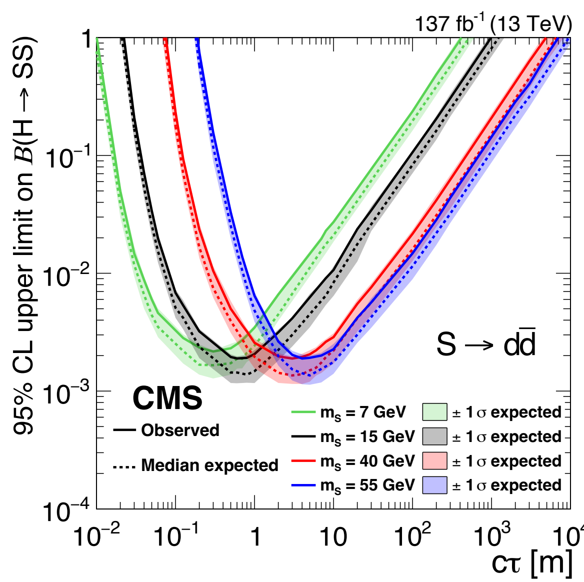
# Search for LLPs via Muon Detector

- First search at the LHC, which uses a muon detector as a sampling calorimeter (speaking of going way beyond TDR!)
- Focuses on H → SS scenario, with a scalar S decaying into a pair of quarks or τ leptons
- Reconstruct hadronic showers in the CMS endcap muon system, based on the number of hits
- Spectacular signature, and largely model-independent

CMS, PRL 127 (2021) 131802

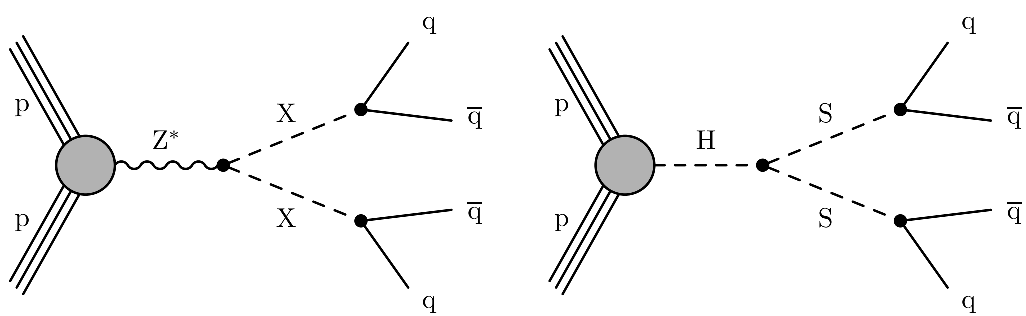


# Search for Displaced Jets

- Displaced jets is a powerful signature for long-lived particles in a variety of models from twin Higgs to SUSY
- Typically requires dedicated triggers, as otherwise the rate of inclusive dijet events is too high
- CMS has invested in several such triggers in Run 2, and achieved superior sensitivity in this type of searches
- A typical displaced jet trigger requires a large scalar sum of jet $p_T$ ($H_T$ > 430-650 GeV) and ≥2 jets with a limit on a maximum number of prompt tracks
- Offers sensitivity to a large set of models, including models with pair-produced dijet resonances

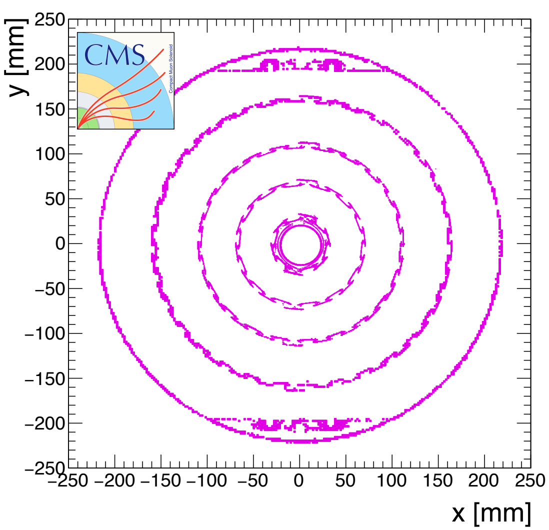


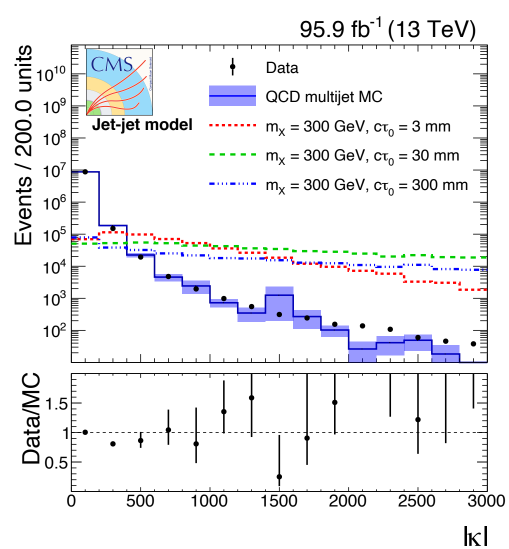
# CMS Search for Displaced Jets

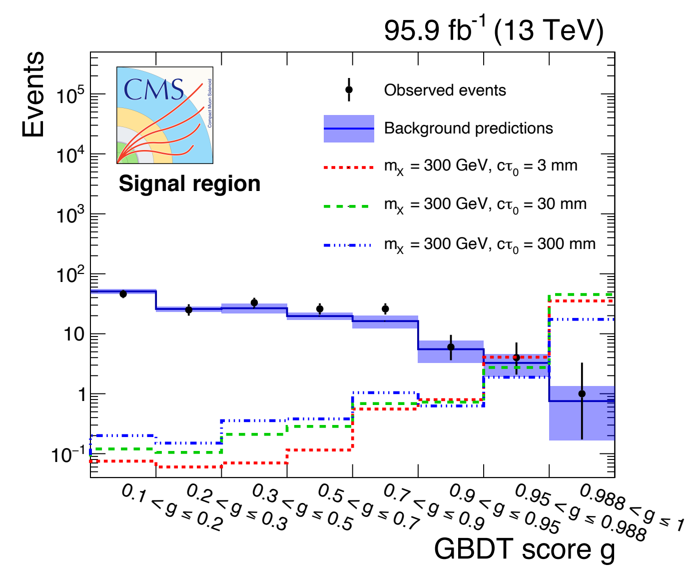


- The latest CMS search is based on 2017-2018 data and is combined with an earlier search with 2016 data
- Eliminates background from nuclear interactions in the pixel detector
- Several discriminating variables are used, including $\kappa$, the sum of signed 2D IP significances over 6 leading vertex tracks
  - ★ Combined in a single boosted decision tree (BDT) discriminant
- One event observed in the last BDT bin, with the background of 0.75 ± 0.59 events

CMS, PRD 104 (2021) 012015

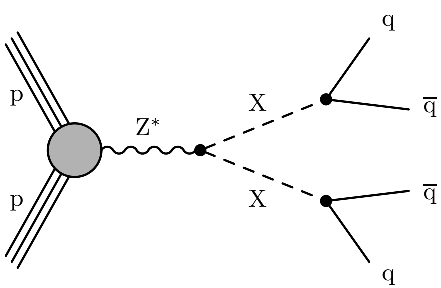


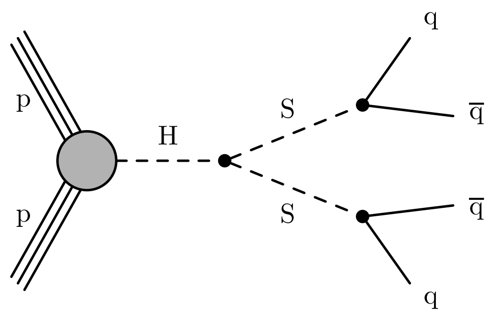



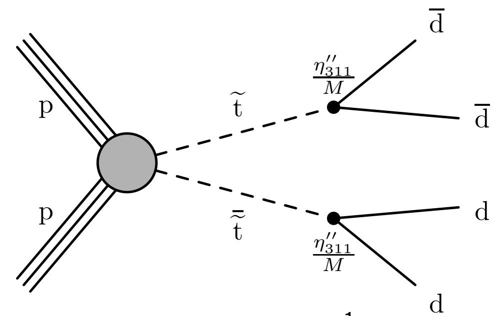



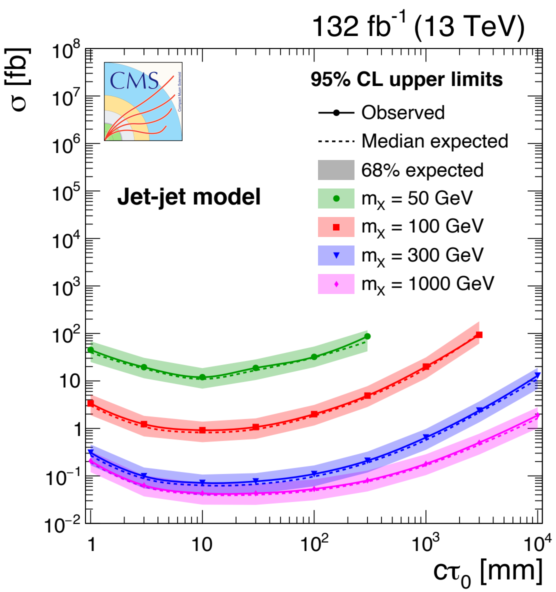
# Search Results

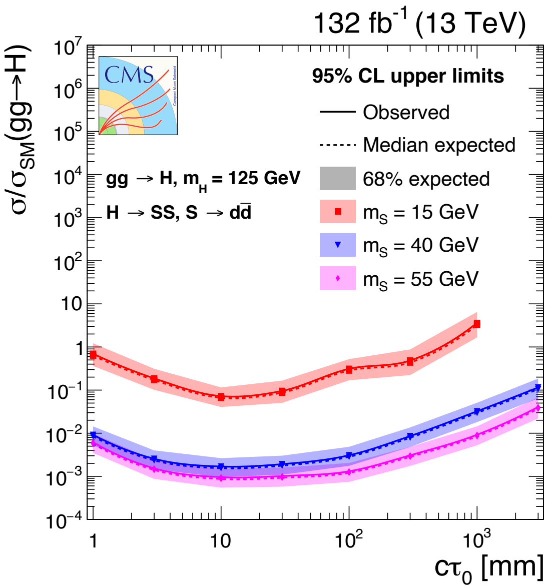
- Limits in numerous models are set:

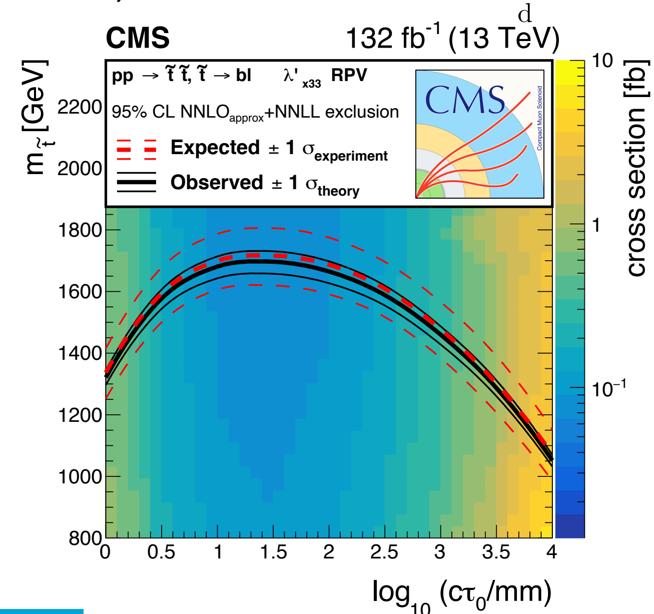


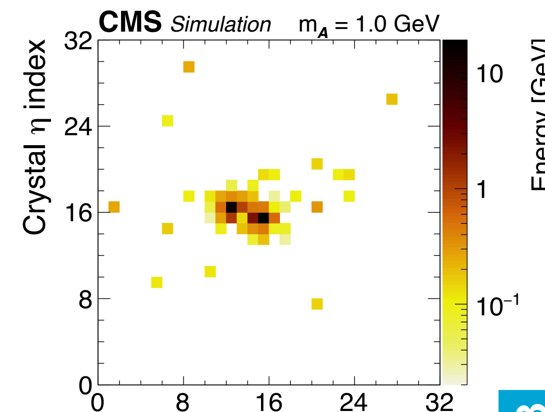



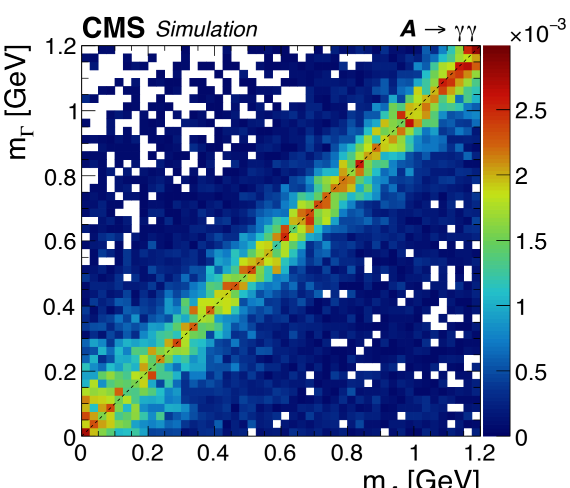



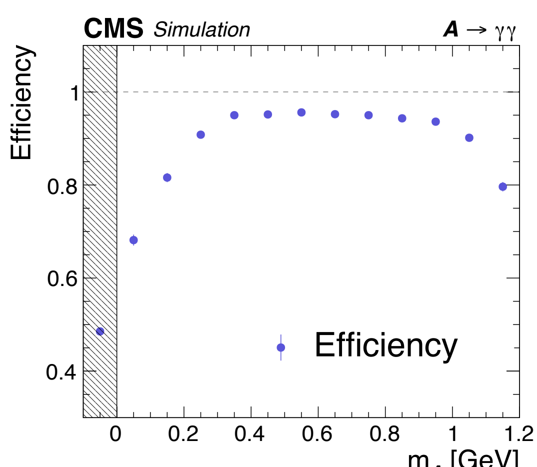

CMS, PRD 104 (2021) 012015

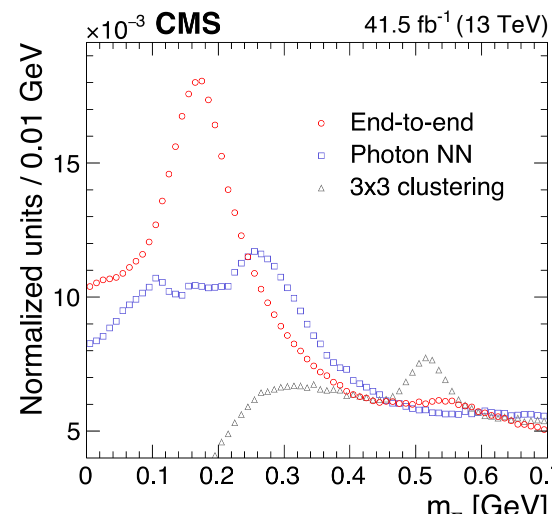
# Machine Learning as a Tool

- Broad use of (deep) machine learning (ML) is to use it as a tool for discriminating complicated signatures from backgrounds
  - ★ Many examples from the LHC from flavor tagging to identifying jets with substructure
- Interesting recent example from CMS: end-to-end deep ML reconstruction of the ECAL to resolve overlapping photon showers
  - ★ Developed specifically for the $H \to aa \to \gamma\gamma\gamma\gamma$ search
  - ★ A mass regression technique that uses low-level ECAL information to best reconstruct m(a) via a merged diphoton decay
  - ★ Capable of dealing with Lorentz boosts as high as 600!
  - ★ Performance in data validated using $\pi^0 \to \gamma\gamma$ decays



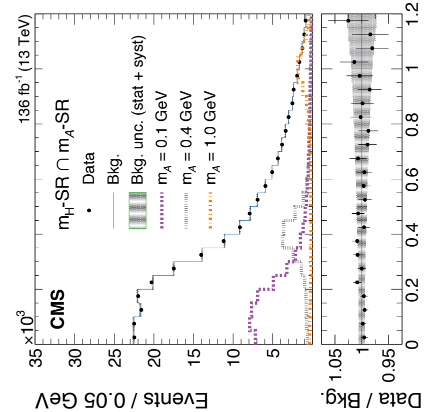



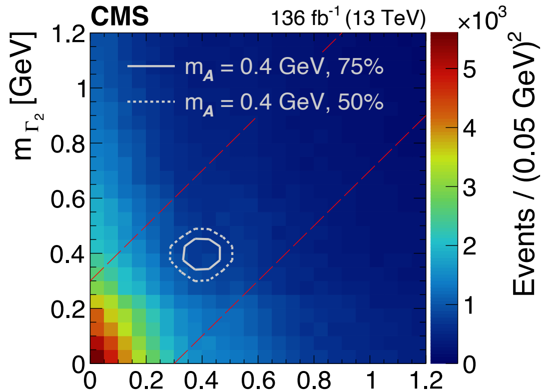




CMS, arXiv:2204.12313

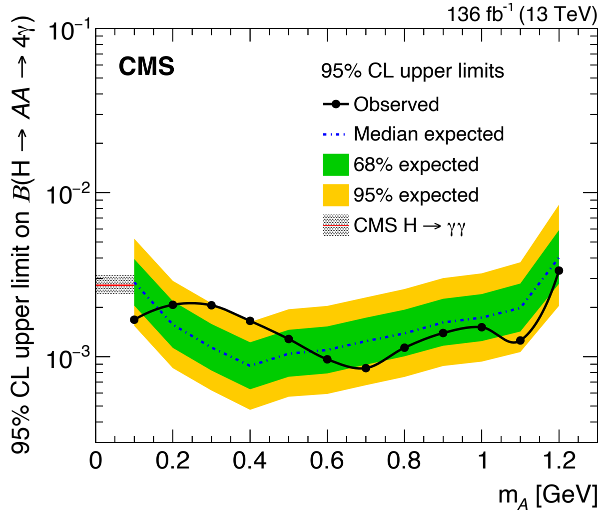
# ...and its Application

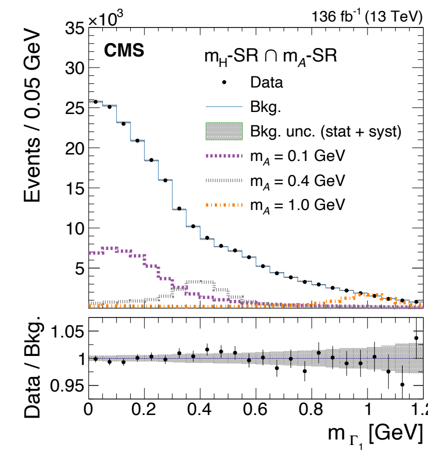
- Based on this regression technique, a dedicated analysis for a very light pseudoscalar a in a 0.1-1.2 GeV mass range has been conducted




- Look for an excess in the plane of two reconstructed γγ masses, for the overall mass in the H boson window



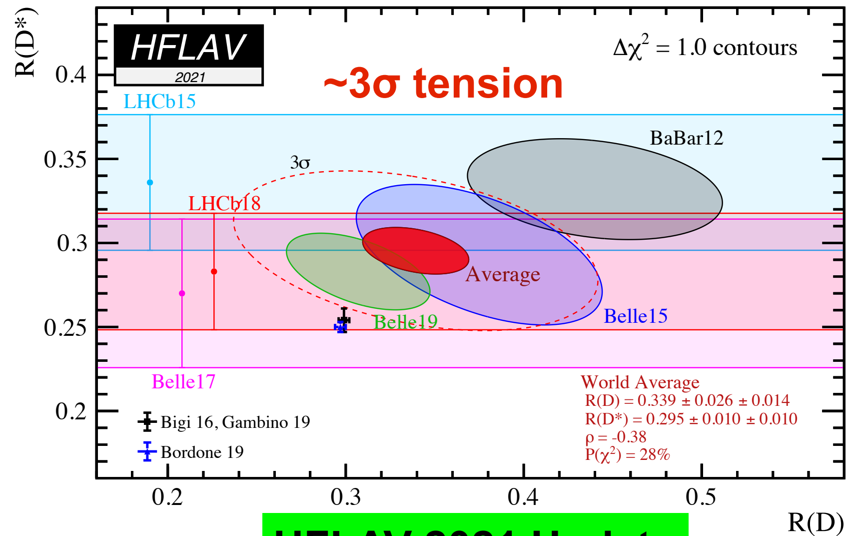




CMS, arXiv:2209.06197

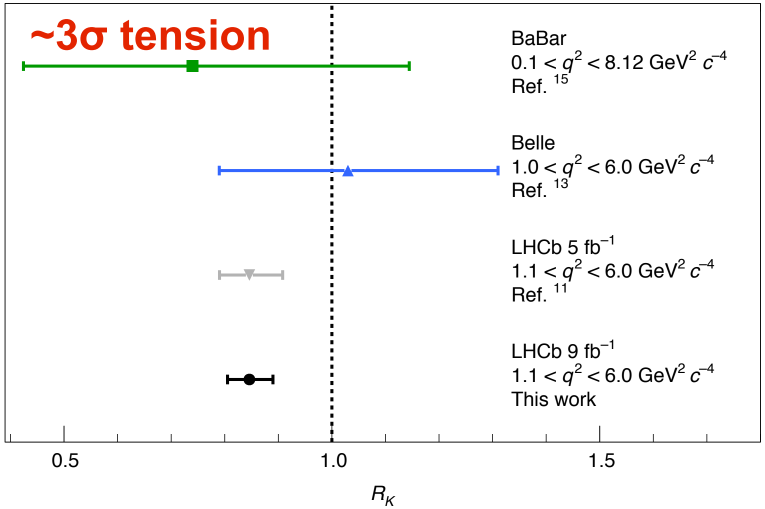
- Sensitivity exceeds that from the generic limits based on H →γγ decays, demonstrating the power of the technique

# Lepton Flavor Anomalies

- Recently, a number of lepton flavor anomalies have been observed in various channels, largely driven by the LHCb experiment:
  - ★ ~3σ tension in R(D/D*), the ratio of $\mathcal{B}(b \to c\tau\nu)/\mathcal{B}(b \to c l \nu)$ [tree-level process]
  - ★ ~2σ deficit in various $b \to s\mu^+\mu^-$ transitions, compared to theory predictions, both in inclusive and differential measurements [loop-level process]
  - ★ ~3σ tension in R(K), R(K*), the ratio of $\mathcal{B}(b \to s\mu^+\mu^-)/\mathcal{B}(b \to se^+e^-)$ [loop-level process]
- Arguably, the strongest hints of new physics to date that survived a dozen of years of the LHC program




HFLAV 2021 Update

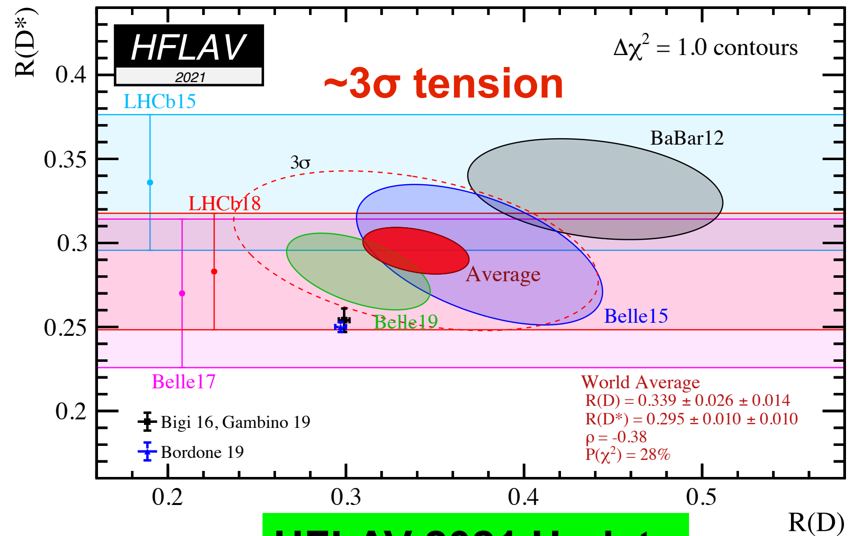



LHCb Nature Phys. 18 (2022) 277

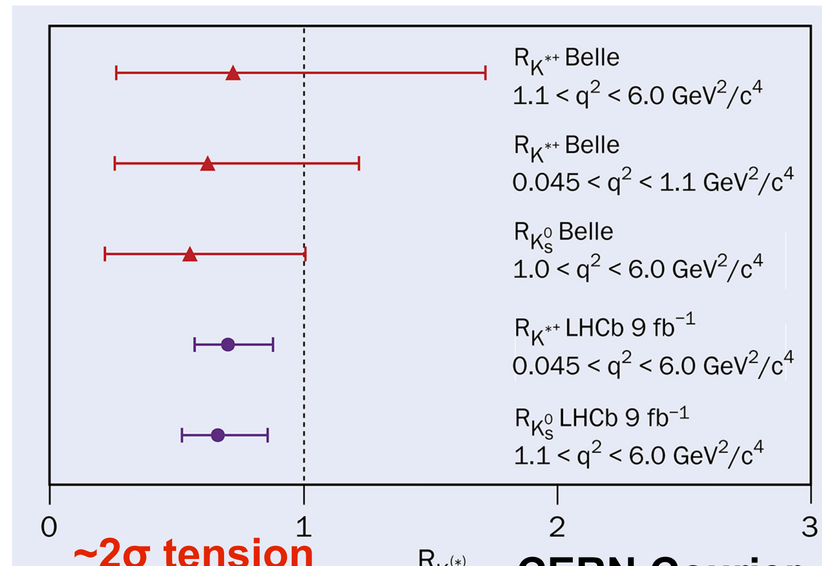
# Lepton Flavor Anomalies



- **Recently, a number of lepton flavor anomalies have been observed in various channels, largely driven by the LHCb experiment:**
  - ★ **~3σ tension in R(D/D*), the ratio of $\mathcal{B}(b \to c\tau\nu)/\mathcal{B}(b \to cl\nu)$ [tree-level process]**
  - ★ **~2σ deficit in various $b \to s\mu^+\mu^-$ transitions, compared to theory predictions, both in inclusive and differential measurements [loop-level process]**
  - ★ **~3σ tension in R(K), R(K*), the ratio of $\mathcal{B}(b \to s\mu^+\mu^-)/\mathcal{B}(b \to se^+e^-)$ [loop-level process]**
- **Arguably, the strongest hints of new physics to date that survived a dozen of years of the LHC program**




**HFLAV 2021 Update**

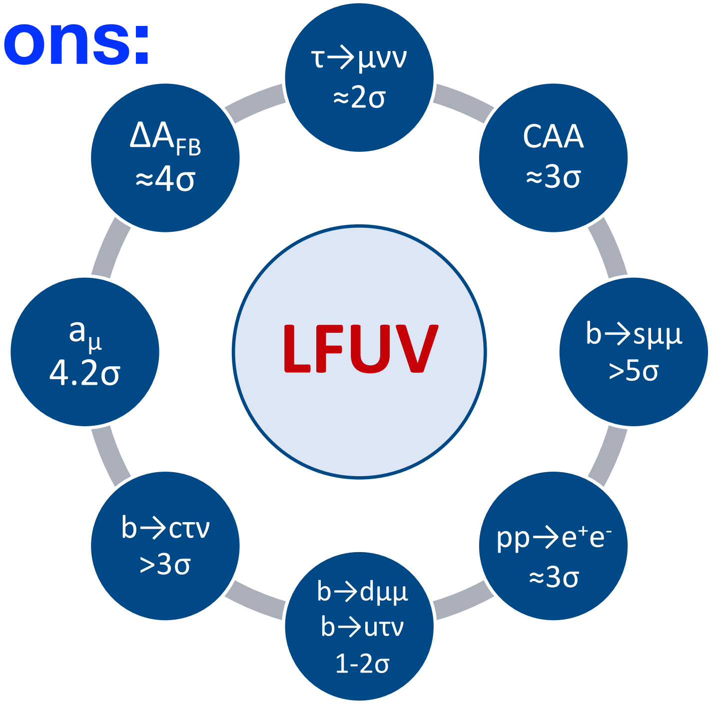



**CERN Courier**

# Common Explanations?



- Interestingly, there are theoretical ways to reconcile several of these (and potentially other) anomalies simultaneously, including the observed effect in trees vs. loops
- Theoretically preferred solutions:
  - ★ Pati-Salam leptoquarks (LQs) with flavor non-diagonal couplings
  - ★ Z'/W' with non-universal couplings




Credit: A. Crivellin

# Enter ATLAS & CMS

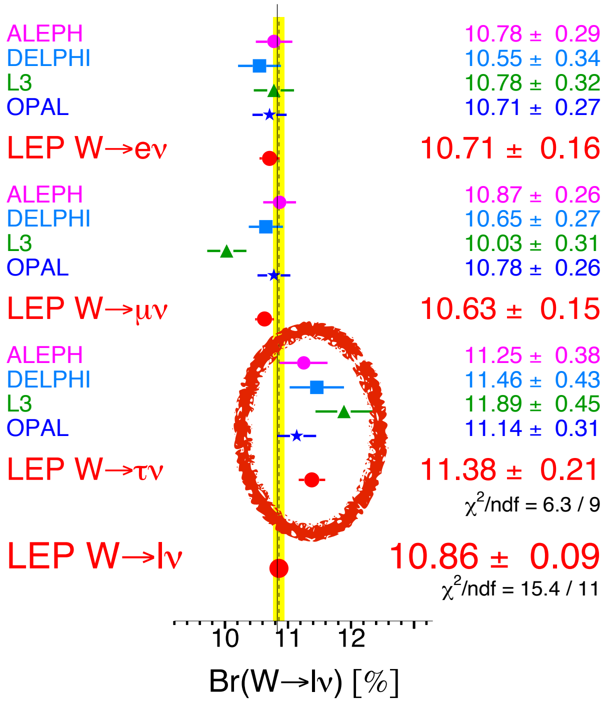
- ATLAS and CMS are pursuing:
  - ★ Direct searches for LQs, Z', and vector-like leptons proposed to explain flavor anomalies
  - ★ Tests of (charged) lepton flavor universality (LFU) - will highlight those
    - ✤ Evidence for H(μμ) clearly demonstrated LFU in Higgs Yukawa
    - ✤ Direct test of flavor anomalies using special triggers (ATLAS, CMS) and parked data (CMS)
  - ★ Searches for (charged) lepton flavor violation (LFV)
  - ★ Searches for flavor changing neutral current processes (FCNC)
- Depending on the model, they may or may not be connected to one the other:
  - ★ LFUV without LFV (e.g., via a heavy Z' boson)
  - ★ LFUV with LFV (e.g., in LQ models)
  - ★ LFV without FCNC (e.g., via R-parity violating SUSY)
  - ★ LFV via FCNC (e.g., $\mu \to eee$ via FCNC Z exchange)
- Consequently, it's important to study them all to get a full picture
  - ★ Also, keeping in mind possible connection to $(g-2)_\mu$

# 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?

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




**ADLO, Phys. Rep. 532 (2013) 119**

# 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 (e.g., $\mu\tau_h$ + 2 b jets) 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 analogous ATLAS analysis, does not use the lepton displacement to separate direct and τ lepton mediated decays

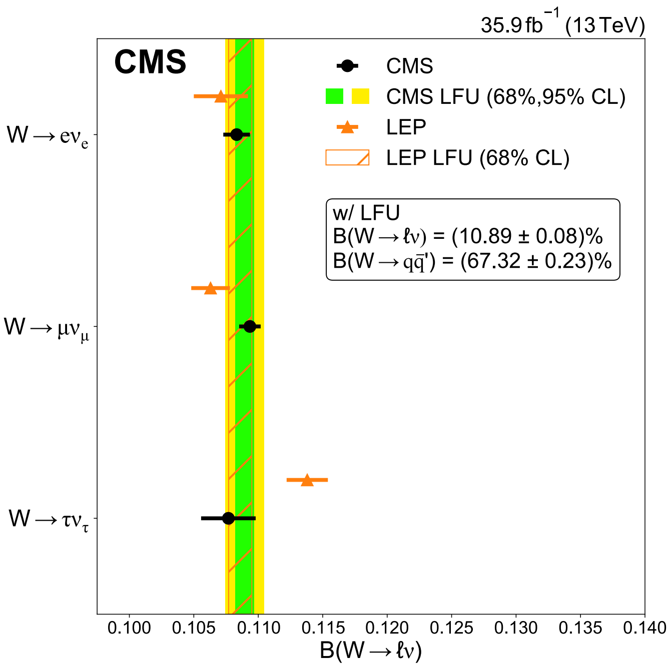
# CMS Results

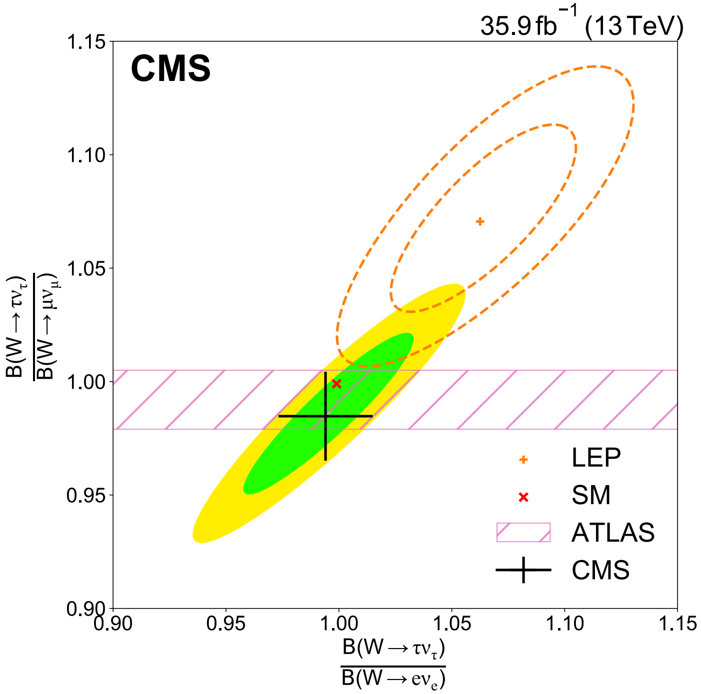


- Results consistent with both LFU and ATLAS [Nature Phys. 17 (2021) 813] results, and complement ATLAS via the inclusion of the electron channel
- Sensitivity to hadronic decays allow to test the CKM matrix unitarity and extract the poorly measured $|V_{cs}|$ element with the precision rivaling the world average

CMS, PRD 105 (2022) 072008

| | CMS | LEP | ATLAS |
|---|---|---|---|
| $R_{\mu/e}$ | $1.009 \pm 0.009$ | $0.993 \pm 0.019$ | $1.003 \pm 0.010$ |
| $R_{\tau/e}$ | $0.994 \pm 0.021$ | $1.063 \pm 0.027$ | — |
| $R_{\tau/\mu}$ | $0.985 \pm 0.020$ | $1.070 \pm 0.026$ | $0.992 \pm 0.013$ |
| $R_{\tau/\ell}$ | $1.002 \pm 0.019$ | $1.066 \pm 0.025$ | — |




**CKM matrix unitarity:**

$$\Sigma_{ij}|V_{ij}|^2 = 1.984 \pm 0.021$$

**Extraction of $|V_{cs}|$:**

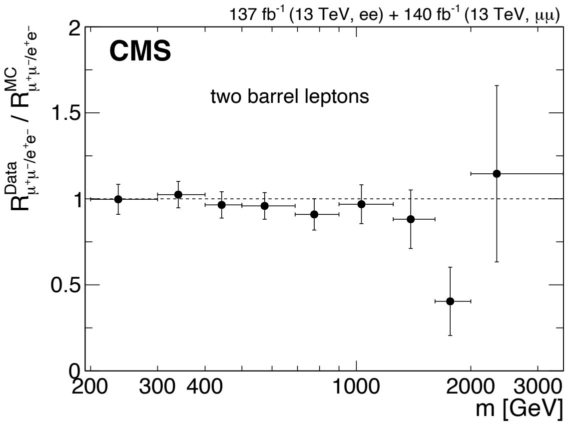
$$|V_{cs}| = 0.967 \pm 0.011$$

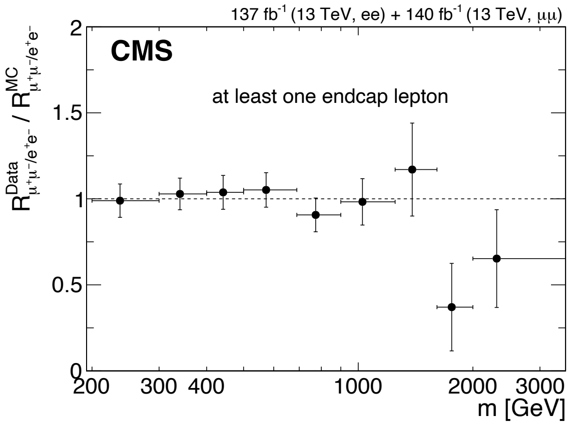
**World average (from D meson decays):**

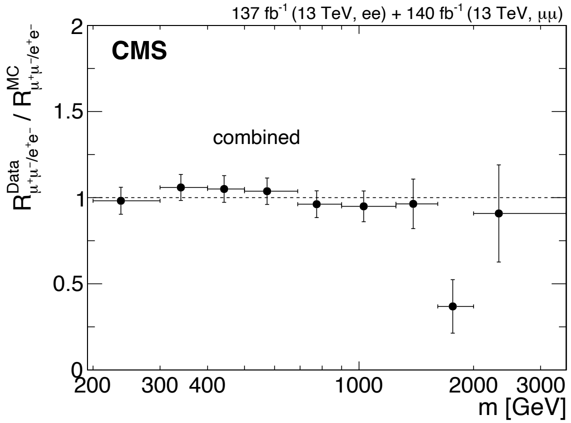
$$|V_{cs}| = 0.987 \pm 0.011$$

# LFU in High-Mass Drell-Yan Pairs

- A spin-off of the CMS Z'/compositeness searches in the dilepton channels
- Obtained a ratio of high-mass $\mu^+\mu^-$ to $e^+e^-$ events (via a double-ratio of data/simulation)
- Possible hint for a small deficit around ~2 TeV



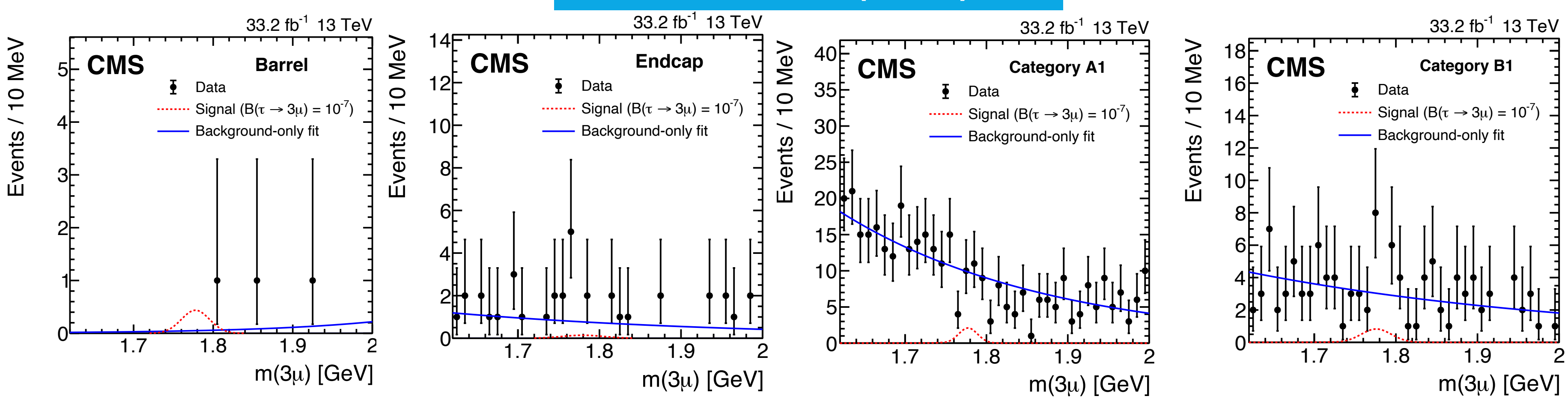




CMS, JHEP 07 (2021) 208

# Search for LFV $\tau \rightarrow 3\mu$ Decay

- The best limit was set a decade ago by Belle: $B(\tau \rightarrow 3\mu) < 2.1\times10^{-8}$ @90% CL
    - ★ At the LHC, ATLAS set a limit of $38 \times 10^{-8}$ using $W(\tau\nu)$ decays
    - ★ LHCb set a limit of $4.6\times10^{-8}$ using τ leptons from $B/D_{(s)}$ meson decays (HF channel)
- An analysis from CMS combines the W and HF channels to maximize the sensitivity
    - ★ The HF channel has $D_s \rightarrow \phi\pi \rightarrow \mu\mu\pi$ as the normalization mode; W channel is normalized through the inclusive W cross section measurement
- Set the limit at $8.0\times10^{-8}$ ($6.8\times10^{-8}$ 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

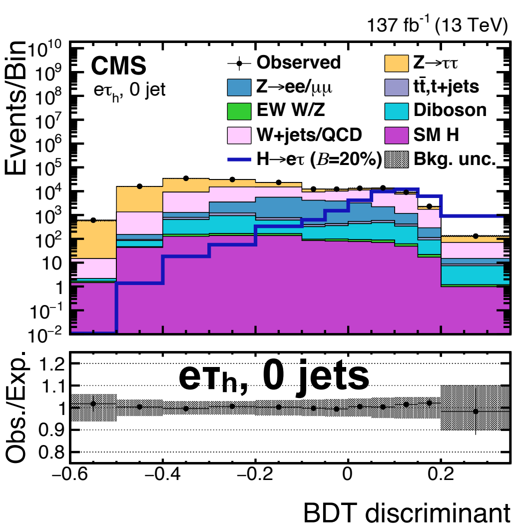
**W channel** CMS, JHEP 01 (2021) 163 **HF channel**

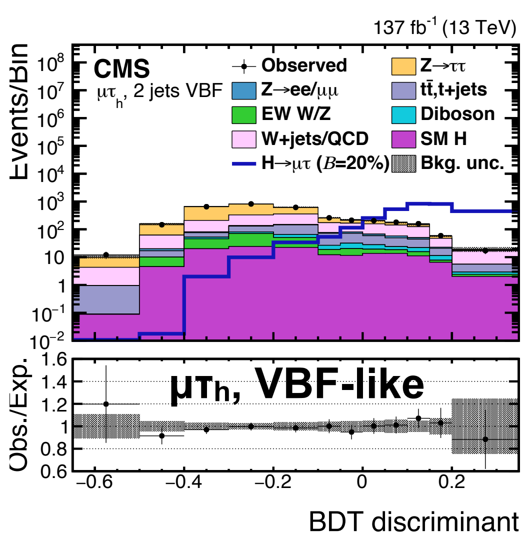


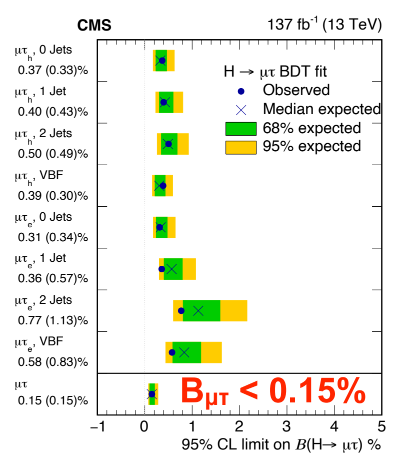
# H(e/μ+τ) Search

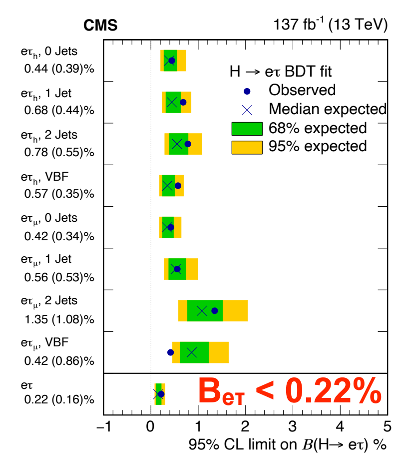
- Search proceeds in 6 different channels, depending on the τ lepton decay mode ($\tau_e$, $\tau_\mu$, $\tau_h$)
- Production mode is categorized according to the number of jets (0, 1, 2), and the 2-jet category is split into the VBF-like and the other
- Signal is enhanced via a BTD that uses kinematic properties of the leptons and $\tau_h$, 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
- Doesn't support a slight 2.2σ excess recently seen by ATLAS ([CONF-2022-060]()), but can't rule it out either

CMS, [PRD 104 (2021) 032013]()



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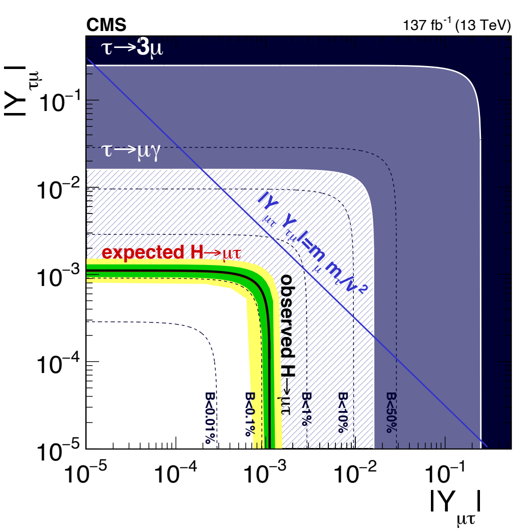
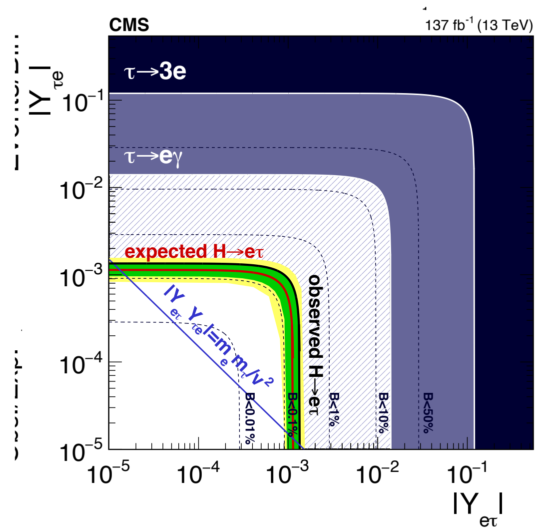
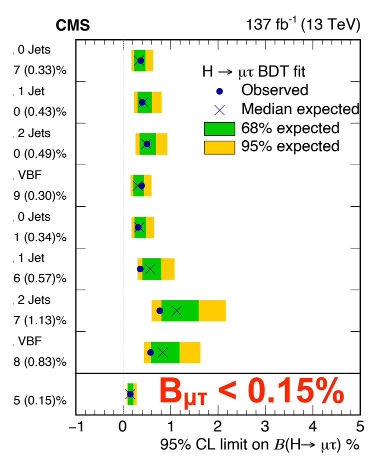
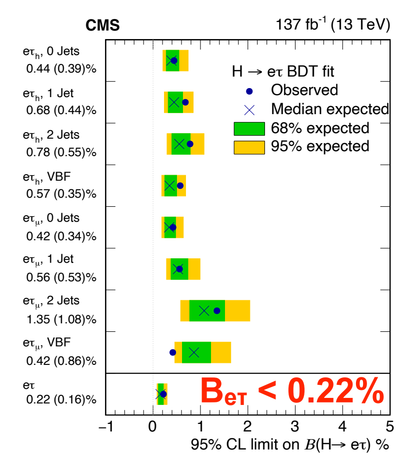
CMS, PRD 104 (2021) 032013



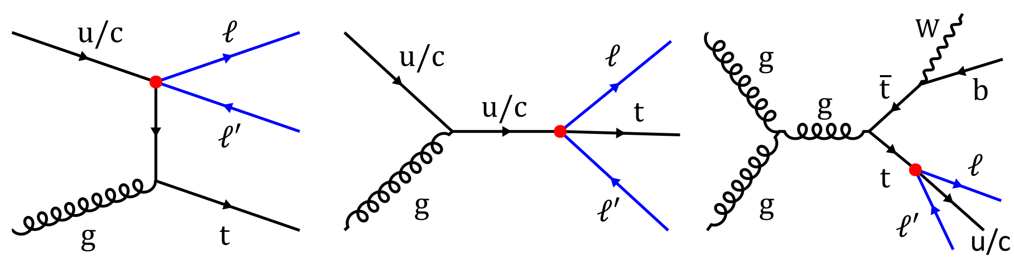



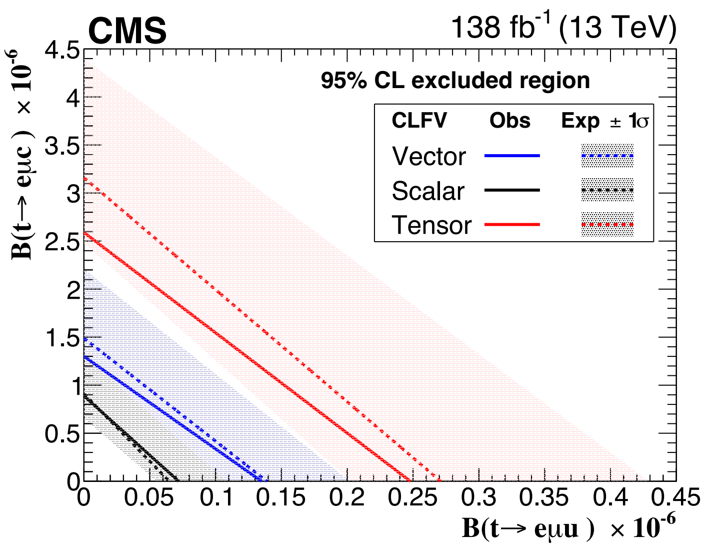
# CMS LFV $t \to e\mu q$ Result

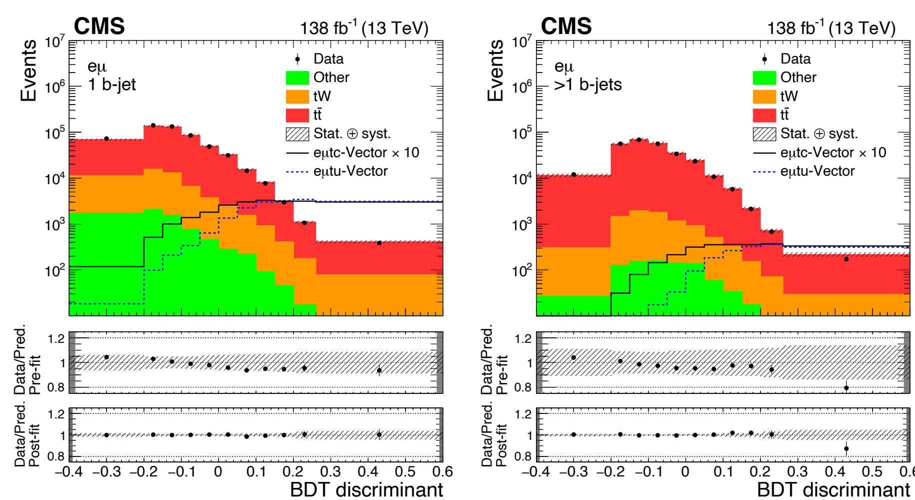


- CMS has a recent result in the $t \to e\mu u/c$ channel, using both the effects of this LFV vertex on production and decay
  - ★ Relies mainly on hadronic decays of the second top quark and on single t production
  - ★ Uses BDT and b-tag categories for optimal signal extraction
- Considers an EFT formalism with the operators corresponding to scalar, vector, and tensor couplings
- Substantially improves on world's best limit reaching sub ~$10^{-7}$ sensitivity on the branching fraction




CMS, JHEP 06 (2022) 082

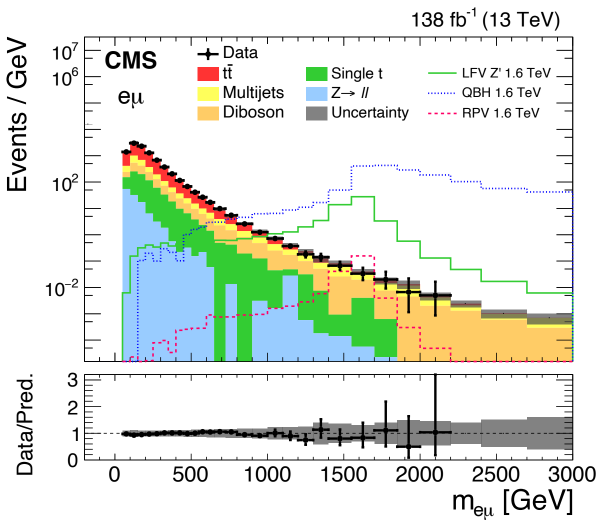


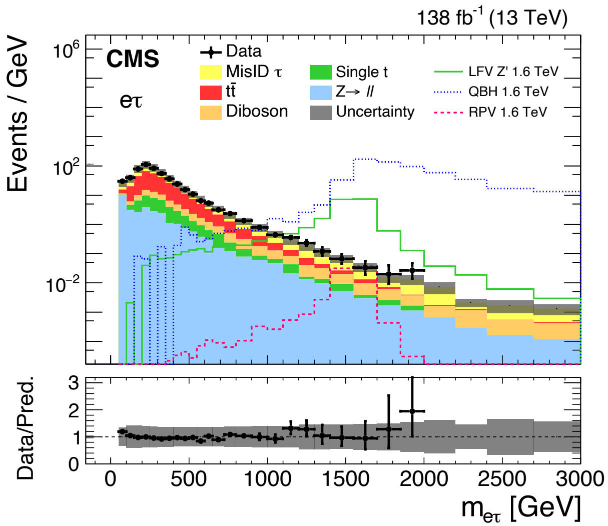



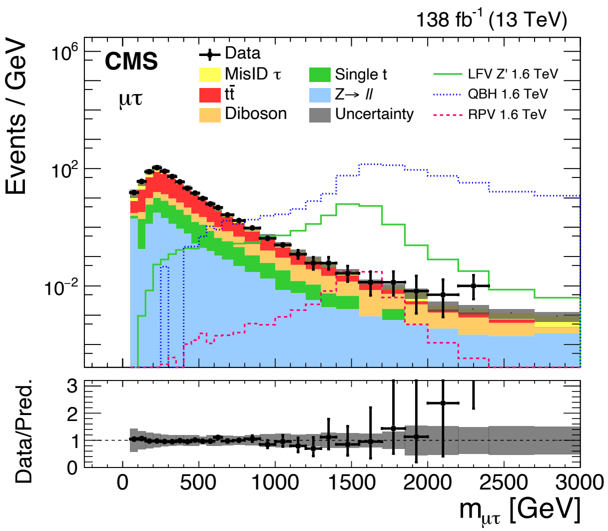
# Search for LFV Resonances

- 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, arXiv:2205.06709



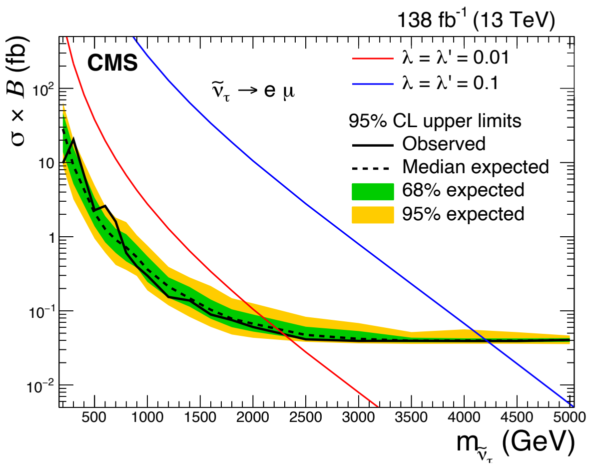



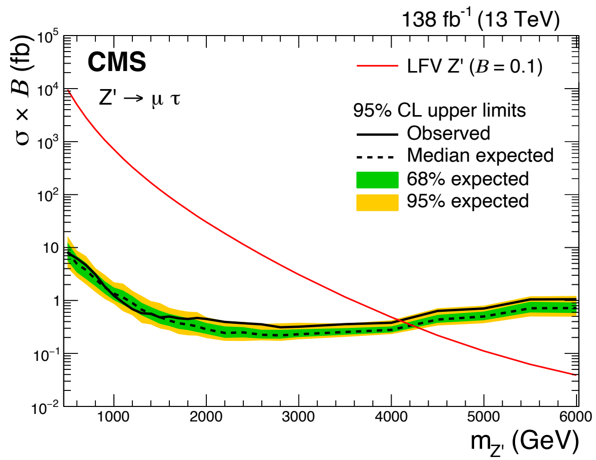



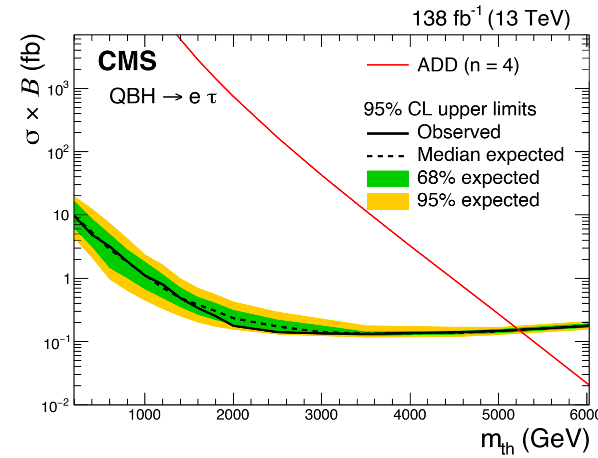
# LFV Resonance Limits

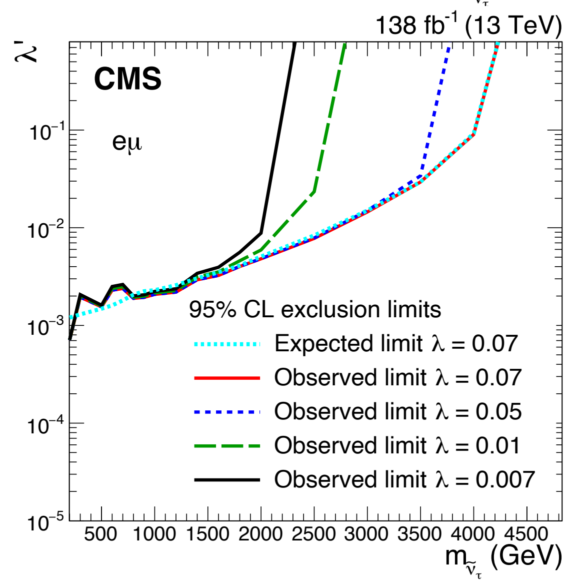
- Set stringent limits on tau sneutrino, LFV Z', QBH, as well as model-independent limits

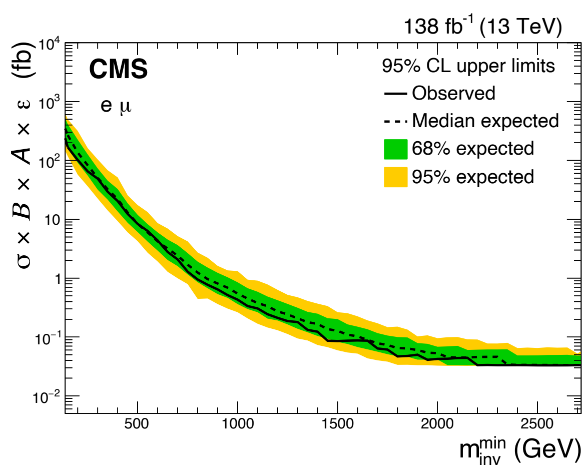
CMS, arXiv:2205.06709

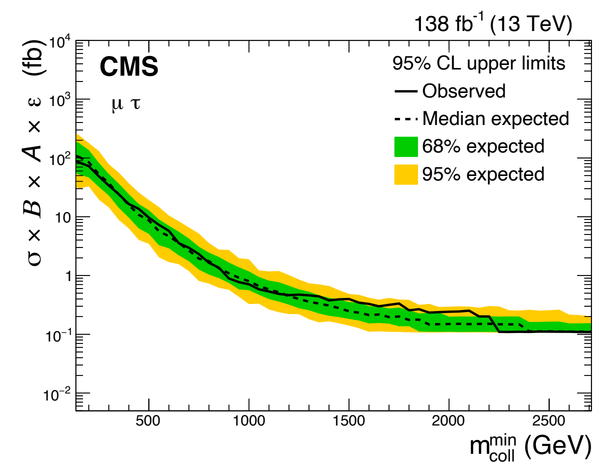


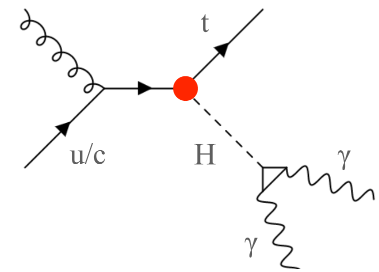



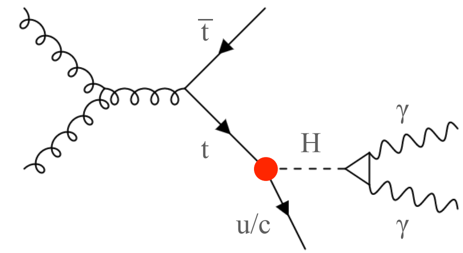
# FCNC with Top Quarks

- 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

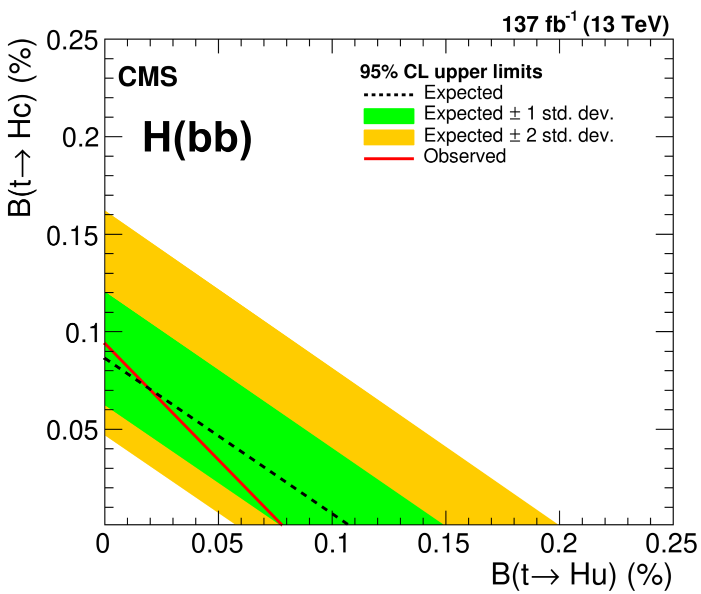
# FCNC in Decays to H Bosons

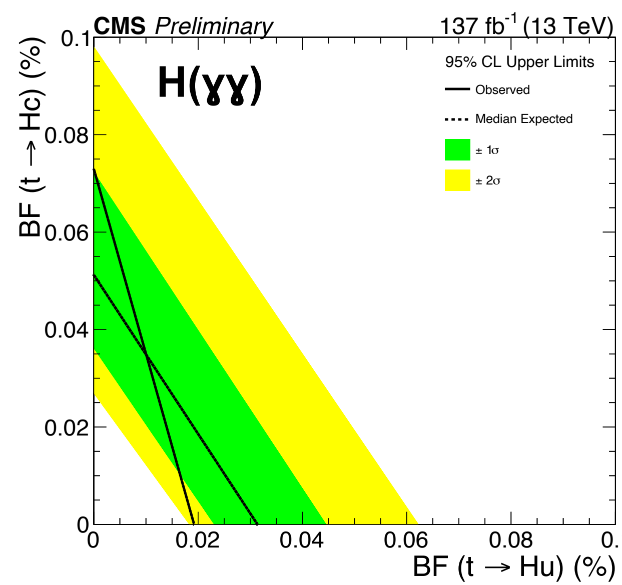
- Promising channels to look are t → Hu, t → Hc
  - ★ Extremely small in the SM (GIM-suppressed, Br ~ $10^{-15...-17}$); can be significantly enhanced in 2HDMs allowing possible detection at the LHC
- Can look for utH/ctH vertices in both single and pair production of top quarks
- Use the Higgs boson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




CMS, JHEP 02 (2022) 169

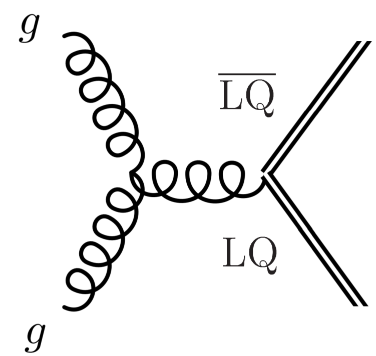


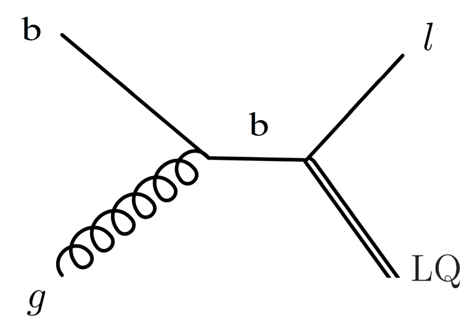




CMS, PRL 129 (2022) 032001

# Leptoquark Searches

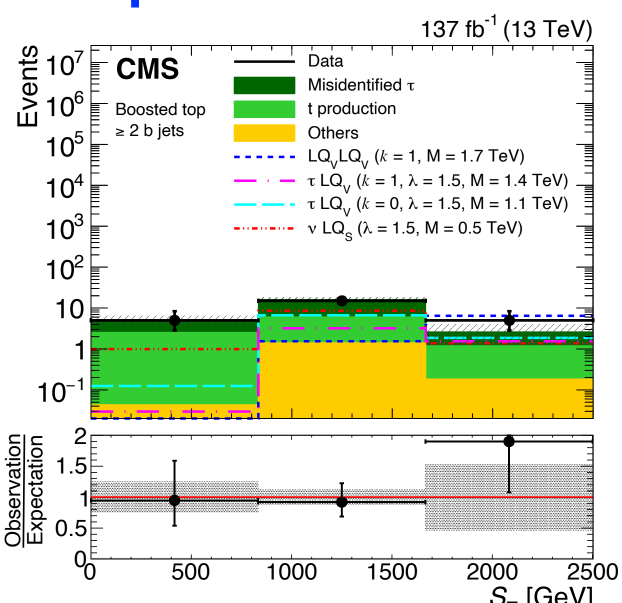
- **Leptoquarks (LQs) remain one of the favorite theoretical models capable of explaining both tree-level anomalies seen in $b \to c\ell\nu$ decays and loop-level anomalies seen in $b \to s\ell\ell$ transitions**
- **Typically require LQs with cross-generational coupling, often with enhanced couplings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



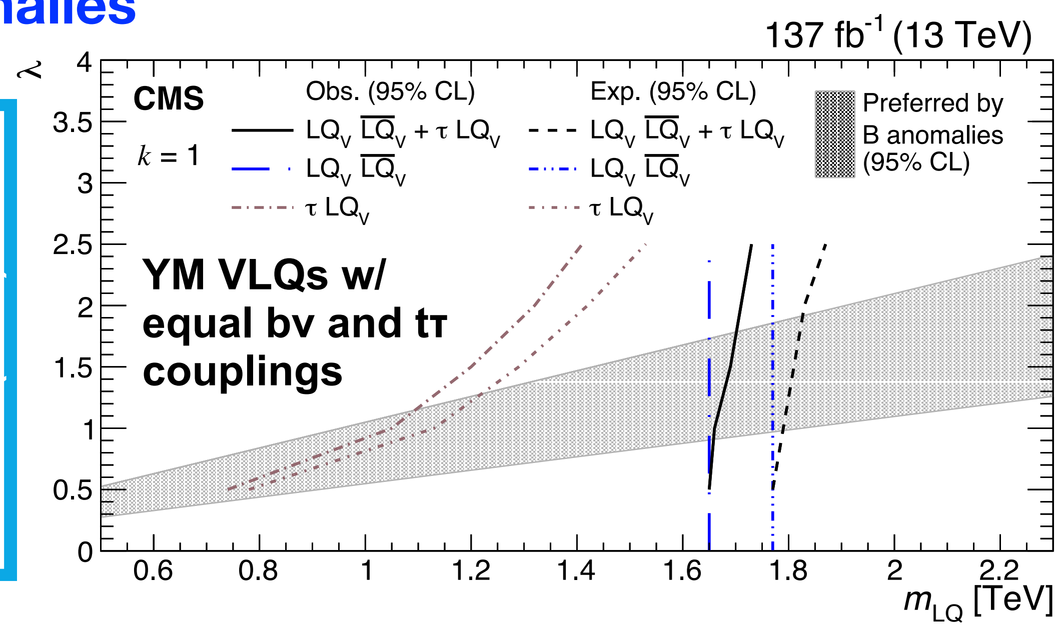



# CMS Search for LQ3

- 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 $\tau_h$ and hadronic top quark decays
- Using $S_T = \Sigma p_T^{objects}$ as a sensitive variable for S/B separation
- Probes interesting range of parameter space for the possible explanation of flavor anomalies



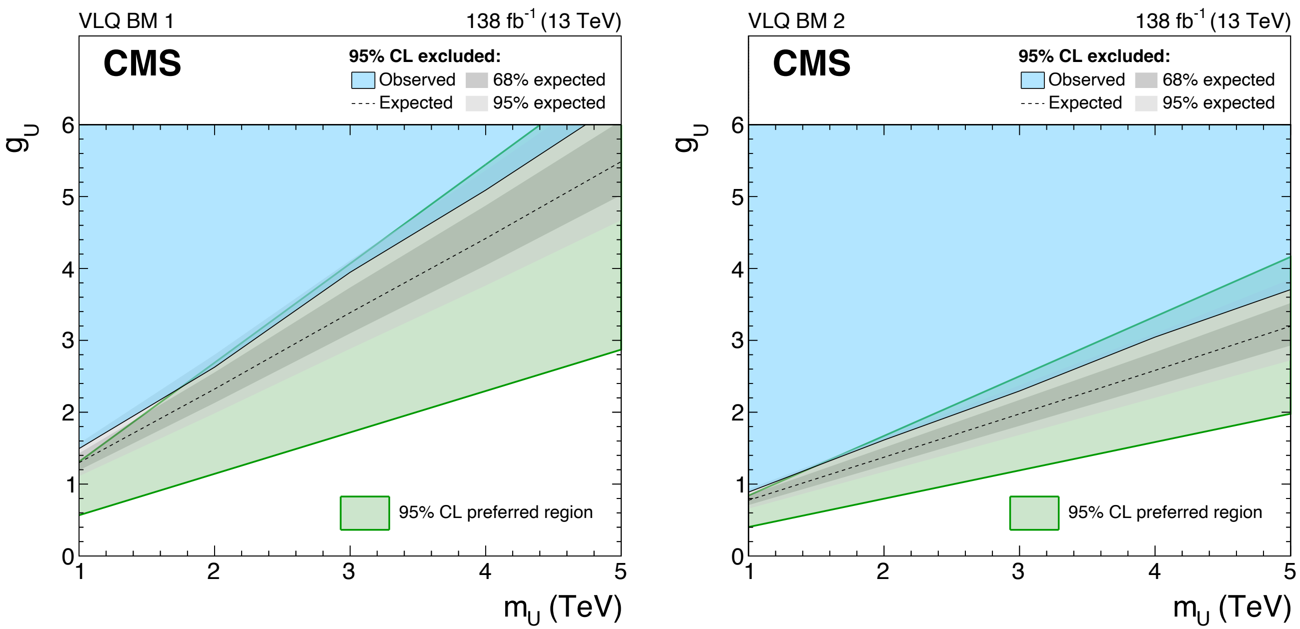

CMS
PLB 819 (2021) 136446

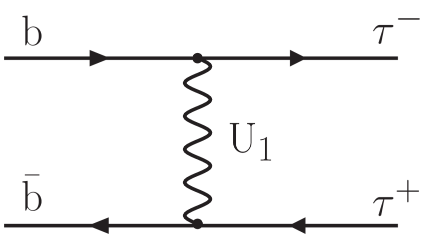


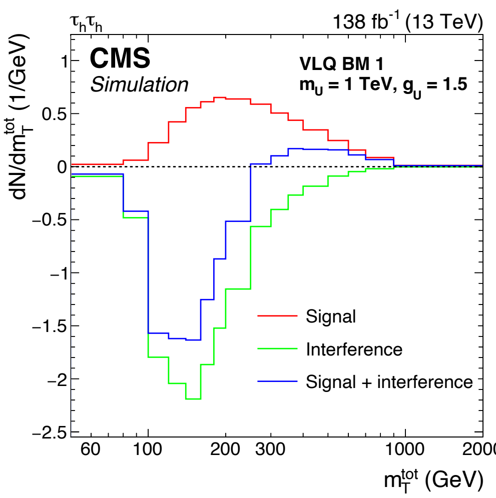
# CMS Searches for LQ3

- A new search for Pati-Salam $U_1$ vector LQ in the ττ channel, a spin-off of the MSSM Higgs search
- Significant interference with the SM DY ττ continuum taken into account
- Started probing interesting parameter space from the point of view of flavor anomalies

CMS, arXiv:2208.02717

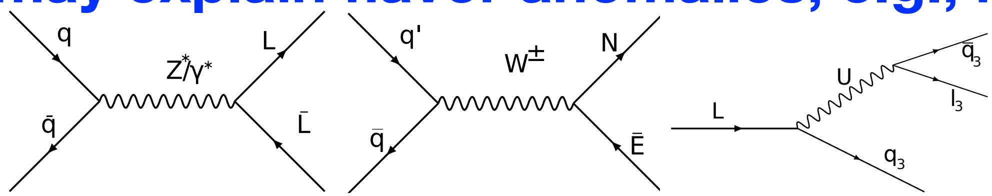


# CMS Search for VLLs

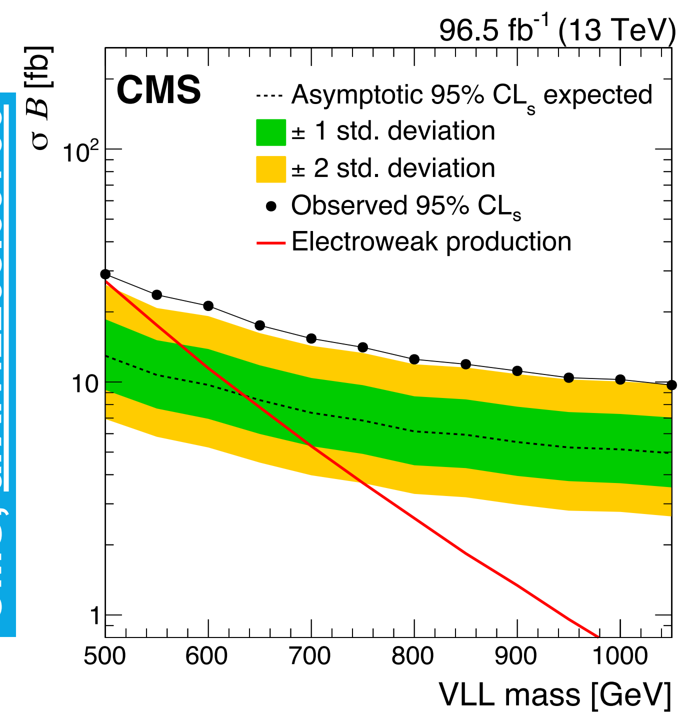
- Vector-like leptons are predicted in several SM extensions that may explain flavor anomalies, e.g., in the 4321 LQ model




| tau multiplicity | production + decay mode | final state |
|---|---|---|
| $0\,\tau$ | $\mathrm{EE} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{b}(\mathrm{t}\nu_\tau)$ | $4\mathrm{b} + 4\mathrm{j} + 2\nu_\tau$ |
| | $\mathrm{EN} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$ | $4\mathrm{b} + 6\mathrm{j} + 2\nu_\tau$ |
| | $\mathrm{NN} \to \mathrm{t}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$ | $4\mathrm{b} + 8\mathrm{j} + 2\nu_\tau$ |
| $1\,\tau$ | $\mathrm{EE} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{b}(\mathrm{t}\nu_\tau)$ | $4\mathrm{b} + 2\mathrm{j} + \tau + \nu_\tau$ |
| | $\mathrm{EN} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{b}\tau)$ | $4\mathrm{b} + 4\mathrm{j} + \tau + \nu_\tau$ |
| | $\mathrm{EN} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$ | $4\mathrm{b} + 4\mathrm{j} + \tau + \nu_\tau$ |
| | $\mathrm{NN} \to \mathrm{t}(\mathrm{b}\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$ | $4\mathrm{b} + 6\mathrm{j} + \tau + \nu_\tau$ |
| $2\,\tau$ | $\mathrm{EE} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{b}(\mathrm{b}\tau)$ | $4\mathrm{b} + 2\tau$ |
| | $\mathrm{EN} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{t}(\mathrm{b}\tau)$ | $4\mathrm{b} + 2\mathrm{j} + 2\tau$ |
| | $\mathrm{NN} \to \mathrm{t}(\mathrm{b}\tau)\mathrm{t}(\mathrm{b}\tau)$ | $4\mathrm{b} + 4\mathrm{j} + 2\tau$ |

- New CMS analysis in ≥3b + (0-2)τ final states
- Complicated analysis relying on DNNs to separate signal from the dominant QCD and tt backgrounds
- Observed a mild excess (1-2$\tau_h$ channels), which unfortunately is hard to associate with any specific mass
  - ★ Important to construct the analysis optimized for discovery, not a limit!

CMS, arXiv:2208.09700



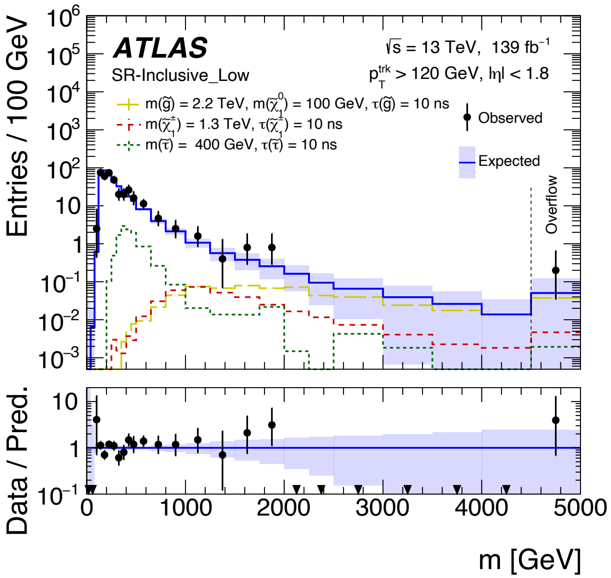
# High-$p_T$ Run 2 Excesses

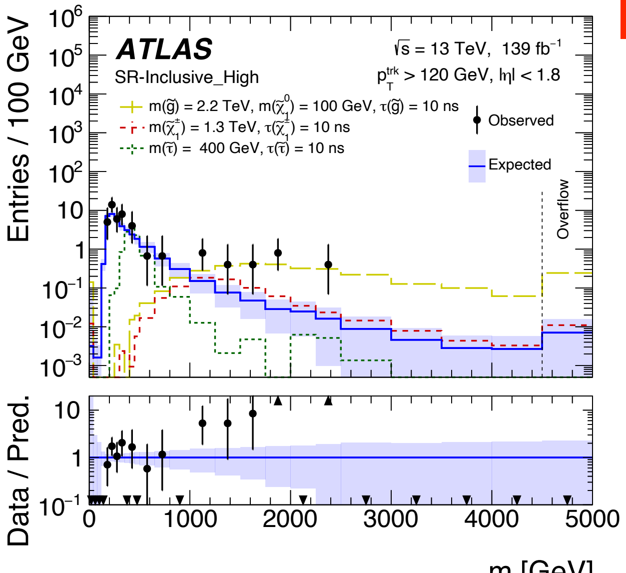
# ATLAS LLP dE/dx Excess

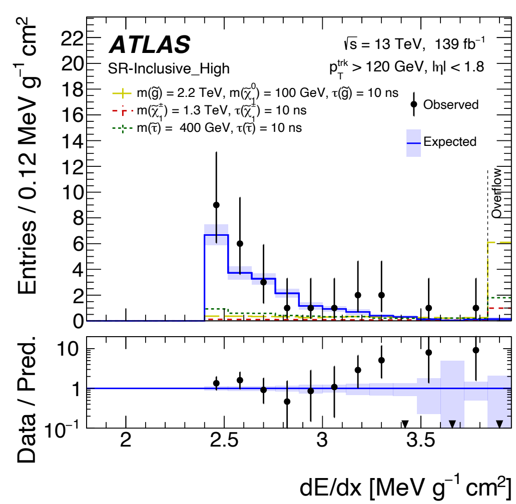


- Search based on high-$p_T$ and high-dE/dx tracks in the ATLAS pixel detector
  - ★ Dedicated time-dependent calibration accounting for the pixel detector aging
  - ★ dE/dx to βγ calibration based on dedicated low-pileup run
- Several signal regions, as well as a number of control and validation regions for background estimation
- An excess of high-dE/dx events in the 1.1-2.8 TeV mass window is seen, with the local (global) significance of 3.6 (3.3)σ
- Excess events very scanned for pixel detector pathologies, and none were found
- However, the time-of-flight information for these events is consistent with β = 1 (which is not inconsistent with the dE/dx results for |q| > e)

ATLAS, arXiv:2205.06013



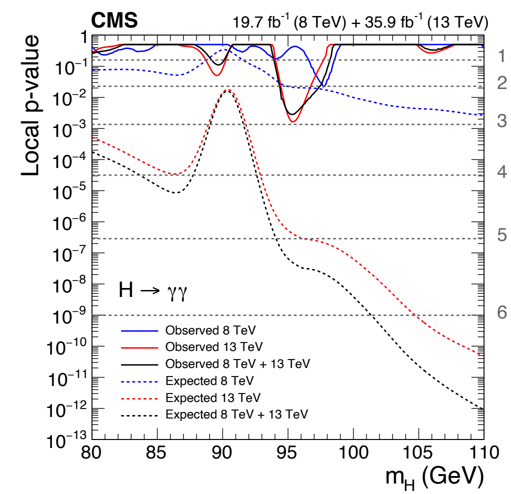



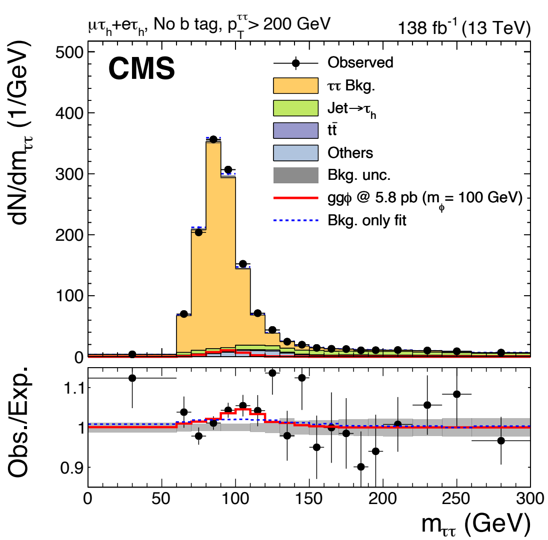

No competitive CMS results yet

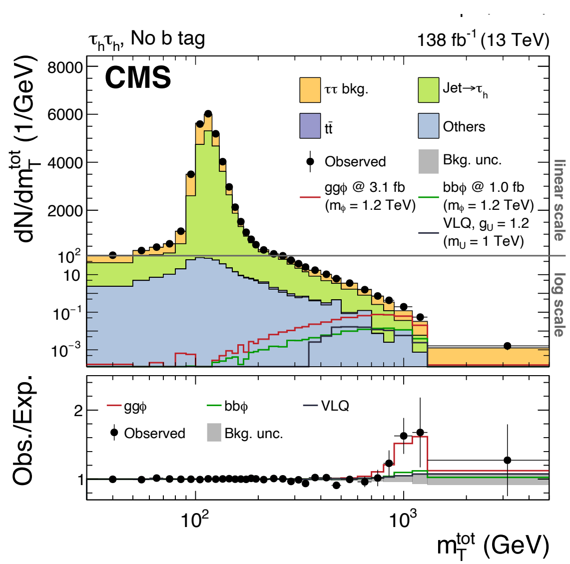
# CMS ~0.1 and ~1.2 TeV ττ Excesses

- Search for MSSM Higgs bosons decaying into the ττ final state also reinterpreted as a search for VLQs
  - ★ Sophisticated background prediction using the "τ-embedding" method
- Two ~3σ excesses are seen in the ditau mass distributions (or its proxy) around 0.1 and 1.2 TeV
  - ★ Excesses are reasonably distributed between various ττ decay channels
  - ★ The ~100 GeV excess appears to be well aligned with the low-mass diphoton excess seen in an earlier analysis of Run 1 + 2016 data

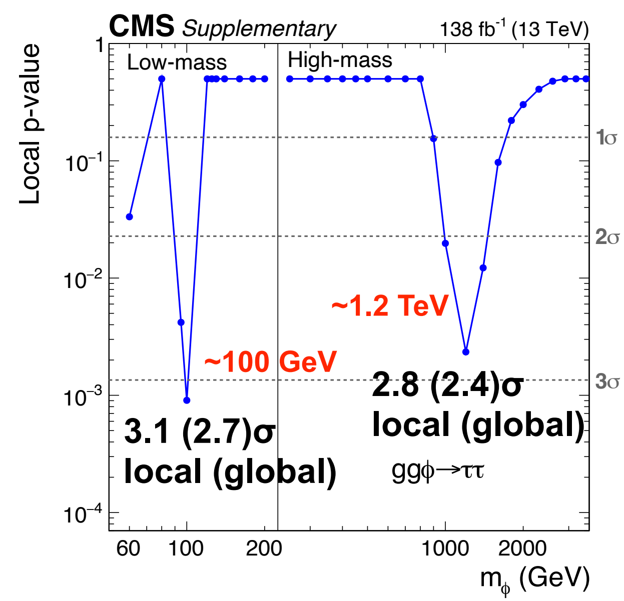



CMS, PLB 793 (2019) 320



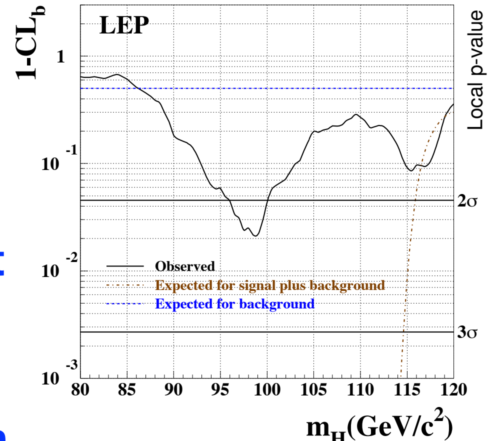




CMS, arXiv:2208.02717

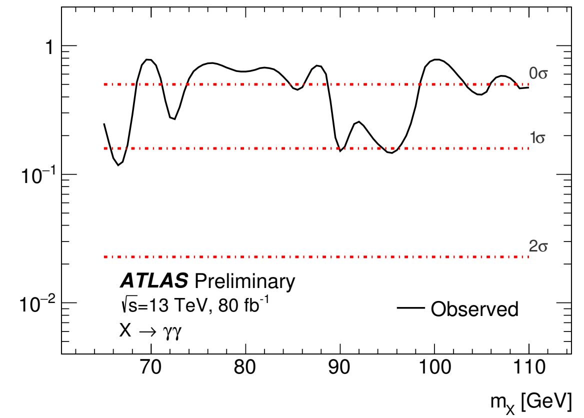


# What Does ATLAS See?

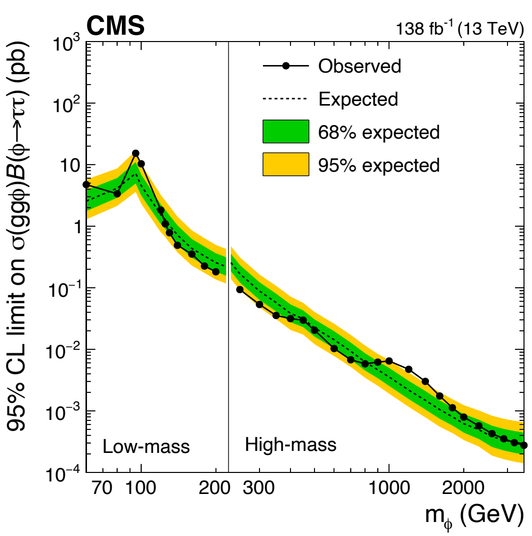
- No full Run 2 result in low-mass diphoton channel yet
  - ★ The 2016 ATLAS result is not inconsistent with the CMS one
- The full Run 2 MSSM H(ττ) result contradicts the 1.2 TeV excess seen in CMS
- The 95-96 GeV light Higgs boson has long been a subject of theoretical interest since an old LEP hint in the H(bb) channel




ADLO, hep-ex/0306033

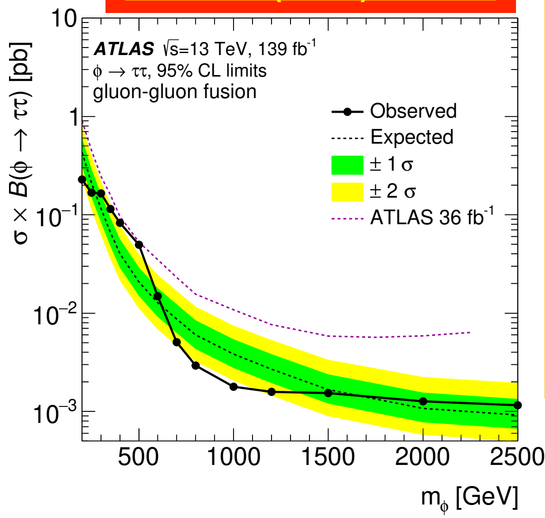



ATLAS-CONF-2018-025

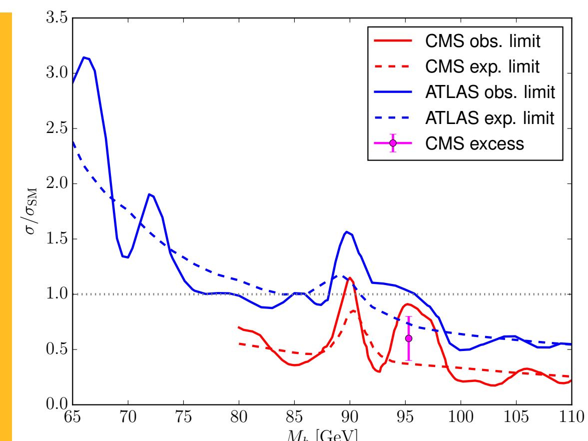



CMS, arXiv:2208.02717

ATLAS PRL 125 (2020) 051801




Heinemeyer, Stefaniak arXiv:1812.05864

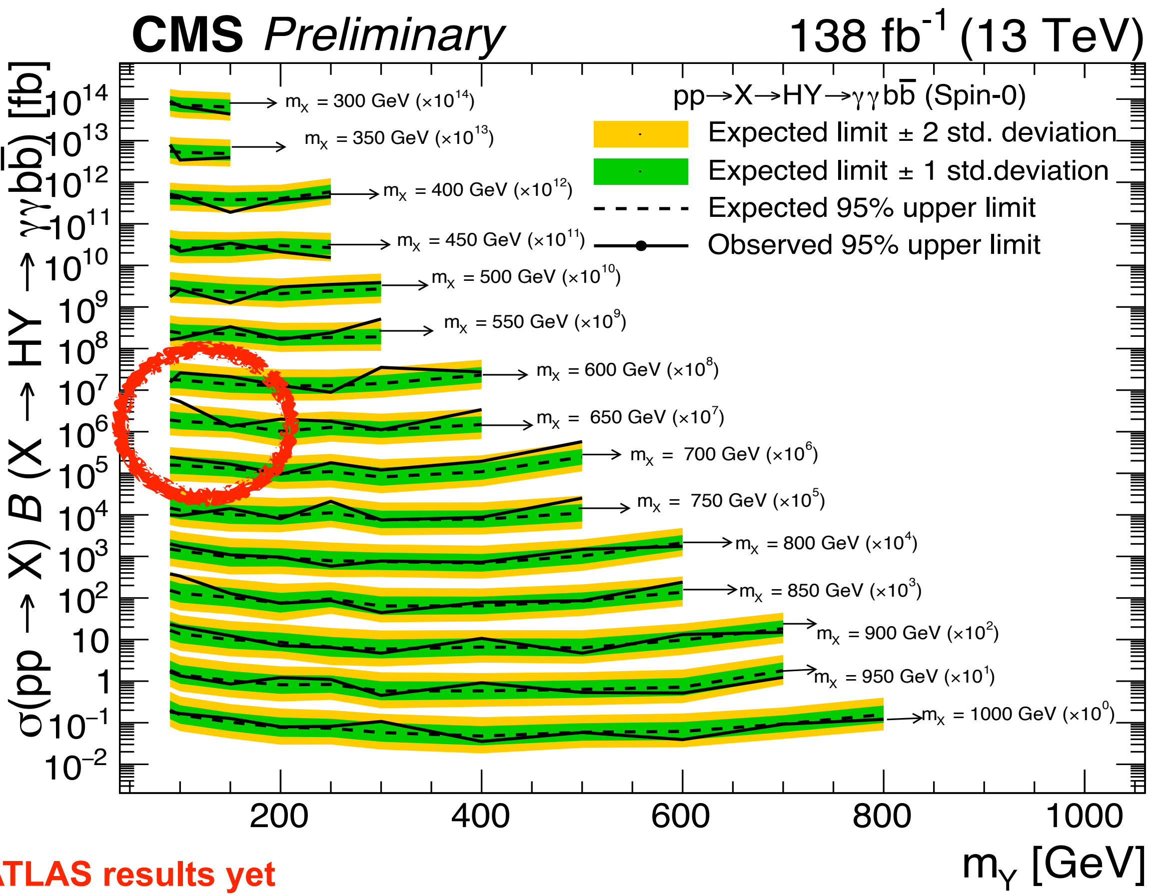



**Looking forward to ATLAS 139 fb$^{-1}$ updates in the γγ channel!**

# CMS Y(bb)H(γγ) Excess

- Recent preliminary result from CMS on resonant search in the $X \to Y(bb)H(\gamma\gamma)$ channel
  - ★ See ~3.5σ (2.8σ globally) excess at M(bb) ~100 GeV, M(X) = 650 GeV

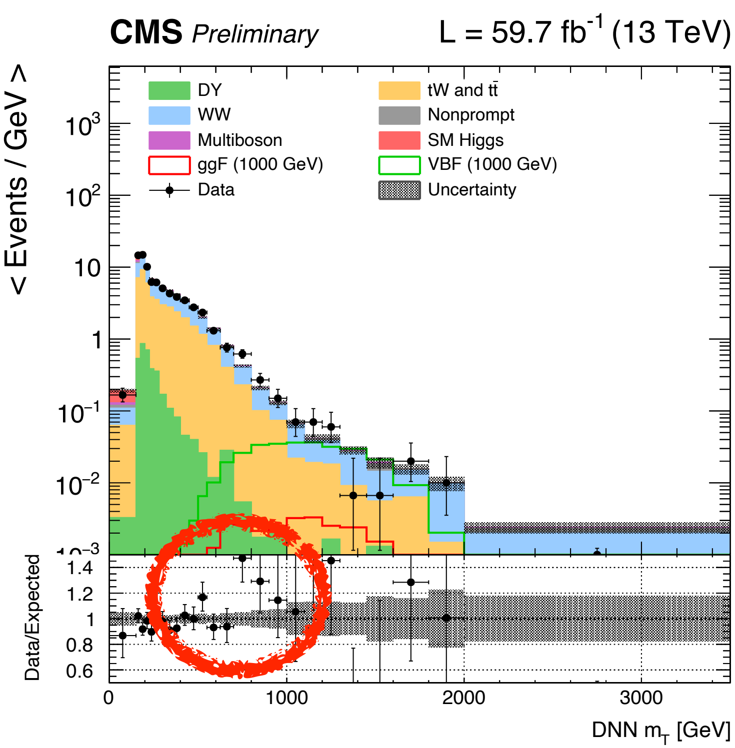
CMS-PAS-HIG-21-011



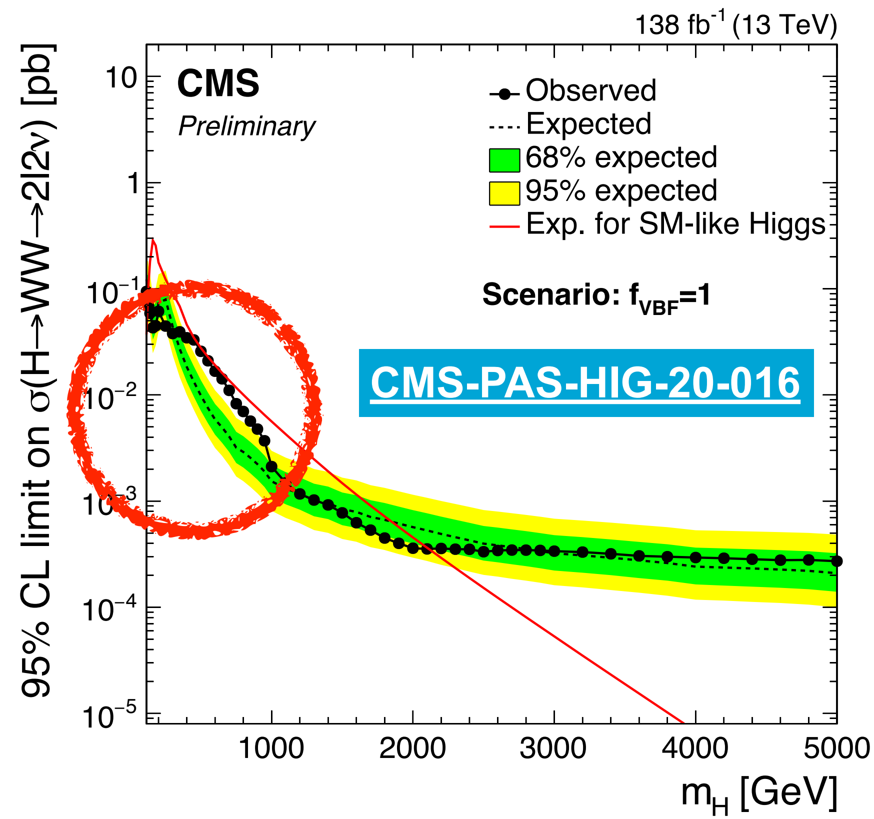

No competitive ATLAS results yet

# Excess in H(WW) Search?

- Curiously, a 650 GeV bump is also observed in the recent CMS high-mass H(WW) search in dilepton channel (low resolution), but only in the VBF category with a 3.8σ (2.8σ global) significance
  - ★ ATLAS Run 2 leptonic H(WW) analysis doesn't see an excess; neither does the Run 2 Z'(WW) semileptonic search; sensitivity is not sufficient to rule out the CMS one
  - ★ However, there is a small VBF H(ZZ → 4l + 2l2ν) excess at 620 GeV (2.4σ; 0.9σ global) in the ATLAS data




CMS-PAS-HIG-20-016



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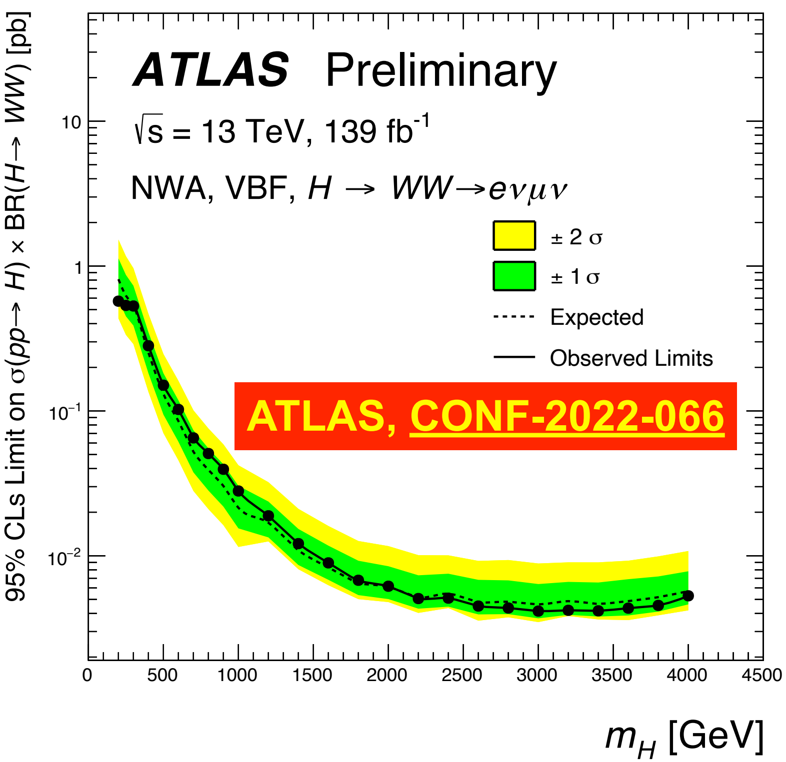
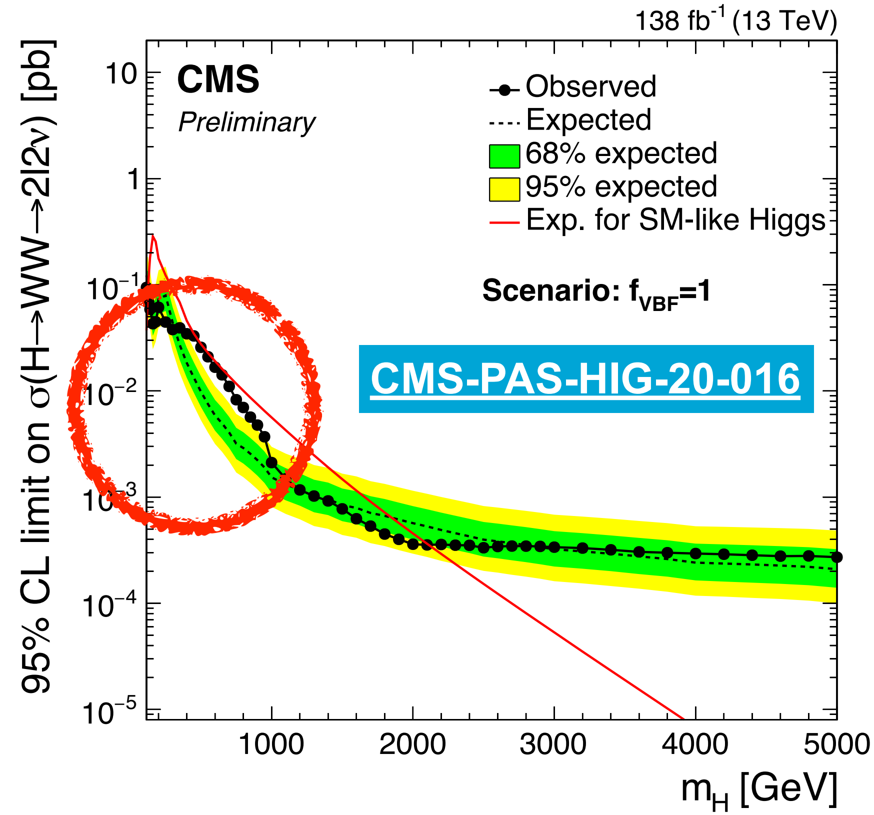



CMS-PAS-HIG-20-016



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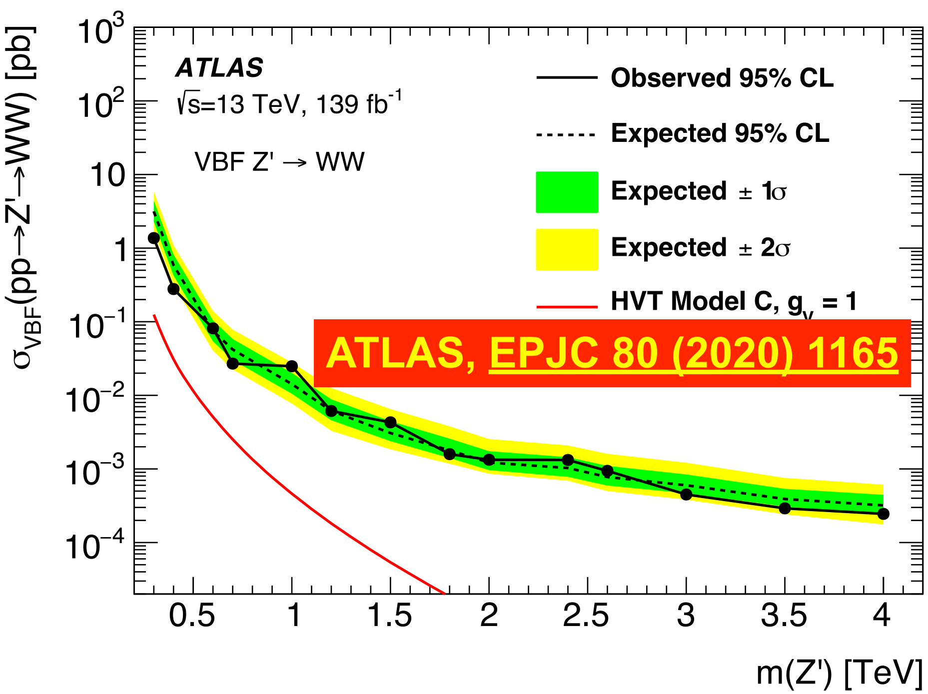
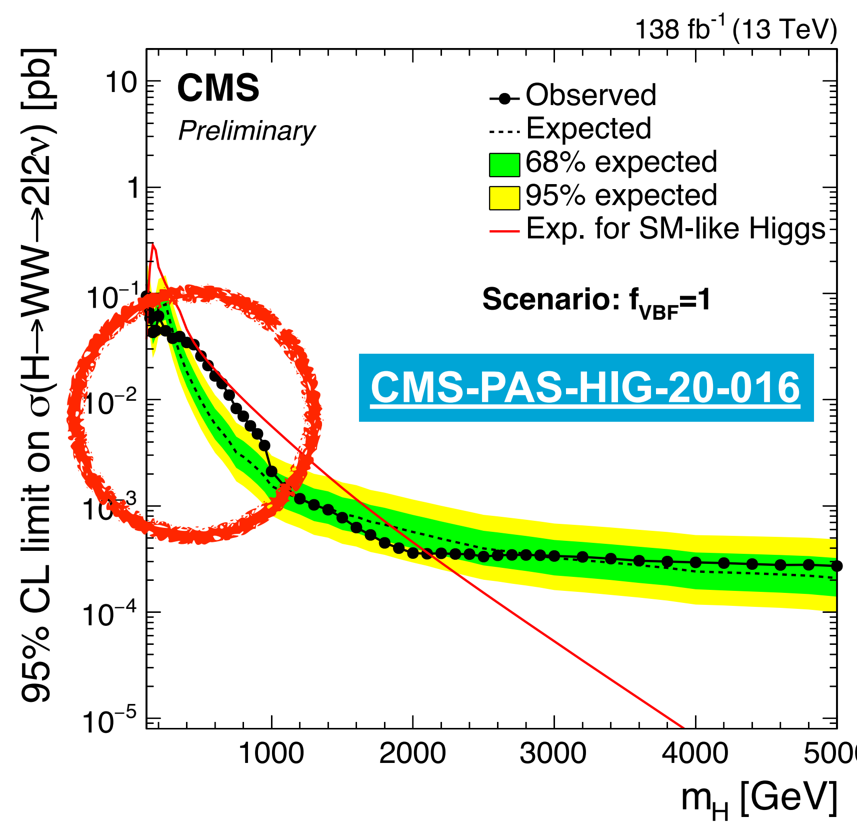



ATLAS, EPJC 80 (2020) 1165




CMS-PAS-HIG-20-016

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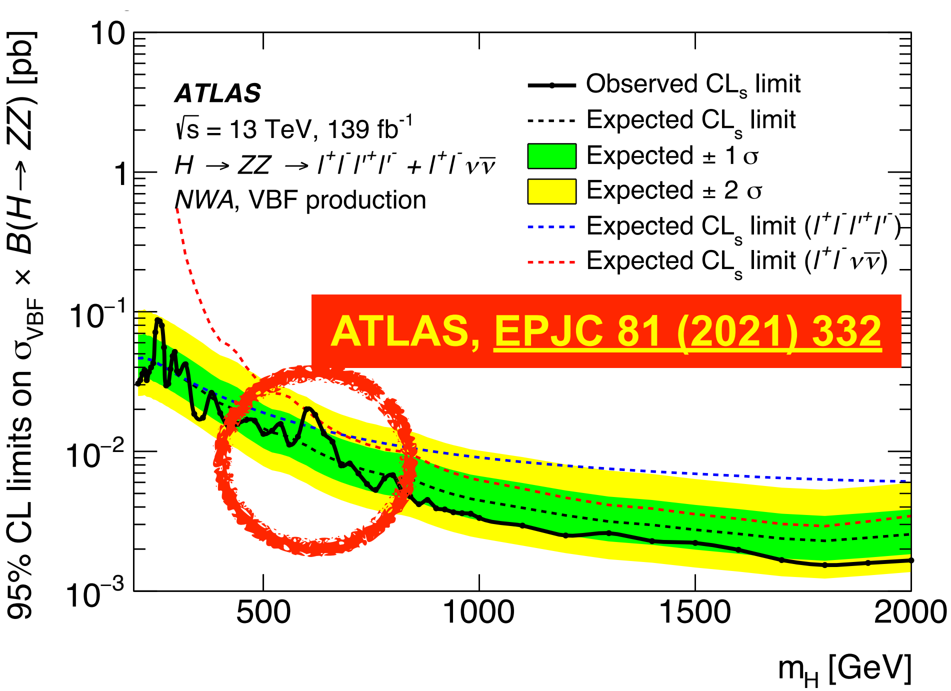
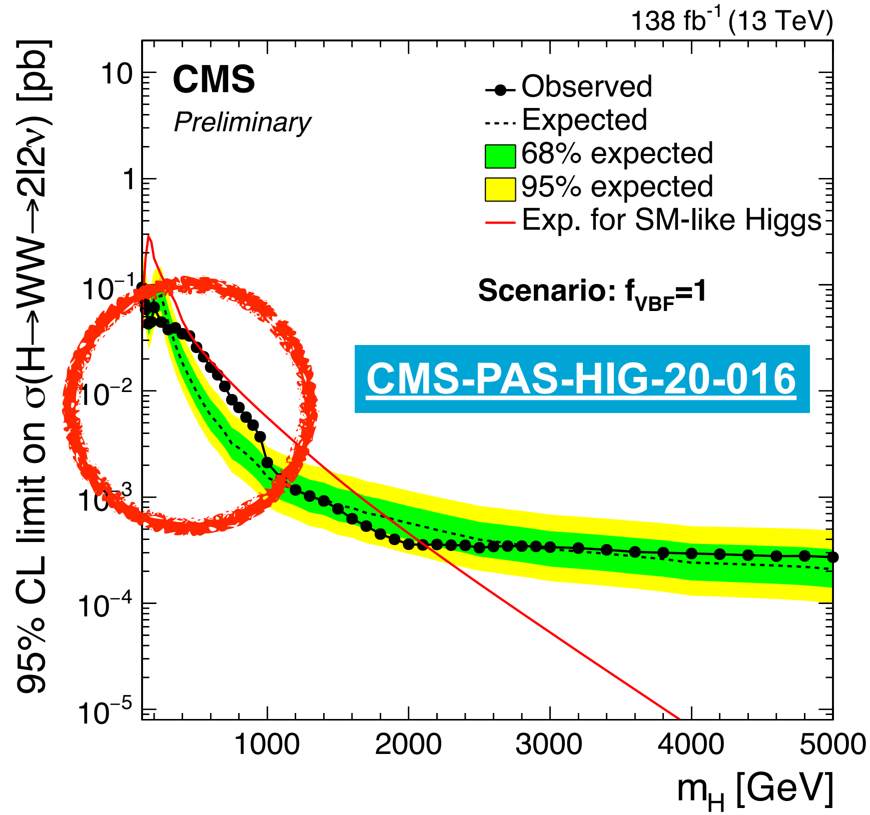
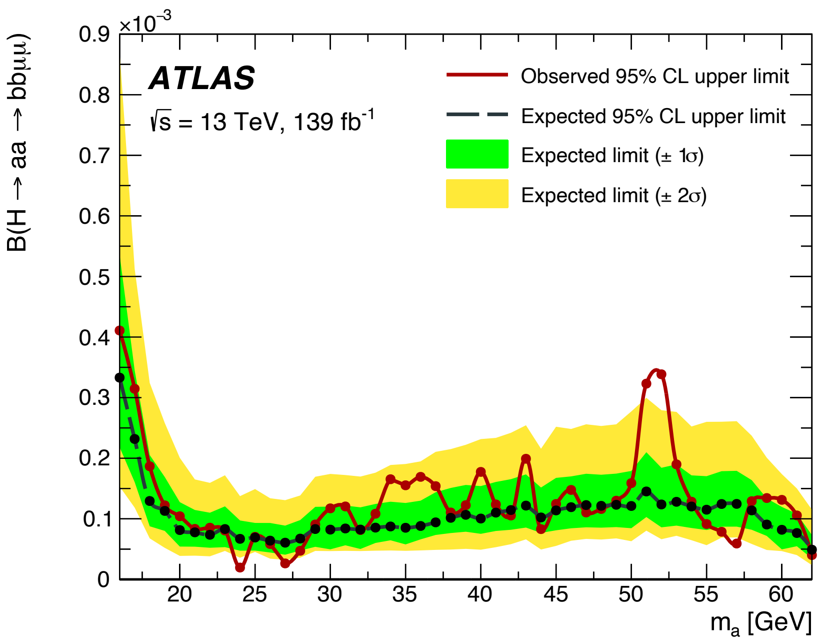


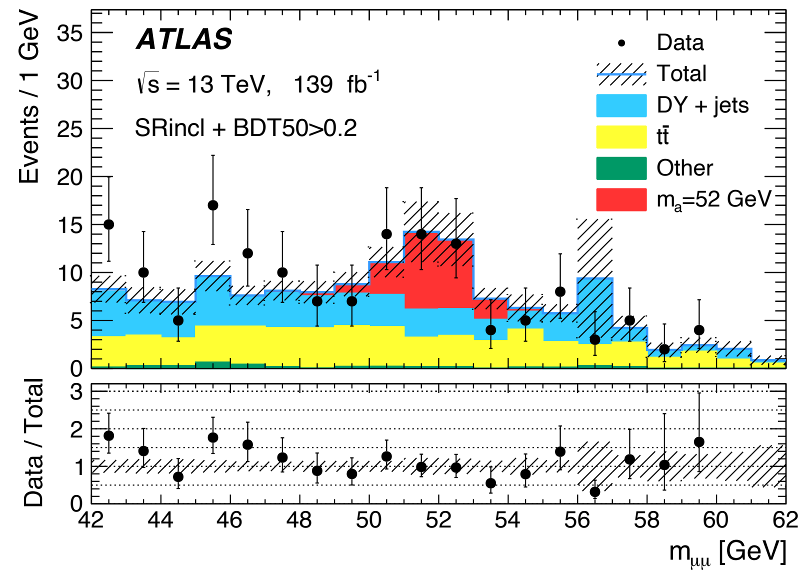



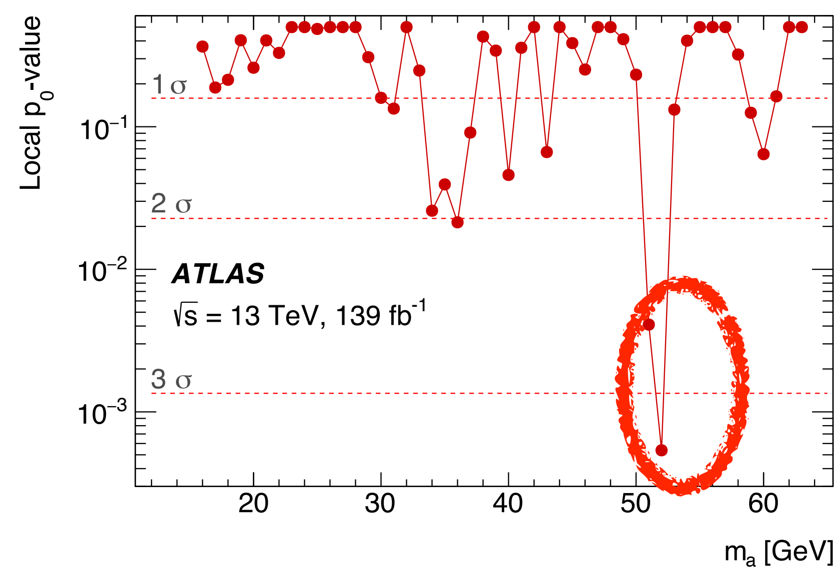
# ATLAS H → a(bb)a(μμ) Excess

- An excess observed in a Run 2 search looking for H → a(bb)a(μμ) in high-resolution dimuon mass distribution
  - ★ Local (global) significance of 3.3 (1.7)σ at M(a) = 52 GeV




ATLAS, PRD 105 (2022) 012006



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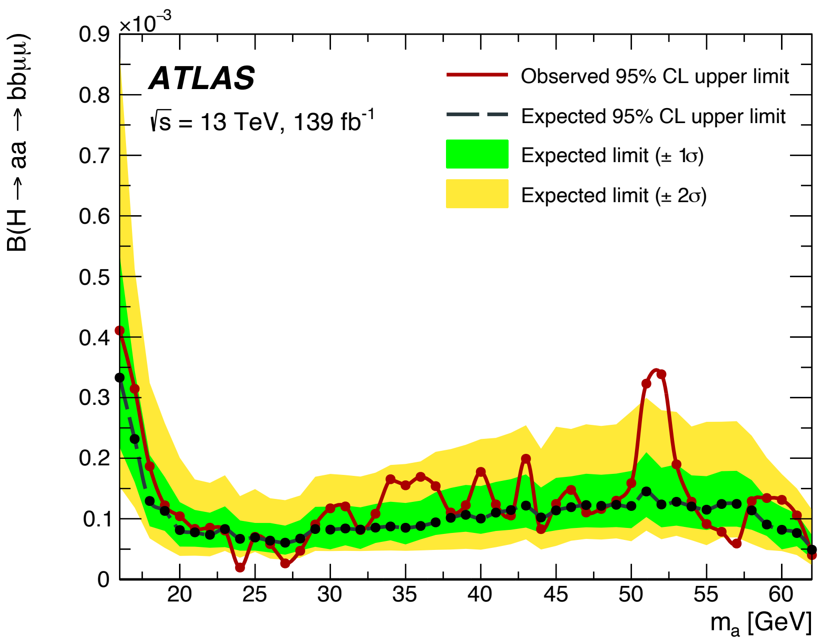
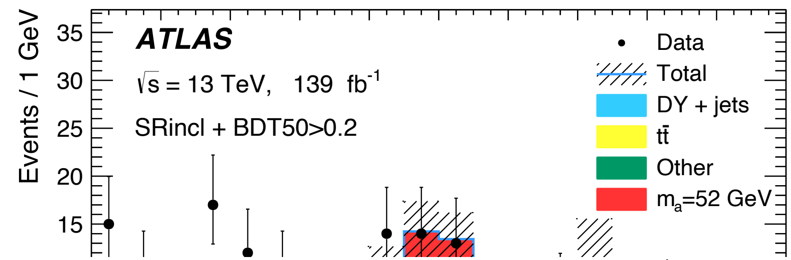
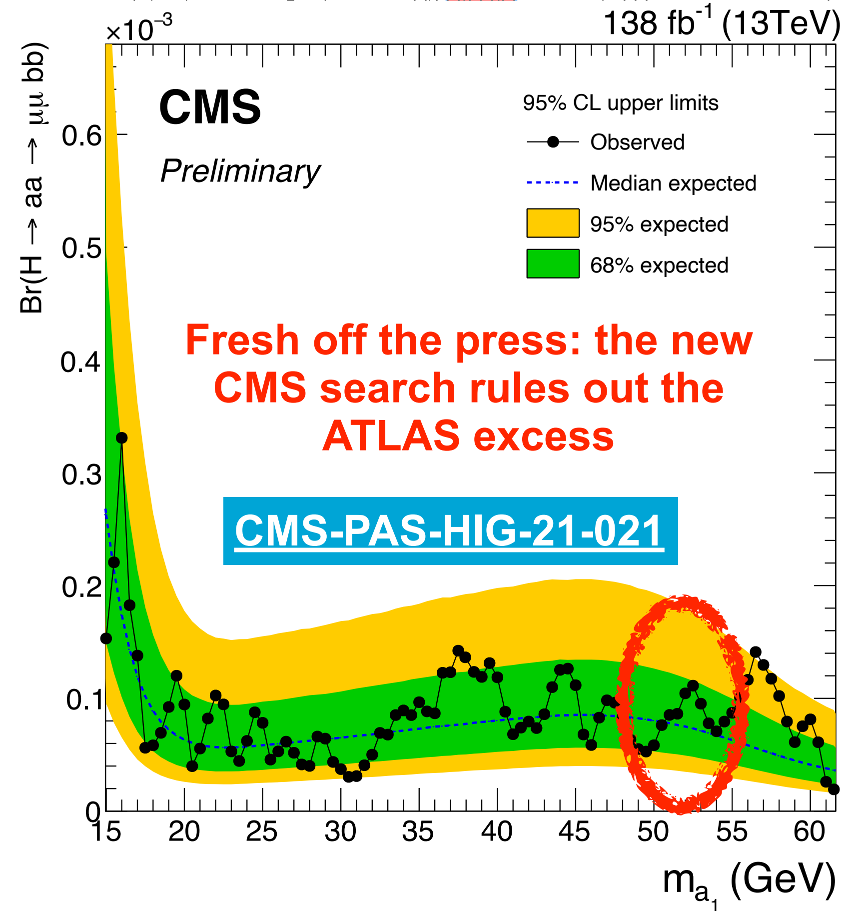



ATLAS, PRD 105 (2022) 012006



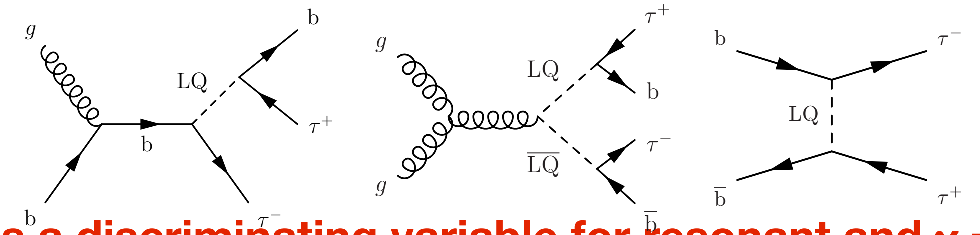




Fresh off the press: the new CMS search rules out the ATLAS excess

CMS-PAS-HIG-21-021

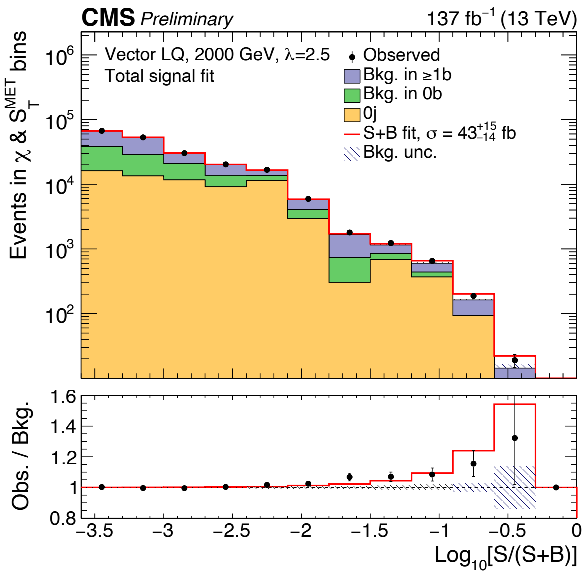
# CMS Excess in LQ3 Search

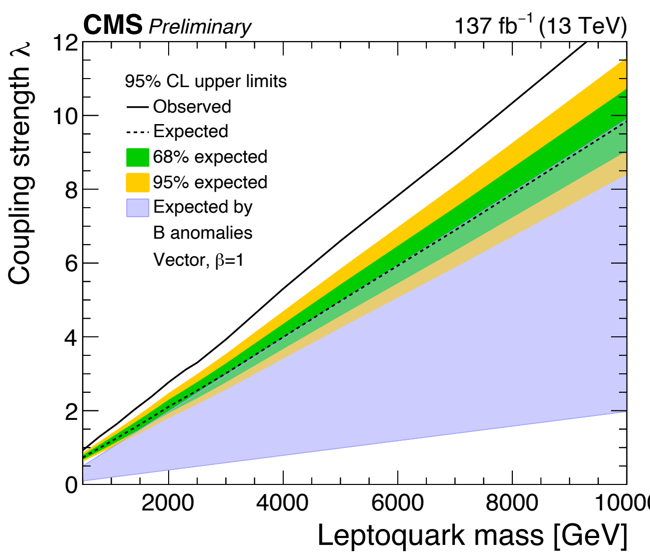
- Another preliminary result from CMS, inspired by the flavor anomalies
- Looks for single, pair, and t-channel production of LQ3 in the ττ+X final states




  - ★ Uses $S_T = \Sigma p_T(\tau) + p_T(j_1) + ME_T$ as a discriminating variable for resonant and $\chi = e^{-2y^*}$, where $y^* = |y_1 - y_2|/2$ the rapidity separation between two leading (tau) jets
- Global fit to multiple search regions for different LQ3 mass and couplings
  - ★ See ~3.5σ excess peaking in non-resonant production at large VLQ masses and couplings; no excess is seen for resonant production; global σ is hard to quantify

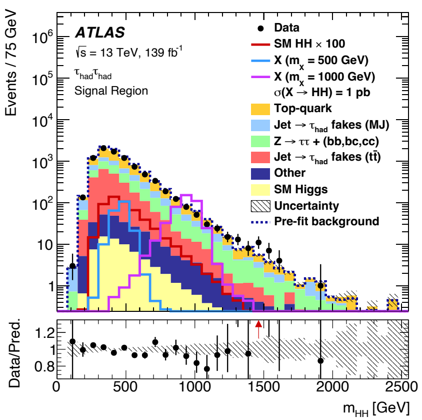
CMS-PAS-EXO-19-016

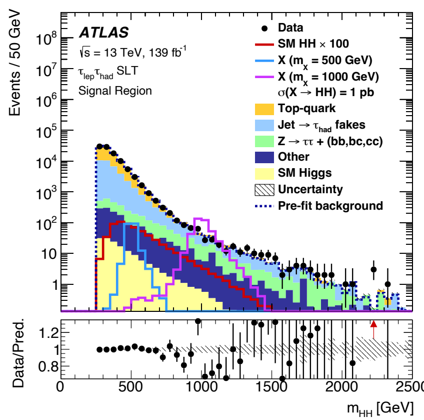


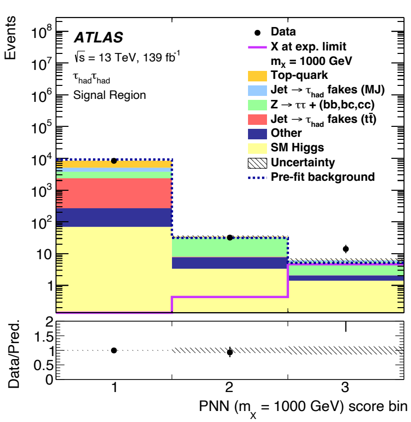



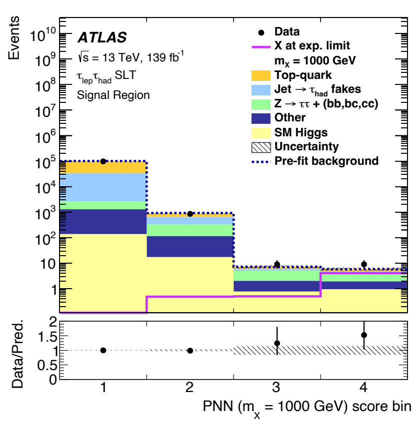
# ATLAS H(ττ)H(bb) Search

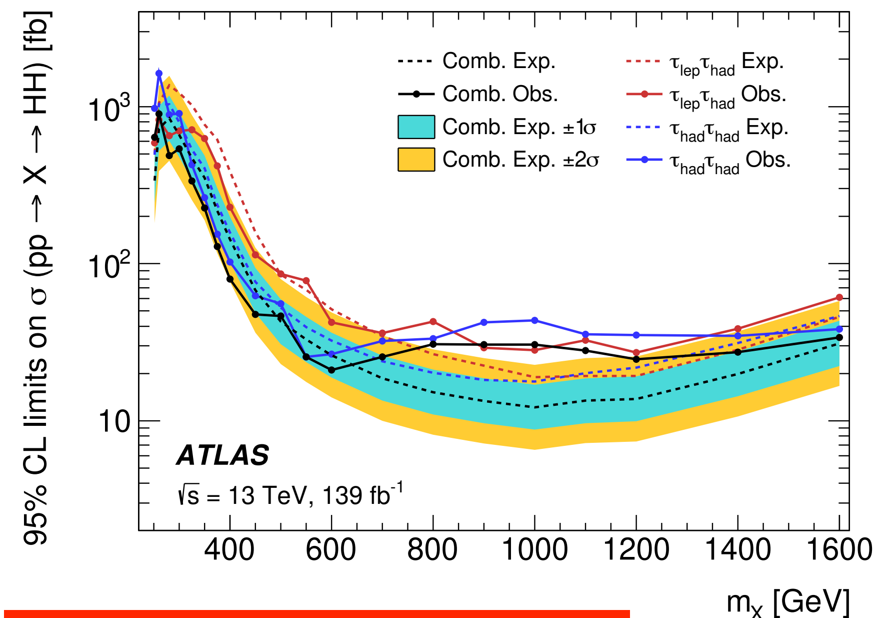
- **ATLAS reported a 3.1 (2.0)σ excess at about 1 TeV in an X → H(ττ)H(bb) resonant search**
  - ★ **An excess can be clearly seen only in the NN discriminant distribution; the mass spectrum before the NN application doesn't show a sizable excess**
  - ★ **Consistent excess in semileptonic and hadronic final states**
- **Not directly comparable with the CMS LQ3 excess but could be related**



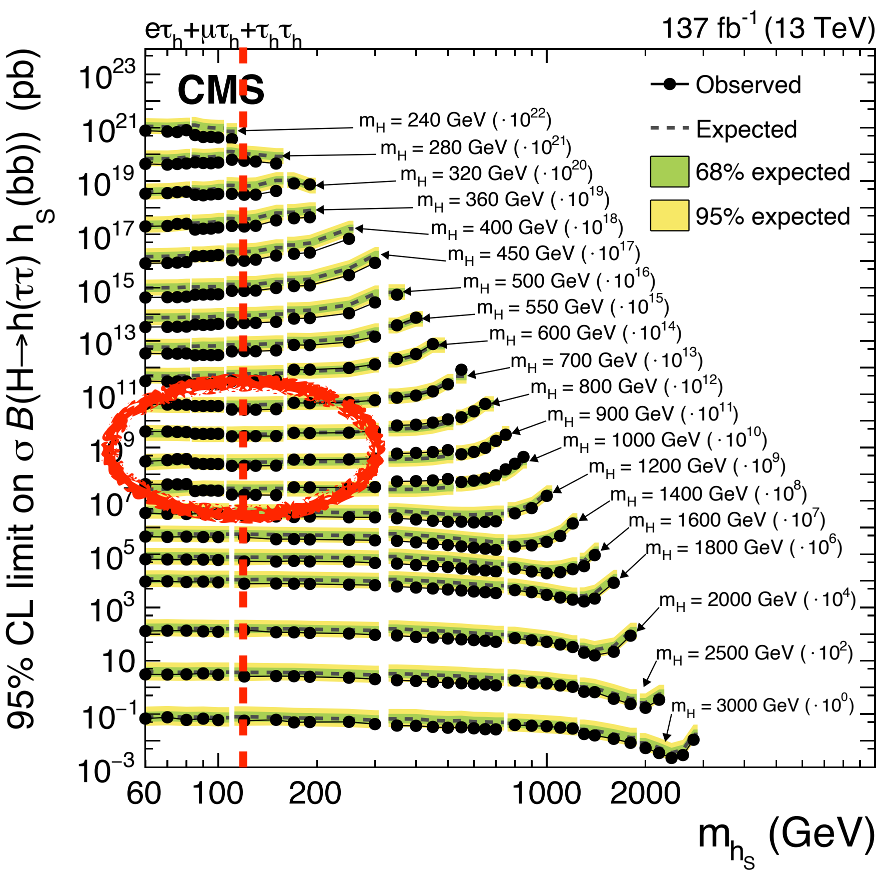



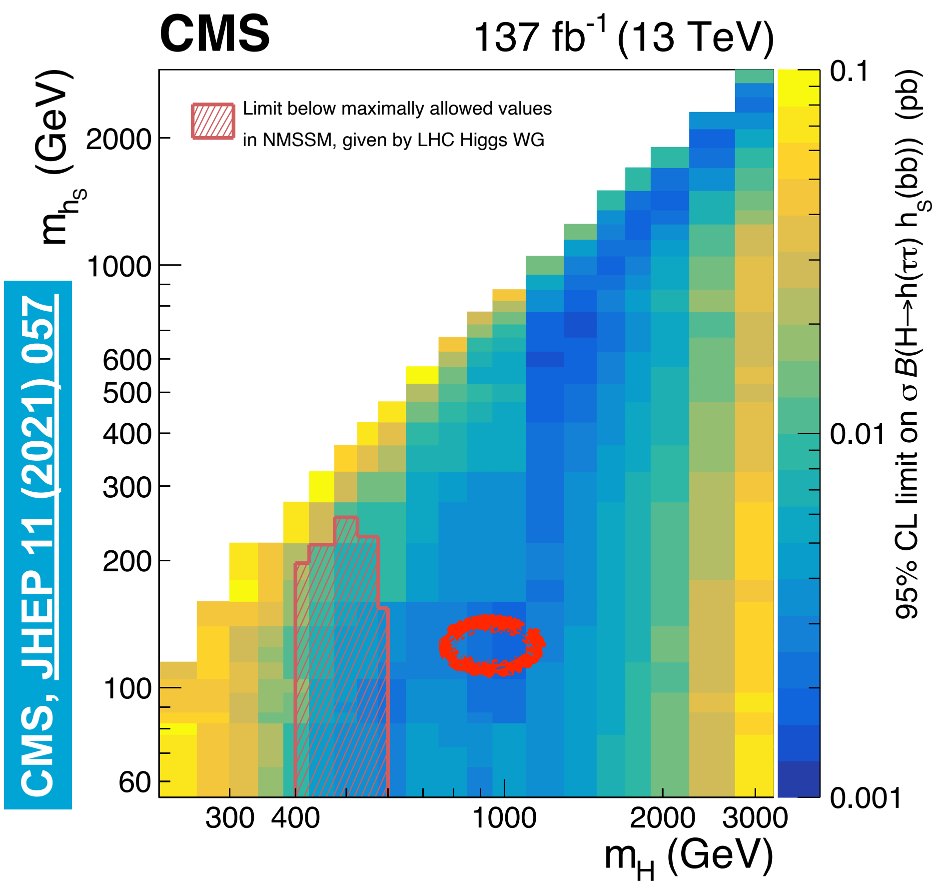

**ATLAS, arXiv:2209.10910**

# What About CMS?

- No resonant X → H(ττ)H(bb) results with full Run 2 data yet
- However, a search was done for H → $H_{125}$(ττ)$h_S$(bb), with $h_S$ being a scalar in a broad mass range for H and $h_S$
  - ★ No excesses seen for m($h_S$) = 125 GeV, with the cross section times branching fraction (7.3%) limit set ~2 fb, which is very similar to the ATLAS observed limit



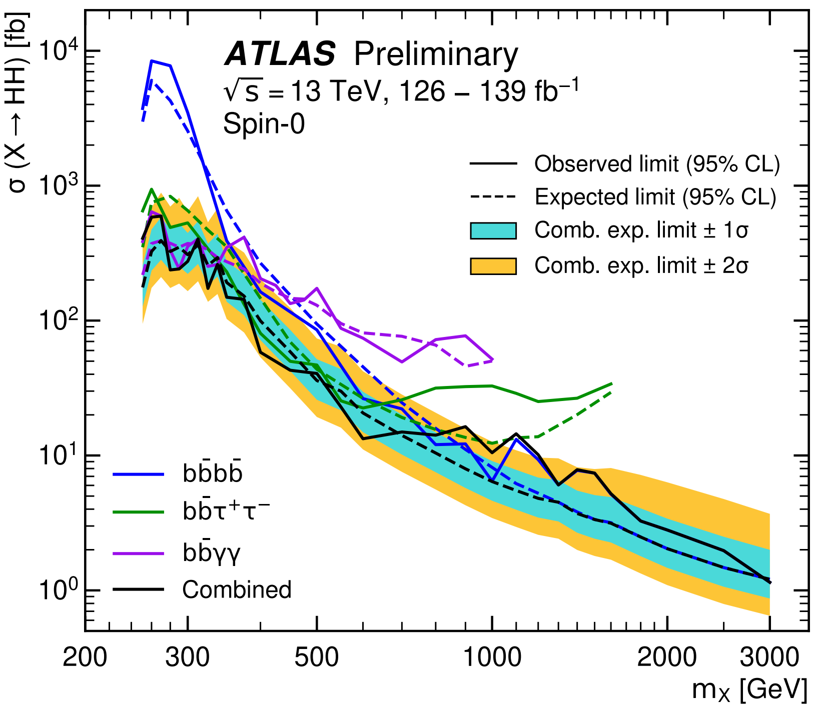

CMS, JHEP 11 (2021) 057



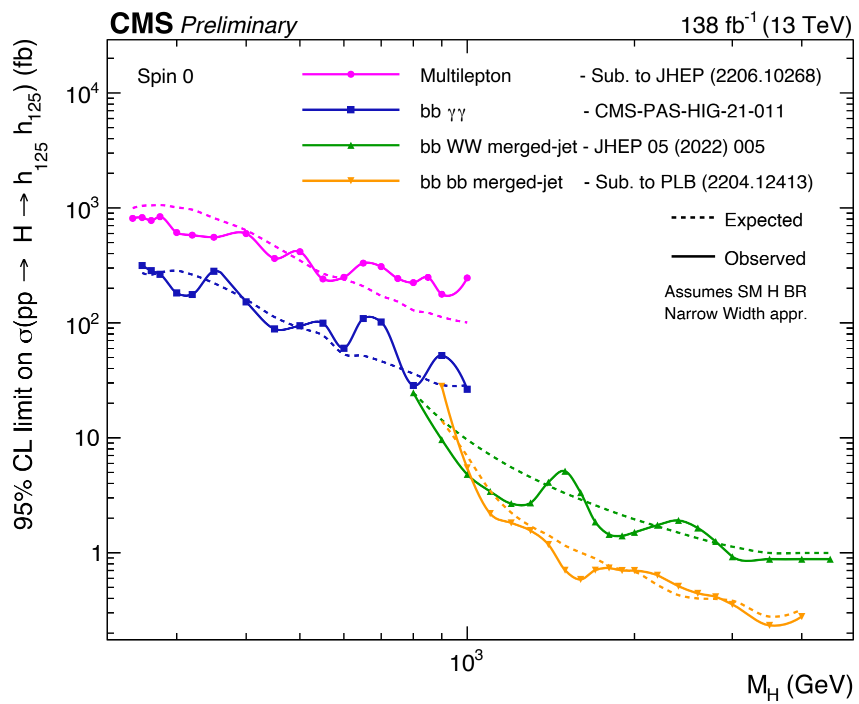
# Other X → HH Searches



- Assuming that the H(bb)H(ττ) channel corresponds to the SM Higgs boson decays, the 1 TeV excess in ATLAS is still present at 3.2σ (2.1σ global) level
- However, CMS rules it out by X→HH searches in more sensitive channels
- This technically doesn't hold in the case when there is another boson with the mass ~125 GeV decaying into either bb or ττ with branching fraction different from the SM ones




ATLAS-CONF-2021-052

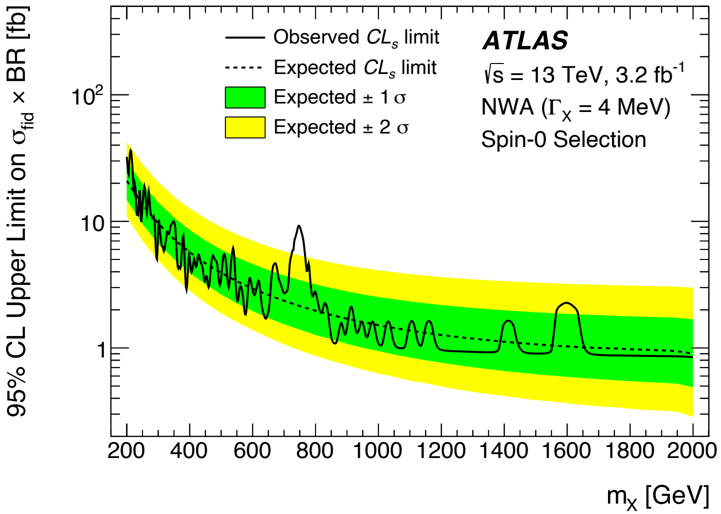



CMS, Summary HH Plot

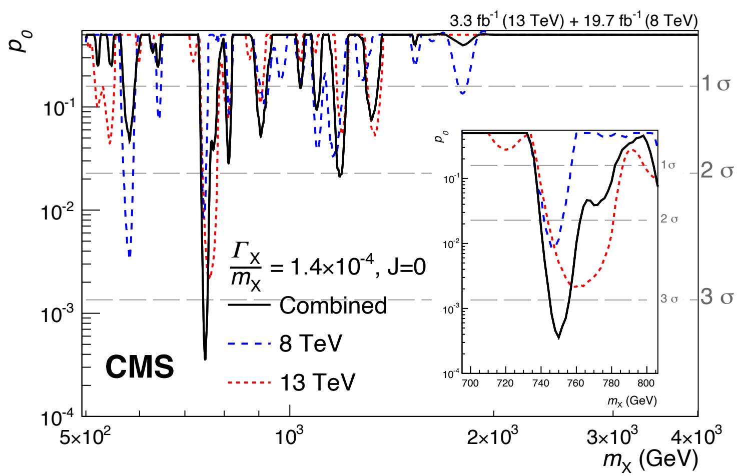
# Excited? - Memento 750!



**ATLAS, JHEP 09 (2016) 001**



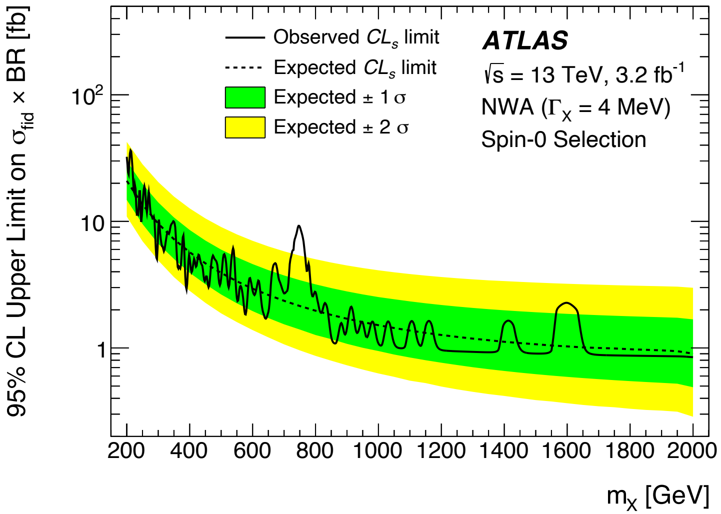

**CMS, PRL 117 (2016) 051802**



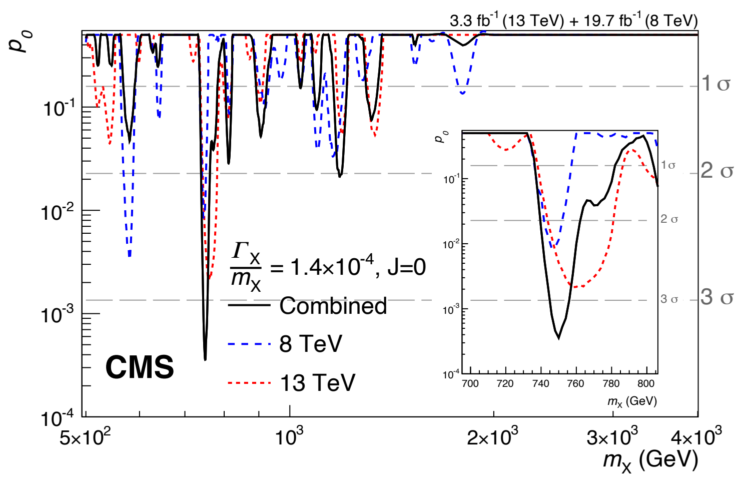
# Excited? - Memento 750!



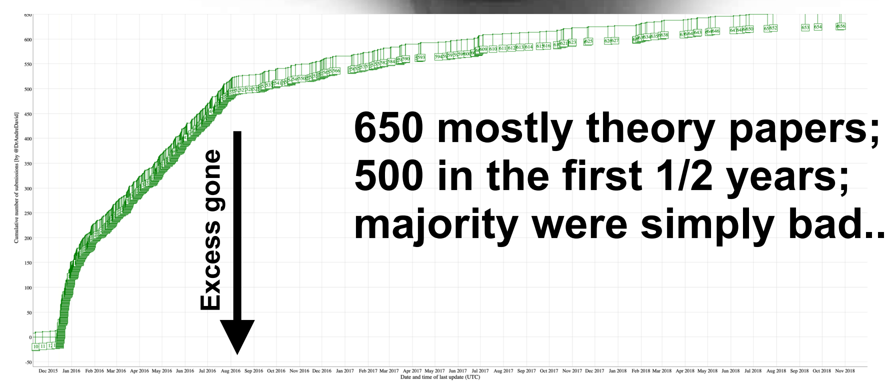
**ATLAS, JHEP 09 (2016) 001**




**CMS, PRL 117 (2016) 051802**








**650 mostly theory papers; 500 in the first 1/2 years; majority were simply bad...**

# 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 several years to complete
  - ★ Those rely on advanced techniques, dedicated triggers, and sophisticated models and analysis methods
- I showed just a very few selected examples in several areas of searches
- At the end of Run 2, there are a few hints of excesses left - will be cross-checked by the LHC experiments with Run 2 and Run 3 data
- While none of them are very significant, there is a certain alignment of several excesses, which makes it exciting to follow them up in coupled channels and across the experiments!
  - ★ Stay tuned, but don't rush to the printing press yet!


NON SEQUITUR
I'VE GOT A FEELING SOMETHING BIG IS JUST AROUND THE CORNER FOR US AND THINGS WILL FINALLY START FALLING OUR WAY...

# Thank You!