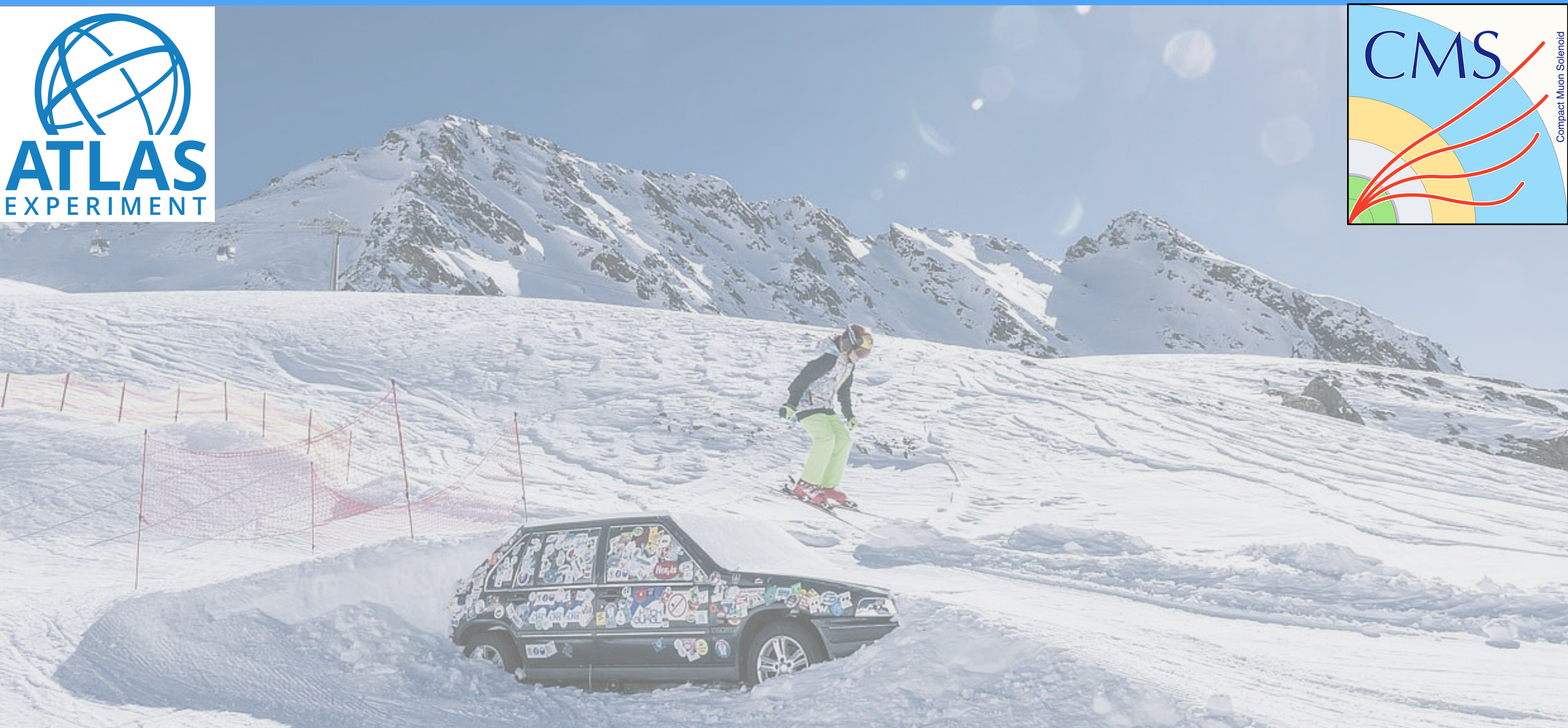
OVERVIEW OF LHC SEARCHES FOR NEW PHYSICS

ATLAS EXPERIMENT

CMS Compact Muon Solenoid



Greg Landsberg

29.03.2023

ALPS 2023 - Anomalies in Particle Physics - Obergurgl

Disclaimer

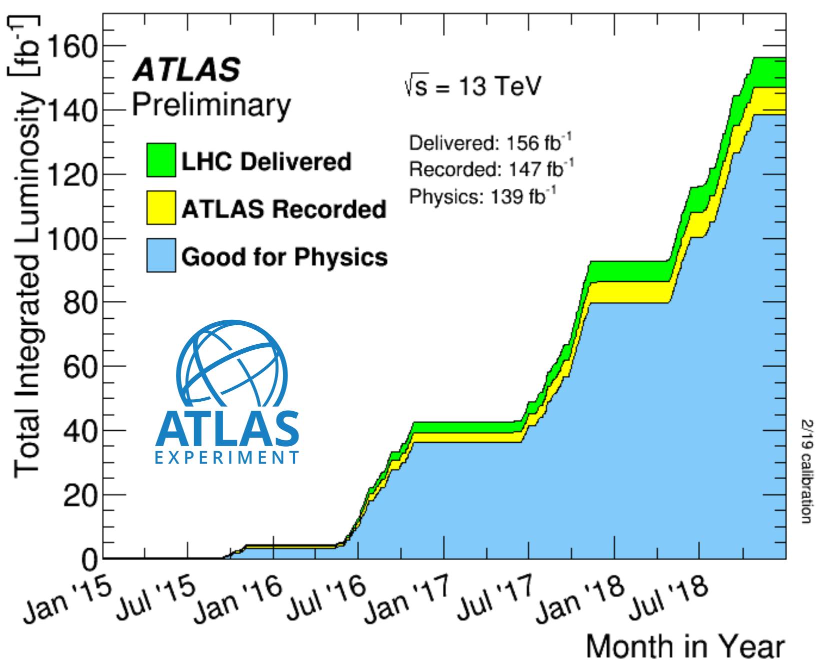
- Given the audience of this conference, I don't want this talk to turn into a shopping list of searches done at the LHC
  - ★ Even if I wanted to, I'd not fit in anywhere close to 40 minutes!
- Instead, I'll focus on things, which I believe may be more interesting to the broad community attending this workshop, and which are aligned with the main theme of this conference - Anomalies in Particle Physics
- 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 and CMS experiments

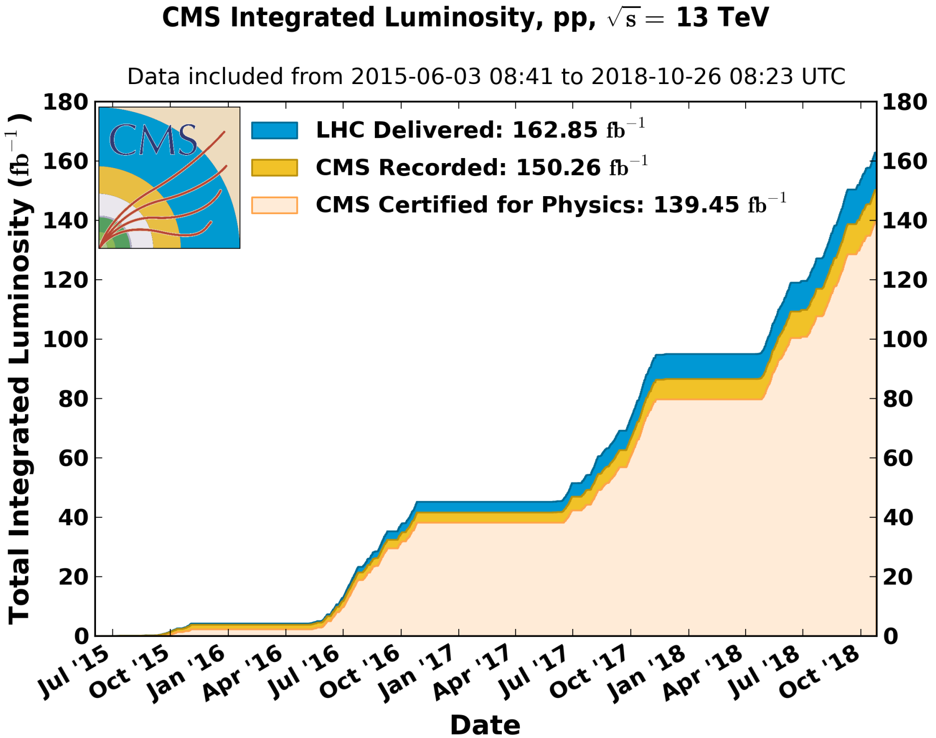
Outline

- 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
- Thank you, LHC, for a spectacular Run 2 and even more exciting ongoing Run 3





Looking for Unknown

- The LHC has been successfully operating for nearly 14 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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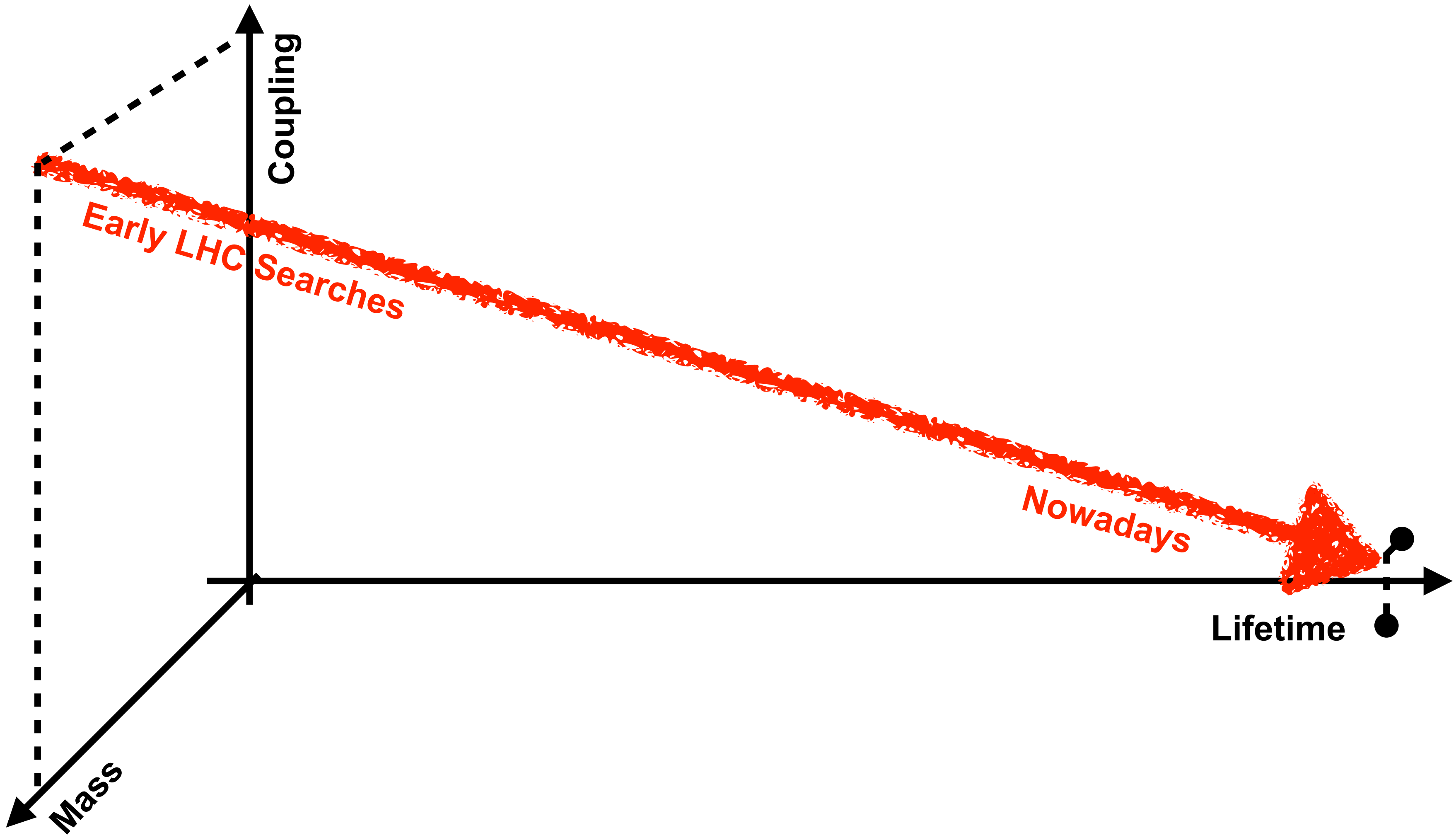
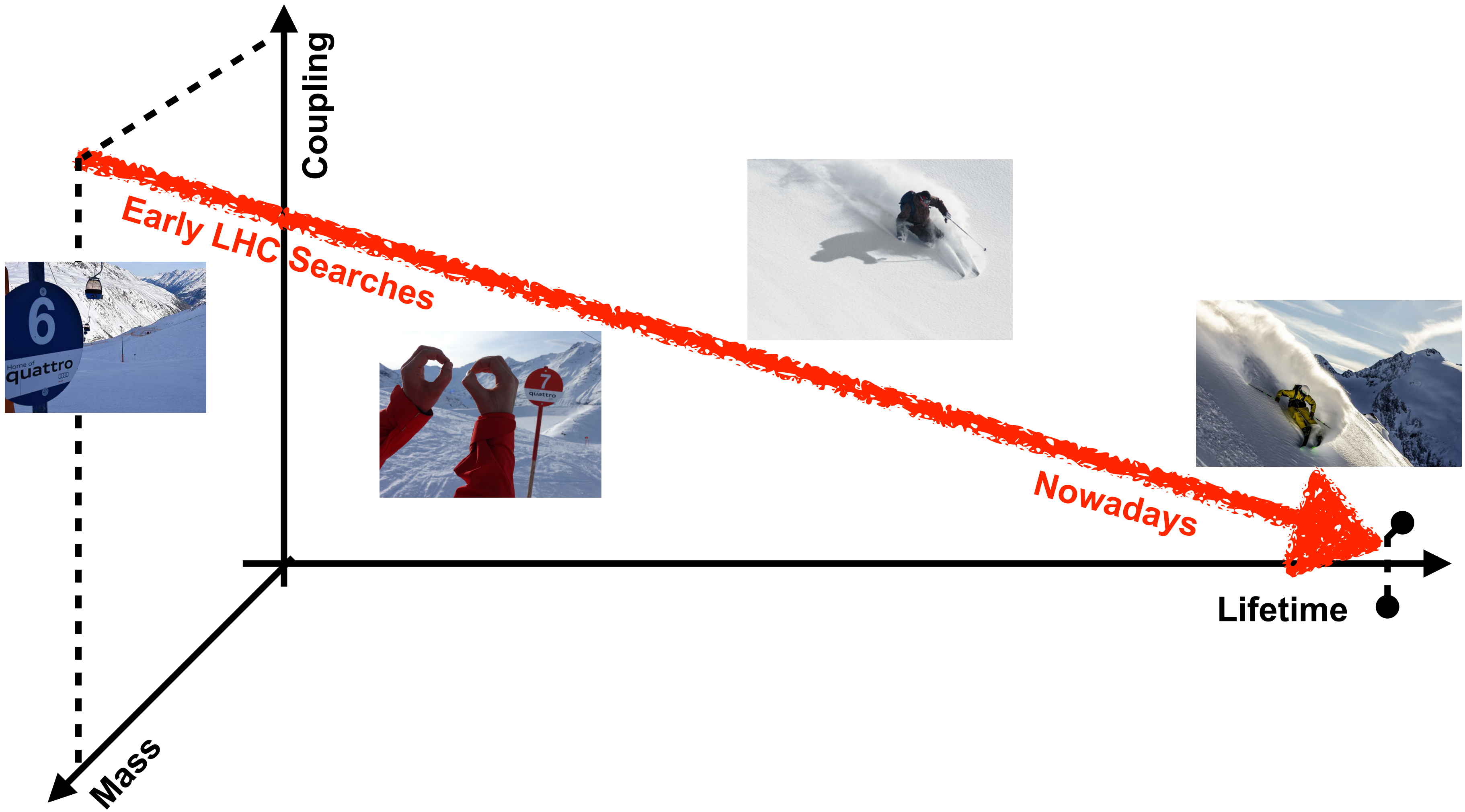
Stairway to Hell

- The paradigm shift



Stairway to Hell

- **The paradigm shift**

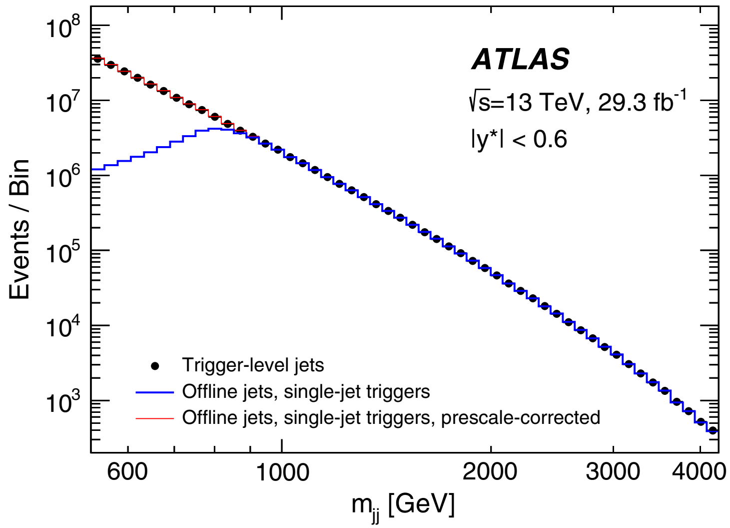


New Tools for the New Paradigm

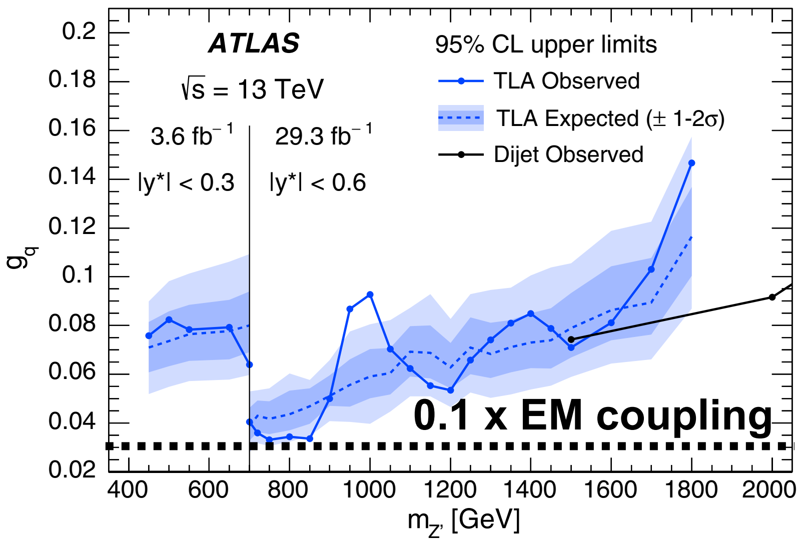
- Use of new triggers not available earlier in the LHC running
  - ★ A variety of triggers optimized for long-lived particles
  - ★ Trigger-level analysis (TLA), aka data scouting - ATLAS and CMS, and triggerless design with real-time alignment and calibration (LHCb)
    - Extensive use of GPU in the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

Toward Small Masses: TLA

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



ATLAS, PRL 121 (2018) 081801



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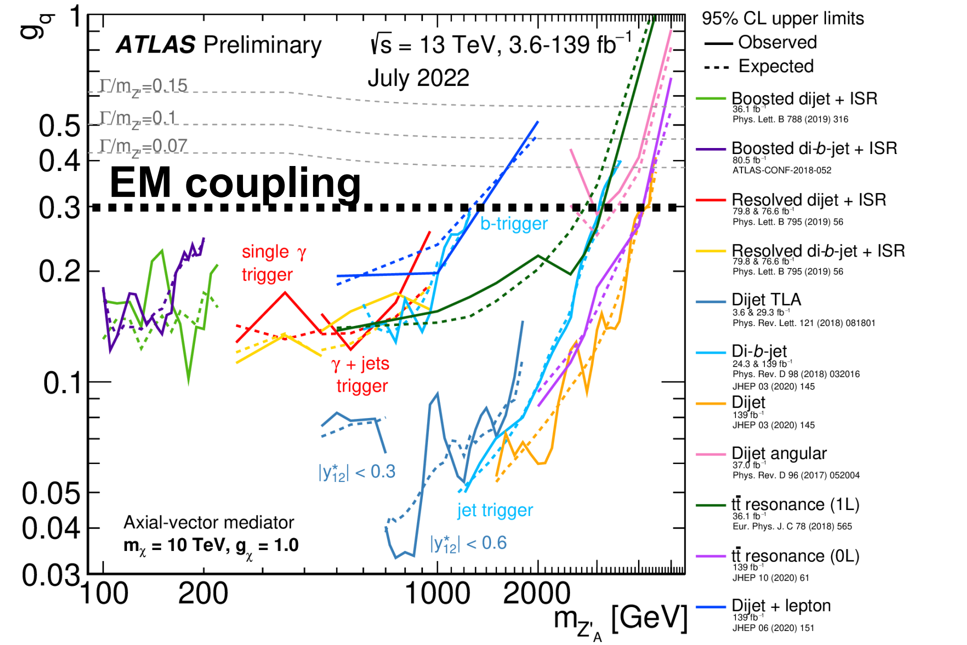

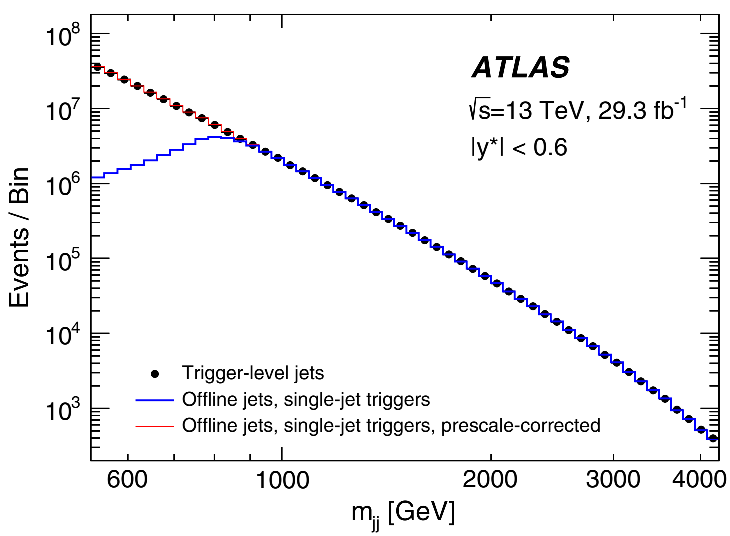

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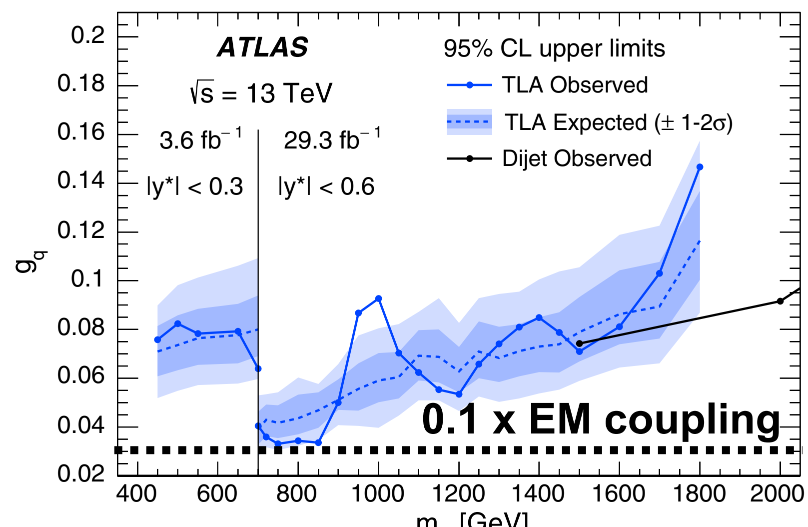
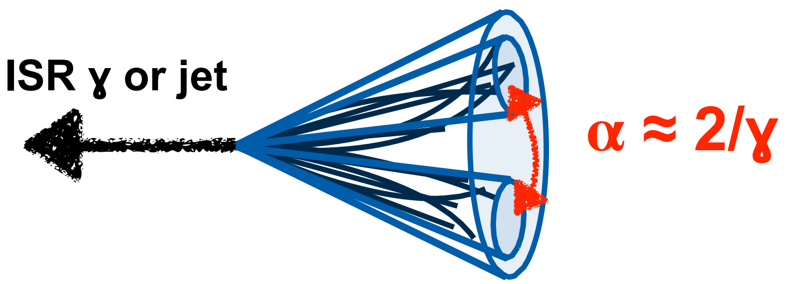
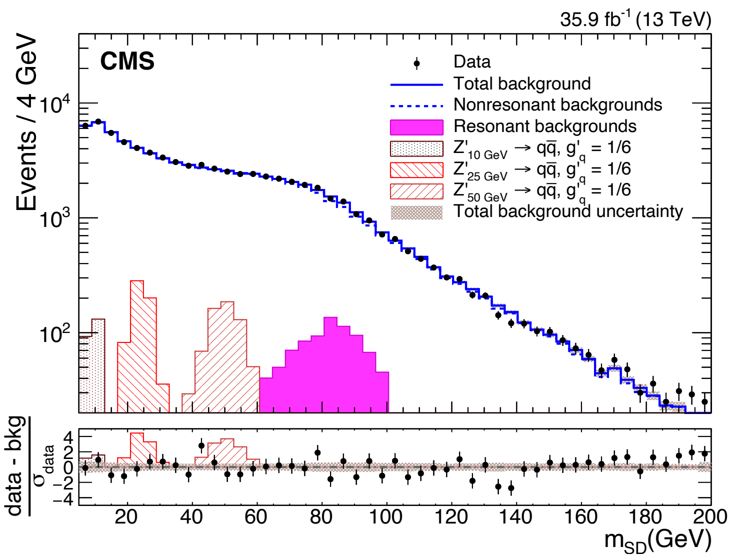


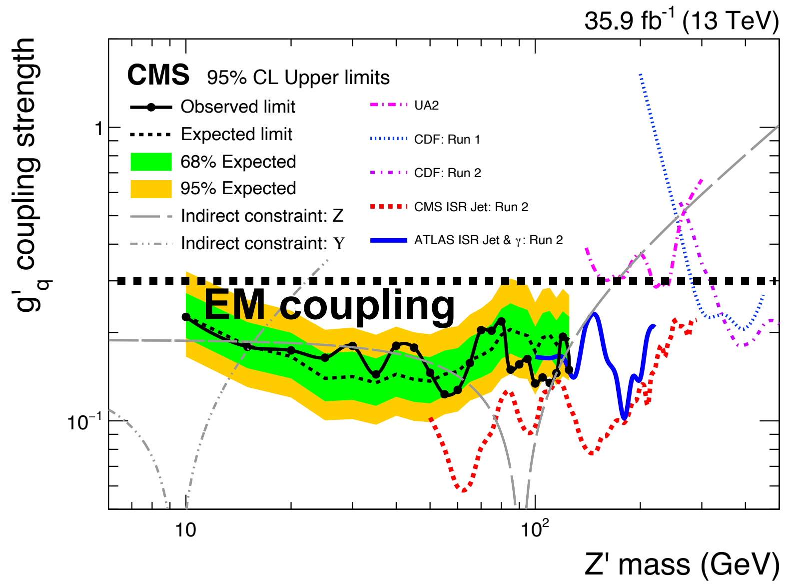
Toward Small Masses: ISR

- 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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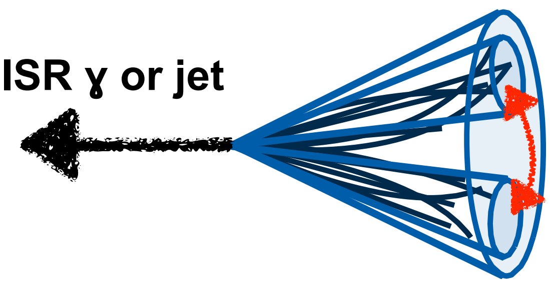
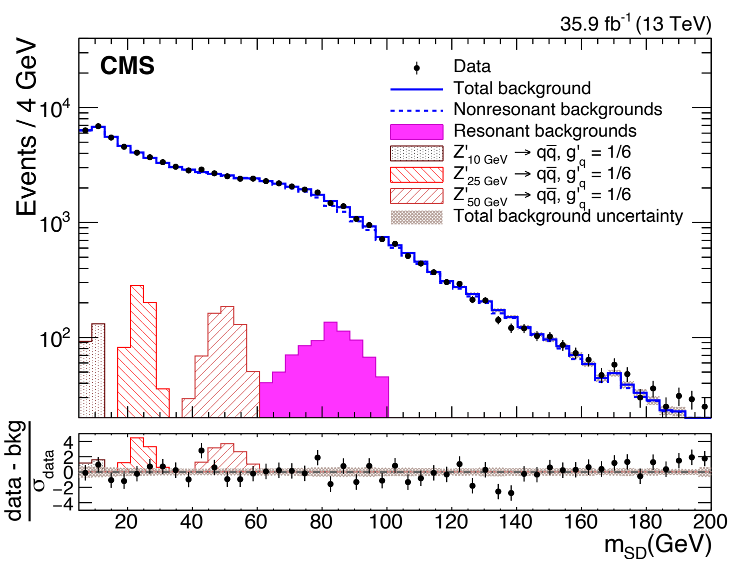


$\alpha \approx 2/\gamma$

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



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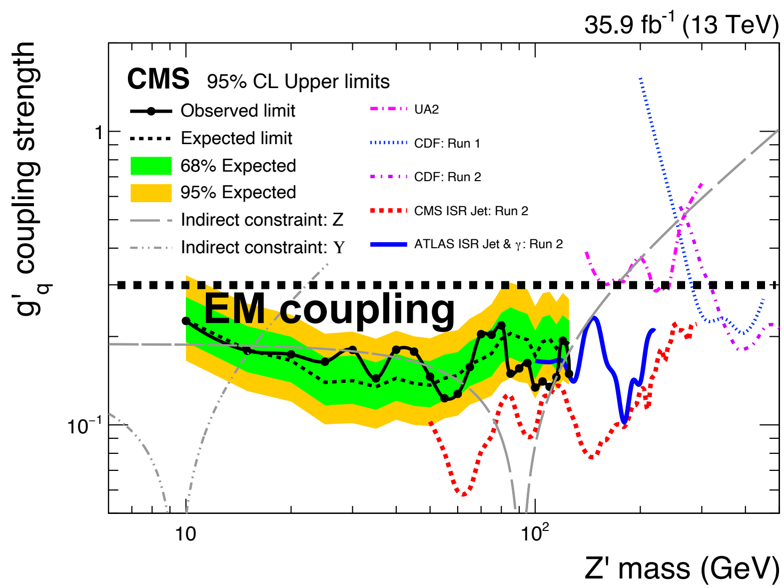

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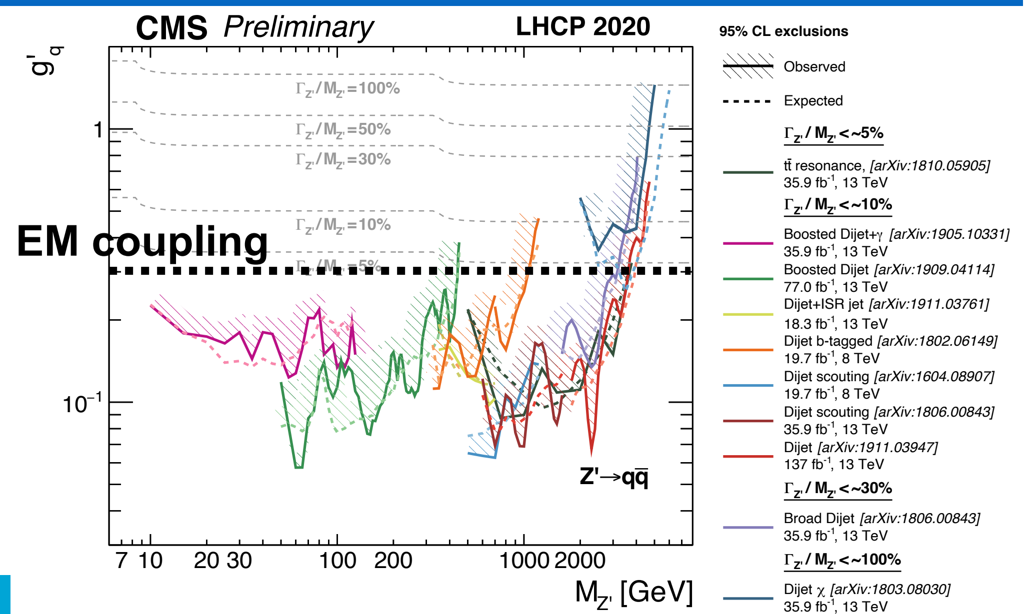

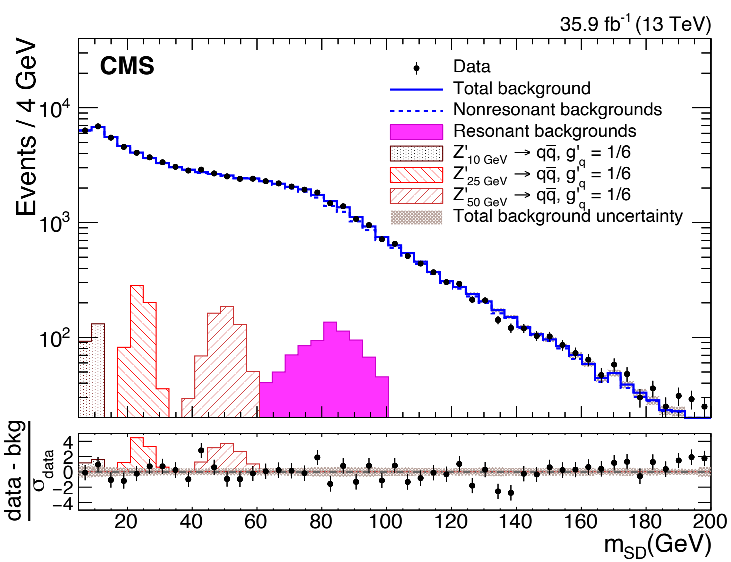

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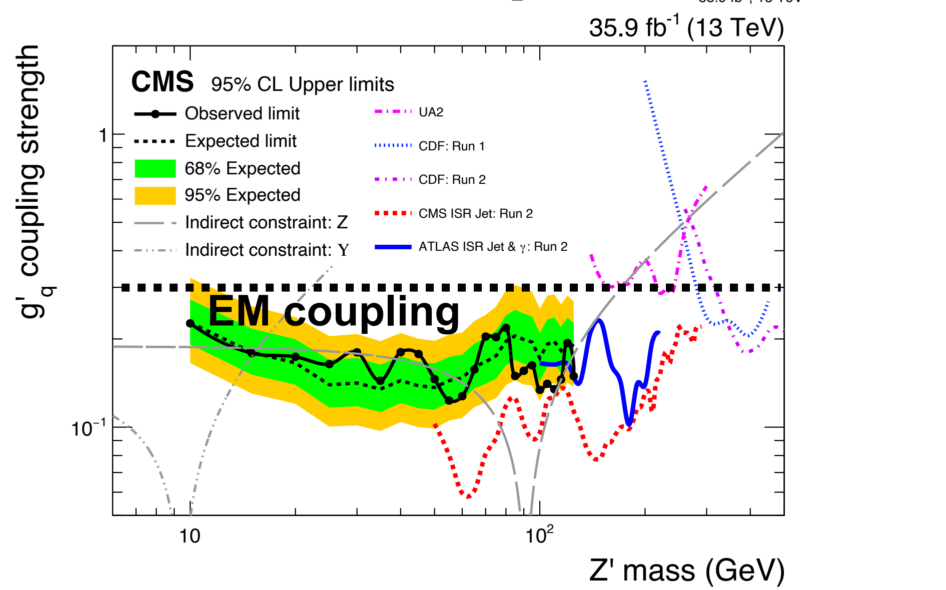
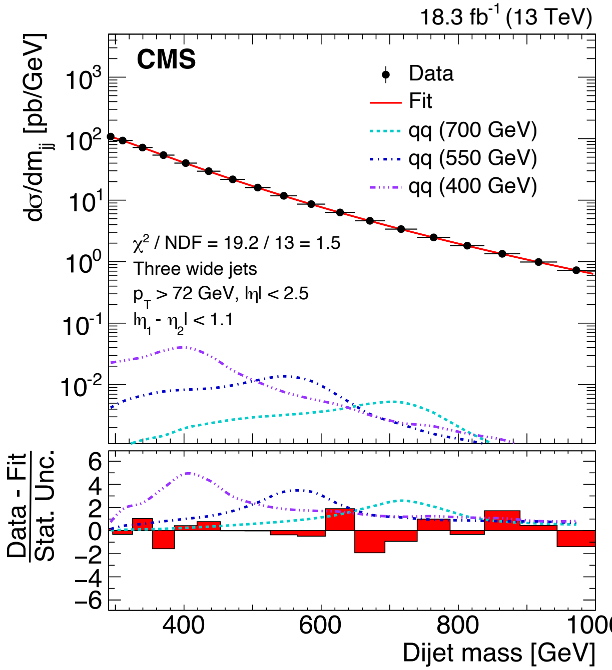
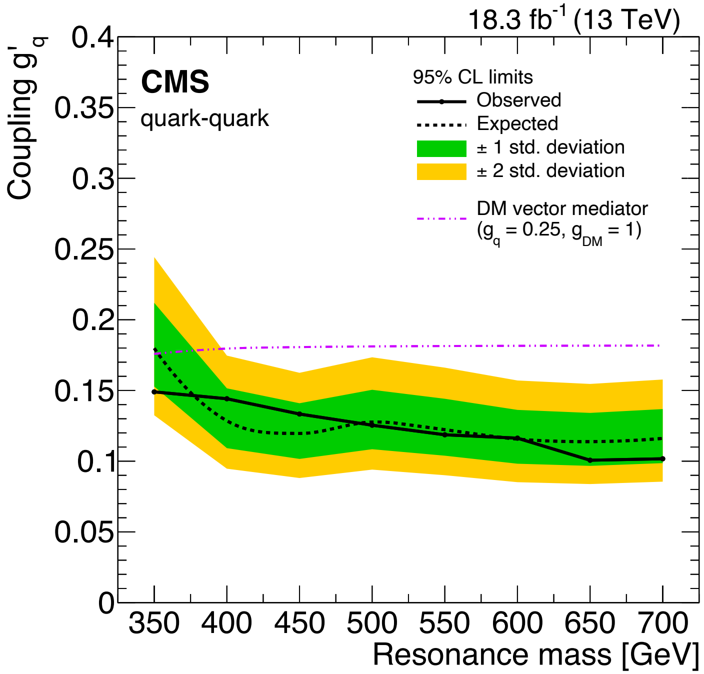


Toward Low Masses: ISR+Scouting

- 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

CMS, PLB 805 (2020) 135448





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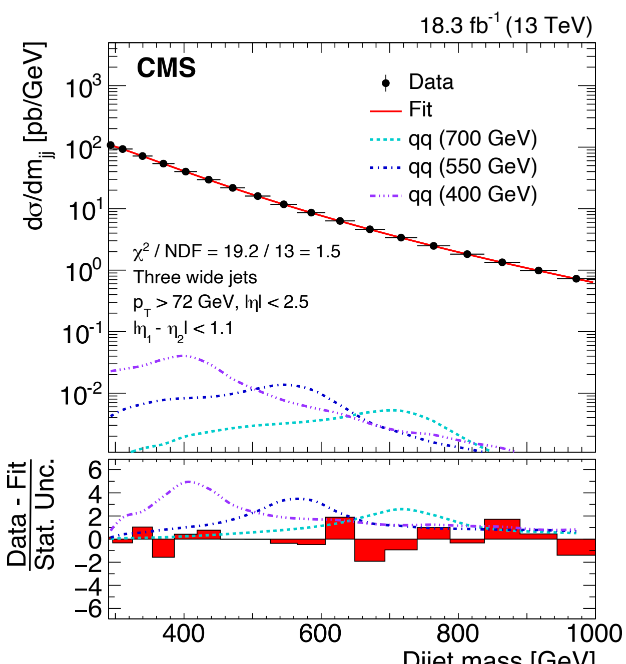
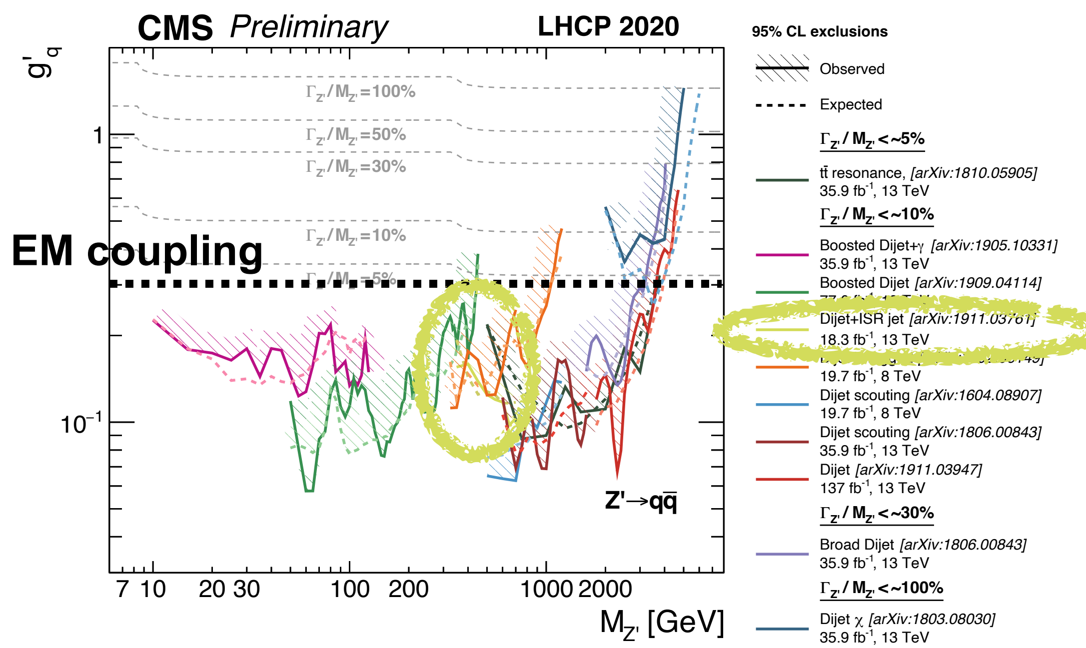
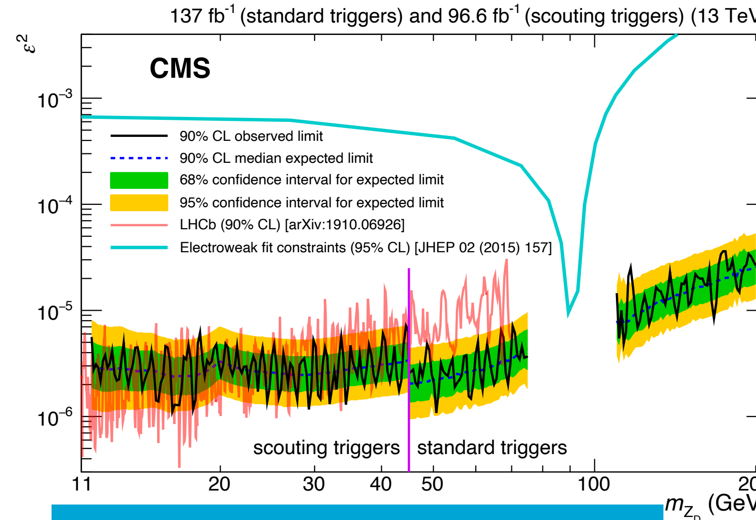




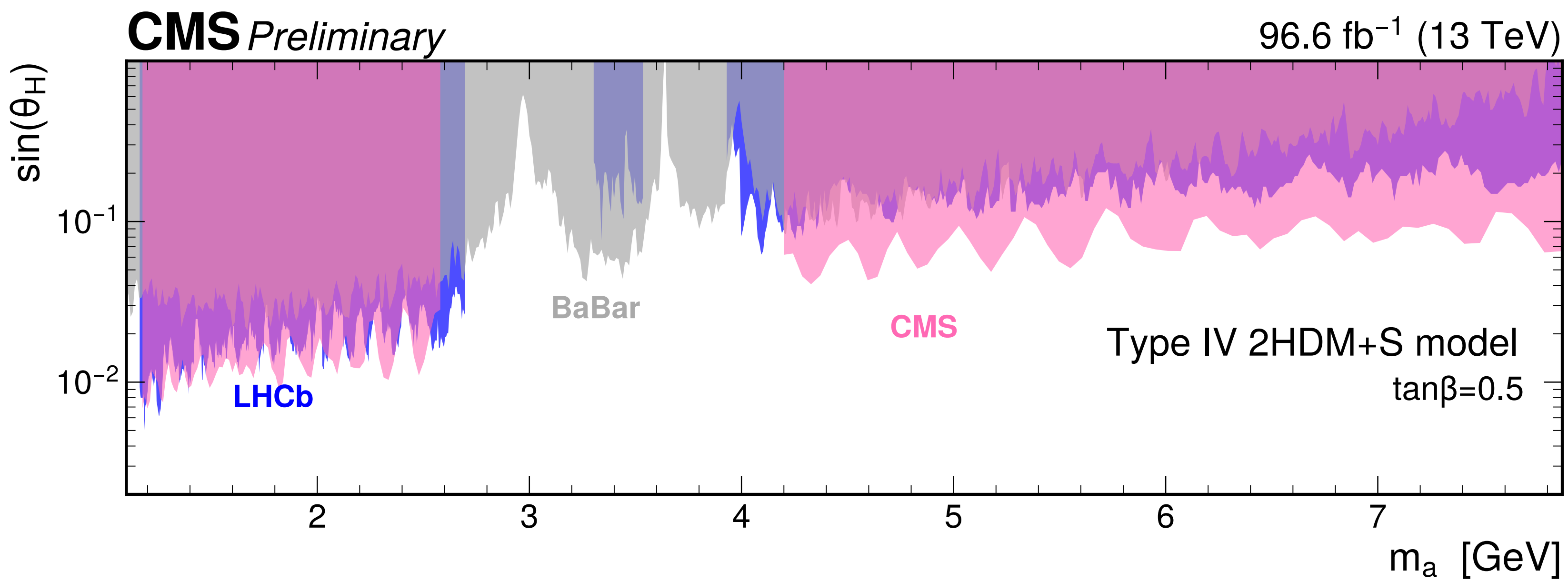
Resonance mass [GeV]

Low-Mass Dimuon Resonances

- CMS searches 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
- New search based entirely on a scouting trigger allowed to lower the mass reach below the Υ resonances in the same models



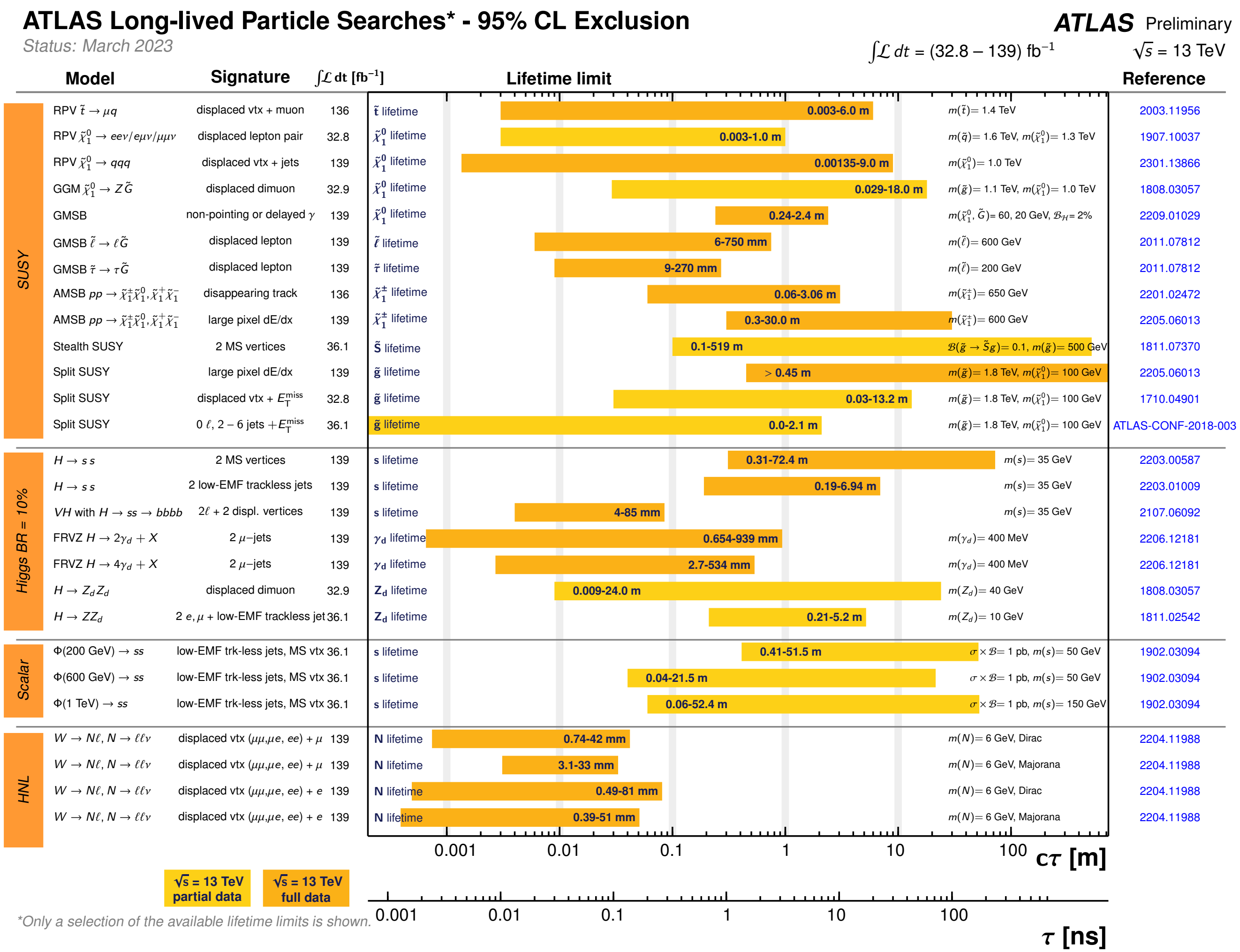
CMS, PRL 124 (2020) 131802



CMS PAS EXO-21-005

Toward Long Lifetimes

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



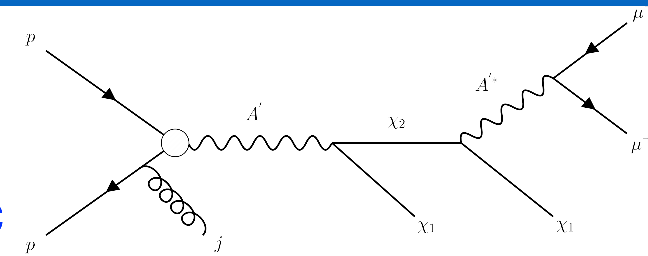
SUSY (RPV and RPC)

H(125) → XY

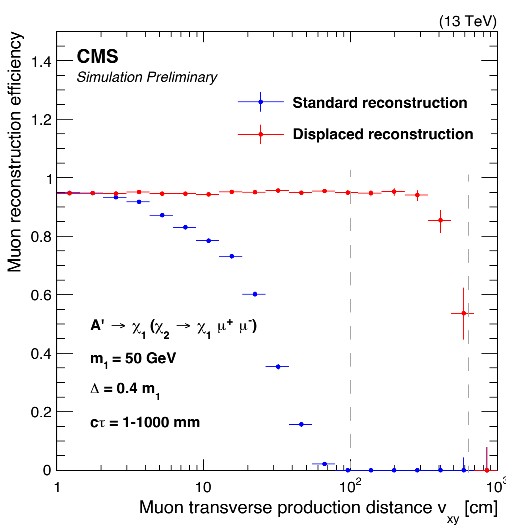
H → SS

HNL

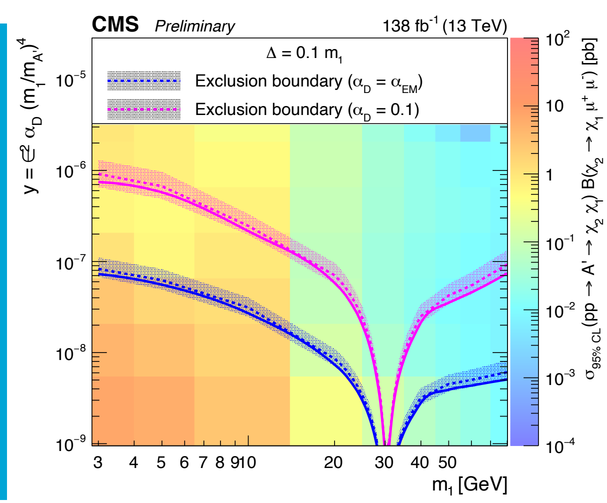
Search for Inelastic DM

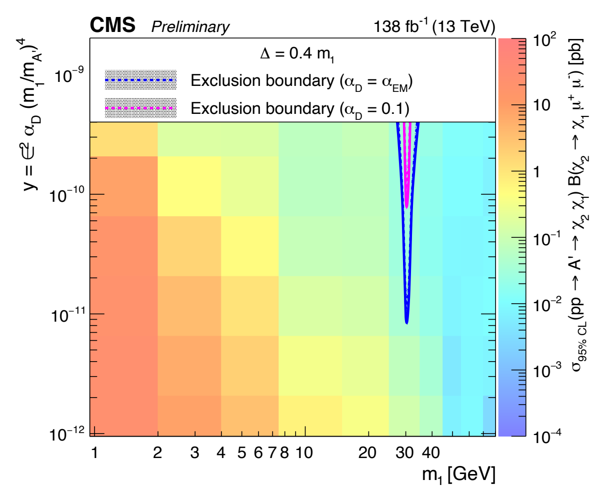


- Originally models of inelastic DM (IDM) were proposed to explain the DAMA anomaly; nevertheless they are generally viable models involving dark sectors - first IDM search at the LHC
- Probe a model w/ 2 nearly mass-degenerate DM states, χ_1 and χ_2 ($m_2 - m_1 = \Delta = (0.1\text{-}0.4)m_1$), as well as a dark photon mediator A' ($m_{A'} = 3m_1$), which is long-lived
- The signature is two collimated displaced muons aligned with p_T^{miss} (also used for triggering)
- Special displaced muon reconstruction capable of extending sensitivity to large cτ
- A' is mixed both with photon and Z, hence peak in sensitivity around m(A') = m(Z)



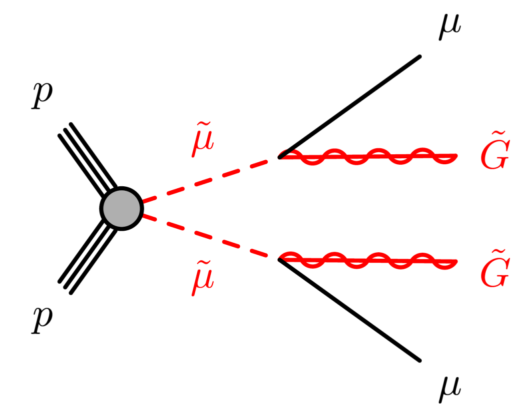
CMS PAS EXO-20-010



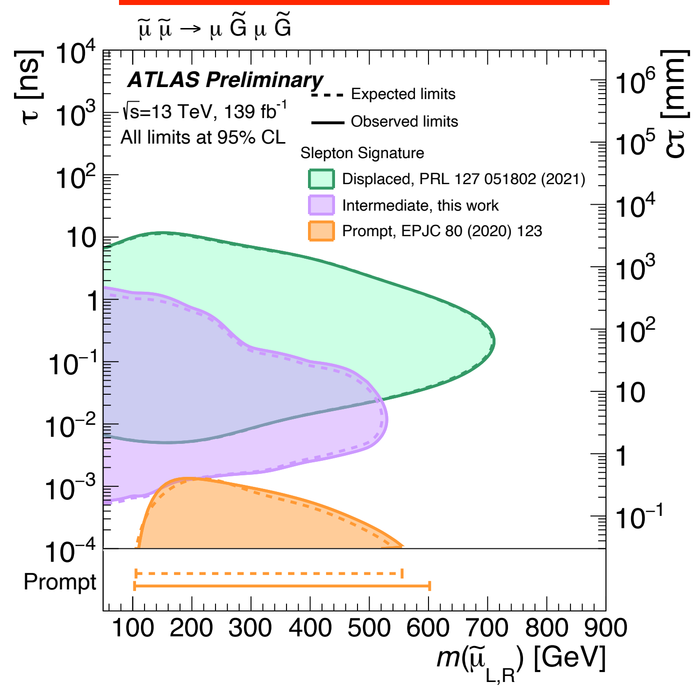


Search for Displaced Dimuons

- In many models (e.g., GMSB SUSY), leptons could be non-prompt, but characterized by a relatively small displacement (cτ ~ 0.3-3 mm)
- Dominant background is from b hadron decays and estimated by extrapolating from $0.1 < d_0^{\pm} < 0.3$ mm control regions
- Data agree well w/ expectations in 3 signal regions corresponding to different dimuon threshold masses
- The new result bridges the prompt searches ($d_0 < 0.3$ mm) and the dimuon LLP analysis (0.3 cm $< d_0 < 300$ cm)



ATLAS CONF-2023-018

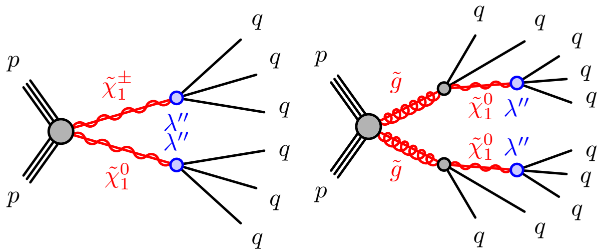


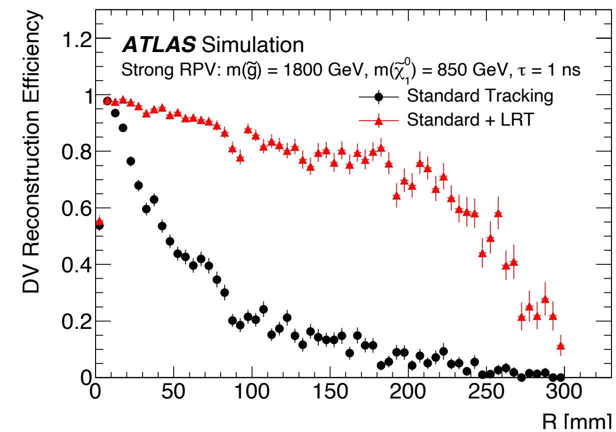
Set of Regions	Expected N_H^{bkg}	Observed N_H^{data}	Threshold $m_{\mu^+\mu^-}$	Additional cut
1	2.1 ± 0.8	1	200 GeV	-
2	12.5 ± 5.2	7	140 GeV	-
3	17.2 ± 7.4	14	125 GeV	$\Delta R_{\mu^+\mu^-} > 3$ rad.

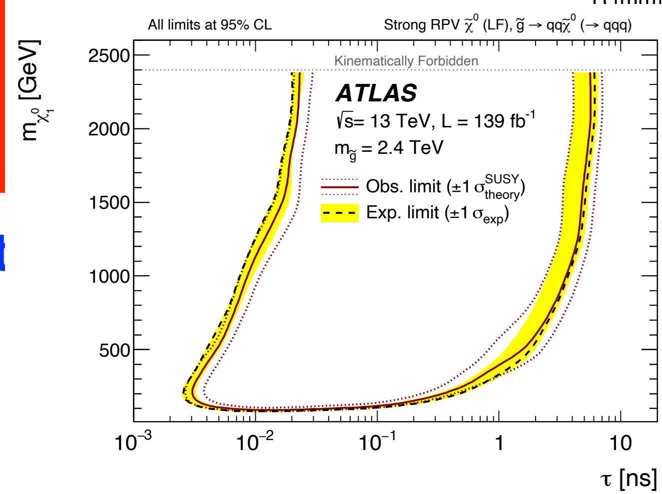
Search for Displaced Jets

- Displaced jets are expected in many weakly coupled new physics models, e.g., RPV SUSY, Twin Higgs, split SUSY
- New ATLAS search in multijet final states, using dedicates track and displaced vertex (DV) reconstruction algorithms to be sensitive to particle with lifetimes up to ~10 ns
  - ★ DVs are vetoed in the areas with large amount of detector material
- Events are recorded using a multijet trigger
- Backgrounds estimated using control samples with a DV not correlated with a jet
- Limit are set in a variety of models, including strong RPV SUSY production

ATLAS arXiv:2301.13866

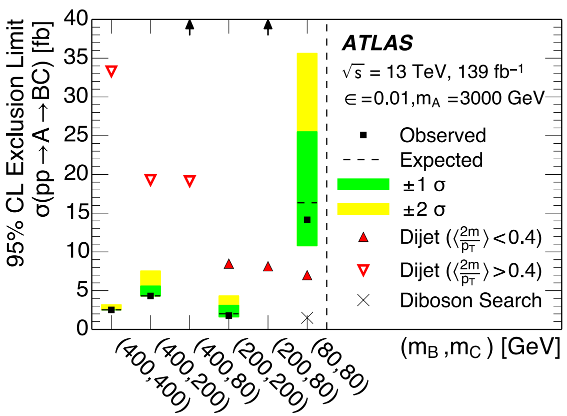


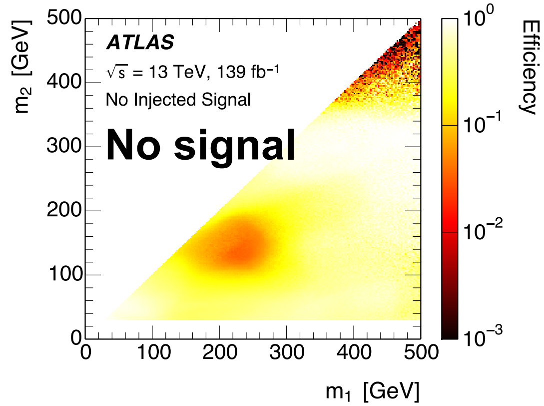


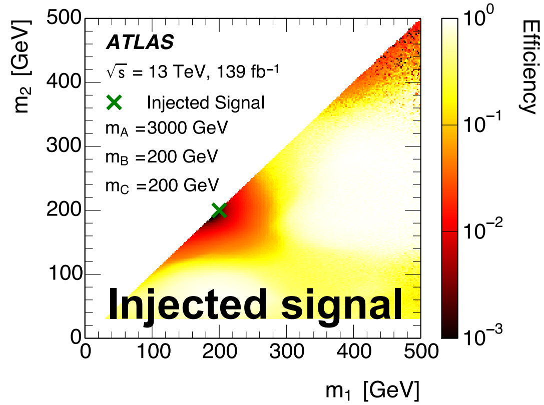


Resonance Search w/ Weak Supervision

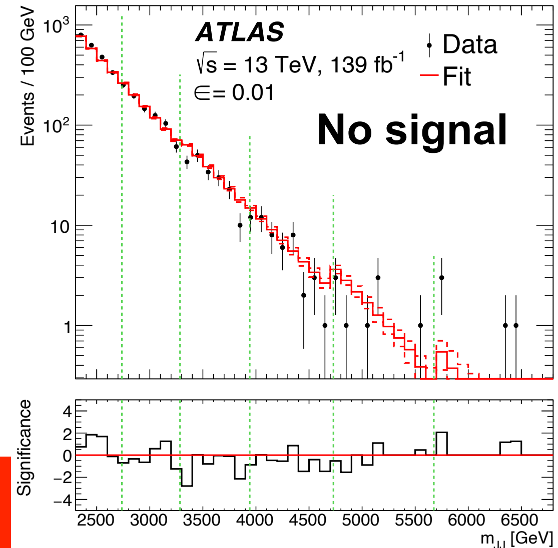
- ATLAS search for A → BC decays with B and C particles reconstructed as massive jets
- Uses weakly supervised machine learning to search for a bump-like signal across a large phase space without a specific physics model
  - ★ Uses data to infer the background model, even in the presence of signal; validated by using signal-suppressed validation region with large jet |Δy| separation
  - ★ NN are trained in the plane of two jet masses mass and learn about localized excesses
  - ★ The dijet mass distribution is then used to look for resonance A
- Sets limits stronger than dedicated searches for dijet resonances or vector boson pairs (far from W/Z)
- ✦ Con: if an excess is seen, it would be very hard to estimate the look-elsewhere effect in such an analysis

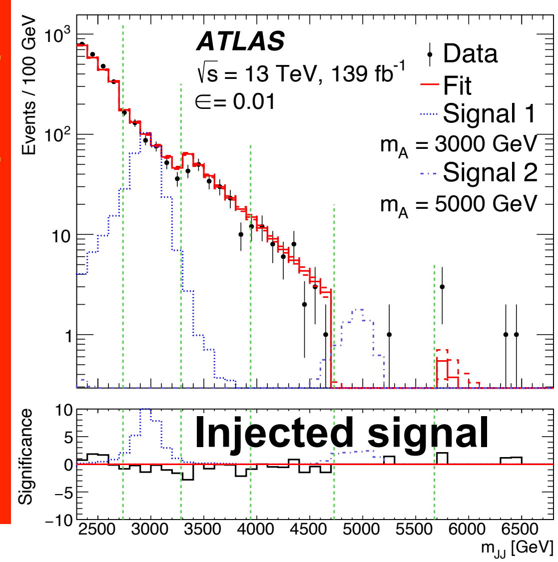






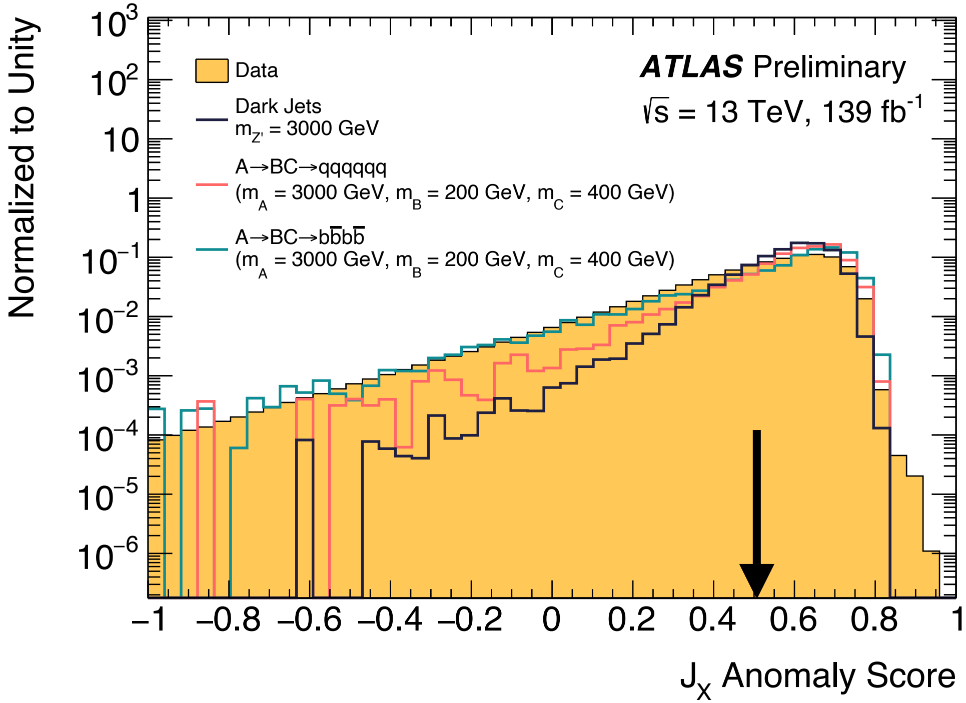
ATLAS, PRL 125 (2020) 131801





Unsupervised Anomaly Detection

- **New ATLAS result focusing on Y → X(J)H(J_{bb}) in the Lorentz-boosted regime (two merged jets)**
  - ★ **H(J_{bb}) is identified via dedicated double-b tagger**
  - ★ **X(J) is sought using jet anomaly score determined by unsupervised ML via a variational recursive neural net trained on jets in data**
    - ✤ **Sensitive to various hadronic decays of X, e.g., into two b quarks, dark jets, or three prongs**



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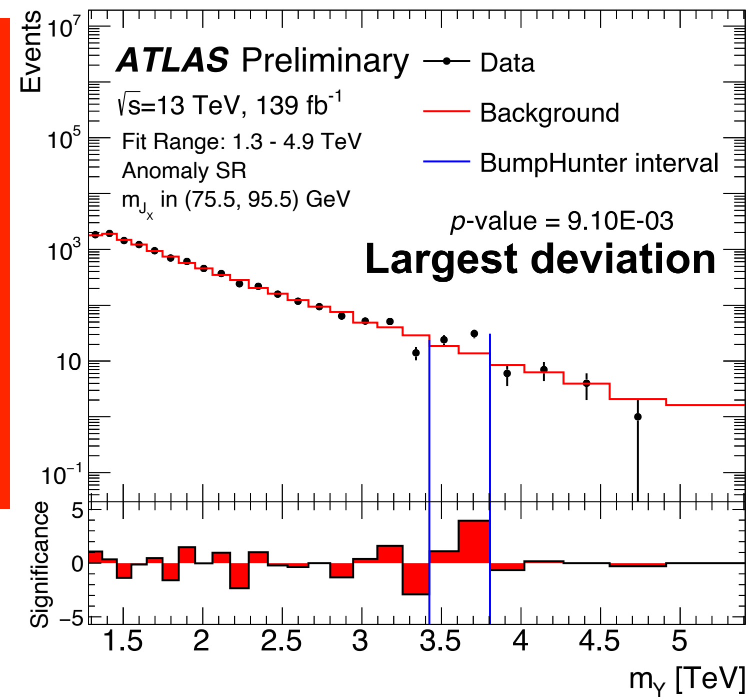
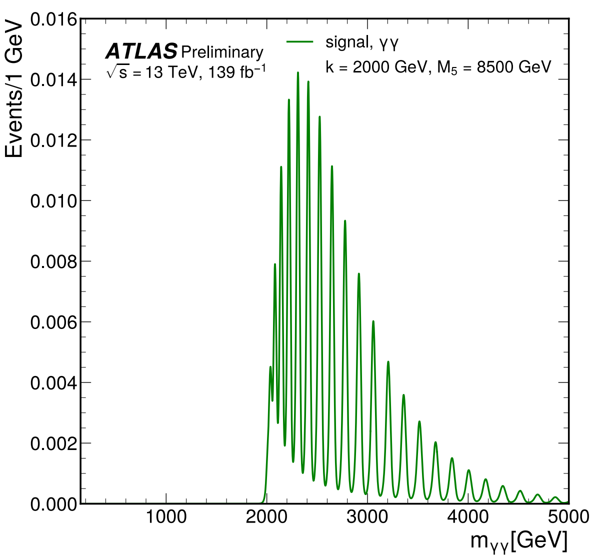
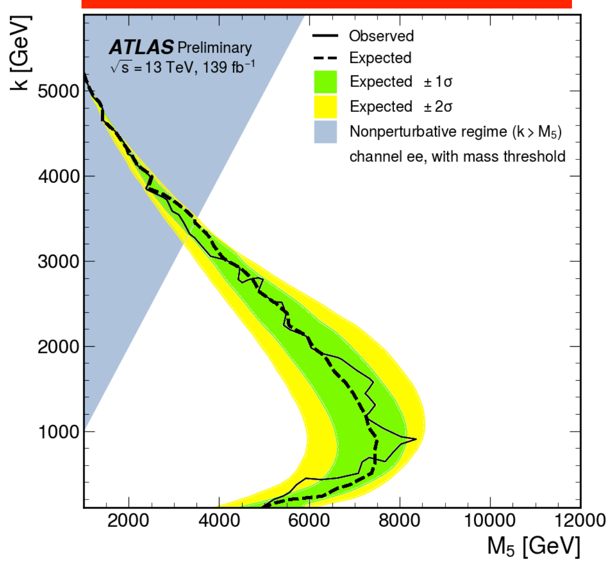


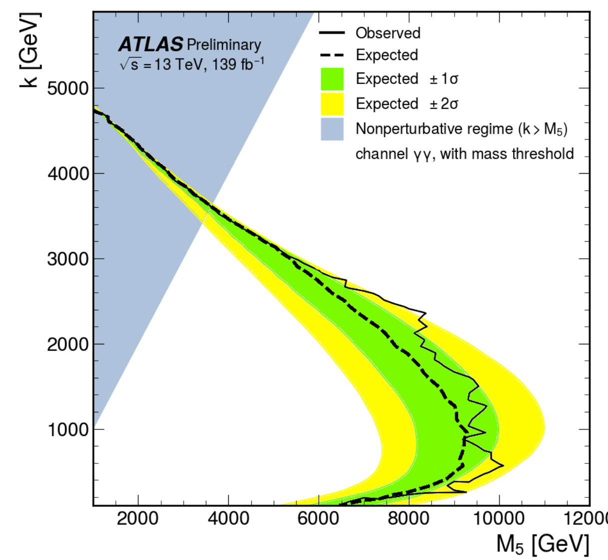
Search for Clockwork Gravity

- In clockwork linear gravity models, periodic signals are expected from multiple copies of SM fields, which manifest themselves as a tower of KK excitations with relatively small mass spacing
- New ATLAS analysis explores ML techniques to do spectral analysis (continuous wavelet transforms - CWT) of the e^+e^- and $\gamma\gamma$ mass spectra, parameterized via k and M_5 (the onset of the tower of excitations and 5D reduced Planck mass)
- $W(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{+\infty} f(m)\, \psi^* \left(\frac{m-b}{a}\right) dm$, with the Morlet wavelet $\psi(x) \equiv \frac{1}{\sqrt{B\pi}} e^{-x^2/B} \left(e^{i2\pi C x} - e^{-\pi^2 B C^2}\right)$, B=2C=2 fed to a binary classifier CNN
- Also looked for generic anomalies with an autoencoder NN and found none beyond 1.5σ

ATLAS CONF-2023-010

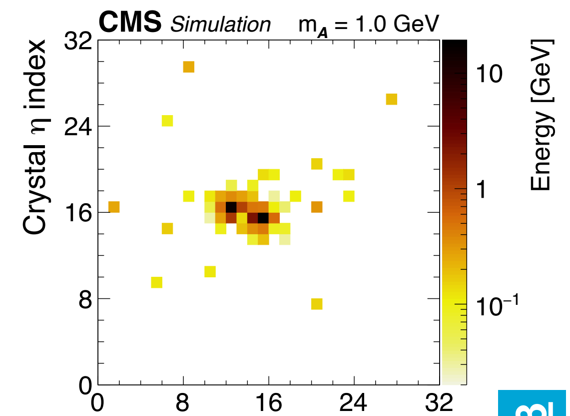


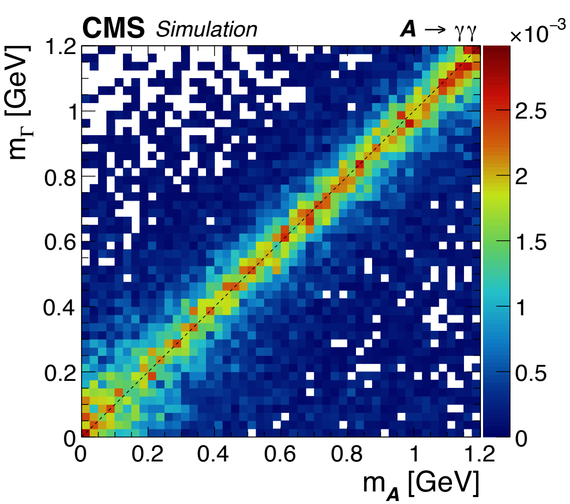


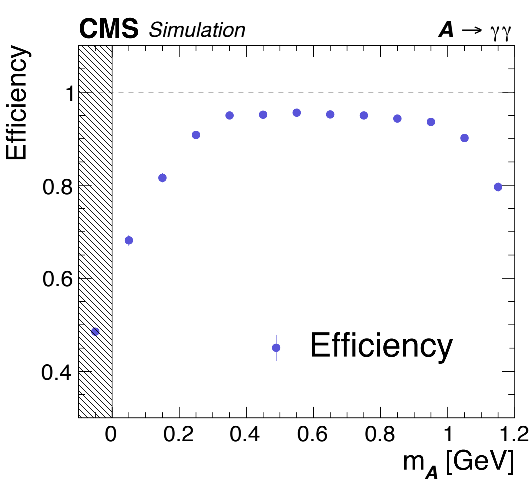


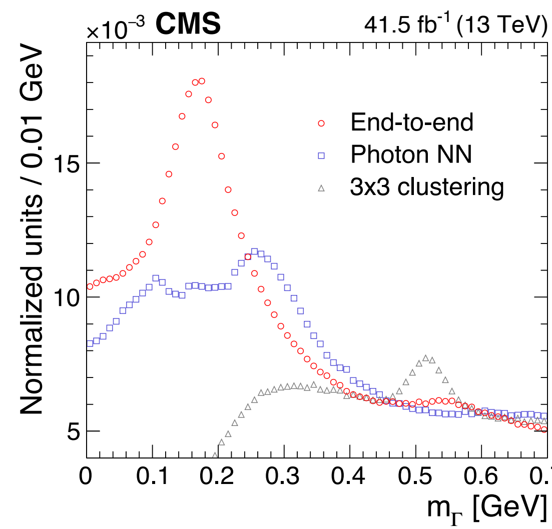
Machine Learning as a Tool

- 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 → aa→γγγγ 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





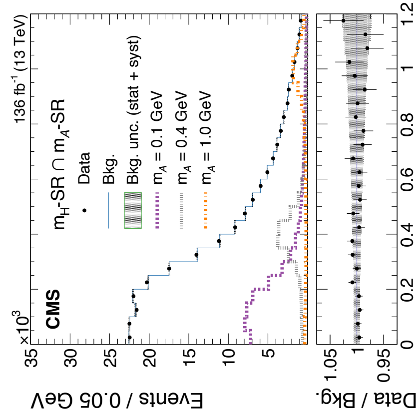


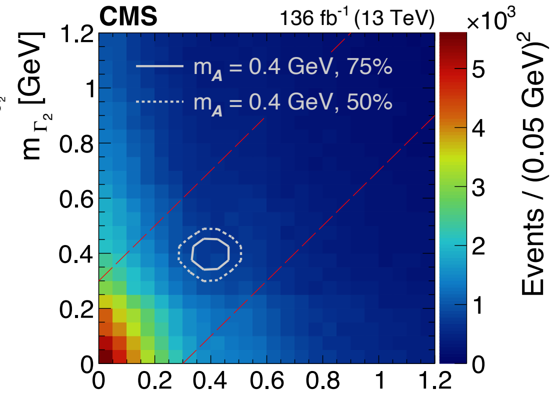


CMS, arXiv:2204.12313

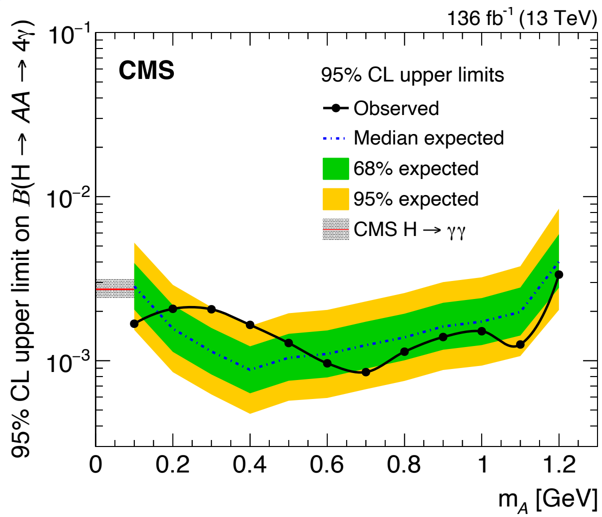
...and its Application

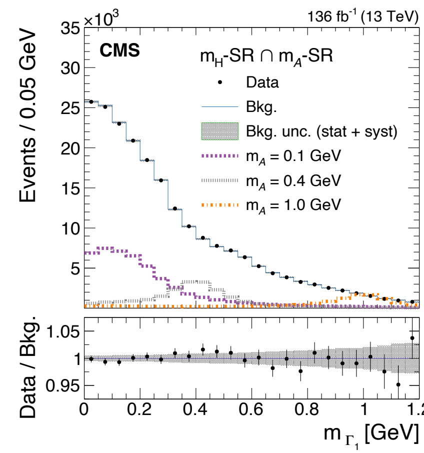
- Based on this regression technique, a dedicated analysis for a very light pseudoscalar a in a 0.1-1.2 GeV mass range has been conducted





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



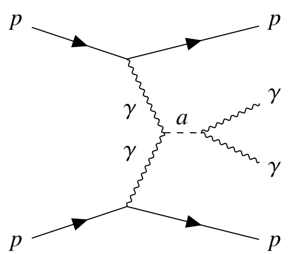


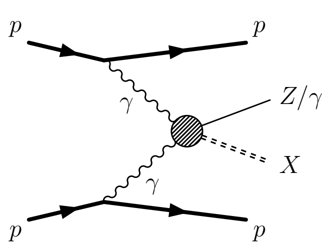
CMS, arXiv:2209.06197

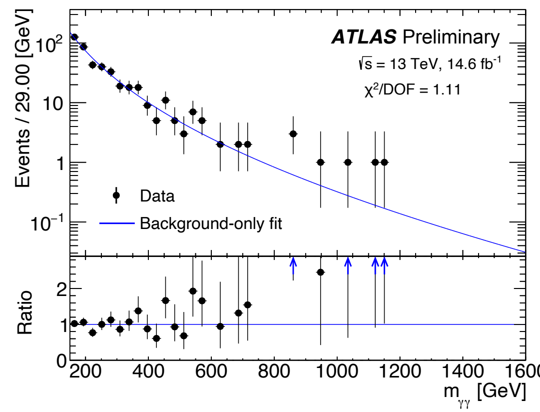
- Sensitivity exceeds that from the generic limits based on H →γγ decays, demonstrating the power of the technique

Searches Using Proton Tags

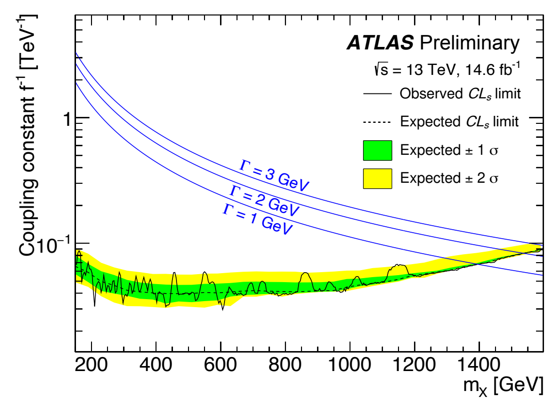
- Forward proton detectors of ATLAS and CMS/TOTEM (FPD and CT-PPS) allow for precise reconstruction/confirmation of the central system produced diffractively either in AA (low-mass) or pp (high-mass) collisions

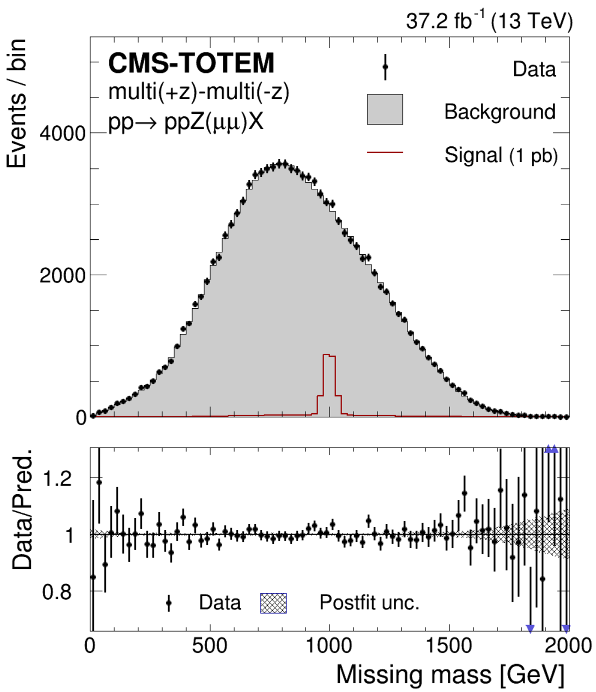




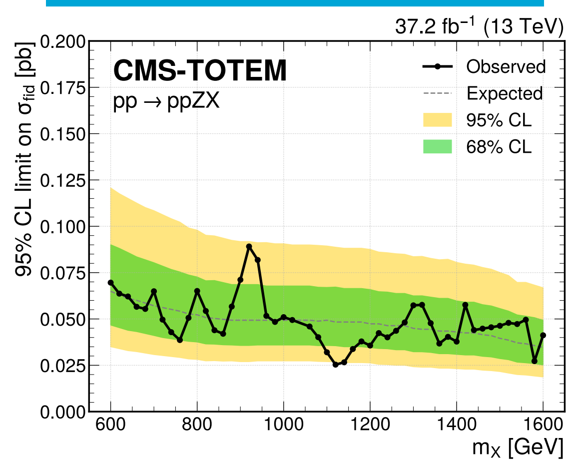


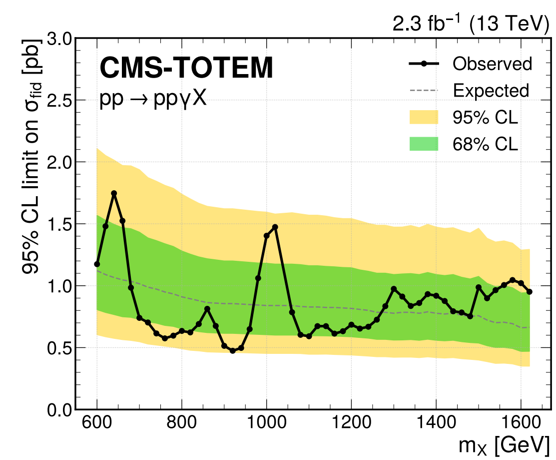
ATLAS CONF-2023-002





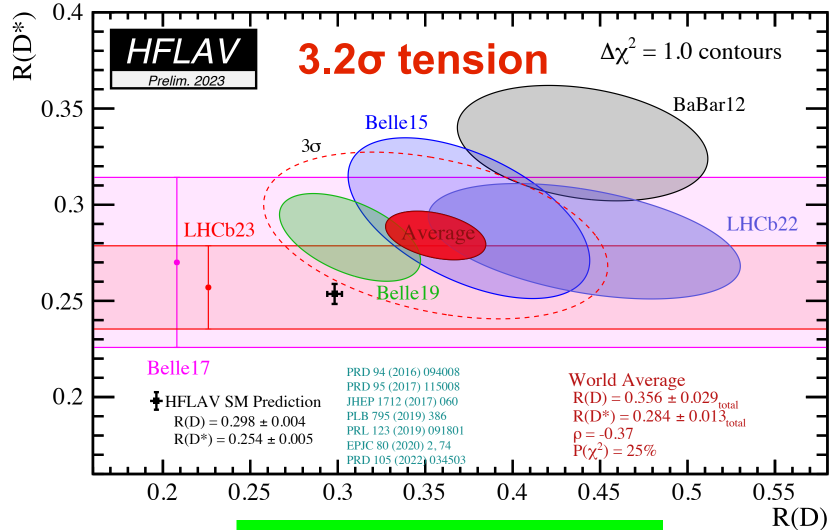
CMS, arXiv:2303.04596



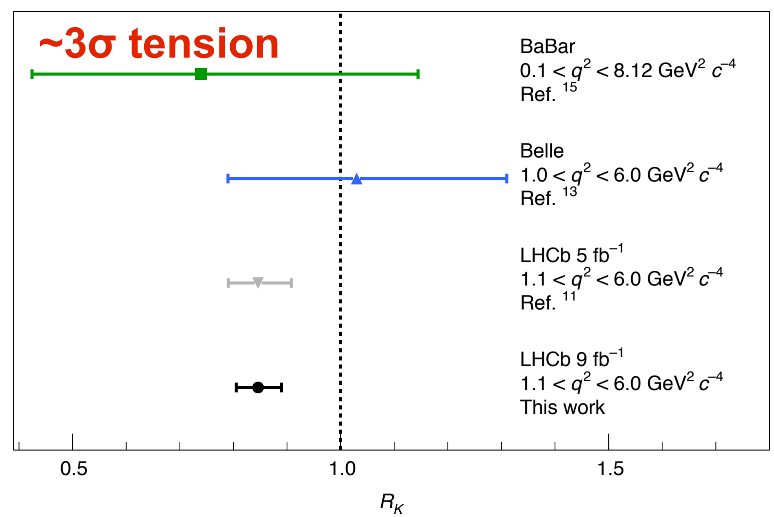


Lepton Flavor Anomalies

- **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] - now gone (a.k.a. LHCb discovers fake electron bkg!)**
- **Subject of acute theoretical and experimental interest over the past 7-8 years**



HFLAV 2021 Update



LHCb Nature Phys. 18 (2022) 277

Lepton Flavor Anomalies

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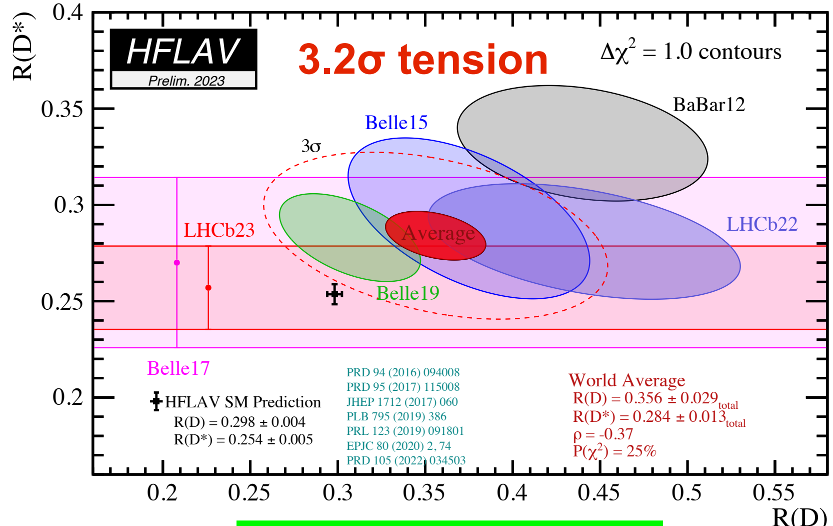
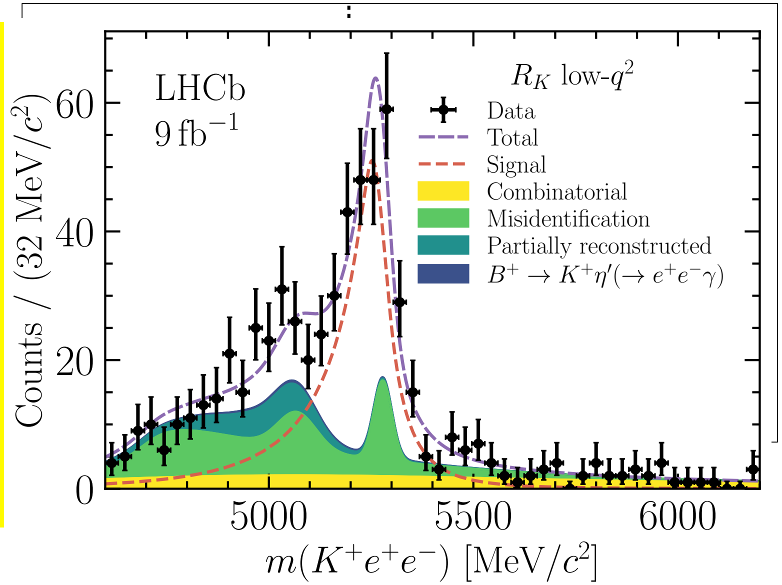


HFLAV 2021 Update

LHCb, arXiv:2212.09153



Lepton Flavor Anomalies

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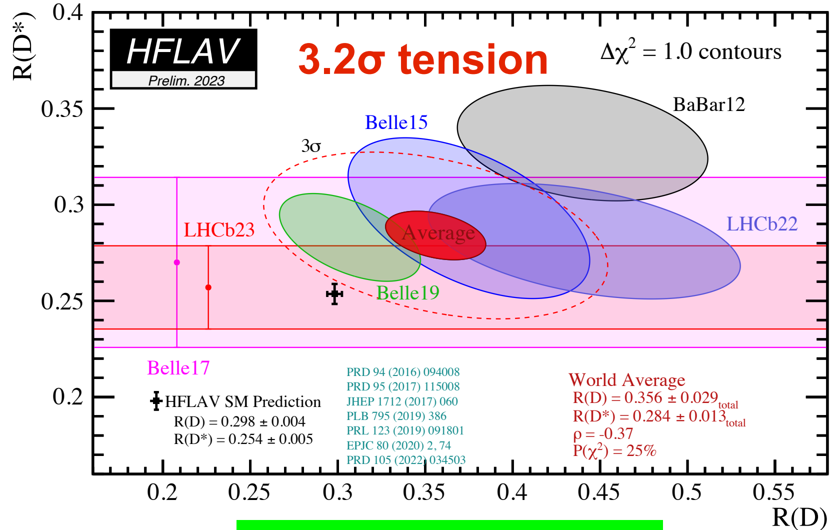

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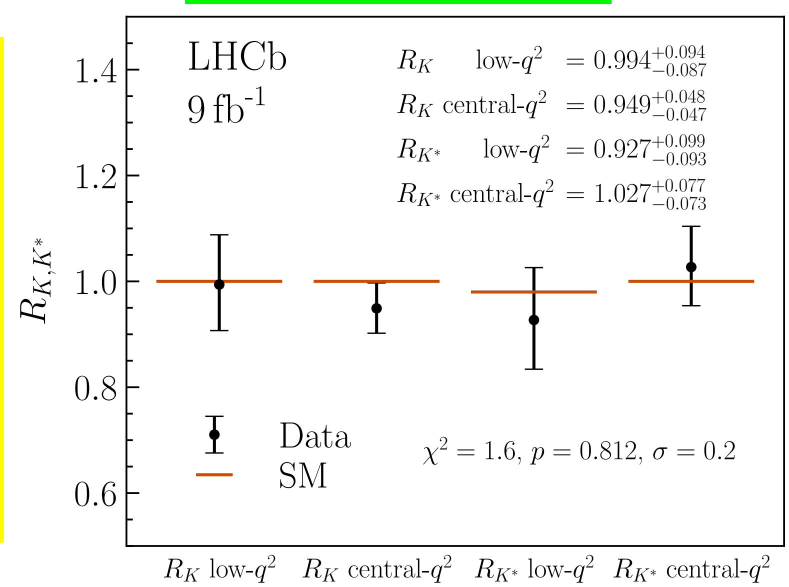
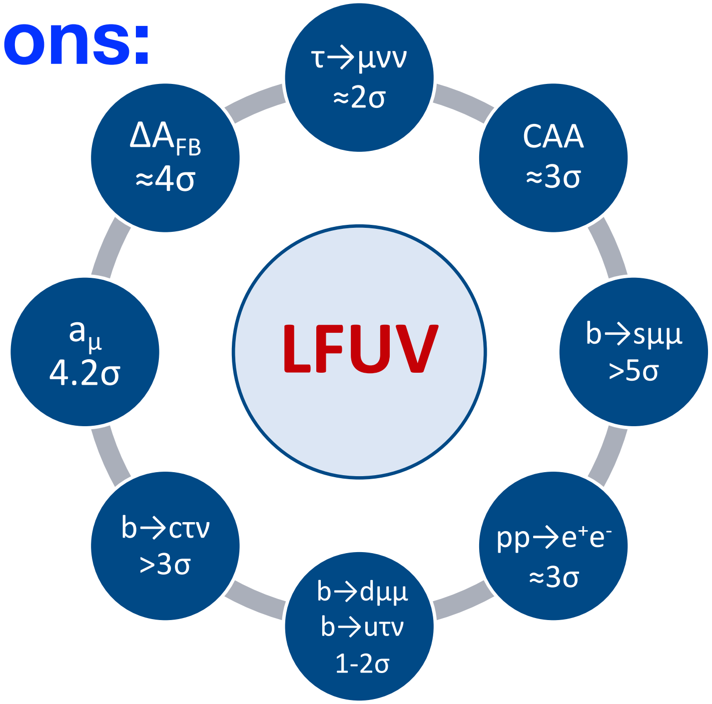


Common Explanations?

- 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

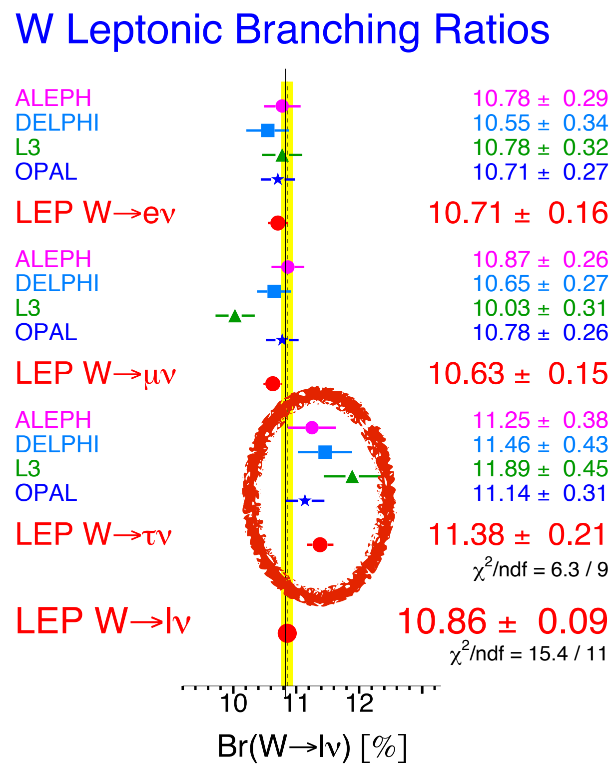
Enter ATLAS & CMS

- 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?**

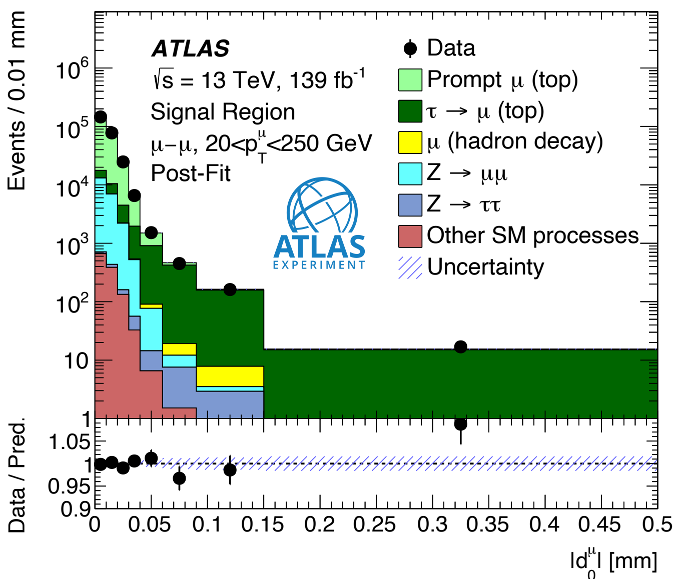
	Lepton non–universality		
Experiment	$\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_{\mathrm{e}})$ [%]	$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_{\mu})$ [%]	$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_{\tau})$ [%]
ALEPH	10.78 ± 0.29	10.87 ± 0.26	11.25 ± 0.38
DELPHI	10.55 ± 0.34	10.65 ± 0.27	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		



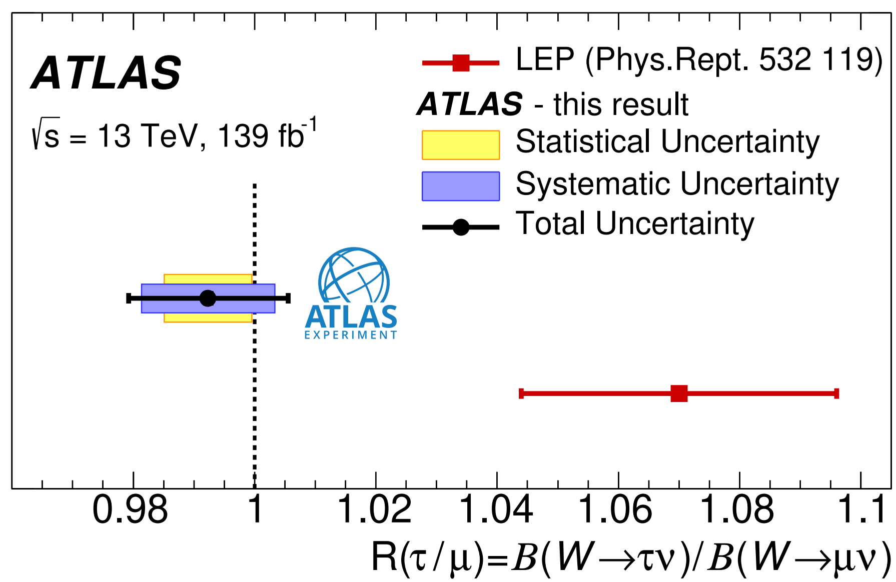
ADLO, Phys. Rep. 532 (2013) 119

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: $R_{\tau/\mu} = 0.992 \pm 0.013$, in good agreement w/ LFU



ATLAS
Nature Phys. 17 (2021) 813



CMS Test of LFU

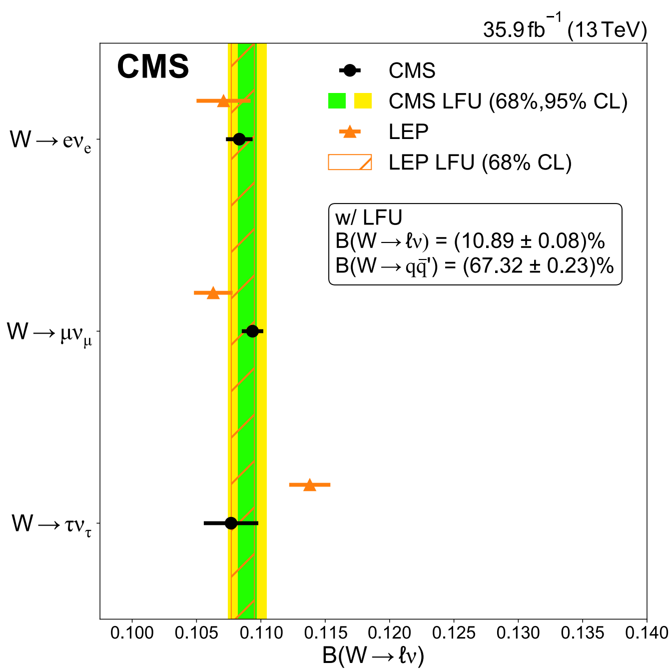
- Inclusive analysis targeting simultaneous extraction of $\beta = \{\beta_e, \beta_\mu, \beta_\tau, \beta_h\}$ W boson branching fractions, using both leptonic and hadronic τ lepton decays
  - ★ Search includes W+jets, WW, tW, and tt production
  - ★ Categorizes events in multiple classes depending on the leptonic and jet content (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 ATLAS analysis, does not use the lepton displacement to separate direct and τ lepton mediated decays

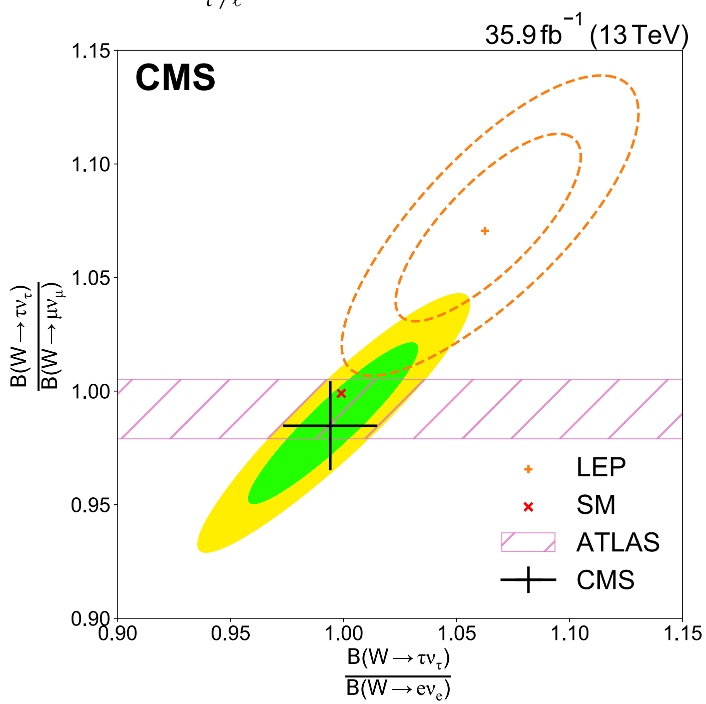
CMS Results

- **Results consistent with both LFU and ATLAS 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
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—

CMS, PRD 105 (2022) 072008





CKM matrix unitarity:

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

Extraction of $|V_{cs}|$:

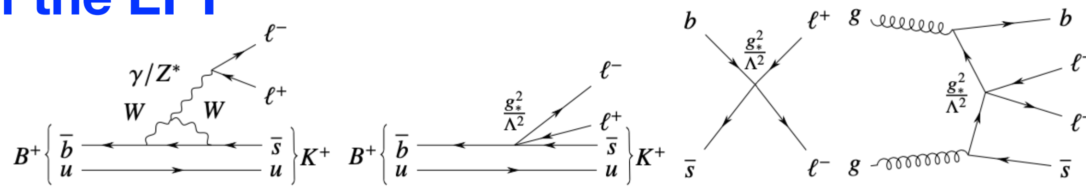
$$|V_{cs}| = 0.967 \pm 0.011$$

World average (from D meson decays):

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

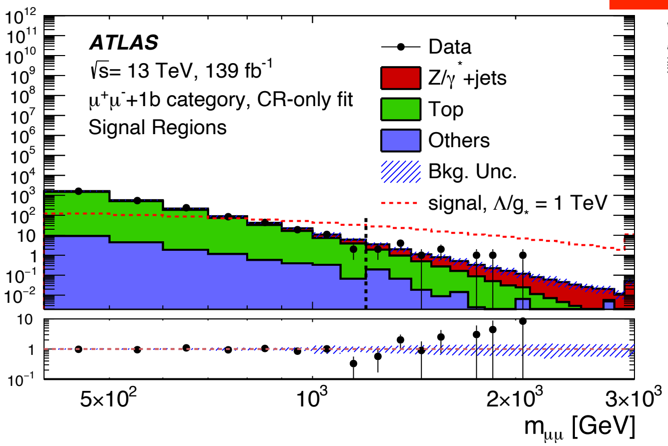
ATLAS LFU in Dilepton + b Jets

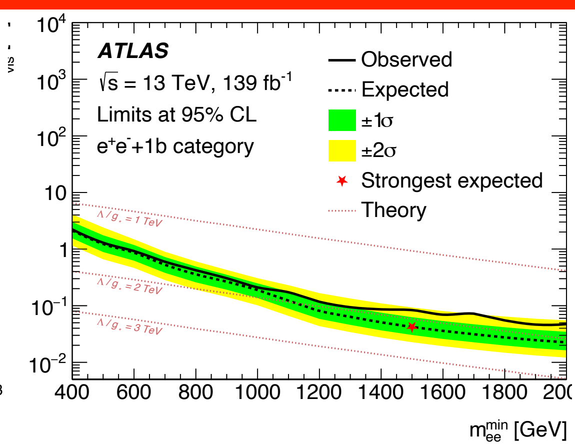
- Flavor anomalies in $b \to s\ell\ell$ transitions can be also probed with high-p_T physics, in the context of the EFT
- Same operators will give rise to signatures with dileptons and jets in the final state

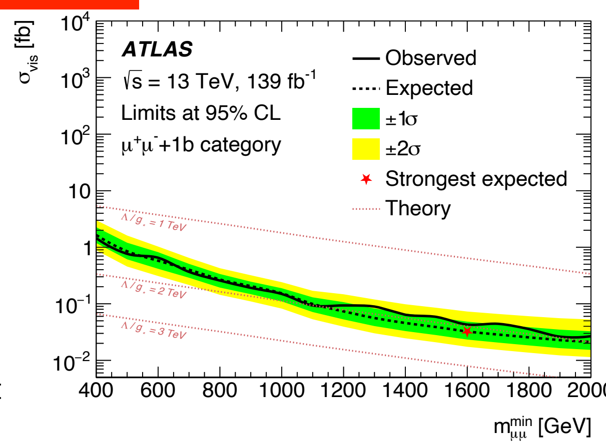


- Recent ATLAS analysis requires a pair of OS electrons and muons and either 0 or 1 b-tagged jet
- The dilepton mass distribution is then analyzed in the EFT or model-independent contexts to set limits on new physics contributions

ATLAS, PRL 127 (2021) 141801

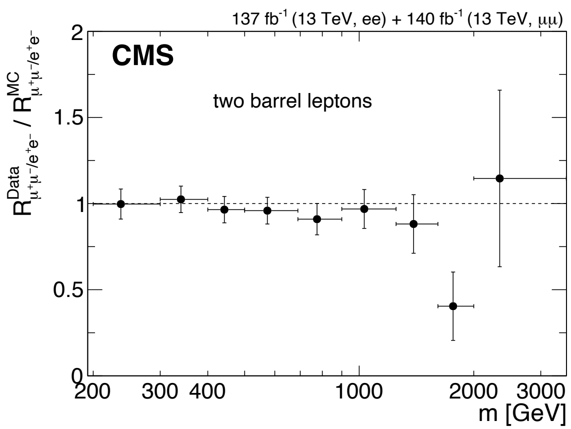


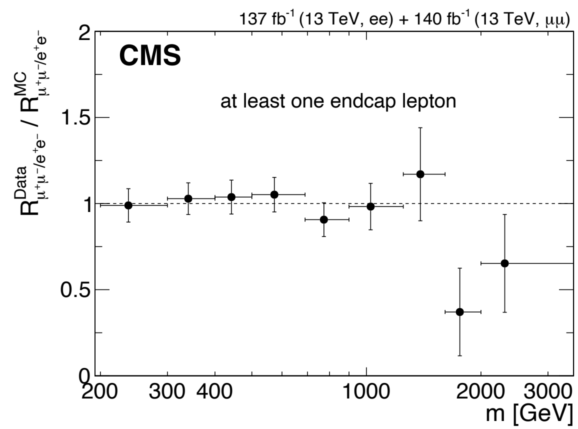


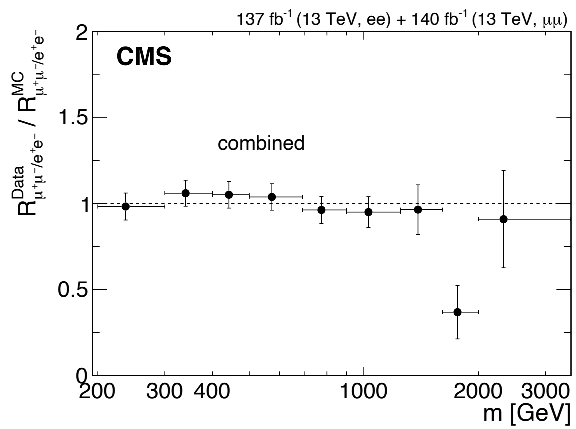


LFU in High-Mass Drell-Yan Pairs

- 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



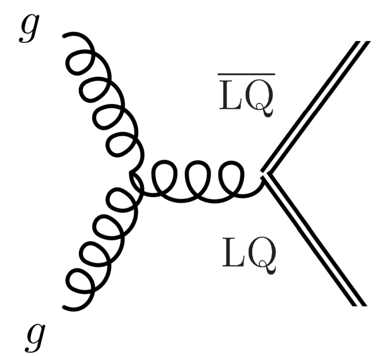


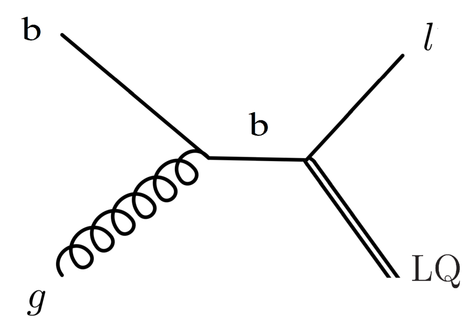


CMS, JHEP 07 (2021) 208

Leptoquark Searches

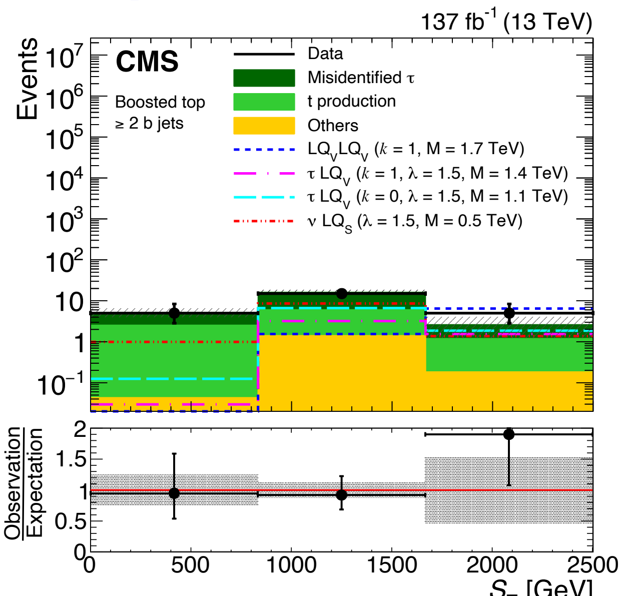
- **Leptoquarks (LQs) remain one of the favorite theoretical models capable of explaining both tree-level anomalies seen in b → c$\ell\nu$ decays and loop-level anomalies seen in b → s$\ell\ell$ transitions**
- **Typically require LQs with cross-generational coupling, often with enhanced couplings to 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**



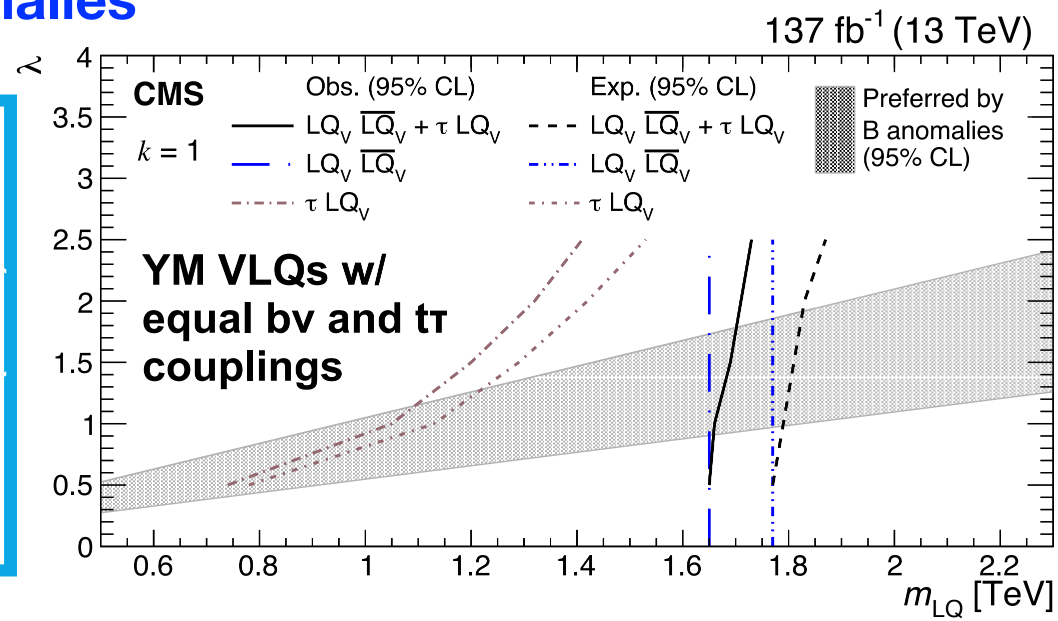


CMS Searches for LQ3

- A 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



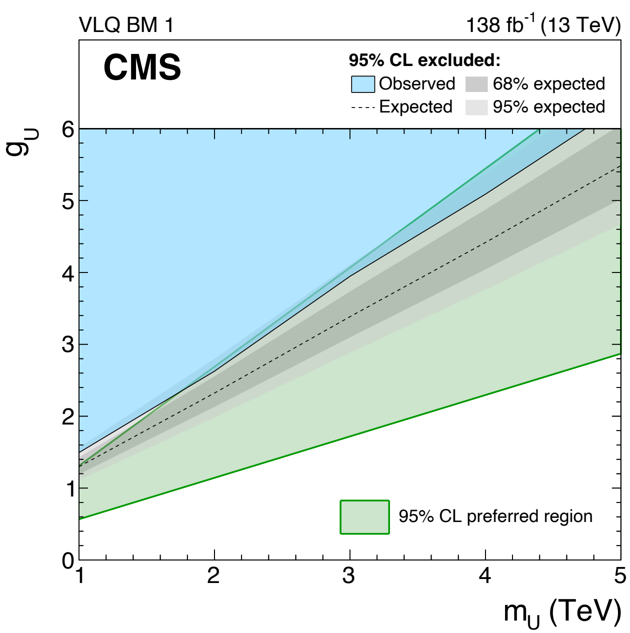
CMS
PLB 819 (2021) 136446

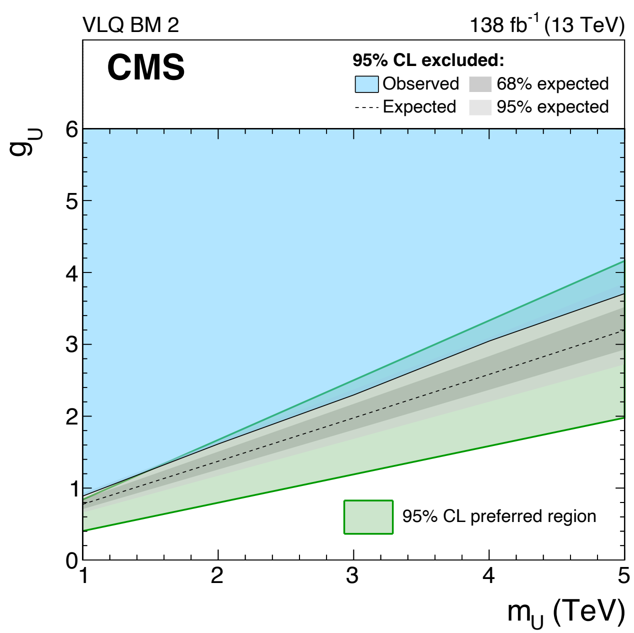


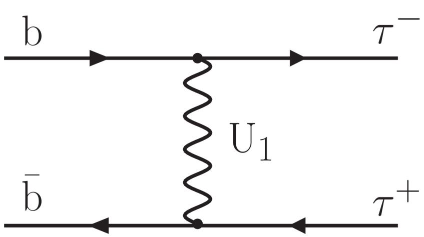
CMS Searches for LQ3

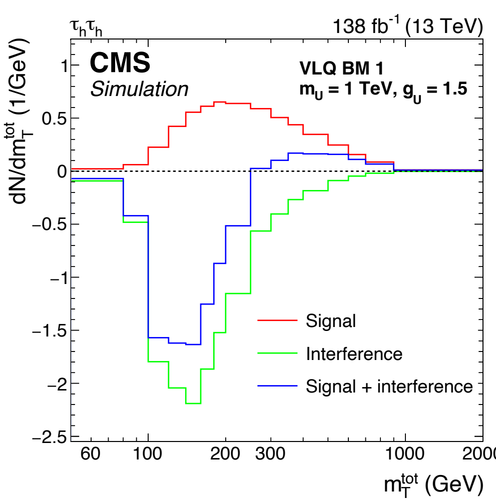
- **A new search for Pati-Salam U_1 vector LQ in the ττ channel, a spin-off of the MSSM Higgs search**
- **Significant interference with the SM DY ττ continuum taken into account**
- **Started probing interesting parameter space from the point of view of flavor anomalies**

CMS [arXiv:2208.02717]





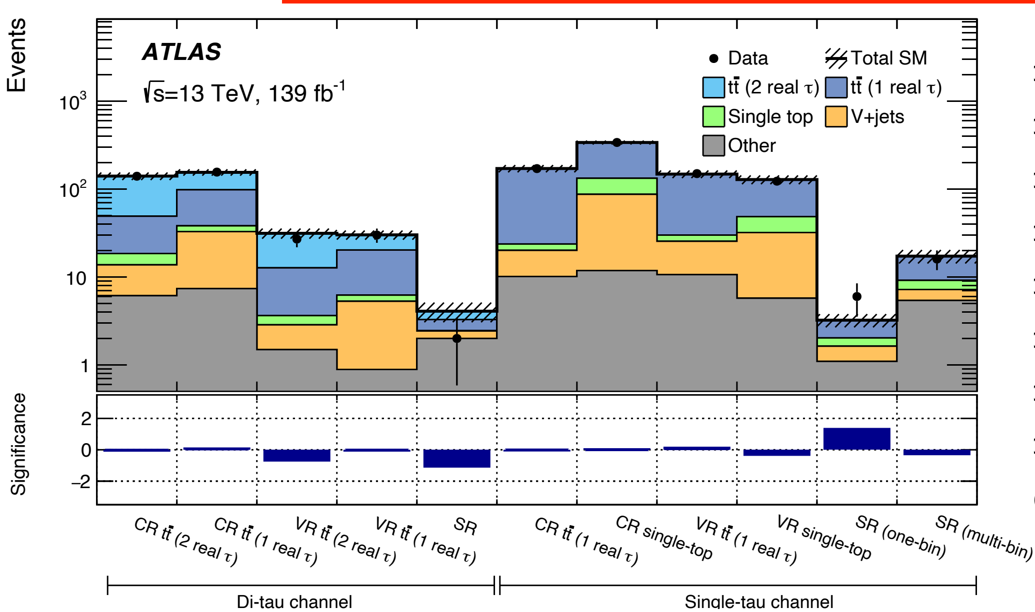


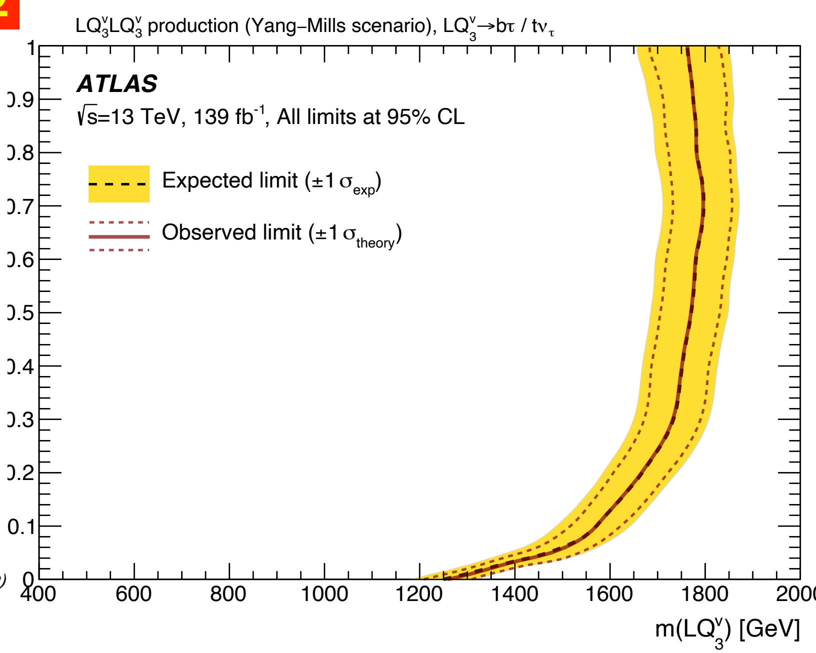


ATLAS Searches for LQ3

- 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 tν_τ
- 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

ATLAS, PRD 104 (2021) 112005

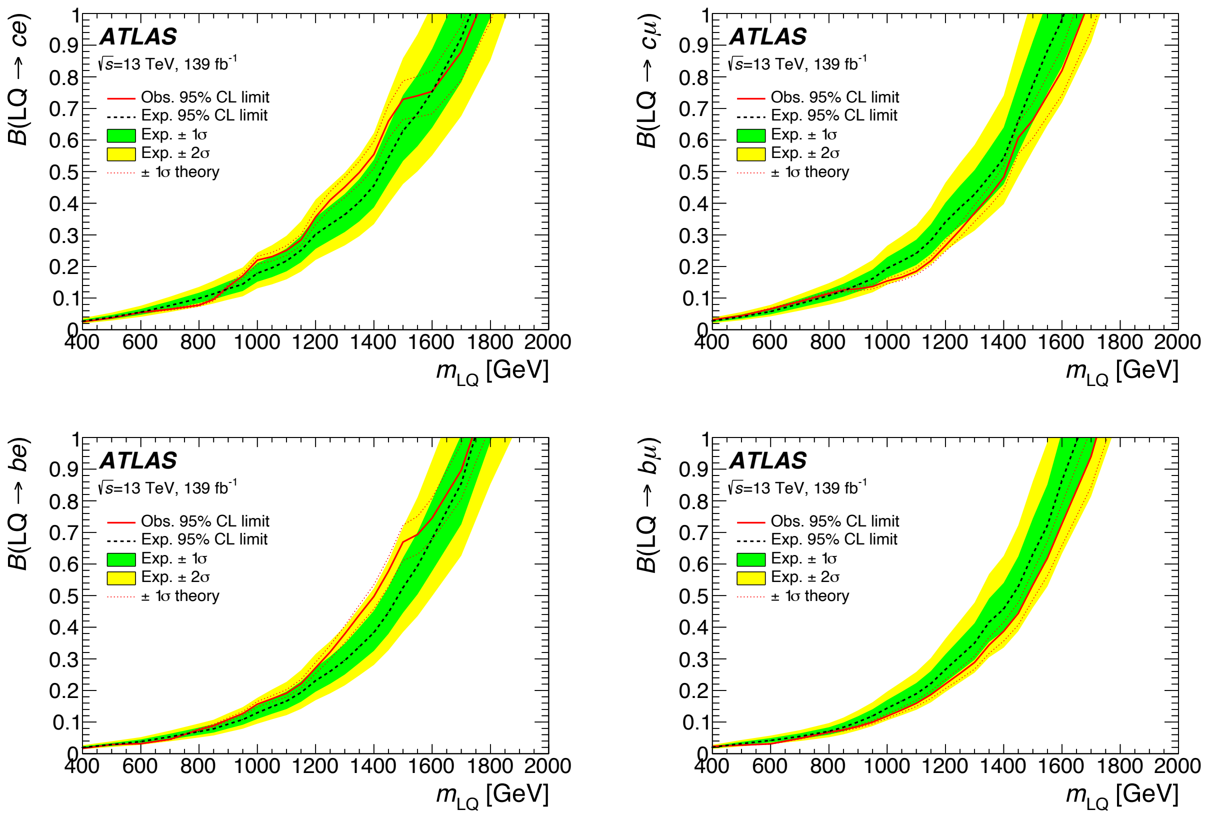




Cross-Generational Couplings

- ATLAS has recently done a search for scalar 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
- More recent search for LQ → (t,b)+(e,μ,ν) considers both scalar and vector LQs

ATLAS, JHEP 10 (2020) 112



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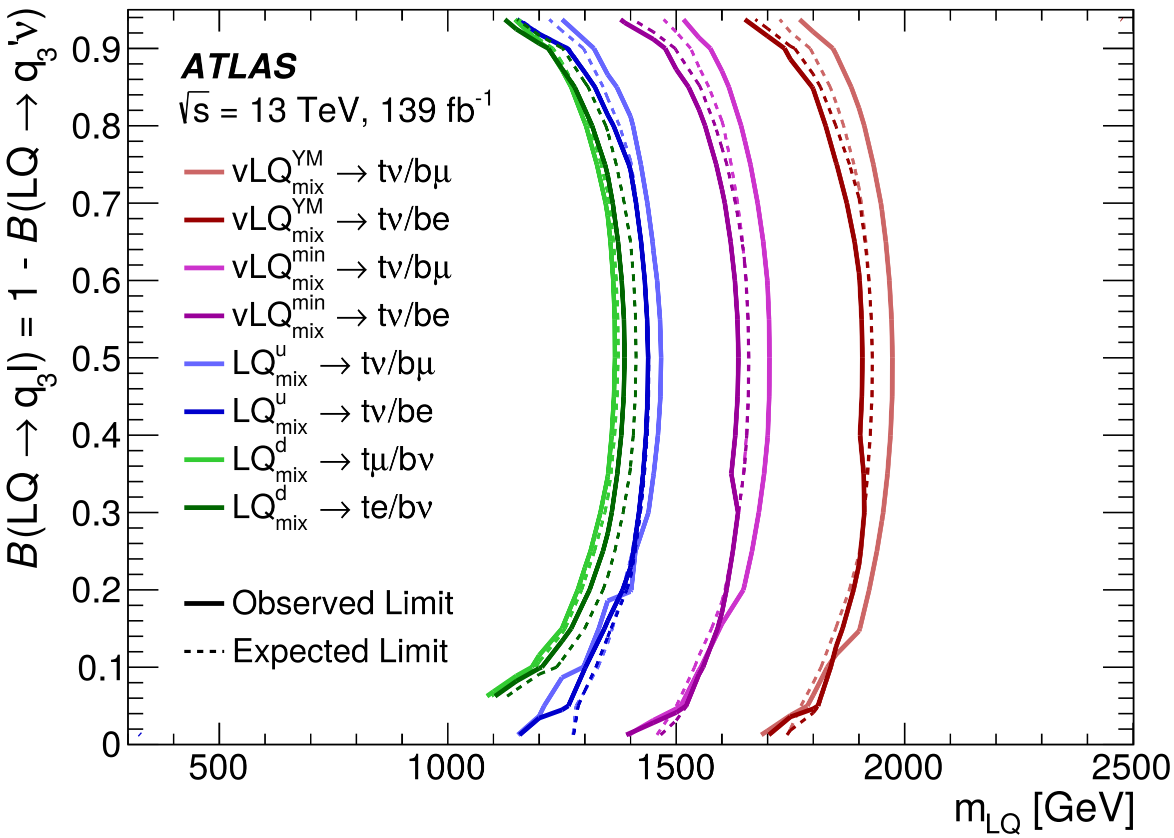
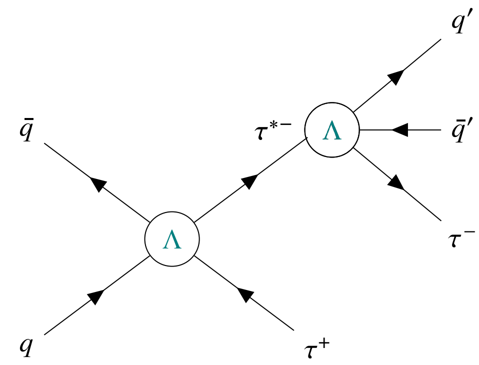
- ATLAS has recently done a search for scalar LQs that have cross-generational couplings, e.g., ce, bμ
- Only pair production is considered and the final states with a pair of OSSF leptons and b- or c-tagged jets are analyzed
- Limits are set as a function of the LQ mass and B(LQ → qℓ) for q = b, c and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



ATLAS, arXiv:2210.04517

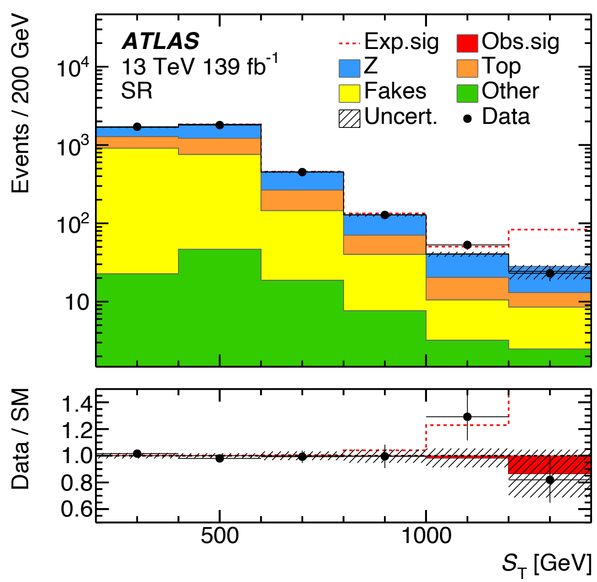
ATLAS Search for LQ3→τq

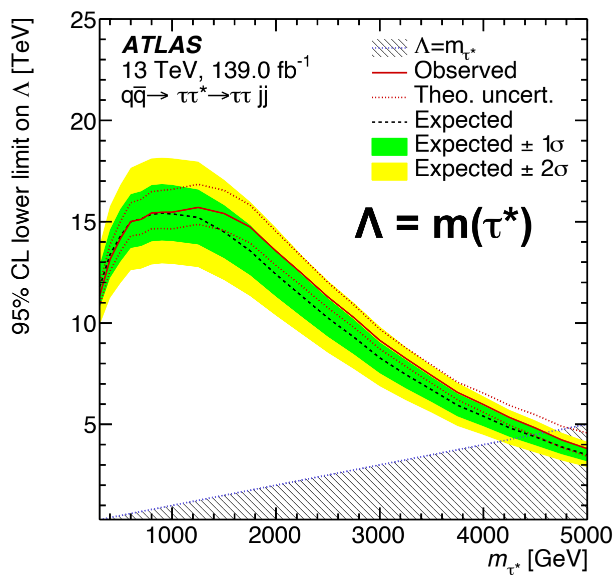
- A new search for LQ3 couple cross-generationally, e.g. to a τ and a c quark, using a $\tau_h\tau_h jj$ final state
- Can also be interpreted as an excited τ* search
- Employs S_T as the sensitive variable
- Typically dominant background from misidentified τ_h is determined from control samples is data and verified in the DY control region

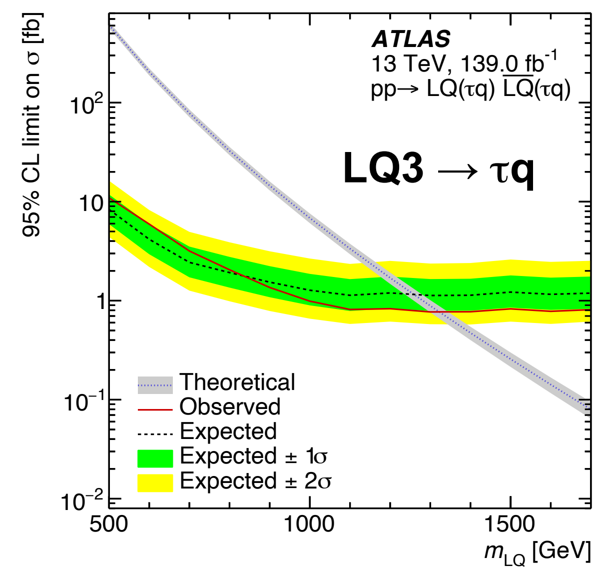


Composite model

ATLAS, arXiv:2303.09444

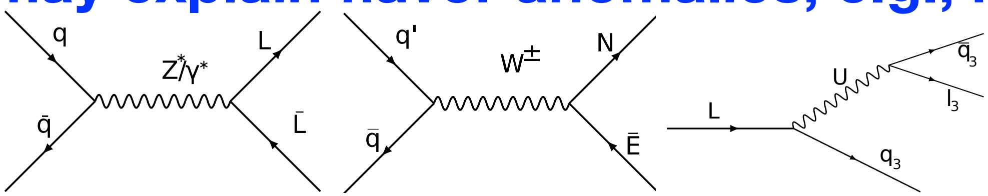






CMS Search for VLLs

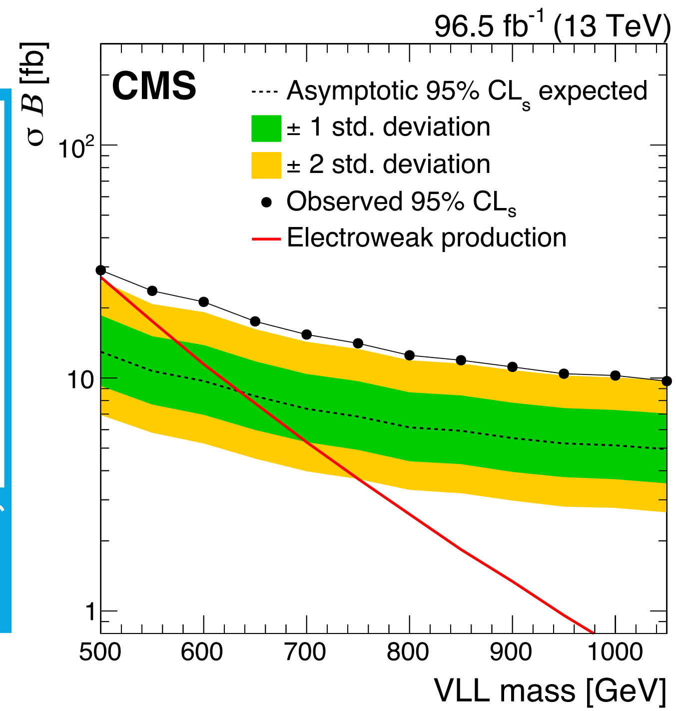
- Vector-like leptons are predicted in several SM extensions that may explain flavor anomalies, e.g., in the 4321 LQ model



tau multiplicity	production + decay mode	final state
0 τ	EE → b(tν_τ)b(tν_τ)	4b + 4j + 2ν_τ
	EN → b(tν_τ)t(tν_τ)	4b + 6j + 2ν_τ
	NN → t(tν_τ)t(tν_τ)	4b + 8j + 2ν_τ
1 τ	EE → b(bτ)b(tν_τ)	4b + 2j + τ + ν_τ
	EN → b(tν_τ)t(bτ)	4b + 4j + τ + ν_τ
	EN → b(bτ)t(tν_τ)	4b + 4j + τ + ν_τ
	NN → t(bτ)t(tν_τ)	4b + 6j + τ + ν_τ
2 τ	EE → b(bτ)b(bτ)	4b + 2τ
	EN → b(bτ)t(bτ)	4b + 2j + 2τ
	NN → t(bτ)t(bτ)	4b + 4j + 2τ

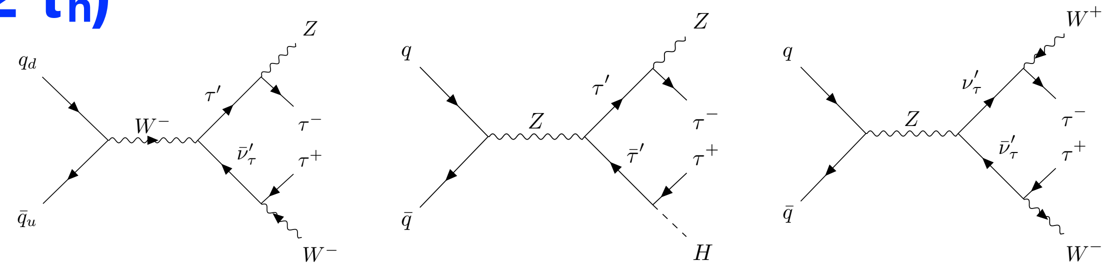
- New CMS analysis in ≥3b + (0-2)τ final states
- Complicated analysis relying on DNNs to separate signal from the dominant QCD and tt backgrounds
- Observed a mild excess (1-2τ_h channels), which unfortunately is hard to associate with any specific mass
  - ★ Important to construct the analysis optimized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

CMS, arXiv:2208.09700



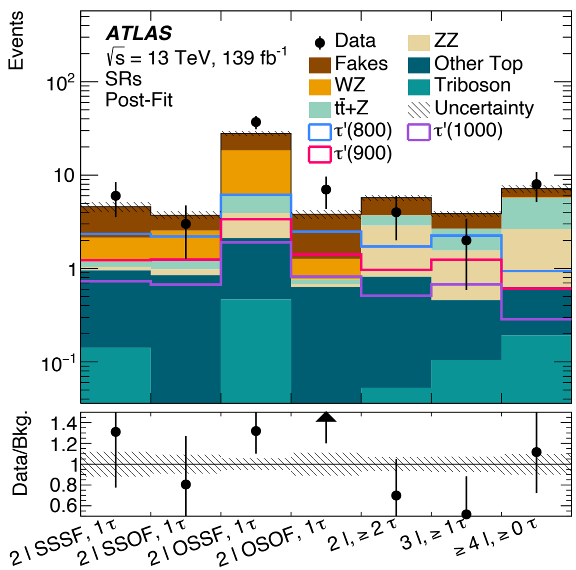
ATLAS Doublet VLL Search

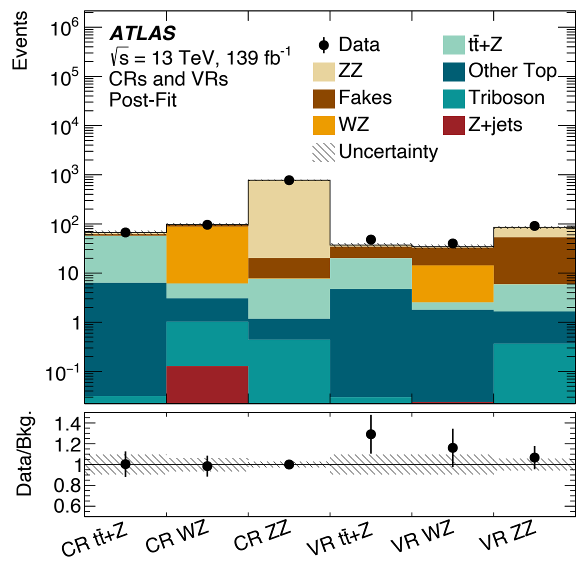
- Very recent result from ATLAS in the multilepton channels with τ leptons (0, 1, ≥2 τ_h)
- BDT-based signal extraction with multiple CRs and VRs

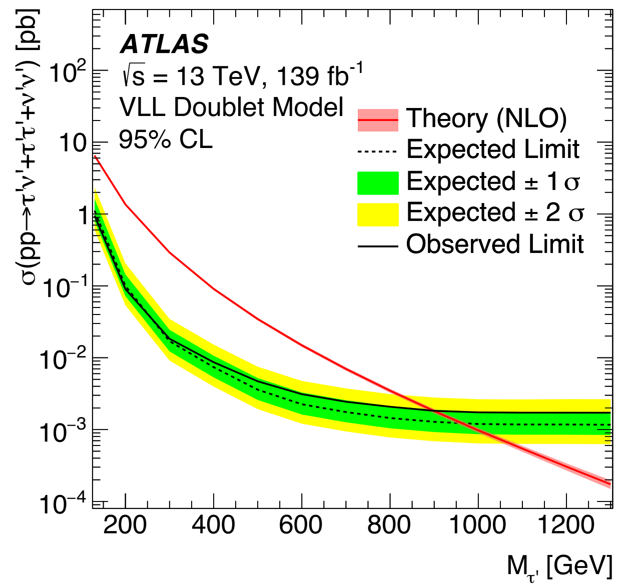


- Similar limits to an analogous earlier CMS analysis

ATLAS, arXiv:2303.05441







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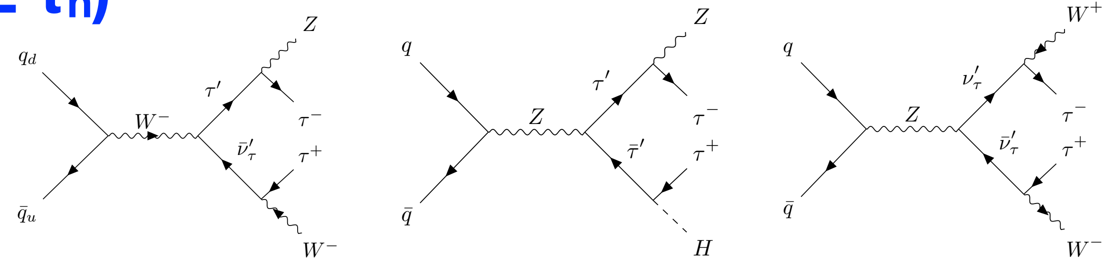
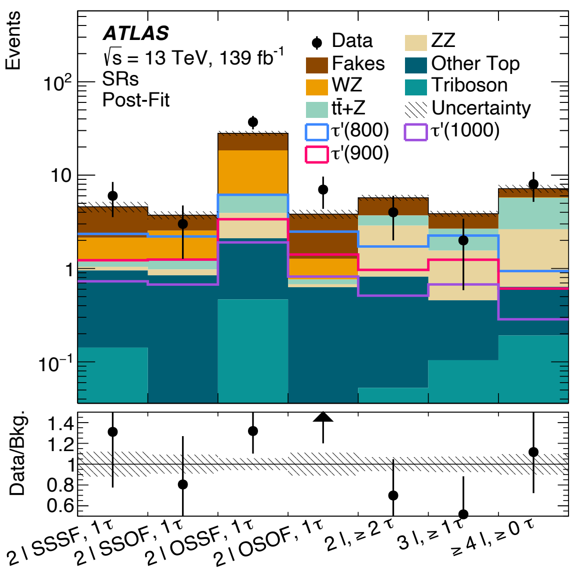
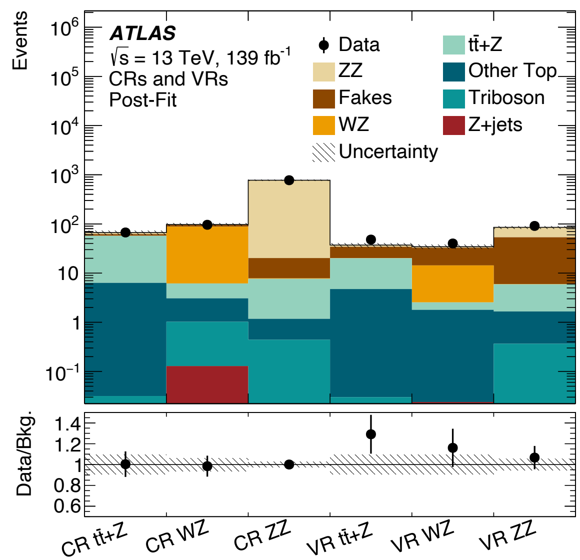


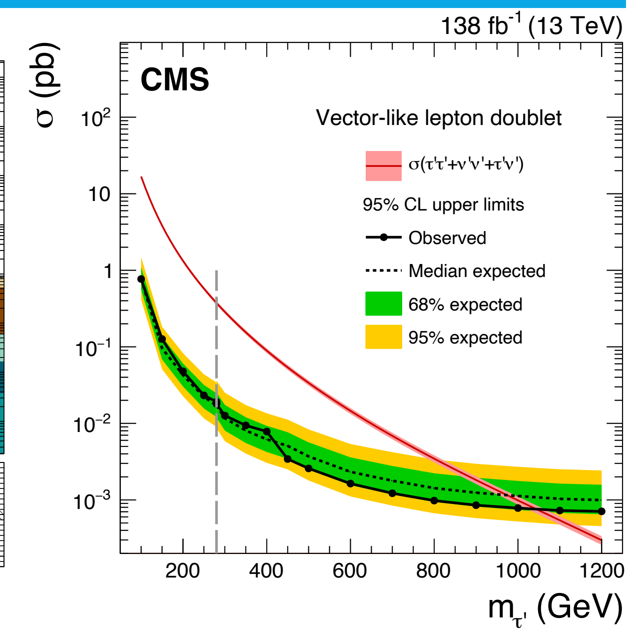
- **Similar limits to an analogous earlier CMS analysis**

CMS, PRD 105 (2022) 112007

ATLAS, arXiv:2303.05441





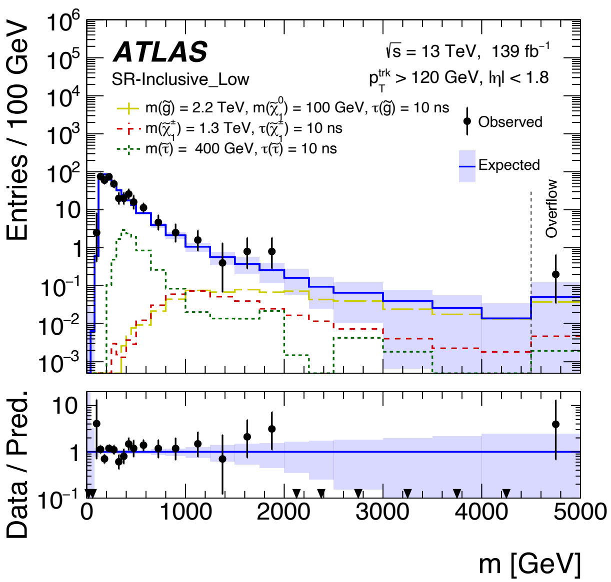


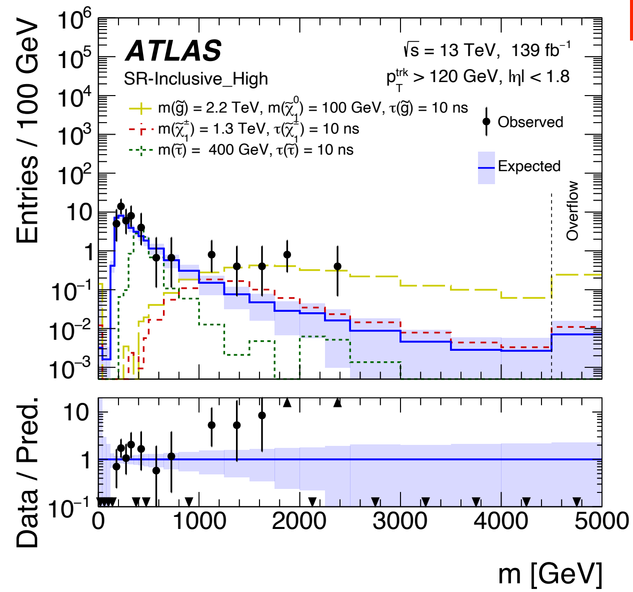
High-p_T Run 2 Excesses

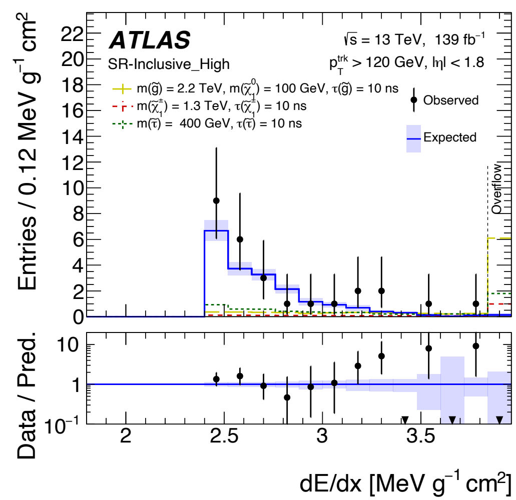
ATLAS LLP dE/dx Excess

- 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





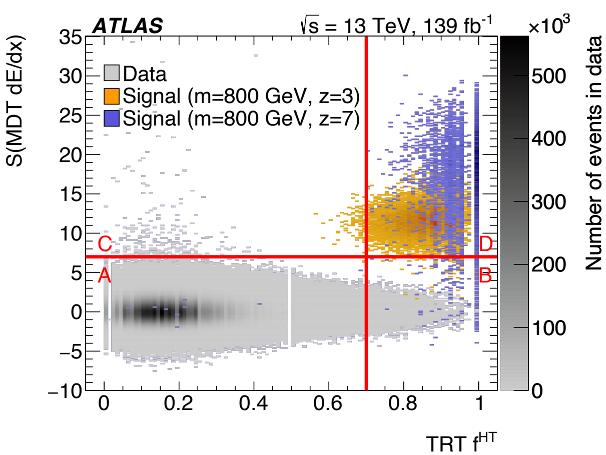


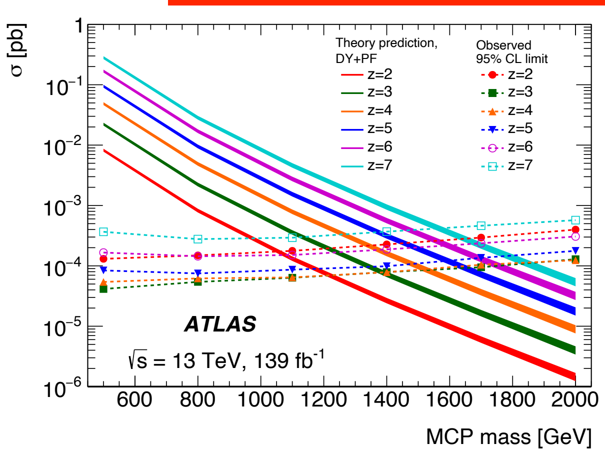
No competitive CMS results yet

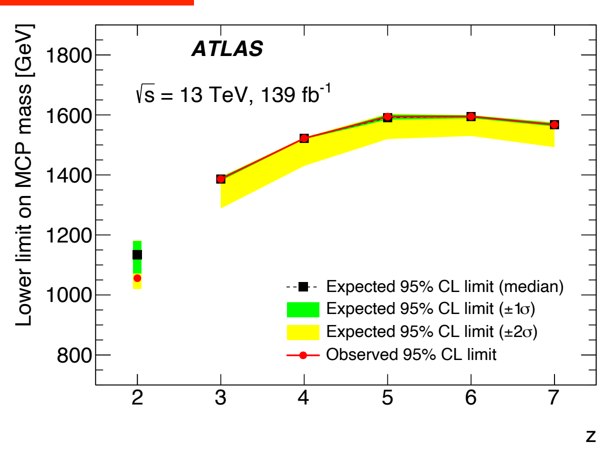
ATLAS Search for MCPs

- Natural question is if this excess could be explained by a lighter particle with a charge Ze, Z > 1
- A dedicated search for multi-charged particles (MCPs) produced via DY or photon fusion using dE/dx in the pixel and MDT detectors, as well as the high- to low-threshold hit ratio in the TRT
- Different approaches for Z = 2 (using pixels) and Z > 2 (pixels saturate)
- Backgrounds estimated from data using the matrix method
- No excess seen; limits are set for Z = 2-7, up to 1.6 TeV on the MCP mass
  - ★ None of the high-dE/dx candidates from previous analysis enter search regions of the MCP search

ATLAS, arXiv: 2303.13613

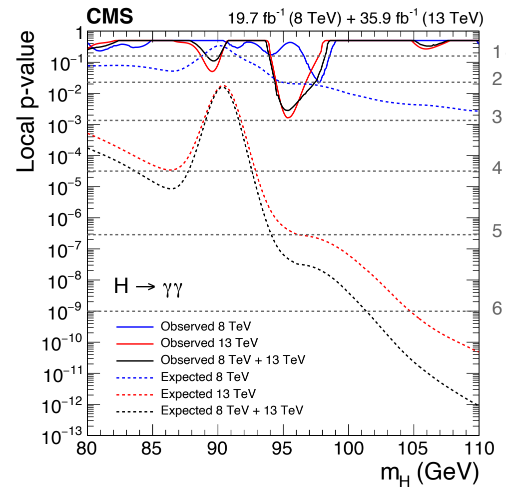




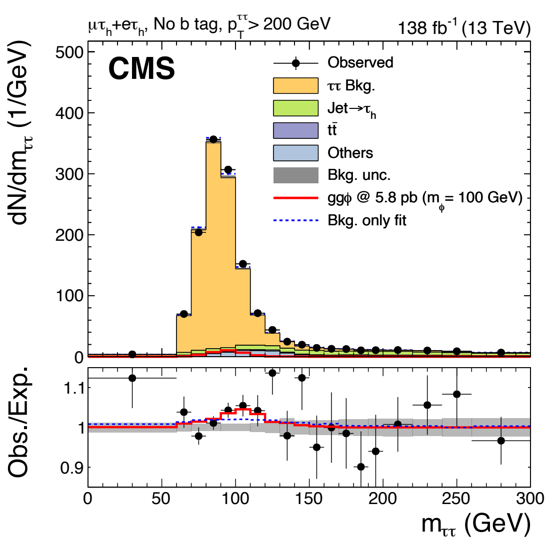


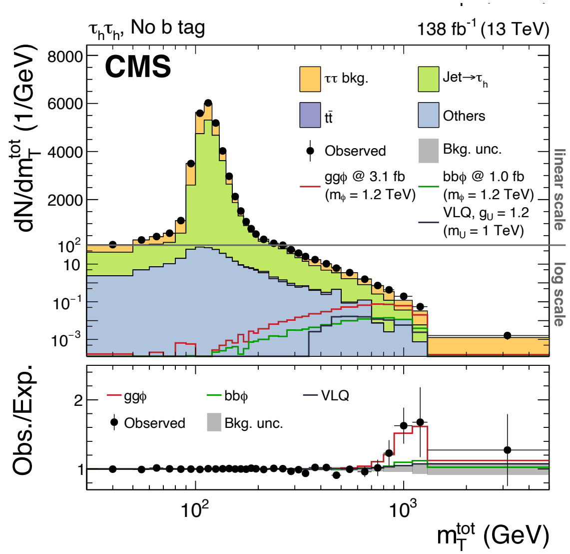
CMS ~0.1 and ~1.2 TeV ττ Excesses

- 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

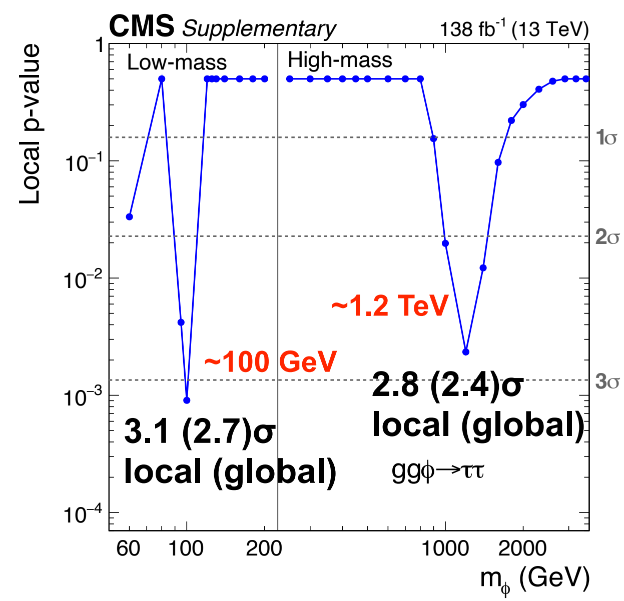


CMS, PLB 793 (2019) 320



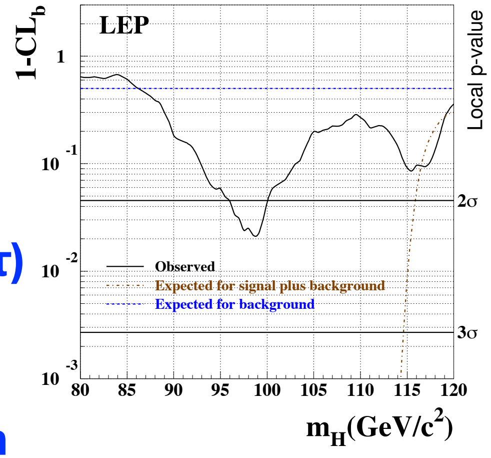


CMS, arXiv:2208.02717

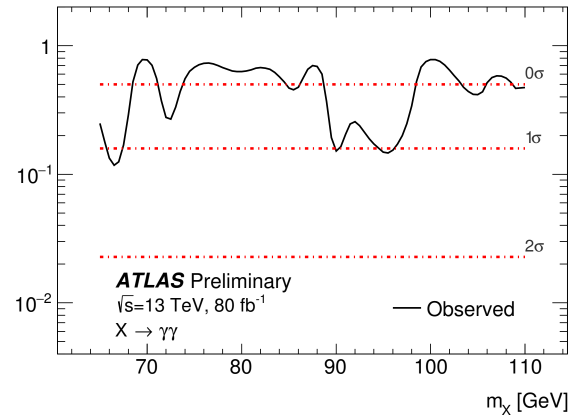


What Does ATLAS See?

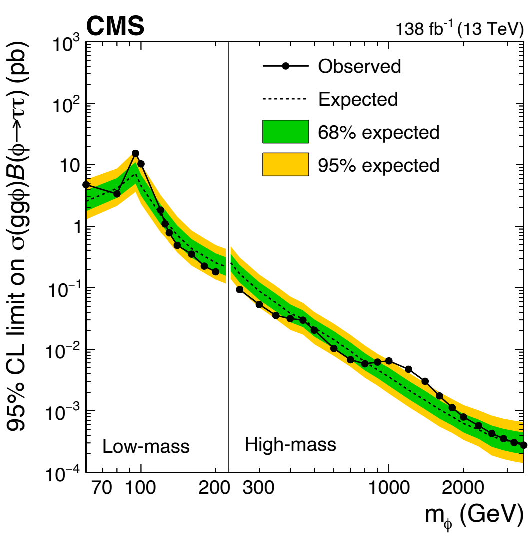
- No full Run 2 ATLAS result in the low-mass diphoton channel yet
  - ★ The 2016 ATLAS result is not inconsistent with the CMS one
- The full Run 2 ATLAS MSSM H(ττ) result contradicts the 1.2 TeV excess seen in CMS
- The 95-96 GeV light Higgs boson has long been a subject of theoretical interest since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



ADLO, hep-ex/0306033

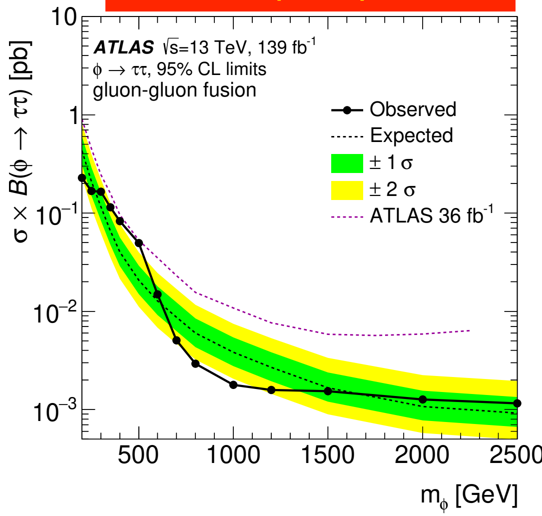


ATLAS-CONF-2018-025

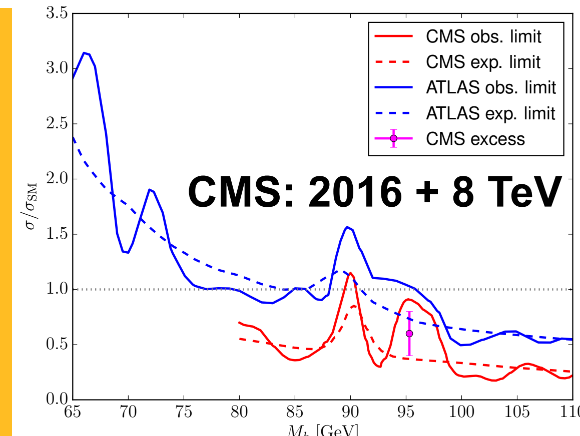


CMS, arXiv:2208.02717

ATLAS PRL 125 (2020) 051801



Heinemeyer, Stefaniak arXiv:1812.05864

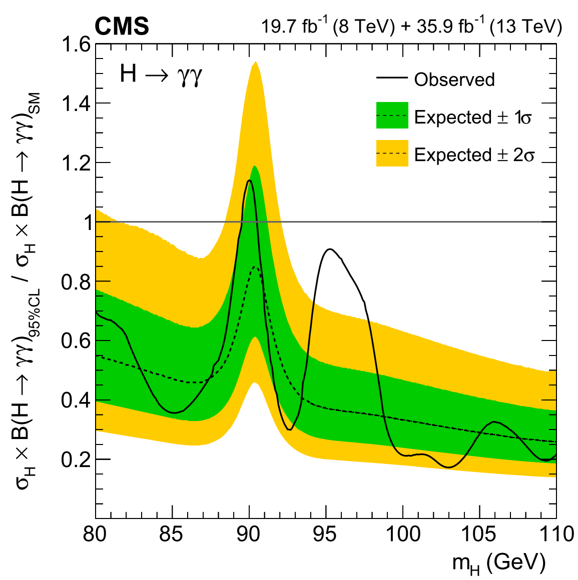


Looking forward to ATLAS 139 fb^{-1} updates in the γγ channel!

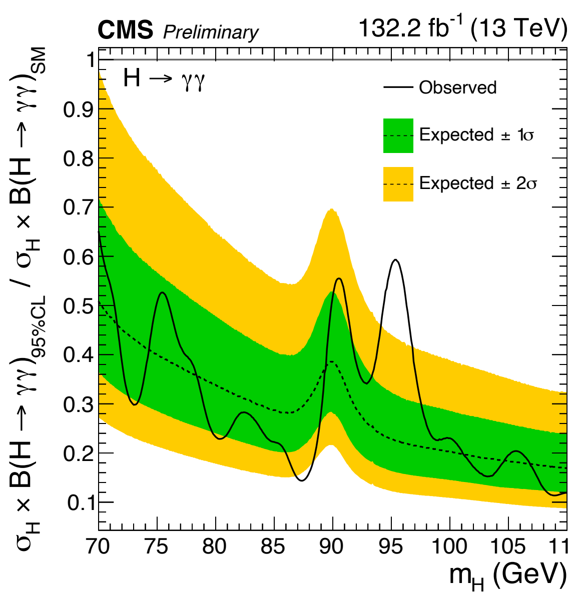
In the Meantime…

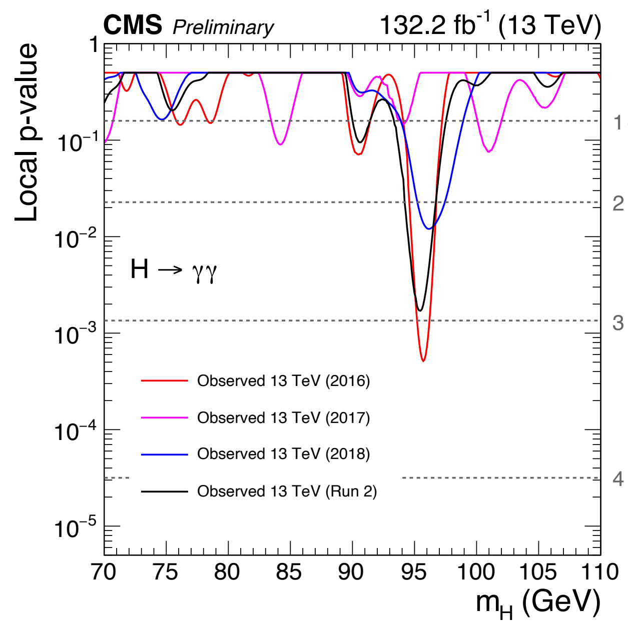
- **CMS has just released a new low-mass h(γγ) analysis based on full Run 2 data**
- **The overall excess is still there, with about the same significance (2.9σ local; 1.3σ global) albeit with twice as low cross section**
- **Still need more data (ATLAS Run 2?) to understand whether the excess is real**

CMS, PLB 793 (2019) 320



CMS PAS HIG-20-002





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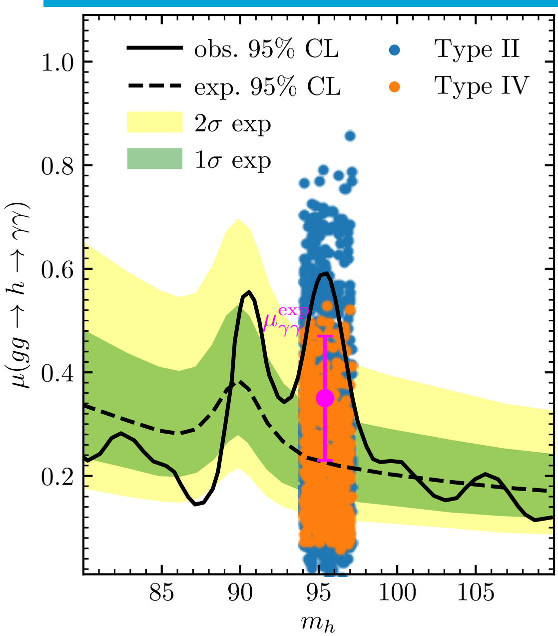
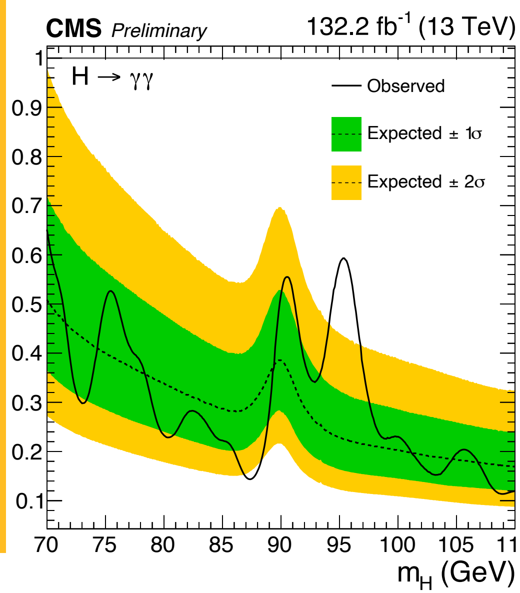
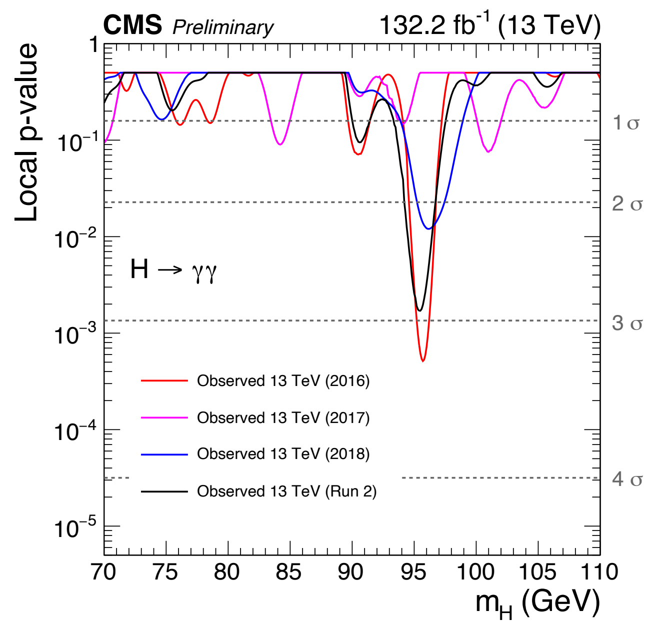
Theorists never sleep…



Biekotter, Heinemeyer, Weiglein arXiv:2303.12018

CMS PAS HIG-20-002

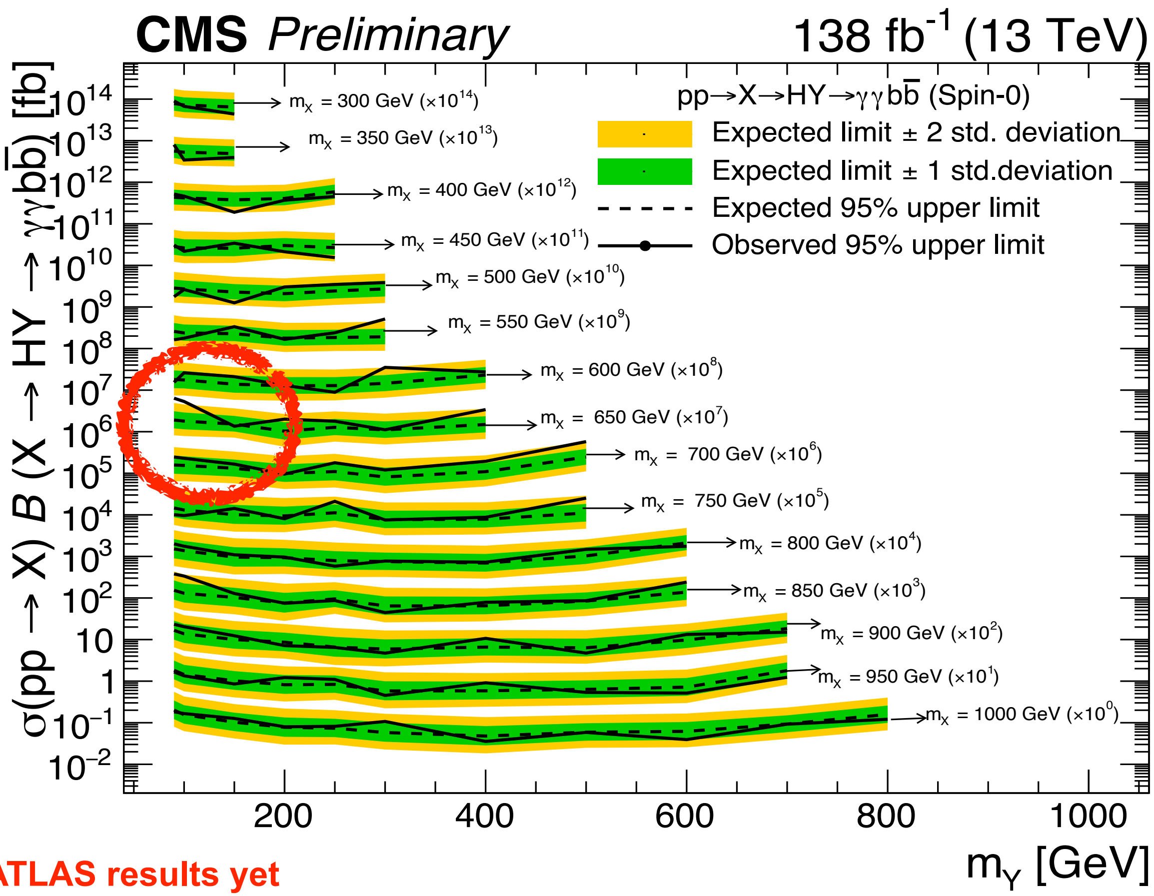




CMS Y(bb)H(γγ) Excess

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

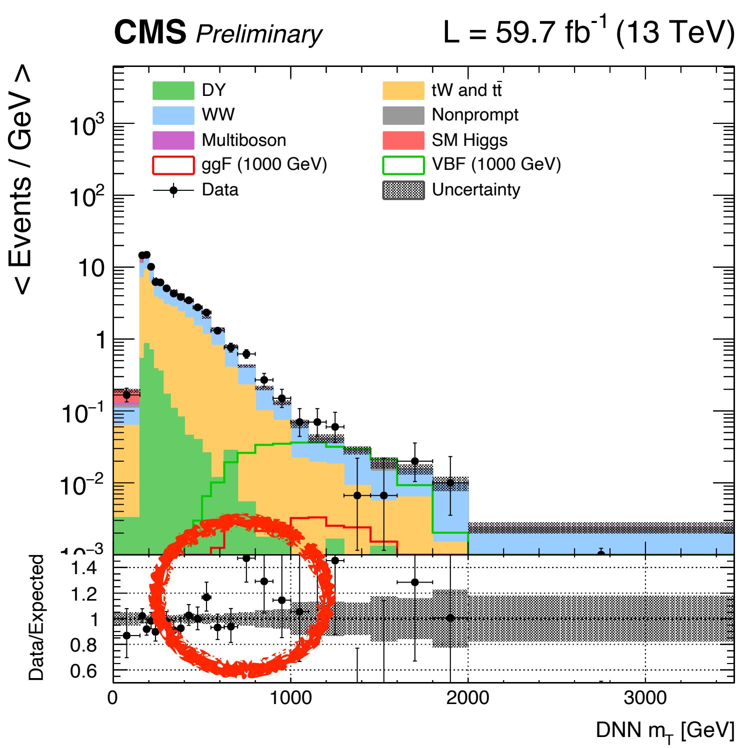
CMS-PAS-HIG-21-011



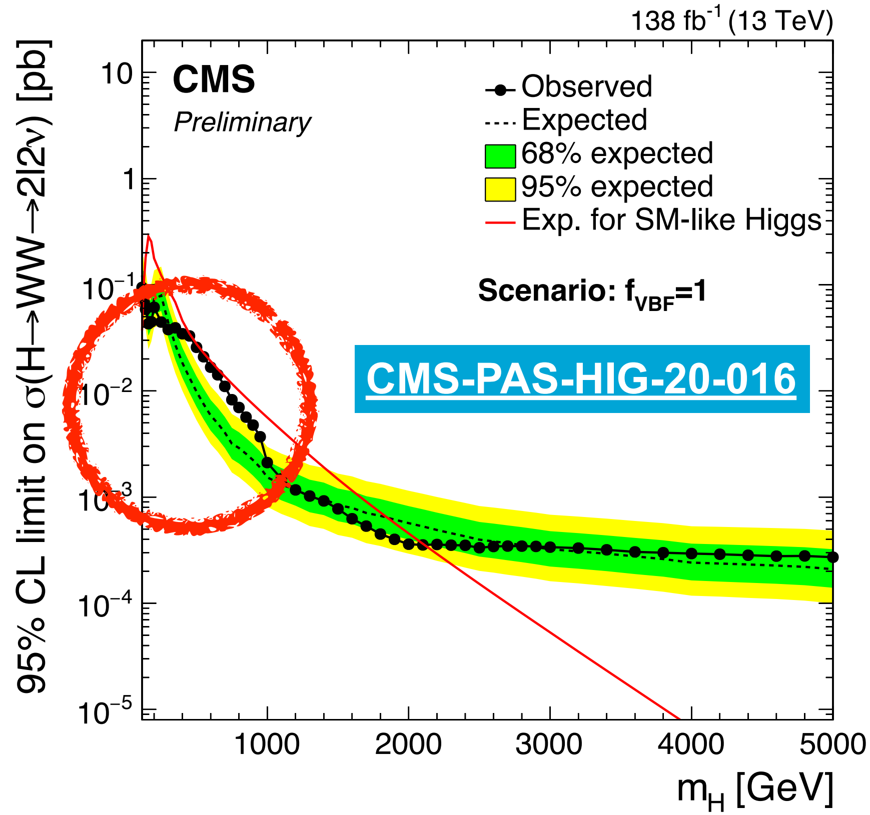
No competitive ATLAS results yet

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 2016 leptonic H(WW) doesn't have an excess, but the sensitivity is not sufficient to rule out the CMS excess; neither does the full Run 2 Z'(WW) semileptonic analysis
  - ★ 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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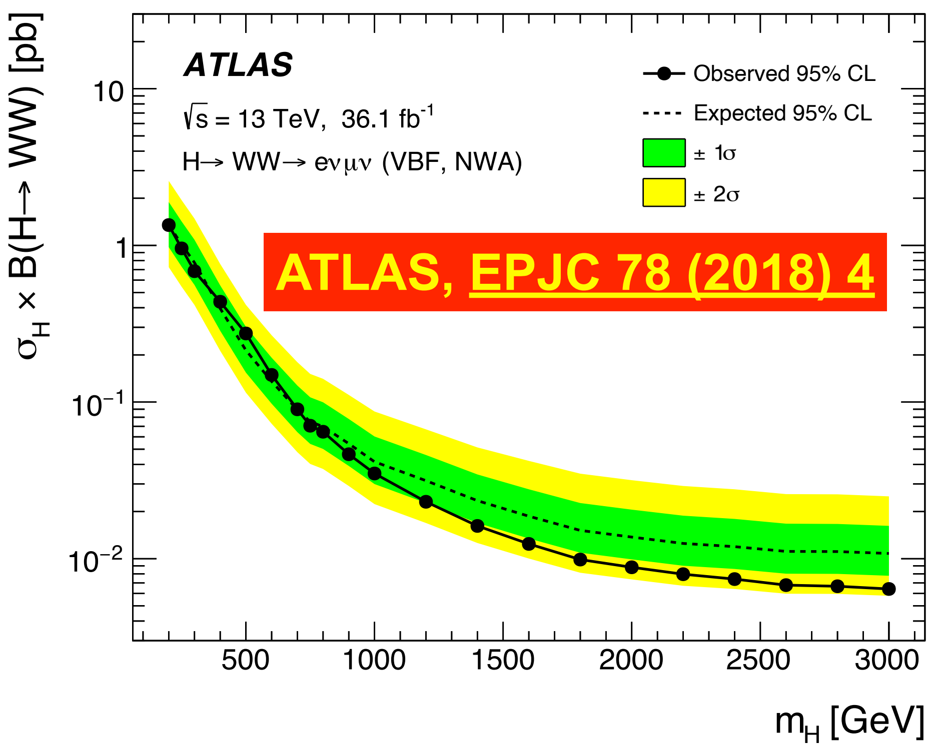

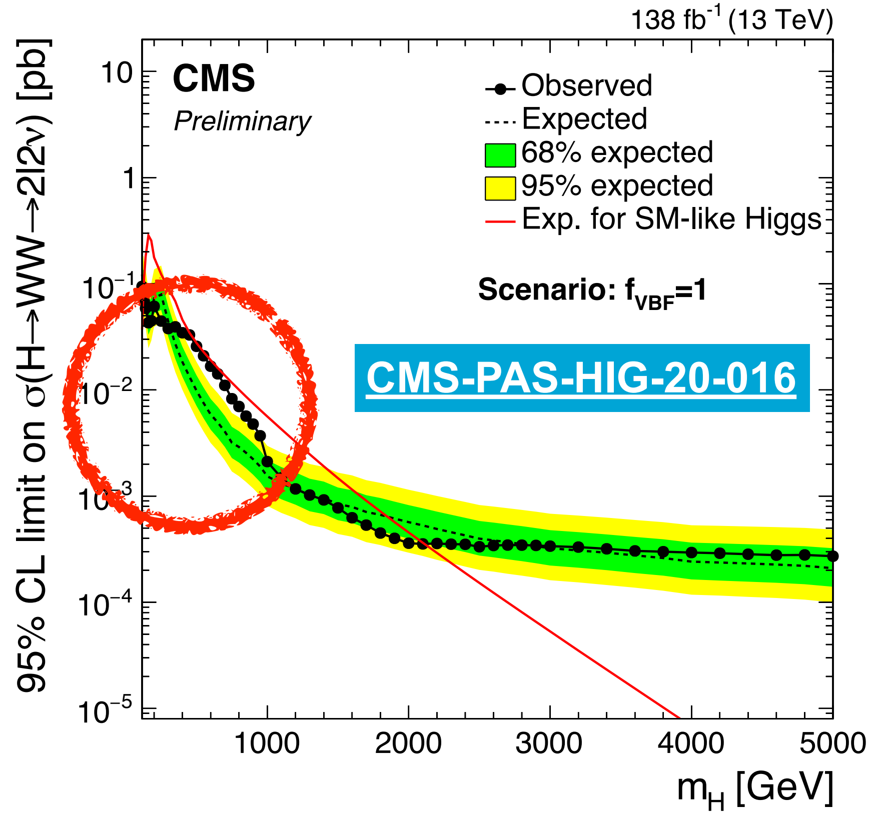

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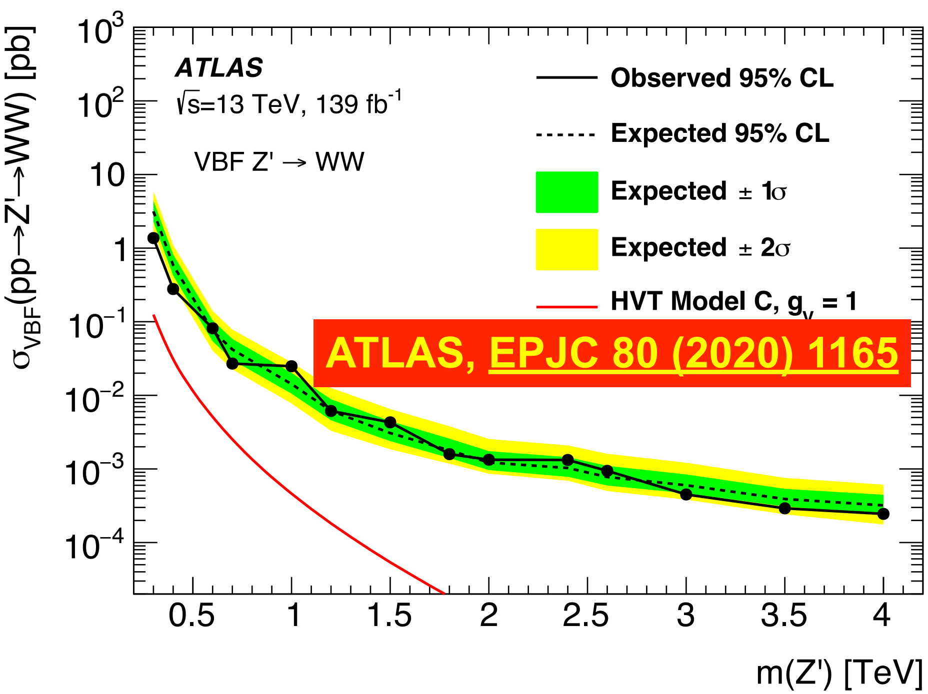

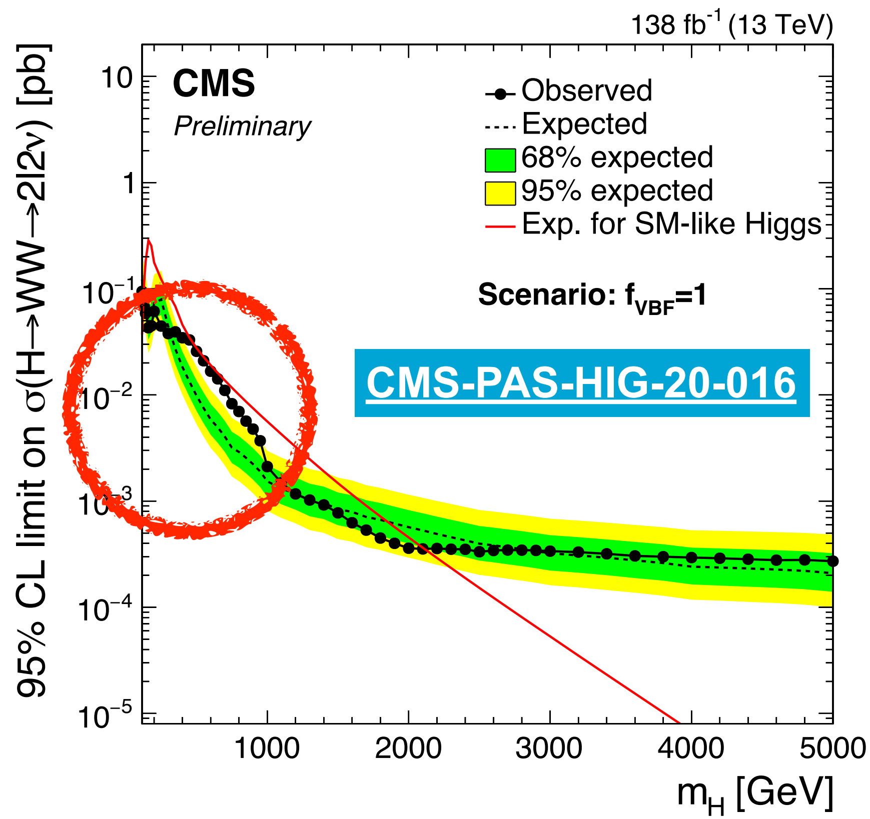

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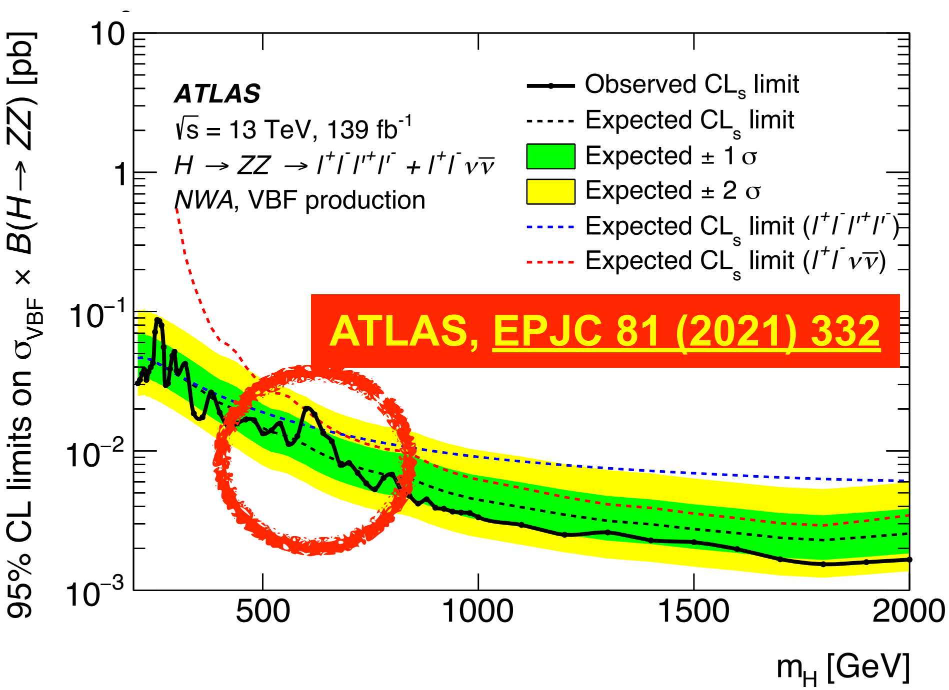
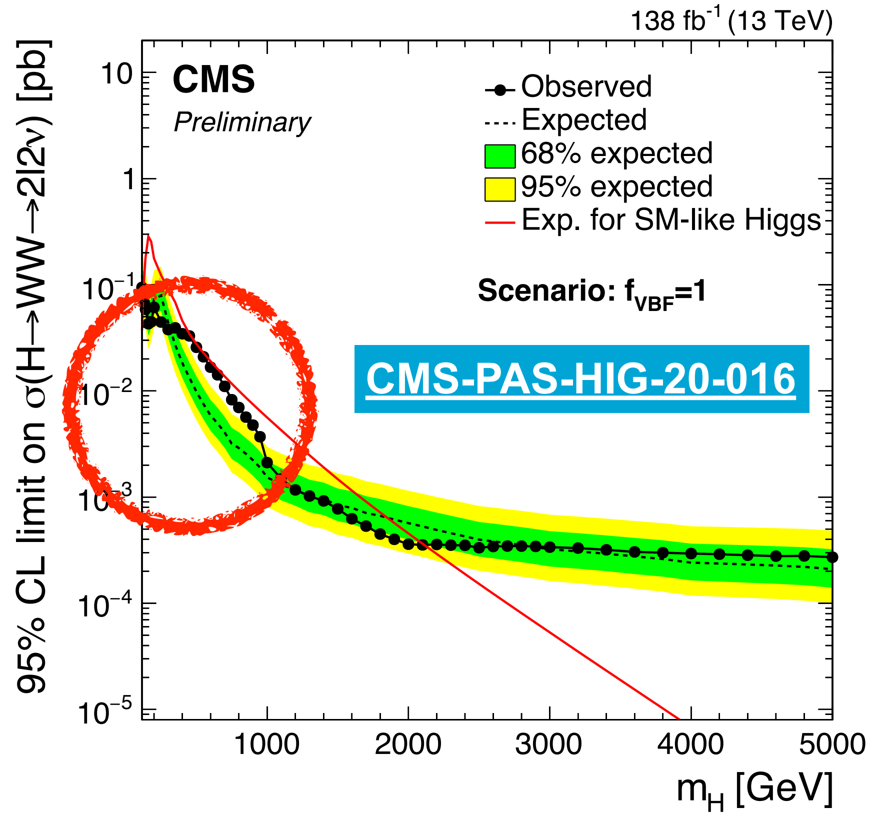
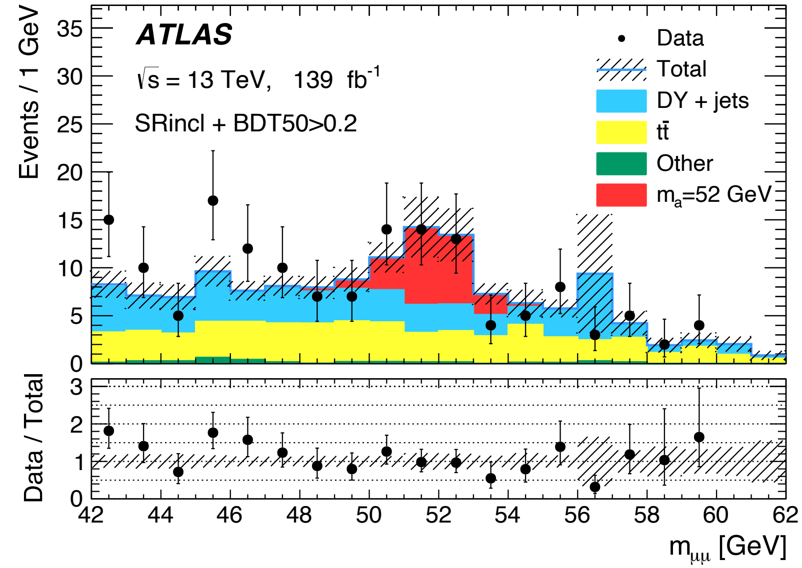
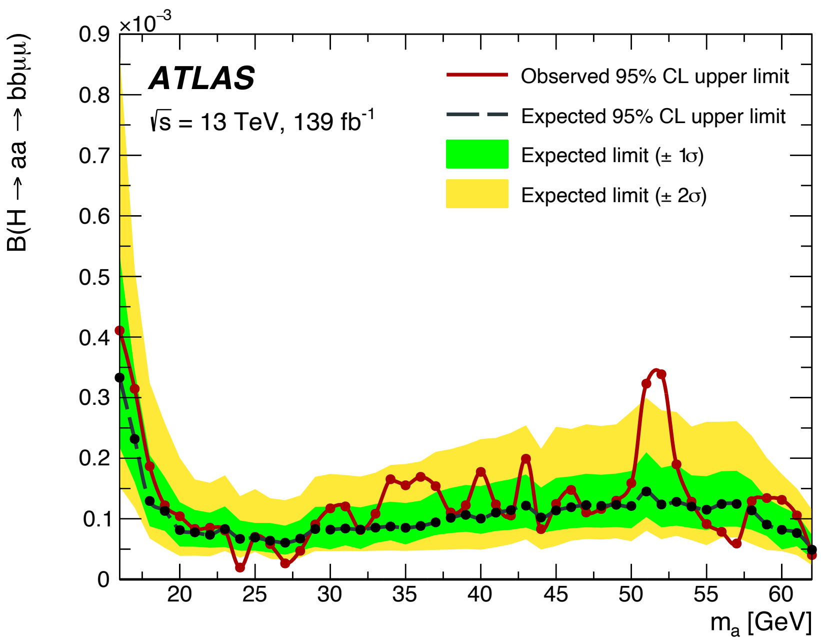




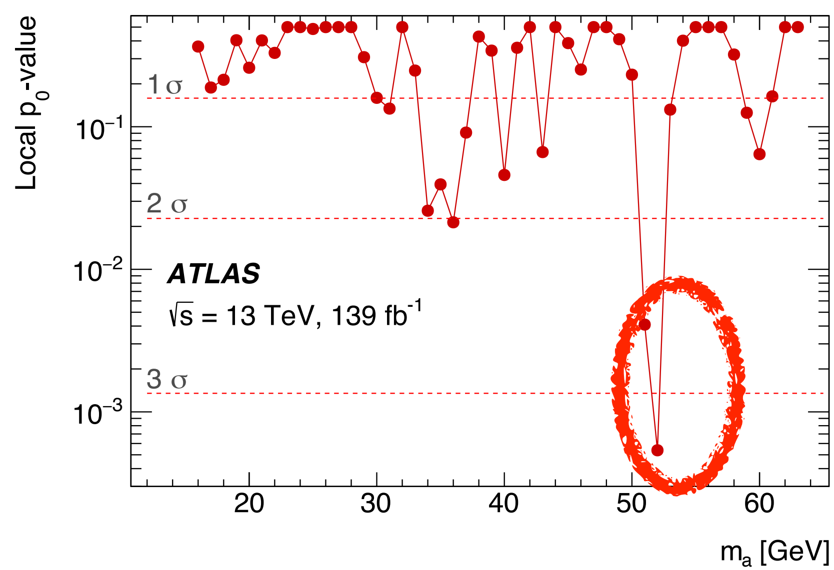
ATLAS H → a(bb)a(μμ) Excess

- 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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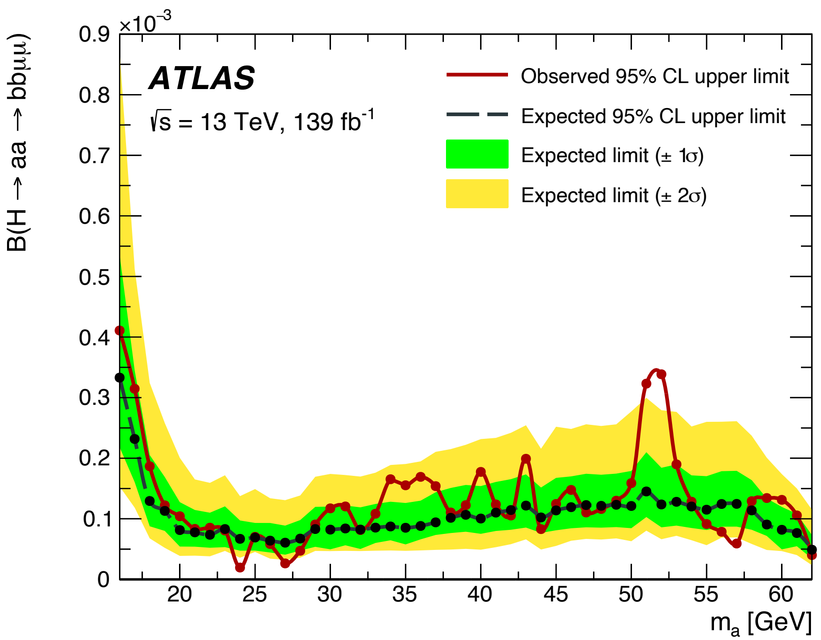
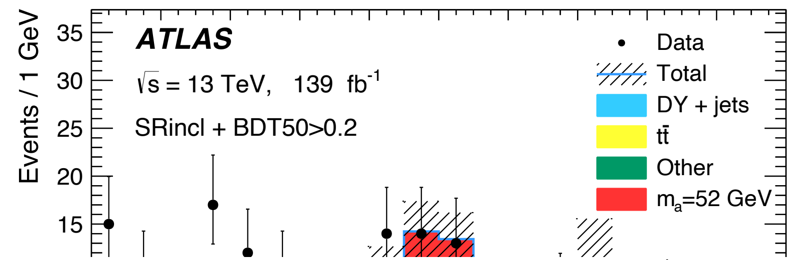
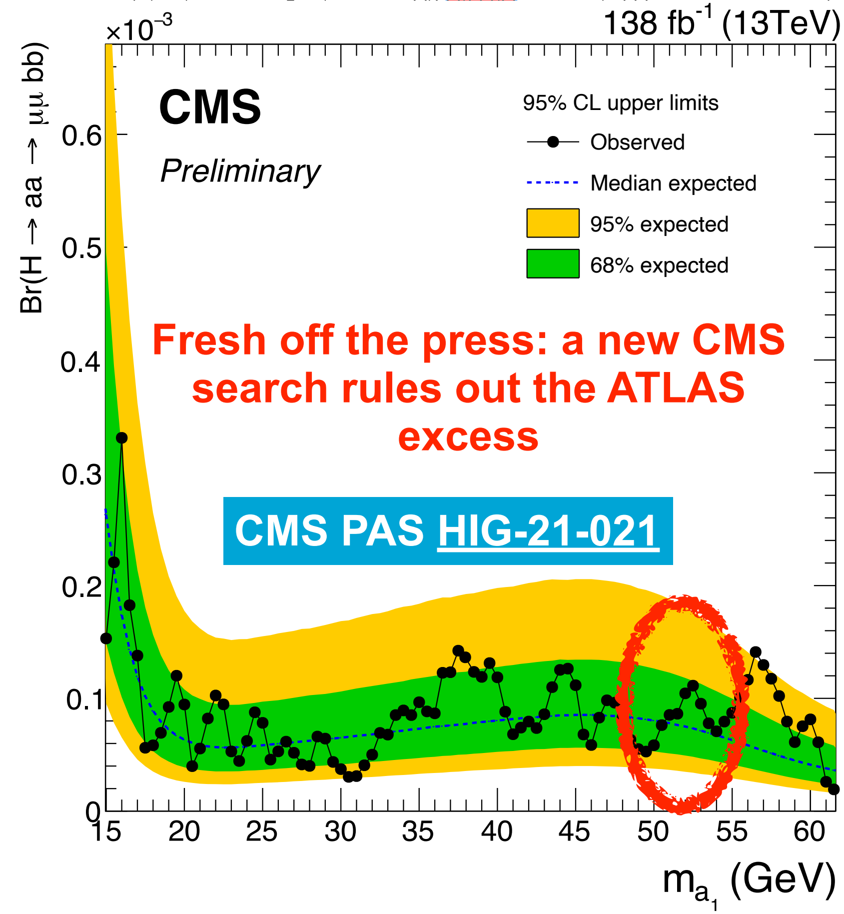


ATLAS, PRD 105 (2022) 012006



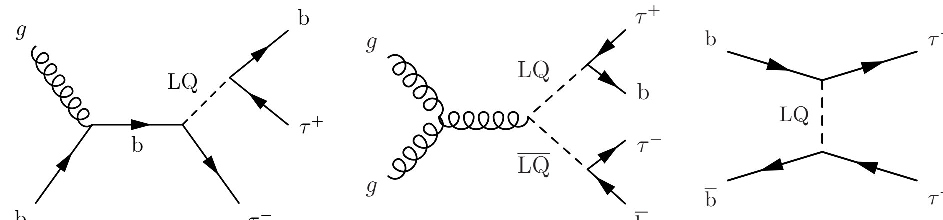


Fresh off the press: a new CMS search rules out the ATLAS excess

CMS PAS HIG-21-021

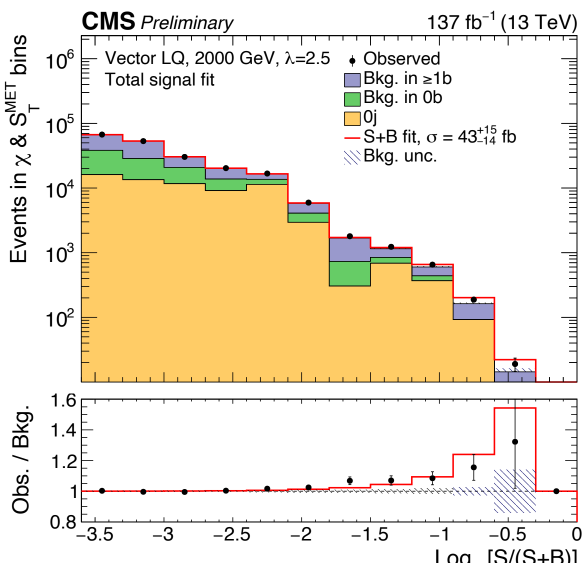
CMS Excess in LQ3 Search

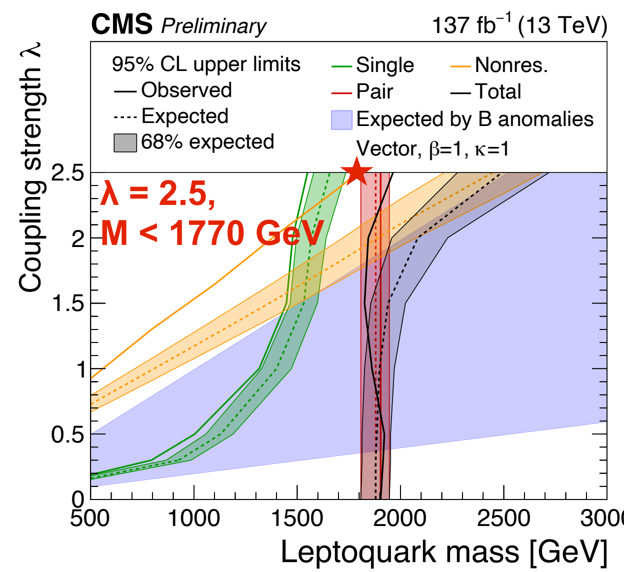
- Another preliminary result from CMS, inspired by the flavor anomalies
- Looks for single, pair, and t-channel production of LQ3 in the ττ+X final states



  - ★ 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

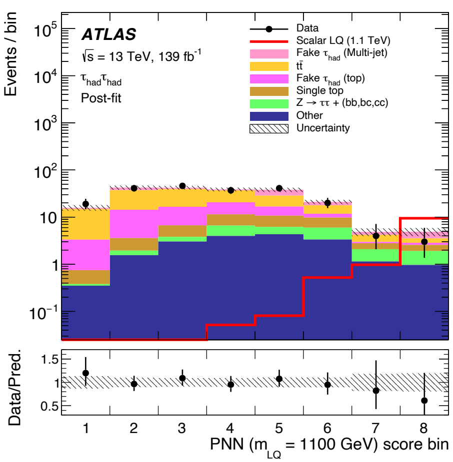


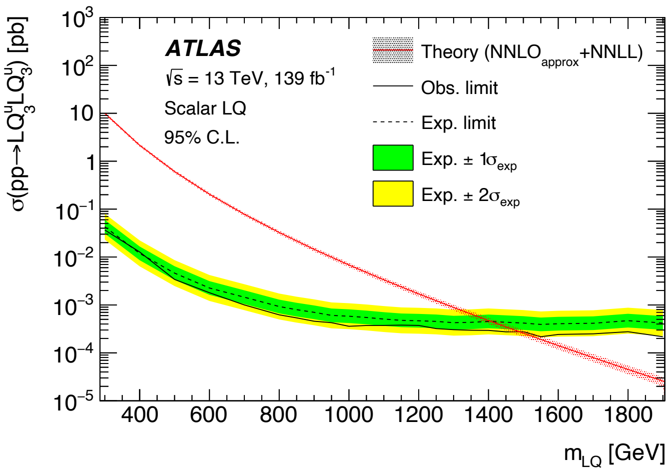


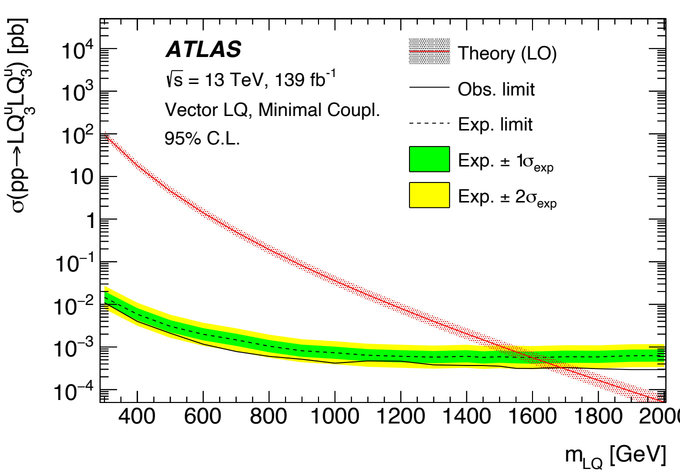
What About ATLAS?

- A related search, just made public, actually sees a deficit at high masses
  - ★ Unlike CMS, ATLAS search is focused on pair production
- Uses NN parameterized w.r.t. m(LQ)
- Not exactly comparable with the CMS analysis (as no t-channel LQ3 exchange considered), but likely indicative that the CMS excess is due to a statistical fluctuation

ATLAS, arXiv:2303.01294



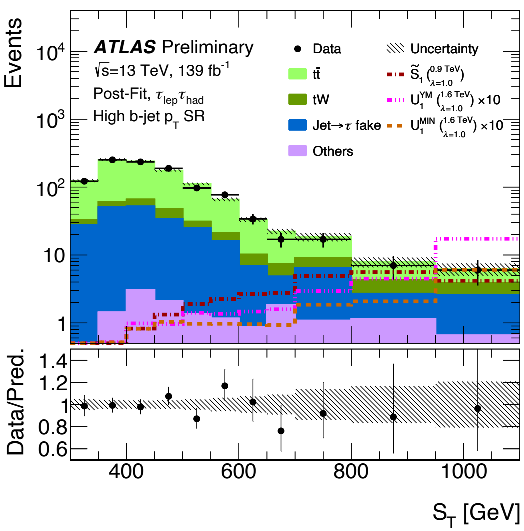


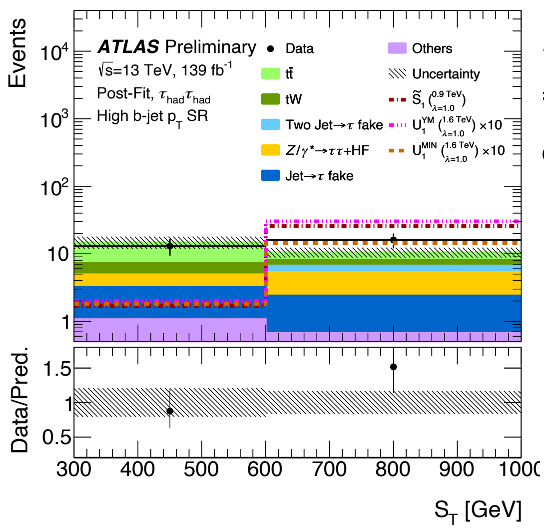


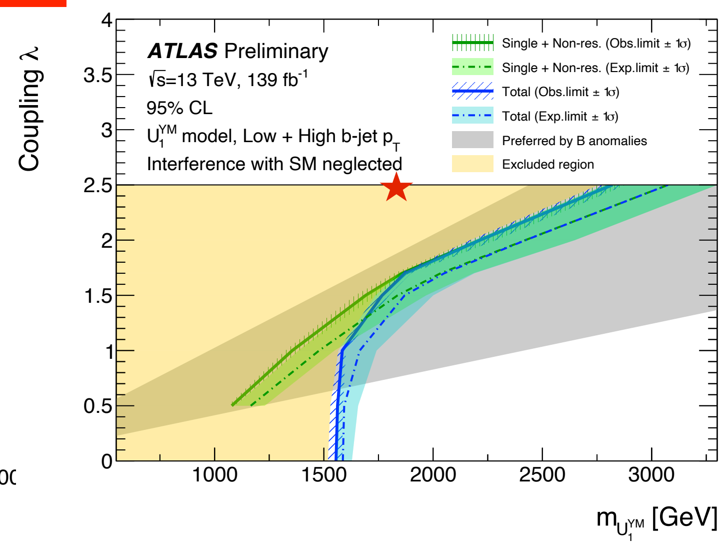
More From ATLAS

- **Fresh off the press: a new search from ATLAS considers single LQ3 production, as well as t-channel diagram with the LQ3 mediator - directly comparable with the CMS search**
- **Requires a τ lepton pair and a high-p_T (> 200 GeV) b jet**
- **No significant excess seen in the S_T distribution in both the $\tau_l\tau_h$ and $\tau_h\tau_h$ channels, with the sensitivity high enough to start ruling out the CMS excess (N.B. ATLAS assumes Br(LQ3 → bτ) = 0.5, while CMS assumes 1)**
- **Additional limits are also set in the low-p_T b jet signal region**

ATLAS, EXOT-2022-39-02

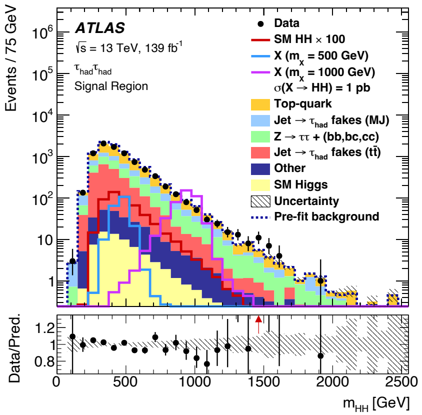


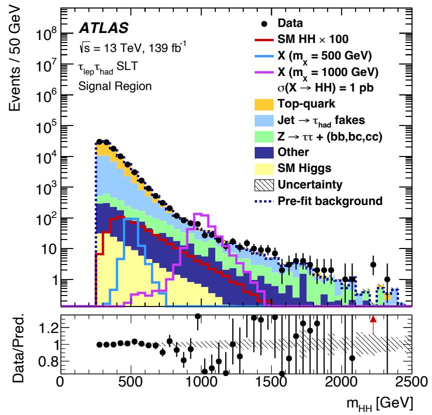


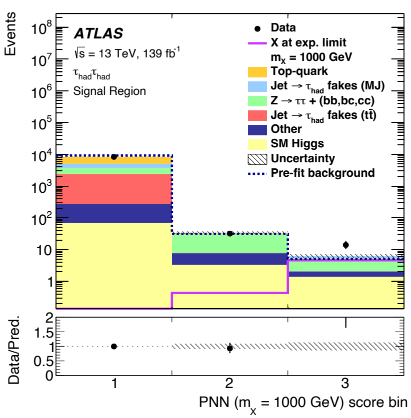


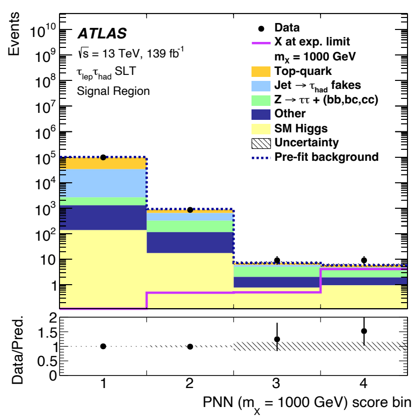
ATLAS H(ττ)H(bb) Search

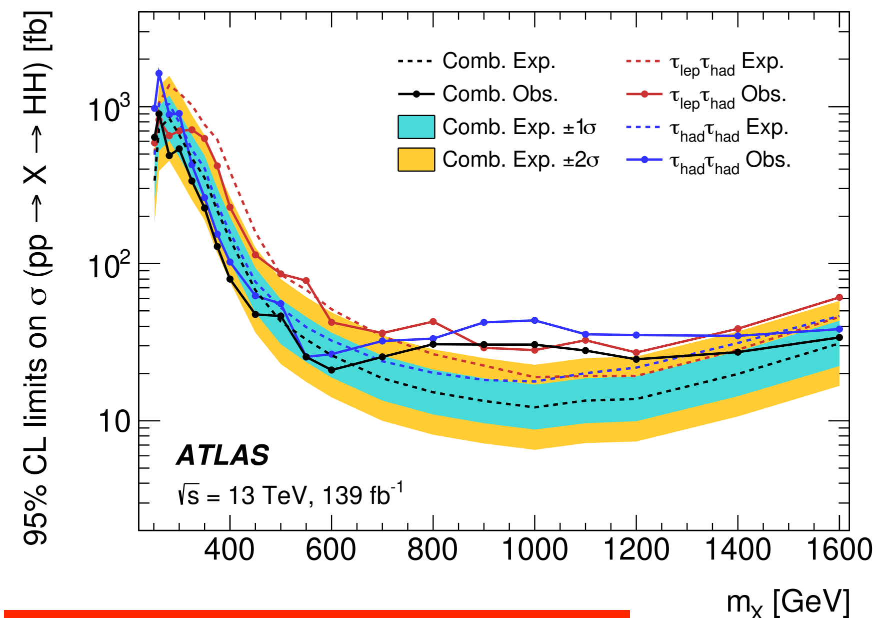
- **ATLAS reported a 3.1 (2.0)σ excess at about 1 TeV in an X → H(ττ)H(bb) resonant search**
  - ★ **An excess can be clearly seen only in the NN discriminant distribution; the mass spectrum before the NN application doesn't show a sizable excess**
  - ★ **Consistent excess in semileptonic and hadronic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







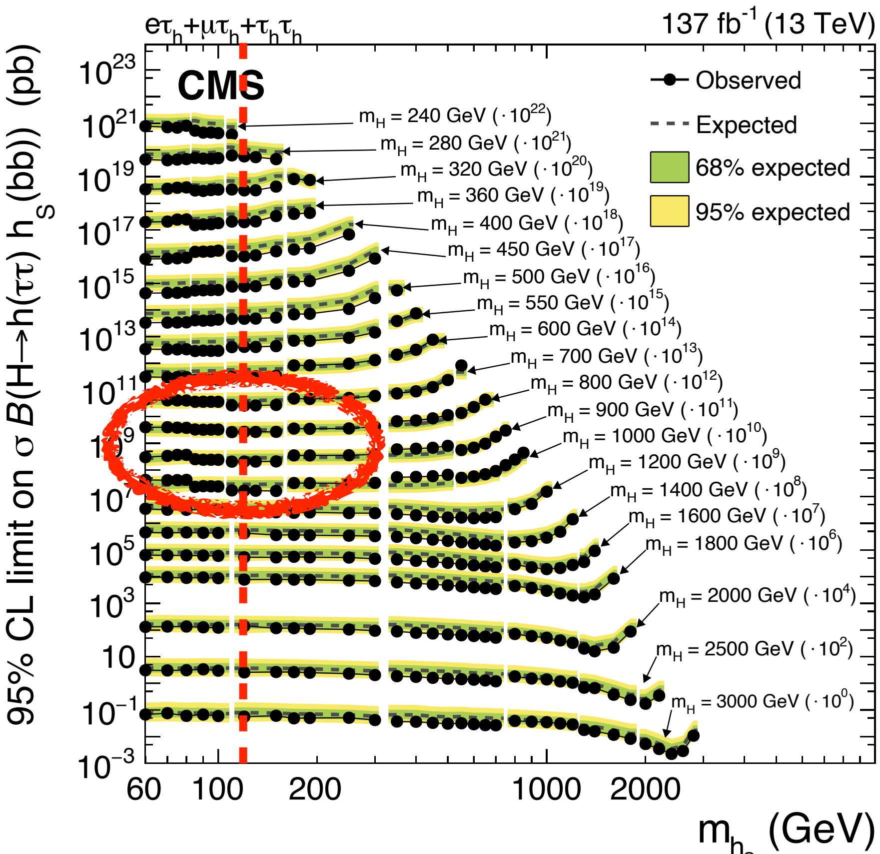




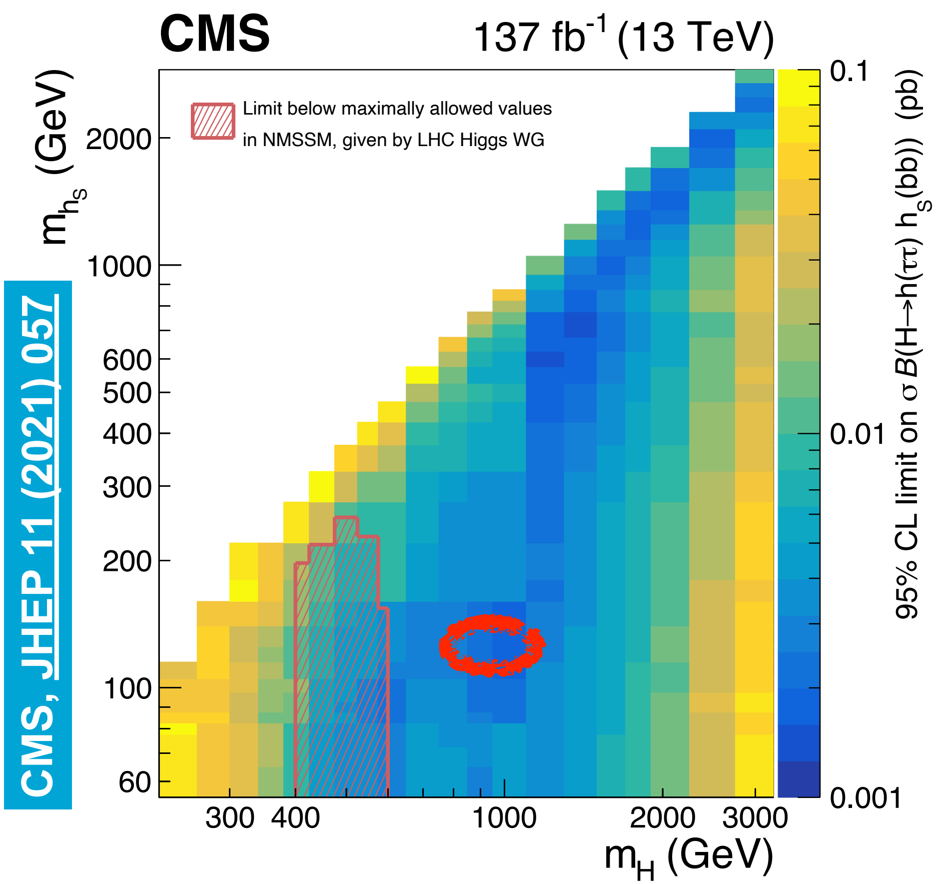
ATLAS, arXiv:2209.10910

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

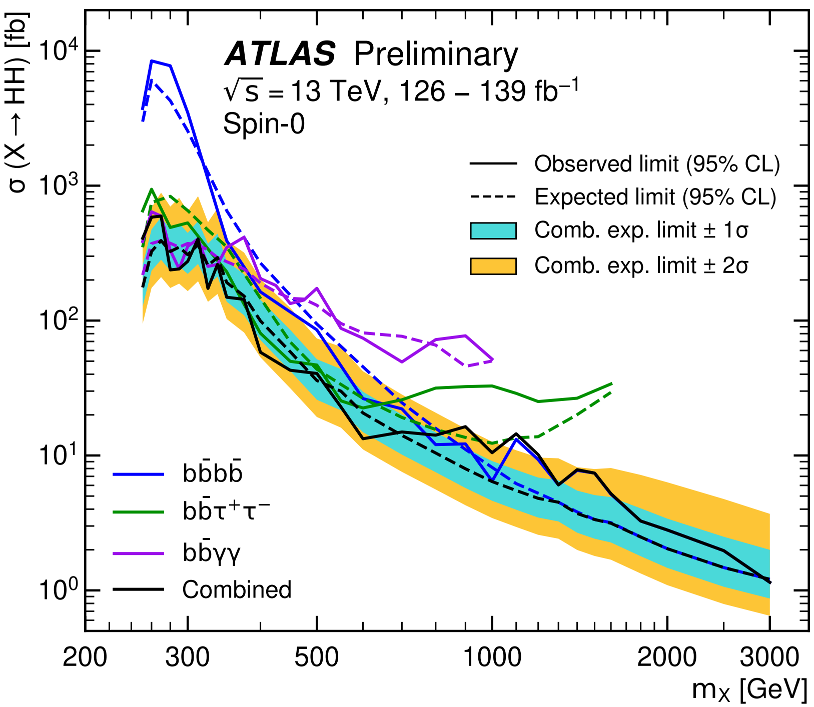


CMS, JHEP 11 (2021) 057

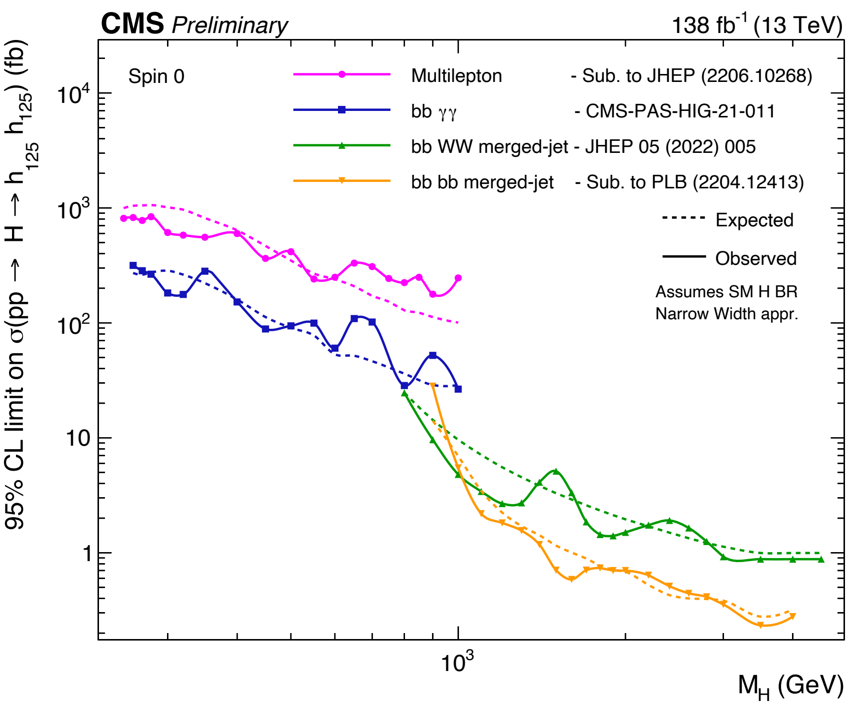


Other X → HH Searches

- 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



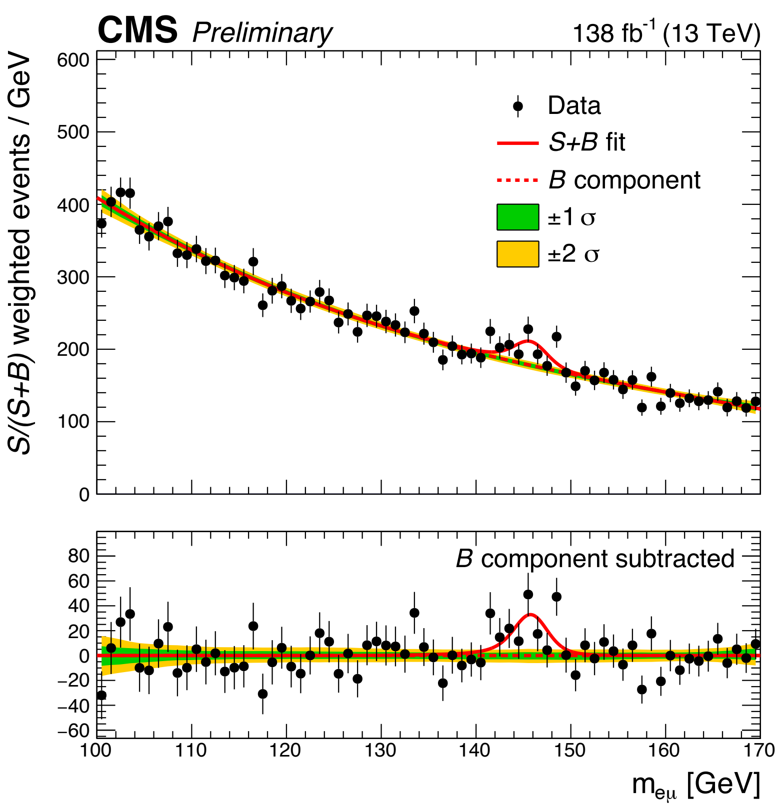
ATLAS-CONF-2021-052



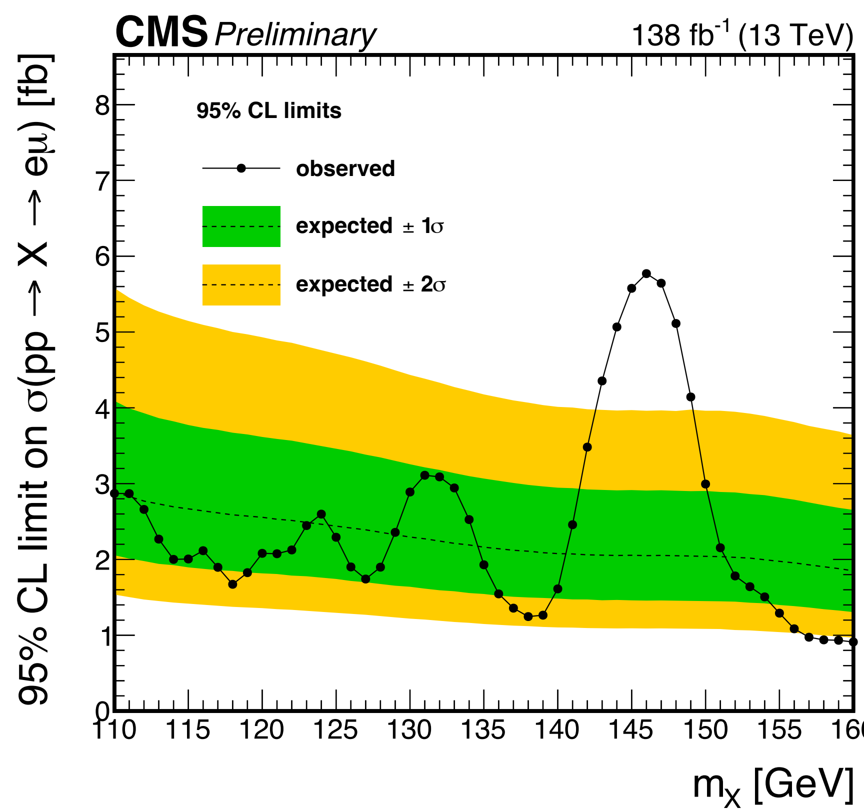
CMS, Summary HH Plot

CMS H(eμ) Excess

- New CMS search for LFV Higgs boson decay H(eμ)
- Apart from setting a stringent limit on the H(125) LFV decay, it also scans the eμ mass
- An excess with a local (global) significance of 3.8 (2.8)σ is seen at a mass of 146 GeV
- Probably already ruled out by an earlier ATLAS analysis, judging by the mass plot
  - ★ Would be nice if ATLAS could produce a limit at 146 GeV based on that analysis



CMS PAS HIG-22-002



Greg Landsberg - Searches for New Physics at the LHC - 29.03.2023

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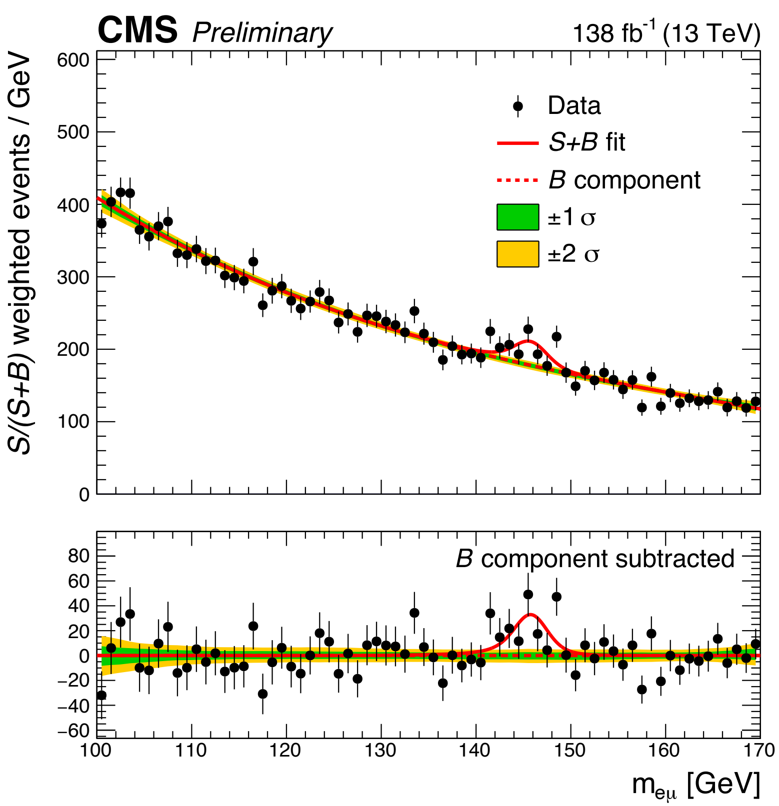
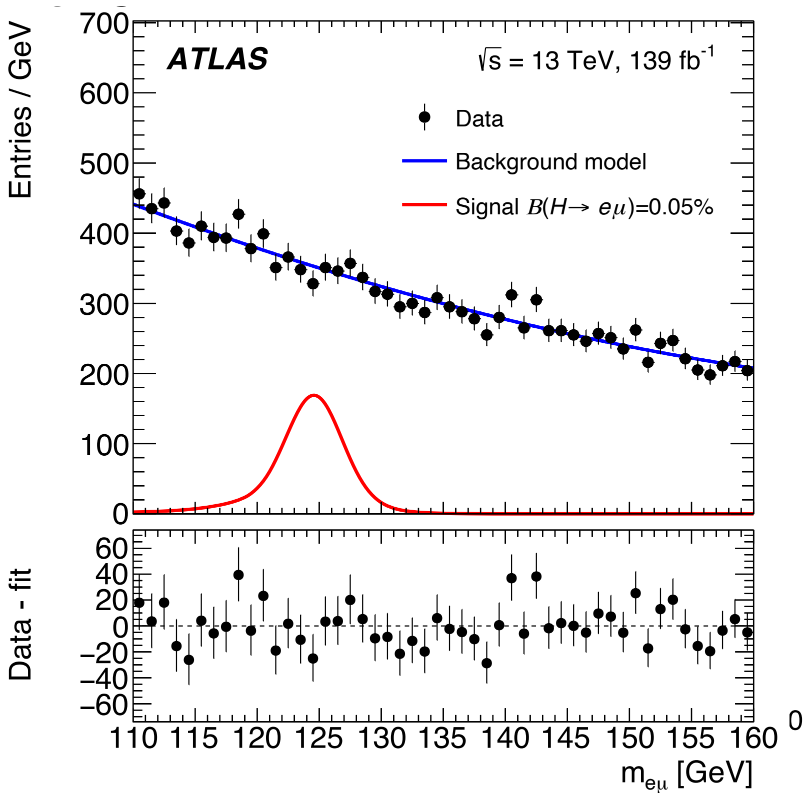


CMS PAS HIG-22-002

ATLAS, PLB 801 (2020) 135148



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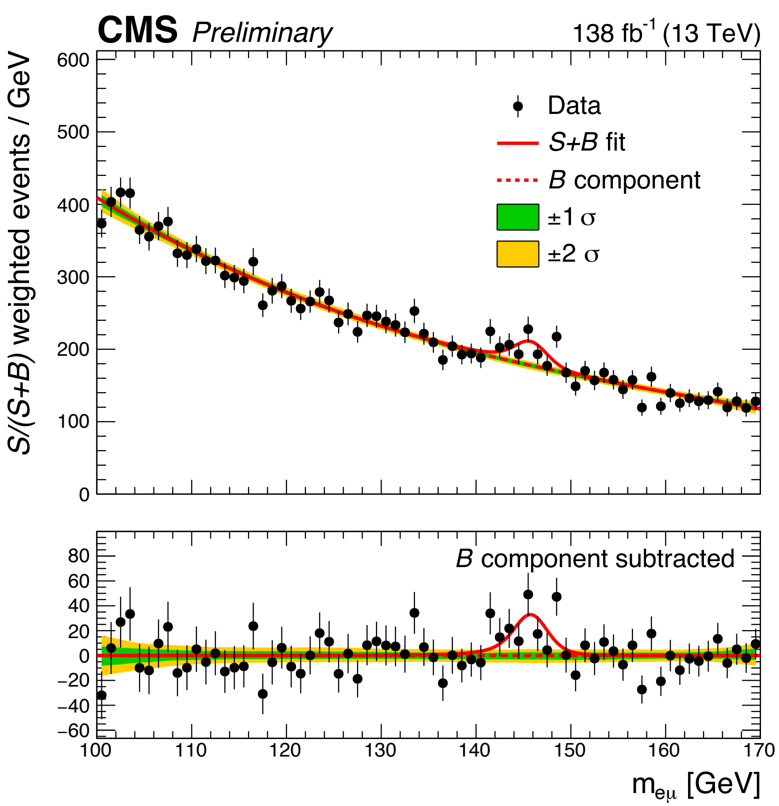

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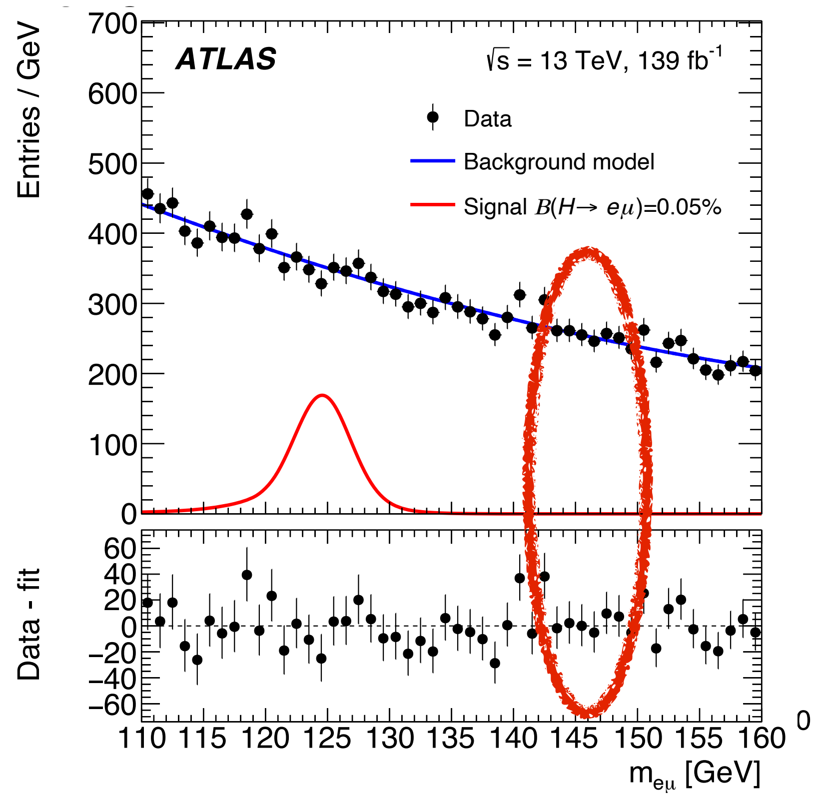
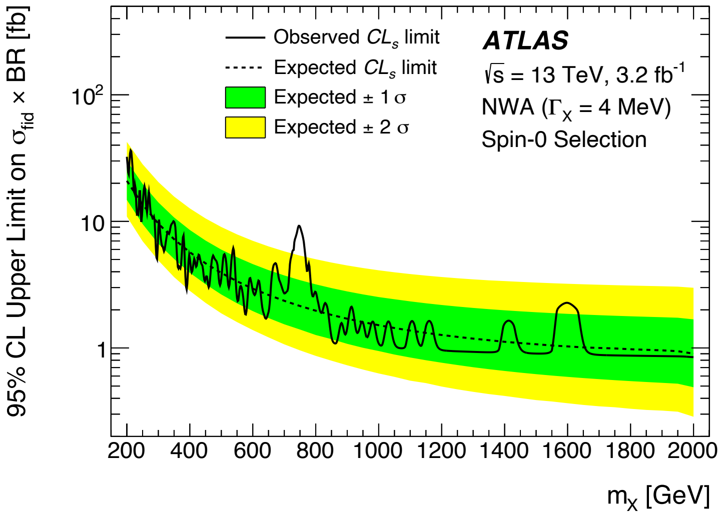
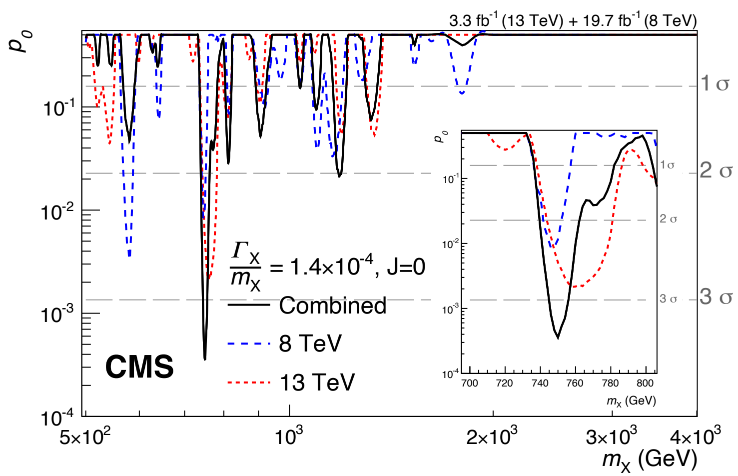


Excited? - Memento 750!

ATLAS, JHEP 09 (2016) 001



CMS, PRL 117 (2016) 051802



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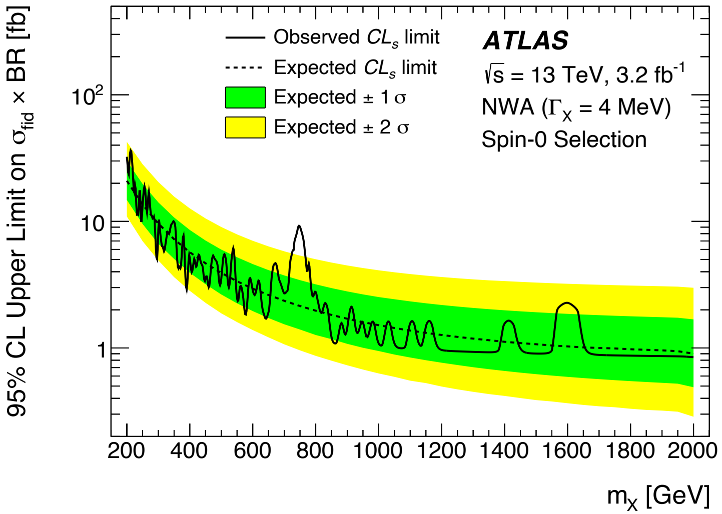
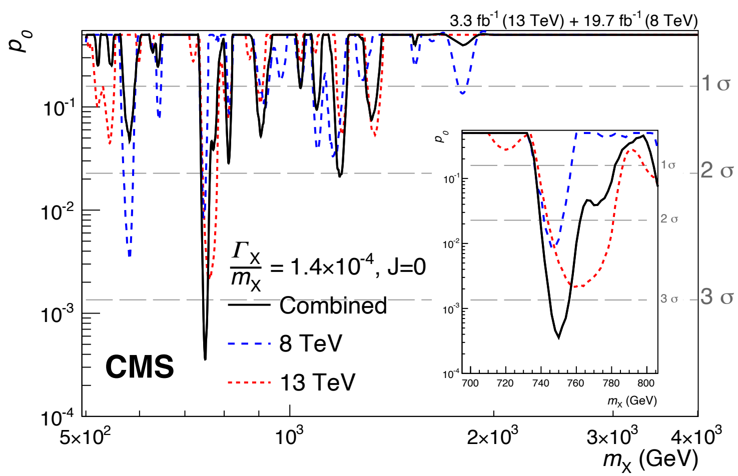
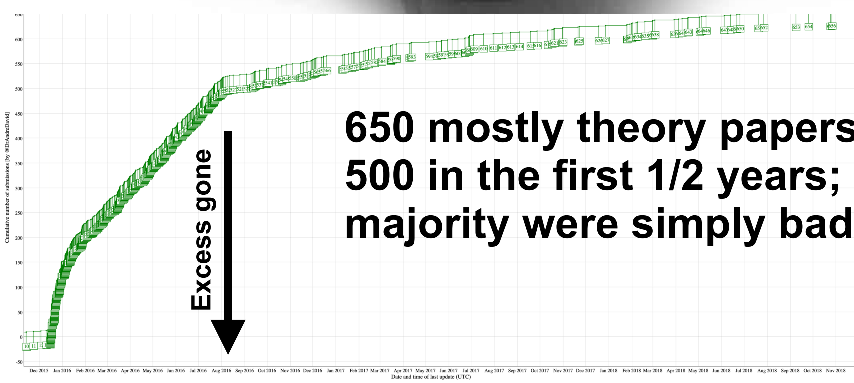
ATLAS, JHEP 09 (2016) 001



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!