Resonance searches with ATLAS & CMS

Louis Portalès, on behalf of ATLAS & CMS

LHCP 2024, Boston – 04/06/2024

Introduction

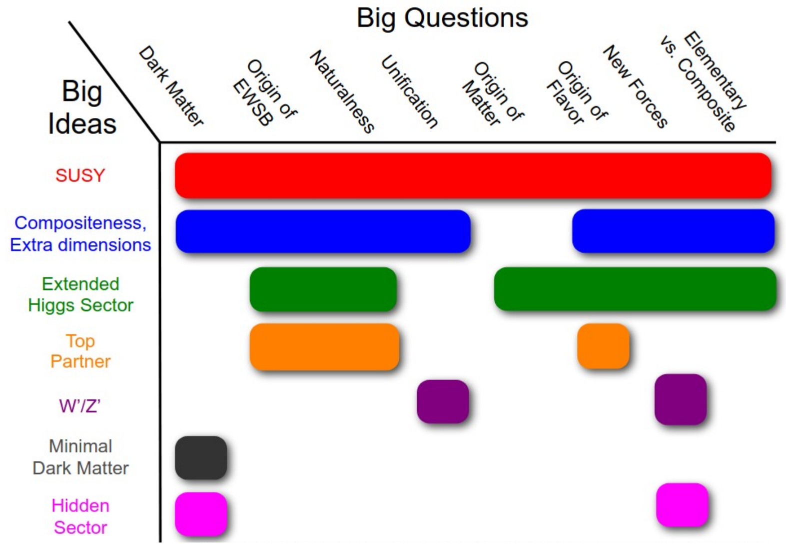
We are all aware of how successful the SM is

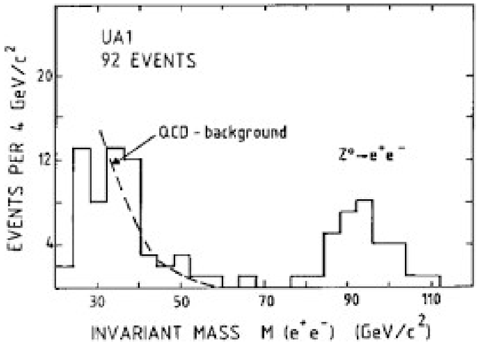
→ *But we also know there has to be something more*
- The SM alone can't explain many things
  - ***Matter/antimatter asymmetry***
  - ***Dark matter***
  - ***Hierarchy problem***
  - ***…***

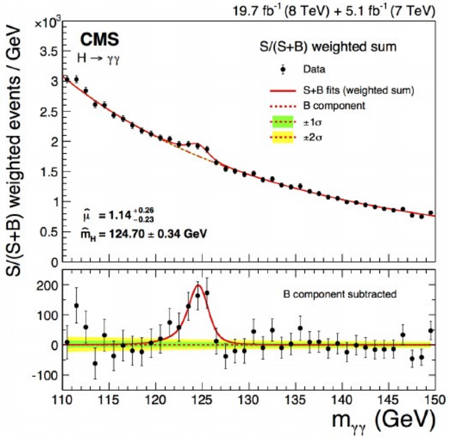
→ *MANY clever ideas from theorists to tackle these issues*
- In most cases, these imply the existence of new fields/particles
  - ***And these could decay into some of our SM particles***

→ *We can test these ideas by looking for new resonances*
- The same way we did to observe the SM particles
  - ***Constructing mass spectra, and looking for bumps***
  - ***Although it is becoming common (for good reasons) to replace the mass with DNNs***
- Except that now we do not know exactly where to look
  - ***So we need to look everywhere!***

New particles WG 2013 Snowmass report







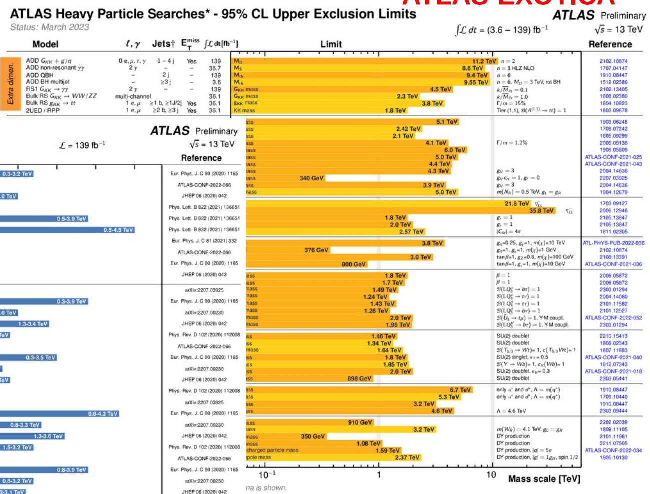
Introduction

“Resonance searches” covers a lot

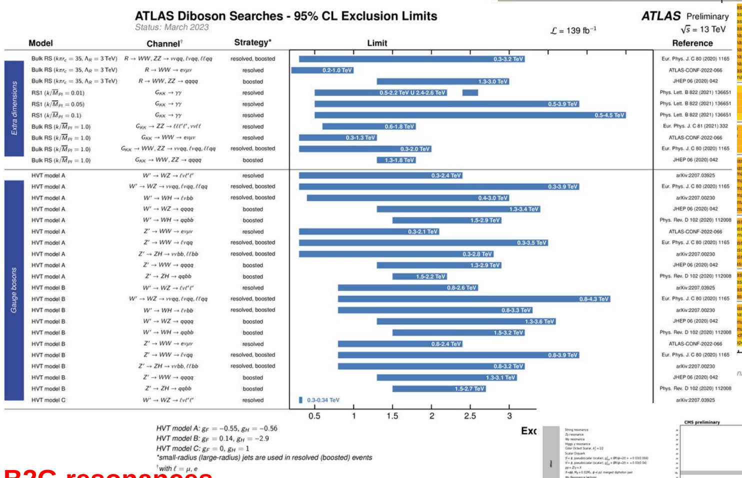
→ *Too much for a single talk*

- Here the focus will (mostly) be on:
  - ***High mass (TeV scale) resonances***
  - ***Extended Higgs sectors***
  - ***Heavy bosons (Higgs,Z’/W’), VLQ, …***
  - ***And even then, hard to be exhaustive***
- More on other specific resonances in plenaries
  - ***LLPs – Guglielmo Frattari*** *(yesterday)*
  - ***BSM Higgs - Shigeki Hirose*** *(yesterday)*
  - ***Feebly interacting particles – Joscha Knolle*** *(tomorrow)*
- And even more in the various “BSM” parallels

ATLAS-EXOTICA

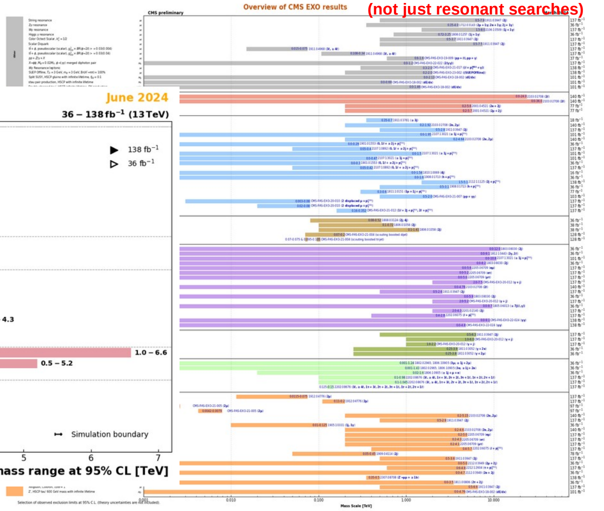


ATLAS-HDBS

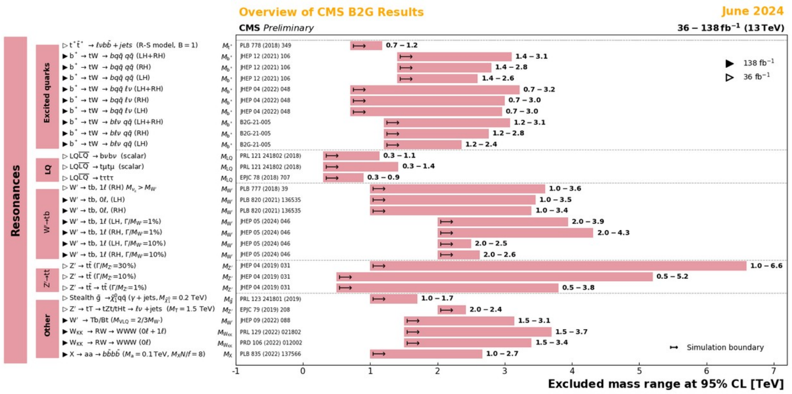


CMS-EXO

(not just resonant searches)



CMS-B2G resonances



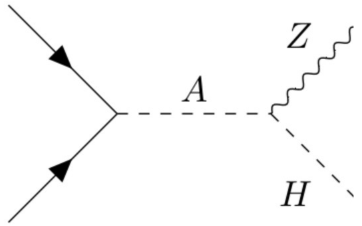
+ more …

Extended Higgs sectors (1)

More Higgs bosons…

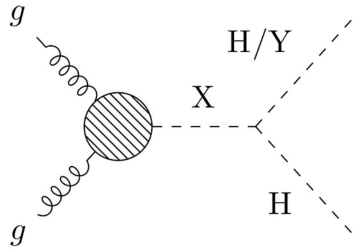
→ *Many models predicting additional Higgs bosons, e.g.*

- 2HDM (e.g MSSM) predict 5 “Higgses”: h (SM), H, A, H+, H-
  - ***2HDM+S (NMSSM) predict 7!***



→ *Many searches looking for these (pseudo)scalars*

- Typically, a new heavy resonance decaying to
  - ***Two h(SM) (X->hh)***
  - ***h(SM) + a vector boson (X->Vh)***
  - ***h(SM) + an additional scalar (X→Yh)***
  - ***Or two SM particles***
- A constant flow of new results from ATLAS & CMS
  - ***Typically extracting model independent limits + 2HDM/NMSSM/WED/… interpretations***



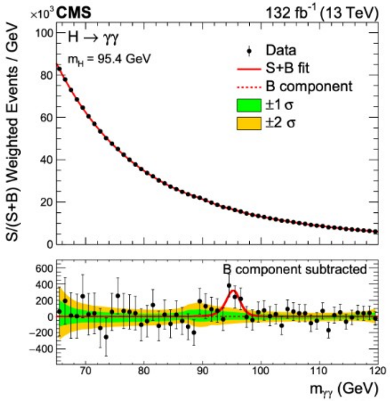
Note:
In large part already covered yesterday by Shigeki Hirose

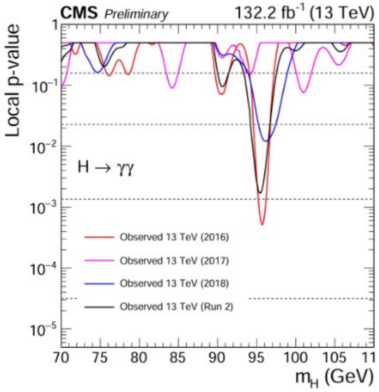
Extended Higgs sectors (2)

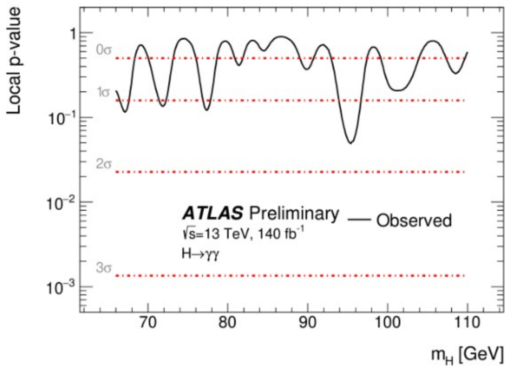
Higgs bosons to SM particles

→ *Low mass h→γγ*

- Low mass Higgs boson from 2HDM
  - ***Here looked for for 70 < mH < 110 GeV***
- Mild excess at 95 GeV
  - ***For both collaborations***
  - ***CMS: 2.9 σ (1.3 σ) local (global)*** 2405.18149
  - ***ATLAS: 1.7 σ local*** ATLAS-CONF-2023-035

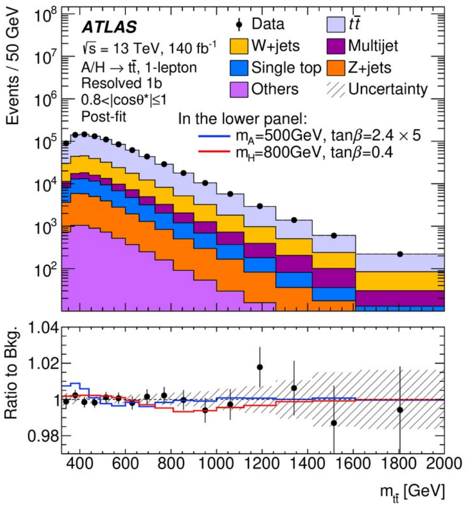


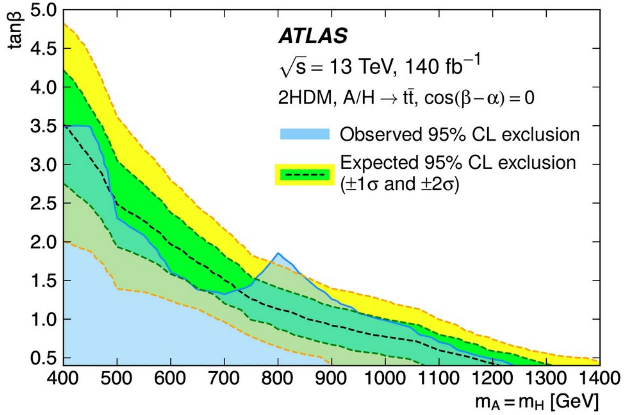




→ *ATLAS: H/A→tt* 2404.18986

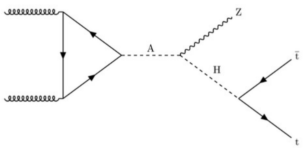
- Looking for (semi)leptonic top decays
  - ***And both resolved and merged hadronic top decays in the semi-lep category***
  - ***Taking advantage of interference with SM***
- Extracting limits for 2HDM+hMSSM signals
  - ***As a function of Mass vs tan β***
  - ***Largest deviation at 800 GeV (2.3 σ local)***

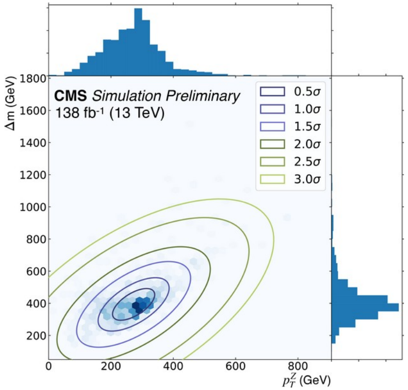


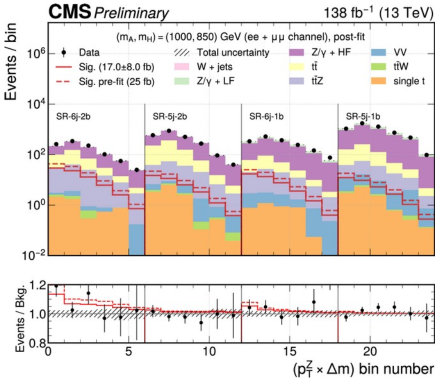


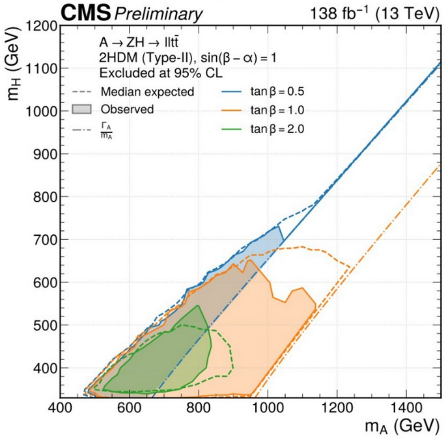
Extended Higgs sectors (3)

New A→ZH results









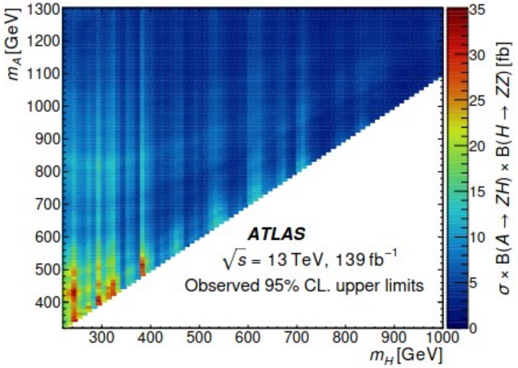
→ *CMS: A→Z(ll)H(tt)* CMS-PAS-B2G-23-006

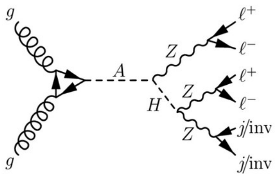
- Probing 2HDM type II
  - ***Splitting events in bins of (b-)jet multiplicity***
  - ***Fitting unrolled pTZ x Δm distribution***
  - ***No deviations from SM observed***

→ *ATLAS: A→Z(ll)H(ZZ)→4l + jj/νν* 2401.04742

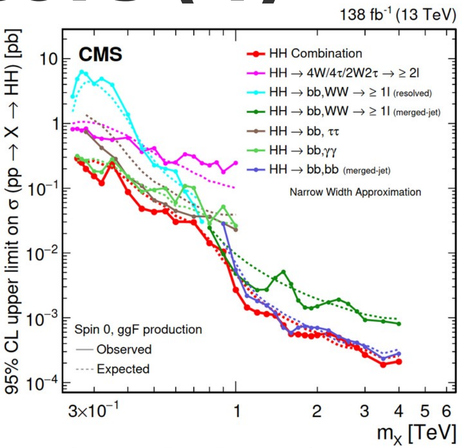
- Probing 2HDM / 2HDM+S
  - ***Fitting m4l in several categories***
  - ***Extracting upper limits on cross-section for both types of signals***
  - ***Testing width impact on 2HDM limits***

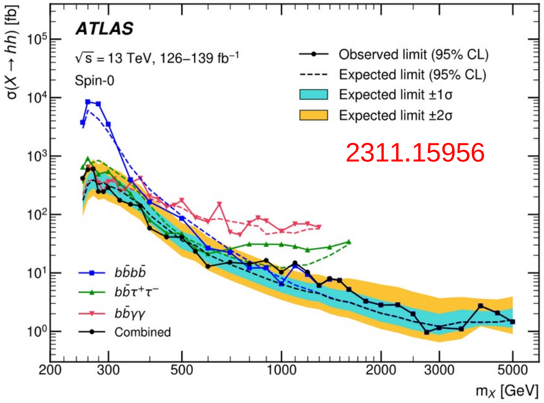
Width assumptions	Mass points [GeV]	Upper limits in the $\sigma(gg \to A)$ [fb]		Ratio w.r.t Narrow width
		Observed	Expected	
Narrow width	$(m_A, m_H) = (320, 220)$	19.6	25.1	1.0
	$(m_A, m_H) = (1190, 600)$	4.8	3.5	1.0
$(\Gamma_A/m_A, \Gamma_H/m_H) = (15\%, 5\%)$	$(m_A, m_H) = (320, 220)$	31.5	36.2	1.4
	$(m_A, m_H) = (1190, 600)$	8.3	6.0	1.7
$(\Gamma_A/m_A, \Gamma_H/m_H) = (30\%, 10\%)$	$(m_A, m_H) = (320, 220)$	38.9	42.5	1.7
	$(m_A, m_H) = (1190, 600)$	8.9	6.6	1.9





Extended Higgs sectors (4)

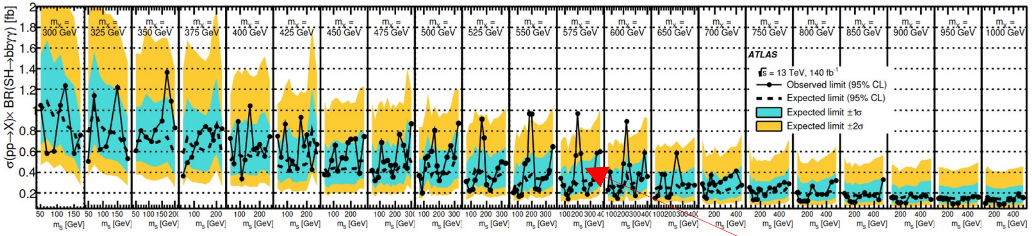


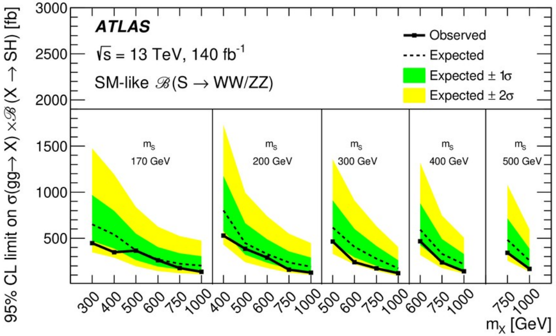


X→HH/YH results & combinations

- → *HH*
  - Model-independent combined limits
    - ***ATLAS: Modest excess 1.1 TeV (3.2σ local, 2.1σ global)***
    - ***Not seen by CMS***

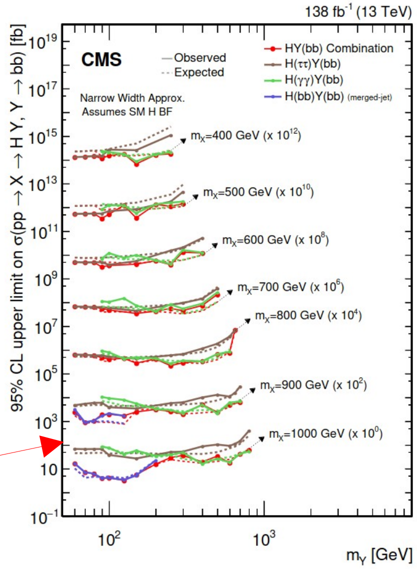
- → *YH (CMS) / SH (ATLAS)*
  - New ATLAS results
    - ***X→S(bb)H(γγ)*** 2404.12915
    - ***X→S(lep)H(γγ)*** 2405.20926
      Including BR(S→WW/ZZ)-dependent limits
  - CMS combination
    - ***Part of broad range review paper 2403.16926***

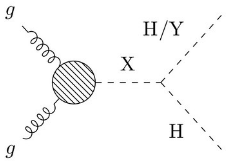




Largest excess:
(mX, mS) = (575, 200) GeV
3.5 (2.0) σ local (global)

Complementary reach from different final states



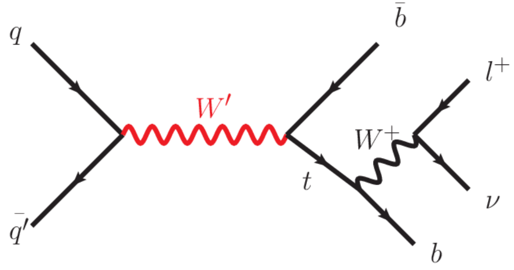


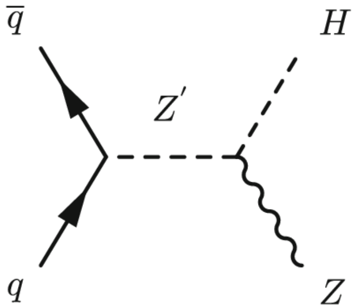
Additional vector bosons (1)

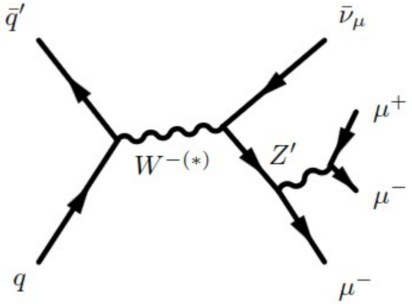
...More vector bosons...

→ *W'/Z' can appear in many different contexts*

- GUT-inspired models, extra dimensions, ...
  - ***On the analysis side, simplified benchmark models are often used***
  - ***e.g. Heavy vector triplets models***



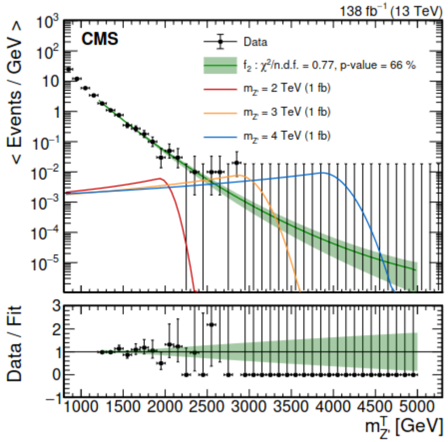


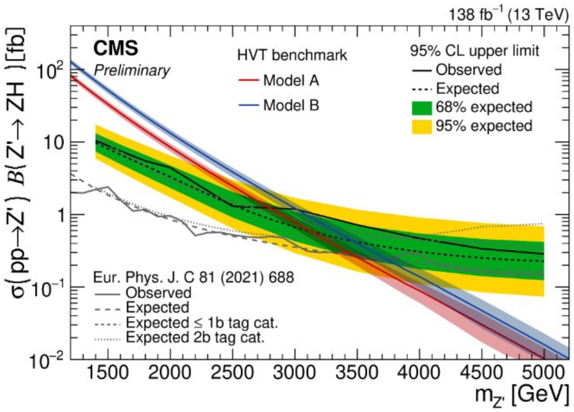


Additional vector bosons (2)

→ *CMS: Z′→Z(ll/νν)H(cc/4q)* CMS-PAS-B2G-23-008

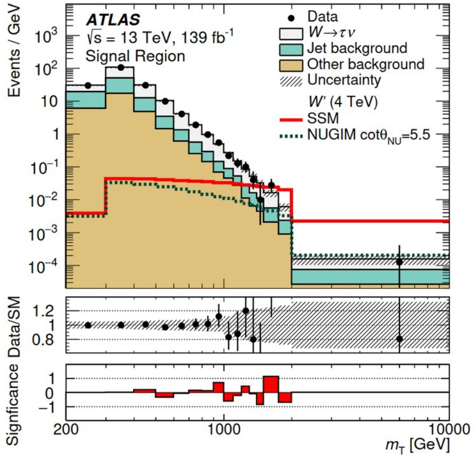
- Complementary to previous Z′→ZH(bb) search 2102.08198
  - ***Orthogonal thanks to requiring a large R jet with no b-tagged subjets***
  - ***SR for H→cc/4q signals using ParticleNet tagger (X→bb/cc/qq vs QCD)***
  - ***Fitting m(T)Z′, using analytical fit to data for background (validated in VR with low tagger score)***
- Competitive limits, especially at high mZ′
  - ***But no significant excess***

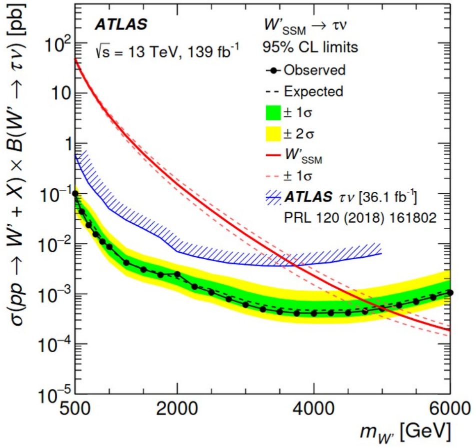




→ *ATLAS: W′→τ+MET* 2402.16576

- Looking in a broad phase space
  - ***1 hadronic τ and large MET balancing its pT: (Δφ(τ,MET)>2.4 and 0.7 < pTτ/MET < 1.3)***
  - ***Main background (W→τν) from MC, fake τ background from data***
  - ***Limits extracted from fit to mTW′***
- Impressive improvement w.r.t. analysis of 2016 data
  - ***Well beyond statistics increase!***
  - ***Mainly attributed to improved hadronic τ identification***
  - ***Still, no significant excess found***





See Mattia's slides from this morning's BSM parallel session for more details

Additional vector bosons (3)

New results from CMS

→ *DY Z'→ττ* *EXO-21-016*

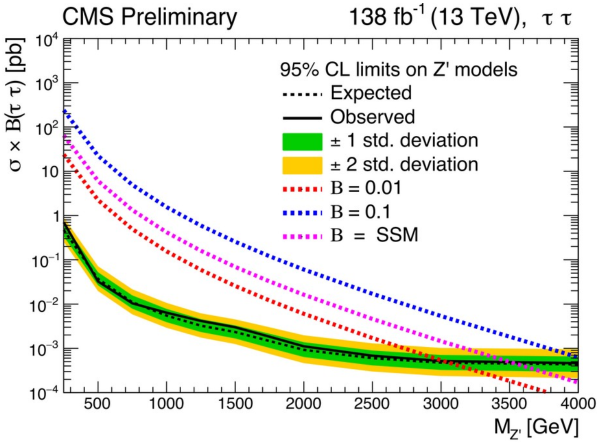
- Probing lepton flavor non-universality
  - *E.g. B-meson anomaly, g_μ – 2*
- Limits set on σBR(Z'→ττ)
  - *Excluding Z'→ττ up to 4.1(3.0) TeV assuming BR(Z'→ττ) = 10%(1%)*

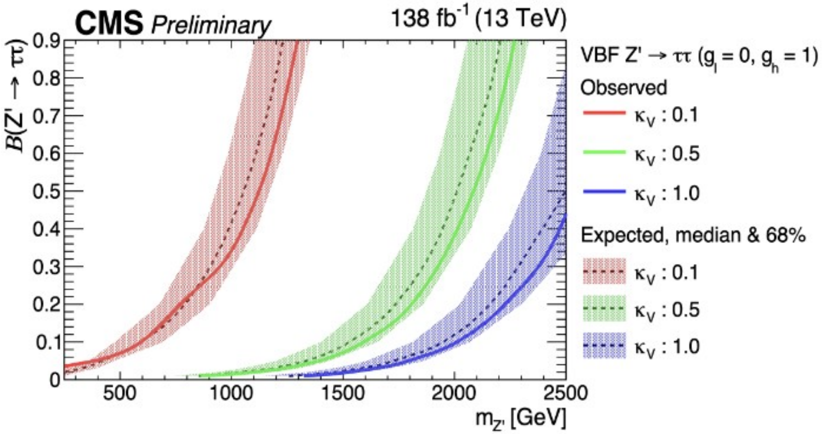
→ *VBF Z'→ττ/WW* *EXO-21-015*

- First LHC search for VBF Z'!
  - *Clear signal topology allowing efficient (QCD) background rejection*
- Limits in mZ' vs BR(Z'→ττ/WW)
  - *Probing different hypotheses of coupling to SM EW bosons*
  - *Excluding Z'→ττ(WW) up to 2.45(1.5) TeV depending on coupling assumptions*

→ *Complementary analyses*

- Sensitive to different Z' mass range
  - *Depending on coupling assumptions*





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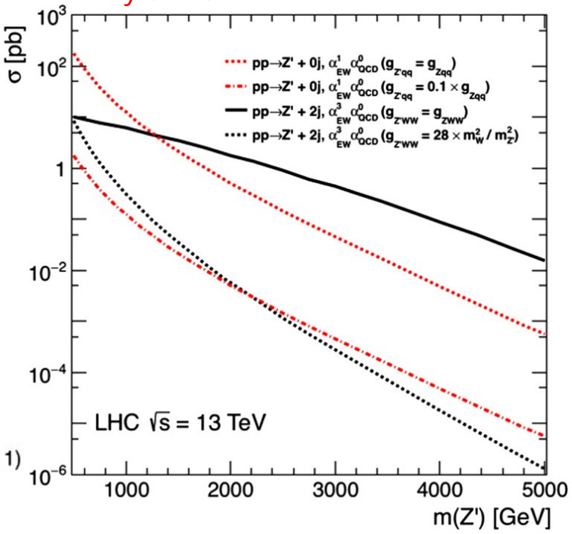
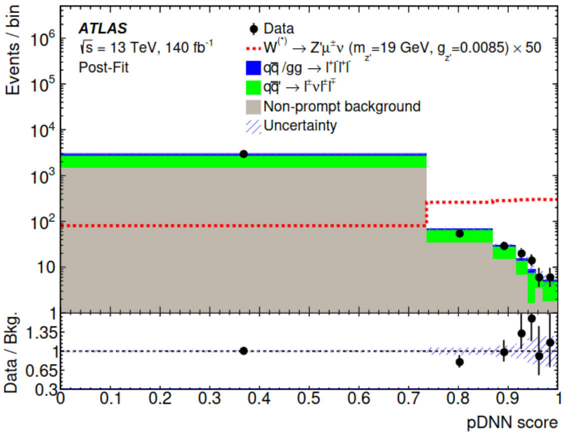


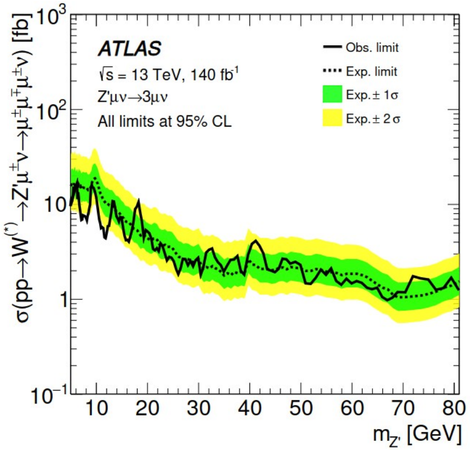
Additional vector bosons (4)

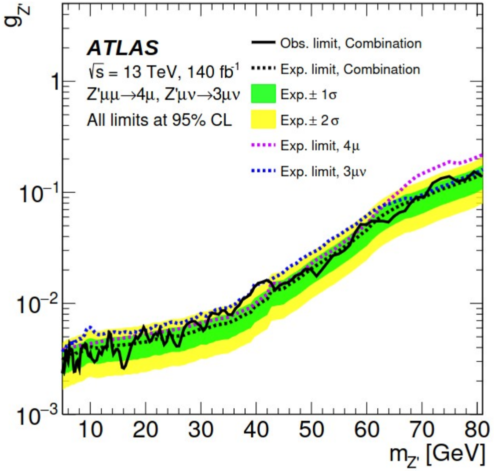
Lower mass W'/Z' are overall more constrained

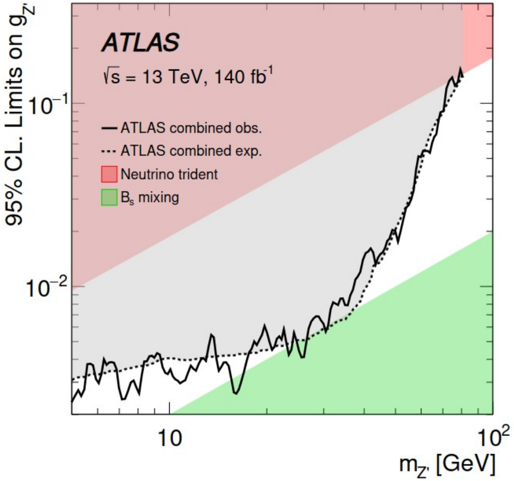
→ *BUT still very relevant!*

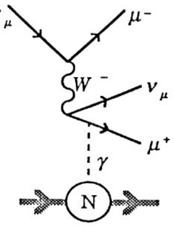
- Recent search for W→Z'(μμ)μν by ATLAS 2402.15212
  - *Probing models with difference in lepton numbers (Lμ – Lτ)*
  - *Z' coupling only to 2nd & 3rd generations*
  - *Could help explaining e.g. muon g-2 anomaly*
- Signal extracted using parametrized DNN
  - *Single network trained for a wide range of signal mass hypotheses*
  - *Limits extracted for Z'μν signal*
  - *AND combined with previous 4-lepton analysis* ***JHEP07 (2023) 090***
  - *Closing the gap between constrains from neutrino trident and Bs mixing measurements*

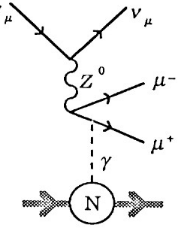










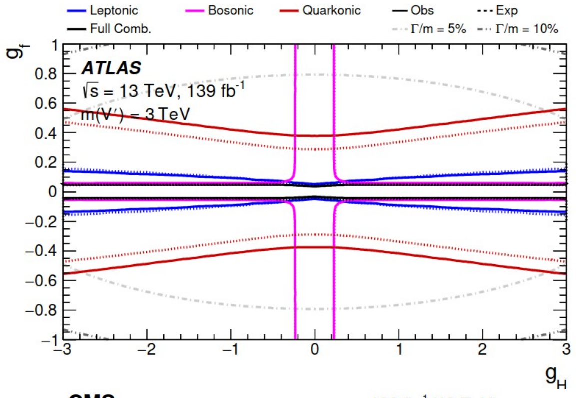


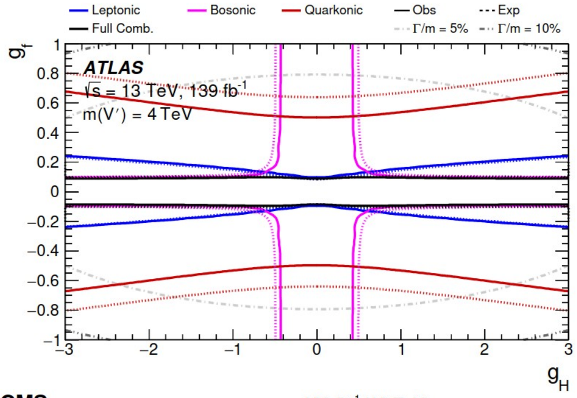
Additional vector bosons (5)

W’/Z’ measurement overviews, HVT interpretations

→ *ATLAS* 2402.10607

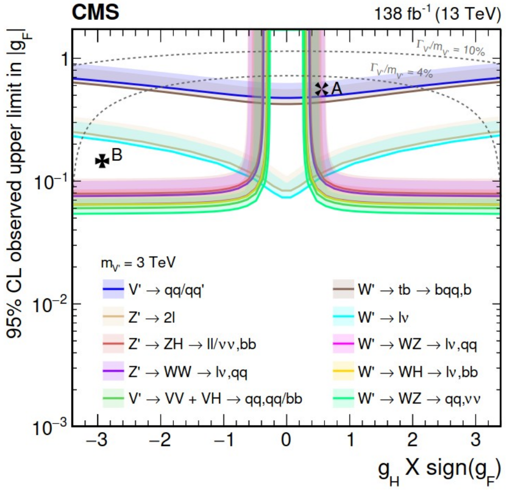
- Heavy spin-1 resonances in VV/qq/ll channels
  - ***Setting limits as a function of V’ mass & couplings***
  - ***Includes a full combination of these results***

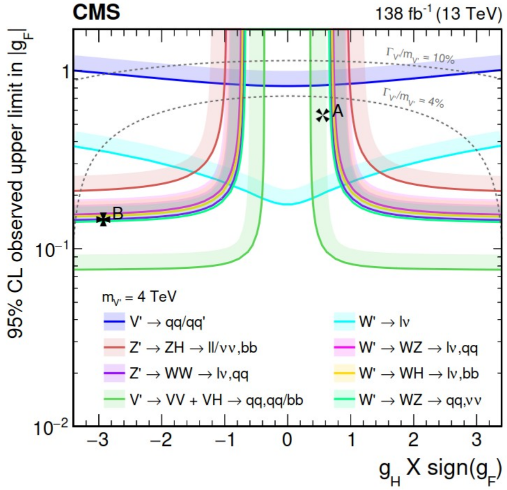




→ *CMS* 2403.16926

- Part of the Higgs boson search review paper
  - ***No combinations, but comparable limits***



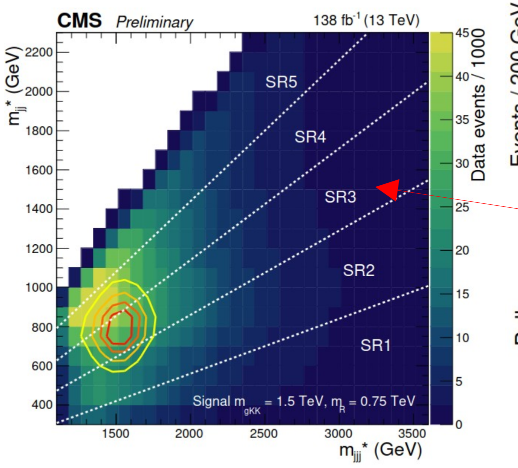


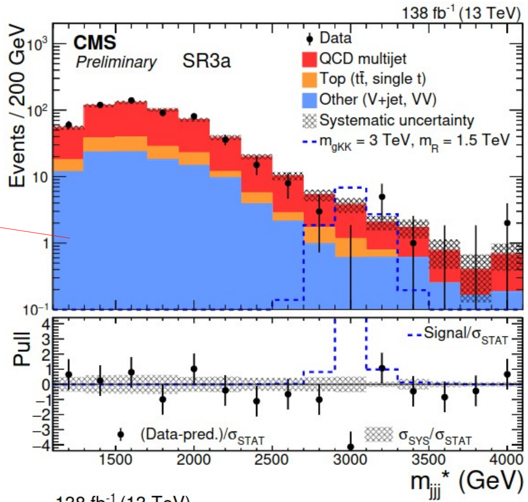
Additional vector bosons (6)

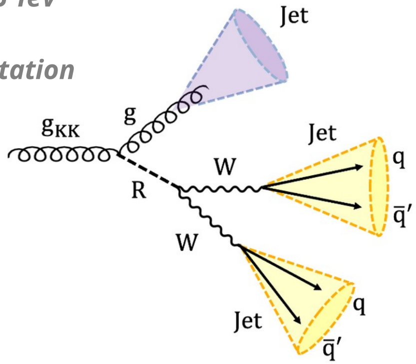
New results from CMS

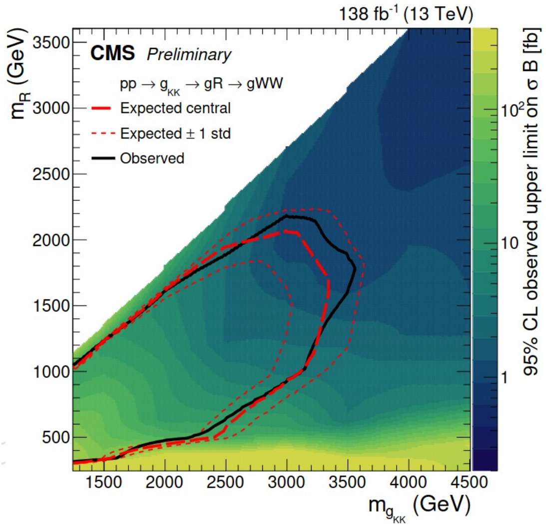
→ $g_{kk} \to gR \to gW(qq)W(qq)$ B2G-23-004

- Probing extended WED model
  - *With suppressed direct g_{kk} decay to SM particles*
- Looking at topologies with merged W decays
  - *But resolved R decay → 3 (large-R) jets*
  - *W jets identified with ParticleNet*
  - *5 SRs defined in m_{gkk}/m_R plane*
    Split further in two according to sub-leading W jet ParticleNet score
- Limits on σxBR as a function of mR and m_{gkk}
  - *Excluding m_{gkk} up to 3 TeV and mR up to 2.05 TeV*
  - *Downward fluctuation of data at ~3-3.5 TeV → yielding tight observed limits w.r.t. expectation*

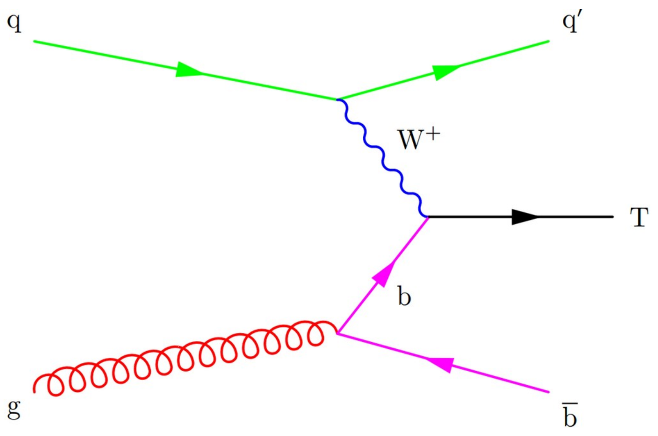






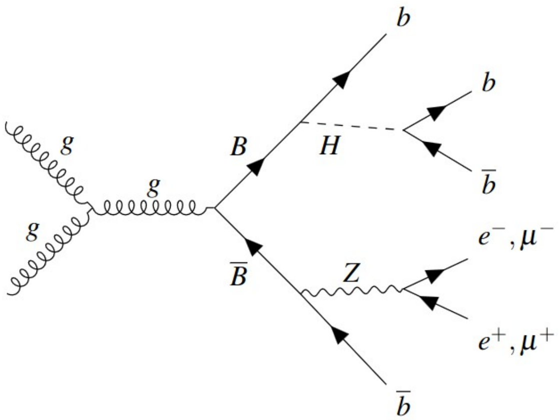


BSM fermions (1)



…more fermions…

→ *VLQs are predicted in several models*
- Esp. models addressing hierarchy & naturalness problems
  - ***e.g. Composite Higgs models***
- Looking for heavy T’, B’
  - ***Preferably coupling to 3rd gen quarks through charged/neutral currents***
  - ***Typically looking for final states with t,b quarks, and Higgs & vector bosons***



Worth noting:
recent VLQ/VLL/HNL searches review from CMS (2405.17605)

BSM fermions (2)

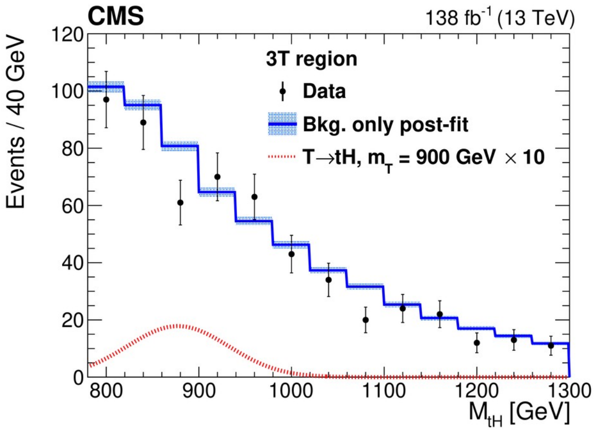
Single-VLQ production

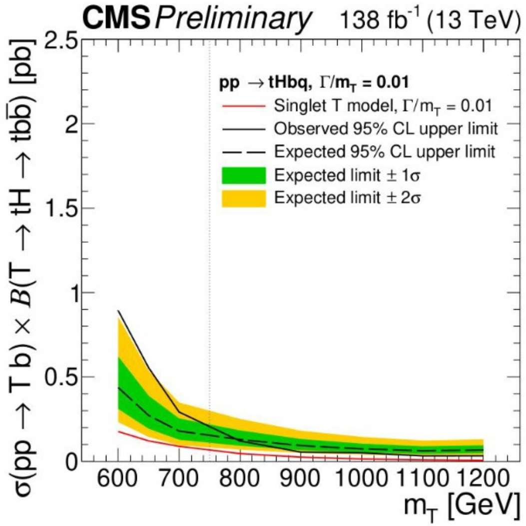
→ *CMS: T′→t+Z/H(bb)* 2405.05071

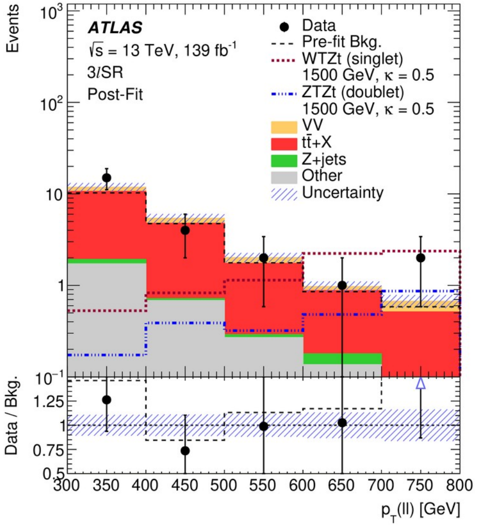
- Fully hadronic final state
  - ***At least 6 jets (3 b-tagged)***
  - ***Jets assigned to Z/H & t decay through multistep χ^2 minimization***
  - ***5-jet (t + Z/H) invariant mass used to extract limits***
- An excess was observed in 2016 data 1909.04721
  - ***Washed out in full run 2 combination***

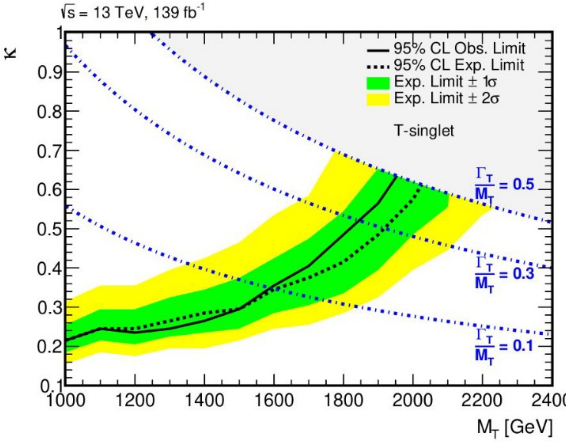
→ *ATLAS: T′→t+Z(ll)* 2307.07584

- Both leptonic & hadronic top decay
  - ***Fitting pTZ in both case and combining limits***
- Limits for singlet and doublet representations
  - ***No significant excess***
  - ***Strongest experimental limits for singlet case***









BSM fermions (3)

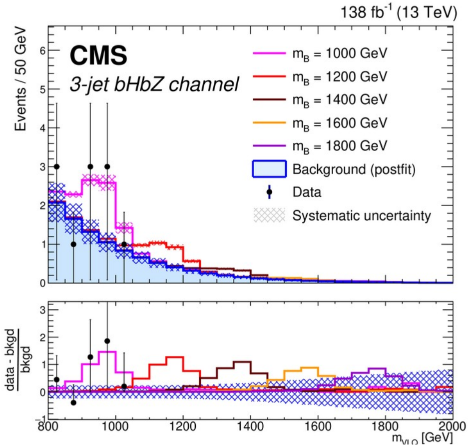
Pair production

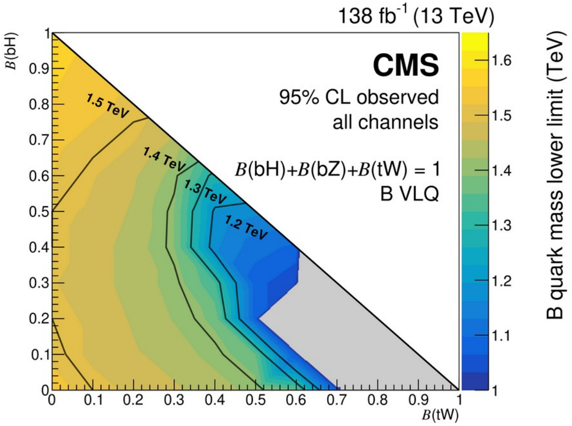
→ *CMS: B′B′→b+Z/H, tW* 2402.13808

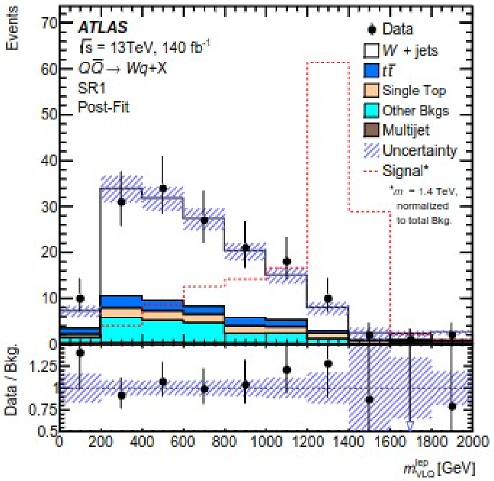
- Search in fully hadronic & jets+Z(ll)
  - *Hadronic decays both resolved & merged*
  - *Fitting VLQ mass spectra in Njet/Nlep categories*
  - *No deviations from SM observed*
  - *Upper limits on B VLQ mass as a function of BR to tW /bH*

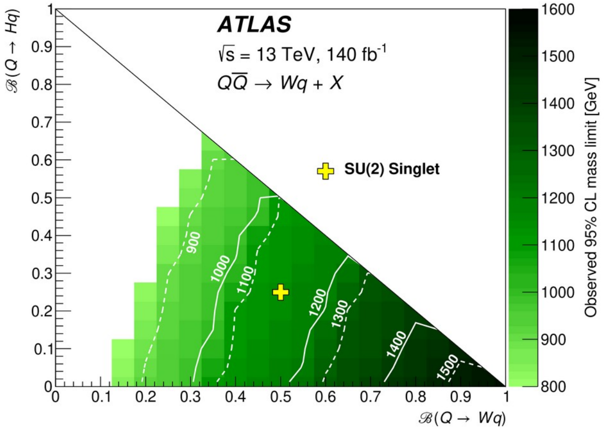
→ *ATLAS new result: T′T′ → WqWq* 2405.19862

- Considering VLQ mixing with light quarks
  - *Much less explored scenario*
- Limits as a function of BR(W/Z/Hq)
  - *MVLQ > 1530 GeV assuming BR(Wq)=1*
  - *Improved by ~ factor 2 w.r.t. previous limits (Run 1)*







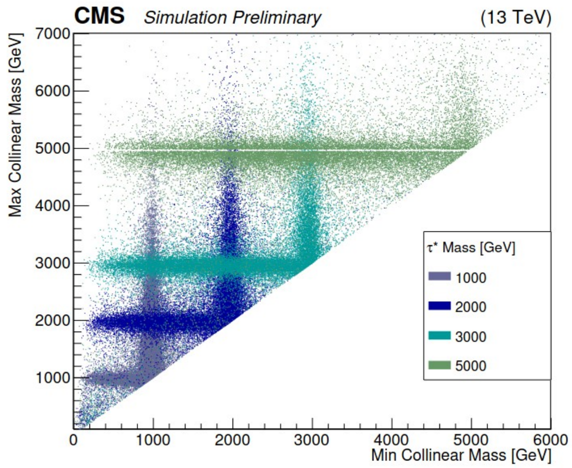


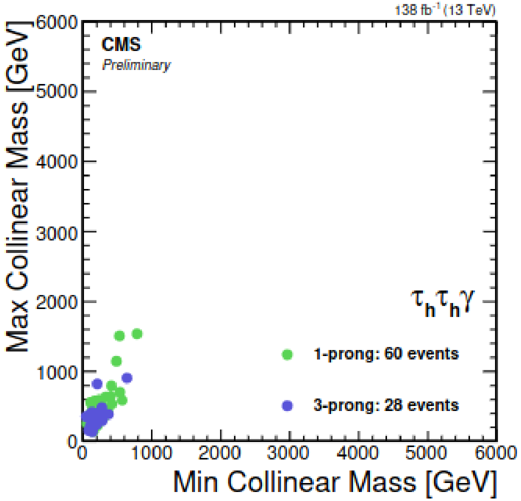
BSM fermions (4)

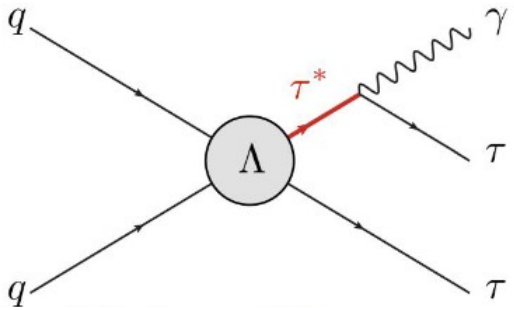
Excited tau Lepton

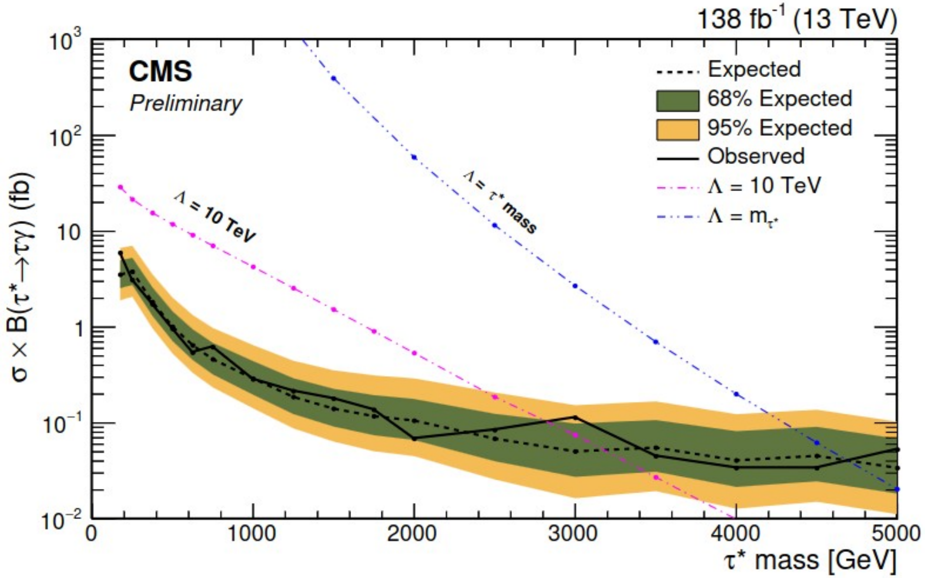
→ ***Brand new result*** *from CMS* EXO-22-007

- And first $\tau\tau\gamma$ search since LEP!
  - ***Looking for $\tau\tau^*$ pairs produced through contact interaction***
  - ***Probing τ compositeness***
- Evaluating both $m_{\tau\gamma}$ combinations
  - ***Assuming colinearity b/w visible tau & neutrinos***
  - ***Defining Mass-specific SRs in mass plane for fit***
  - ***Excluding m_{τ^*} > 2.8 (4.7) TeV for Λ = 10 TeV (m_{τ^*})***
    → comparable to previous τ^* search by ATLAS 2303.09444









“New” tools for searches

… more ideas to look deeper

→ *Our searches are only as good as the tools we use to design them*

- The detectors are what they are, but we can make the most out of them
  - ***E.g. getting away from the typical objects we reconstruct***

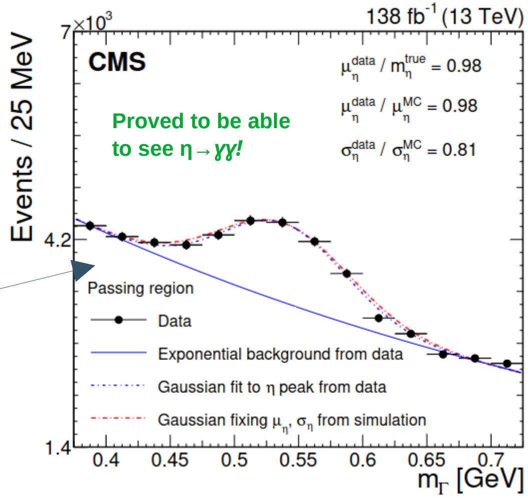
- And we can exploit “new” tools
  - ***Two great examples for searches: Scouting & anomaly detection algorithms***

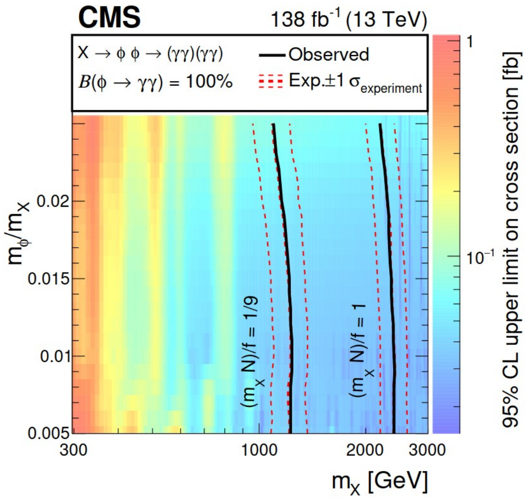
Searches with “new” objects

Getting creative with our detectors

→ CMS: X→$\phi\phi$→$\gamma\gamma\gamma\gamma$ 2405.00834

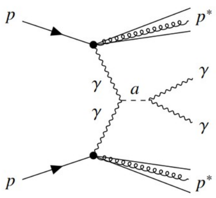
- Looking at topologies with highly merged photons
  - *Could not rely on standard photon reconstruction*
  - *New (ML) reco. Algorithm designed for that purpose*
- Deriving model independent limits
  - *No significant excess found*

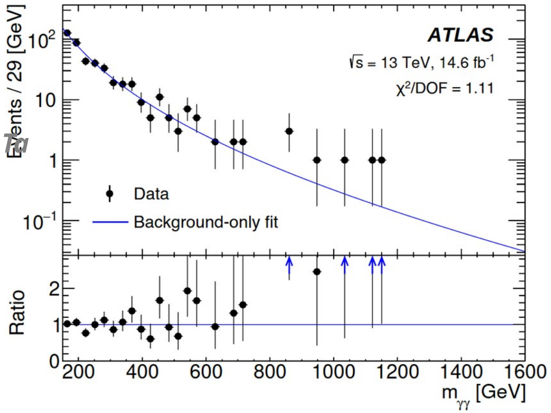


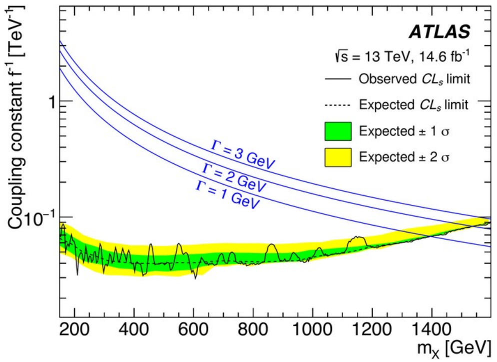


→ ALPs search *with AFP* JHEP 07 (2023)

- Through Light-by-Light scattering
  - *Tagging forward protons with AFP*
- Unbinned fit to diphoton mass
  - *Mild excess at 454 GeV (2.5 σ local)*







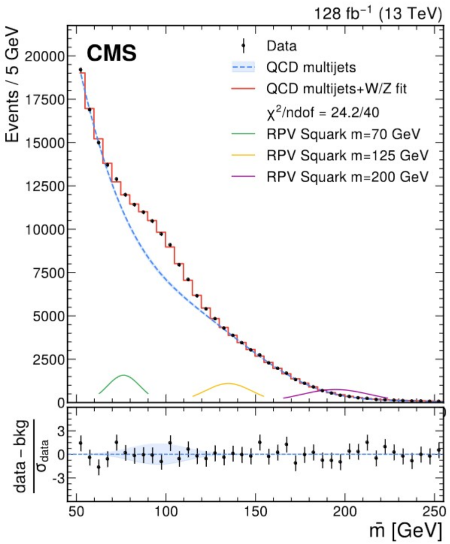
Searches with scouting

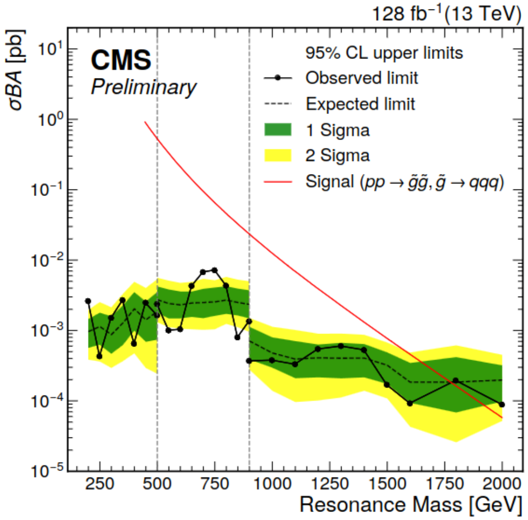
How to maximize data statistics for searches

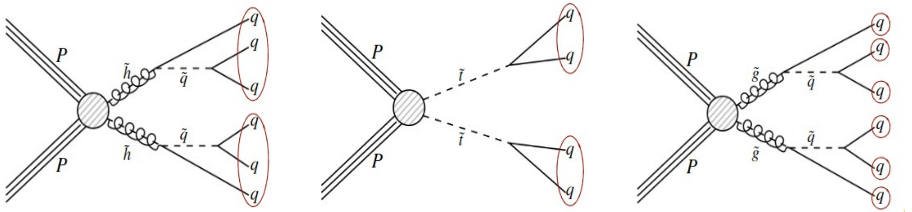
→ *High trigger rates at the cost of granularity*
- Standard HLT: ~ 1 kHz x 1 MB/evt → 1 GB/s
- Scouting (Run2): ~ 5 kHz x 10 kB/evt → 10 MB/s
  - ***Allows for much looser requirements on trigger objects***

→ *Extremely well suited for searches with*
- Multijets 2404.02992
  - ***Most stringent limits to date on RPV Gluinos & top squarks production***
  - ***Small excess at 770 GeV (2.6 σ local) in 3-jet mass***
- Muons JHEP 12 (2023) 070
  - ***Covered in FIP plenary talk tomorrow***

→ *Extended scouting program for Run 3*
- See review of scouting & parking in CMS 2403.16134
  - ***More allocated rate, more complete set of objects (e.g. e/γ)***
  - ***See also Trigger performance talk by S. Donato***

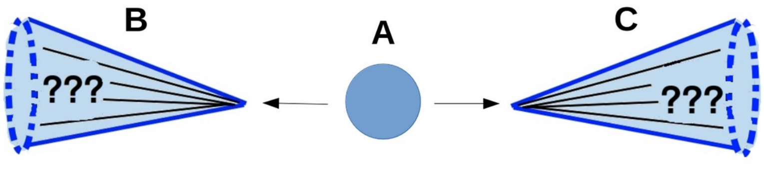






Worth noting:
Similar approach in ATLAS: Trigger-Level Analysis, e.g. Phys. Rev. Lett. 121, 081801 (2018)

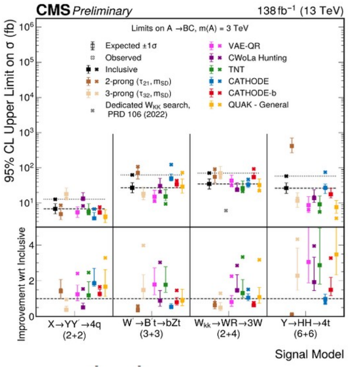
Anomaly detection

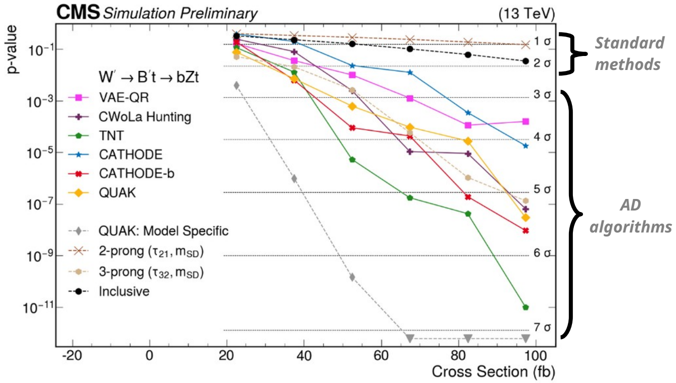


Looking for everything at once

→ *Alternative model-independent paradigm in searches*

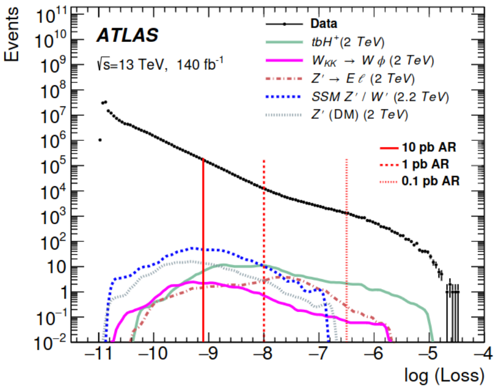
- Looking for e.g. resonances in multi-jet final states
  - ***With anomalous behavior w.r.t. SM (e.g. jet substructure)***
- A plethora of algorithms developed for this task
  - ***Outlier detection with VAE, weak supervision, …***
  - ***For the most part fully data-driven approaches***

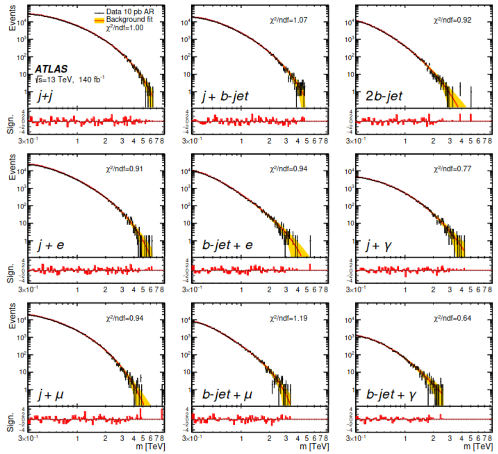




→ *Recent showcases of the approach*

- CMS CMS-PAS-EXO-22-026
  - ***Search for di-jet resonances, w/ minimal kinematics assumptions***
  - ***Benchmarking several algorithms, selecting events with high "anomaly score"***
  - ***Large sensitivity improvement (~x3-7) w.r.t. conventional approaches***
- ATLAS PRL 132 (2024) 8, 081801
  - ***BumpHunter algorithm (AE)***
  - ***Search for anomalous object pairs (di-(b)jet, (b)jet+e/μ/γ)***





→ *See* *dedicated session on Wednesday*

Conclusion

A broad program of search for new resonances at ATLAS and CMS

→ ***New Higgs bosons, Vector bosons, fermions, and more***
- Probed both in theory-driven and model-independent searches
- Including this year several large scale combinations and review papers!

→ ***Analyses are showing more and more creativity in their methods***
- And taking advantage to the fullest of our detectors capabilities,
  and of the new tools and techniques becoming available

→ ***So far, no excess significant enough to challenge the SM***
- A few mild ones here and there to be carefully checked

→ ***Run 3 is ongoing, with higher energy and more data to analyze***
- And we should expect a multitude of new and exciting results with it!


Backups

Extended Higgs sectors (5)

On finite width & interference in HH

→ *In most cases HH searches consider NWA*

- Some analyses probing width effect
  - ***BUT neglecting interference with SM***
  - ***Push from theory community to include their effect***

→ *Ramping effort to understand experimental sensitivity*

- Focusing on simplest BSM scenario for now
  - ***SM + real singlet***
- Scanning the width/interference impact on total cross-section as a function of:
  - ***New scalar mass (MX)***
  - ***hhX coupling (λHHX in figure)***
  - ***Mixing angle (sin α)***
- Preliminary conclusions:
  - ***For low (<~400 GeV) and high (>~700 GeV) mX negligible interference effects where our analyses are sensitive***
  - ***For medium mX, interference effects are larger***
- More work needed to understand the actual sensitivity
  - ***Effects may still be drowned due to experimental resolution***

2403.16926