The 10th Annual
Large Hadron Collider Physics Conference
May 16-20, 2022
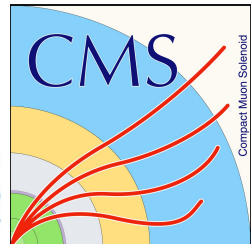
2022
LHCP
TAIPEI
Online

Resonant and Non-resonant searches at ATLAS & CMS
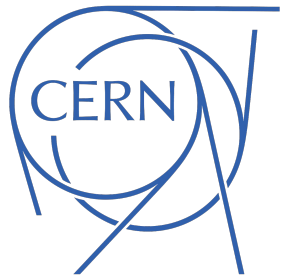
Saranya Ghosh

on behalf of the ATLAS & CMS collaborations

Outline

A subset of recent resonant and non-resonant search results from
ATLAS & CMS experiments will be covered in this talk:

- Probe Majorana neutrinos & Weinberg operator through VBF processes [CMS-PAS-EXO-21-003]

- Search for Z' bosons decaying to pairs of heavy Majorana neutrinos [CMS-PAS-EXO-20-006]

- Search for a heavy composite Majorana neutrino [CMS-PAS-EXO-20-011]

- Search for $t\bar{t}H/A{\rightarrow}t\bar{t}t\bar{t}$ production [ATLAS-CONF-2022-008]

- Search for doubly charged Higgs boson [ATLAS-CONF-2022-010]

- Search for pp+Z/γ+X using CMS + TOTEM PPS [CMS-PAS-EXO-19-009]

- Search for low mass boosted resonances decaying into two photons [ATLAS-CONF-2022-018]

- Search for vector-like leptons in ≥ 3b + N τ final states [CMS-PAS-B2G-21-004]

- Search for vector-like quarks in leptonic final states [CMS-PAS-B2G-20-011]

- Search for pair-produced scalar and vector leptoquarks [ATLAS-CONF-2022-009]

- Leptoquark summary plots

- Summary

- Outlook

Searches covered in other talks at this conference:

- SUSY searches (M. Aparo, T. Kamon, S. Kamarkar)
- Searches for long lived particles (M. Darwish, L. Henry, H. Oide, M. Shapiro)
- Dark Matter (O. Brient, S. Mukherjee, B. Bruers)
- BSM Higgs searches, Exotic Higgs decays (G. Caratta, H. Saka)
- Searches in context of B-meson anomalies (E. Must)
- In this session:
  - Mono-X searches (B. Bruers)
  - Dijet, Dileptons searches (N. Salidou)
  - Di/Triboson resonances (I. Zoi)

Results shown using pp collision data at √s= 13 TeV using full Run 2 data (137 - 140 /fb unless otherwise specified)

Probe Majorana neutrinos & Weinberg operator through VBF processes

CMS-PAS-EXO-21-003

- First probe of Majorana neutrinos & Weinberg operator in VBF processes at LHC.
  - First test of Weinberg operator at colliders - in context of Type-I "seesaw" models with heavy Majorana neutrino. Seeks to explain neutrino masses.

- Final state: same-charge dimuon final state with 2 forward jets (VBF)

- Background estimation : data driven for non-prompt lepton background and simulation for prompt lepton background, normalisation from control regions (CRs)

- Results show data agrees with SM background
  - Upper limits set on $|V_{\mu N}|^2$ for m_N up to ~23 TeV.
 - Weinberg operator: observed (expected) upper limit $|m_{\mu\mu}|$= 10.84 (12.84) GeV
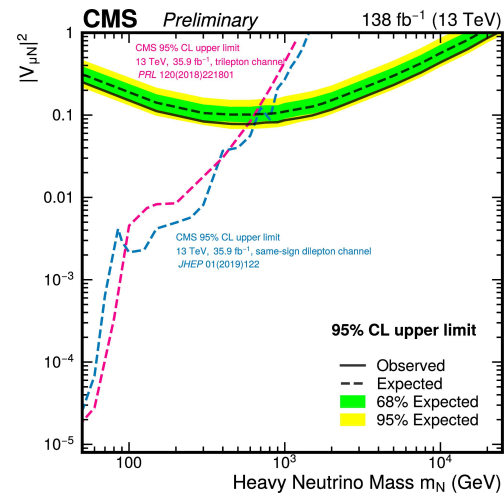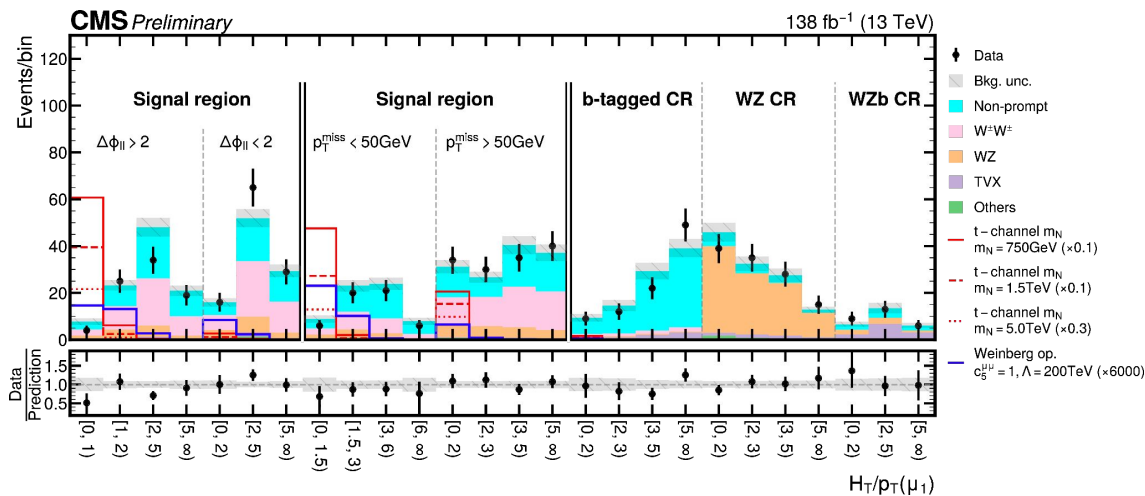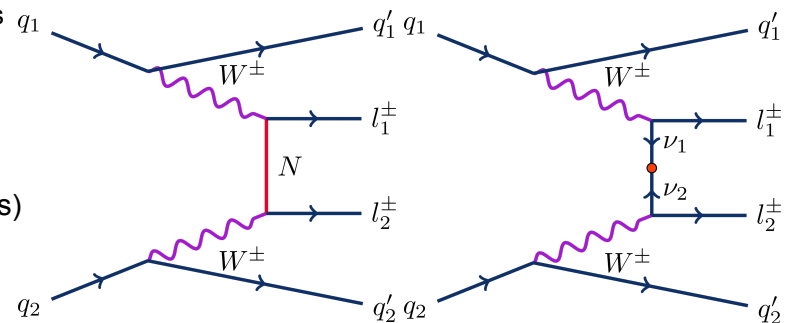
# Search for Z' bosons decaying to pairs of heavy Majorana neutrinos

CMS-PAS-EXO-20-006

- Search targets heavy Majorana neutrinos in context of left-right symmetry model
  - Explains neutrino masses & matter-antimatter asymmetry thru CP violation
  - 3 additional gauge bosons ($W^{\pm}_R$ & Z') & 3 right-handed neutrinos (N_e, N_μ, N_τ)

- Targeted kinematic region: $m_{N'} \ll m_{Z'}$; also sensitive to $m_{N'} < m_{Z'}$

- Final state: 2 same-flavor leptons + at least 2 jets
  - Multiple signal regions based on number of leptons, jets, wide jets
  - Binned in reconstructed Z' boson invariant mass in signal regions

- Background from simulation, normalisation derived from control regions
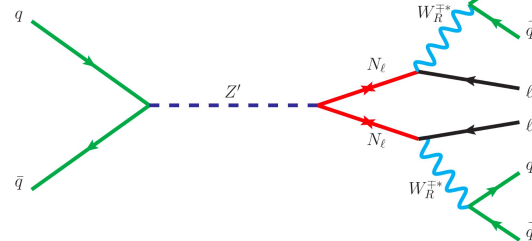
- Yields consistent with SM background
 - Most restrictive direct limits in the phase space of $m_{Z'}$ vs $m_{N\ell}$
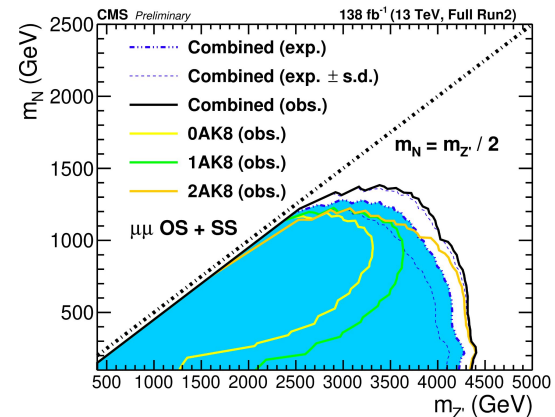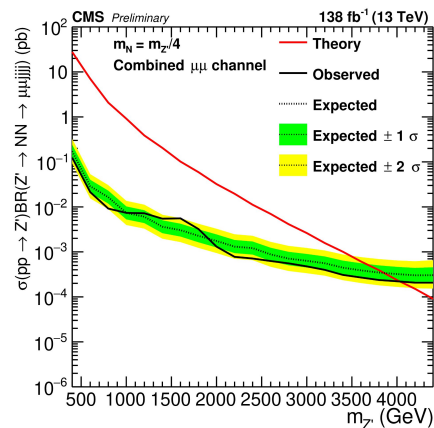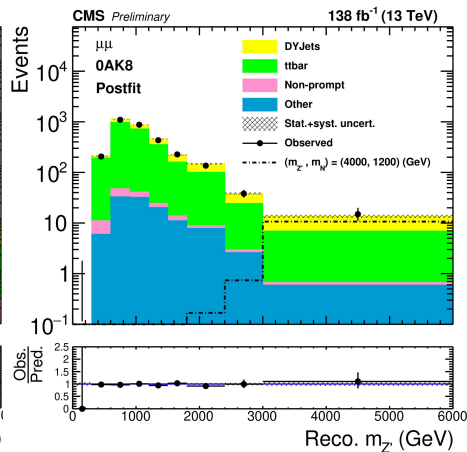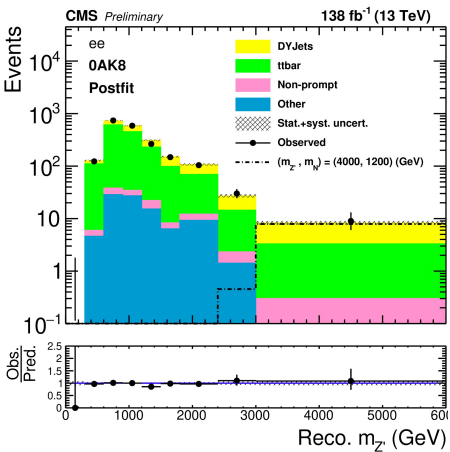
Search for a heavy composite Majorana neutrino

CMS-PAS-EXO-20-011

- Search for heavy composite Majorana neutrino (HCMN, $N\ell$, ℓ = e, μ, τ)
  - Heavy -> mass scale beyond the electroweak energy scale
  - Compositeness models account for mass hierarchy, matter-antimatter asymmetry

- Final state: 2 same-flavor leptons (e or μ) & 2 quarks (≧1 large area jet)

- Background estimation : data control region used to correct the MC simulation for the background estimation

- Data in agreement with SM expectations
  - Upper limit placed on $\sigma(pp \to \ell N\ell) \times B(N\ell \to \ell qq')$.
 - Considerable improvement in sensitivity to HCMNs at the LHC.
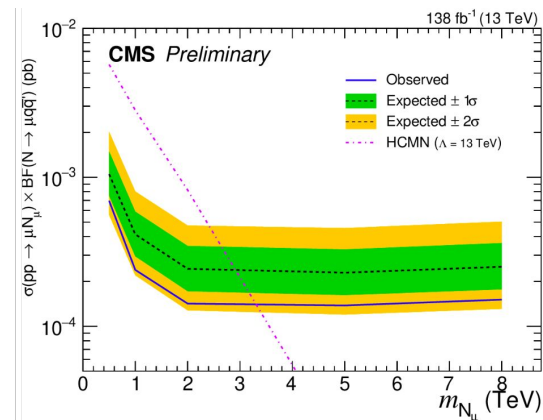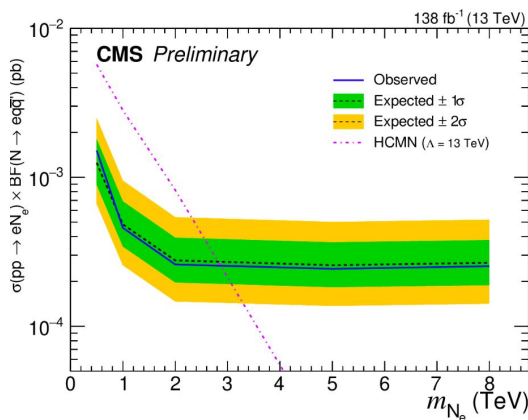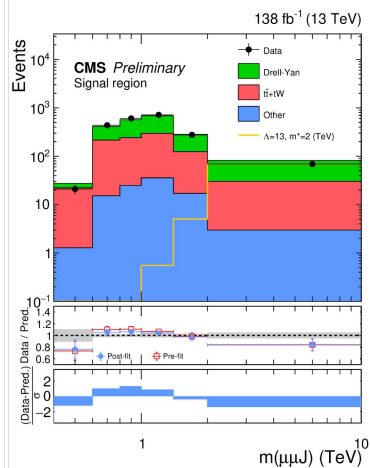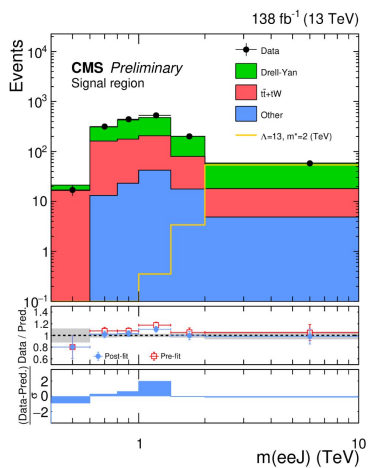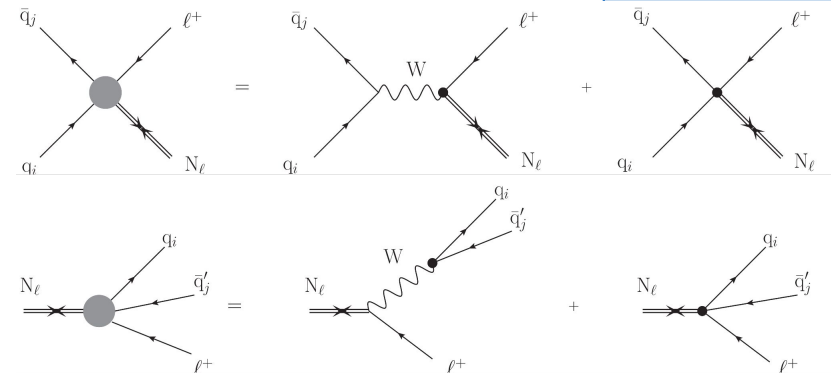
Search for t$\bar{\text{t}}$H/A→t$\bar{\text{t}}$t$\bar{\text{t}}$ production in multilepton final state

- Search for new heavy scalar/pseudoscalar Higgs boson (H/A) : $t\bar{t}H/A(\to t\bar{t})$.

  ○ Produced in association with a top quark pair, with the Higgs boson decaying into a pair of top quarks : $t\bar{t}H/A(\to t\bar{t})$.
  ○ In context of two-Higgs doublet models (2HDM)

- Final state: exactly 2 leptons with same-sign electric charge or at least 3 leptons
  ○ Signal-enriched region : at least 6 jets, including 2 b-tagged, H_T > 500 GeV

- Dedicated control regions to constrain the dominant backgrounds, MVA techniques for signal extraction.
  ○ 2 sequential BDT classifiers: first separates SM $t\bar{t}t\bar{t}$ events from remaining backgrounds (define SR), then mass-parametrised BDT for discrimination of signal vs all background.
  ○ Most backgrounds from simulation, normalised using control regions. Charge misID bkg determined in data driven way.

- No significant excess of events over the SM expectation observed, results interpreted in the context of 2HDM type-II.
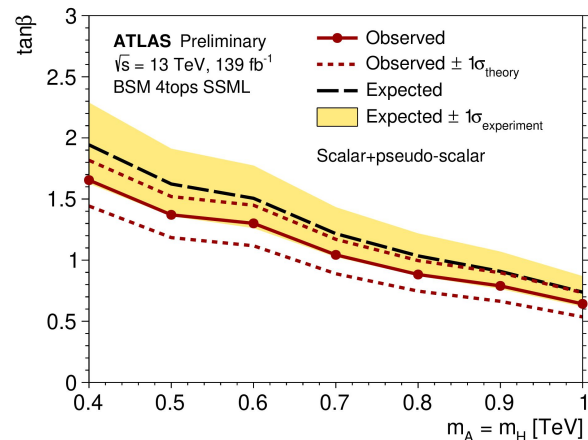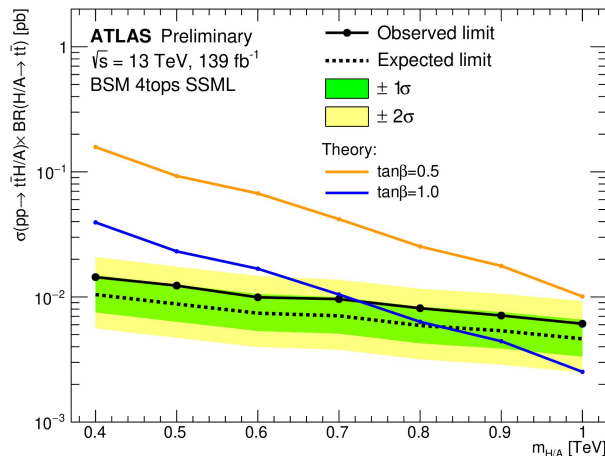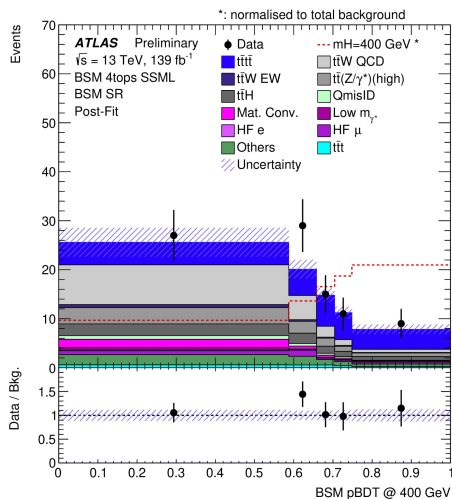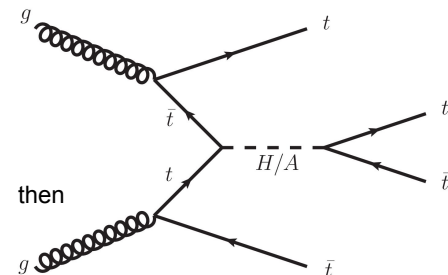
ATLAS-CONF-2022-008

Search for doubly charged Higgs boson production

ATLAS-CONF-2022-010

- Search for $H^{\pm\pm}$ in multilepton final states: high mass $e\pm e\pm$, $\mu\pm\mu\pm$, or $e\pm\mu\pm$ resonances in 2ℓ, 3ℓ, and 4ℓ final states.
  - Left-right symmetric models, 3-3-1 models, type-II seesaw models, the Zee–Babu neutrino mass model, Georgi-Machacek model
  - Interpretation allows (equally) for decays to e, μ, or τ, and includes LFV final states

- Event selection at least two light leptons.
  - Signal, control & validation regions defined based on lepton multiplicity, $m_{\ell\ell}$, kinematics.

- Prompt bkg from simulation, normalised from CRs. Non-prompt bkg using data driven method.

- Data in agreement with SM expectations
  - Lower limits set on the mass of $H^{\pm\pm}$ between 520 GeV & 1030 GeV depending on lepton multiplicity channel
  - Observed combined lower limit on the $H\pm\pm$ mass is 1080 GeV
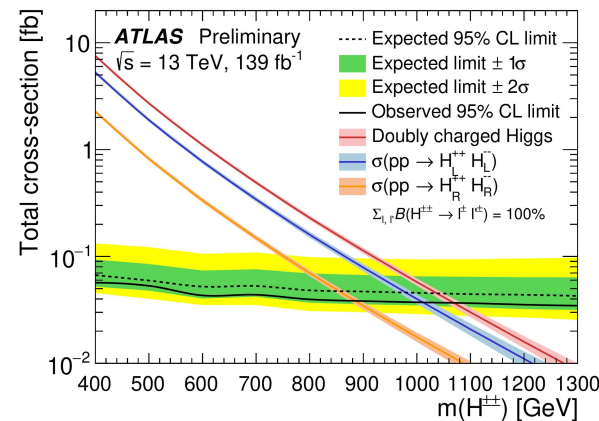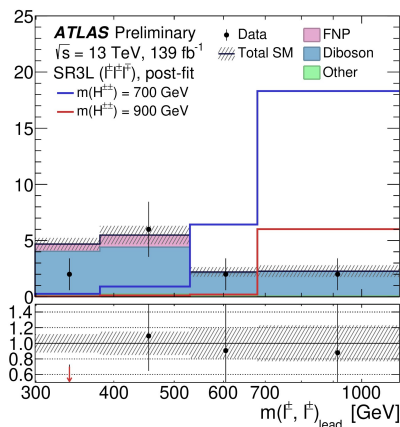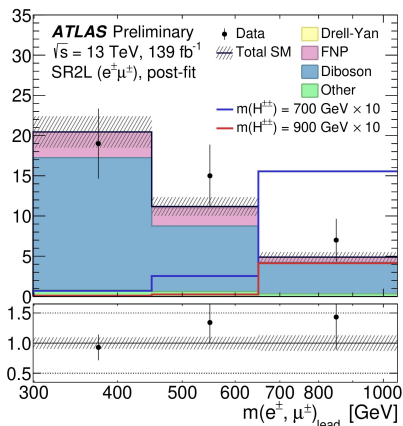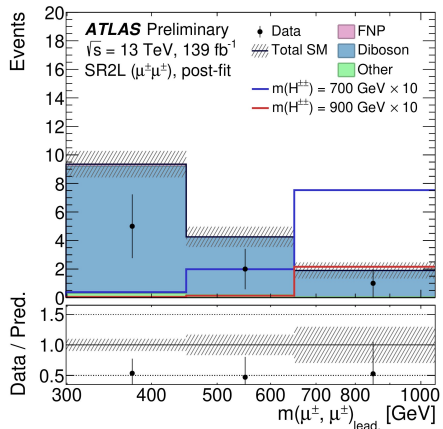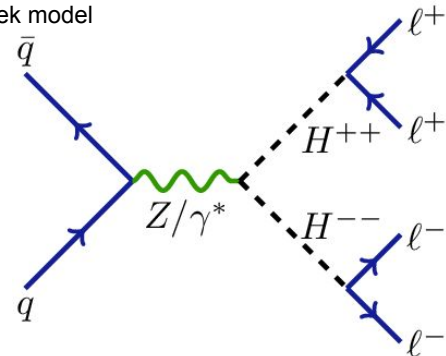
# Search for pp+Z/γ+X using CMS + TOTEM PPS

CMS-PAS-EXO-19-009

- Search for unspecified massive particle X produced in association with Z boson or photon in proton-tagged events from pp collisions: first of its kind search at LHC!

- Uses data recorded by the CMS detector and the CMS-TOTEM precision proton spectrometer in 2017 (37/fb).

- Events selection and categorisation:
  - At least one proton reconstructed in each arm of CT-PPS detector
  - Same flavour dilepton events (ee or μμ) for Z boson or single photon events
  - Background modeling using opposite flavour events (eμ)

- Missing mass spectrum fitted in 600-1600 GeV range to search for deviations from bkg expectation.

- No significant resonant deviations in data with respect to the background predictions:
  - Model-independent upper limits on cross section of pp → pp + Z/γ + X set
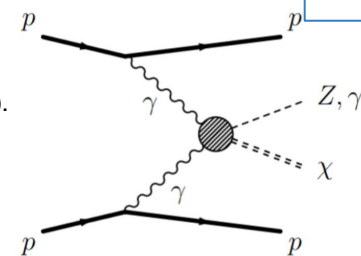
$$m_{\text{miss}}^2 = \left[\underbrace{(P_{p_1}^{\text{in}} + P_{p_2}^{\text{in}})}_{LHC} - (\underbrace{P_V}_{CMS} + \underbrace{P_{p_1}^{\text{out}} + P_{p_2}^{\text{out}}}_{PPS}) \right]^2$$
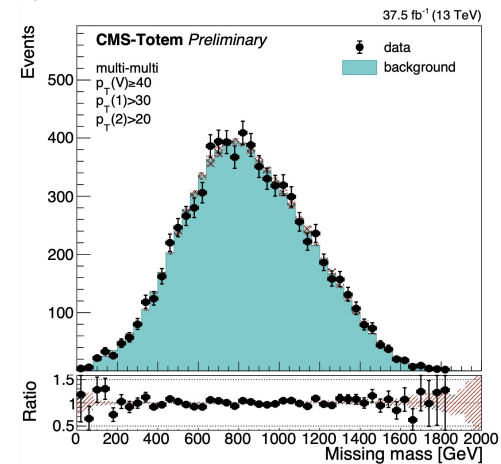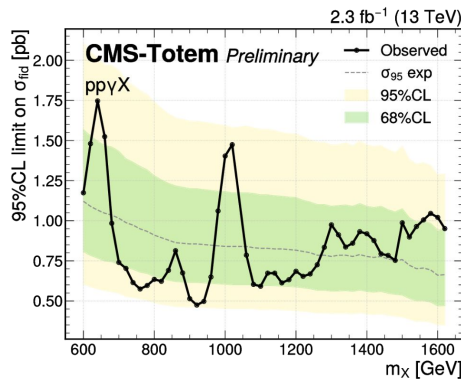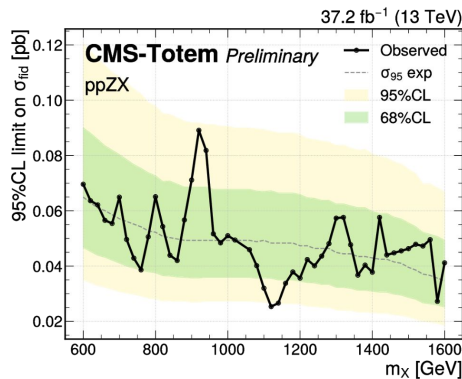
Search for low mass boosted resonances decaying into two photons

ATLAS-CONF-2022-018

- Search for boosted resonances in the 10 to 70 GeV mass range and decaying into two photons
  - Exploits kinematics of events with close-by pairs of photons -> reach invariant masses down to 10 GeV
  - Targets axion-like particles (ALPs) in a wide variety of BSM scenarios

- Event selection: at least 2 photon with p_T > 22 GeV, diphoton p_T > 50 GeV

- Signal, background estimation:
  - Dominant backgrounds: continuum diphoton production; photon-jet & jet-jet with jets misidentified as photons
  - Data-driven background estimate: continuum background shape parametrized by an analytic function
  - Search for narrow resonant signal with shape modeled by a double-sided Crystal Ball (DSCB) function

- Largest deviation corresponding to a local significance of 3.05σ, global significance of of 1.48σ
  - Limits placed on the production cross-section times branching ratio as a function of the resonance mass
 - Limits translated into ALP parameter space, in terms of ALP mass m_a and its decay constant f_a
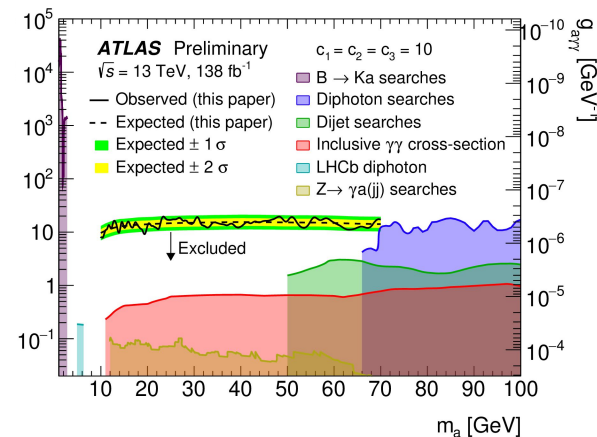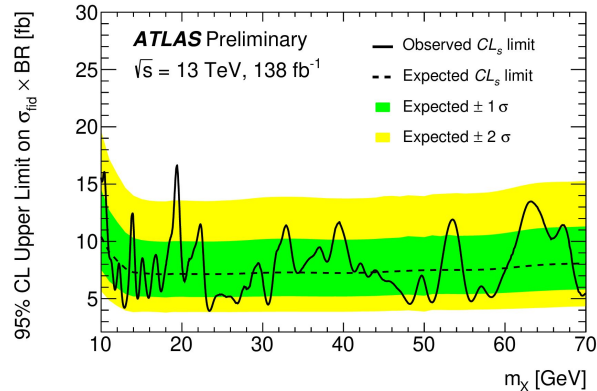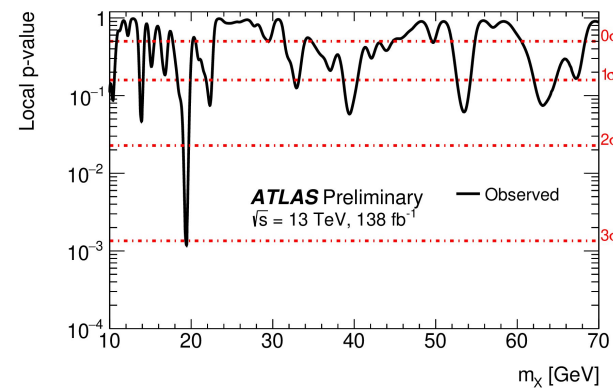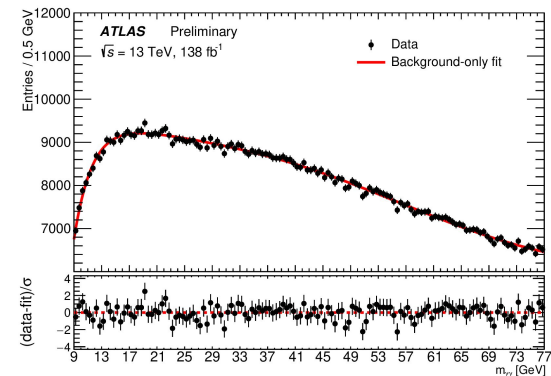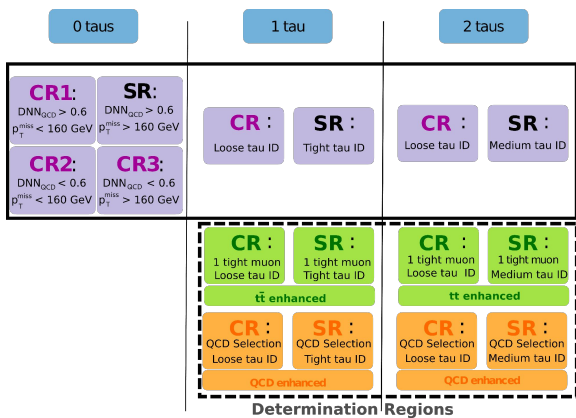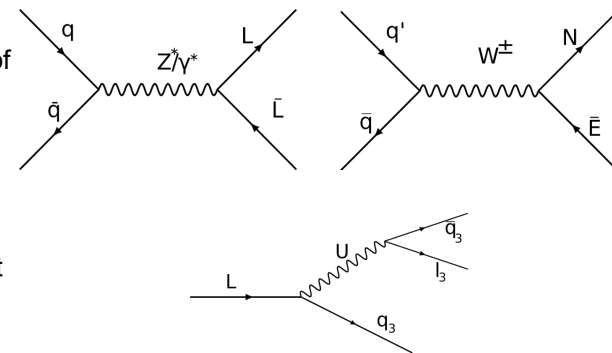
Search for vector-like leptons in ≥ 3b + Nτ final states

- Search for pair production of vector-like leptons (VLLs) using 2017+2018 datasets (96.5 /fb)
  - In context of 4321 model motivated by the B anomalies

- VLLs decay via intermediate leptoquark (U) to 2 quarks and 1 lepton. Flavour nonuniversal couplings of leptoquark assumptions imply decays almost entirely to third-generation fermions.

- Select events with a high b jet multiplicity & a number of τ leptons.
  - Events binned in number of τ leptons.
  - Dedicated selections for signal and background control regions for different τ multiplicity.

- Further binning in terms of number of jets or Machine learning based DNN classifiers (vs QCD and vs tt background) used for signal extraction.

- Mild excesses (2.8σ) observed in signal sensitive bins of 1-τh and 2-τh regions for both 2017 & 2018 data.
 - No VLL masses excluded, limits are set on cross-section x BR between 10 and 30 fb.
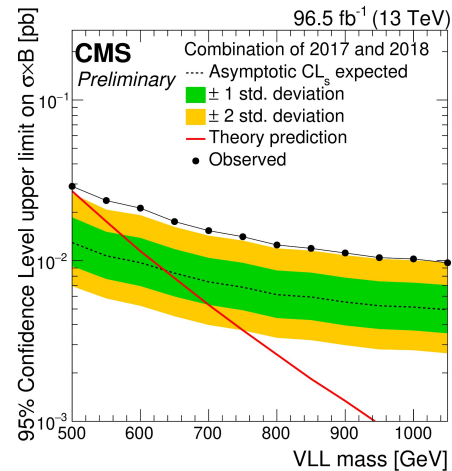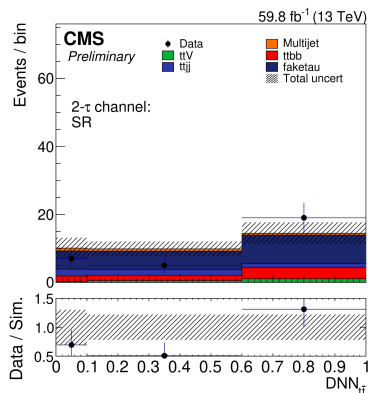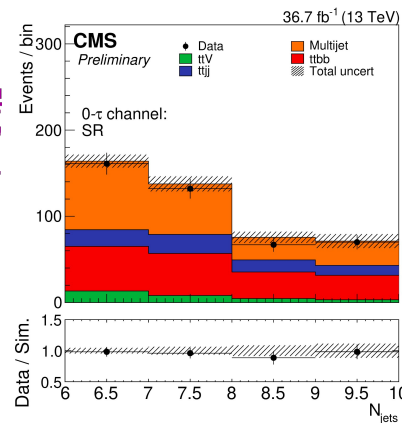
Search for vector-like quarks in leptonic final states NEW!

CMS-PAS-B2G-20-011

- Search for pair production of vector-like T and B quark-antiquark pairs
  - Motivated by several models such as Little Higgs, Composite Higgs
  - Targets explanation for flavour-nonuniversal results of B meson anomalies

- Search for TT and BB in 3 channels containing charged leptons (electrons or muons):
  - Single-lepton channel: multilayer perceptron network for signal separation
  - Same-sign dilepton channel & multilepton channels : rare in SM, use jet and lepton momentum sum distributions

- Exclusion limits placed:
  - T quarks upto 1.54 TeV, B quarks upto 1.56 TeV, depending on branching scenario
 - Strongest limits to date (T in tH & BW channels; B in tW channel)
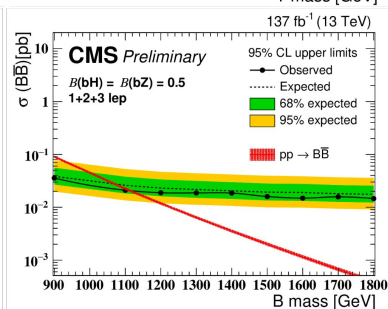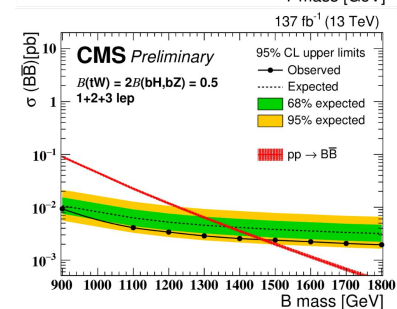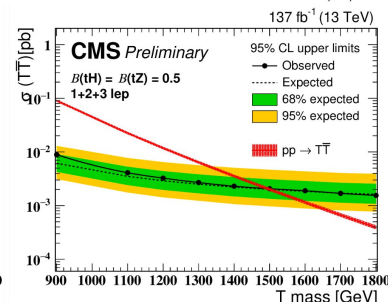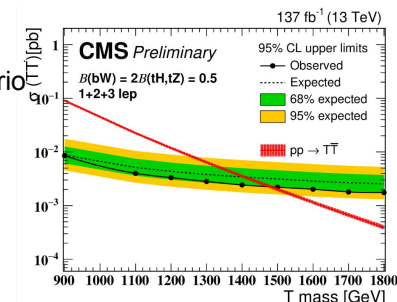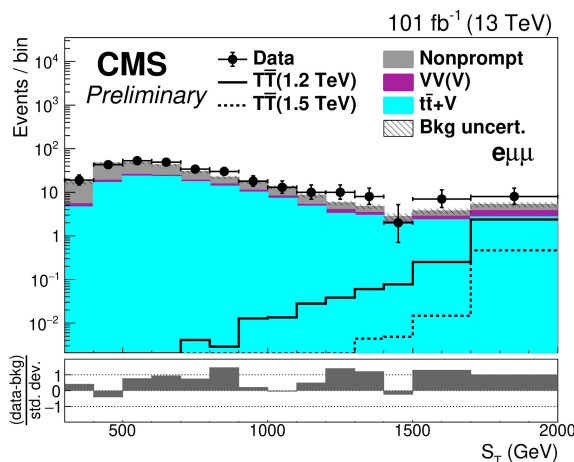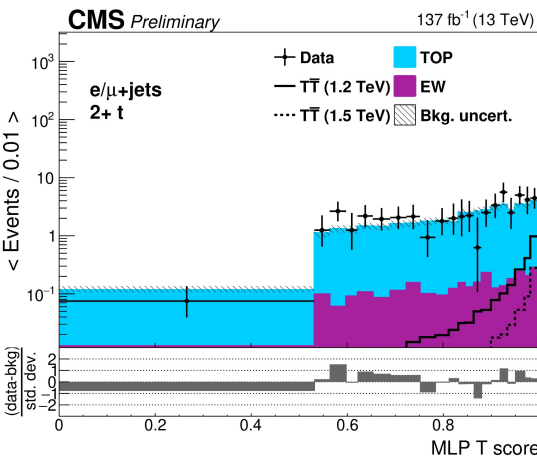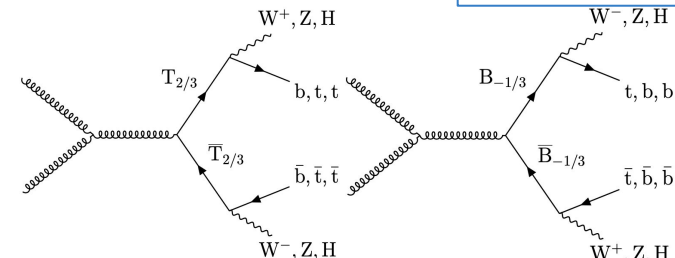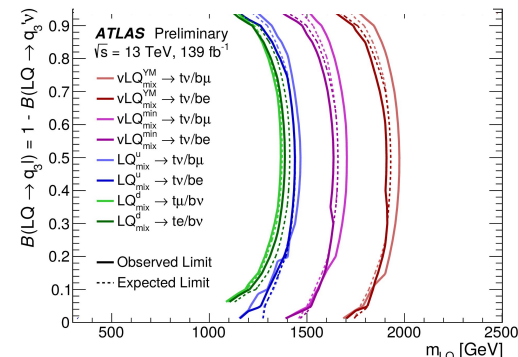
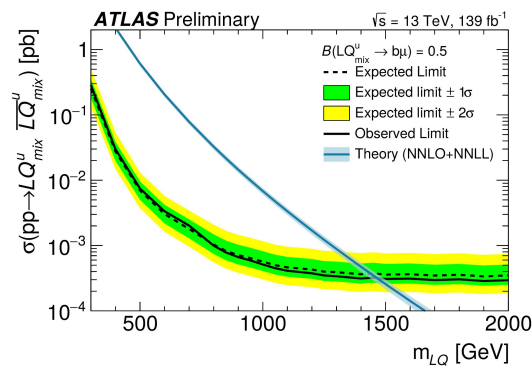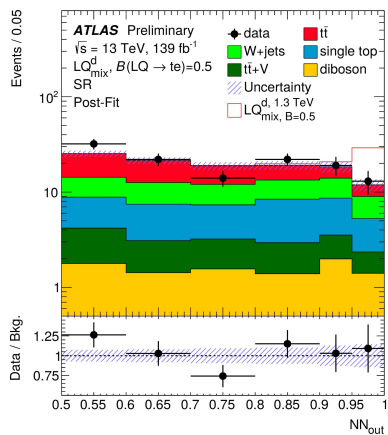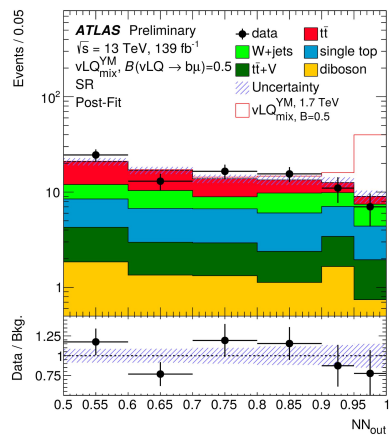# Search for pair-produced scalar and vector leptoquarks

ATLAS-CONF-2022-009

- Search for pair-produced scalar and vector leptoquarks decaying into quarks and leptons of different generations
  - Motivated by eight different models, including those seeking to explain B anomalies
  - Leptoquark decays into charged & neutral leptons of 1st & 2nd generation with similar branching fraction

- Final state signature : 1 lepton, high missing transverse momentum, at least 4 jets & 1 b-quark.
  - Dedicated Neural Networks (NNs) used for the separation of signal and background
  - This is done separately for both scalar and vector LQ pair-production.

- Statistical interpretation based on a simultaneous fit to the control and signal regions

- No significant deviations from SM expectation
  - Upper limits on cross-section for 8 models as function of leptoquark mass and branching ratio to charged lepton.
  - Lower limits on leptoquark mass set across a range of branching ratios for all models
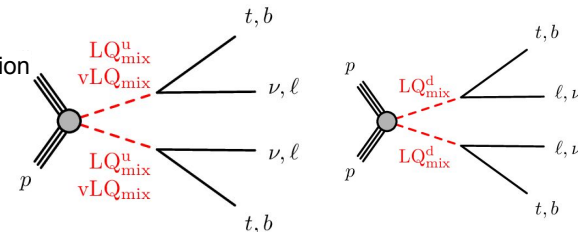
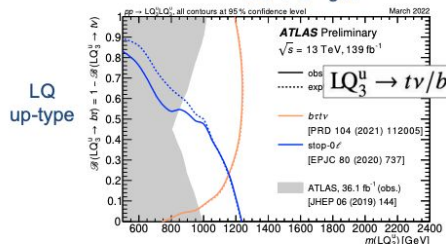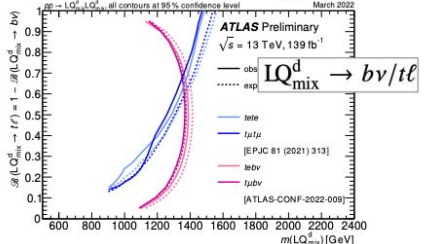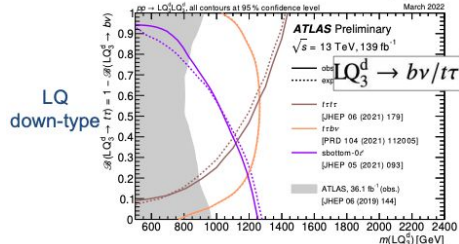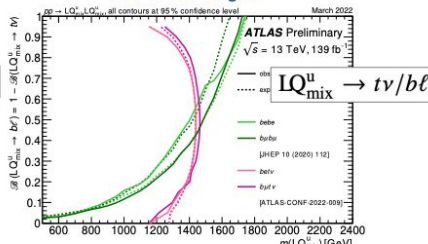|	Exp. limit [GeV]	Obs. limit [GeV]
$LQ_{mix}^u \to t\nu/b\mu$	1440^{+60}_{-60}	1460
$LQ_{mix}^u \to t\nu/be$	1440^{+60}_{-60}	1440
$LQ_{mix}^d \to t\mu/b\nu$	1380^{+50}_{-60}	1370
$LQ_{mix}^d \to te/b\nu$	1410^{+60}_{-60}	1390
$vLQ_{mix}^{YM} \to t\nu/b\mu$	1930^{+50}_{-50}	1980
$vLQ_{mix}^{YM} \to t\nu/be$	1930^{+50}_{-70}	1900
$vLQ_{mix}^{min} \to t\nu/b\mu$	1660^{+50}_{-50}	1710
$vLQ_{mix}^{min} \to t\nu/be$	1650^{+50}_{-60}	1620

LEPTOQUARK SUMMARY PLOTS

- 4 scenarios; all decays in 3rd gen quarks as final state
- 5 dedicated LQ searches + 2 SUSY searches re-interpretations used

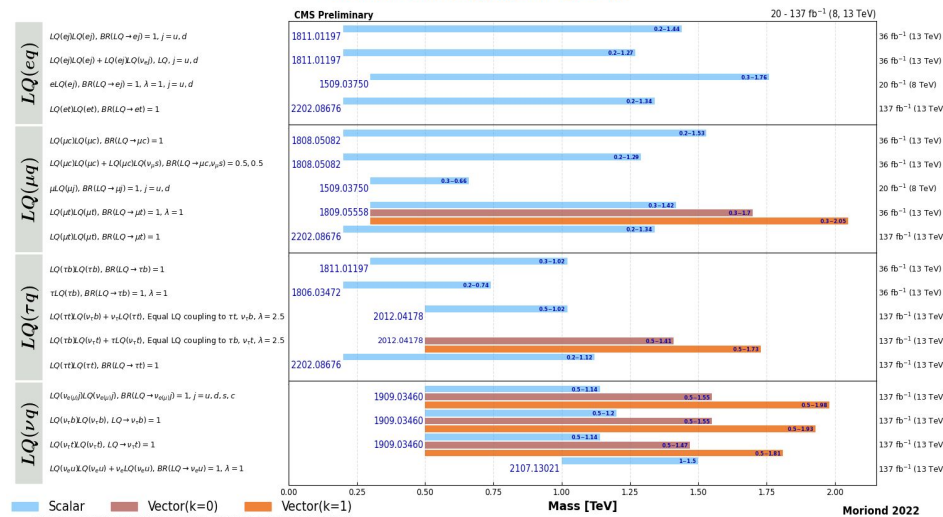CMS also provides a summary plot of LQ searches, with arxiv references as a function of mass

http://cdsweb.cern.ch/record/2805984/files/ATL-PHYS-PUB-2022-012.pdf

https://twiki.cern.ch/twiki/pub/CMSPublic/SummaryPlotsEXO13TeV/barplot_EQ_MUQ_TAUQ_NUQ.pdf

SUMMARY

Results presented here are only a small subset of search results from ATLAS & CMS.
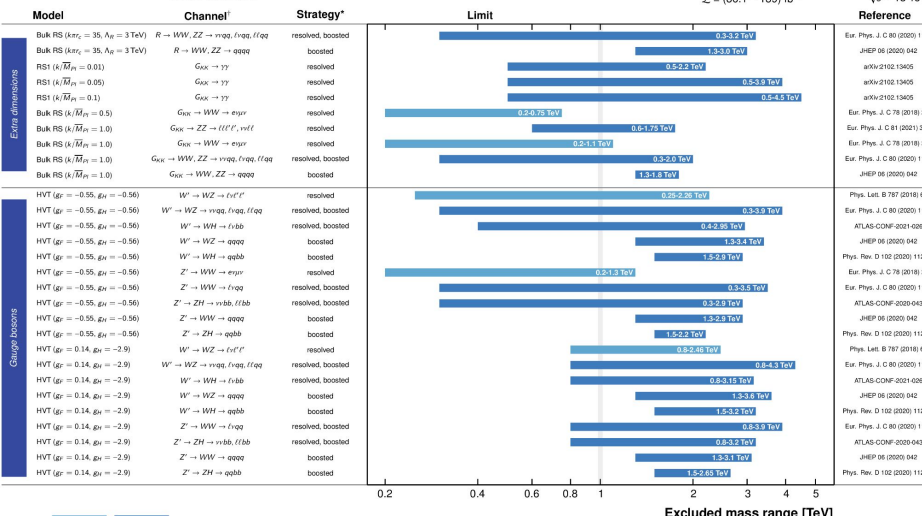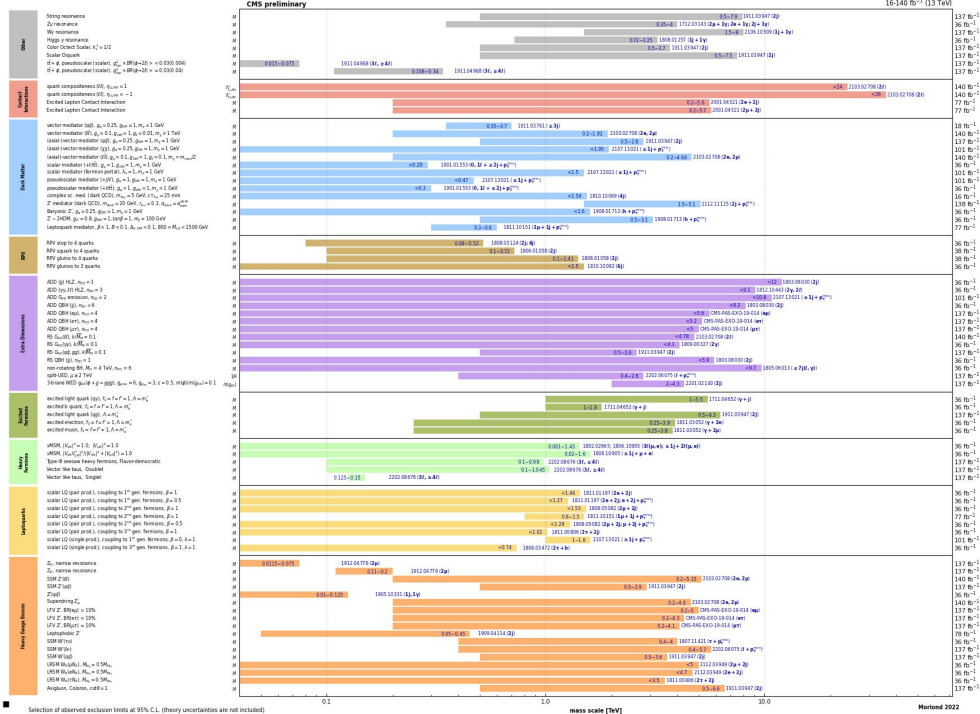
For more, see:

ATLAS:
- Exotica searches
- Higgs and Diboson searches
- SUSY searches

CMS:
- Exotica searches: Preliminary results, Publications
- Beyond 2nd Generation: Preliminary results, Publications
- SUSY searches: Preliminary results, Publications

OUTLOOK

- ## New and improved analyses
  - Many analyses shown either target new signatures or include significant improvements in analysis techniques

- ## More to come from Run-2 data
  - Expect to see many new Run-2 results from ATLAS and CMS this summer / year

- ## Looking forward to an exciting Run-3
  - LHC Run-3 is here, brings larger combined datasets, slight bump in energy
  - Newer parts of the phase space expected to be probed & some exciting excesses to follow up on!

Thank you!