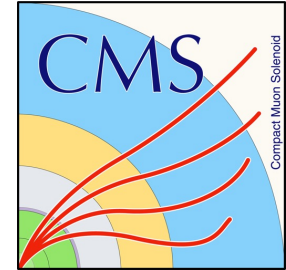# Direct searches for BSM resonances

Mingshui Chen (IHEP Beijing)

On behalf of the ATLAS and CMS collaborations

31st Lepton Photon Conference
MELBOURNE CONVENTION & EXHIBITION CENTRE
17 – 21 JULY
2023

Searches for new resonances at LHC

- Standard Model (SM) is successful for particle physics

- Still a lot of open questions that point to beyond the SM - Hierarchy problem, Dark Matter, flavor anomalies, etc...

- Resonance search is a direct way to probe new physics

- New resonances are predicted in many new physics models:

  - Two-Higgs-doublet model (A, H±, ...)

  - Heavy Vector triplet (W', Z')

  - Vector-like quark, LeptoQuark

  - Axion Like Particles (ALP), Long Lived Particles (LLP), dark sector

  - Supersymmetry

  - Many more...

- LHC is the most direct probe of nature and most powerful discovery machine - **Hope to find hints of BSM**
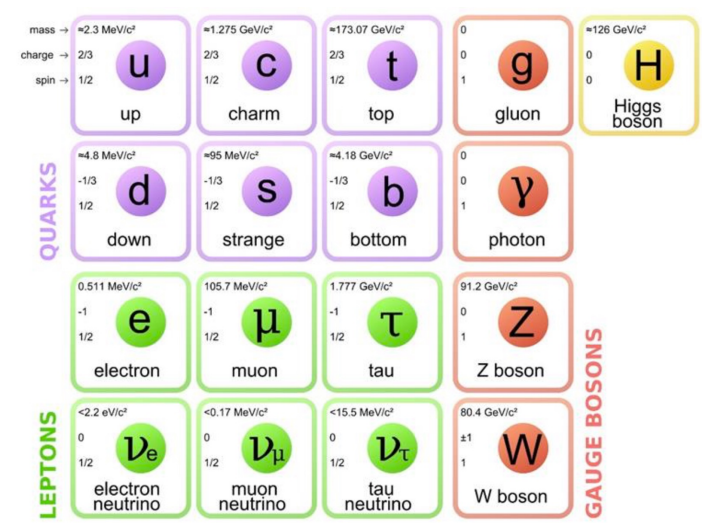
SM of Elementary Particles

A glance at the ATLAS/CMS resonance searches
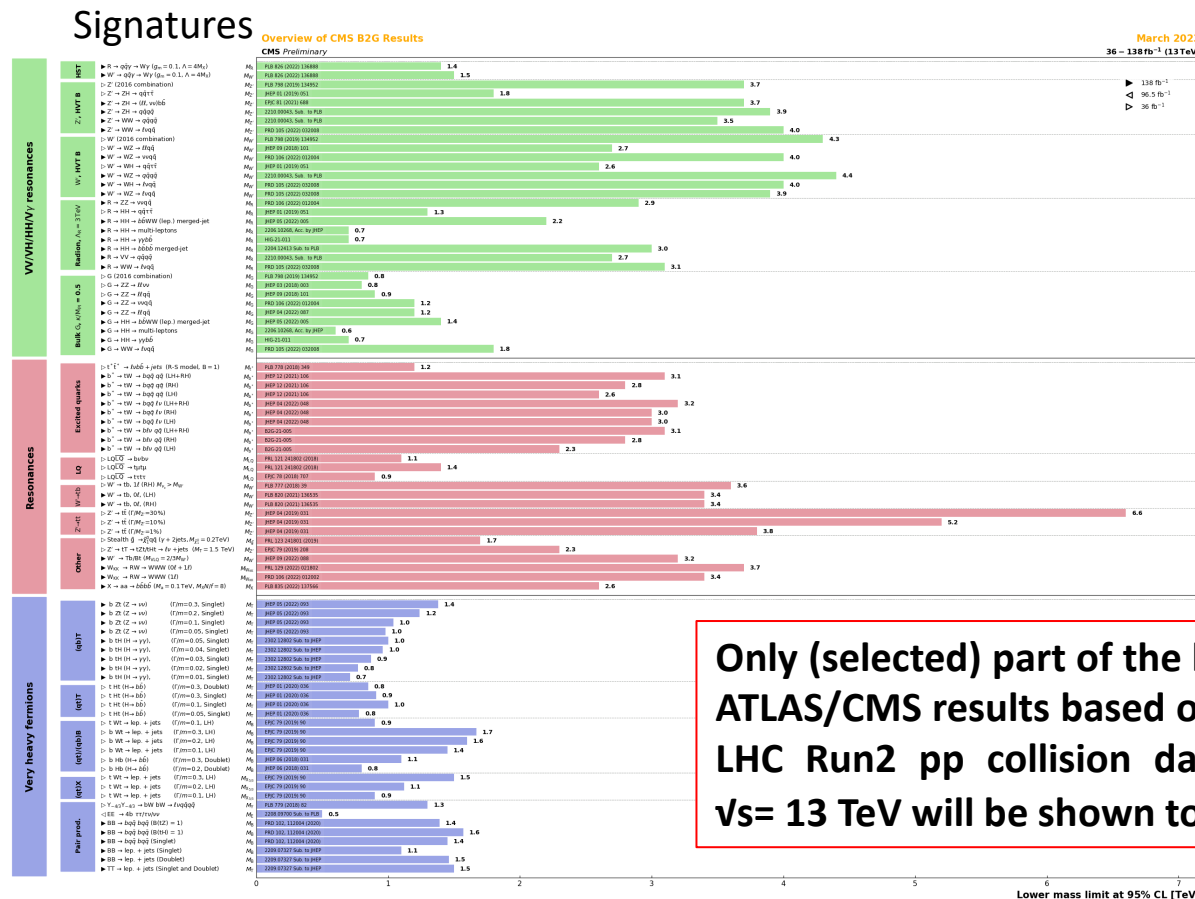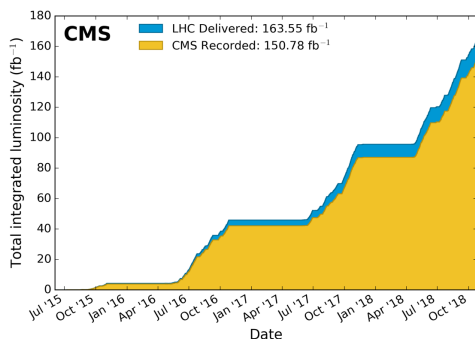
Only (selected) part of the latest ATLAS/CMS results based on full LHC Run2 pp collision data at √s= 13 TeV will be shown today

Probing well into the TeV regime for many final states!

Higgs as a handle or additional Higgs bosons

- The discovery of **the Higgs boson** in 2012 by the ATLAS and CMS has led to a comprehensive program of measurements and searches at LHC.

    ➤ **Provides a new handle for resonance search**

- Many BSM theories predict the existence of a **heavy scalar boson decaying into two Higgs bosons** or **additional scalars** in the extended Higgs sector

Search for resonant X -> HH -> bbWW
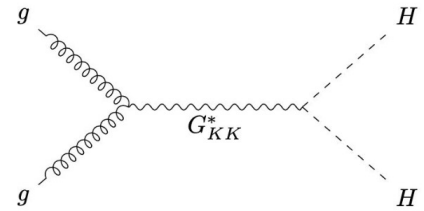
- **Search for spin-0 or 2 resonances within the mass range 250-900 GeV**
- 2nd largest HH branch ratio and consider at least one W boson decaying to leptons
  - high lepton trigger efficiency, but with large ttbar background
- Uses mass-parameterized Deep Neural Network with Lorentz Boost Network as pre-processor
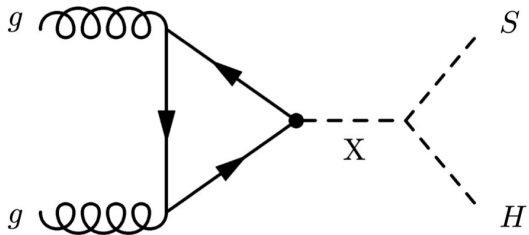 - DNN score distributions used to extract signal

CMS-PAS-HIG-21-005
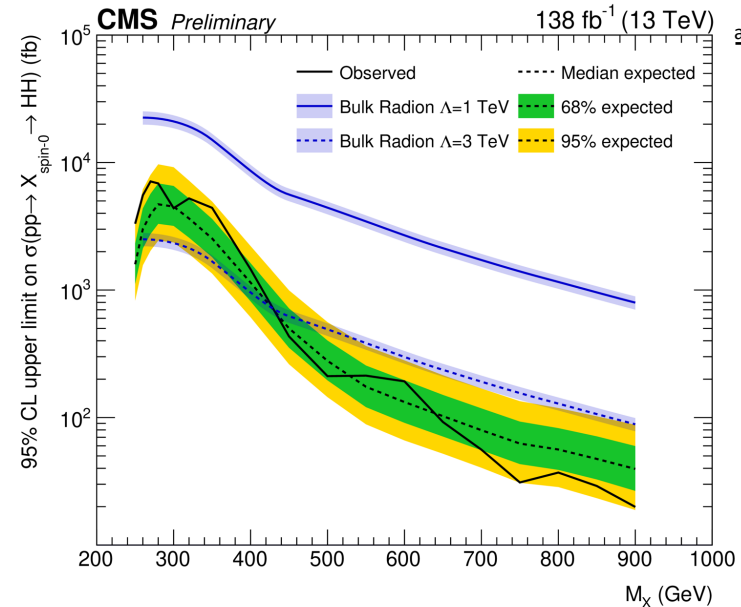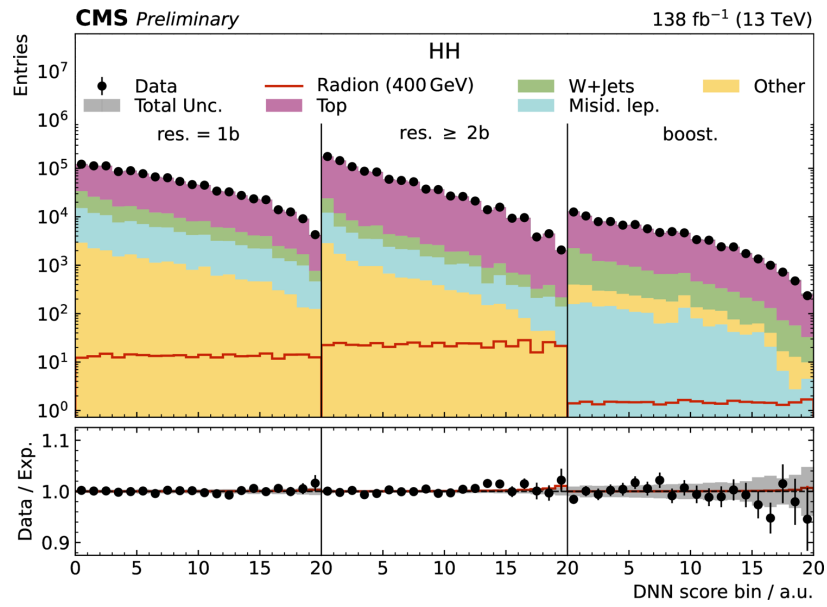
see also
CMS search
at higher Mx region
and ATLAS search

Events categorized according to DNNs and the topology of the H→bb decay

Cross section limits as a function of m_X

Heavy scalar particle decaying into a Higgs boson and new scalar singlet
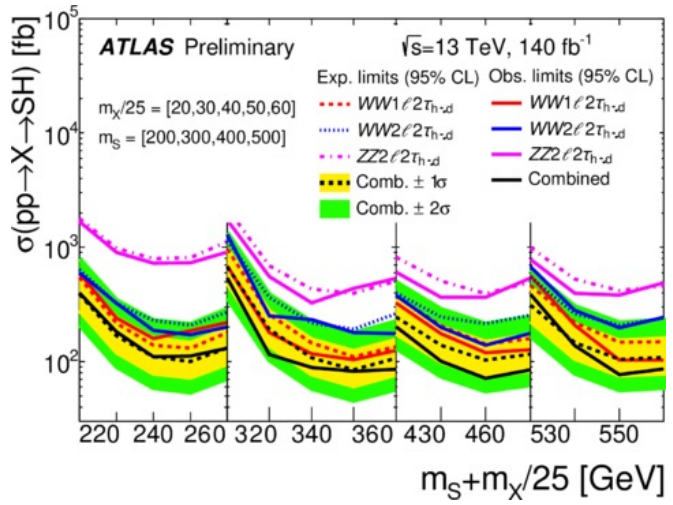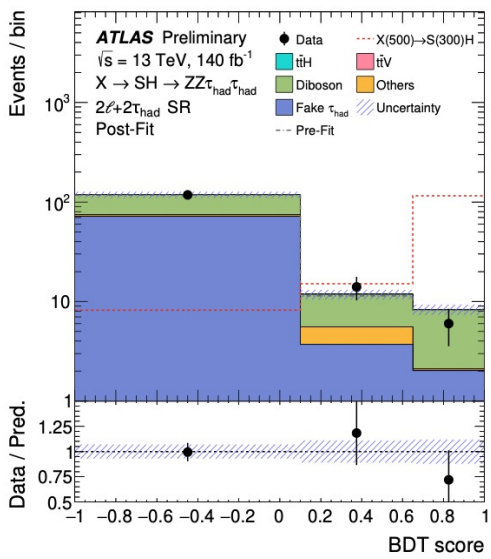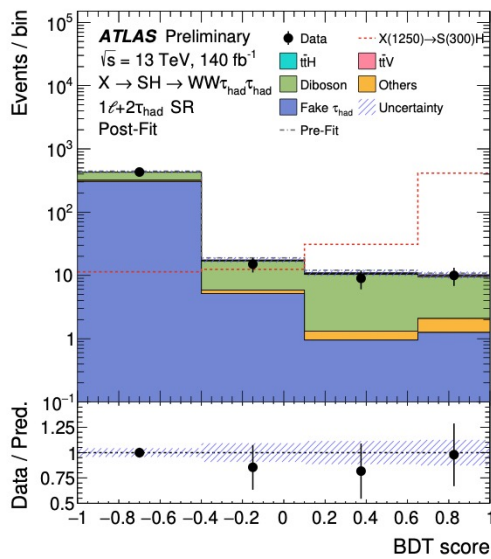
$$X \rightarrow SH$$

Analysis explores

- X masses from 500 – 1500 GeV
- S masses from 200 – 500 GeV
- Higgs decays to tau pairs (hadronically decaying τ)
- S decays to WW/ZZ -> light leptons

ATLAS-CONF-2023-31

This signature-based search is the first kind and is competitive with other searches using different final states in the high mass regions.

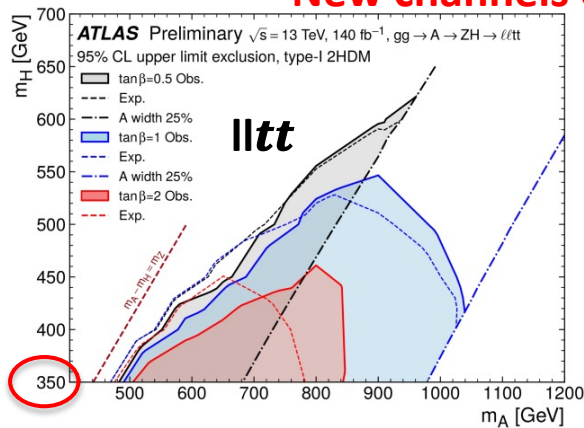# 2HDM $A \rightarrow ZH \rightarrow \text{ll} tt$ or $vvbb$

Search for a heavy CP-odd Higgs boson (A), decaying into a Z boson and a heavy CP-even Higgs boson (H)

- Two-Higgs-doublet model (2HDM):
  - Five Higgs bosons after electroweak symmetry breaking: h, H, A, $H+$, $H-$
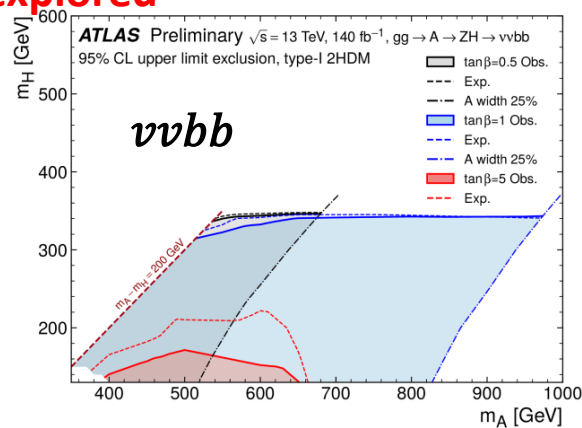 - $m_A > m_H$ is favored
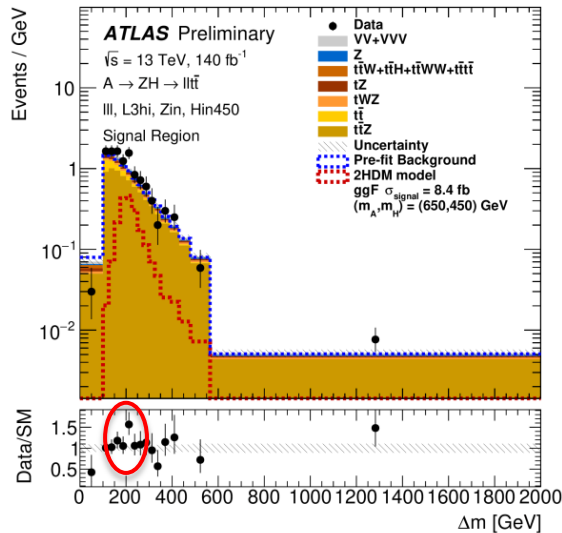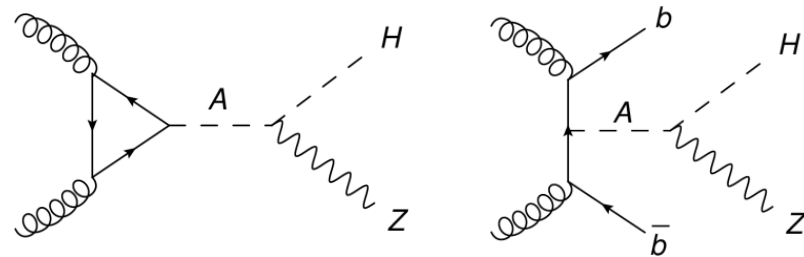
lltt: $Z \rightarrow$ ll and $H \rightarrow tt \rightarrow$ semi-leptonic
- 3 leptons: eee, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$
- at least 4 jets and exactly 2 b-tagged

$vvbb$: $Z \rightarrow vv$ and $H \rightarrow bb$
- $p_T^V(E_T^{miss}) > 150$ GeV
- at least 2 jets, exactly 2 b-tagged or >2 b-tagged

New channels explored
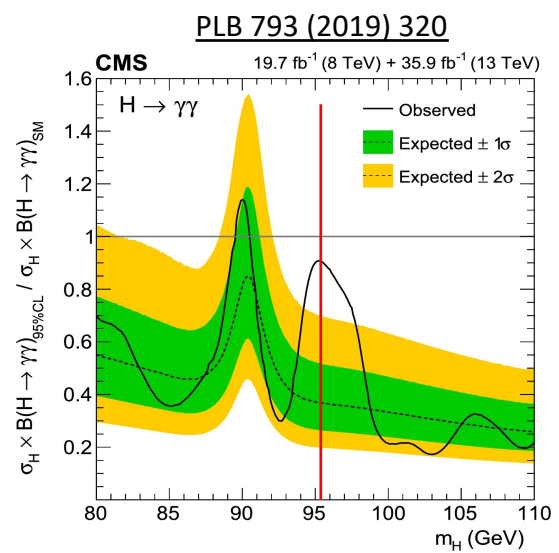

Largest local signifcance of **2.85 σ at (m_A, m_H) = (650, 450) GeV for lltt**

Search for low mass SM-like H $\to \gamma\gamma$

- **Search for narrow signal peak over smoothly-falling background** (direct $\gamma\gamma$, γ + jet, jet+jet processes) except for relic $Z \to ee$
- Events with two high energy isolated photons

PLB 565 (2003) 61-75

PLB 793 (2019) 320
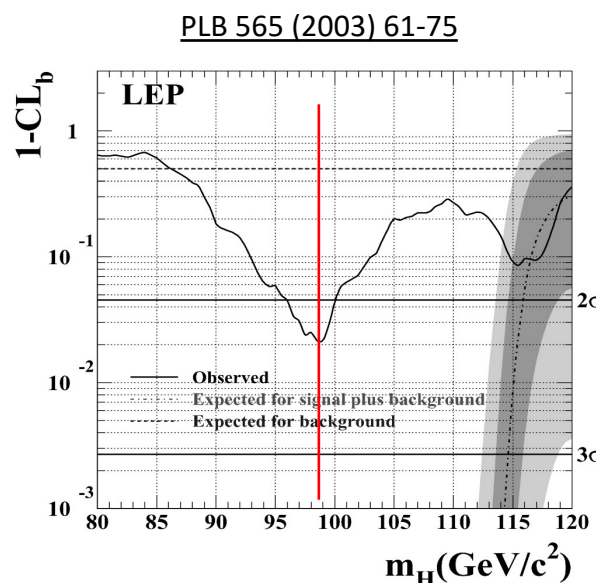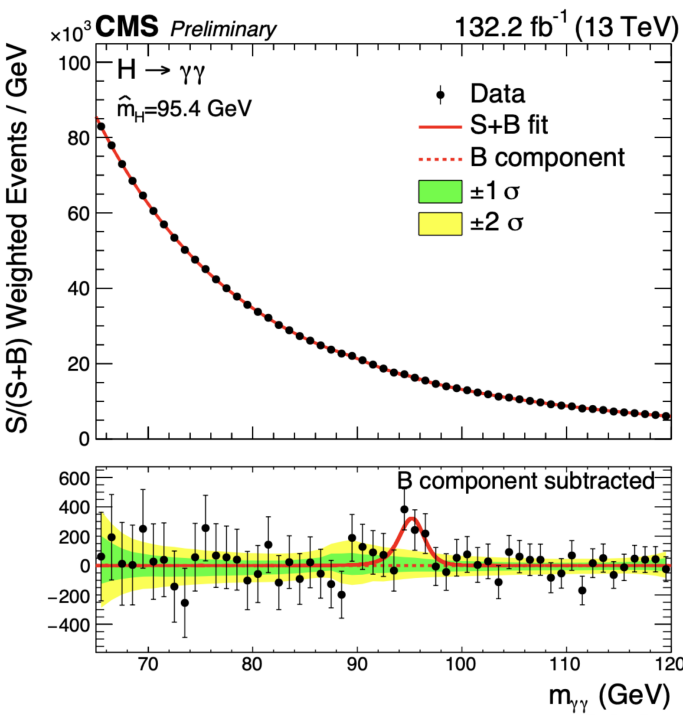
LEP:
local 2.3 σ @ m_H ≈ 98 GeV

previous CMS result at 8+13 TeV Local (global)
2.8σ (1.3σ) @ 95.3 GeV

Search for low mass SM-like H → γγ

Updated results with full Run-2 data
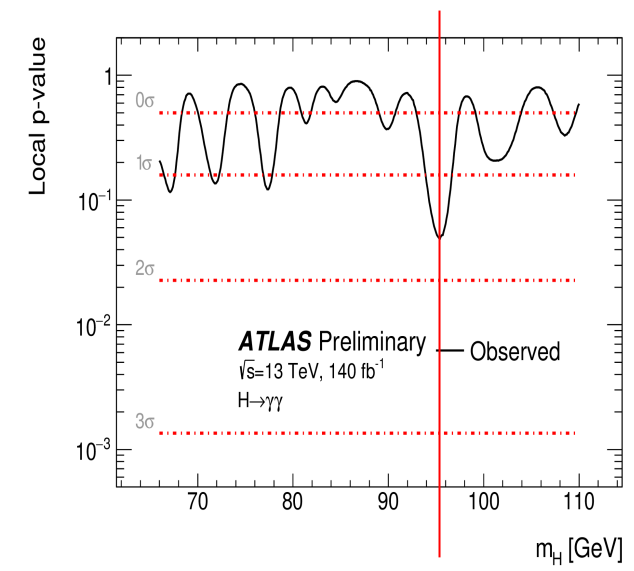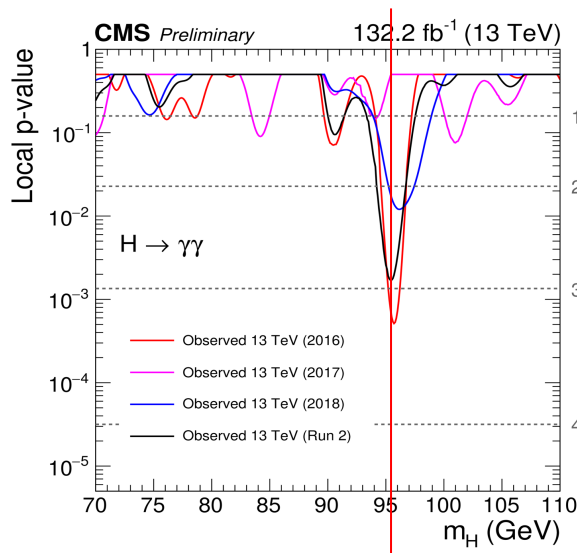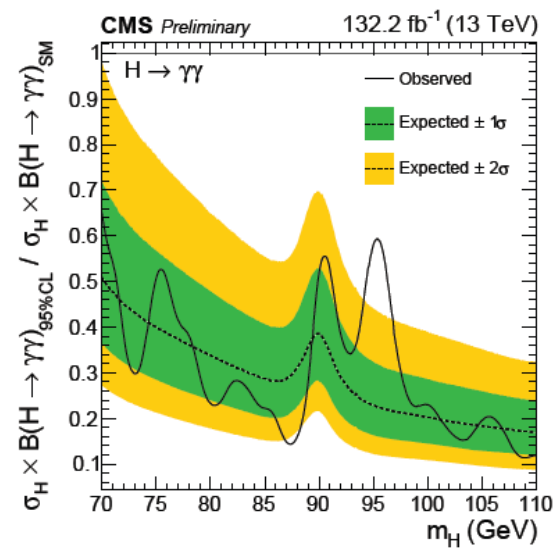
CMS 132.2/fb @ 13 TeV:
local (global) 2.9 (1.3) σ @ $m_H ≈$ 95.4 GeV
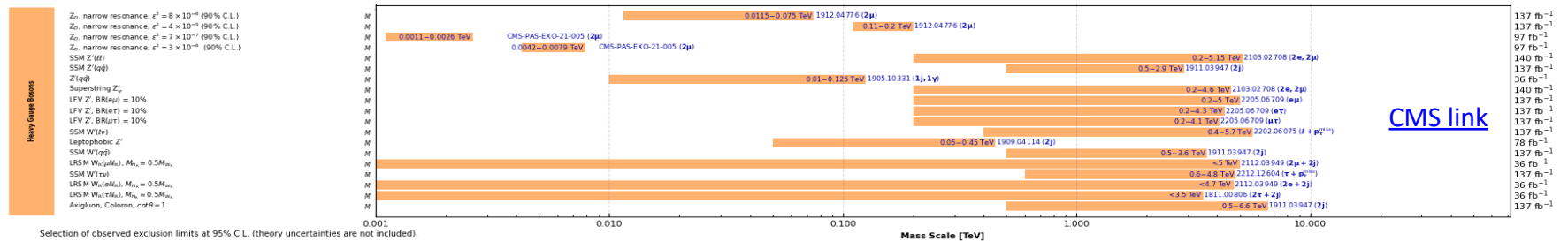
ATLAS 140/fb @ 13 TeV:
local 1.7 σ @ $m_H ≈$ 95.4 GeV

The excess did not grow with luminosity, but remains intriguing.

Spin-1 **W'/Z'**: in many models, e.g. composite Higgs

Possible solution to hierarchy problem

[ATLAS link](#)
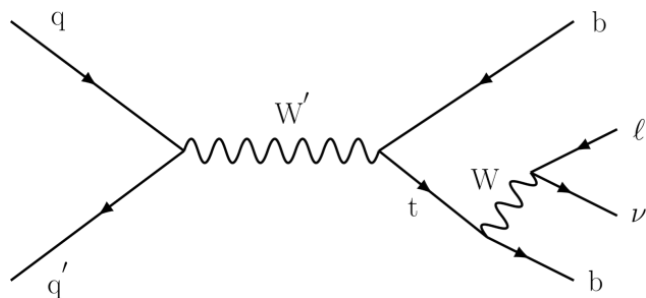
[CMS link](#)

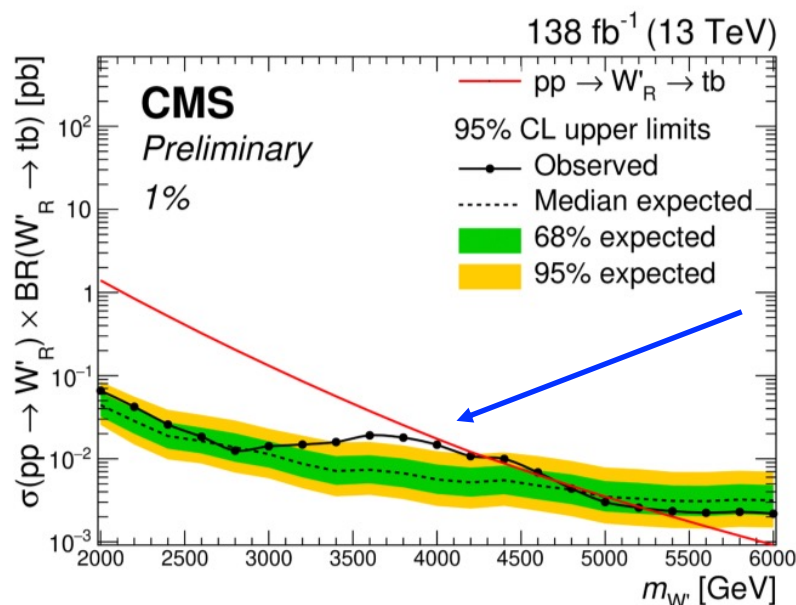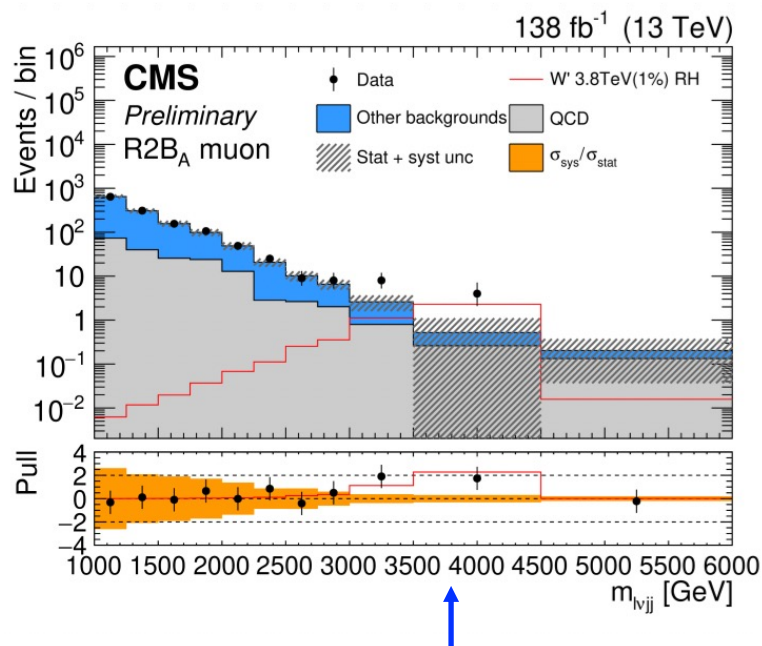# $W' \rightarrow bt$ in leptonic final states

- One muon or electron, and at least two AK4 jets
- Categorization based on b-tagging condition of top jet and W' jet
- **Most stringent limits** to date on W' bosons decaying to a top and a bottom quark

Local (global) 2.6 (2.0)σ for a W' at 3.8 TeV with a relative width of 1%

Right-handed W' bosons with masses up to **4.3 TeV** are excluded at 95% CL.

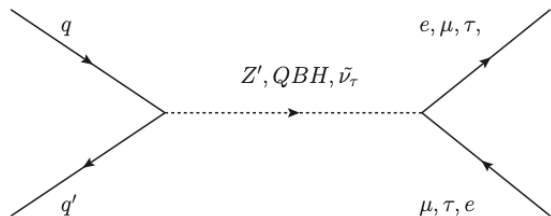# Search for LFV $e\mu$ or $l\tau$ resonance

Lepton-Flavour-Violation predicted in many BSM models

- from Z' decay
- from τ-sneutrino decay — R parity violating SUSY
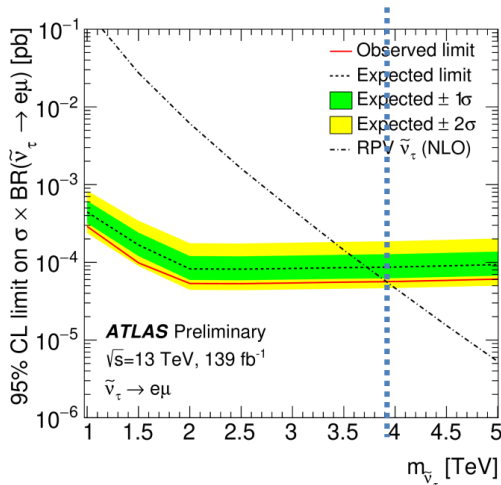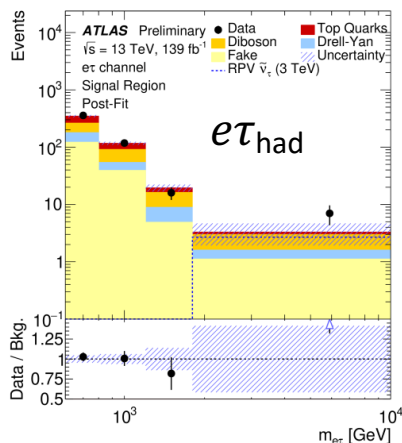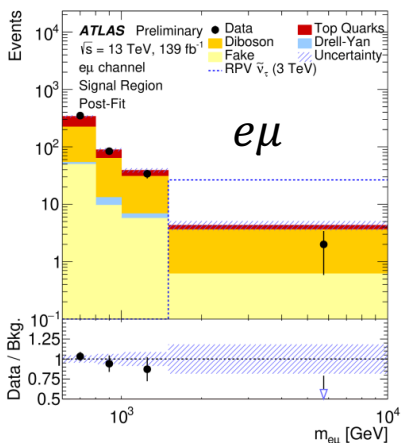- from Quantum Black Hole in models with Extra Spatial Dimensions

Two opposite-sign leptons:

- $e\mu$, $e\tau_{had}$ or $\mu\tau_{had}$
- back-to-back in φ

Significantly improved limit w.r.t. previous searches

Search for narrow trijet resonances
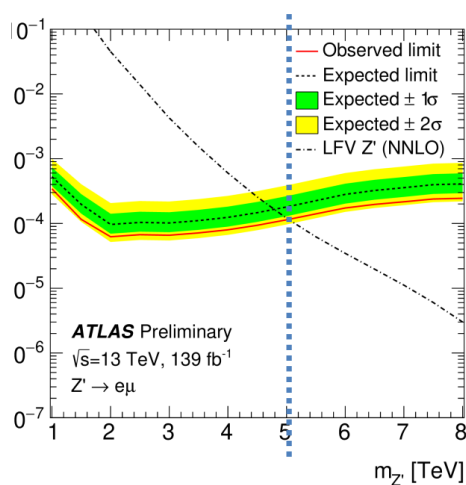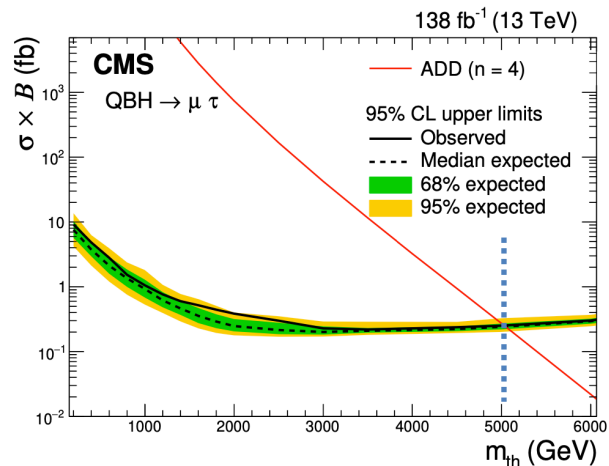
First generic search for new resonances decaying to three jets, predicted in several BSM models:

- **Right-handed** Z (Z_R) directly to 3 gluons: $Z_R \rightarrow 3g$
- **Excited quarks** to qV -> 3q,
- **Kaluza-Klein gluon** -> Radion + g -> 3g

- Analysis strategy follows established dijet bump-hunt searches
- Background model with fit to data using empirical functions
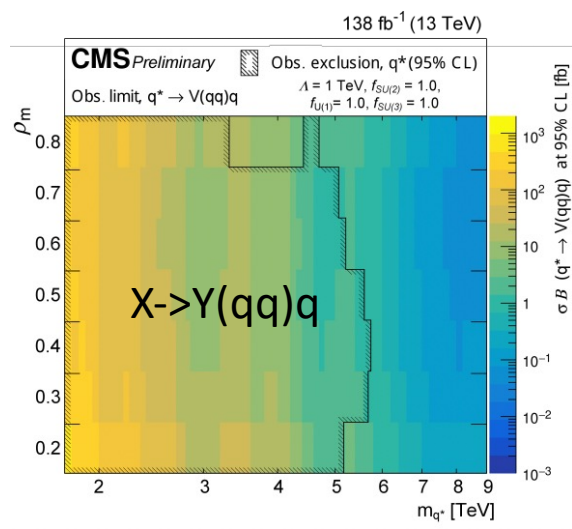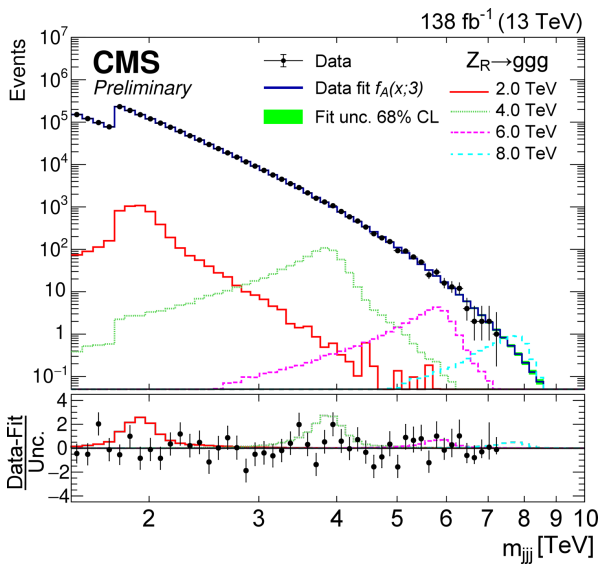
ρ_m: mass ratio between Y and X
First search in range $\boldsymbol{\rho_m}$ 0.2 to 0.8
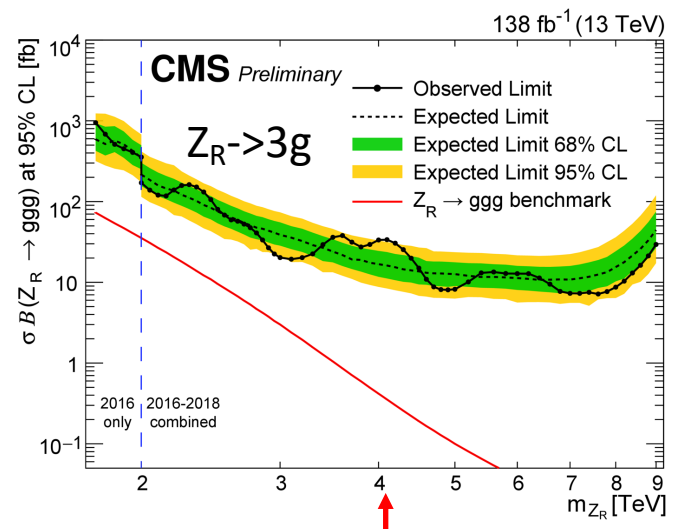
Local 2.1(2.2)σ at 4.1 TeV for nominal (narrow) width

LeptoQuarks

Colored states with both baryon and lepton quantum numbers
Could explain recent hints of lepton universality violations in the flavour sector

CMS summary
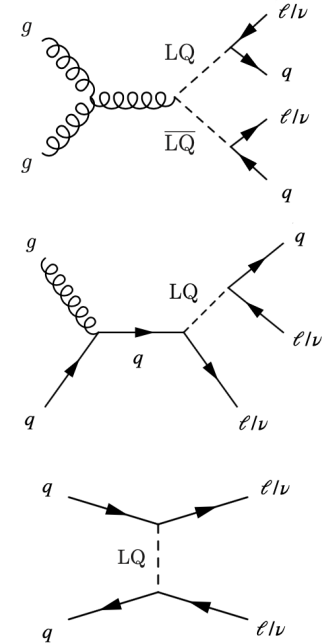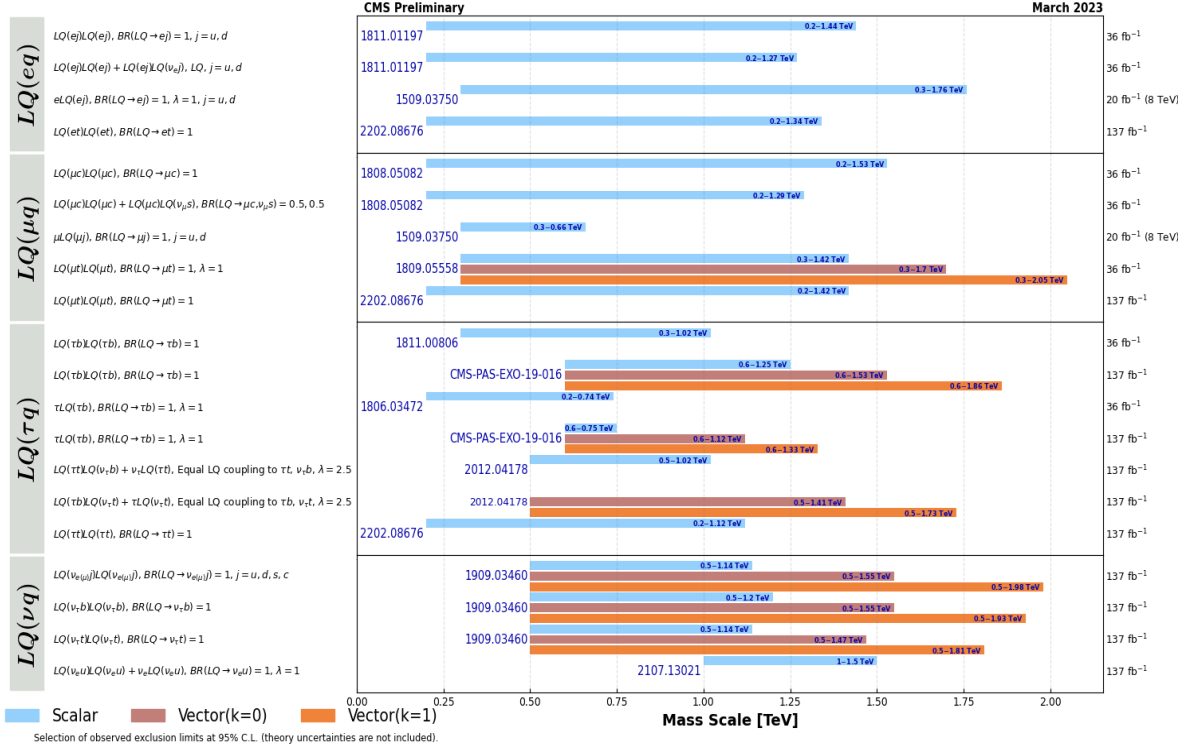
Several different production modes (**pair, single and non-resonant**) and final states explored

Similar sensitivities from ATLAS

Search for 3rd generation LeptoQuark

Search for pair produced LQ decaying into bτ pairs

- Analysis channels: $\tau_h\tau_h$ + > 1b and $\tau_h\tau_{e/\mu}$ + > 1b

- Parametric Neural Network (PNN) trained using also LQ mass as input to distinguish from top backgrounds

  - Maintain good separations for all LQ masses
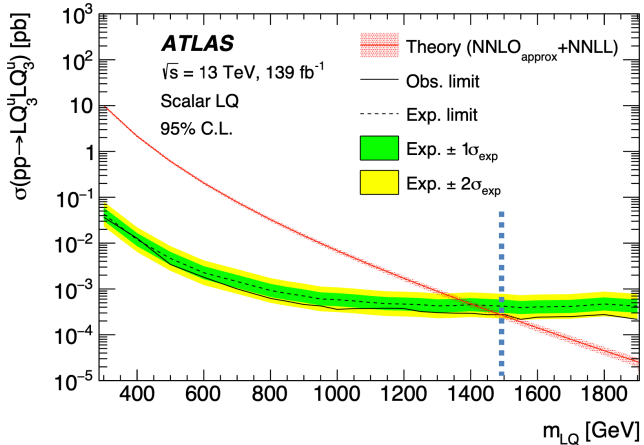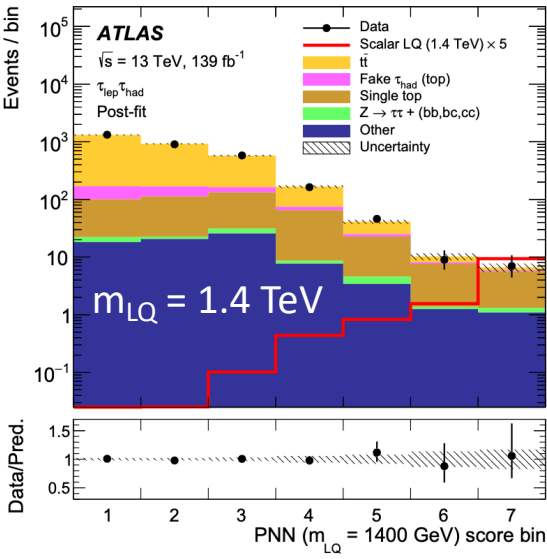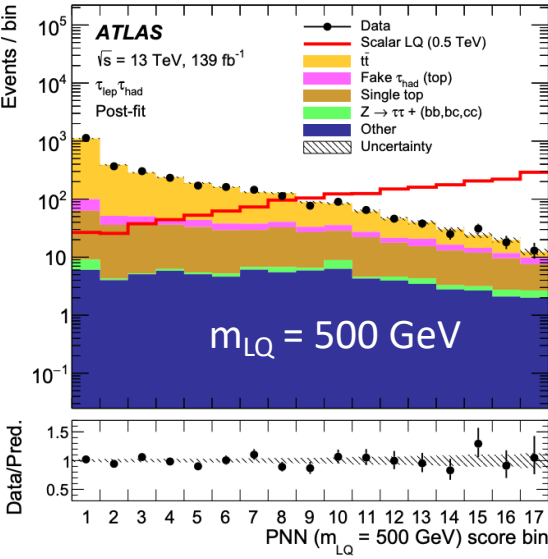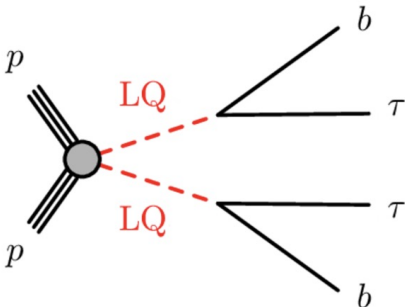
[CMS analysis](#) explored single, pair, as well as non-resonant production of LQ

LeptoQuark produced in lq collisions and coupling to τ leptons

- **New production mode** probed thanks to recent advances in precision of lepton PDFs

- Final state with a jet, significant missing transverse momentum, and a **τ lepton** reconstructed through its leptonic or hadronic decays

- These results extend the constraints on the leptoquark-τ-b couplings and leptoquarks to light flavour quarks through previous searches in other production modes

CMS-PAS-EXO-22-018
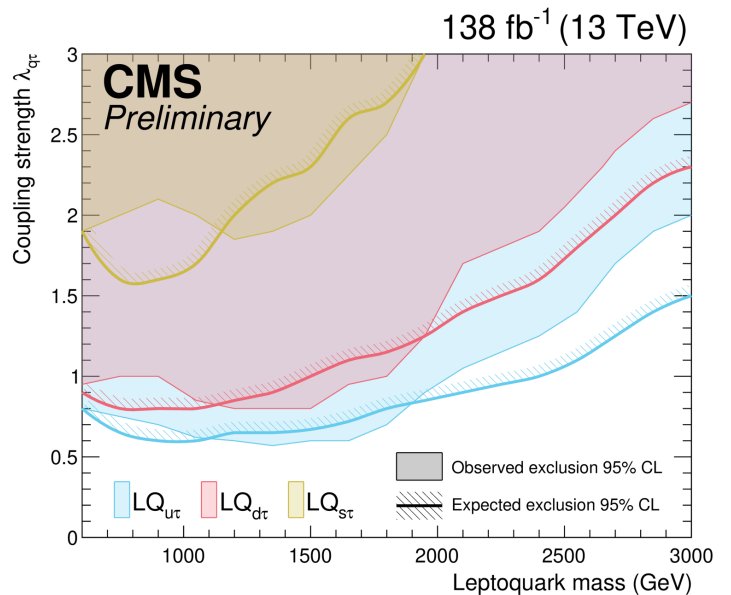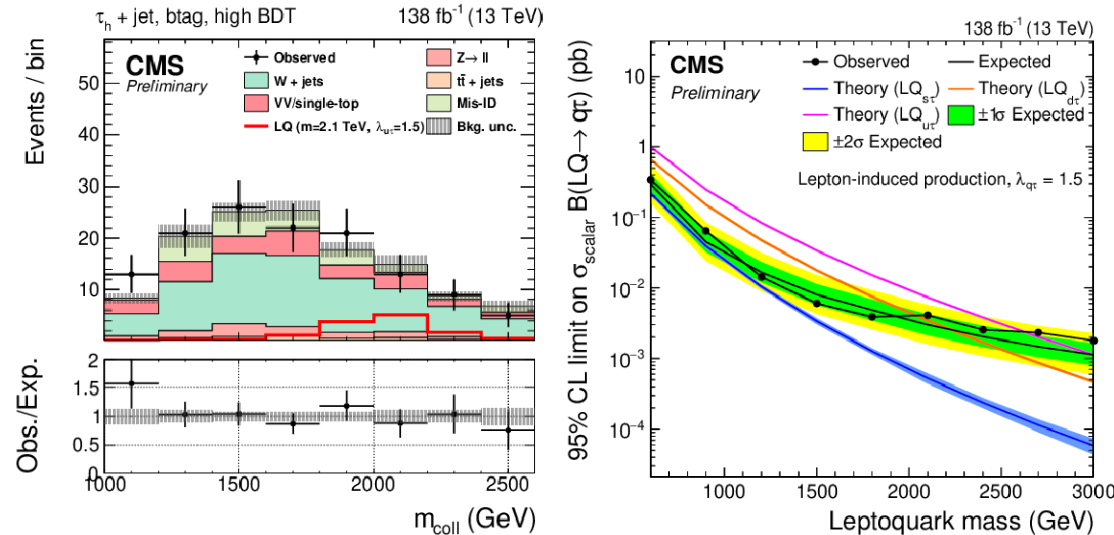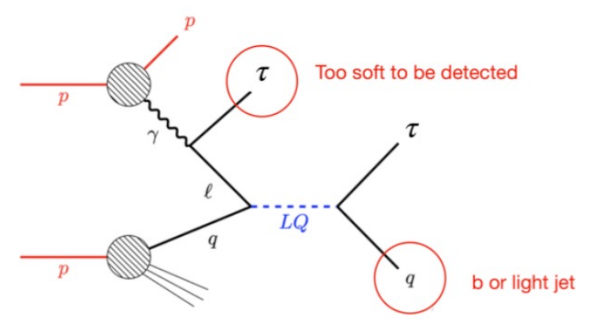
ALP, LLP, Dark Sector

- **Axion Like Particles** (spin-0 **pseudoscalar**)
  - Specific case of axion is solution to Strong-CP-problem
  - Possible portal to dark matter

- **Long Lived Particles**
  - May answer many questions related to hierarchy and naturalness
  - Massive mediators, small phase space, small coupling

- **Dark mesons**
  - Strongly-coupled dark matter candidate

Pseudoscalar a with top quarks

Many BSMs (2HDM+S, NMSSM, etc.) predict light "a", may explain galactic γ emission excess

- Two searches in ATLAS:
  - Direct pseudo-scalar production: $\mathrm{t\bar{t}}a$
  - $\mathrm{t\bar{t}}$ with $t \to H^+b$, $H^+ \to W^+a$, $a \to \mu\mu$

- Targets di-muon decays, for high mass resolution
  - $15 < m(a) < 72$ GeV
  - $120 < m(H^\pm) < 160$ GeV

- CMS $\mathrm{t\bar{t}}a$ analysis considers also ee and $\tau\tau$ decays, and in a wider mass range

$a \to \mu\mu$

$a \to \tau\tau$
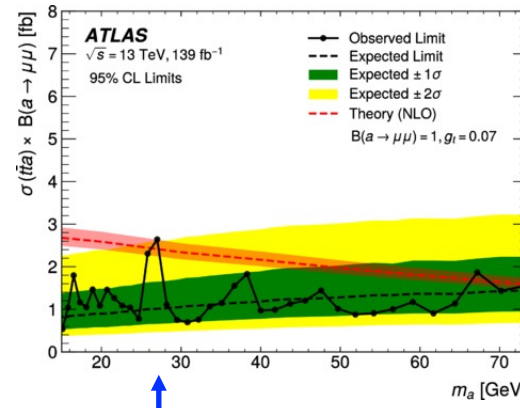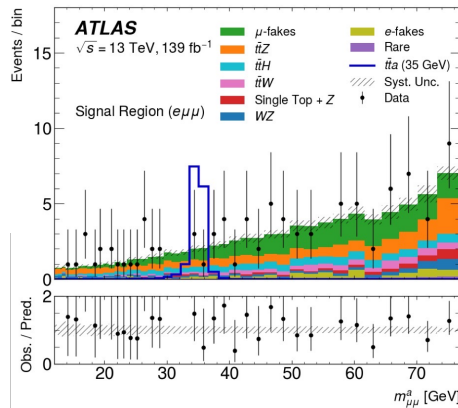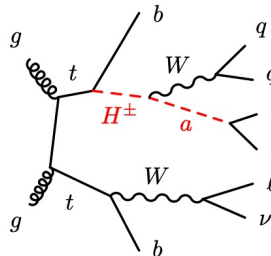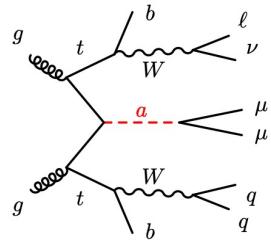
Local 2.7σ @ m_a=27 GeV
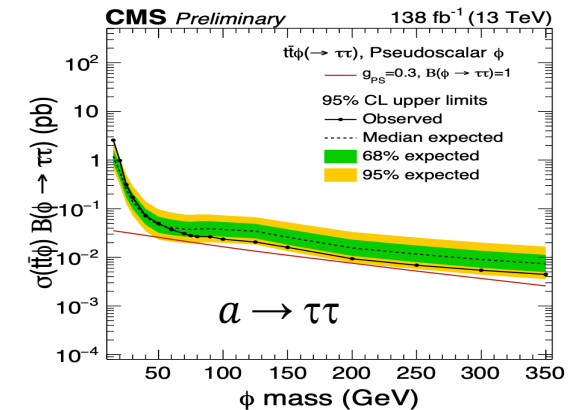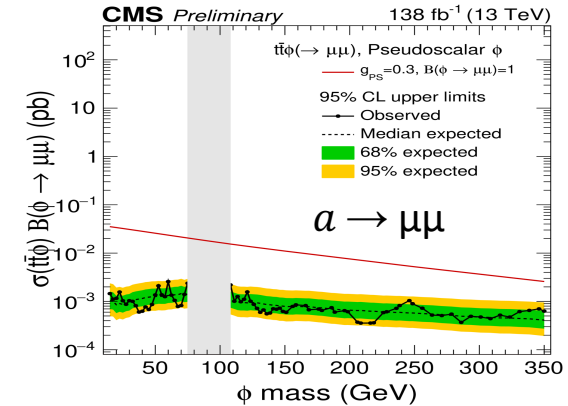
Search for axion like particle through $H \to Za \to 2l2\gamma$
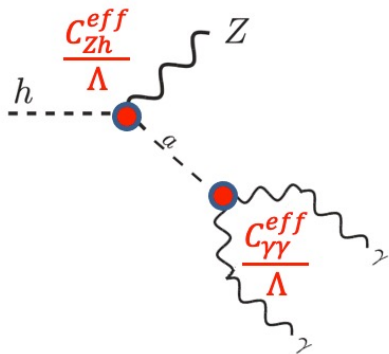
- Photon ID modified due to overlapping photons in ALP→γγ decay
- Parametric BDT trained using event kinematics, mass hypothesis, and photon quantities for rejecting background

2.6σ @ m_a=3 GeV
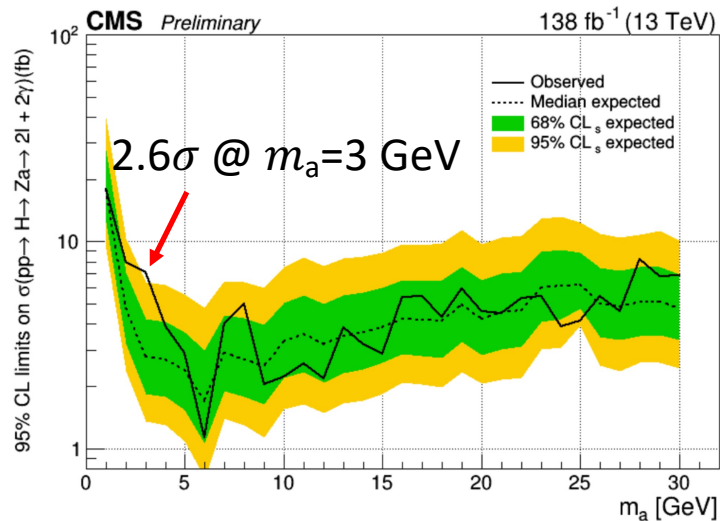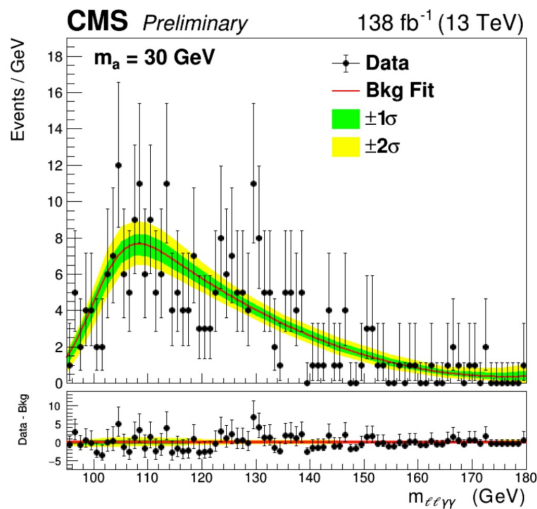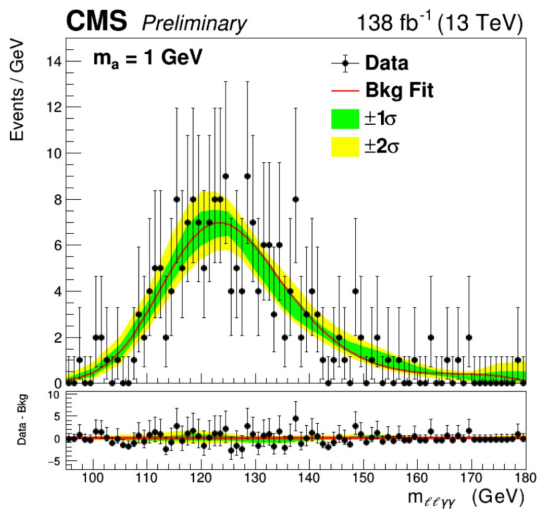
Limits set at the ~1-20 fb level
First search of its kind!

Search for LLPs with muon detector showers

- Covers long-lived particles (**LLP**) with decays far away from interaction point (sensitive to large $c\tau$), complementary to searches using decays in the tracker region

- Excellent background suppression from shielding material

- Large **cluster of hits (>100 hits)** in the muon system with no jets or tracks

- Muon system acts as a **sampling calorimeter**: sensitive to a broad range of decays: q, τ, γ, e...

- Unique signature due to the presence of steel in the CMS muon system

CMS *Simulation Supplementary*

LLP

CSC hit Cluster

Search for LLPs with muon detector showers

- Event selection: large missing transverse momentum p_T^{miss} (≥ 200 GeV) phase space
- Split events into 3 mutually exclusive categories: double clusters, single CSC cluster, single DT cluster
- Use data-driven ABCD method for background estimation: N_{hits} as main discriminator

N_{hits} as main discriminator

Twin higgs model (dd decay)

Twin higgs model (mixed decay)
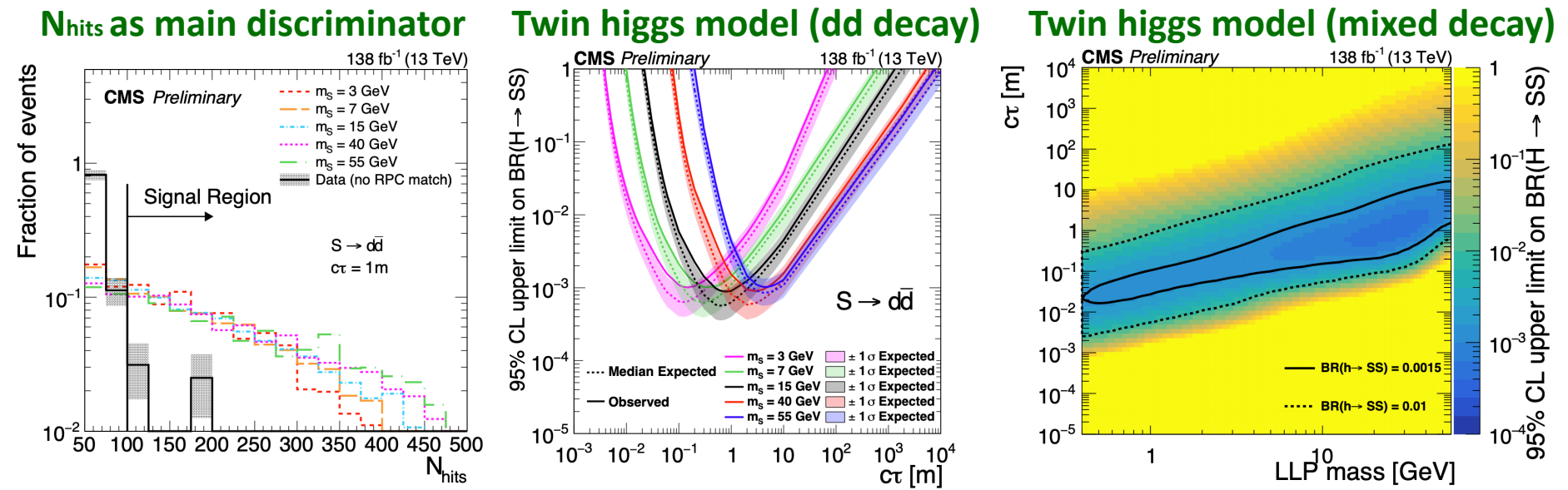
- No excess above SM background observed
- First sensitivity to **sub-GeV mass LLPs** at BR(H →ss) = 10^{-3} level
- First sensitivity to **dark shower model** produced from Higgs decay at BR(H →ss) = 10^{-3}

Search for long-lived HNLs with muon detector showers

NEW **RESULT!**
CMS-PAS-EXO-22-017

- The long-lived Heavy Neutral Lepton (**HNL**) is produced via a W boson decay and through its mixing with an SM neutrino.

- Decay products of HNLs could interact with the shielding materials in the CMS Muon System and create hadronic and electromagnetic showers detected by the muon chambers

  - Sensitive to HNLs with masses < 10 GeV and cτ of the order of meters

- Sensitive to HNL couplings to all three generations of leptons.

Mingshui Chen (IHEP Beijing)   Direct Searches for BSM Resonances, Lepton Photon 2023   22
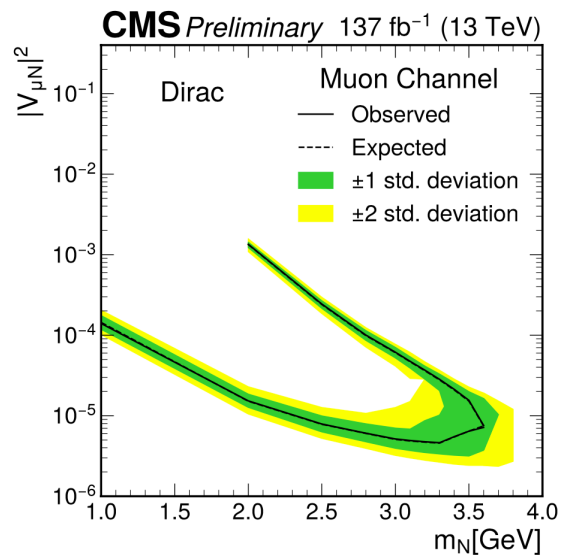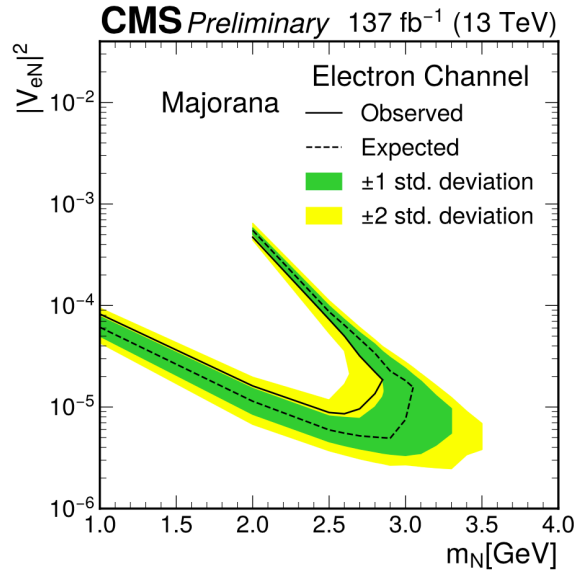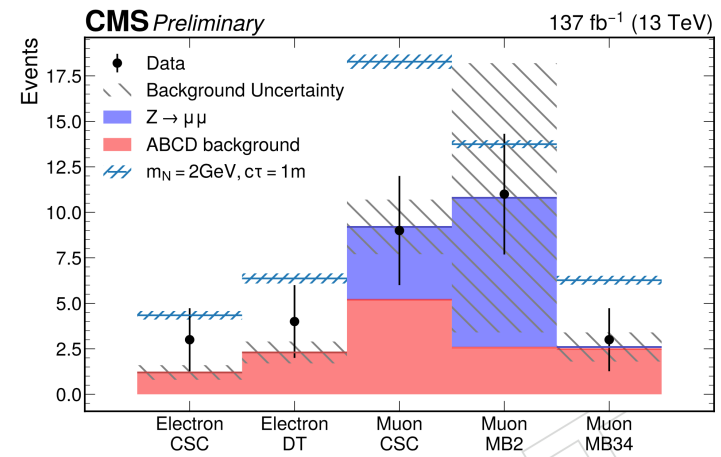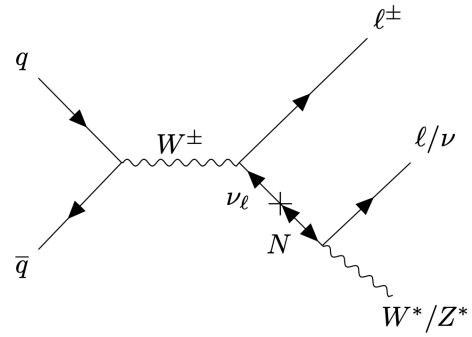
Dark Matter could arise in the form of composite mesons: originating from strongly-coupled, SU(2) dark flavour symmetry conserving models and decaying gaugephobically to top and bottom quarks

First search for pair-produced dark pions:

- Either 3*t*1*b* or 2*t*2*b* with no intrinsic missing transverse energy
- Fully hadronic top decay channel is considered, resulting in eight to ten jets of which at least four originate from bottom quarks
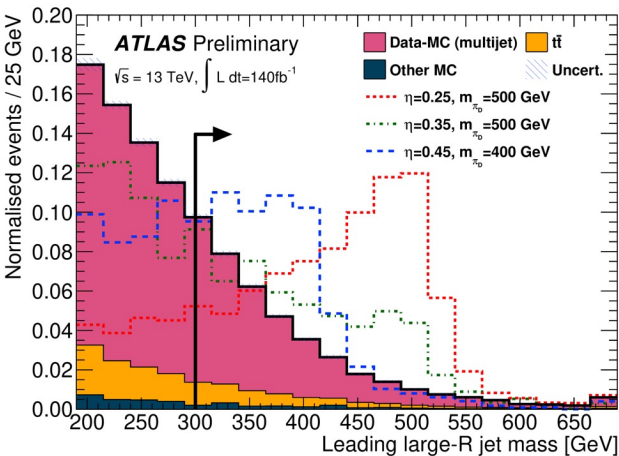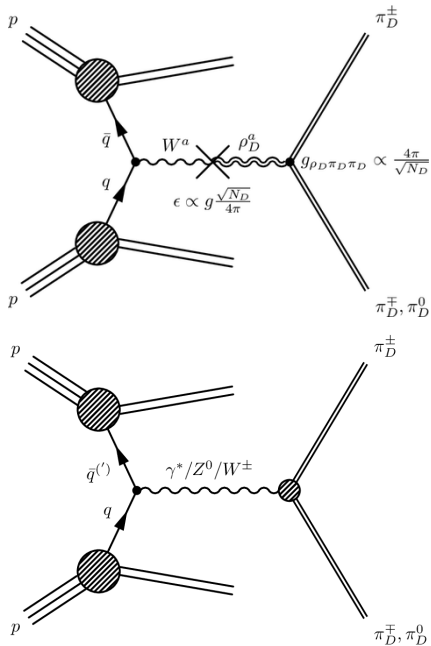
Large-*R* jets are reclustered with a fixed radius parameter of *R* = 1.2
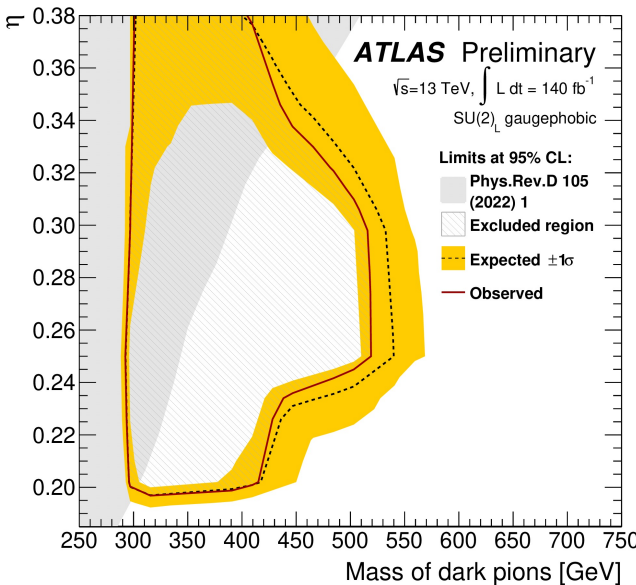
$$\eta = m_{\pi_D} / m_{\rho_D}$$

Searches for SUSY

A whole search program by itself

- Can answer many of the unresolved questions
- Its lightest supersymmetric particle (LSP) potential dark matter candidate

ATLAS summary
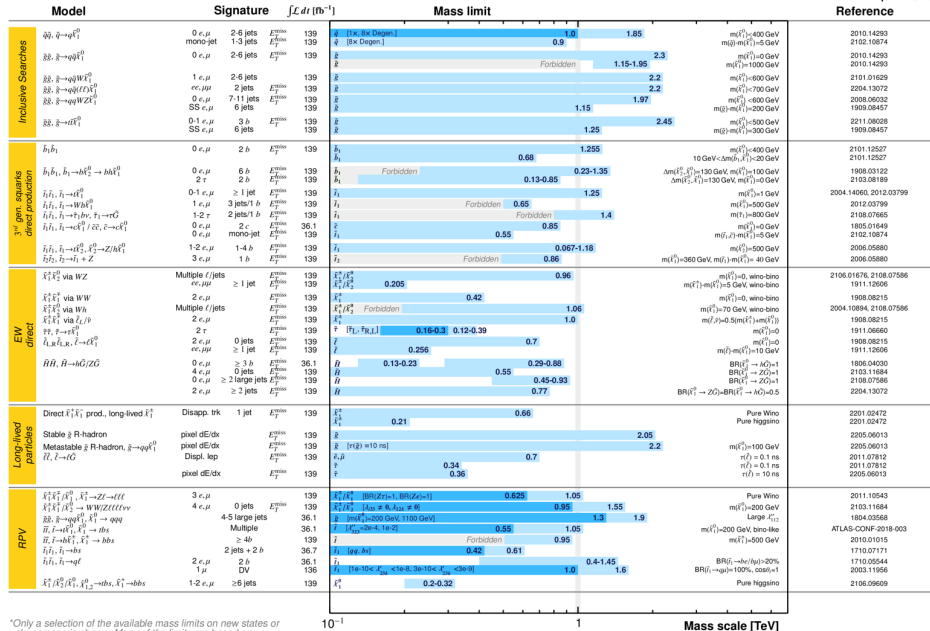
gluino limit ~2 TeV

stop/sbottom limit ~1 TeV

EWKino/slepton < TeV

Similar sensitivities from CMS
CMS SUSY summary plots

Search for EW SUSY production in states with two tau leptons

- Search with hadronic τ_h final states which has higher BR

- Improvements in Recurrent Neural Network tau identification

- **First sensitivity for stau R-only scenarios** (right-handed stau pair production) at LHC
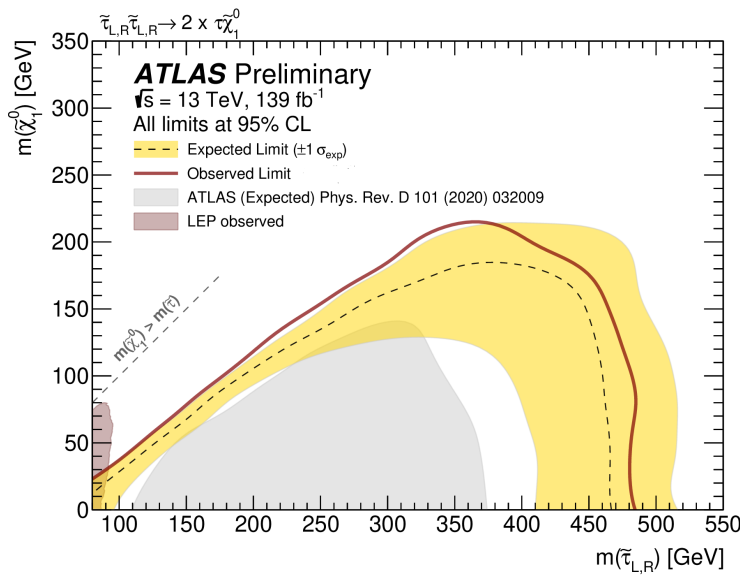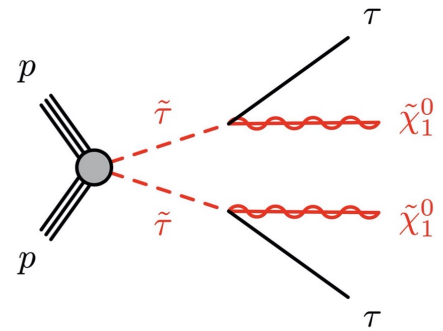
Significantly improved limit w.r.t. previous searches for $\tilde{\tau}_{L,R}$ scenarios
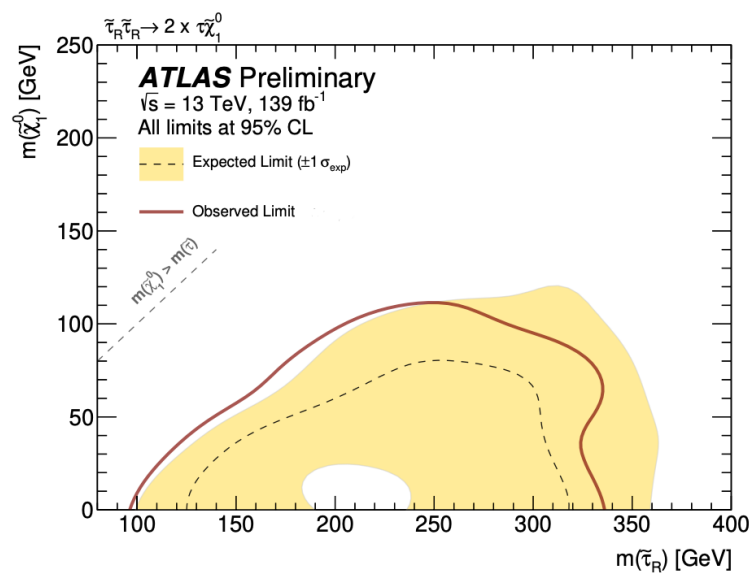
$\tilde{\tau}_R$ masses excluded up to 330GeV

Search for SUSY in final states with disappearing tracks

Search for **semi-stable charginos** in the final states characterized by varying numbers of jets, b-tagged jets, electrons, muons and disappearing tracks.

- Targets a wide range of production modes appearing in simplified models of R-parity conserving SUSY, including gluino, top and bottom squarks, and EWKino pair production
- Transverse length of signal-candidate tracks: characterize chargino lifetimes
- dE/dx energy loss of signal-candidate tracks: increase sensitivity to charginos with a large mass
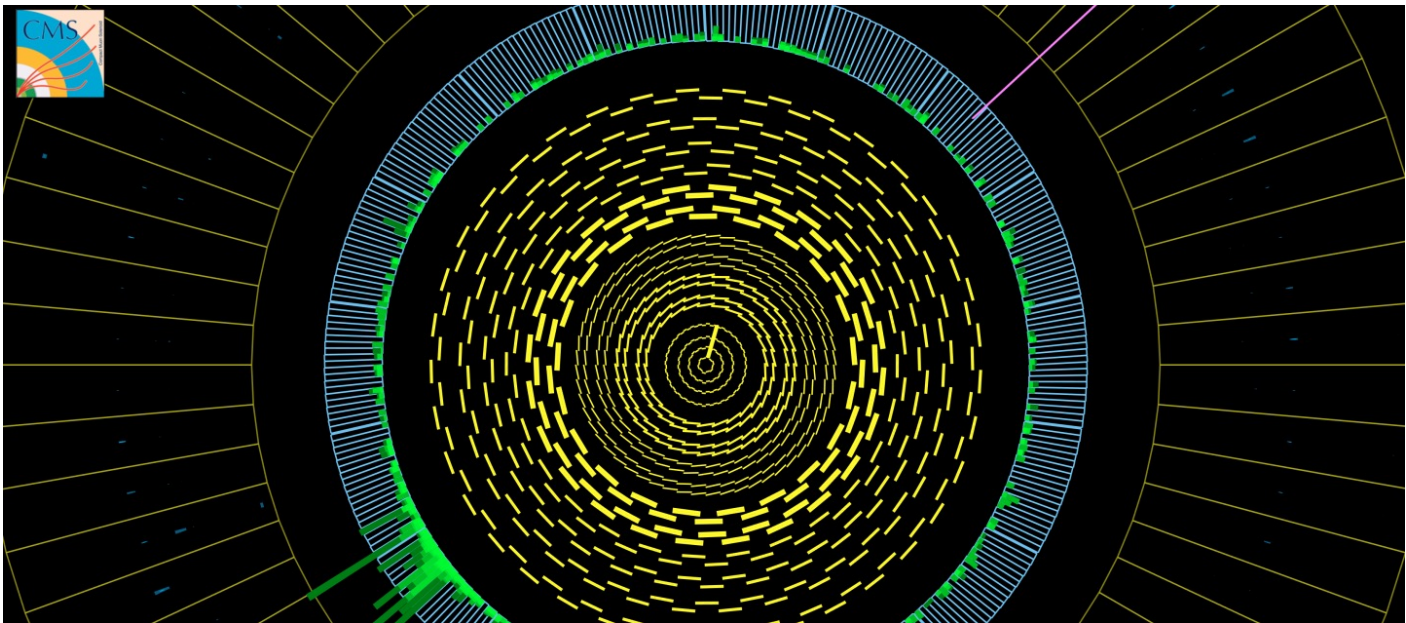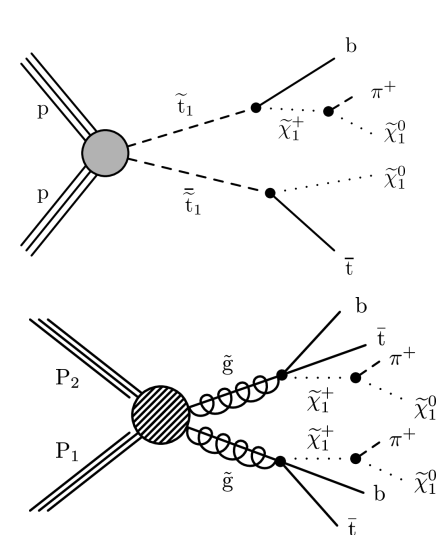
CMS simulated event displays showing a disappearing track

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Previous analyses:
ATLAS EPJ C 82 (2022) 606
CMS PLB 806 (2020) 135502
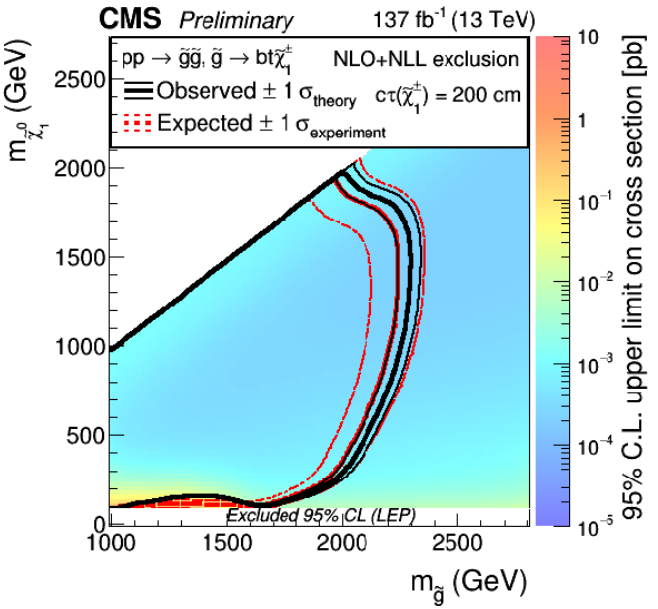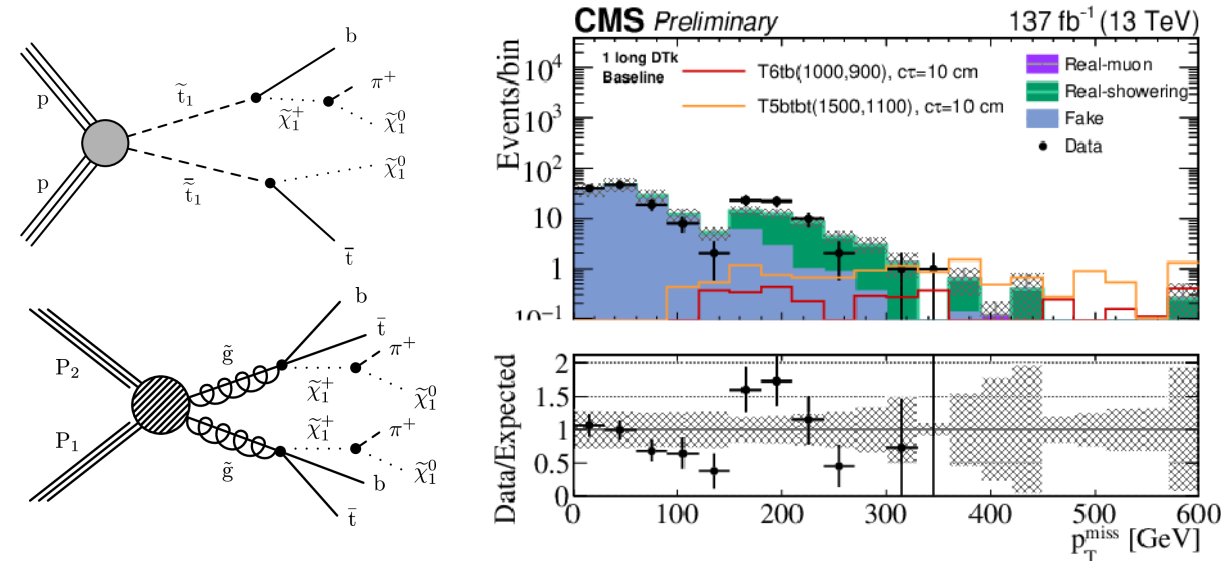
gluino masses excluded up to 2.3 TeV

- Two-body final states: **jet+Y**, where Y can be a lepton (electron or muon), a photon, or another jet

- Representation of autoencoder architecture used to train and select anomaly regions (AR)

- AutoEncoder (AE):

  - Commonly used with unsupervised learning

  - Trained with 1% randomly selected events

  - Alerts to anomalous events with high loss

Anomaly score distribution for data & anomaly scenarios

$$loss = \frac{1}{n} \sum_{i=1}^{n=1287} (x_i - \hat{x}_i)^2$$
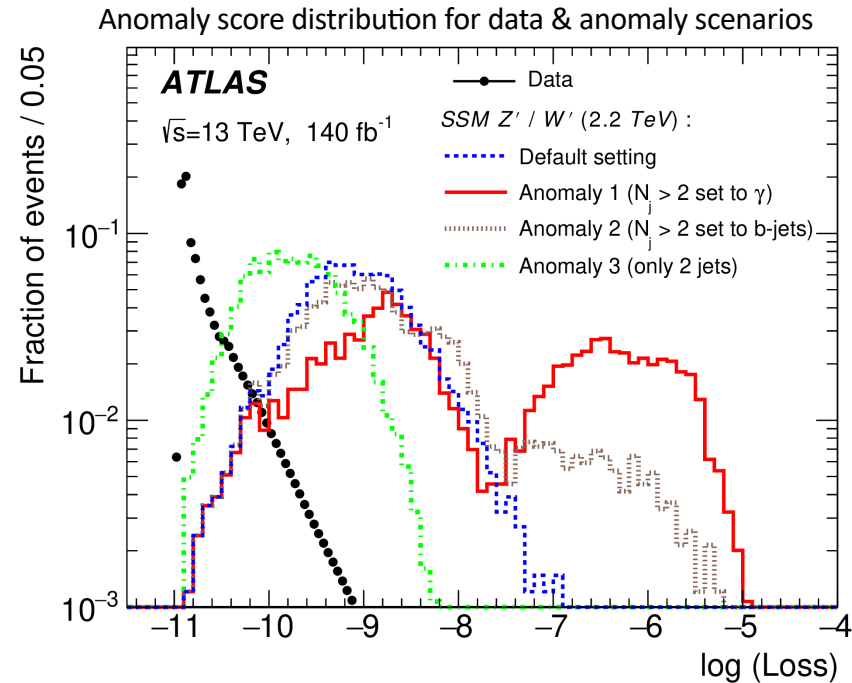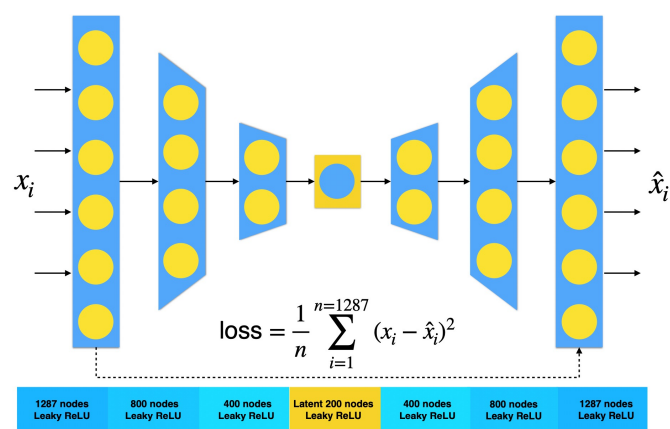
1% of randomly chosen collision data triggered with an isolated lepton.

Invariant mass spectra in each anomaly region are examined for any localized excesses

Improvements of the discovery sensitivity

Largest excess reported by BumpHunter at $m_{j\mu}$ = 4.8 TeV with 0% width in 10 pb AR: local significance of 2.9σ
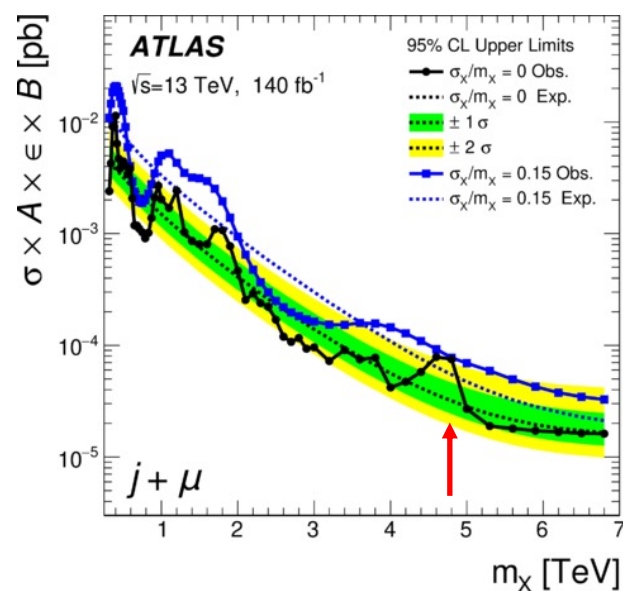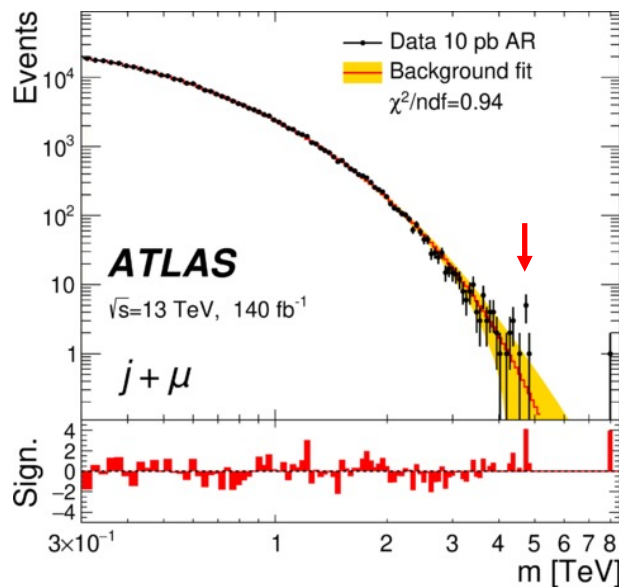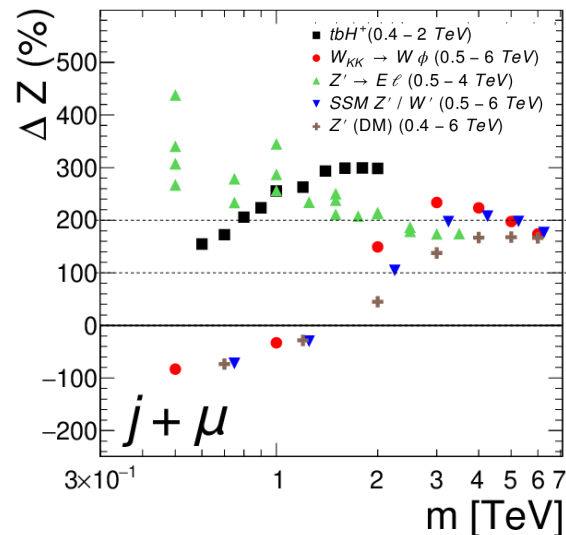

No significant resonance-like signal found

Summary

- Resonance search remains an active area
  - Wide variety of models, parameter space under exploration
  - Many new results with LHC Run 2 data from ATLAS and CMS
    - New signatures, new techniques
- No direct evidence of new physics yet, but several mild excesses
  - Where to look at with more data
- Future prospects:
  - Continued data analysis in Run-3 and HL-LHC
  - Further development of analysis techniques and novel ideas
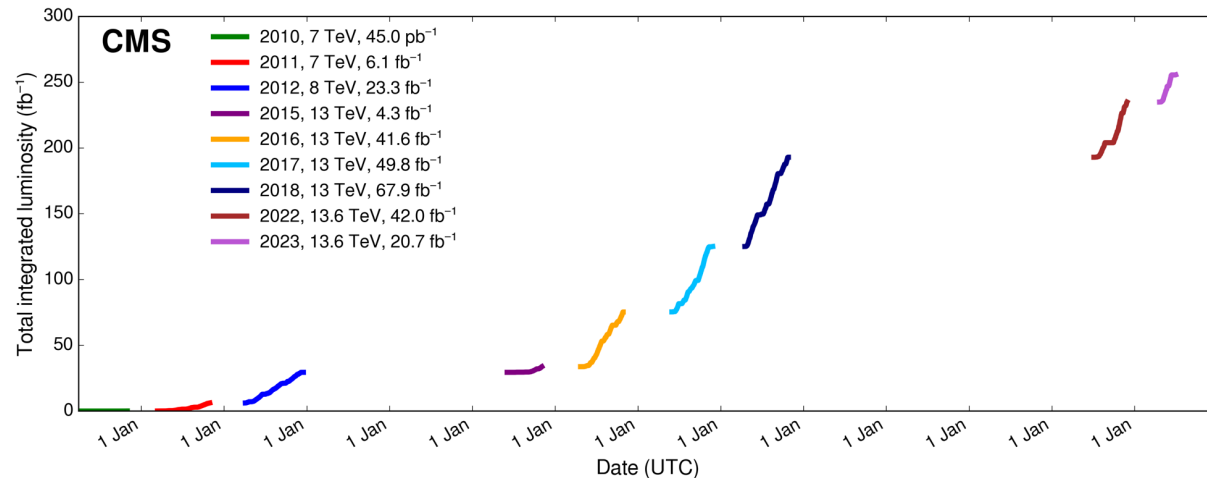
Thank you!

List of talks on direct searches @ LP2023 from ATLAS and CMS

Searches for BSM physics using challenging and long-lived signatures with the ATLAS detector (Emily Filmer)

Searches for supersymmetric particles with prompt decays with with the ATLAS detector (John Kenneth Anders)

Searching for new symmetries in the Higgs sector at ATLAS (Yanlin Liu)

Searches for Dark Matter with the ATLAS Experiment at the LHC (James Frost)

Searches for BSM resonances in ATLAS (Makayla Vessella)

Search for new physics with long-lived and unconventional signatures in CMS (Daniel Diaz)

Leptoquark searches at CMS (Ben Kilminster)

Dark matter and strong SUSY searches from CMS (Varun Sharma)

Searches for electroweak SUSY and compressed SUSY spectra from CMS (Harjot Kaur)

Searches for additional scalars with two photons in the final state at CMS (Junquan Tao)

Searches for new physics in CMS in events with jets, leptons and photons in the final state (Andrew Evan Hart)

Searches and tests for lepton-flavour-violating processes at CMS (Luigi Marchese)

And comprehensive results available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome
https://cms-results.web.cern.ch/cms-results/public-results/publications/