Exotics and BSM in ATLAS and CMS (non SUSY, non DM)

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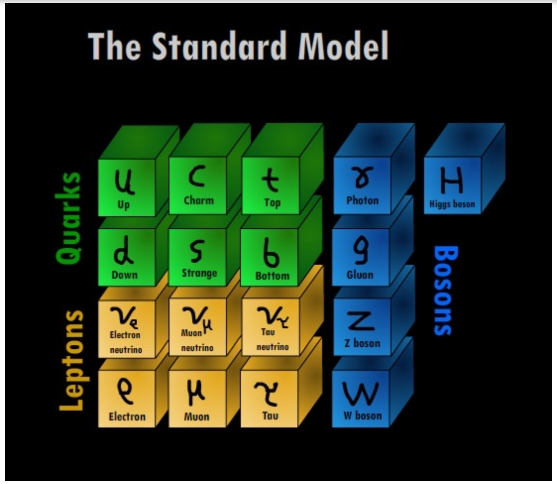
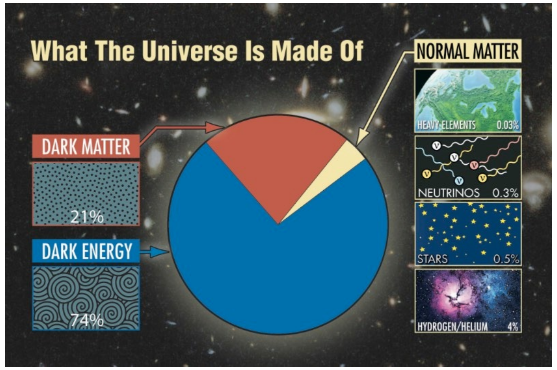
On behalf of the ATLAS & CMS Collaboration

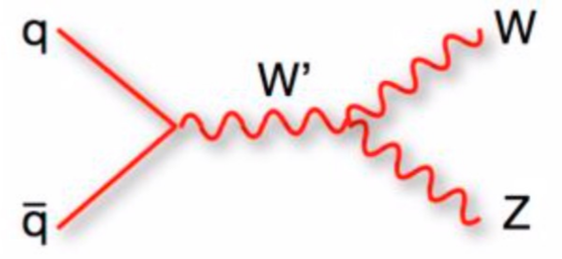
Corfu2023, 08/28-09/07/2023

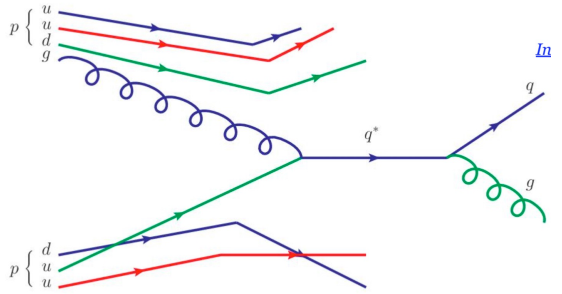
Why Exotics?

- Tremendous success has been achieved by the SM. There are, however, too many free parameters. And some fundamental questions remain unanswered.
  - Why 3 generations of quarks & leptons
  - Hierarchy problem
  - Dark matter/energy
  - …
- Many extensions to the SM aim to solve these problems, which generally predict new phenomena: new resonance, non-resonance, …
  - HVT, Compositeness, Extra dimensions, SUSY, …
  - Z’, W’, Leptoquarks, long-lived particle, …

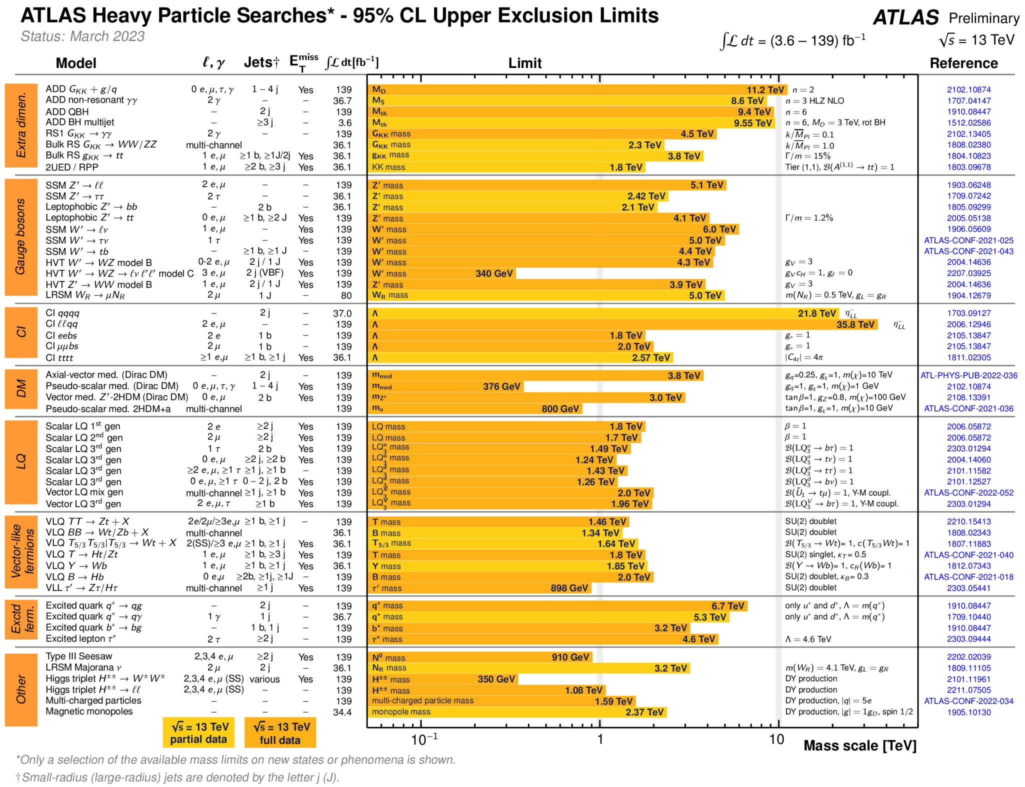


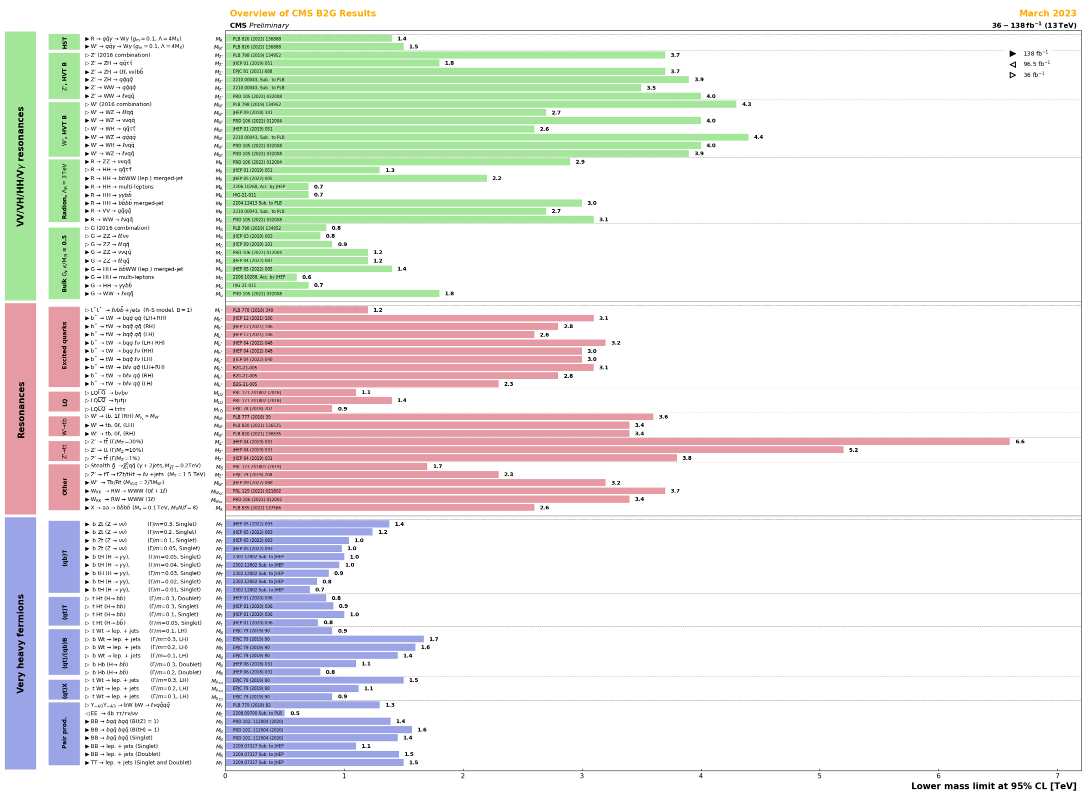






Exotics Search at ATLAS & CMS



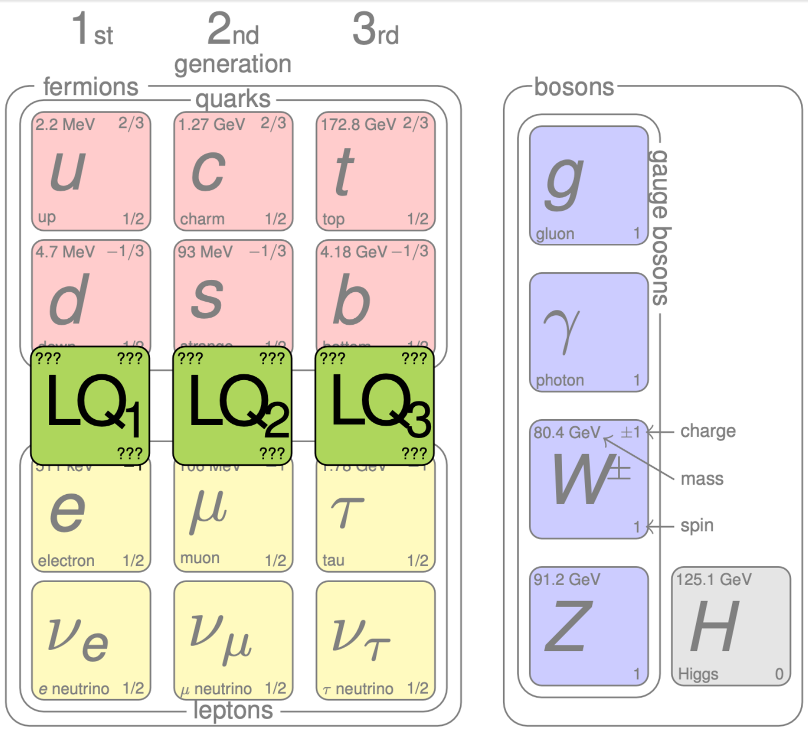


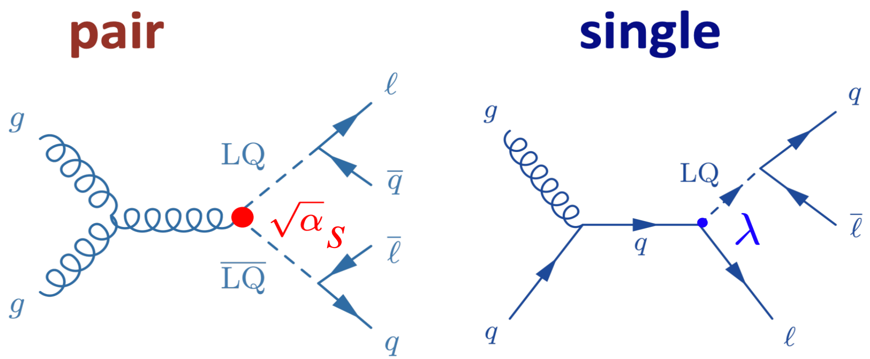
- **Search for exotics using various final states at ATLAS & CMS on LHC, with full Run-2 data: 13TeV, ~140 fb^{-1}**
  - **Mostly hunt for high mass bumps**
  - **Also explore unconventional signatures**

- **Unable to cover all the analyses. Only show the recent results while keeping balance between different topics and final states**

Leptoquarks (LQ)

- Explore similarity between leptons & quarks; Hypothesized in many BSM models(GUTS, RPV, SUSY, …)
- Carry both lepton and baryon numbers; Couple to lepton and quark at the same interaction vertex
- Raise interests due to B anomalies observed in various experiments
  - LQ possibly contribute to LFU anomalies at tree level

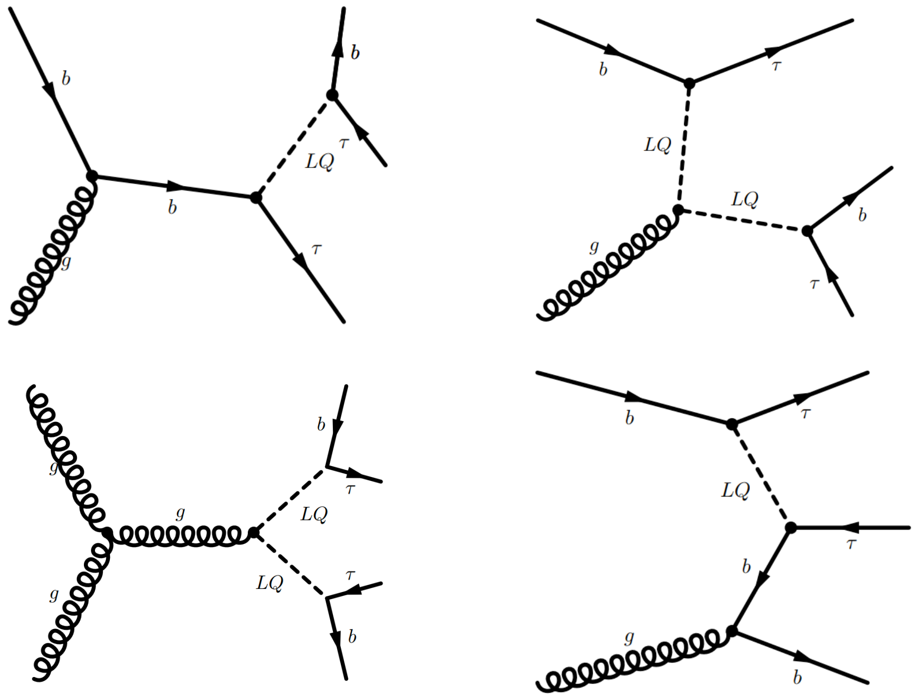


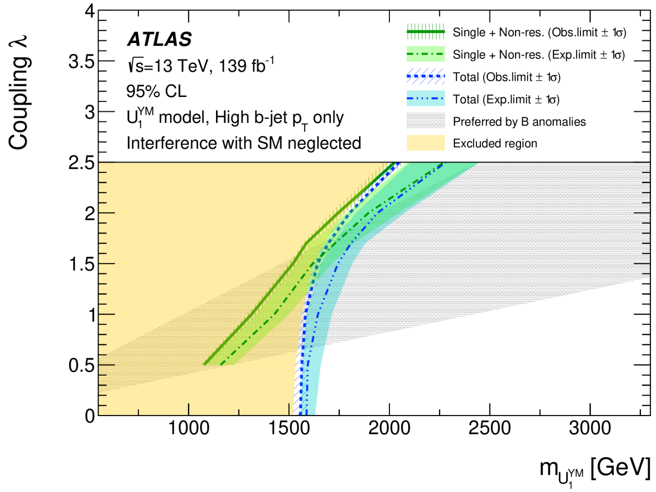


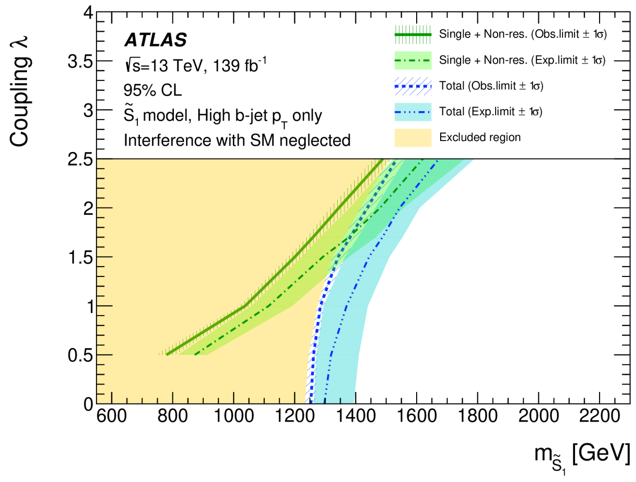
LQ: singly produced

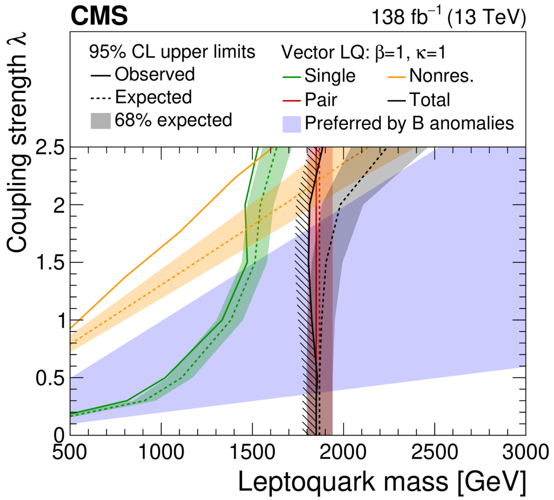
New! ATLAS arxiv:2305.15962, submitted to JHEP
CMS arxiv:2308.07826, submitted to JHEP

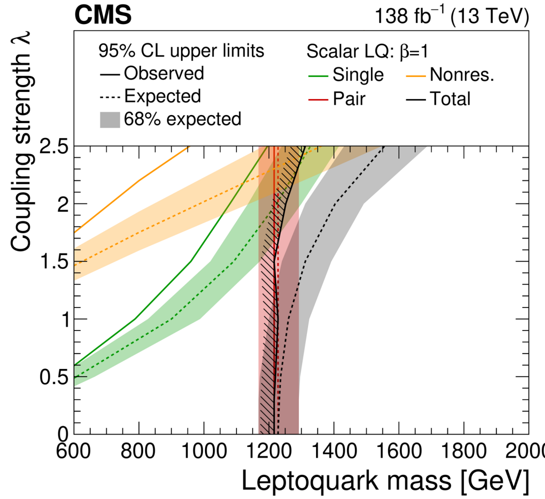
- Strong coupling of LQs to 3rd-generation, in light of *B* anomaly
- First search by LHC for singly produced LQ->bτ, for which optimized to search for 3rd-gen LQs via ***bg*->LQτ->*b*ττ**
  - Also receive contribution from pair and non-resonant LQ production
- Coupling λ (0.5, 2.5) to cover where LQs could possibly explain the *B*-anomaly, and extended to higher value
- Final signatures: $\tau_l\tau_{had}$ or $\tau_{had}\tau_{had}$ (l=e, μ), ≥1jet, ≥ 1b-jet







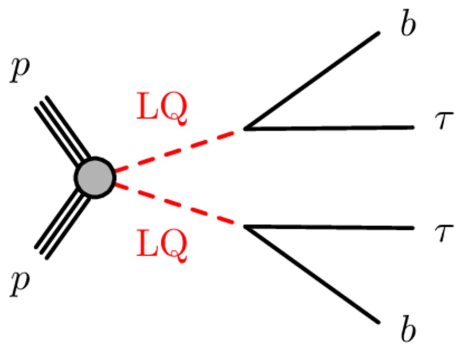




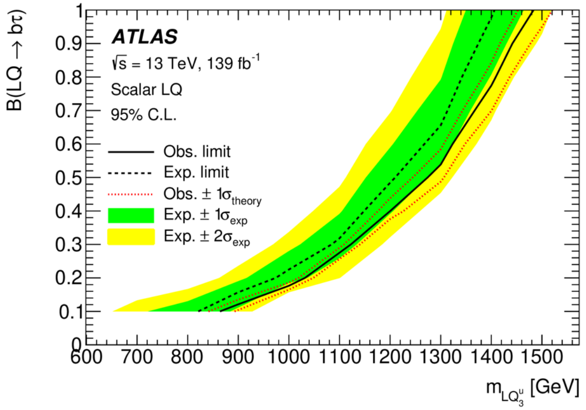
LQ: pair produced

LQLQ->bτbτ

arxiv:2303.01294, submitted to EPJC



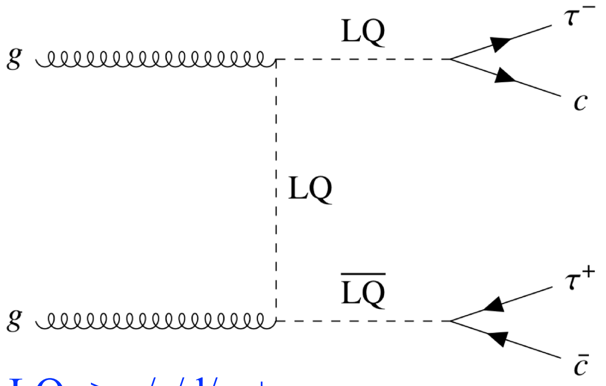
- Target up-type LQ;
- Strong coupling to 3rd-generation



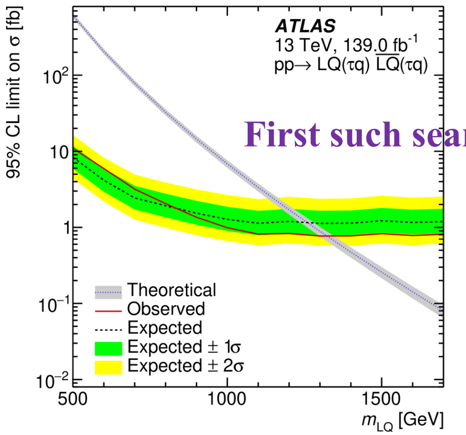
Scalar LQ limit: 1.49 TeV, for 100% BR
Vector LQ limit: 1.69(1.96) TeV for Min(YM) coupling

LQLQ->qτqτ

JHEP 06 (2023) 199



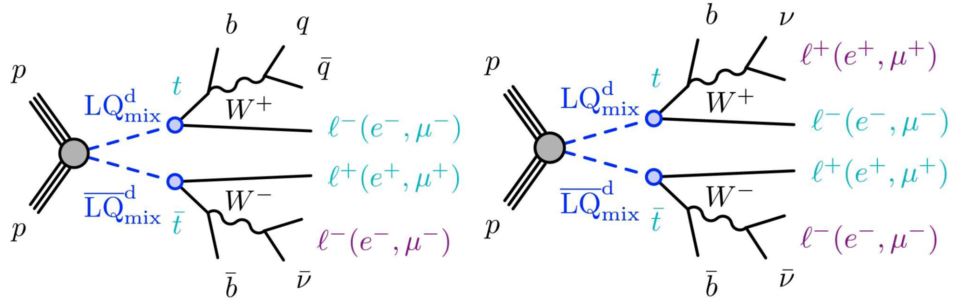
- LQ -> c/s/d/u + τ
- Br(LQ->qt)=1 (q=c, s, d, u)



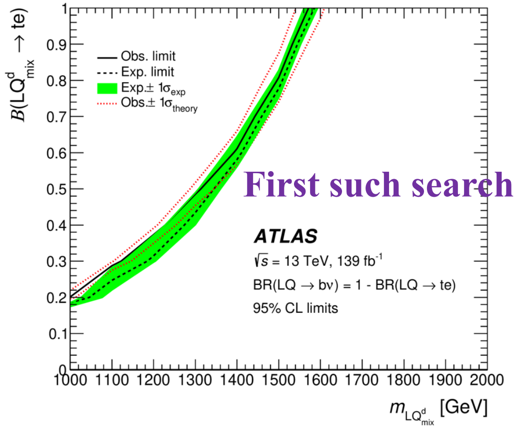
Scalar LQ limit: 1.3 TeV, for 100% BR

LQLQ->tltl (l=e,μ)

arxiv:2306.17642, submitted to EPJC



- Explore flavour-off-diagonal couplings, while preserving flavour symmetries
- t-pair decay leptonically (at least one lepton)

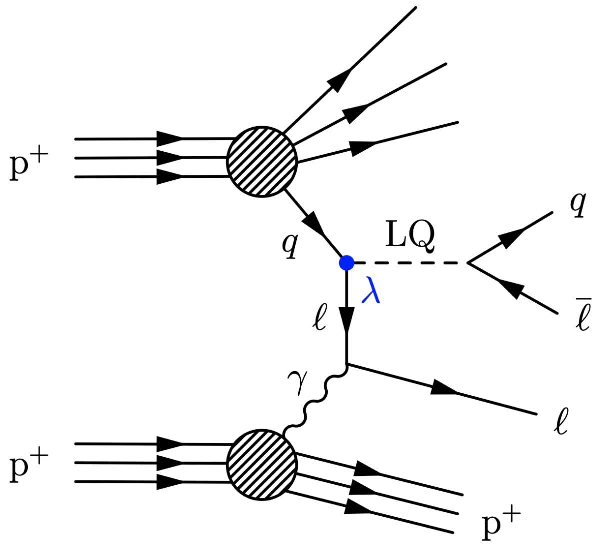


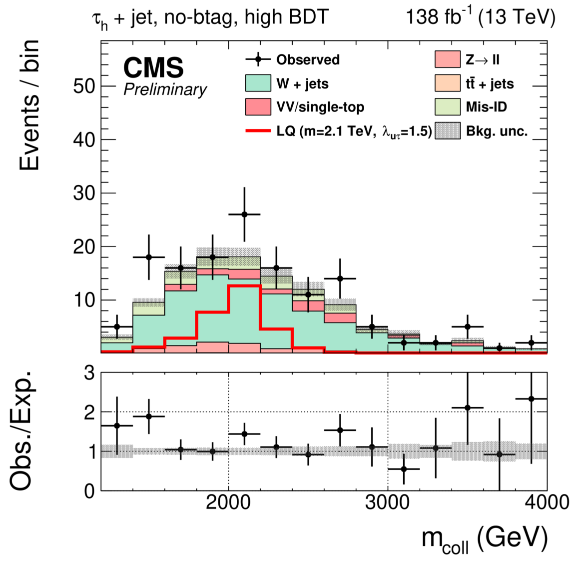
Scalar LQ limit: 1.58 TeV, for 100% BR
Vector LQ limit: 1.67(1.95) TeV for Min(YM) coupling

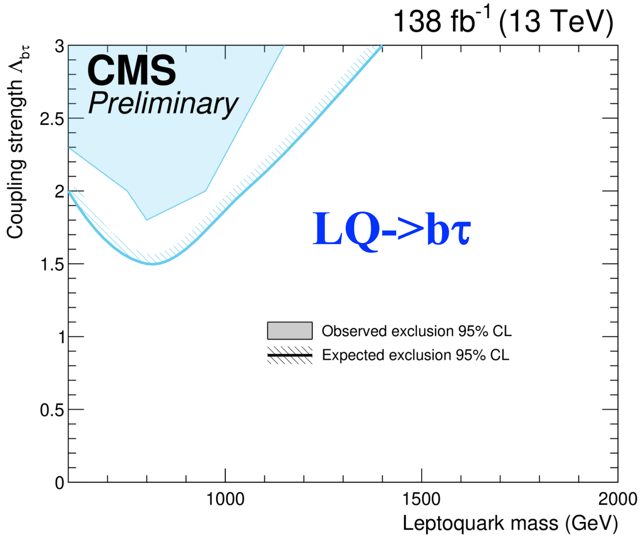
LQ: lepton-induced

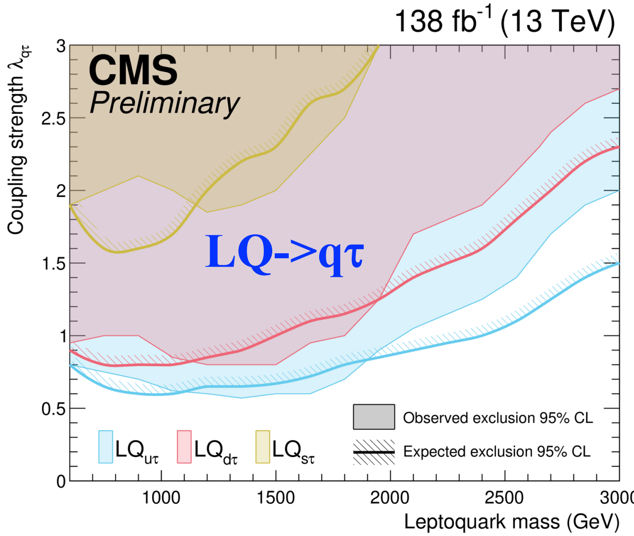
CMS-PAS-EXO-22-018

- Probe LQ production from lepton-quark collisions, with improved determination of lepton PDFs
- First search for scalar LQ coupling to τ leptons, produced in lepton-quark collisions; coupling to u, d, s and b quarks are considered
- Final state: high pT central lepton, high pT jet, soft forward lepton
  - Focus on τ: τ_e, τ_μ, τ_h
- Complement the constraint on the LQ-τ-b couplings from previous searches in other production modes
  - Competitive at high mass and coupling for τ-b









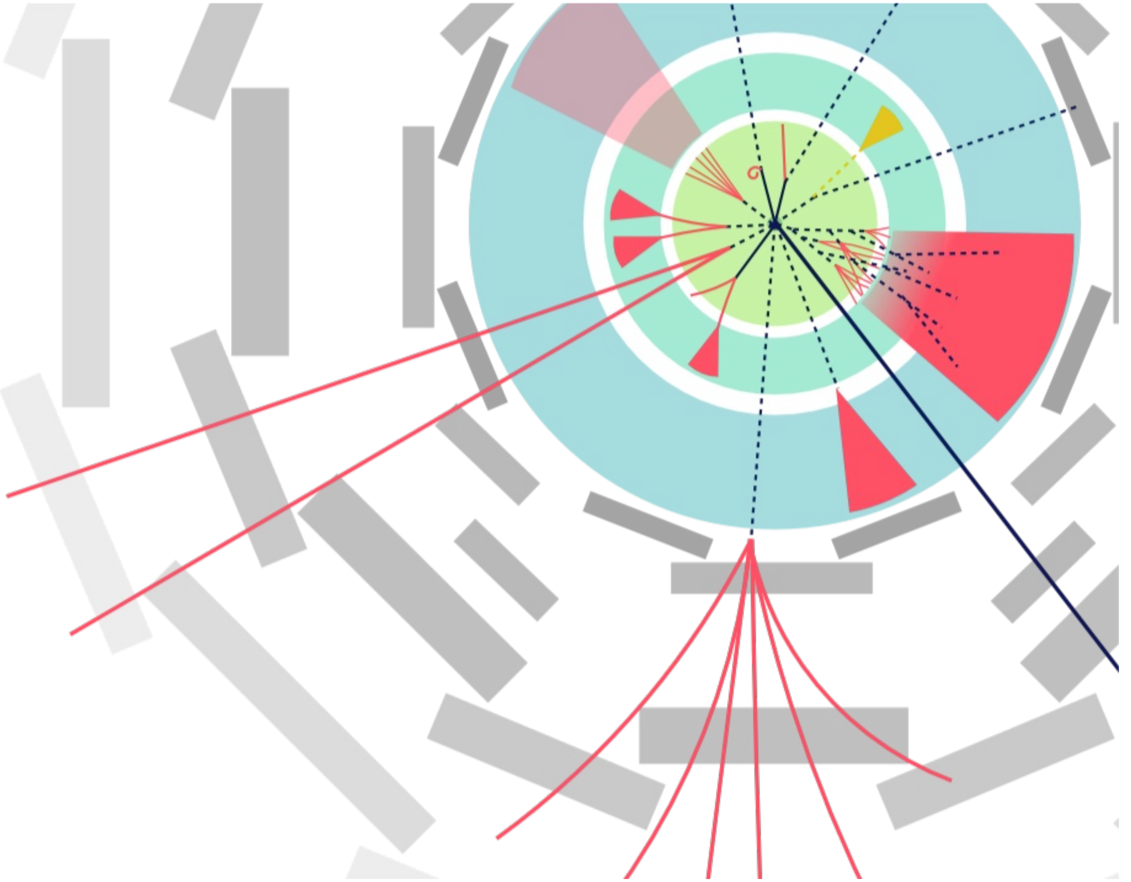
Unconventional Signatures: Long Lived Particles

- Most new physics analyses aim at prompt decays from signal, while there is huge phase space of possible BSM signatures

- LLP is predicted by many extensions to SM
  - Decay in the detector after a few cm

- Technical challenges:
  - Non-standard reconstruction
  - Displacements, timing and ionization
    - Dedicated triggers

- Advantages:
  - Probe unexplored models at TeV scale
  - Almost no irreducible SM background

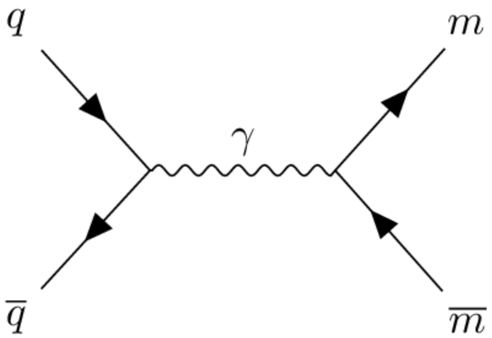


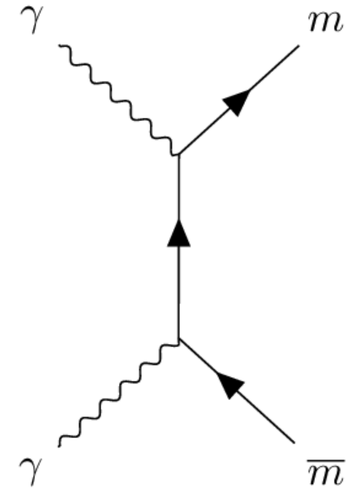
Highly Ionizing Particles (HIPs)

New!

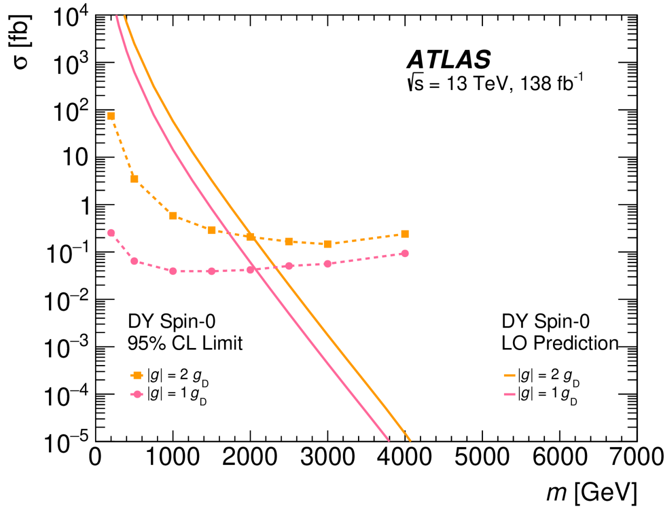
arxiv:2308.04835, submitted to JHEP

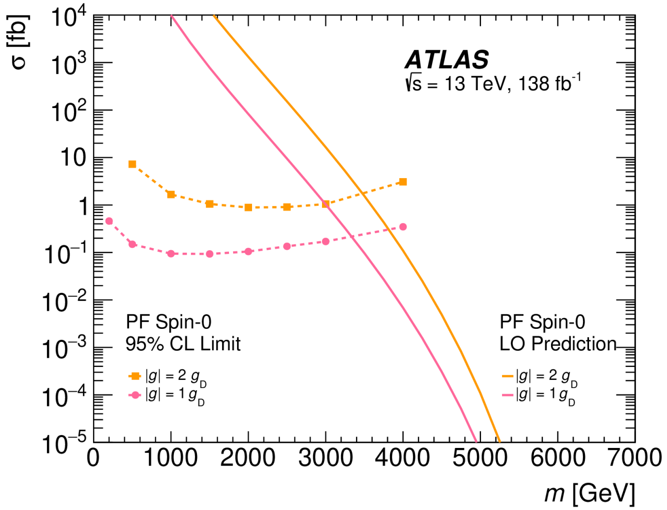
- Target spin-0 and -1/2 monopoles of magnetic charge $1g_D$ and $2g_D$, and high-electric-charge objects, for mass 200 – 4000 GeV.
  - Sensitive to TeV-mass HIPs
- Complementary to dedicated MoEDAL
  - Probe $|\eta|<1.375$, sensitive for $1g_D$ and $2g_D$
- Two main discrimination variables
  - The fraction of all the TRT hits exceeding the high threshold
  - Average of fractions of EM energy
- Cross-sect limits improved by a factor of ~3 for DY-production of monopoles with magnetic charge $1g_D$ and $2g_D$

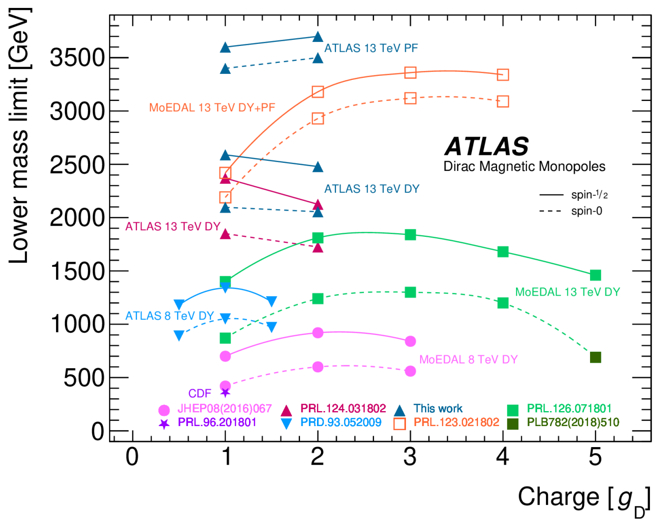




First ATLAS limits on photon-fusion pair production of monopoles





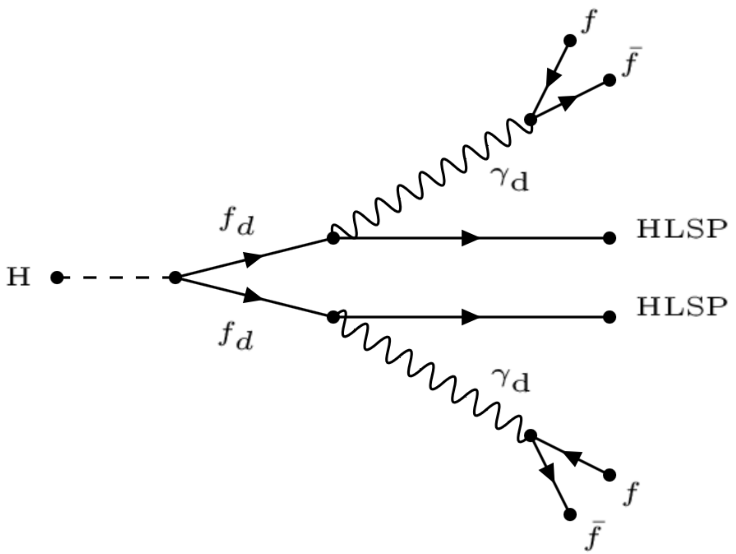


Displaced Lepton Jets

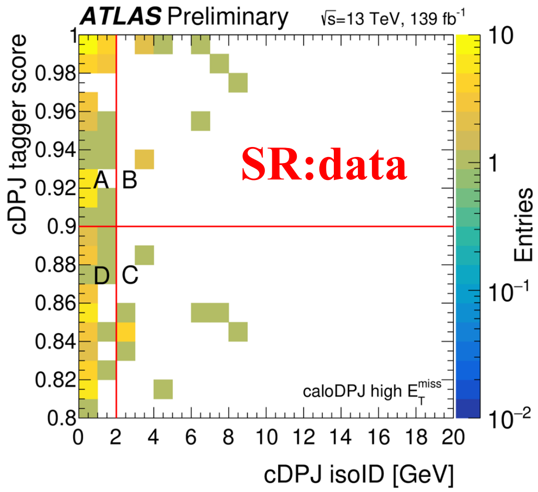
New!

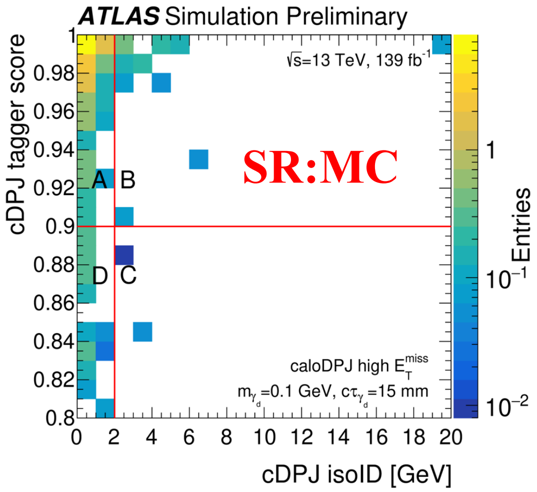
ATLAS-CONF-2023-051

- Explore the scenario where SM and dark sector interact through Higgs portal to produce BSM states, and via vector portal for subsequent decay
- Search for displaced dark photons with mass 0.1 – 40 GeV, focusing on Higgs decay produced via VBF
  - Collimated jets of photons or light hadrons
- Study for the first time the VBF Higgs production
- Sensitivity significantly improves, in particular for mass below $2m_{\mu}$, and above 6 GeV

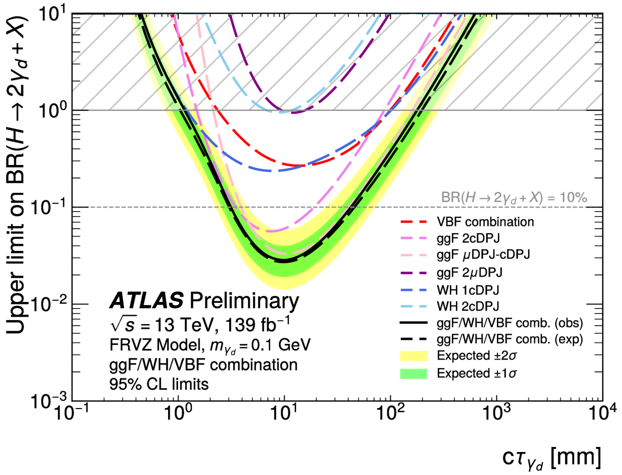


HLSP: Hidden lightest stable particle

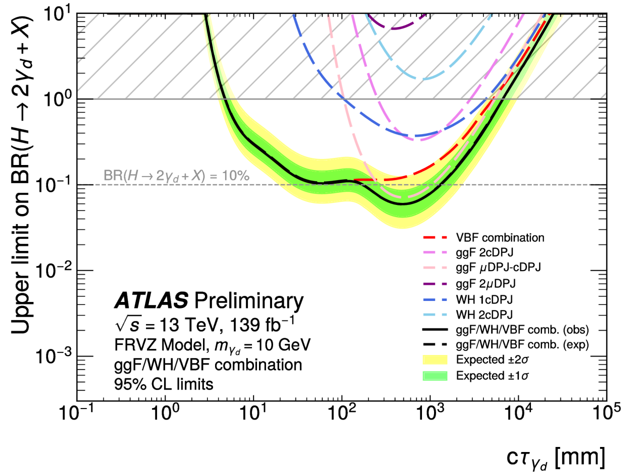




$m_{\gamma d}$=0.1 GeV



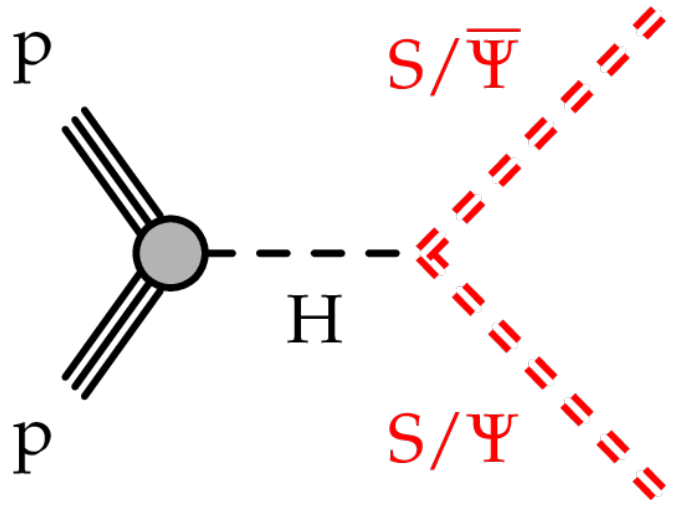
$m_{\gamma d}$=10 GeV

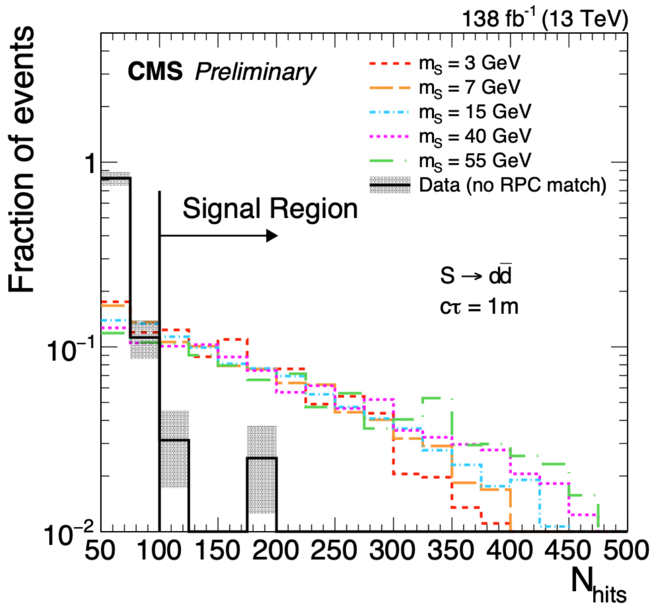


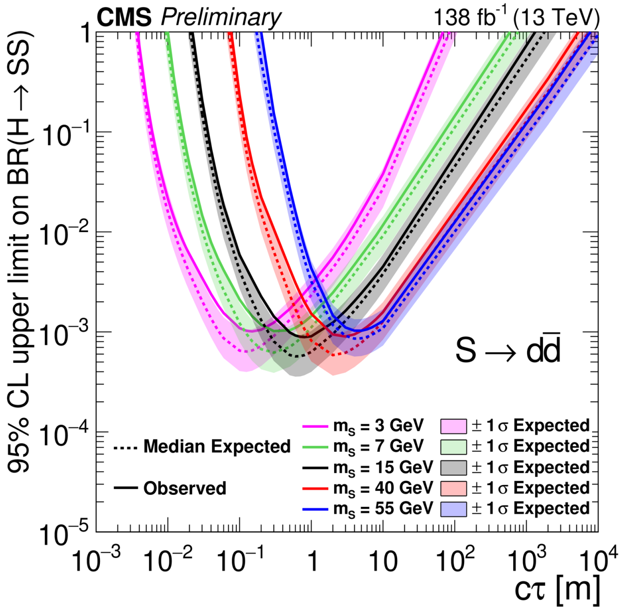
LLP decay in muon system

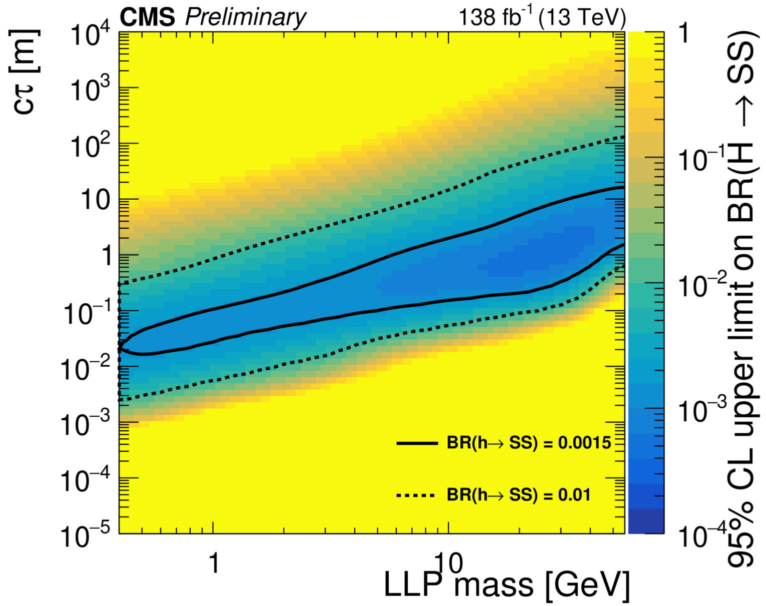
CMS-PAS-EXO-21-008

- First search using both barrel and endcap CMS muon detectors. Largely model independent, sensitive to a broad range of LLP decay modes and masses below GeV
- Use muon detectors as a sampling calorimeter to identify LLP particle showers
  - Jet showers are strongly suppressed by materials before the muon detectors
  - Absorber material before muon detectors suppresses the background to low level.
- Set first LHC limit on dark showers models, sensitive to *BR* of H->dark quarks as ~ 10^{-3}





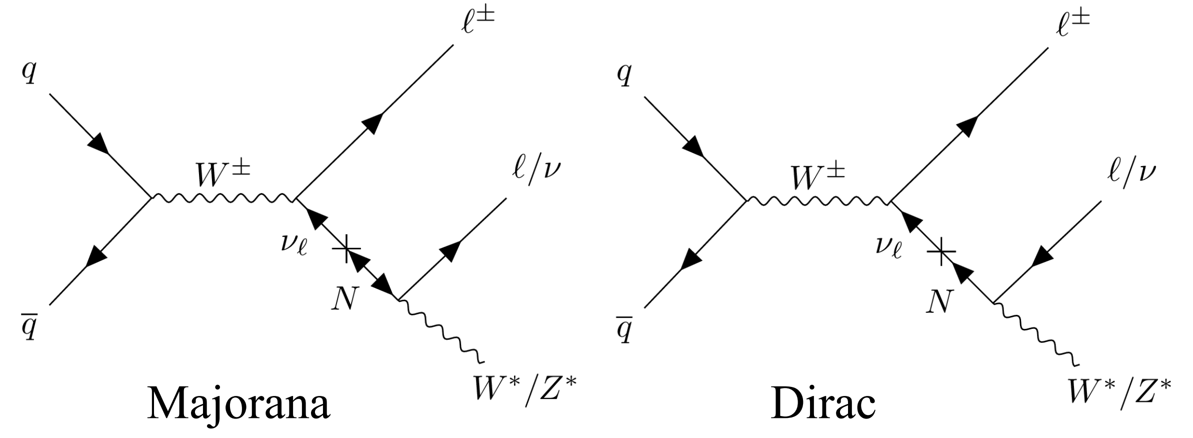


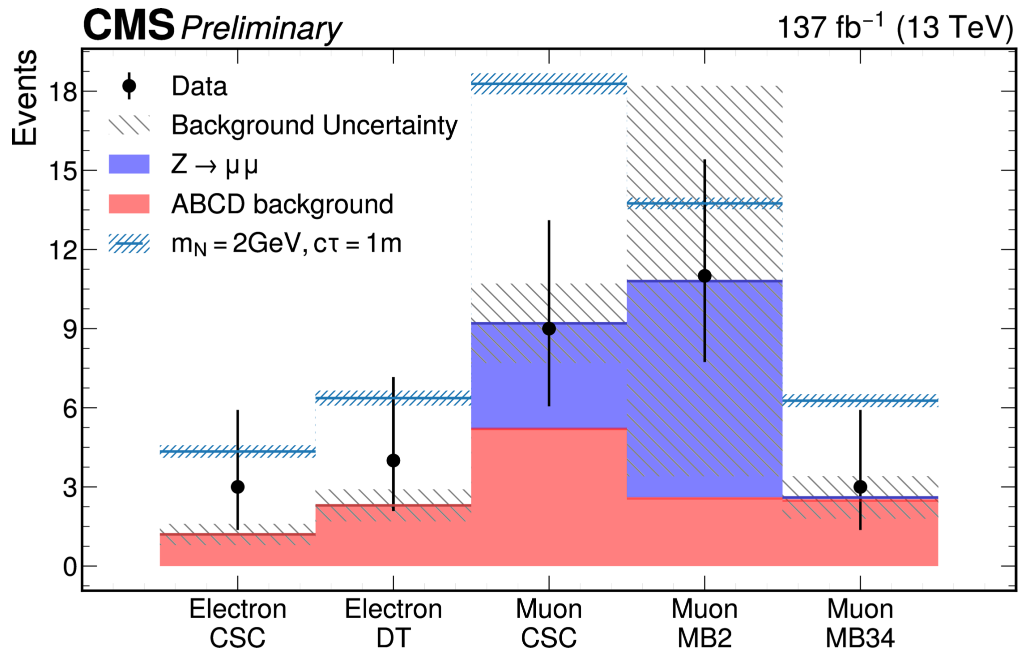


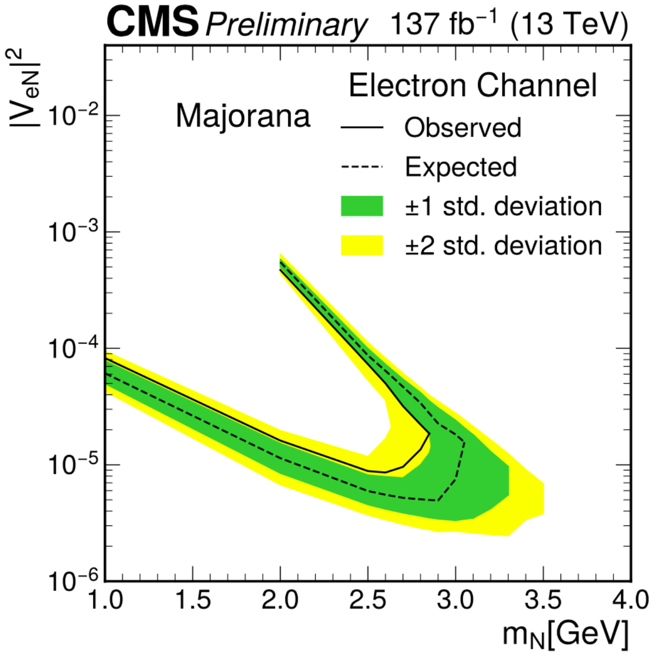
Heavy neutral leptons (HNL)

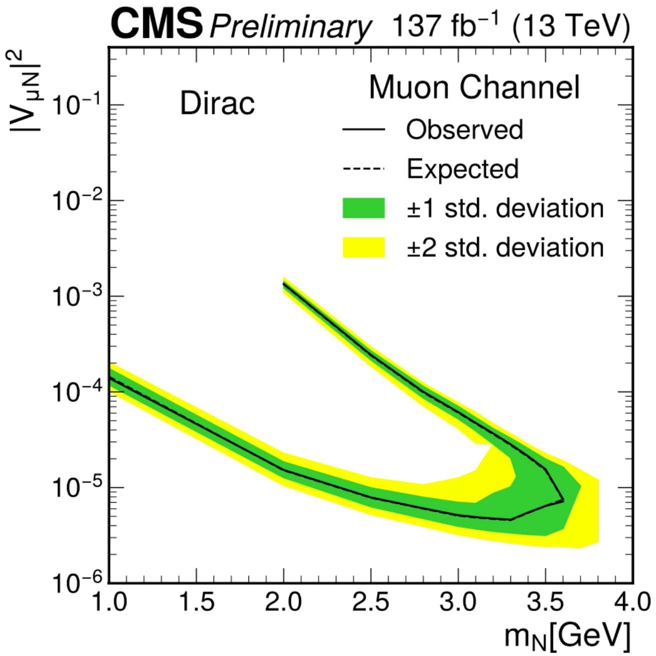
CMS-PAS-EXO-22-017

- HNL is produced via a W decay and through its mixing with an SM neutrino: Majorana or Dirac
- Decay products interact with shielding materials and create hadronic and EM showers detected by muon chambers
  - e/μ + shower in muon chambers
- Sensitive to HNL below < 10 GeV and cτ ~ m
- Sensitive to HNL coupling to all 3 generation of leptons





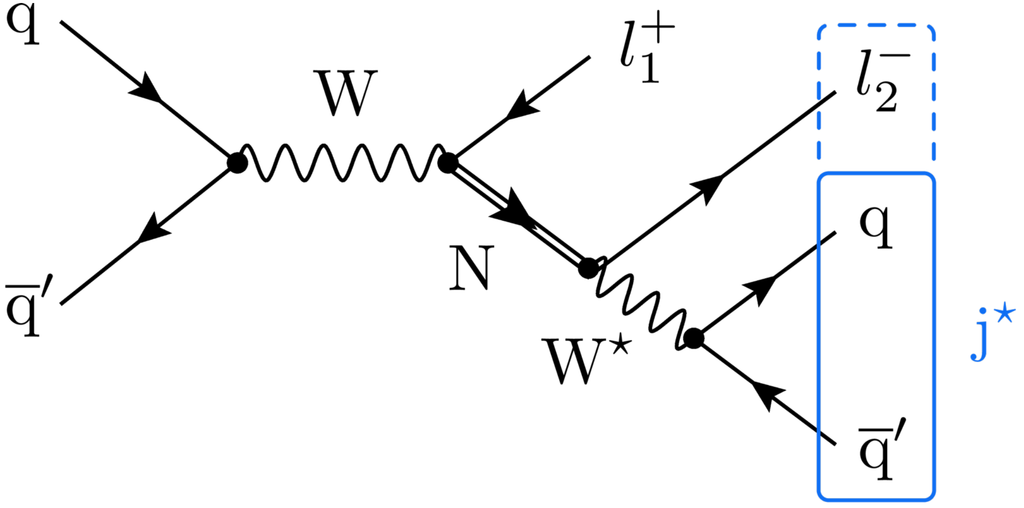


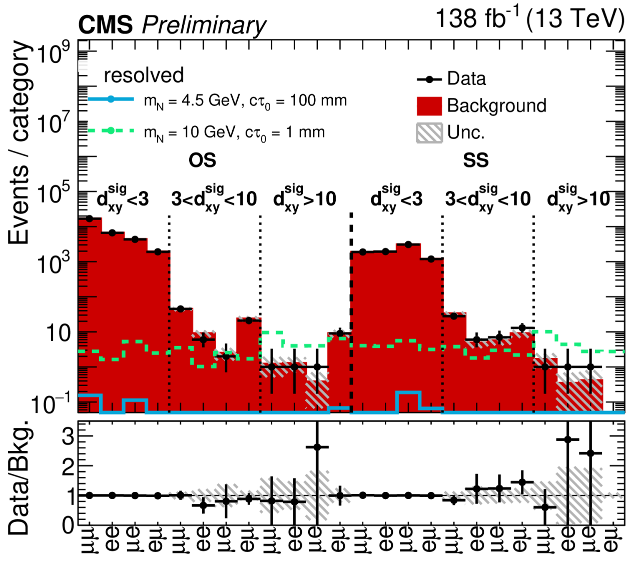


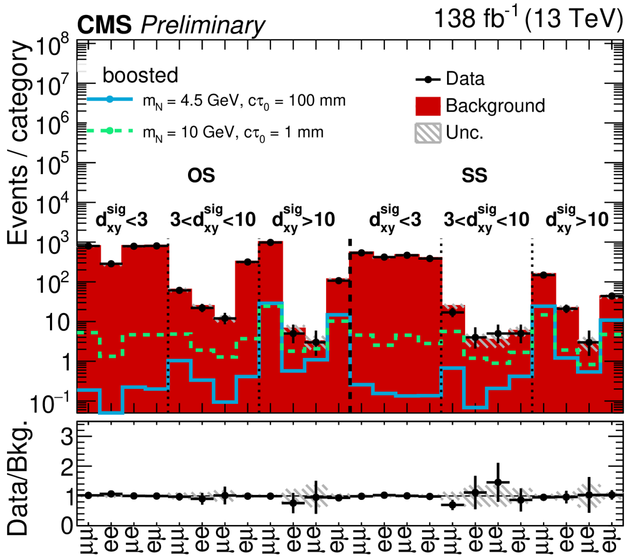
Heavy neutral leptons (HNL)

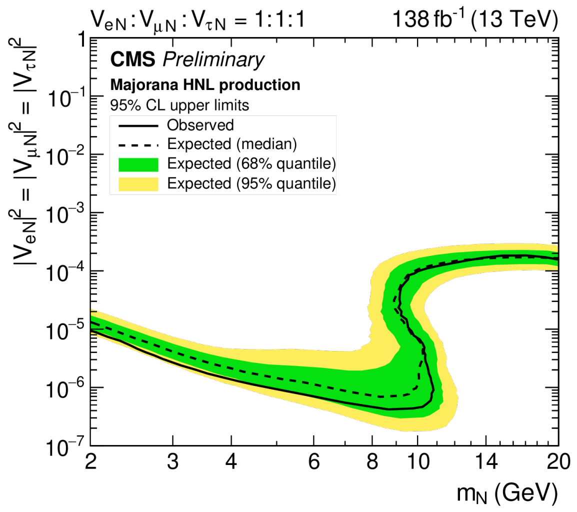
CMS-PAS-EXO-21-013

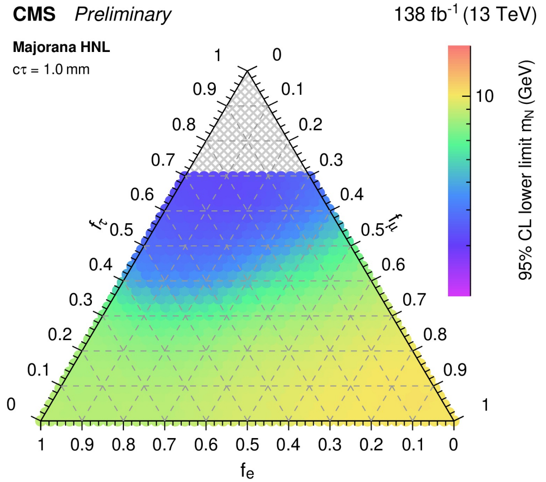
- Aim at long-lived HNL, Dirac or Majorana, predicted through seesaw mechanism
- Consider coupling to all 3 lepton generations
- Signatures: 2*l* (*l*=e or μ) and jets
  - One *l* prompt, the other displaced
- Novel jet (displaced) tagger: based on DNN, using various features of jet and its constituent particles







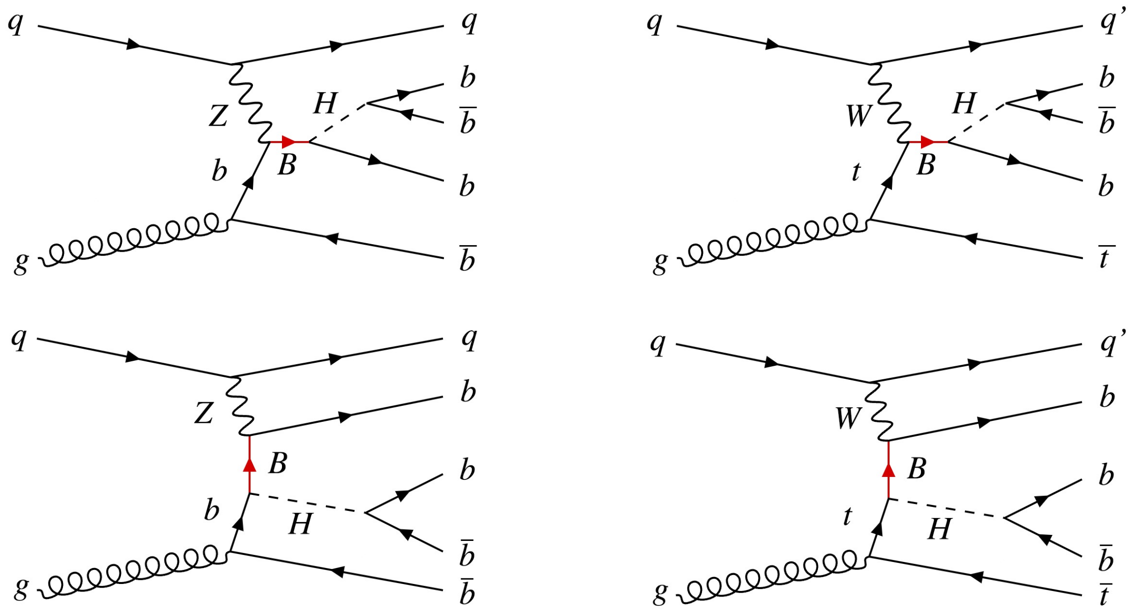


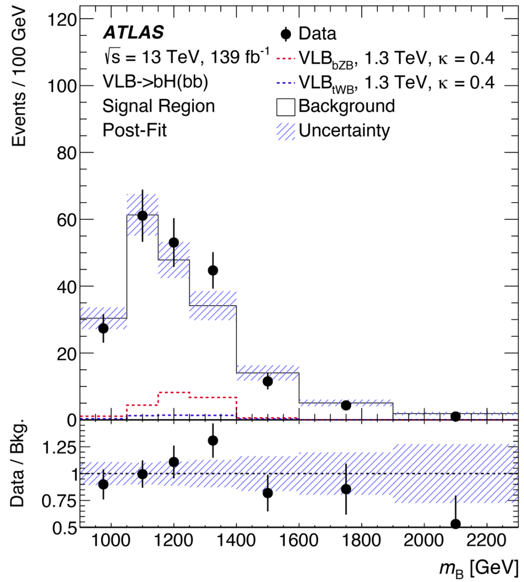


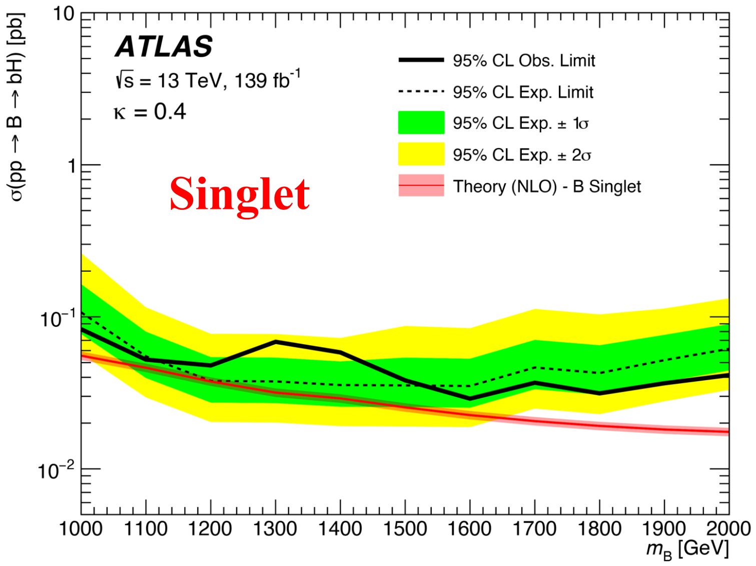
Vector-like quarks (VLQ)

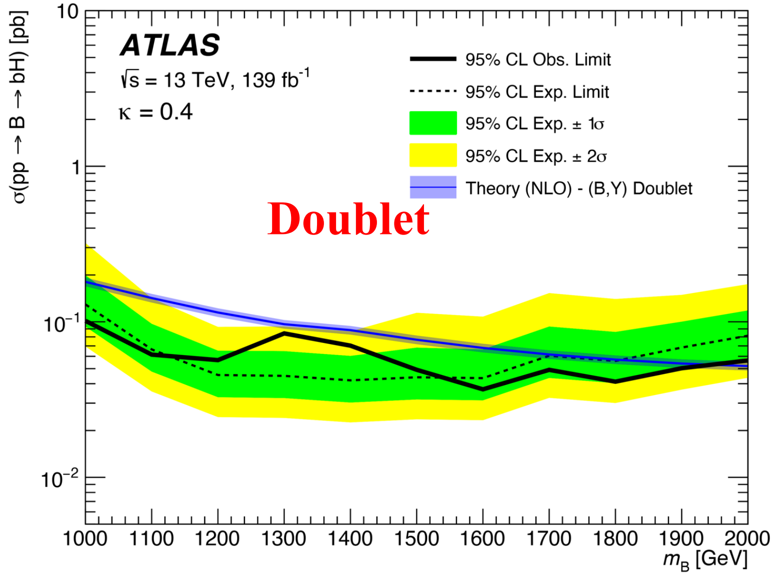
arxiv:2308.02595, submitted to JHEP

- Singly produced B by resonant s-channel or non-resonant t-channel
  - t-channel becomes sizeable in large-width scenarios
- First search at ATLAS, using single production of VLQ B quark in bH(->bb) final state
- Achieve much stronger limits for (B, Y) doublet, due to larger singlet x-section times H->bb branching ratio





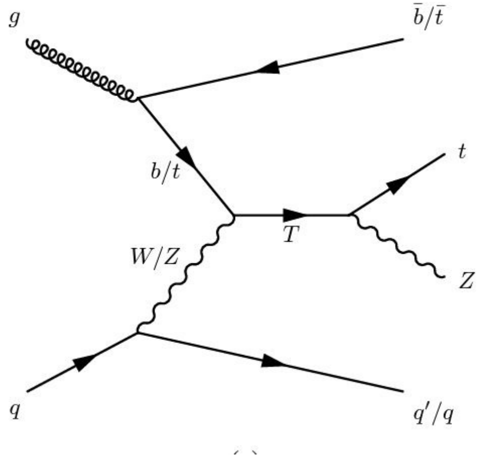


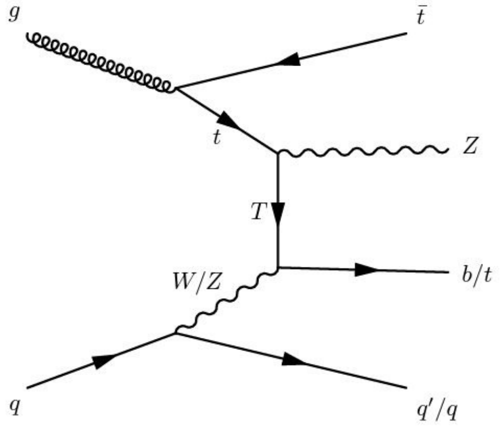


Vector-like quarks (VLQ): tops to multilepton

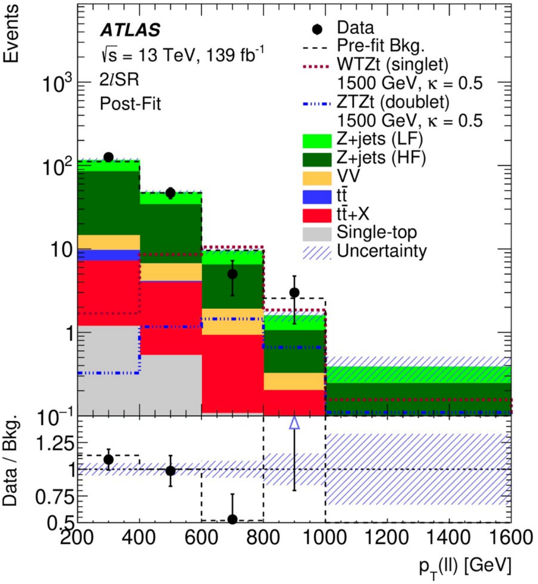
arxiv:2307.07584, submitted to PRD

- Electroweak process is involved, leading to dependence on its couplings and representation(singlet, doublet, or triplet)
- Target on singly produced T->Zt , in s- and t-channels
- Final state: 2l or 3l, b-jet, forward jet.
  - 2l: pair of electrons or muons form Z decay with opposite-sign charges,
  - 3l: top quark also decays leptonically

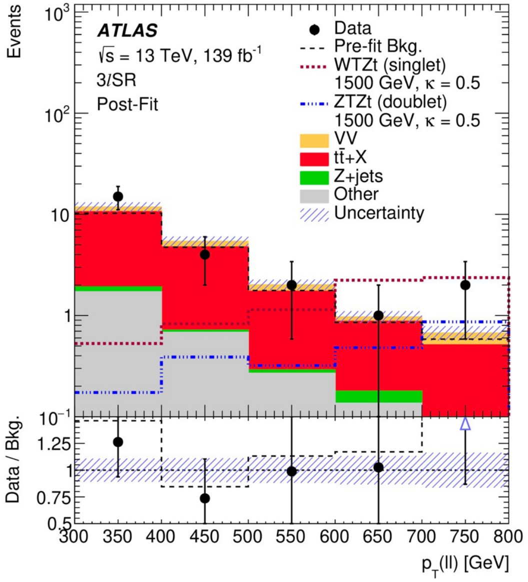


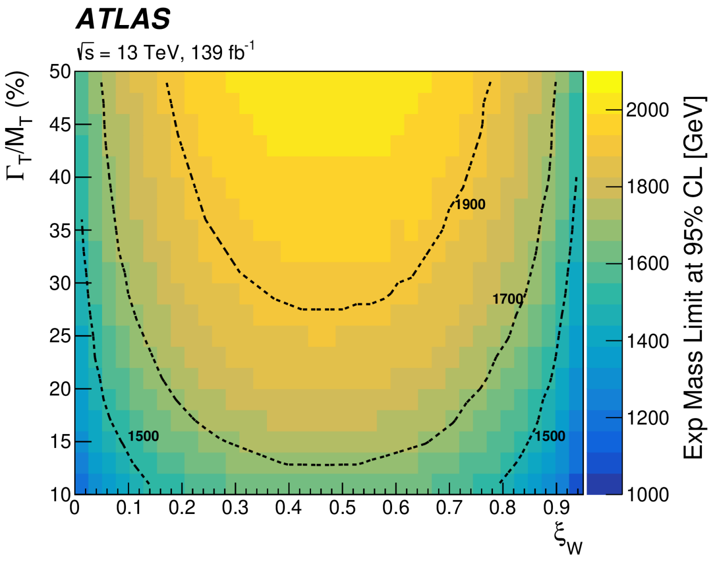


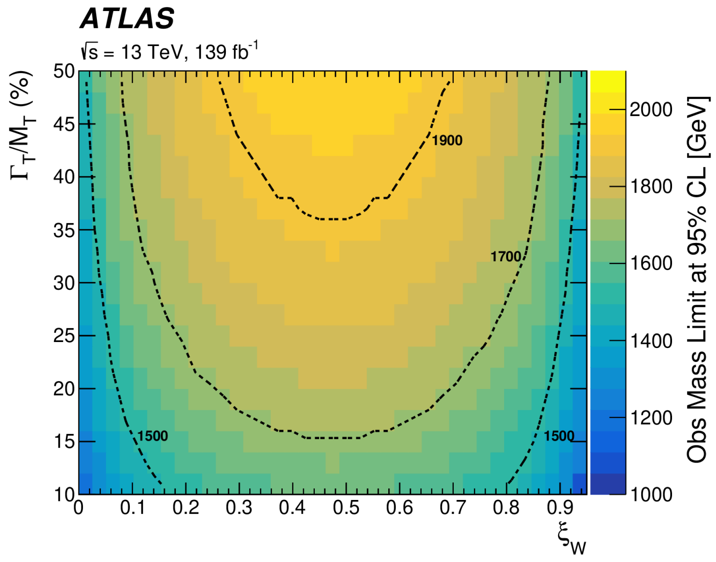
dilepton



trilepton





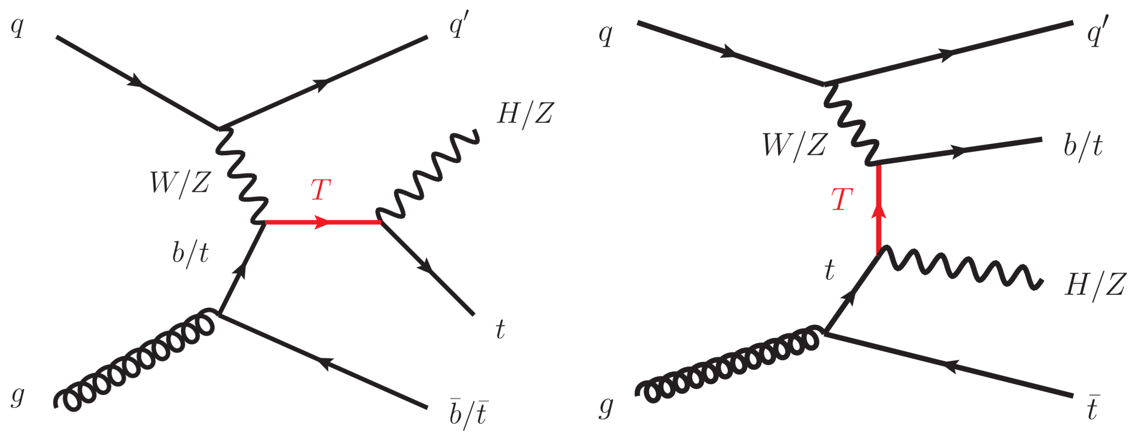


Vector-like quarks (VLQ): T->Ht/Zt

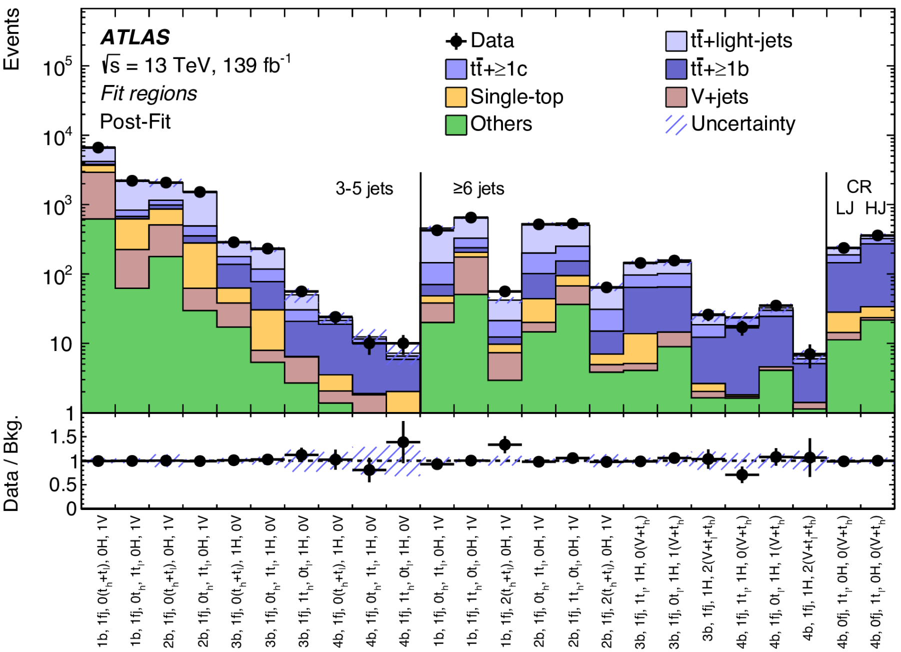
arxiv:2305.03401, accepted by JHEP

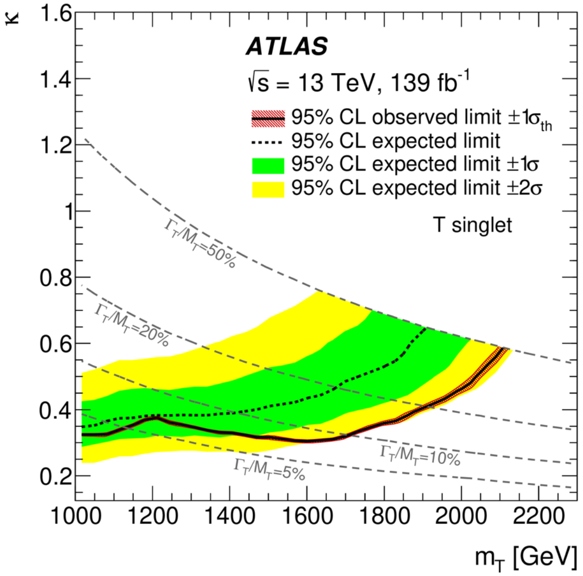
- Target up-type VLQ T: T->Ht/Zt, considering both b- and t-associated production modes
  - Leptonically decaying top, hadronically decaying H(->bb) & Z(->qq)
  - Final state: lepton(e/μ)+jets; multiple jets from T and bosons, a recoiling forward jet
- 24 fit regions defined based on multiplicity of jets, b-jets, forwarded jets, H-tagged (H) jet, V-tagged (H) jets

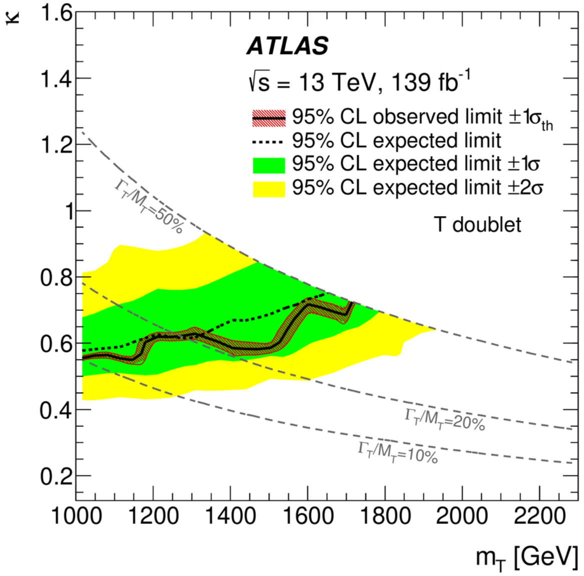
resonant **non-resonant**



Singlet: $m_T < 2.1$ TeV for $\kappa \geq 0.6$; $\kappa > 0.3$ for $m_T = 1.6$ TeV
Doublet: $m_T < 1.68$ TeV for $\kappa \geq 0.75$; $\kappa > 0.55$ for $m_T = 1.0$ TeV



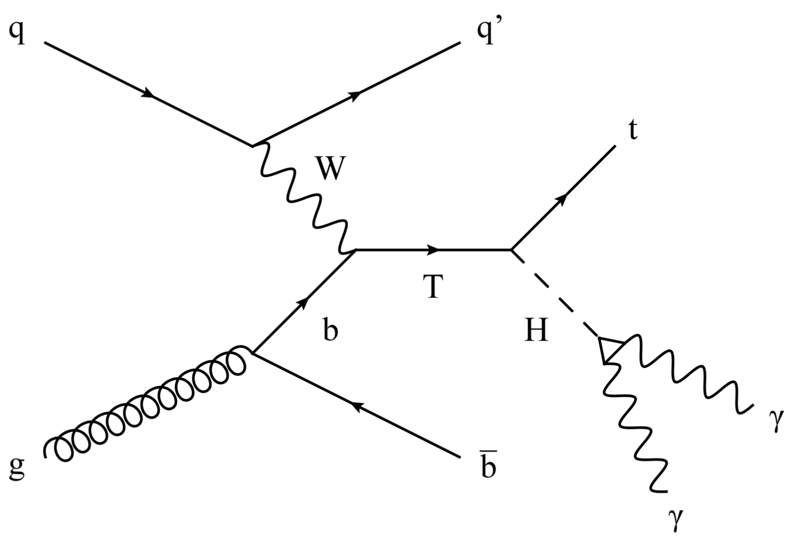


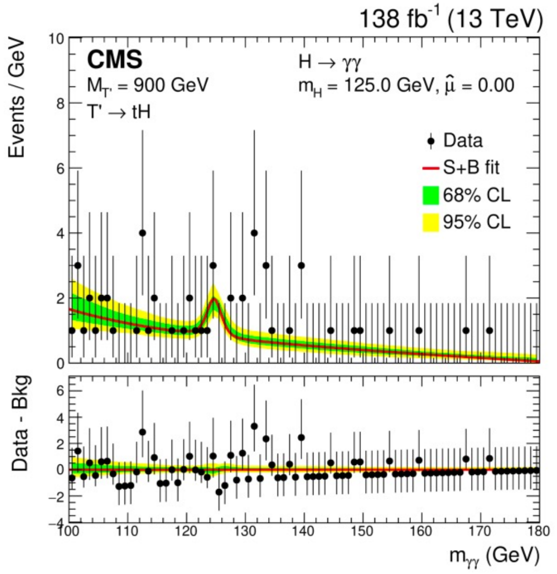


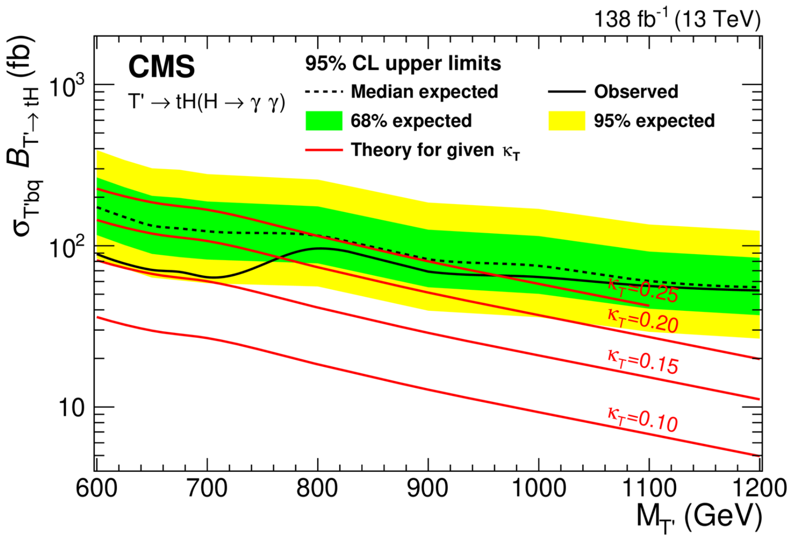
Vector-like quarks (VLQ): T->Ht (H->γγ)

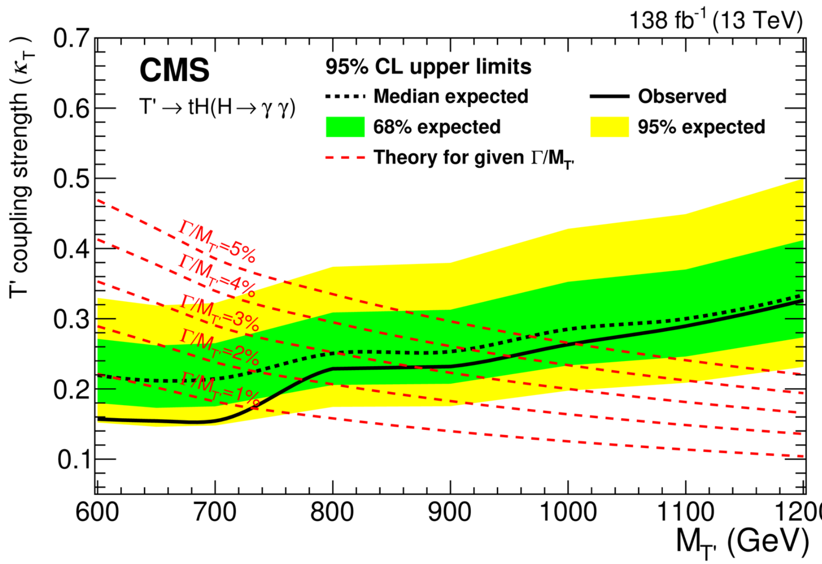
arxiv:2302.12802, submitted to JHEP

- Singly produced T-> t H(->γγ)
  - First T search at the LHC using H-> γγ
  - Exploit the excellent resolution (1-2%) of reconstructed H mass
- Leptonic and hadronic decay of top quark are treated separately to maximize sensitivity
- T excluded up to a mass of 960 GeV for κ_T=0.25 and Γ/M_T<5%





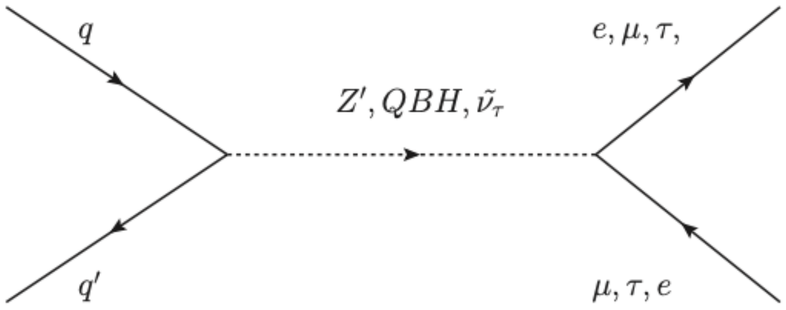


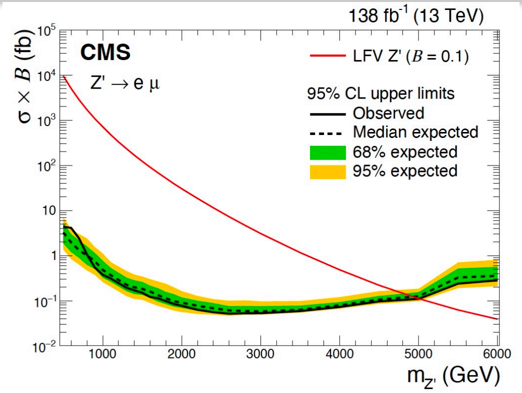


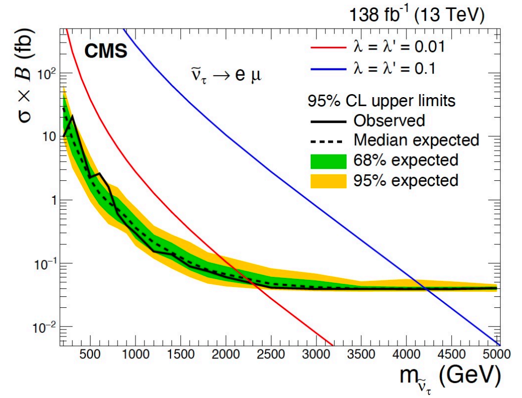
Lepton Flavour Violation (LFV)

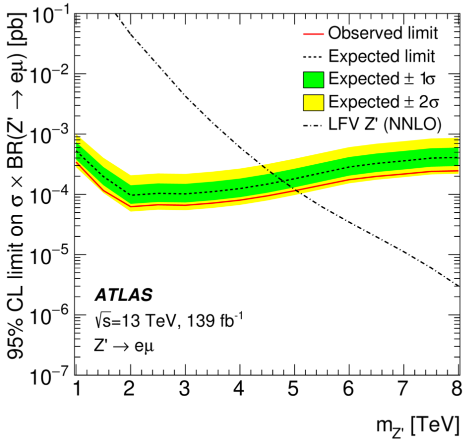
ATLAS arxiv:2307.08567, submitted to JHEP
CMS JHEP 05 (2023) 227

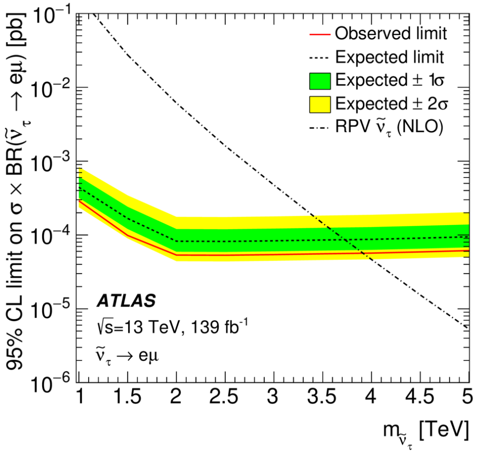
- LFV in charged leptons, predicted by various BSM models
  - Z', RPV τ-sneutrino, Quantum black holes
- Opposite-sign charged lepton pair:
  - eμ, $e\tau_{had}$ or $\mu\tau_{had}$
- Significant sensitivity improvement
  - More accurate data-driven bkgd estimates, better particle reconstruction and identification, combined with 4 times larger data sample,

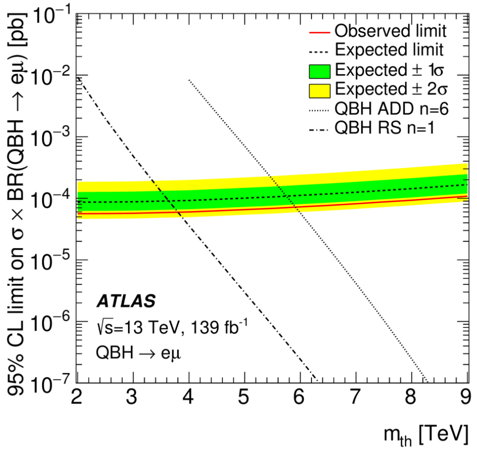


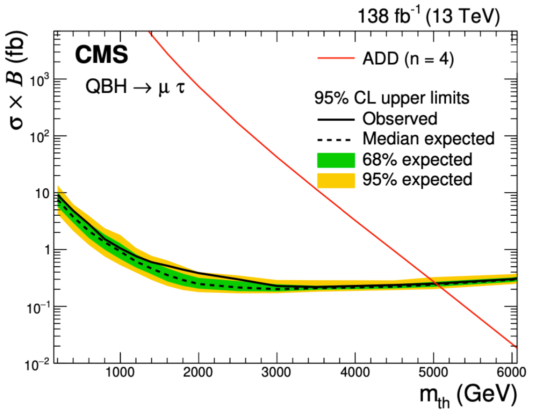








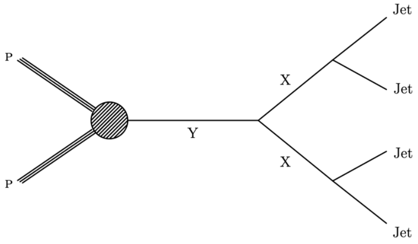


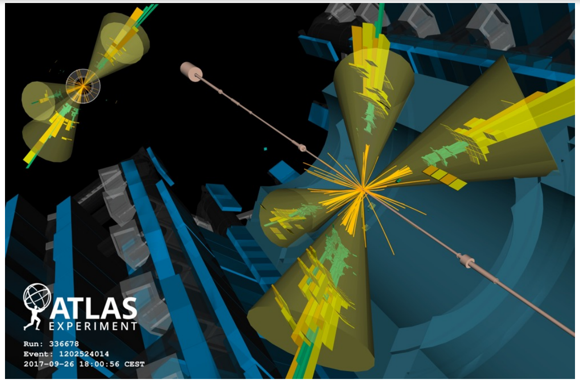


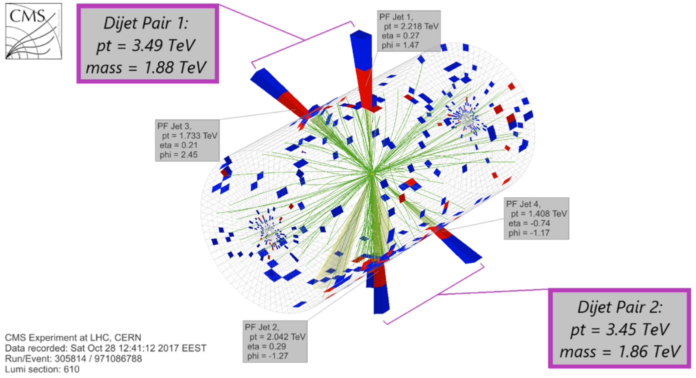
Paired dijet resonance

arxiv:2307.14944, submitted to PRD

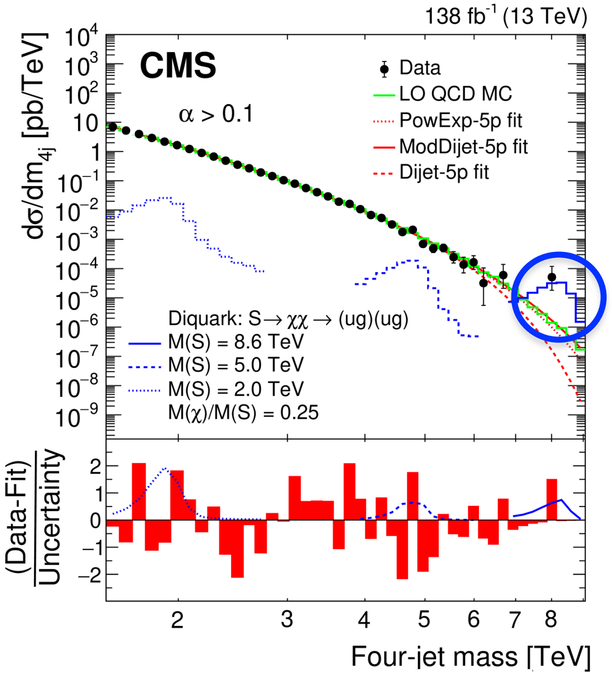
- Search for invariant mass of tetrajet, prompted by the CMS result
- Generic resonance Y->XX->jets
  - Both m_{4j} and m_{2j} are studied
- The most significant excesses found:
  - m_{4j} @ 3.2 TeV for $0.24 < \alpha < 0.26$
  - m_{2j} @ 0.8 TeV for $0.26 < \alpha < 0.28$
- Highest m_{4j} observed:
  - ATLAS: 6.6 TeV, with $< m_{2j} > = 2.2$ TeV
  - CMS: 8 TeV

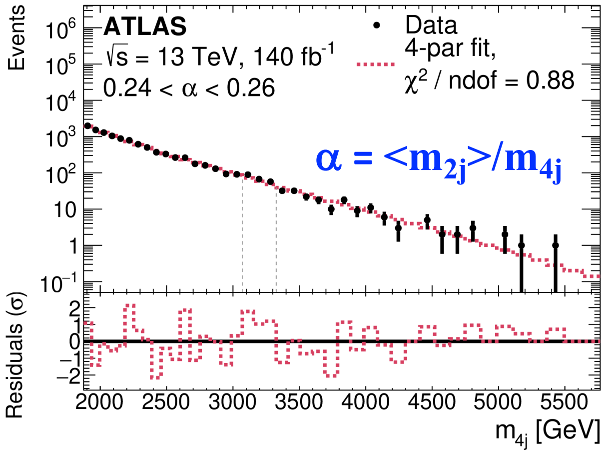


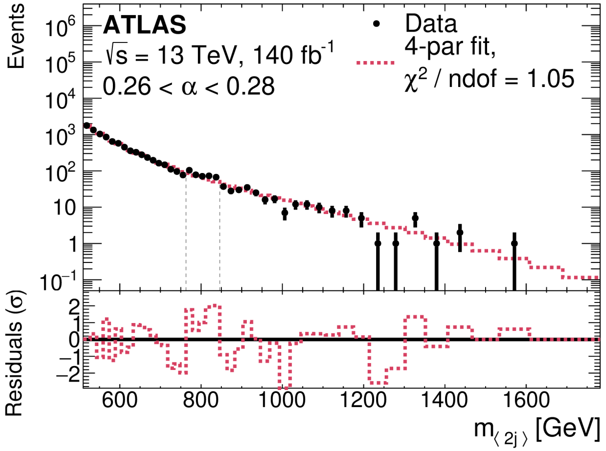


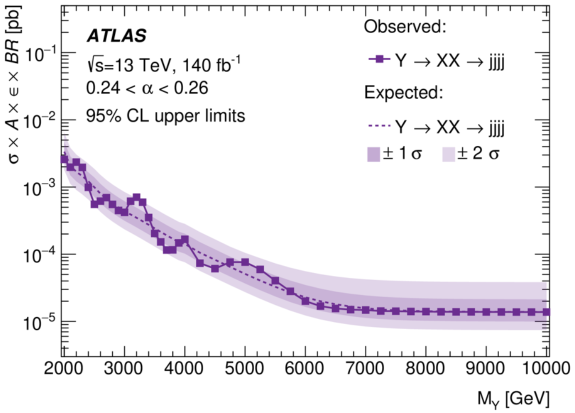


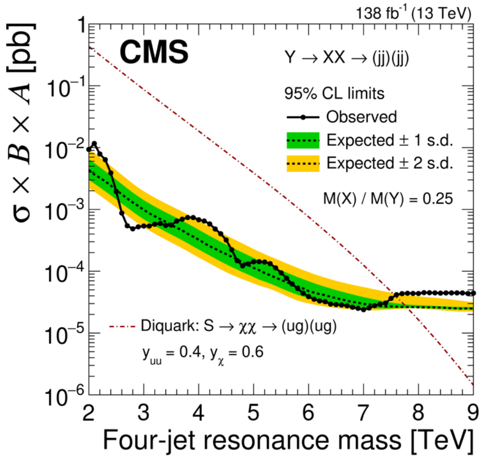
JHEP 07 (2023) 161







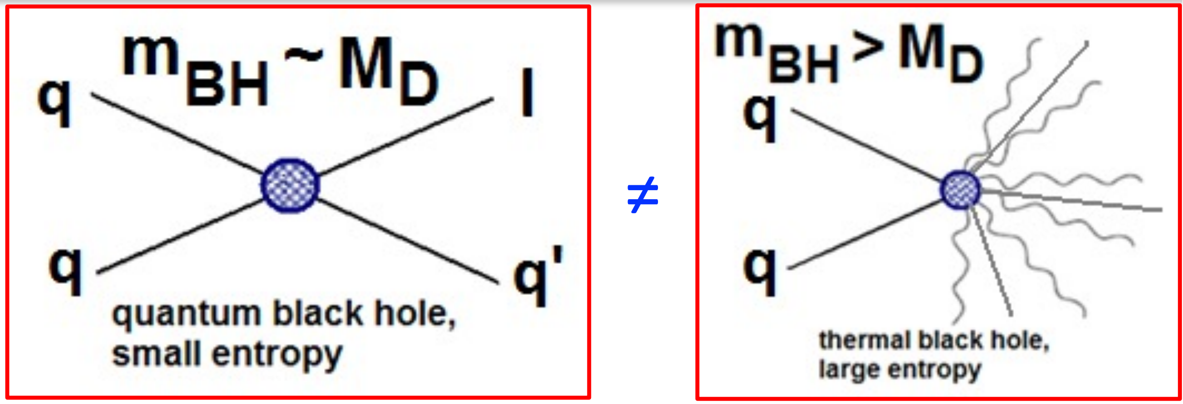


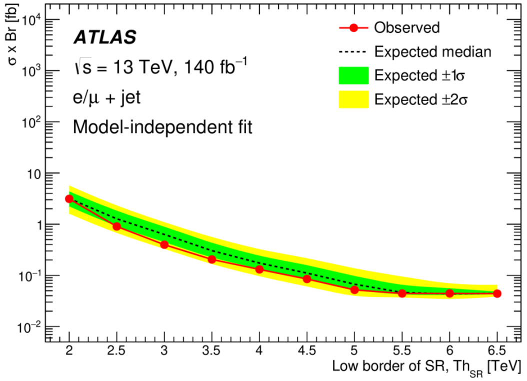


Quantum black hole (QBH)

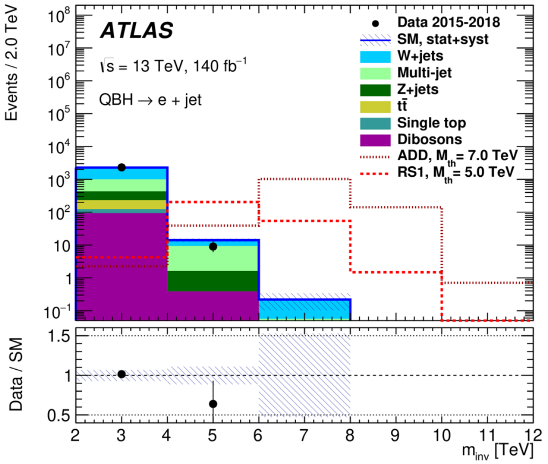
arxiv:2307.14967, submitted to PRD

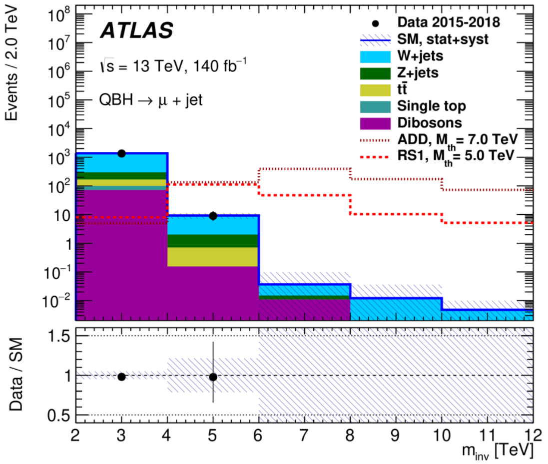
- QBHs are predicted in low-scale quantum gravity theories that offer solutions to the mass hierarchy problem
  - It could violate SM global symmetries (e.g. baryon number violation) and cause sizeable impact on observables.
- Signature: l lepton(e or μ) + 1 jet, providing best branching ratio and S/B ratio in ADD and RS1 models
- Better optimized strategy, condition and cuts compared to previous 8 TeV search

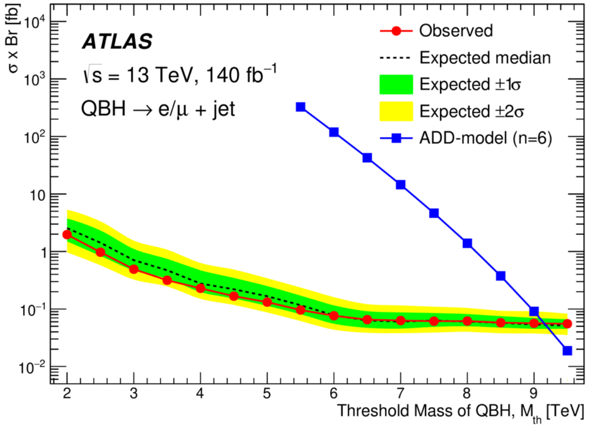


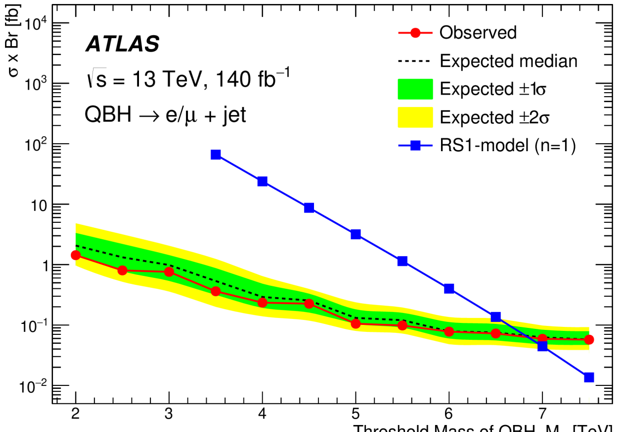


Improve a factor of **3.5** with respect to previous result





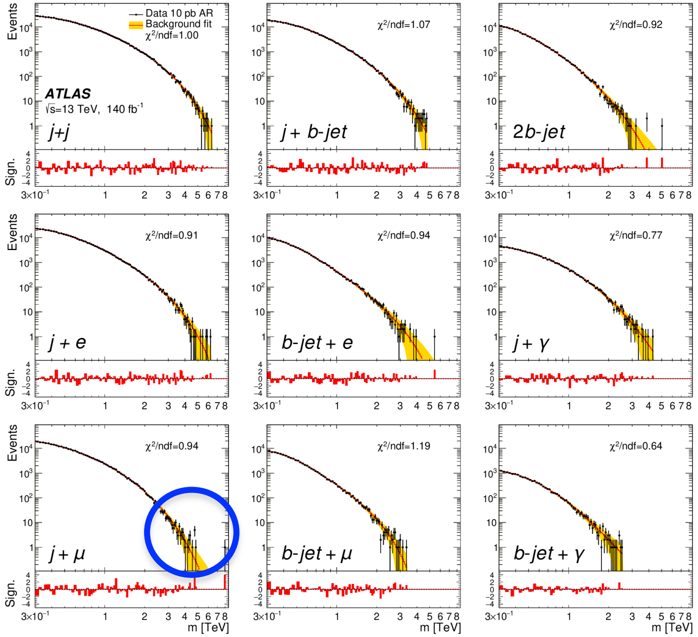


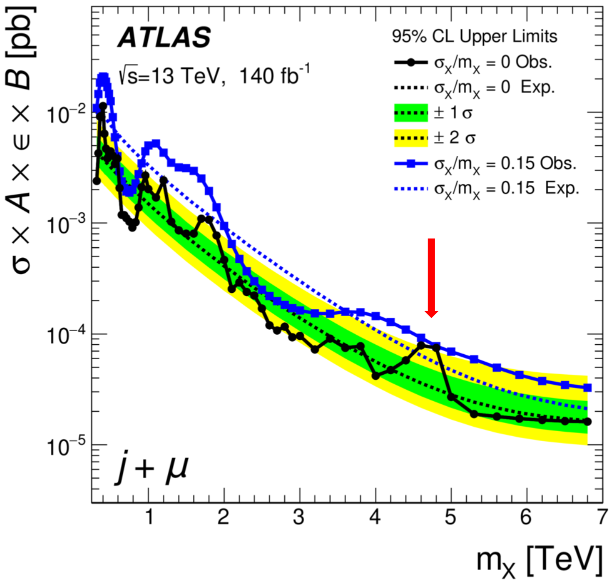


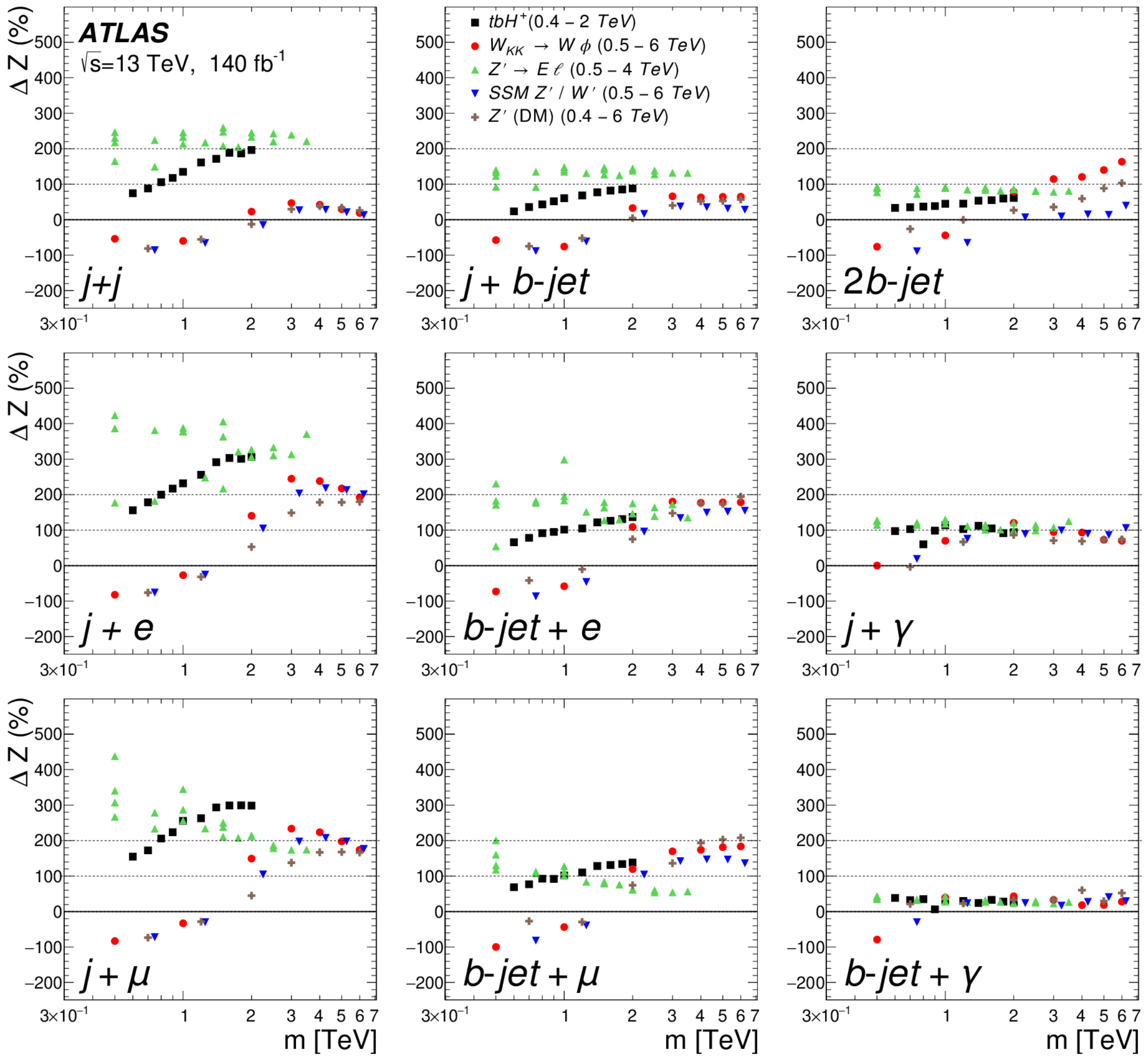
ML for anomaly-detection

arxiv:2307.01612, submitted to PRL

- Machine learning (ML) anomaly-detection methods
  - autoencoder (AE), trained using mostly SM background events
- Generic search for resonances in 2-body final states, for the first time in ATLAS
  - jet+Y: jet (light or b-jet); Y= l (e/μ), γ, light jet or b-jet
- Large improvement compared to previous results
  - The most significant excess near 4.8 TeV in $m_{j\mu}$



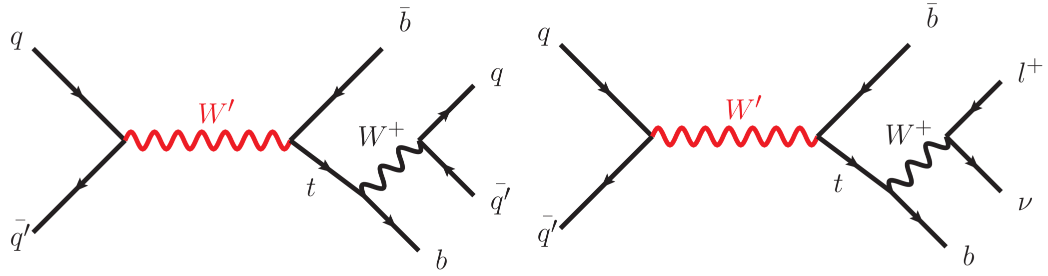


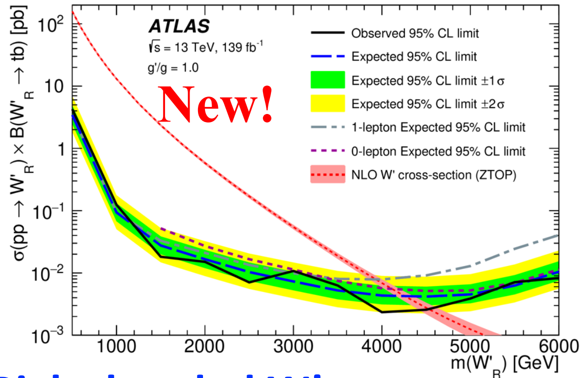


W'->tb

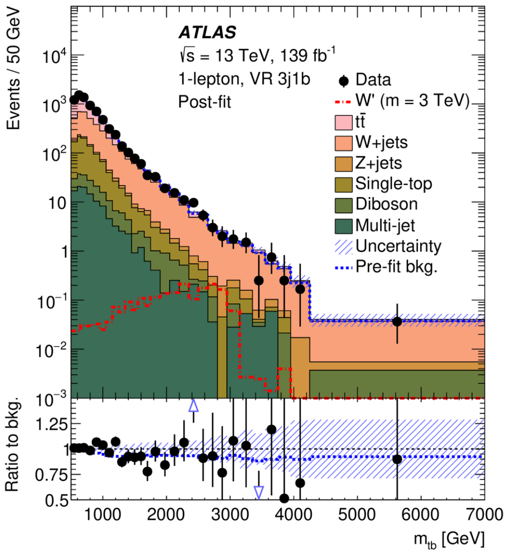
CMS-PAS-B2G-20-012
arxiv:2308.08521, submitted to JHEP

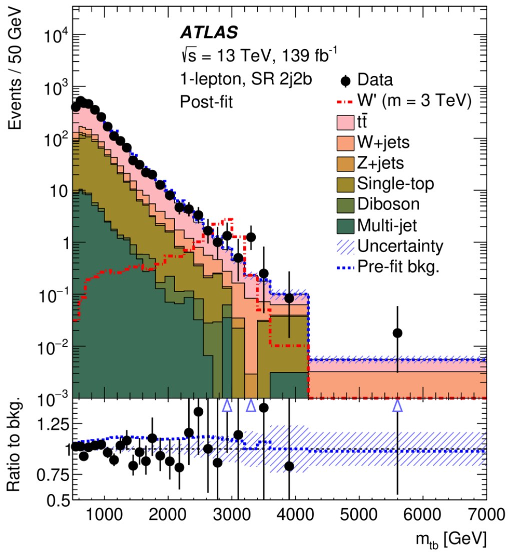
- W' couples preferentially to 3rd generation, favored to explain the B-anomaly
- Final states:
  - lepton+jets (ATALS & CMS): optimal sensitivity to high W' mass
  - all-hadronic (ATLAS)
- Most stringent constraints to date on W' decaying to top and bottom quarks

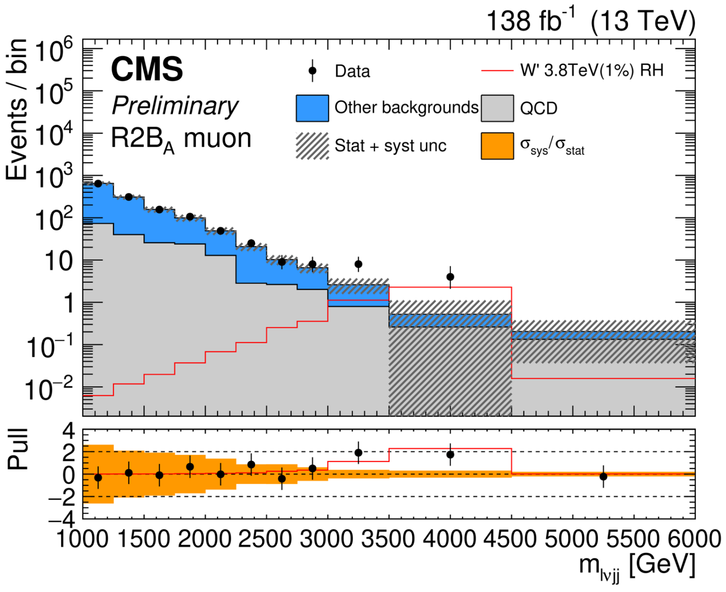


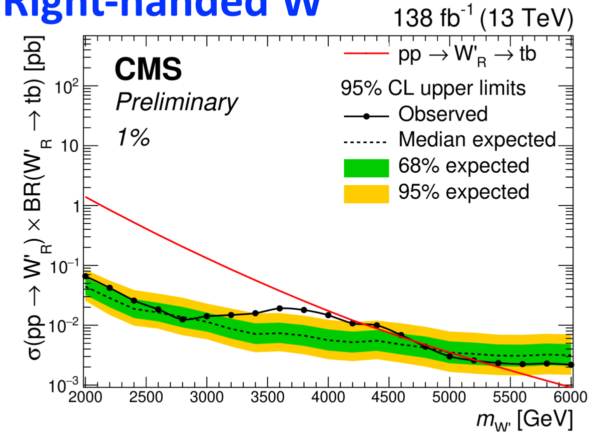


Right-handed W'





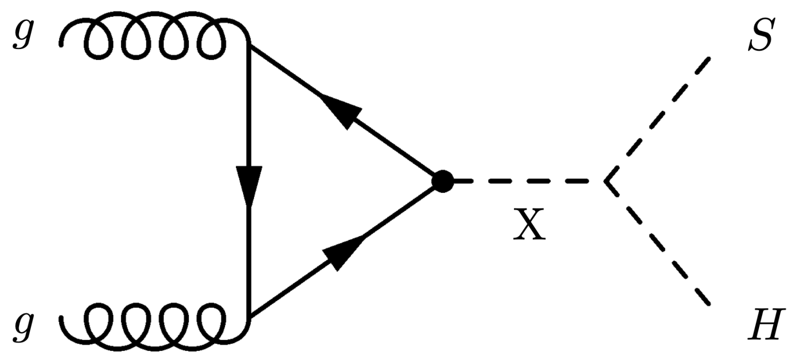


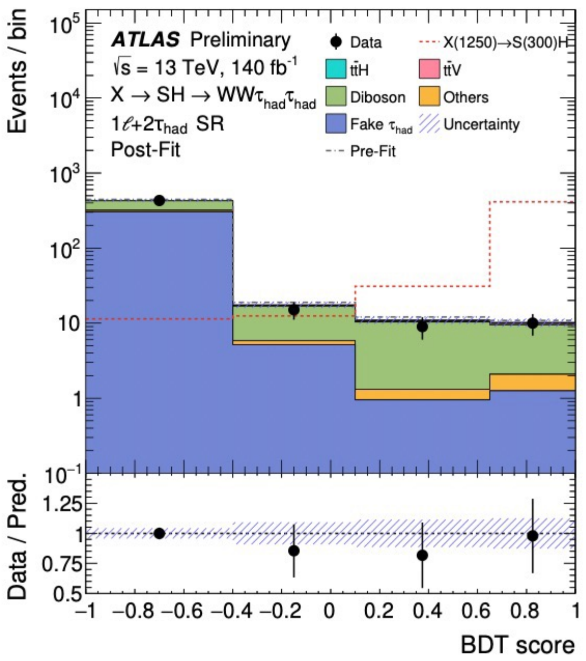


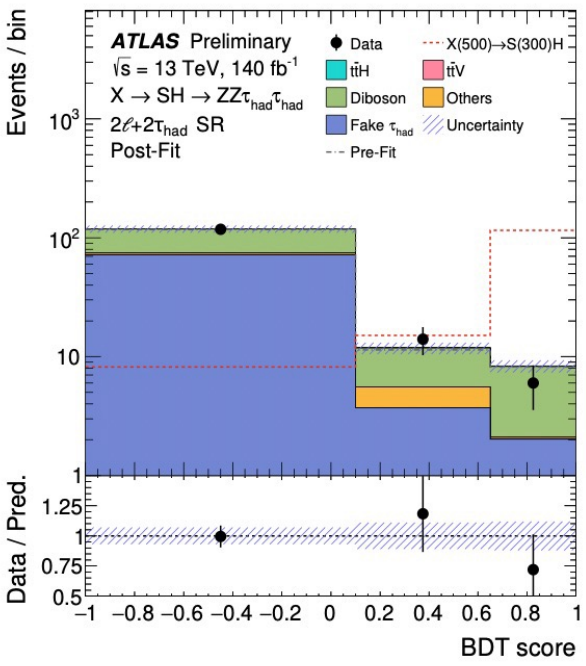
X->SH

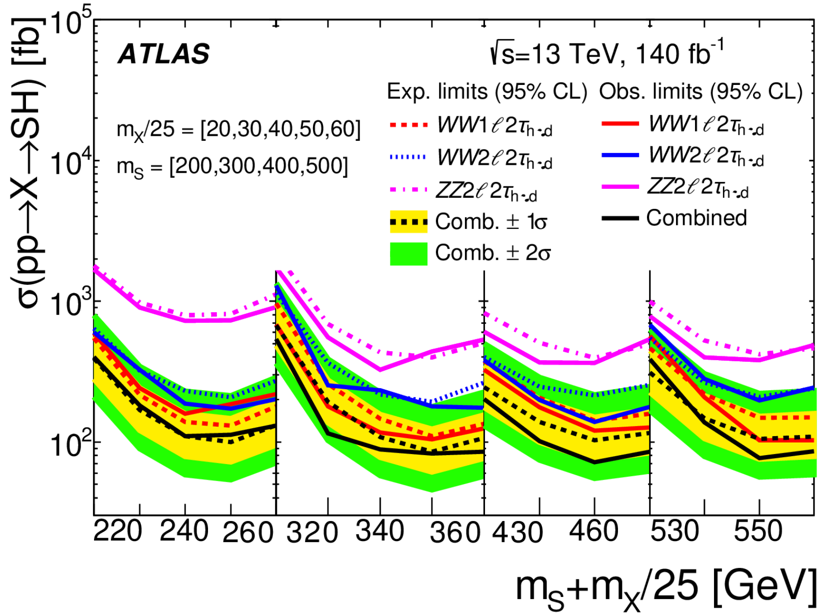
arxiv:2307.11120, submitted to JHEP

- Heavy CP-even scalar X->SH, with S decaying into WW or ZZ
  - X mass: 500 –1500 GeV
  - S mass: 200 – 500 GeV; scalar singlet, assumed to have the same relative coupling as a SM-Higgs
  - H->$\tau_{had}\tau_{had}$, one or two leptons(e,μ) from S->WW/ZZ
- First of its kind and competitive with other searches using final states VVbb, VVγγ, bbττ, bbbb in high mass



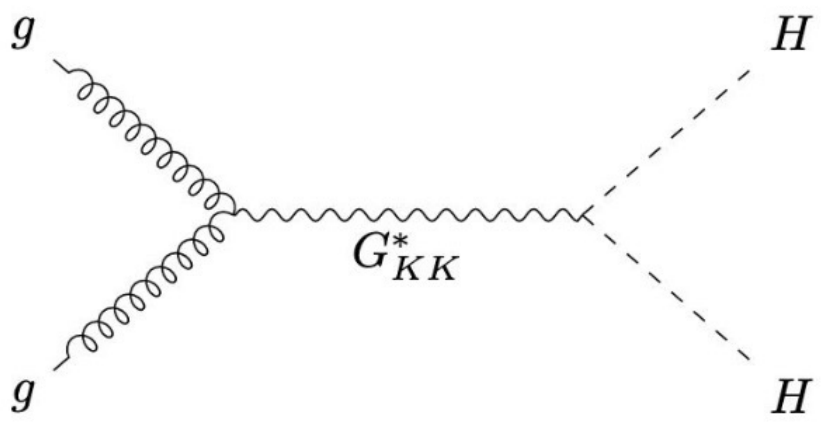


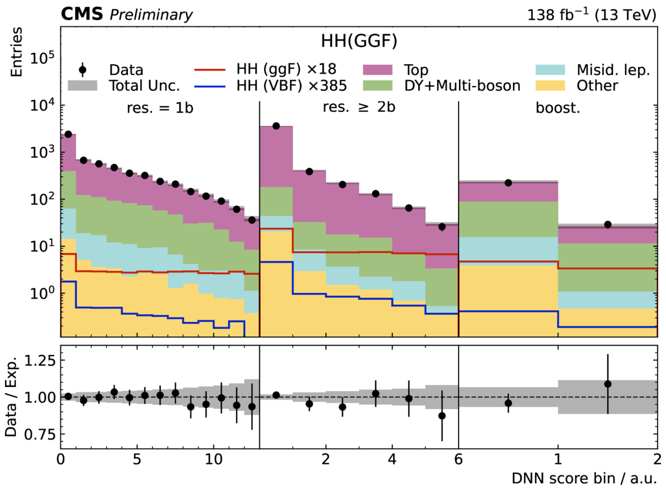


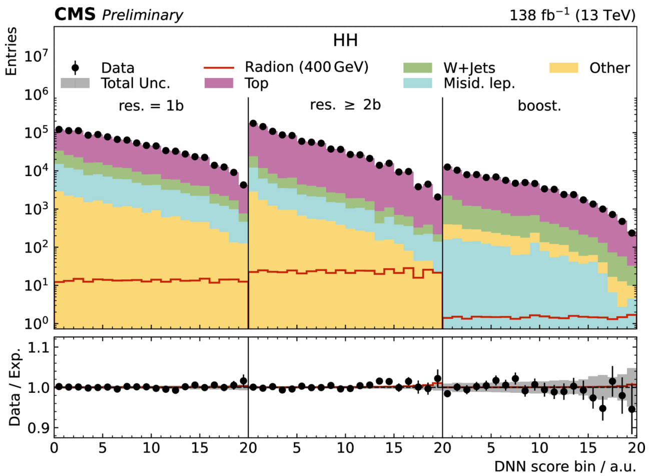


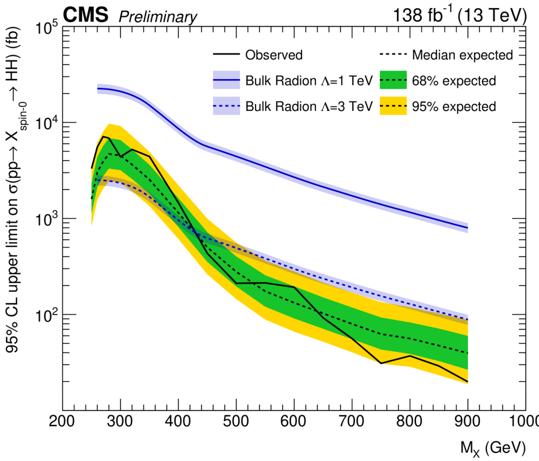
X->HH->bbWW

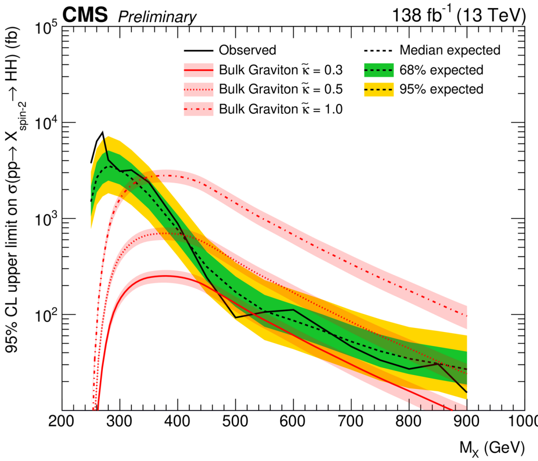
- Target HH resonance with spin 0 and 2 in mass range of 250 - 900 GeV
- Search for HH->bbWW, resonant and nonresonant HH produciton both included
  - Has 2nd largest branching ratio, following HH->bbbb
  - W decay to leptons(e, μ): 1 lepton; 2-lepton
- DNN distribution is used to extract signal





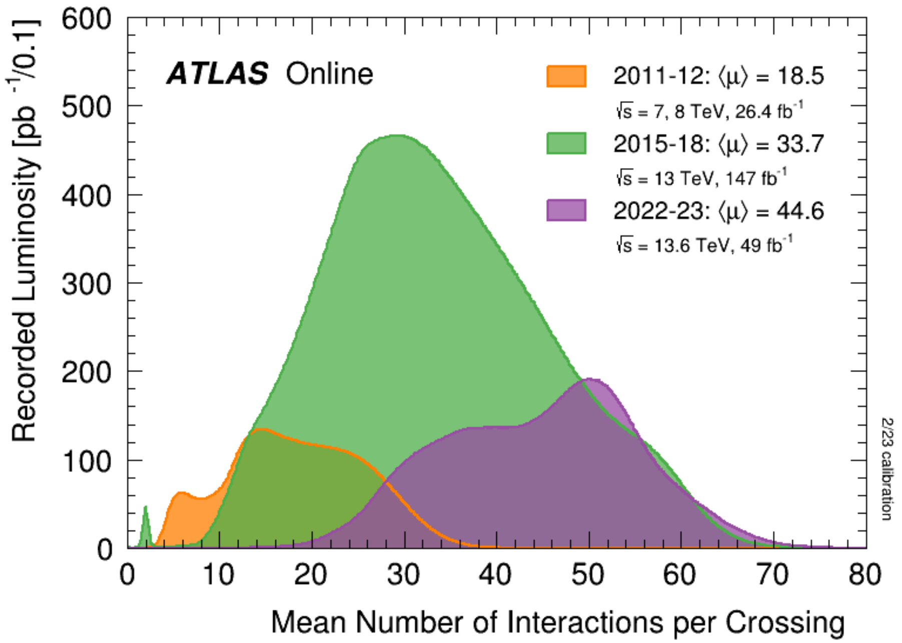






Summary

- ➢ **Relentless efforts have been made by ATLAS & CMS to explore new physics in many ways, productive with excellent results covering different aspects**
  - ✓ **Full Run-2 data brings significant statistical power**
  - ✓ **No signal is observed and stringent limits are set**

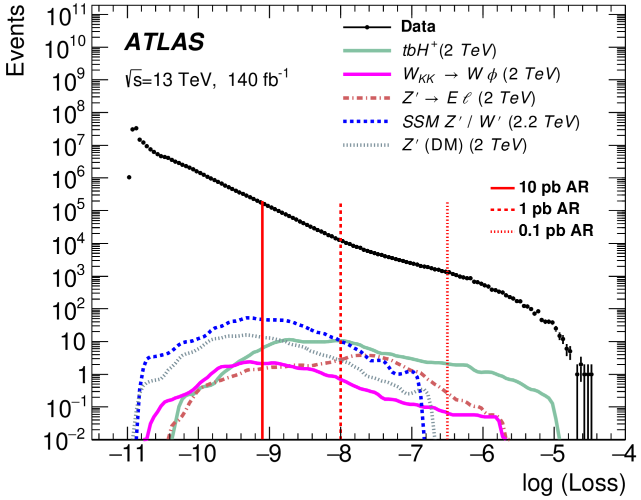


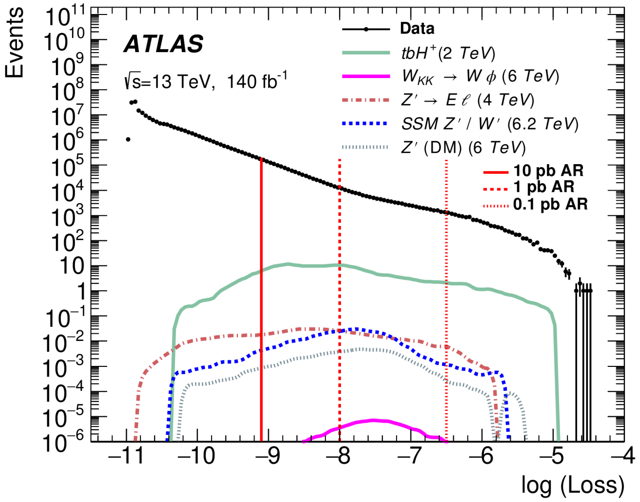
- ➢ **Next: finish up more Run-2 results, and aim to analyze Run-3 data**
  - **Better analysis techniques, including machine learning, may yield sensitivity beyond expectation**
  - **LLP/unconventional signatures become more important: 0-background searches benefit more from luminosity increase**

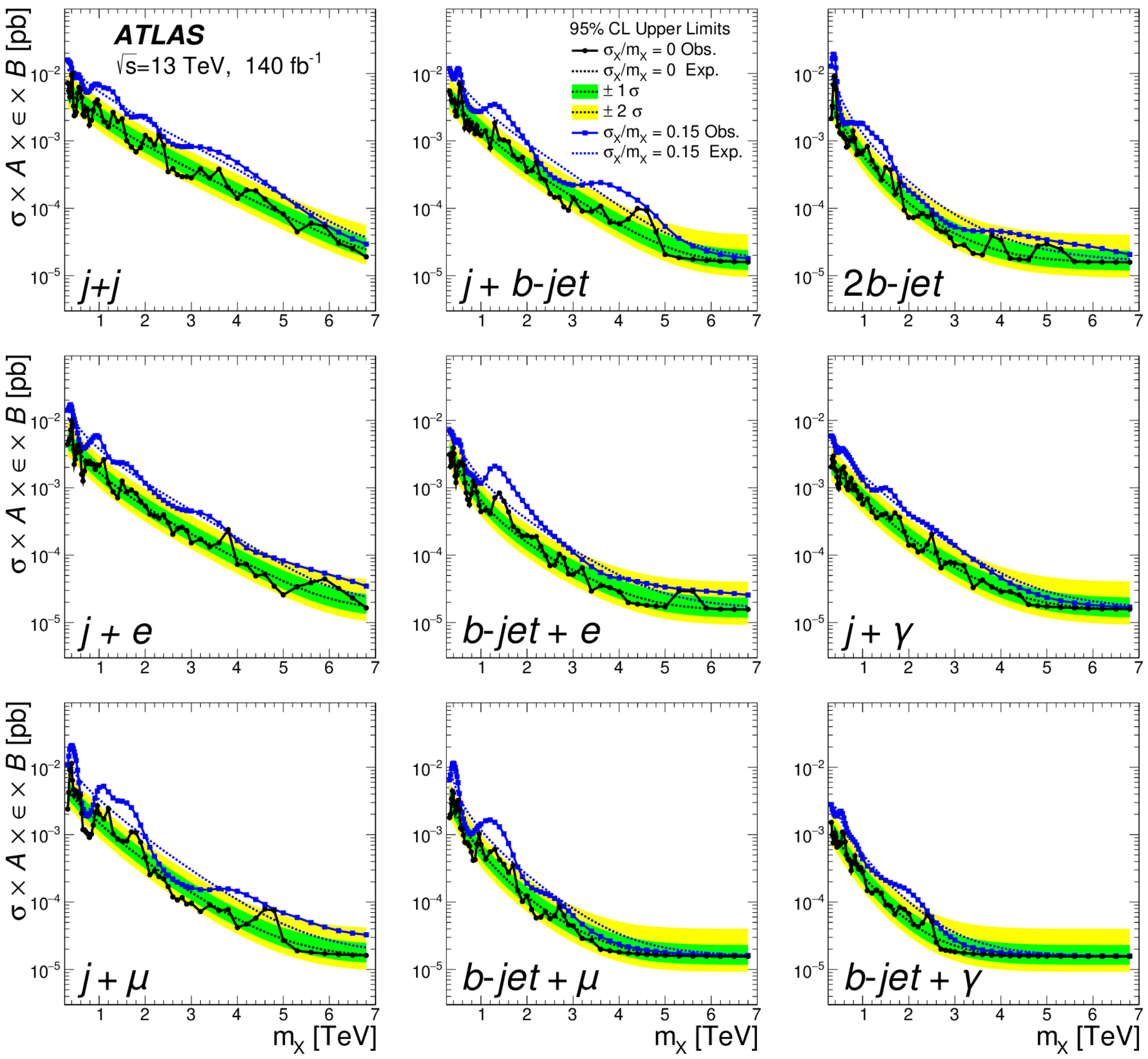
backup

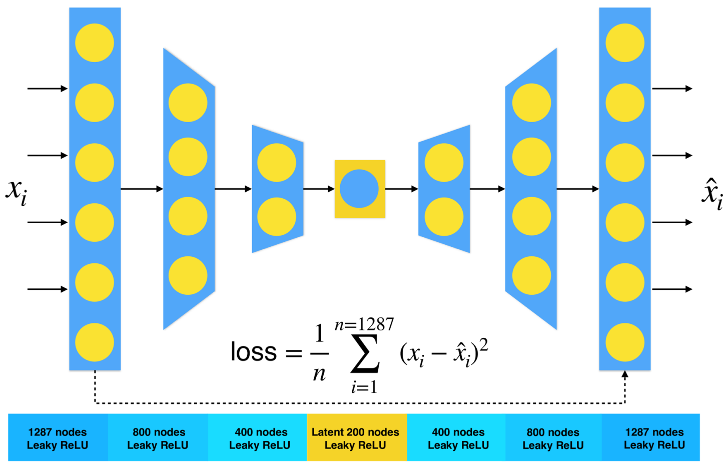
Explore machine learning

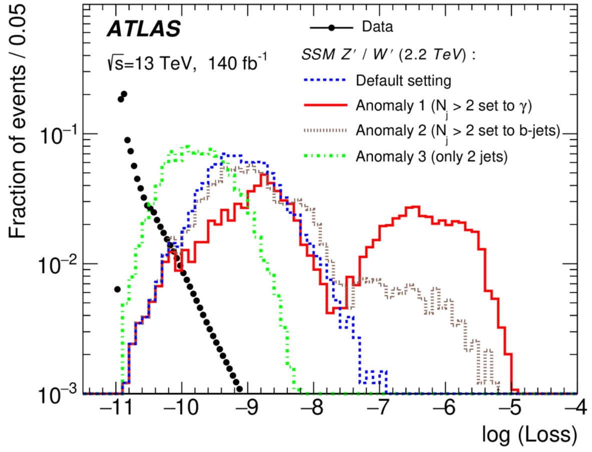
arxiv:2307.01612, submitted to PRL











Multi-charged particles(MCPs)

arxiv:2303.13613, submitted to PLB

- Target MCPs, with $|q| = ze$, $2 \leq z \leq 7$
- Exploit muon-like signatures
  - Muon trigger
  - MET trigger
  - Late-muon trigger: use info in later buncher-crossing
- Search for high pT muon-like tracks with high *dE/dx* in subdetectors
  - Main bkgd: high pT muons (data-driven)