Other Exotics Searches

2025 03 26
2025 Recontres De Moriond - Electroweak

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on behalf of the **ATLAS & CMS Collaborations**


Vector-Like Fermions
High-Mass Resonances
Dark Matter
New Physics?

Search for Vector-Like Leptons coupling to first and second generation leptons

ATLAS, Run 2 Dataset, 140 fb^{-1}

Submitted to JHEP
Inspire Record

Search for electroweak production of Vector-Like Leptons in multiple tau and b-jet final states

ATLAS, Run 2 Dataset, 140 fb^{-1}

Approved as a CONF
CDS Record

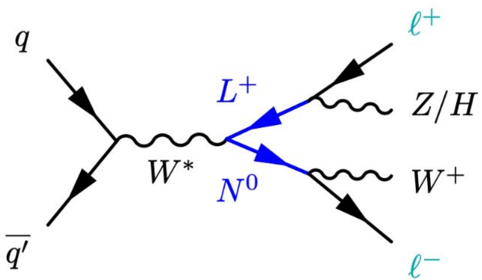
Motivation & Overview

- Vector-Like Fermions well respected part of the BSM picture
  - VLFs mass term does not arise from Higgs coupling
  - → smaller constraints from Higgs measurements

Baseline Model

- VLLs produced in pairs
- Neutral (N) and charged (L) states
- Decay modes depend on the multiplet state:

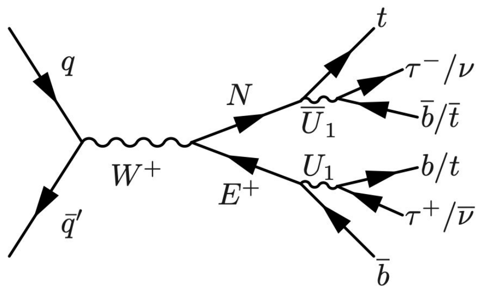
$$L \to \nu W,\ \ell Z, \ell H \qquad N \to \ell W$$



NN, LL modes also targeted

"4321" Model

- Specifically to address B-meson flavour anomalies
- VLL couples with LEPTOQUARK field U_1
- Both VLL and U_1 couple to 3rd generation quarks/leptons



NN, LL modes also targeted

Complex signatures:

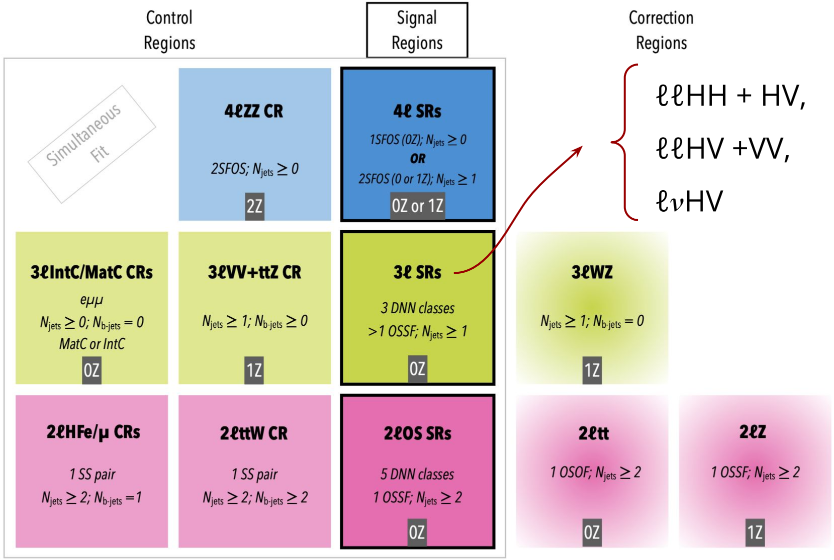
⟺

Jets,
b-quarks,
leptons,
hadronic tau decays,
top quarks

Analysis Strategy

- Main Backgrounds:
  - Top-Pairs, Z+Jets, Top-Pair+W/Z, Di-Boson production and more

- Event Classification:
  - Deep Neural Network to classify events into a vast array of SRs and Control Regions (CRs)
  - Extensive classification reflecting event content and VLLs decay mode



VLL to electron/muons analysis workflow

- Control Regions:
  - Constraining the normalization of each main background

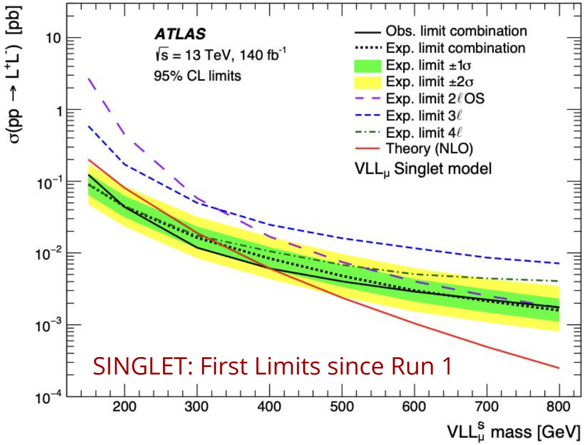
- Correction Regions:
  - Derivation of data-driven correction factors (e.g. heavy flavour fractions in tt+jets)

All Regions fitted simultaneously

Results

VLL ⟶ 1st/2nd Gen Leptons

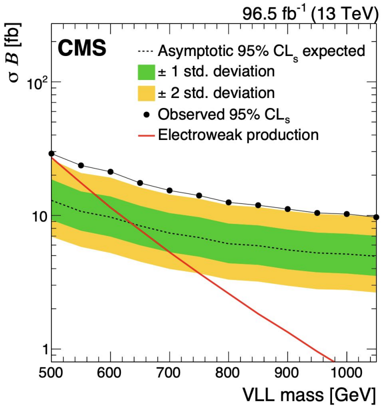
- No significant deviations from SM
- VLL Exclusion Limits for:
  - VLL as weak isospin SINGLET
  - VLL as weak isospin DOUBLET (first time!)



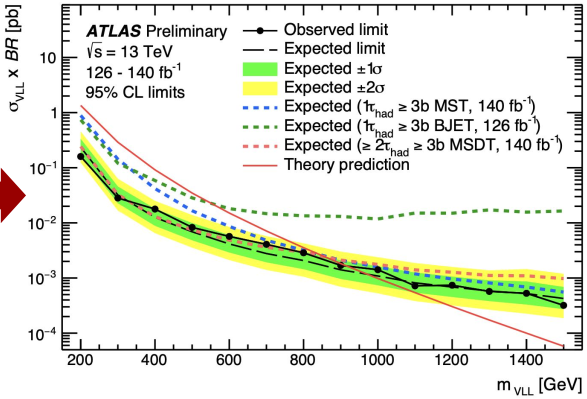
"4321" Model

- No significant deviations from SM
- First ATLAS limits on the "4321" model
- Excess seen by previous CMS result **NOT** confirmed
- VLL excluded for M < 950 GeV

Phys.Lett.B 846 (2023) 137713



THIS SEARCH



Search for Dark Matter production in association with a Dark Higgs Boson decaying to a pair of b-quark

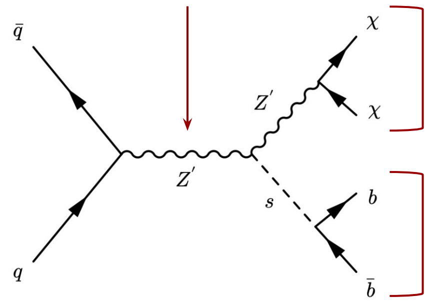
ATLAS, Run 2 Dataset, 140 fb^{-1}

Accepted by PRL
Inspire Record

Motivation & Overview

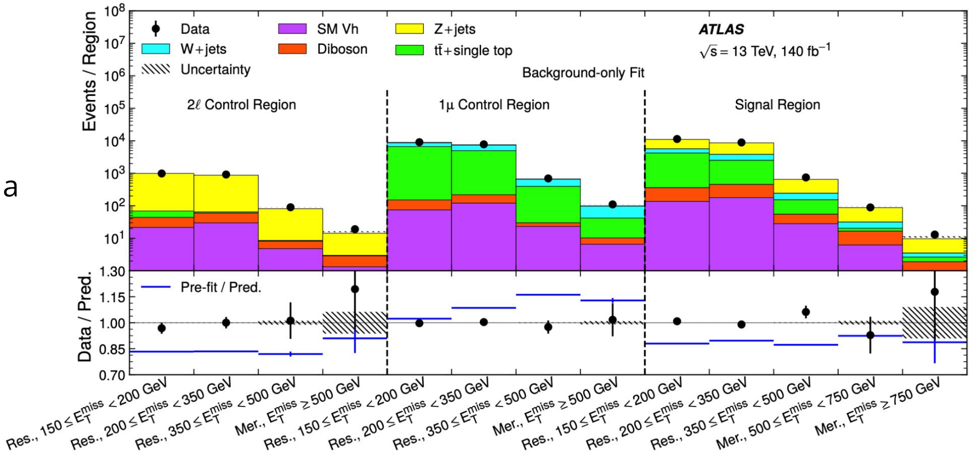
- Dark Matter searches are a staple of collider BSM programme
    - Invisible DM particle (χ) generates “Missing Energy” signature
- Theoretical Setup:
    - DM particles couple with “Dark Higgs” scalar **s**
    - **Z’** decays to DM pair **Z’**→**χχ** via coupling g_χ
    - Large g_χ results in frequent **Z’** →**Z’S** radiation
- Experimental Signature:
    - Large Missing Energy (MET)
    - 2 b-initiated jets (either resolved or merged into a single large-Radius jet)
    - No Leptons
- Main Backgrounds: W/Z+jets
    - Normalized in dedicated control regions

SM-DM mediator
a.k.a. “PORTAL”



Invisible DM, to form Missing Energy

Visible matter, recoils off DM



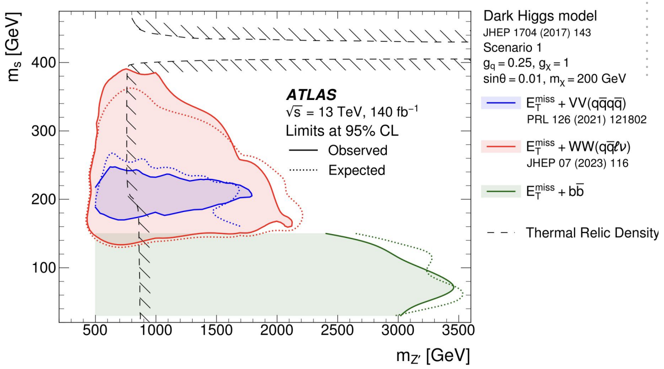
A Rich Interpretation

Scenario 1

Traditional Benchmark scenario at colliders.

Scan over (m_s, mZ’),
g_q = 0.25, g_χ = 1.0, m_χ = 200 GeV

Strongest limits to date for low-mass Dark Higgs

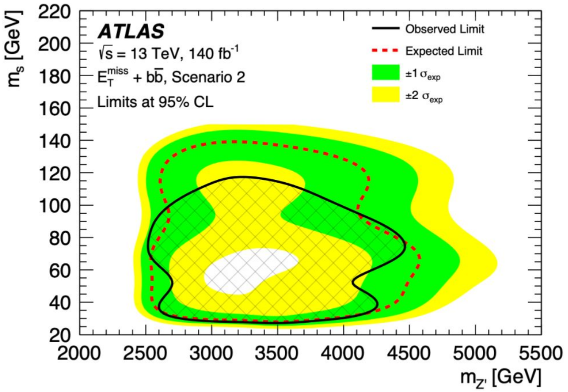


Scenario 2

Z’-DM coupling g_χ varies to always satisfy the Relic Density requirement

g_q = 0.25, m_χ = 200 GeV

Higher Z’ mass exclusion due to larger g_χ coupling

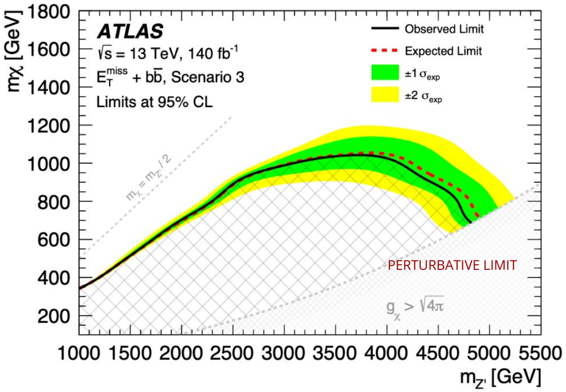


Scenario 3

Scenario of optimal sensitivity for the present search

Fixed m_s = 70 GeV

Scan over the ($m_{Z'}$, m_χ) plane



No statistically significant evidence for Dark Matter production found

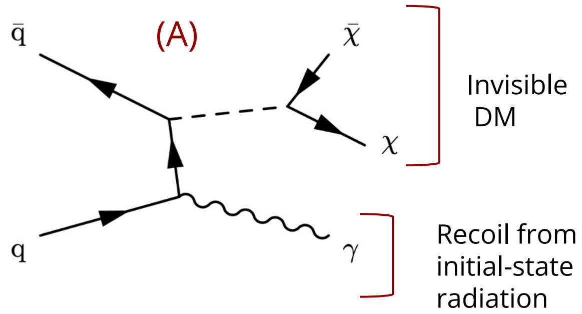
Search for New Physics in Photon plus missing energy final state

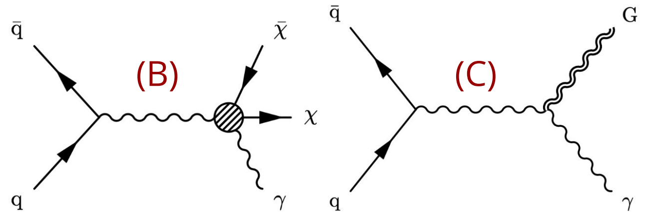
CMS, Run 2 Dataset, 137.2 fb^{-1}

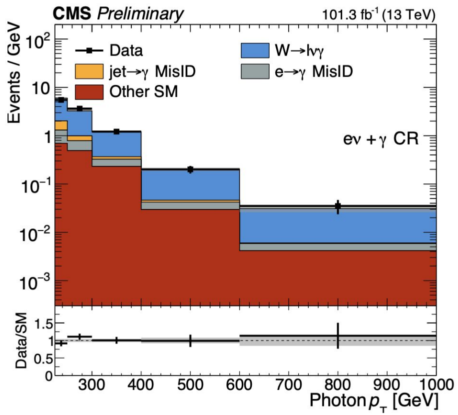
SUS-23-016

Motivation & Overview

- MET+Photon signature:
  - Highly complementary to flagship MET+Jet searches
  - Photon final state → exceptional experimental cleanness
- Theoretical Targets:
  - A] Simplified DM Model (ATLAS+CMS benchmark)
  - B] Preferential DM coupling to EWK sector with suppression scale Λ
  - C] Extra dimensions with Graviton at the effective Planck mass
- Handling of Background Sources
  - Z(νν)+γ & W(lν)+γ → Simultaneous fit with Control Regions
  - Fake Photons → Data-Driven Fake Factors
  - (NEW!) Beam Halo → Veto on horizontal muons, Control Regions based on azimuth angle





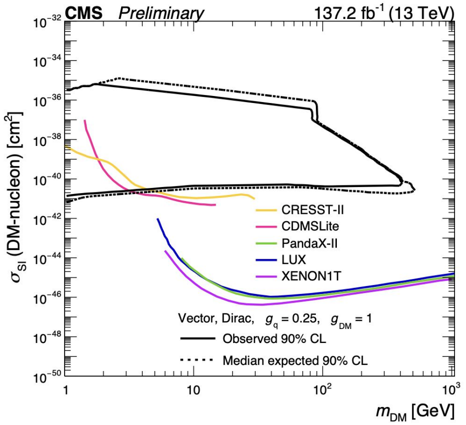


Another rich Interpretation

Scenario A
SIMPLIFIED DM MODEL

Scan over (m_{med}, m_χ),
g_q = 0.25, g_χ = 1.0,

Limits interpreted in terms of spin-independent DM-Nucleon cross section

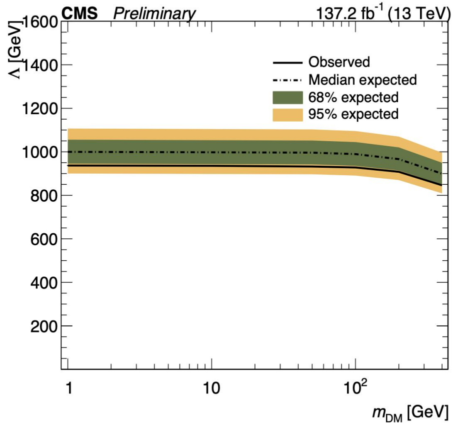


Limits also produced for spin-dependent

Scenario B
CONTACT EWK INTERACTION

Assume m_χ in [1, 100] GeV

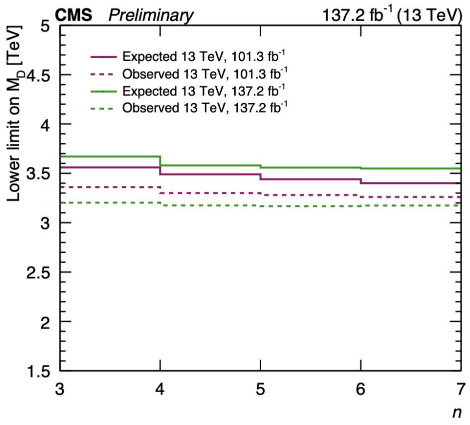
Suppression scale Λ excluded below 936 GeV



Scenario C
EXTRA DIMENSIONS

Scan over effective Planck scale

M_D and N_{Dim}



No statistically significant evidence for Dark Matter production found

Search for top-pair resonances in the fully hadronic final state

CMS, Run 2 Dataset, 138 fb^{-1}

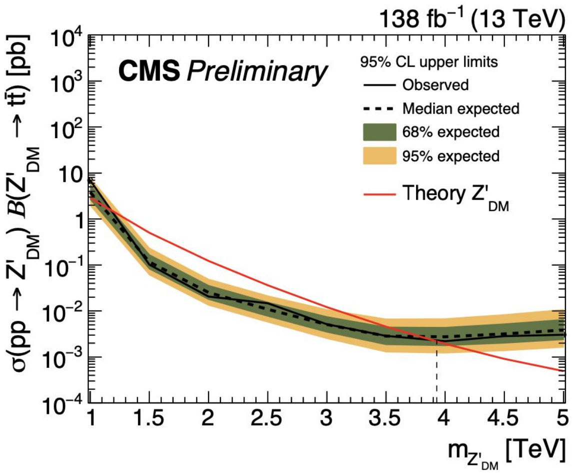
CMS-PAS-B2G-24-003

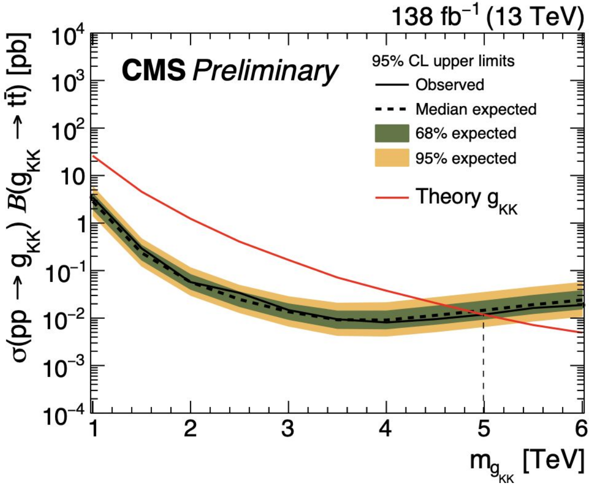
Analysis Overview

- Testing for new resonances with enhanced top coupling
  - Theoretically plausible due to large top-Higgs coupling
  - Benchmarks: generic **Z'** resonance and **Kaluza-Klein** excited **gluon**

- Analysis Strategy:
  - Large-Radius Jet identified as "Top Candidate" through Deep Neural Network
  - DNN output used to support data-driven estimation of QCD background contribution

- Results
  - No significant deviation from SM prediction
  - Strongest exclusion power for narrow resonant production
  - Sensitivity limited by:
    - Trigger at low Z' mass
    - Reconstruction in high lorentz boost at high Z' mass





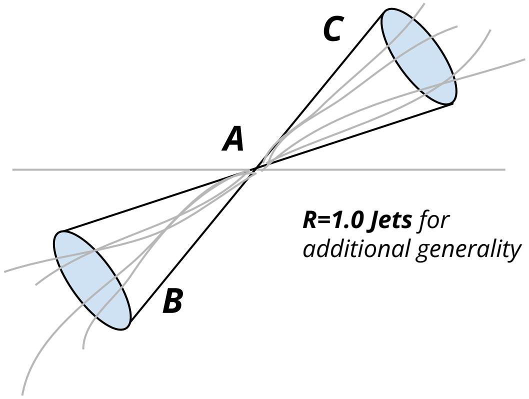
Weakly supervised anomaly detection for resonant New Physics int the di-jet final state

ATLAS, Run 2 Dataset, 140 fb^{-1}

Submitted to PRD
Inspire Record

Overview & Strategy

- Target Signature:
  - pp → **A → BC**, A, B, C massive BSM resonances
  - A, B decaying to SM quarks → Fully hadronic final state
  - Adjacent to DiBoson (WW,WZ,ZZ) searches



- Model Independent Search:
  - Event Selection not from signal simulation, but from data properties
  - ML application to "learn" the underlying distribution of key event features in data to:
    1. Reject events most compatible with being sampled from background sources
    2. Enhance localized outliers in the "features space"
    3. Interpret the results in terms of excess significance

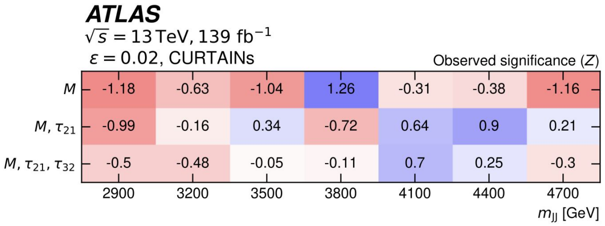
Results

Analysis interpreted through:

A. Model independent significance of largest excess per SR, per Feature Space choice

B. Exclusion Limits for simplified di-boson models

A - Model Independent Significance



No statistically significant deviation from the SM background estimate found under any choice for:

- Unsupervised ML working point
- Background modelling technique

Results

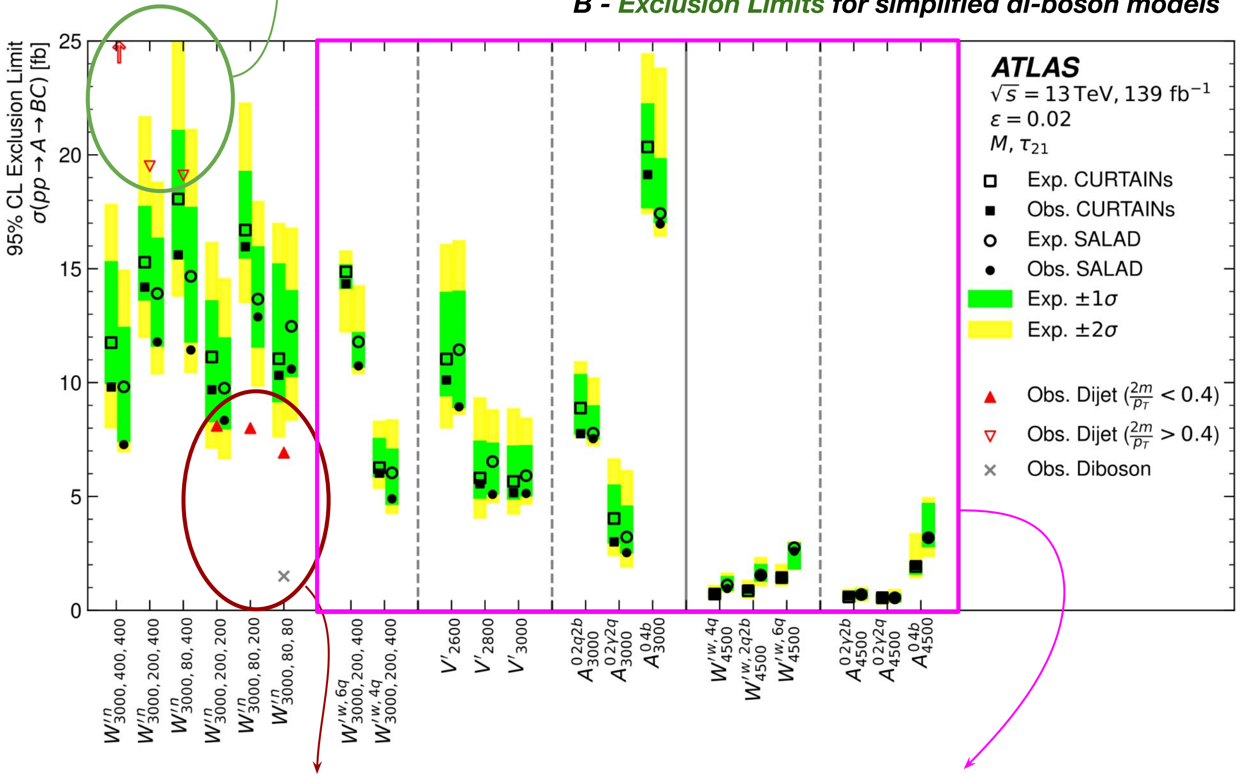
Analysis interpreted through:

A. Model independent significance of largest excess per SR, per Feature Space choice

B. Exclusion Limits for simplified di-boson models

Analysis **outperform** existing limits for B,C masses far from the W,Z mass

B - Exclusion Limits for simplified di-boson models



Analysis **outperformed** by existing, optimized searches close to the W,Z mass,

New Coverage for non-traditional di-boson signal hypotheses (incl. HVT, Pseudo-Scalar resonances decaying to a Higgs and a BSM resonance)

Search for resonant production of pairs of dijet resonances through broad mediators

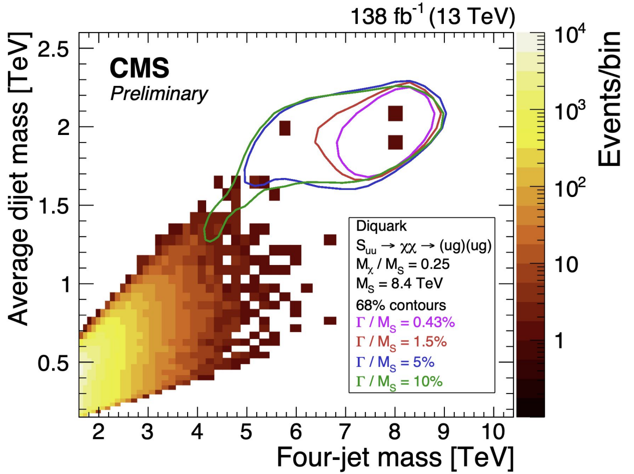
- a reinterpretation of *JHEP* 07 (2023) 161 -

CMS, Run 2 Dataset, 140 fb^{-1}

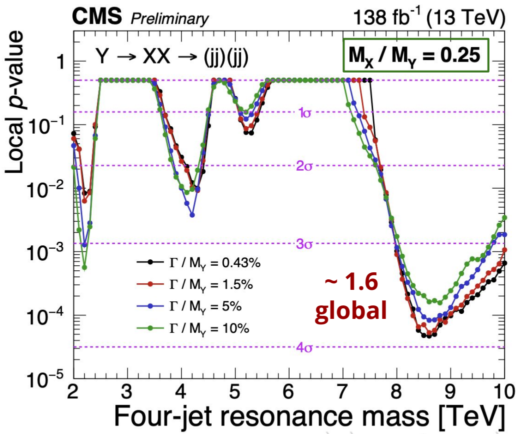
CMS-PAS-EXO-24-038

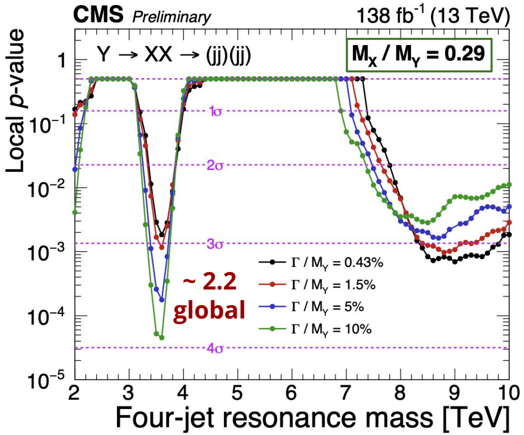
Analysis Summary: 4-jet resonant search

- Original Analysis showed interesting high-mass events
- Re-Interpreting for Large-Width:
  - Two BSM-particle chain pp → **Y** → XX → 4j
  - Benchmarks: **Y** = Di-Quark state | X = Vector-Like Quark
  - X → Narrow Width | **Y** → Large Width → 0.5 to 10% of M_S



- High Mass (~8 TeV) events:
  - Suited to both narrow and wide signal hypothesis
- Low-Mass (3.5 TeV) excess:
  - Well suited by a broad resonance
  - Highly dependent on the MY/MX ratio
- Global significances below 2.5σ





Other Recent Exotics Searches

ATLAS

"Search for New Physics in the cc+MET final state", Inspire

"Search for single VLQ (T/Y) to Wb", JHEP 02 (2025) 075

"Search for same-sign top-pair production", JHEP 02 (2025) 084

"Combination of searches for singly produced vector-like top quark", Phys. Rev. D 111 (2025) 012012

"Search for Dark Matter in W or Z hadronic decays and missing energy", JHEP 11 (2024) 126

"VLQ Top Pair production in final states with a W boson", Phys. Rev. D 110 (2024) 052009

"Search for H/A decaying to a top quark pair", JHEP 08 (2024) 013

CMS

"Search for Dark Matter in association with one or two top quarks", EXO-22-014

"Model-agnostic search for di-jet resonances with anomalous jet substructure" EXO-22-026

"Search for Dark Matter in association with a bottom quark pair", SUS-23-008

"Search for heavy Higgs A/H in the ttZ channel", B2G-23-006

"Search for Dark Matter in association with a H decaying to a tau lepton pair", CMS-PAS-SUS-23-012

"Enriching the CMS physics programme with Data Scouting and Data Parking" EXO-23-007

"Dark Sector searches at CMS", EXO-23-005

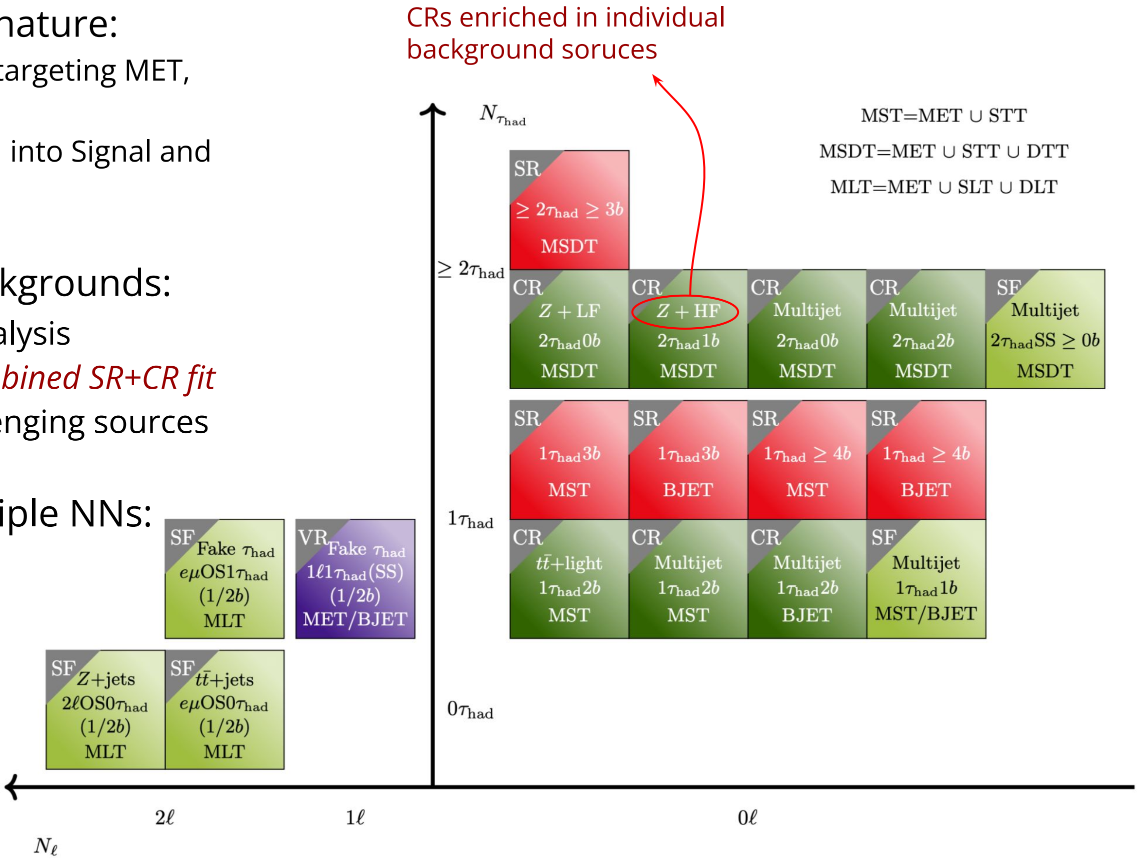
BACKUP

VLL 4321 | Analysis Strategy

- Handling diverse experimental signature:
  - STEP #1: Employ a "trigger cocktail", targeting MET, single(multi) taus, etc
  - STEP #2: DNN-powered classification into Signal and Control Regions

- Diverse signature ⟵⟶ diverse backgrounds:
  - Similar handling to the VLL-eμ analysis
  - Normalization constrained in *combined SR+CR fit*
  - Data-Driven scale factor for challenging sources

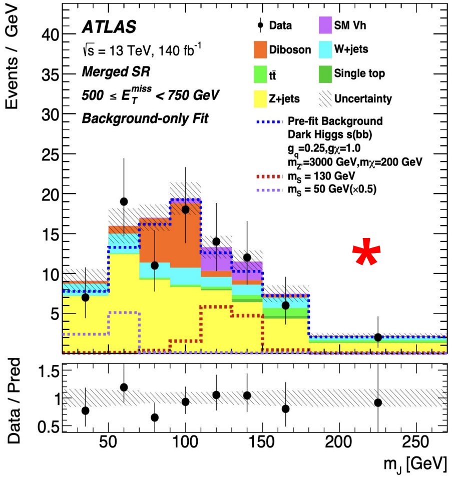
- Signal Enhancement through multiple NNs:
  - Inputs:
    - Triggers passed
    - Object kinematics
    - b-tagging scores
    - Scalar sum of momenta
    - And much more



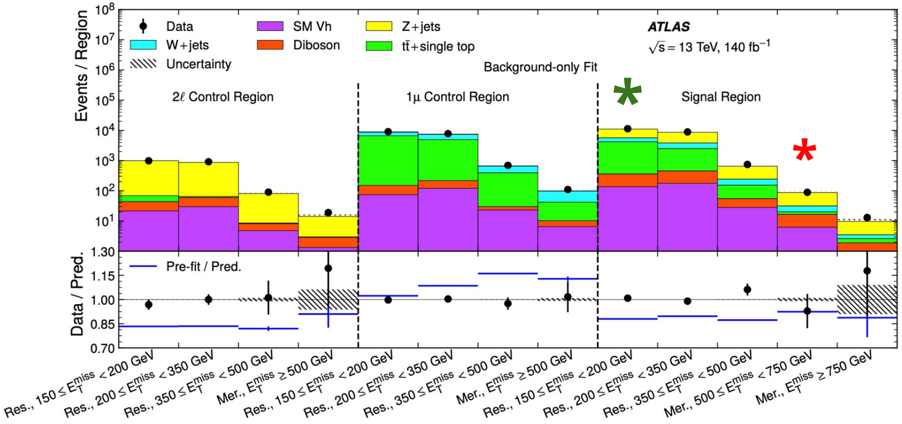
Mono S(bb) | Analysis Strategy

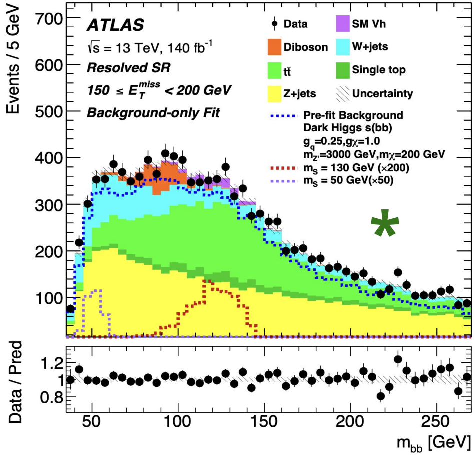
- Main sources of SM background and how to treat them:
  - *W/Z + Jets* → Main source of background
  - *Top Quark pairs* → Constrained through transverse mass cut
  - *QCD* → Highly constrained by MET significance cuts

- W/Z + Jets background modelled via Monte Carlo Simulation
  - Total background normalization usually "poorly" modelled
  - Normalization constrained in two control regions:
    - W-targeted: 1 muon + baseline event selection
    - Z-targeted: opposite sign leptons + baseline event selection



SIGNAL REGION DATA/MC





Preamble: An alternative analysis paradigm for BSM searches at colliders

- Traditional collider searches rely on well tested workflow:

Signal Model ⇄ (ENHANCES / INSPIRES) Event Selection → (EXTRACT) Limits / Significance

Limits / Significance → (EXCLUDE / OBSERVE) Signal Model

- *Machine Learning* advancements applied to HEP offers a *complementary workflow* for BSM Searches:

DATA → (INFORMS) Bulk Properties → (EXTRACTS) Outliers → (COMPUTE) Significance for Generic BSM

Significance for Generic BSM → (ENABLE) Reinterpretability for Generic Physics Models

Reinterpretability for Generic Physics Models → (COMPLEMENTS THE TRADITIONAL COVERAGE OF) DATA

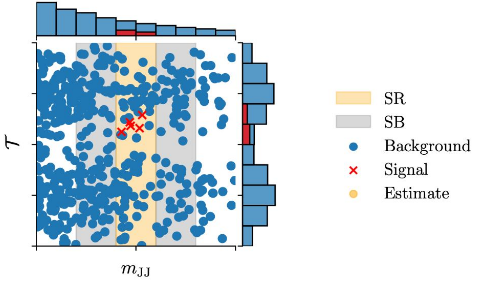
Di-Boson AD – Analysis Model

- Baseline Definitions
  - Signal Regions (SR) Mass Sidebands (SBs) in m_{BC}
  - Feature spaces → jet mass & subjettiness:

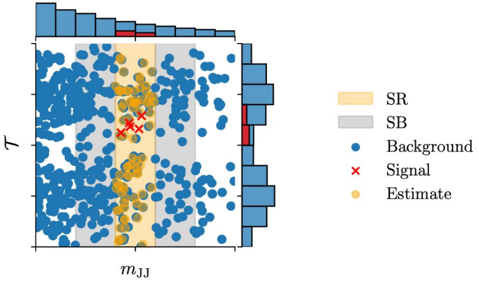
$$\mathcal{T}_0 : \{M_{jet}\}$$
$$\mathcal{T}_1 : \{M_{jet}, \tau_{21}\}$$
$$\mathcal{T}_2 : \{M_{jet}, \tau_{23}\}$$

- Background Estimation
  - Technique A (SALAD): SB-informed ML reweighting of MC background
  - Technique B (CURTAIN): Mapping of SB event features into the SR, via Normalizing Flows
- Data-Driven Signal Enhancement
  - Weakly Supervised Classifier (CWoLA): Reject data most compatible with distribution of feature space T in background
- Signal Extraction
  - Extract localized excess fitting with classical dijet function:

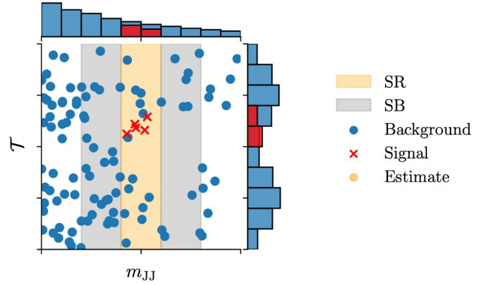
$$N(x) = p_0(1-x)^{p_1} x^{-p_3+p_4 \log x} \qquad x \equiv m_{BC}/13\ \text{TeV}$$



(a) Definition of Regions



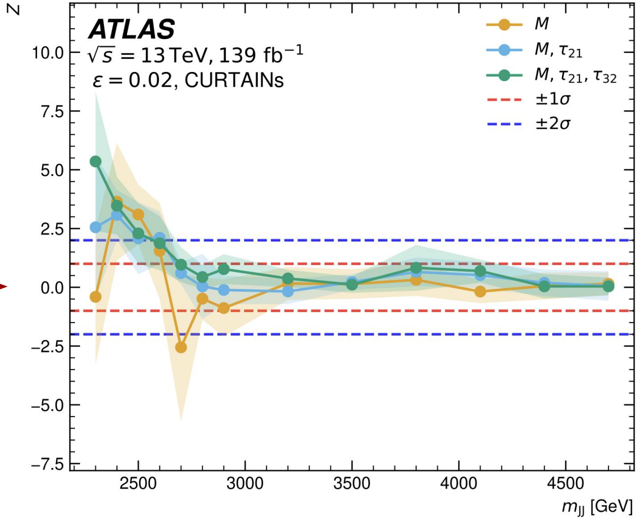
(b) Background Estimation



(c) Classification of Signal

Di-Boson AD | Validation and Uncertainties

- Workflow tested on 3 independent signal-depleted datasets:
    a. Reverse rapidity cut:
    b. Synthetic Dataset based on MC + Data-Trained diffusion model
    c. Synthetic Dataset based on random SB/SR sampling
- Validation Condition:
    - Median significance over all validation datasets $\rightarrow \mathrm{Avg}(Z) < 1$
    - Significance variance over all validation datasets $\rightarrow \mathrm{Var}(Z) < 1$



- Systematic Uncertainties:
    - No Signal Model uncertainties by construction (there's no signal model!)
    - Main factor: fit uncertainty derived from statistical uncertainty in data
    - Background modelling procedure uncertainty:
        i. → Non closure derived in Validation Dataset (C) applied as template uncertainty