Exotics at CMS

Eirini Tziaferi
National and Kapodistrian University of Athens (NKUA)

on behalf of the CMS collaboration

Introduction

- The shortcomings of the SM motivates a **comprehensive program of “exotics” searches for beyond-the-SM (BSM) physics** at high energy colliders.

- Many BSM models describe new phenomena in the **final states with gluon, light and heavy flavor jets, leptons, and heavy bosons**.

- The **CMS EXO group**, the largest physics analysis group of CMS, oversees the majority of all the BSM analyses covering a wide range of models across different phase spaces – 239 published paper so far.

- **A selection of recent analyses from Run2 and early Run3,** focusing in the aforementioned final states, **will be presented.**

Datasets	**Year**	**Integ. Lumi**	**√s**
Run2	2016-2018	~140 fb^{-1}	13 TeV
Run3	2022	~35 fb^{-1}	13.6 TeV

- A full list can be found in here.

Analyses with full Run2 (2016-2018) data

Dark sector

Dark Sector: EXO-23-005

- New review paper on CMS **Dark Sector** searches has been submitted very recently in Physics Reports.

- Among these there are **searches on Hidden Valleys** including
  - Semivisible jets
  - Emerging jets
  - Soft Unclustered Energy Patterns (SUEPs)

- Hidden Valley (HV) models can address questions including the nature of dark matter and the hierarchy problem.

arXiv > hep-ex > arXiv:2405.13778

Search...

Help

High Energy Physics - Experiment

[Submitted on 22 May 2024]

Dark sector searches with the CMS experiment

CMS Collaboration

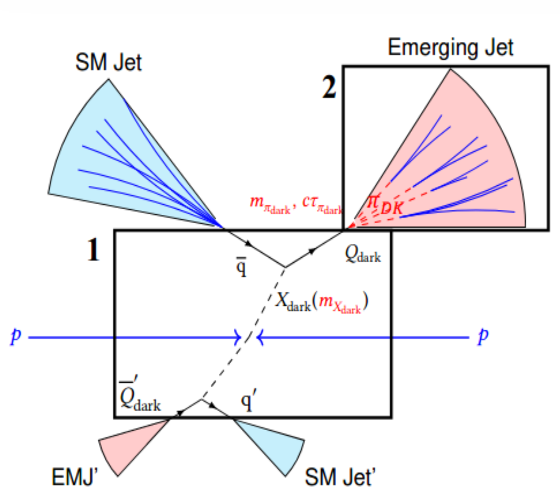
Astrophysical observations provide compelling evidence for gravitationally interacting dark matter in the universe that cannot be explained by the standard model of particle physics. The extraordinary amount of data from the CERN LHC presents a unique opportunity to shed light on the nature of dark matter at unprecedented collision energies. This Report comprehensively reviews the most recent searches with the CMS experiment for particles and interactions belonging to a dark sector and for dark-sector mediators. Models with invisible massive particles are probed by searches for signatures of missing transverse momentum recoiling against visible standard model particles. Searches for mediators are also conducted via fully visible final states. The results of these searches are compared with those obtained from direct-detection experiments. Searches for alternative scenarios predicting more complex dark sectors with multiple new particles and new forces are also presented. Many of these models include long-lived particles, which could manifest themselves with striking unconventional signatures with relatively small amounts of background. Searches for such particles are discussed and their impact on dark-sector scenarios is evaluated. Many results and interpretations have been newly obtained for this Report.

Run2 – Dark Sector: EXO-22-015

Emerging Jets (EMJ)

This search examines a **hypothetical dark QCD sector that couples to the SM through a scalar mediator**.

Signal Model:



1. $pp \rightarrow 2X_{dark} \rightarrow 2(qQ_{dark})$

2. $Q_{dark} \xrightarrow{\text{hadronizes}} N\,\pi_{dark} \xrightarrow{\text{travel } c\tau} \text{SM particles}$

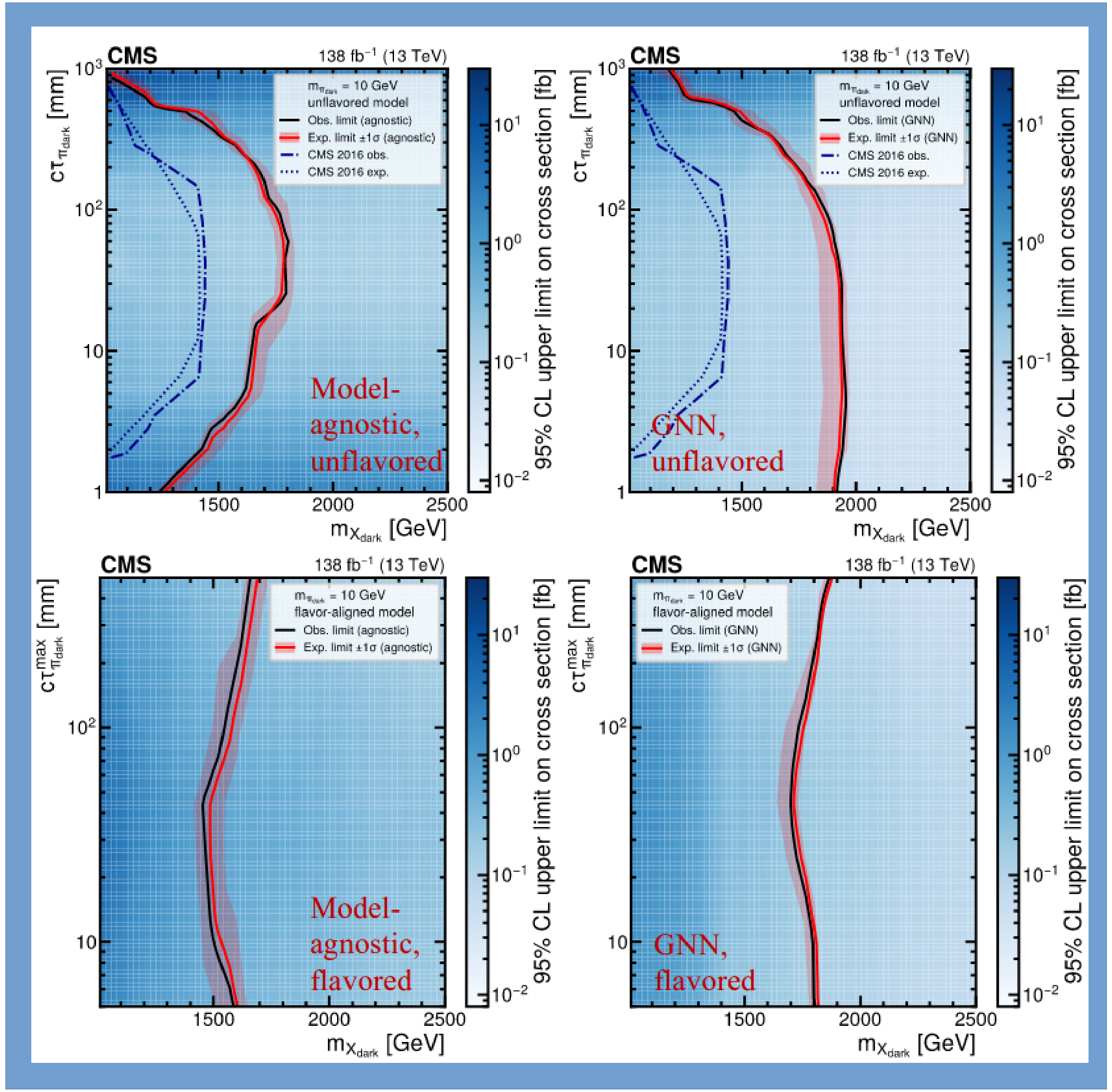
- Unflavored scenario: Q_{dark} couples to d quark
- Flavor-aligned scenario: Q_{dark} couples to d-type quarks
- Free parameters: $m_{\pi dark}$, $c\tau_{\pi dark}$, m_{Xdark}

Experimental signature: High HT, 4 high pT jets, ≥2 EMJ-tagged jets

Background: SM jets mistagged as EMJs → estimated from CRs

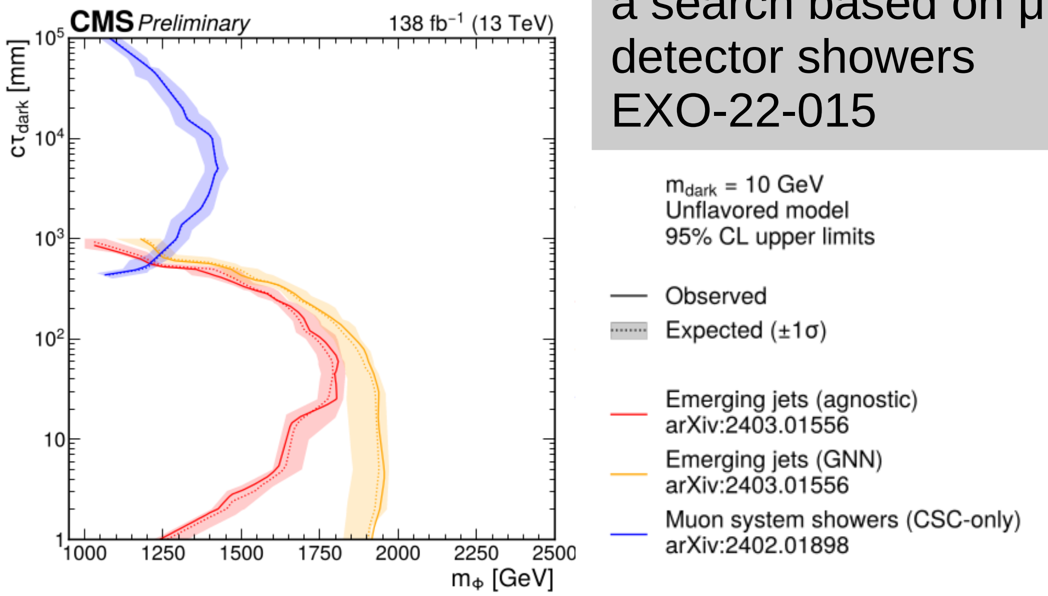
Methods used:
- Cut based approach → model generic
- GNN (Particle Net) → higher sensitivity to signal

Emerging Jets

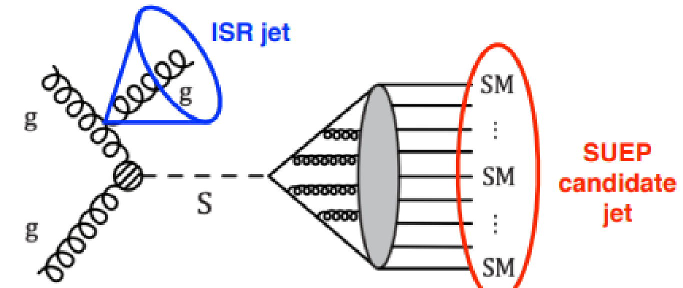


- No excess of events beyond the SM expectations is found hence derive limits.
- **Current limits significantly surpass CMS 2016 limits in the unflavored scenario.**
- GNN provides better limit than model-generic method, especially at low lifetimes.
- **The first direct exclusion of the flavor-aligned scenario.**

Complementarity with a search based on μ detector showers EXO-22-015



Search for Soft Unclustered Energy Patterns (SUEPs)



$S \rightarrow q_{dark}\, \overline{q_{dark}}$, q_{dark} → dark mesons (φ) → dark photons (A')→ SM particles

Signal Model

- Dark QCD showers can produce final states with many, isotropically-distributed, low pT tracks.
  - focus on boosted scenario ⇒ mediator S recoils against ISR jet ⇒ dijet system

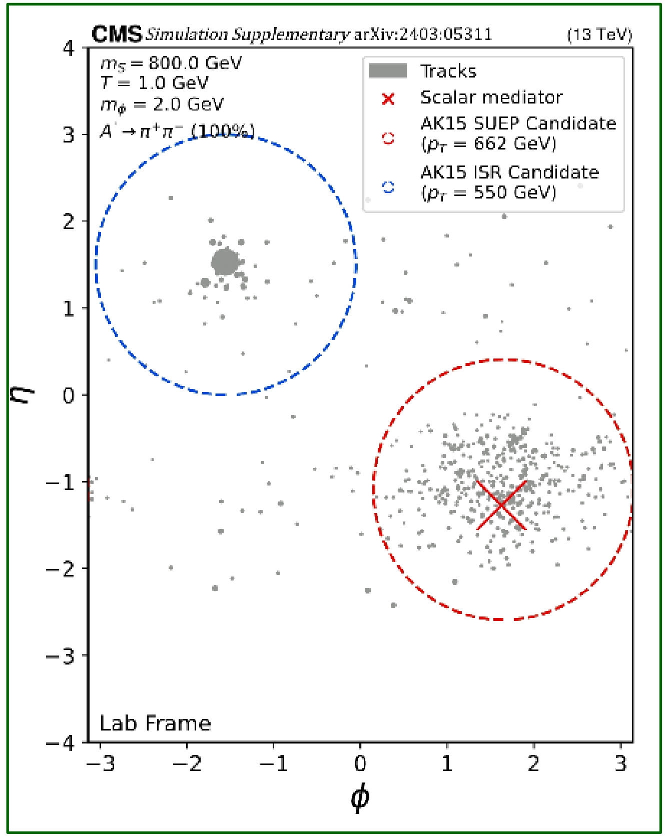
- Interesting case when there is a **prompt decay, and 't Hooft coupling is large**: large angle emission is enhanced, and large number of particles is produced.

Experimental signature

High multiplicity of tracks and high sphericity

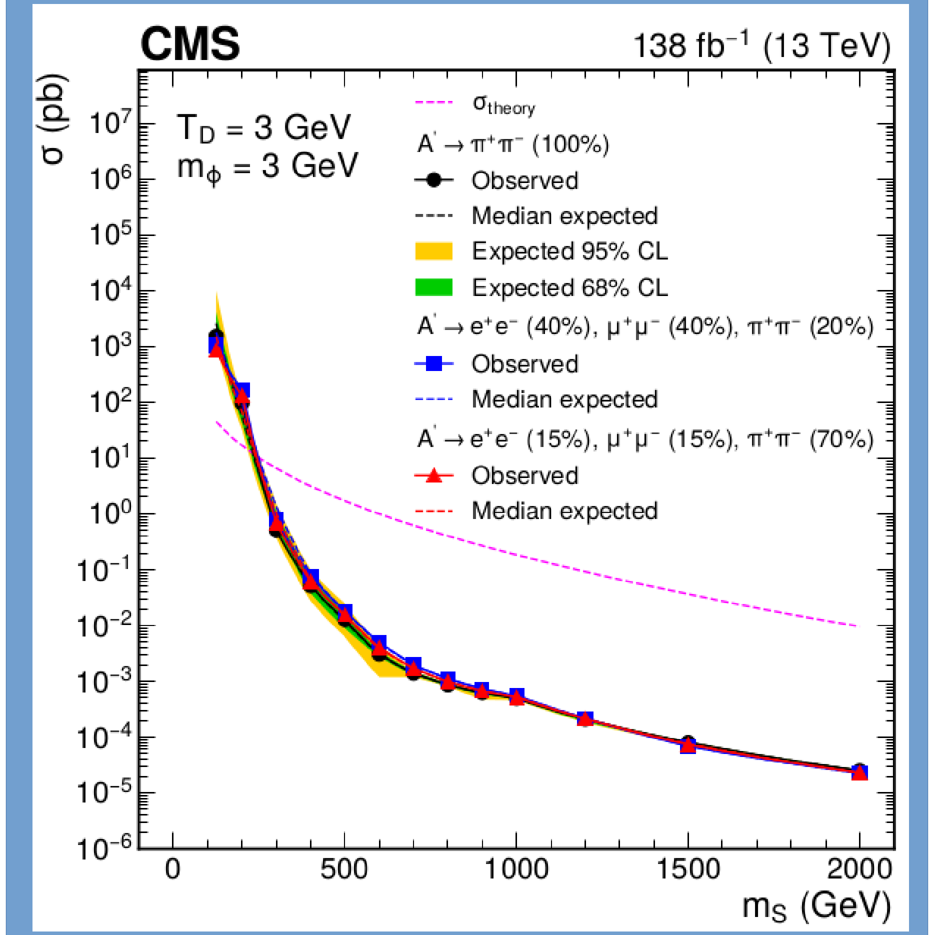
Main Background

QCD multijet events → estimated with an extended ABCD method (sphericity vs. $n^{SUEP}_{constituent}$)



Search for Soft Unclustered Energy Patterns (SUEPs)

Run2 – Dark Sector: EXO-23-002

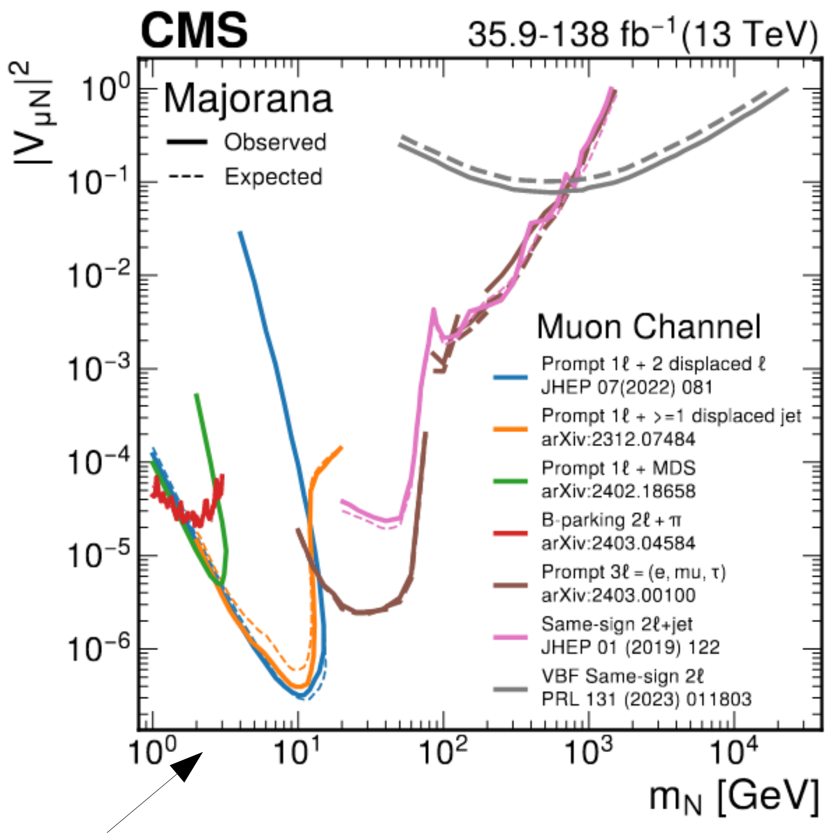


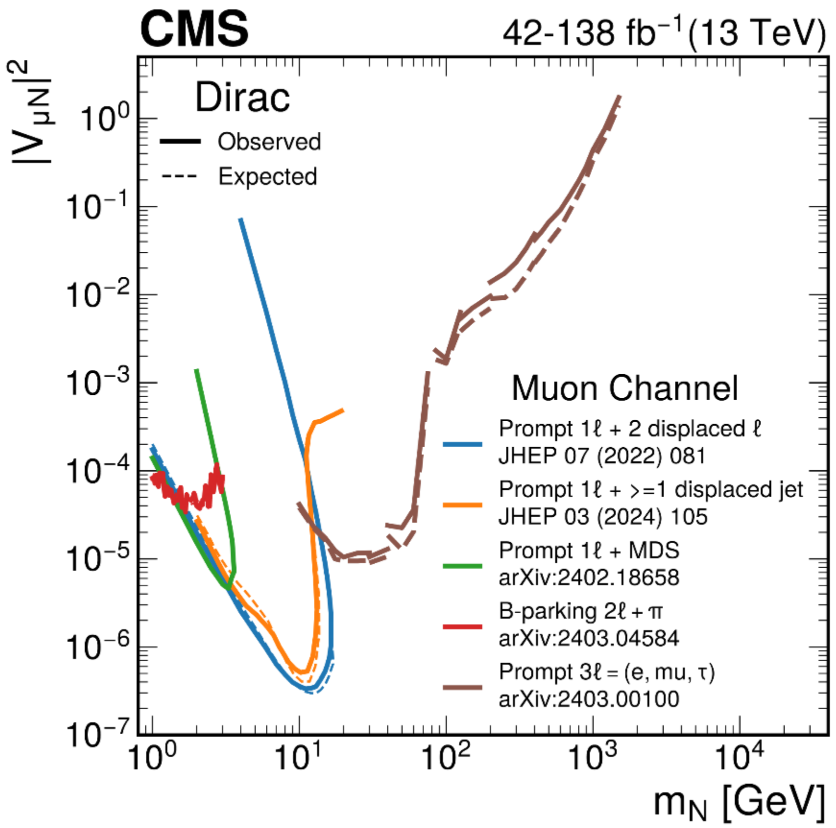
- We observe no significant excess of events over the SM prediction hence derive limits.
- The dark meson p_T spectrum can be described by a Boltzmann distribution determined by m_φ, and a temperature T_D at the scale of the cutoff, Λ_D.
- $n^{SUEP}_{constituent}$ scales like ~ $\frac{m_S}{m_\varphi} \sim \frac{m_S}{T_D}$
- Consider **three A' decay cases** with different branching fractions (A' → e^+e^-,$\mu^+\mu^-$,$\pi^+\pi^-$) → similar sensitivity
- **Very good sensitivity to medium-high m_S**
- Here T_D, m_φ have benchmark values but **ranges of the m_S – m_φ – $m_{A'}$ –T_D parameter space can be excluded.**

- This is the **first search for SUEP at LHC!**
- **Stringent limits** are placed on the most **SUEP-like HV** scenarios with highly isotropic dark showers producing a large multiplicity of tracks.

Heavy Neutral Leptons (HNL)

- **New review paper on CMS searches in HNL will be submitted very soon in Physics Reports.**
  - Among them a summary of CMS searches for HNLs in the Type I see-saw model.
  - These searches are complementary, with each dominating in a specific mass region.





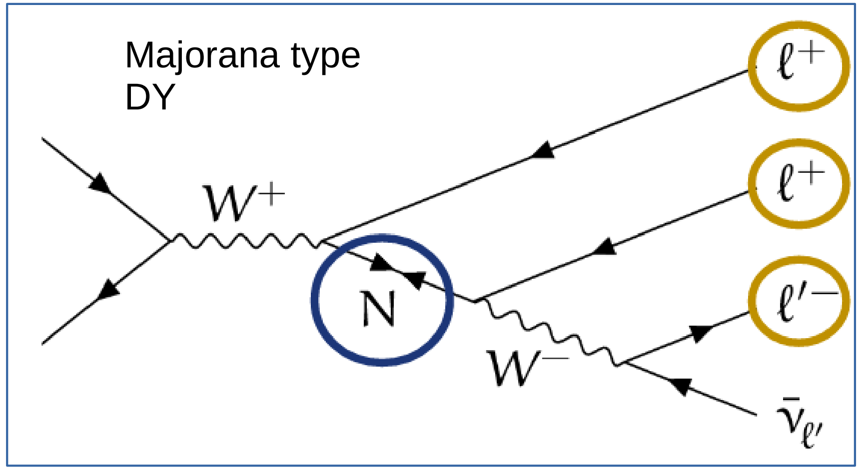
Low mass limits come from long-lived HNL.

Search for HNL with three prompt l's

Type I see-saw mechanism introduces new heavy neutral leptons (HNLs) with right-handed chirality that are singlets under all SM gauge groups, but mix with the SM neutrinos.

Signal Model

A **simplified model with a single HNL** either **Majorana or Dirac type** → couples through the neutrino mixing matrix exclusively **to a single generation of SM neutrinos.**
HNL is produced in association with $\ell^{\pm}$ (DY or VBF).



Final state: three charged leptons

Flavor channels: eee,μμμ,eeμ,eμμ, eeτ_h, μμτ_h,eμτ_h

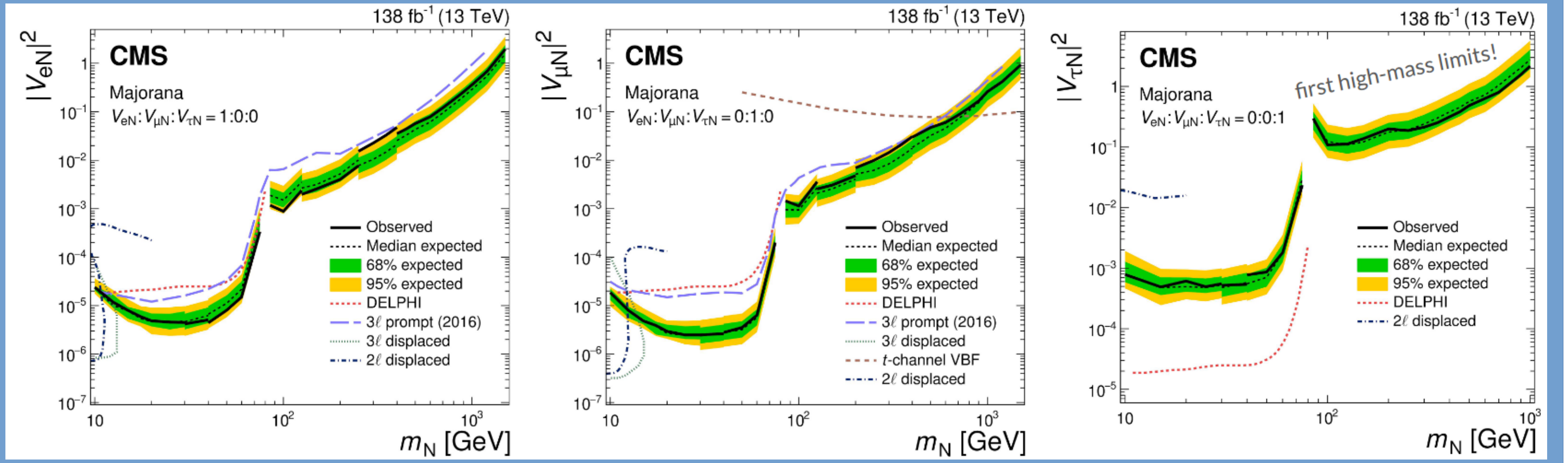
Background

Main: prompt-leptons: diboson (WZ,ZZ) estimated from MC using also CRs
Other: non-prompt leptons: tt, Z+jets estimated with tigh-to-loose ratio method

Two strategies based on event categorization and/or on ML discriminants.

Search for HNL with three prompt l's

- No significant excess is found for any final state or in any SR hence derive exclusion limits on Majorana (shown here) or Dirac HNLs.
- **Limits on e/μ neutrino coupling to prompt HNLs significantly improved w.r.t. CMS 2016 data anlysis** due to not only the increased data but also the improved lepton identification and background estimation.
- **Complementary to displaced searches** (3l, 2l) at low m_N and **t-channel** VBF search at high m_N.
- **First limits on τ neutrino coupling to prompt HNLs from LHC.**

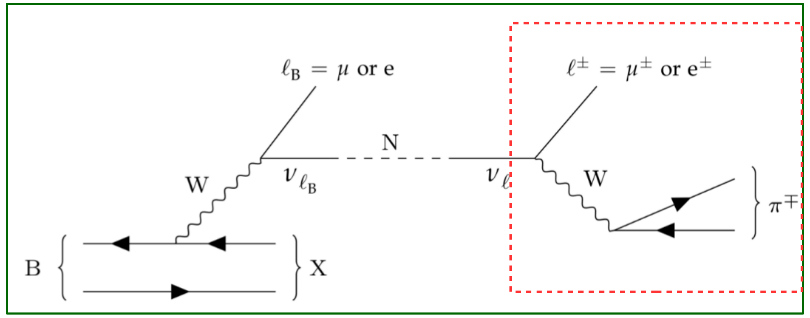


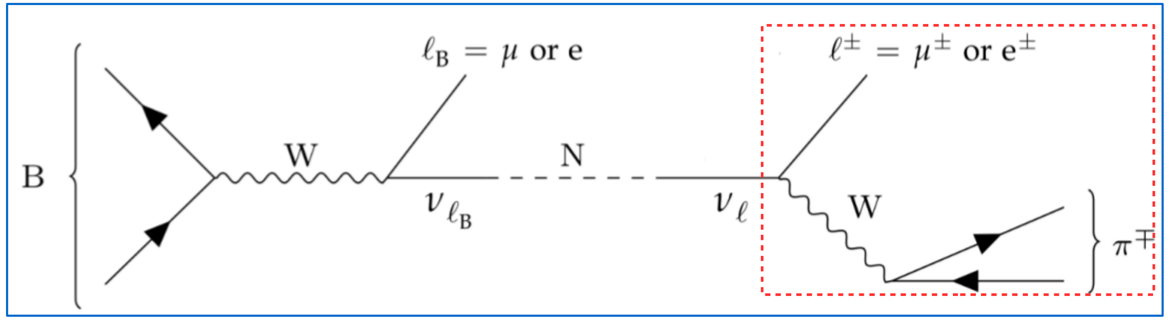
Run2 – HNL: EXO-22-019

LL HNL in the decays of B mesons

2018 data only at 13 TeV – dedicated data stream: “parking”

This search probes **HNL** that can be **produced** in the **leptonic** or **semileptonic** **decays of B meson, with masses 1-3 GeV and lifetime O(1m).**





Diplaced **ℓπ** vertex

Experimental signature

- the $\ell_B(\ell^\pm\pi^\mp)$ event topology
- peak in the invariant mass of the system $\ell^\pm\pi^\mp$
- a displaced vertex (DV) associated with the two tracks that form this system.

Flavor channels: ee,eμ,μμ

Utilize parametric neural networks (pNN) exploiting both analysis-level and track-level quantities.

Background

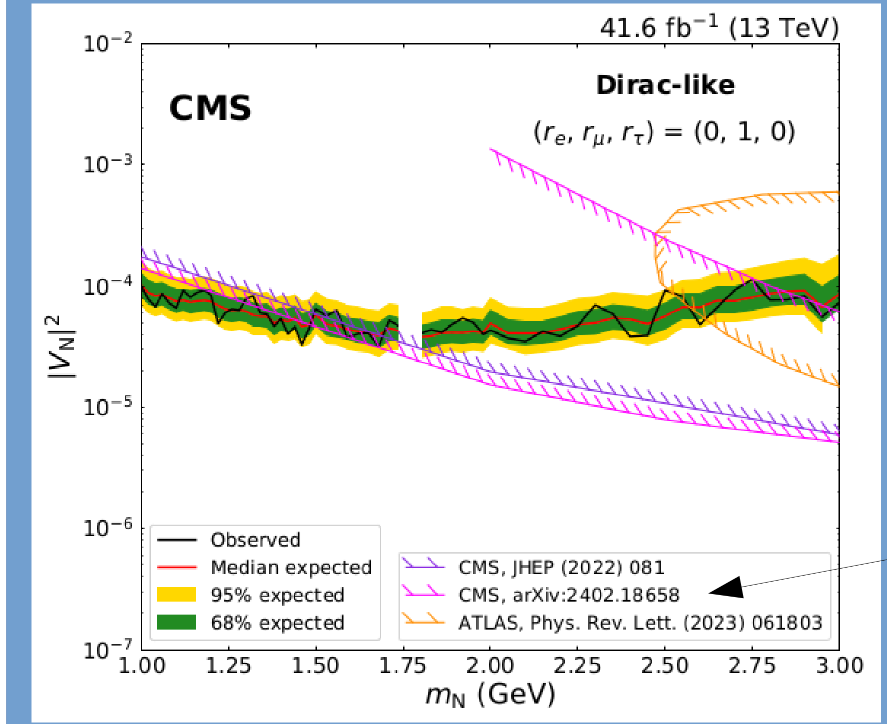
Several peaks in the m($\ell^\pm\pi^\pm$) distributions associated with known decay modes of SM particles→ veto them using pNN.

Only residual bkg left: $D^0 \to K^\pm\pi^\pm$ → no signal extraction between 1.74-1.80 GeV.

Run2 – HNL: EXO-22-019

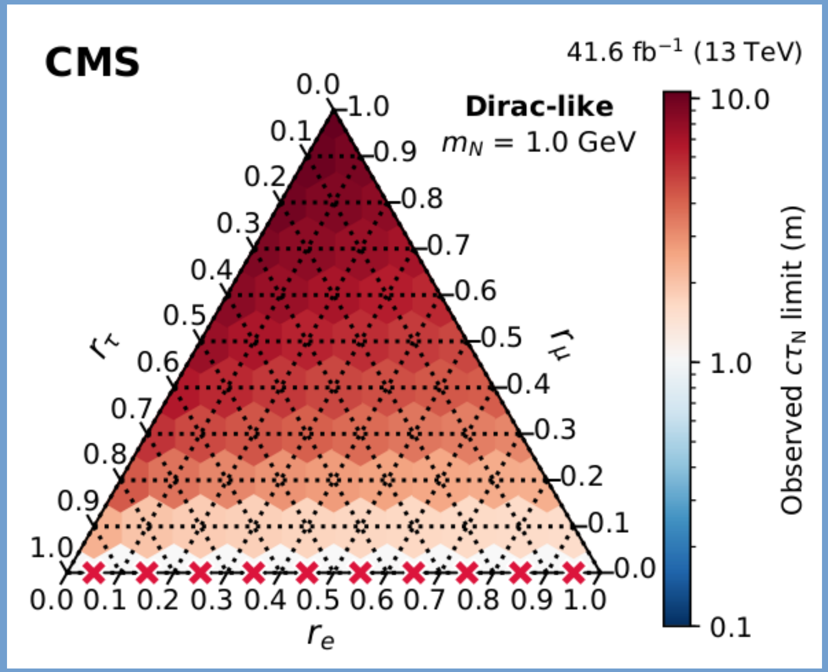
LL HNL in the decays of B mesons

μ exclusive mixing scenario



LL HNL in the μ system (see next slide)

66 different mixing scenarios

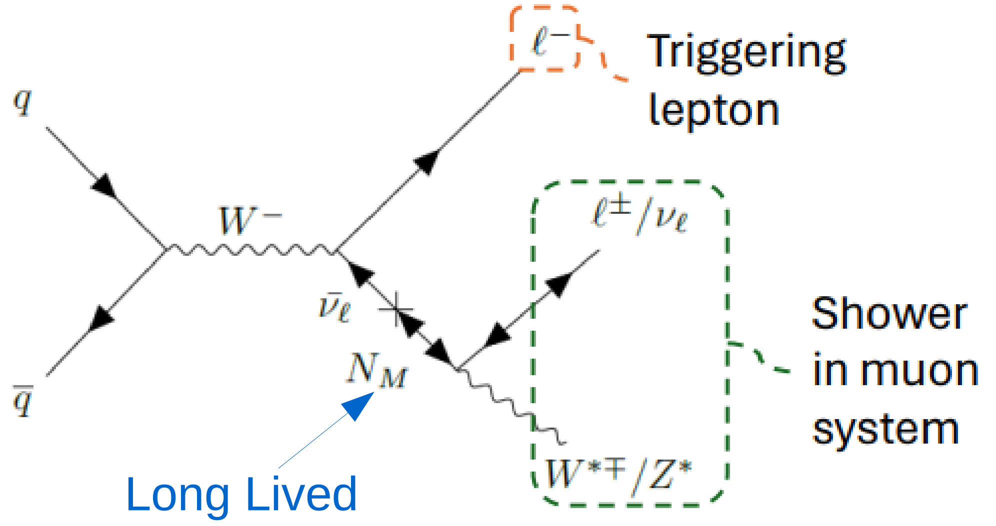


- No significant excess is observed in any of the $\ell^{\pm}\pi^{\mp}$ invariant mass distributions.
- **The limits on $|V_N|^2$ for masses $1 < m_N < 1.7$ GeV are the most stringent from a collider experiment to date!**
- **Limits on $c\tau_N$ in the form of ternary plots for masses $m_N \leq 2.0$ GeV are presented for the first time!**

Run2 – HNL: EXO-22-017

LL HNL decaying in the μ system

- HNL that decays in the CMS μ system can lead to hadronic shower which is detected as a cluster of μ detector hits (either in CSC or DT chambers).
- Ideal to probe lower mass (<10GeV), longer lifetime O(1m) parameter space.
- Sensitive to HNL from its hadronic decay products.



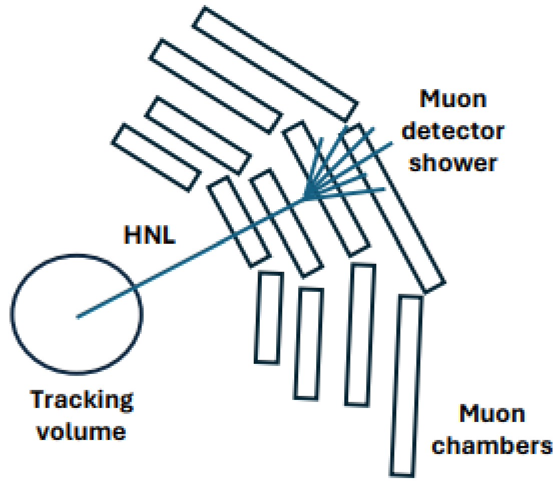
Analysis strategy

Prompt μ/e for good triggering efficiency
Muon detector showers have a huge discriminant power.

Background

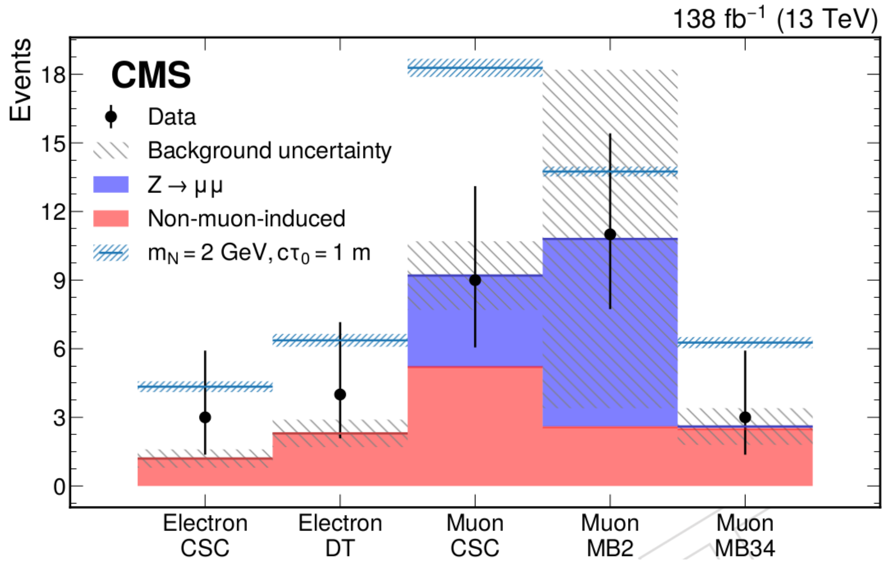
non-μ-induced background (W, QCD, tt, VV) → estimated with ABCD method: cluster size (Nhit) vs. Δφ(cluster,ℓ)

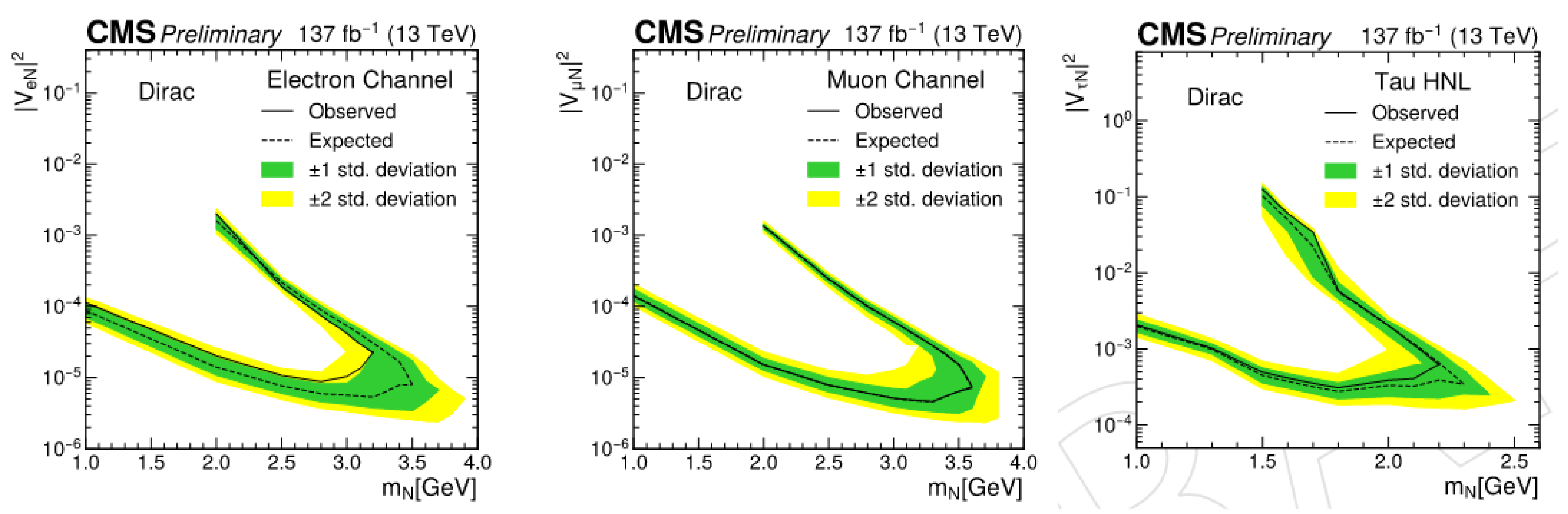
μ-induced background: (Z→ μμ in μ ch.) → estimated from CR



LL HNL decaying in the μ system

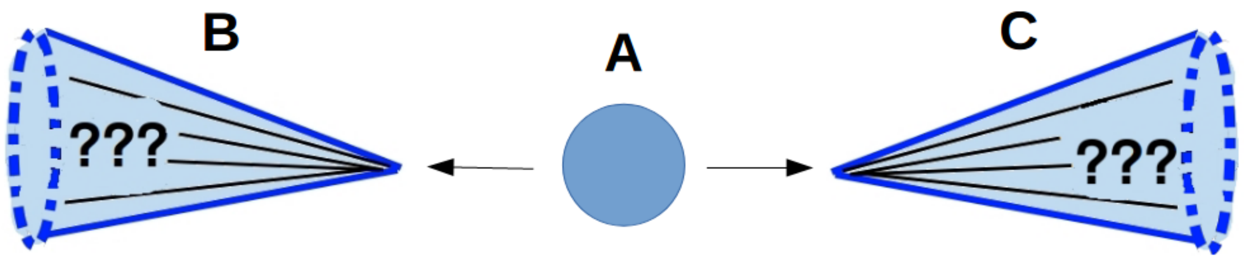
- No significant excess observed in all categories.
- Set limits on HNL couplings
  - Sensitive to all three lepton flavors
  - Majorana and Dirac interpretation
- **Complimentary to existing CMS searches.**
- **Extends current sensitivity by ~1.3x to ~2.3x at 2 GeV!**





Dijet resonance anomaly search

Targeting dijet resonance with a heavy particle A, decaying into daughters B and C.



Signal Model: **model agnostic search** for new resonances in the dijet final state
Goal is broad sensitivity to many different kinds of B/C jets with ‘anomalous substructure’.

Main Background: QCD

- **Multiple complementary ML-based anomaly detection techniques** to tag ‘anomalous’ jets that have substructure distinct from QCD
  - Outlier detection (**VAE-QR**)
  - Weak supervision (**CWoLa Hunting**, **TNT**, **CATHODE**)
  - Multi-signal priors (**QUAK**)

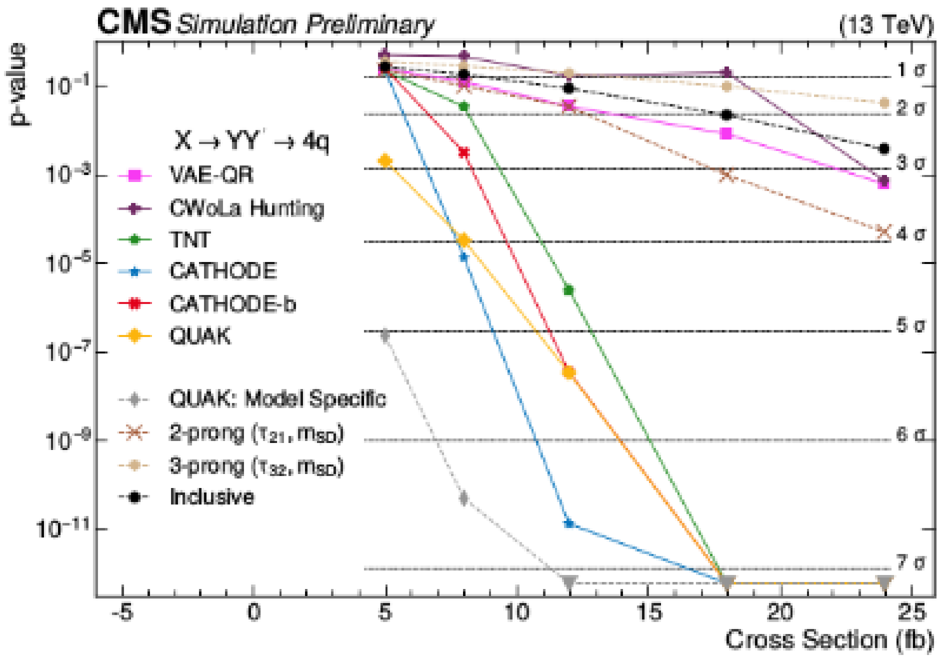
4/5 methods entirely data driven, no use of MC. Anomaly detector trained directly on data!

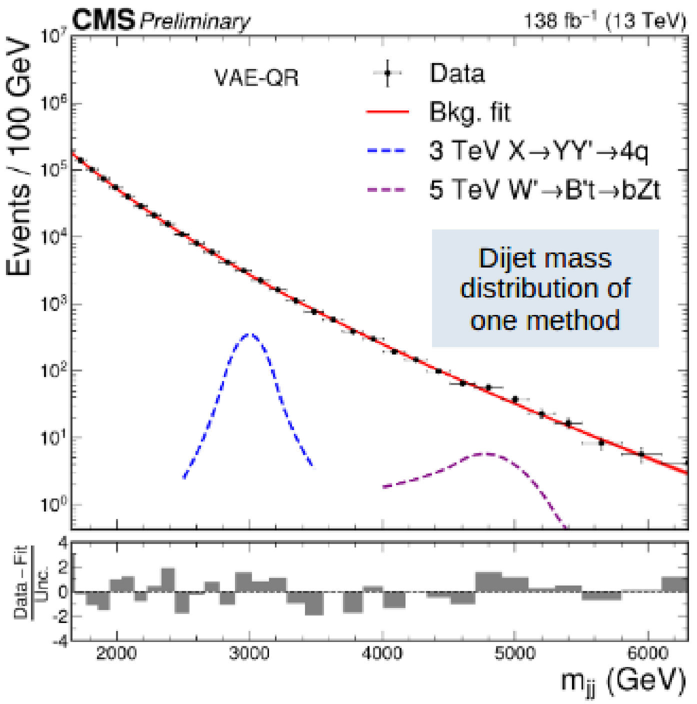
- Selects events with two large radius jets → train anomaly detectors → cut on ‘anomaly score’ → **bump hunt in dijet mass**

Run2: EXO-22-026

Dijet resonance anomaly search

- **Test methods in MC** by injecting signal and running full analysis chain.
- Compare extracted significance of **anomaly methods** to **inclusive bump hunt**, **standard cut-based approaches** and a **model-specific search**.
- No significant excesses from any method.





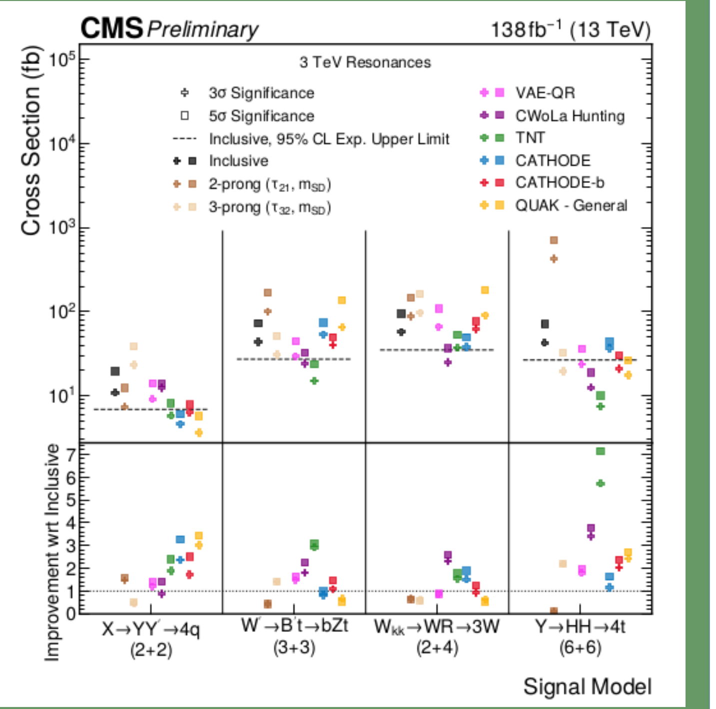
Anomaly detection can lead to discoveries that standard methods might miss!

Run2: EXO-22-026

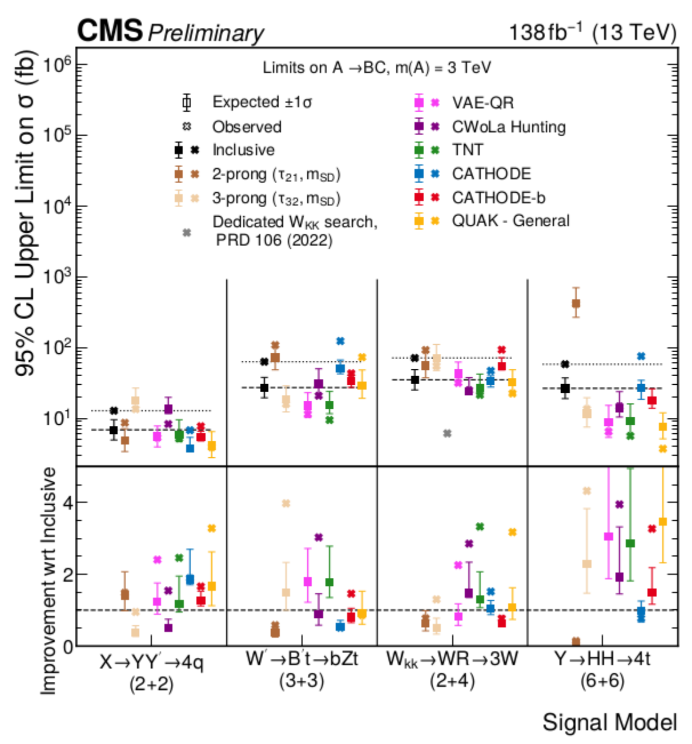
Dijet resonance anomaly search

- **Novel limits derived on several benchmark signal models with varying substructure.**
  - Discovery sensitivity of different methods also assessed.
- **Anomaly detection found to improve upon sensitivity of standard methods, but dedicated searches always will be needed in case of something interesting found.**
- **First usage of anomaly detection in a physics analysis in CMS!**

Discovery sensitivity for A → BC



Limits

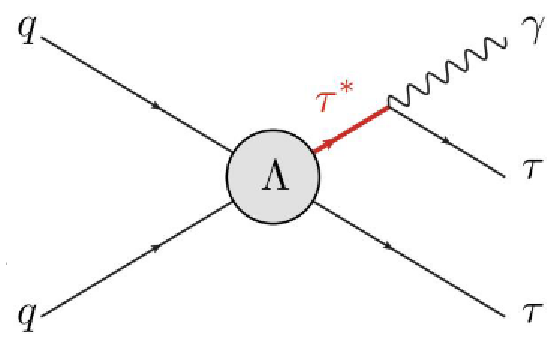


Run2: EXO-22-007

Search for τ* → ττγ

went public a week ago!

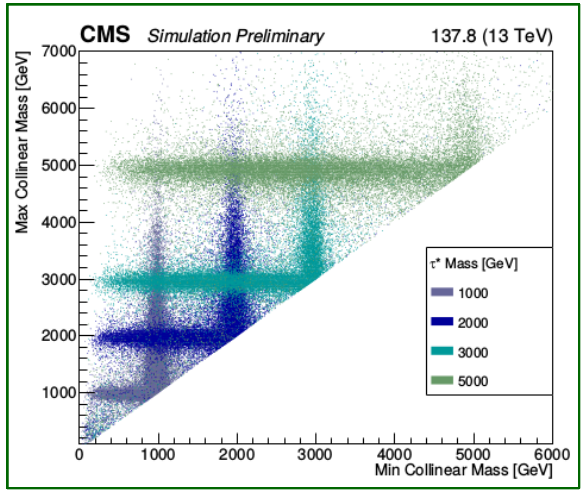
Signal Model:

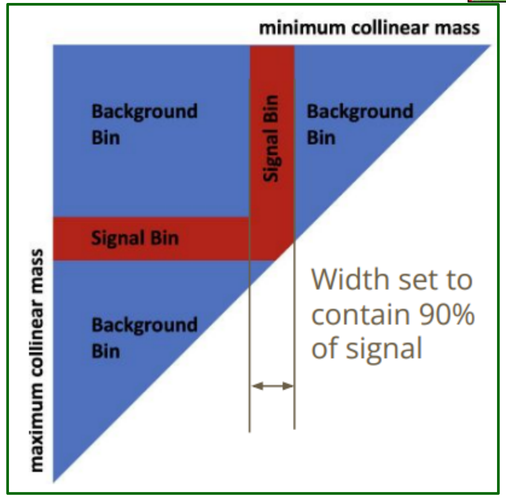


Excited state would give evidence of **compositeness** (scale Λ).

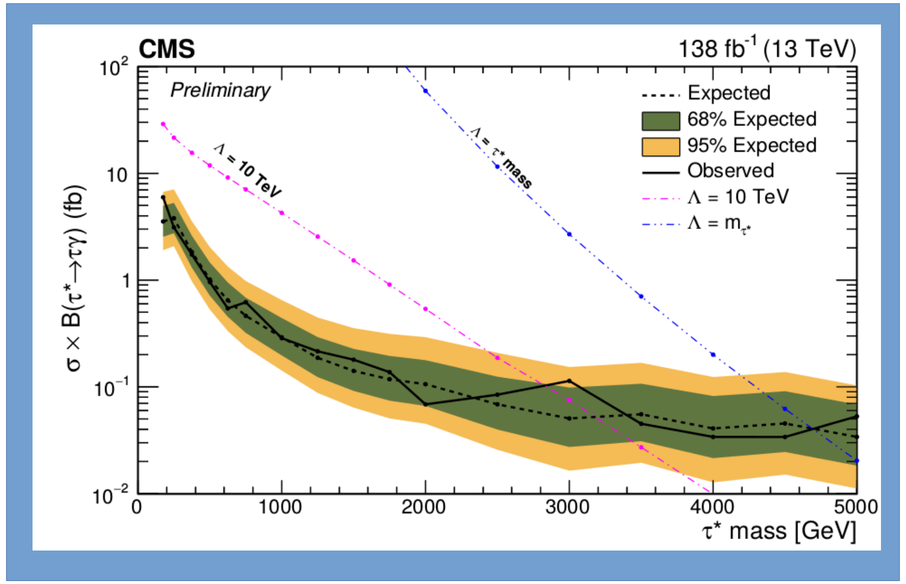
Flavor channels: $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$
ee,μμ,eμ: used as CR

Reconstruct full τ decays by assuming ν's are collinear with visible components to form "collinear mass": 2 pairs → **min-max value on 2D plane**





Main background: Real τ → estimated by MC
Fake τ (mis-reconstructed jets) → estimated by ABCD method (charge of 2 τ's vs. isolation)



- **No excess above the expected background is observed → derive limits.**
- **These results are comparable and complementary (different strategy based on ττjj) to those from ATLAS.**

Run2: EXO-21-015

Search for VBF Z' → ττ (WW)

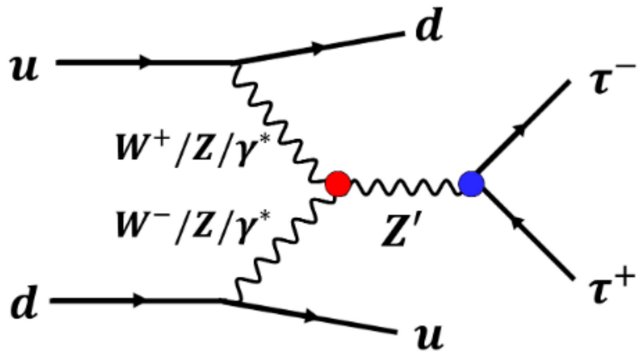
went public a week ago!

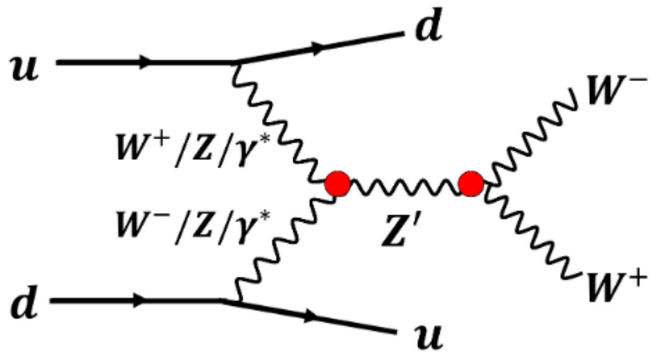
Signal Model

Non-universal fermion couplings favoring higher-generation fermions

Benchmark Models

$g_{Z'VV} = \kappa_V g_{ZVV}$
κ_V ranges from 0.1-1





Flavor channels: eμ, $\mu\tau_h$, $e\tau_h$, and $\tau_h\tau_h$

Experimental signature

1 lepton pair and 2 energetic jets with $\eta_1 \cdot \eta_2 < 0$ (VBF criteria)

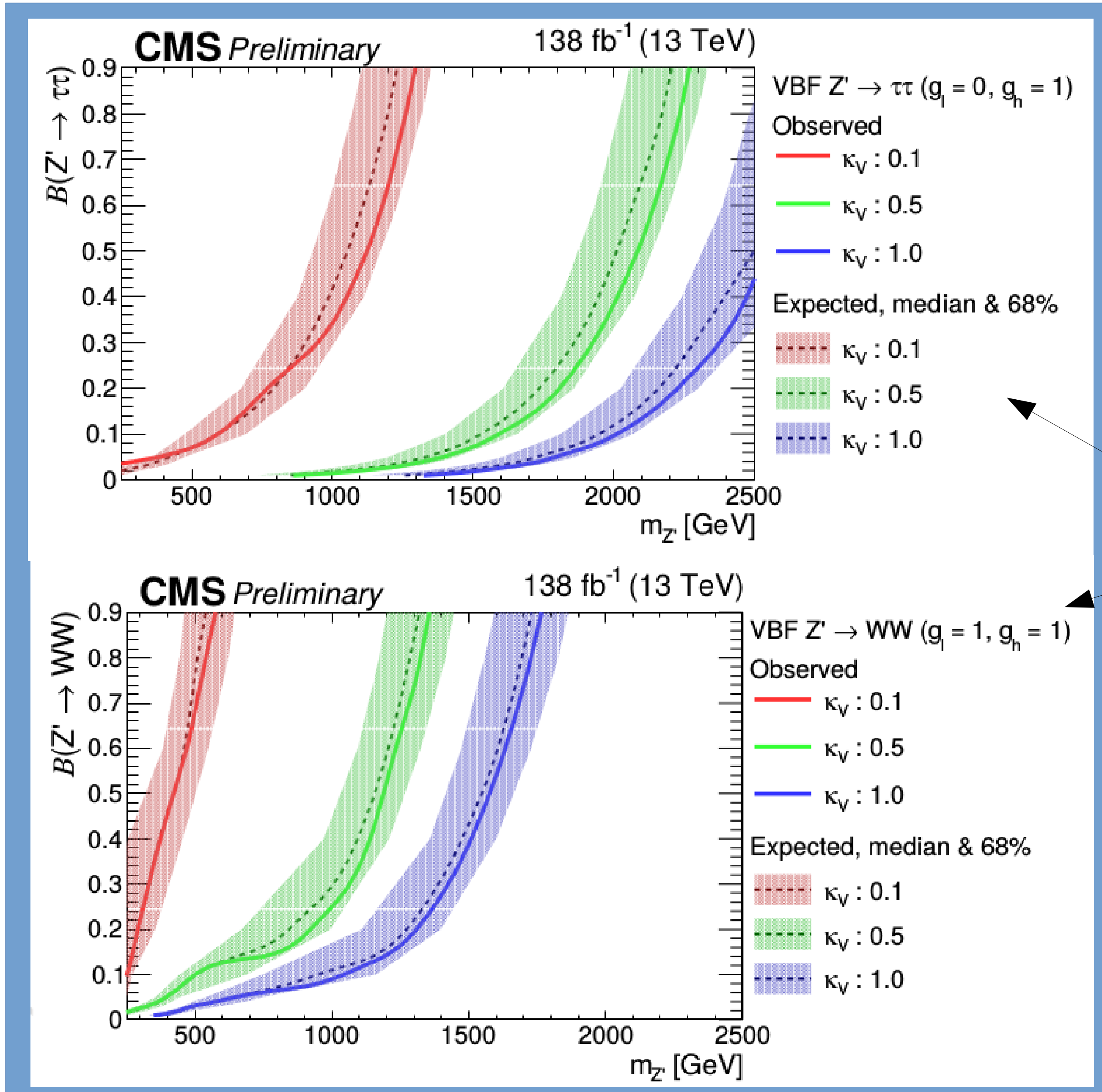
Bump hunt search on $m(\ell_1,\ell_2,p_T^{miss})$ spectrum.

Main background

W+jets, Z+jets,QCD → estimated from dedicated CRs and tt→ estimated with ABCD method (#b jets vs.VBF criteria)

Run2: EXO-21-015

Search for VBF Z’ → ττ



- The mass spectra are consistent with the SM predictions → derive limits.
- Independent couplings of the Z’ to 1st+2nd (g_l) and 3rd (g_h) generations.
- Different scenarios:
  - **non-universal coupling**
  - **universal coupling**
- **This is the first ever search for Z’ produced through VBF performed at the LHC!**

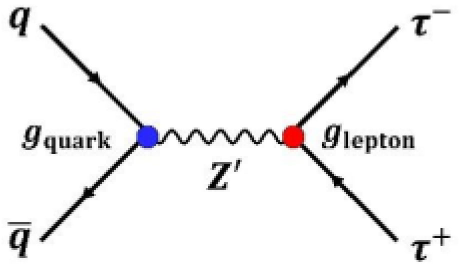
Search for DY Z' → ττ

went public a week ago!

Run2: EXO-21-015

Signal Model

Heavy neutral gauge bosons (Z') decaying to two τ's.



Experimental Signature

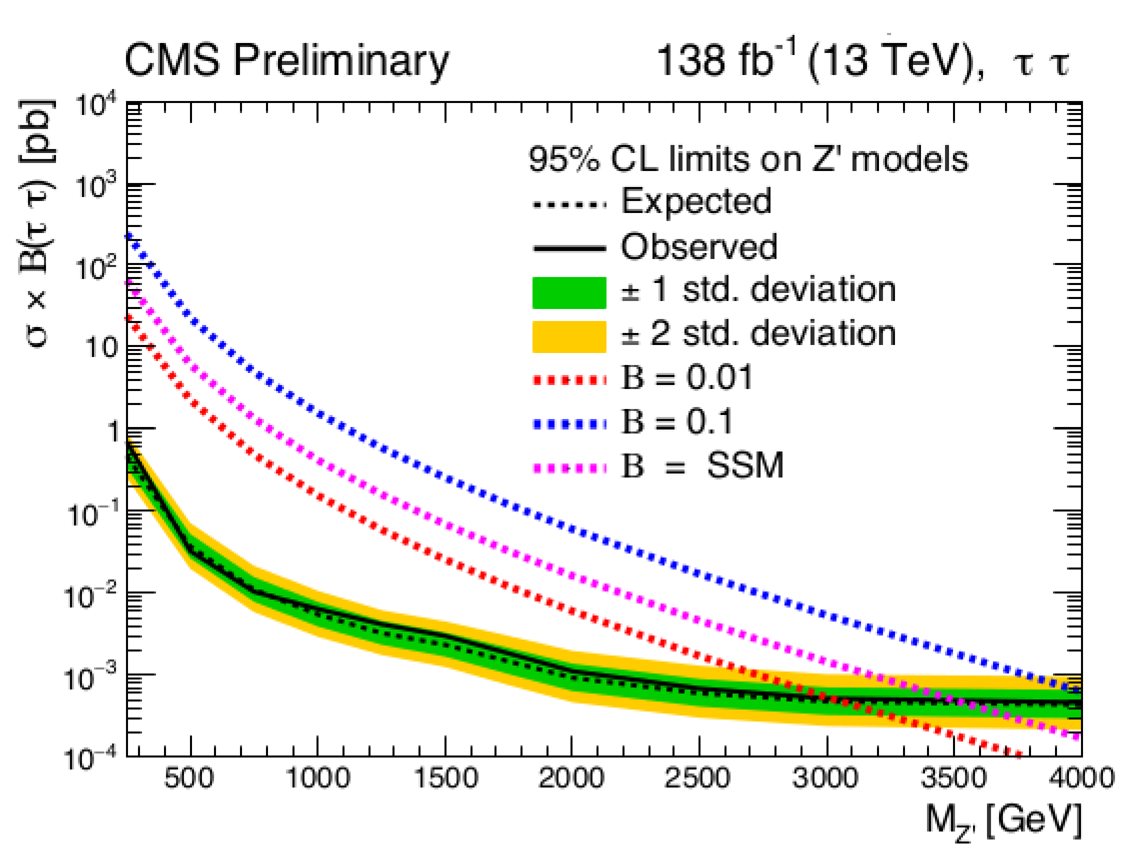
an OS pair of back-to-back τ leptons

Flavor channels and main background

$\tau_e\tau_h$ and $\tau_\mu\tau_h$: DY, W+jet,tt

$\tau_h\tau_h$: DY, QCD

estimated from CRs



Discriminating variable

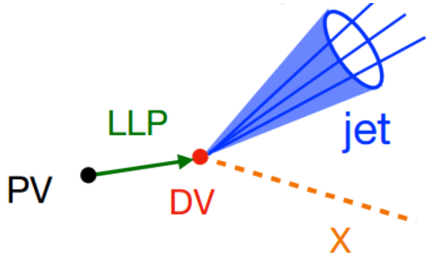
$$m_{\text{rec}}(Z') = \sqrt{(E_1^{\tau\text{vis}} + E_2^{\tau\text{vis}} + |\mathbf{p}^{Z'\text{miss}}|)^2 - |\mathbf{p}_1^{\tau\text{vis}} + \mathbf{p}_2^{\tau\text{vis}} + \mathbf{p}^{Z'\text{miss}}|^2}$$

These exclusion limits are the most stringent to date for this type of search!

Analyses with early Run3: 2022 data

Run3: EXO-23-013

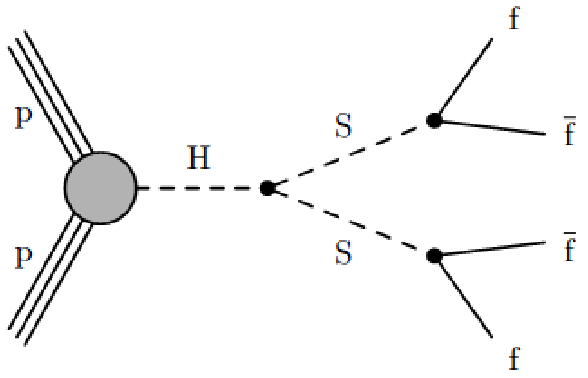
Search for displaced jets



Signal Models

Many BSM models naturally predict the **production of hadronically decaying LLPs leading to displaced-jet signatures**, i.e. SUSY, hidden sectors or other models with dark matter candidates, models with HNL etc.

Benchmark model: Higgs boson decays to LLPs



f=fermion=d/b/τ
$m_{LLP} \leq 60$ GeV

Experimental signature

≥ 1 LLP hadronically decaying inside the tracking system.
A pair of jets (dijet) arising from the LLP decay.

Main Background

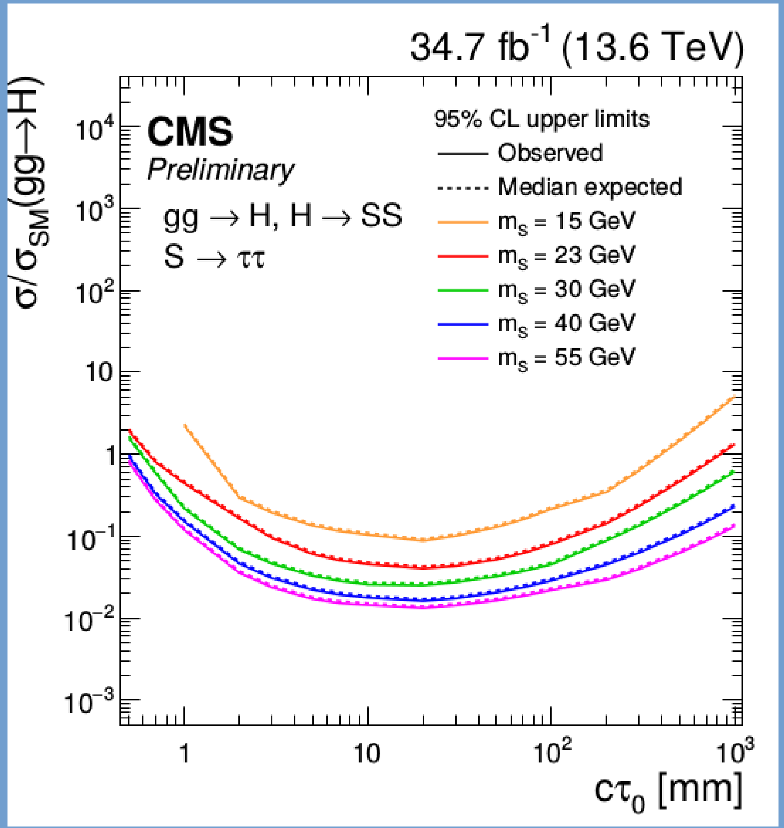
QCD multijet events → estimated with ABCD method using two GNN taggers ($g_{displaced}$ vs. g_{prompt})

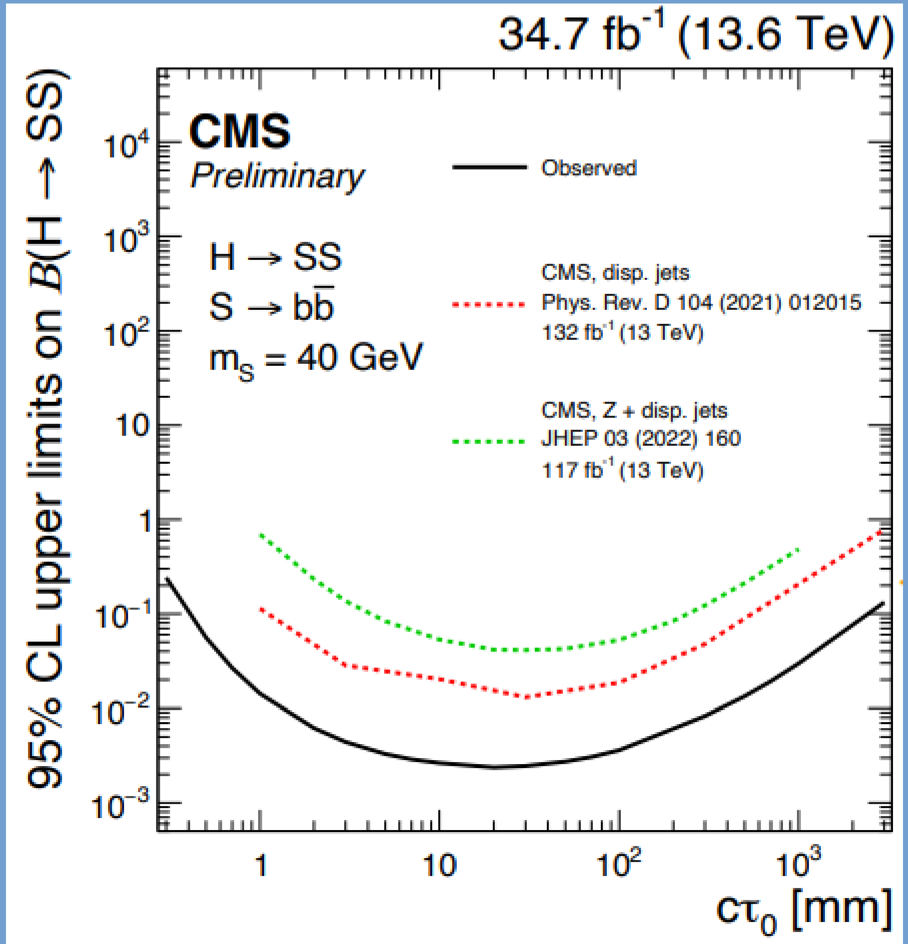
Major improvements:

- In 2022 data, **novel displaced-jet triggers** were implemented → (acceptance 10 times higher than Run 2 - DP-2023-043)
- **New displaced vertex (DV) reconstruction**: additional DVs within the dijet
  Strongly driven by the physics consideration on tackling complex LLP decay systems like S→bb
- **New LLP tagging based on graph neural networks (GNN)**

Search for displaced jets

Run3: EXO-23-013





The first-ever displaced hadronic τ results with decay lengths smaller than ≈1m!

Despite a much smaller integrated lumi, significant improvements over other existing searches!
(up to a factor of 10).

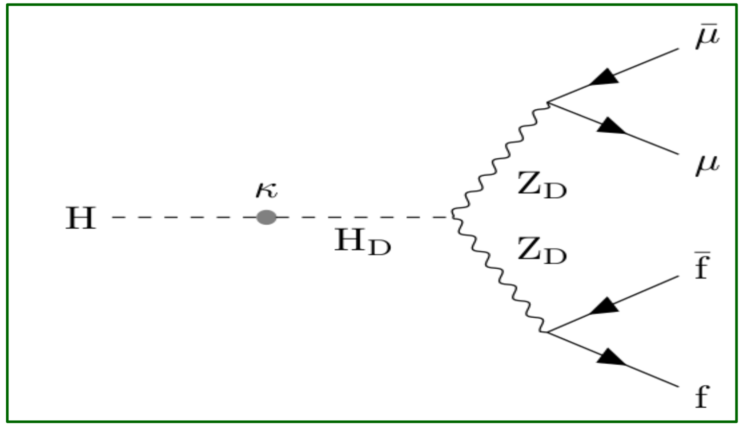
Run3: EXO-23-014

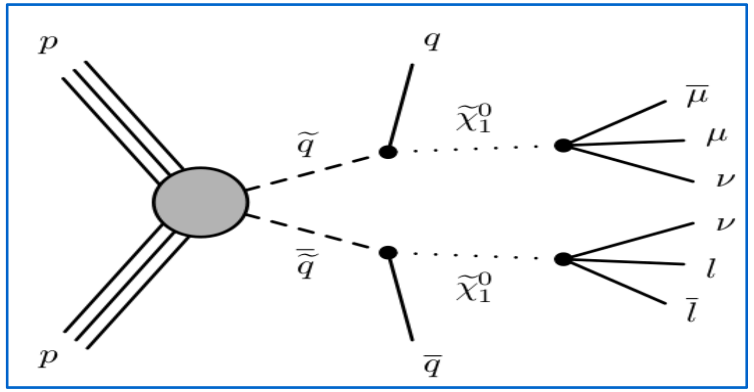
Search for displaced μ's

Generic, inclusive search for LLP decaying into pairs of oppositely-charged μ's (displaced dimuons) within the tracker and beyond.

The search is designed to be largely model-independent.

Benchmark models: Dark photon model and **RPV SUSY model**





Experimental signature : a pair $\mu^+\mu^-$ originating from a common SV

Main Background

No genuine LLPs with m_{LLP} > 10 GeV in the SM

- backgrounds are due to mis-reconstructed prompt μμ from DY process and QCD → estimated with CRs

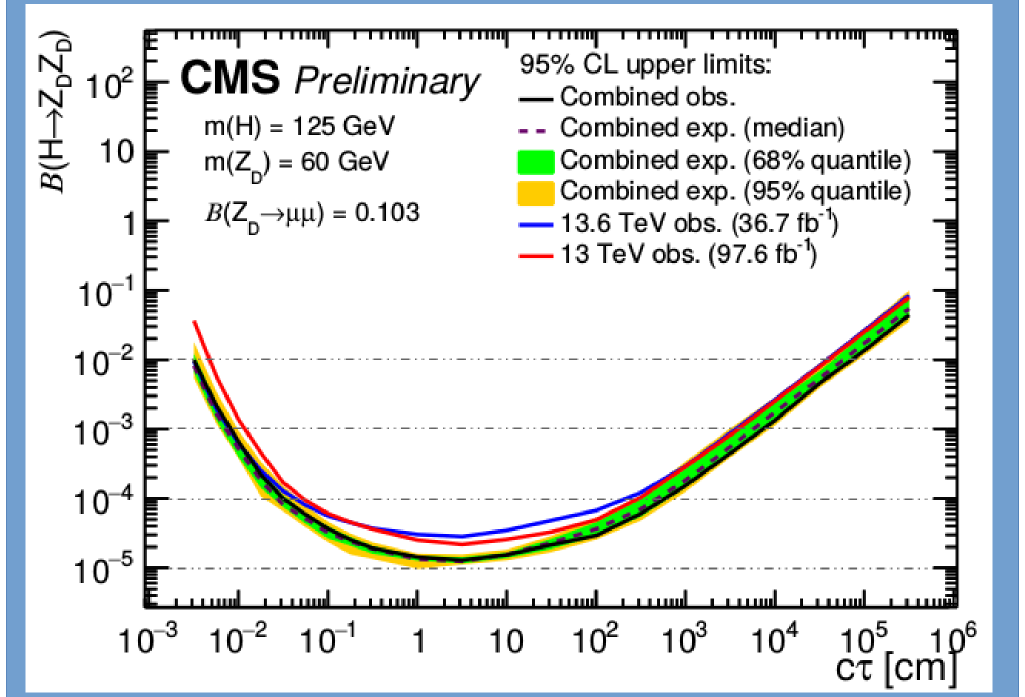
Major improvements:

- In 2022 data, **novel displaced-muon triggers** were implemented → (m_{LLP} > 10 GeV is accessible).
- **New HLT algorithms:** p_T thresholds depend on the μ impact parameter.

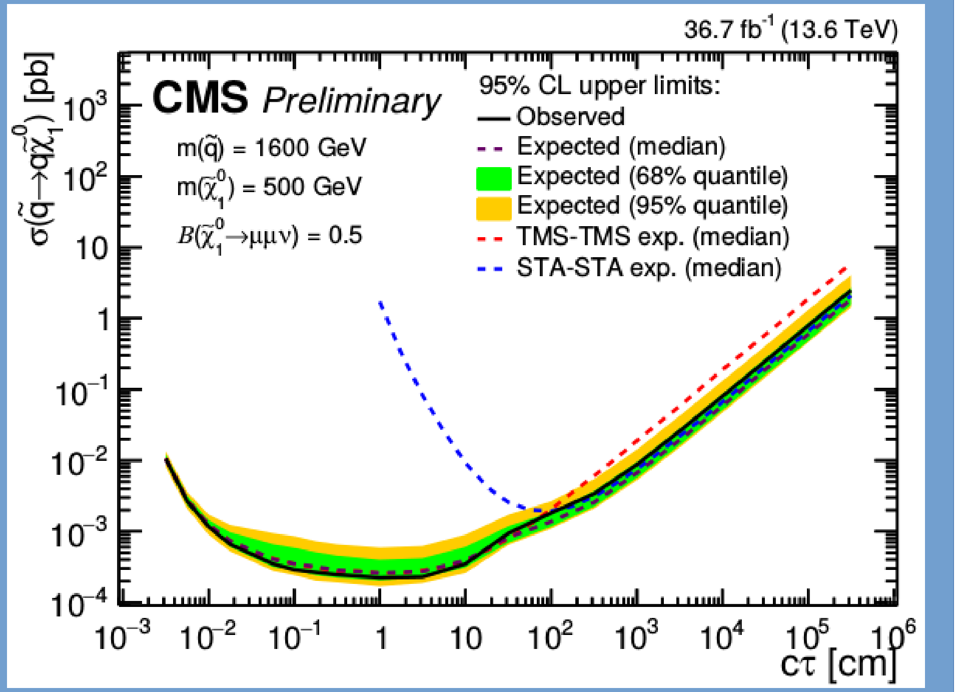
Run3: EXO-23-014

Search for displaced μ's

Limits for $m(Z_D)$: 10-60 GeV



Limits for $m(\tilde{q})$: 125-1600 GeV



- **2022 limits generally comparable, or even better, than the published Run2 limits, despite the smaller integrated luminosity.**
- **The limits set on these models are the most stringent to date in wide regions of lifetimes for LLPs with masses larger than 10 GeV!**

Summary

- Very **rich program for BSM physics at CMS** performing generic searches and testing many models of new physics.

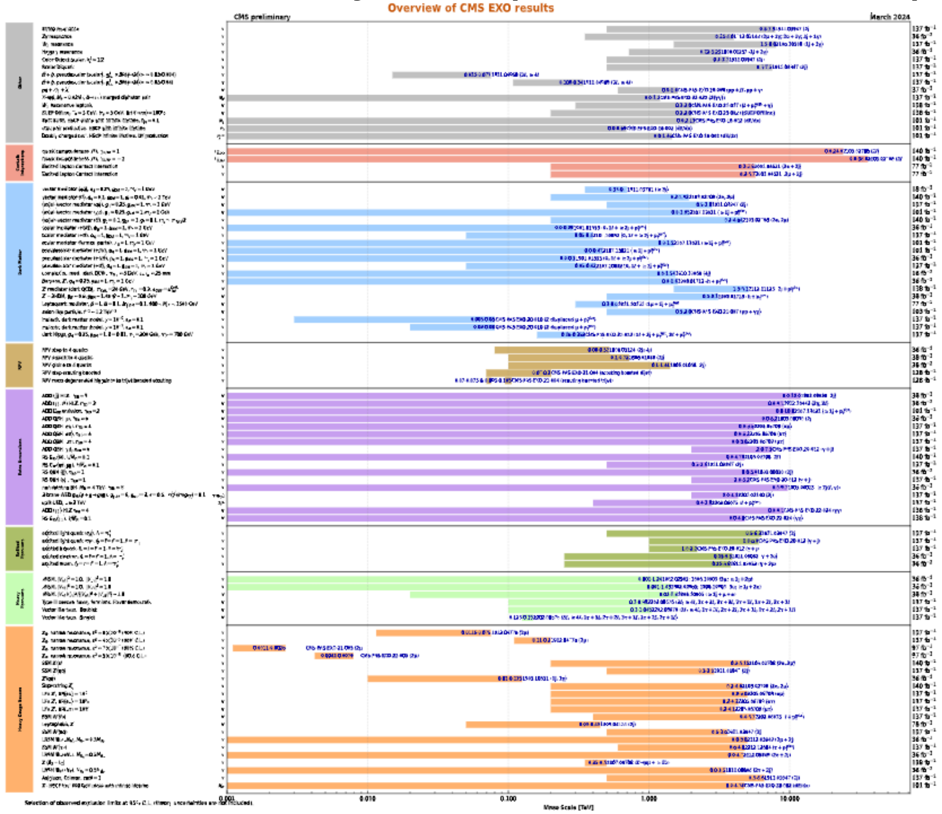
- **Two review papers** from a series of others have been submitted, with more to come soon.
  - CMS searches from Run 1 to Run 3
  - New interpretations and combinations of results

- **Significant improvements** due to **new**
  - analysis approaches, data driven methods to estimate background, taggers, reconstruction techniques etc.
  - final states explored.

- Due to all these improvements **the first analyses with the early Run 3 data already demonstrate better sensitivity.** Soon, we should be able to **fully exploit the discovery potential**, leading to either a new discovery or improved limits **beyond the lumi scaling.**

- Recent results with **early Run 3 data**
  - EXO-23-013: Displaced jets
  - EXO-23-014: Displaced dimuons

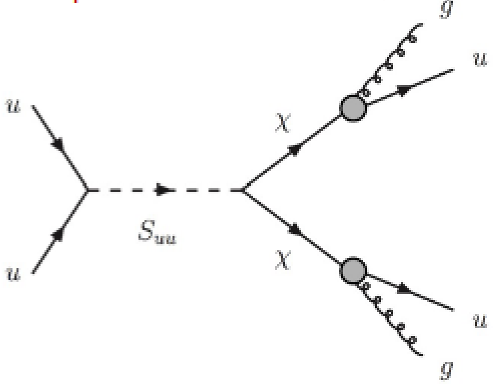
EXO Summary Plot (clickable version)

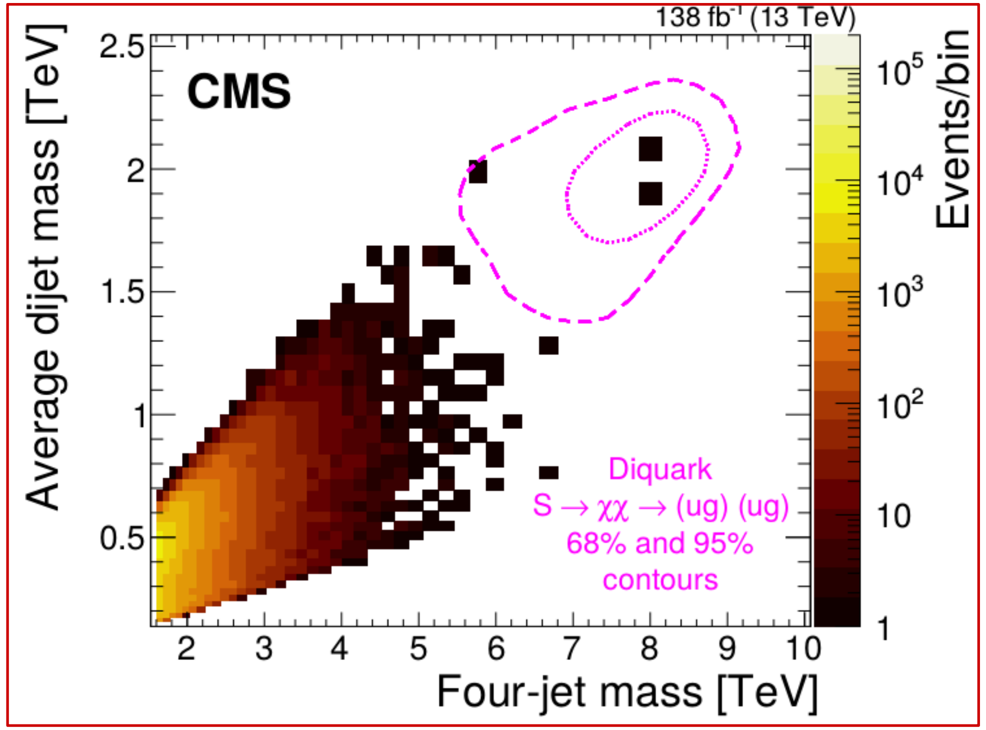


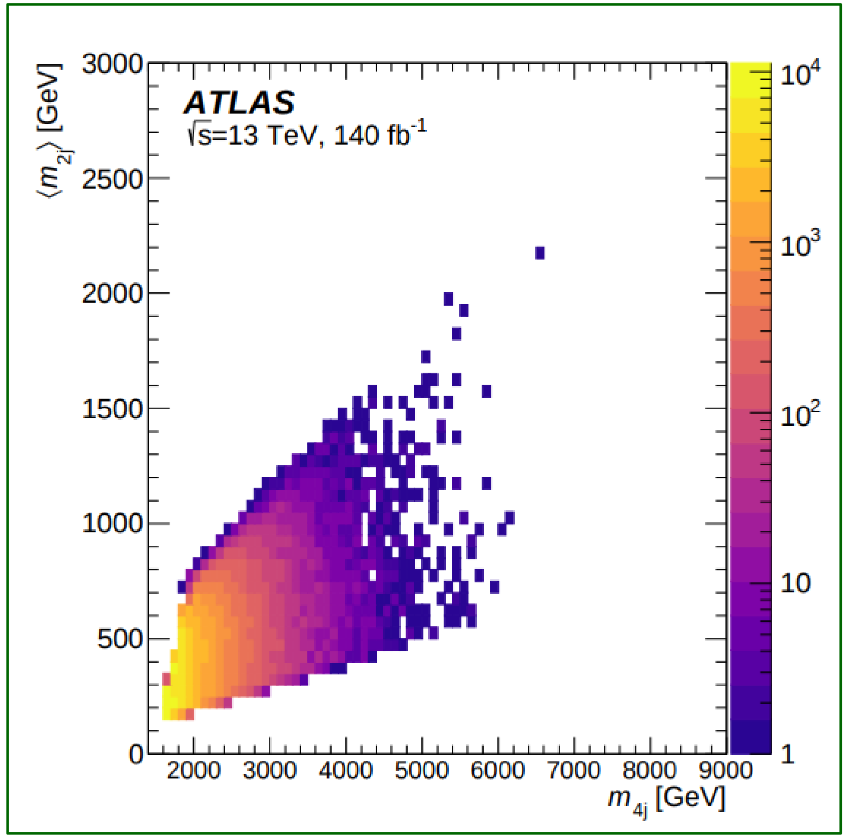
Back up

Paired dijet searches

Diquark → Vector Like Quarks

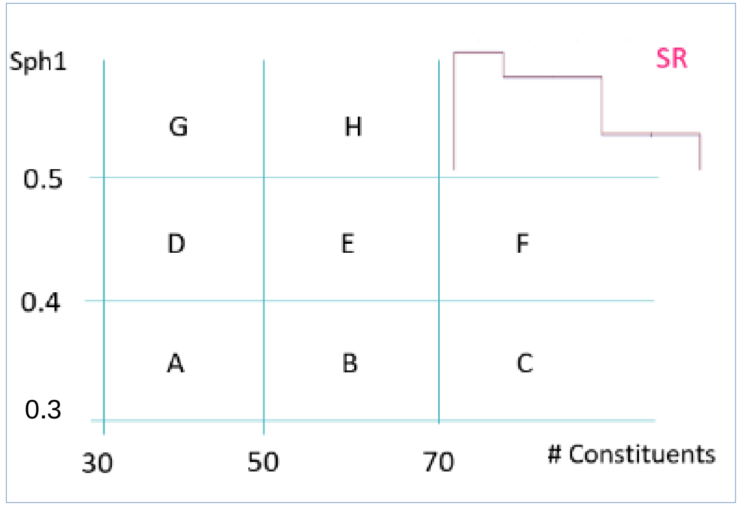






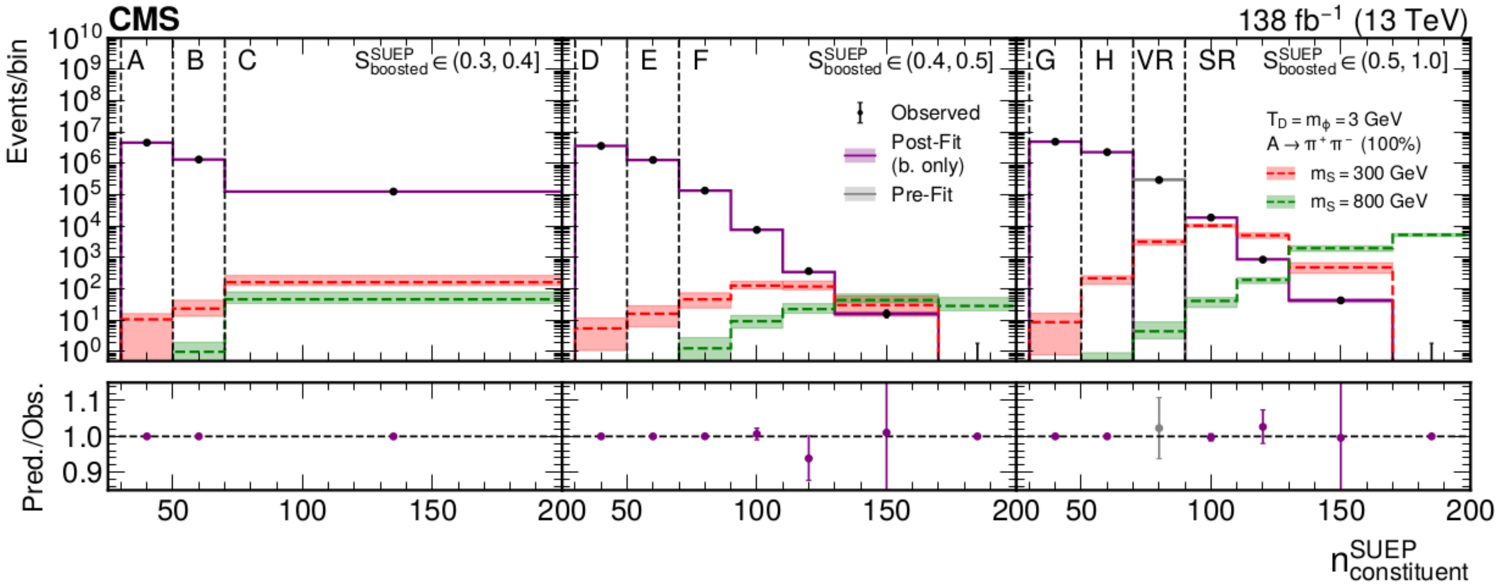
- Interesting events seen in full Run 2 data at high four jet and average dijet masses from both **CMS** and **ATLAS** collaborations.
- Currently the Run 3 data are being analyzed.

Search for Soft Unclustered Energy Patterns (SUEPs)



Extended ABCD method
to correct for the linear correlation of the discriminating variables

$$N^{i}_{\mathrm{SR}} = N^{i}_{\mathrm{F}} \frac{N_{\mathrm{F}} N_{\mathrm{H}}^{2} N_{\mathrm{D}}^{2} N_{\mathrm{B}}^{2}}{N_{\mathrm{G}} N_{\mathrm{C}} N_{\mathrm{A}} N_{\mathrm{E}}^{4}}$$

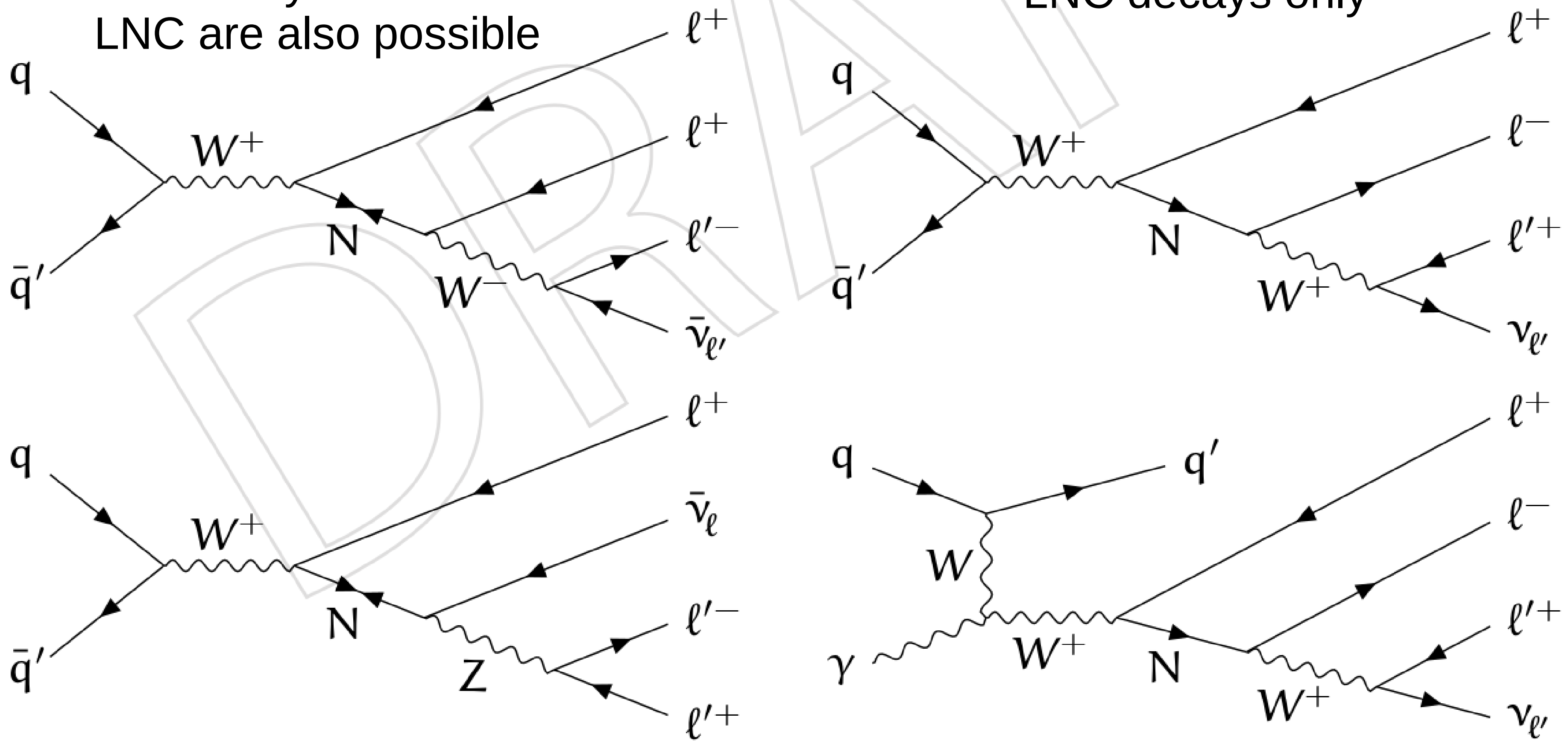


Run2 – HNL: **EXO-22-011**

Search for HNL with three prompt l's

Majorana type
LNV decays shown but
LNC are also possible

Dirac type
LNC decays only



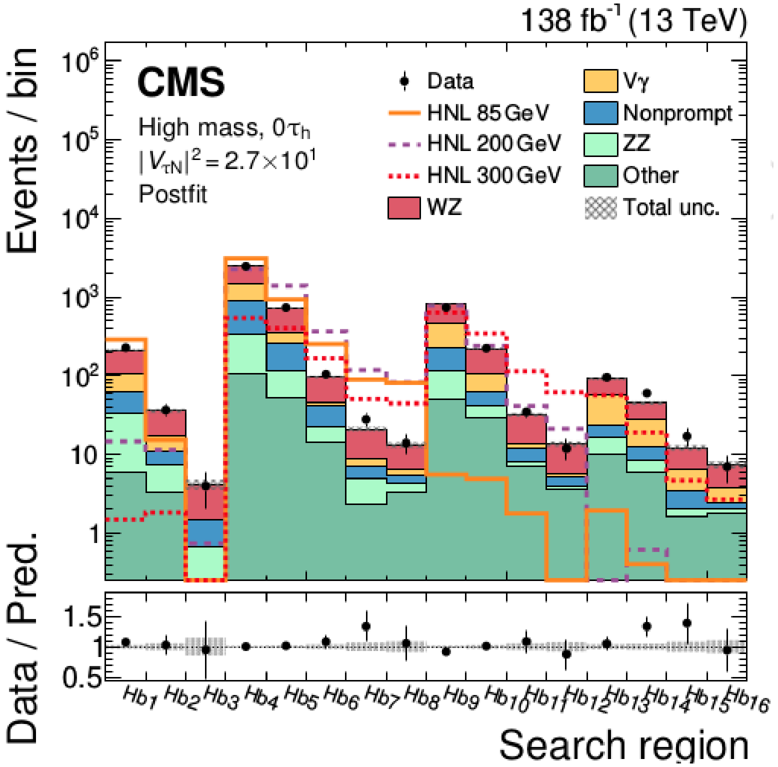
The leptons that couple directly to the HNL are restricted to the SM generation that couples with the HNL, whereas the leptons from the W and Z boson decays can be from any SM generation.

Run2 – HNL: EXO-22-011

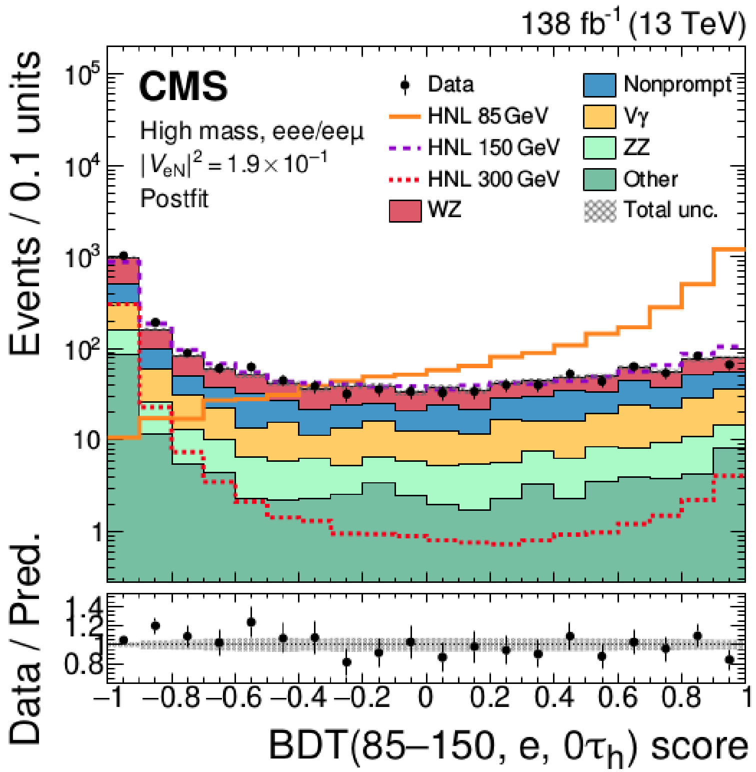
Search for HNL with three prompt l's

Two strategies based on event categorization and/or on ML discriminants.

A number of orthogonal SR
- La1-La8 and Lb1-Lb8 where L:low mass (m_N<m_W or m_Z), a: no OSSF pair, b: OSSF pair, 1-8 different min m($\ell^+\ell^-$) cut
- Ha1-Ha9 and Hb1-Hb16 where H: high mass ($m_{N>}m_W$ or m_Z)



Train BDTs for S/B discrimination separately for:
- five different mass ranges
- HNL coupling to e, μ, or τ lepton
- events with or without τ_h



LL HNL in the decays of B mesons

B mesons decays are a much more abundant source of neutrinos (hence potentially HNLs) compared to W boson decays as $\sigma(pp \rightarrow B)$ about four orders of magnitude larger than $\sigma(pp \rightarrow W)$.

This search is made possible thanks to the collection of the **B-parking dataset**.

- Data parking involves storing a large amount of raw detector data collected by algorithms with low trigger thresholds to be processed when sufficient computational power is available to handle such data.

In this search single muon triggers were used with

- Low pT thresholds (~10 GeV)
- Large transverse impact parameter thresholds, to capture displaced muons resulting from decays of B mesons (LL)

41.6 fb^{-1},$O(10^{10})$ bb decays

Dijet resonance anomaly search

The CWoLa Hunting (weak supervision) method for anomaly detection was applied by ATLAS in a dijet resonance search.

The feature space used by the NNs is only 2D, hence great potential to extend this method to include additional features and more final states in order to ensure broad coverage of unanticipated scenarios.

A → BC