Search for vector-like quarks, heavy neutral leptons, and long-lived particles

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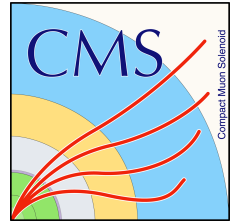
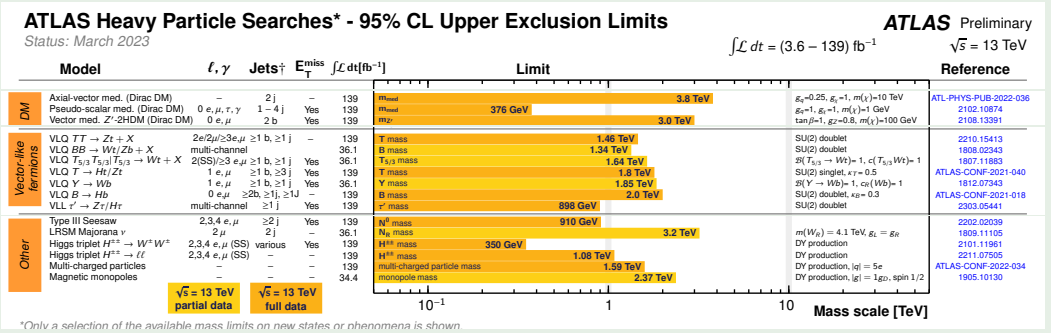
on behalf of
ATLAS and CMS Collaborations

MoriondEW2024 - La Thuile, Italy



Unexplained phenomena → Standard Model (SM) is not complete

- parameters fine tuning, matter/anti-matter asymmetry, dark-matter...

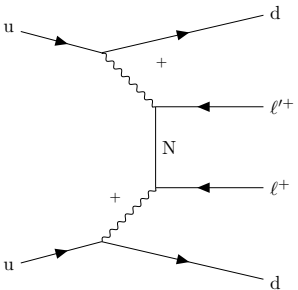


CMS results overview

Several beyond Standard Model (BSM) searches, focus here on:

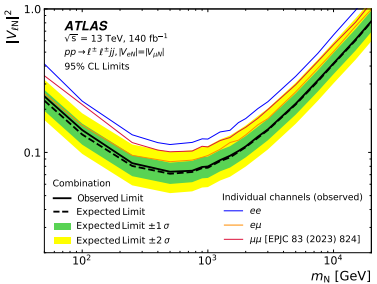
- Heavy Neutral Leptons (HNL), Long-Lived particles (LLP), Vector-like quarks (VLQ)

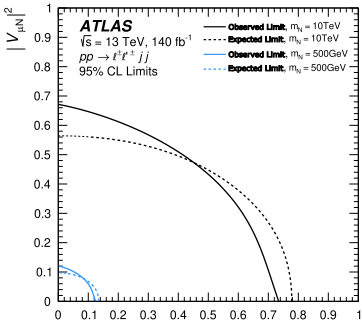
NEW! HNL via WW scattering in ee, $e\mu$ final states EXOT-2023-16



- $\ell^\pm\ell^\pm(ee, e\mu)$
- $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2$
- $p_{\mathrm{T}}^{\ell 2}$ discriminating variable

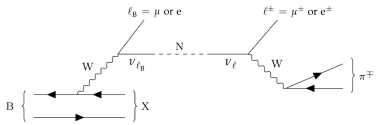
- Neutrino oscillations implies non-zero ν masses
- Neutrinoless double β decay: probe Majorana mass terms
- BSM theories: Type-I Seesaw, LRSM, GUT, dim-5 Weinberg operator





- Limits on the mixing matrix elements $|V_{eN}|^2$, $|V_{eN}V_{\mu N}^*|$
- Obs (exp) lim: $|m_{ee}| < 24.5(23.6)$, $|m_{e\mu}| < 12.5(14.8)$ GeV
- Comb w/ $\mu\mu$: 95% CL in $(|V_{eN}|^2, |V_{\mu N}|^2)$ plane

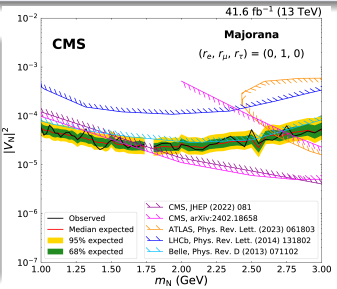
NEW! $N \to \ell^{\pm}\pi^{\mp}$ in B mesons leptonic and semileptonic decays EXO-22-019

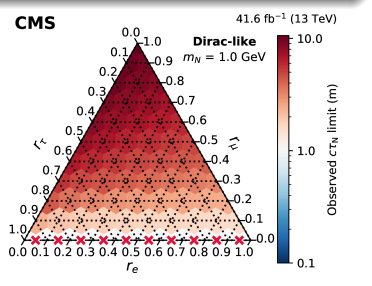


- Special dataset 41.6fb^{-1} $10^{10} b\bar{b}$ 80% purity

- νMSM: predict sterile neutrino N, Majorana (LNV, LNC) or Dirac (LNC) type. Mass m_N, lifetime $\tau_N \sim |V_N|^{-2} m_N^{-5}$
- Mixing to SM ν families. Amplitudes and ratios: $|V_N|^2 \equiv |V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2$, $r_\ell \equiv |V_{\ell N}|^2 / |V_N|^2$
- Inclusive semileptonic $B \to \ell_B N X$ ($B = B^0, B^{\pm}, B_s^0, B_c^{\pm}$) or leptonic. Gen. $1 < m_N < 3$ GeV, 1 mm$< c\tau_N <$ 1 m

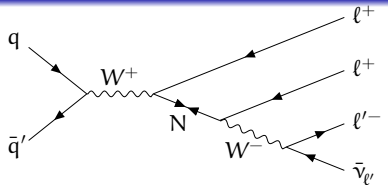
- Trigger $p_T(\mu) > 7 - 12$ GeV, $|\eta| < 1.5$, $d_{xy}/\sigma_{xy} > 3 - 6$
- Channels: $\mu\mu$, $e\mu$, μe (OS,SS)
- Select $p_T(\mu_{2(e)} > 2(1.5)$ GeV, $|\eta| < 2(1.48)$, $d_{xy}/\sigma_{xy} > 1.5$
- par Neur Net pNN-score$>$ 0.99





- $|V_N|^2 < 2.0 \cdot 10^{-5}$ ($m_N = 1.95$ GeV, Majorana), $c\tau_N <$ 10.5 m ($m_N = 1$ GeV, Dirac)

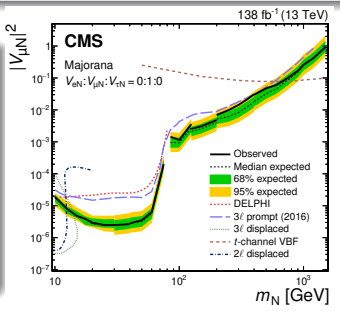
NEW! HNL in final states with e, μ, hadronic τ EXO-22-011

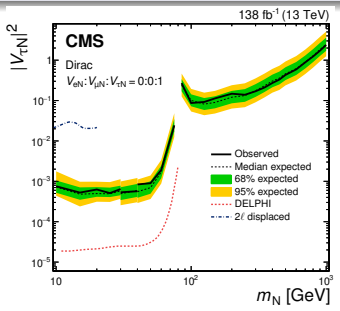


- Heavy N: Majorana (LNV, LNC) or Dirac (LNC) type
- Mixing matrix: exclusively to a single generation SM ν
- Prod: Drell-Yan $q\bar{q}' \to W^\pm \to N\ell^\pm$; VBF $q\gamma \to N\ell^\pm q'$
- Channels: eee, $ee\mu$, $e\mu\mu$, $\mu\mu\mu$, $ee\tau_h$, $e\mu\tau_h$, $\mu\mu\tau_h$

Event selection

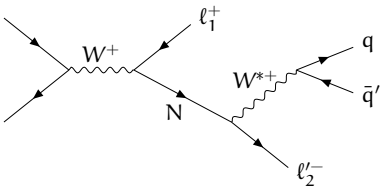
- $= 3\ell$ tight, $p_T(\ell_1) > 15$ GeV
- $p_T(\tau_h) > 20$ GeV, 1 or 3 prongs
- jets $p_T > 25$ GeV, $= 0b$-tags,
- regions taylored to $m_N \gtrless m_W$
- on some, use BDT discriminant



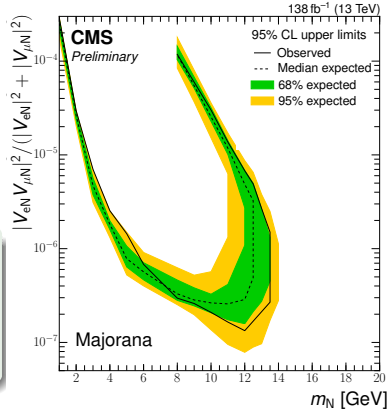


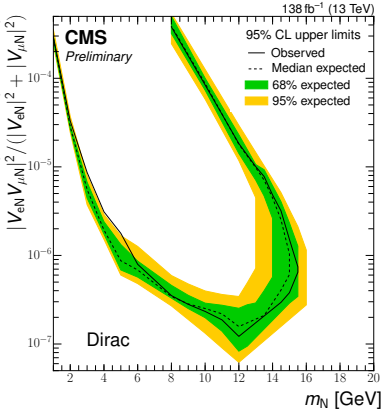
- Limits on mixing matrix elements $|V_{eN}|^2$, $|V_{\mu N}|^2$, and $|V_{\tau N}|^2$ (first time for $m_N > m_W$)
- Complementary to other searches, improved range of $(m_N, |V_{eN}|^2)$ exclusion limits

NEW! Long-lived HNL in lepton + displaced jet channel EXO-21-011



- Prompt lepton + displaced lepton and hadronic jet associated to same secondary vertex

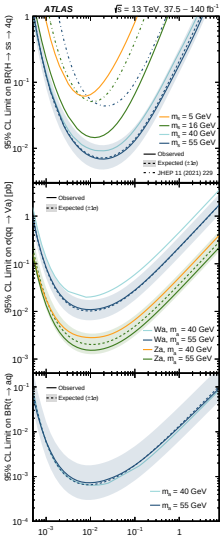




95% CL upper limits

- Best limits to date for $11 < m_N < 16$ GeV
- Depending on scenario, squared mixing parameters as low as 2.6×10^{-7} excluded

NEW! Long-lived bosons with displaced vertices in ID EXOT-2021-32



More details here

- "Higgs portal" neutral spin-0 boson $s \to q$
- Axion-like Nambu-Goldston boson a associated to W/Z ($a \to gg$) or in $t\bar{t}$ decay ($a \to gg/c\bar{c}$)

→ All three models: hadronic decay vtx displaced wrt collision point

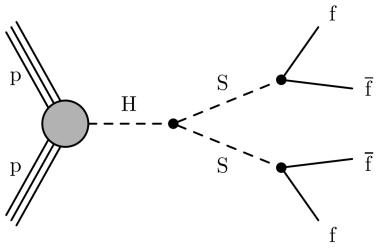
- BDT$_j$-score> 0.5, exploiting tracks $|d_0|$, p_T... to select displaced jets

- First time use of new large-impact parameter tracks reconstruction
- Dedicated jet pair trigger enriching vector boson fusion Higgs prod
- Signal regions: split in $n_{DV} = 1(\geq 2)$ with BDT$_{j_0} \times$BDT$_{j_1} > 0.9(0.7)$

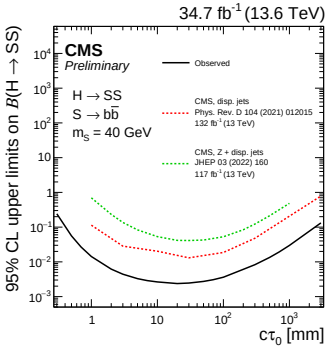
95% CL upper limits on all models. (*) $\mathscr{O}(10)$ impr. (†) First time probed

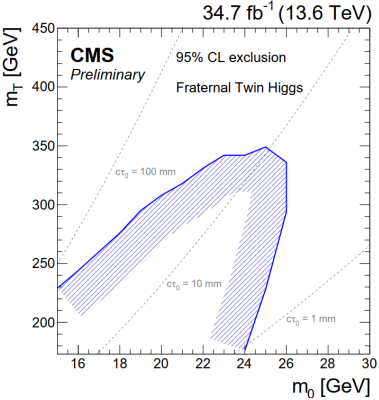
- $\mathscr{B}(H \to ss \to 4b) > 1\%$ ($m_s = 55$ GeV, $c\tau_s = 6 - 68$ mm) (*)
- $\mathscr{B}(H \to ss \to 4c) > 10\%$ ($m_s = 5$ GeV, $c\tau_s = 3 - 20$ mm)(†)
- $\mathscr{B}(qq \to Va) > 0.1$ pb ($m_a > 40$ GeV, $c\tau_a = 1.2 - 192$ mm) (†)
- $\mathscr{B}(t \to aq) > 0.1\%$ ($m_a > 40$ GeV, $c\tau_a = 4 - 36$ mm) (†)

NEW Run-3! Low-mass LLP with displaced jets EXO-23-013



- Novel trigger, machine learning, reconstruction techniques



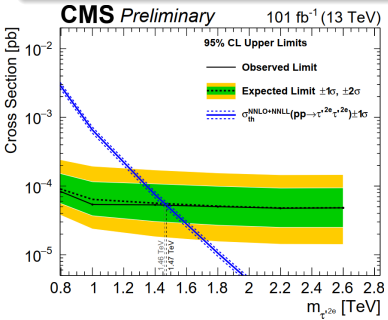


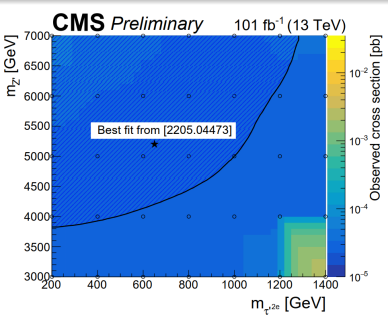
95% CL upper limits with 34.7fb^{-1} at 13.6 TeV

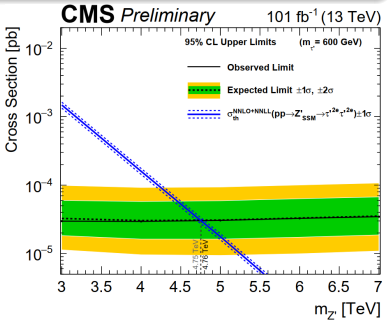
- Best limits to date for $15 < m_{LLP} < 55$ GeV, $c\tau < 1$ m
- First exclusions of hadronic τ lepton decays ($c\tau < 1$ m)
- $\mathscr{B}(H \to SS \to 4b(d)) > 1\%$ excluded for $m_{LLP} > 40$ GeV, $2(1) < c\tau < 370(380)$ mm

NEW! Heavy LLP with large ionization energy loss EXO-18-002

- Search for heavy stable charged particle based on silicon dE/dx







95% CL upper limits with 101fb^{-1} at 13 TeV

- D-Y production of τ' leptons pair $|Q| = 1(2e)$ excl. below 1.20(1.47) TeV
- $\mathscr{B}(Z' \to \tau'\tau') = 1$ excl. as a function of $m_{\tau'(2e)}$ vs $m_{Z'}$
- $m_{Z'_{SSM}} < 4.76$ GeV excluded for $m_{\tau'(2e)} = 600$ GeV

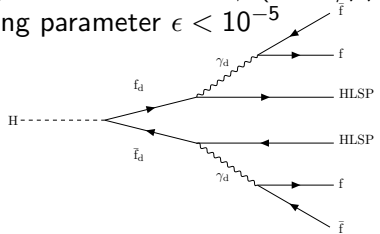
Long-lived dark photons (Falkowski-Ruderman-Volansky-Zupan) EXOT-2022-15

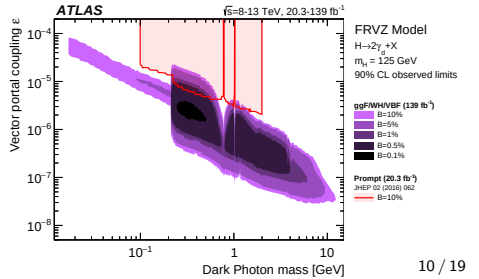
- VBF produced 125 GeV Higgs boson $\rightarrow$ exotic decay to dark fermions f_d
- Prompt hidden lightest stable particle (HLSP) and γ_d from $f_d \rightarrow$HLSP$\gamma_d(\rightarrow ee/\mu\mu/q\bar{q})$
- $c\tau_{\gamma_d} < 7 - 13$ m, $m_{\gamma_d} \sim \mathcal{O}(\text{MeV-GeV})$, kinetic mixing parameter $\epsilon < 10^{-5}$

Event selection

- Trigger: tri-muon/narrow-scan/E_T^{miss}
- ≥ 2 jets, p_T(jet)> 30 GeV, $|\Delta\eta_{jj}| > 3$, $m_{jj} \geq 1000$ GeV, $|\Delta\phi_{jj}| < 2.5$
- 0-leptons/b-jets, $E_T^{\text{miss}} \geq 100$ GeV
- non-collision bkgd veto: beam induced, cosmic
- ≥ 1 Dark Photon Jet (μ or calo). Respectively:
  - ≥ 2 muon-spectrometer-only tracks ($\Delta R = 0.4$)
  - electromag fract< 0.4, QCD tagger> 0.5

- Combin. *ggF*, *WH* modes: 95%CL excl. $\mathcal{B}(\text{H}\rightarrow 2\gamma_d+\text{X}) > 10\%$ for $173 < c\tau_{\gamma_d} < 1296$ mm

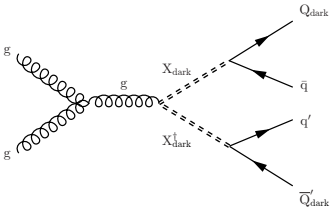




NEW! Emerging jets EXO-22-015

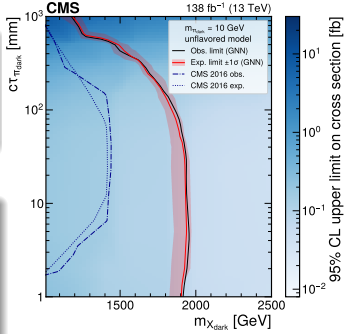
Long-lived dark mesons pair

- Unflavored or flavor-aligned model
- Explored: $5 < c\tau_{\pi_{dark}} < 500$ mm, $1000 < m_{X_{dark}} < 2500$ GeV



Event selection

- Trigger $H_T > 1050$ GeV
- Large H_T, > 4 jets, 2 tagged EJ
- Agnostic and ML tagger



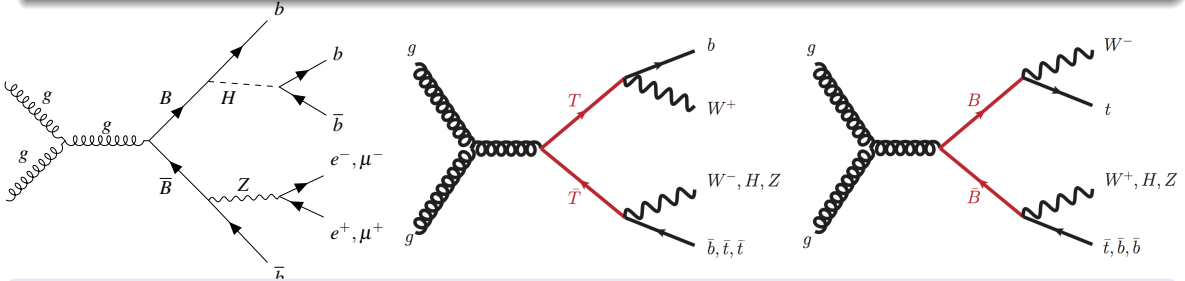
Exclusion

- $m_{X_{dark}} < 1950$ GeV (unflav) for $c\tau_{\pi_{dark}} \sim 100$ mm, $m_{\pi_{dark}} \sim 10$ GeV
- $m_{X_{dark}} < 1850$ GeV (flav) for $c\tau_{\pi_{dark}} \sim 500$ mm, $m_{\pi_{dark}} \sim 10$ GeV

Vector-like quarks (VLQ)

New heavy fermions, introduced by many models

- Little/Composite Higgs, string theory, large extra-dimensions...
- Left-/right-handed components transform identically
- Mass term included in $\mathscr{L}$, independent of Yukawa couplings to H
- Mix mainly to 3^{rd} generation quarks to cancel H mass divergences



- Singlet, doublet or triplet. Charge e: $T(+2/3)$, $B(-1/3)$, $X(5/3)$, $Y(-4/3)$
- VLQ decay modes: $T \to tH$, tZ, bW; $Y \to bW$; $B \to bH$, bZ, tW; $X \to tW$

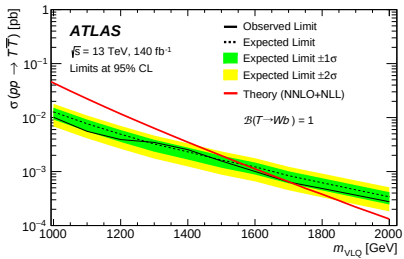
$T\bar{T} \to WbWb$, lepton+jets channel EXOT-2019-06

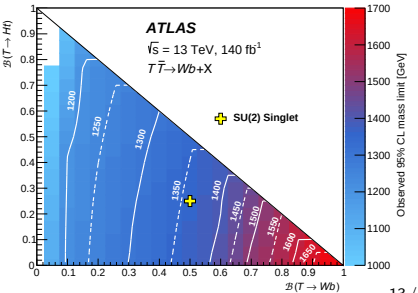
- Optimized for $T \to Wb$ (100%)
- Sensitive to all VLQs, combined BR
- Explored: $1 < m_{VLQ} < 2$ TeV

Event selection

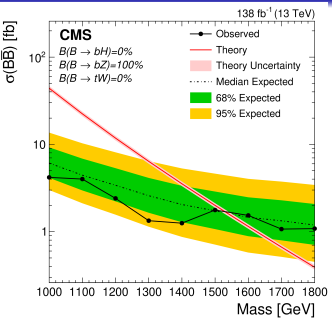
- Trigger: $p_T(\ell) > 27$ GeV or $E_T^{\text{miss}} > 200$ GeV
- ≥ 3 jets, ≥ 1 b-tagged jet, ≥ 1 large-R jet
- W_{lep}: $\Delta R(\ell, \nu) < 0.7$; W_{had}: $\Delta R(W_{had}, b_{had}) > 1.0$
- $|m_T^{lep} - m_T^{had}| < 500$ GeV
- $S_T (= \sum p_T$ of selected objects $+ E_T^{\text{miss}}) > 1900$ GeV

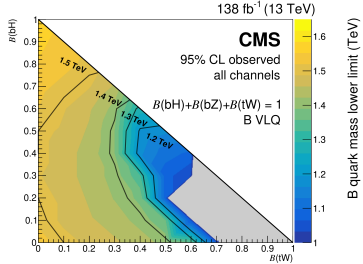
- Exclusion (95% CL): SU(2): $m_T < 1360$ GeV
- $\mathscr{B}(T \to Wb) = 1$: $m_T < 1700(1570)$ GeV
- in the $\mathscr{B}(T \to Wb)$ vs $\mathscr{B}(T \to Ht)$ plane





$B\bar{B}$, dileptonic and fully hadronic channels B2G-20-014





- Combinations: $bHbH$, $bHtW$, $bZtW$, $bHbZ$, $bZbZ$
- All hadronic, last two also with $Z \to ee/\mu\mu$
- Categories in jet/large-jet multiplicities, ISR/FSR

Event selection

- Trigger eff: 98% for $p_T(\ell) > 50$ GeV, 99% for $H_T(= \sum p_T \text{ of selected objects}) > 1350$ GeV
- Depending on channel: $3-6$ jets, $1-4$ $b/b\bar{b}$-tagged

$$\chi^2_{mod} = (\Delta m_{VLQ} - \overline{\Delta m}_{VLQ})/\sigma^2_{\Delta m_{VLQ}} + \sum_{Z/H/W/t} (\Delta m_i - \overline{\Delta m}_i)/\sigma^2_{\Delta m_i}$$

$\to$ Used to choose channel, jet config, as discriminant

Exclusion (95% CL) in $\mathscr{B}(B \to tW)$ vs $\mathscr{B}(B \to bH)$

- $\mathscr{B}(B \to bH) = 1$: $m_B < 1570$ GeV
- $\mathscr{B}(B \to bZ) = 1$: $m_B < 1540$ GeV

Conclusions: new results, improvements, first time measurements

Heavy Neutral Leptons - HNL

- Majorana neutrino in WW scattering: $|m_{ee}| < 24.5$, $|m_{e\mu}| < 12.5$ GeV
- Light neutrino in B decays: $|V_N|^2 < 2.0 \cdot 10^{-5}$, $c\tau_N < 10.5$ m
- Three leptons final states: improved range $(m_N, |V_{eN}|^2)$, first time $|V_{\tau N}|^2$ $(m_N > m_W)$
- Long-lived N in ℓ+jets: best limit to mixing parameters in $11 < m_N < 16$ GeV range

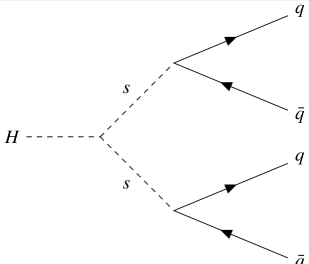
Long-Lived Particles - LLP

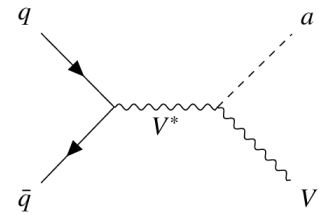
- Bosons with displaced inner detector vertices: new ($\mathscr{B}$ vs $c\tau_{s,a}$) limits for various $m_{s,a}$
- Higgs to neutral scalars in displaced jets: best limits for $15 < m_{LLP} < 55$ GeV, $c\tau < 1$ m
- Large silicon dE/dx deposit: $m_{Z'_{SSM}} < 4.76$ GeV excluded for $m_{\tau'(2e)} = 600$ GeV
- Long-lived dark photons: $\mathscr{B}(\mathrm{H} \to 2\gamma_d + \mathrm{X}) > 10\%$ for $173 < c\tau_{\gamma_d} < 1296$ mm
- Long-lived dark mesons excluded in ($m_{X_{dark}}$ vs $c\tau_{\pi_{dark}}$) plane $m_{\pi_{dark}} \sim 10$ GeV

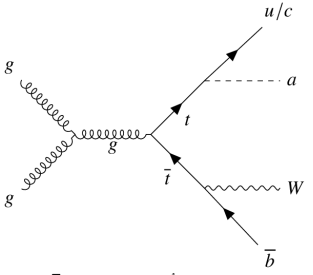
Vector-Like Quarks - VLQ

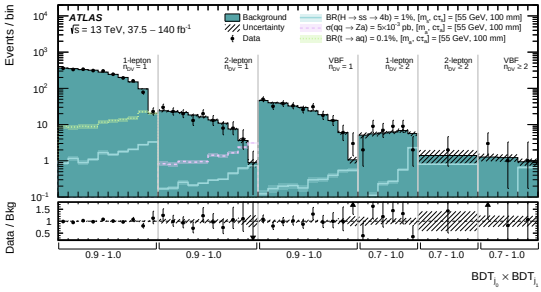
- Vector-like $T\bar{T} \to WbWb$ exclusion in $\mathscr{B}(T \to Wb)$ vs $\mathscr{B}(T \to Ht)$ plane
- Vector-like $B\bar{B}$ exclusion in $\mathscr{B}(B \to tW)$ vs $\mathscr{B}(B \to bH)$ plane

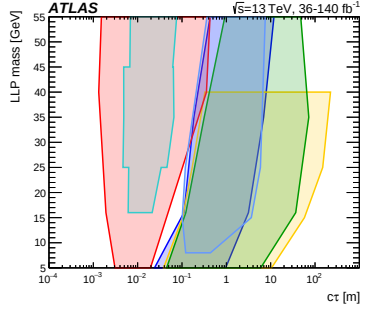
More details on LLP bosons with displaced vertices in ID EXOT-2021-32







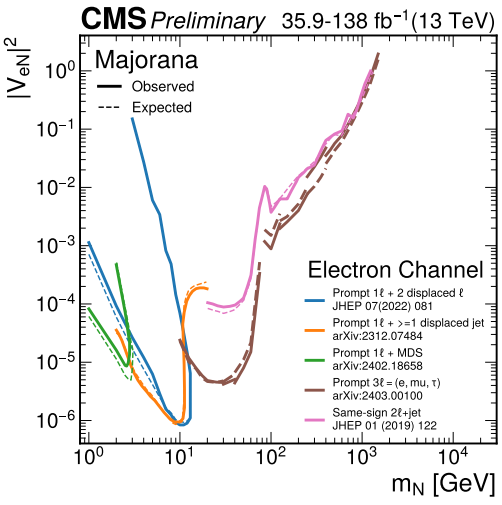


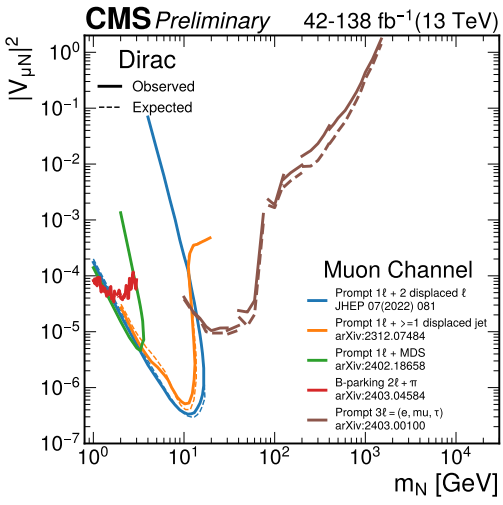


Hidden Sector, m_H = 125 GeV
B(H→ss) = 10%
95% CL observed limits

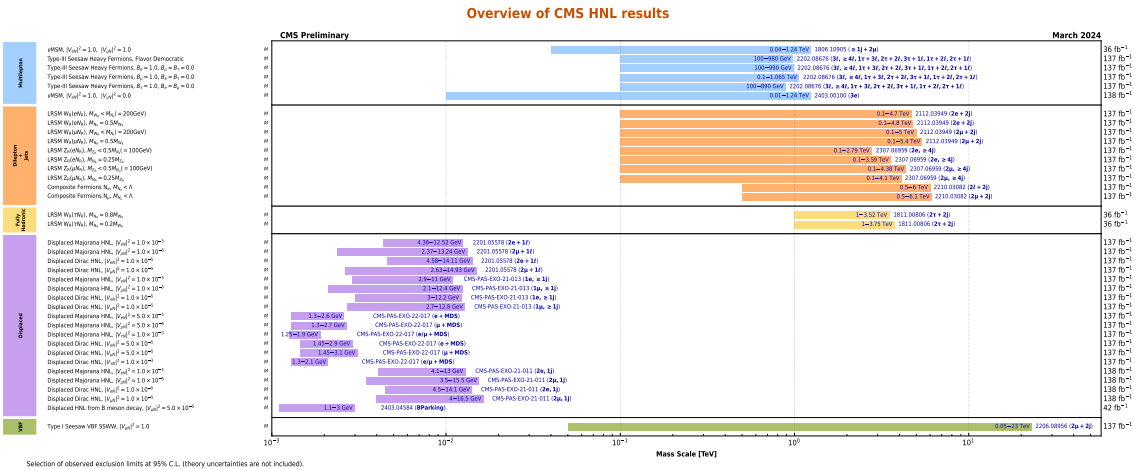
Searches:
- **Muon System (2 Vtx Only), 139 fb^{-1}** Phys. Rev. D 106 (2022) 032005
- **Muon System (1 Vtx + 2 Vtx), 36 fb^{-1}** Phys. Rev. D 99 (2019) 052005
- **Calorimeter, 139 fb^{-1}** JHEP 06 (2022) 005
- **Tracker+Muon System, 36 fb^{-1}** Phys. Rev. D 101 (2020) 052013
- **Tracker, 139 fb^{-1}** JHEP 11 (2021) 229
- **Tracker (this result), 37.5-140 fb^{-1}**

CMS Summary of neutrino exclusion limits





More CMS results overview



Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

Source with full table

References

- "Search for heavy Majorana neutrinos via scattering of same-sign W boson pairs in the ee and $e\mu$ final states in proton-proton collisions at $\sqrt{s} = 13$ TeV, EXOT-2023-16
- "Search for long-lived heavy neutrinos in the decays of B mesons produced in proton-proton collisions at $\sqrt{s} = 13$ TeV", EXO-22-019
- "Search for heavy neutral leptons in final states with electrons, muons, and hadronically decaying tau leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV", EXO-22-011
- "Search for long-lived heavy neutral leptons in proton-proton collision events with a lepton and a jet from a secondary vertex at $\sqrt{s} = 13$ TeV", EXO-21-011
- "Search for light long-lived particles in pp collisions at $\sqrt{s} = 13$ TeV using displaced vertices in the ATLAS inner detector", EXOT-2021-32
- "Search for low-mass long-lived particles using displaced jets in proton-proton collisions at $\sqrt{s} = 13.6$ TeV", EXO-23-013
- "Search for heavy long-lived charged particles with large ionization energy loss in proton-proton collisions at $\sqrt{s} = 13.6$ TeV", EXO-18-002
- "Search for light long-lived neutral particles from Higgs boson decays via vector-boson-fusion production from pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector" EXOT-2022-15
- "Search for new physics with emerging jets in proton-proton collisions at $\sqrt{s} = 13$ TeV", EXO-22-015
- "Search for pair-production of vector-like quarks in lepton+jets final states containing at least one b-tagged jet using the Run 2 data from the ATLAS experiment" EXOT-2019-06
- "A search for bottom-type vector-like quark pair production in dileptonic and fully hadronic final states in proton-proton collisions at 13 TeV", B2G-20-014