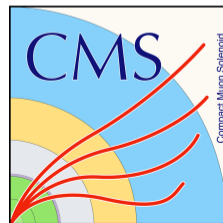


Search for vector-like quarks, heavy neutral leptons, and long-lived particles

Sergio Grancagnolo (Università del Salento)
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...

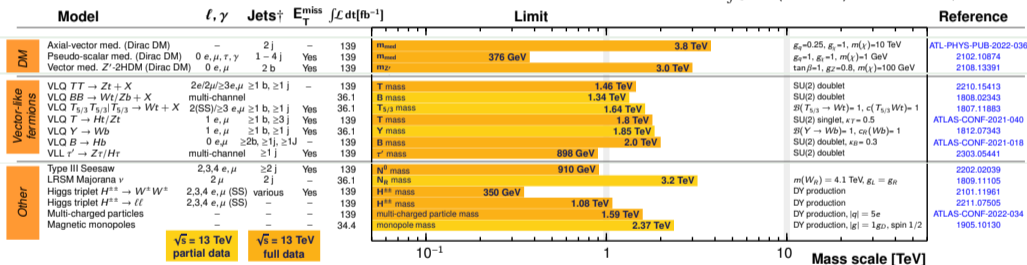
ATLAS Heavy Particle Searches* - 95% CL Upper Exclusion Limits

Status: March 2023

ATLAS Preliminary

$\int \mathcal{L} dt = (3.6 - 139) \text{ fb}^{-1}$

$\sqrt{s} = 13 \text{ TeV}$



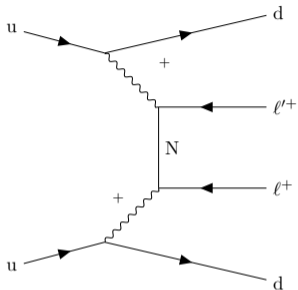
*Only a selection of the available mass limits on new states or phenomena is shown.

CMS results overview

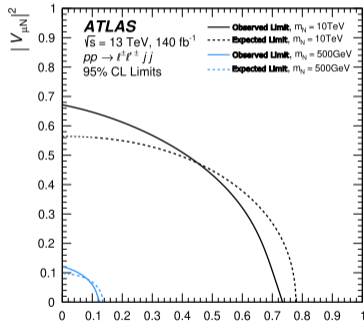
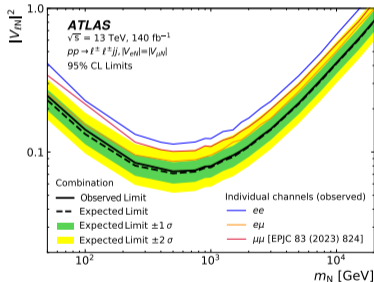
Several beyond Standard Model (BSM) searches, focus here on:

- 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



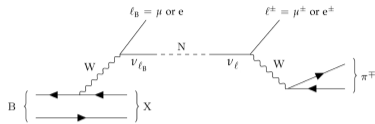
- Neutrino oscillations implies non-zero ν masses
- Neutrinoless double β decay: probe Majorana mass terms
- BSM theories: Type-I Seesaw, LRSM, GUT, dim-5 Weinberg operator



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

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

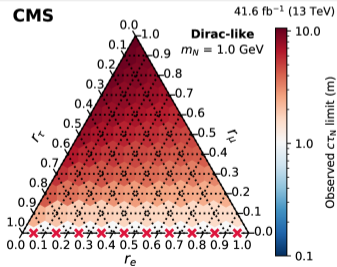
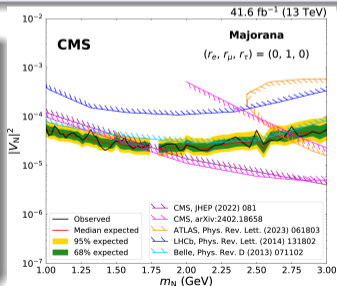
NEW! $N \rightarrow \ell^\pm \pi^\mp$ in B mesons leptonic and semileptonic decays EXO-22-019



- ν MSM: 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 $B \rightarrow \ell_B N X$ ($B = B^0, B^\pm, B_s^0, B_c^\pm$) or leptonic. Gen. $1 < m_N < 3$ GeV, $1 \text{ mm} < c\tau_N < 1 \text{ m}$

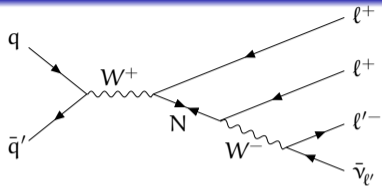
- Special dataset 41.6 fb^{-1}
 $10^{10} b\bar{b}$ 80% purity

- Trigger $p_T(\mu) > 7 - 12$ GeV, $|\eta| < 1.5$, $d_{xy}/\sigma_{xy} > 3 - 6$
- Channels: $\mu\mu, e\mu, \mu e$ (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)

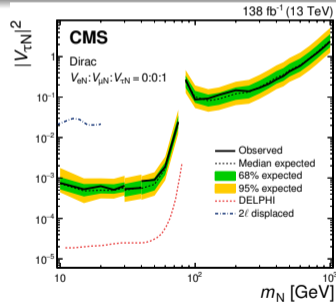
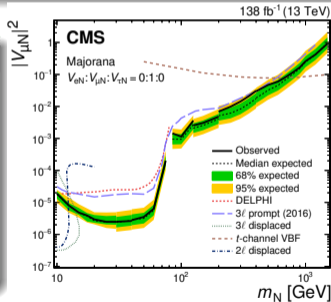
NEW! HNL in final states with e, μ , hadronic τ EXO-22-011



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

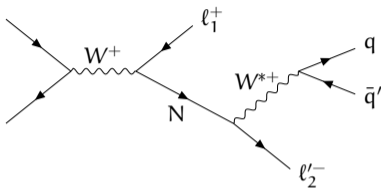
Event selection

- $= 3\ell$ 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 tailored to $m_N \gtrsim m_W$
- on some, use BDT discriminant

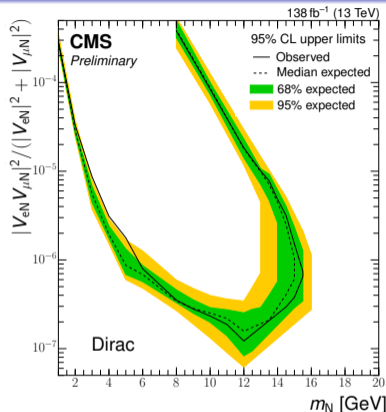
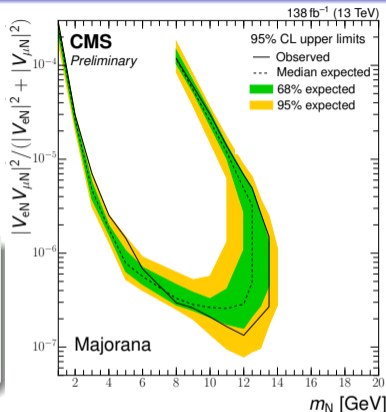


- Limits on mixing matrix elements $|V_{eN}|^2$, $|V_{\mu N}|^2$, and $|V_{\tau N}|^2$ (first time for $m_N > m_W$)
- Complementary to other searches, improved range of $(m_N, |V_{eN}|^2)$ exclusion limits

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



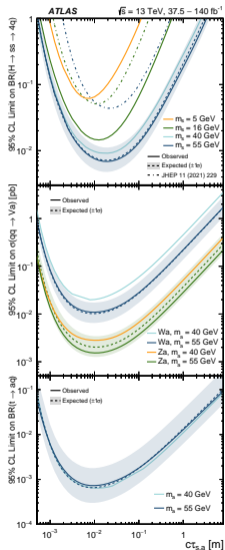
- Prompt lepton + displaced lepton and hadronic jet associated to same secondary vertex



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

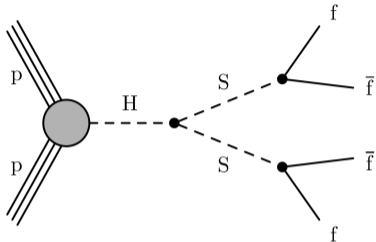
- “Higgs portal” neutral spin-0 boson $s \rightarrow q$
- Axion-like Nambu-Goldstone boson a associated to W/Z ($a \rightarrow gg$) or in $t\bar{t}$ decay ($a \rightarrow gg/c\bar{c}$)
- All three models: hadronic decay vtx displaced wrt collision point
 - $\text{BDT}_j\text{-score} > 0.5$, exploiting 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 $\text{BDT}_{j_0} \times \text{BDT}_{j_1} > 0.9(0.7)$

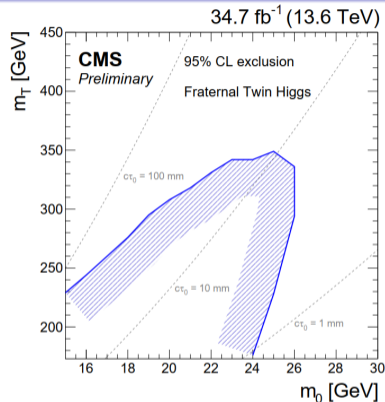
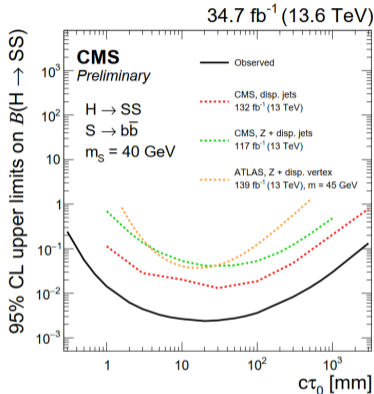
95% CL upper limits on all models. (*) $\mathcal{O}(10)$ impr. (†) First time probed

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

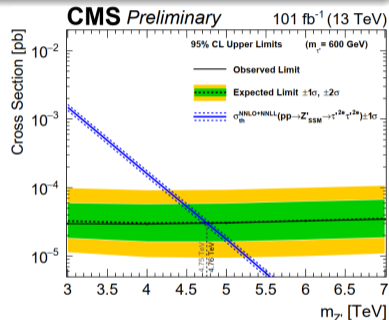
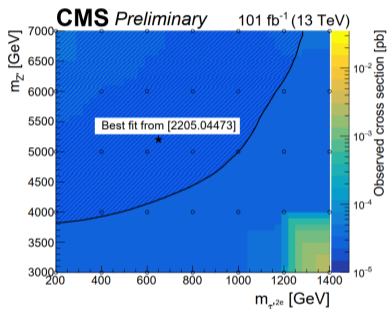
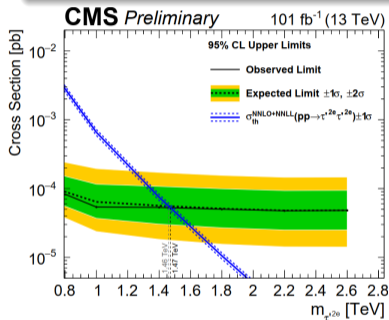


95% CL upper limits with 34.7fb⁻¹ at 13.6 TeV

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

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

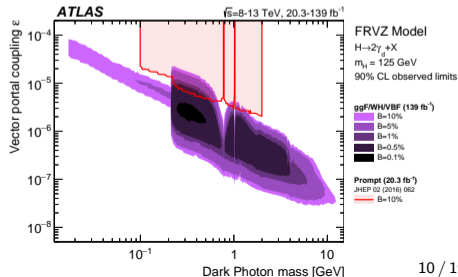
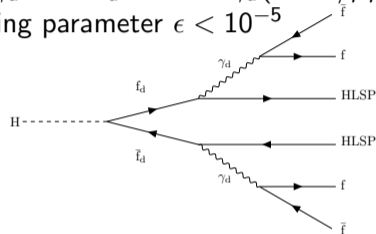
- D-Y production of τ' leptons pair $|Q| = 1(2e)$ excl. below 1.20(1.47) TeV
- $\mathcal{B}(Z' \rightarrow \tau' \tau') = 1$ excl. as a function of $m_{\tau'(2e)}$ vs $m_{Z'}$
- $m_{Z'_{SSM}} < 4.76 GeV$ excluded for $m_{\tau'(2e)} = 600 GeV$

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 $f_d \rightarrow \text{HLSP} \gamma_d (\rightarrow ee/\mu\mu/q\bar{q})$
- $c\tau_{\gamma_d} < 7 - 13$ m, $m_{\gamma_d} \sim \mathcal{O}(\text{MeV-GeV})$, kinetic mixing parameter $\epsilon < 10^{-5}$

Event selection

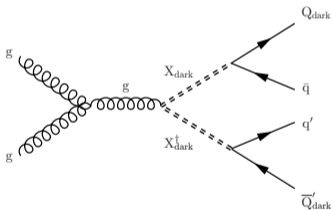
- Trigger: tri-muon/narrow-scan/ E_T^{miss}
- ≥ 2 jets, $p_T(\text{jet}) > 30$ GeV, $|\Delta\eta_{jj}| > 3$, $m_{jj} \geq 1000$ GeV, $|\Delta\phi_{jj}| < 2.5$
- 0-leptons/b-jets, $E_T^{\text{miss}} \geq 100$ GeV
- non-collision bkgd veto: beam induced, cosmic
- ≥ 1 Dark Photon Jet (μ or calo). Respectively:
 - ≥ 2 muon-spectrometer-only tracks ($\Delta R = 0.4$)
 - electromag fract < 0.4 , QCD tagger > 0.5
- Combin. ggF , WH modes: 95%CL excl.
 $\mathcal{B}(H \rightarrow 2\gamma_d + X) > 10\%$ for $173 < c\tau_{\gamma_d} < 1296$ mm



NEW! Emerging jets EXO-22-015

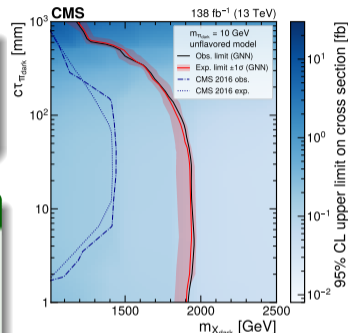
Long-lived dark mesons pair

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



Event selection

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



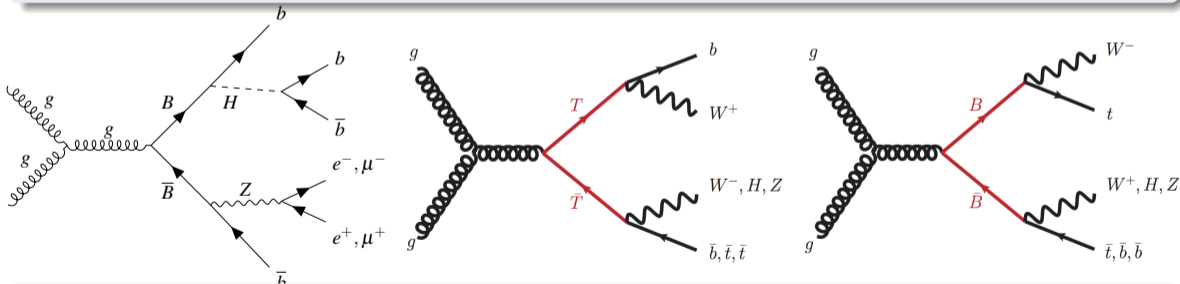
Exclusion

- $m_{\chi_{\text{dark}}} < 1950$ GeV (unflav) for $c\tau_{\pi_{\text{dark}}} \sim 100$ mm, $m_{\pi_{\text{dark}}} \sim 10$ GeV
- $m_{\chi_{\text{dark}}} < 1850$ GeV (flav) for $c\tau_{\pi_{\text{dark}}} \sim 500$ mm, $m_{\pi_{\text{dark}}} \sim 10$ 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 \mathcal{L} , independent of Yukawa couplings to H
- Mix mainly to 3rd 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: $T \rightarrow tH, tZ, bW$; $Y \rightarrow bW$; $B \rightarrow bH, bZ, tW$; $X \rightarrow tW$

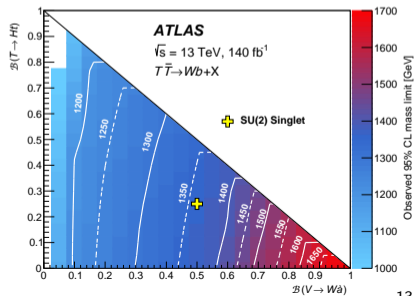
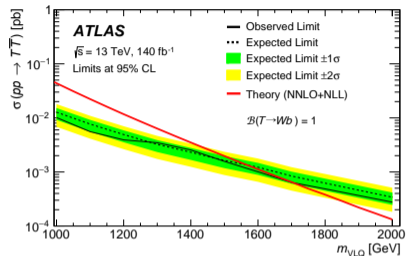
$T\bar{T} \rightarrow WbWb$, lepton+jets channel EXOT-2019-06

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

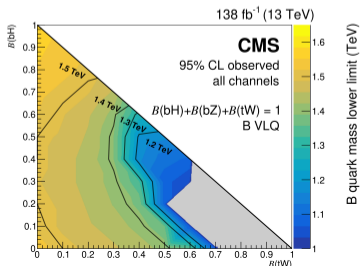
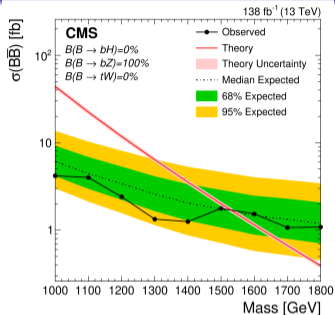
Event selection

- 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
- $S_T (= \sum p_T \text{ of selected objects} + E_T^{\text{miss}}) > 1900$ GeV

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



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



- Combinations: $bHbH$, $bHtW$, $bZtW$, $bHbZ$, $bZbZ$
- All hadronic, last two also with $Z \rightarrow ee/\mu\mu$
- 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

$$\chi_{mod}^2 = (\Delta m_{VLQ} - \overline{\Delta m_{VLQ}}) / \sigma_{\Delta m_{VLQ}}^2 + \sum_{Z/H/W/t} (\Delta m_i - \overline{\Delta m_i}) / \sigma_{\Delta m_i}^2$$

→ Used to choose channel, jet config, as discriminant

Exclusion (95% CL) in $\mathcal{B}(B \rightarrow tW)$ vs $\mathcal{B}(B \rightarrow bH)$

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

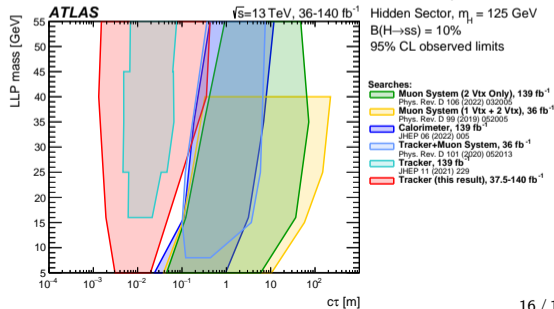
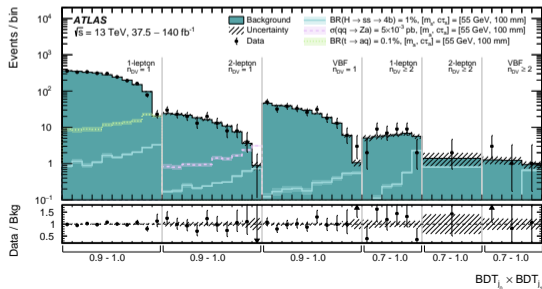
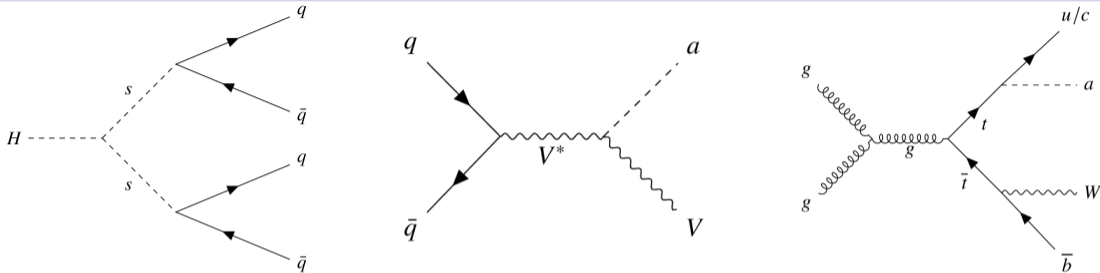
Long-Lived Particles - LLP

- Bosons with displaced inner detector vertices: new $(\mathcal{B}$ 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 $m_{T'(2e)} = 600$ GeV
- Long-lived dark photons: $\mathcal{B}(H \rightarrow 2\gamma_d + X) > 10\%$ for $173 < c\tau_{\gamma_d} < 1296$ mm
- Long-lived dark mesons excluded in $(m_{\chi_{dark}} \text{ vs } c\tau_{\pi_{dark}})$ plane $m_{\pi_{dark}} \sim 10$ GeV

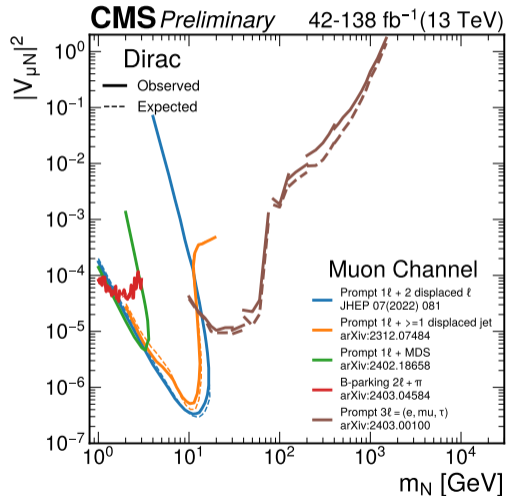
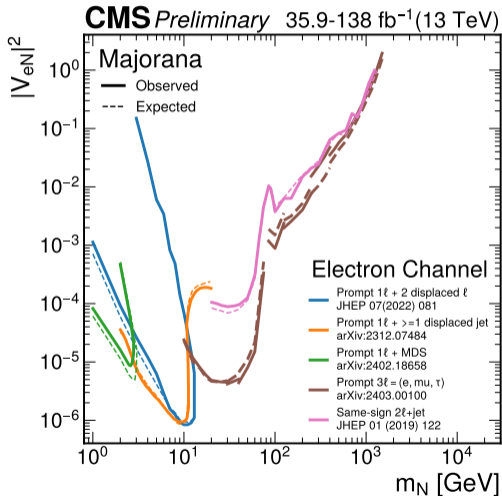
Vector-Like Quarks - VLQ

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

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



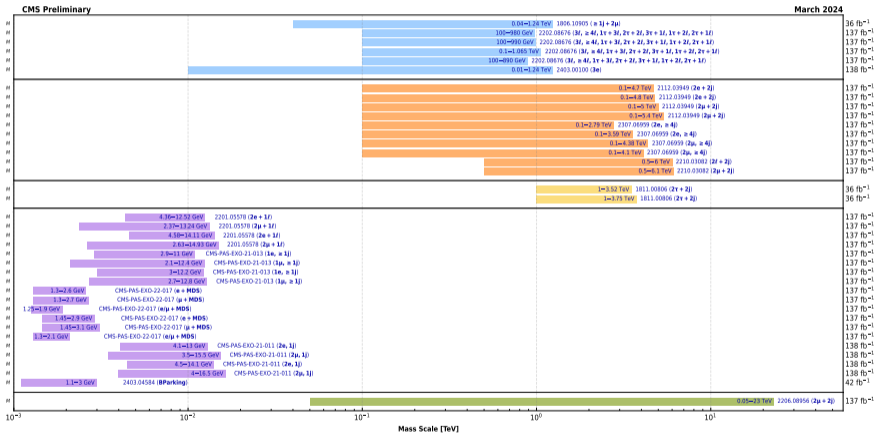
CMS Summary of neutrino exclusion limits



More CMS results overview

Overview of CMS HNL results

| | |
|-------------------------|--|
| Multiplets | <ul style="list-style-type: none"> νMSM, $V_{\mu 1} ^2 = 1.0$, $V_{\tau 1} ^2 = 1.0$ Type-II Seesaw Heavy Fermions, Flavor Democratic Type-III Seesaw Heavy Fermions, $B_\mu = 1.0$, $B_\tau = 0$, $\beta = 0.0$ Type-III Seesaw Heavy Fermions, $B_\mu = 1.0$, $B_\tau = 0$, $\beta = 0.0$ Type-III Seesaw Heavy Fermions, $B_\mu = 1.0$, $B_\tau = 0$, $\beta = 0.0$ νMSM, $V_{\mu 1} ^2 = 1.0$, $V_{\tau 1} ^2 = 0.0$ |
| Dietsos + jets | <ul style="list-style-type: none"> LRSM $W_1(\nu_{\mu 1})$, $M_{H_u} < M_{H_d} = 200\text{GeV}$ LRSM $W_1(\nu_{\mu 1})$, $M_{H_u} = 0.5M_{H_d}$ LRSM $W_1(\nu_{\mu 1})$, $M_{H_u} < M_{H_d} = 200\text{GeV}$ LRSM $W_1(\nu_{\mu 1})$, $M_{H_u} = 0.5M_{H_d}$ LRSM $Z_1(\nu_{\mu 1})$, $M_{H_u} < 0.5M_{H_d} = 100\text{GeV}$ LRSM $Z_1(\nu_{\mu 1})$, $M_{H_u} = 0.25M_{H_d}$ LRSM $Z_1(\nu_{\mu 1})$, $M_{H_u} < 0.5M_{H_d} = 100\text{GeV}$ LRSM $Z_1(\nu_{\mu 1})$, $M_{H_u} = 0.25M_{H_d}$ Composite Fermions N_u, $M_{H_u} < \Lambda$ Composite Fermions N_u, $M_{H_u} < \Lambda$ |
| Single Neutrinos | <ul style="list-style-type: none"> LRSM $W_1(\nu_{\mu 1})$, $M_{H_u} = 0.8M_{H_d}$ LRSM $W_1(\nu_{\mu 1})$, $M_{H_u} = 0.2M_{H_d}$ |
| Displaced | <ul style="list-style-type: none"> Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-3}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-3}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 5.0 \times 10^{-3}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 5.0 \times 10^{-3}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-3}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 5.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 5.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-3}$ Displaced Majorana HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-3}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced Dirac HNL, $V_{\mu 1} ^2 = 1.0 \times 10^{-4}$ Displaced HNL from B meson decay, $V_{\mu 1} ^2 = 5.0 \times 10^{-4}$ |
| VB | Type I Seesaw VBF SSWW, $ V_{\mu 1} ^2 = 1.0$ |



Source with full table

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