ICHEP 2024 PRAGUE

42nd International Conference on High Energy Physics

18-24 July 2024 · Prague · Czech Republic

ichep2024.org

Long-lived Heavy Neutral Leptons with a Semi-leptonic Signature at CMS

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on behalf of the CMS Collaboration

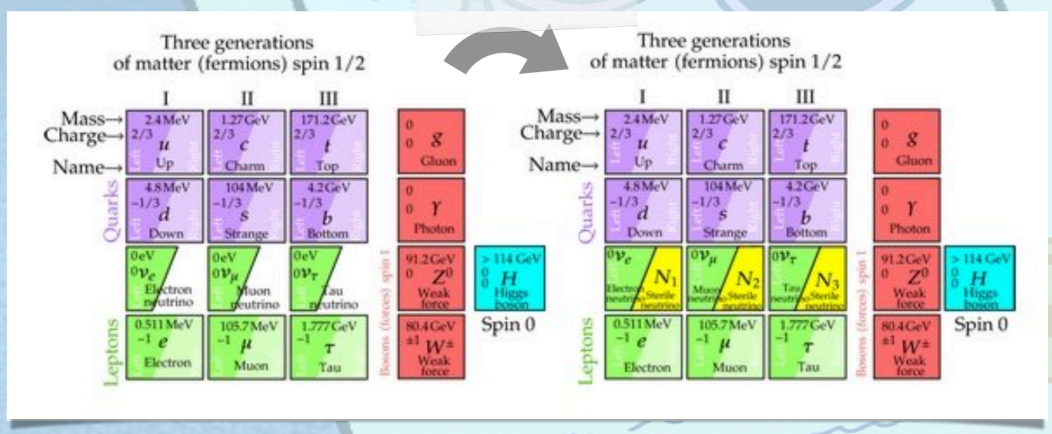
Standard Model Issues

The SM is unable to explain

- Neutrino masses
- matter vs. anti-matter excess
- Dark matter candidate

The Neutrino Minimal Standard Model (νMSM)

- All three issues can be solved by adding three new fundamental fermions, right handed Heavy Neutral Lepton (HNL): N1, N2 and N3.
- This is an elegant proposal as it simply symmetrizes SM by including HNL, so no new scale is involved. [1-2]



The Neutrino Minimal Standard Model (νMSM)

- N1 can be sufficiently stable to be a DM candidate, M(N1)~ a few keV
- M(N2) ≈ M(N3) ~ a few GeV → CPV can be increased dramatically to explain Baryon Asymmetry of the Universe (BAU)
- Since ν has mass and no charge, can be: Dirac ($\nu_L \neq \bar{\nu}_R, \nu_R \neq \bar{\nu}_L$) OR Majorana ($\nu_L = \bar{\nu}_R, \nu_R = \bar{\nu}_L$) (we looked for both scenarios) [3]

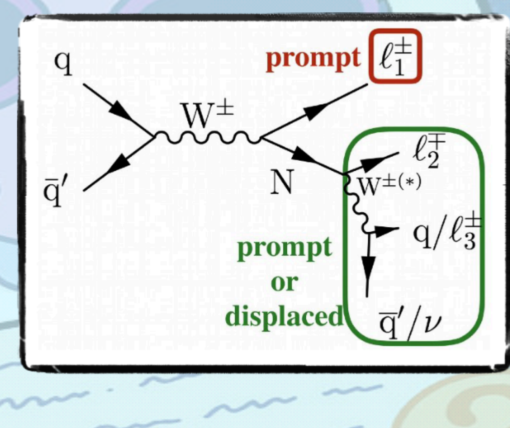
Long-lived Heavy Neutral Leptons

- Right Handed neutrinos produced through type-1 seesaw mechanism as a minimal extension of the SM
- Produced via ν-N mixing with coupling strength $|V_{Nl}|^2$
- Consider Dirac(LNC) and Majorana(LNC + LNV) nature
- lifetime $\tau \; \alpha \; \Sigma_i |V_{Nl}|^{-2} m_N^{-5}$

Long-lived Heavy Neutral Leptons

- Naturally long-lived for M_N = [1, 20] GeV → focus on displacements within CMS tracker = fully reconstructed displaced lepton and tracks
- Channel : $W^{\pm} \to L^{\pm} + N, N \to L^{\pm} + q\bar{q}$

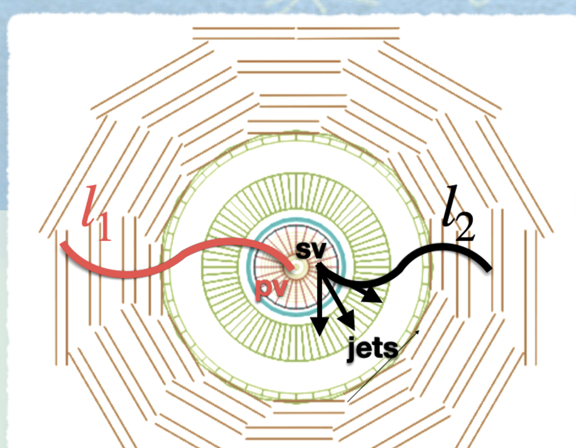
  (Final state : prompt lepton + displaced pair(lepton-jet))
  - Relatively large cross section
  - High momentum lepton (easy to trigger)



HNLs in the CMS Detector

Experimental Signature

- prompt lepton ($l_1 = e$ or μ)
- displaced lepton ($l_2 = e$ or μ)
- Secondary Vertex associated to l_2 track
- displaced jet (ΔR < 0.7 with l_2)



Analysis Strategy

- Trigger on prompt lepton
- Reconstruct Secondary Vertex from displaced l2 and displaced jet with tuned Inclusive Vertex Finder[4]
- ML for signal extraction: Particle Flow Network (PFN) → HNL decay has distinct signature (like heavy flavour jets)
- Data-driven Background estimation: ABCD method

Event Selection:

- $m(l_1, l_2) > 10$ GeV
- $\Delta\phi(l_1, l_2) > 0.4$
- → PFN Training selection
- PFN response > x (different value over channels)
- $m(l_1, SV) \in [50,85]$ GeV
- $m(\mu^{\pm}, \mu^{\mp}) \notin [85,95]$ GeV

Particle Flow Network (PFN)

Machine Learning Model

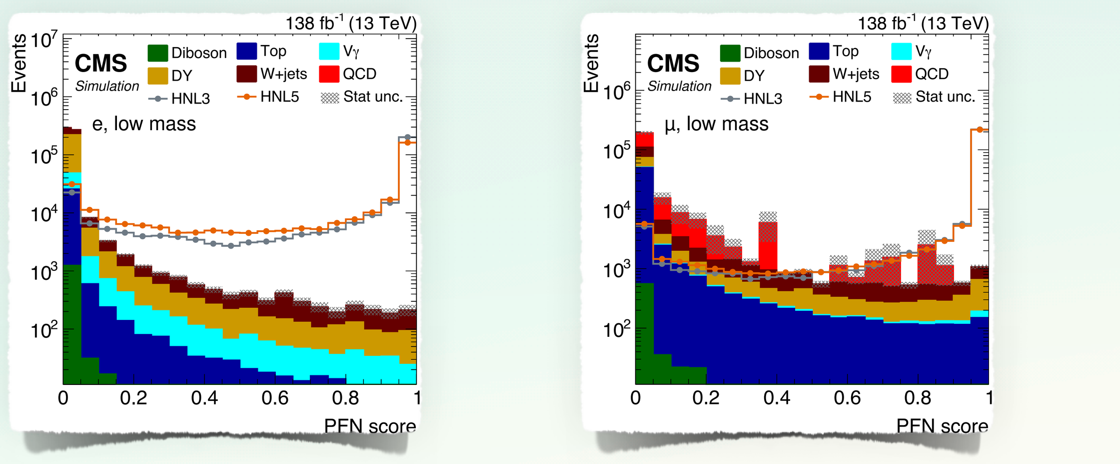
- Use only displaced part of event: Secondary Vertex(SV), displaced l2, displaced jet
- PFN is a neural net architecture based on Deep Sets Framework [5]

  Uses low-level variables as the info of individual particles in displaced jet

  Also high-level variables of SV, l2 and jet
- Train separate networks:

  $l_2 = e$ or μ

  Low Mass HNL (< 6 GeV) – High Mass HNL (≥ 6 GeV)
- Working points have been chosen to have very small backgrounds but still decent signal efficiency



The PFN score distribution of predicted events yields after applying the event selection

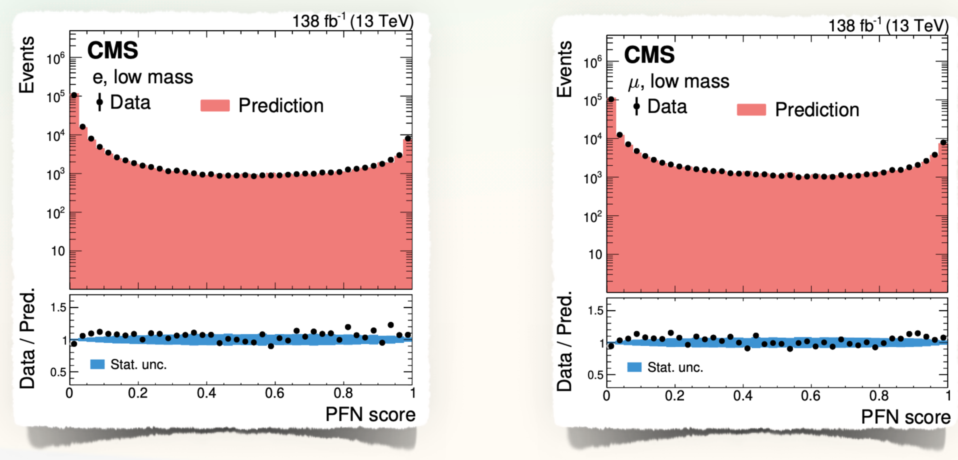
PFN Validation

- To validate the consistency between data/MC w.r.t PFN signal output shape → We need HNL-like events to test this, which is very challenging to find
- B-jets don't work because they are considered background by the PFN and cannot model signal.
- Use long-lived $K_S^0 \to \pi^+\pi^-$ decays within the jets of DY+jets to emulate HNL decays
- Emulate displaced lepton with the highest pT pion, use jet that contains K_S^0 for individual PFN particles (= additional PF candidates for the network)
- m K_S^0 = 0.497GeV → use low mass PFNs
- Run2 Data/MC for PFN > 0.9:

  e 1.09 ± 0.024 , μ 1.09 ± 0.023
- Run2 Data/MC for PFN > 0.975:

  e 1.09 ± 0.032 , μ 1.09 ± 0.034
- Agreement in each year consistent with max 10%

  → apply overall 10% unc. on signal

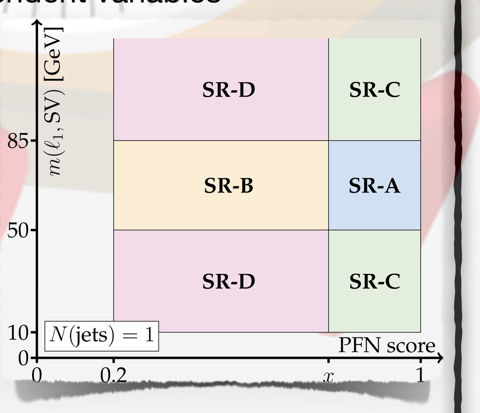


Background Estimation

- Use PFN output and m(l1,SV) as statistical independent variables
- Correlation factor generally < 20%
- $A_{bkg}^{pred,i} = B_{bkg}^{i} \times \frac{C_{bkg}^{i}}{D_{bkg}^{i}}$ for each bin i separately
- Define several control regions using data and MC

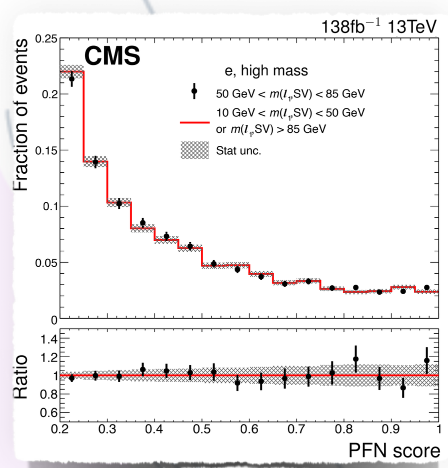
  → generally good closure

  → use CR to estimate systematic uncertainty for background N(jets) ≥ 1



PFN and m(l,SV) Statistical Independence

- Use control region selection with inverted Njets cut
- Check if PFN output shape is similar inside and outside the m(l1,SV) window
- Good agreement seen in shape for all PFN versions
- Good indication of variables being statistically independent
- Other tests have also been performed, including p-value likelihoods.
- Conclusion PFN score and m(l1,SV) statistically independent



Systematic uncertainties

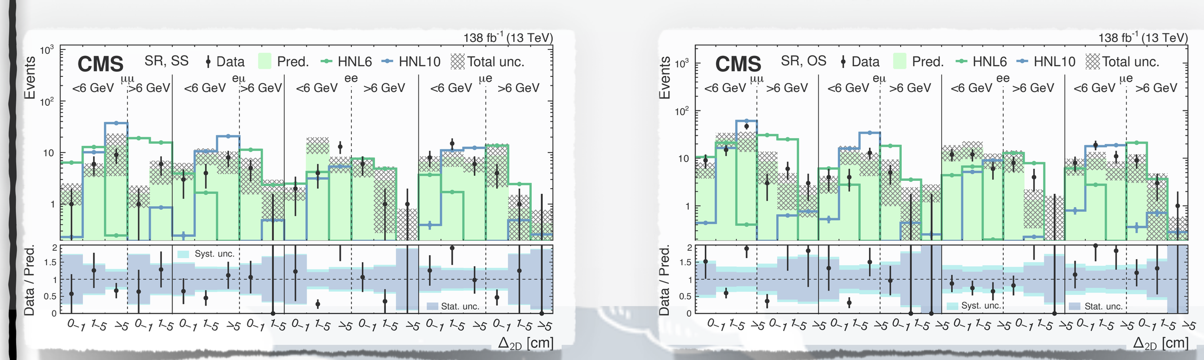
Source	Type	Uncertainty [%]
Signal yield		
NNLO *K*-factor	Normalization	4
Luminosity	Normalization	1.6
Pileup modeling	Shape	4.6
e (μ) trigger efficiency	Shape	1 (<1)
Prompt e (μ) selection efficiency	Shape	2–4 (1–3)
Nonprompt e (μ) selection efficiency	Shape	1–20 (<1)
Tracking efficiency	Shape	7.3
Jet energy scale & resolution	Shape	1–2
PFN score	Shape	10
Background yield		
CR closure	Shape	20–30
DY scale factor (OS μμ, low mass)	Shape	20–50

Summary of systematic uncertainty sources in the signal and background prediction.

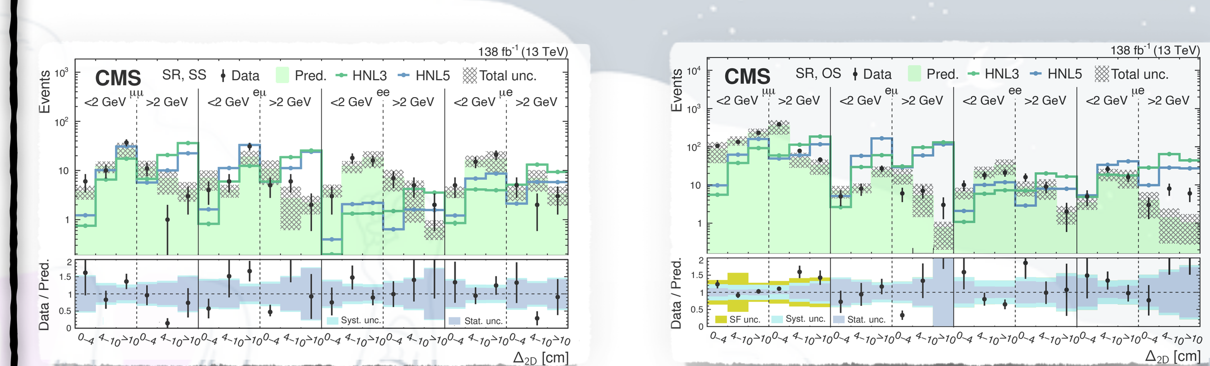
Signal Region Observation

- Signal region binned in m_{SV} and Δ_{2D} displacement
- Observe good agreement with background prediction (no significant excess)

high mass PFN signal region used for $m_N \geq 6$ GeV



low mass PFN signal region used for $m_N < 6$ GeV



Limits on HNL couplings

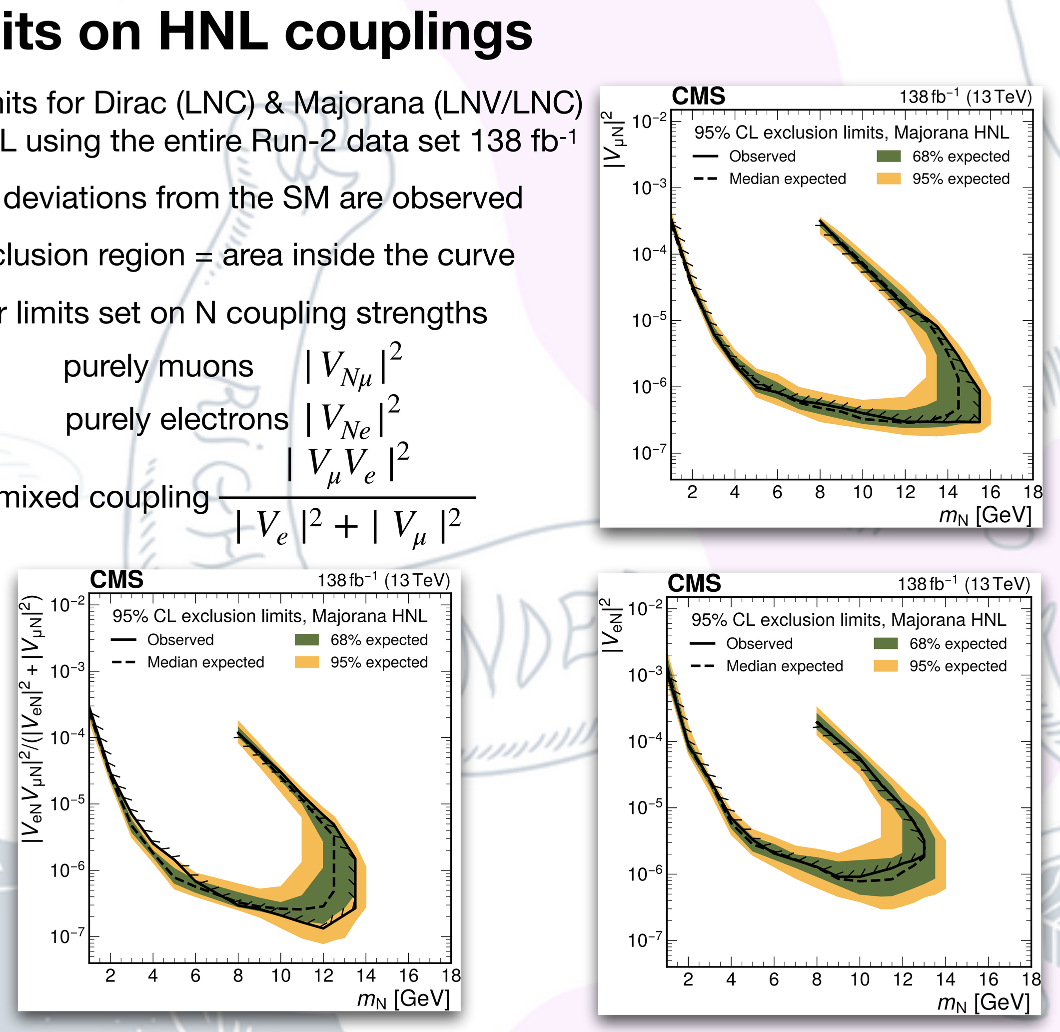
- Limits for Dirac (LNC) & Majorana (LNV/LNC) HNL using the entire Run-2 data set 138 fb⁻¹
- No deviations from the SM are observed
- Exclusion region = area inside the curve

Upper limits set on N coupling strengths

purely muons $|V_{N\mu}|^2$

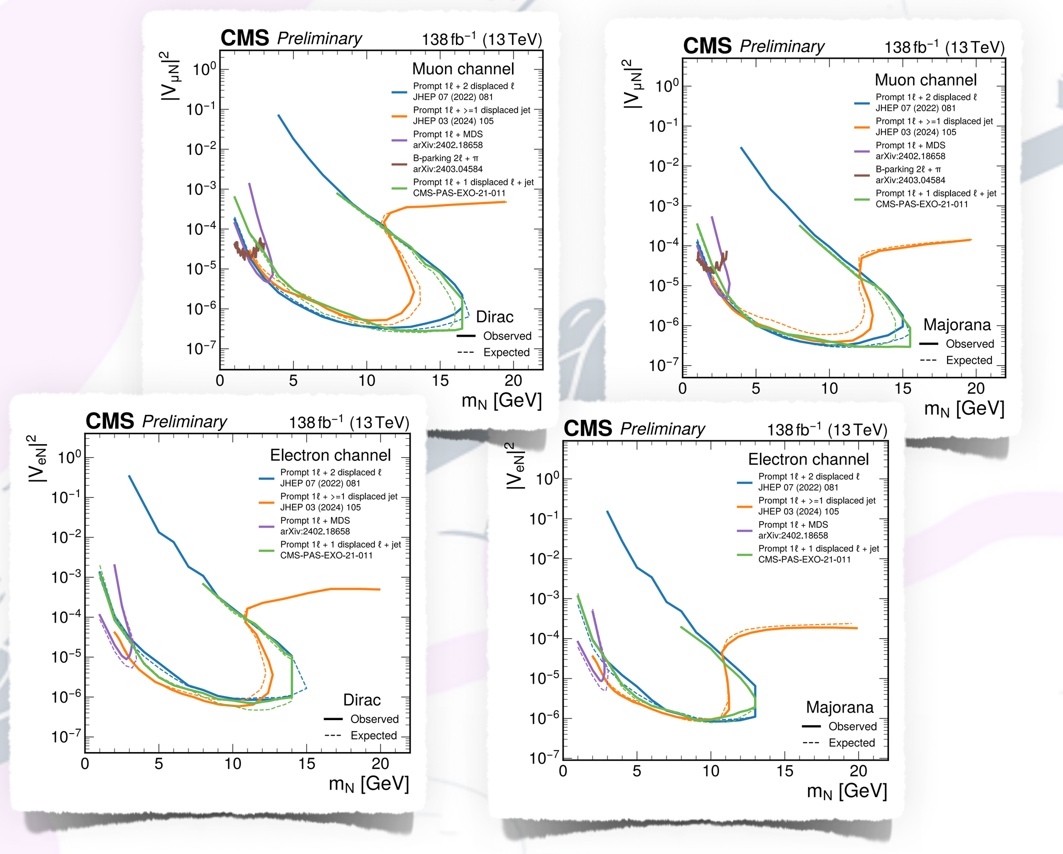
purely electrons $|V_{Ne}|^2$

mixed coupling $\frac{|V_e V_\mu|^2}{|V_e|^2 + |V_\mu|^2}$



Full Picture

- For masses above 11 GeV, the presented limits exceed all previous results in the semileptonic decay channel



Summary

- Presented the displaced HNL search with a displaced lepton-jet pair final state using Run-2 data.
- Employed machine learning (PFN) for signal-background separation.
- Improved previous CMS limits on HNL couplings in the high mass range, enhancing the current state-of-the-art exclusion limits.
- Accessed phase space that has not been reached by other experiments.
- No excess observed.

stay tuned for run 3 result!

References

[1] T. Asaka, S. Blanchet, and M. Shaposhnikov, "The νMSM, dark matter and neutrino masses", *Phys. Lett. B* **631** (2005) 151, doi:10.1016/j.physletb.2005.09.070, arXiv:hep-ph/0503065.

[2] M. Drewes, Y. Georis, and J. Klarić, "Mapping the viable parameter space for testable leptogenesis", *Phys. Rev. Lett.* **128** (2022) 051801, doi:10.1103/PhysRevLett.128.051801, arXiv:2106.16226.

[3] Search for long-lived heavy neutral leptons in proton-proton collision events with a lepton and a jet from a secondary vertex at √s=13TeV (CMS-PAS-EXO-21-011) https://cds.cern.ch/record/2892670

[4] CMS Collaboration, 'The CMS experiment at the CERN LHC', JINST 3:S08004,2008.

[5] P. Komiske, E. Metodiev, and J. Thaler, "Energy flow networks: deep sets for particle jets", *JHEP* **01** (2019) 121, doi:10.1007/JHEP01(2019)121, arXiv:1810.05165.