14th Workshop of the Long-Lived Particle Community

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

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on behalf of the CMS Collaboration

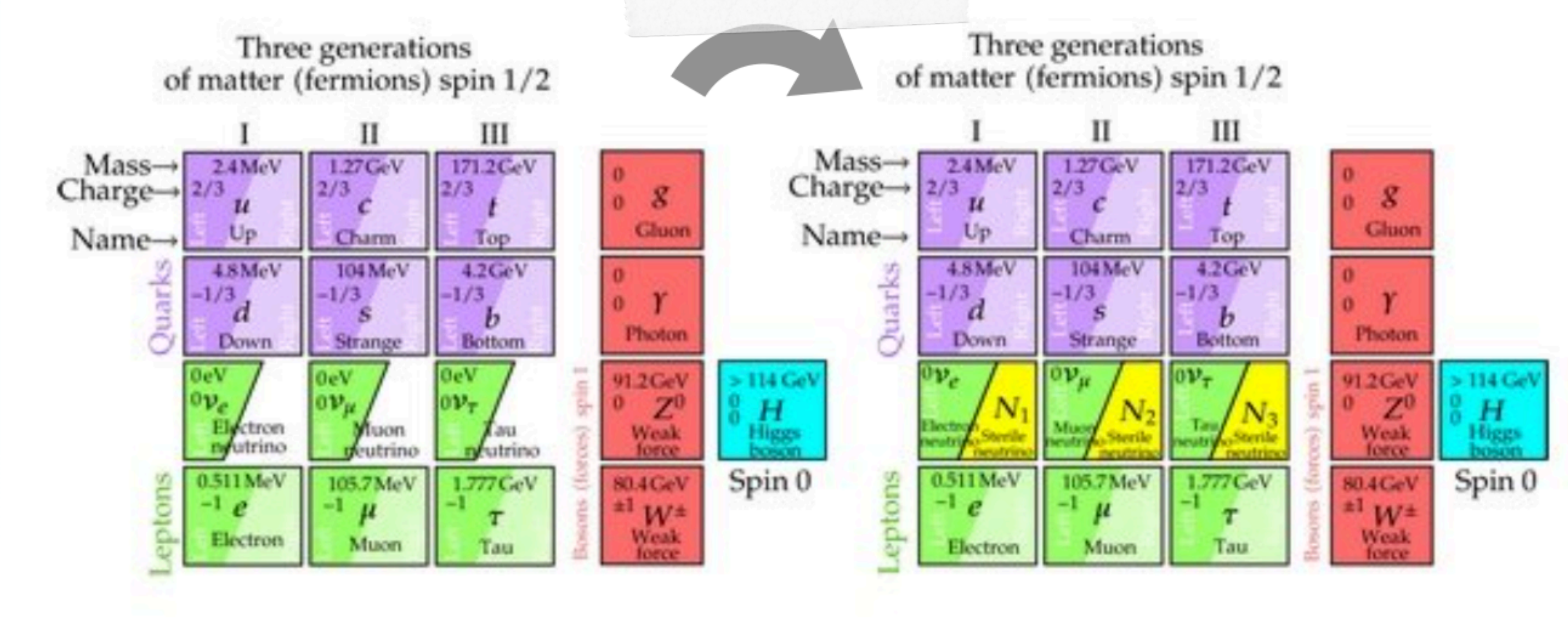
Standard Model Issues

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.



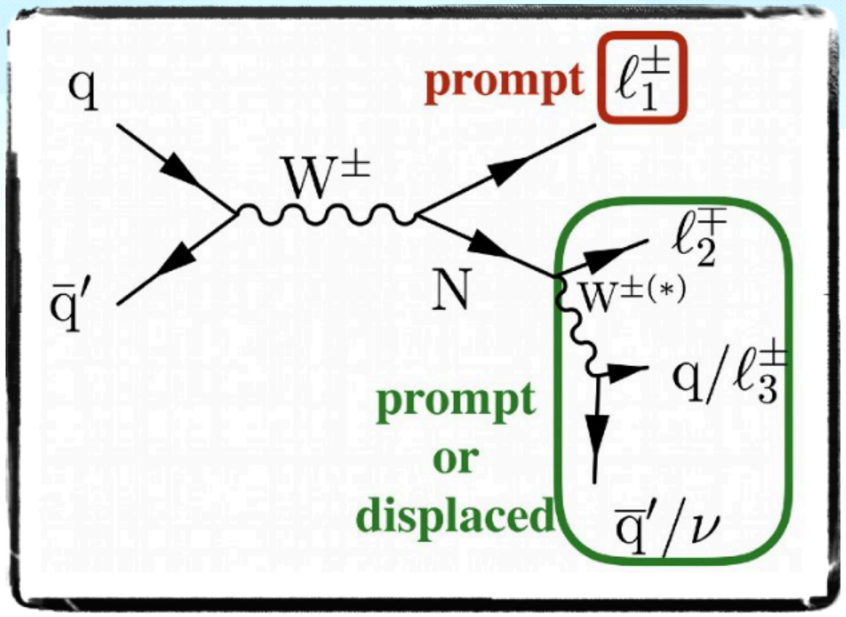
The Neutrino Minimal Standard Model (νMSM)

- N1 can be sufficiently stable to be a DM candidate, M(N1)~ a few keV
- $M(N_2) \approx M(N_3)$ ~ 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).

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 $\tau \, \alpha \, \Sigma_i |V_{Nl}|^{-2} m_N^{-5}$
- Naturally long-lived for M_N = [1, 16.5] GeV → focus on displacements within CMS tracker = fully reconstructed displaced lepton and tracks
- Channel : $W^{\pm} \rightarrow L^{\pm} + N, N \rightarrow L^{\pm} + q\bar{q}$

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



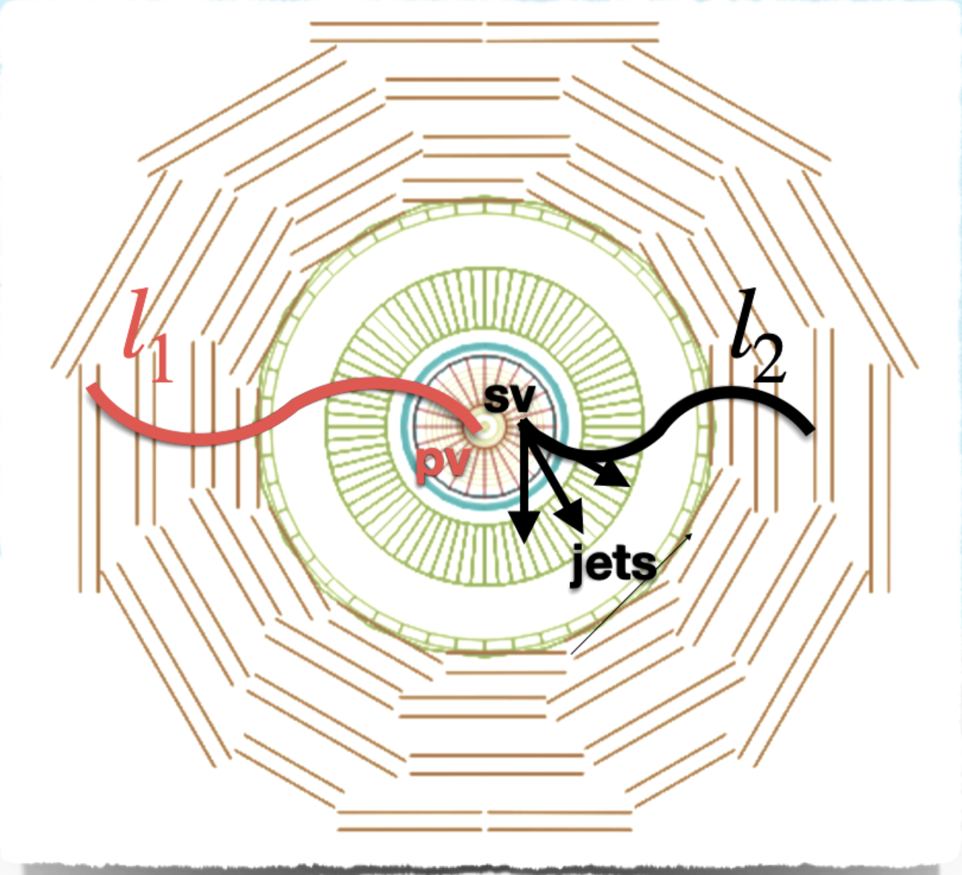
HNLs in the CMS Detector

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 ($\Delta R < 0.7$ with l_2)

Analysis Strategy

- ☑ Trigger on prompt lepton
- ☑ Reconstruct Secondary Vertex from displaced l2 and displaced jet with tuned Inclusive Vertex Finder
- ☑ 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

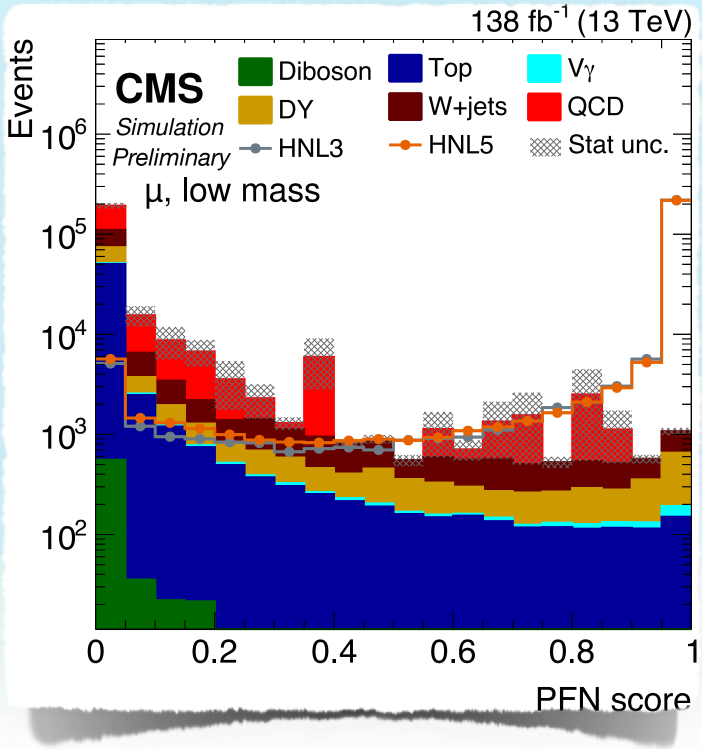
Particle Flow Network (PFN)

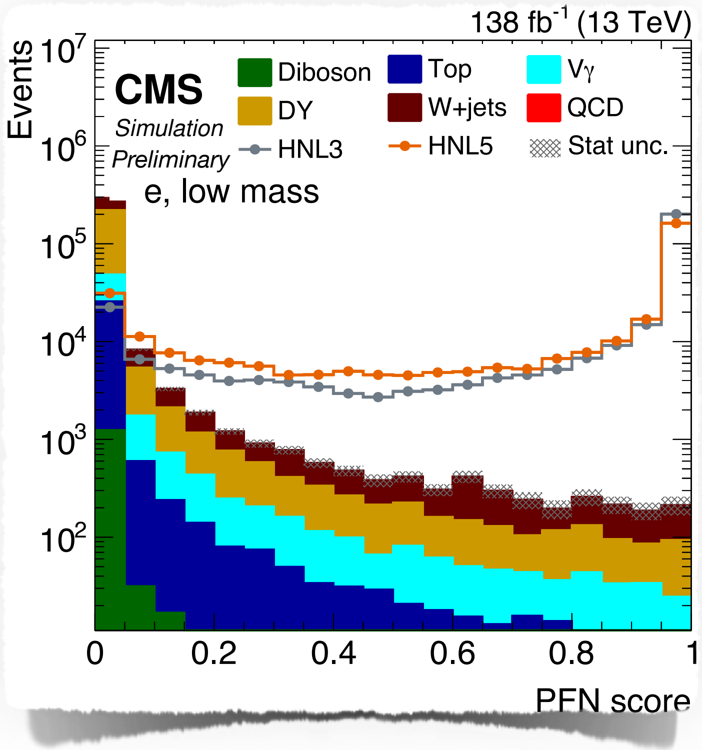
Machine Learning Model

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



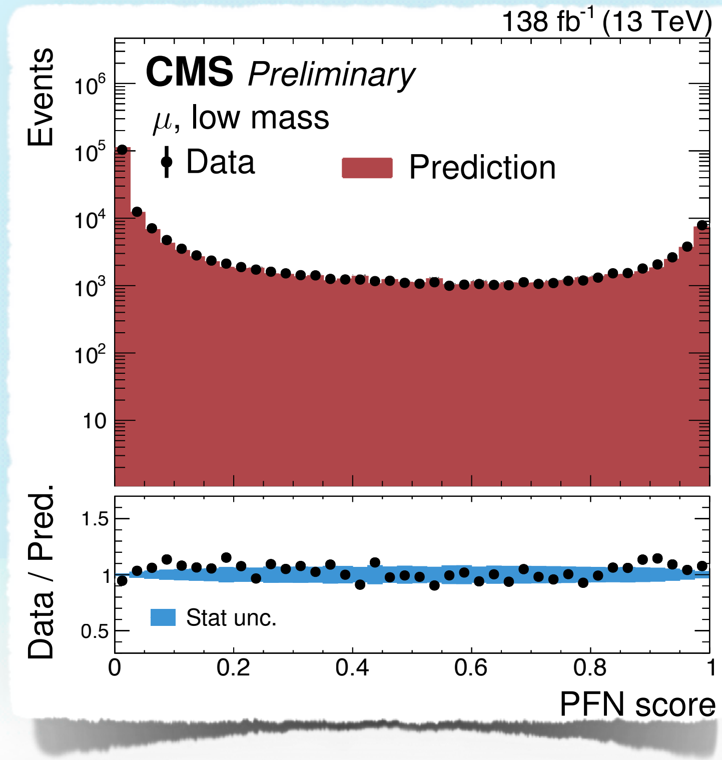


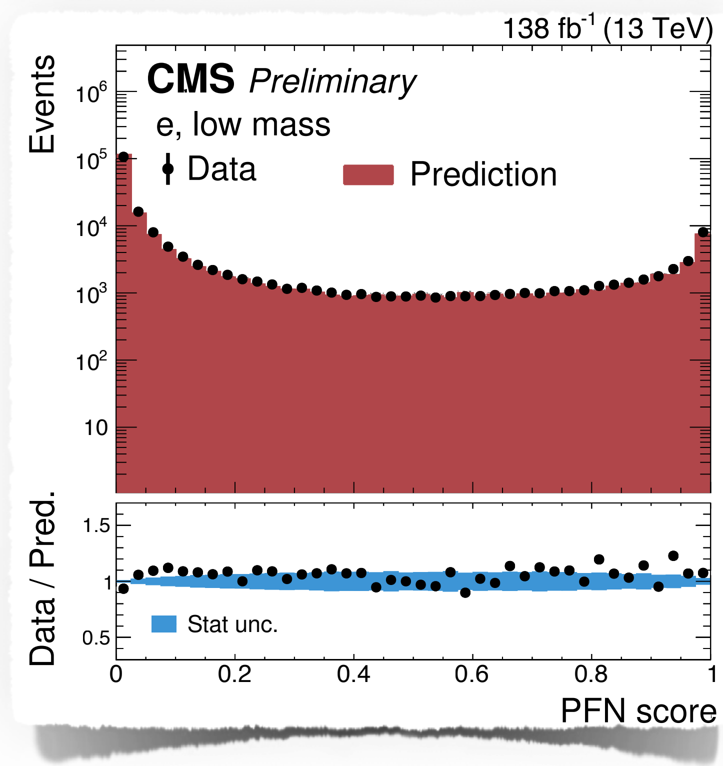
PFN Validation

- 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

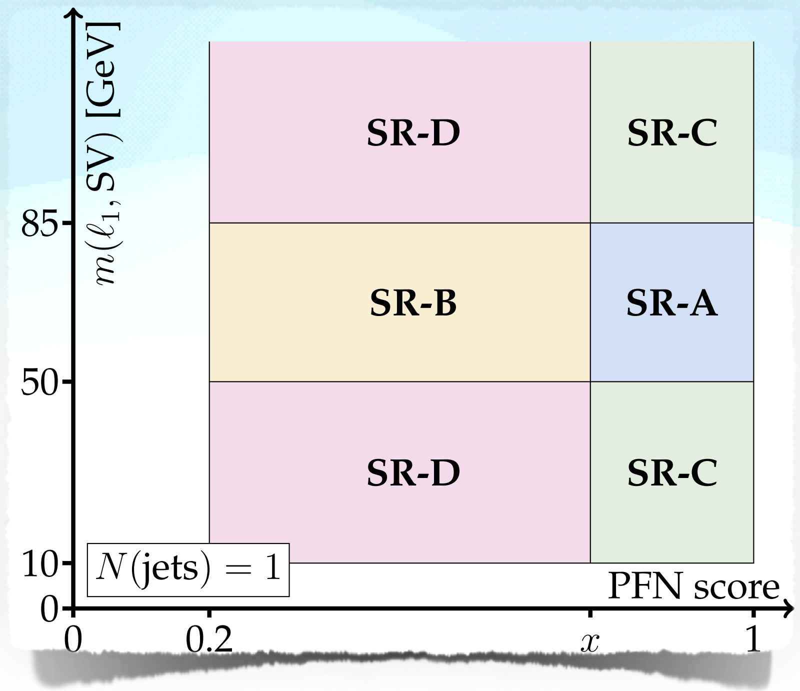




Background Estimation

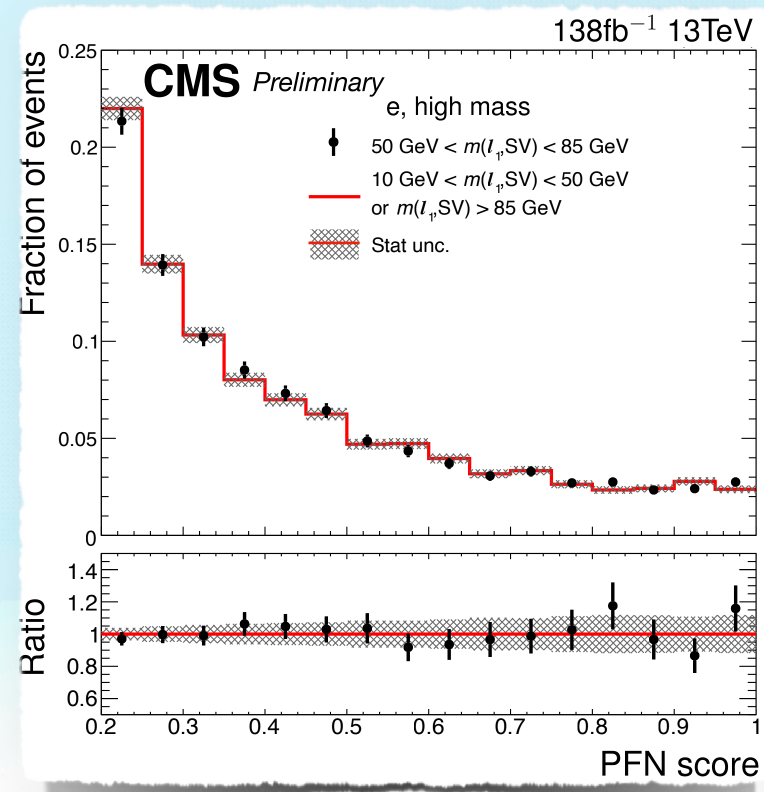
- Use PFN output and m(l1,SV) as statistical independent variables
- Correlation factor generally < 20%
- Bin in signal region using M_{SV} and Lxy
- $$A_{bkg}^{pred,i} = B_{bkg}^{i} \times \frac{C_{bkg}^{i}}{D_{bkg}^{i}}$$ for each bin i separately
- Define several control regions using data and MC

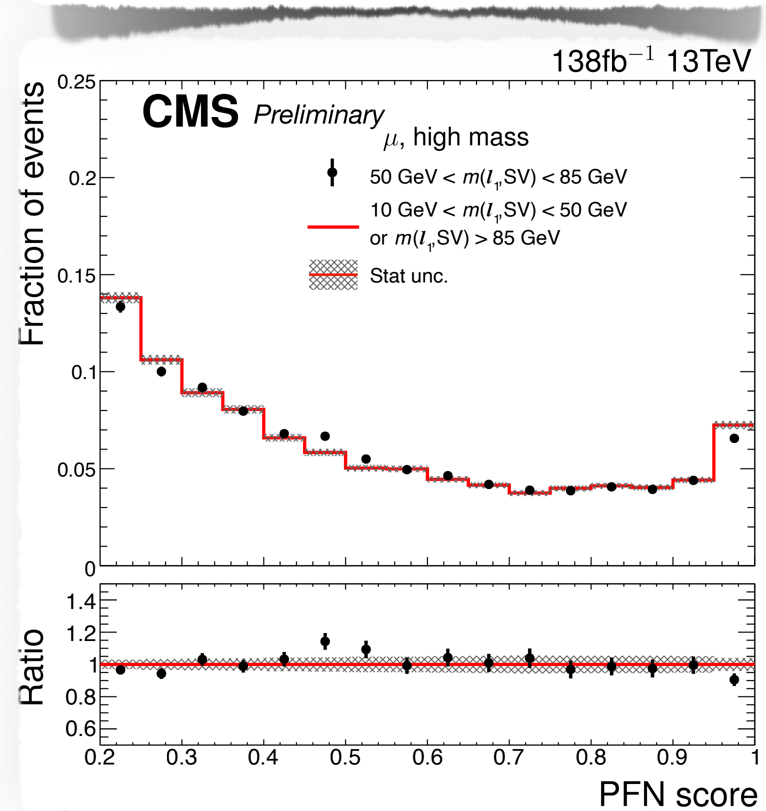
  → generally good closure
  → use CR to estimate systematic uncertainty for background N(jets) ≥ 1



PFN and m(l_1,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





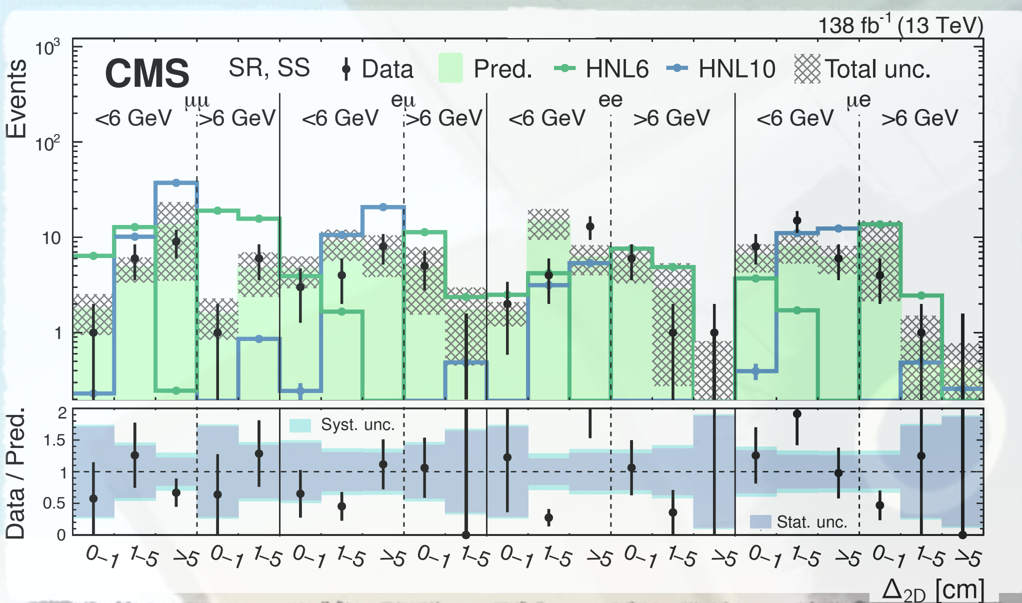
Systematic uncertainties

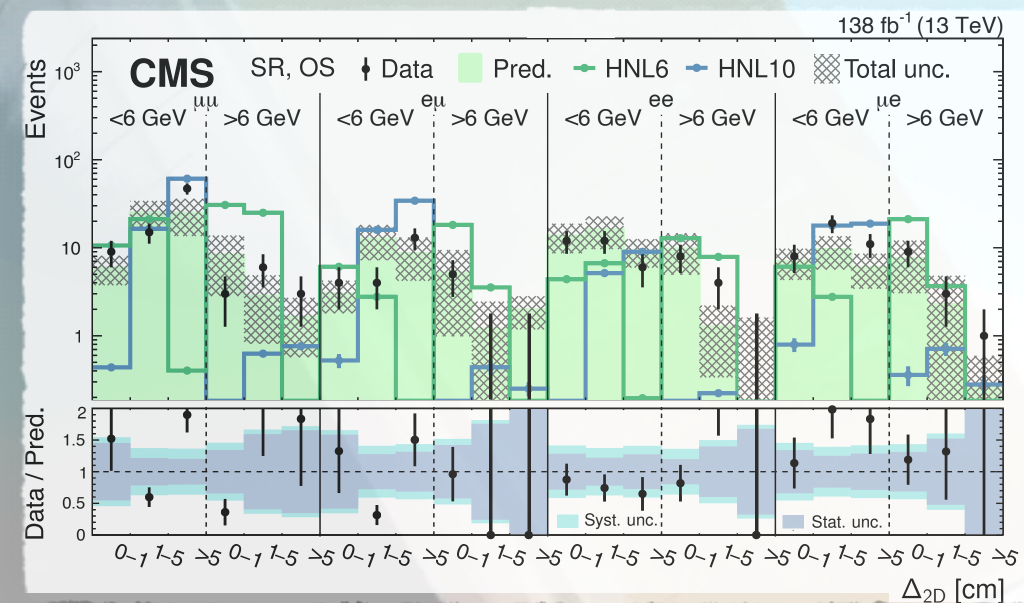
Source	Type	Uncertainty [%]
	Signal yield	
NNLO *K*-factor	Normalization	4
Luminosity	Normalization	1.6
Pileup modeling	Shape	4.6
e (μ) trigger efficiency	Shape	1 (<1)
Prompt e (μ) selection efficiency	Shape	2–4 (1–3)
Nonprompt e (μ) selection efficiency	Shape	1–20 (<1)
Tracking efficiency	Shape	7.3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

Signal Region Observation

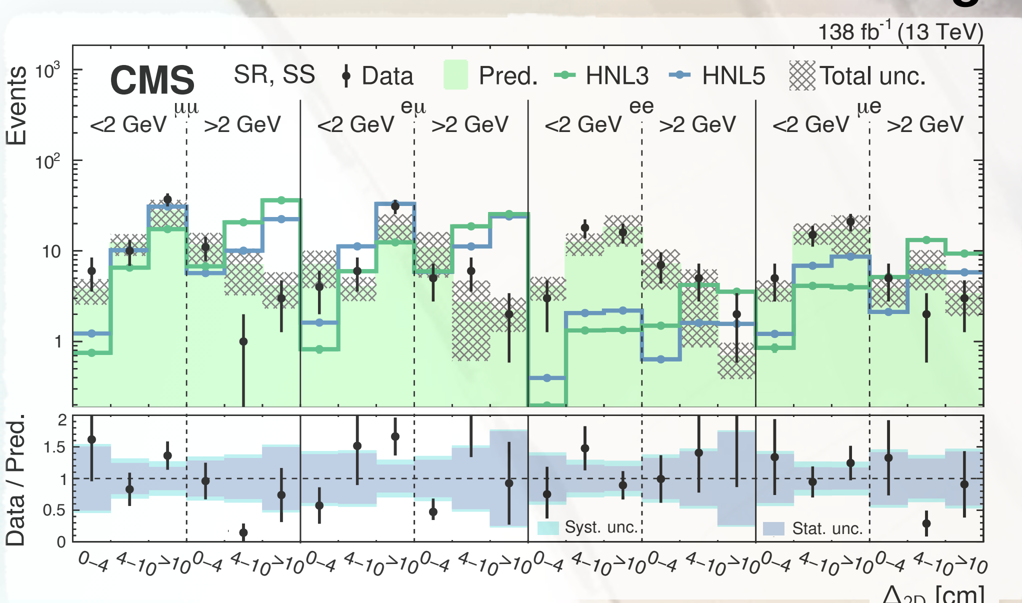
- Signal region binned in m_{SV} and Δ_{2D} displacement
- Observe good agreement with background prediction (no significant excess)

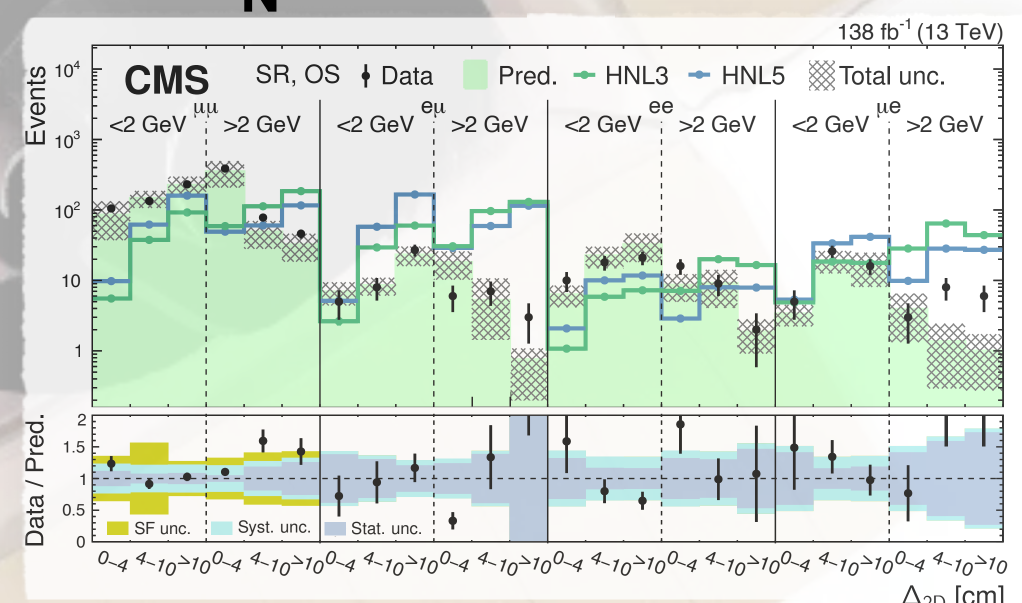
high mass PFN signal region used for $m_N \geq 6$ GeV





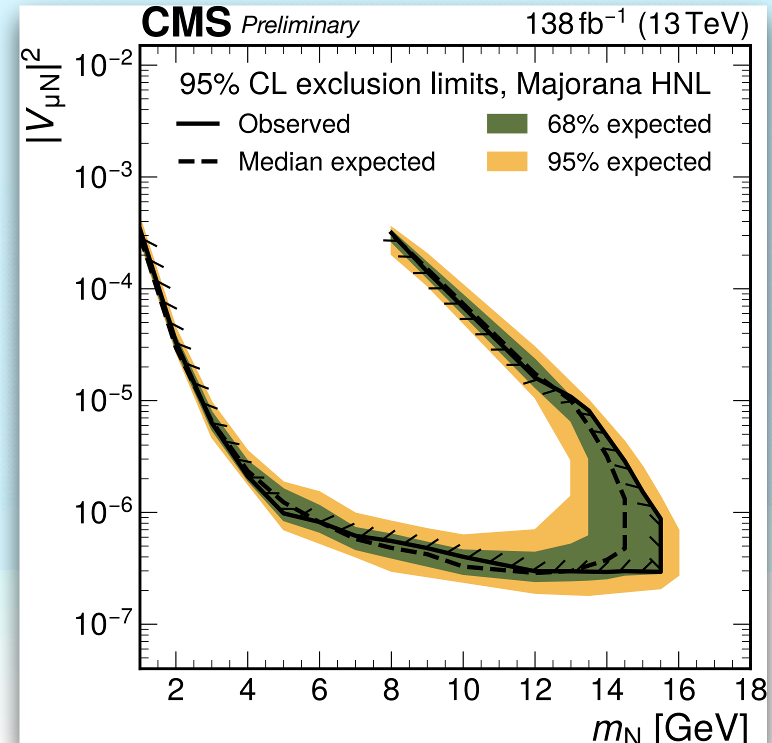
low mass PFN signal region used for $m_N < 6$ GeV





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

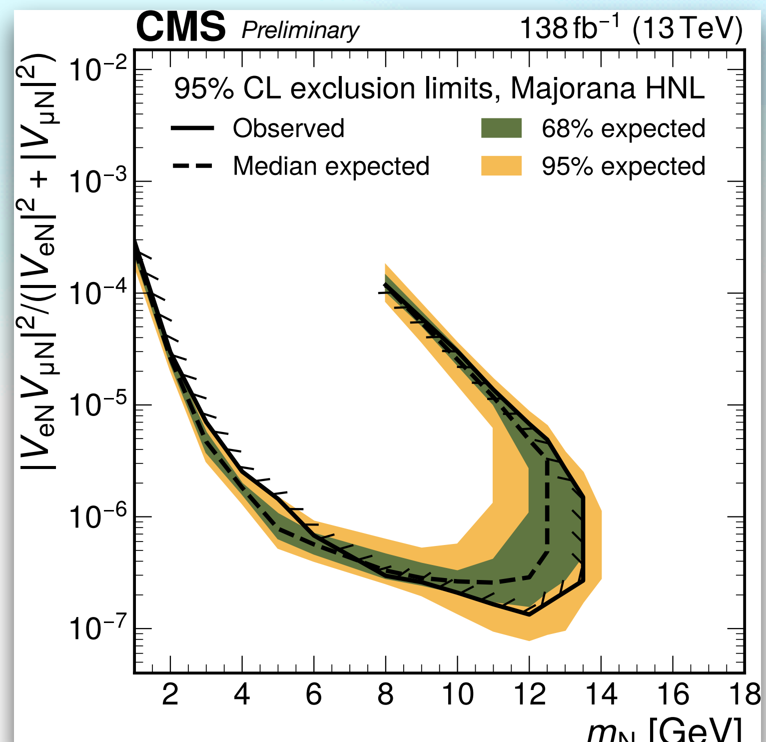


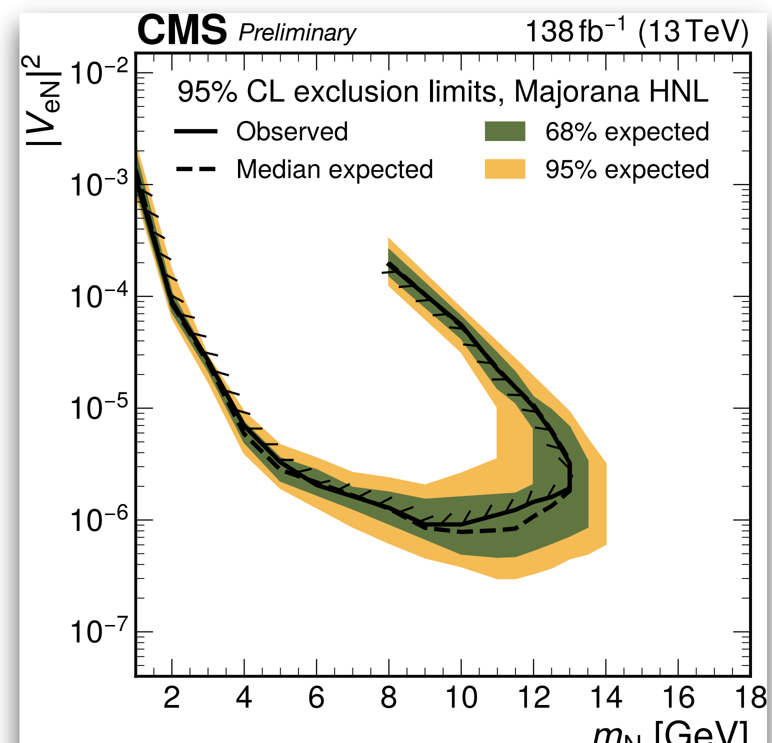
Upper limits set on N coupling strengths

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

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

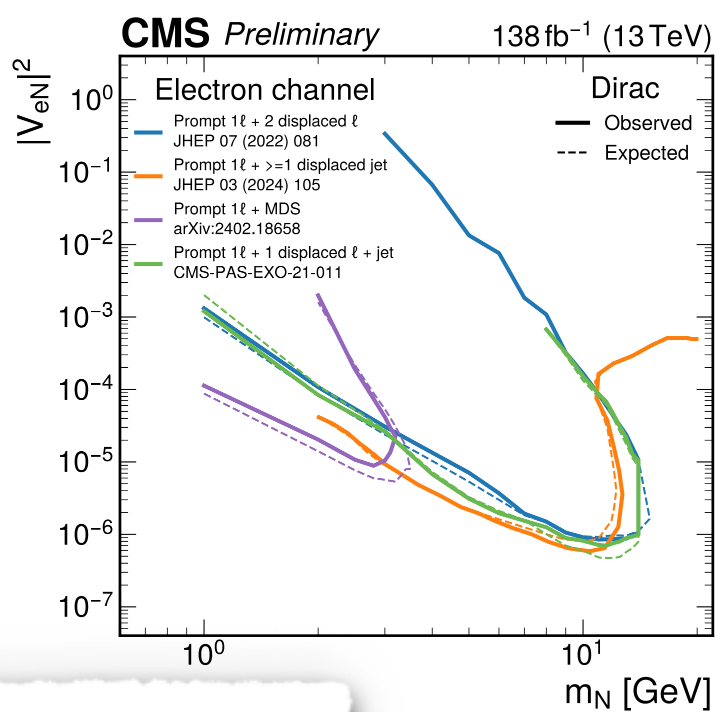
mixed coupling $\dfrac{|V_\mu V_e|^2}{|V_e|^2 + |V_\mu|^2}$

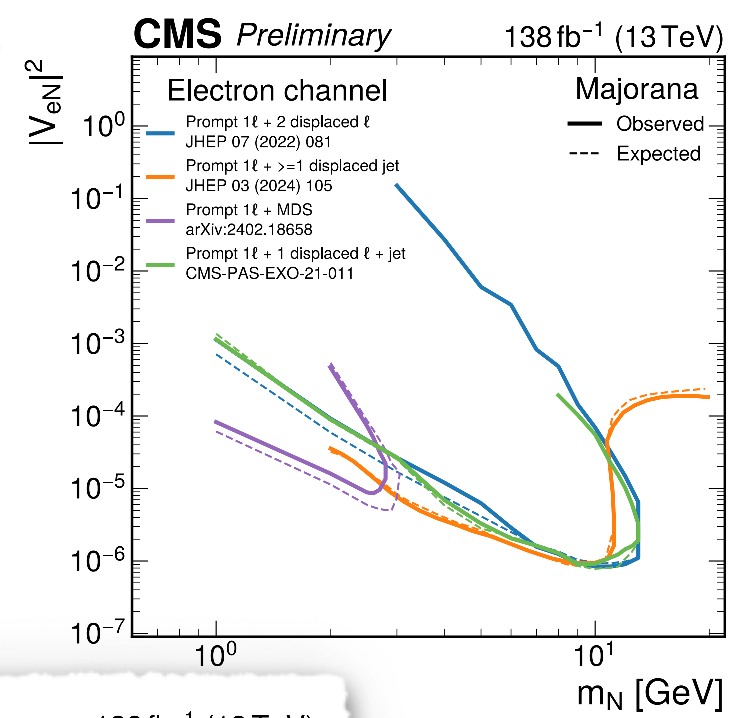


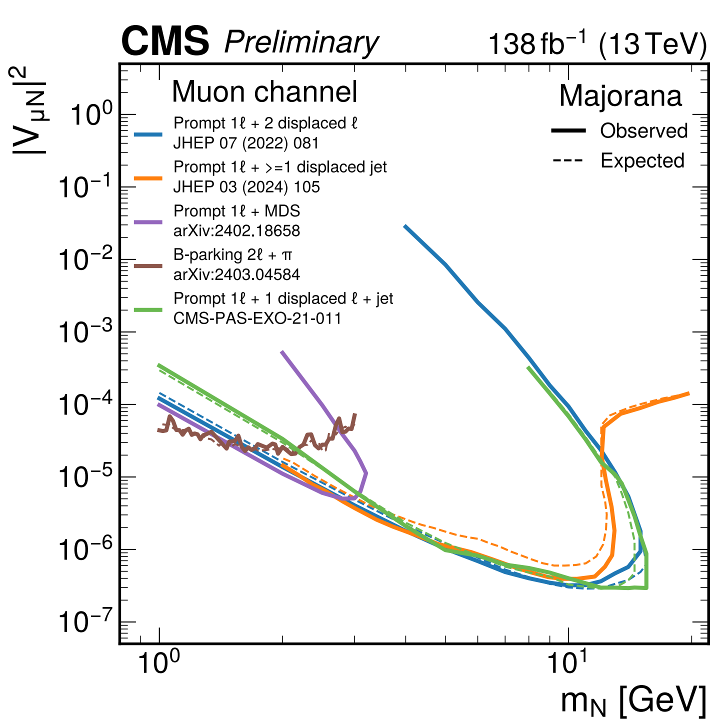


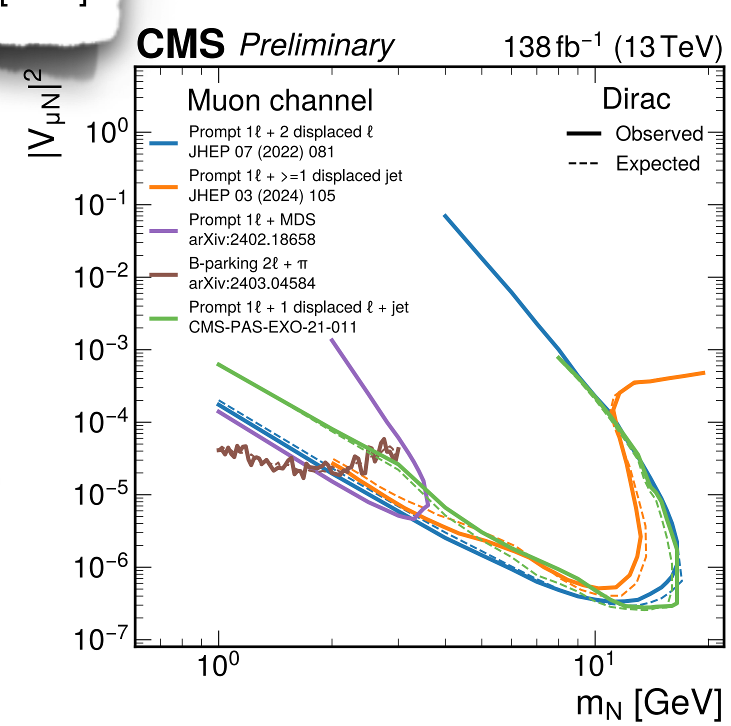
Full Picture

- 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!

Thanks