Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

Searching for Heavy Neutral Leptons with muon detectors in the CMS experiment

[Martin Kwok](#) (Fermilab)

[LLP2024 - Tokyo](#)

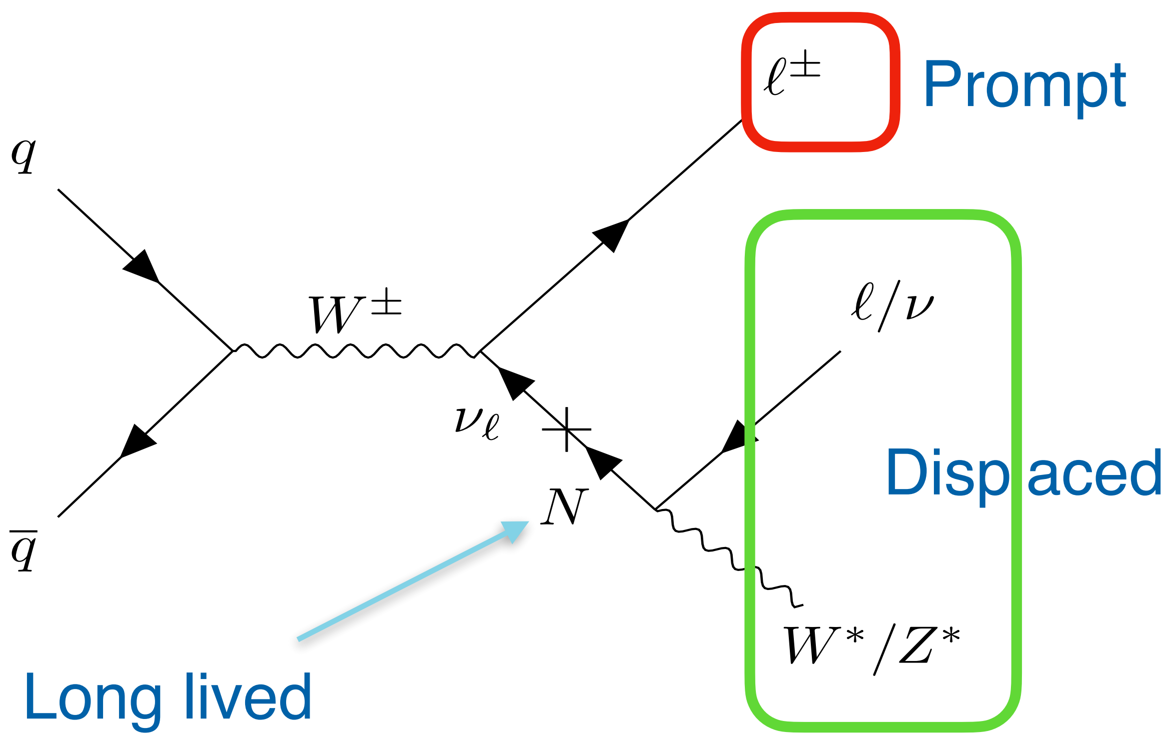
4 July, 2024

Search for Heavy Neutral Lepton

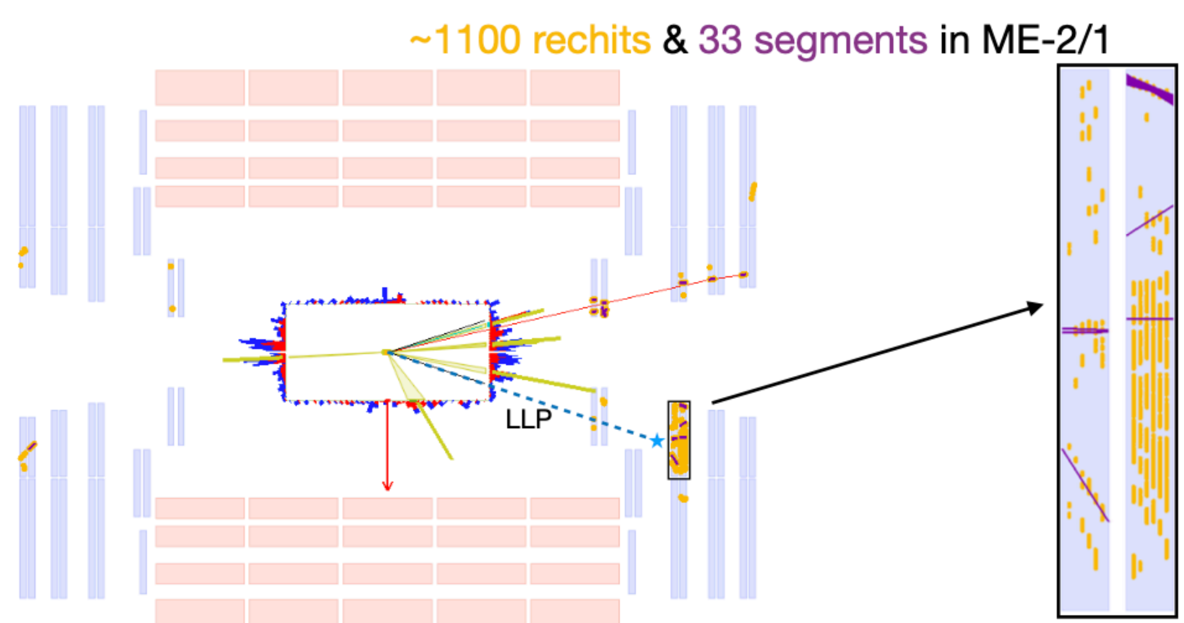
- Non-zero SM Neutrino mass needs an explanation!
  - HNL enables see-saw mechanism
  - Connected to other unsolved problems (Baryon asymmetry, DM candidate, Anomalous g-2 [1],[2],[3],[4],[5])

- HNL that decays in the CMS muon system can lead to hadronic shower
  - Ideal to probe **lower mass (<10GeV) / longer lifetime O(1m)** parameter space
  - Consider a single HNL Type-1 See-saw model

HNL

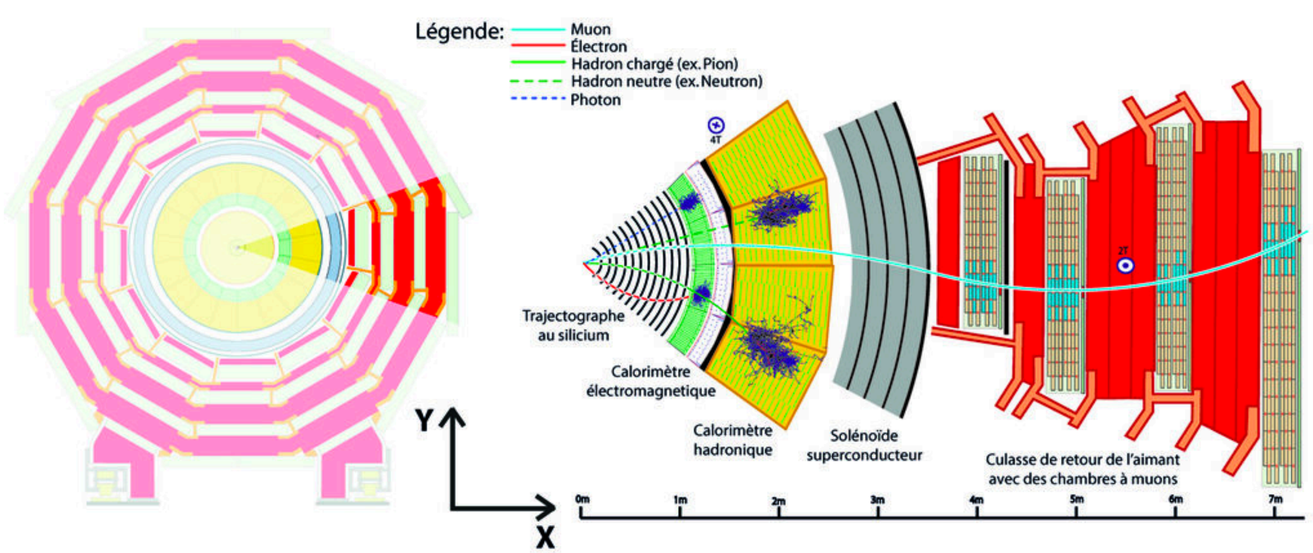


Muon Detector Shower(MDS)

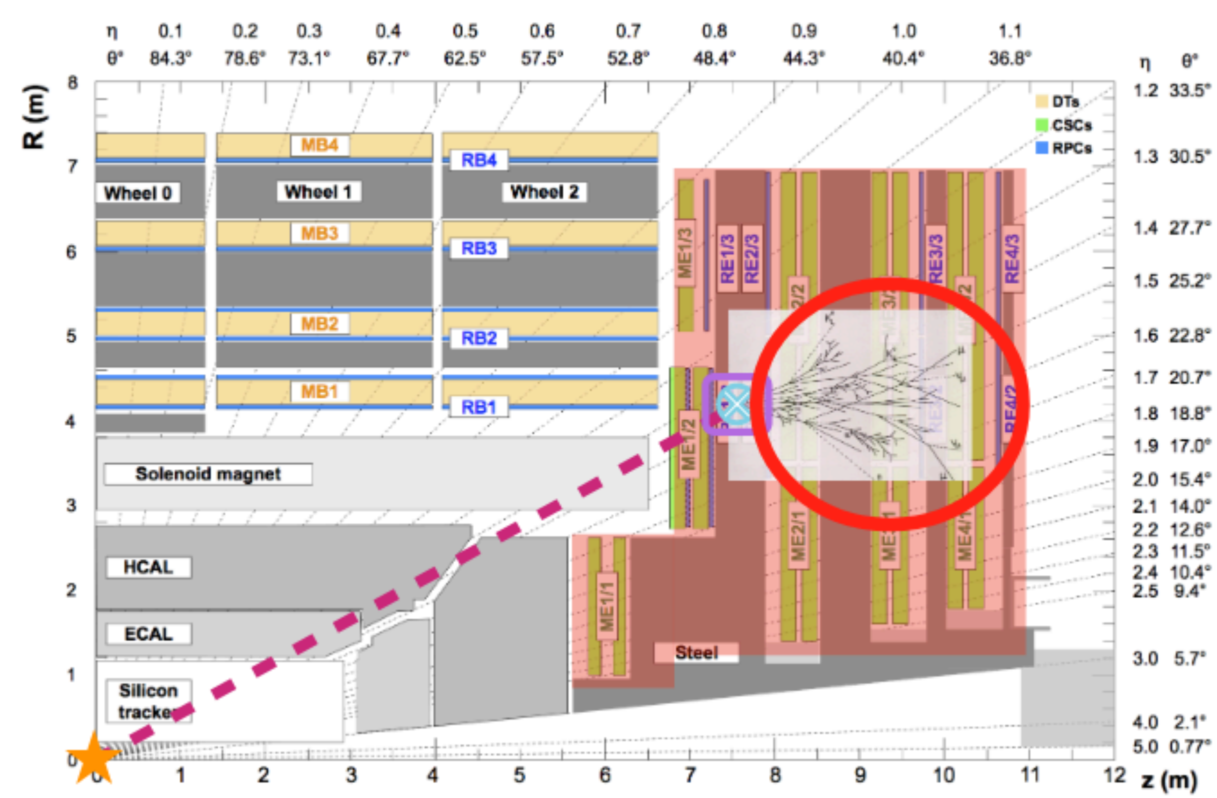


Muon Detector Shower (MDS)

- Teaching a particle detector new tricks
- LLP decays hadronically in the muon system:
  Shower is detected as multiple hits in either the CSC or DT chambers
- Steel between muon stations can act as absorbers in a sampling calorimeter
  - Shielding of 12-27 interaction length (Background suppression factor ~10^7)



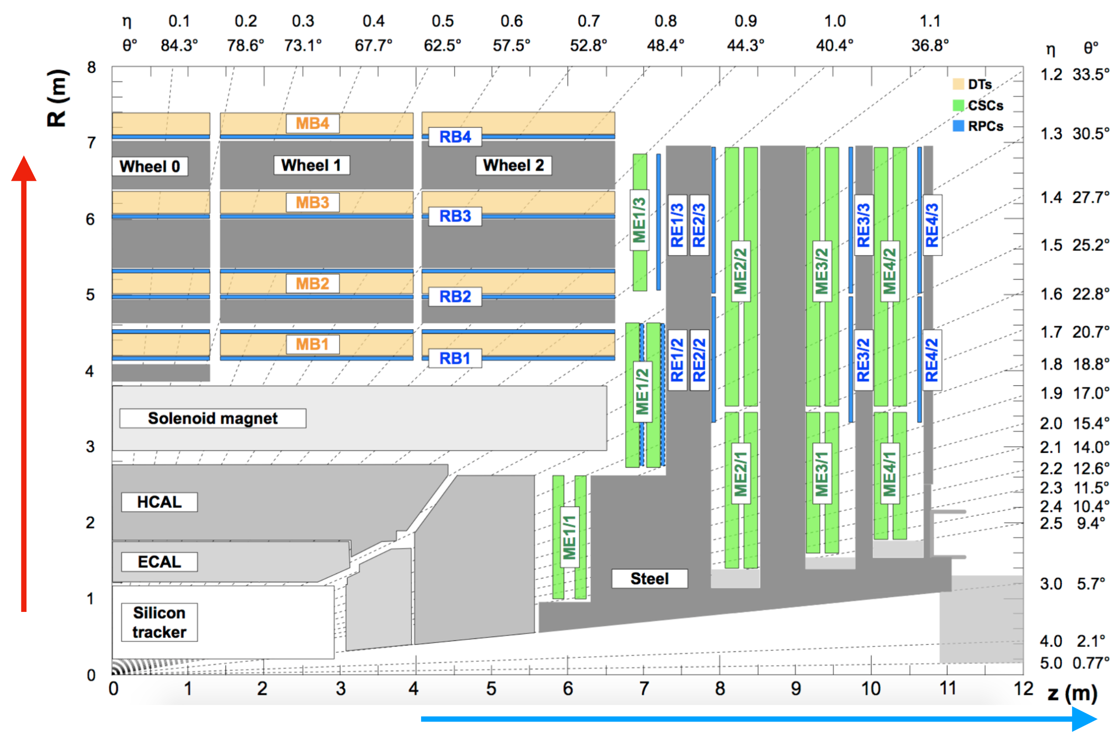
SM particles seen at CMS



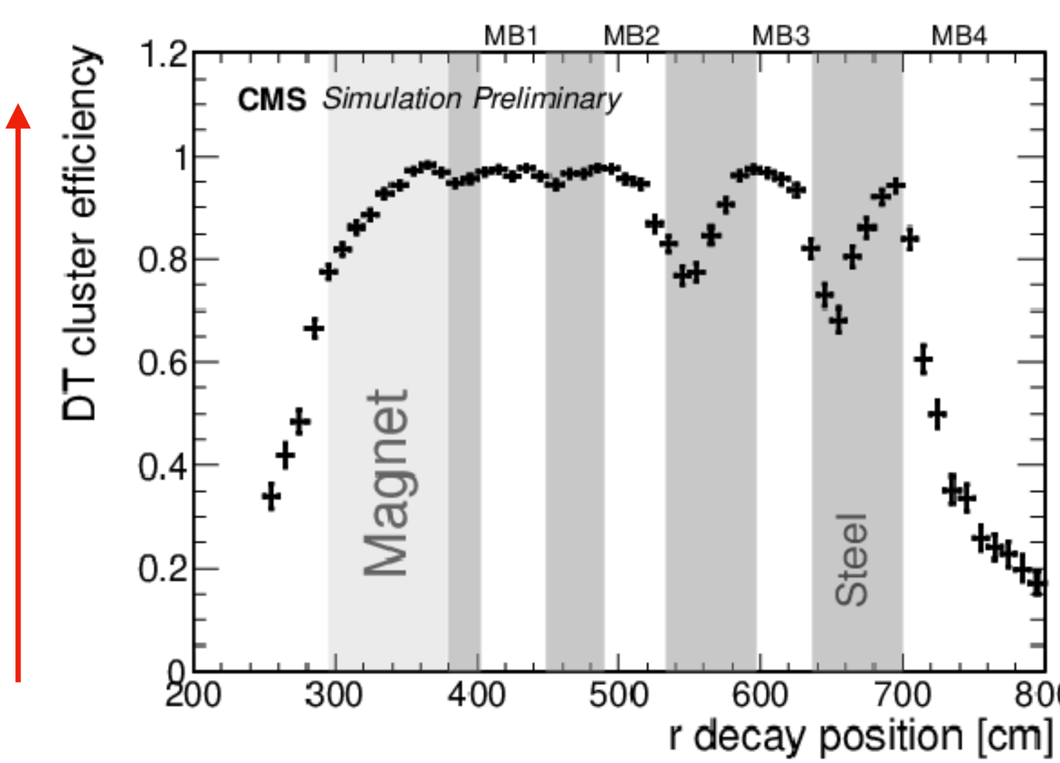
LLP as Muon Detector Shower

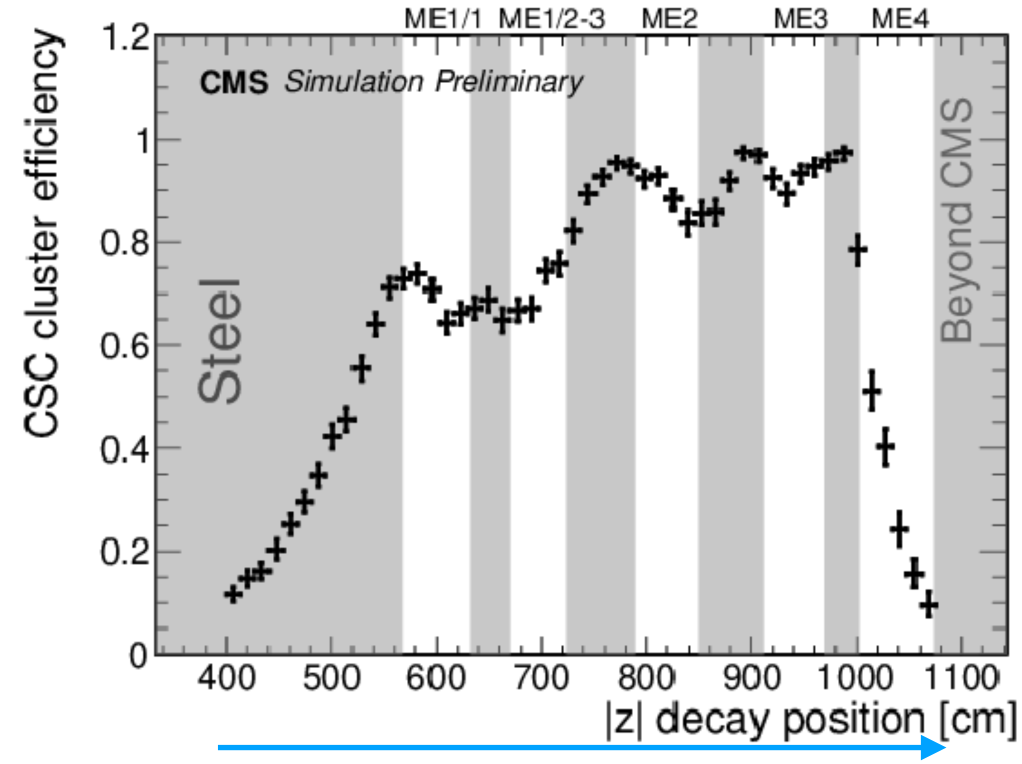
Fermilab

Muon Detector Shower (MDS)



- Sensitive to LLP with longer $c\tau$ ~O(1-10m)
- Good efficiency in both barrel and end-cap





$H \rightarrow S \rightarrow d\bar{d}$ **decay,** $c\tau = 1 - 10\ m$

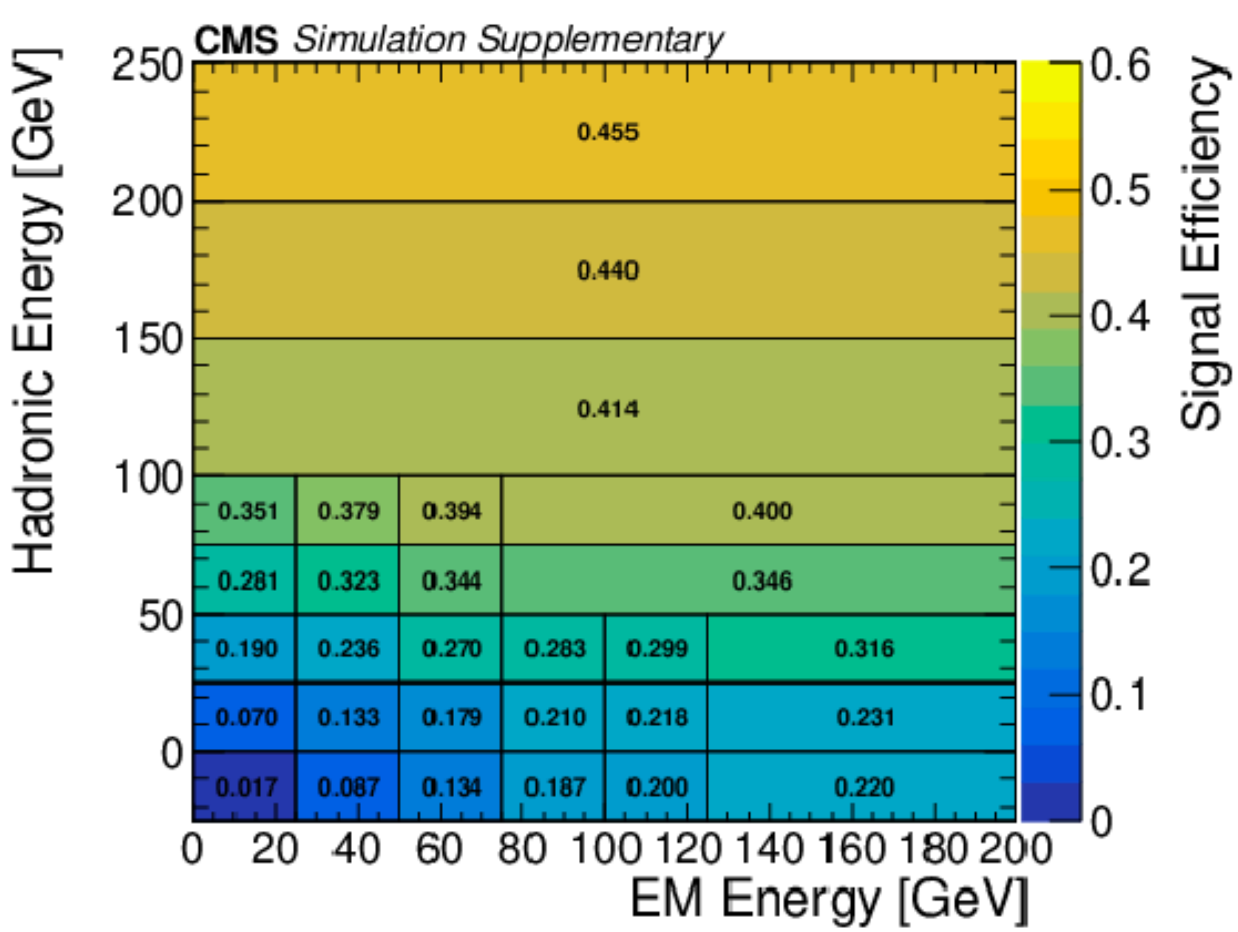
CMS-EXO-21-008

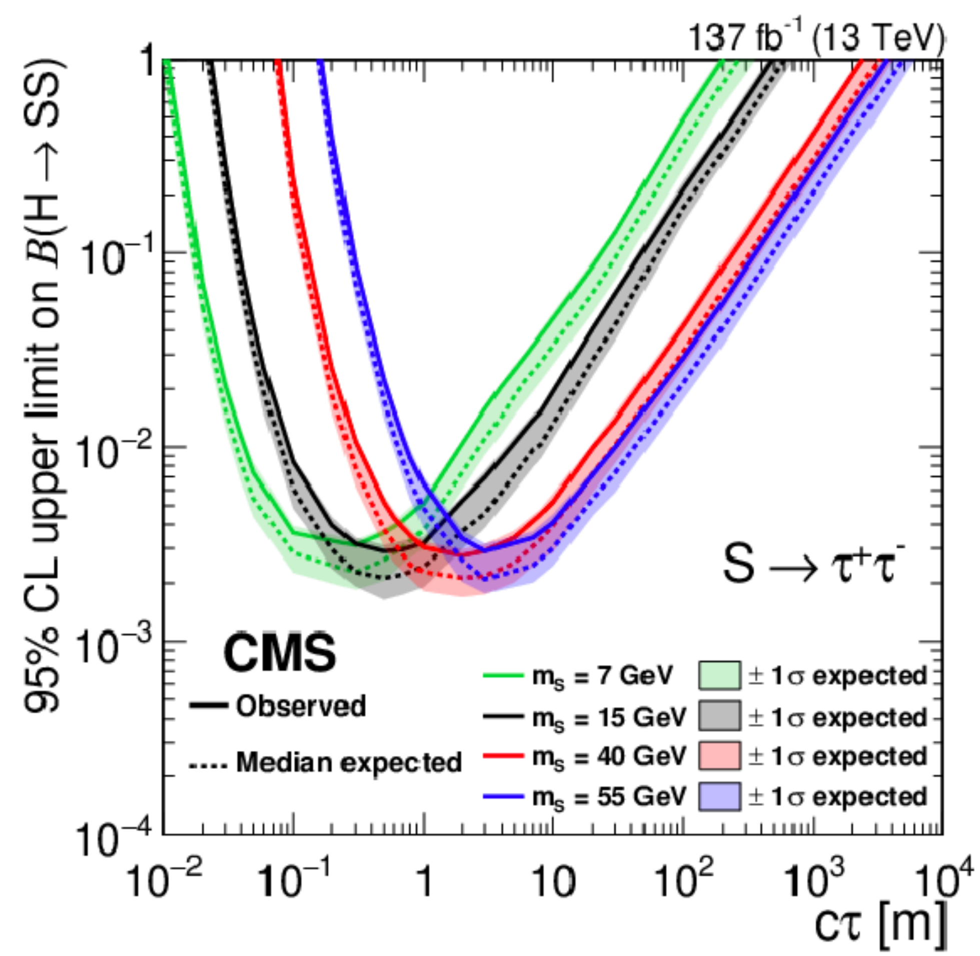
Fermilab

Muon Detector Shower (MDS)

EXO-20-015

- Cluster efficiency can be well parametrized by the hadronic energy and EM energy of the LLP
  - Sensitive to “anything” (quarks, electrons, photons, taus) except muons!
- Independent of LLP mass!





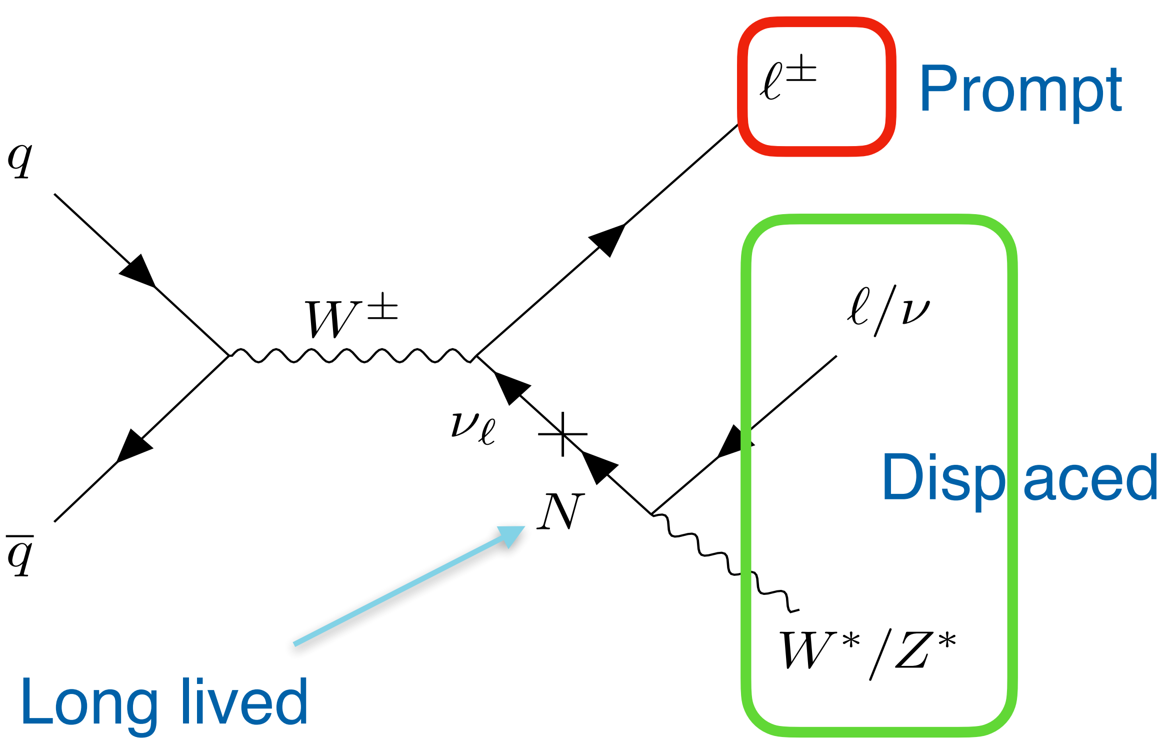
Fermilab

Searching long-lived HNL with MDS

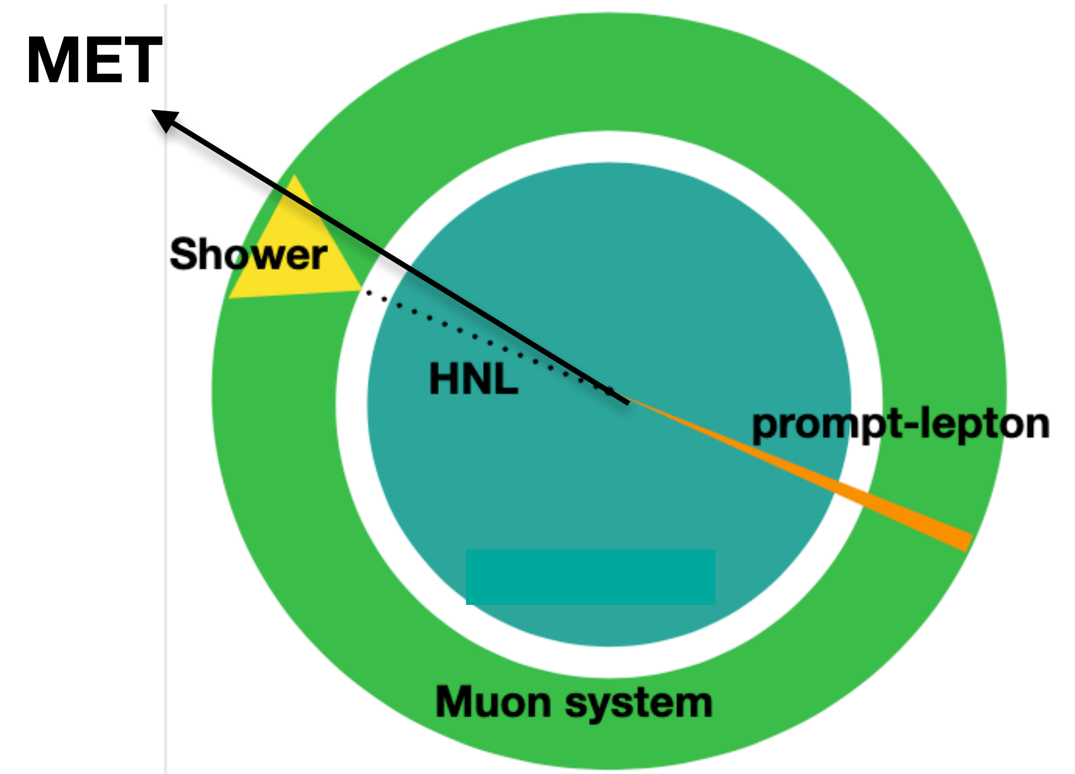
Analysis Strategy

- Simple event topology:
  - Prompt lepton + single MDS cluster

- Consider all decay modes of the HNL
  - No penalty of signals due to W/Z branching ratios



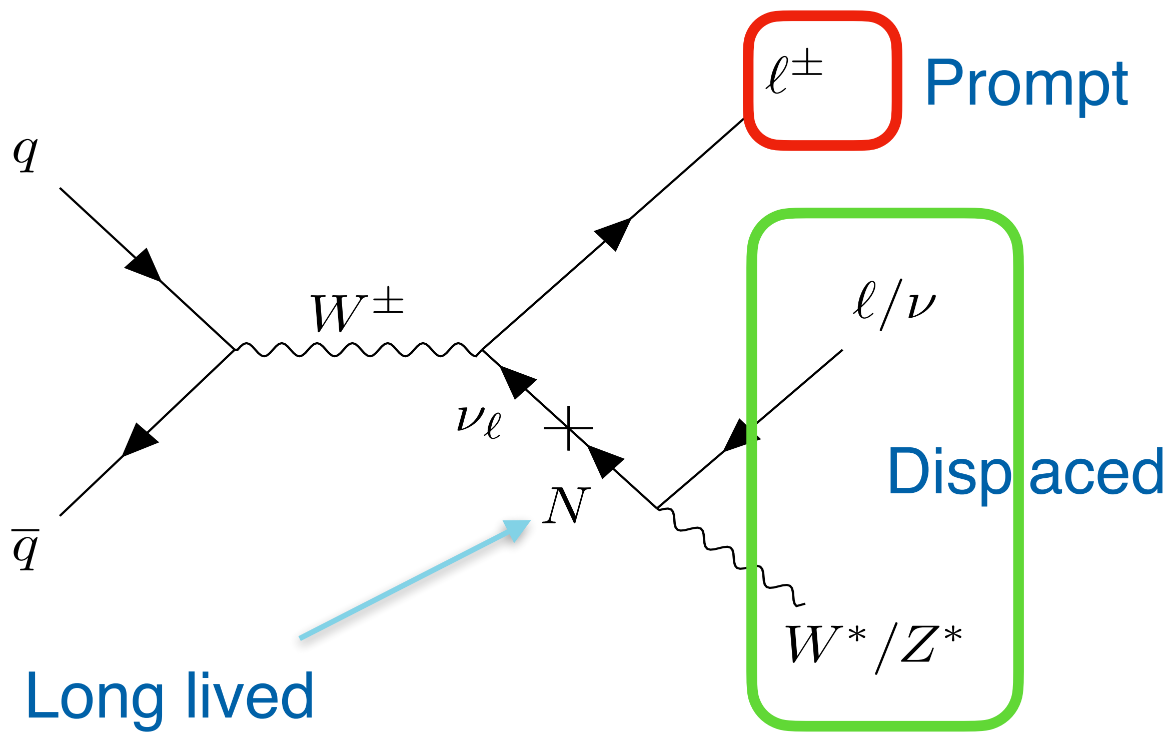
HNL signals



Fermilab

Analysis Strategy

- Simple event topology:
  - Prompt lepton + single MDS cluster
- Consider all decay modes of the HNL
  - No penalty of signals due to W/Z branching ratios



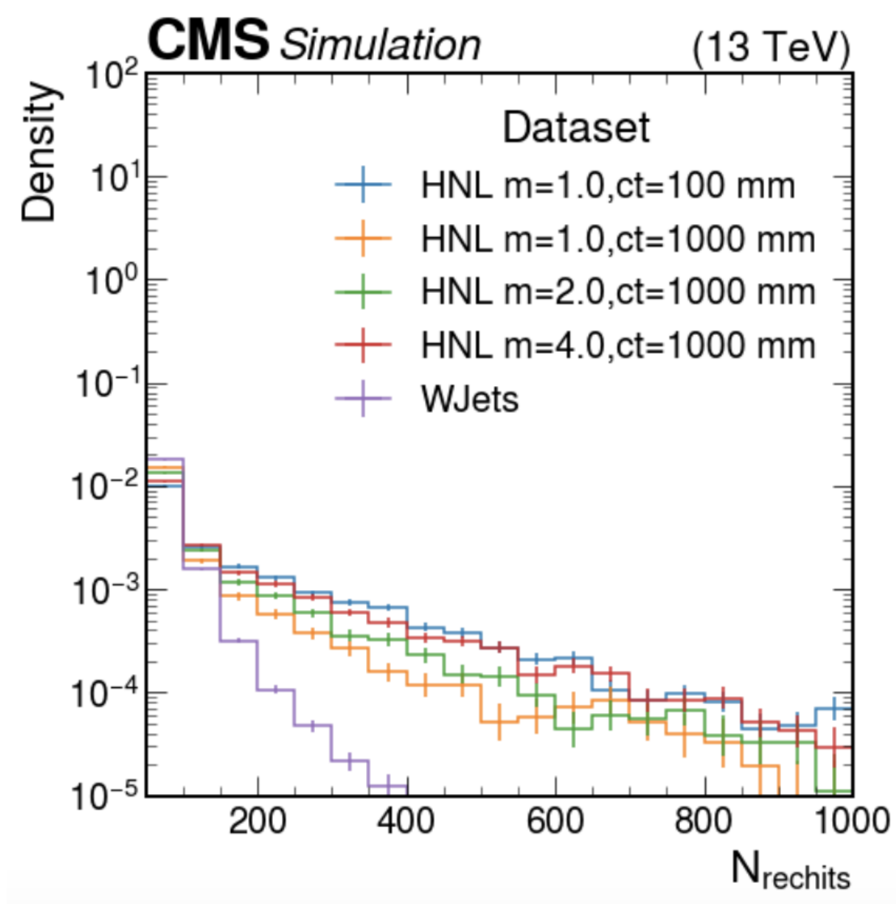
Lepton side

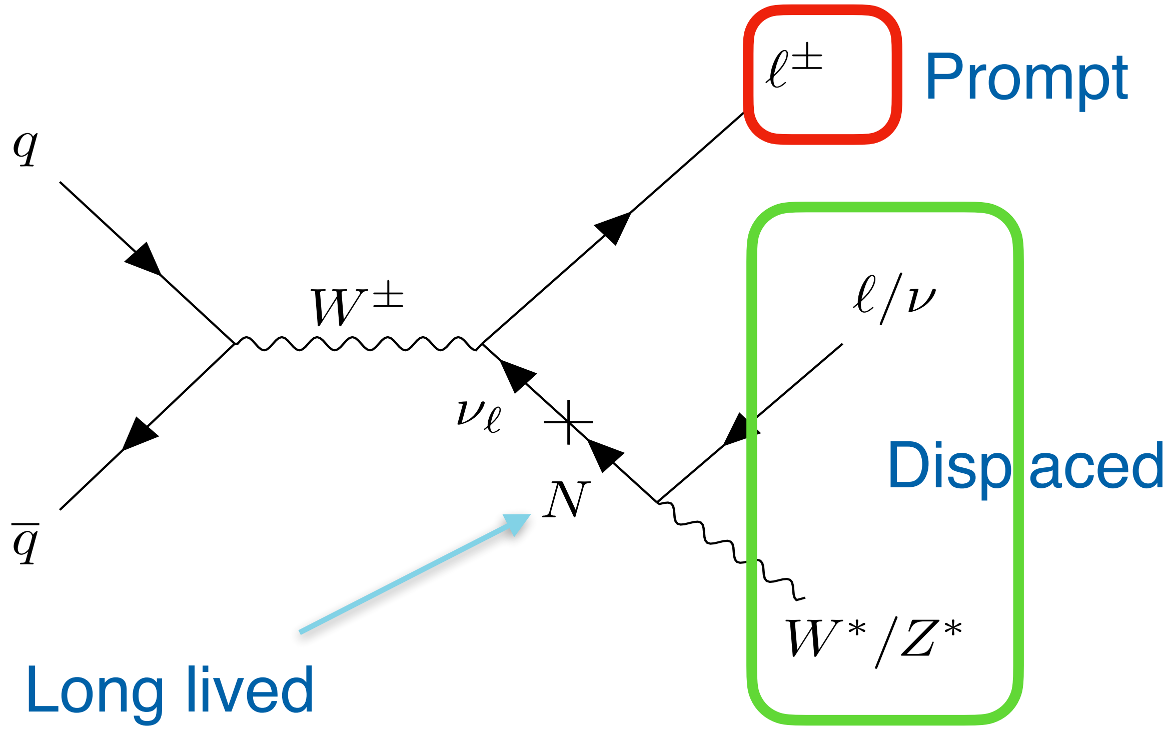
- Efficient single electron/muon Trigger!
  - Muon: pT> 25(28) GeV
  - Electron: pT>30(35) GeV
  - MET > 30 GeV

Analysis Strategy

- Simple event topology:
  - Prompt lepton + single MDS cluster

- Consider all decay modes of the HNL
  - No penalty of signals due to W/Z branching ratios





Cluster side

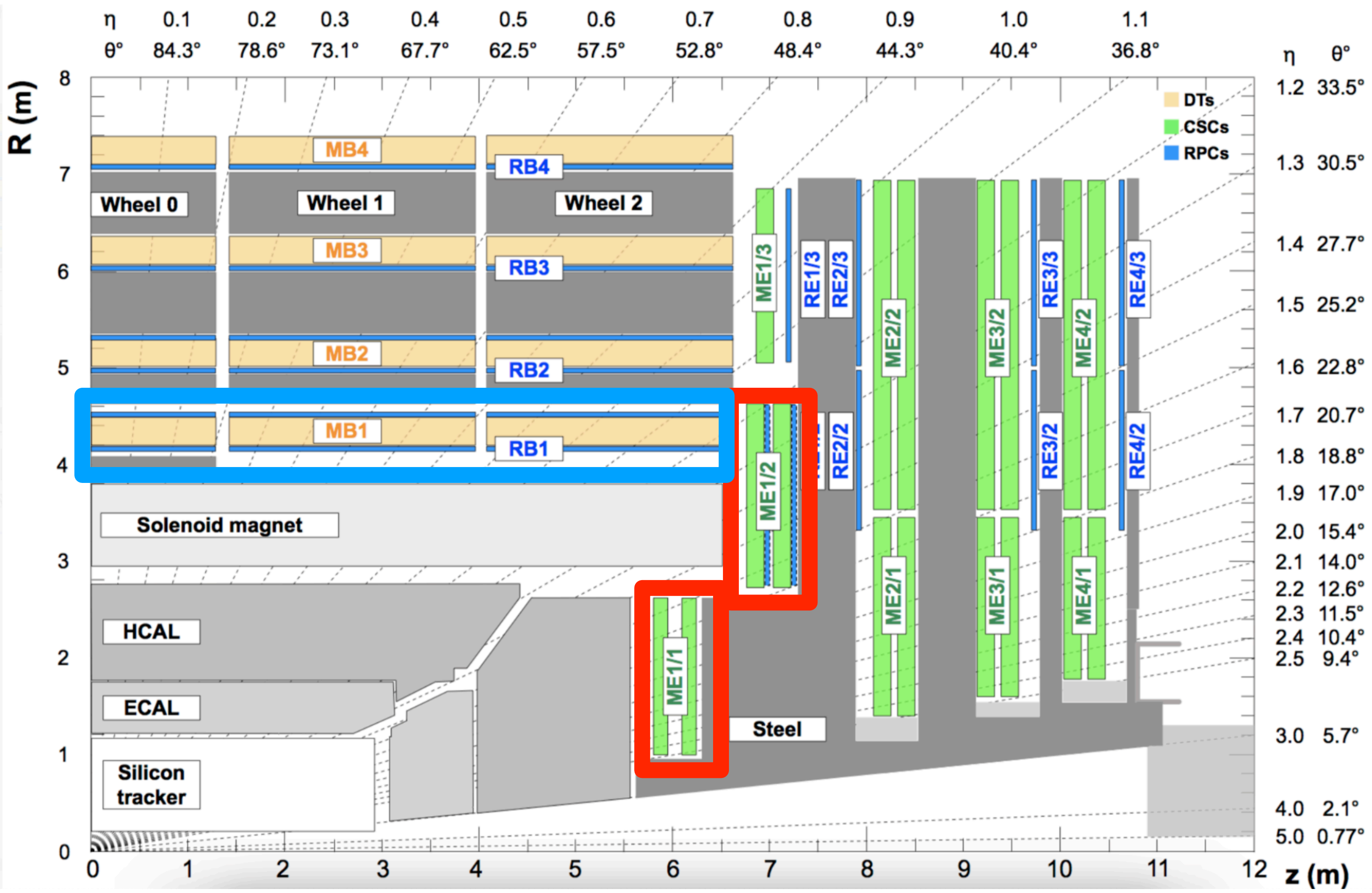
- Improve S/B ratio
- Veto SM objects that can make cluster
- Reject OOT clusters
- Cluster size (N_{hit}) as main discrimination

Cluster selection

- Reject punchthrough jets:
  - Veto clusters matched to jets (ΔR < 0.4)
- Reject muon bremsstrahlung shower:
  - Veto clusters matched to muons (ΔR < 0.8)

- CSC:
  - Veto clusters with RecHits in ME-1/1, ME-1/2
  - Veto clusters that are matched to RE1/2 hits
  - Veto clusters that are matched to MB1segments or RB1 hits
  - $-5\ \mathrm{ns} < t_{cls} < 12\ \mathrm{ns}$

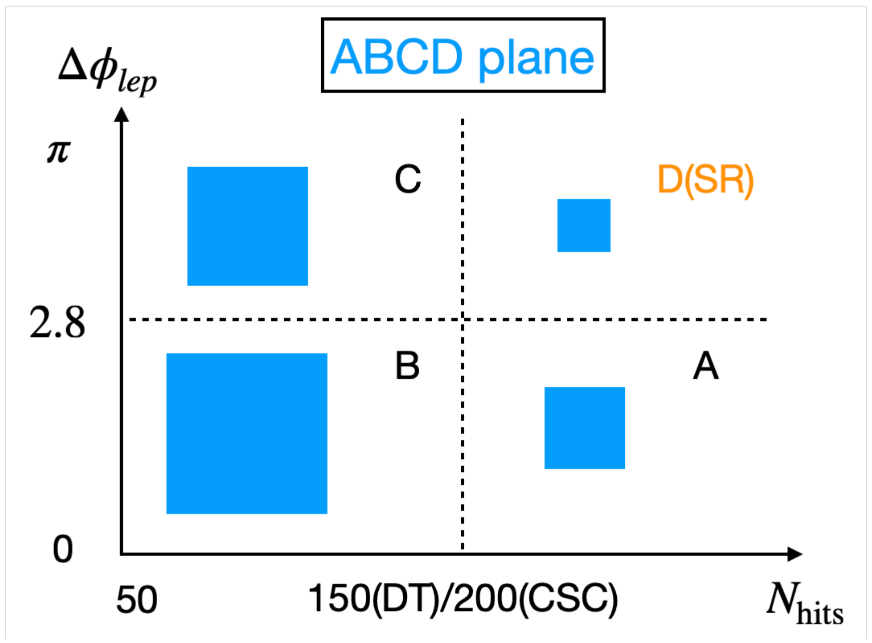
- DT:
  - Veto clusters with > 1 RecHit in MB1 and in adjacent wheel
  - Veto region with no instrumentation (DT chimney)
  - $BX_{cls} = 0$



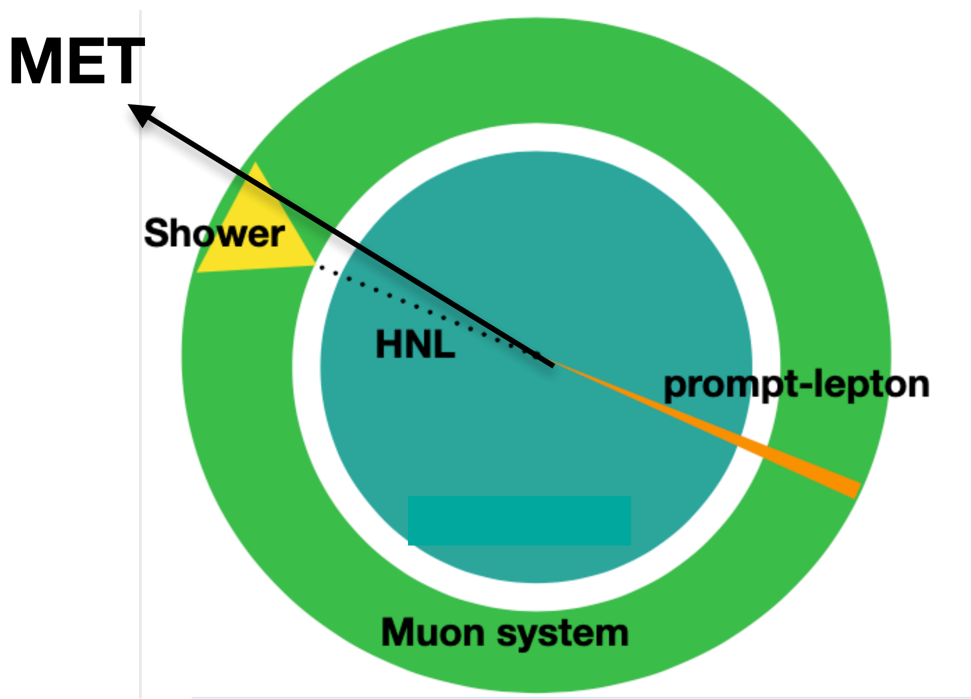
Fermilab

ABCD background estimation

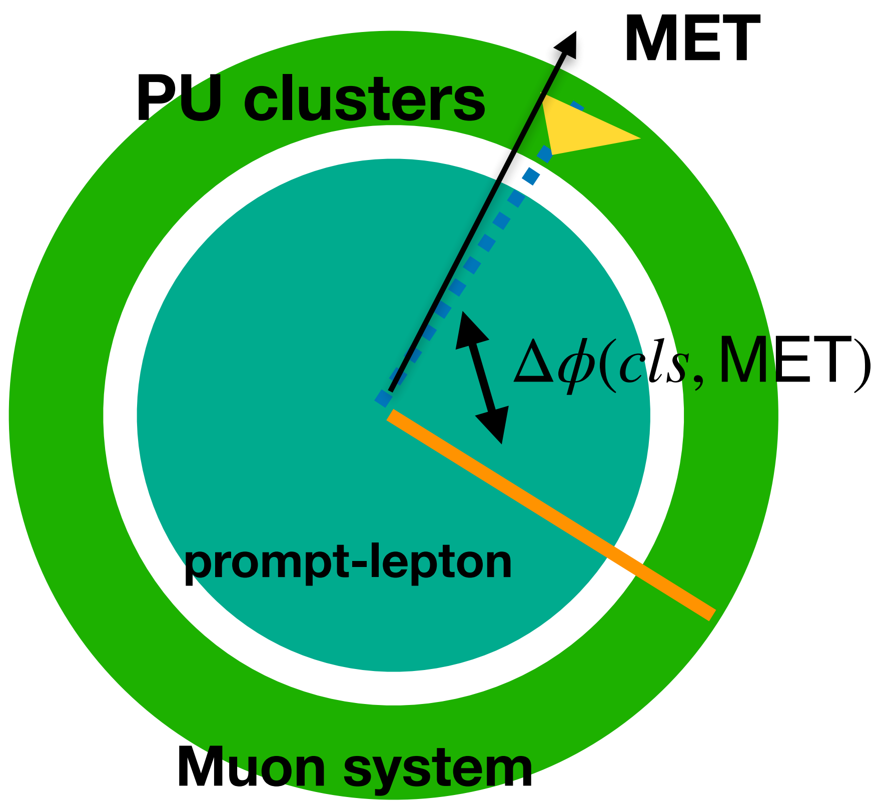
- After cluster selections, background clusters and leptons are uncorrelated
  - Use ABCD method with N_{hits} and $\Delta\phi_{lep}$
  - Signals are back-to-back with cluster with large N_{hits}
- Use Out-of-Time(OOT) and in-time large $\Delta\phi(cls, \text{MET})$ region as validation of ABCD method region



HNL signals

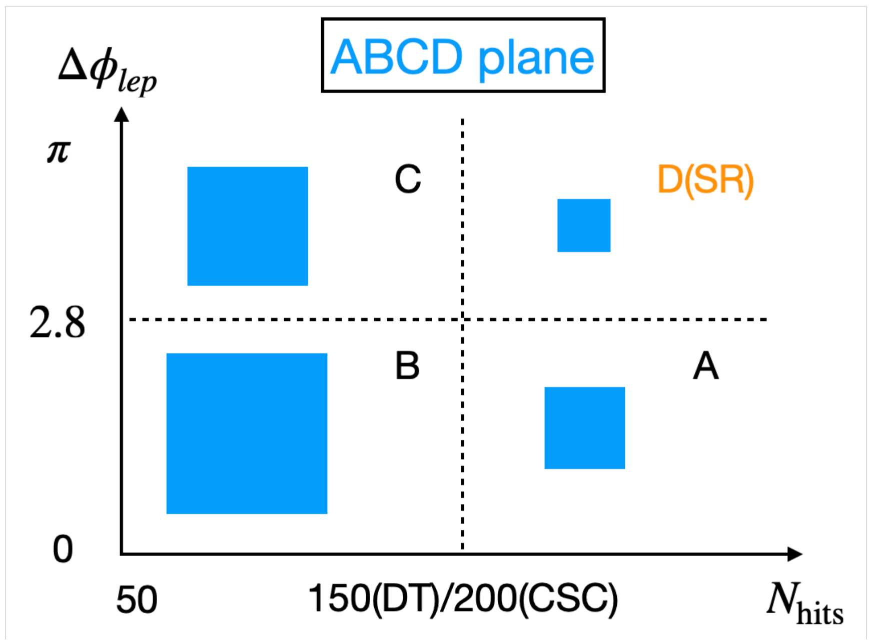


Backgrounds



ABCD background estimation

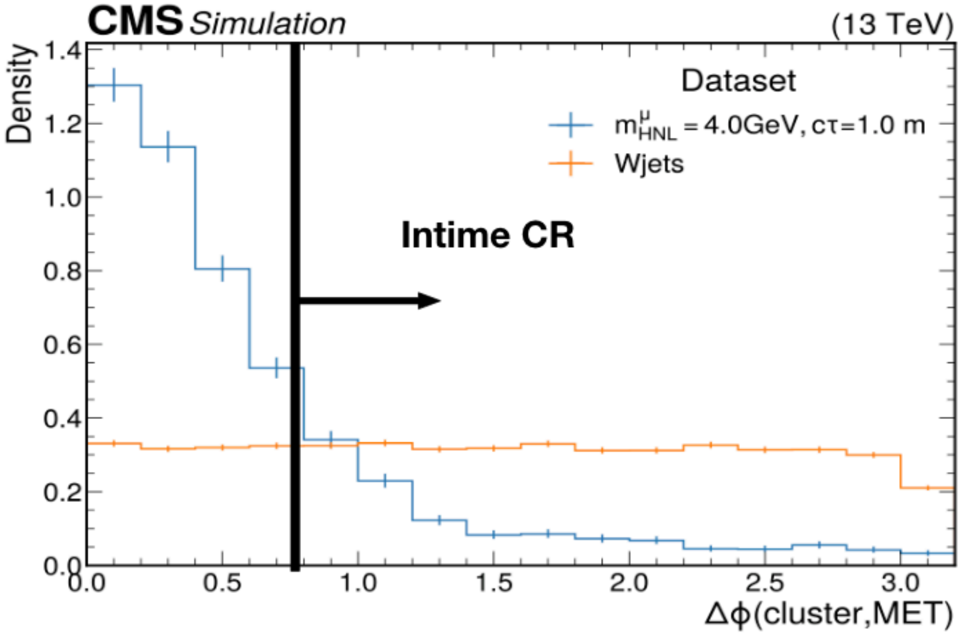
- After cluster selections, background clusters and leptons are uncorrelated
  - Use ABCD method with N_{hits} and $\Delta\phi_{lep}$
  - Signals are back-to-back with cluster with large N_{hits}
- Use Out-of-Time(OOT) and in-time large $\Delta\phi(cls,\text{MET})$ region as validation of ABCD method region

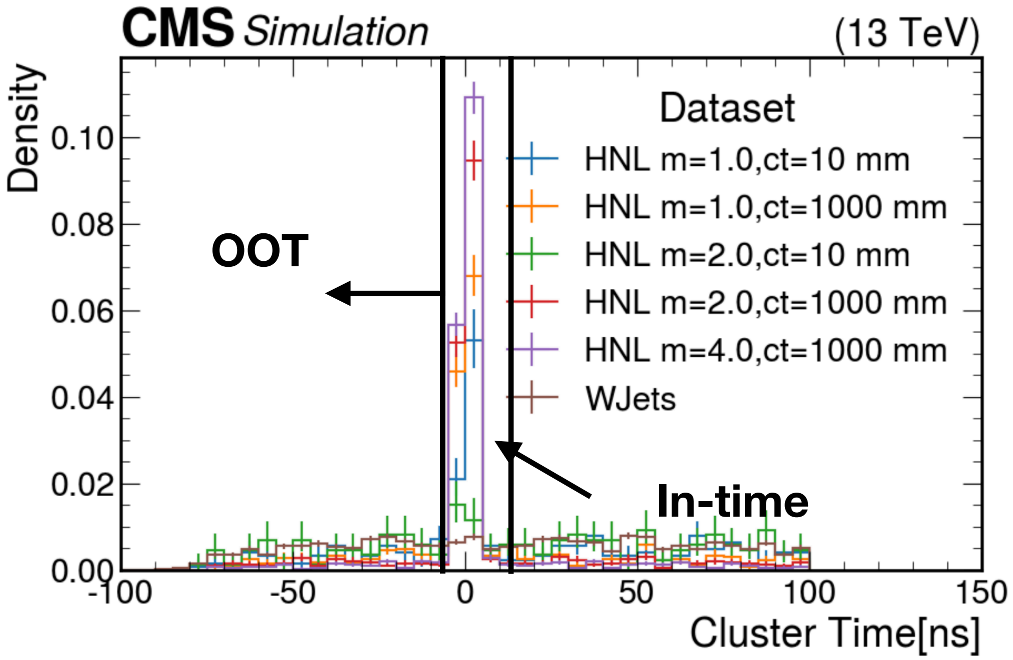


In-time CR

OOT CR

CSC clusters





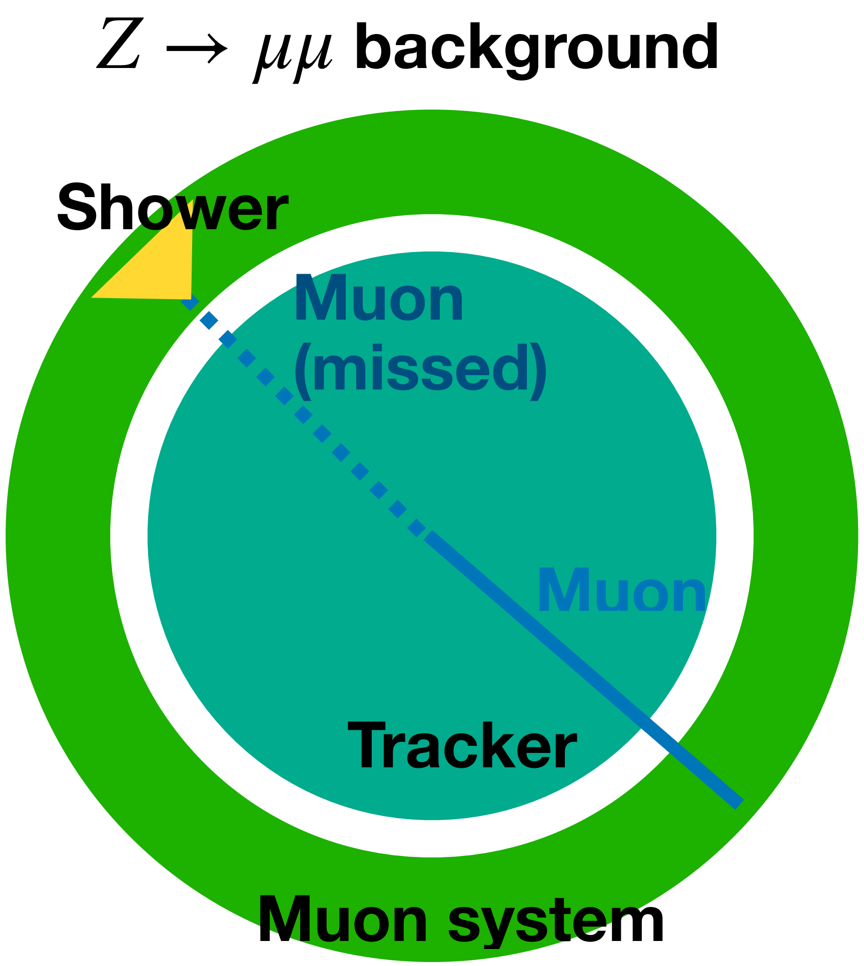
Closure test result

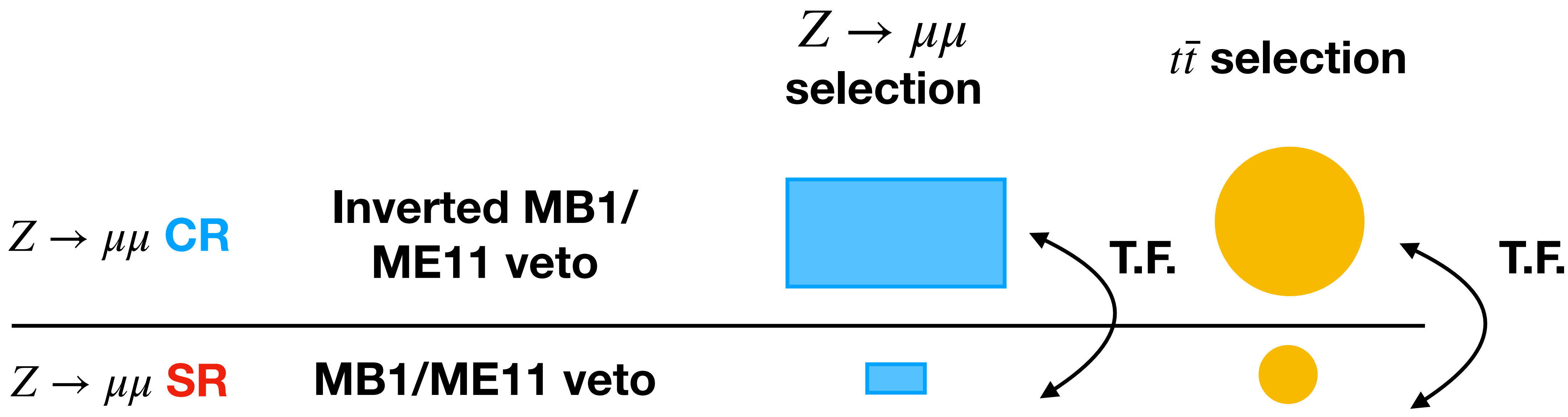
- Good agreement for closure tests both in-time/OOT validation regions
- Repeated this test with relaxed cluster selections in W+Jet MC
  - Also obtained good agreement (with limited statistics)

Event category	Validation region	A	B	C	D	D (pred.)
Muon, DT-MB2	OOT	9	6924	944	0	1.2 ± 0.4
Muon, DT-MB3/MB4	OOT	11	593	86	1	1.6 ± 0.5
Muon, CSC	OOT	103	31074	4044	9	13.4 ± 1.3
Electron, DT	OOT	14	3301	366	2	1.6 ± 0.4
Electron, CSC	OOT	33	13774	1647	2	4.0 ± 0.7
Muon, DT-MB2	In time	10	5087	467	2	0.9 ± 0.3
Muon, DT-MB3/MB4	In time	9	785	107	2	1.2 ± 0.4
Muon, CSC	In time	31	7445	532	1	2.2 ± 0.4
Electron, DT	In time	8	2446	220	0	0.7 ± 0.3

$Z \to \mu\mu$ background in muon channel

- In rare cases, $Z \to \mu\mu$ could create MDS + μ topology if one of the muons are not reconstructed
- To estimate this background, we
  - invert the most stringent veto to define a CR
  - measure CR-to-SR transfer factor (T.F.) using $t\bar{t}$ events





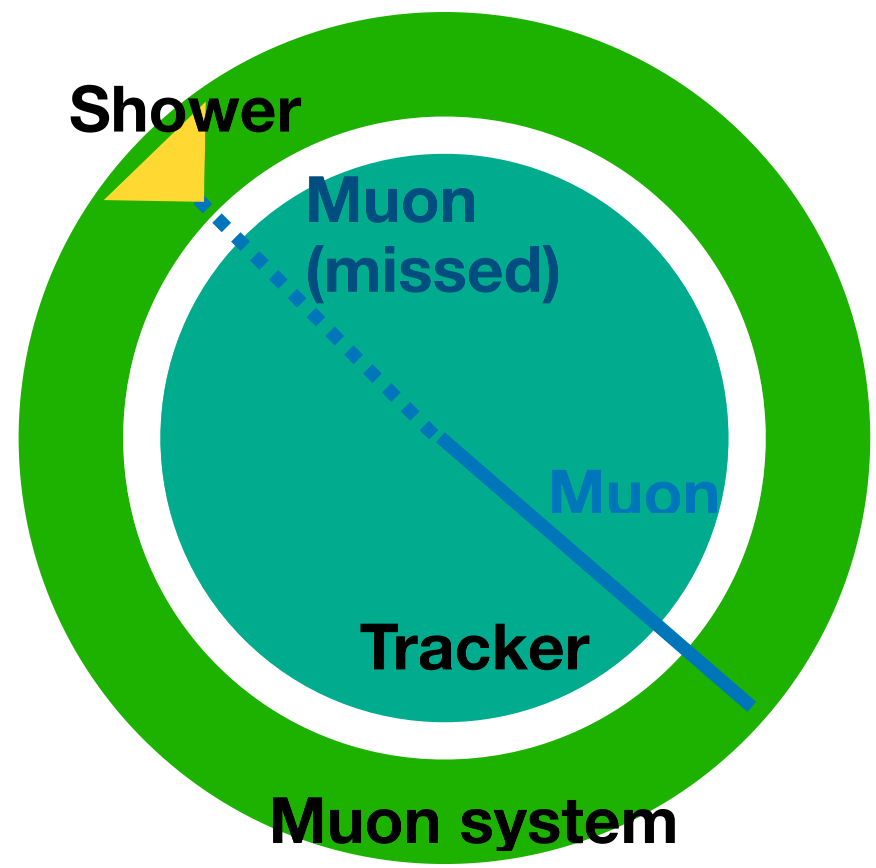
Zmumu Bkg in CR x T.F = Zmumu Bkg in SR

$Z \to \mu\mu$ background in muon channel

- In rare cases, $Z \to \mu\mu$ could create MDS + μ topology if one of the muons are not reconstructed

- To estimate this background, we
  - invert the most stringent veto to define a CR
  - measure CR-to-SR transfer factor (T.F.) using $t\bar{t}$ events

- Validated with MC and data with smaller cluster sizes



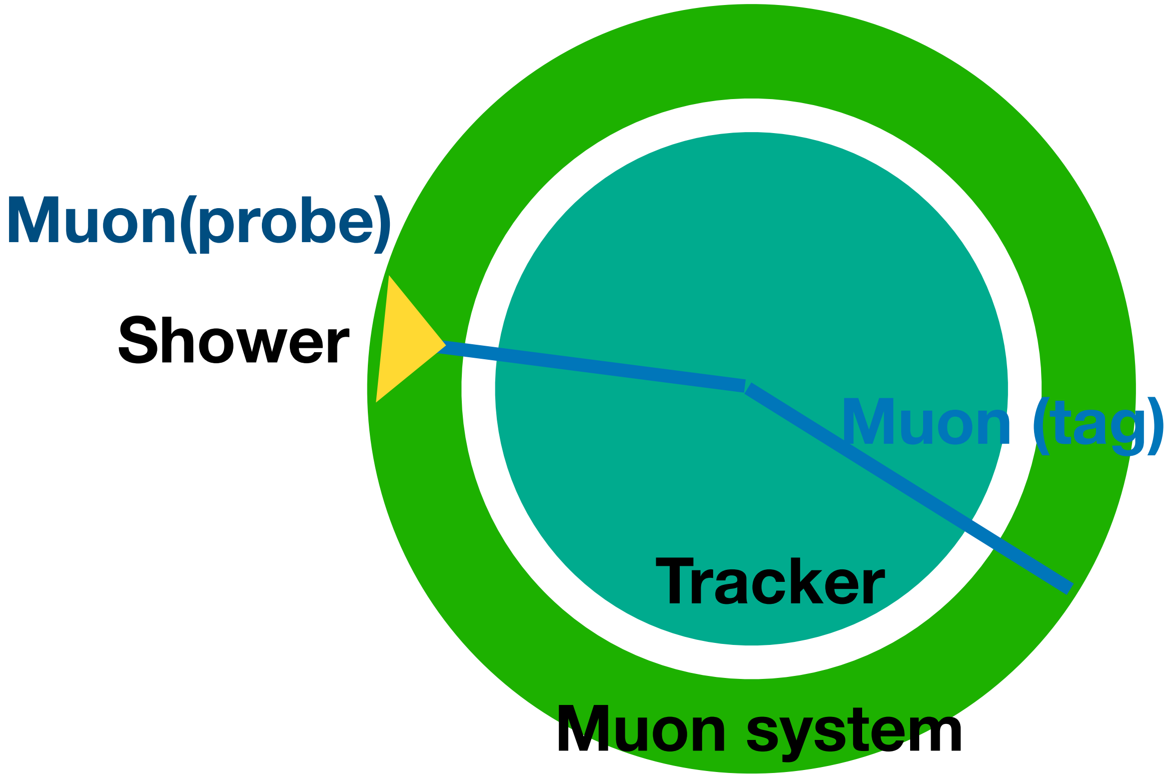
		$W + J$ CR	$Z \to \mu\mu$ CR	T.F.	$Z \to \mu\mu$ SR
Region	N_D^{CR}	$\lambda^{CR}_{\text{ABCD bkg,D}}$	$\lambda^{CR}_{Z\to\mu\mu,D}$	ζ	$\lambda^{SR}_{Z\to\mu\mu,D}$
CSC	129	45 ± 2	84 ± 12	$(4.8 \pm 1.3)\%$	3.9 ± 1.2
DT-MB2	35	12.2 ± 1.5	22.8 ± 6.1	$(36 \pm 31)\%$	8.2 ± 7.4
DT-MB3/MB4	6	2.9 ± 0.7	3.1 ± 2.6	$(2 \pm 1)\%$	0.06 ± 0.06

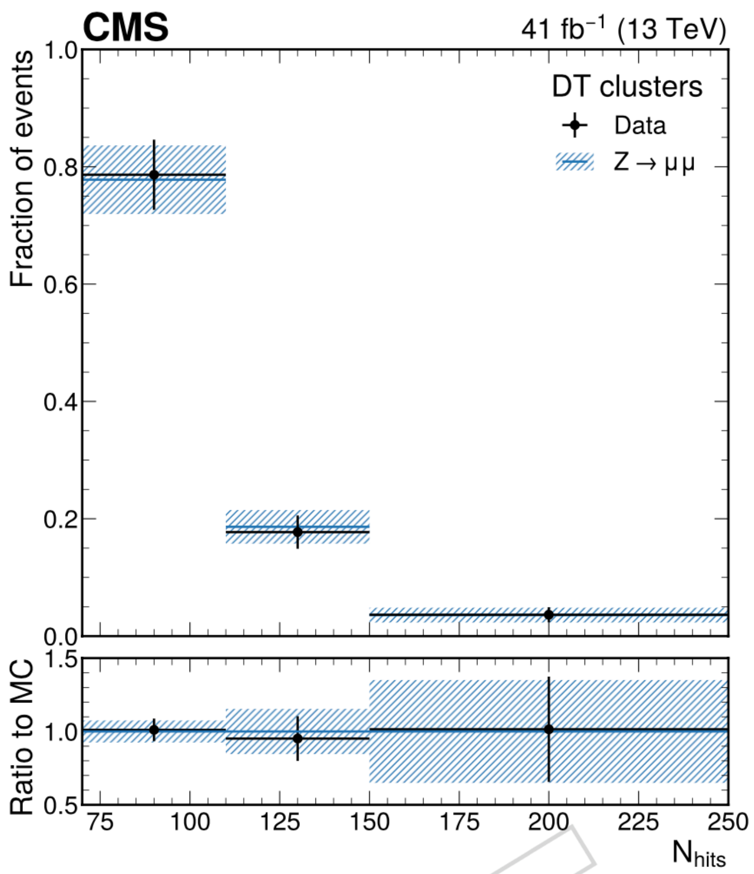
Zmumu Bkg in CR x T.F = Zmumu Bkg in SR

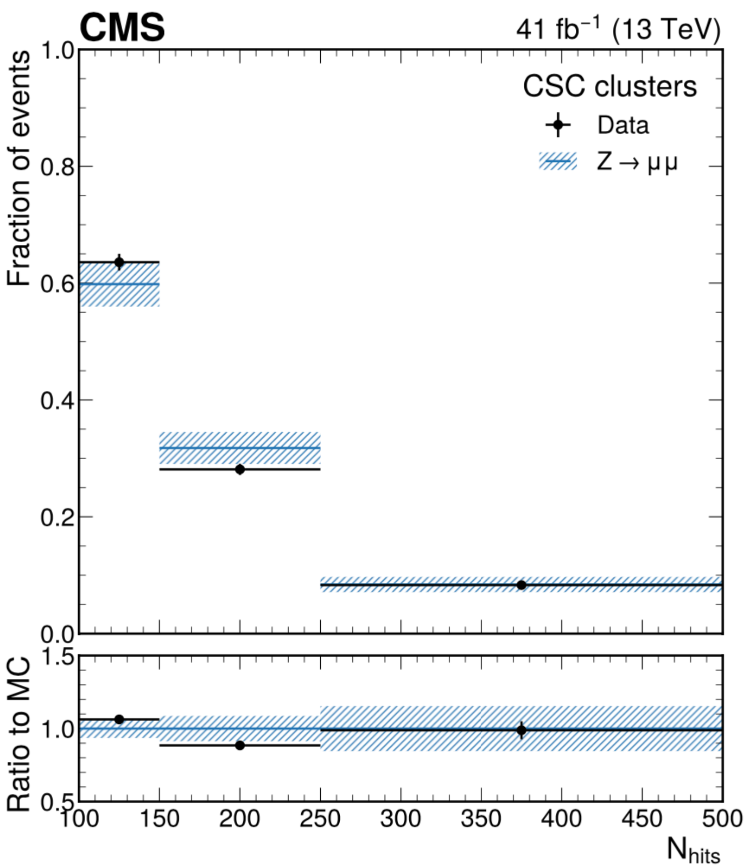
Systematics uncertainties

- Background unc. dominated by statistical unc. of ABCD method
  - And uncertainty of T.F. for muon channel

- Uncertainty of cluster properties measured with tag-and-probe method in $Z \rightarrow \mu\mu$ brems
  - Validates the clusters in signal simulation



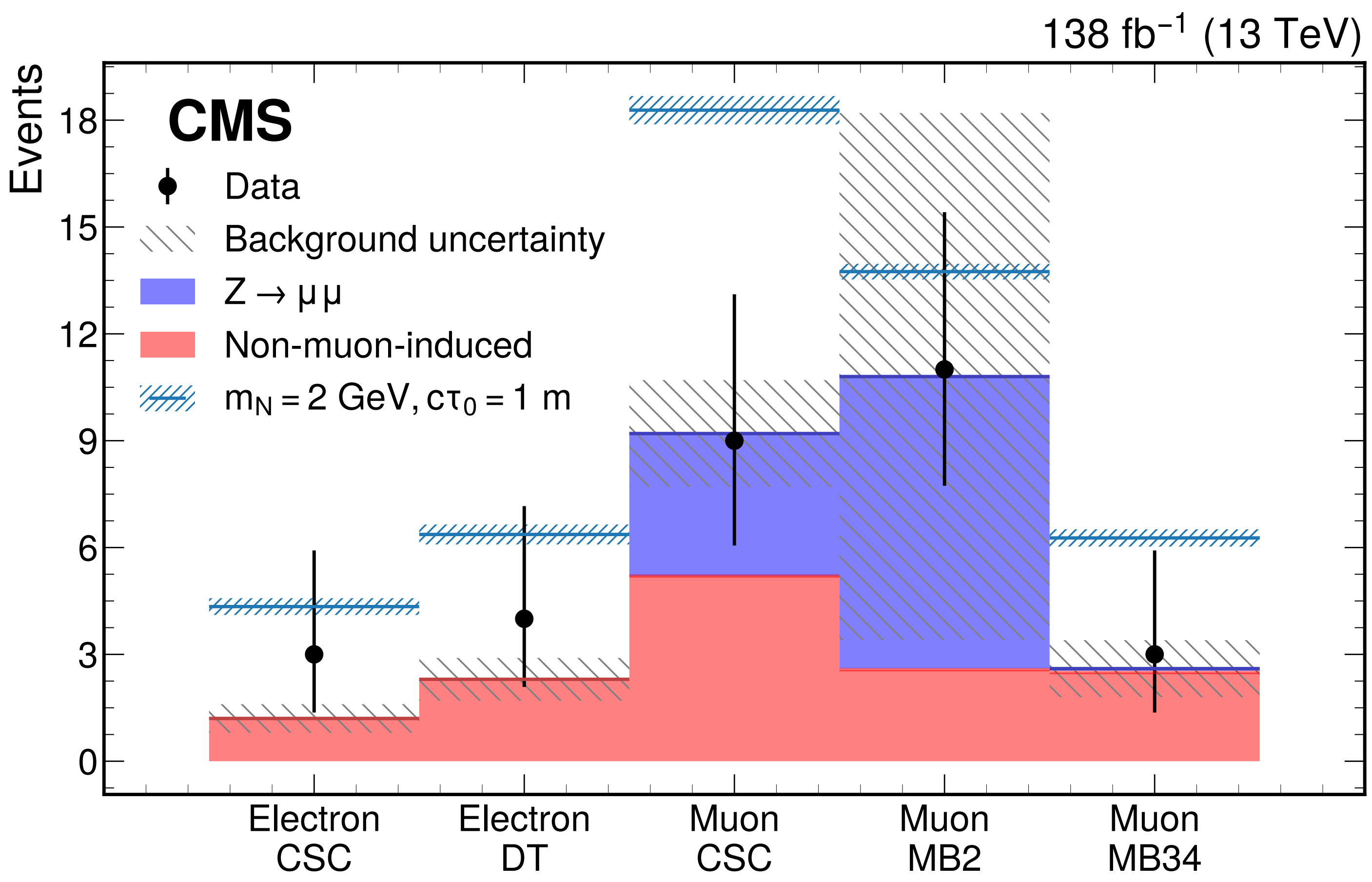


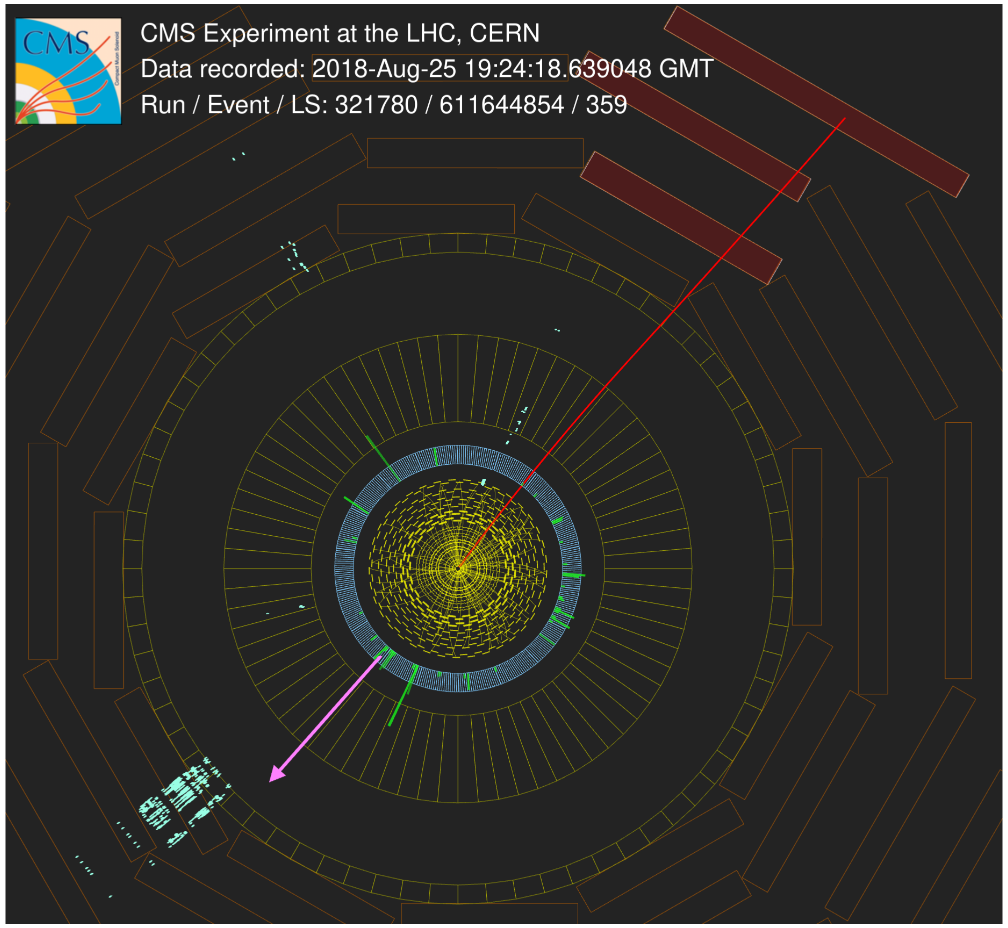


Result

- No significant excess observed
  - ~1 sigma fluctuation in electron channel
- Proceed to set limits on HNL coupling v.s. mass plane

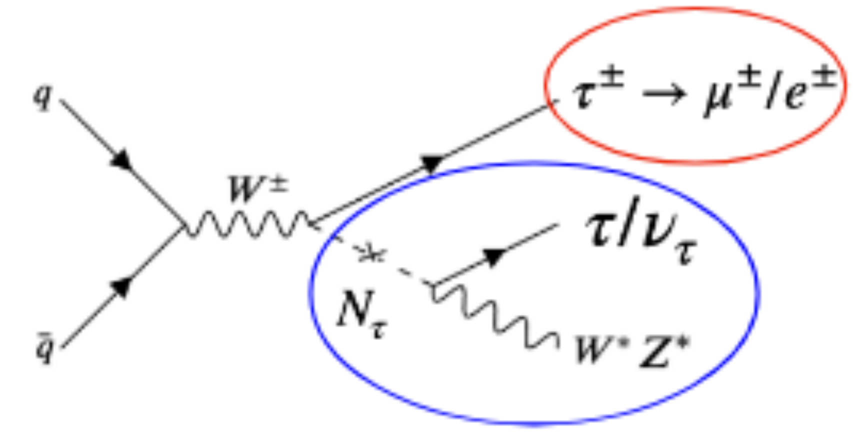
EXO-22-017

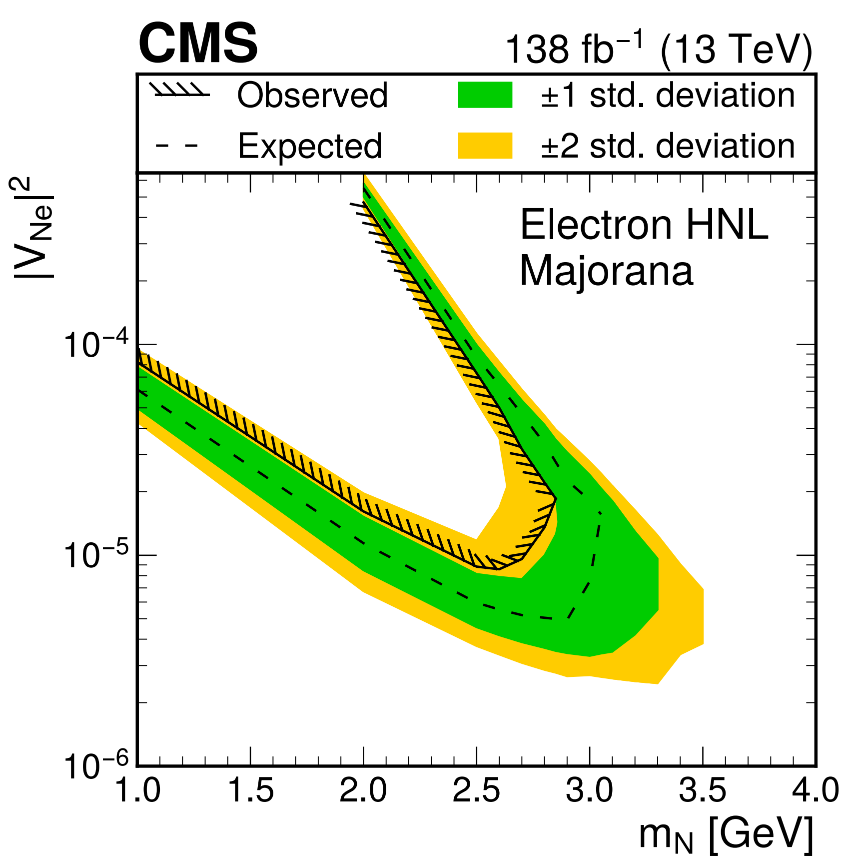


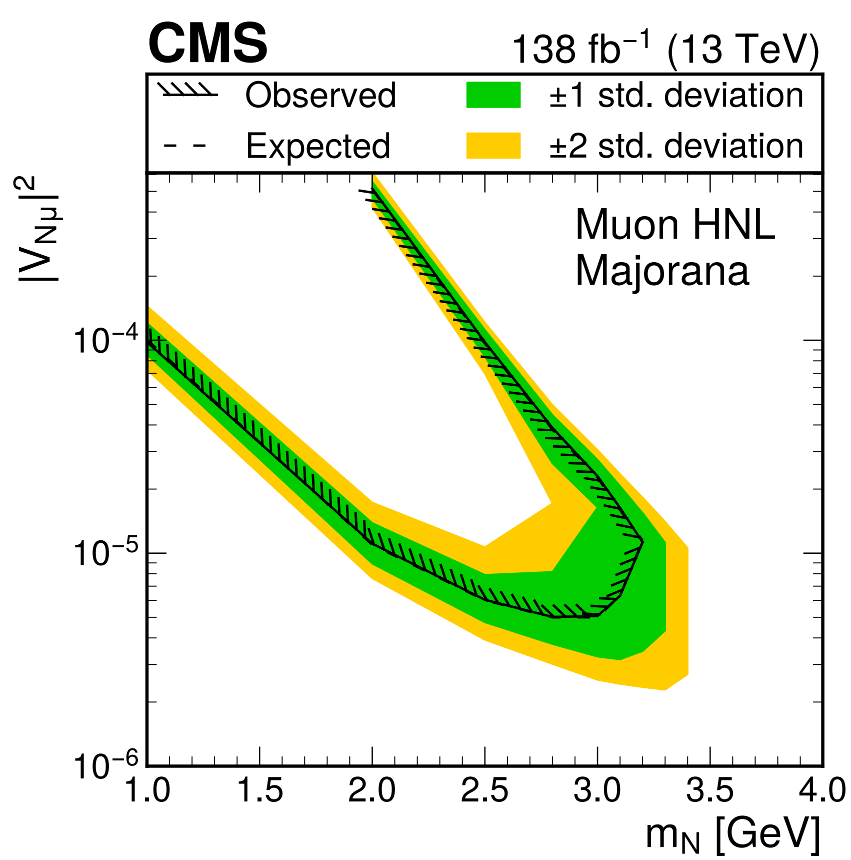


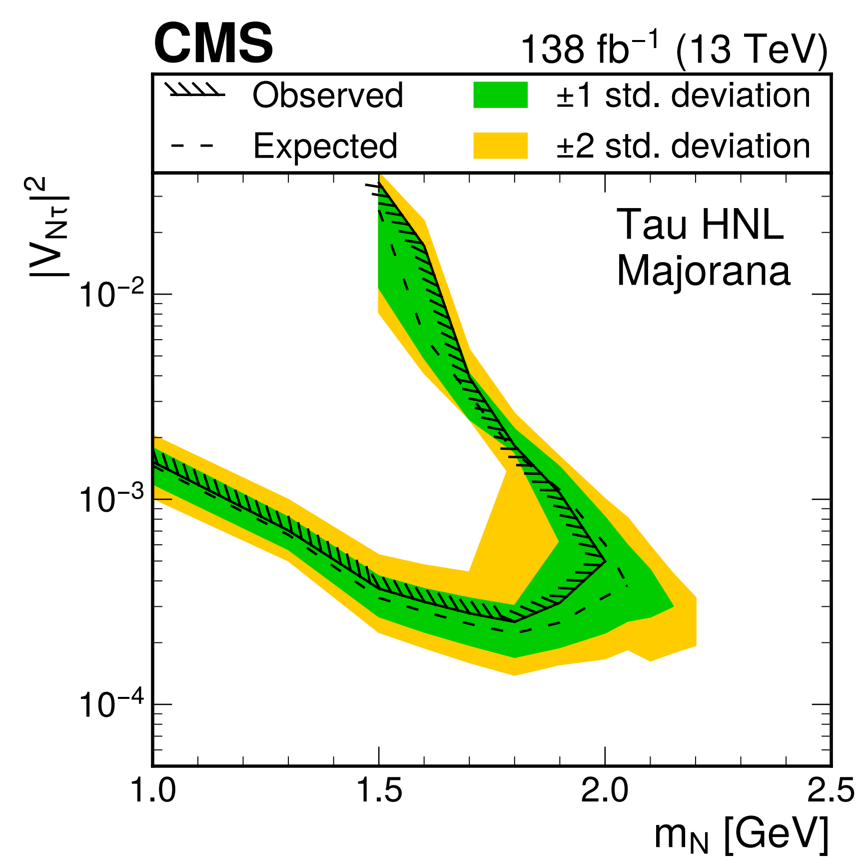
Limits on Majorana HNL

- Flavour independence:
  - MDS works for well for HNL mixings with e/mu/taus
  - Limits are different largely due to trigger acceptance



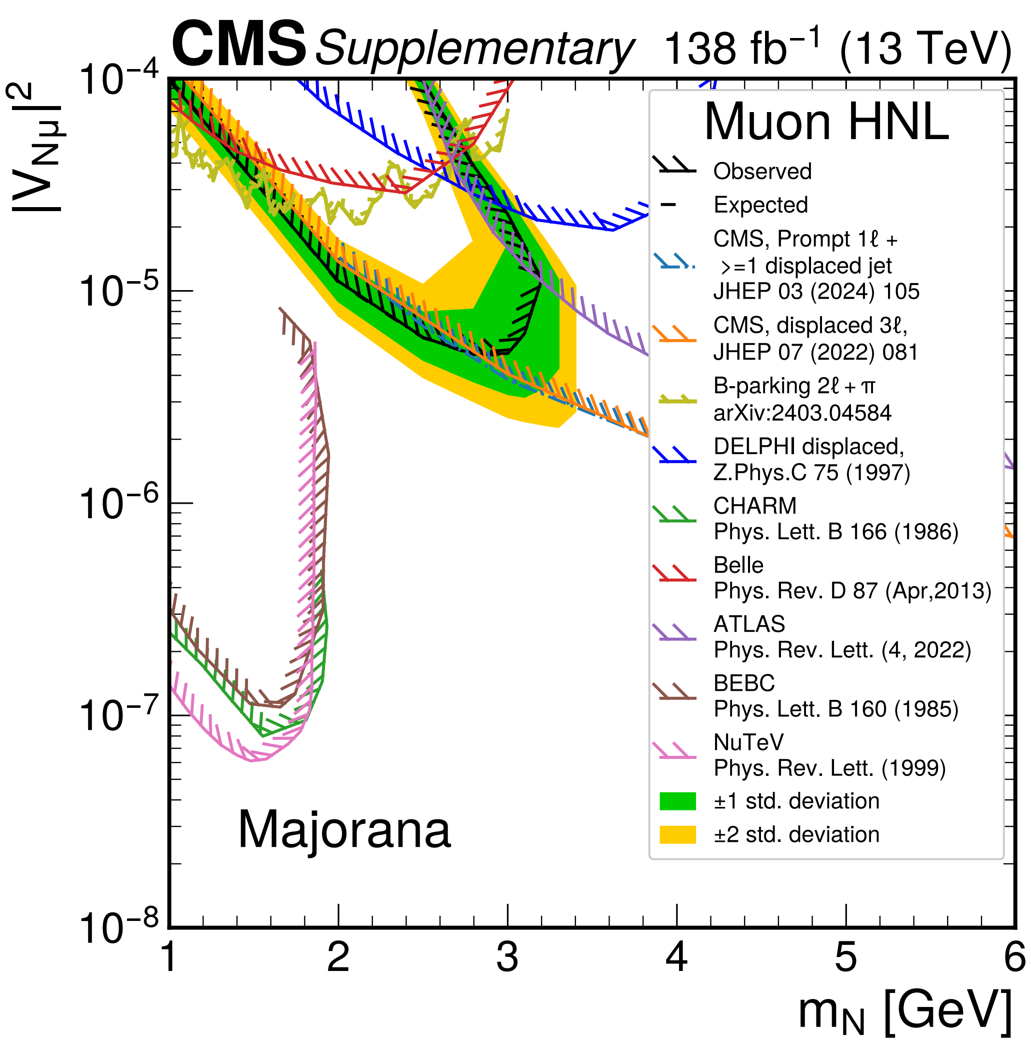


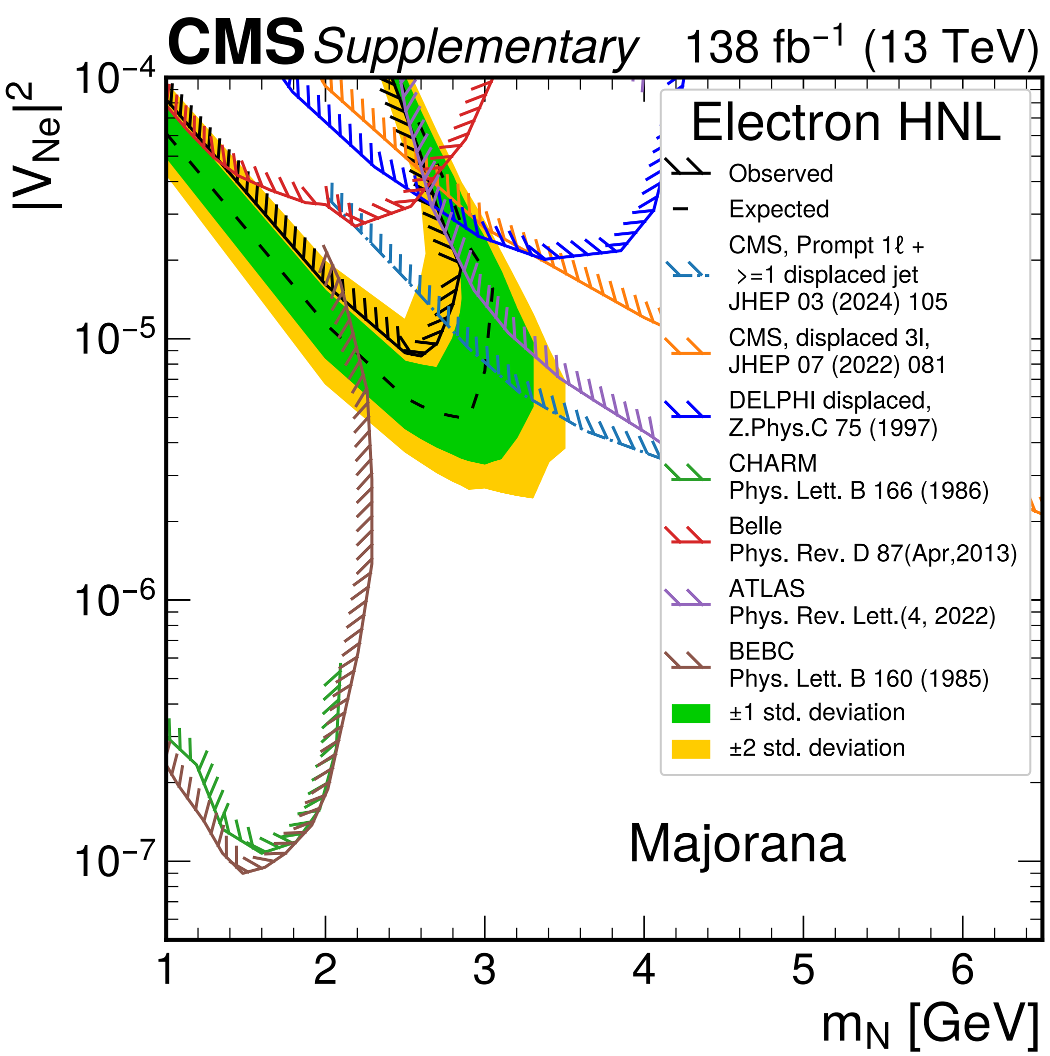




Limits on Majorana HNL

- Flavour independence:
  - MDS works for well for HNL mixings with e/mu/taus
  - Limits are different largely due to trigger acceptance
- Probes low-mass/small coupling parameter space
  - Most stringent limits around 2 - 3 GeV





Mixed-HNL coupling

- Flavour independence opens up mixed coupling interpretation

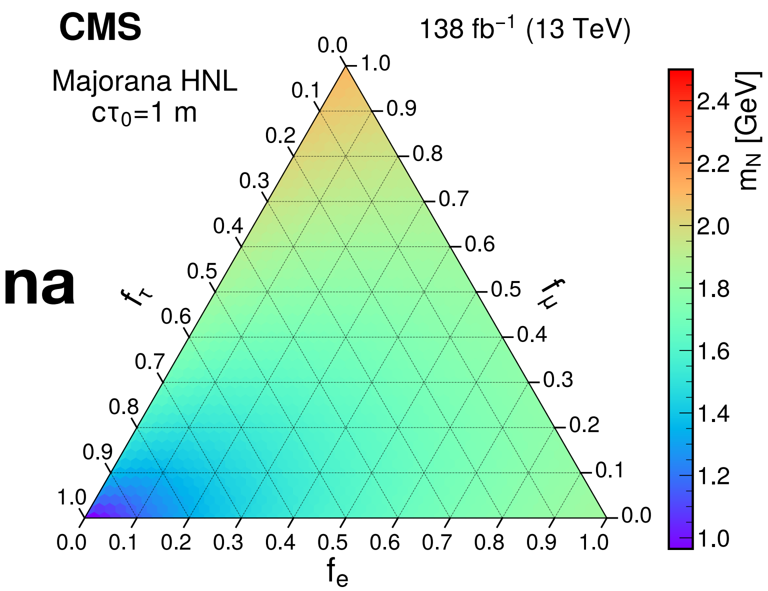
$$f_\ell = \frac{|V_{\ell N}|^2}{|V_{eN}|^2 + |V_{\mu N}|^2 + |V_{\tau N}|^2}$$

  - Constrains the sum of relative couplings to 1

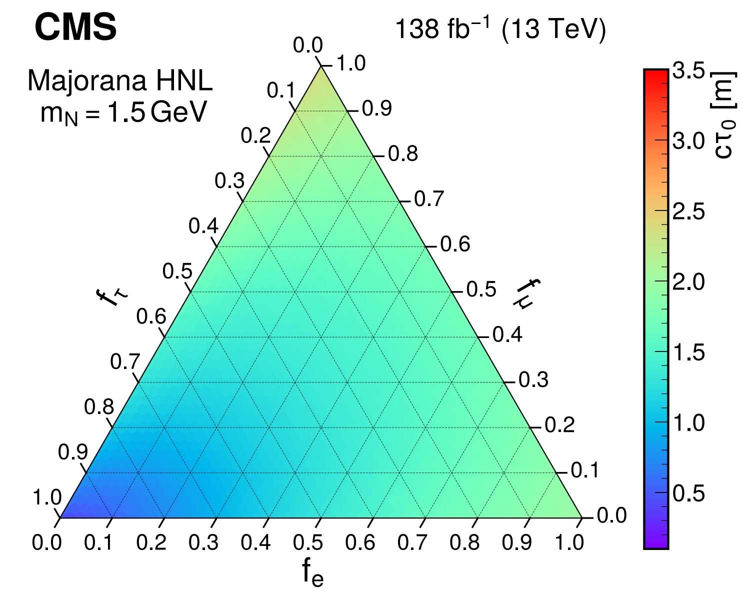
- Selected several benchmark at the edge of our sensitivity

Majorana

$c\tau = 1m$

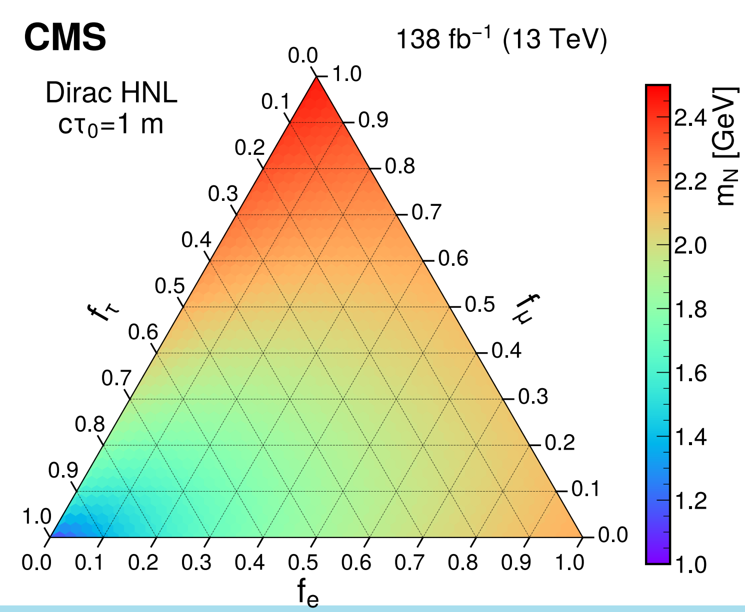


$m_N = 1.5$ GeV

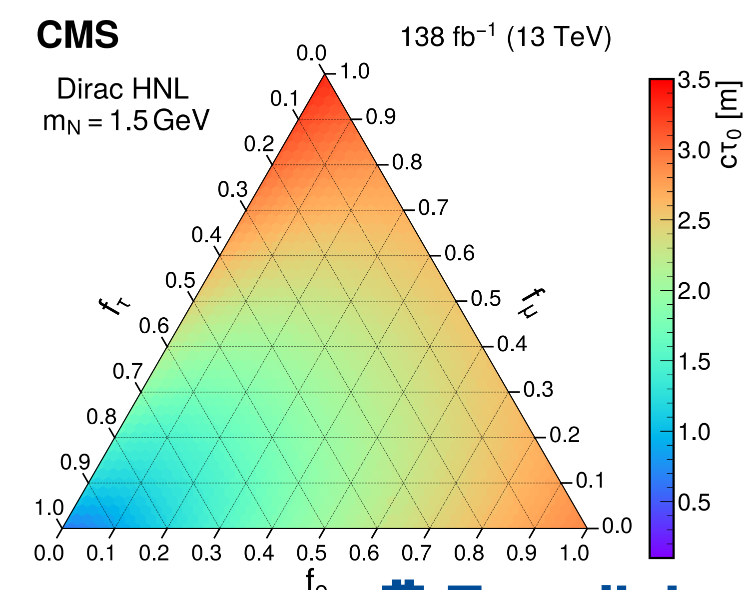


Dirac

$c\tau = 1m$

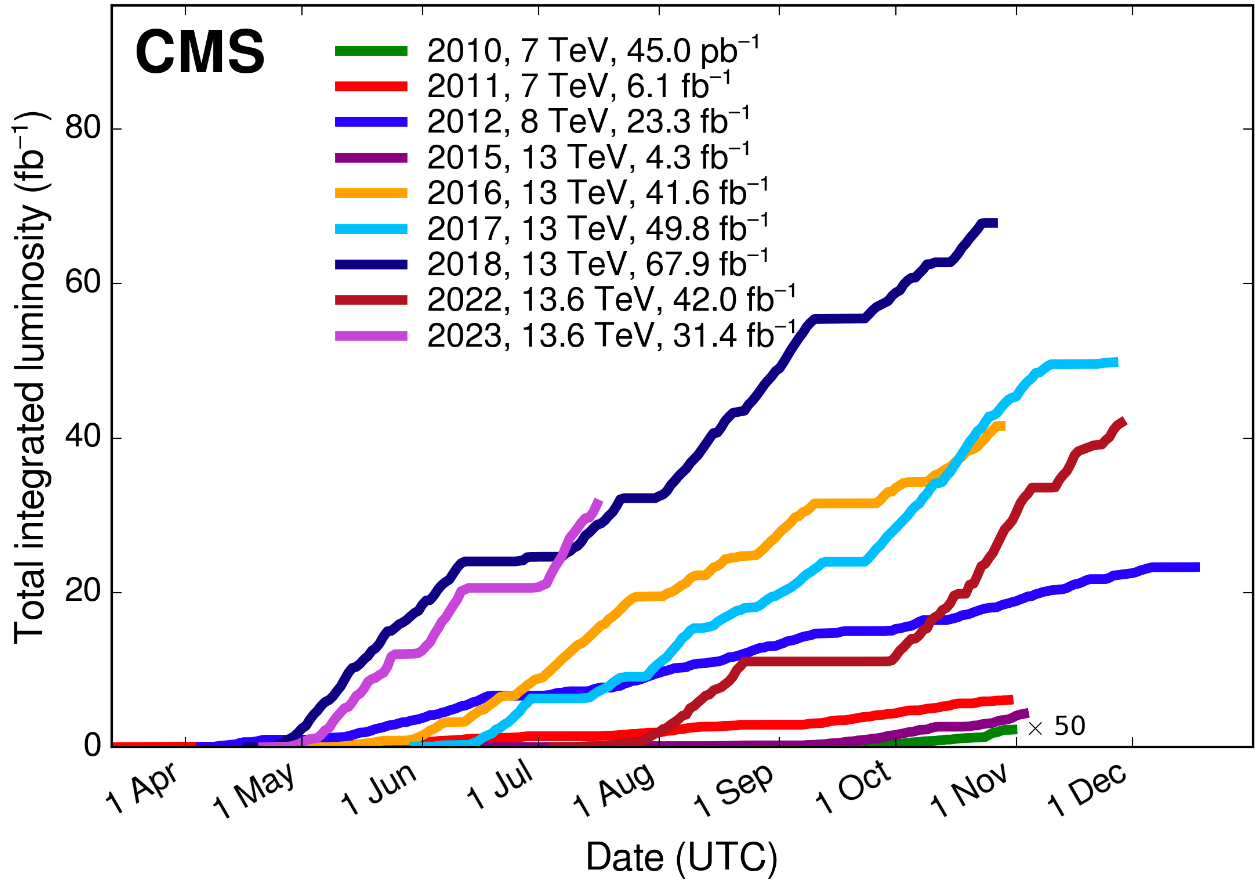


$m_N = 1.5$ GeV



Fermilab

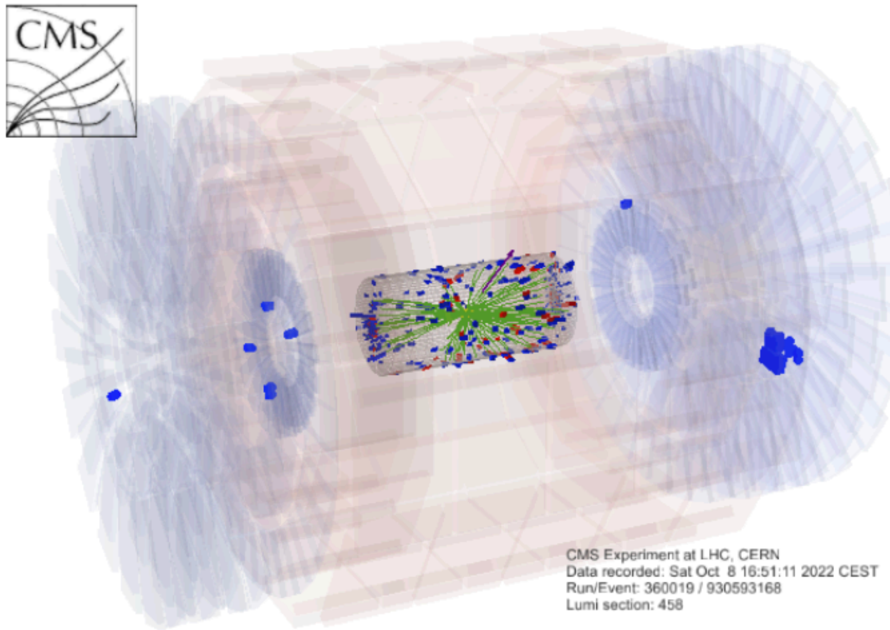
Can we do better in Run 3?



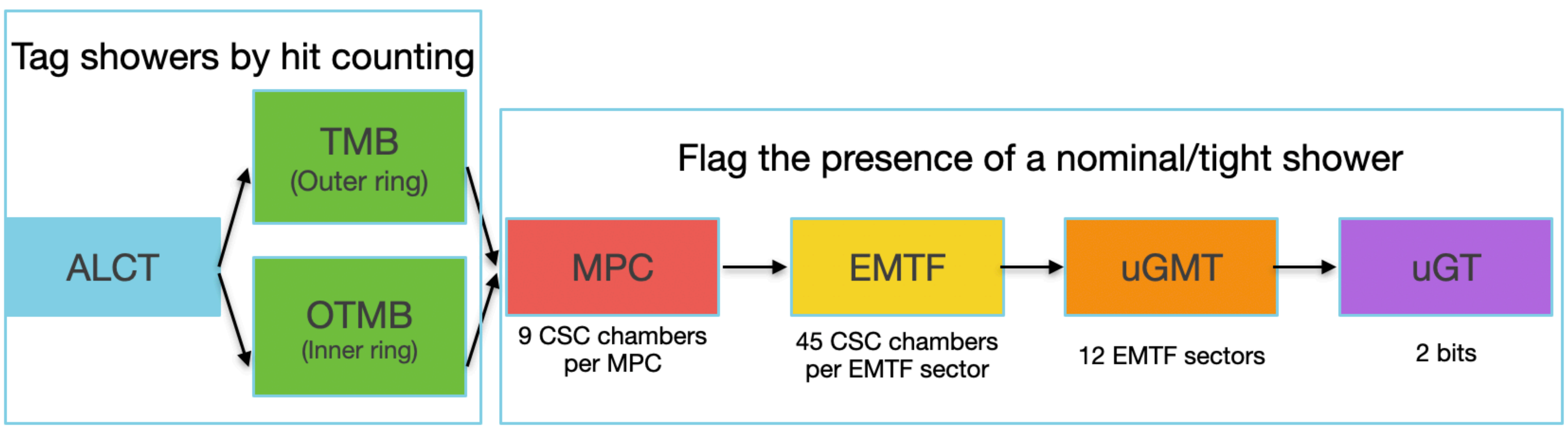
Muon Shower Triggers

DP note

- Many CMS run 2 LLP analysis do NOT have a dedicated LLP trigger
  - Major CMS Run 3 effort
- New dedicated trigger object implemented at L1 and HLT
  - MDS object available at HLT!



Event display in 2022 data

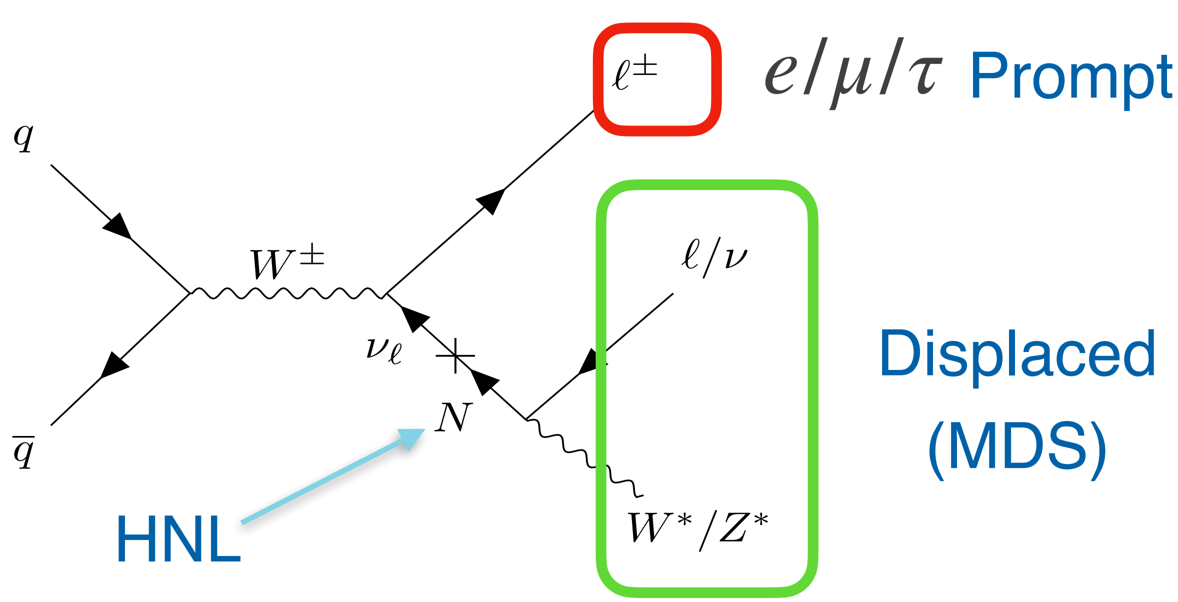


Overview MDS trigger (HMT) logic

Muon Shower Triggers for HNL

- HNL search was less trigger limited due to the presence of a clean lepton except for hadronic τ!
- New trigger allow us to trigger on the MDS + $\ell = e/\mu/\tau_h$ at HLT
  - MDS suppresses the rate
  - **Very loose cut** on the associated objects
  - Enable us to probe **long-lived** hadronic-τ channel
- Deployed in 2024 run!

HNL : MDS + $e/\mu/\tau$

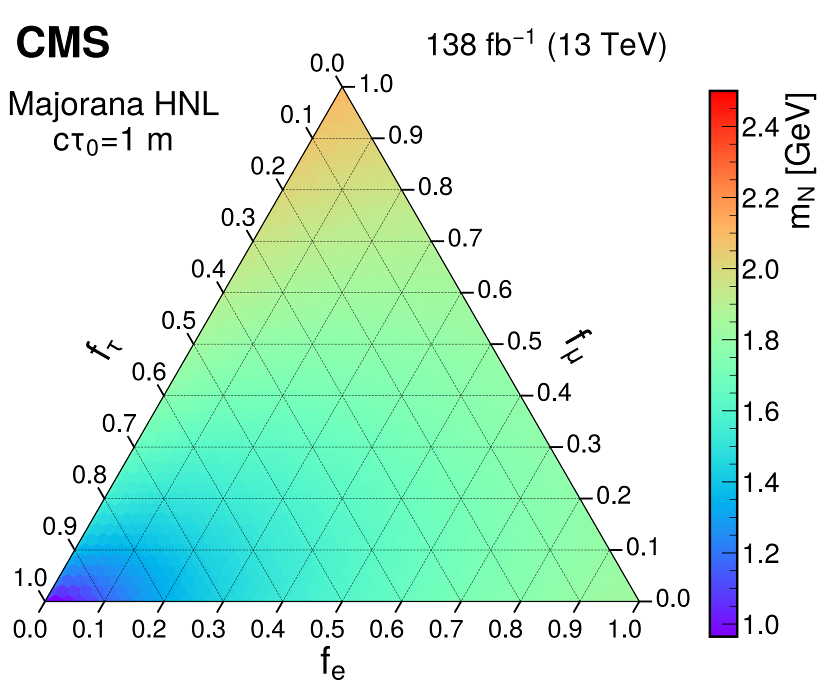


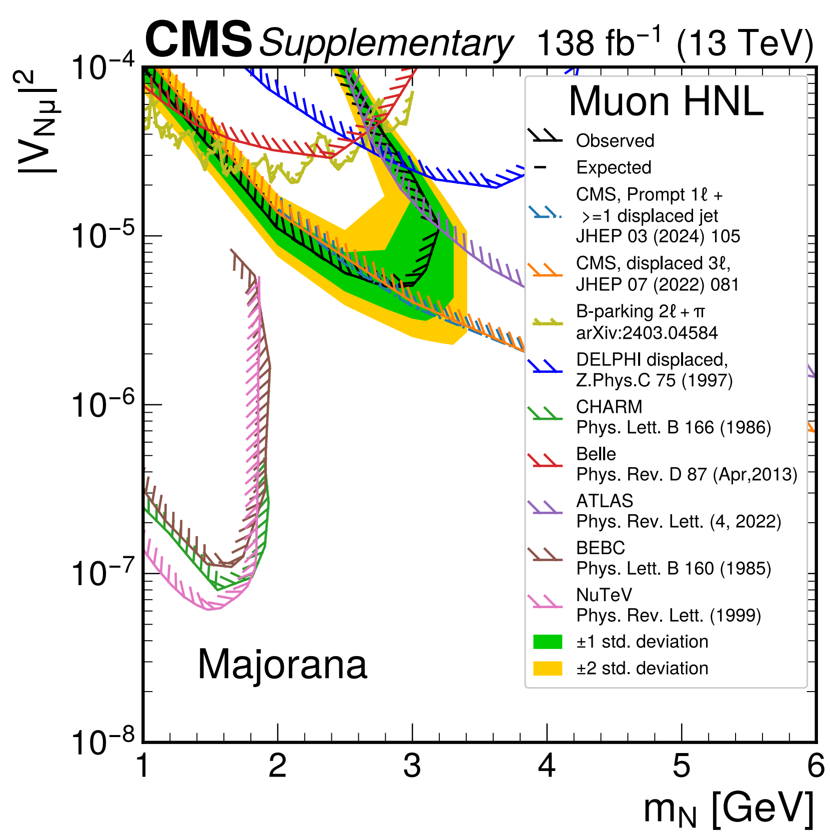
- Single Lepton trigger thresholds:
  - Muon: ~25 GeV
  - Electron: ~30 GeV
  - τ_h : >100 GeV

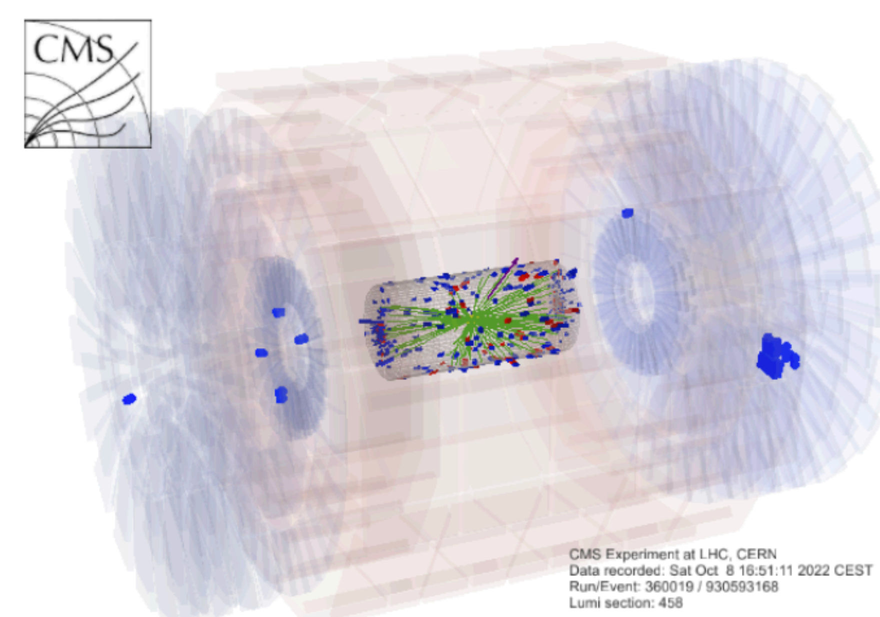
Summary

- Muon Detector Shower(MDS) is a power new tool
  - Search with Run-2 data improves previous CMS limits ~2.3x at around 1-3 GeV
  - New triggers enable us to probe hadronic tau channel with MDS

- Stay tuned for Run 3 results!







Thank you!