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

Martin Kwok (Fermilab)

Université Catholique de Louvain -

Centre for Cosmology, Particle Physics and Phenomenology Seminar

5 September, 2023

Outline

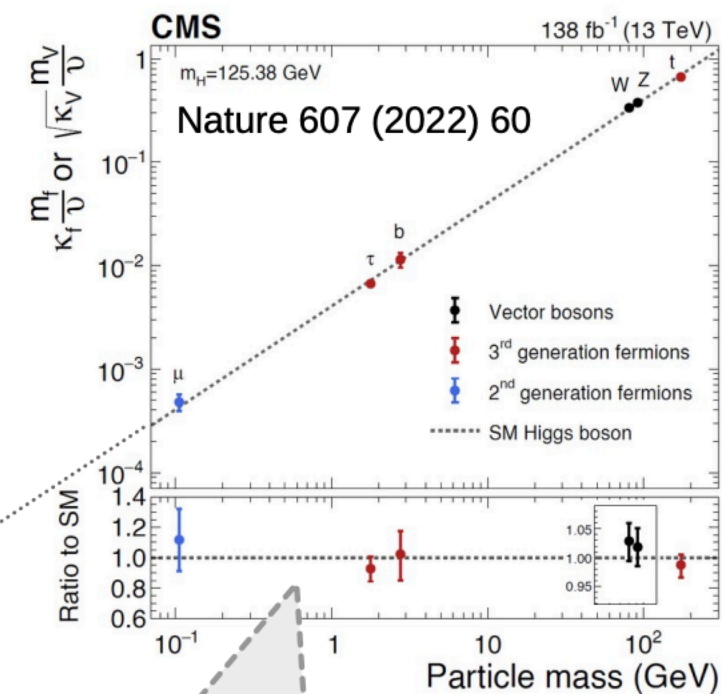
- What is HNL?
- What is Muon Detector Shower(MDS)?
- How to search for HNL with MDS?
- What's to expect in Run 3?

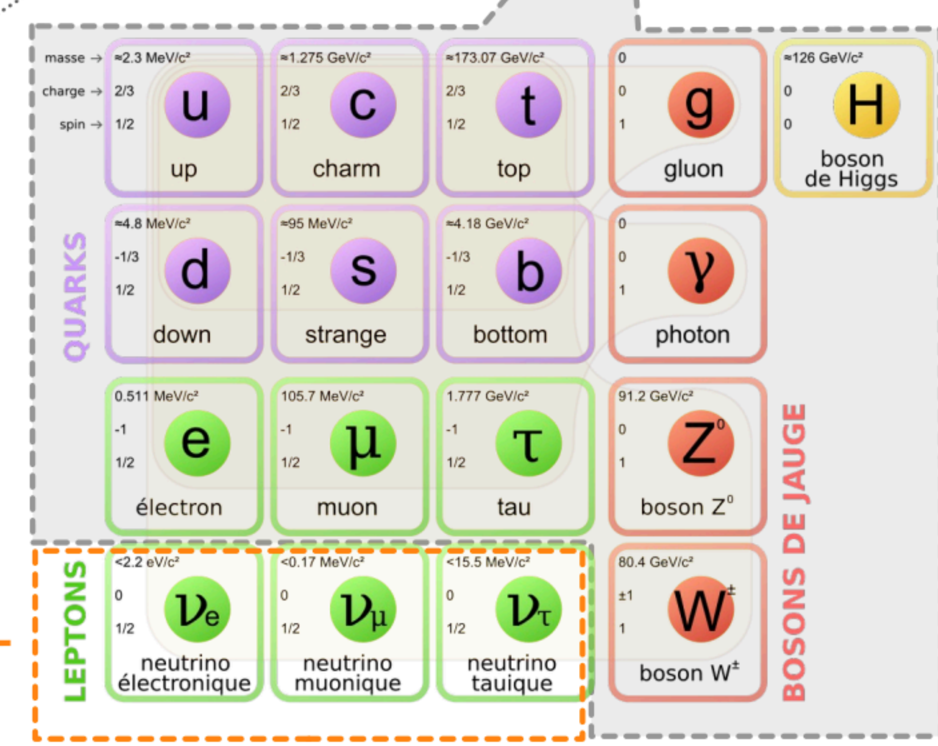
Heavy Neutral Lepton

- SM is very successful, yet incomplete…
- Neutrino oscillation is a lab-accessible BSM effect!
  - Established experimentally ~2000s
  - Peculiarly light (but non-zero mass)

- But Left-handed weak currents cannot have mass term
- Idea: extend SM neutrino sector by adding new particle N
  - Allow Majorana/Dirac mass term for SM neutrinos

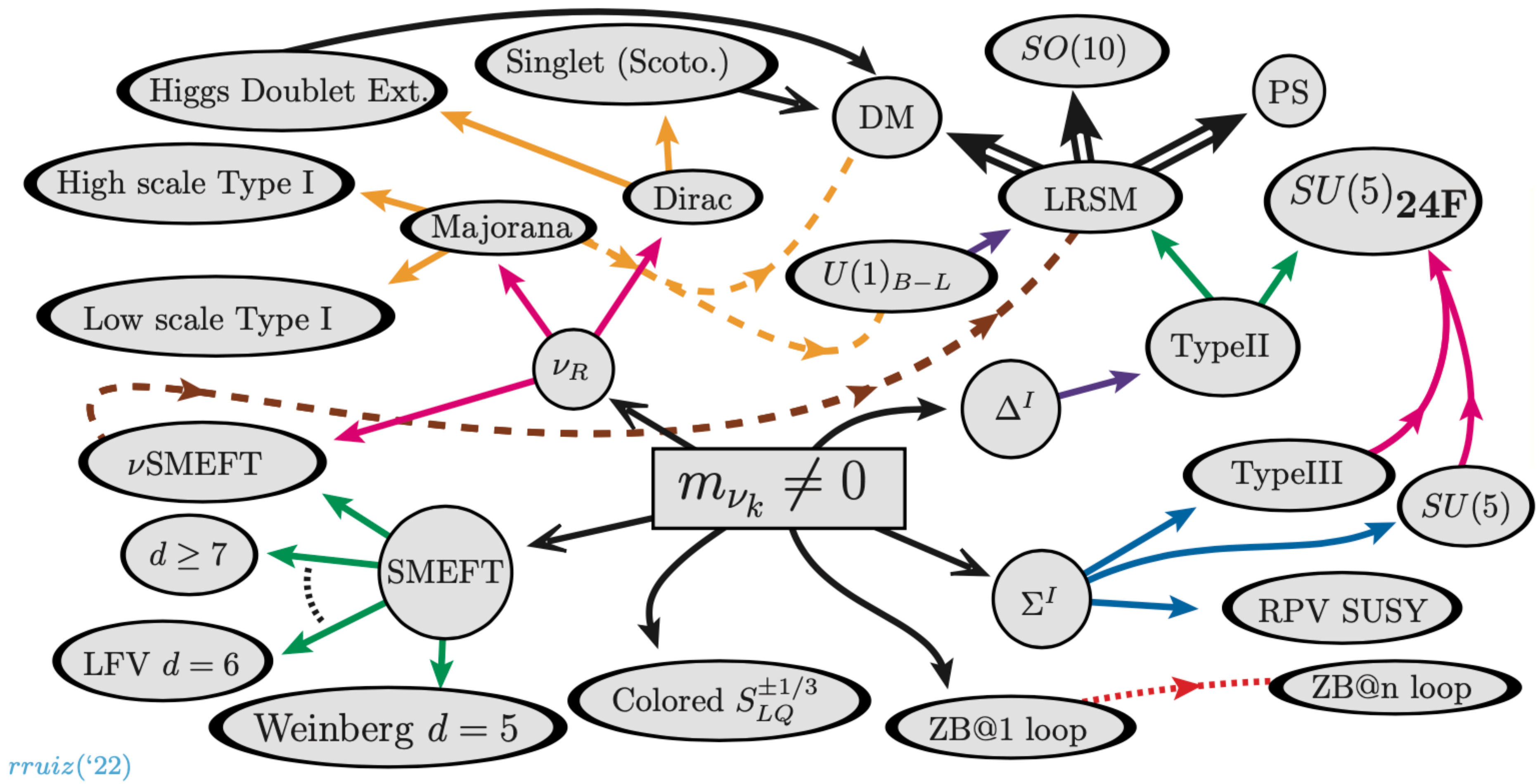
- Gives SM neutrino mass via see-saw mechanism
  - Connected to other unsolved problems (Baryon asymmetry, DM candidate, Anomalous g-2 [1],[2],[3],[4],[5])





Theory landscape

- Simple idea, but can be realized in many different ways
  - How many are there?
  - What are their masses?
  - interaction with gauge bosons?

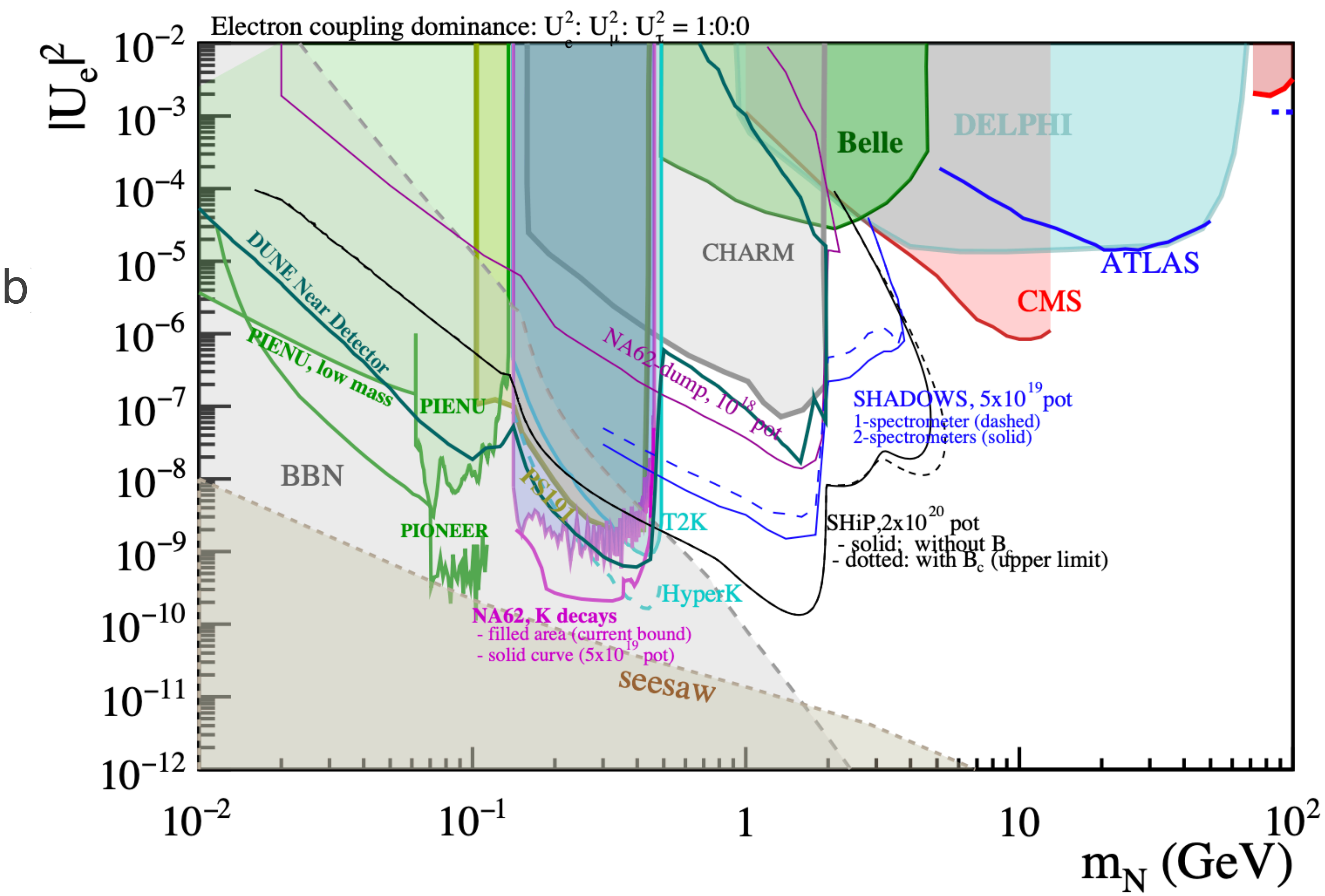


Credit: R. Ruiz

Experimental landscape

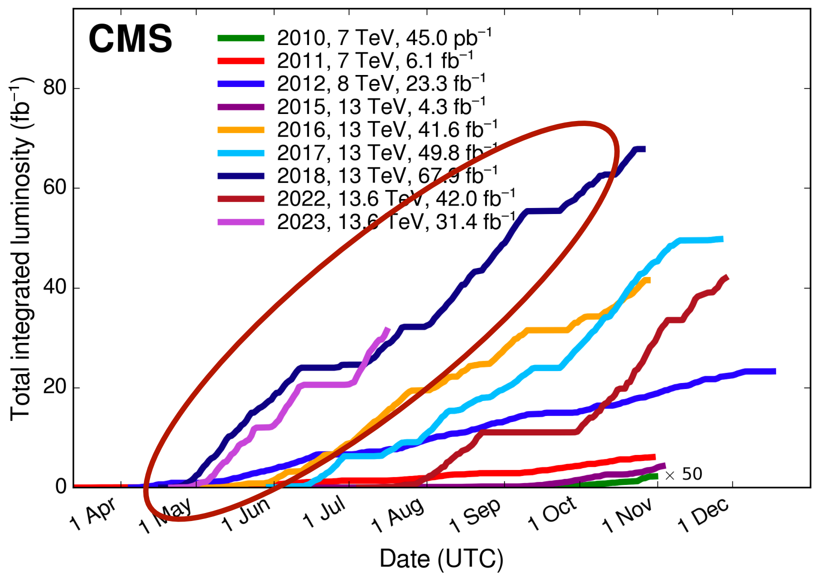
- Very rich phenomenon
- Searched for with all possible methods
  - Collider & fixed target
  - Nuclear decay
  - Atmospheric/solar neutrinos

- Accessible production/decay mode depends on the HNL mass
  - Kaon decays (e.g. NA62)
  - B or D meson decay (e.g. Belle, LHCb
  - Below W,Z: $Z \to N\nu$
  - Above W,Z mass: decay to on-shell W/Z production

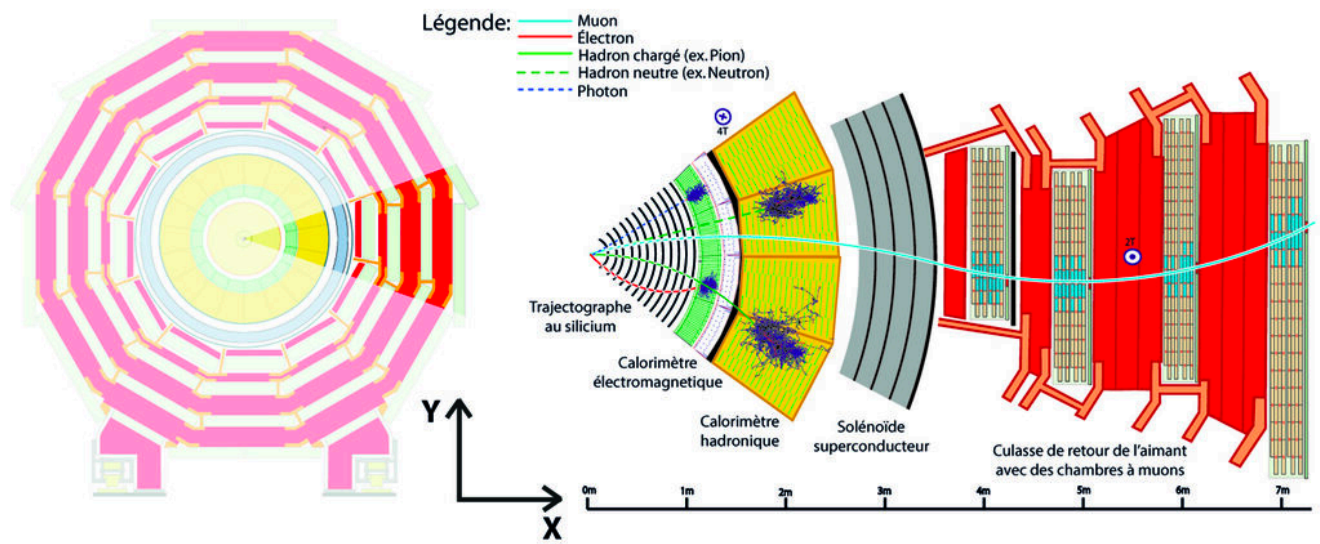


The CMS experiment at the LHC

- A lot of the above phenomenon can be accessed at the LHC



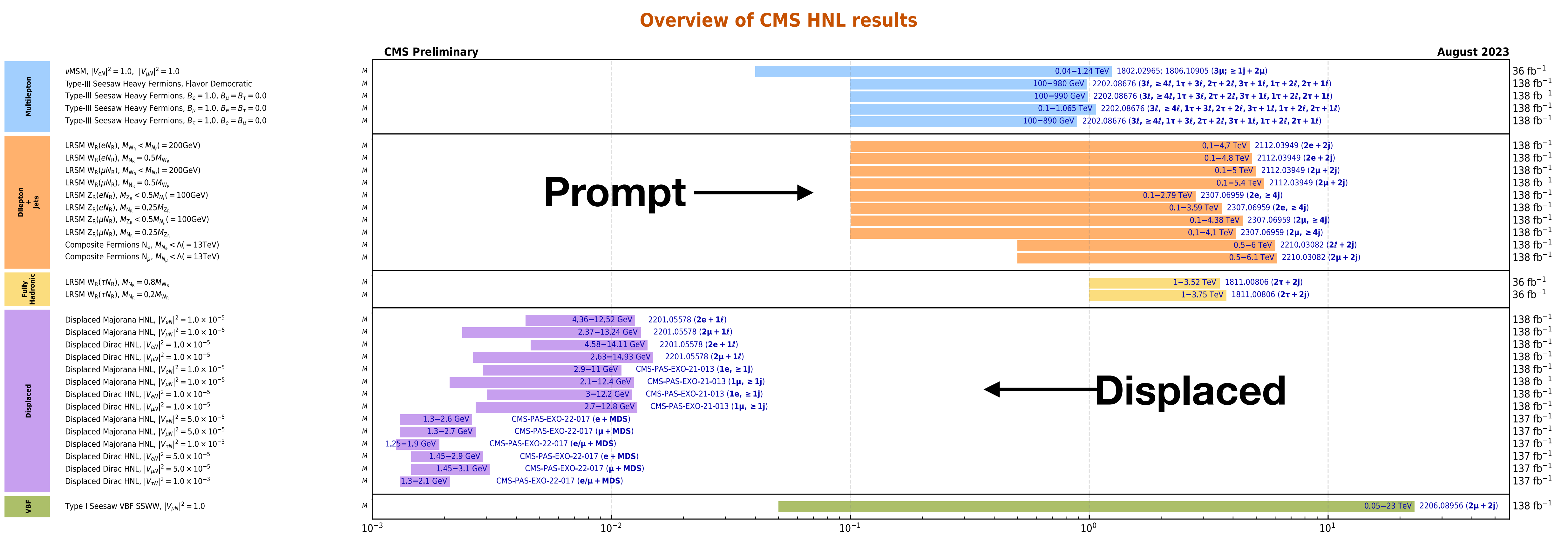
- CMS is a hermetic, general purpose detector submerged in strong solenoidal magnetic field



HNL searches at CMS

- Prompt HNLs:
  - Probe different HNL models and/or final states (Multi-lepton / $2\ell + j$ / $2\tau + 2j$)
  - 100 GeV ~ TeV
- Displaced HNLs:
  - Typically type-I see-saw model, produced through W
  - ~1 - 10 GeV
- **The list is growing!**

pdf

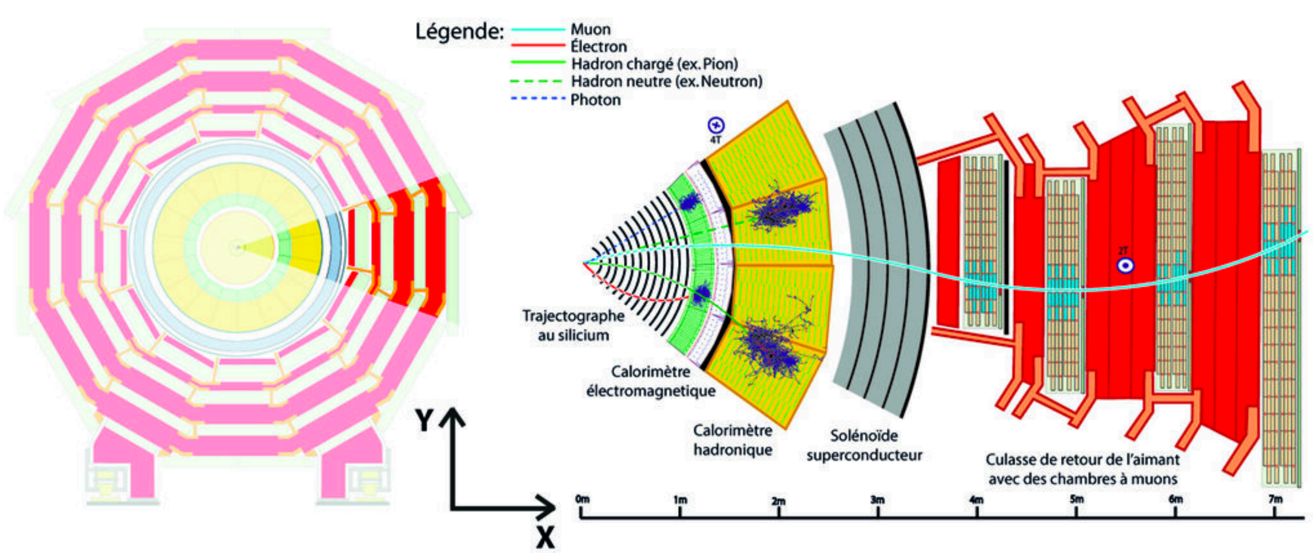


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

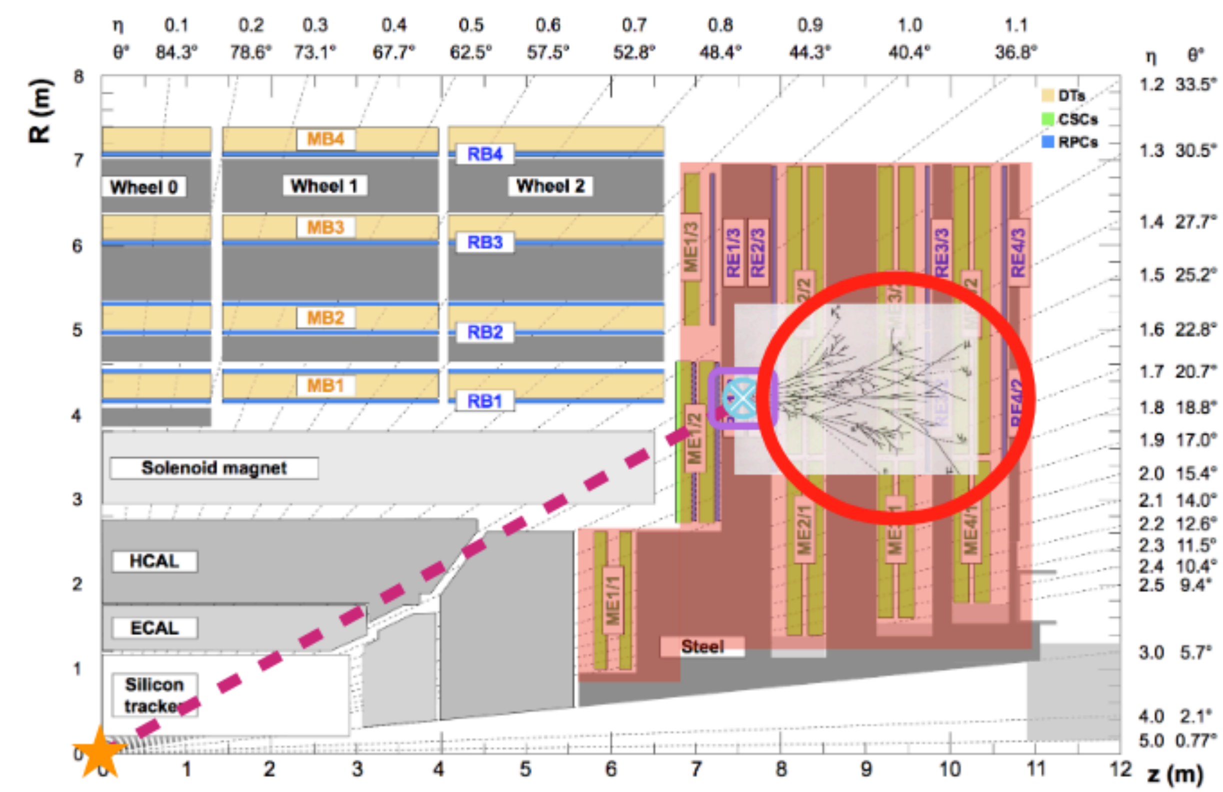
Fermilab

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)
  - Unique feature of CMS muon system

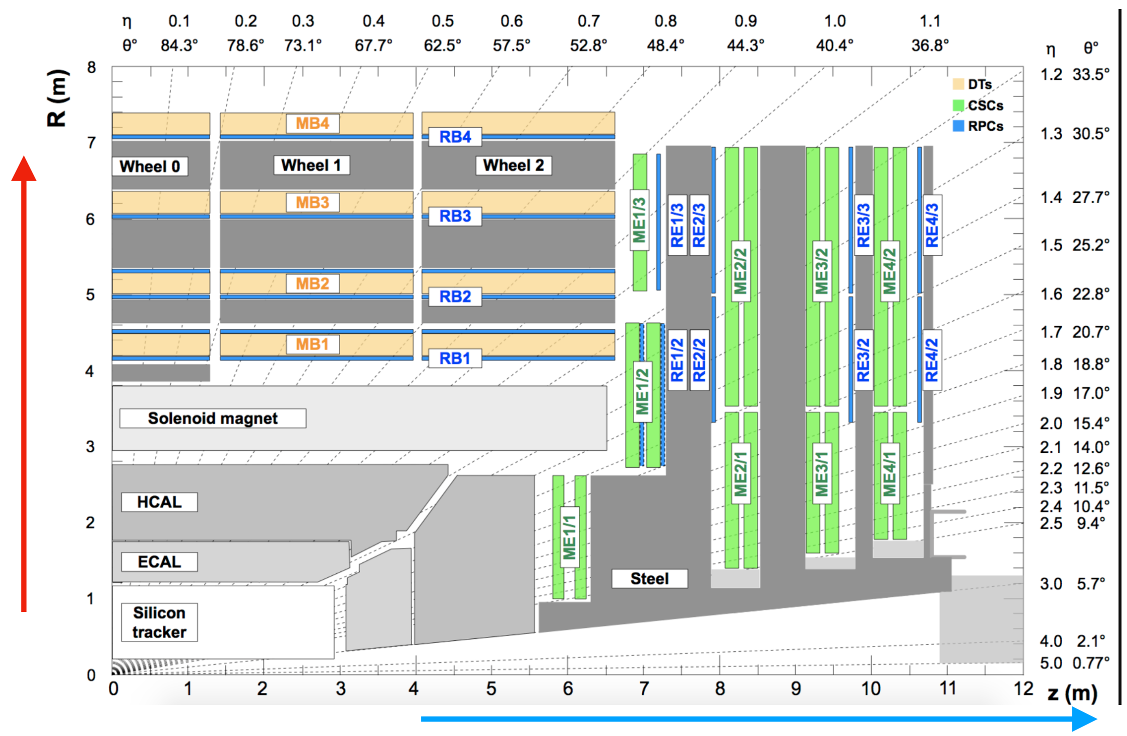


SM particles seen at CMS

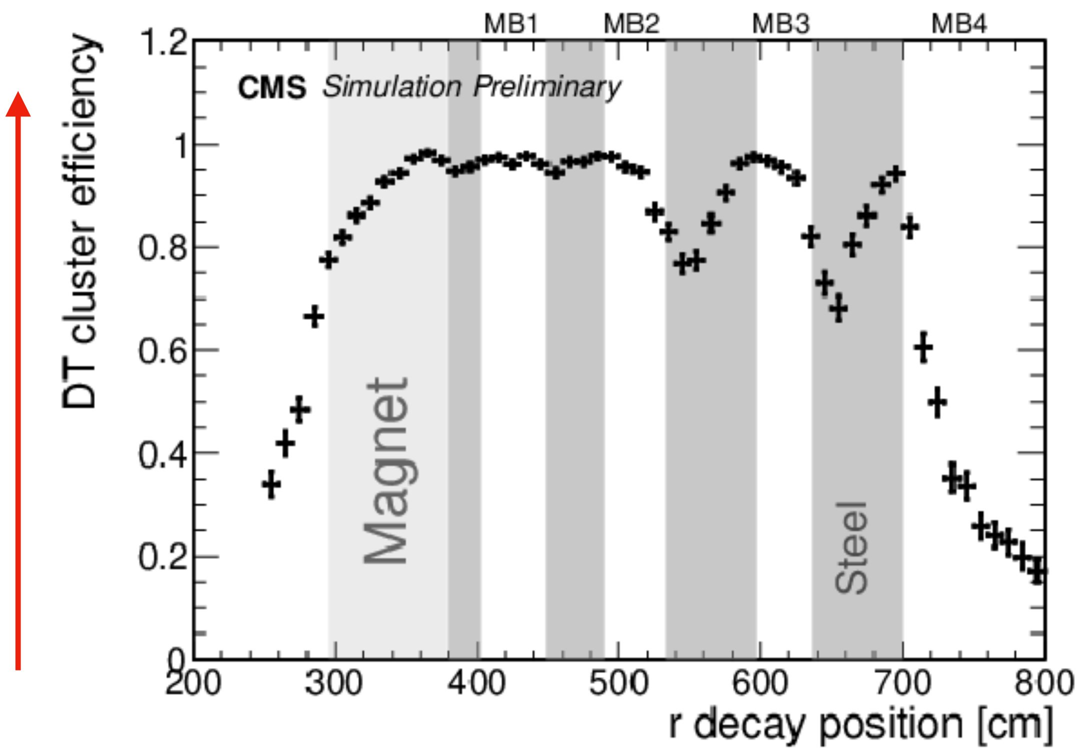


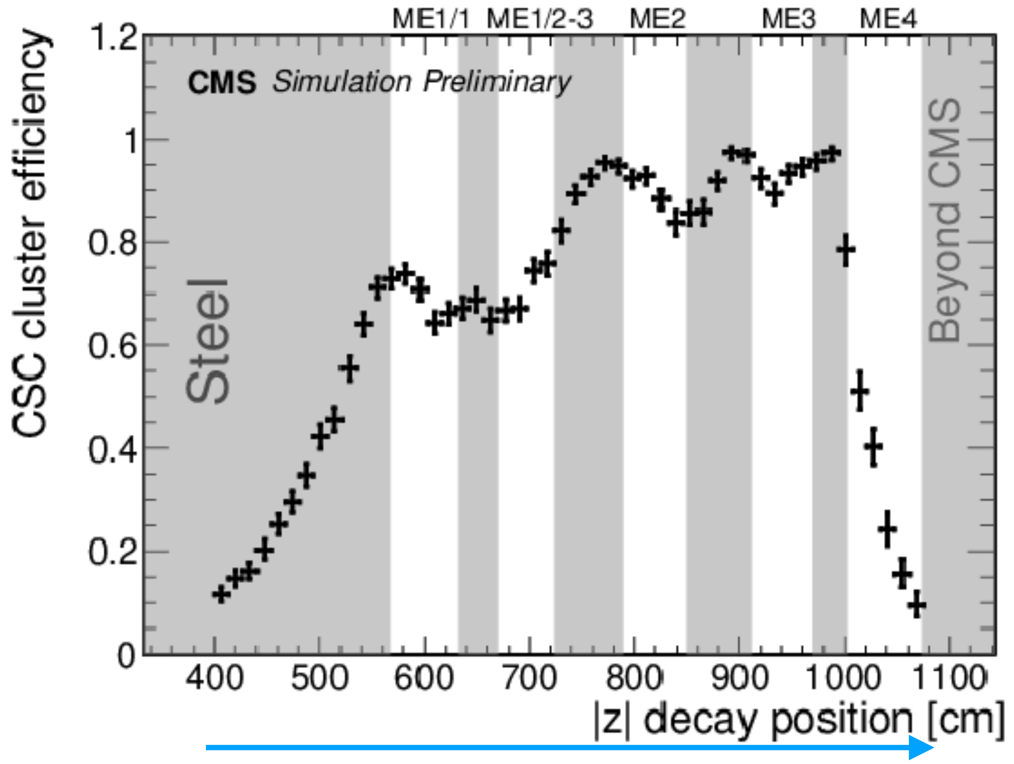
LLP as Muon Detector Shower

Muon Detector Shower (MDS)



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





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

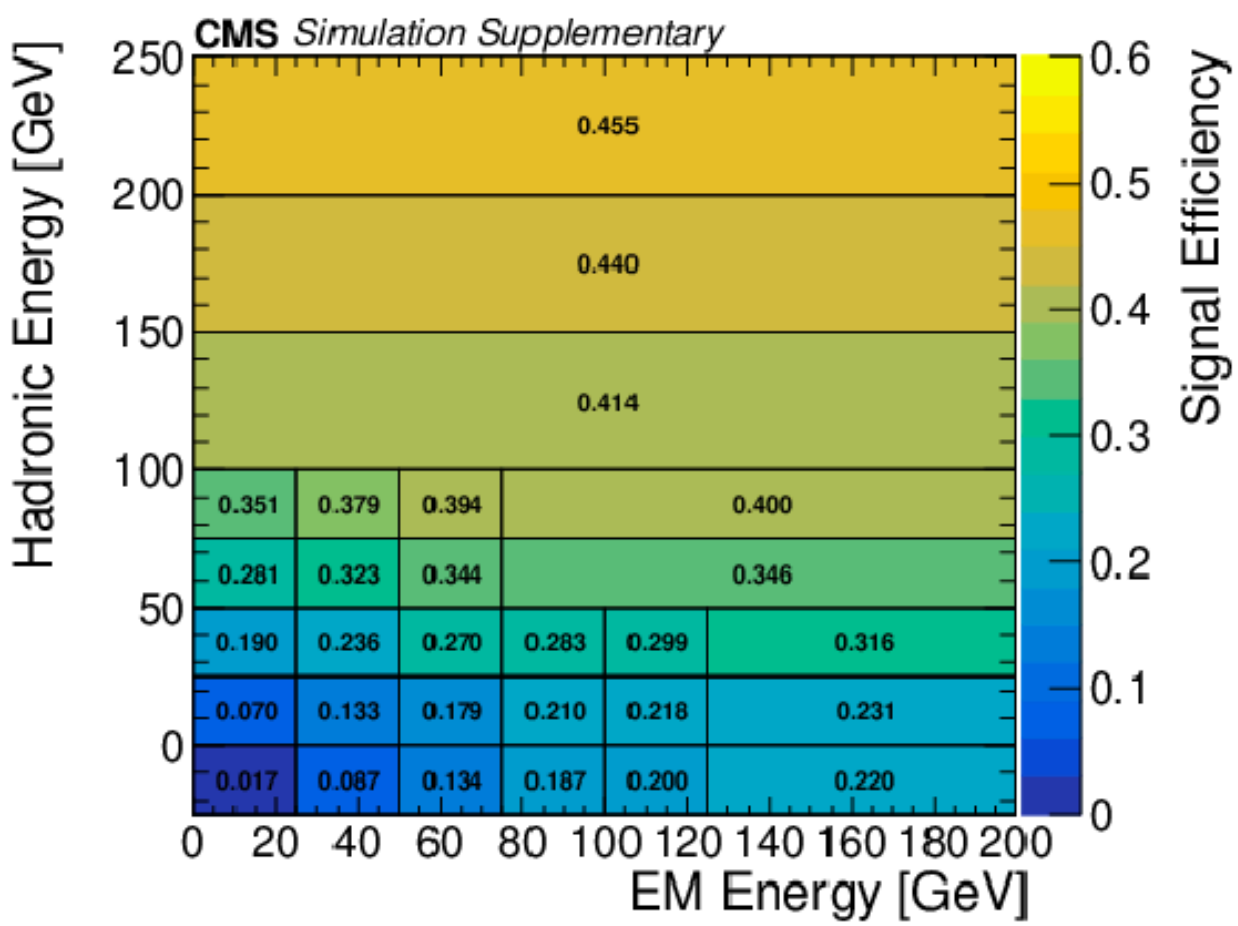
CMS-PAS-EXO-21-008

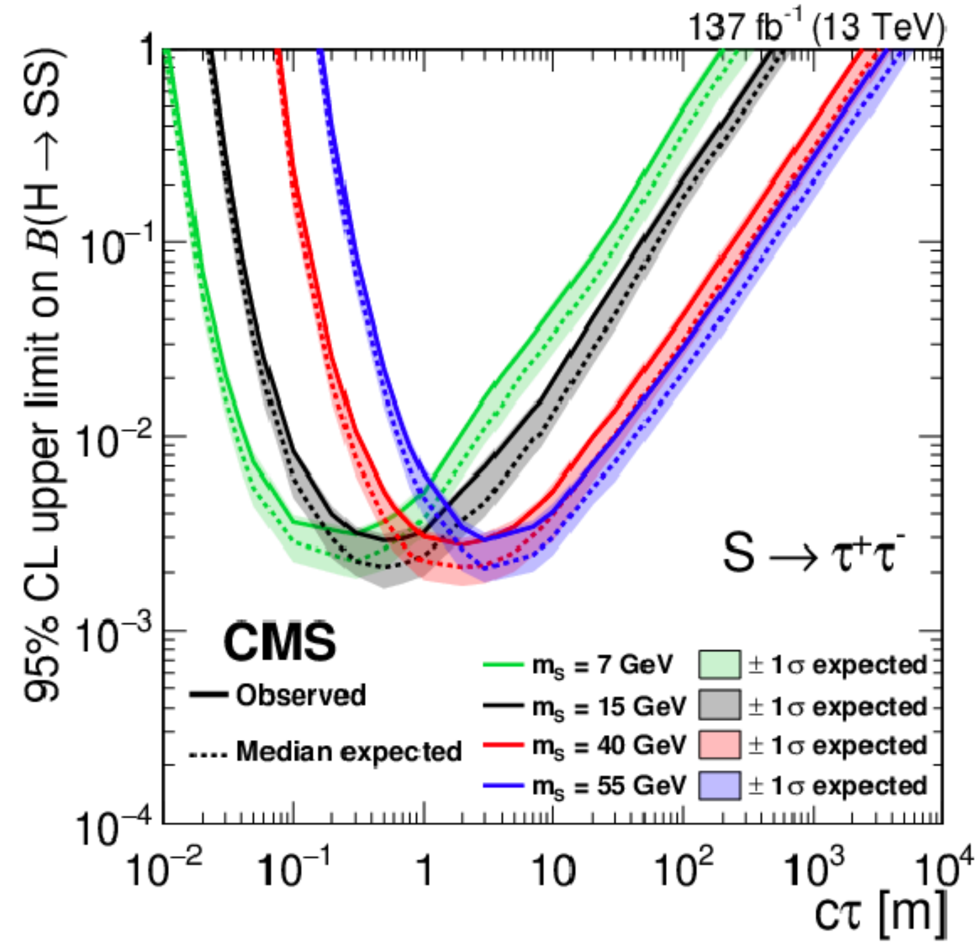
Fermilab

Muon Detector Shower (MDS)

EXO-20-015

- Cluster efficiency can be well parametrized by the hadronic energy and EM energy of the LLP
- Independent of LLP mass!

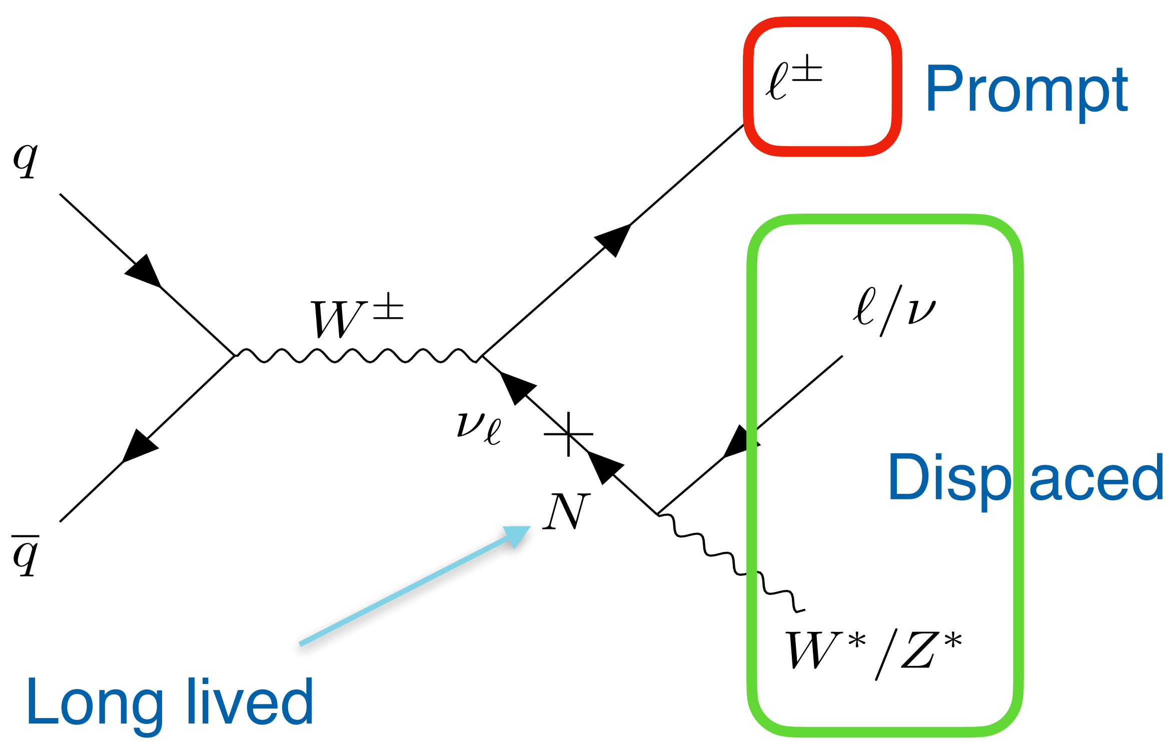


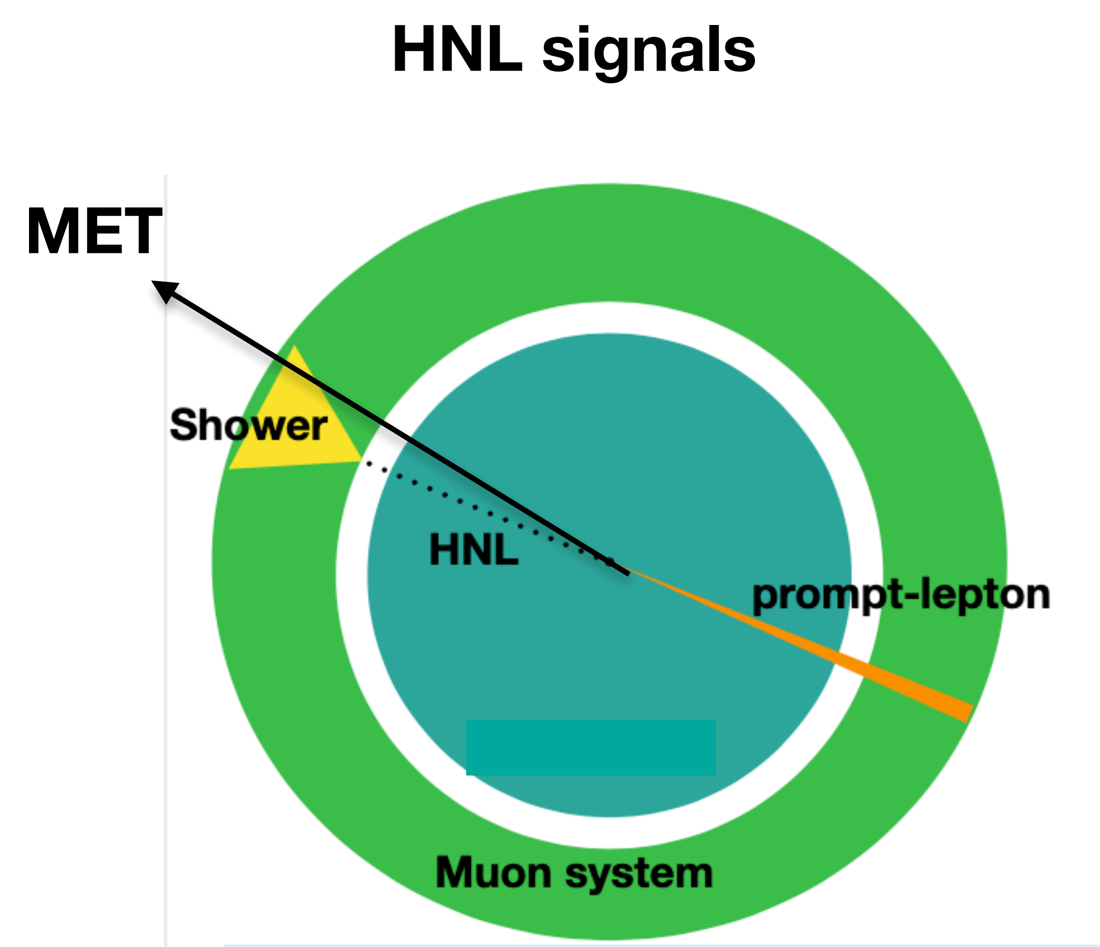


Searching long-lived HNL with MDS

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

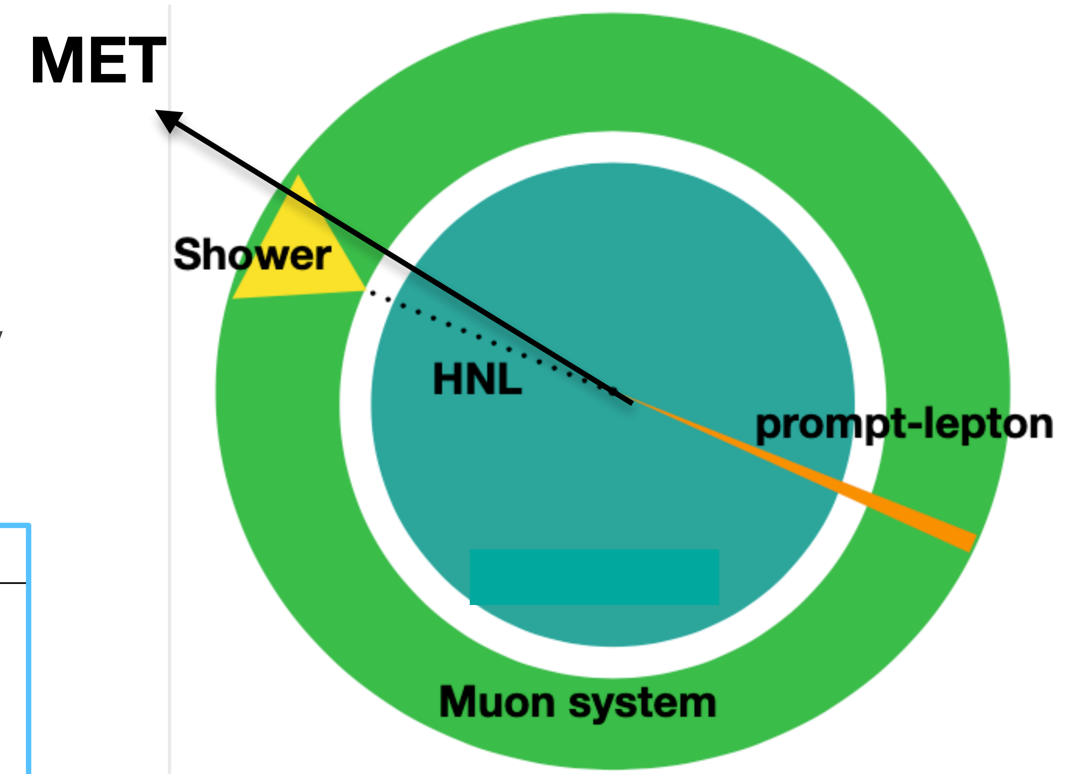




Analysis Strategy

- Prompt Lepton selections:
  - One tight ID electron/muon for good triggering efficiency
  - Dominated SM background: W+Jets

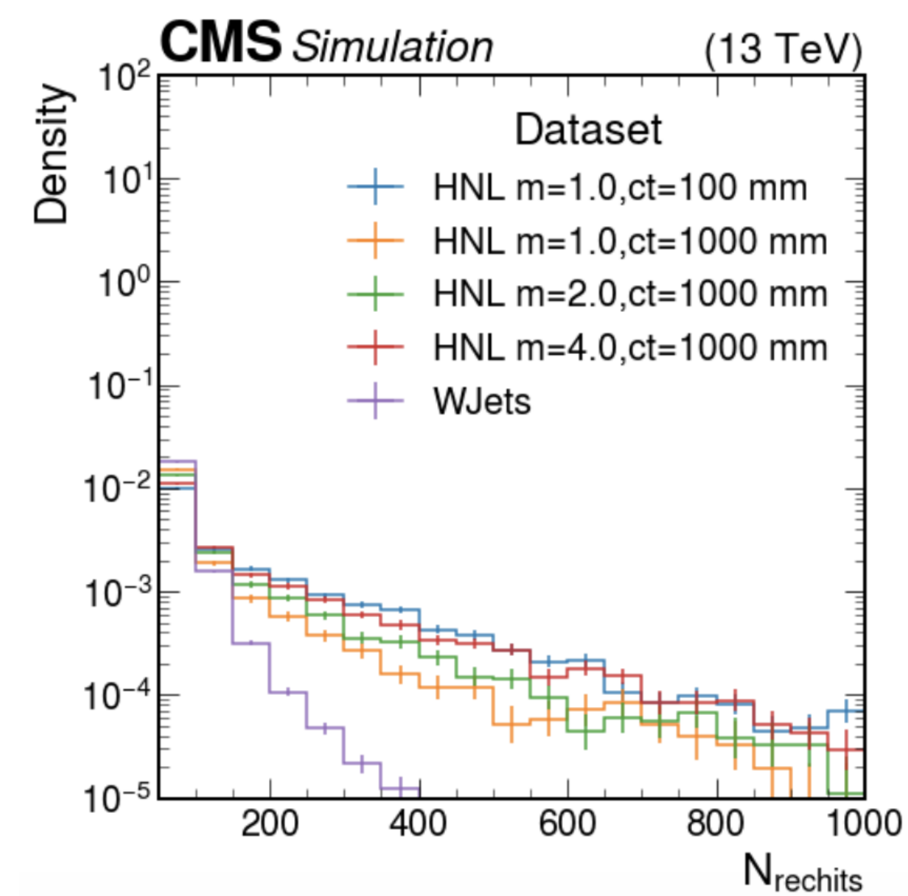
Object	Muon Channel	Electron Channel
Lepton	$p_T > 25(28) GeV, \|\eta\| < 2.4$	$p_T > 30(35) GeV, \|\eta\| < 2.4$
Lepton	TightID, $I_{rel} < 0.15$	TightID
Lepton	N_{lepton}=1	
MET	$p_T^{miss} > 30$ GeV	



- Cluster selections:
  - Improve S/B ratio
  - Veto specific patterns of extra detector activities to suppress punch-through jets/ muon bremm.

- Cluster size (Nhit) as main discrimination
  - ABCD method with $\Delta\phi$(cluster,lep) and cluster size

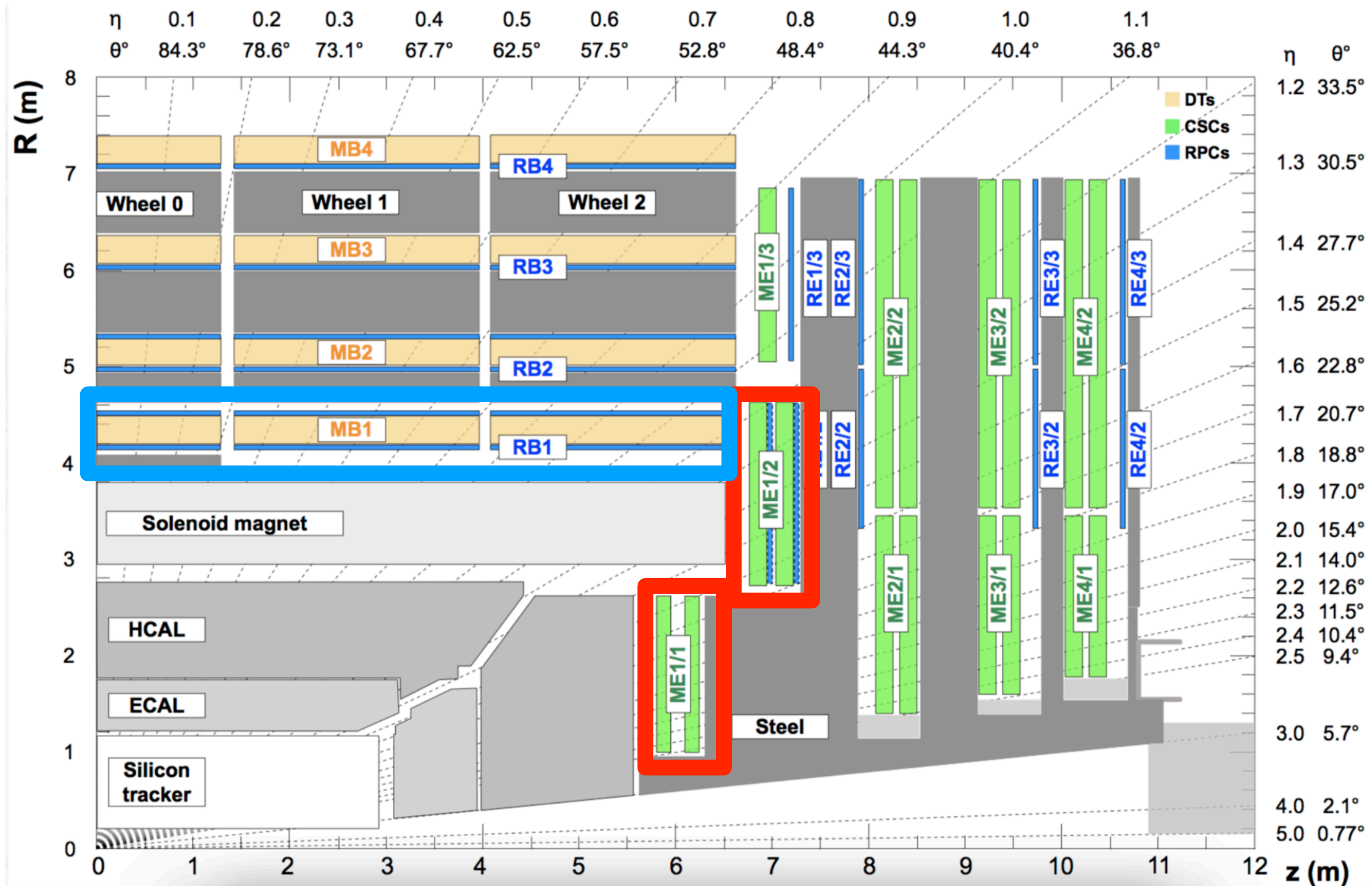
- Validate with control region(s)



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
- DT:
  - Veto clusters with > 1 RecHit in MB1 and in adjacent wheel
  - Veto region with no instrumentation (DT chimney)



Fermilab

Event selection summary

Object	Muon Channel	Electron Channel
Lepton	$p_T > 25GeV, \|\eta\| < 2.4$	$p_T > 35GeV, \|\eta\| < 2.4$
Lepton	TightID, $\sigma_{IP3D} < 4$, $I_{rel} < 0.15$	TightID
Lepton	N_{lepton}=1	
MET	$p_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV	
CSC cluster	$N_{rechits} > 50$	
CSC cluster	No muons with $p_T > 20$ GeV,$\|\eta\| < 2.4$ within $\Delta R(cls, \mu) < 0.8$	
CSC cluster	No jets with $p_T > 10$ GeV,$\|\eta\| < 2.4$ within $\Delta R(cls, j) < 0.4$	
CSC cluster	No ME-11/ME-12 hits matched within $\Delta R < 0.4$	
CSC cluster	No RE1/2 rechits matched within $\Delta R < 0.4$	
CSC cluster	No MB1 segments or RB1 rechits matched within $\Delta R < 0.4$	
CSC cluster	$-5ns < t_{cluster} < 12.5ns$	
CSC cluster	$t_{spread} < 20ns$	
CSC cluster	Cut-based ID, see [9]	
DT cluster	$N_{rechits} > 50$	
DT cluster	No muons with $p_T > 10$ GeV,$\|\eta\| < 3.0$ within $\Delta R(cls, \mu) < 0.8$	
DT cluster	No jets with $p_T > 20$ GeV,$\|\eta\| < 3.0$ within $\Delta R(cls, j) < 0.4$	
DT cluster	No more than 1 MB1 hits within $\Delta R < 0.5$	
DT cluster	Matched to >= 1 RPC hit(s) in the same wheel within $\Delta\phi < 0.5$	
DT cluster	Mode of the BX of RPC hits=0, RPC matched within $\Delta\phi < 0.5$	

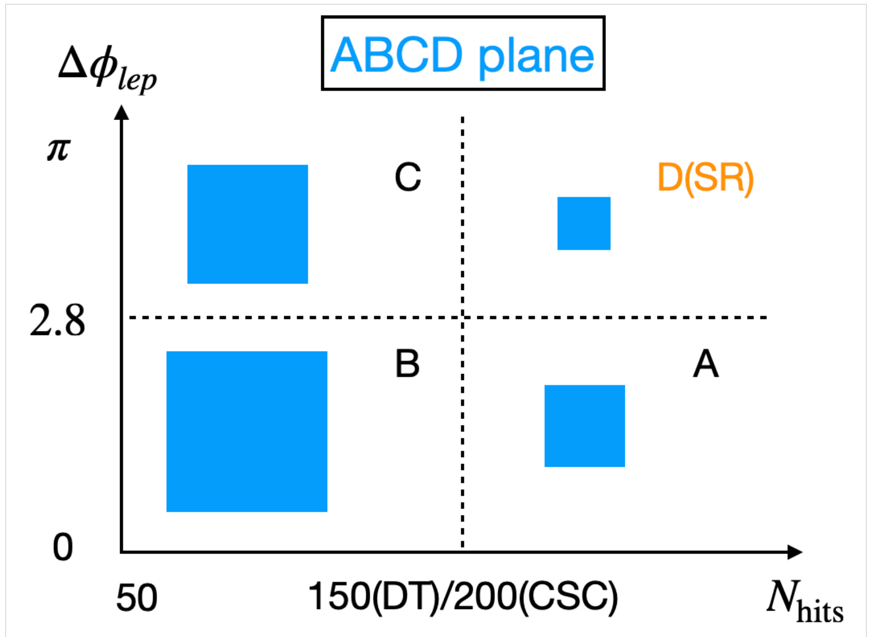
Event-level selection: suppress QCD backgrounds

Veto background sources: Punch-through jets Muon brem.

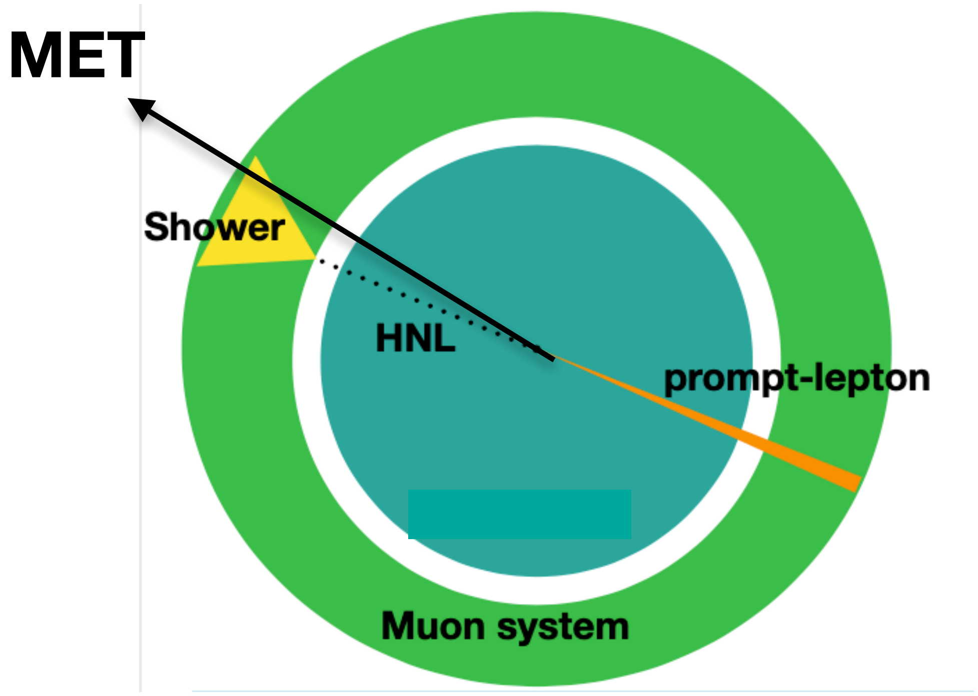
Timing selection: Remove OOT pileup

ABCD background estimation

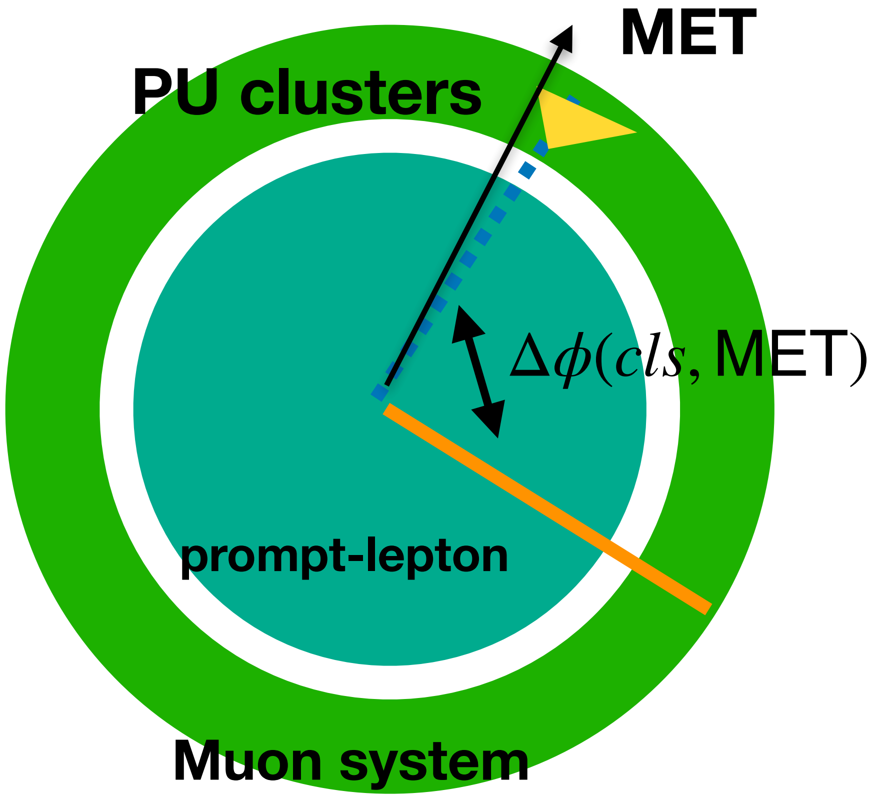
- After cluster selections, background clusters and leptons are uncorrelated
  - Use ABCD method with N_{hits} and $\Delta\phi_{lep}$
  - Signals are back-to-back with cluster with large N_{hits}
- Use Out-of-Time(OOT) and in-time large $\Delta\phi(cls, \text{MET})$ region as validation of ABCD method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



HNL signals



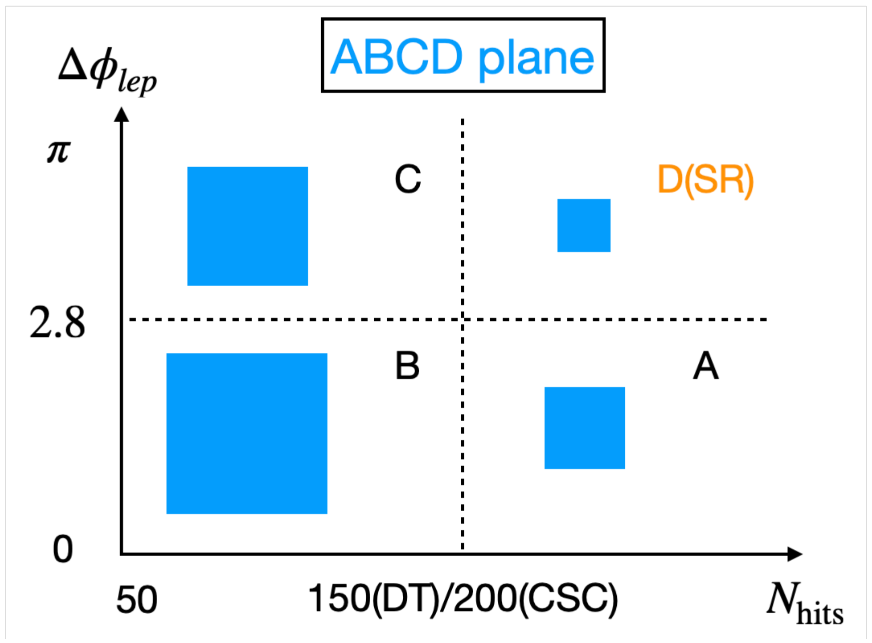
Backgrounds



Fermilab

ABCD background estimation

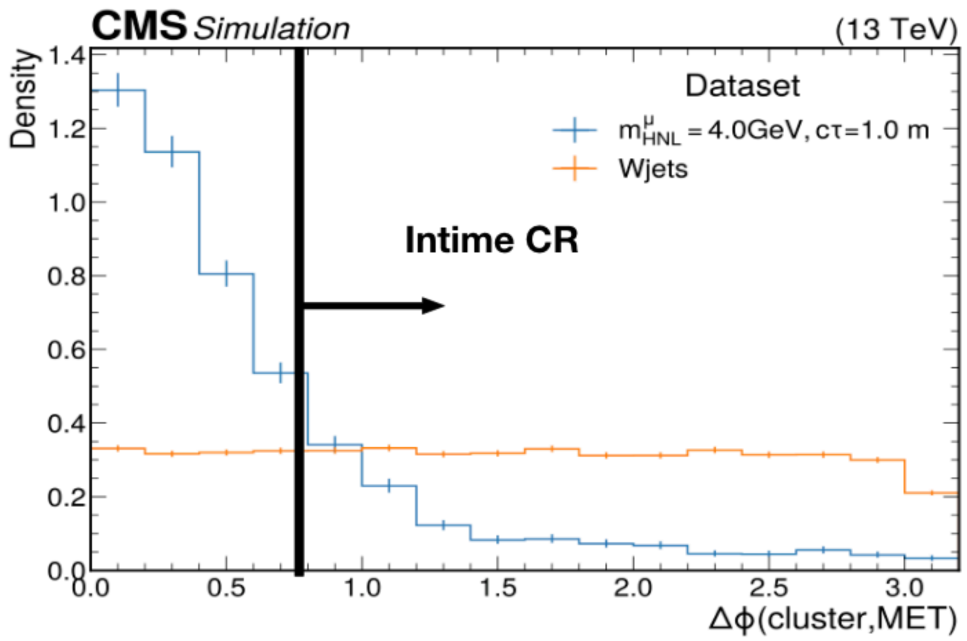
- After cluster selections, background clusters and leptons are uncorrelated
  - Use ABCD method with N_{hits} and $\Delta\phi_{lep}$
  - Signals are back-to-back with cluster with large N_{hits}
- Use Out-of-Time(OOT) and in-time large $\Delta\phi(cls, \mathrm{MET})$ region as validation of ABCD method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

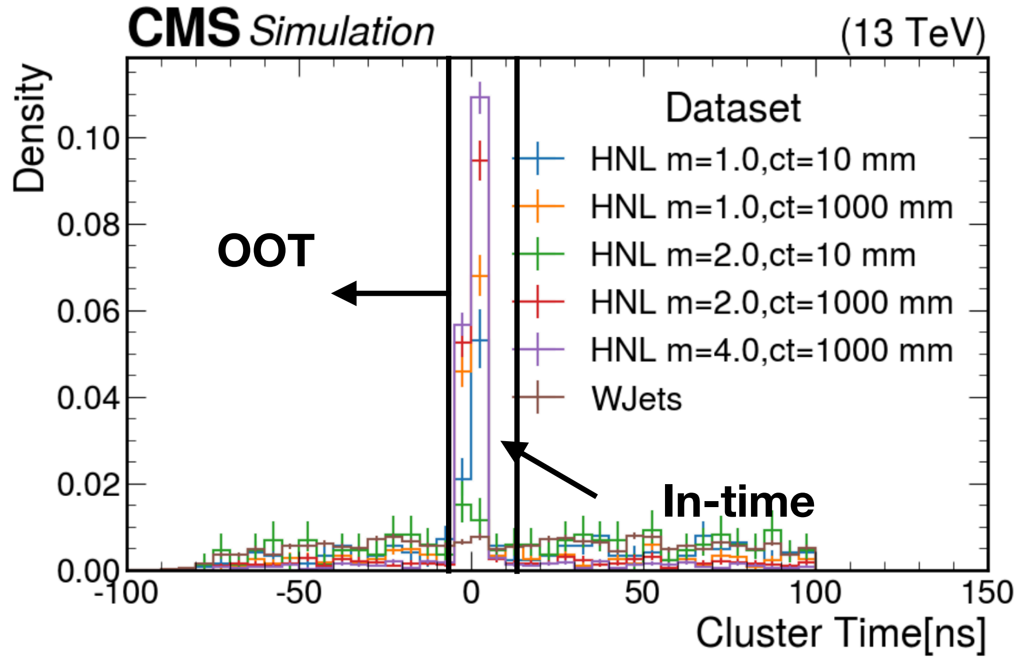


In-time CR

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)

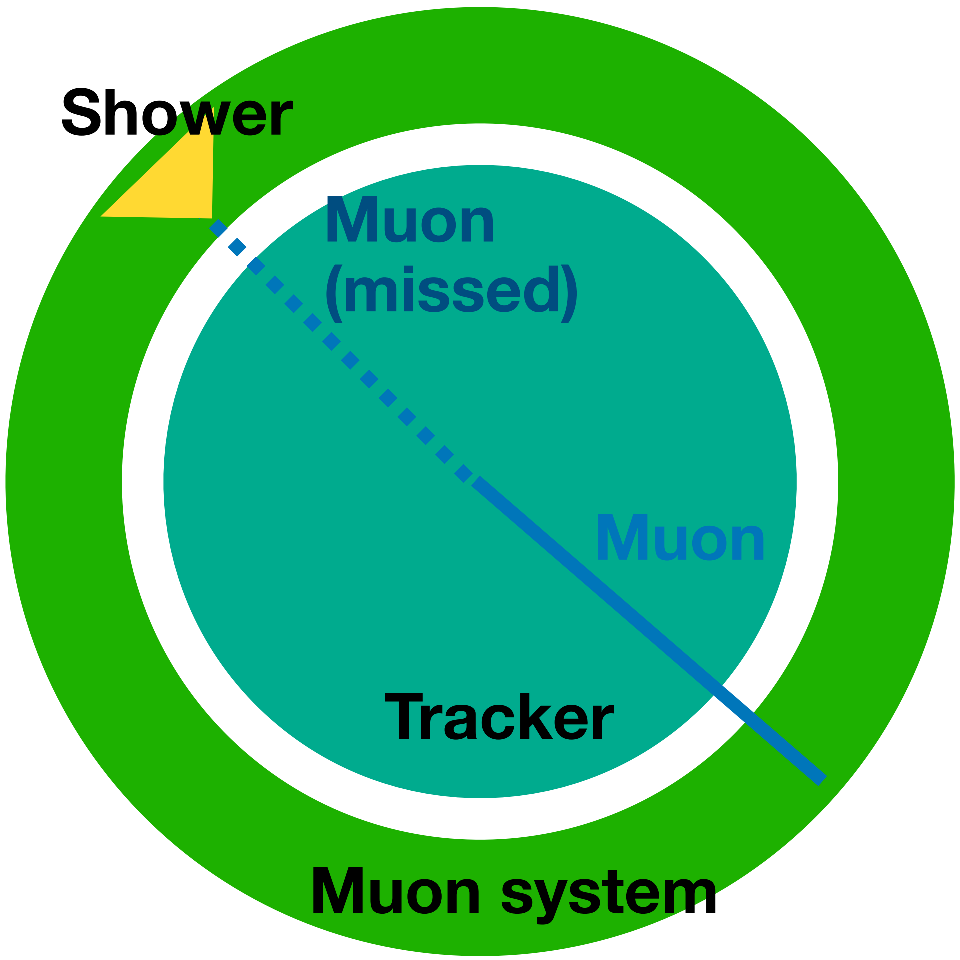
Event category	Validation region	A	B	C	D	D (pred.)
Muon, DT-MB2	OOT	9	6924	944	0	1.2 ± 0.4
Muon, DT-MB3/MB4	OOT	11	593	86	1	1.6 ± 0.5
Muon, CSC	OOT	103	31074	4044	9	13.4 ± 1.3
Electron, DT	OOT	14	3301	366	2	1.6 ± 0.4
Electron, CSC	OOT	33	13774	1647	2	4.0 ± 0.7
Muon, DT-MB2	In time	10	5087	467	2	0.9 ±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

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

- Bkg not tested in the closure-test : $Z \rightarrow \mu\mu$ bkg
- $Z \rightarrow \mu\mu$ could be an addition background process if
  - One muon not reconstructed, but creates showers in the muon system
  - Since muon is not reconstructed, create fake MET in the event

- 4 steps to predict the Zmumu bkg:
  1. Define Zmumu-enriched CR region (inverting ME11/12 and MB1 veto)
  2. Subtract ABCD background in CR
  3. Measure the transfer factor from CR to SR with $t\bar{t}$ sample
  4. Multiply the transfer factor to the Zmumu component in CR:

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



$Z \rightarrow \mu\mu$ background summary

- Summary of $Z \rightarrow \mu\mu$ background prediction

		$W+J$ CR	$Z \rightarrow \mu\mu$ CR	T.F.	$Z \rightarrow \mu\mu$ SR
Region	N_D^{CR}	$\lambda^{CR}_{\mathrm{ABCD\ bkg,D}}$	$\lambda^{CR}_{Z\rightarrow\mu\mu,D}$	ζ	$\lambda^{SR}_{Z\rightarrow\mu\mu,D}$
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

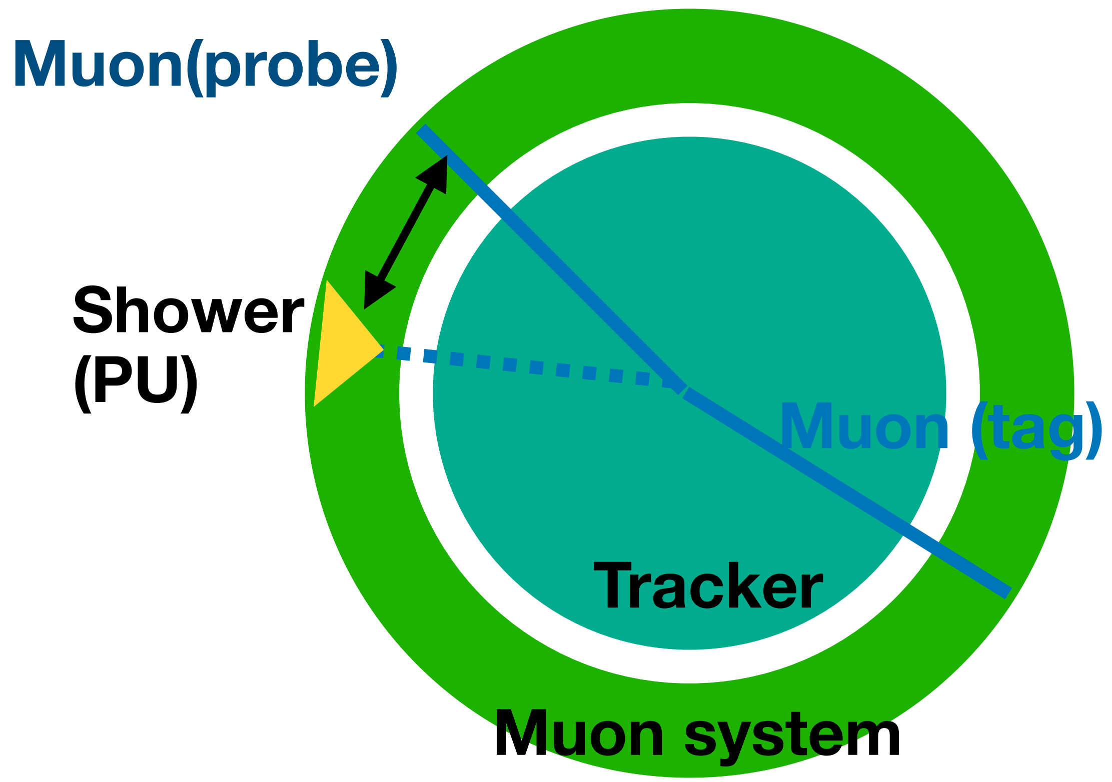
Zmumu Bkg in CR x T.F = Zmumu Bkg in SR

- Checked additional validations with MC and data

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
  - Corrections are applied to account for differences between data/MC if necessary
  - Uncertainties are propagated as systematic unc.



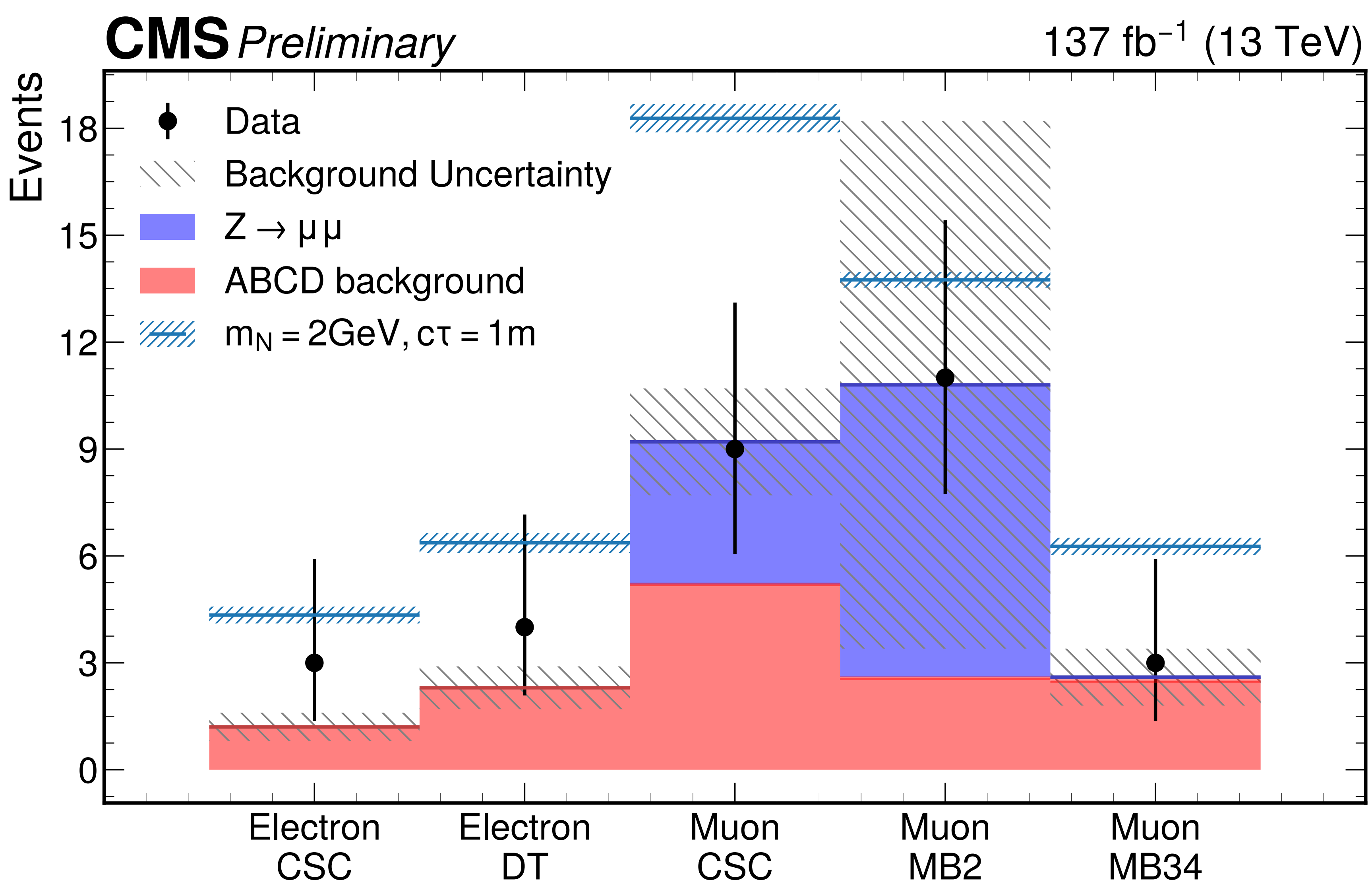
Signal systematics

Systematic Uncertainty	Object	Size of unc.
Luminosity	-	1.6%
Pile-up	-	1%
W cross section	-	3.8%
W p_T	-	1.6%
Trigger	Muon	$< 0.1\%$
Identification	Muon	$0.4 - 0.5\%$
Isolation	Muon	$0.2 - 0.6\%$
Trigger	Electron	$0.2 - 0.3\%$
Identification	Electron	$2.2 - 8.0\%$
Jet energy scale	MET	2.0%
Cluster reconstruction	CSC cluster	13%
Cut-based ID	CSC cluster	5.1%
Jet veto	CSC cluster	0.06%
Muon veto	CSC cluster	4.5%
CSC readout	CSC cluster	1.0%
Hits and segment veto	CSC cluster	0.1%
Cluster time	CSC cluster	0.9%
Cluster time spread	CSC cluster	2.8%
Cluster reconstruction	DT cluster	16%
MB1 veto	DT cluster	7.4%

Result

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

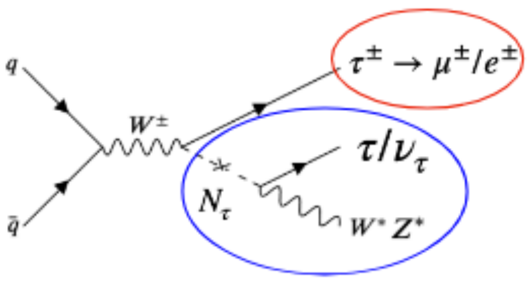
PAS-EXO-22-017

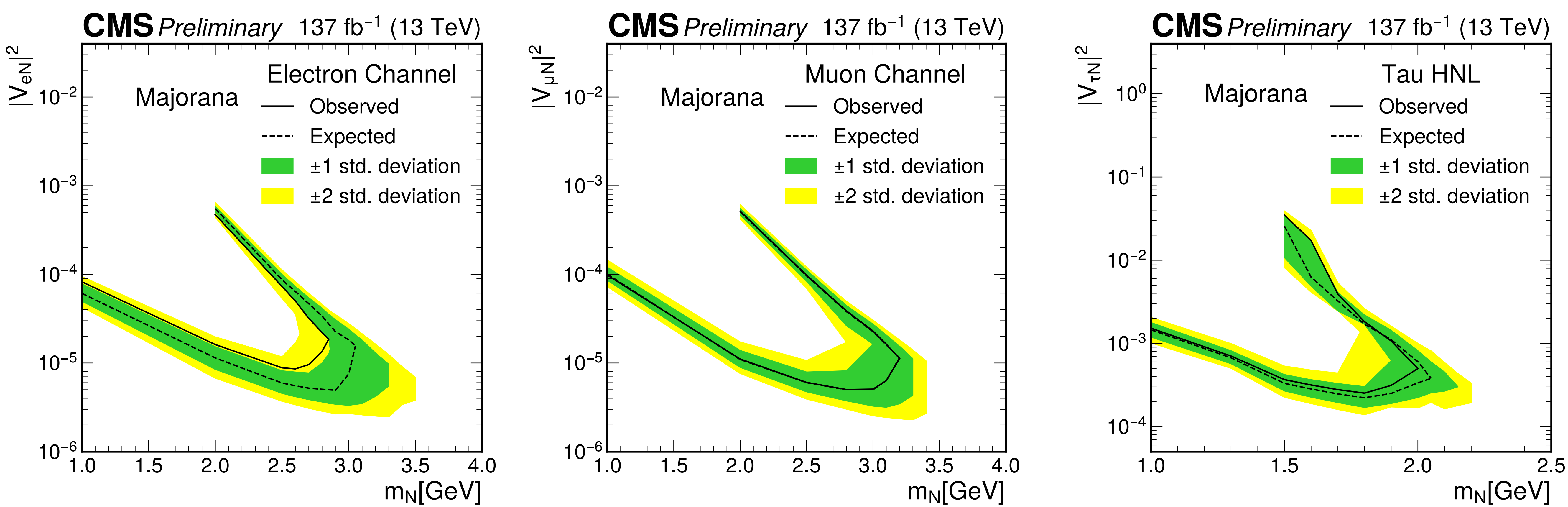


Fermilab

Limits on Majorana HNL

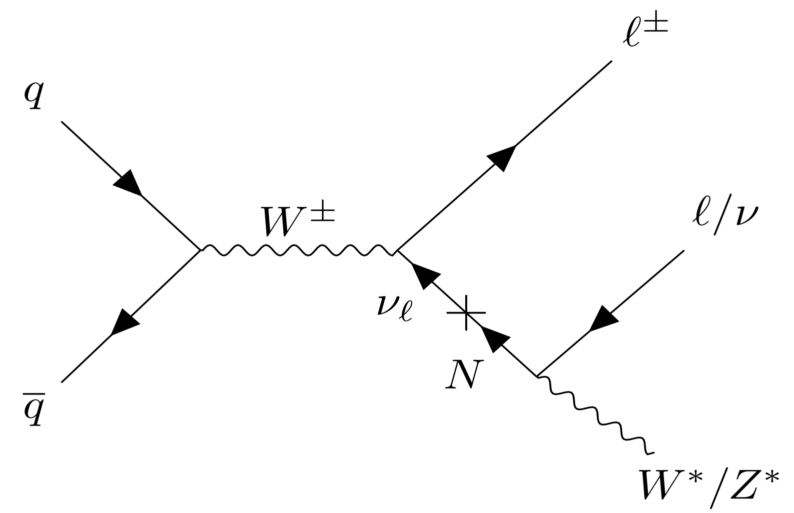
- Probes low-mass/small coupling parameter space
- ~2.3x better than EXO-21-013 in electron (muon) channel at 2GeV
  - Sensitivity driven by CSC channel
- Flavour independence:
  - Can set limit on τ-HNL as well, triggered with muon/e from prompt-τ decay
  - Worse limit than electron/muon type due to trigger acceptance

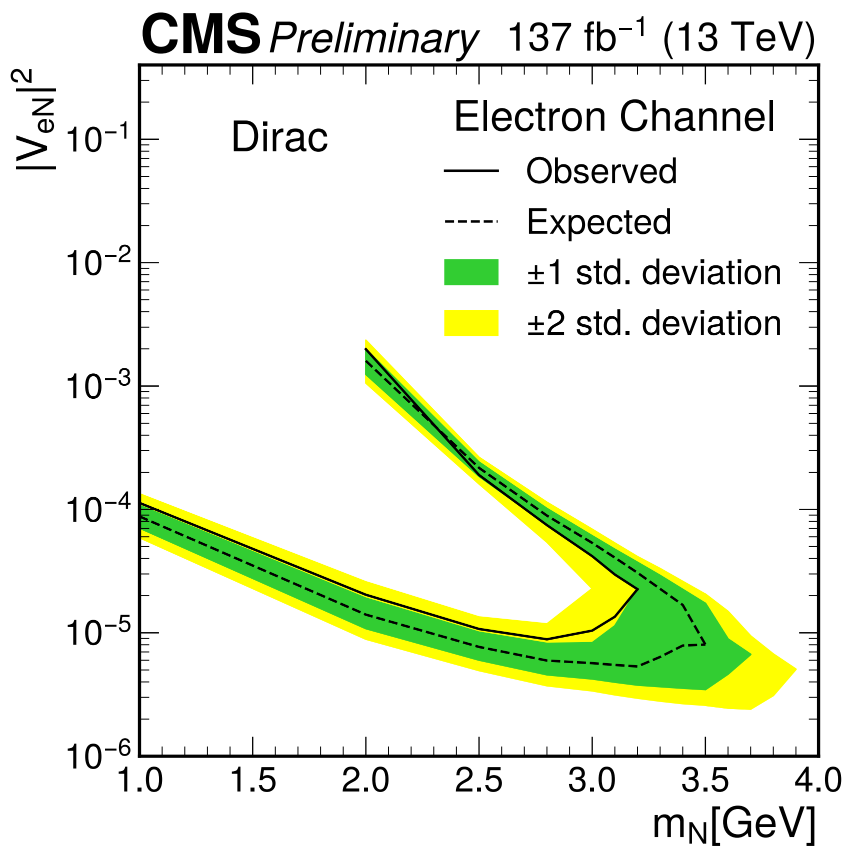


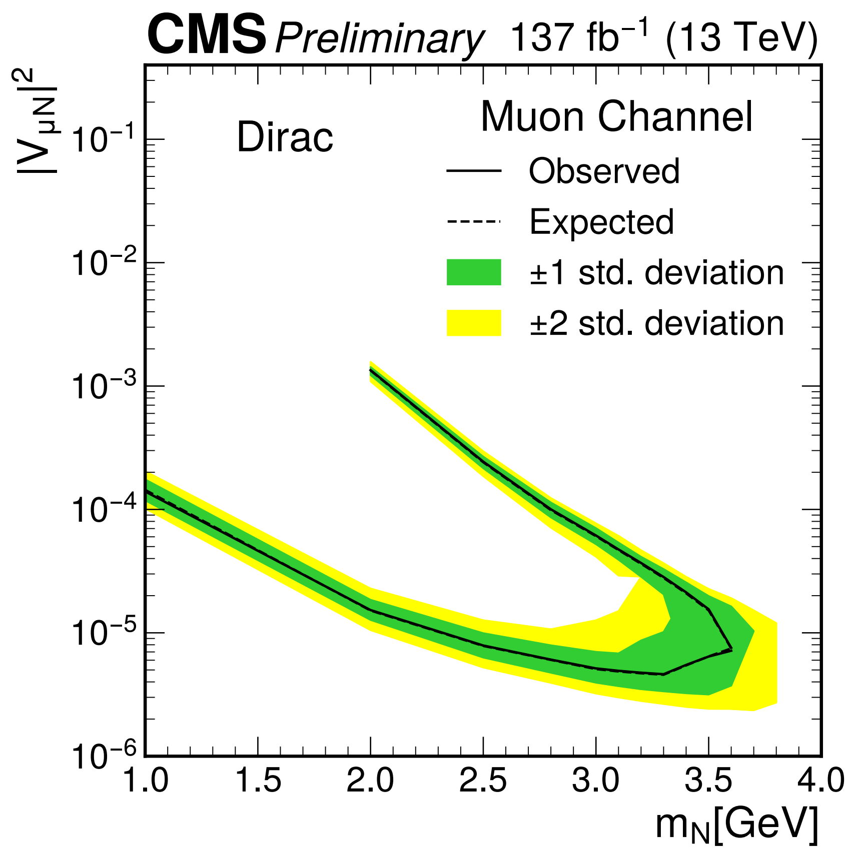


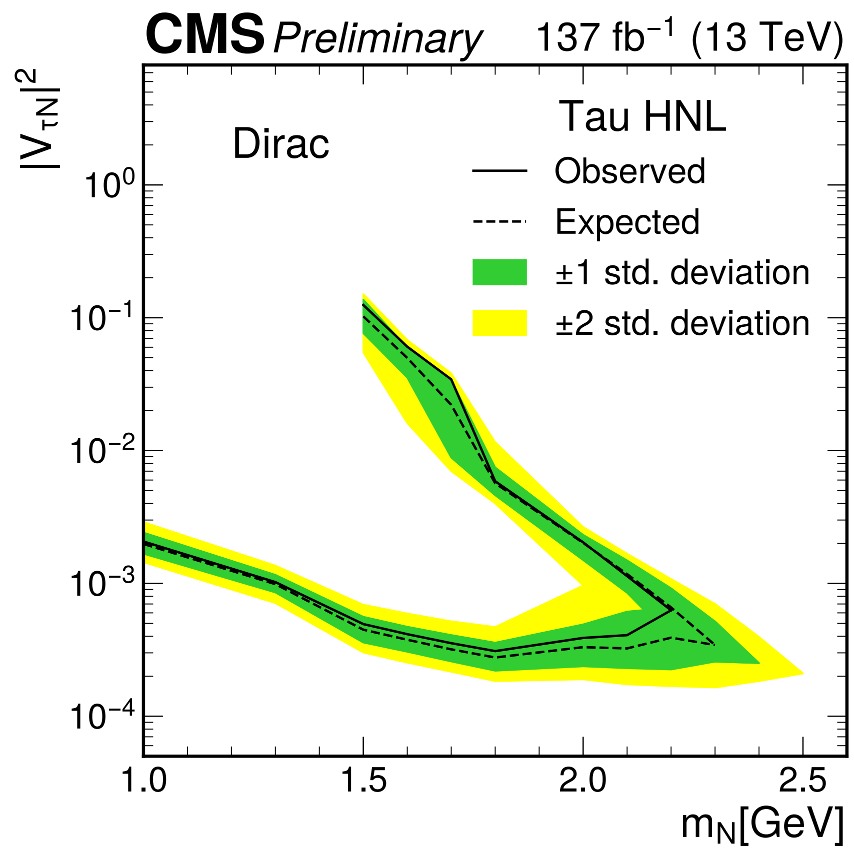
Limits on Dirac HNL

- Also interpreted as Dirac HNL model
- MDS do not distinguish the charge of the lepton final state
  - Not reconstructing the sign of the 2nd lepton
  - Same efficiency/cross-section limit for Dirac/Majorana HNL









Mixed-HNL coupling

- Flavour independence opens up mixed coupling interpretation

$$V = \begin{pmatrix} V_{eN} & 0 & 0 \\ 0 & V_{\mu N} & 0 \\ 0 & 0 & V_{\tau N} \end{pmatrix}$$

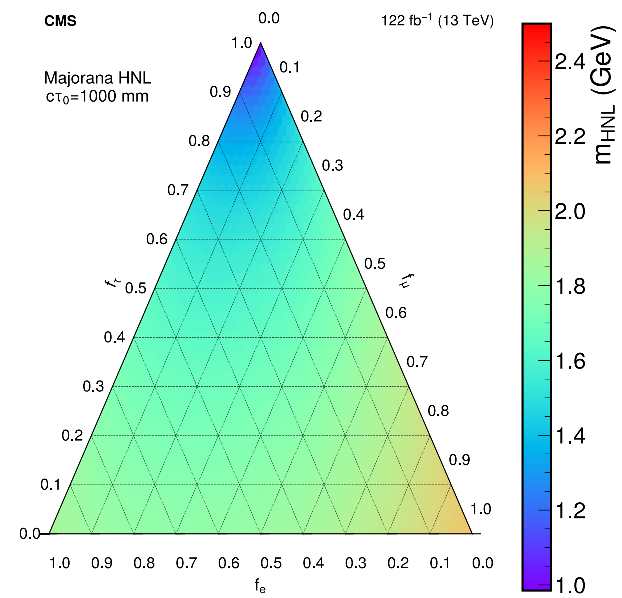
  - Constrains the sum of relative couplings to 1

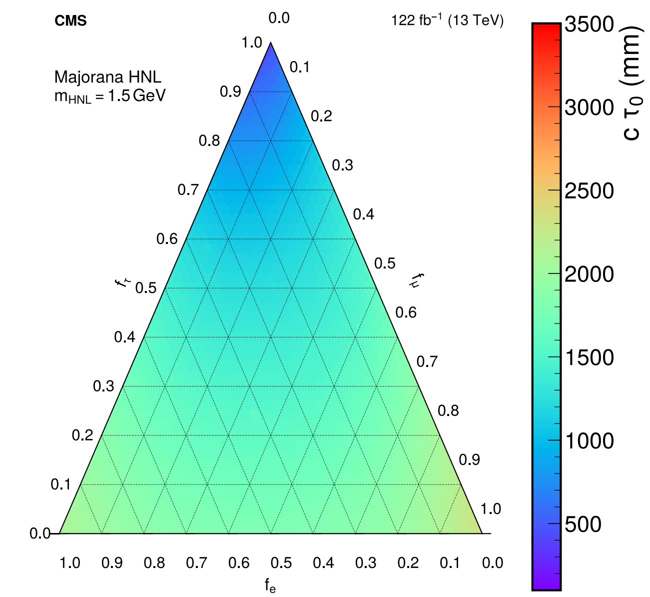
- Selected several benchmark at the edge of our sensitivity

$c\tau = 1m$

$m_N = 1.5$ GeV

Majorana

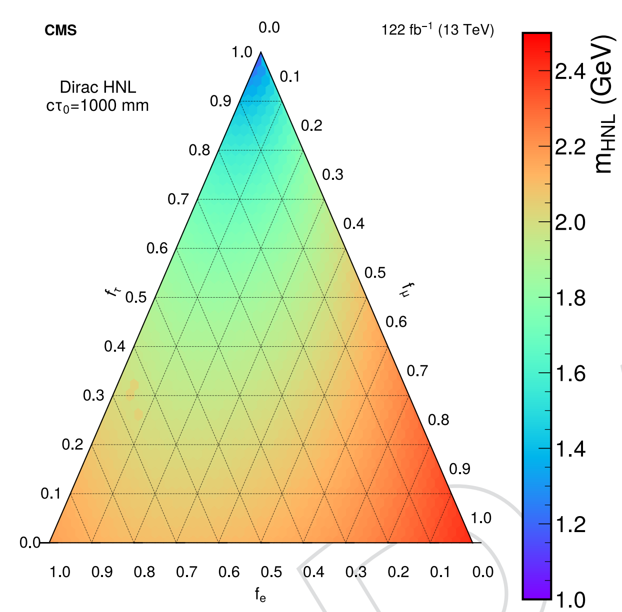


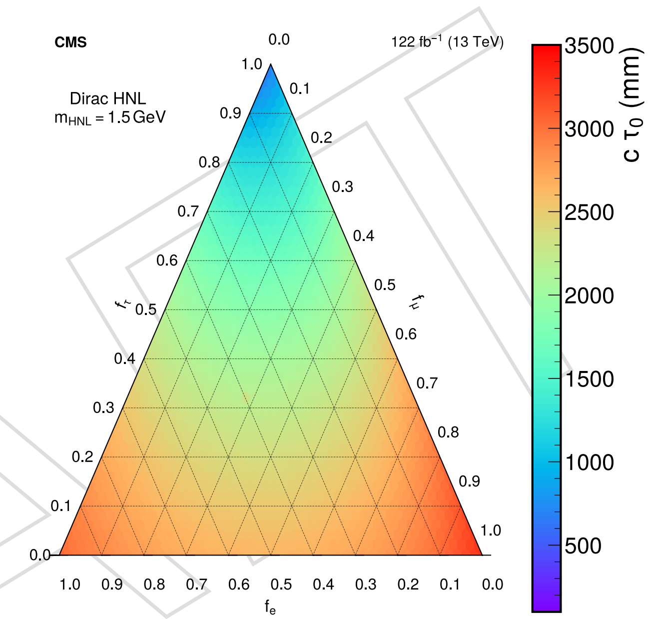


$c\tau = 1m$

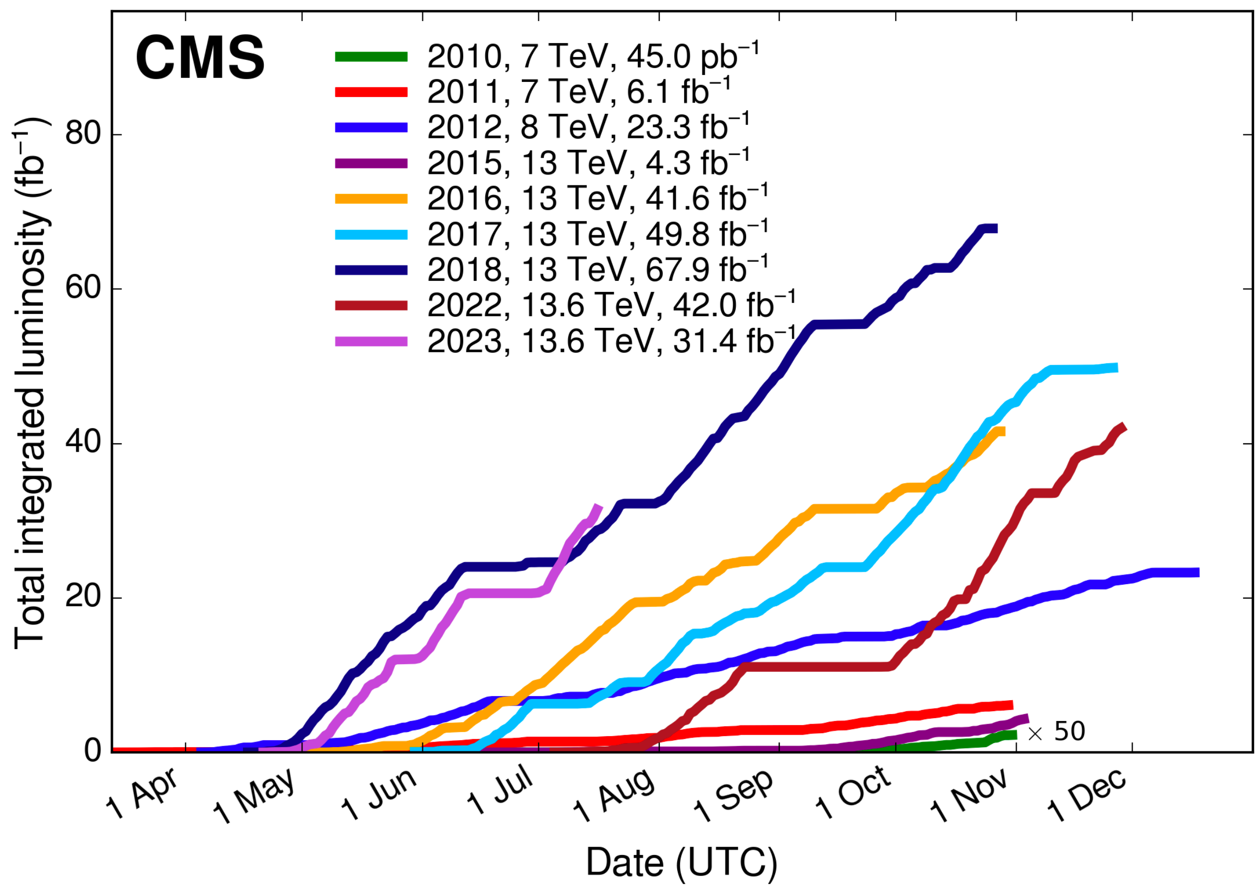
$m_N = 1.5$ GeV

Dirac





Can we do better in Run 3?

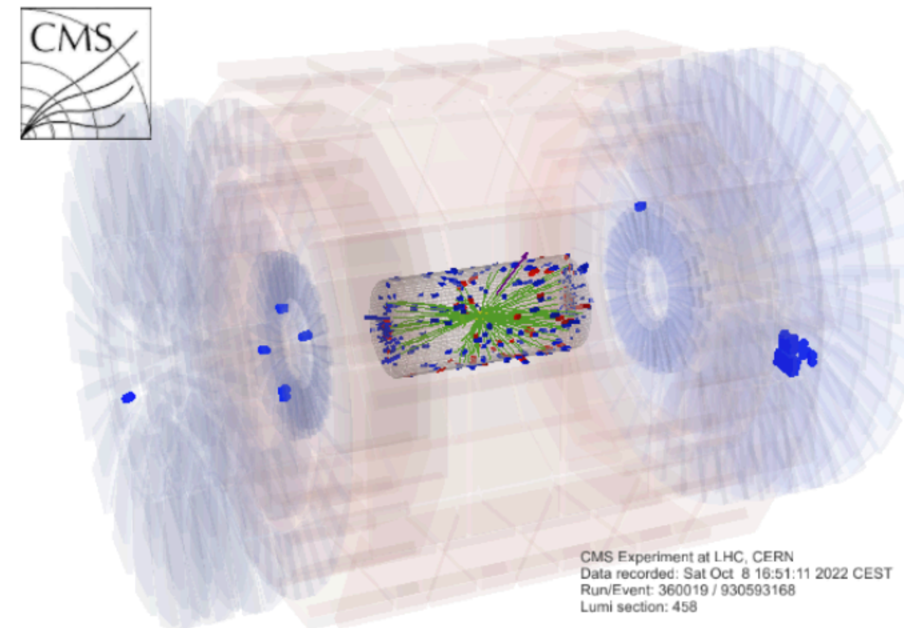


Muon Shower Triggers

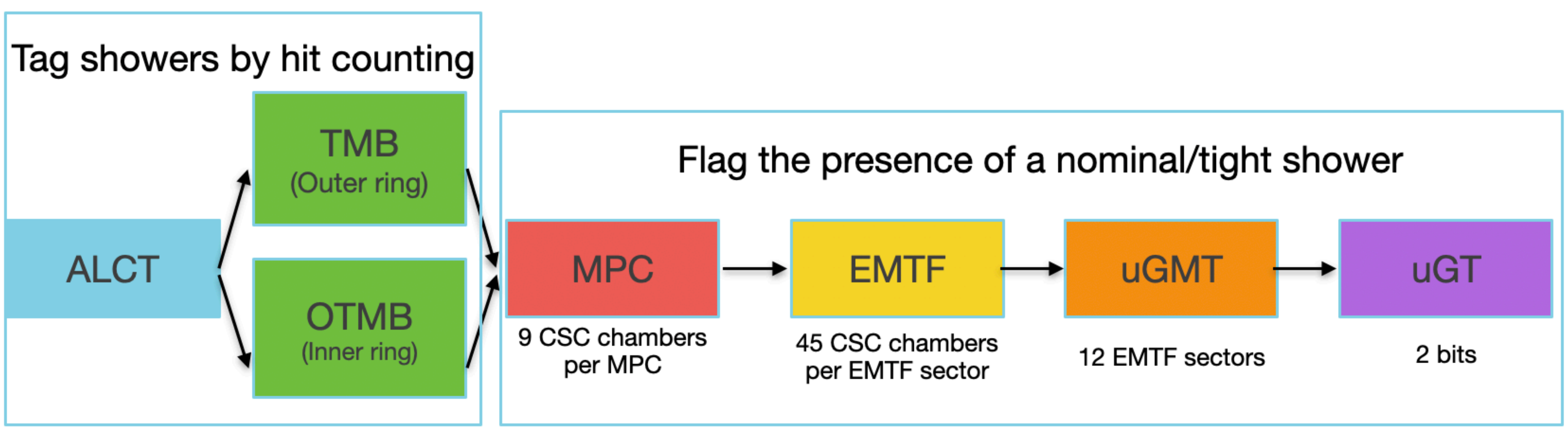
- Many CMS run 2 LLP analysis do NOT have a dedicated LLP trigger
  - Major CMS Run 3 effort
- In MDS's case, the signal acceptance is ~O(1%)
  - Potentially **huge signal gain** from triggering on MDS

- "Simple" algorithm is not simple to implement
- But!
  Commissioned successfully 2022 data taking!

DP note



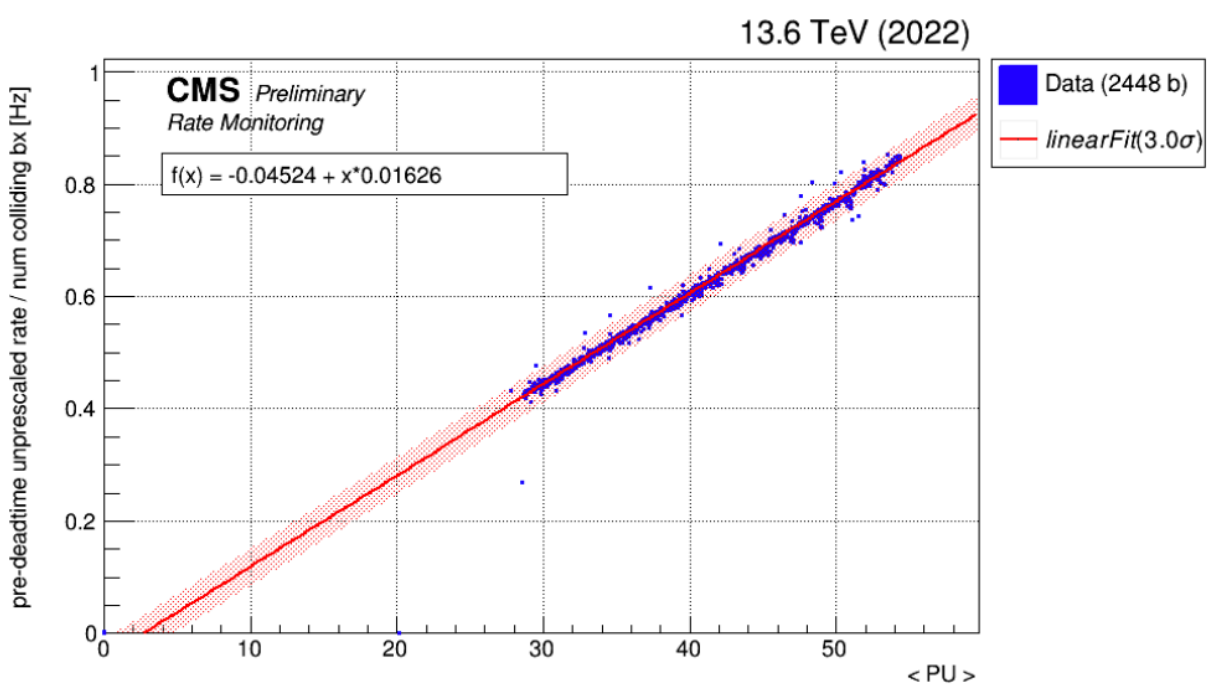
Event display in 2022 data



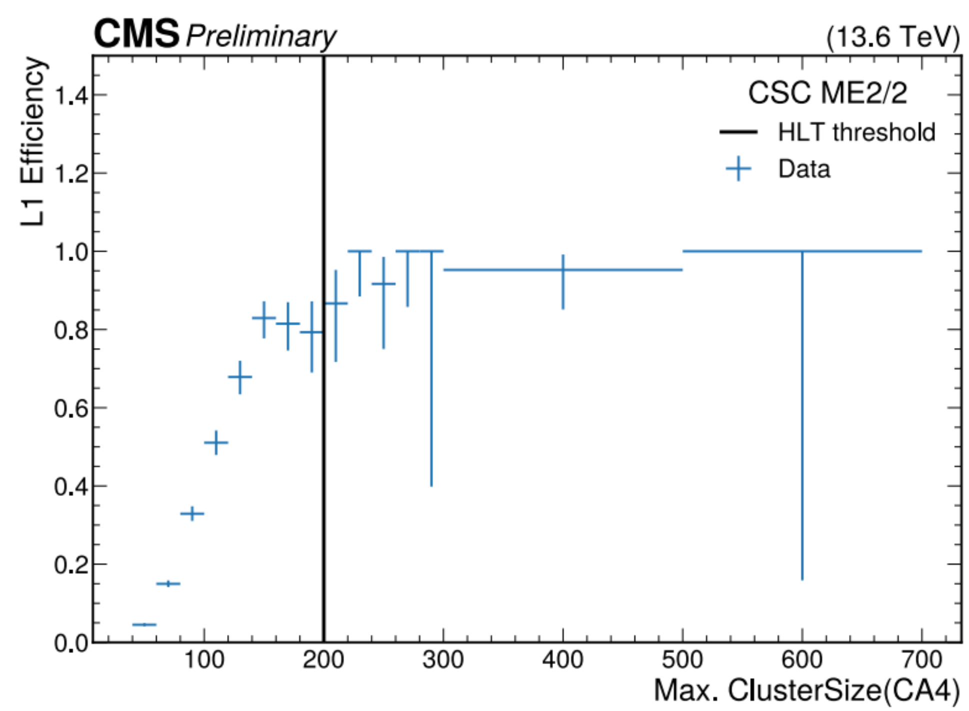
Overview MDS trigger (HMT) logic

Muon Shower Triggers

- New L1 seeds triggering based on hit multiplicities in CSC chambers
  - Runs clustering algorithm in HLT
- Active for majority of 2022 data taking
  - Linear with PU, fully efficient for HLT
- Analysis effort on-going!



Rate v.s PU in 2022 data

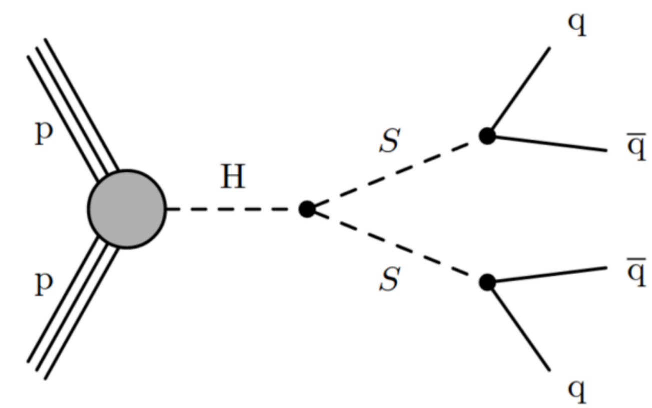


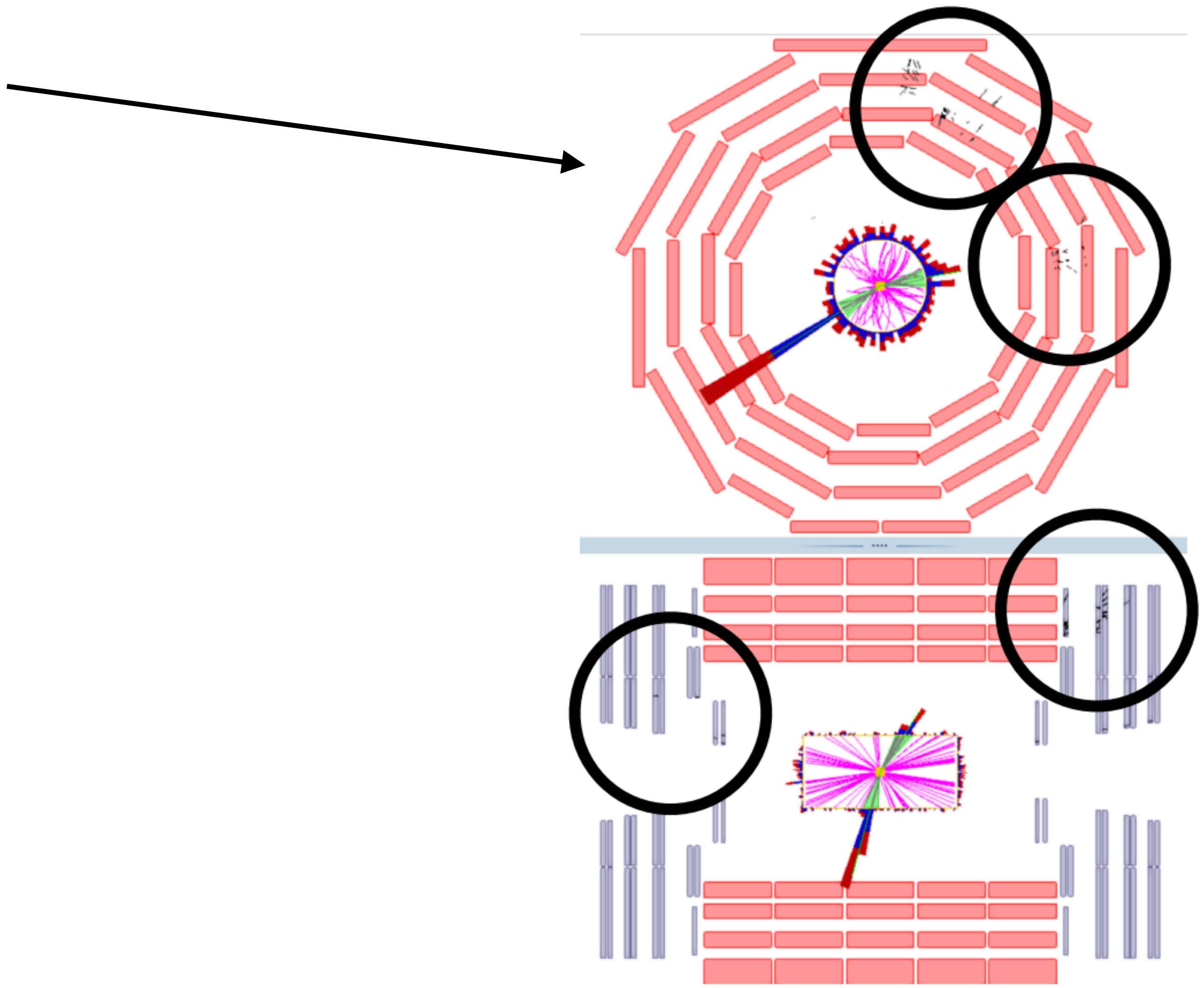
L1 Efficiency in 2022 data

Muon Shower Triggers in 2023

- New capability enabled
  many new ideas for LLP triggers!

- Double-shower (lower thresholds)
- Heavy Ion run triggers
- Cross-triggers with taus
- + many more!





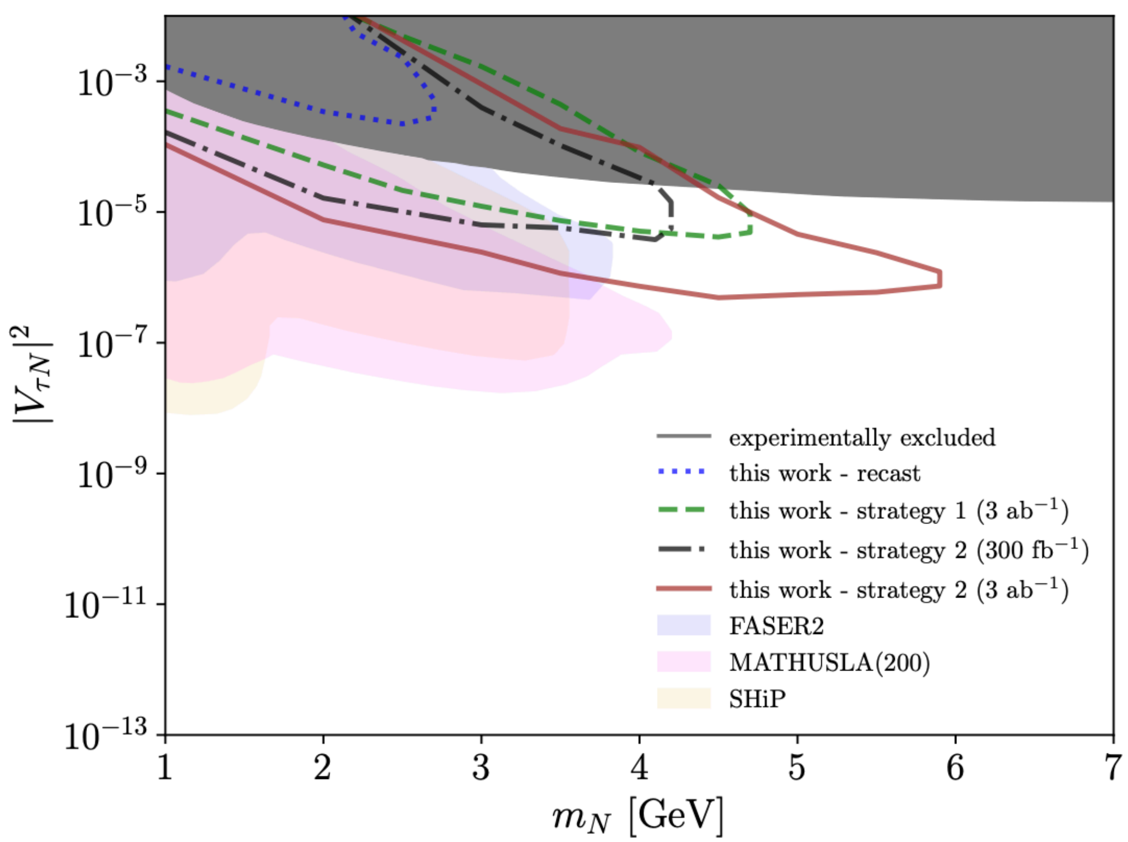
Double shower events from signal MC

HNL prospects

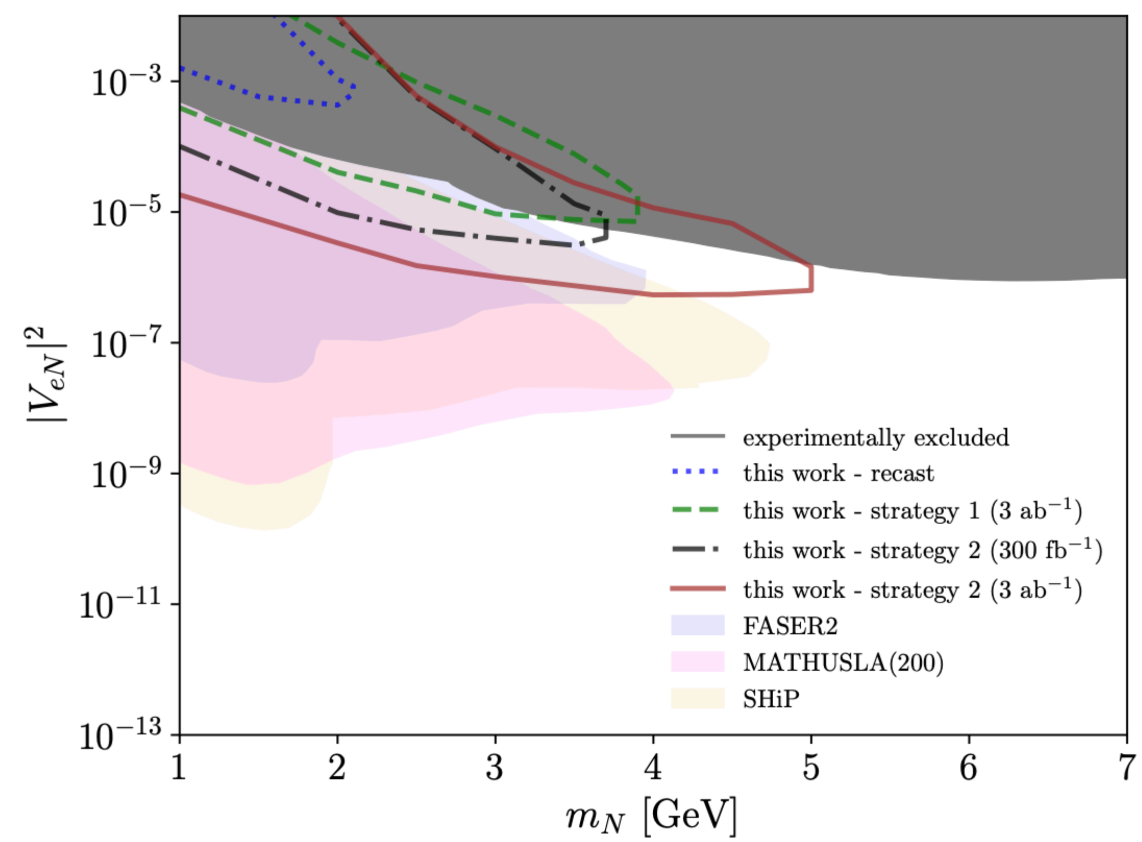
2210.17446

- Simple parametrization of cluster efficiency made extrapolation easier
- Can probe down to $|V_{\tau N}|^2 \sim 5 \times 10^{-7}$ with full HL-LHC data

$|V_{\tau N}|^2$



$|V_{eN}|^2$



Summary

- CMS has a lot of on-going effort for searching for HNLs
  - Latest addition: 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

- Stay tuned for Run 3 results!