Facultad de Ciencias | Universidad Autónoma de Madrid | Instituto de Física Teórica UAM-CSIC

HNLs at the LHC
Going Beyond Minimality

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CERN Neutrino Platform Pheno Week 2023

Funded by the European Union

PheNumenal

EXCELENCIA SEVERO OCHOA

Why Heavy Neutral Leptons?

Spin
1/2

Color
single

Isospin
single

Charge
0

Mass
how dare you!?

Social life
not much

Curriculum Vitae

Heavy Neutral Leptons

Heavy neutrinos, right-handed neutrinos, sterile neutrinos

Work experience

- Neutrino masses

Other skills

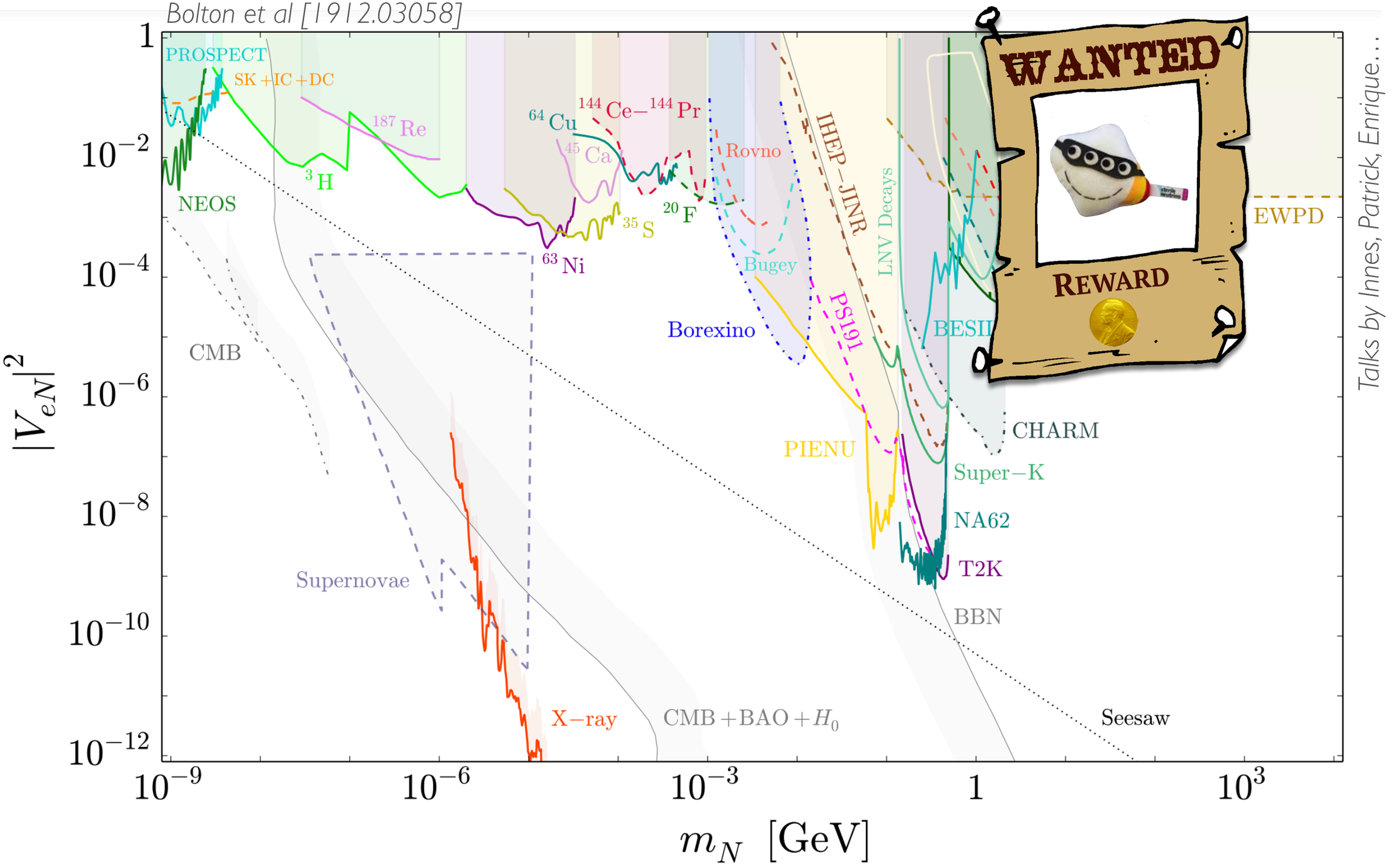
- Osc. anomalies
- Dark matter
- Baryogenesis
- Cooking

popularity

Searches for HNL

Searches for HNL

Bolton et al [1912.03058]



Talks by Innes, Patrick, Enrique…

— Basic Ingredients —

— Current Status —

— Going Beyond —

— Are we testing any Realistic Model? —

Which Masses?

Which Masses?

too light

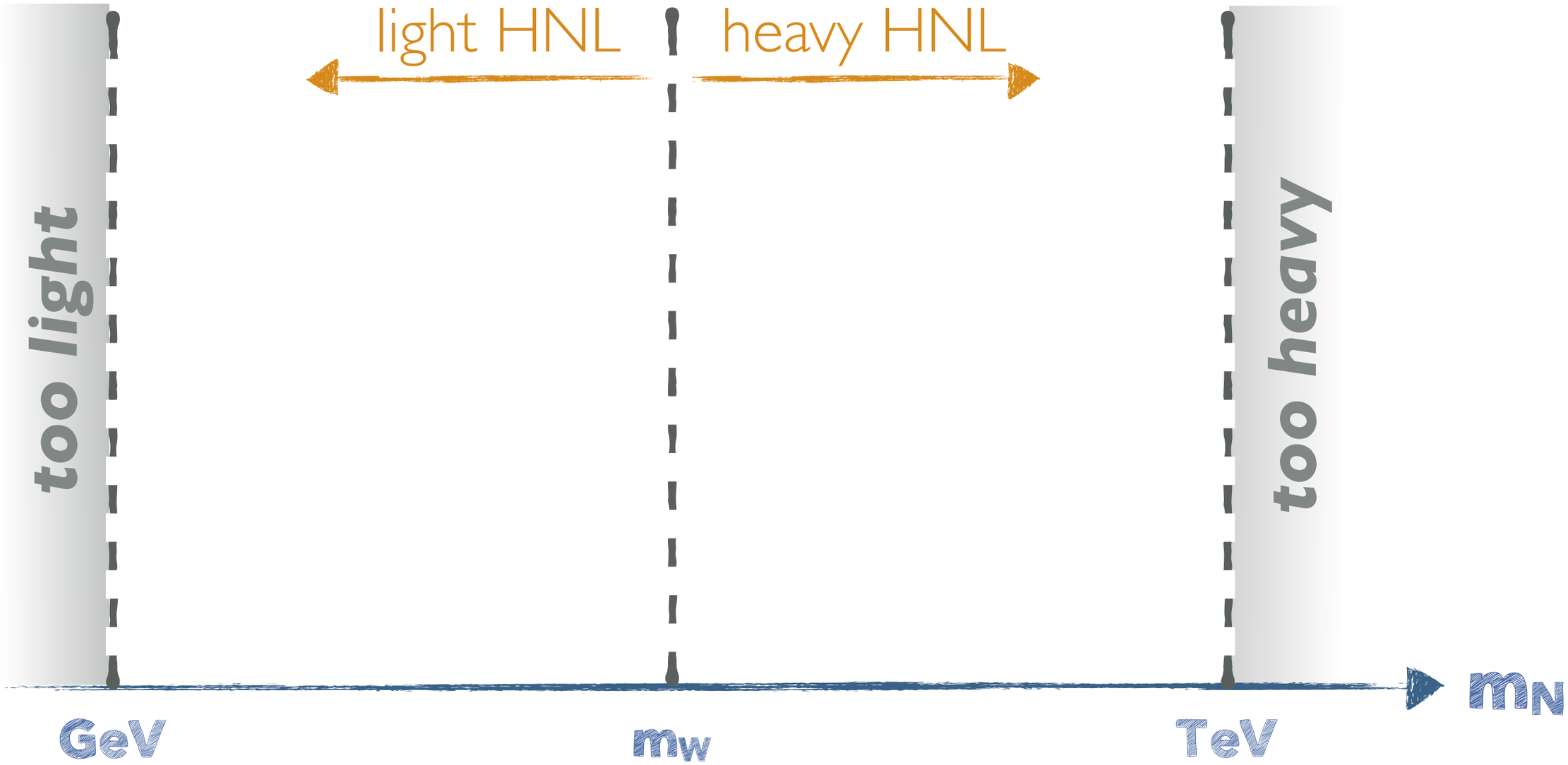
too heavy

GeV

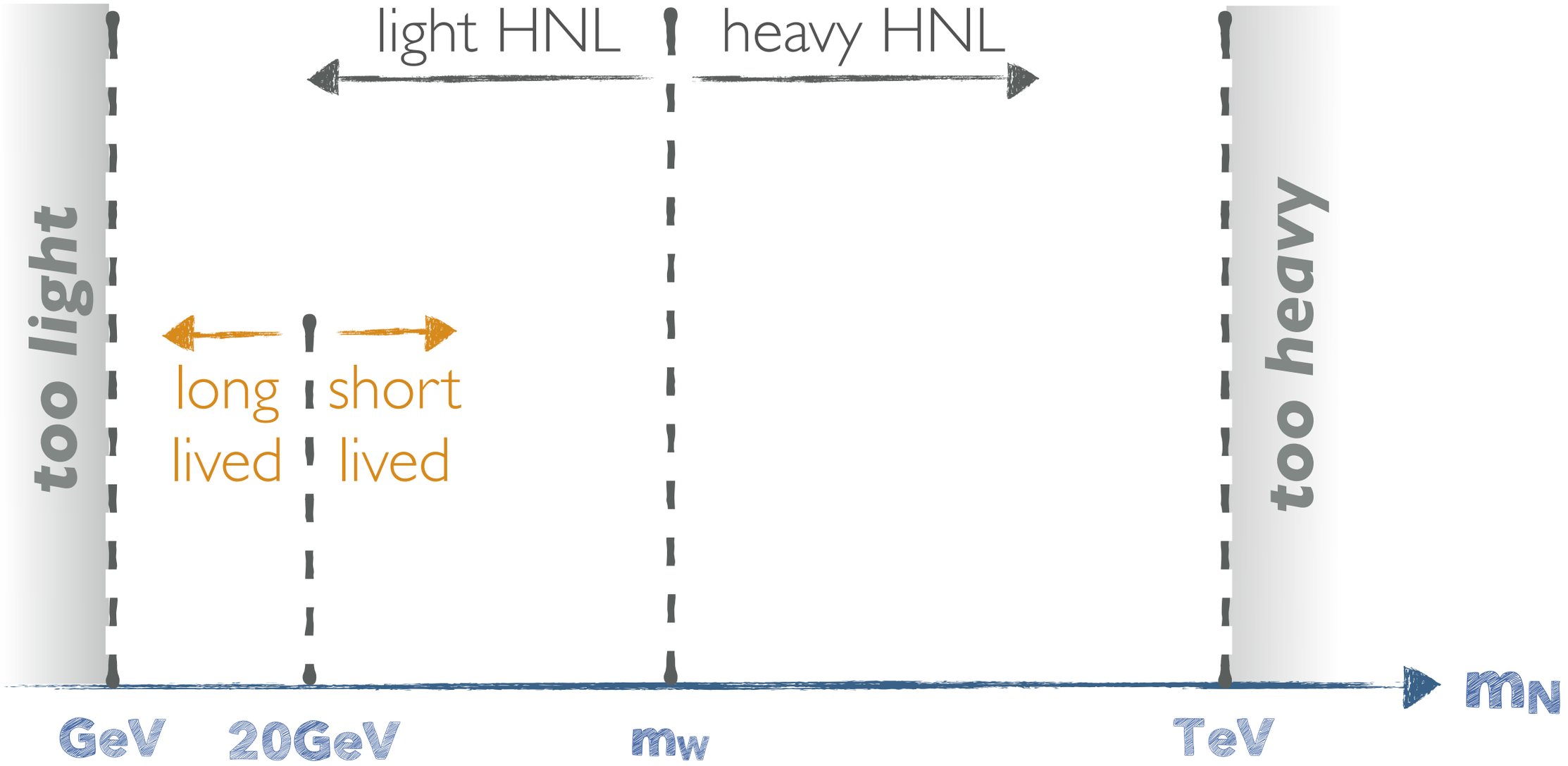
TeV

m_N

Which Masses?



Which Masses?



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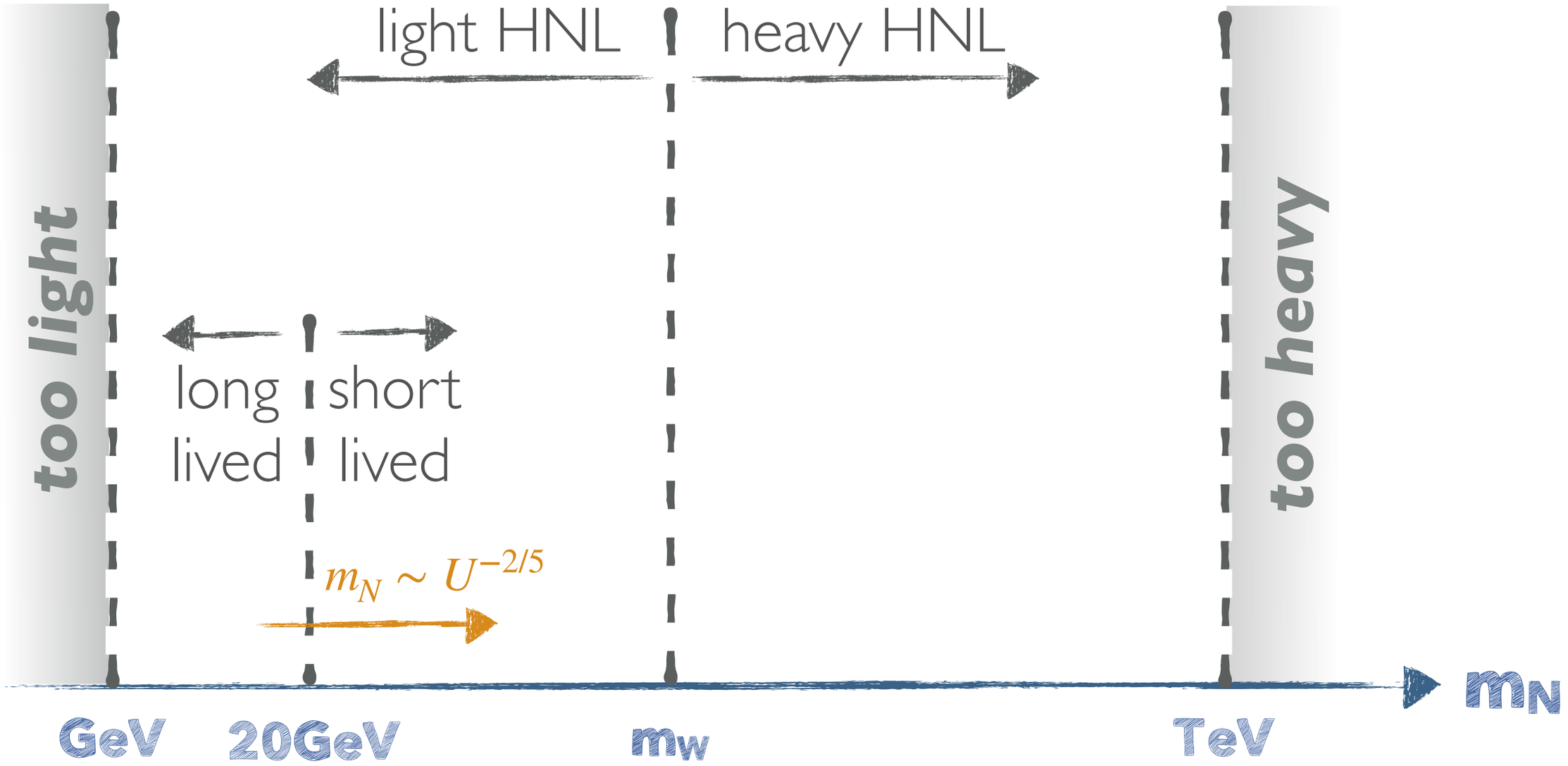
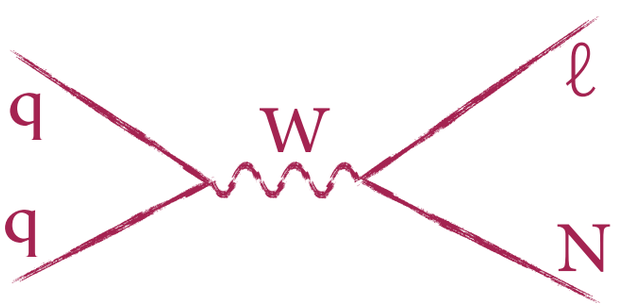
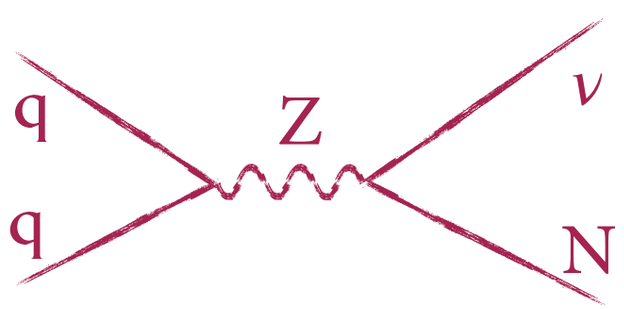
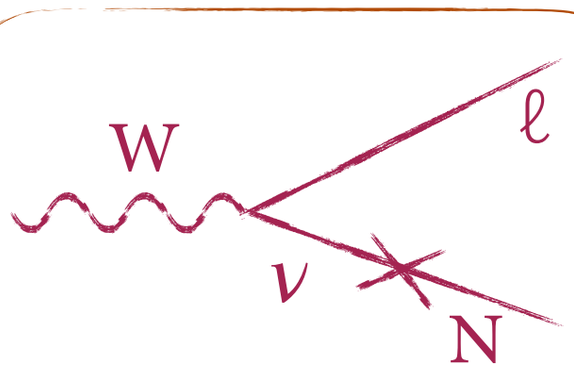


HNL Production

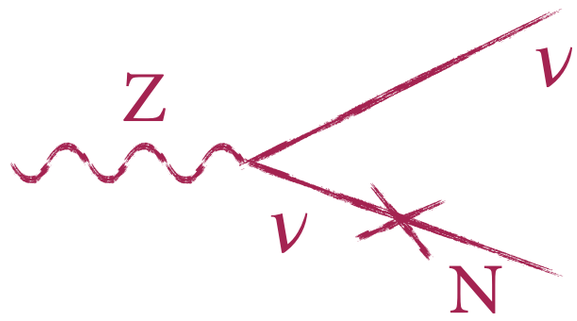
- *Dominant diagrams: Drell-Yan W and Z (and Higgs?)*







$$\mathrm{BR}_{W^\pm \to \ell^\pm N} \propto |V_{\ell N}|^2$$

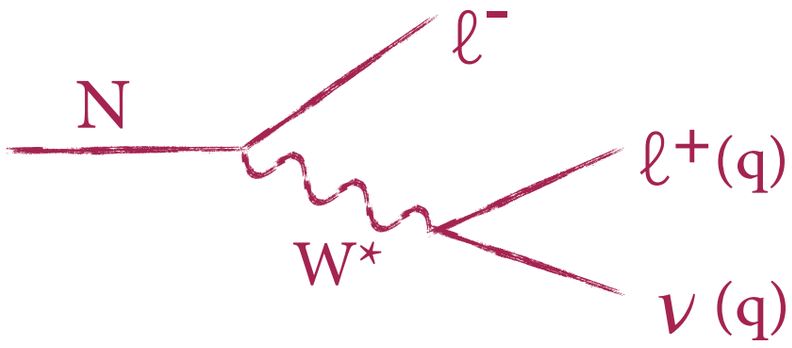


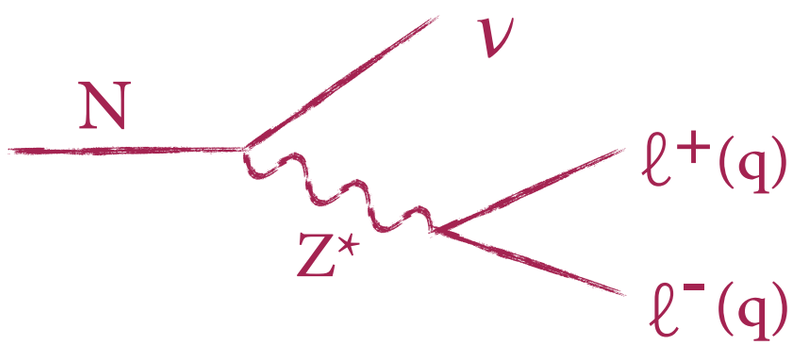
$$\mathrm{BR}_{Z \to \nu N} \propto \sum_{\ell} |V_{\ell N}|^2$$

$$\mathrm{BR}_{H \to \nu N} \propto \frac{m_N^2}{m_W^2} \sum_{\ell} |V_{\ell N}|^2$$

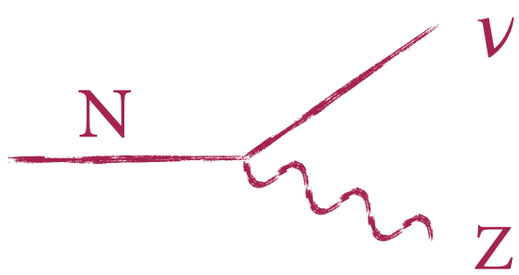
HNL Decays

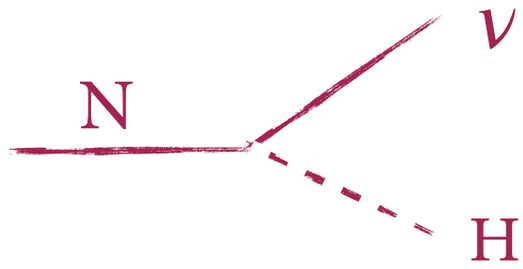
- *Light HNL: off-shell W and Z*





- *Heavy HNL: on-shell W, Z, H*





Several Channels at LHC

- *Same Sign Dilepton channel* — LNV—

$$pp \to W^{(*)} \to \ell^{\pm} N \to \ell^{\pm}\ell^{\pm} + nj$$

- *Opposite Sign Dilepton channel* — LNC—

$$pp \to W^{(*)} \to \ell^{\pm} N \to \ell^{\pm}\ell^{\mp} + nj$$

- *Trilepton channel* — LNV?—

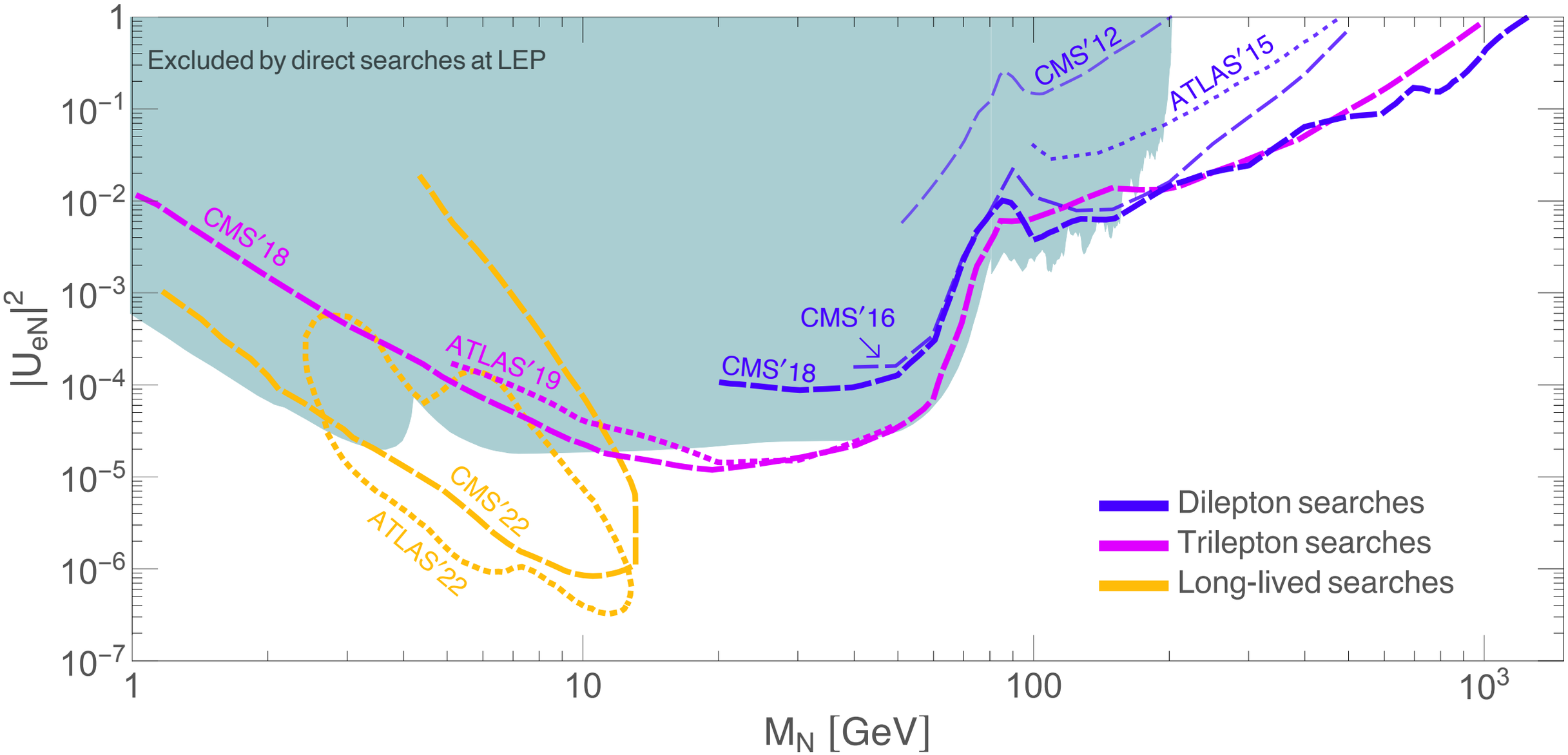
$$pp \to W^{(*)} \to \ell^{\pm}_{\alpha} N \to \ell^{\pm}_{\alpha}\ell^{\pm}_{\beta}\ell^{\mp}_{\gamma}\nu$$

- *Displaced vertices* — LNV?—

$$pp \to W^{(*)} \to \ell^{\pm}_{\alpha} N \quad // \quad N \to \ell^{\pm}_{\beta}\ell^{\mp}_{\gamma}\nu$$

Current Status

Abada, Escribano, XM, Piazza [2208.13882]



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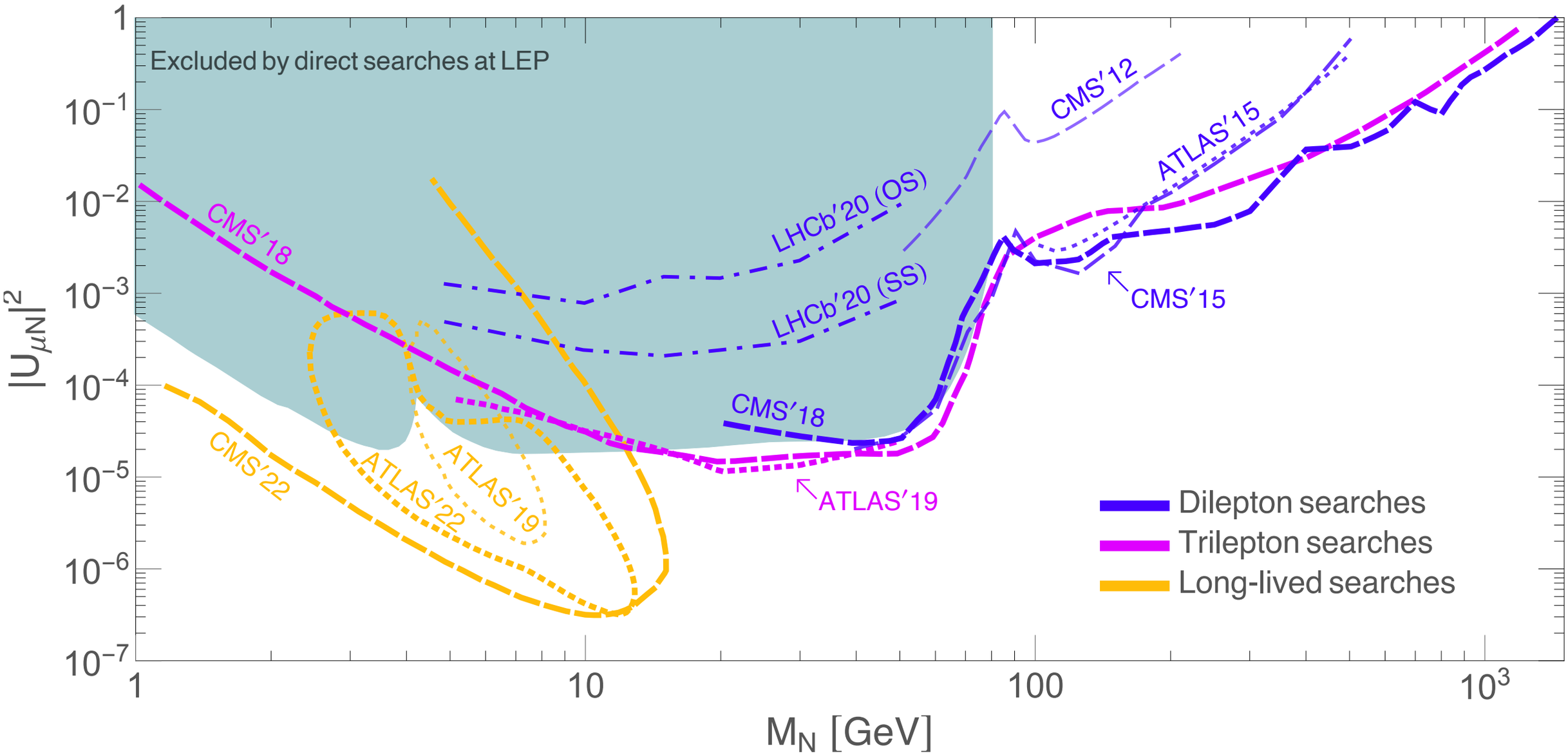
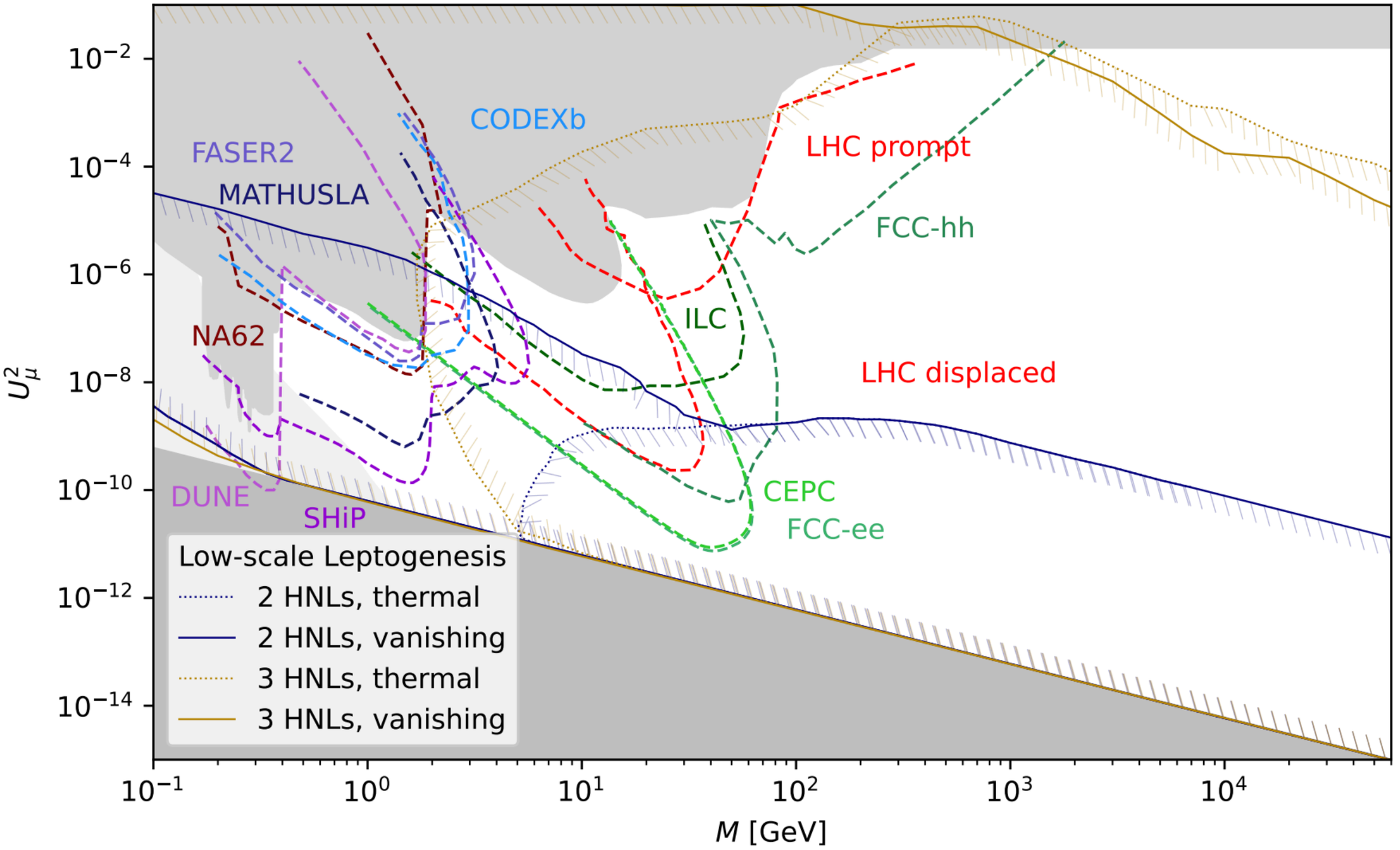


Future Collider Landscape

Abdullahi et al [2203.08039]



What do we learn from these analyses?

- *Exp searches consider 1HNL mixing to 1 flavor at a time*

- *They are sensitive to very large mixings*

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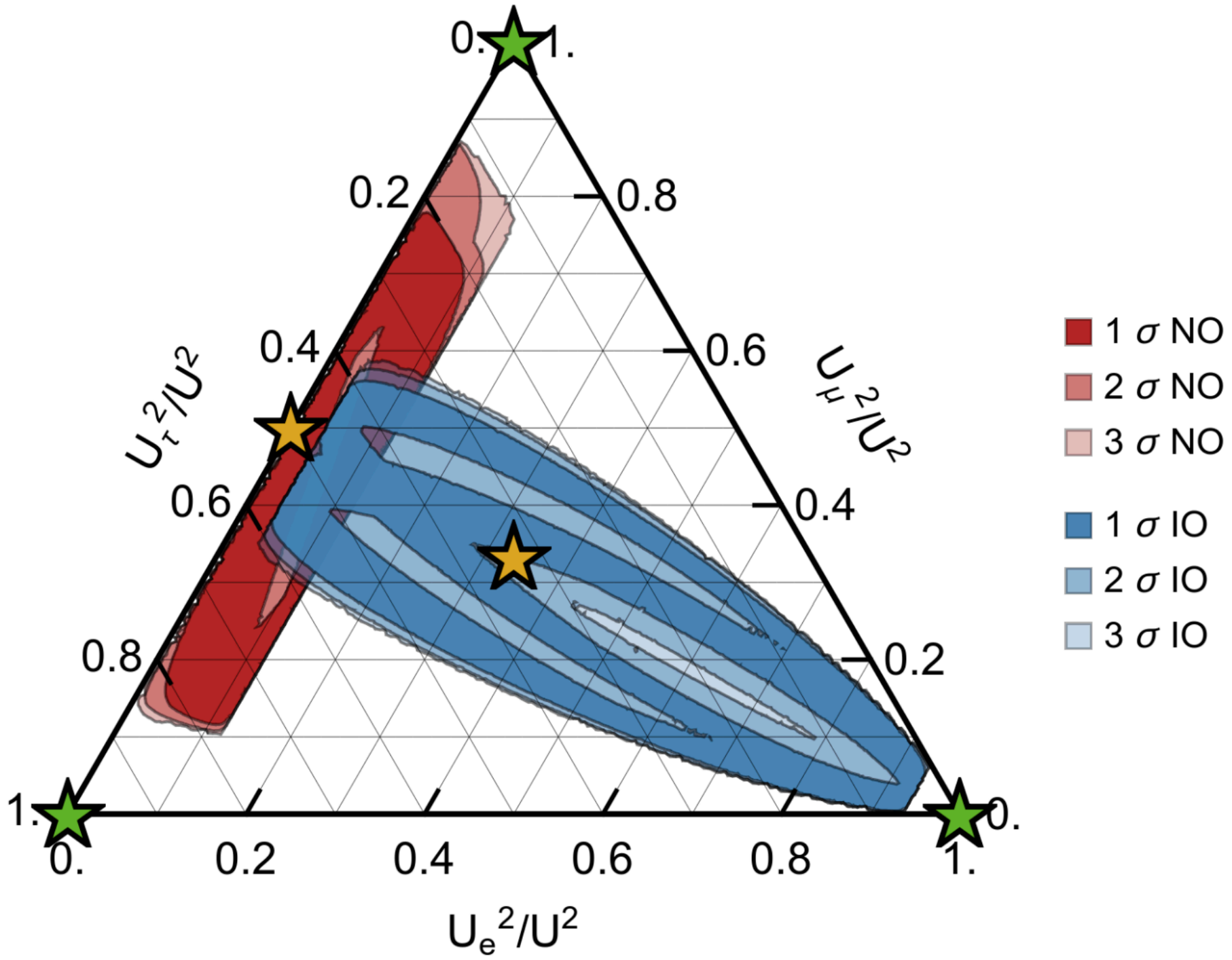
— Need to Go Beyond —

New Benchmarks

— Drewes et al [2207.02742] —



Single Flavor Dominance

- *Setting bounds on, e.g.* $pp \to \mu\mu jj$

$$\sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu jj)$$

$$\downarrow$$

$$|U_{\mu N}|^2 \, \mathrm{BR}(N \to \mu jj)$$

$$\downarrow$$

$$|U_{\mu N}|^2$$

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Mixing to a single flavor ←

$$|U_{\mu N}|^2$$

Single Flavor Dominance

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Mixing to a single flavor $\leftarrow$

$$|U_{\mu N}|^2$$

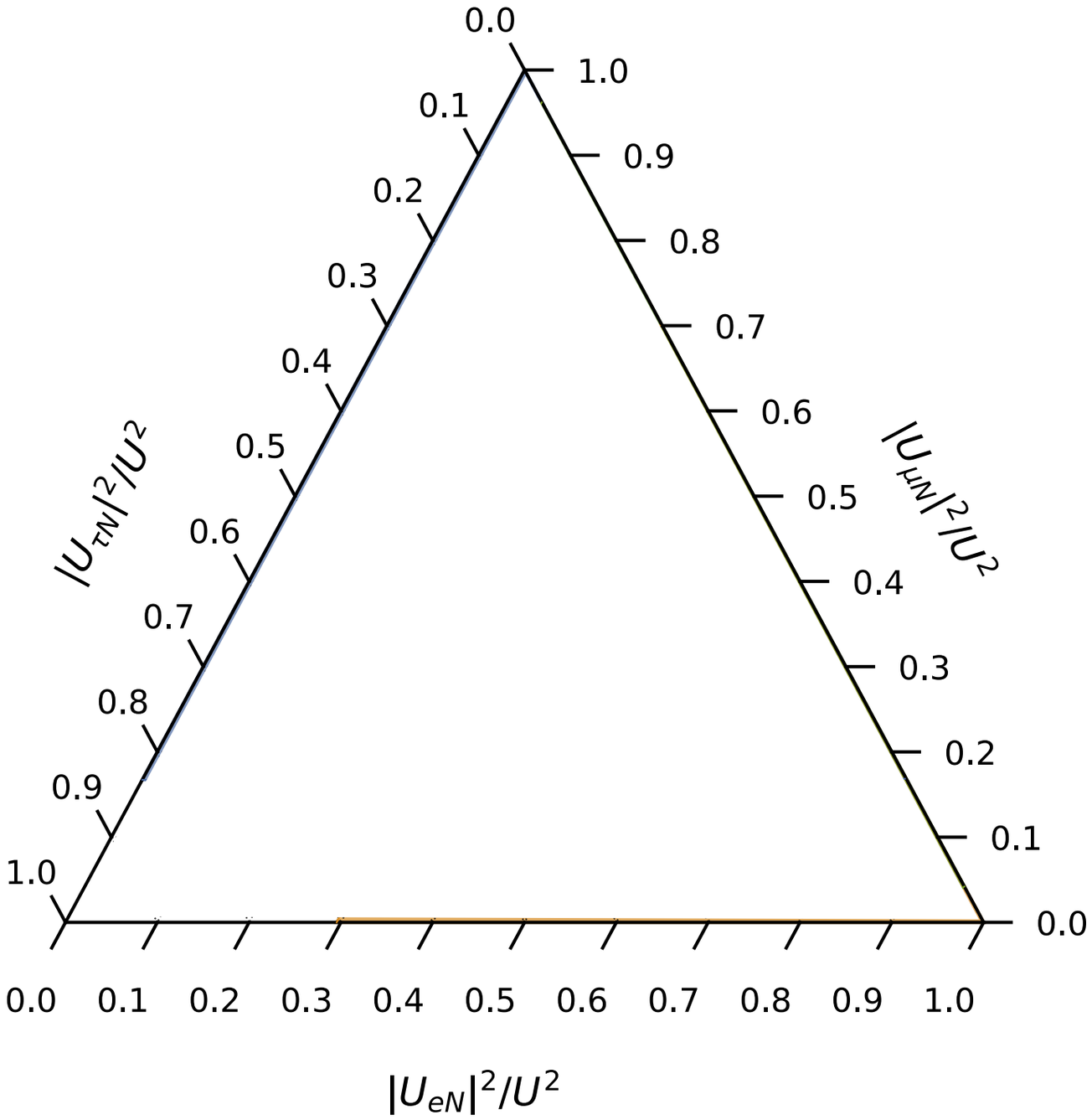
Recast — dileptons

— Abada, Escribano, XM, Piazza [2208.13882]—

For a fixed mass and U^2

$M_N = 30$ GeV, $U^2 = 10^{-3}$

- $\mu^\pm\mu^\pm$, CMS '18
- $e^\pm e^\pm$, CMS '18
- $e^\pm\mu^\pm$, CMS '18



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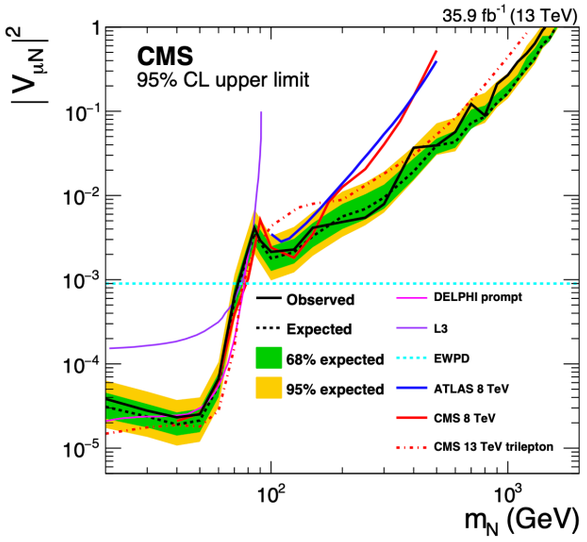

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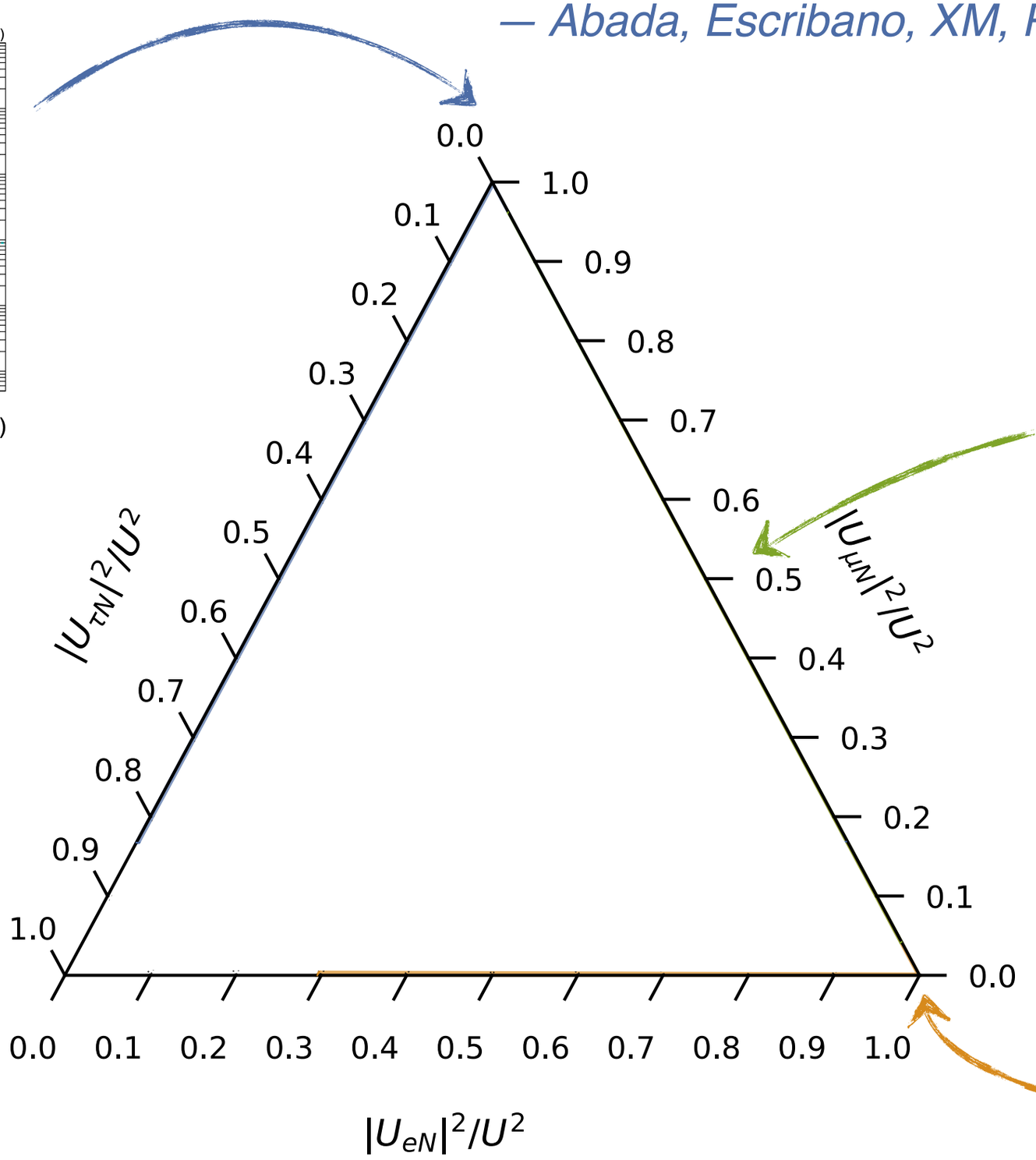

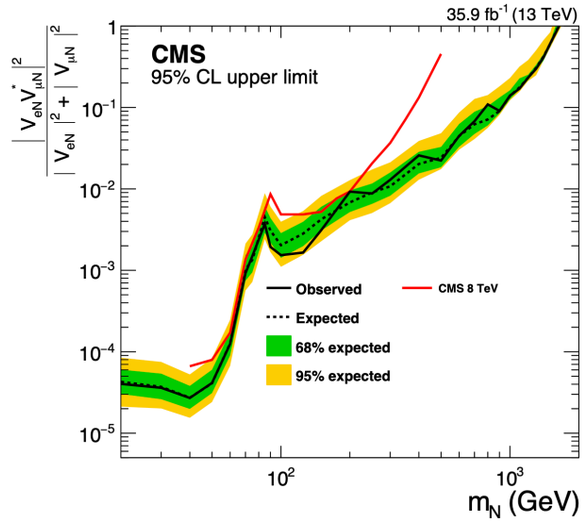

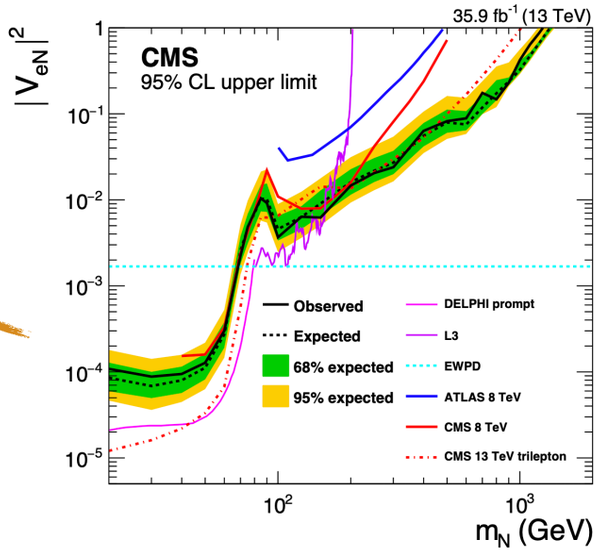

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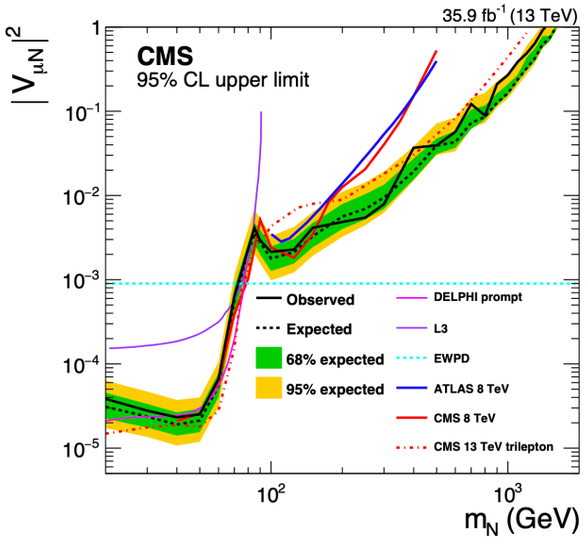

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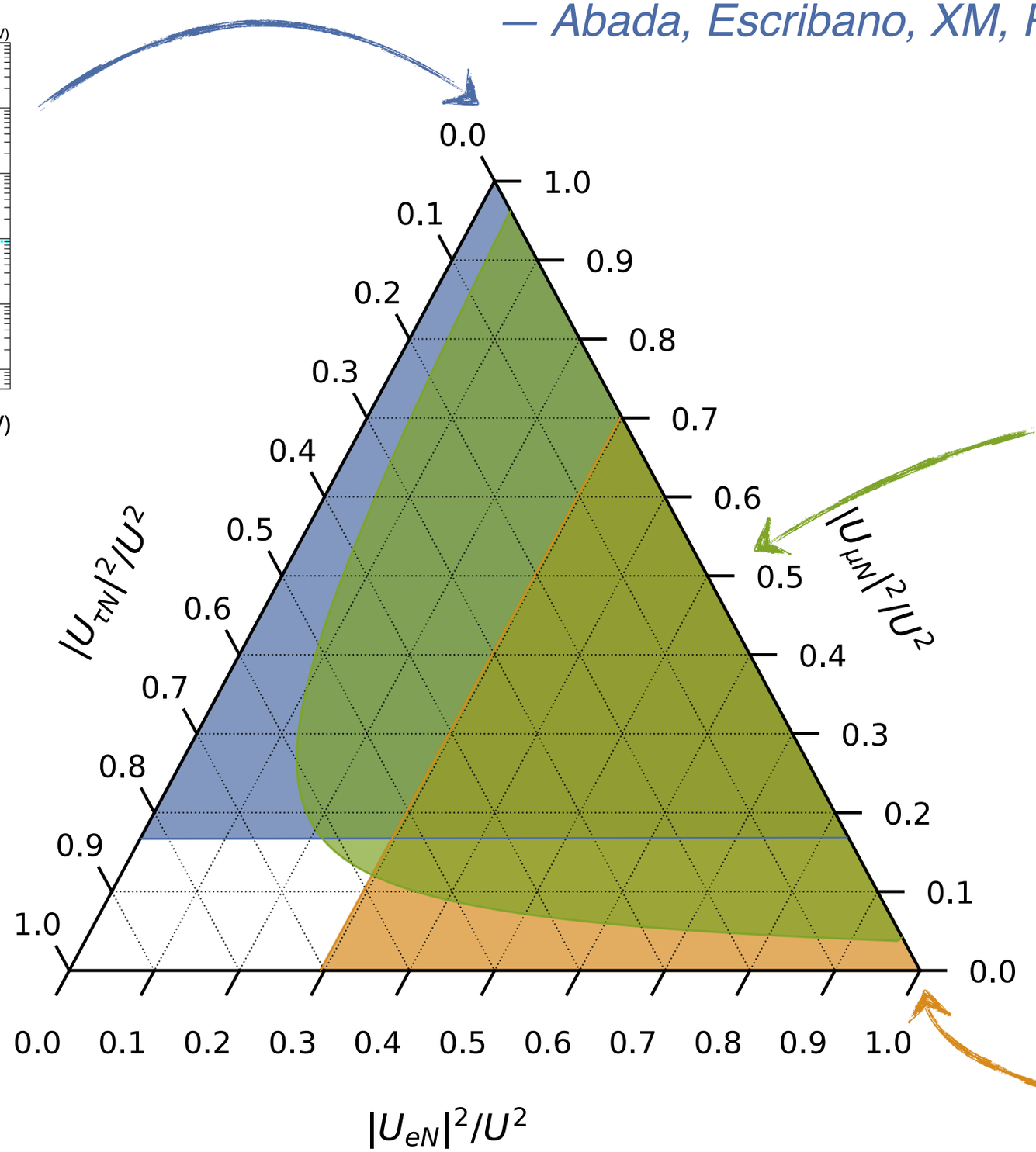
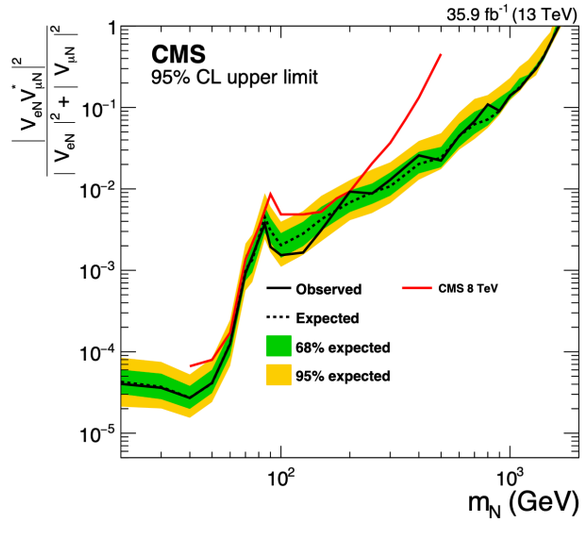
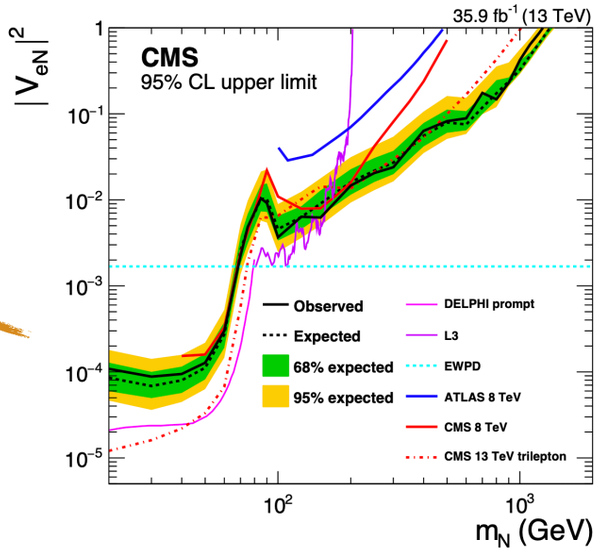
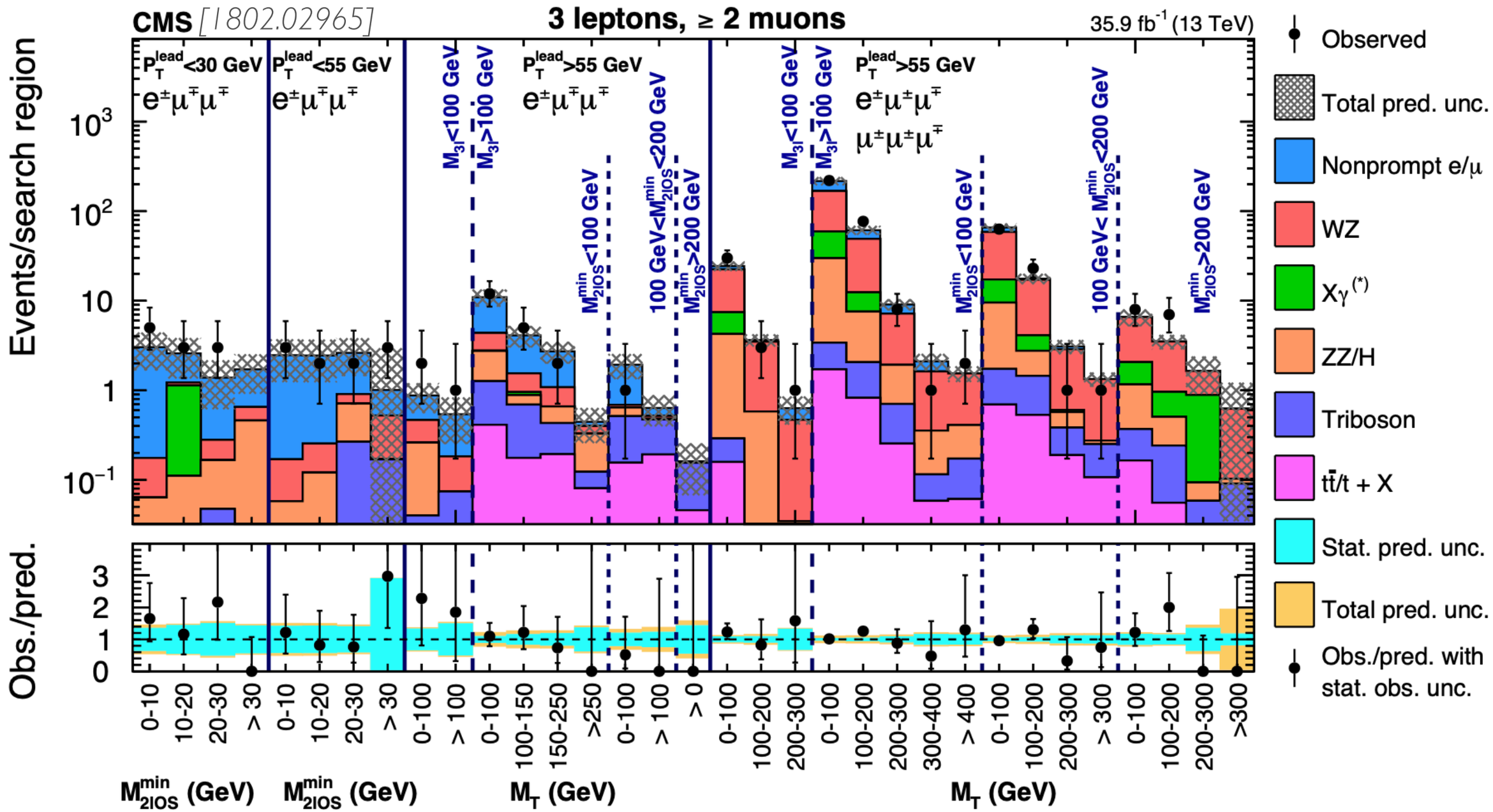






Recast — Trileptons



Recast — Trileptons

- *Setting bounds on, e.g.* $pp \to \mu\mu e\nu \oplus \mu\mu\mu\nu$

$$\sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu e\nu) \;\oplus\; \sigma(pp \to \mu N) \times \mathrm{BR}(N \to \mu\mu\nu)$$

$$|U_{\mu N}|^2 \mathrm{BR}(N \to \mu e\nu) \;\oplus\; |U_{\mu N}|^2 \mathrm{BR}(N \to \mu\mu\nu)$$

Mixing to a single flavor

$$|U_{\mu N}|^2$$

Recast — Trileptons

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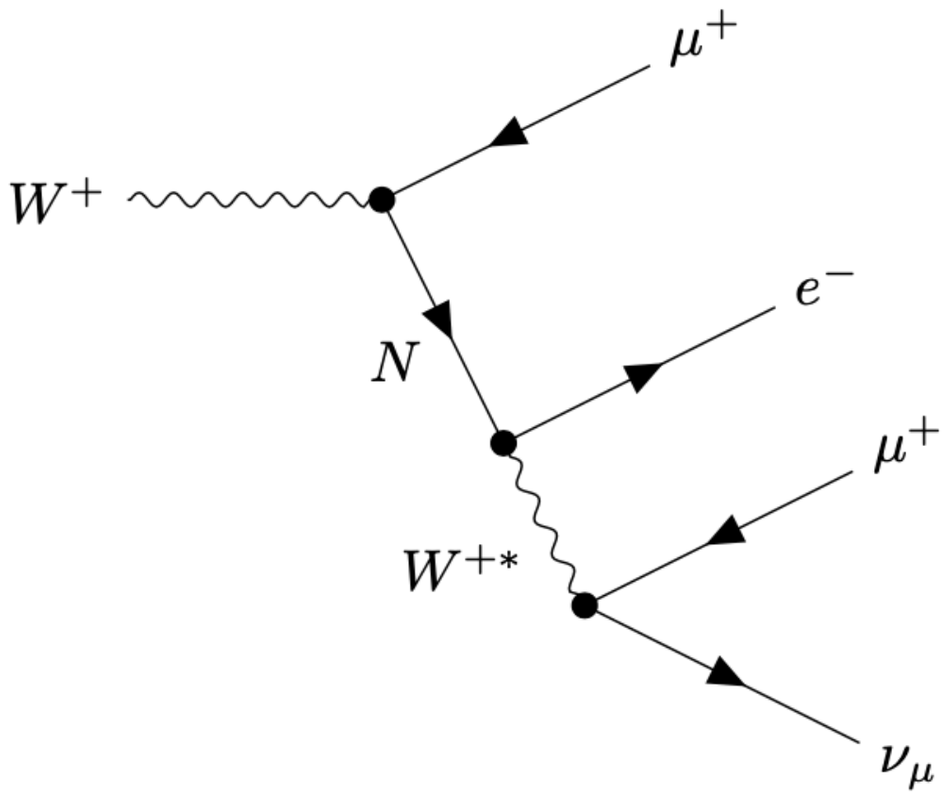
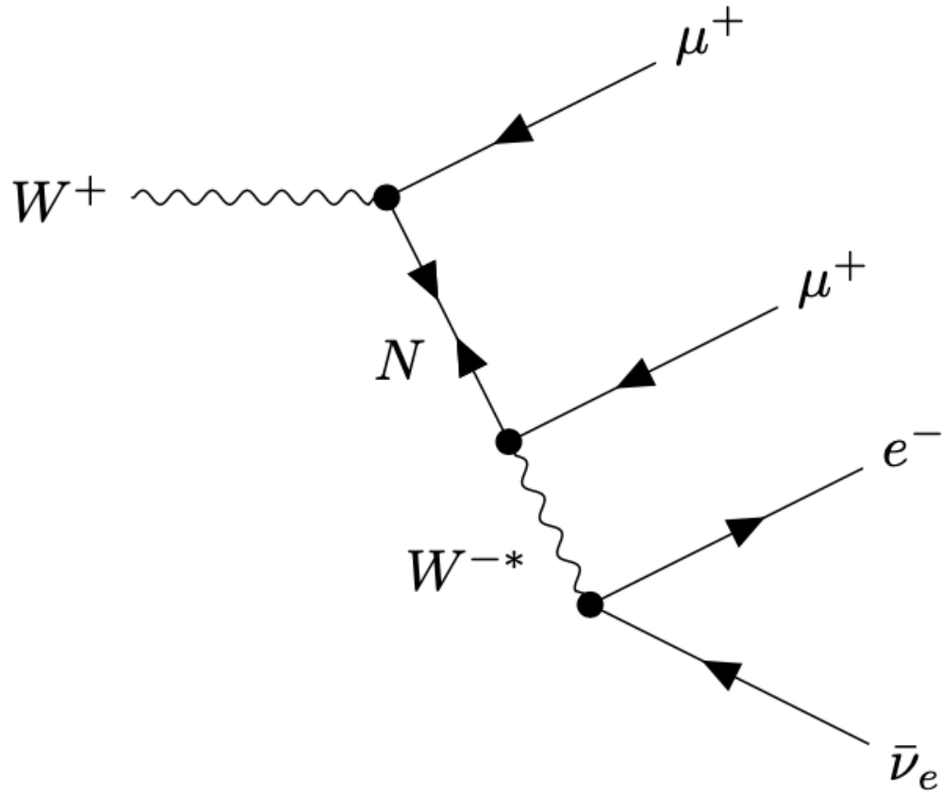
Recast — Tri-leptons

- *More mixings, more diagrams*

— Tastet et al [2107.12980] —



(a) LNC

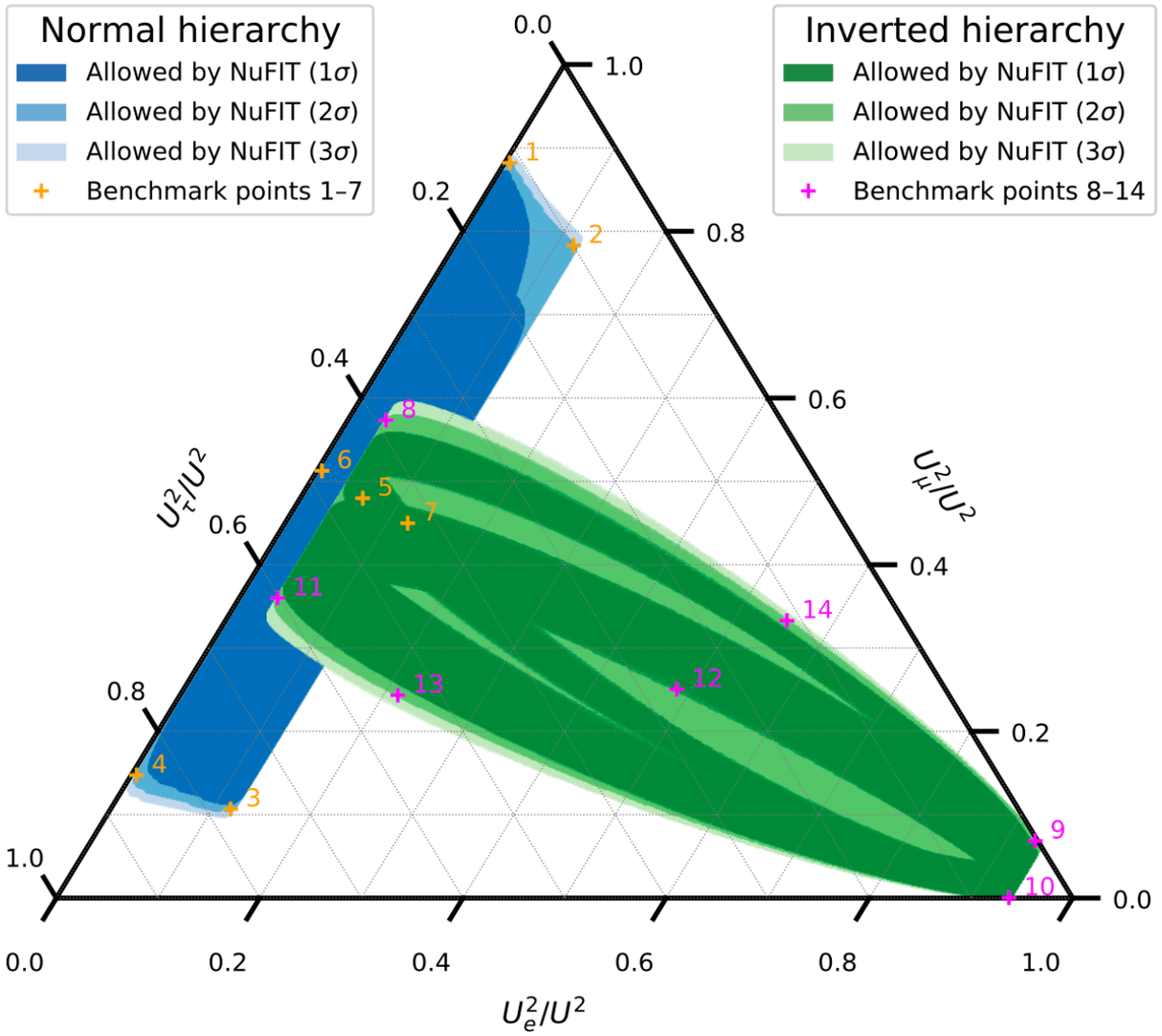


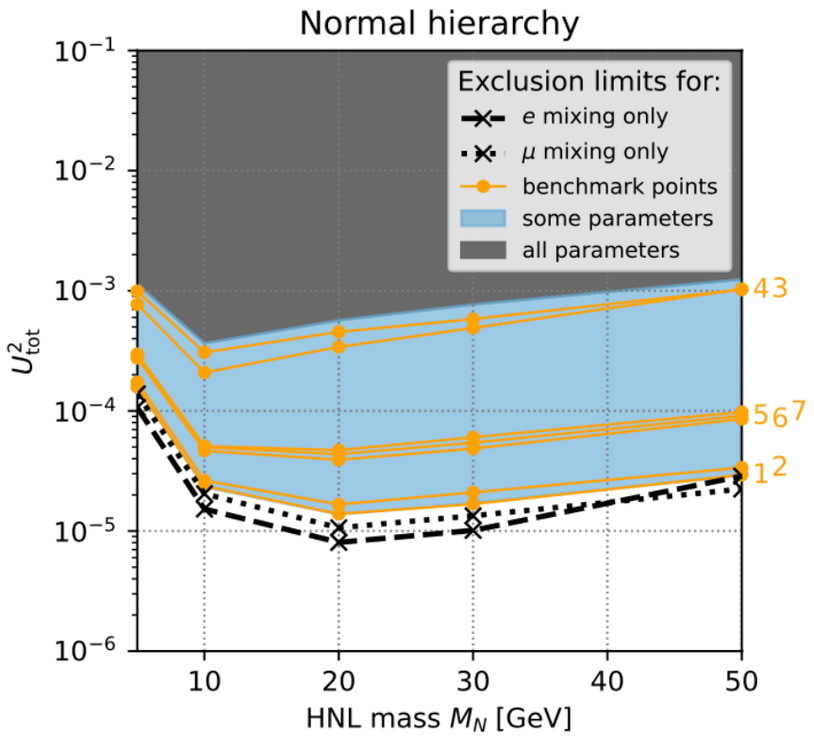
(b) LNV

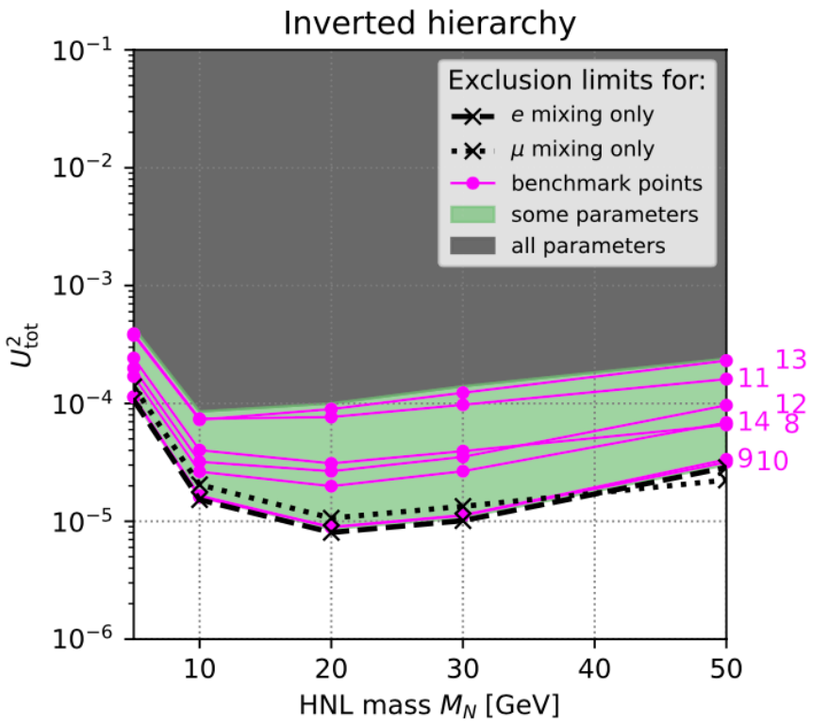
Recast — Tileptons

- *Simplest realistic framework*

— Tastet et al [2107.12980] —



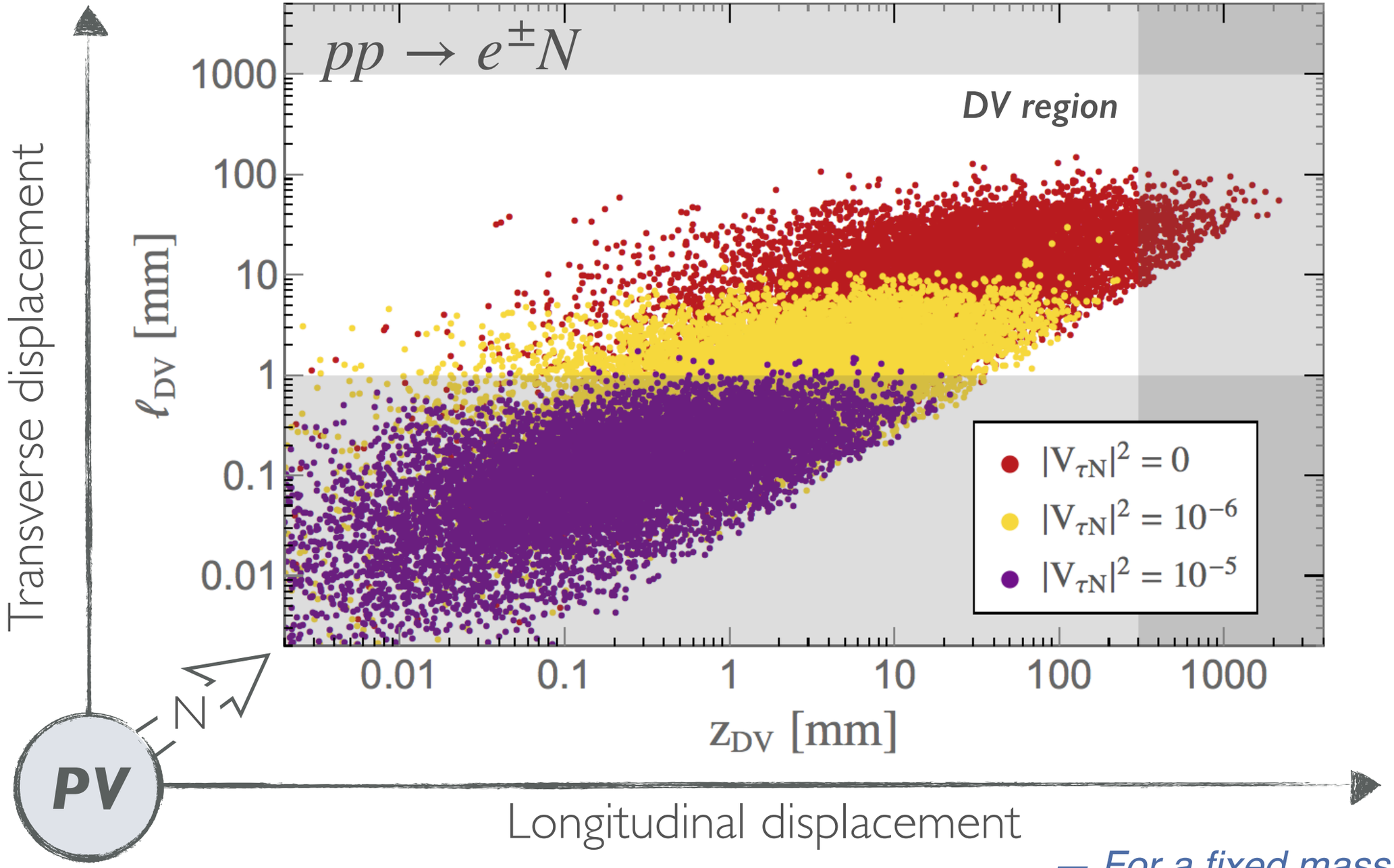




Recast — Displaced Vertices

- *The efficiency is highly mixing-pattern dependent*

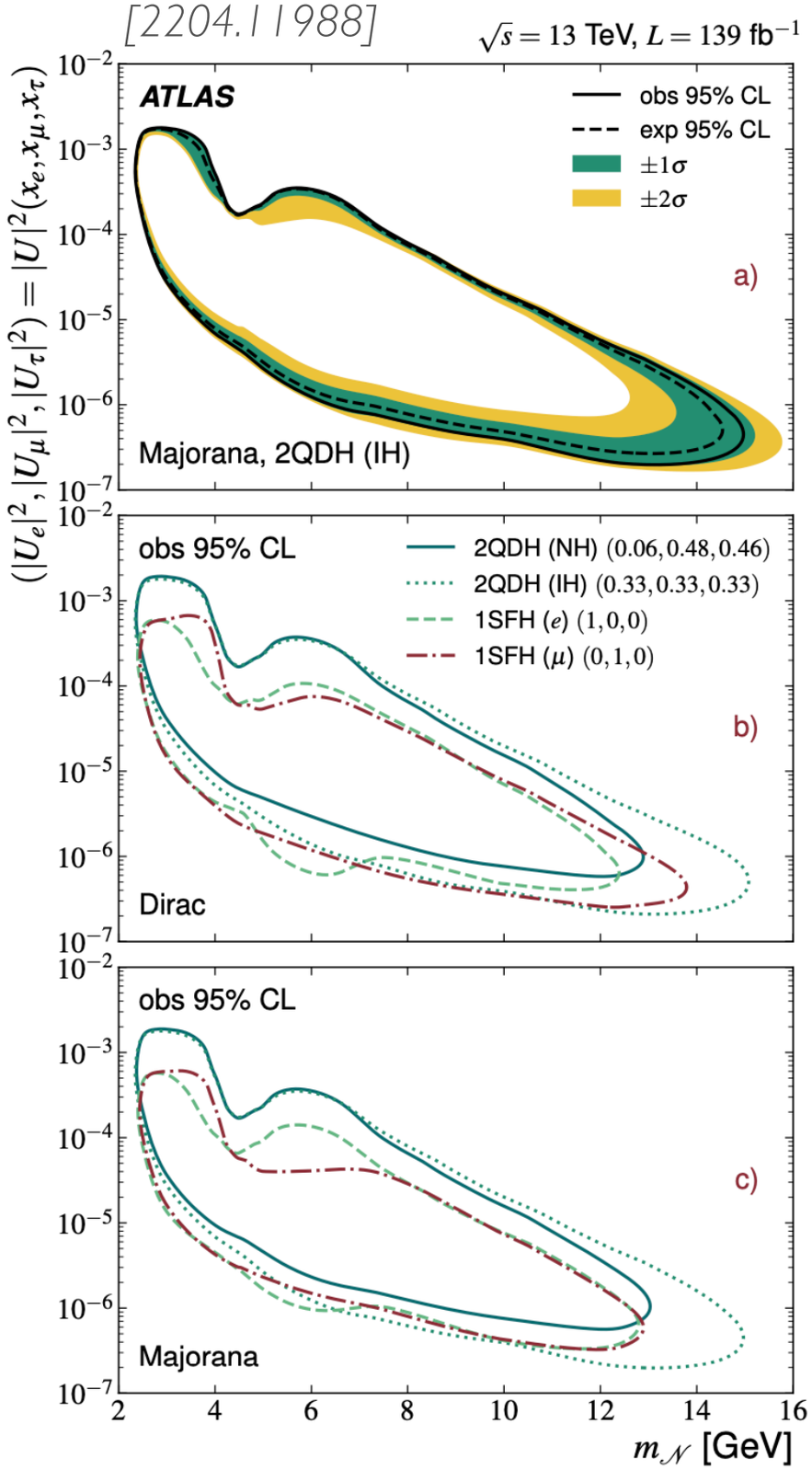
— Abada, Bernal, Losada, XM [1807.10024] —



— For a fixed mass and U_{eN} —

Single Mixing — DV

[2204.11988]



What do we learn from these analyses?

- *Exp searches consider 1HNL mixing to 1 flavor at a time*

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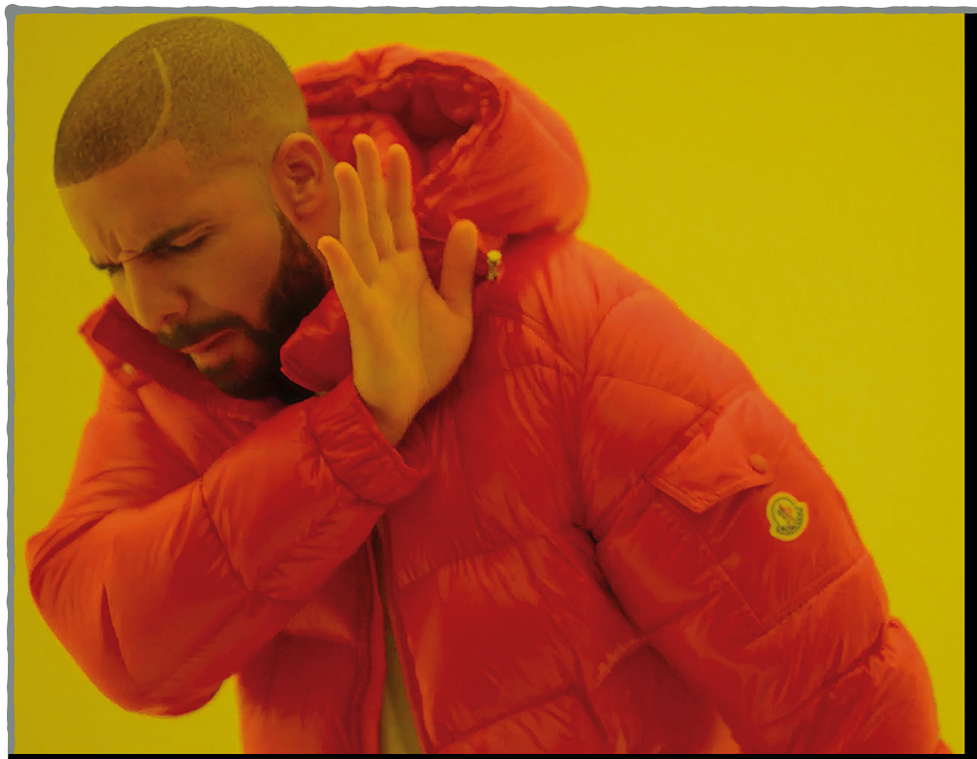
—What are we actually testing?—

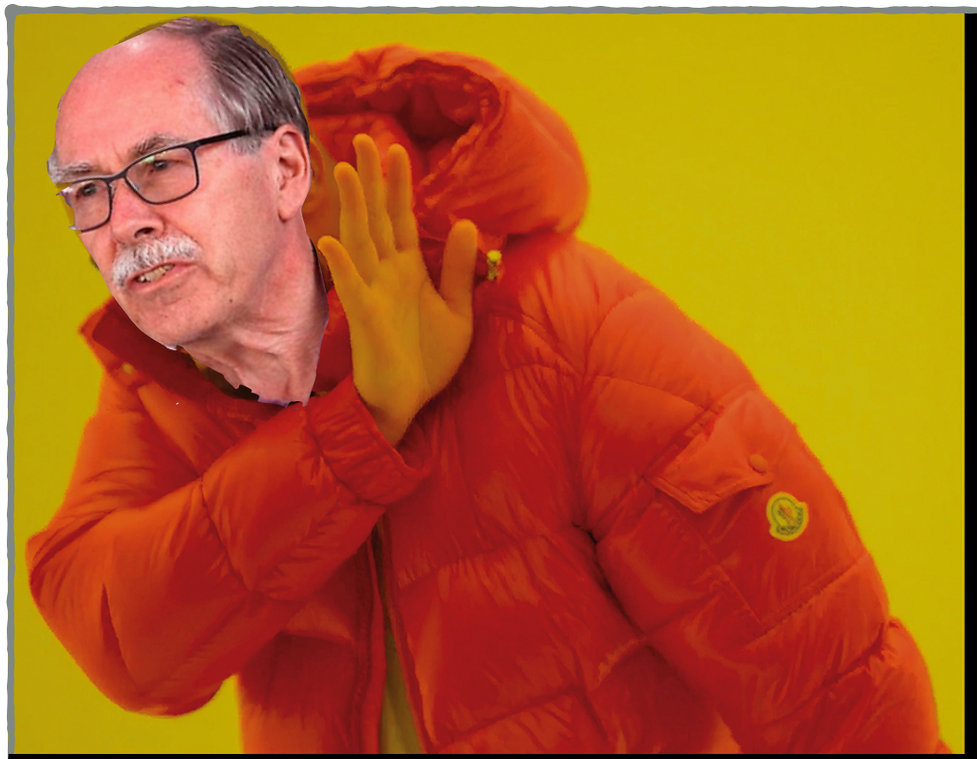
Symmetry Protected Scenarios



Two HNL with
same mass
same mixing
opposite phase

Symmetry:
lepton number

Symmetry Protected Scenarios



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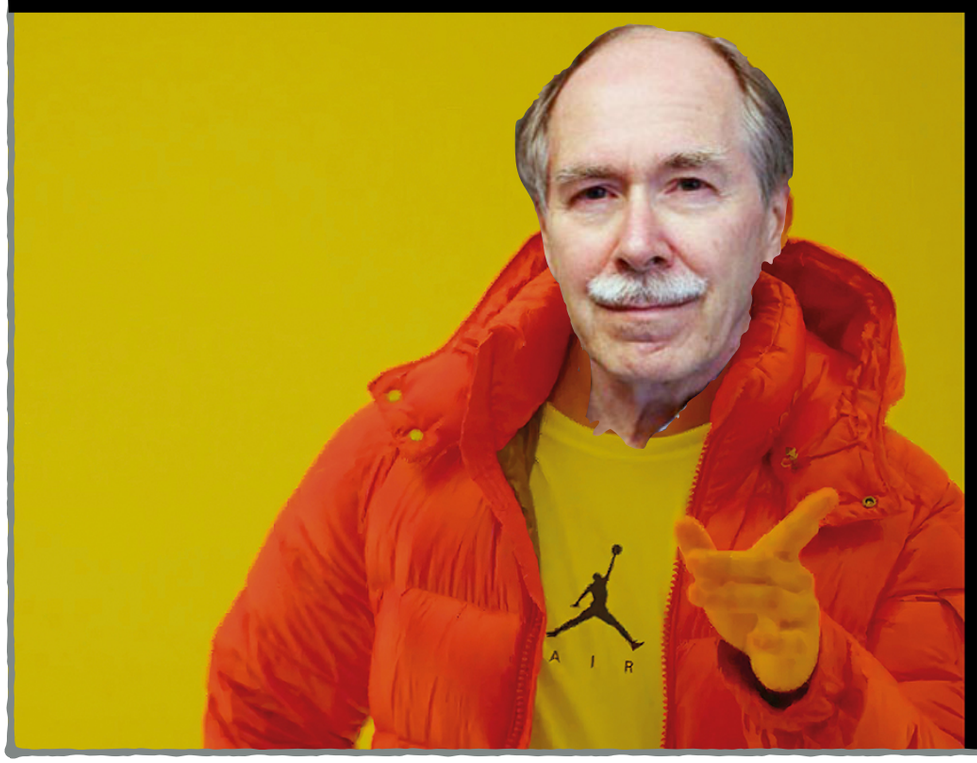

Symmetry:
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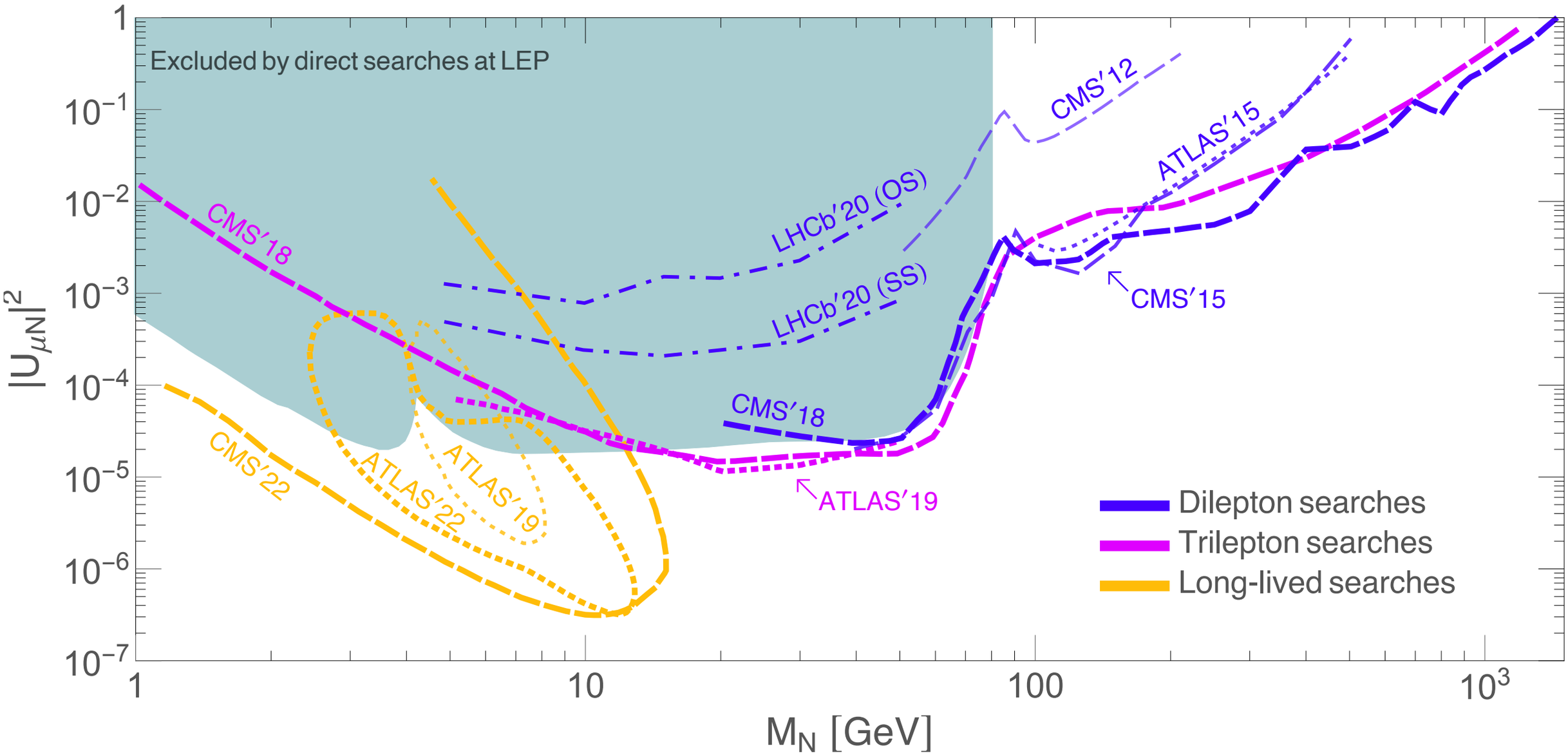
What are we actually testing?

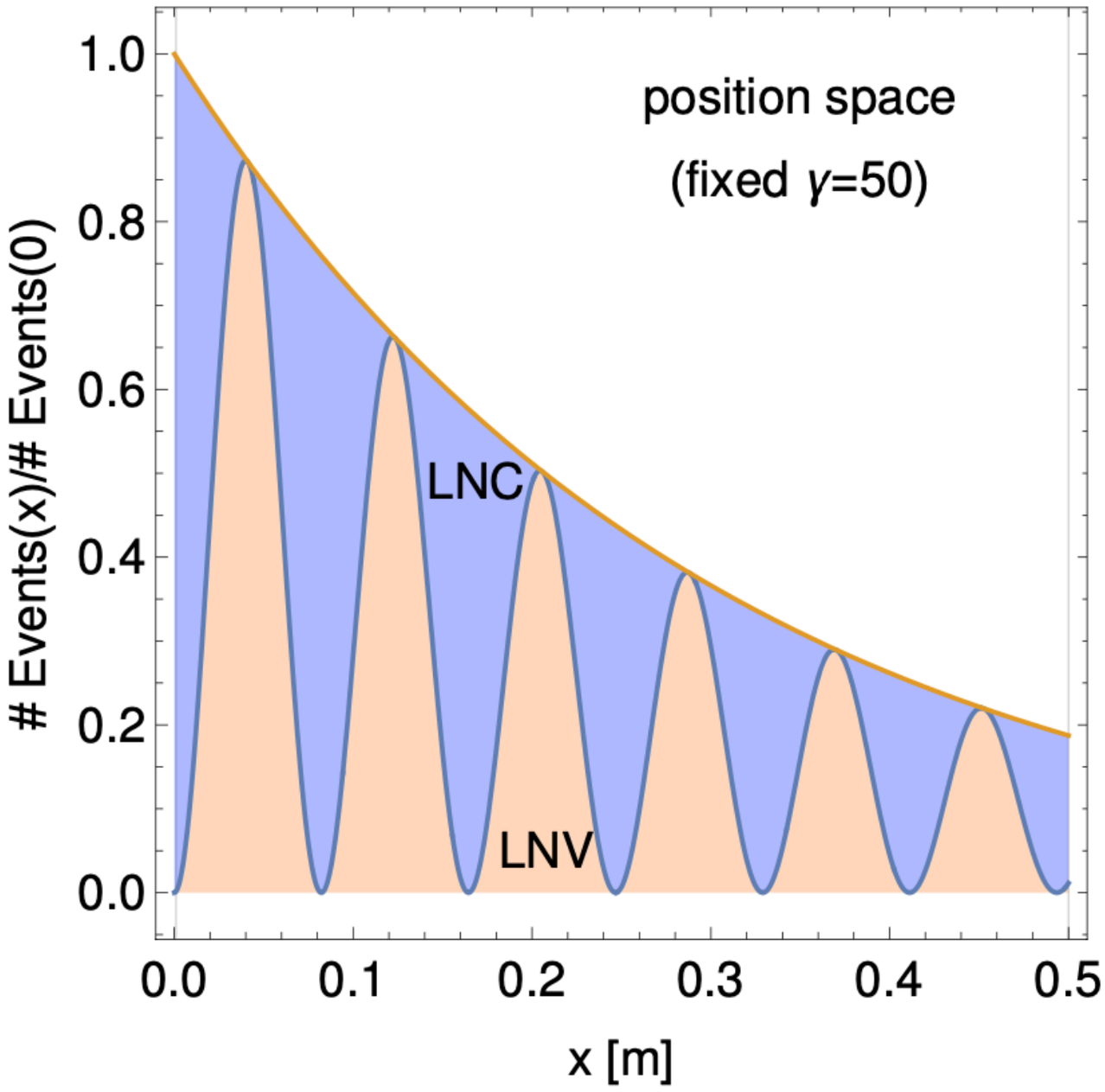
Abada, Escribano, XM, Piazza [2208.13882]



LNV in Symmetry Protected Scenarios

- *Potential oscillations between HNLs*

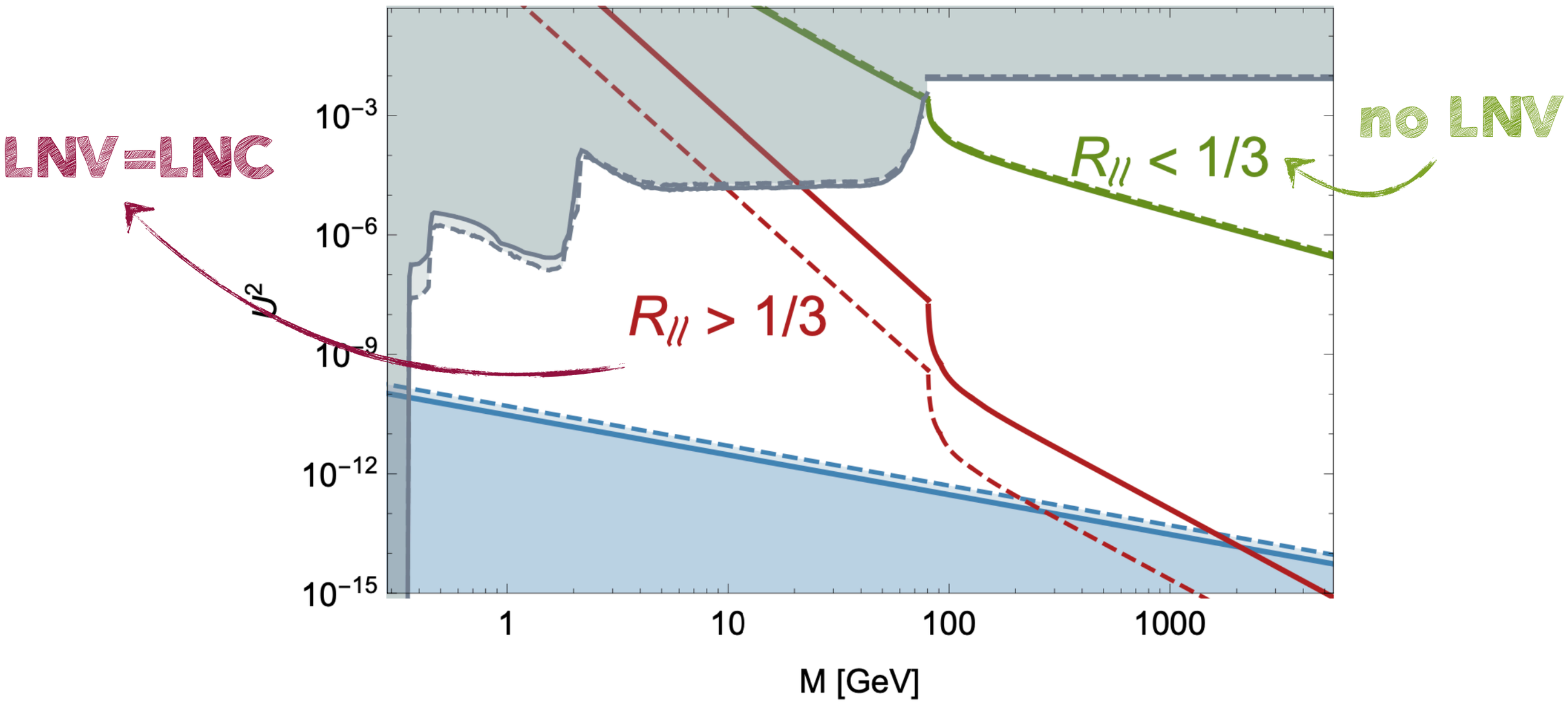
— Antusch et al [1709.03797] —



LNV in Symmetry Protected Scenarios

- *Connected to active neutrino masses*

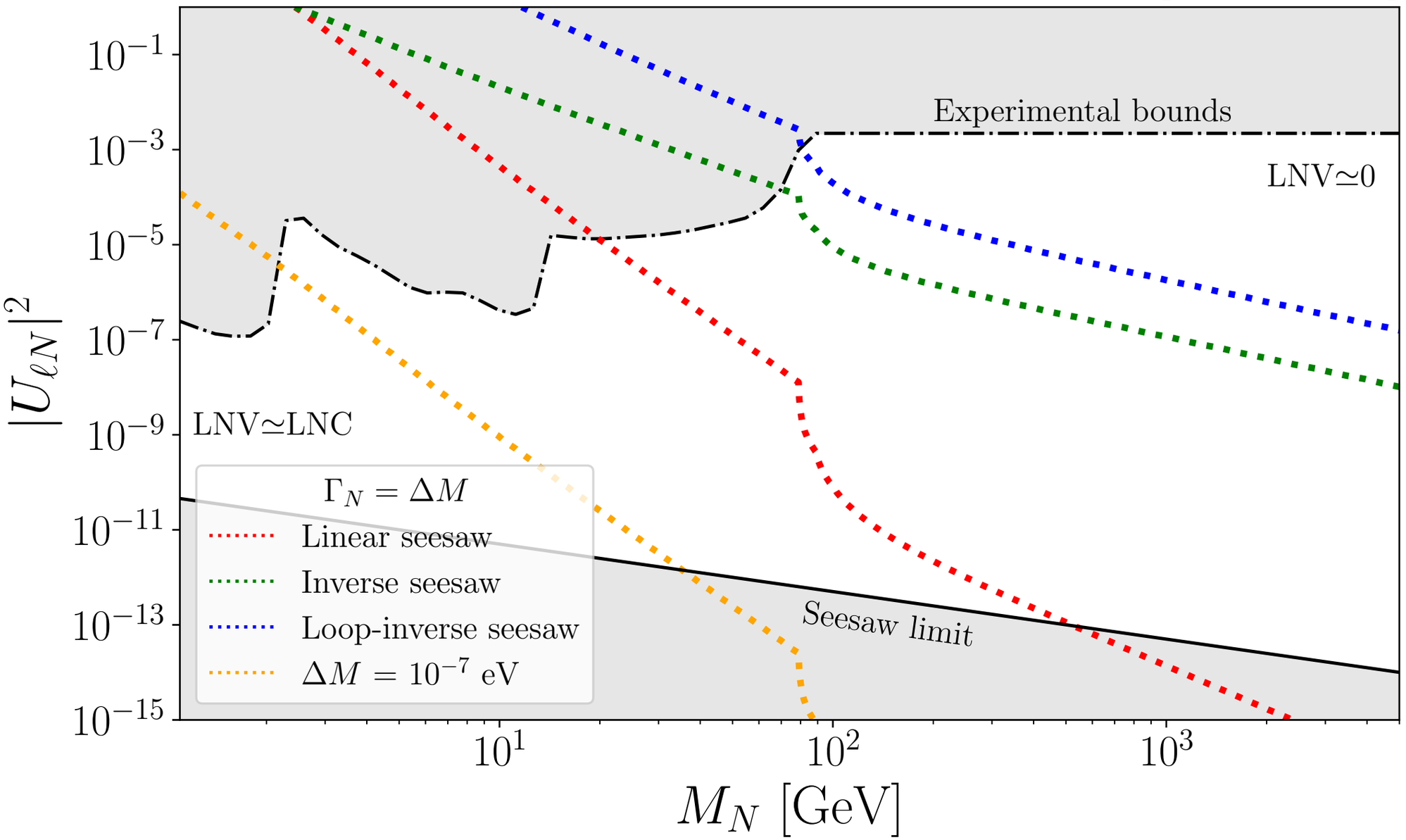
— Drewes et al [1907.13034] —



LNV in Symmetry Protected Scenarios

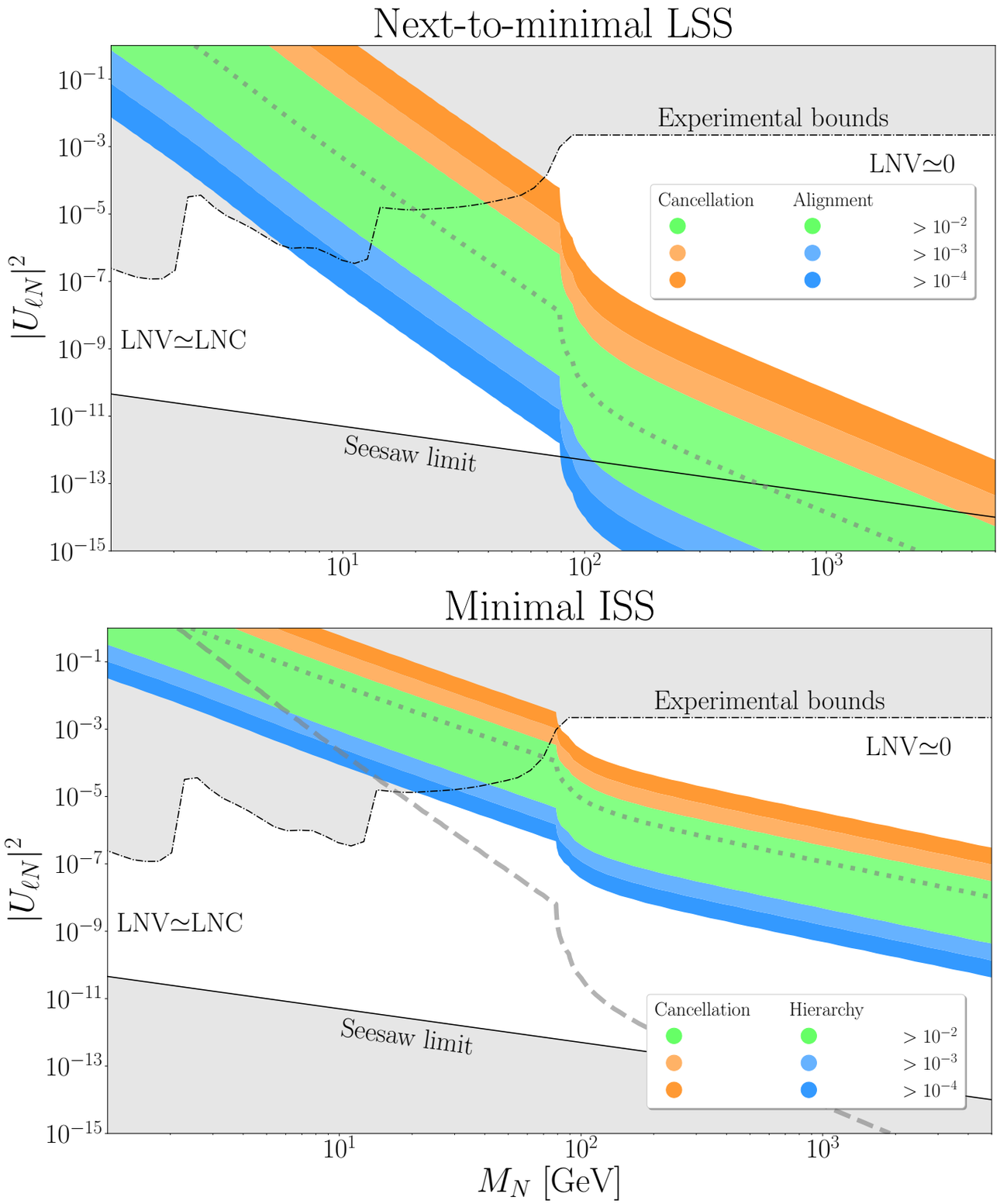
- *Discriminate between low-scale seesaws*

Fernández-Martínez, XM, Naredo-Tuero [2209.04461]



Discriminate Between Low-Scale Seesaws

Fernández-Martínez, XM, Naredo-Tuero [2209.04461]



Summary

- *Colliders are good places to search for HNLs*

  — LEP, LHC and more to come —

- *LHC is already improving LEP*

- *Analyses are improving*

  — trileptons, DV, OS dileptons —

- *Still things to be improved*

  — going beyond single mixing hypothesis —

- *LNV signals still relevant for symmetry protected scenarios*

  — help discriminating low-scale seesaws —

Thank you!

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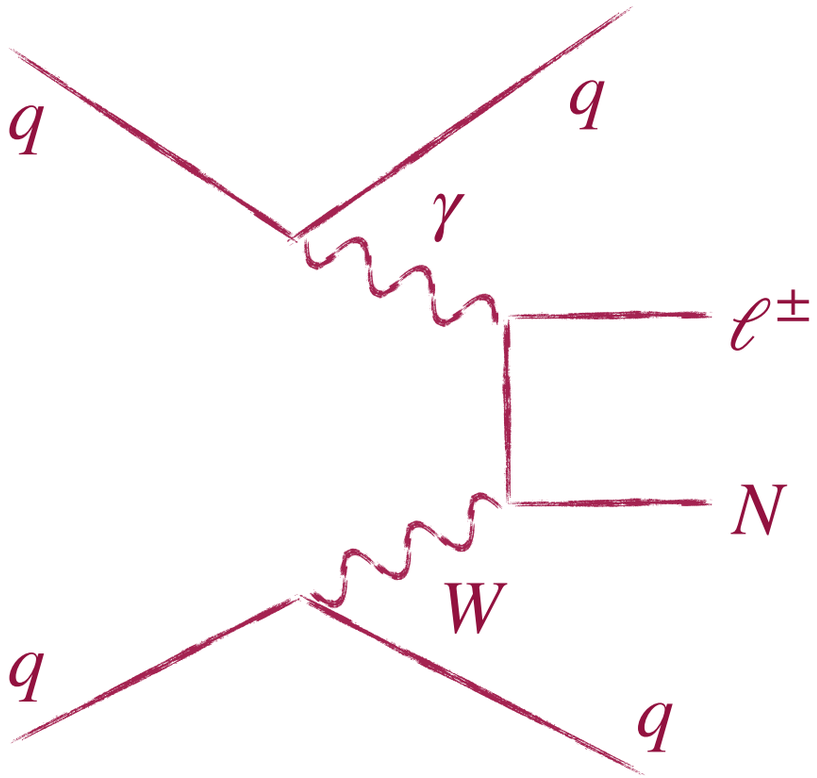
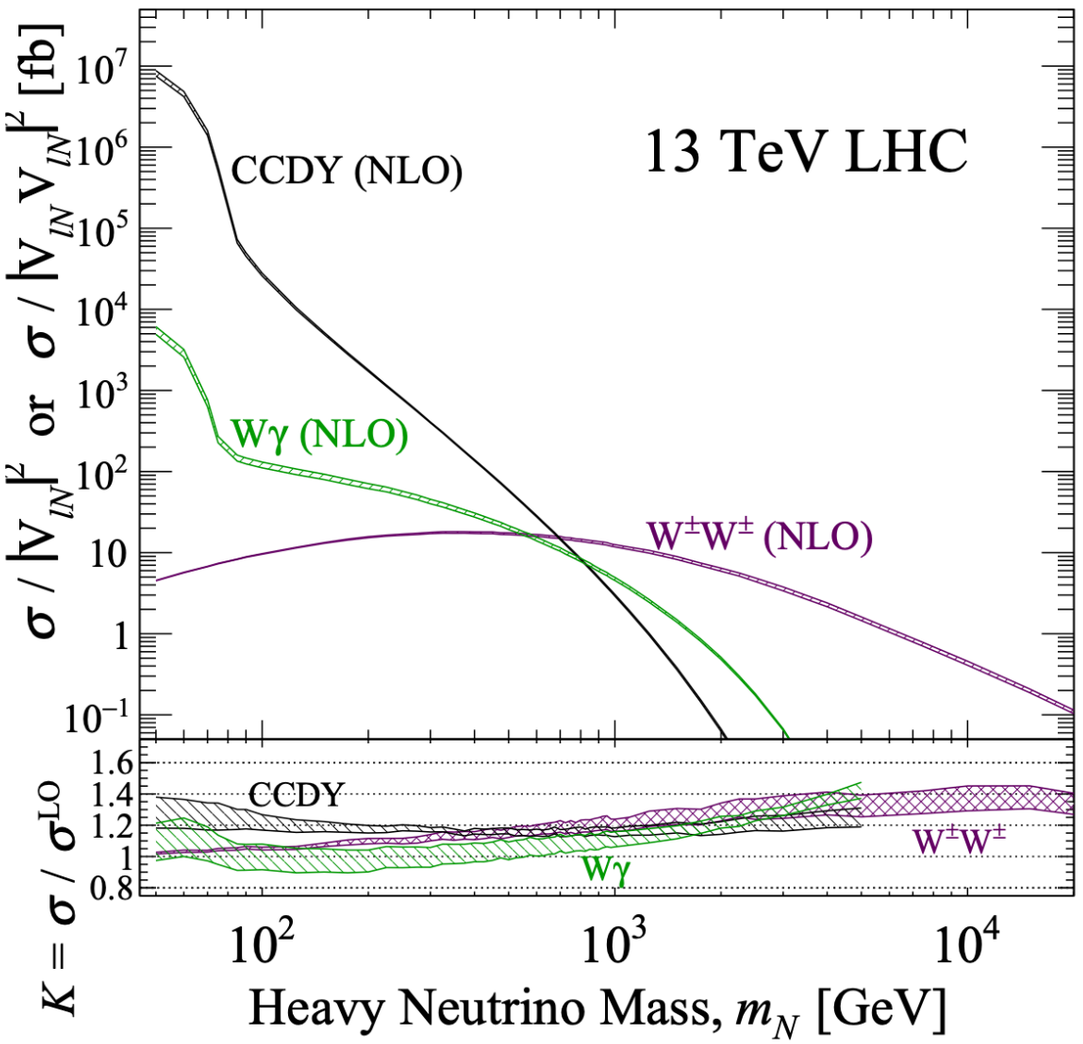
Back up

HNL Production

- *Dominant diagrams: Drell-Yan W and Z (and Higgs?)*
- *For higher masses, also Vector Boson Fusion*



Fuks et al. [2011.02547]

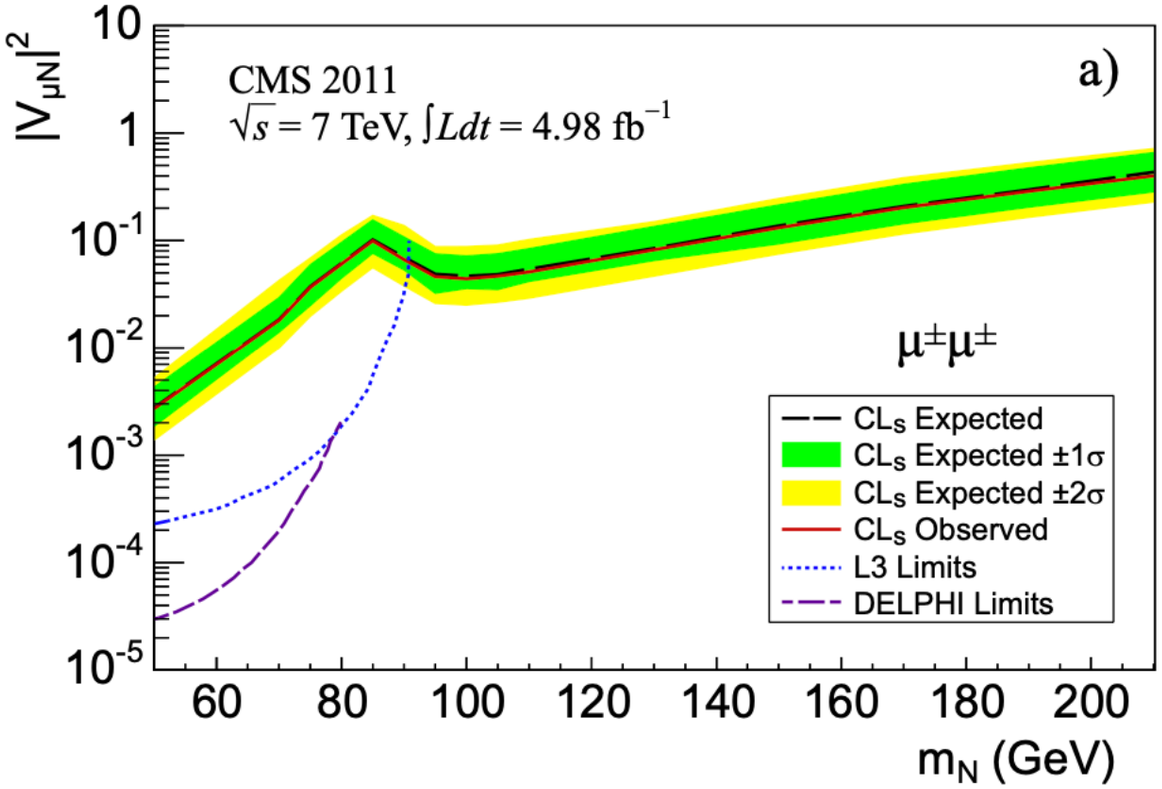


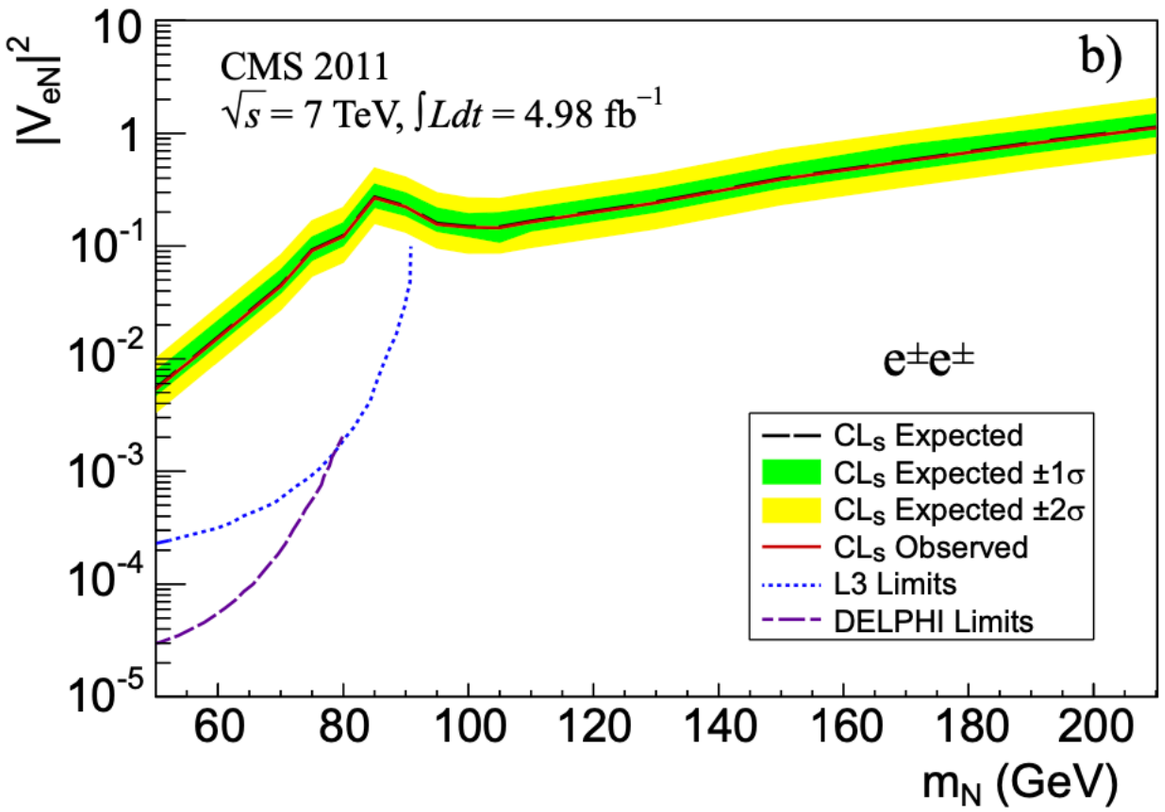
Di-leptons at LHC

- *Same sign dilepton channel* — *LNV signature*—

$$pp \to W^{(*)} \to \ell^{\pm} N \to \ell^{\pm}\ell^{\pm} + nj$$

[1207.6079]



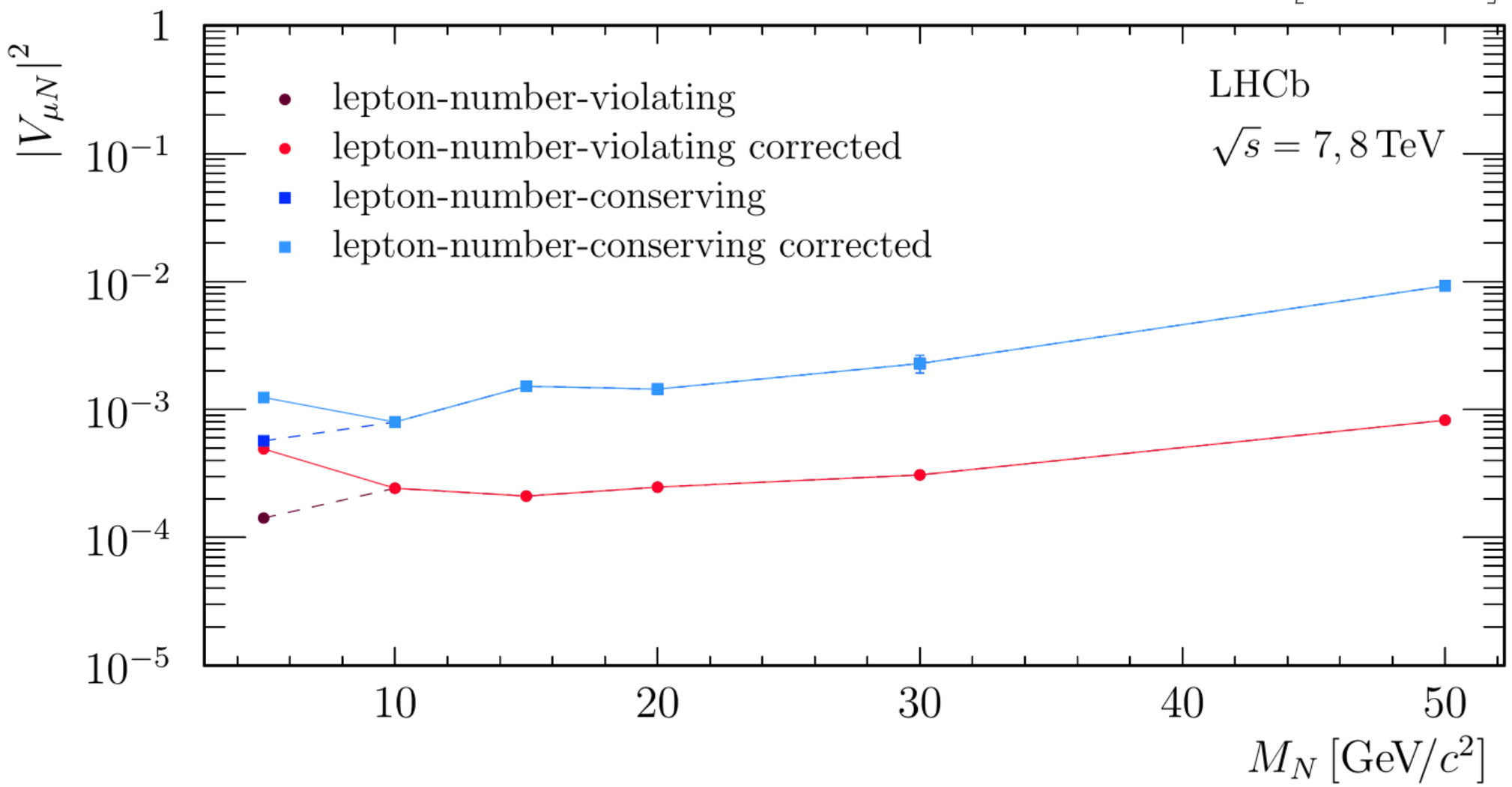


Di-leptons at LHC

- *LNC searches are also possible*

$$pp \to W^{(*)} \to \ell^{\pm} N \to \ell^{\pm}\ell^{\mp} + nj$$

[2011.05263]

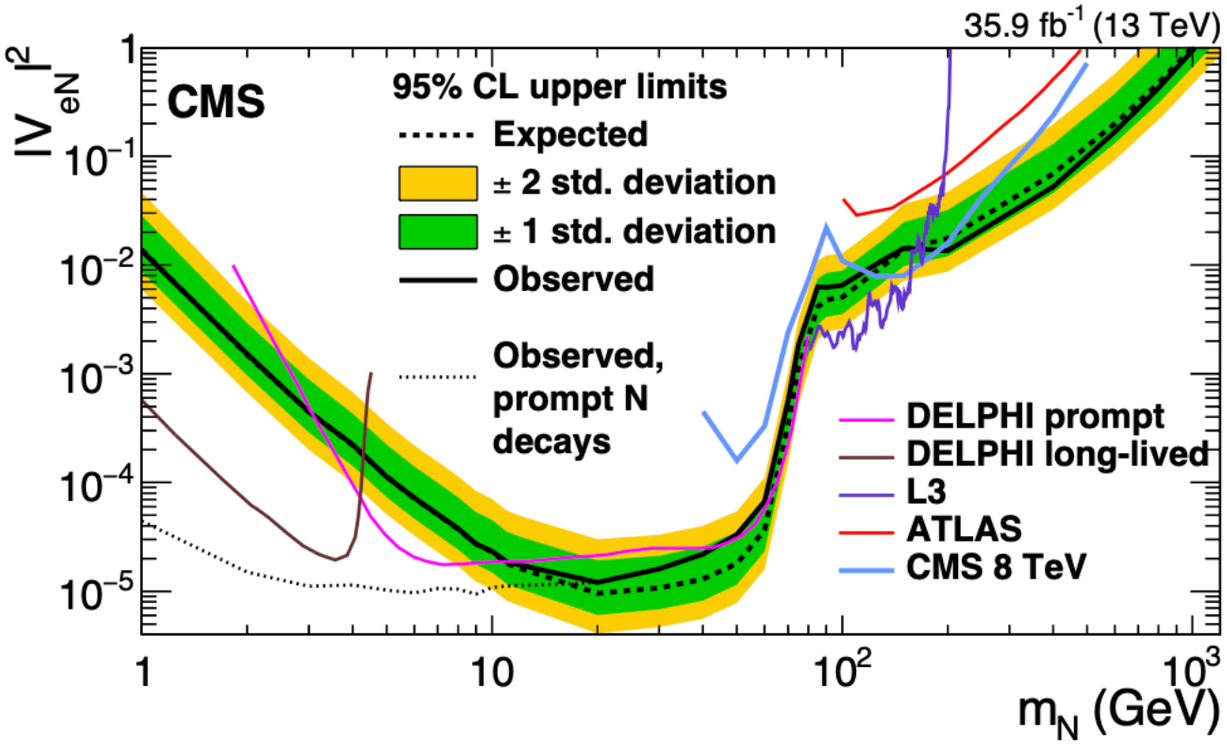


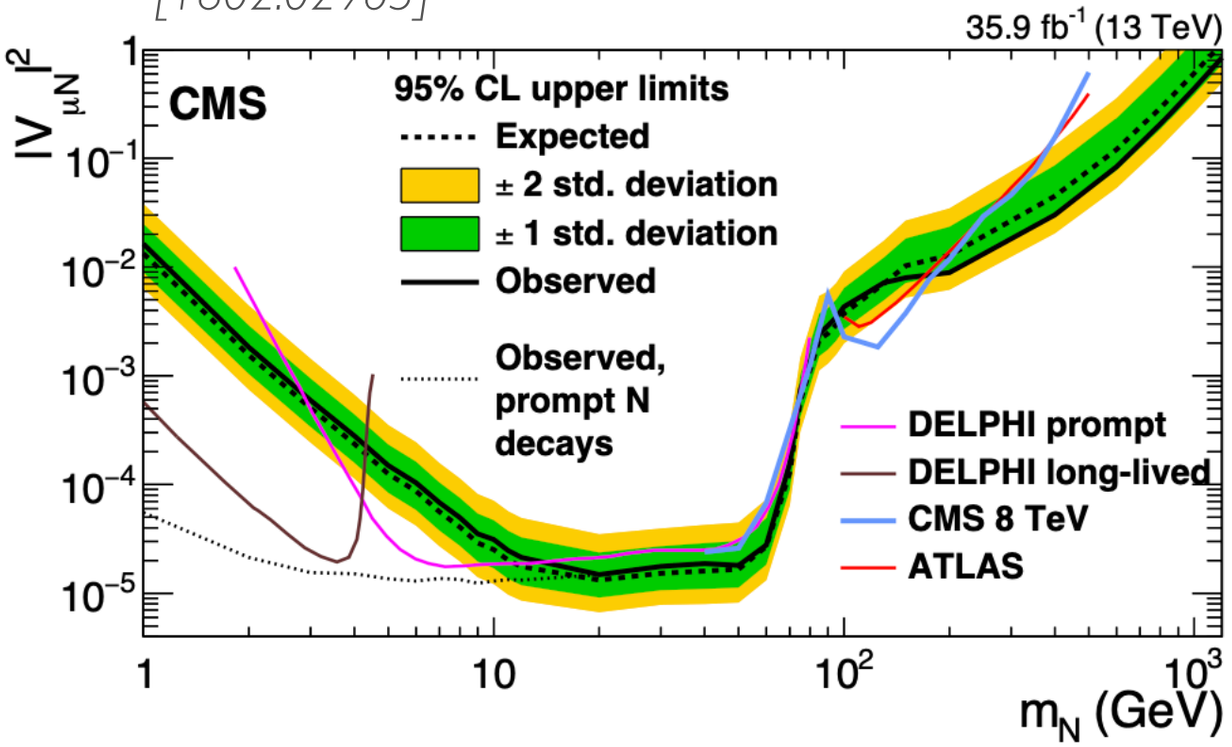
Tri-leptons at LHC

- *Trilepton* — *LNV signature?*—

$$pp \to W^{(*)} \to \ell^{\pm}_{\alpha} N \to \ell^{\pm}_{\alpha} \ell^{\pm}_{\beta} \ell^{\mp}_{\gamma} \nu$$

[1802.02965]



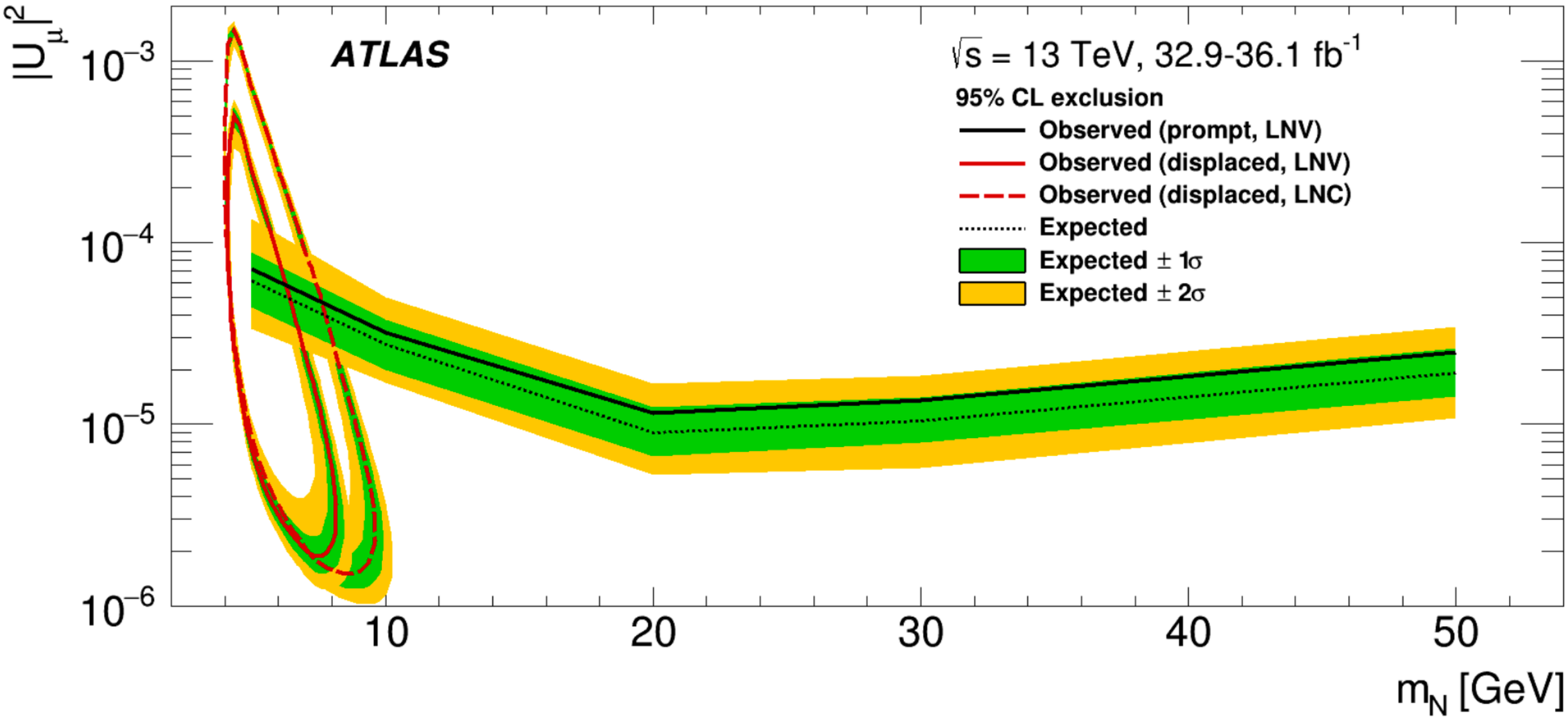


Long-Lived at LHC

- *Displaced Vertices* — *LNV signature?*—

$$pp \to W^{(*)} \to \ell^{\pm}_{\alpha} N \quad // \quad N \to \ell^{\pm}_{\beta} \ell^{\mp}_{\gamma} \nu$$

[1905.09787]

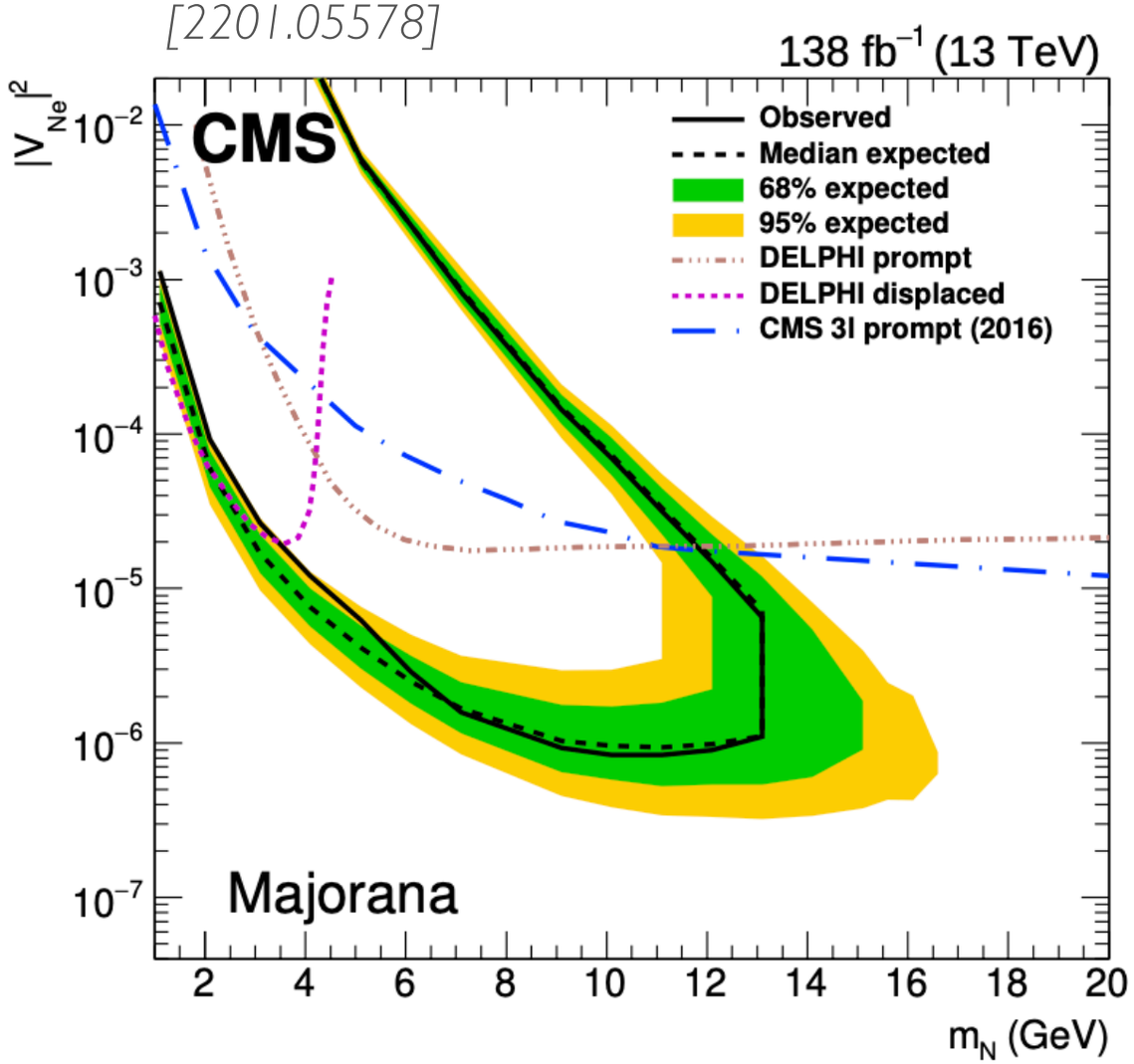


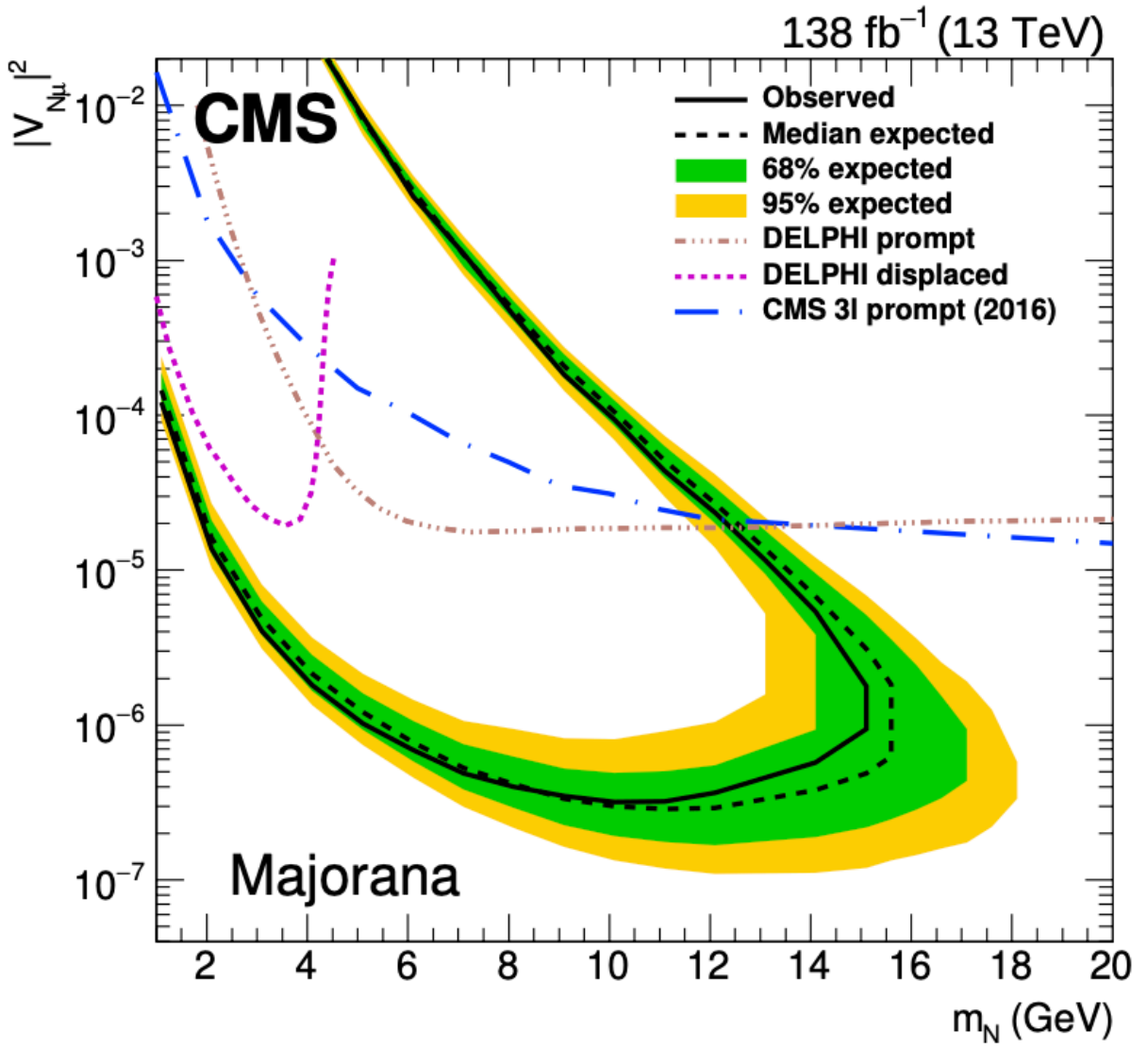
Long-Lived at LHC

- *Displaced Vertices* — *LNV signature?*—

$$pp \to W^{(*)} \to \ell^{\pm}_{\alpha} N \quad // \quad N \to \ell^{\pm}_{\beta} \ell^{\mp}_{\gamma} \nu$$

[2201.05578]





Long-Lived at LHC

- *Displaced Vertices* — *LNV signature?*—

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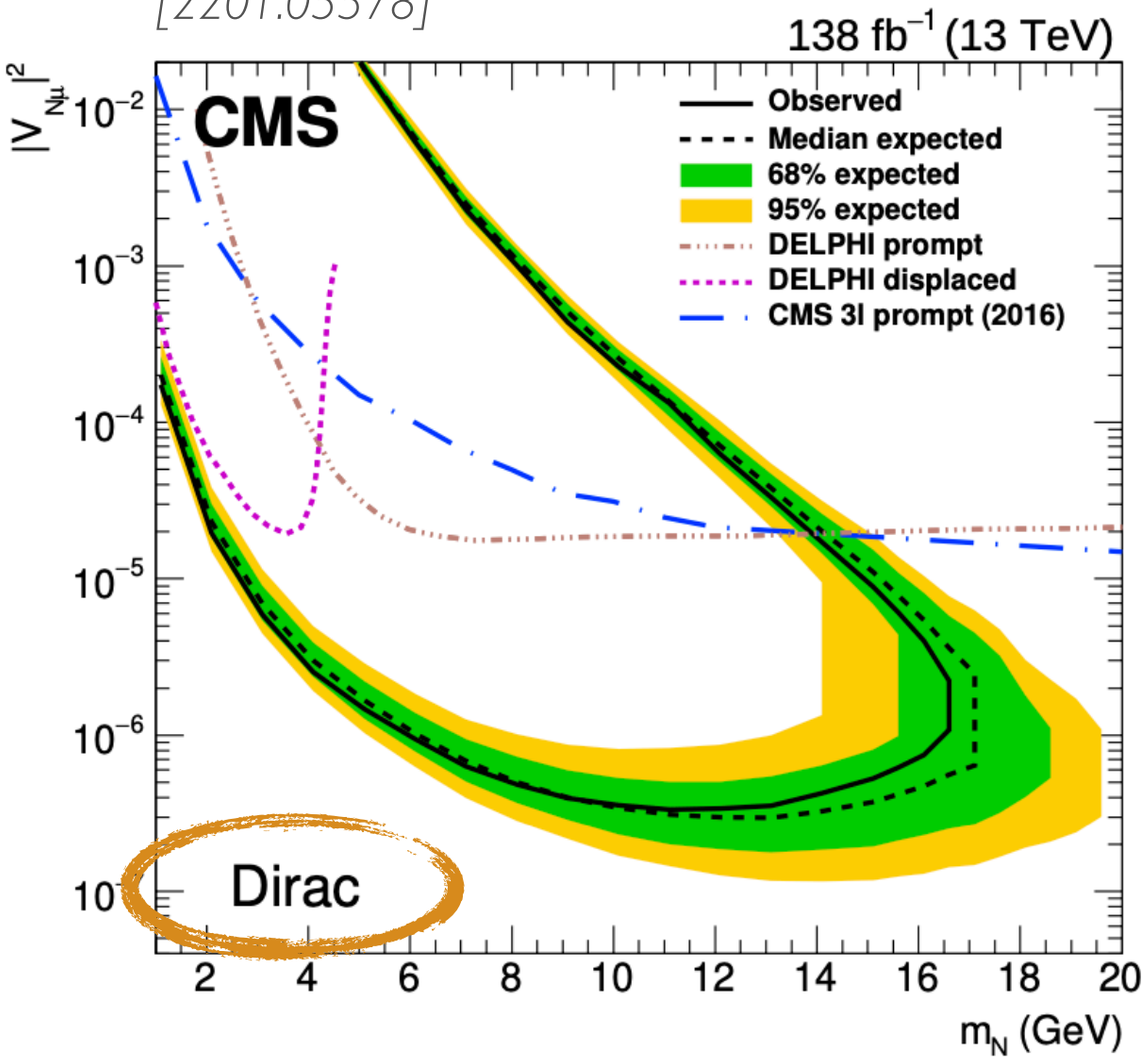
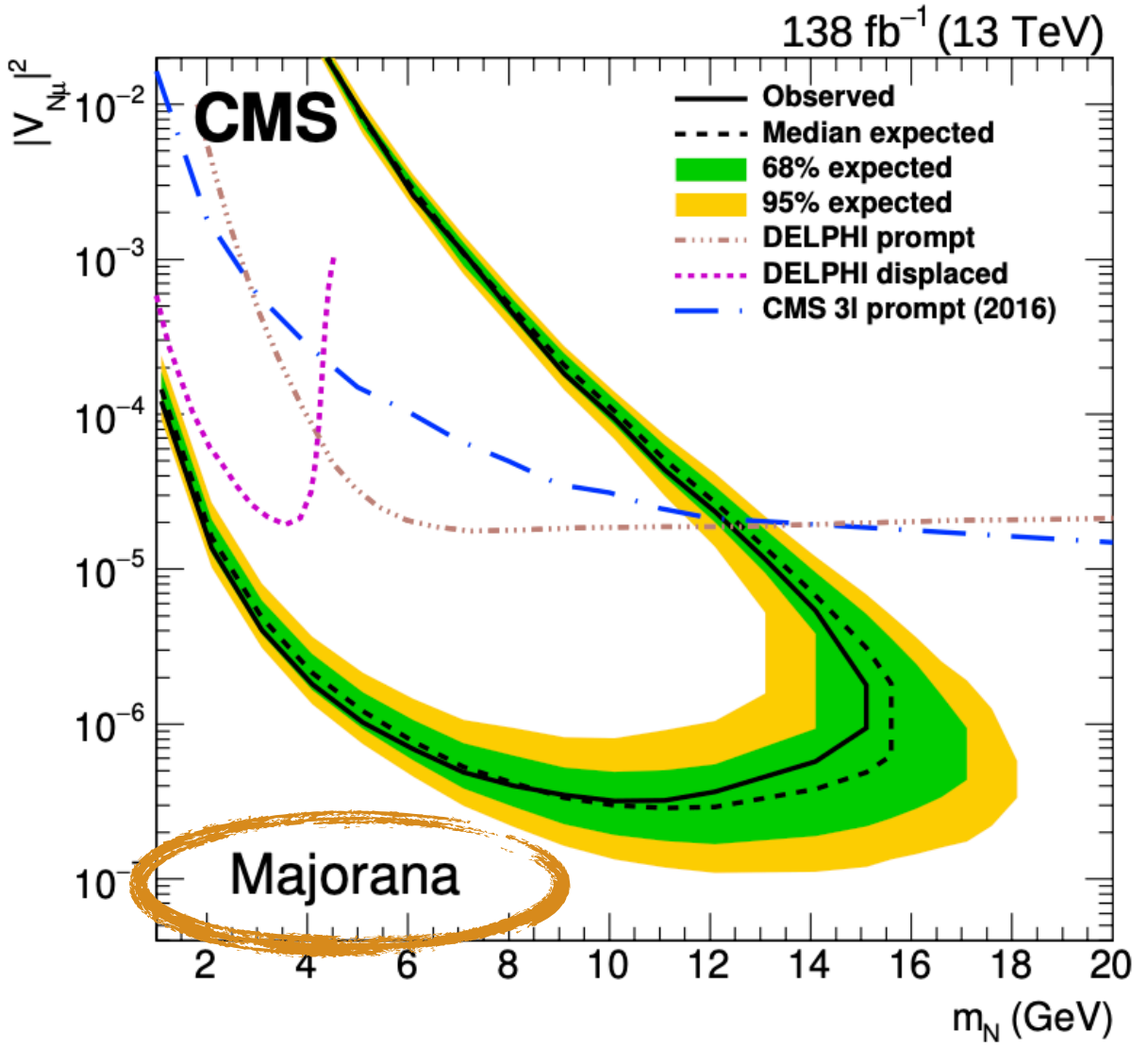
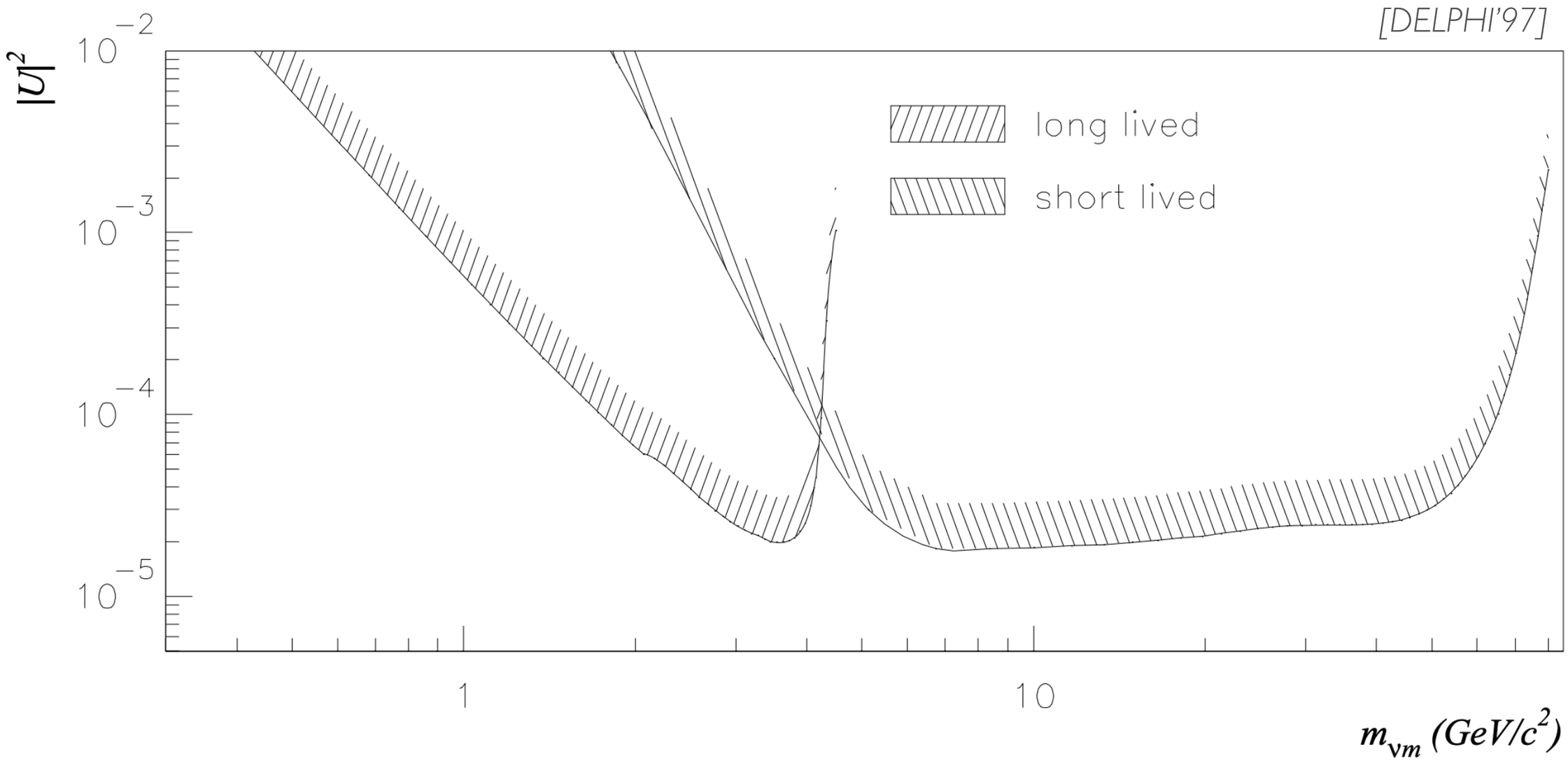
[2201.05578]



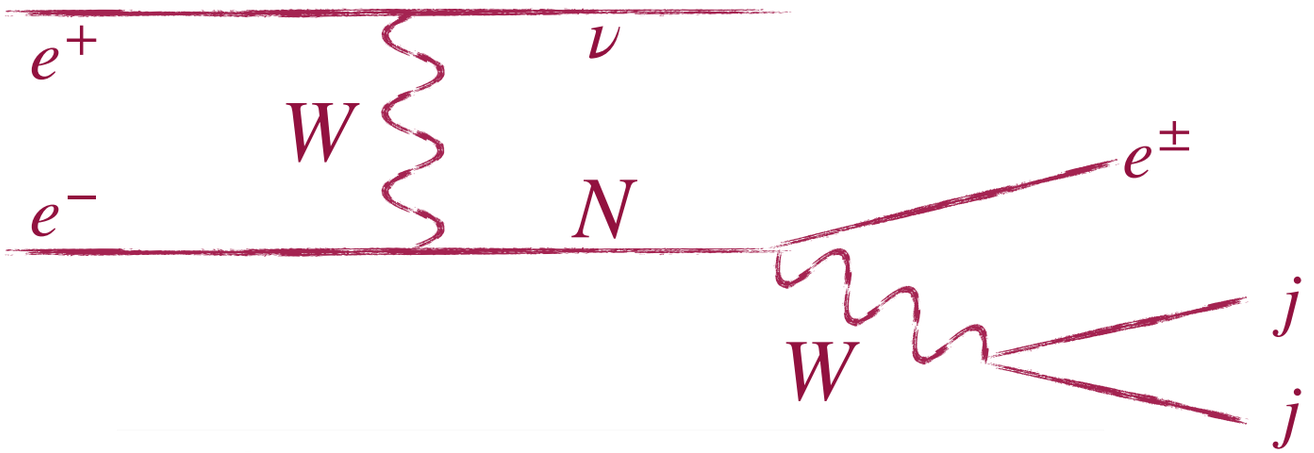


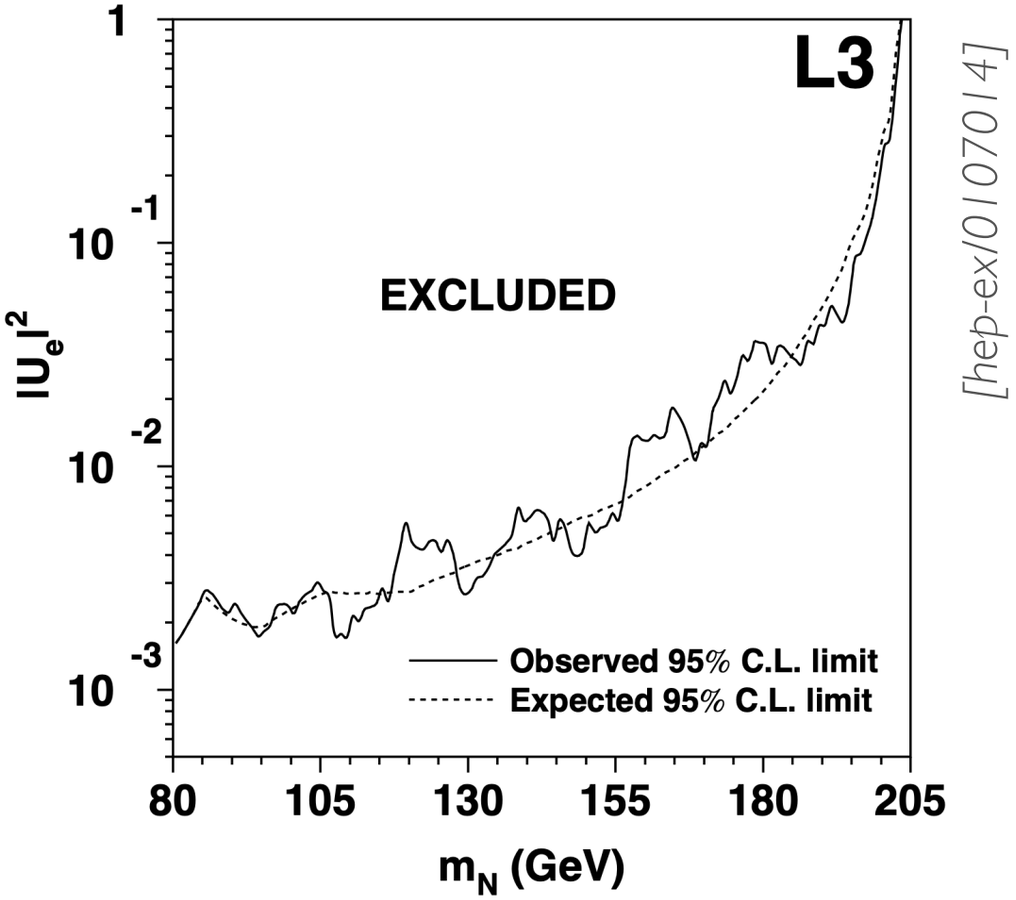
- *Light HNL: Drell-Yan Z (on-shell)* — *Sensitive to all flavor mixings*—

$$e^+e^- \to Z \to \nu N \to \nu l/\ell + nj$$



- *Heavy HNL: t-channel W* — *Sensitive to electron mixing*—





[hep-ex/0107014]