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

Heavy Neutrinos at Colliders

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MINISTERIO DE CIENCIA E INNOVACIÓN | UNIÓN EUROPEA FONDO EUROPEO DE DESARROLLO REGIONAL "Una manera de hacer Europa" | AGENCIA ESTATAL DE INVESTIGACIÓN

HIDDeν Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

EXCELENCIA SEVERO OCHOA

Motivation

BSM Behind Neutrino Masses

electron neutrino

muon neutrino

tau neutrino

BSM Behind Neutrino Masses

electron neutrino

muon neutrino

tau neutrino

sterile neutrino

ν_s

Curriculum Vitae

Sterile Neutrino

Heavy neutrino, right-handed neutrino, heavy neutral lepton

Spin 1/2

Color single

Isospin single

Charge 0

Mass how dare you!?

Social life not much

Work experience

- Neutrino masses

Other skills

- Osc. anomalies
- Dark matter
- Baryogenesis
- Cooking

citations

ν_e

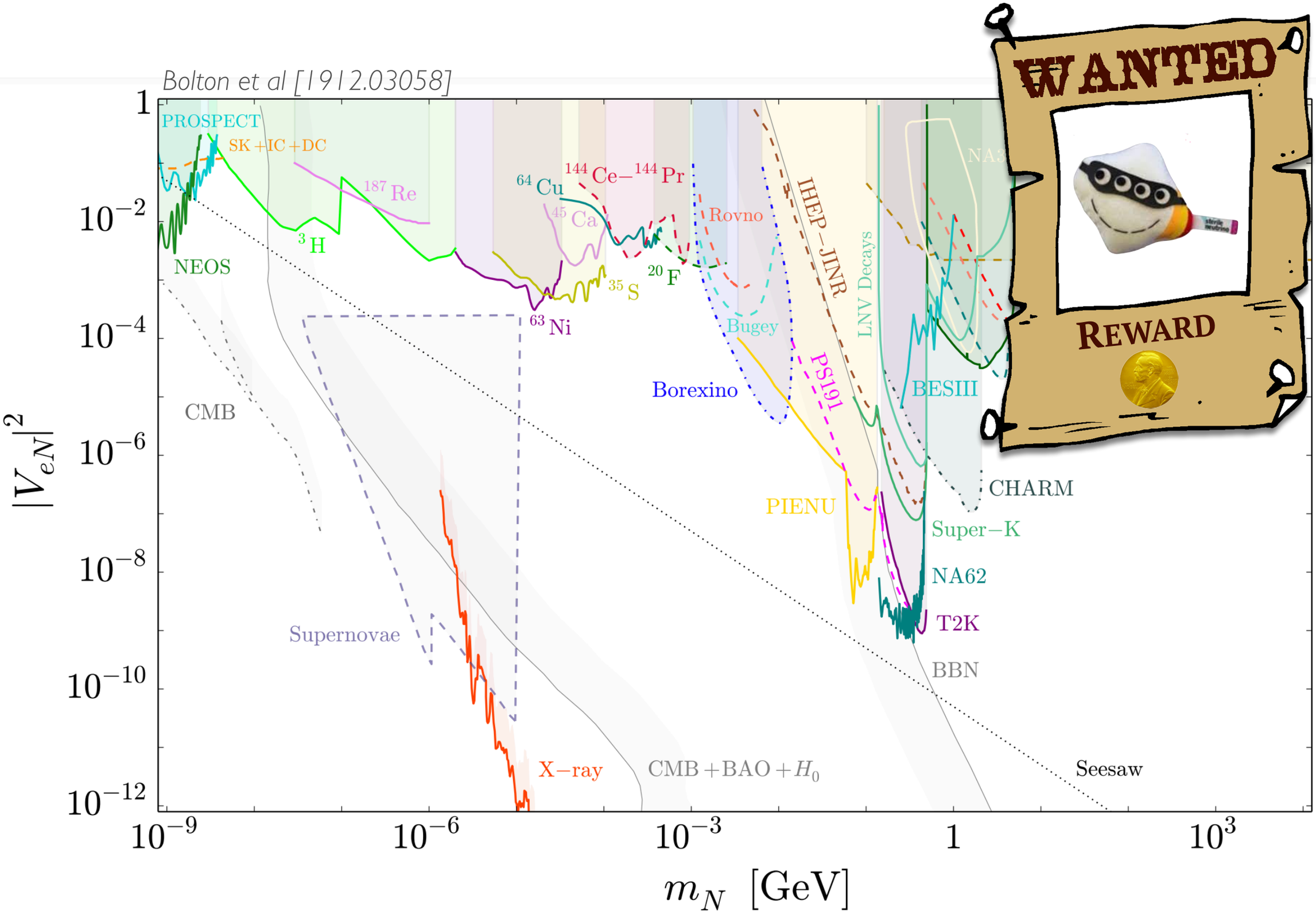
electron
neutrino

ν_s

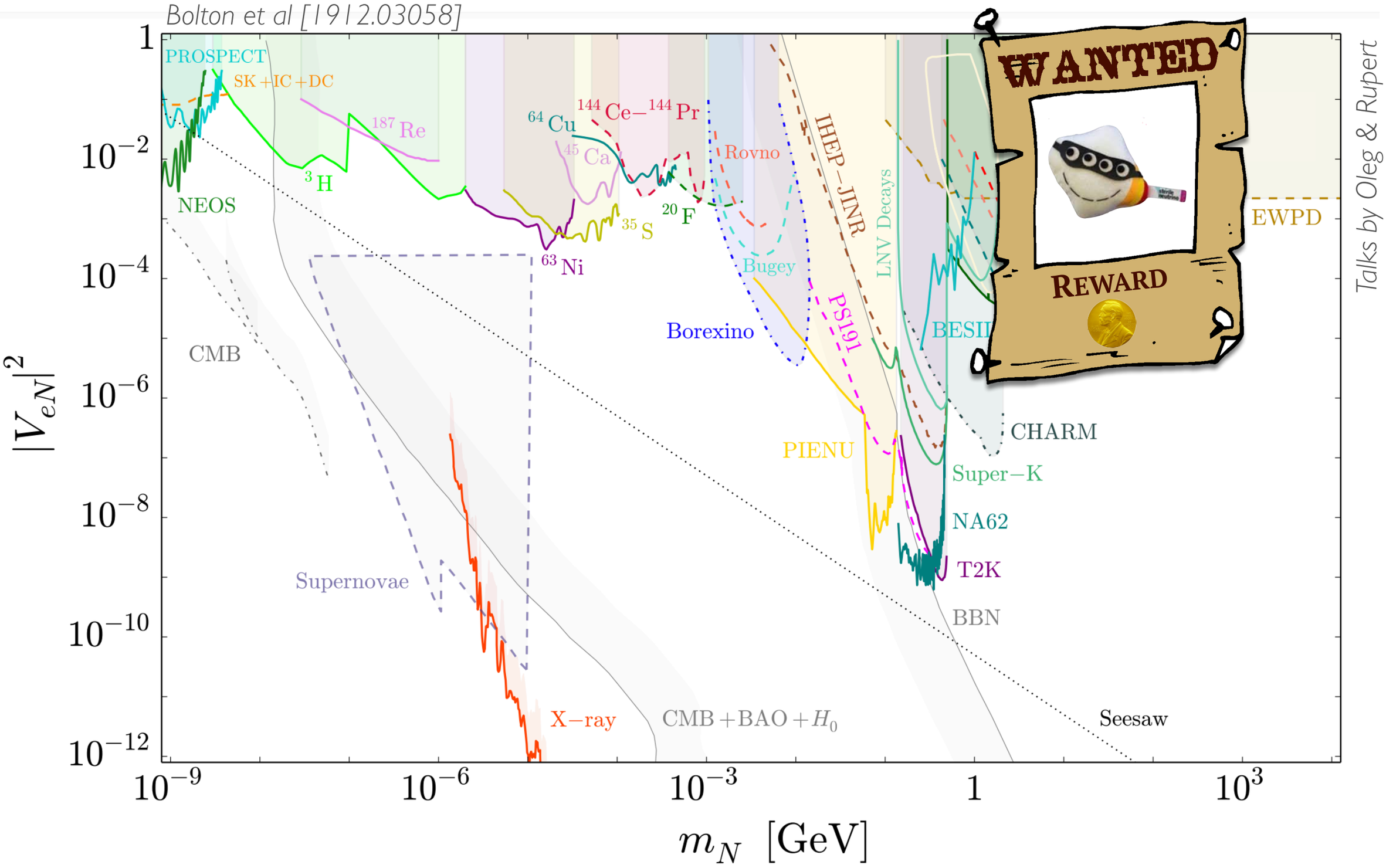
terile
utrino

Searches for HNL

Searches for HNL



Searches for HNL



Basic Ingredients

Current Status

Going Beyond

HNL at Colliders

— Basic Ingredients —

— Which Mass? —

— Production —

— Decay —

— Current Status —

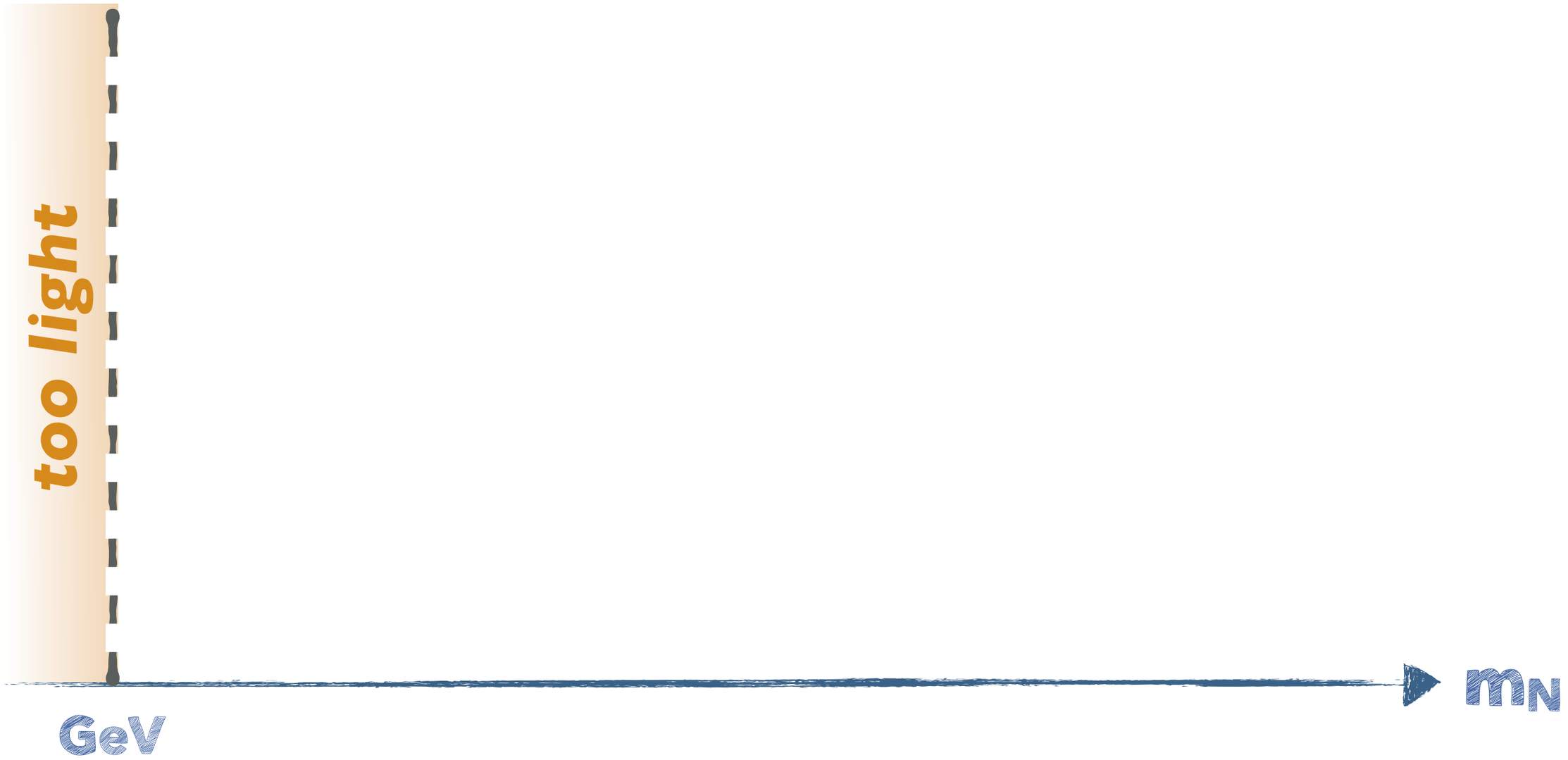
— from Past to the Future - are we improving? —

— Going Beyond —

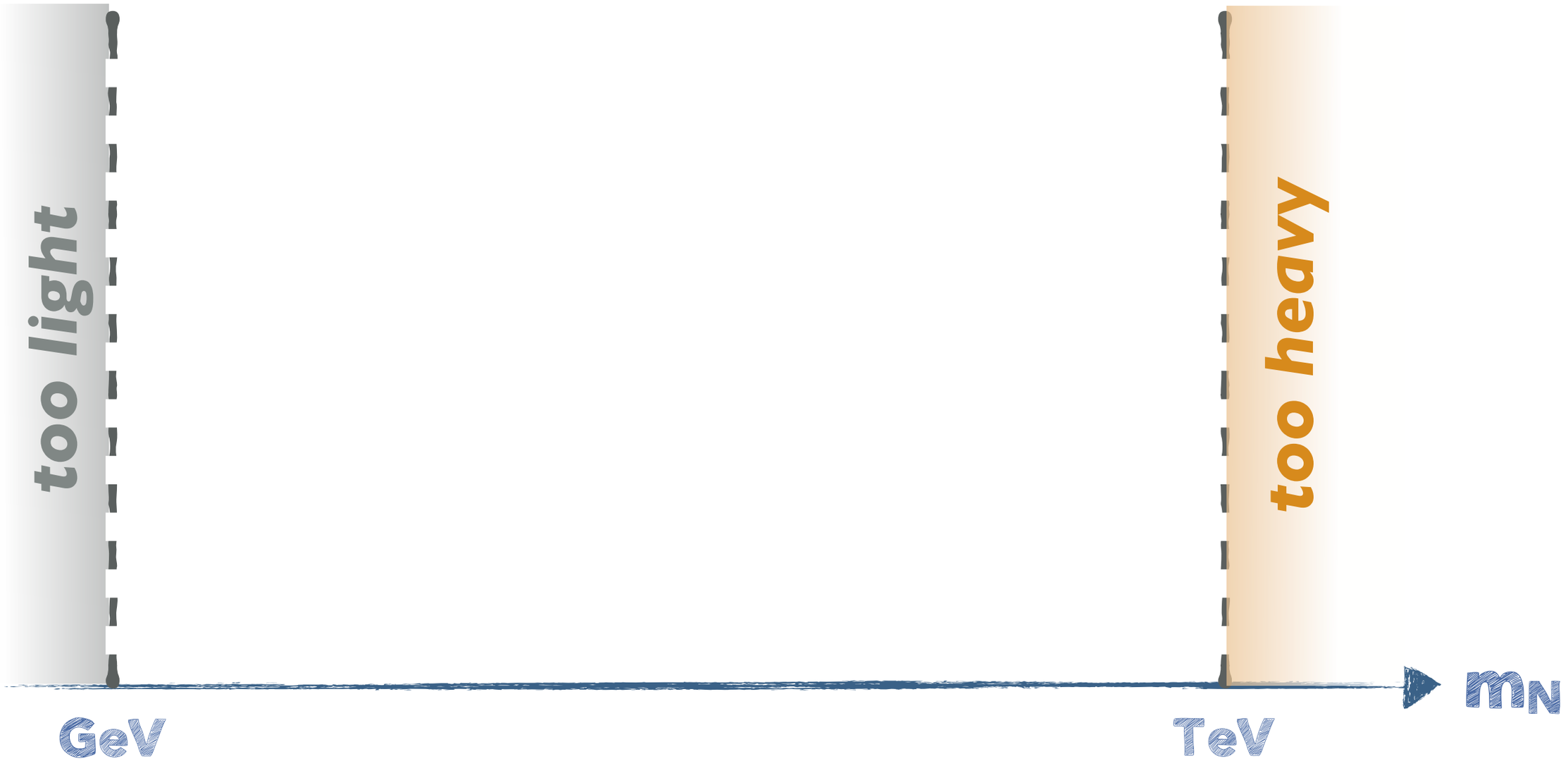
— Are we testing any Realistic Model? —

Which Masses?

Which Masses?



Which Masses?



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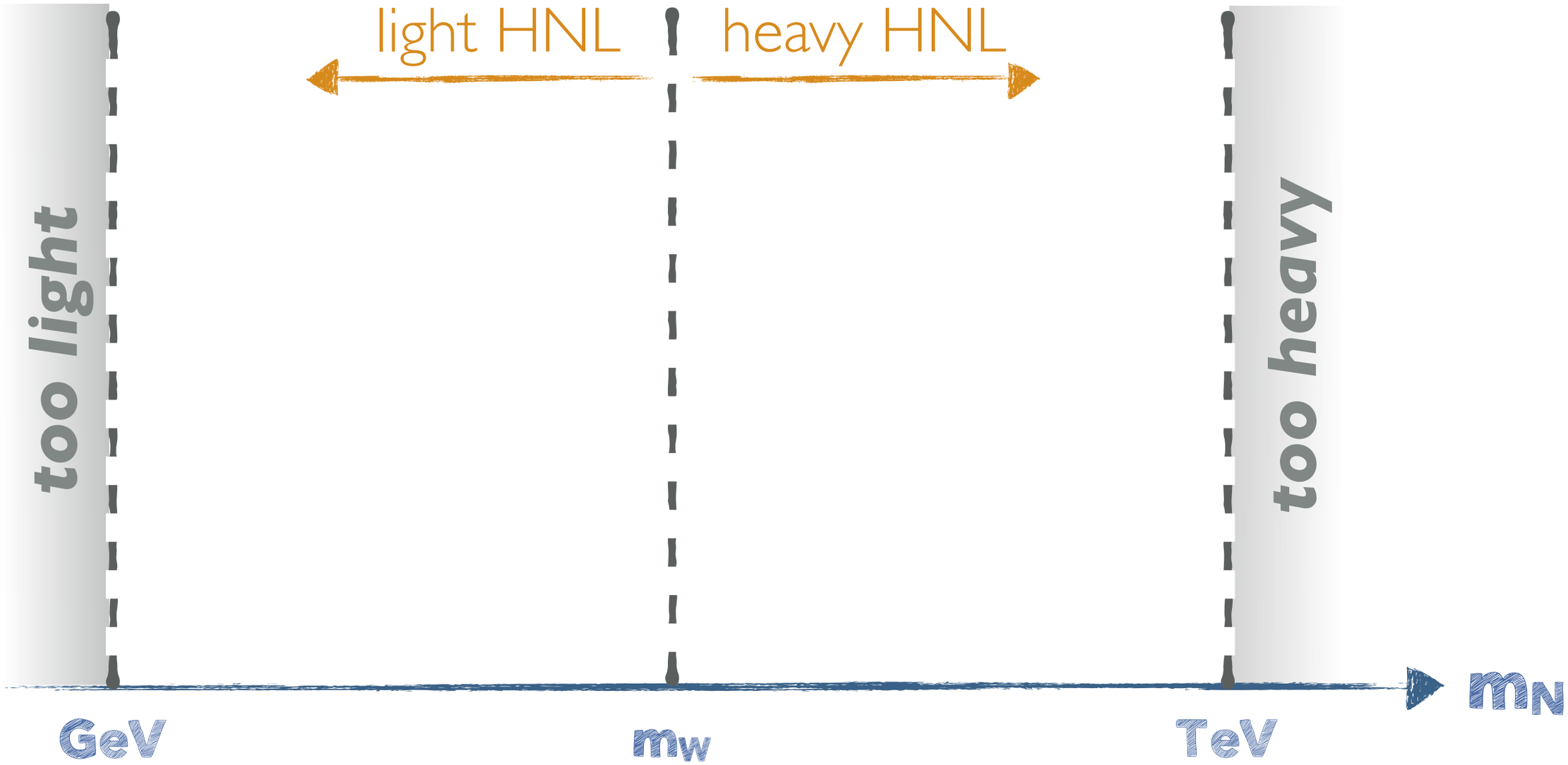

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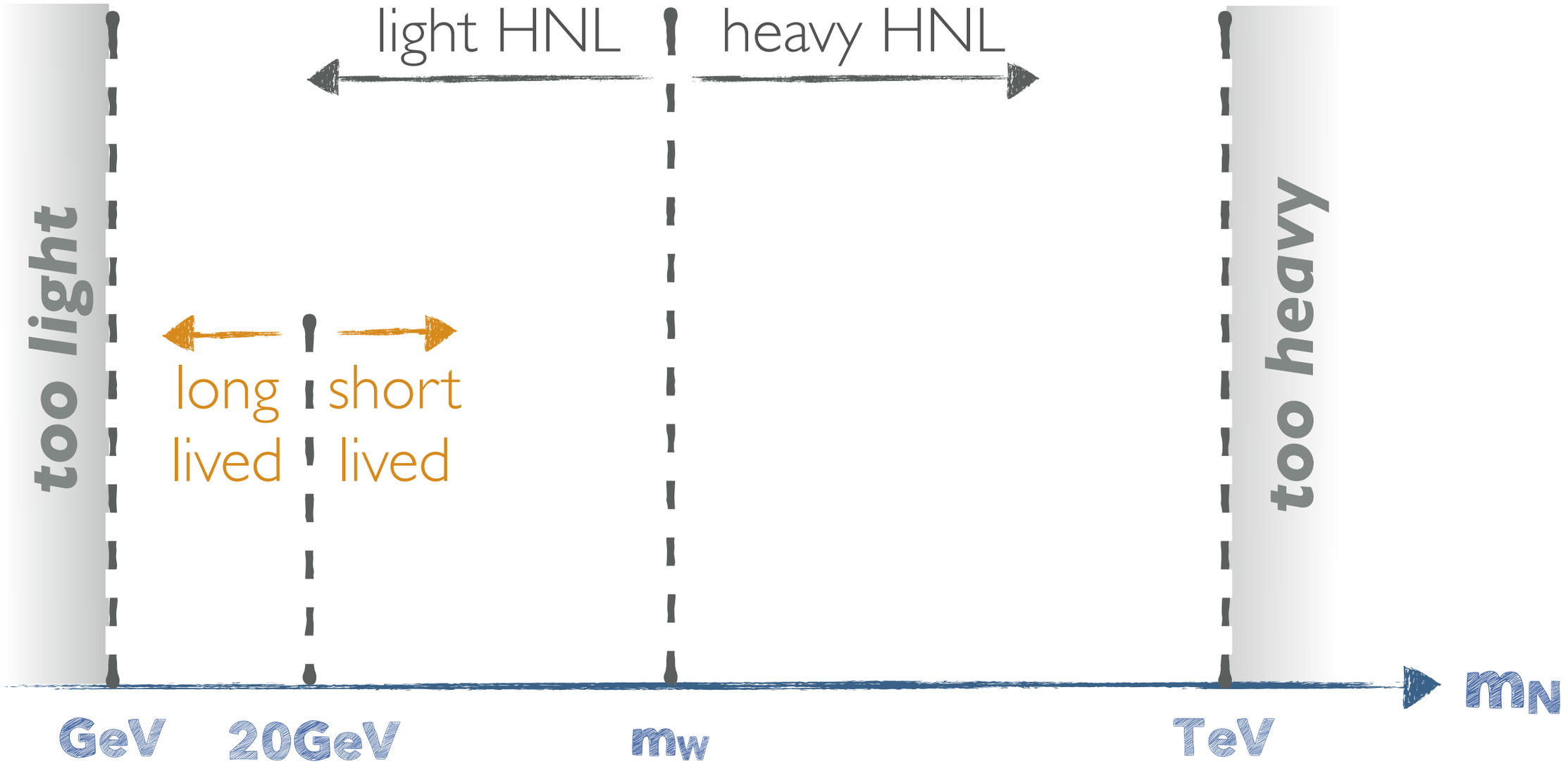
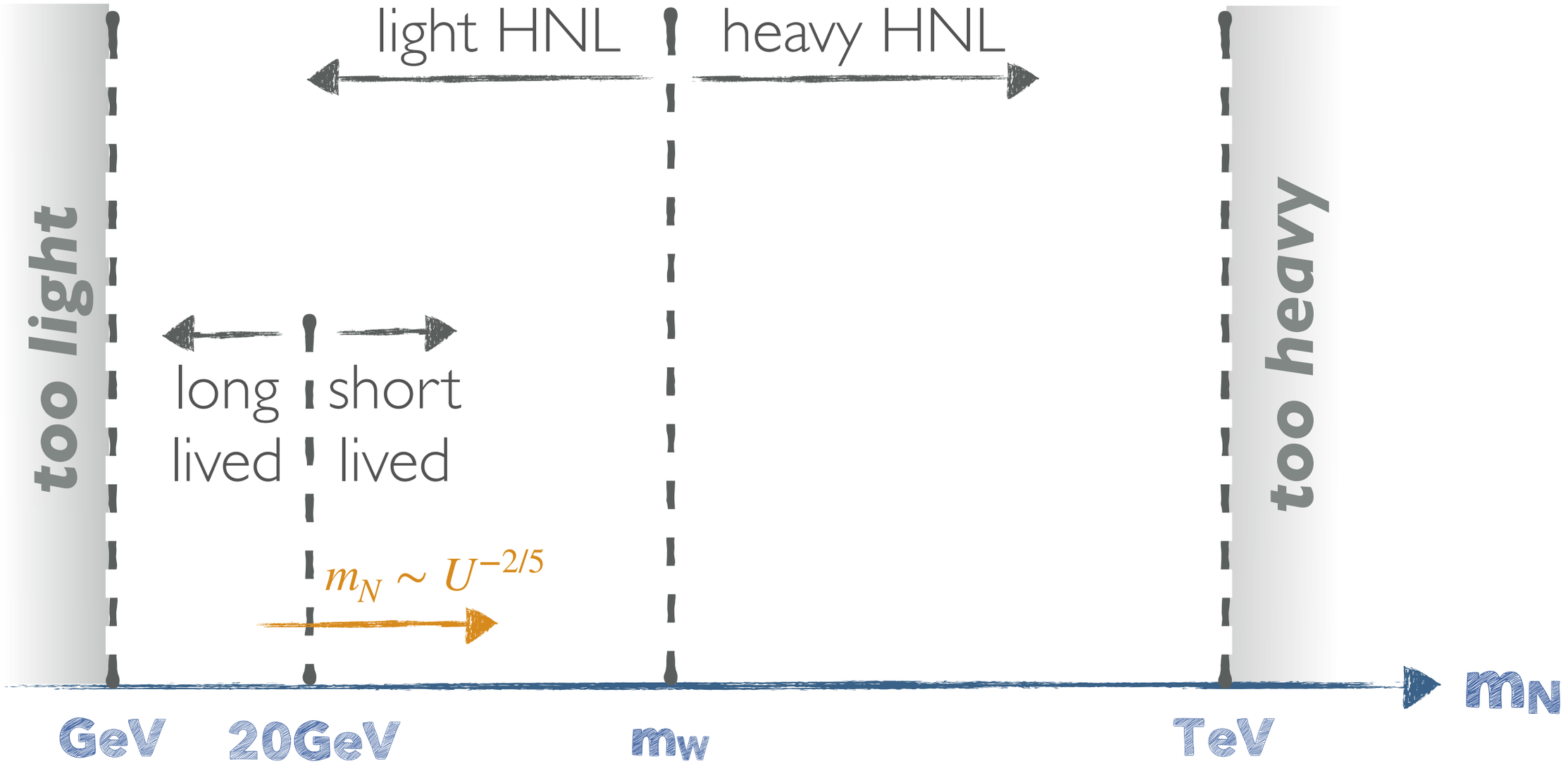
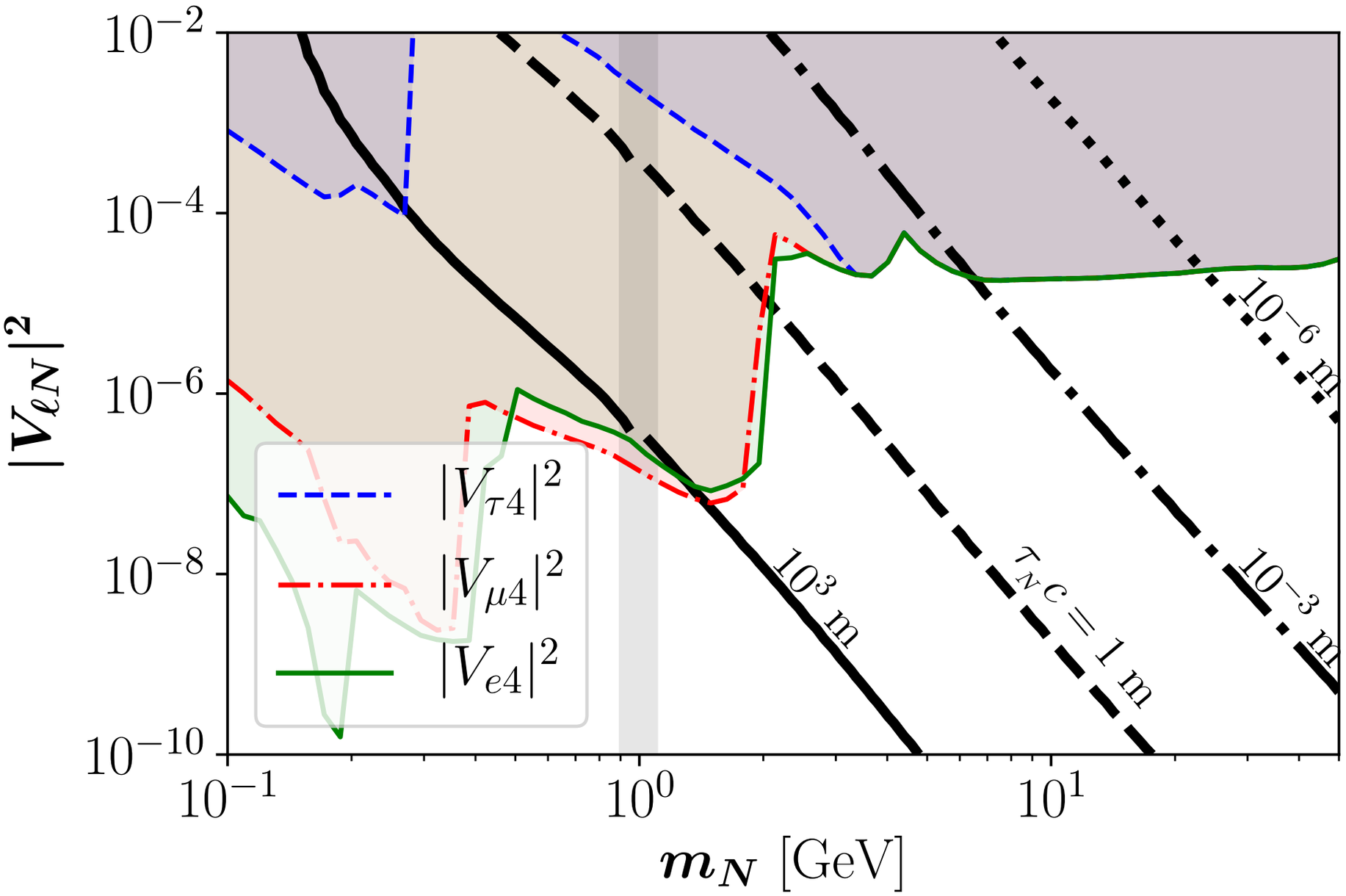


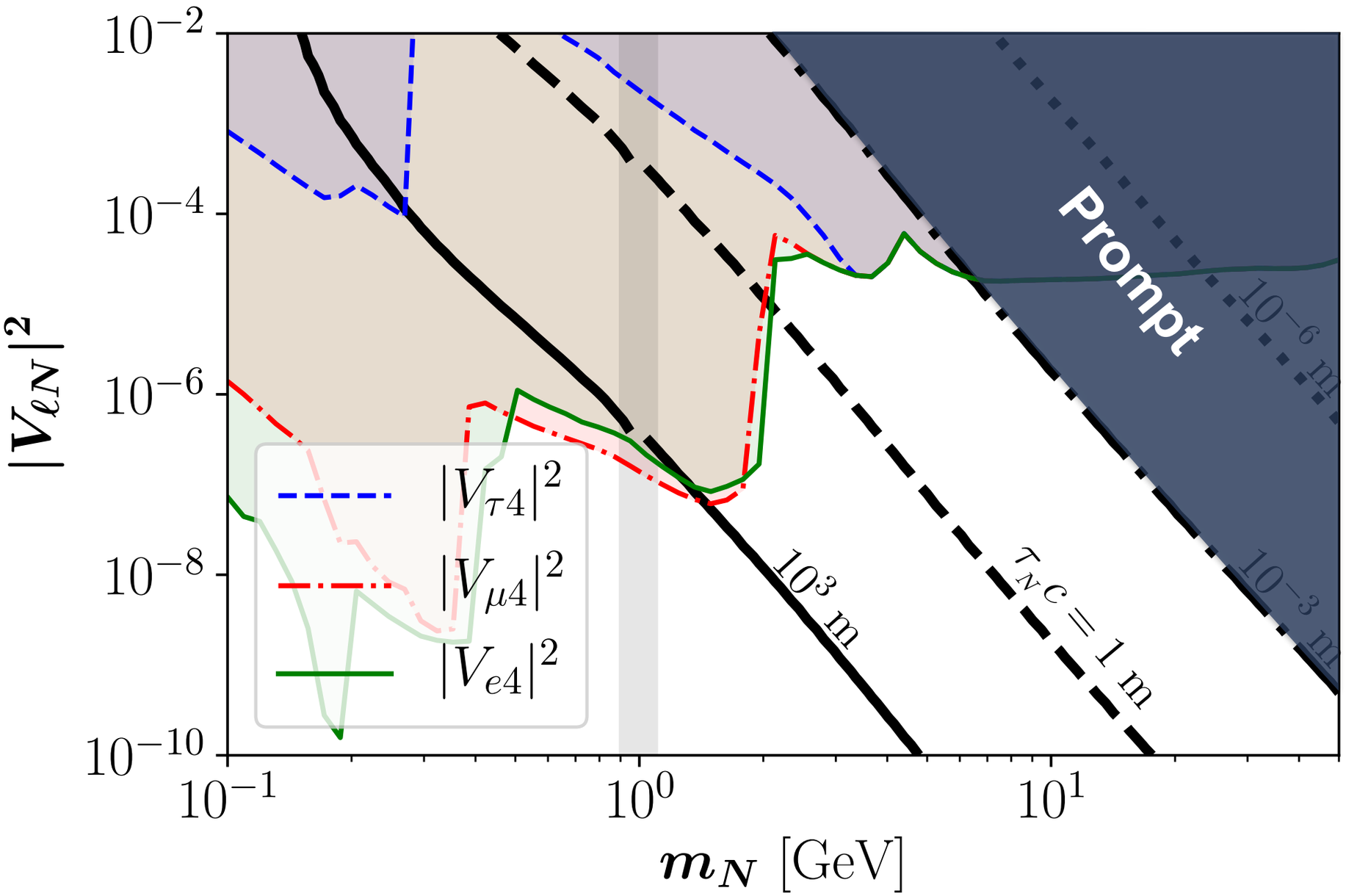
Which Masses?



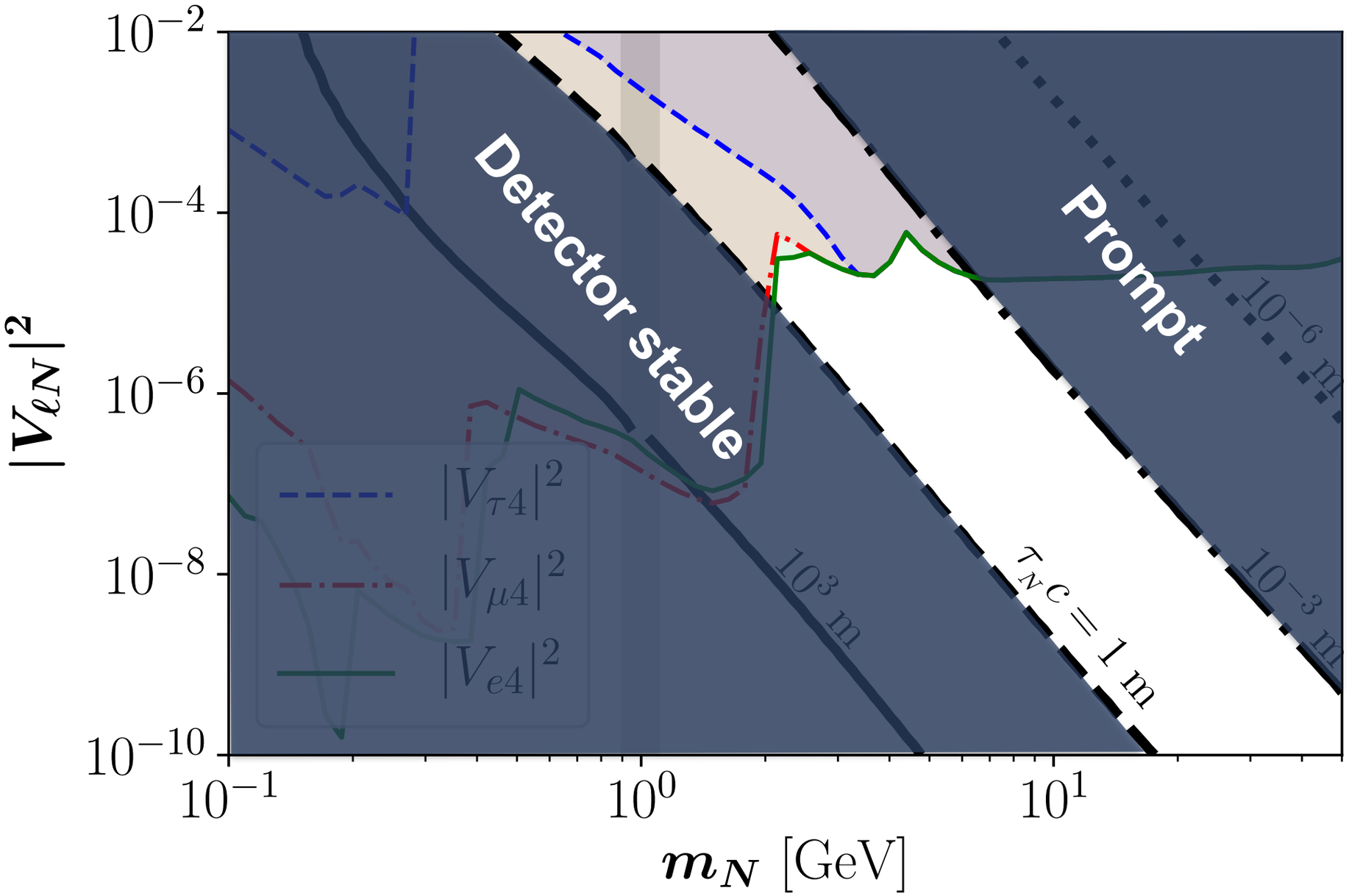
Long-Lived HNL and DV



Long-Lived HNL and DV



Long-Lived HNL and DV



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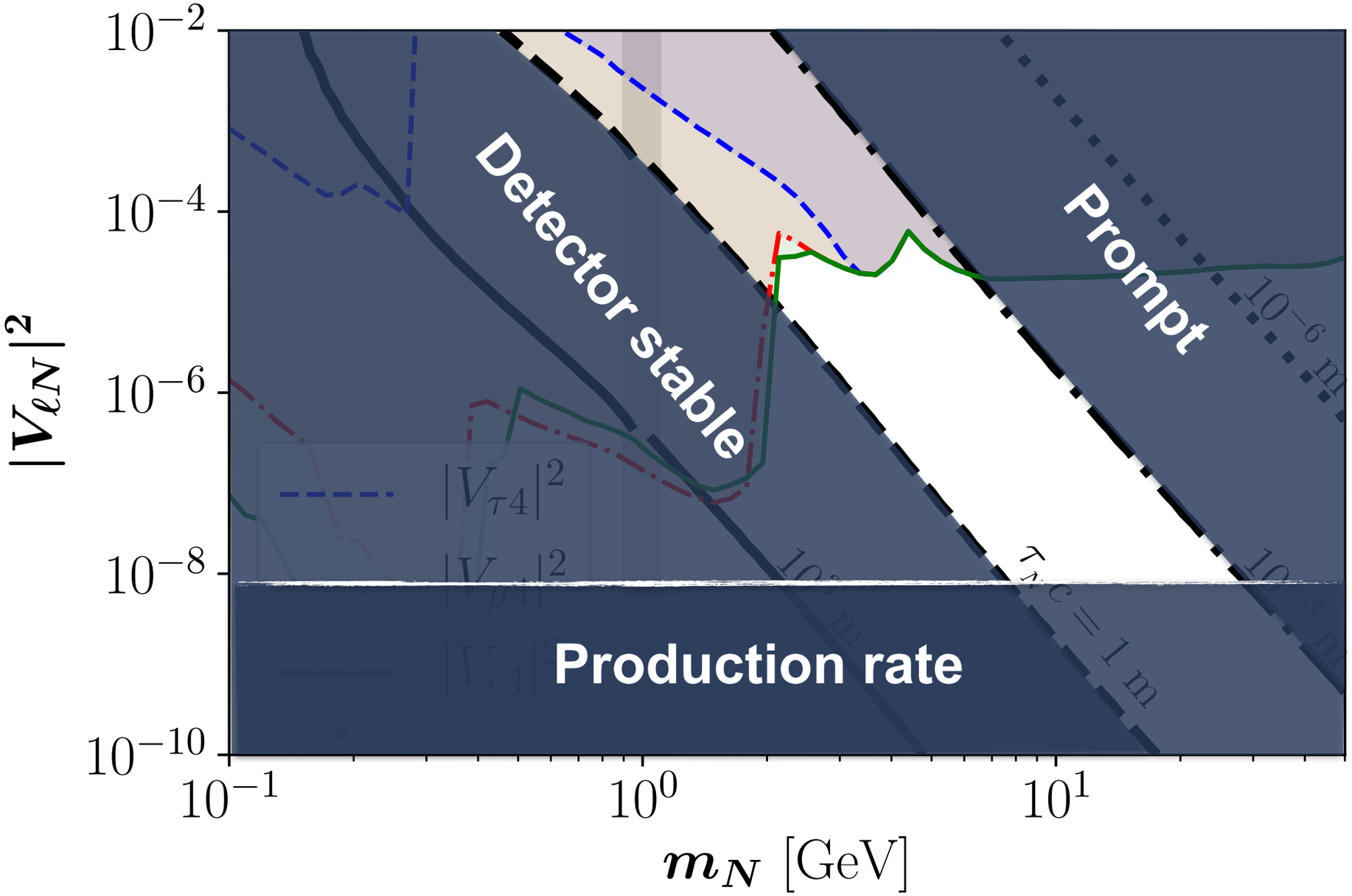
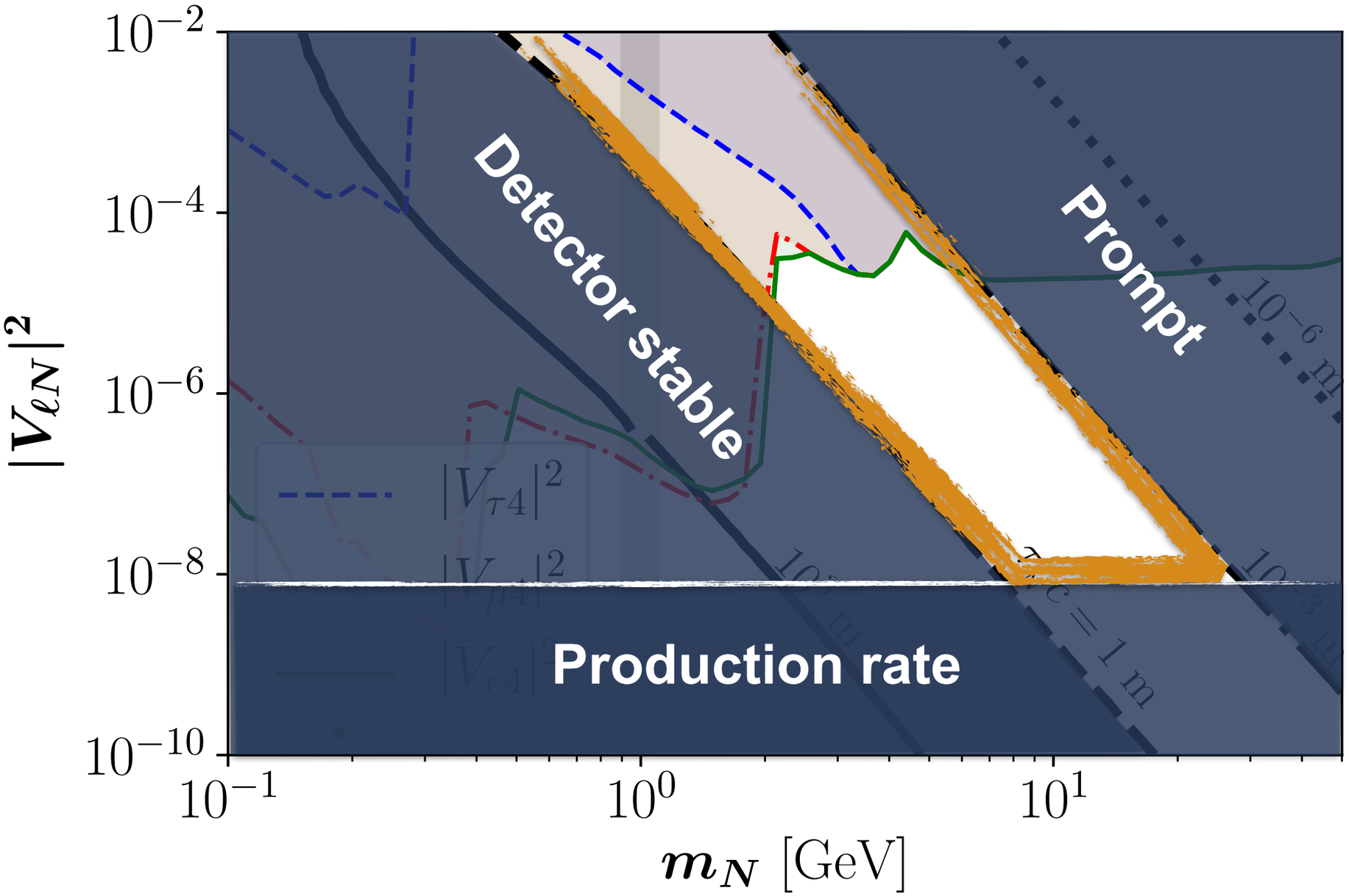


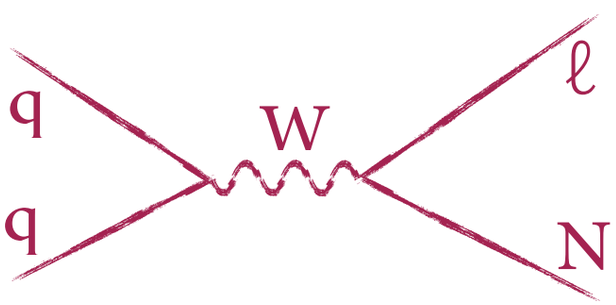
Long-Lived HNL and DV

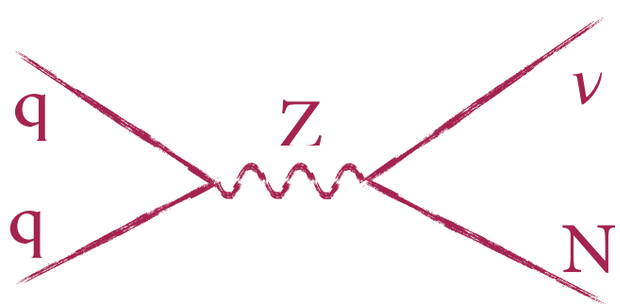


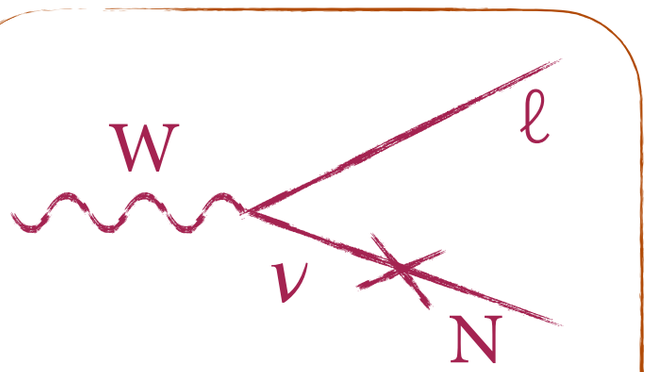
HNL Production

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

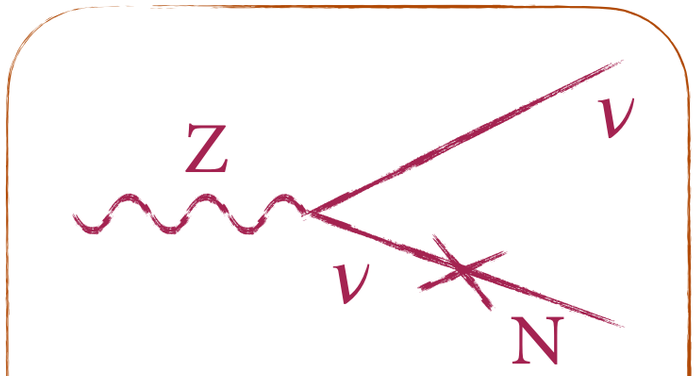
— on-shell HNL, for off-shell see Oleg's talk—



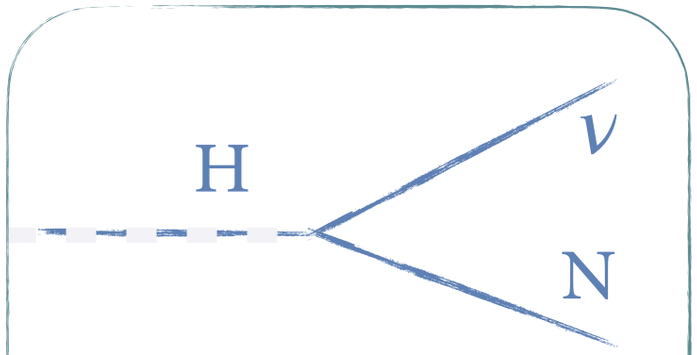




$$\mathrm{BR}_{W^\pm \to \ell^\pm N} \propto |V_{\ell N}|^2$$



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



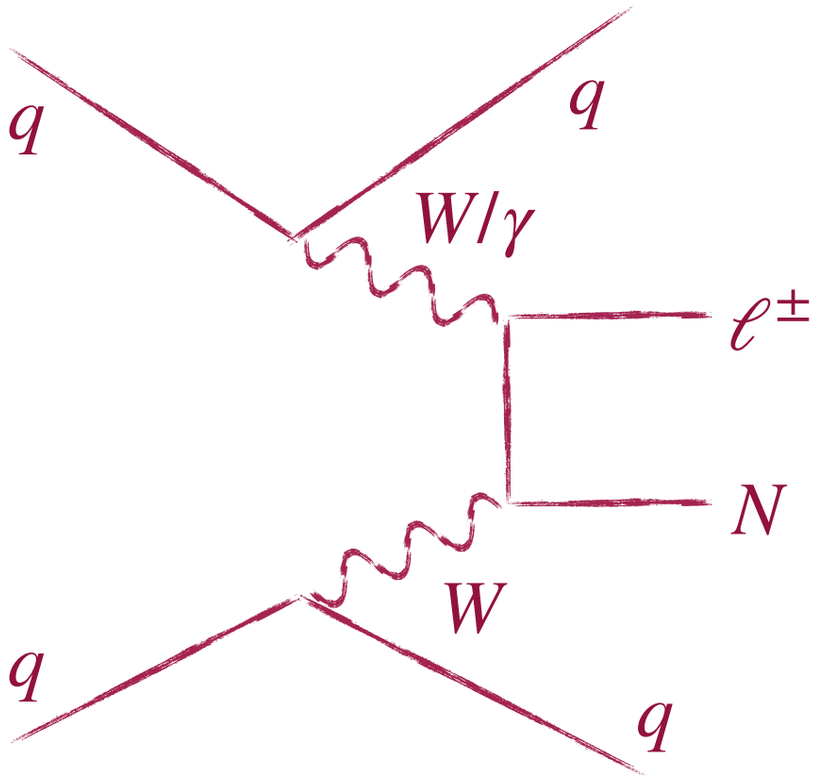
$$\mathrm{BR}_{H \to \nu N} \propto \frac{m_N^2}{m_W^2} \sum_{\ell} |V_{\ell N}|^2$$

HNL Production

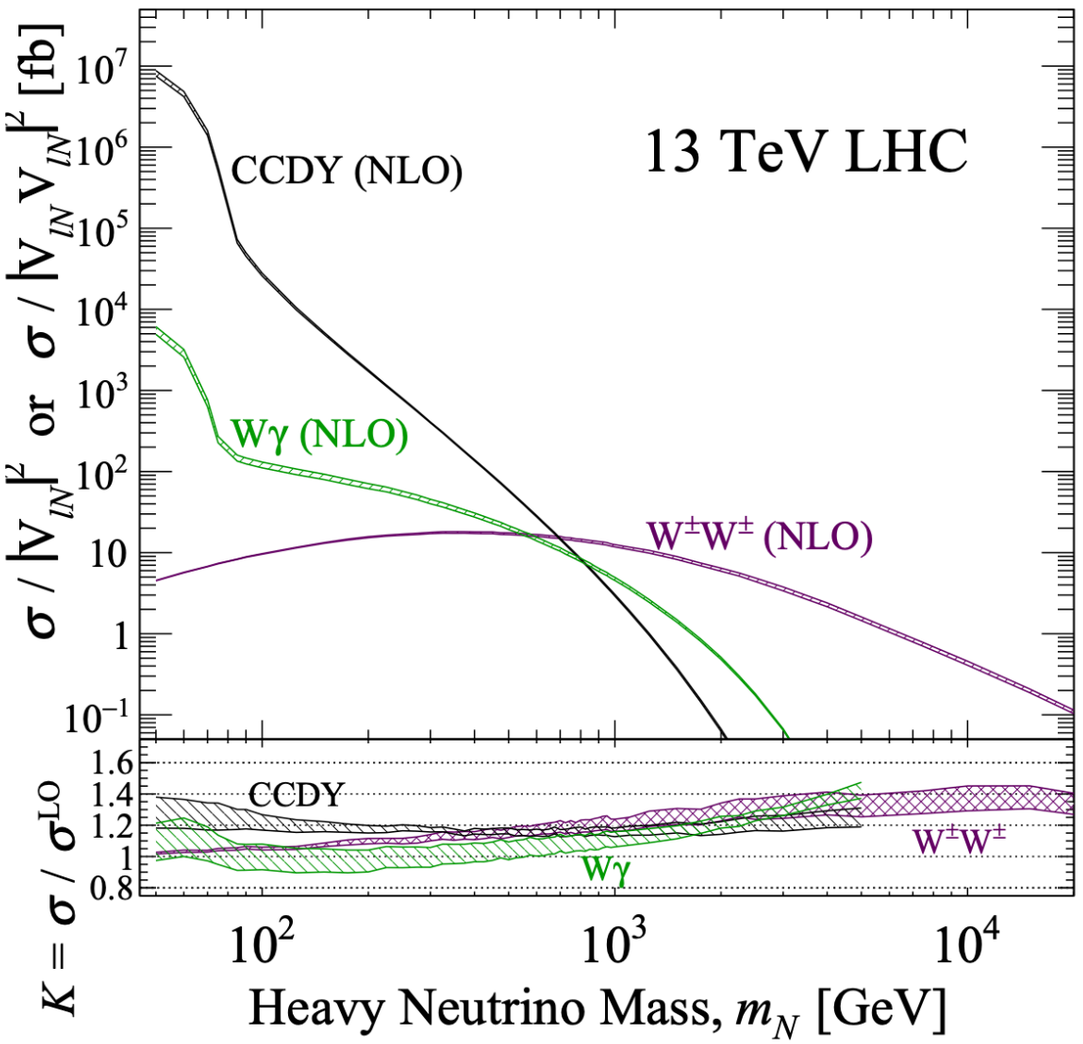
- *Dominant diagrams: Drell-Yan W and Z (and Higgs?)*

— on-shell HNL, for off-shell see Oleg's talk—

- *For higher masses, also Vector Boson Fusion*

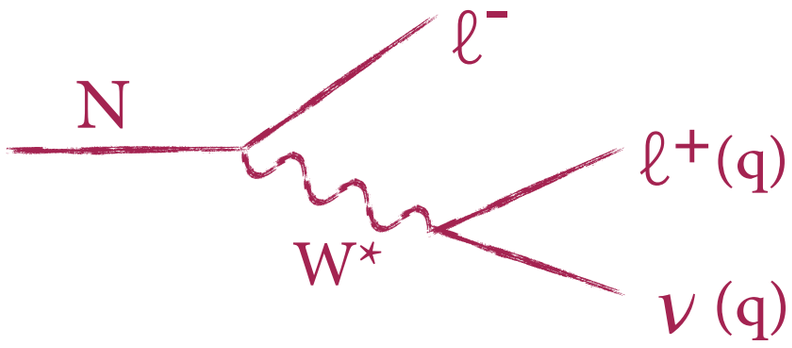


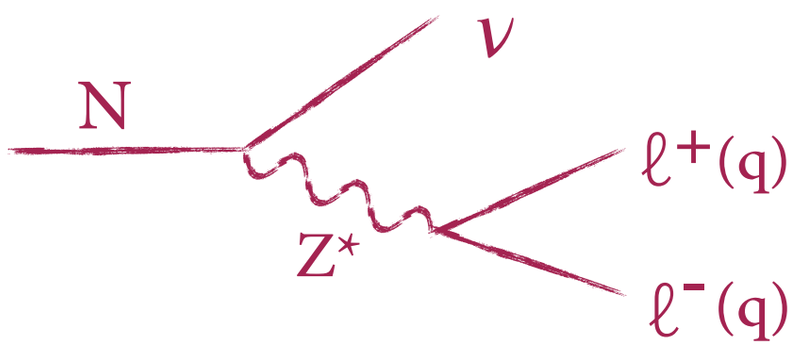
Fuks et al. [2011.02547]



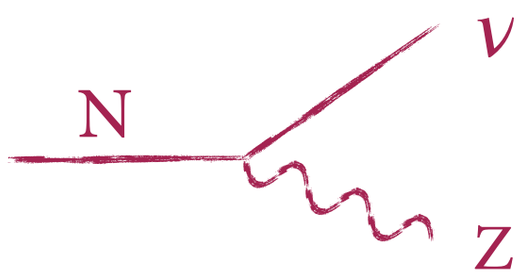
HNL Decays

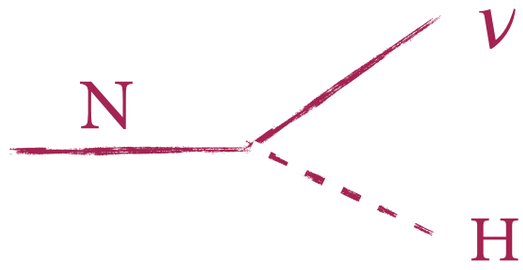
- *Light HNL: off-shell W and Z*



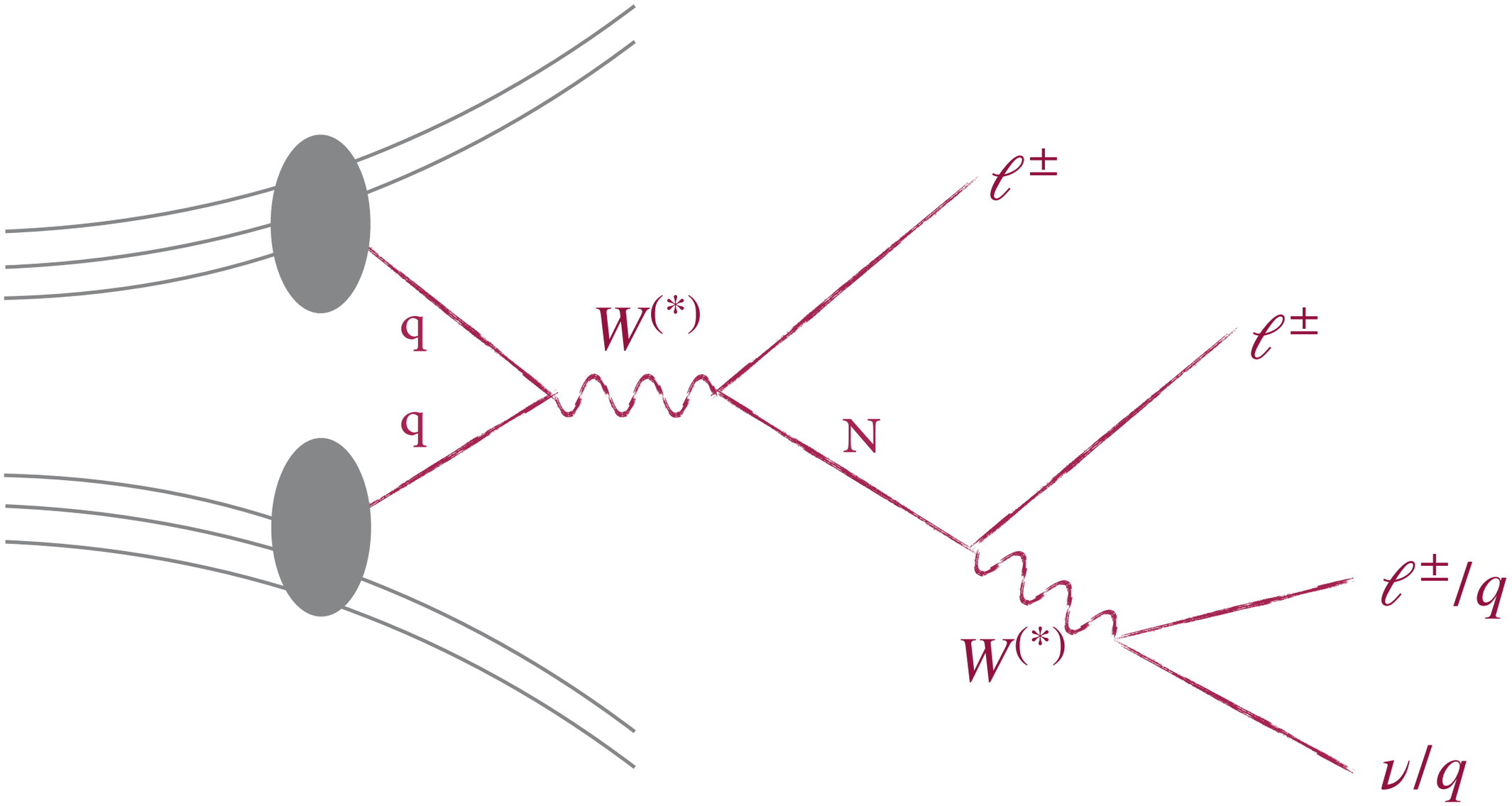


- *Heavy HNL: on-shell W, Z, H*





Full Process



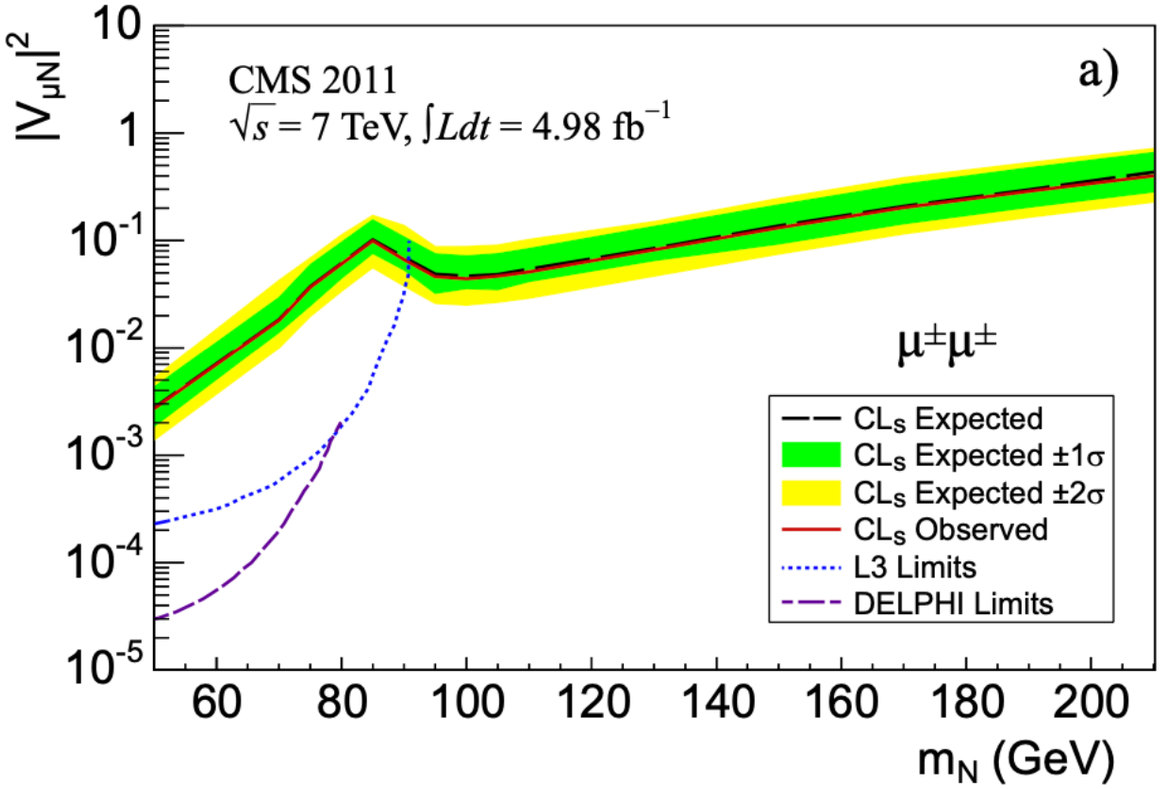
—Current Status—

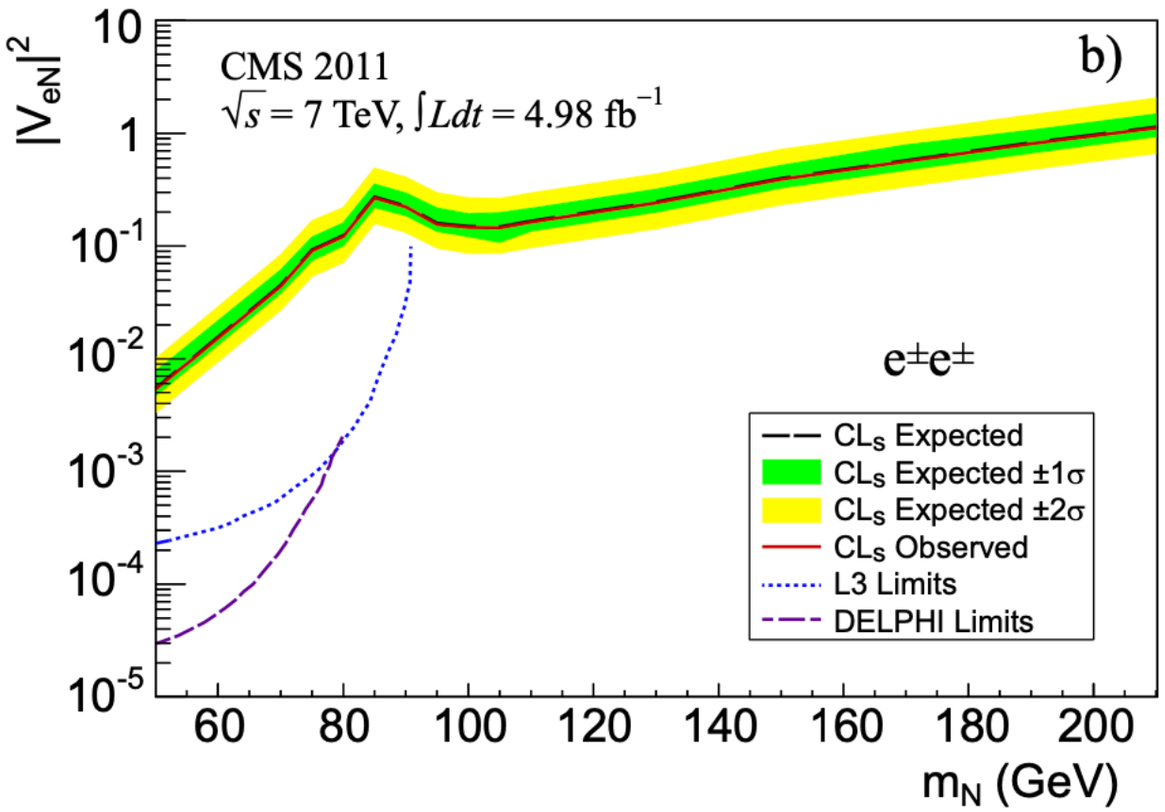
Di-leptons at LHC

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

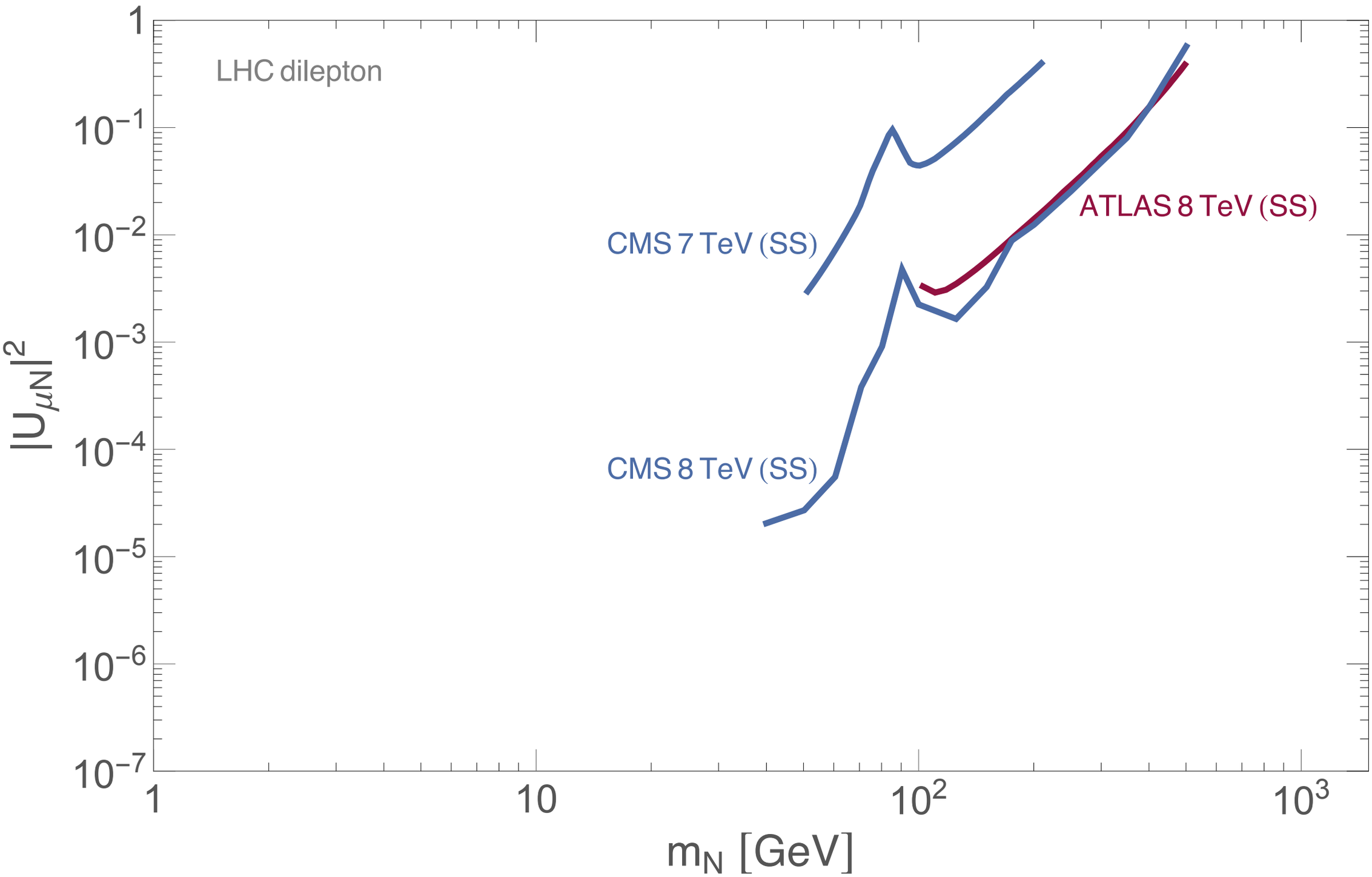
$$pp \to W^{(*)} \to \ell^{\pm} N \to \ell^{\pm}\ell^{\pm} + nj$$

[1207.6079]

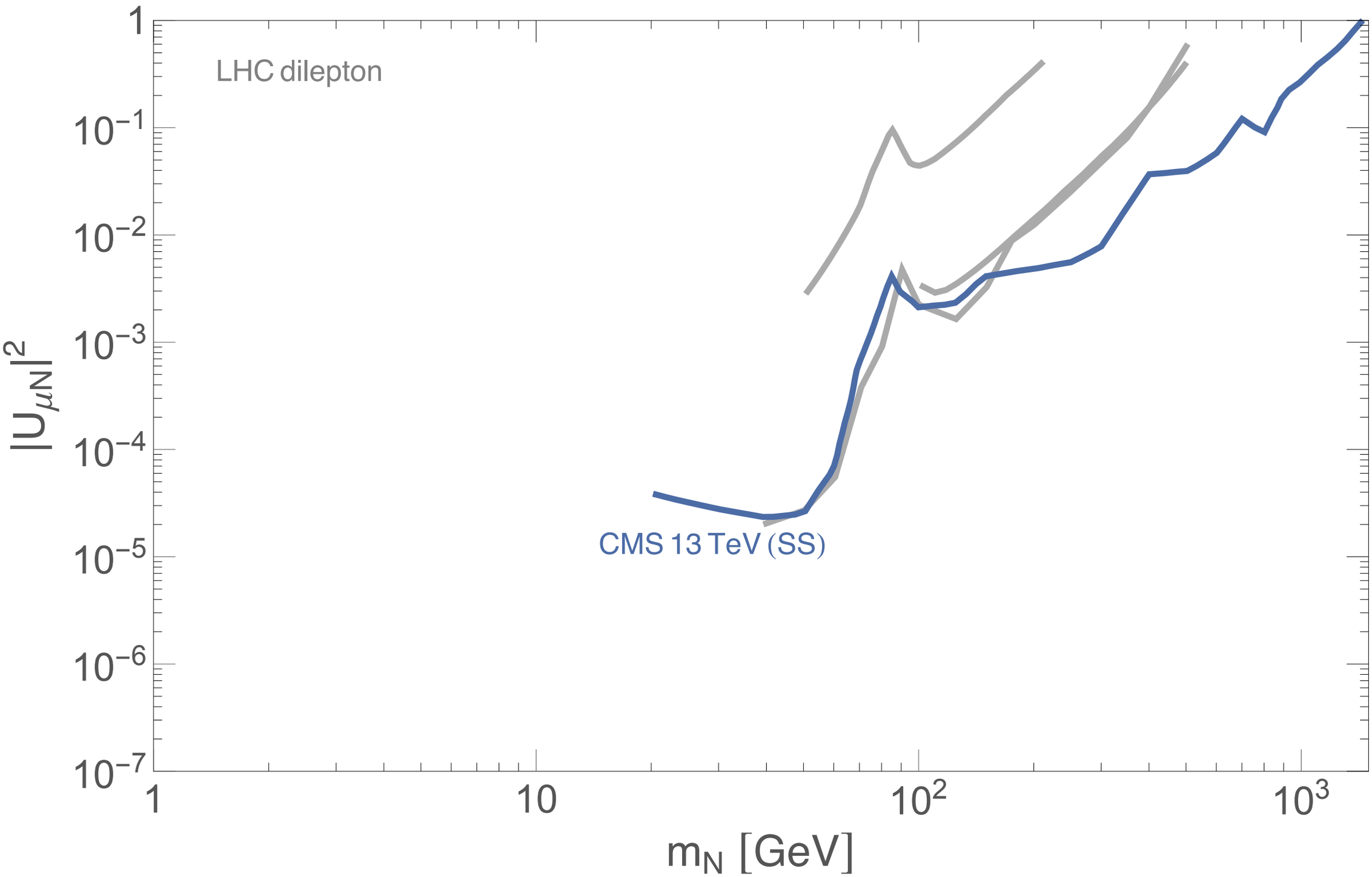




Di-leptons at LHC



Di-leptons at LHC

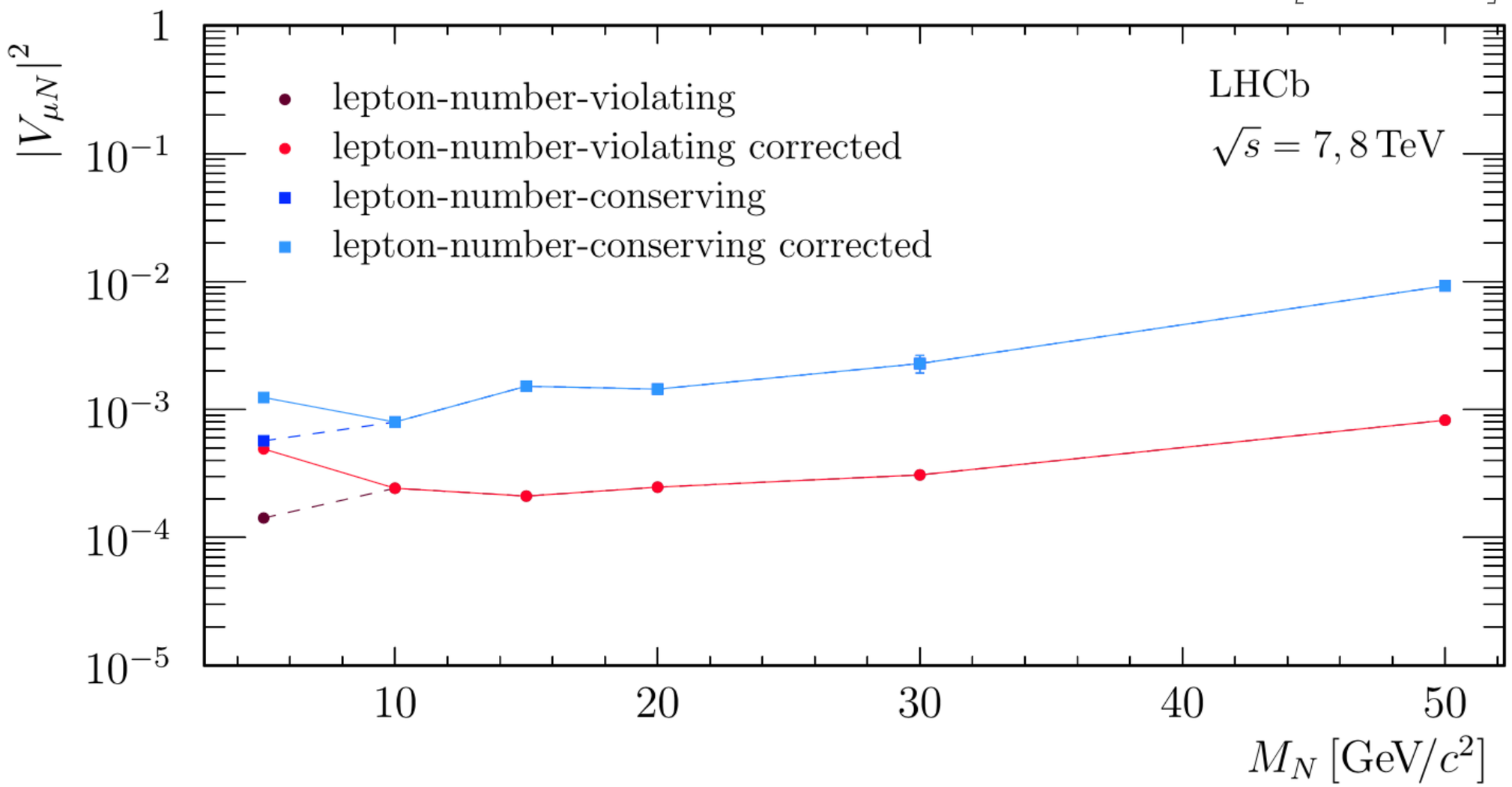


Di-leptons at LHC

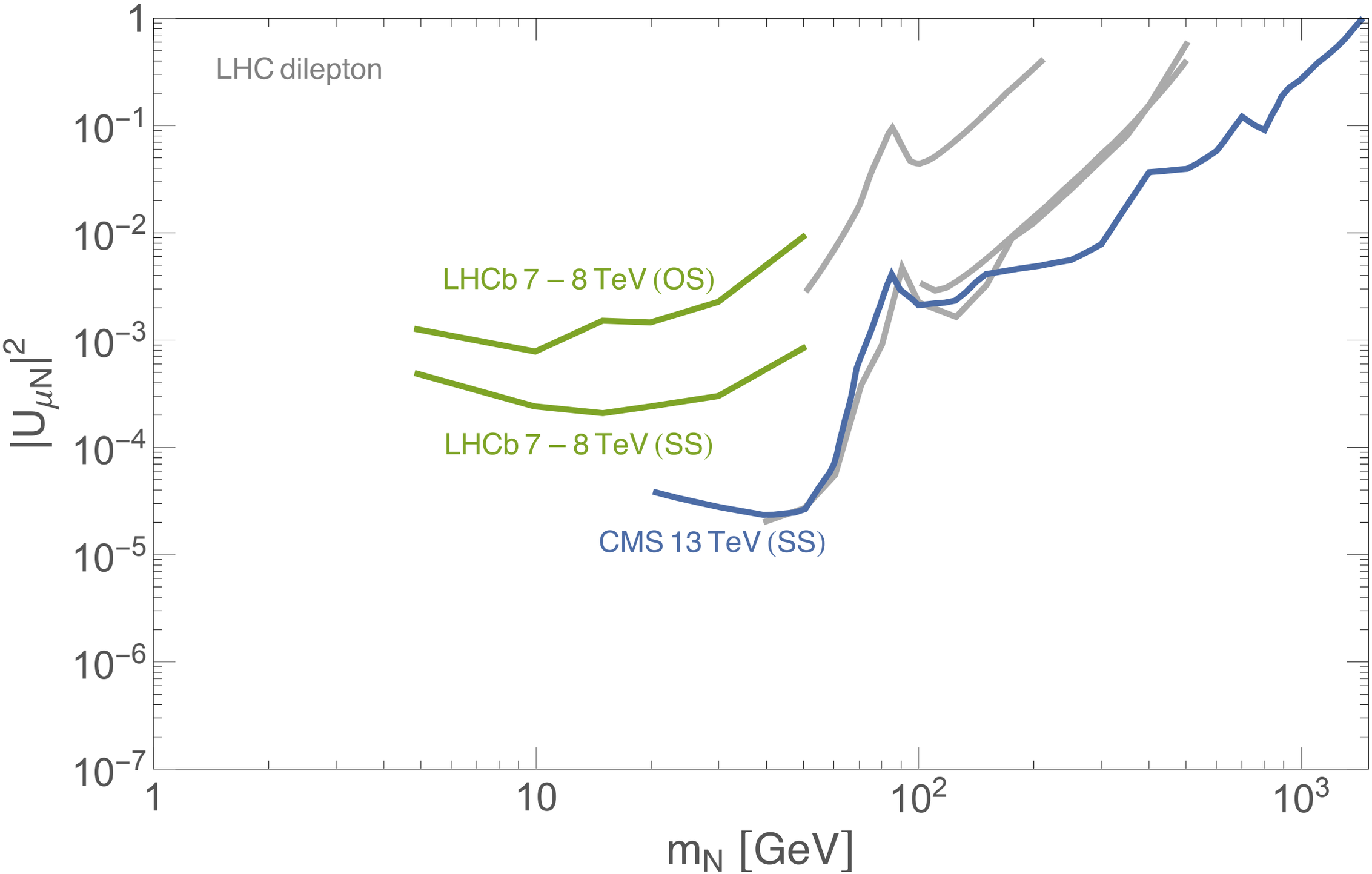
- *LNC searches are also possible*

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

[2011.05263]



Di-leptons at LHC

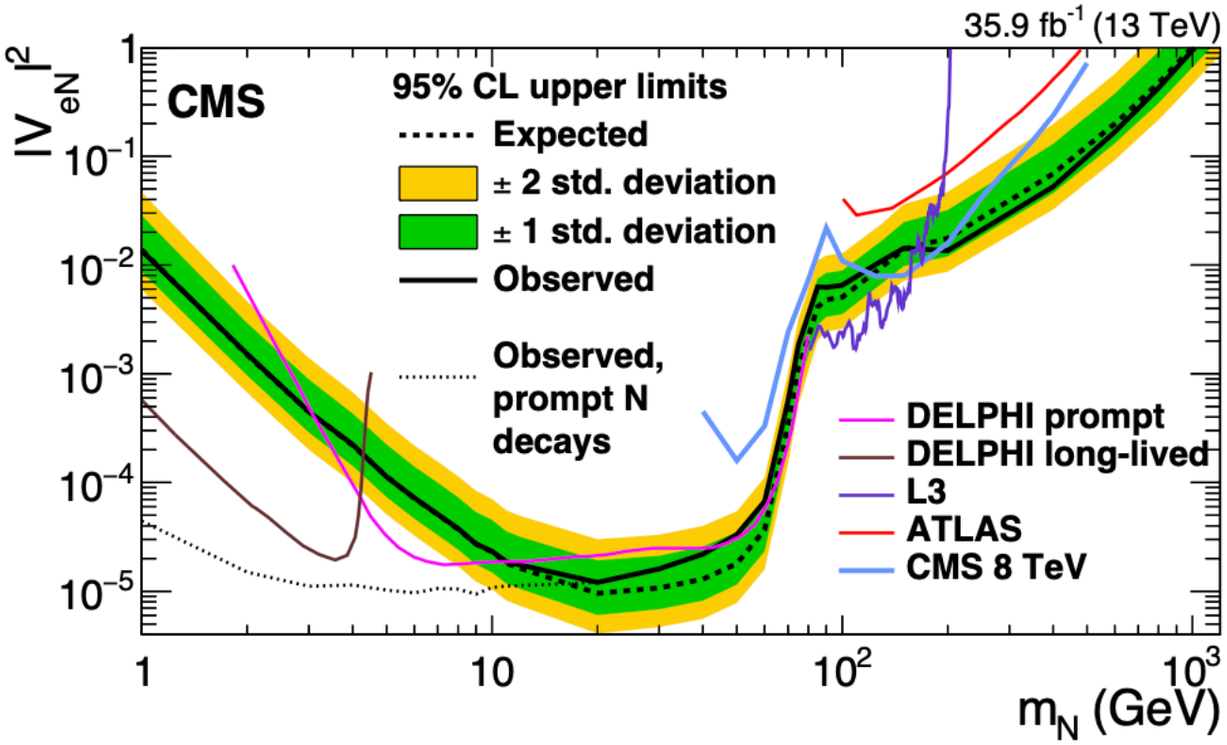


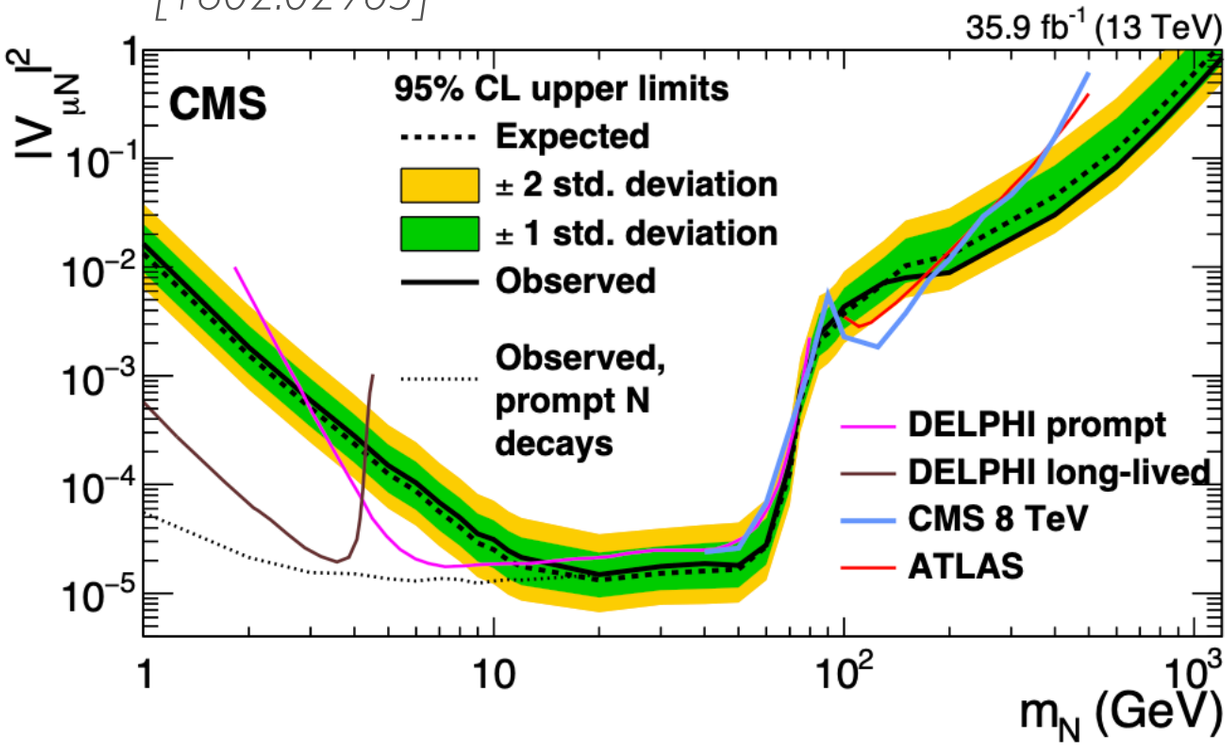
Tri-leptons at LHC

- *Trilepton* — *LNV signature?*—

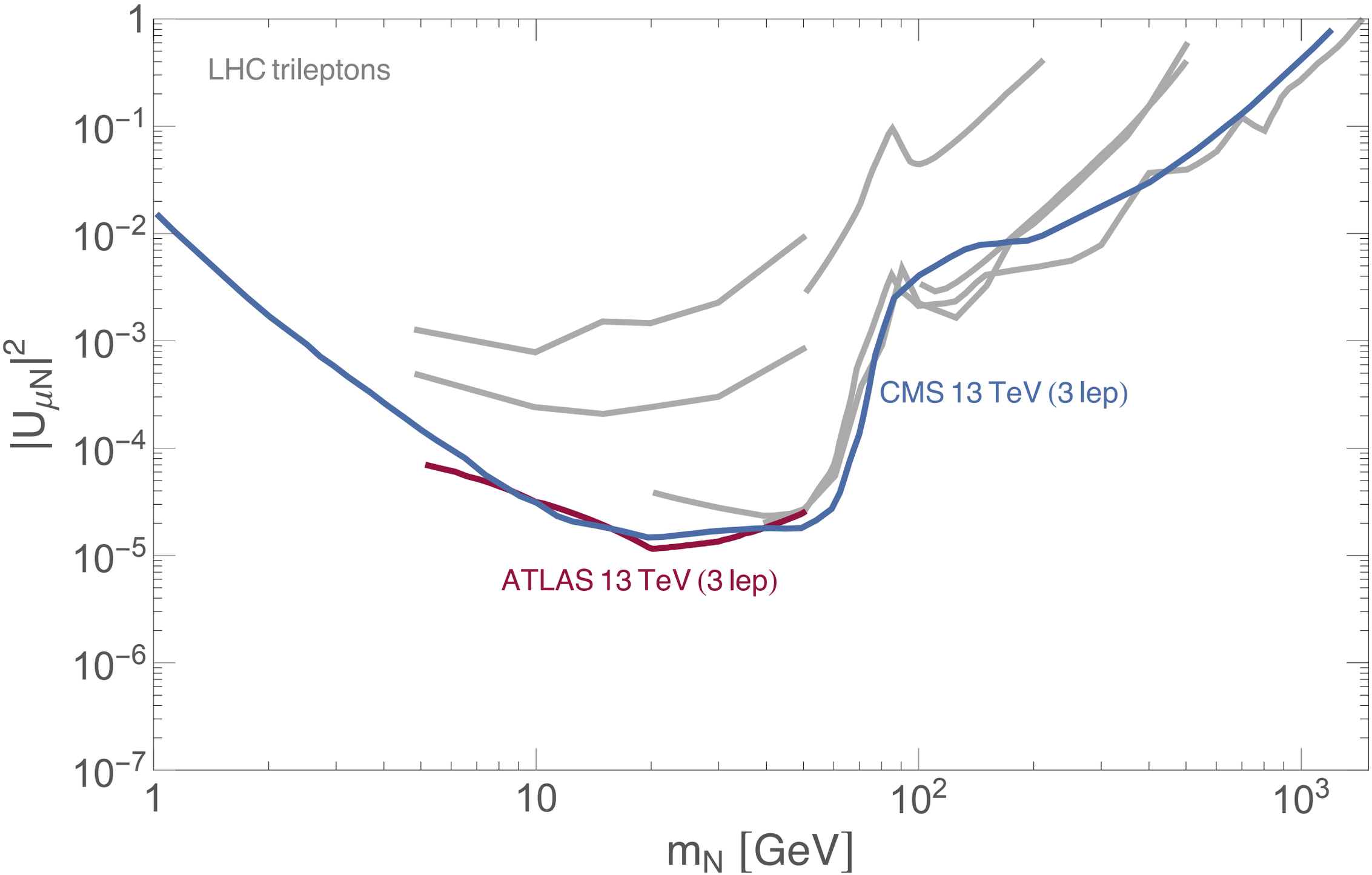
$$pp \to W^{(*)} \to \ell^{\pm}_{\alpha} N \to \ell^{\pm}_{\alpha} \ell^{\pm}_{\beta} \ell^{\mp}_{\gamma} \nu$$

[1802.02965]





Tri-leptons at LHC

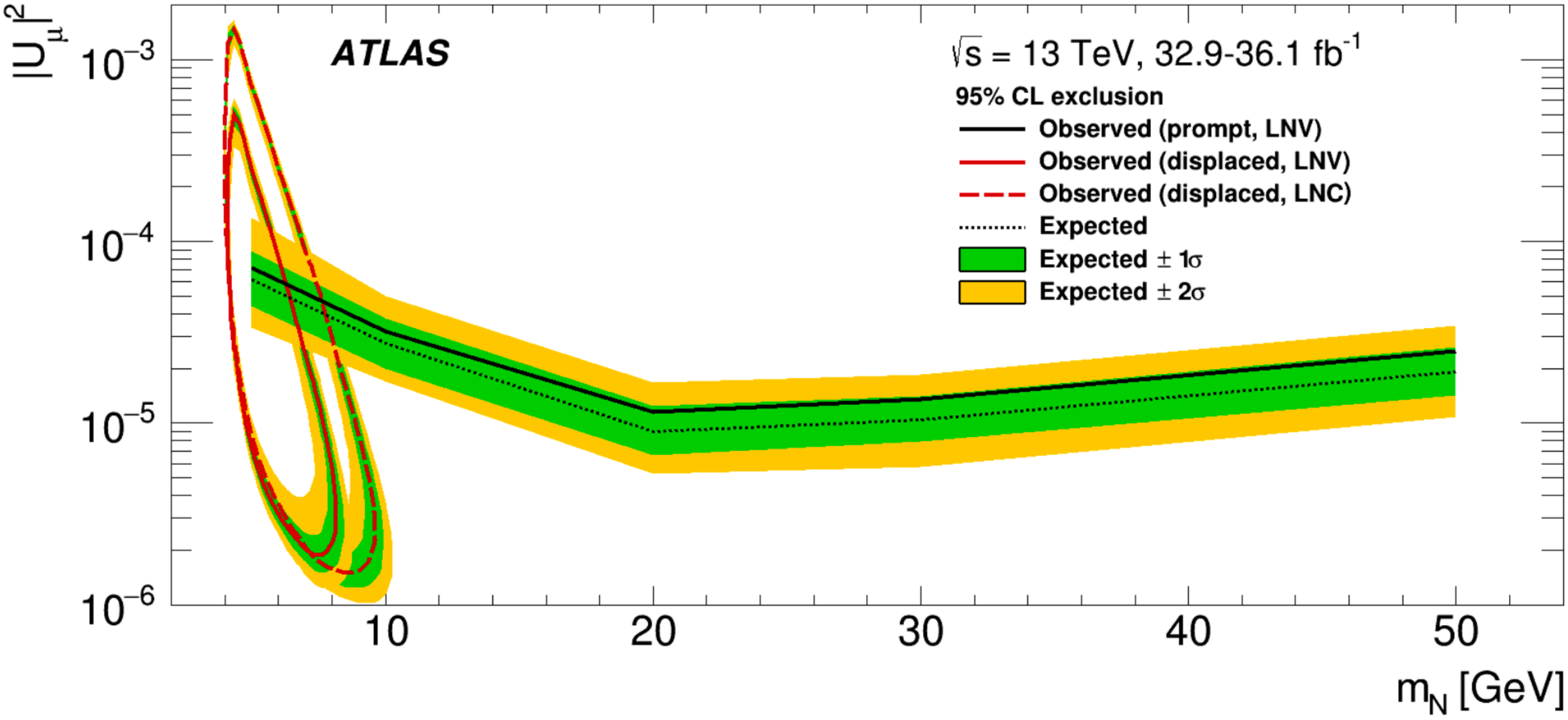


Long-Lived at LHC

- *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]

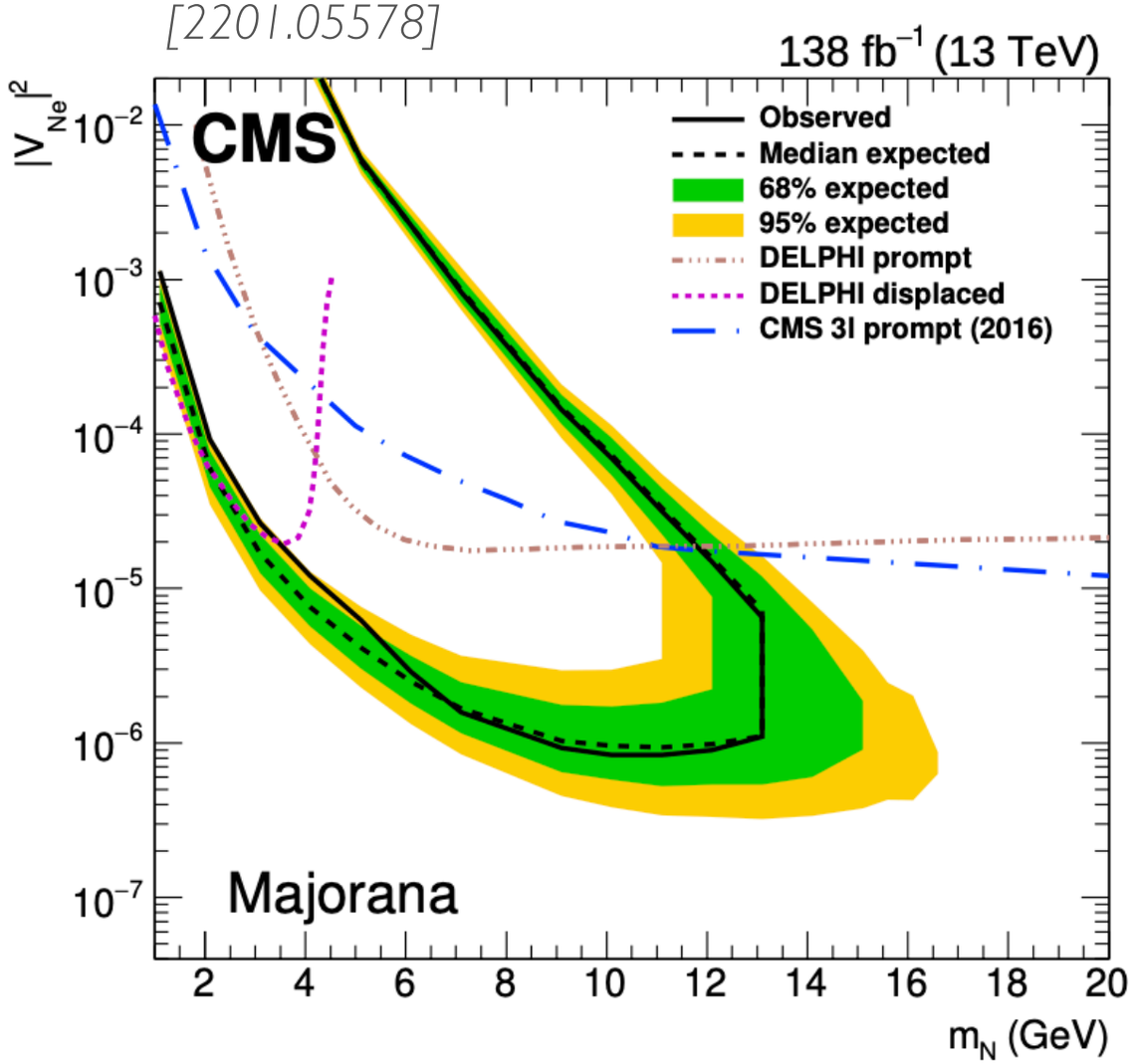


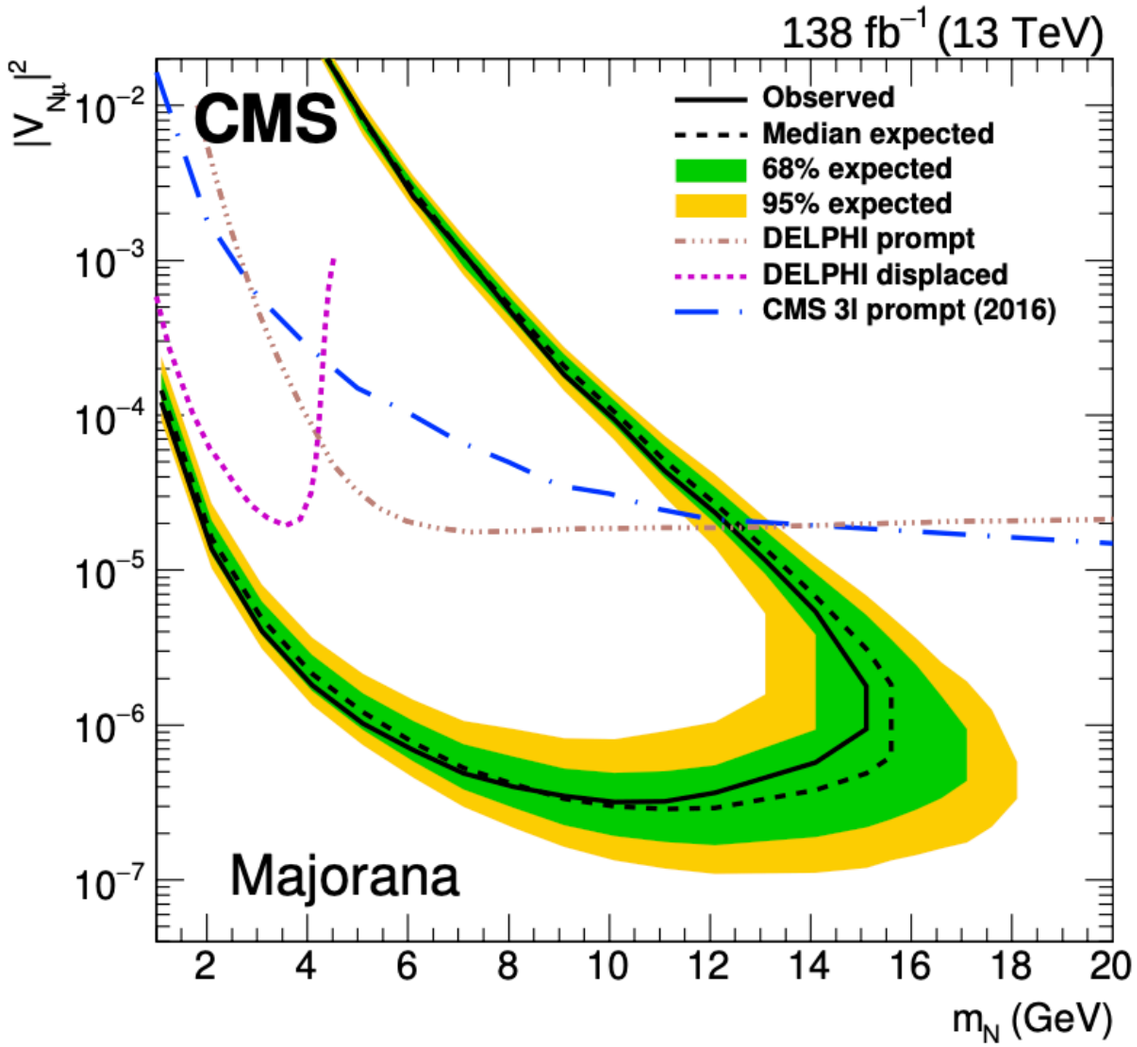
Long-Lived at LHC

- *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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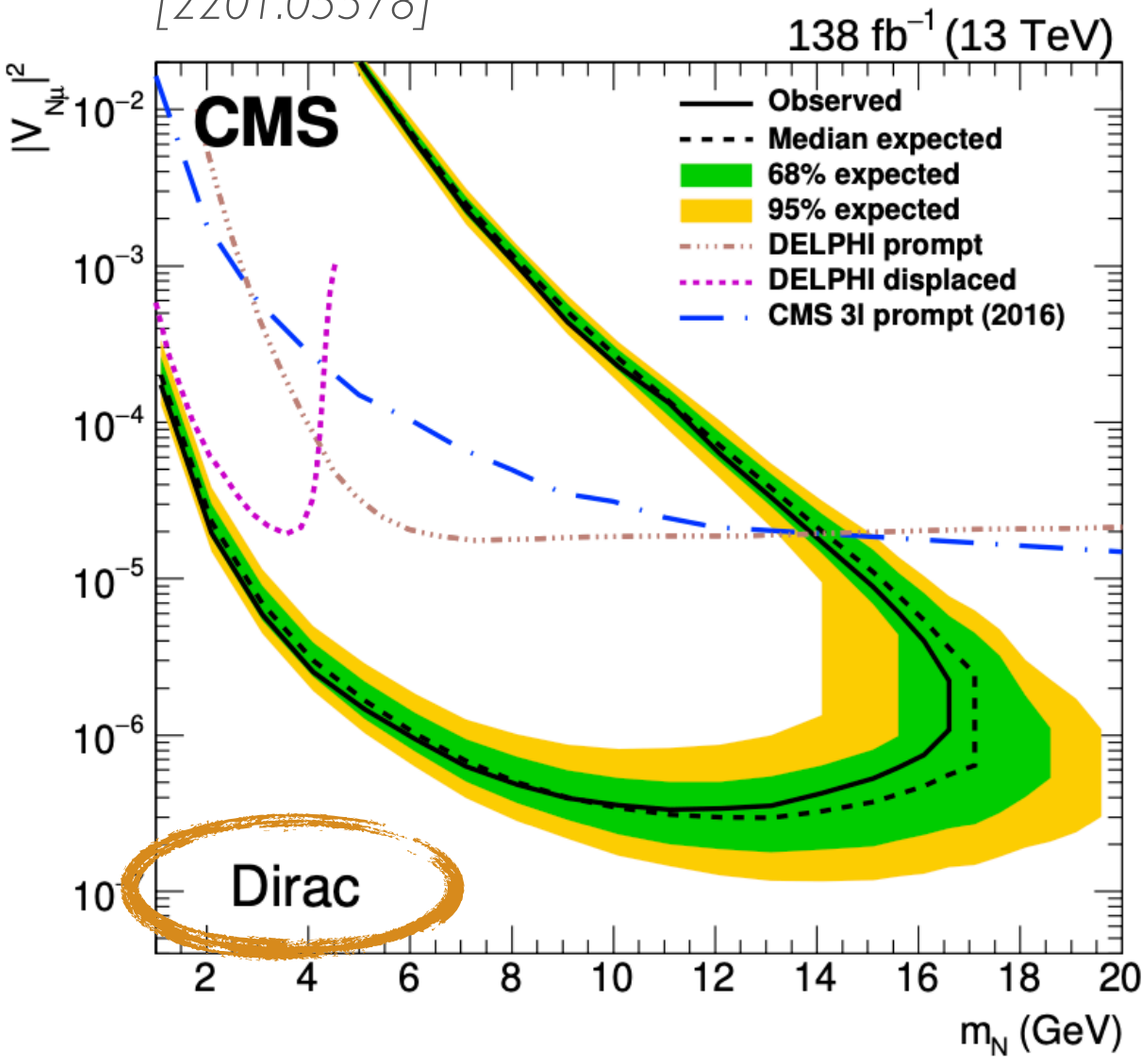
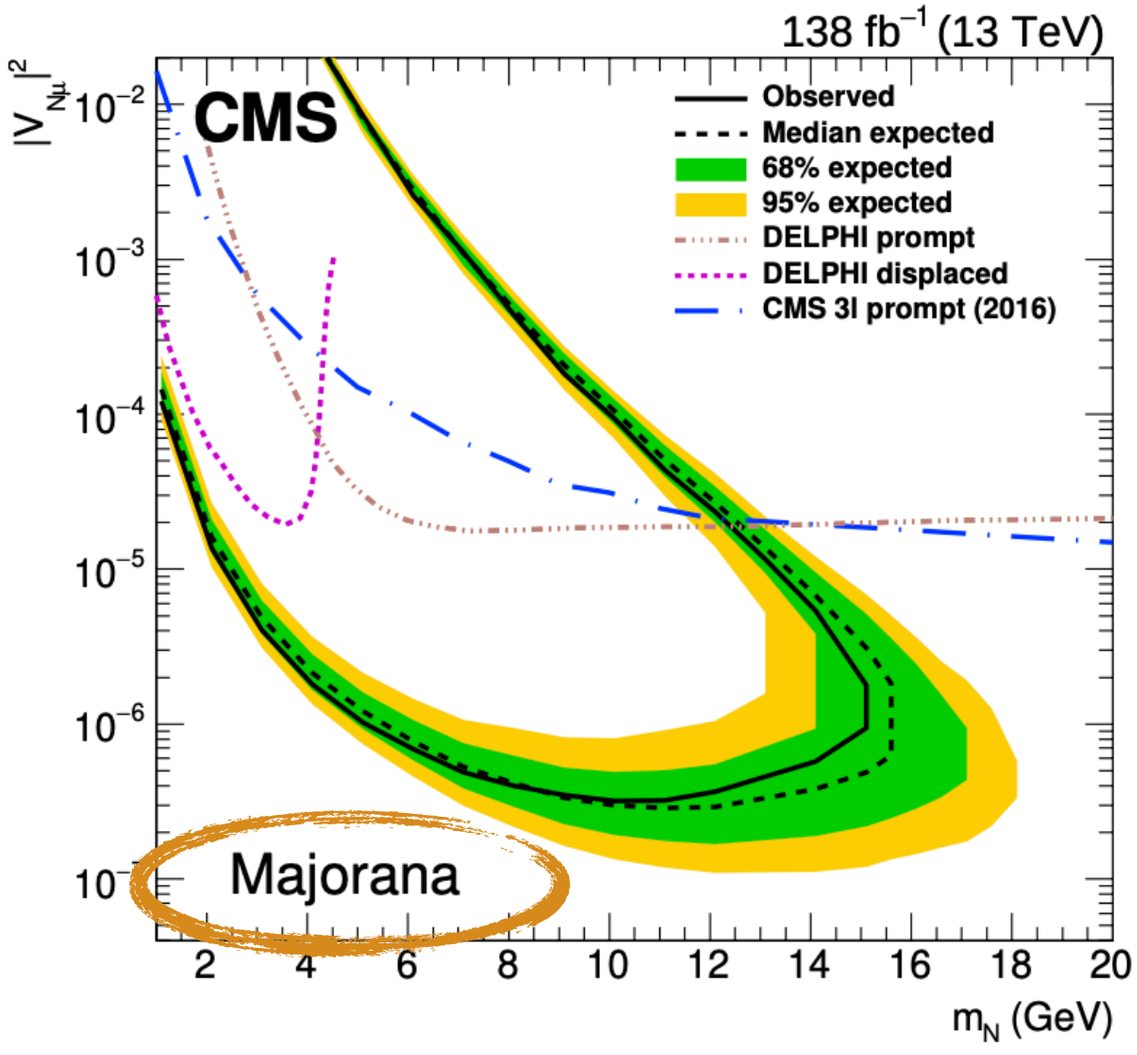
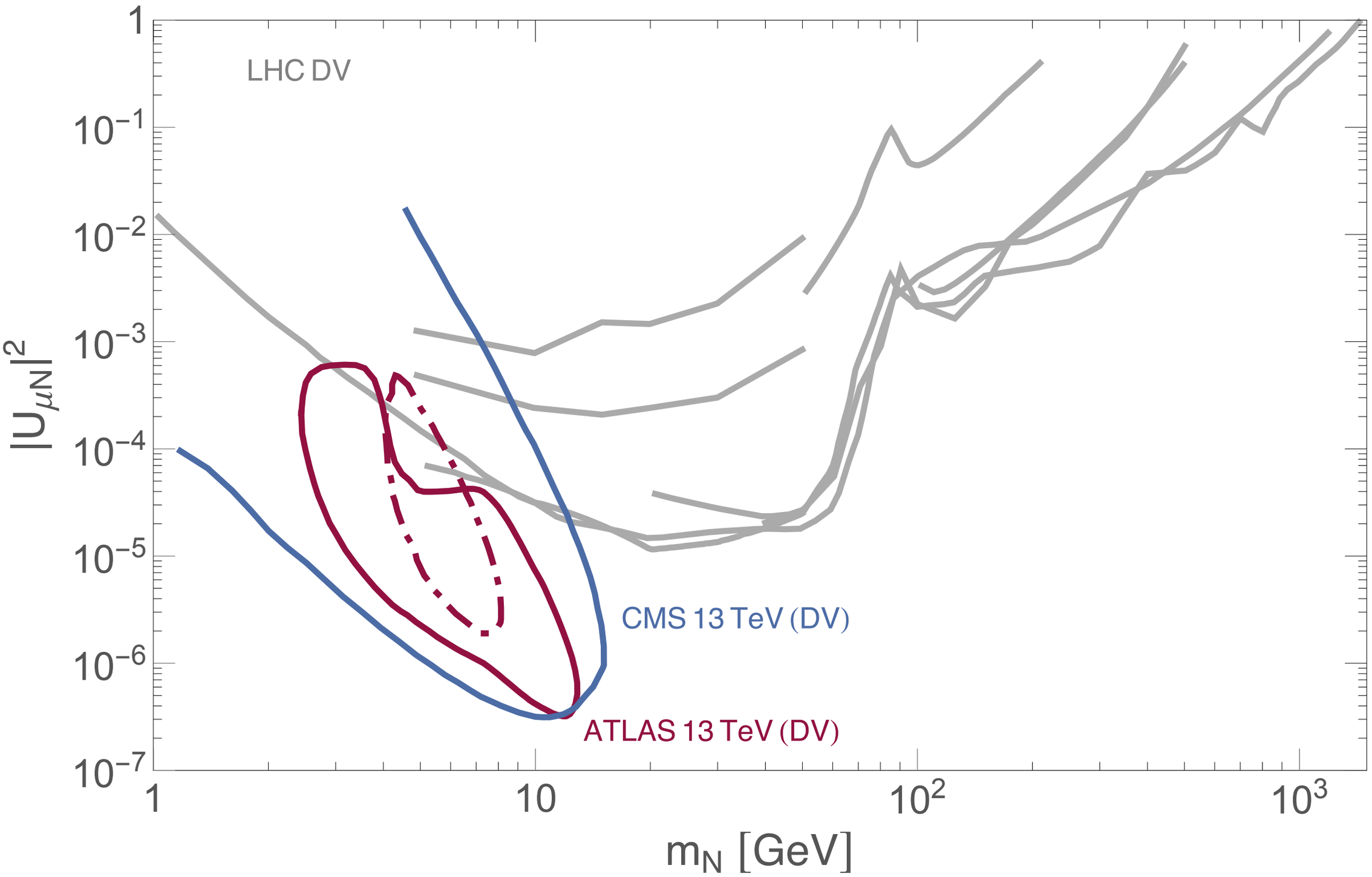
[2201.05578]

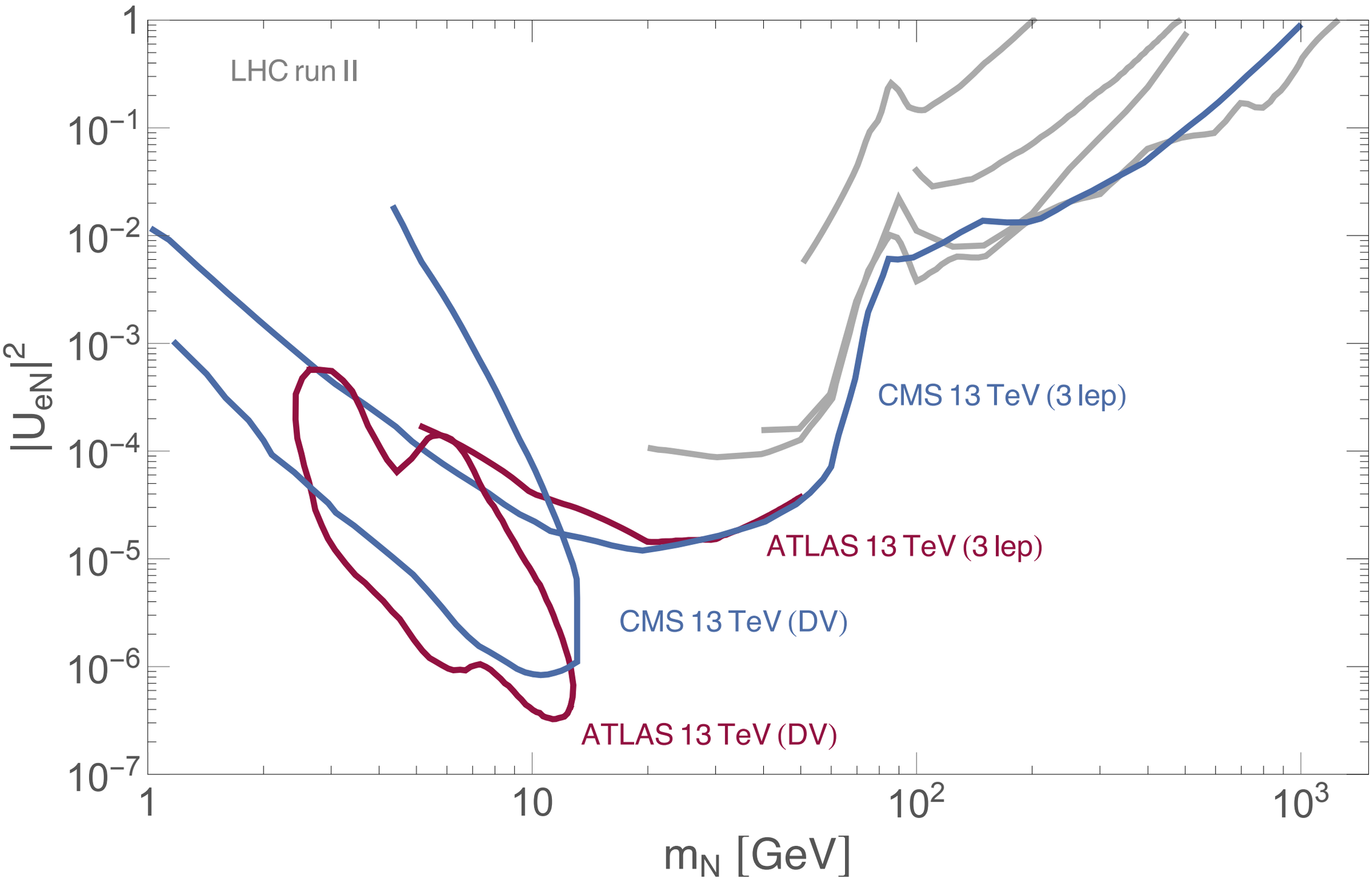




Long-Lived at LHC

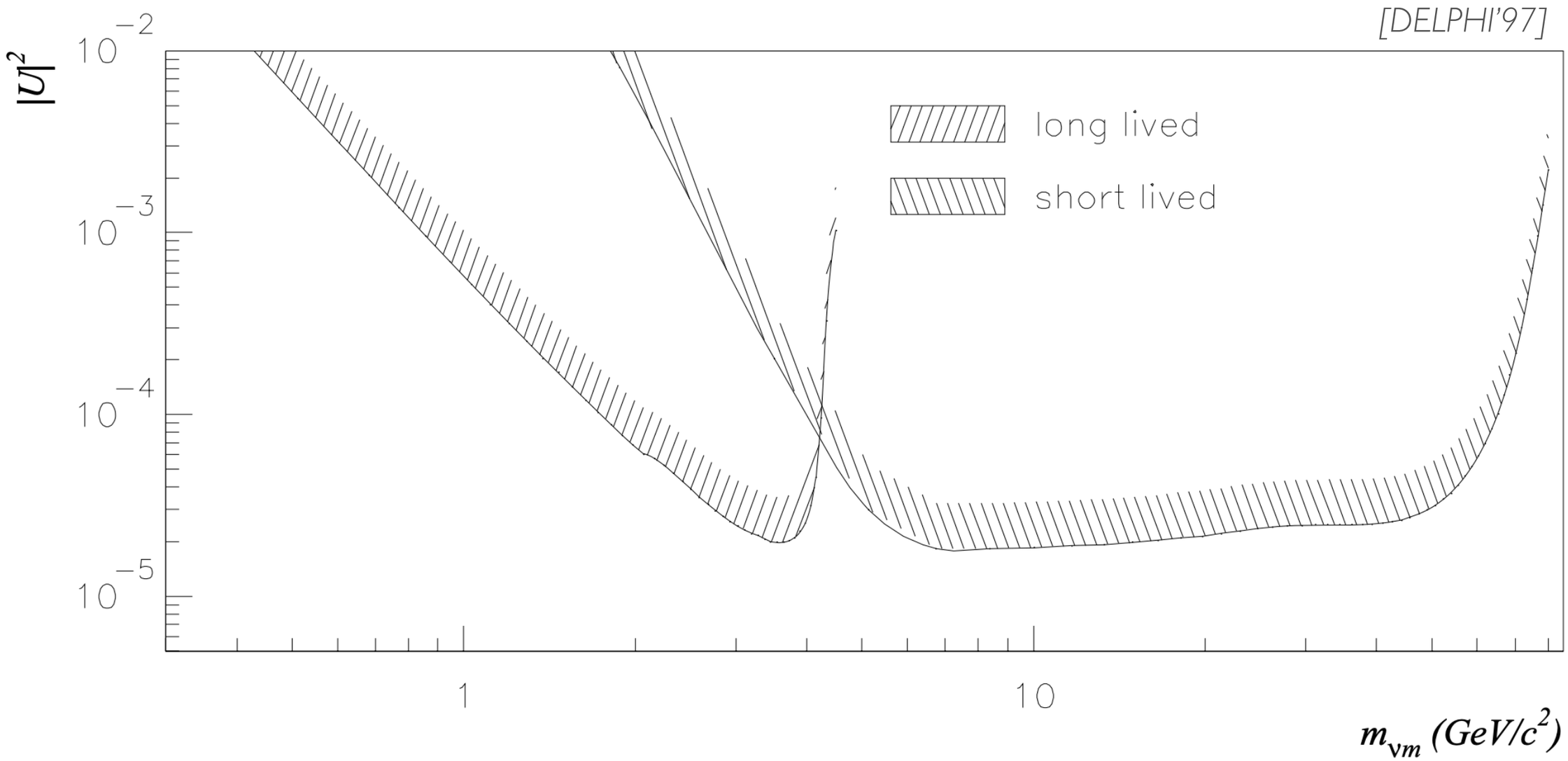


Electron Mixing



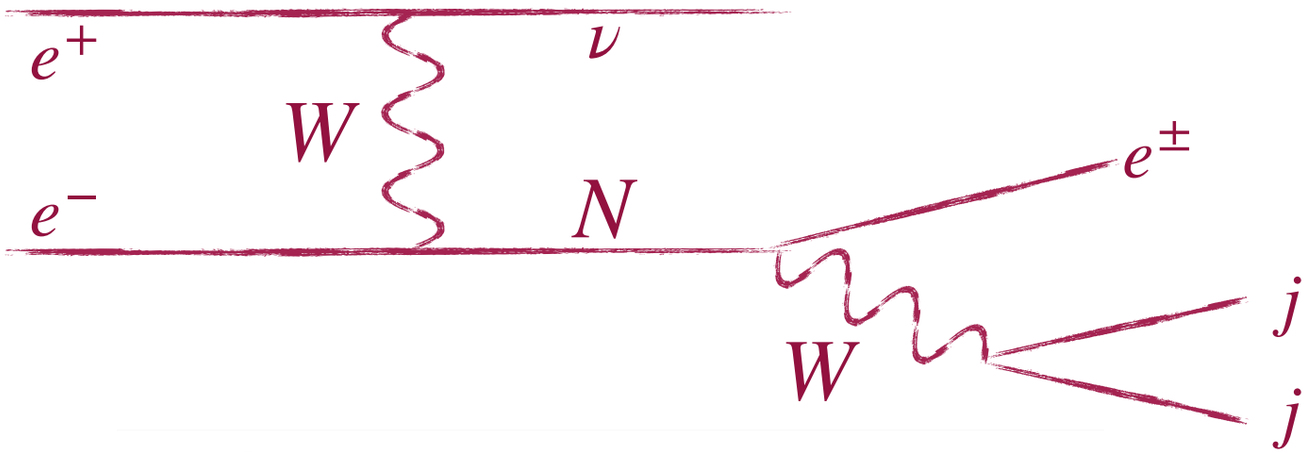
- *Light HNL: Drell-Yan Z (on-shell)* — *Sensitive to all flavor mixings*—

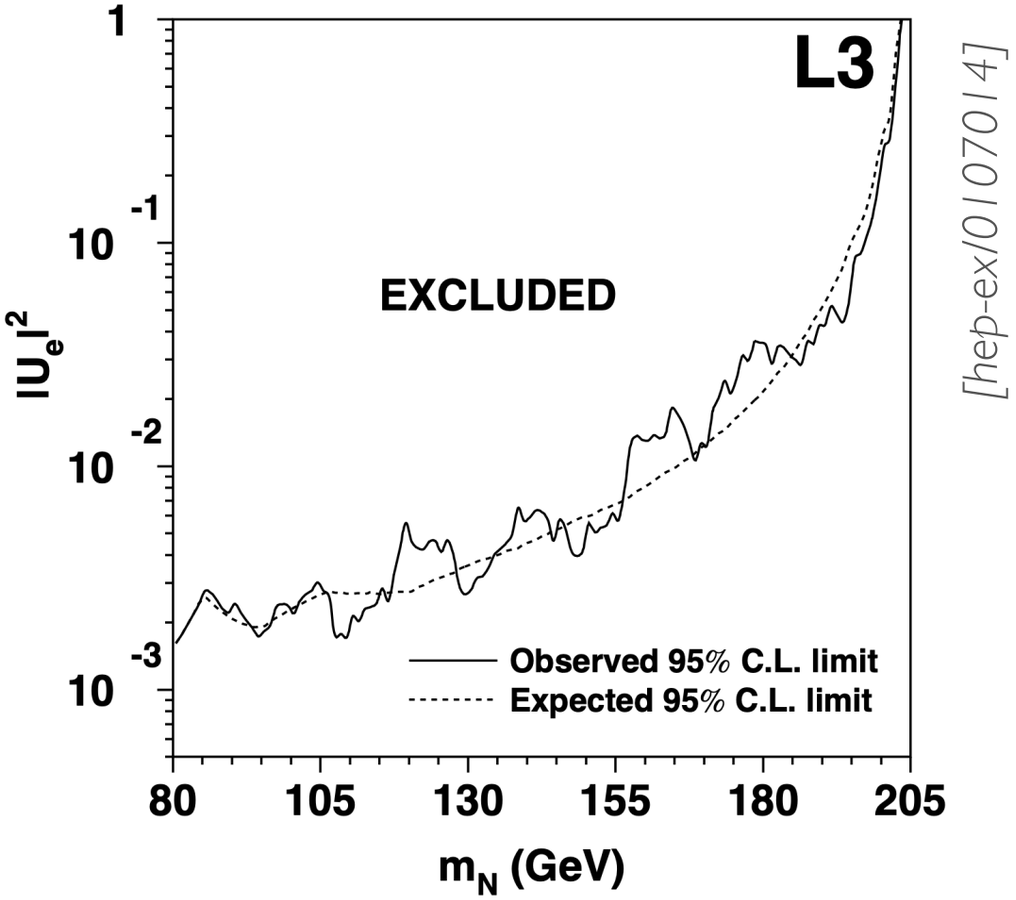
$$e^+e^- \to Z \to \nu N \to \nu l/\ell + nj$$



- *Heavy HNL: t-channel W*

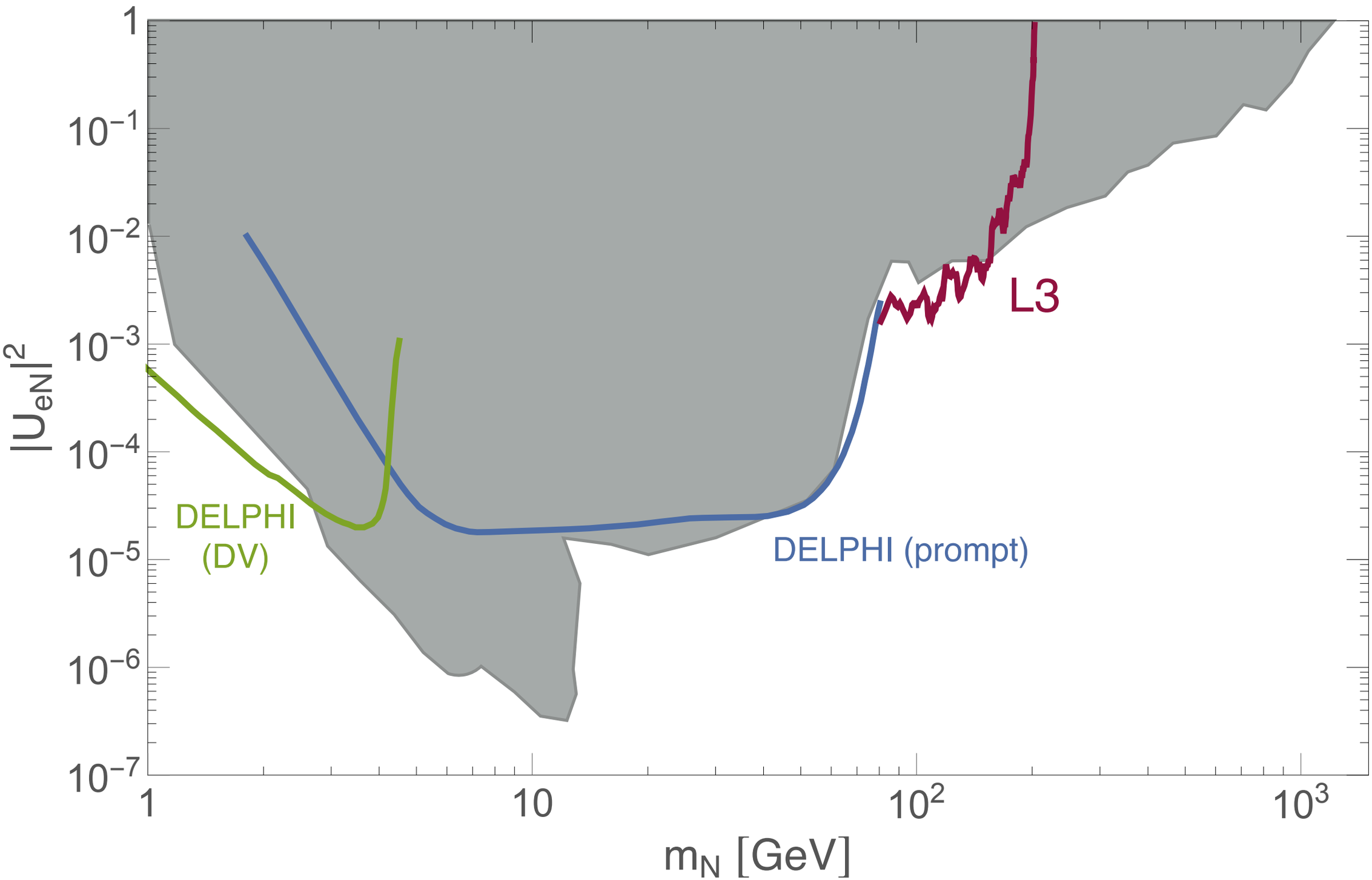
— Sensitive to electron mixing—





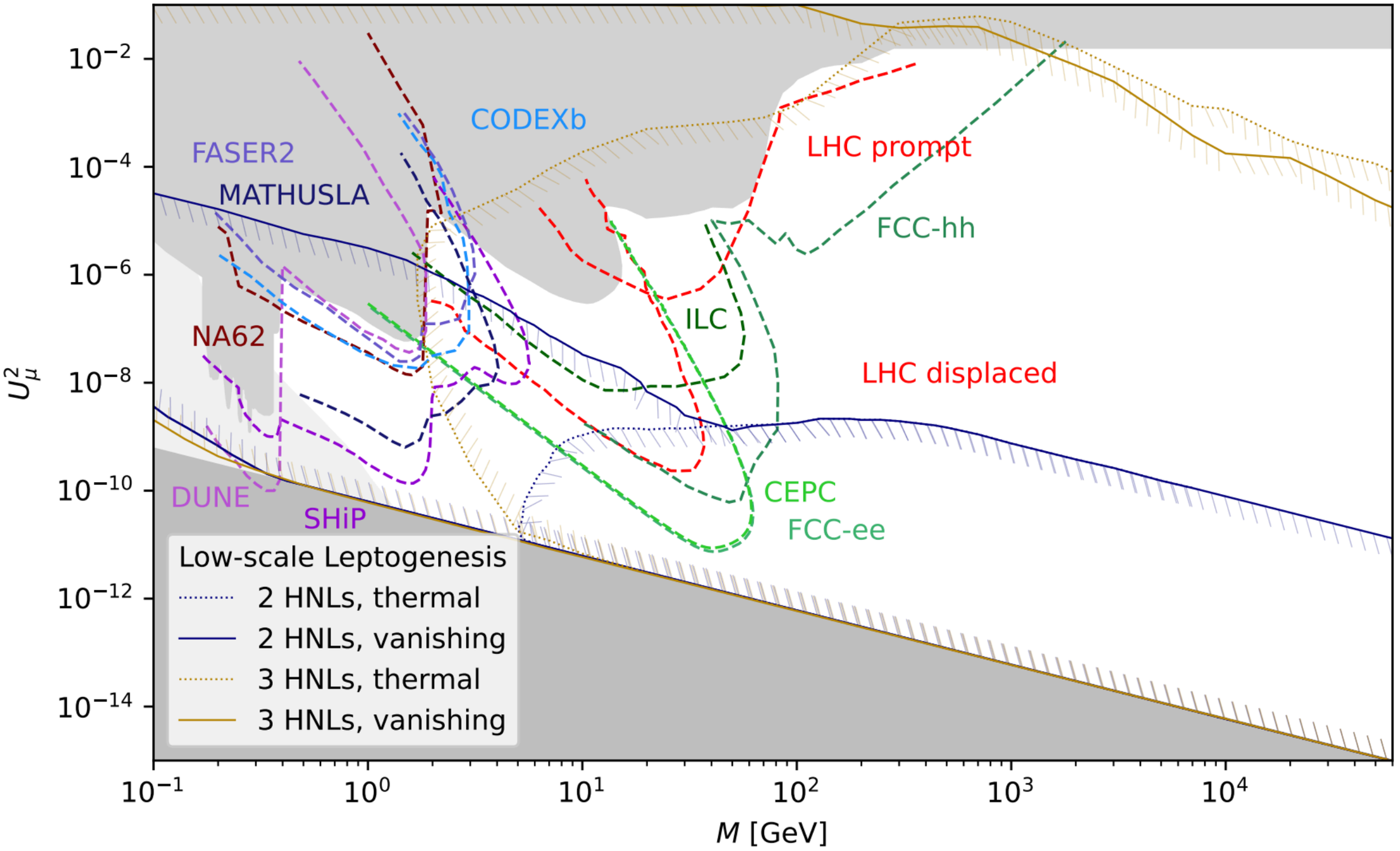
[hep-ex/0107014]

LEP


1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$|U_{eN}|^2$
1
10
10^2
10^3
m_N [GeV]
L3
DELPHI (prompt)
DELPHI (DV)

Future Collider Landscape

Abdullahi et al [2203.08039]

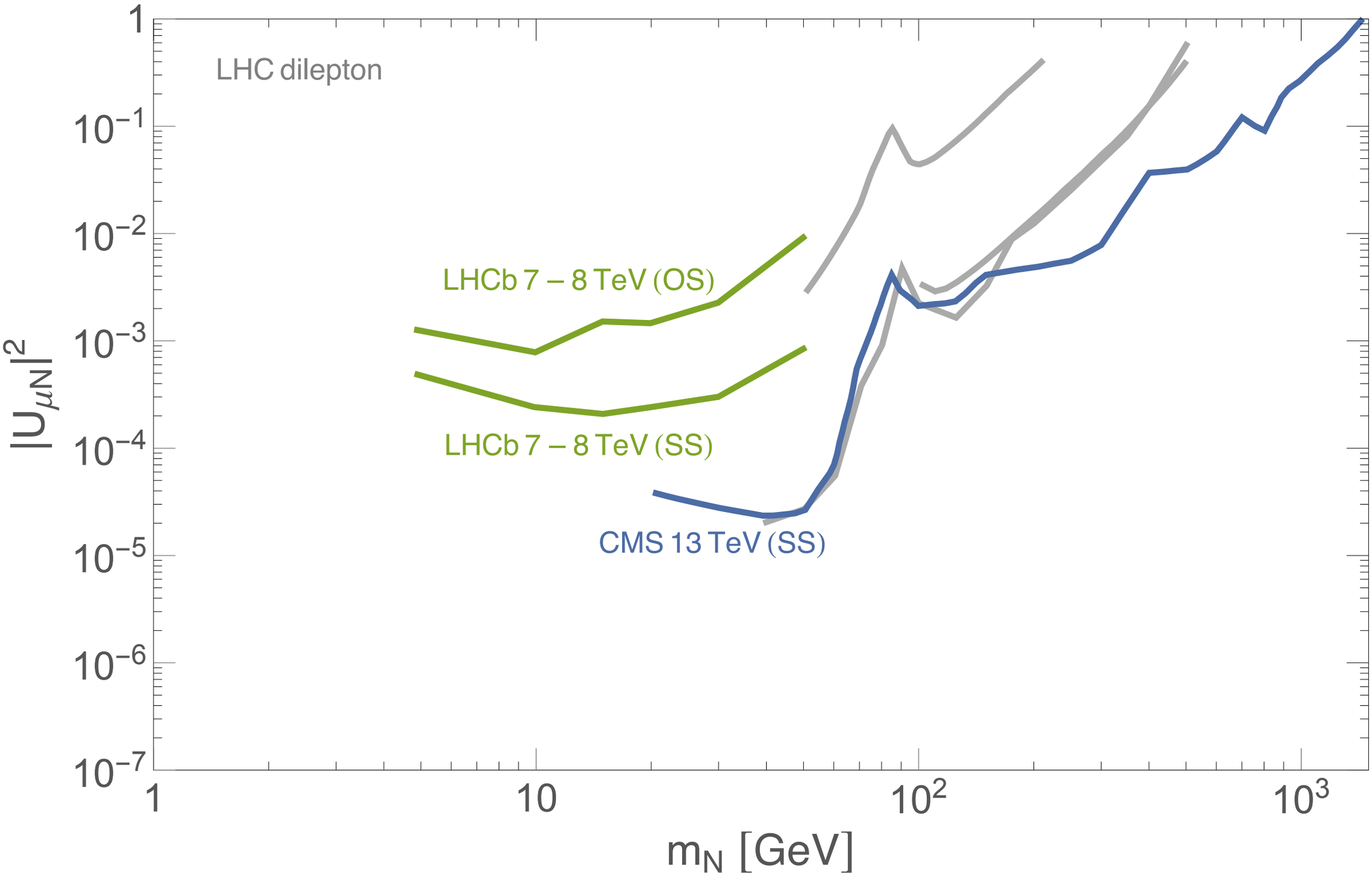


— Going Beyond —

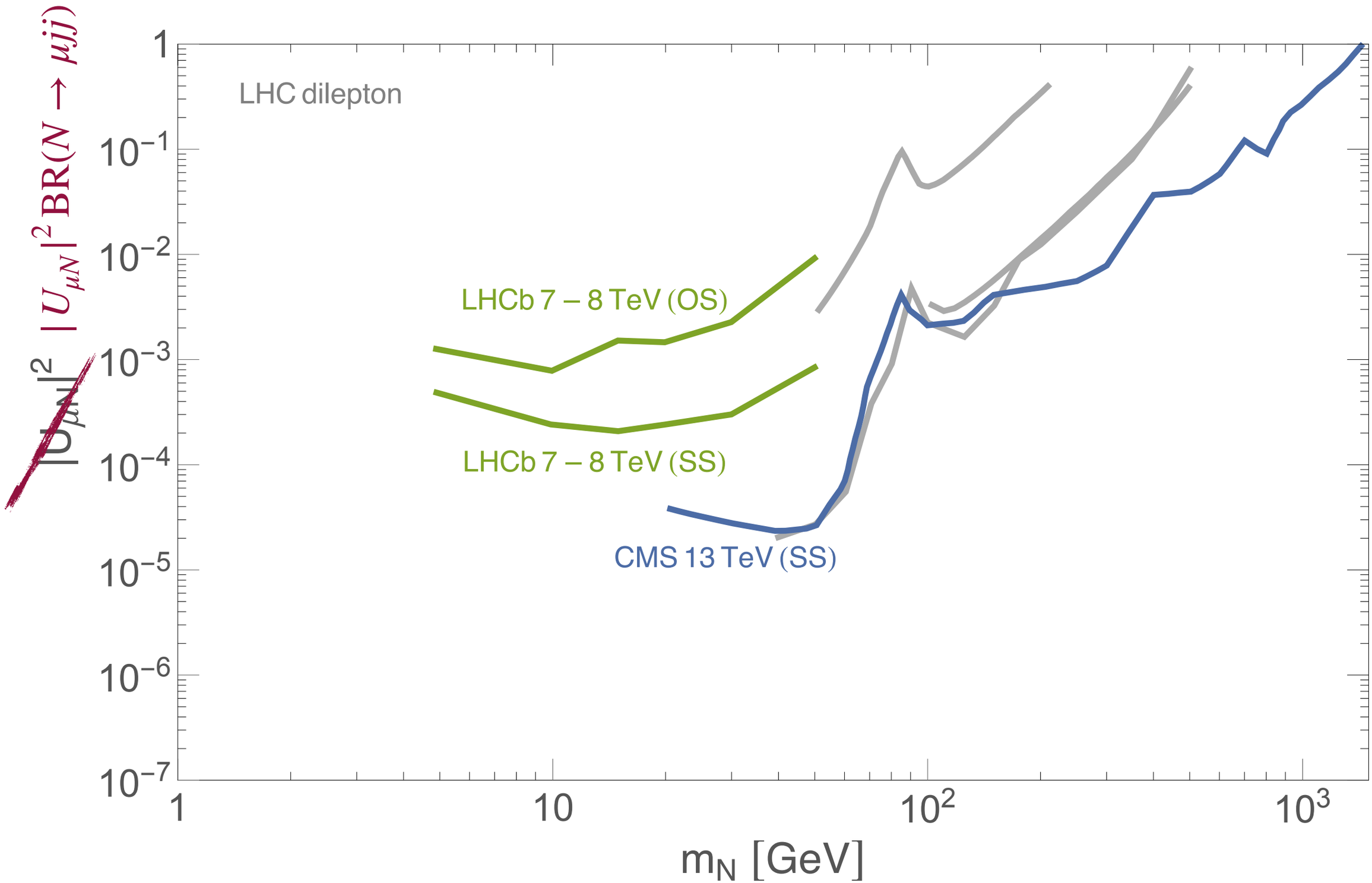
- *Exp searches consider 1HNL mixing to 1 flavor at a time*
- *Are sensitive to very large mixings*

What do we learn from these analyses?

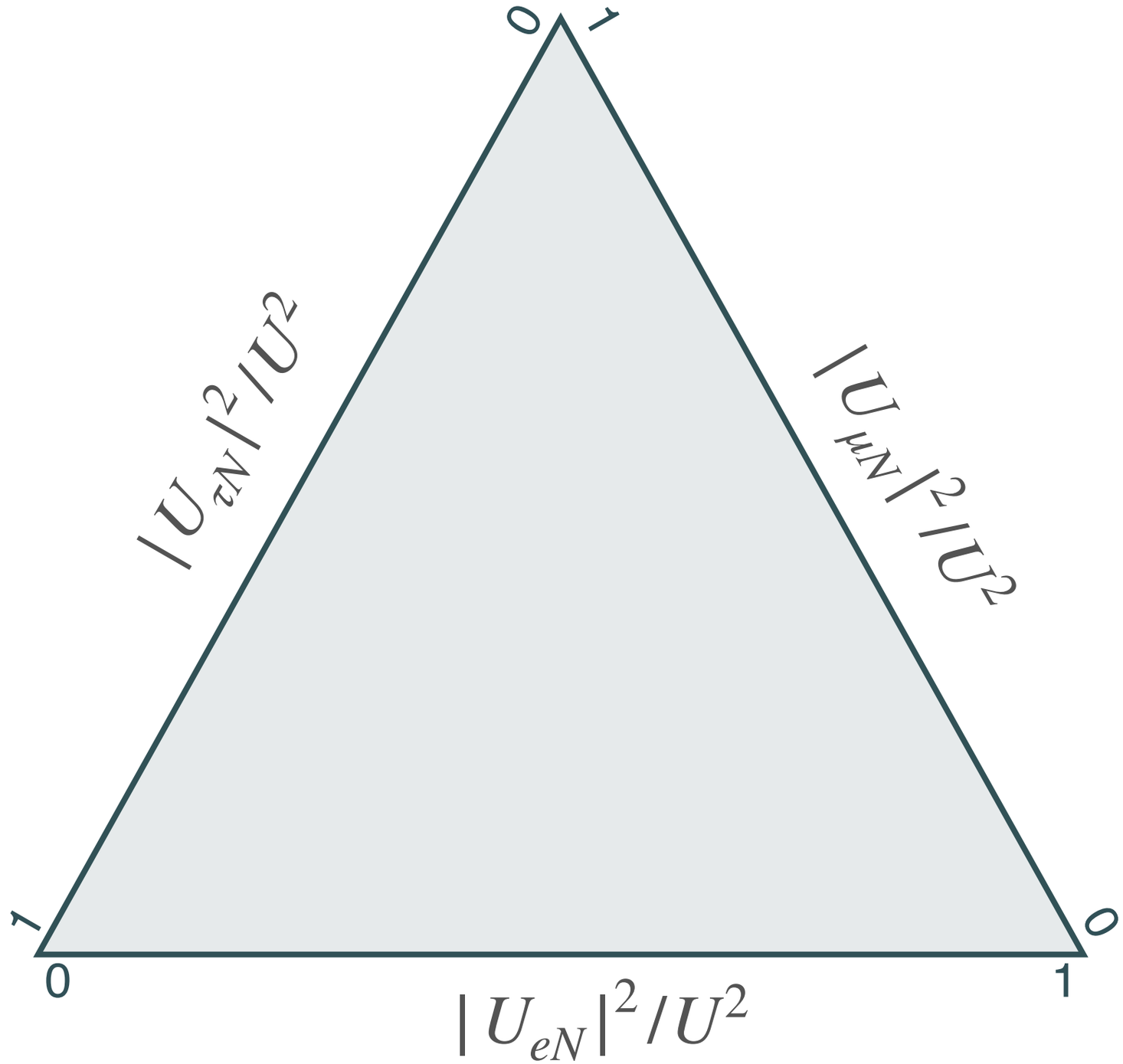
Single Mixing — dileptons



Single Mixing — dileptons

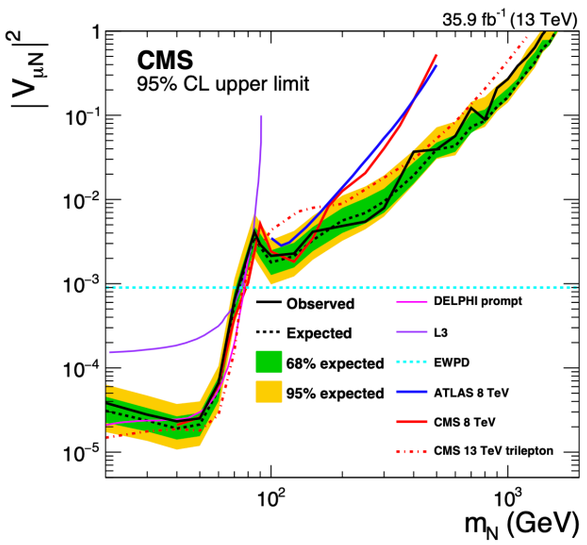


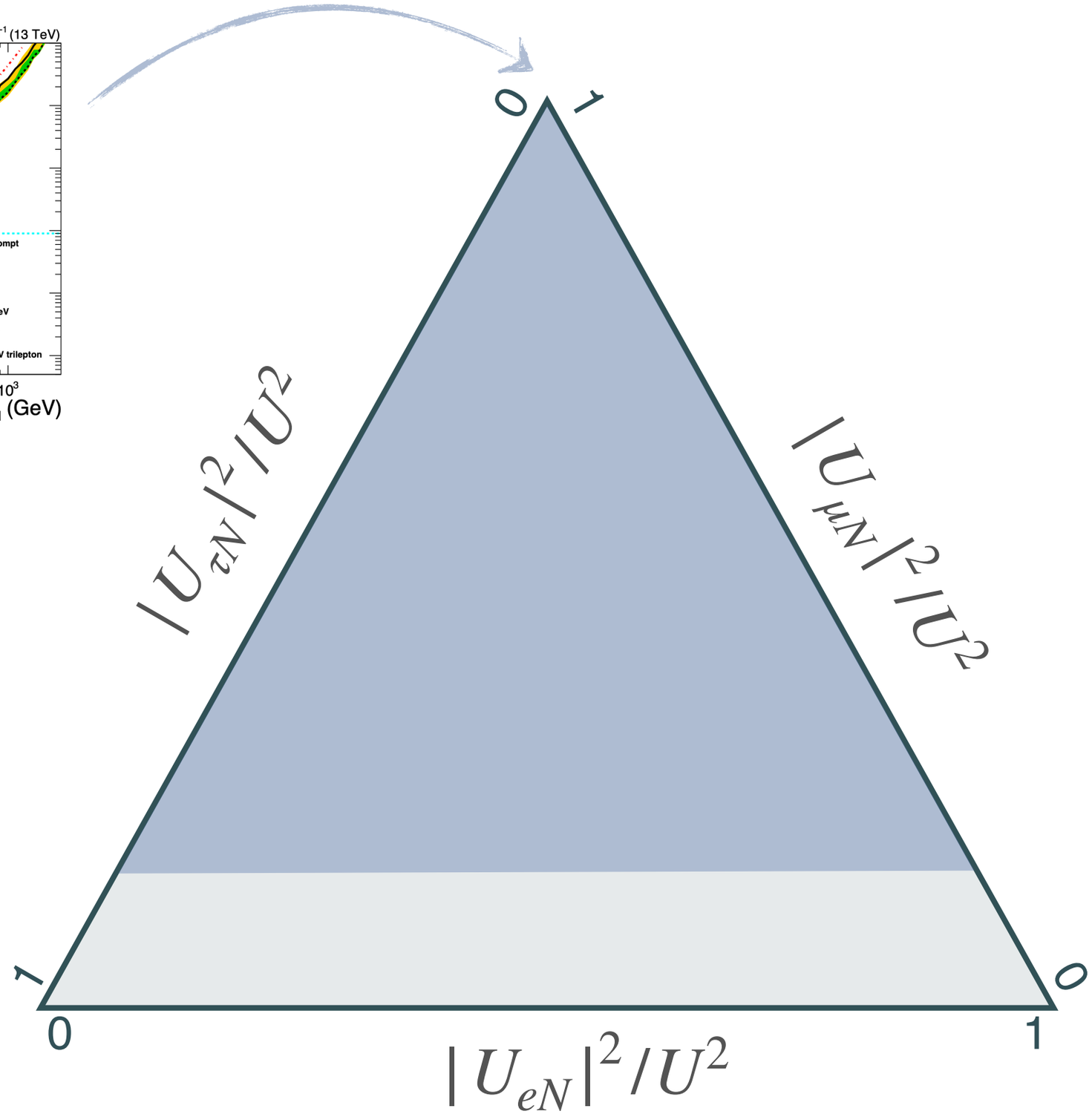
Single Mixing — dileptons



— For a fixed mass and U^2 —

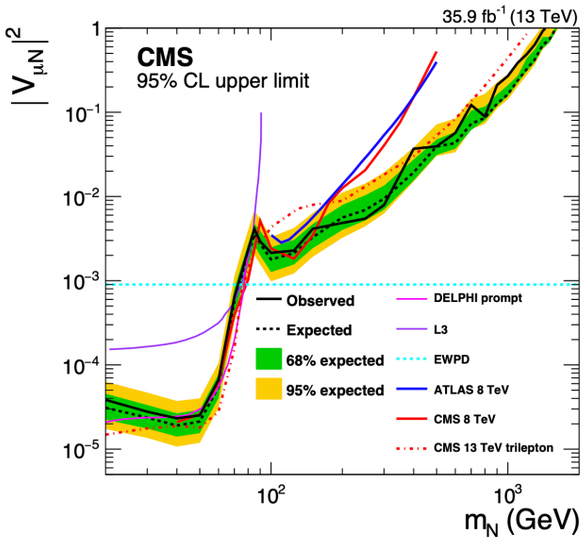
Single Mixing — dileptons

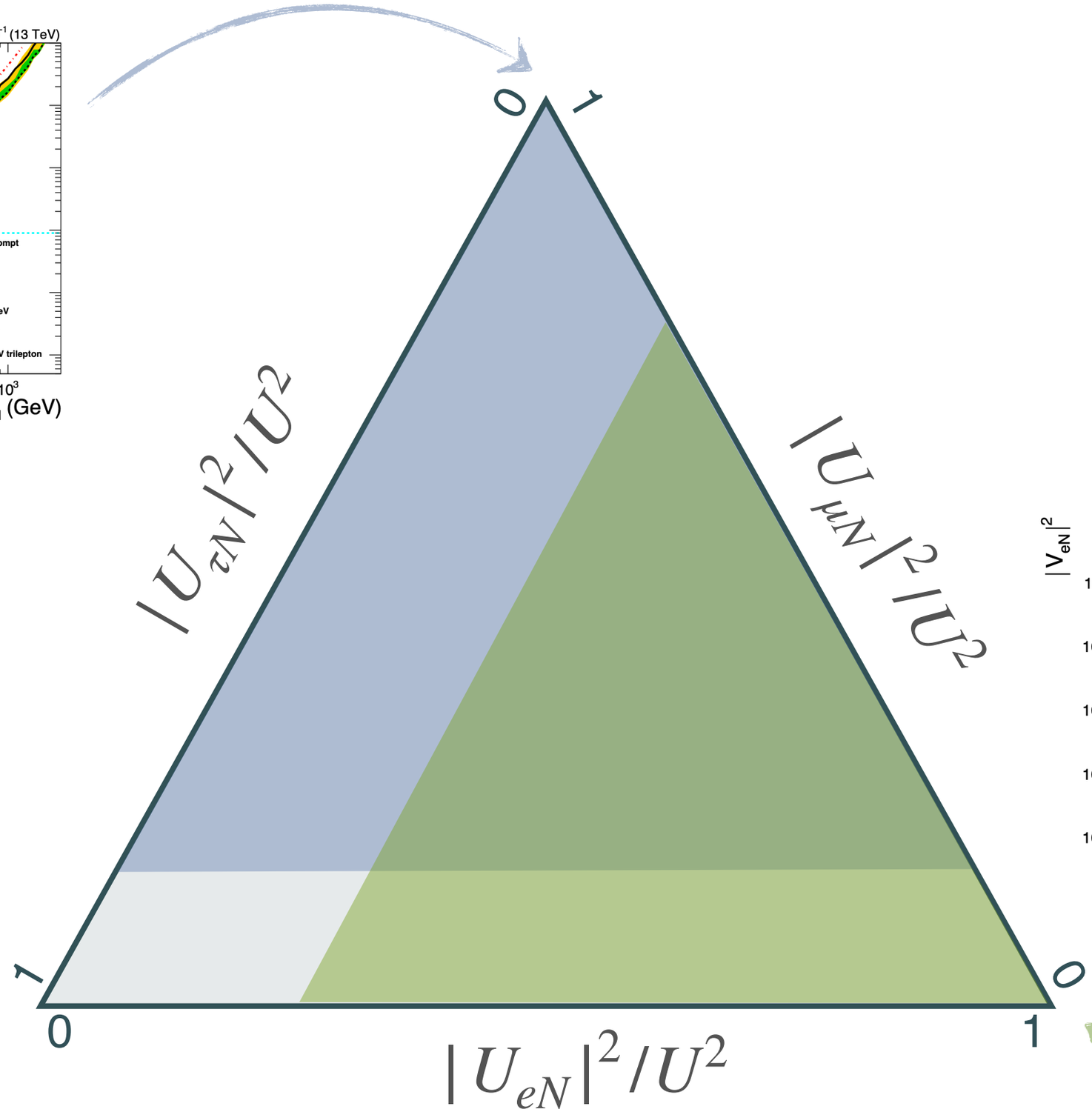




— For a fixed mass and U^2 —

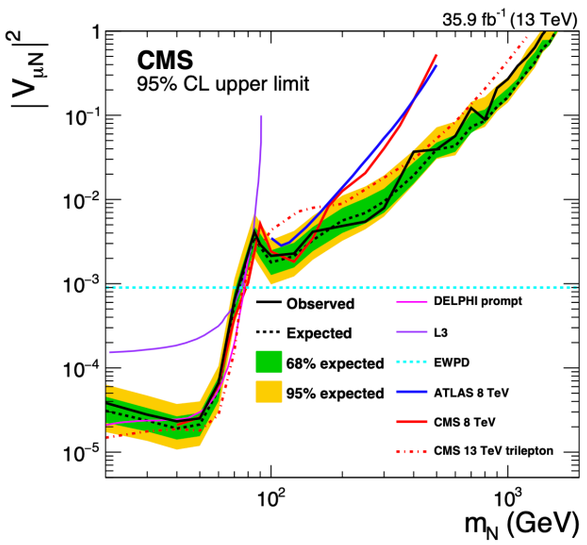
Single Mixing — dileptons

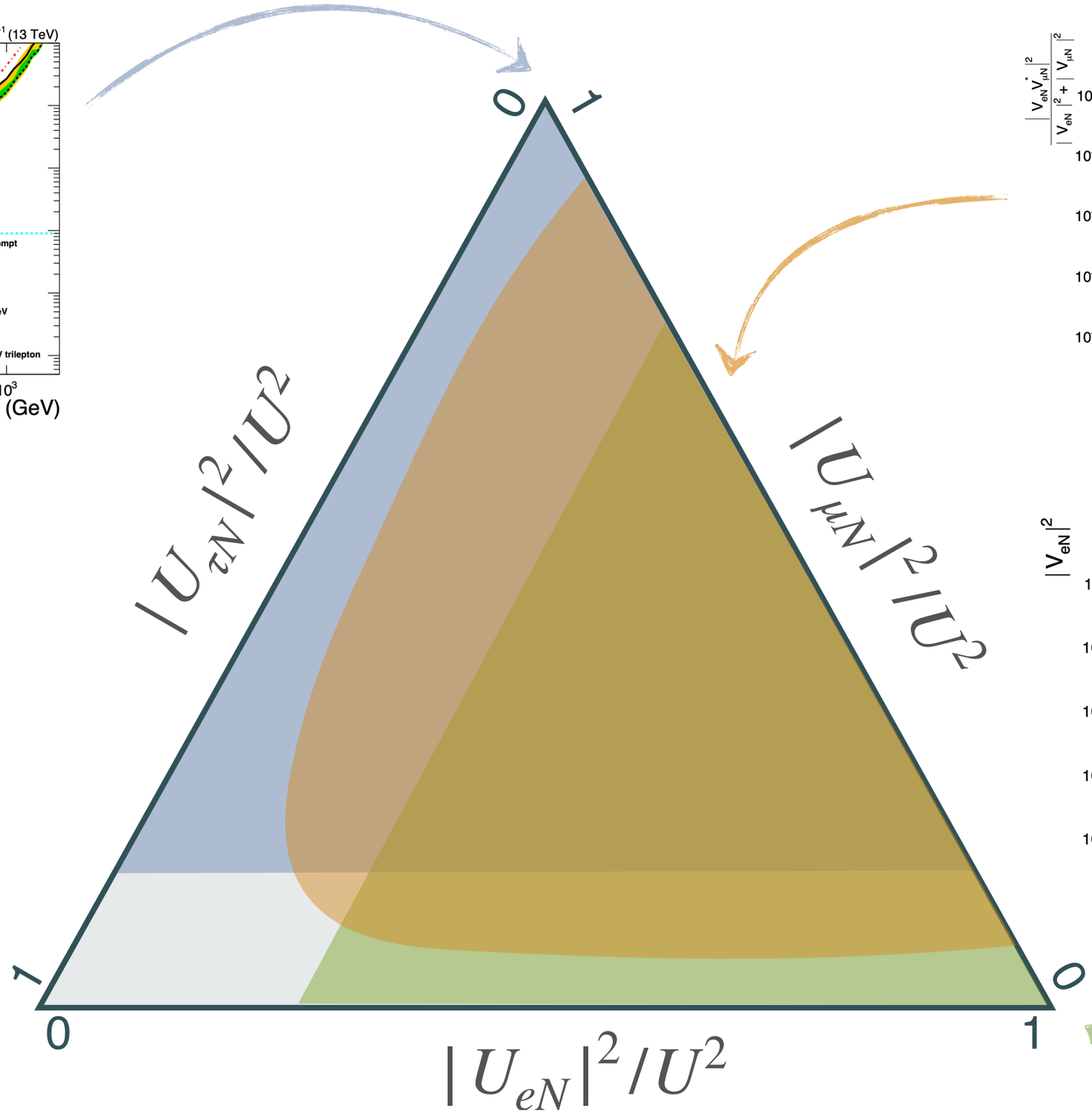


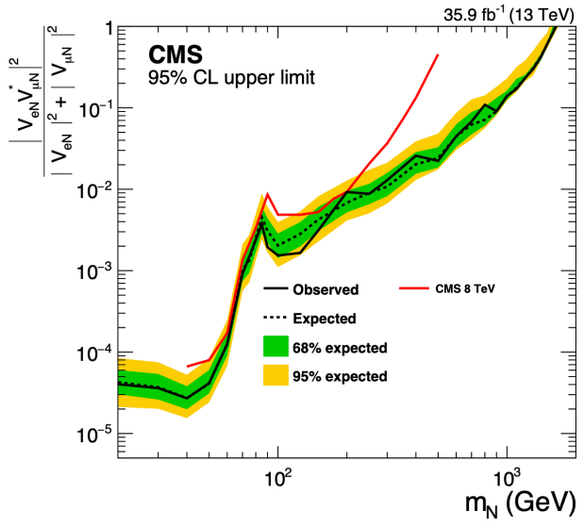


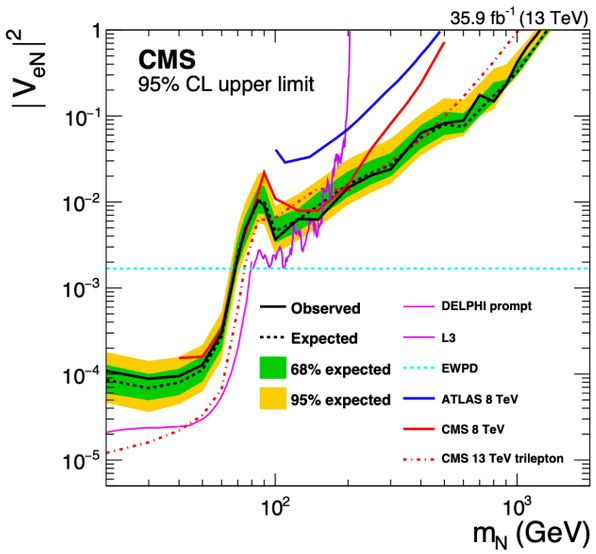
— For a fixed mass and U^2 —

Single Mixing — dileptons





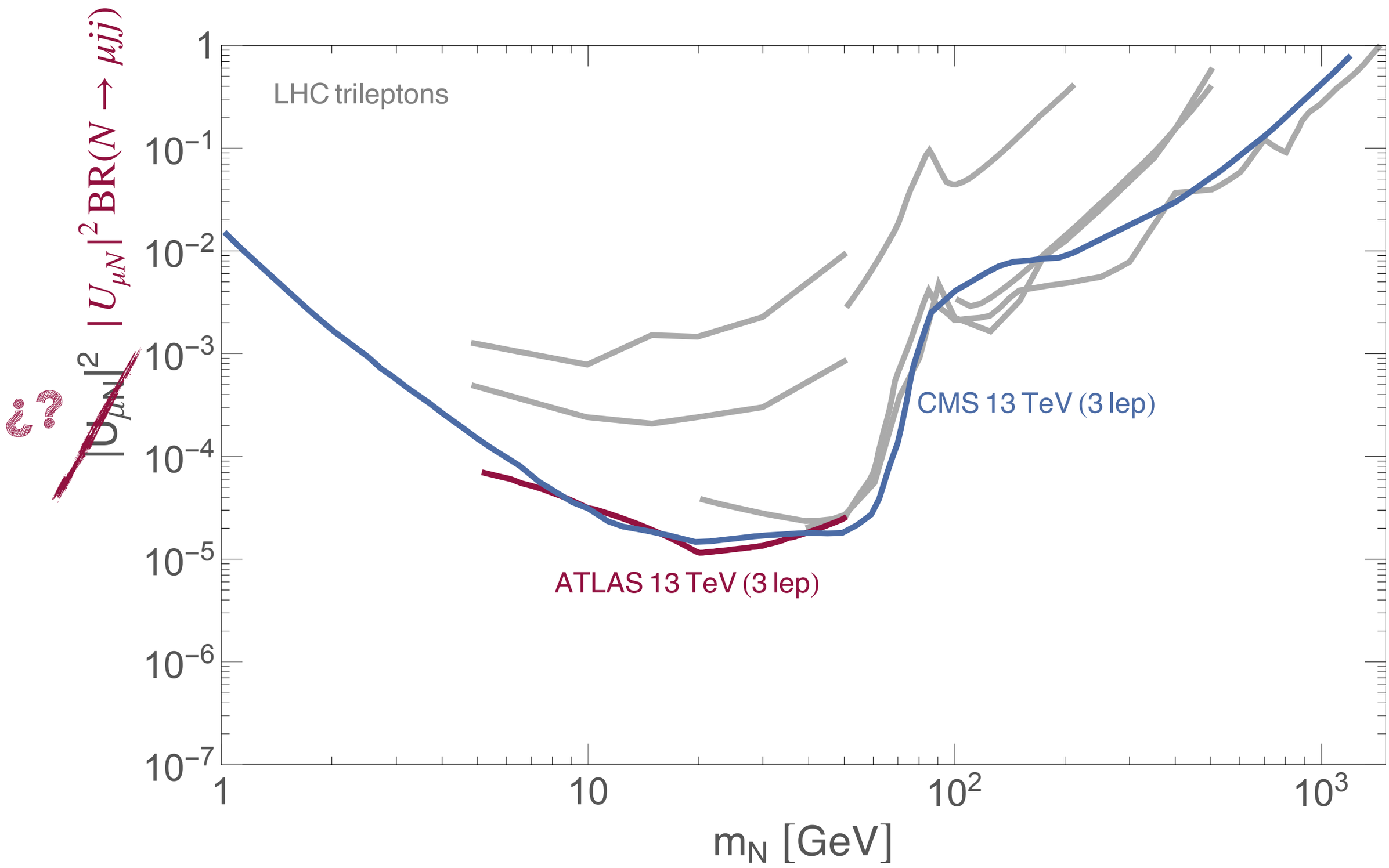




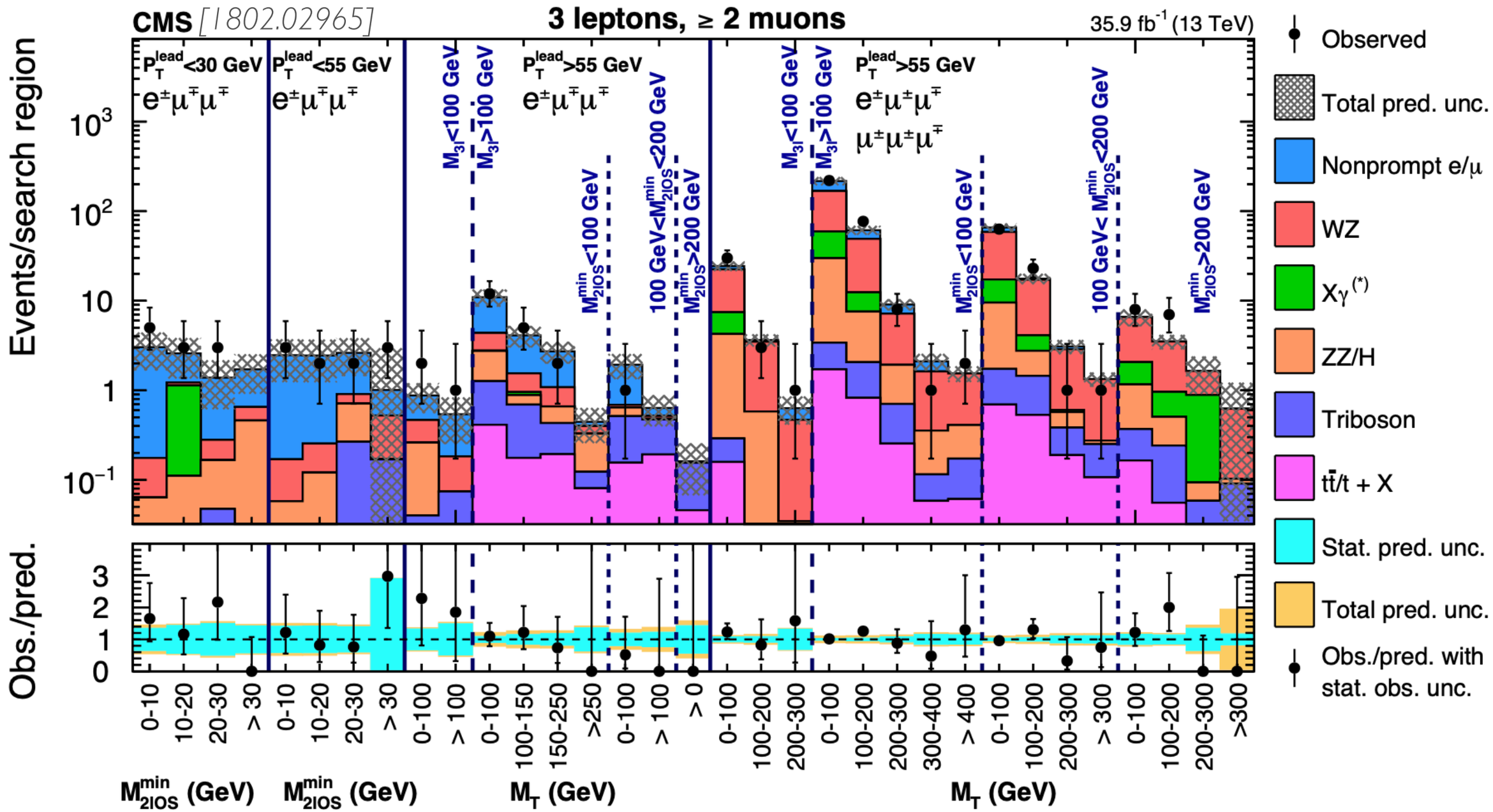
— For a fixed mass and U^2 —

— More in Abada, Escribano, XM, Piazza [in preparation]—

Single Mixing — trileptons



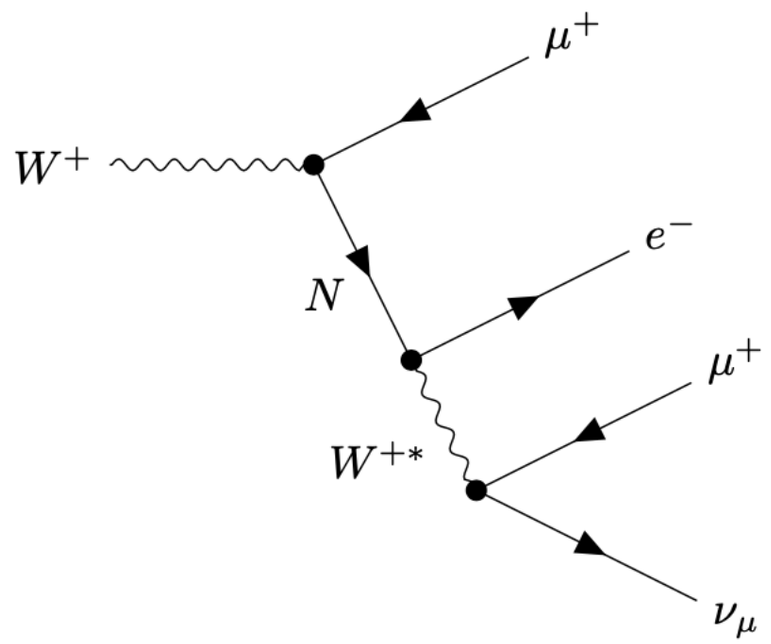
Single Mixing — trileptons



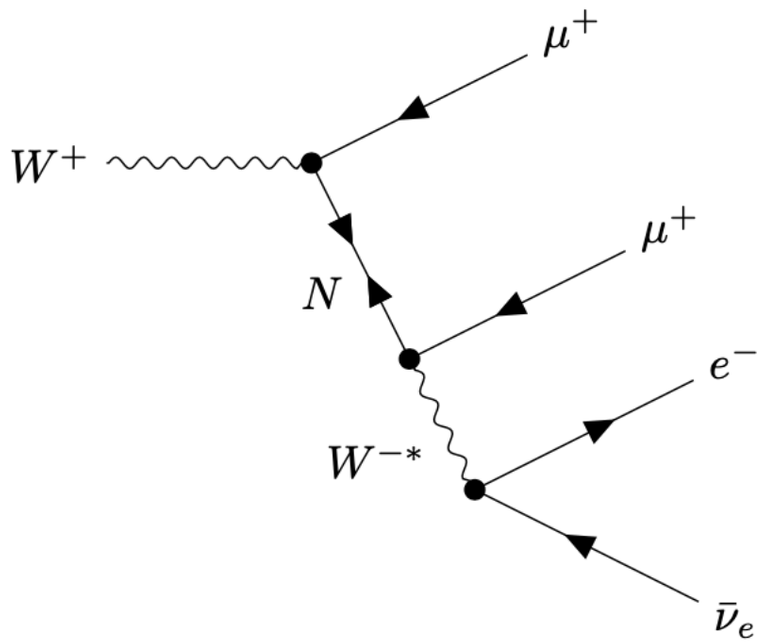
Single Mixing — tri-leptons

- *More mixings, more diagrams*

— Tastet et al [2107.12980] —



(a) LNC

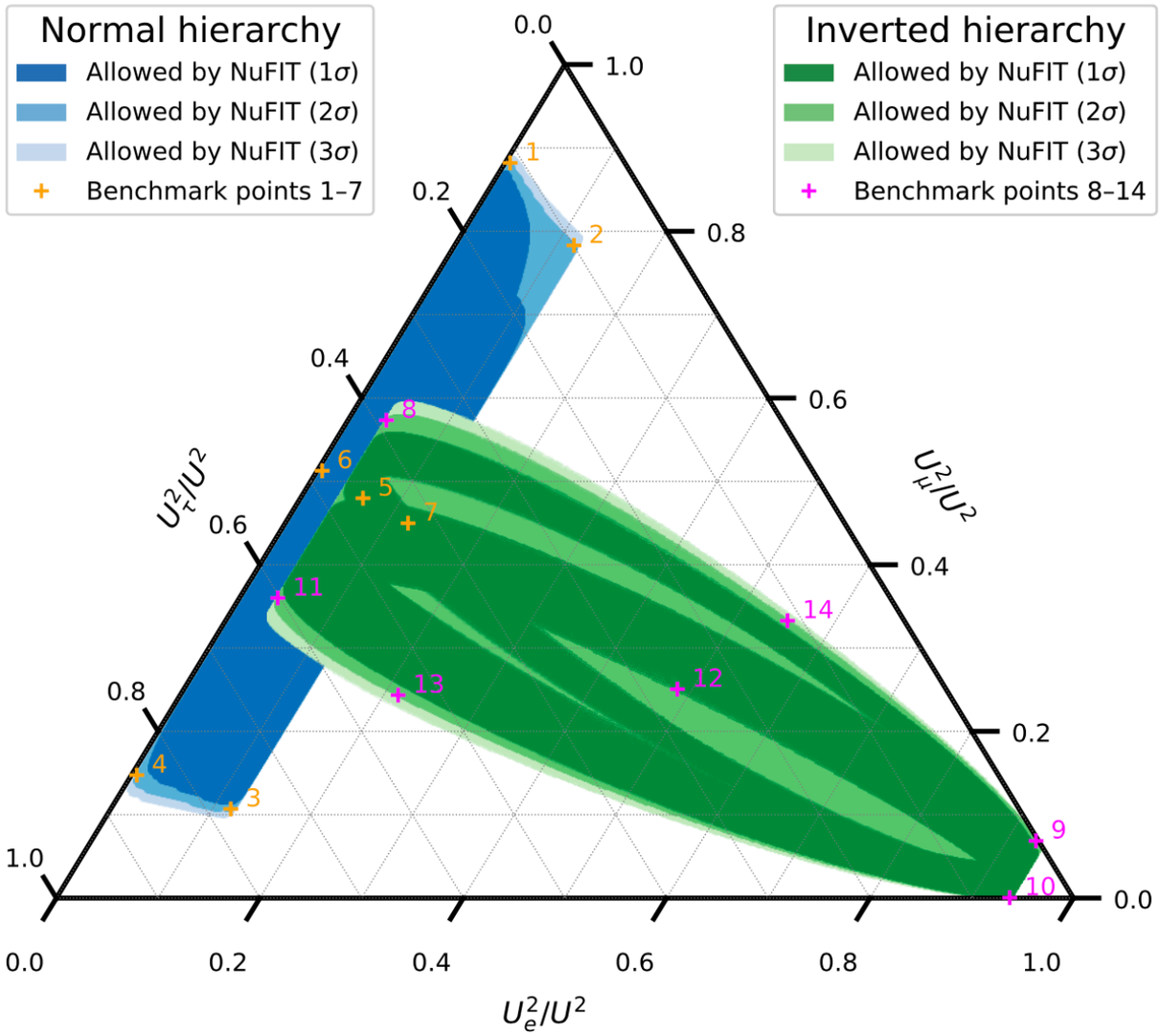


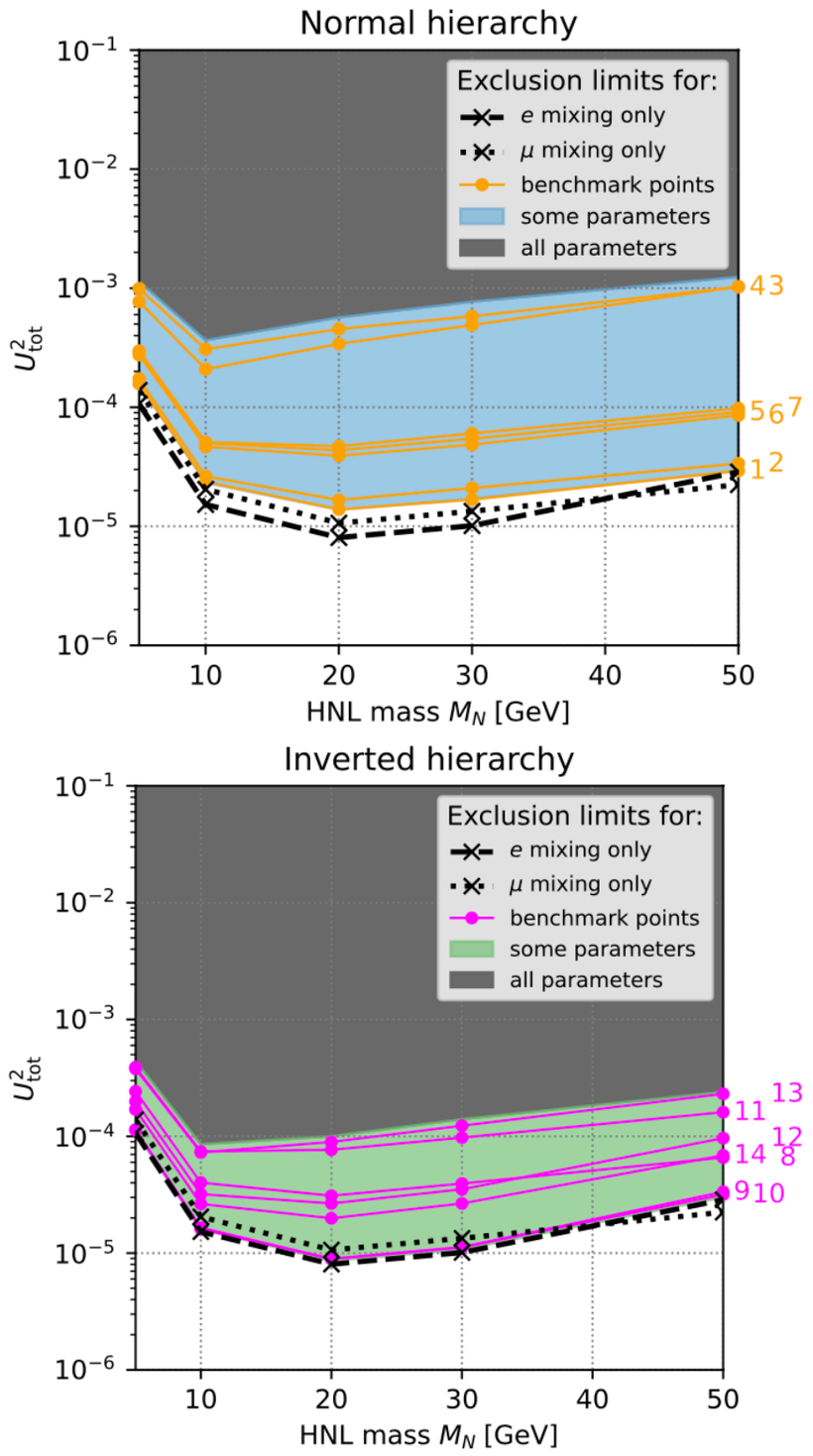
(b) LNV

Single Mixing — tripletons

- *Simplest realistic framework*

— Tastet et al [2107.12980] —

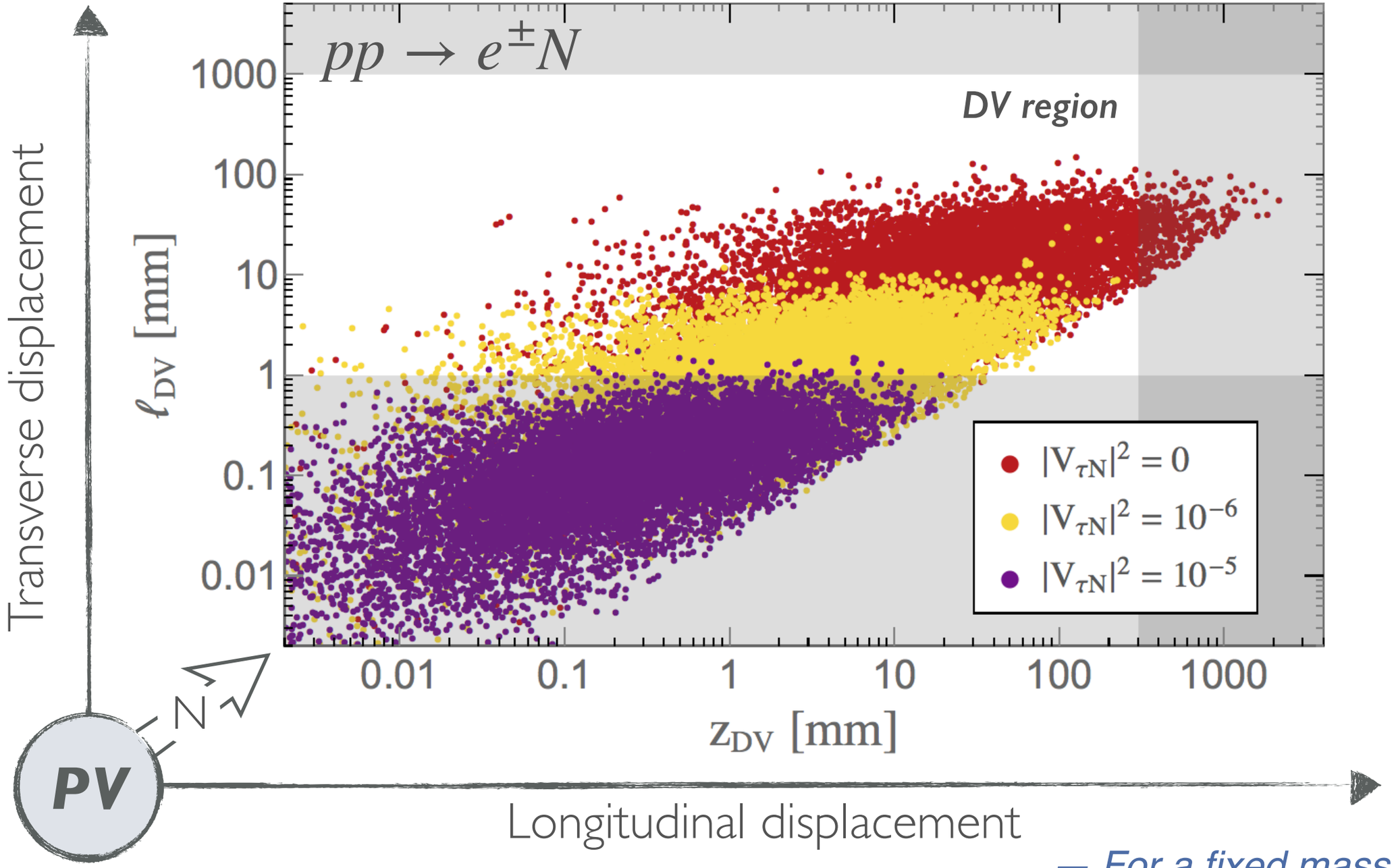




Single Mixing — DV

- *The efficiency is highly mixing-pattern dependent*

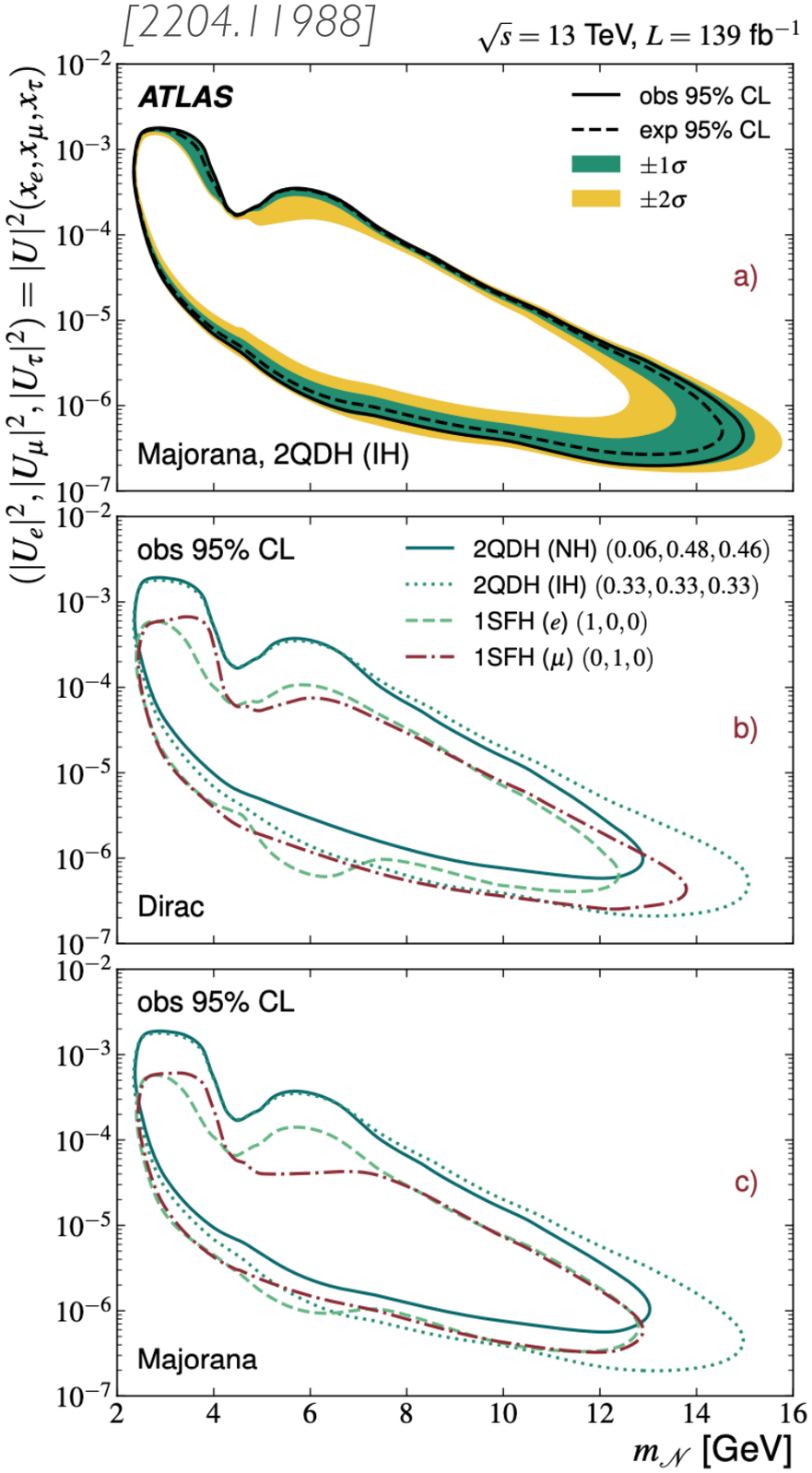
— Abada, Bernal, Losada, XM [1807.10024] —



— For a fixed mass and U_{eN} —

Single Mixing — DV

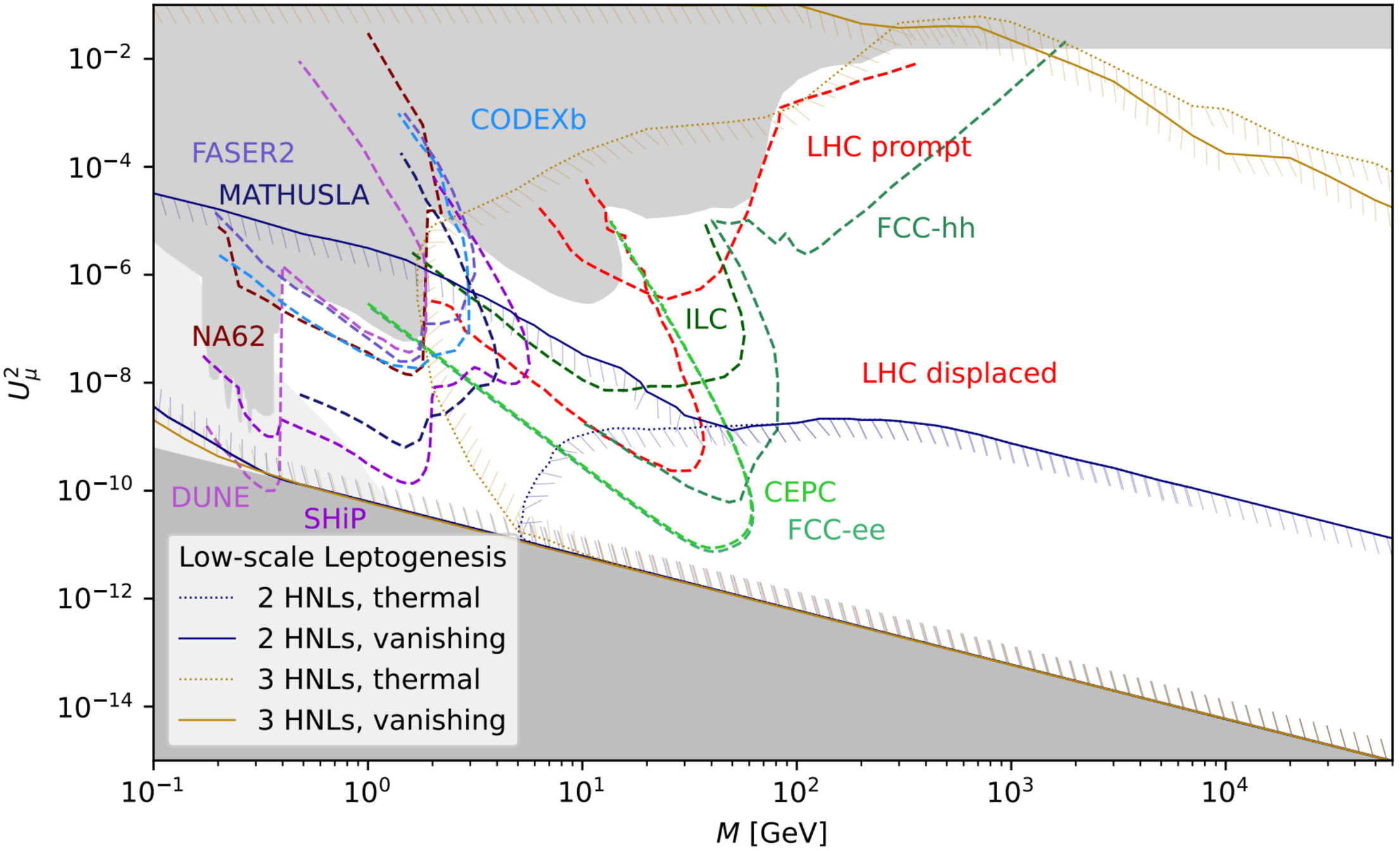
[2204.11988]



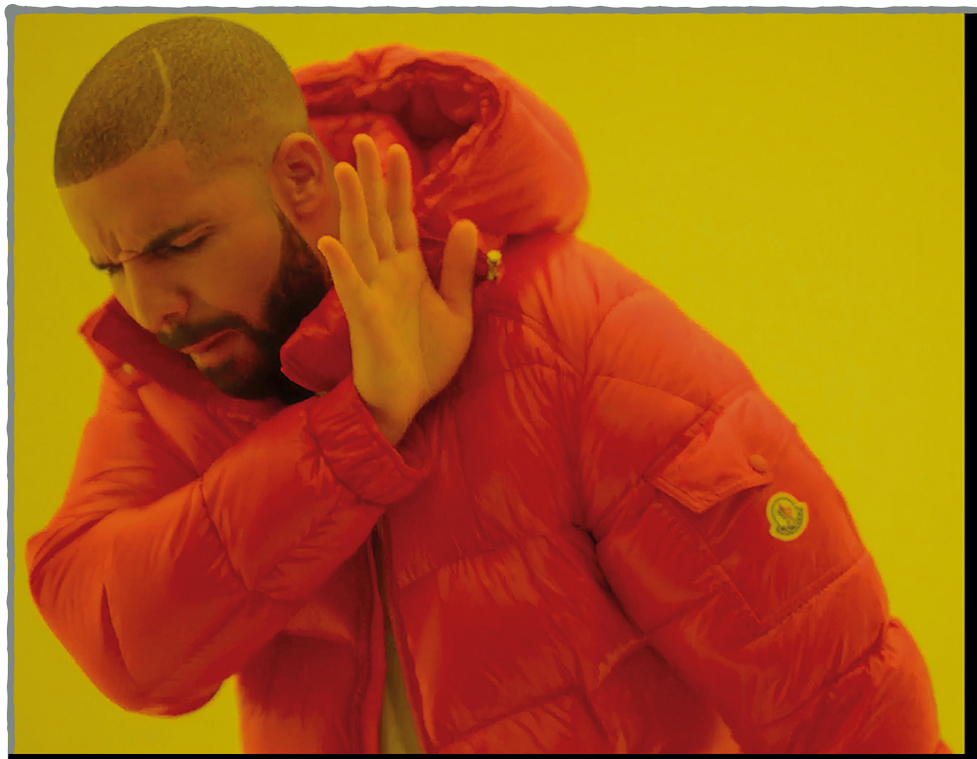
—What are we actually testing?—

What are we actually testing?

Abdullahi et al [2203.08039]



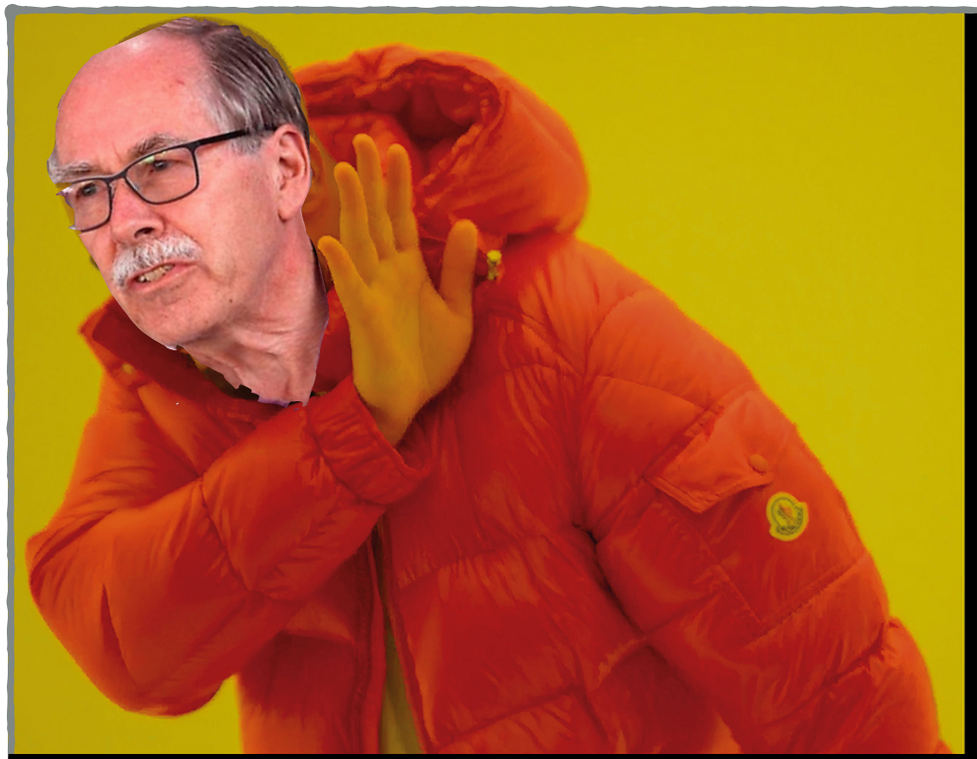
Symmetry Protected Scenarios



Two HNL with
same mass
same mixing
opposite phase

Symmetry:
lepton number

Symmetry Protected Scenarios



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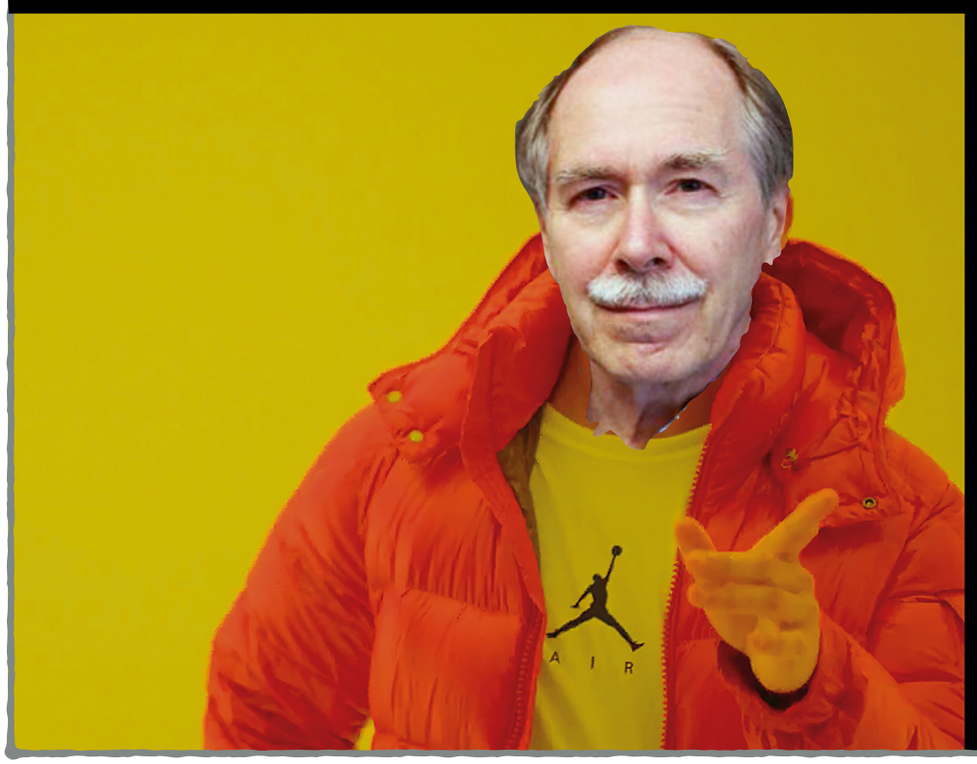
same mixing
opposite phase

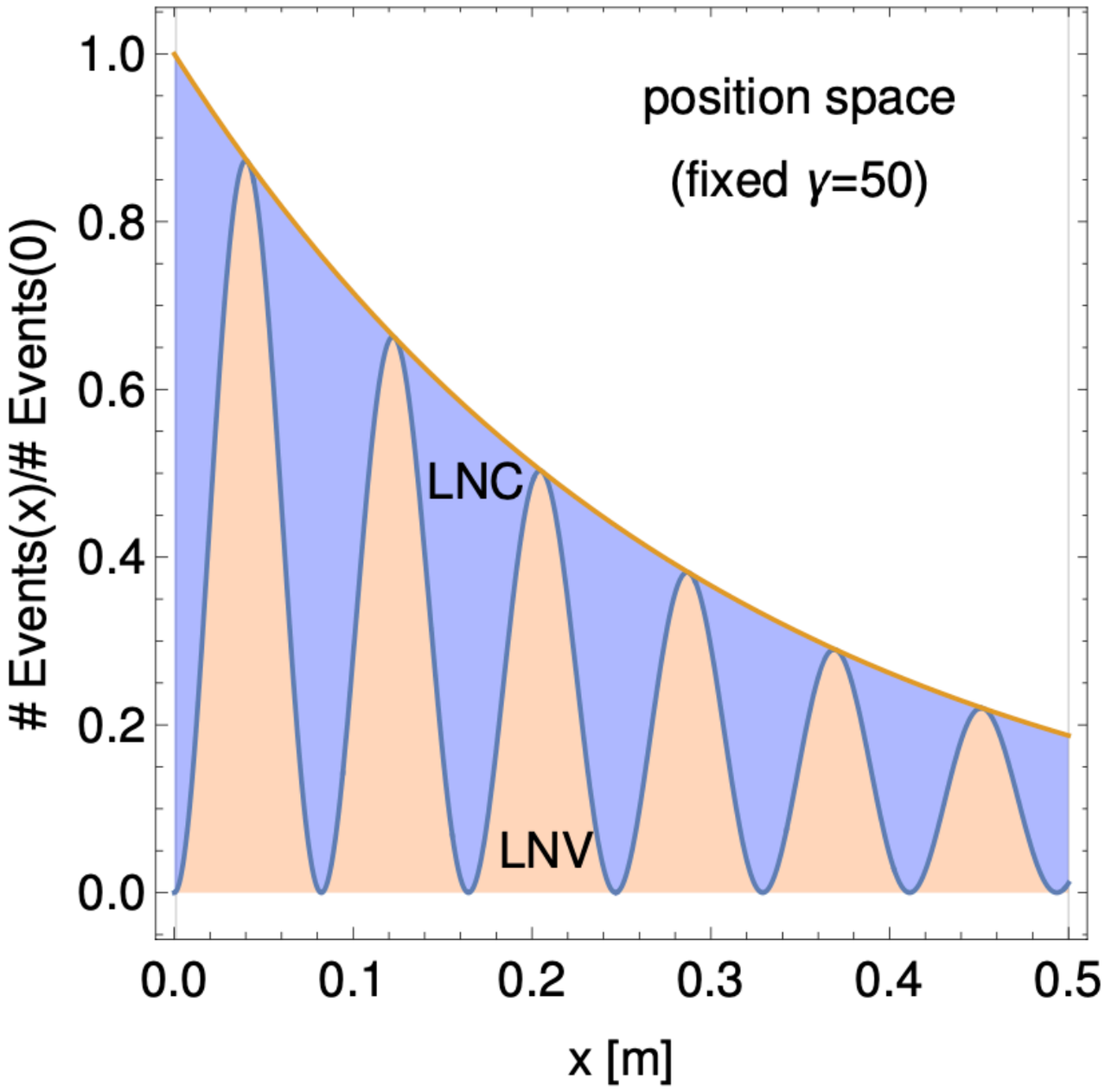


Symmetry:
lepton number

LNV in Symmetry Protected Scenarios

- *Potential oscillations between HNLs*

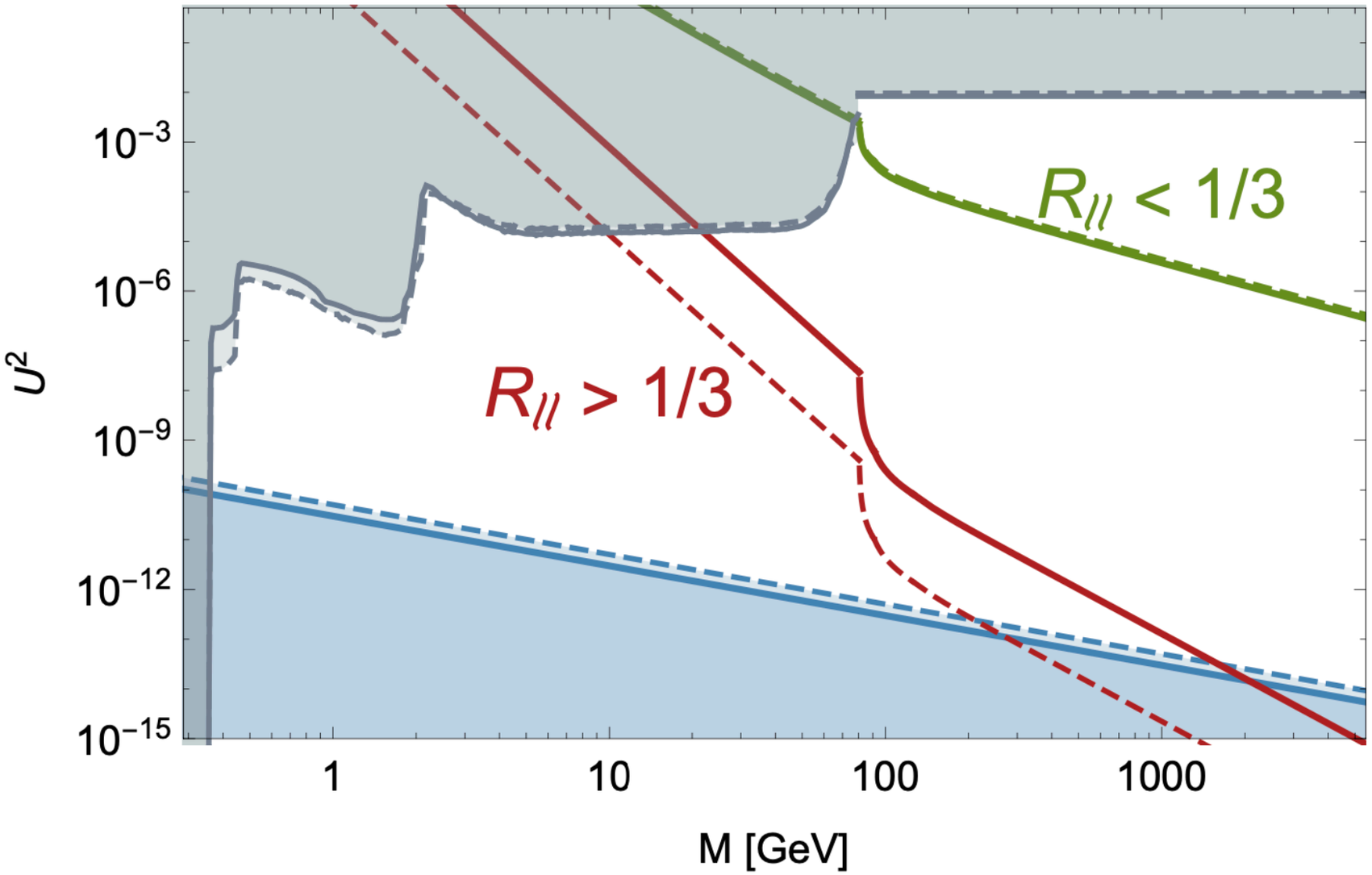
— Antusch et al [1709.03797] —



LNV in Symmetry Protected Scenarios

- *Connected to active neutrino masses*

— Drewes et al [1907.13034] —



LNV in Symmetry Protected Scenarios

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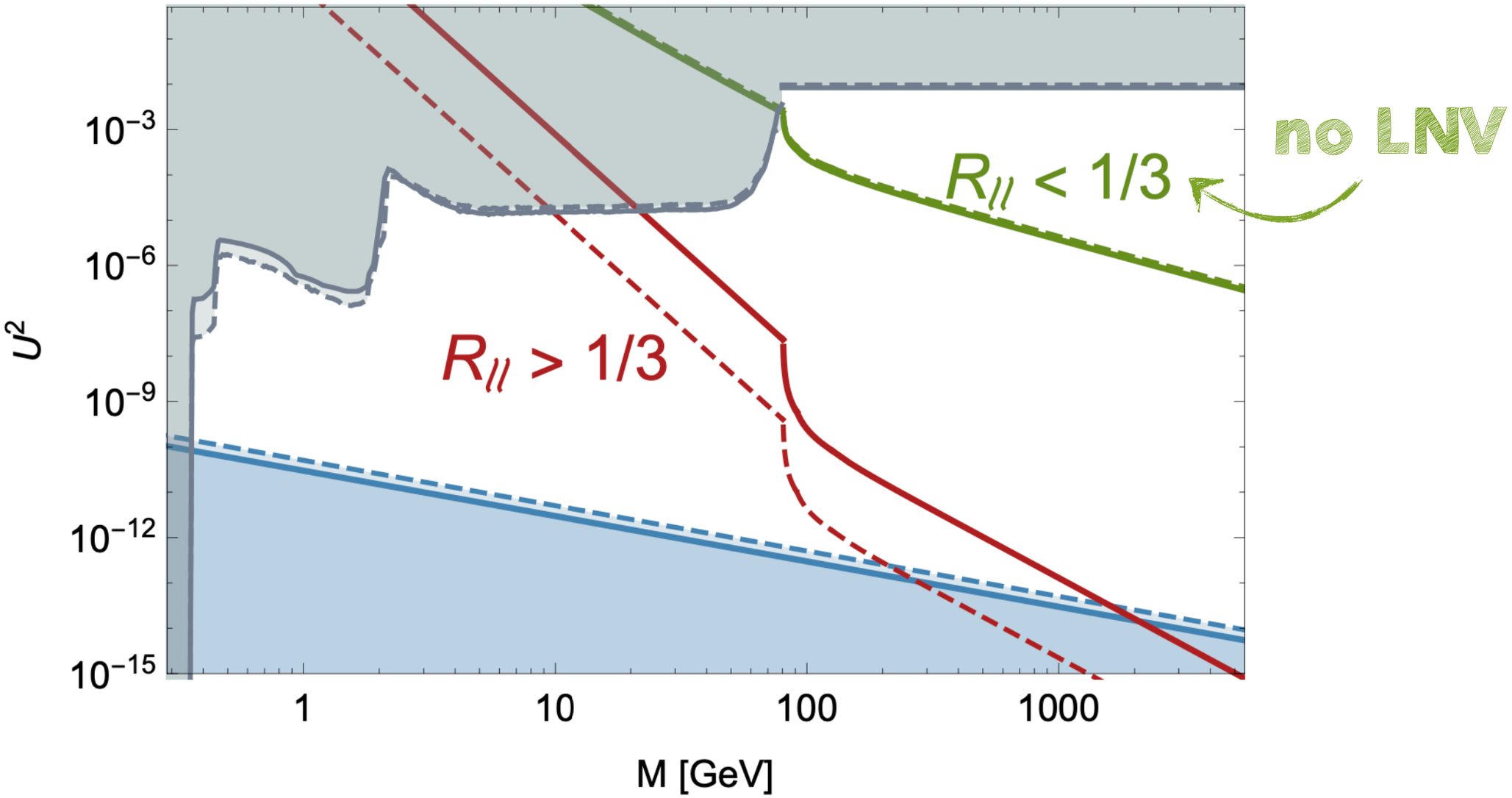

LNV in Symmetry Protected Scenarios

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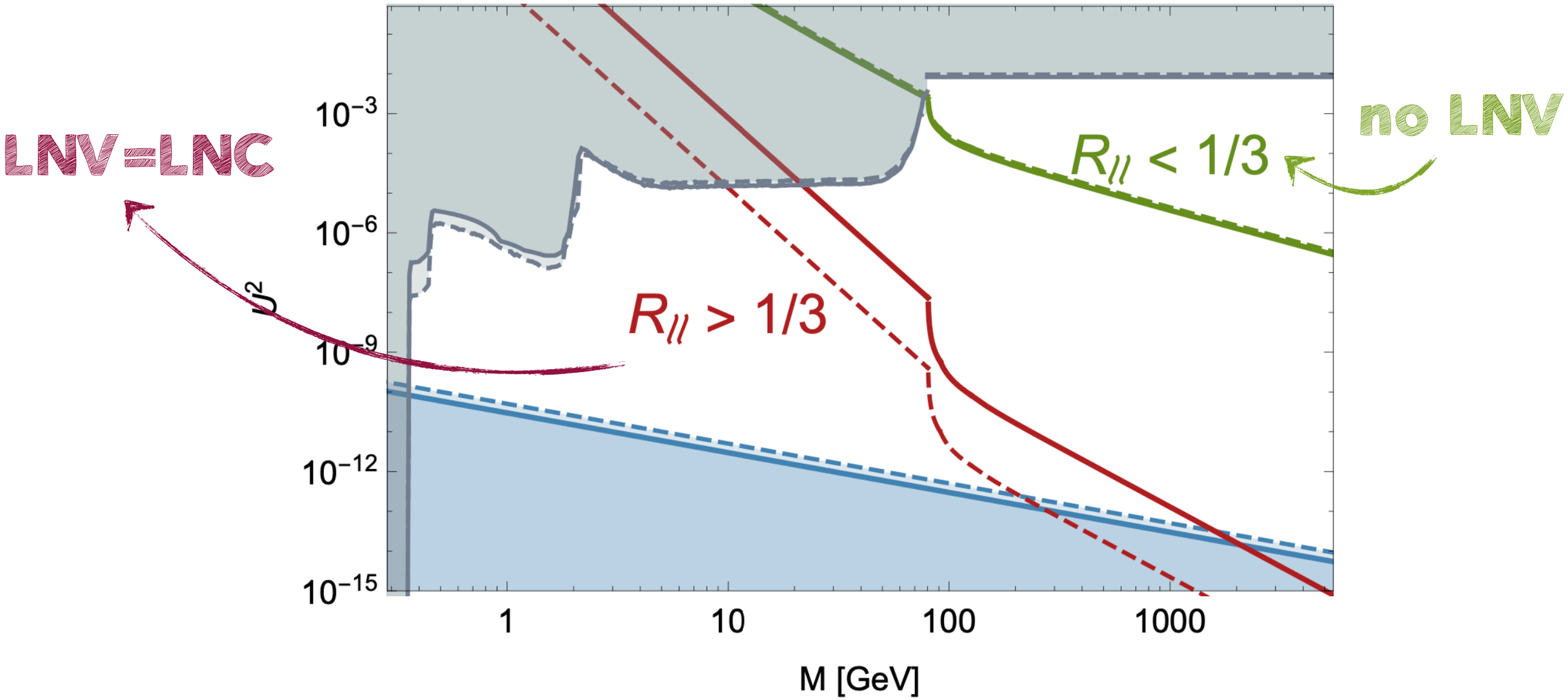
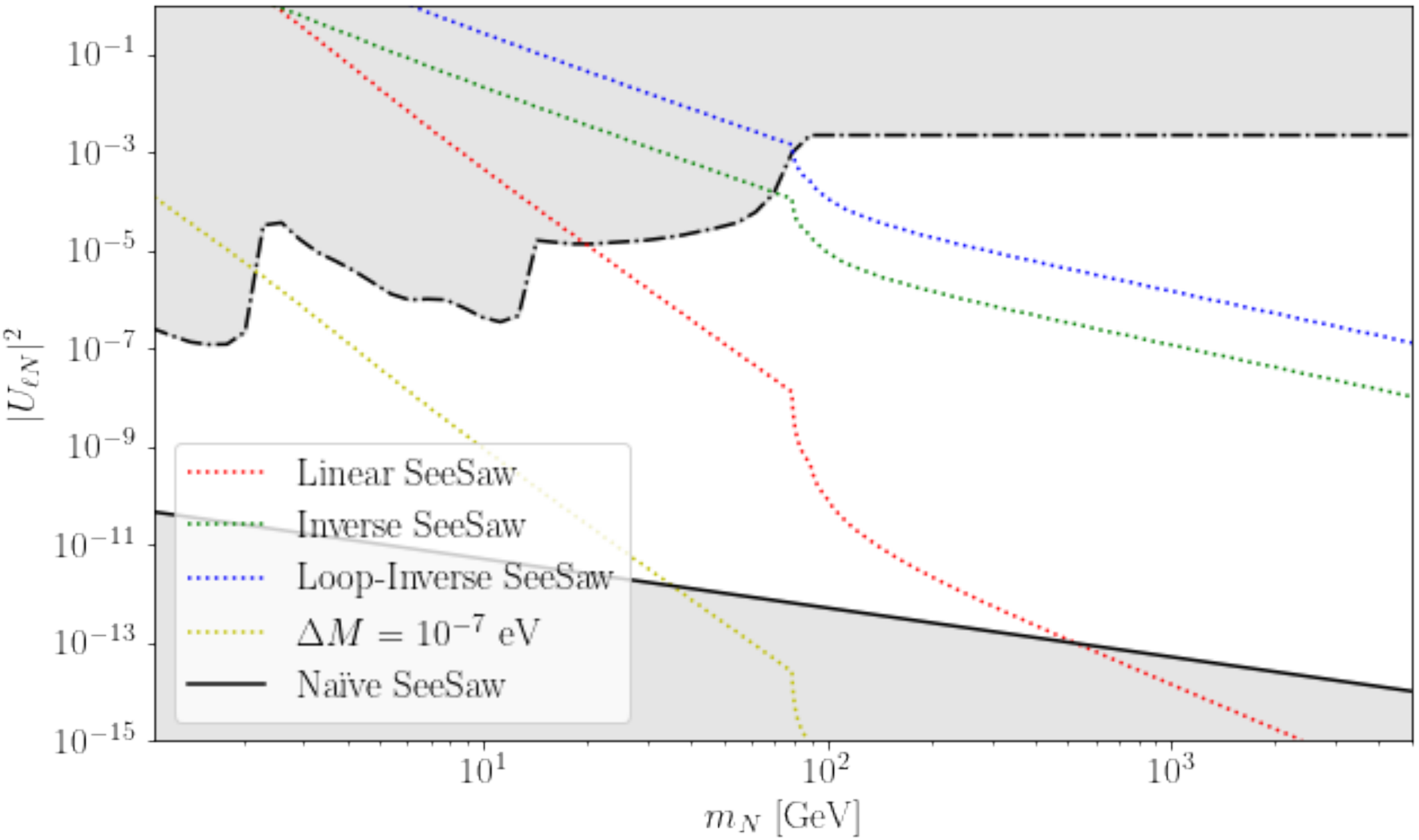


LNV in Symmetry Protected Scenarios

— Courtesy of Daniel Naredo —



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 —

- *There might be hope for LNV signals*

Thank you!

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