Heavy Neutral Leptons (HNL) at CEPC
(and other e^+e^- colliders) — theory perspective

Jürgen R. Reuter

NARODOWE CENTRUM NAUKI
Opus

DESY. HELMHOLTZ

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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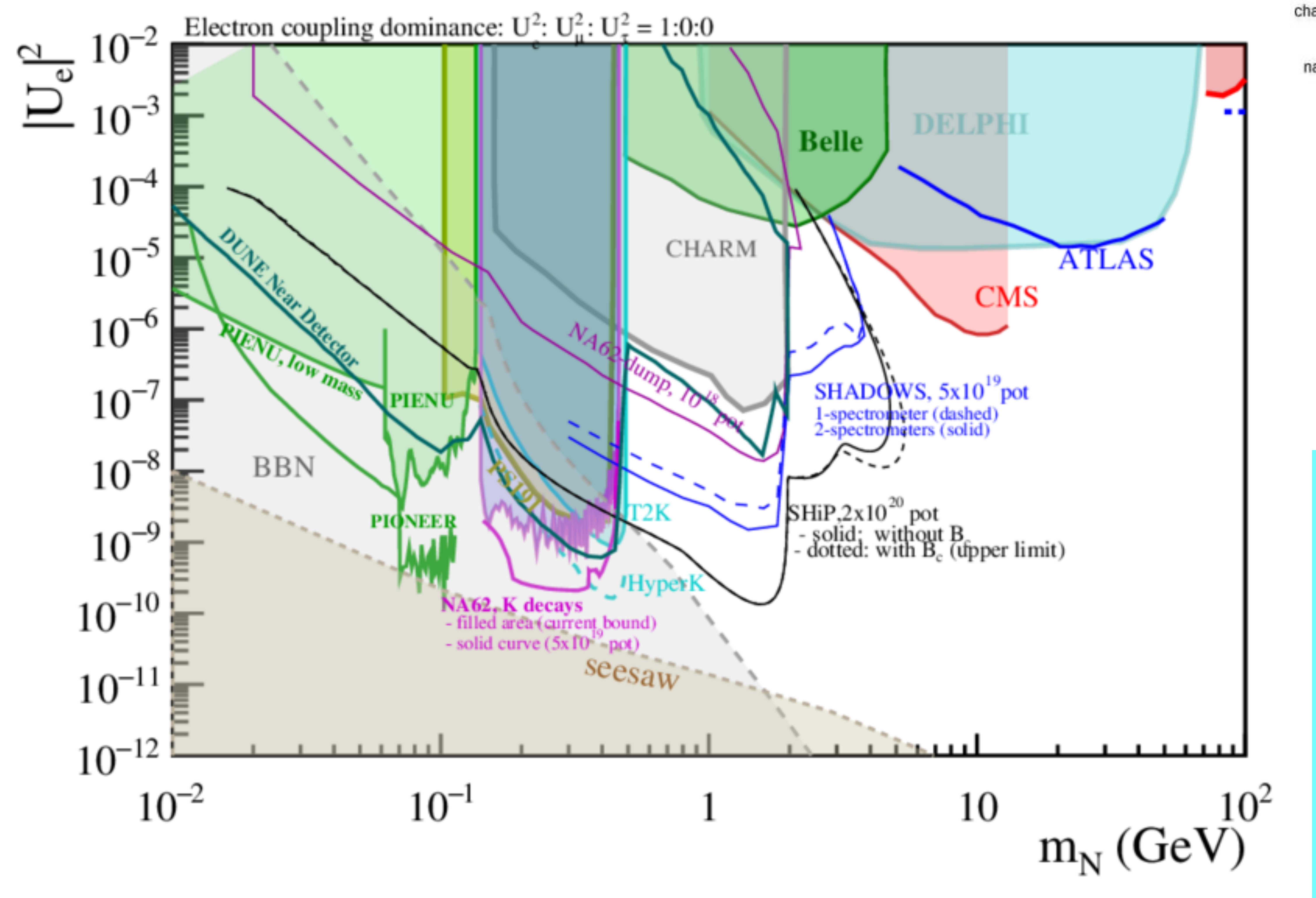
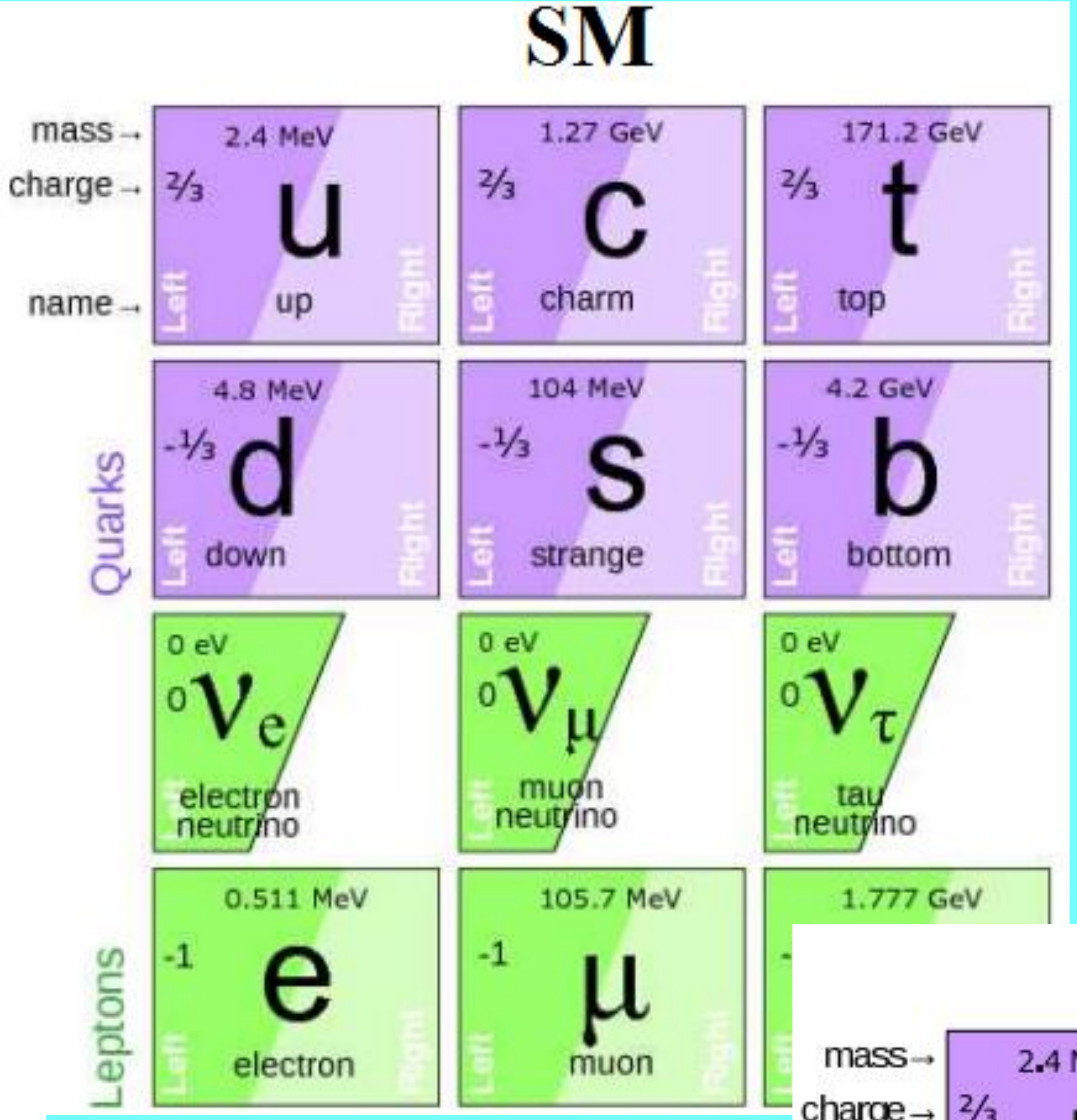
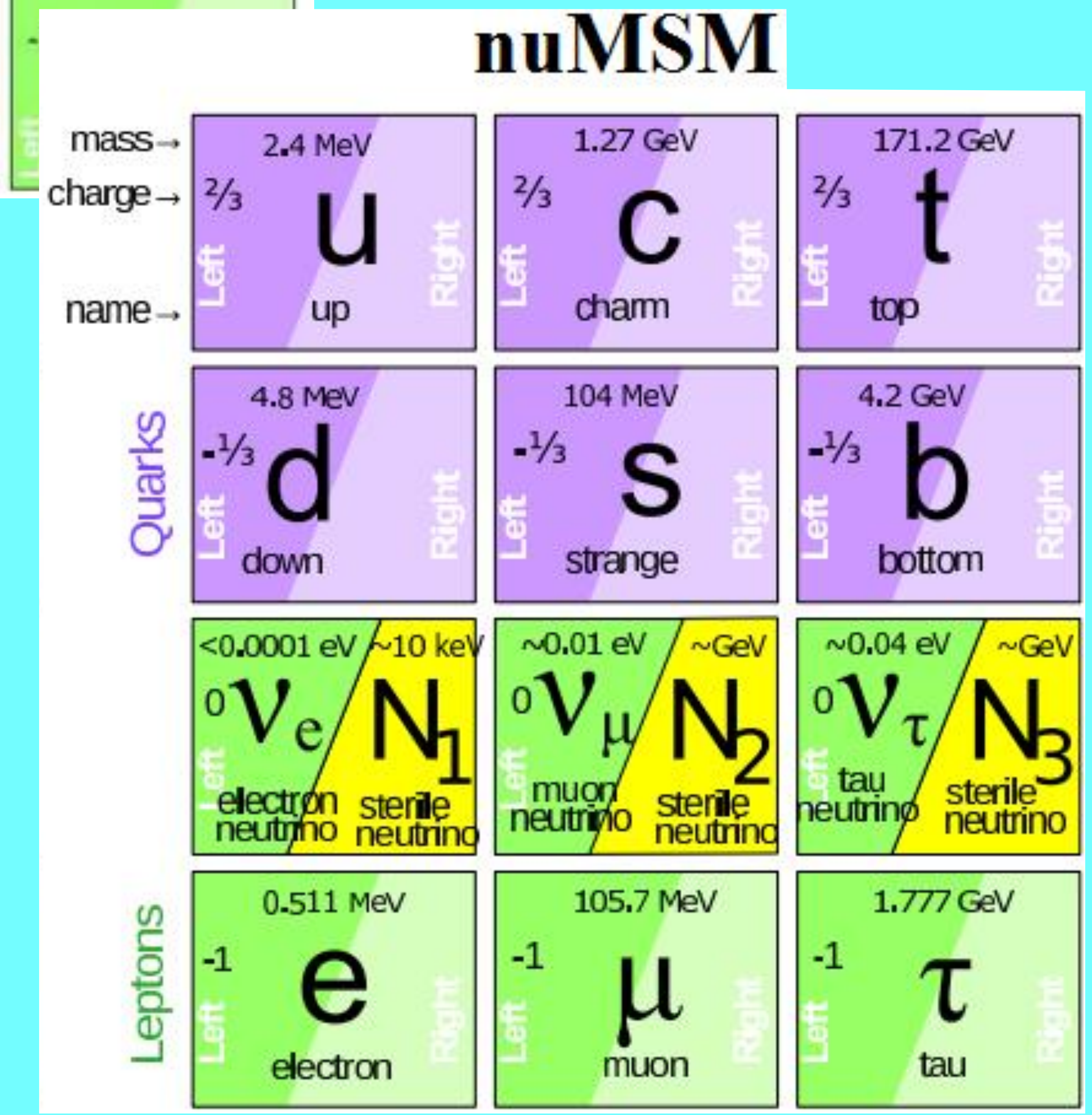
The quest for Heavy Neutral Leptons (HNL)



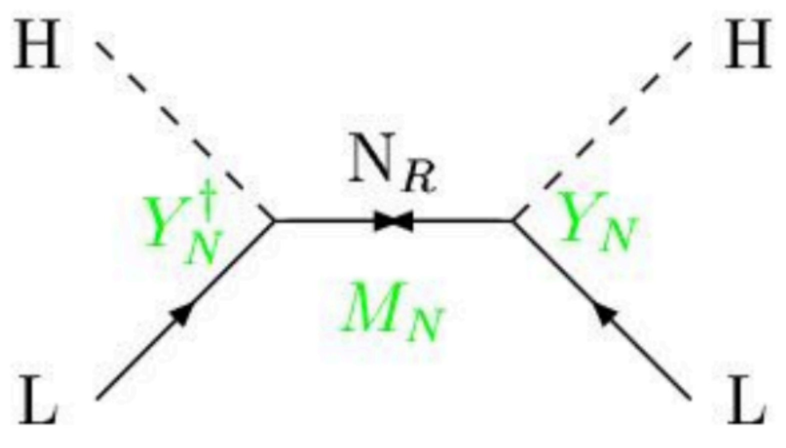




The neutrino mystery

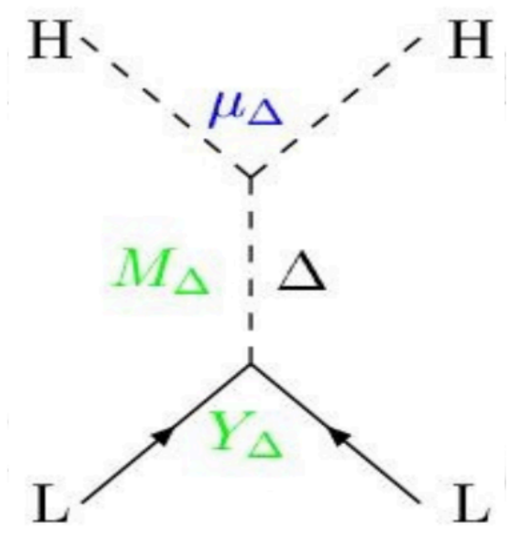
- Neutrinos masses is already physics beyond the standard model
- Simple extension of SM: just add ν_R and Yukawa couplings $\nu_R = (\mathbf{1}, \mathbf{1}, 1)$ $\quad -m_\nu(\bar{\nu}_L \nu_R + h.c.)\left(1 + \frac{h}{v}\right)$
- Singlet allows for a Majorana mass term: $-M_\nu \overline{\nu^C} \nu$ [Minkowski, 1977; Mohapatra/Senjanovic, 1980; Yanagida, 1981]
- Dedicated "seesaw" models for neutrino physics: type I (singlet fermion), type II (triplet scalar), type III (triplet fermion)

Right-handed singlet: (type-I seesaw)



$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet: (type-II seesaw)



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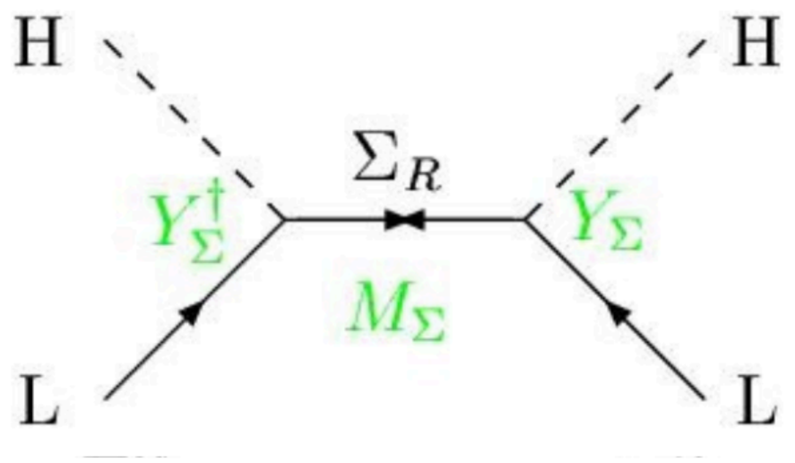
Fermion triplet: (type-III seesaw)



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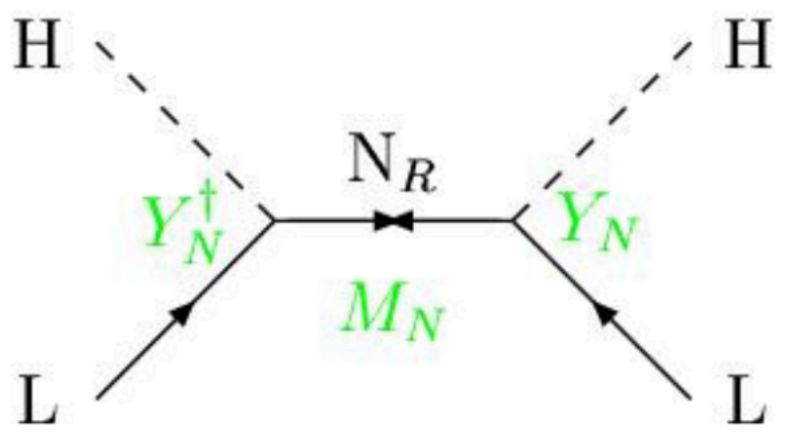

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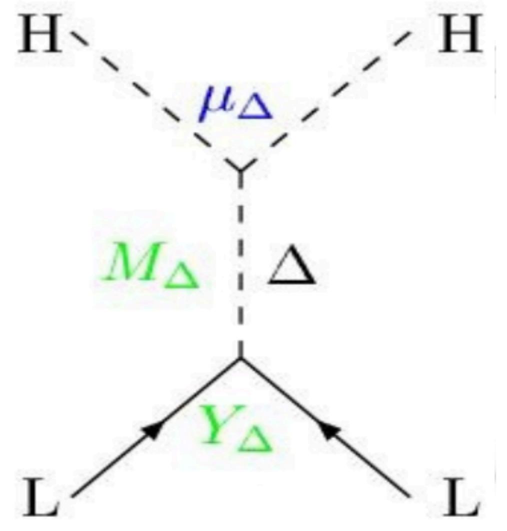

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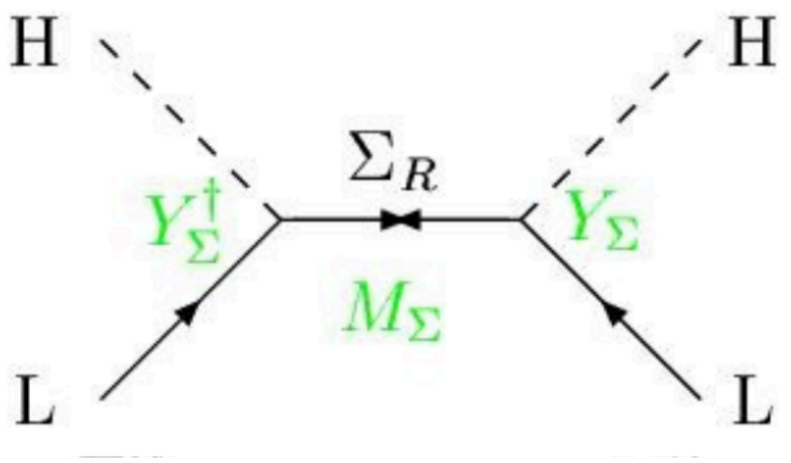

$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

- Pheno of neutrino oscillations, flavor etc.
- Connections to Dark Matter (DM) (?)
- Lepton sector CP violation (?)
- Leptogenesis / Baryogenesis / Baryon Asymmetry of Universe (BAU)
- Lepton Flavor/Number Violation
- Fundamental Majorana Particles (?)

Explanations for tiny masses

- Suppression by large scale ("classic seesaw")
- Accidentally small numbers (neutrino Yukawas, "tuned")
- Symmetry protection: e.g. B—L, flavor/discrete symmetries, Froggatt-Nielsen type, e.g. Hagedorn et al., 1408.7118

$$F = \begin{pmatrix} F_e(1+\epsilon_e) & iF_e(1-\epsilon_e) & F_e\epsilon'_e \\ F_\mu(1+\epsilon_\mu) & iF_\mu(1-\epsilon_\mu) & F_\mu\epsilon'_\mu \\ F_\tau(1+\epsilon_\tau) & iF_\tau(1-\epsilon_\tau) & F_\tau\epsilon'_\tau \end{pmatrix}, \quad M_M = \begin{pmatrix} \bar{M}(1-\mu) & 0 & 0 \\ 0 & \bar{M}(1+\mu) & 0 \\ 0 & 0 & M' \end{pmatrix}$$

Neutrino-Yukawa couplings

Heavy Neutrino mass matrix

Model realisations:

- Inverse seesaw type $\varepsilon, \varepsilon' \ll \mu \ll 1$ Mohapatra 1986; Mohapatra/Valle 1986
- Linear seesaw type c $\mu \ll \varepsilon, \varepsilon' \ll 1$ Akhmedov/Lindner/Schnapka/Valle 1995
- νMSM type $\varepsilon, \varepsilon', \mu \ll 1$ Asaka/Shaposhnikov 2005/06; Kersten/Smirnov, 2007
- "Mass communist" type $\mu \ll 1\,,\ M' \longrightarrow M$

Constraints on "complete" neutrino models

Mixing of light ("flavored") and heavy ("sterile") neutrinos

$$\nu_{L\ell} = \sum_{k=1}^{3} U_{\ell k}\nu_k + \sum_{k'=4}^{n_R+3} V_{\ell k'} N_{k'}.$$

$$\Delta\mathcal{L} = -\frac{g_W}{\sqrt{2}} W_\mu^+ \sum_{k=1}^{3}\sum_{\ell}^{\tau} \left[\overline{\nu}_k U_{\ell k}^* \gamma^\mu P_L \ell\right] - \frac{g_W}{\sqrt{2}} W_\mu^+ \sum_{k'=4}^{n_R+3}\sum_{\ell}^{\tau} \left[\overline{N}_{k'} V_{\ell k'}^* \gamma^\mu P_L \ell\right] + \text{H.c.}$$

Search for $0\nu\beta\beta$ decay (KAMLAND-Zen, 970 kg · yr)

$$T_{1/2}^{0\nu} > 2.3 \cdot 10^{26}\,\text{yr}$$

$$\left|\sum_{k'=4}^{n_R+3} \frac{V_{ek'}^2}{m'_k}\right| < (1.82 - 3.22) \cdot 10^{-6}\ \text{TeV}^{-1}$$

2203.02139

Direct searches at LHC, e.g. $pp \to \ell_i \ell_j \ell_k + E_T^{miss}$

1905.09798; 1911.04968; 2008.07949; 2305.14931; 2312.07484; 2407.10717

$$|V_{\ell N}|^2 \lesssim 2 \cdot 10^{-7} - 10^{-2} \text{ for } 1\,\text{GeV} < m_N < m_W$$
$$|V_{\ell N}|^2 \lesssim 2 \cdot 10^{-2} - 1 \quad \text{for } m_W < m_N < 1.2\,\text{TeV}$$

Indirect constraints from EWPO/global fits, e.g. $|V_{\mu N}|^2 < 4.41 \cdot 10^{-4}$ at 95% CL

Perturbativity bound on HNL total width $\Gamma_N^{tot} \lesssim 0.x \cdot M_N$

Direct constraints: absolute mass scale (KATRIN, β-decay kinematics) $m_{\nu_e} \lesssim 0.8$ eV, at $90\,\%$ C.L. 2105.08533

Constraints from cosmology (large scale structure, CMB) $\sum_m m_{\nu_m} \lesssim 0.12$ eV, at $95\,\%$ C.L. 1807.06209

Neutrino oscillation measurements of $U_{\ell k}$: fits to unitarity assumption of $U_{\ell k}$; when relaxed, more freedom e.g. 2004.13719

Searches for charged lepton number violation: $\mu \to e\gamma, \tau \to e\gamma, \tau \to \mu\gamma, \mu \to eee, \tau \to \{e,\mu\}^3$ 1605.05081, 0908.2381, 1001.3221

Bestiary of Heavy Neutrino lifetimes

- "Light"/"heavy" HNL decay width scales as $\Gamma_N \sim V_{\ell N}^2 M_N^5 G_F^2, \quad V_{\ell N}^2 M_N^3 G_F$
- Decay length in lab frame: $\lambda_N = \frac{\beta\gamma}{\Gamma_N} \sim \frac{|\vec{p}\,|}{V_{\ell N}^2 M_N^6 G_F^2}$
- 3 regimes: prompt decays, displaced vertices, long-lived
- Neutrino widths: $\Gamma_N \gtrsim \mathcal{O}(1\,\text{keV})$ prompt decays only,

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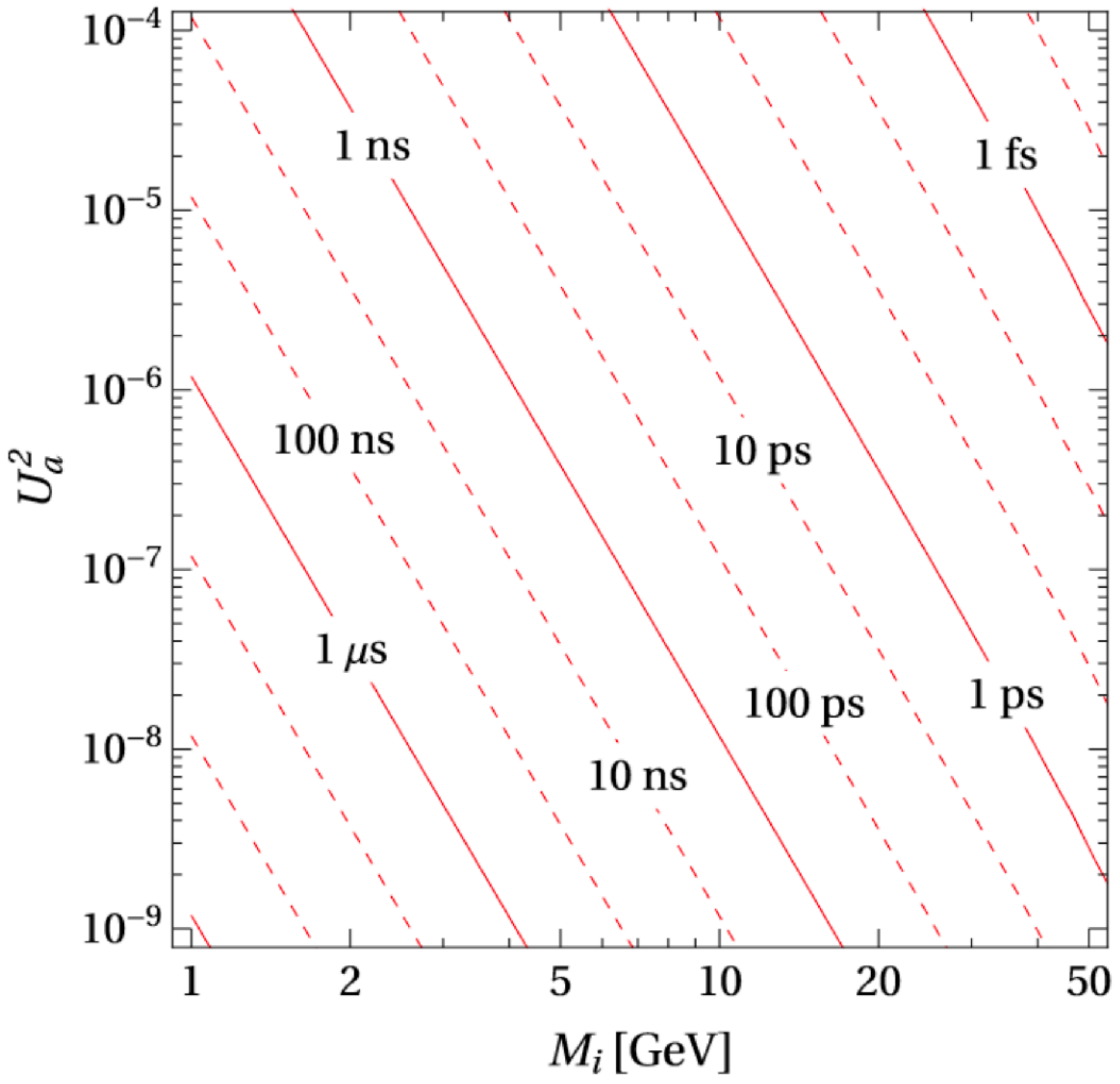

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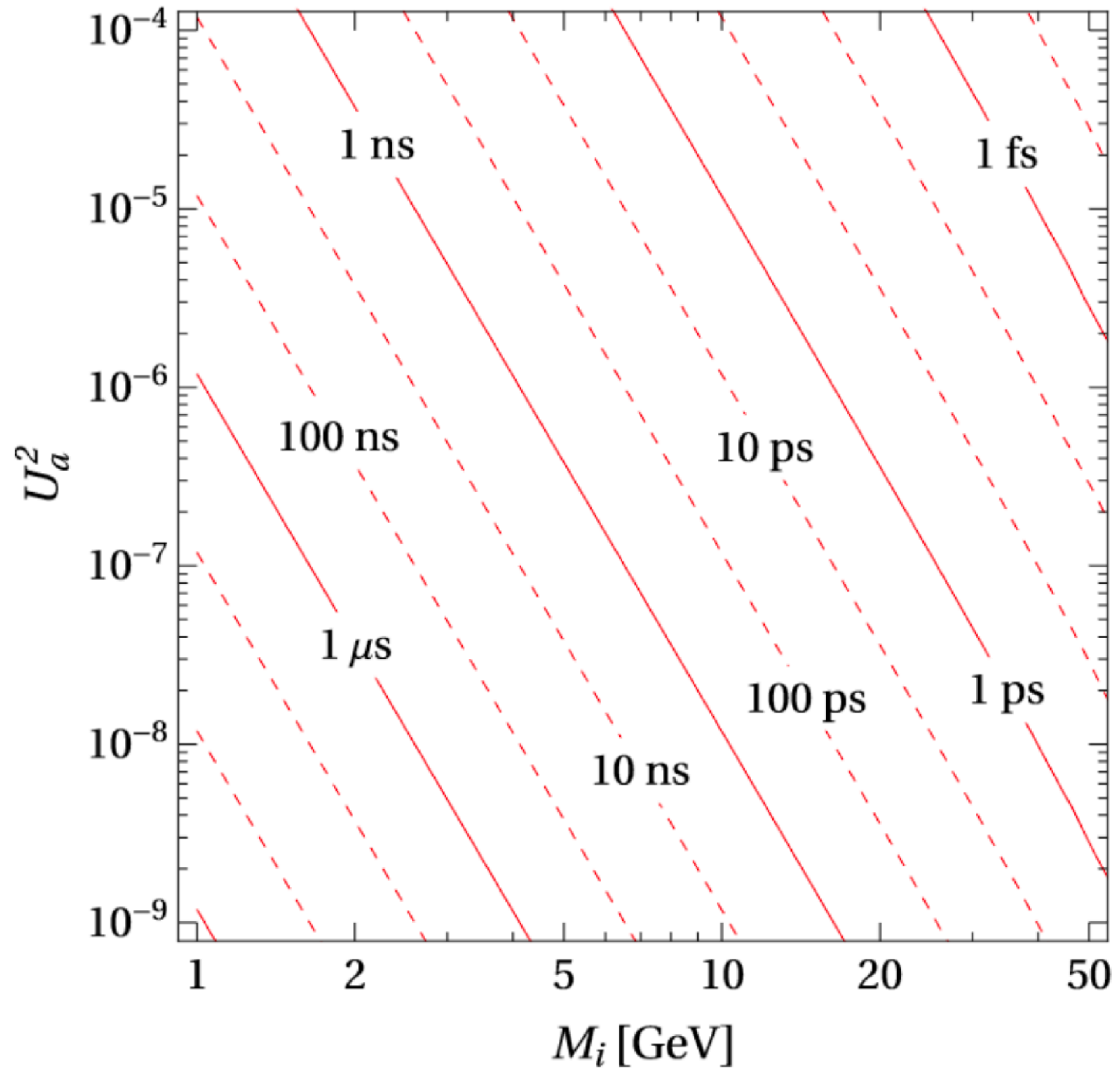

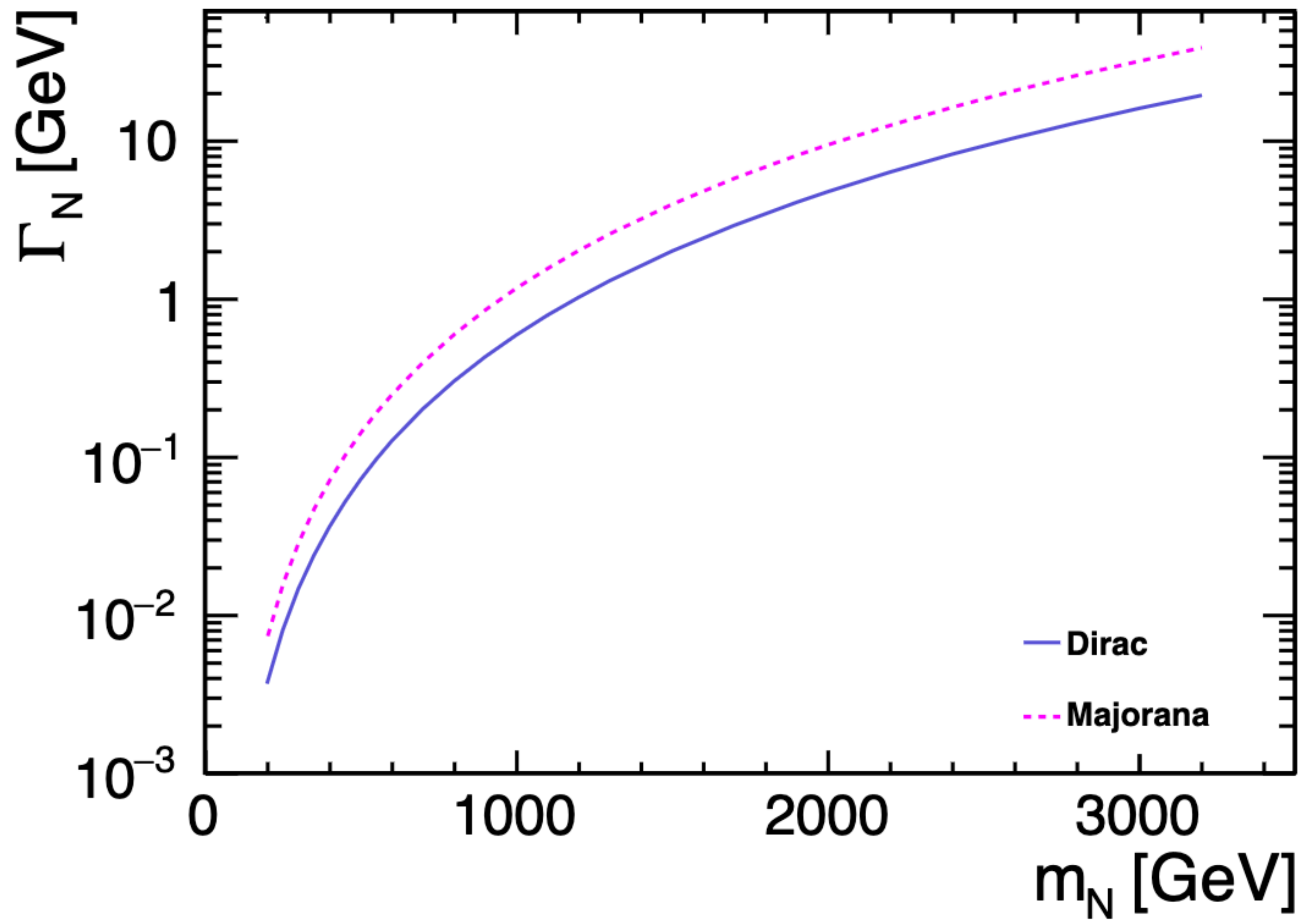

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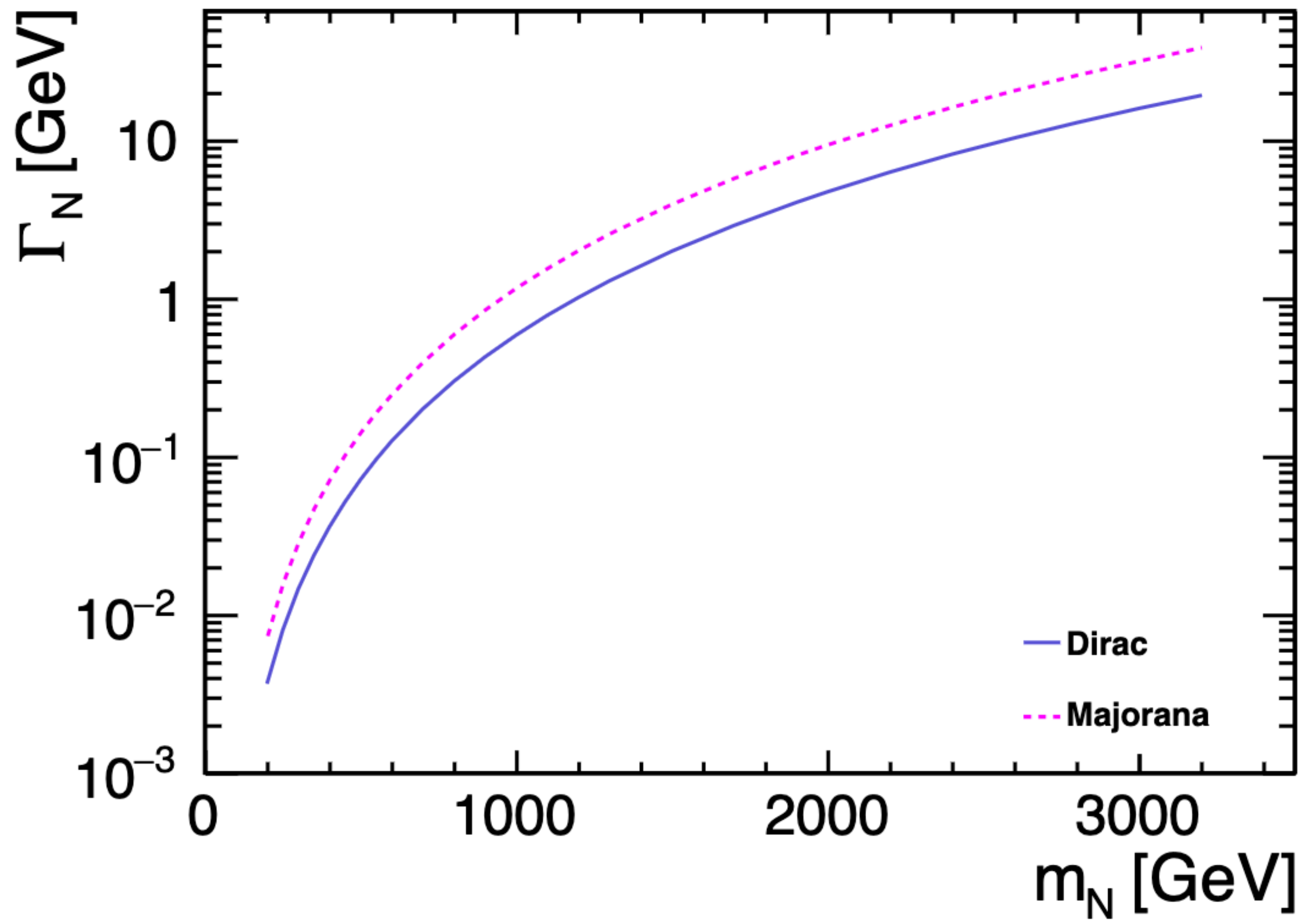
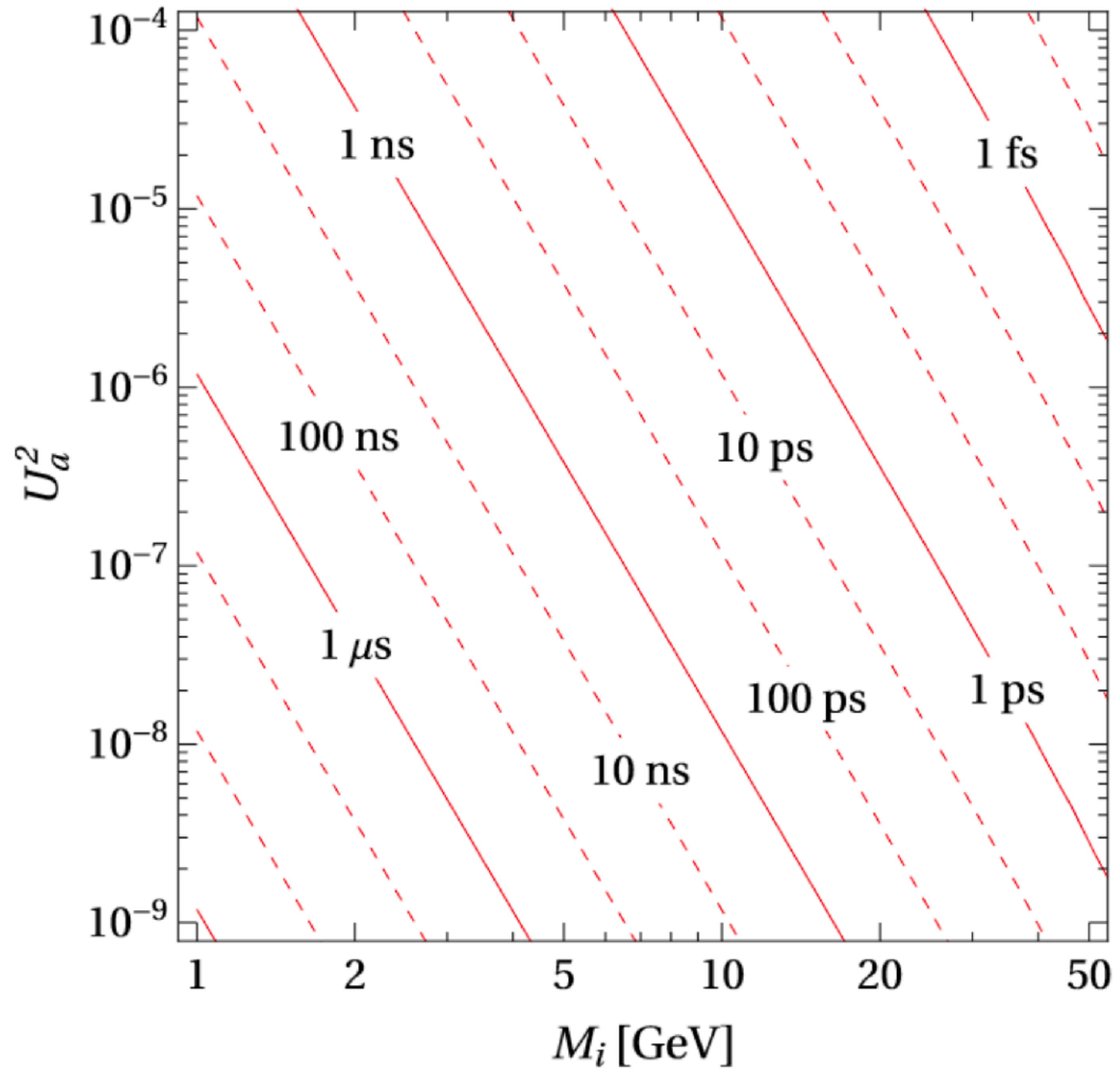
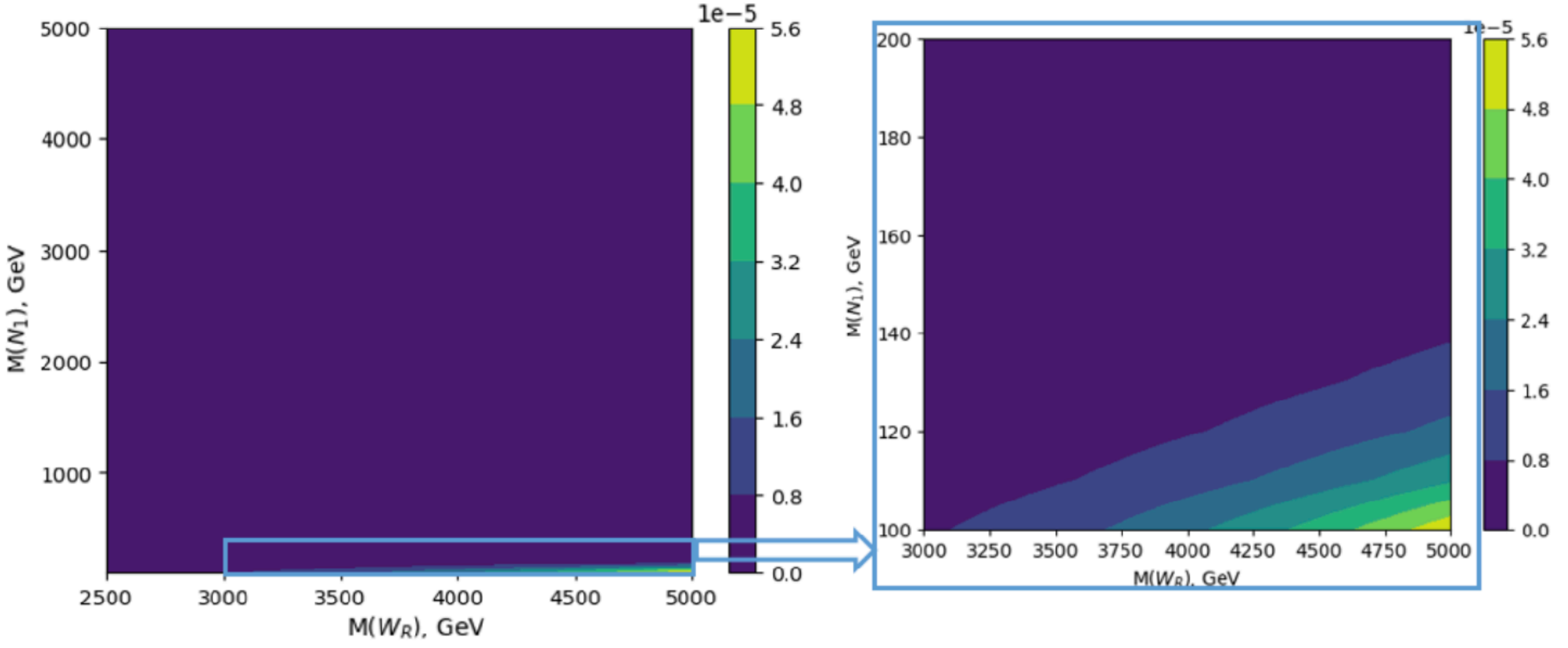
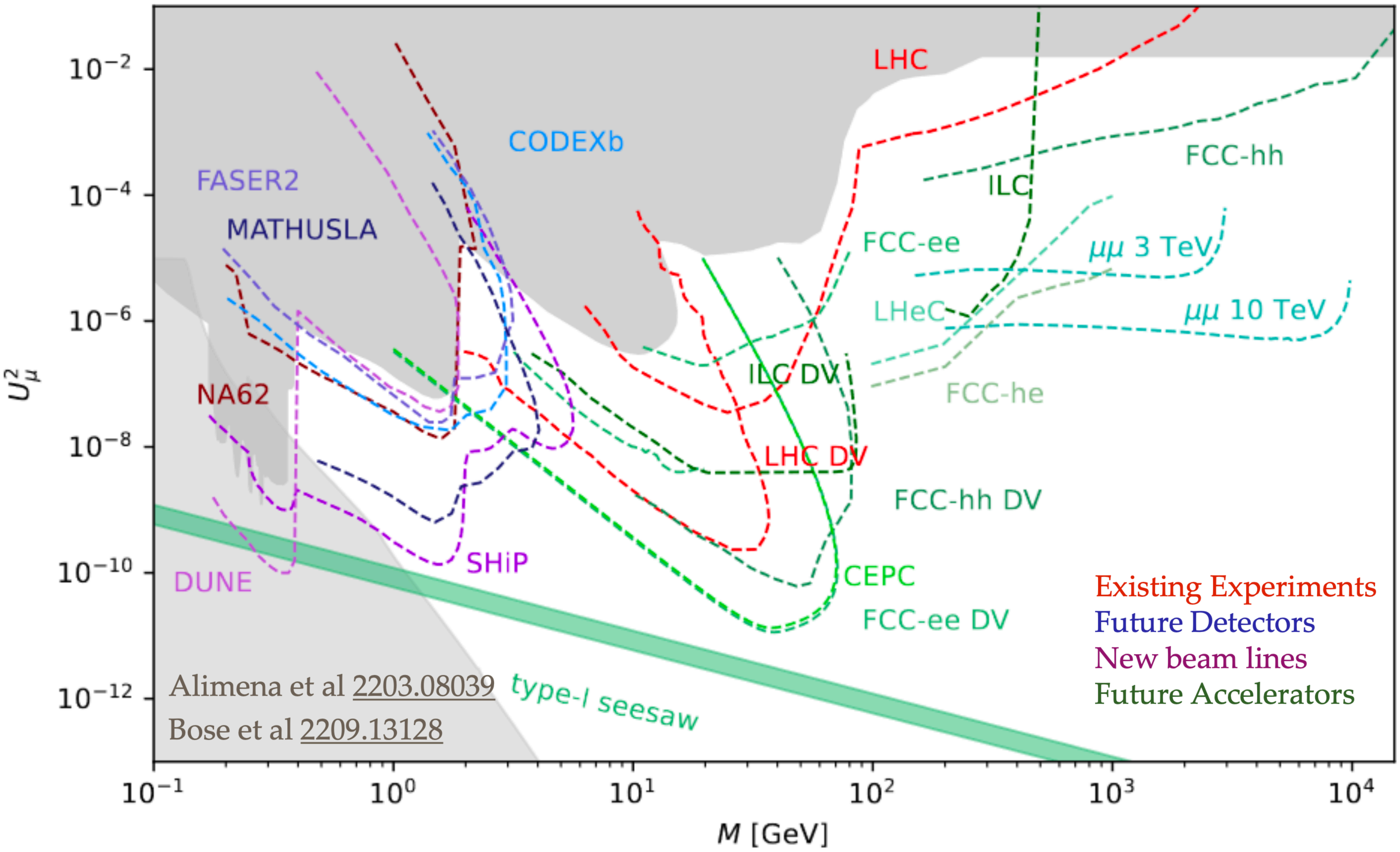






Searches for Heavy Neutral Leptons



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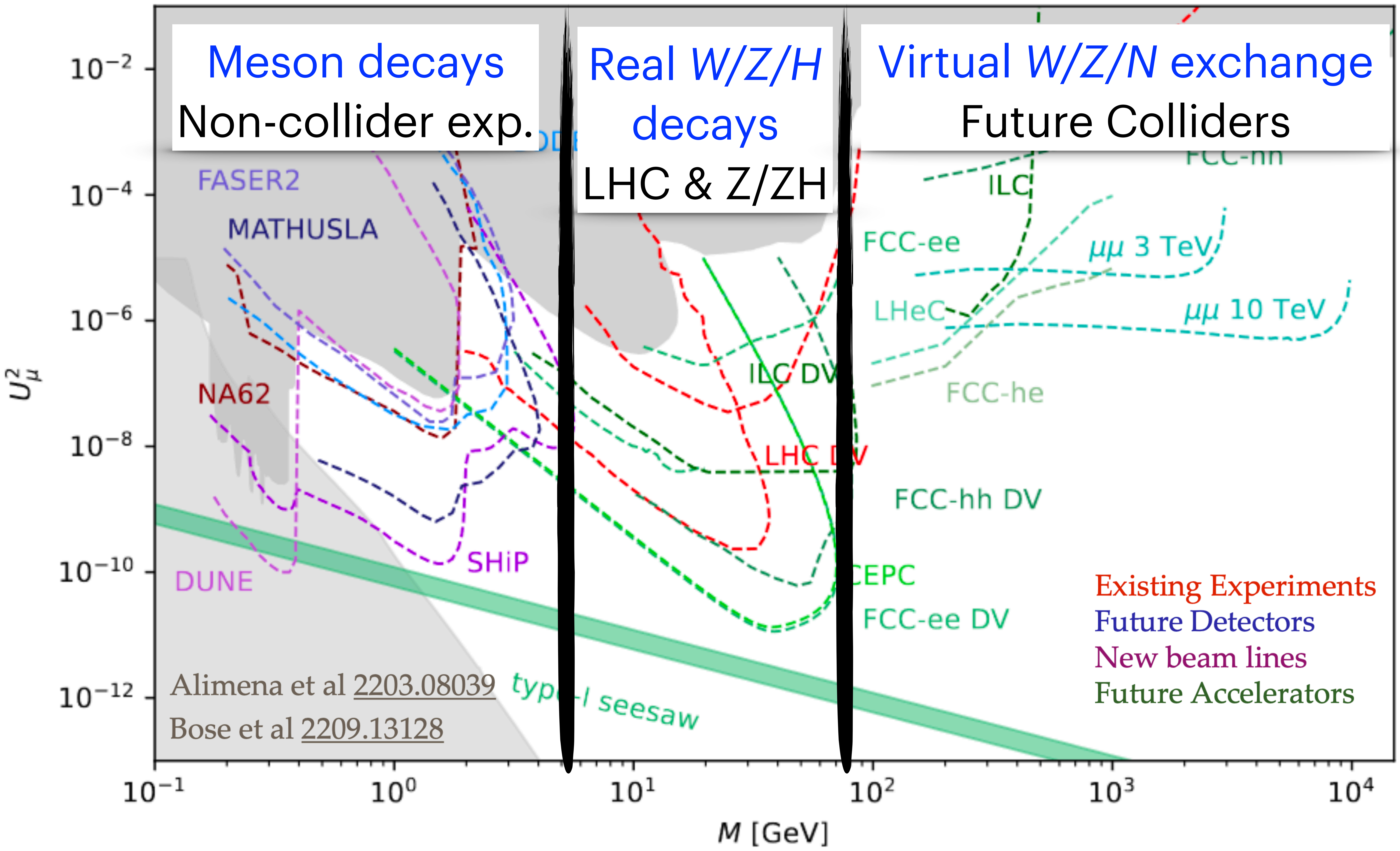

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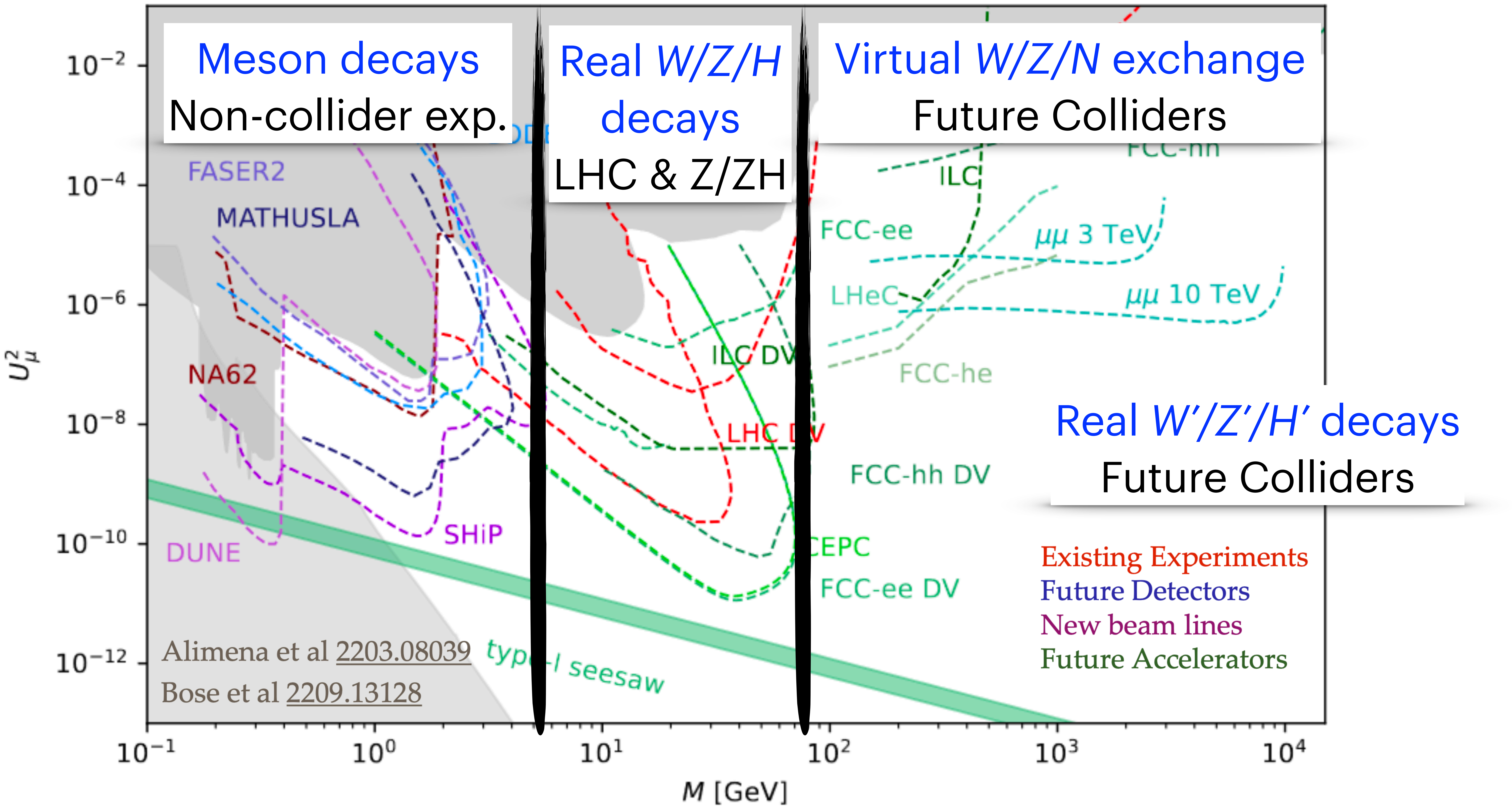

Simplified neutrino model (HNL model)

- Simplified model with right-handed (νSM) and sterile neutrinos
- After EWSB heavy (sterile) neutrinos do mix with νSM neutrinos
- Lagrangian: $\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_N + \mathcal{L}_{WN\ell} + \mathcal{L}_{ZN\nu} + \mathcal{L}_{HN\nu}$

$$\mathcal{L}_N = \xi_\nu \cdot \left(\bar{N}_k i\partial\!\!\!/ N_k - m_{N_k}\bar{N}_k N_k\right) \qquad \text{for } k = 1,\, 2,\, 3$$

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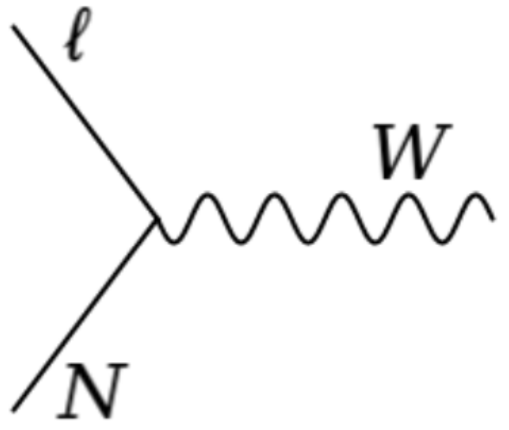

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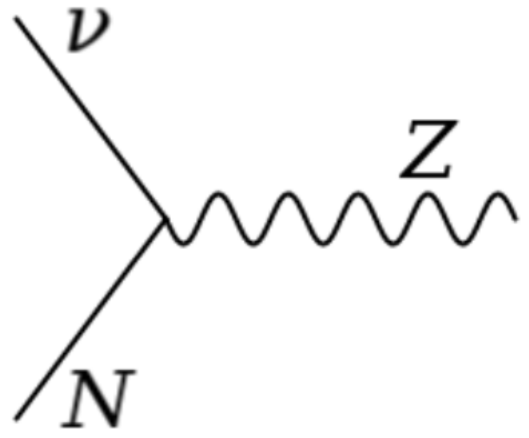

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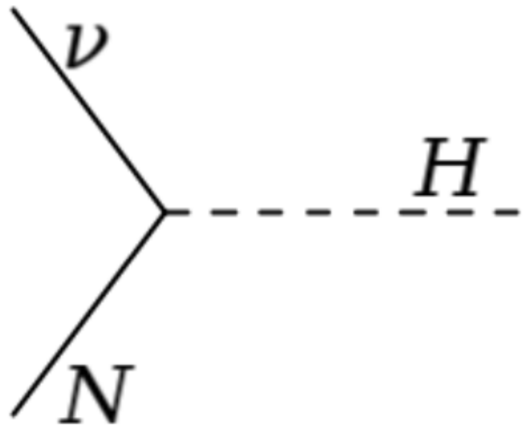

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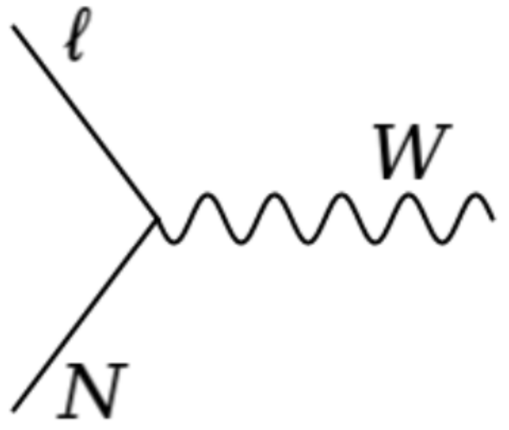

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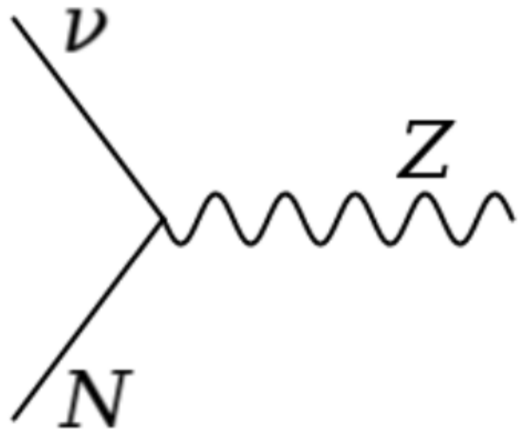

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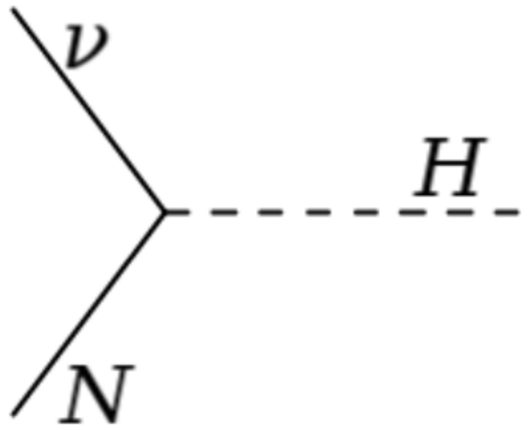

Incomplete literature:

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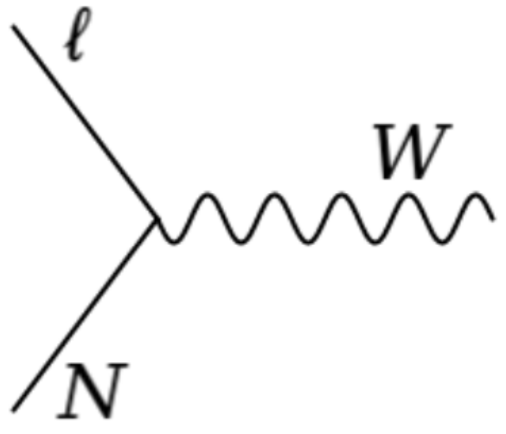

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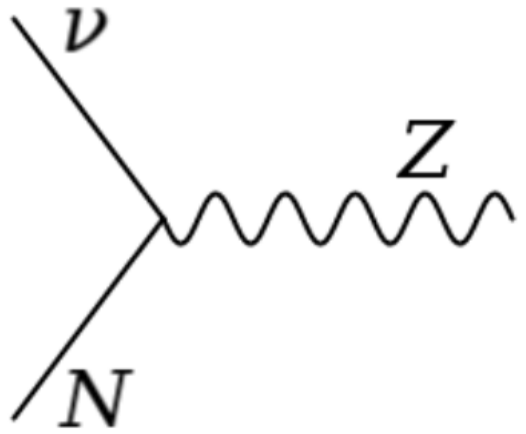

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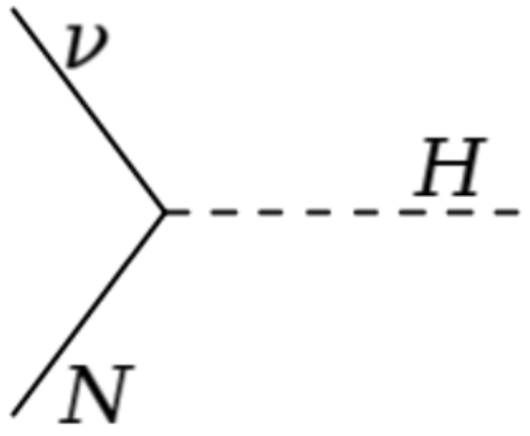

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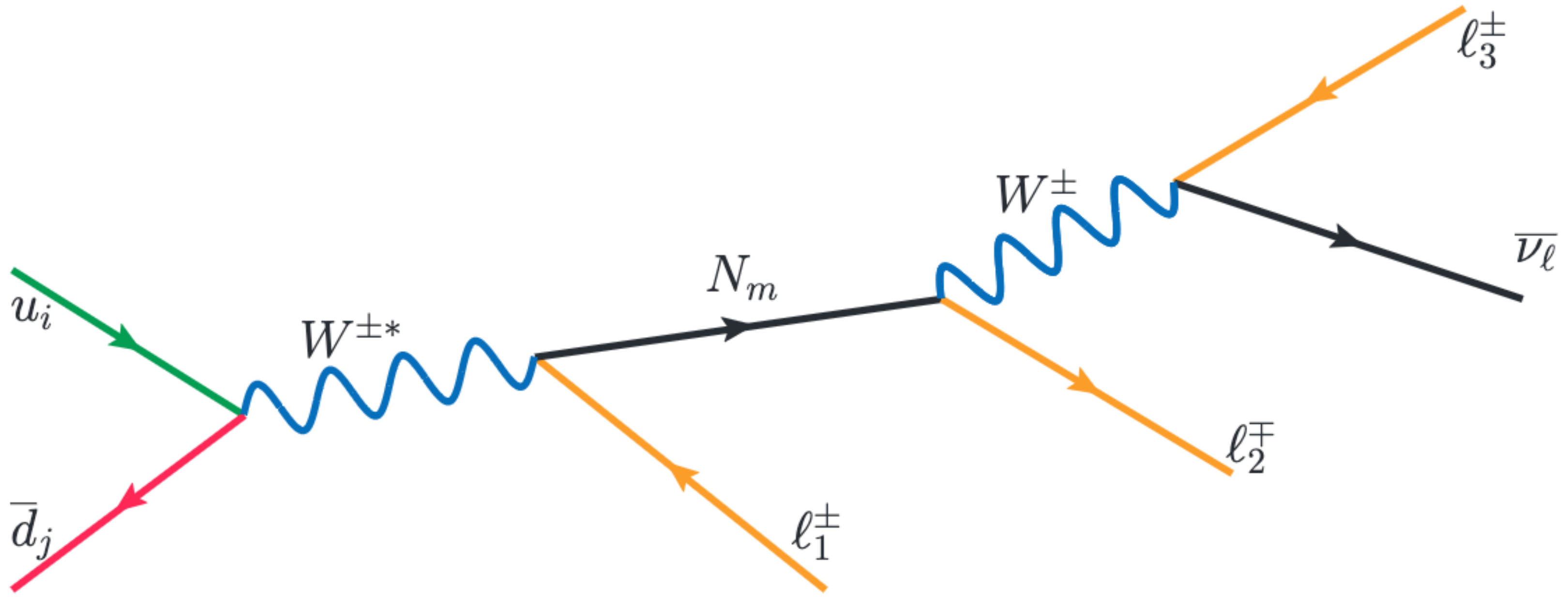
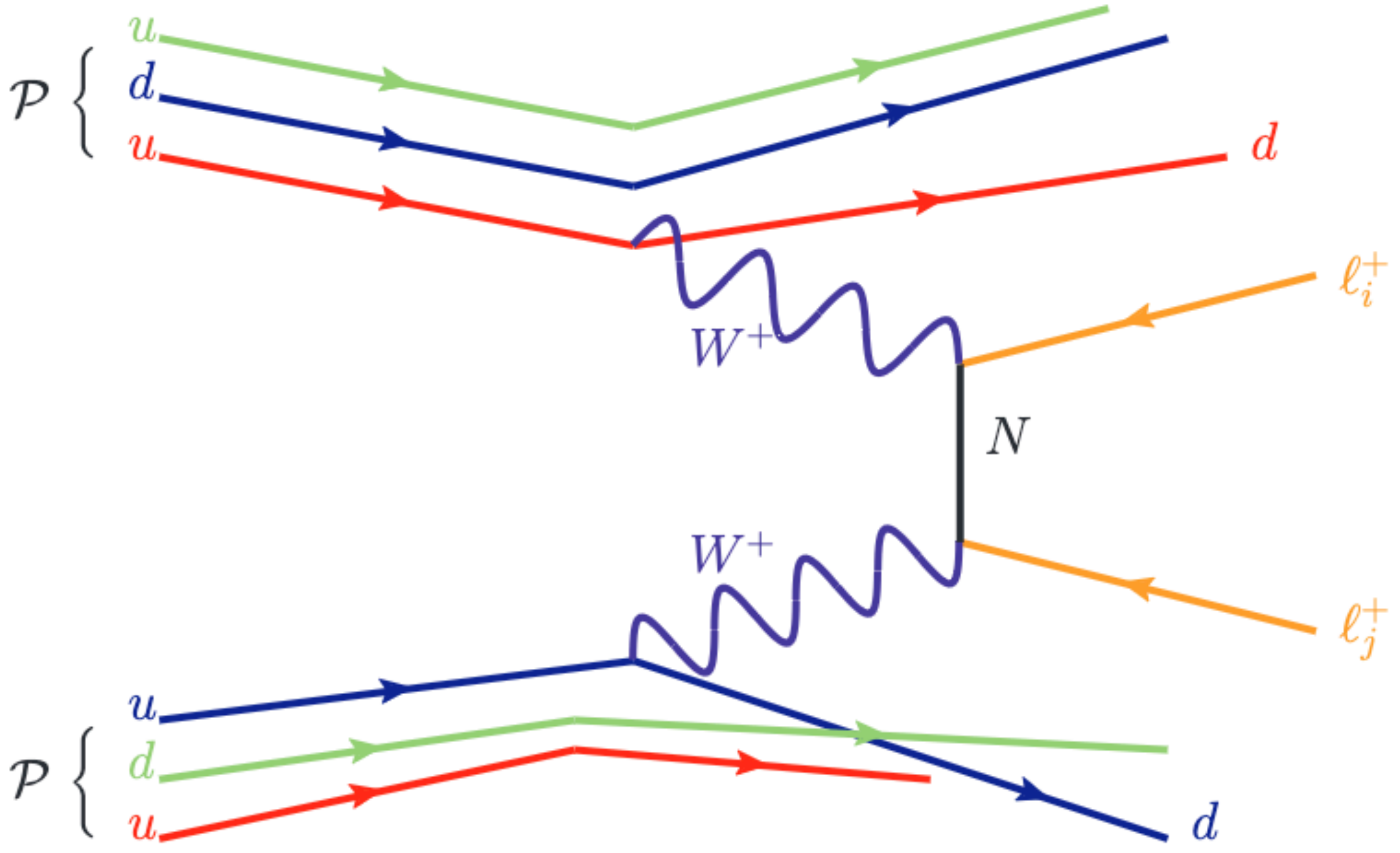
- ☑ Single Heavy-N model:
  5 parameters $(V_{N,e/\mu/\tau}, M_N, R_{LNV}/R_{LNV})$
- ☑ General Heavy-N model:
  3 neutrino masses: $M_{N_1}, M_{N_2}, M_{N_3}$
- ☑ Nine real mixing parameters:
  $V_{\ell k},\ \ell = e, \mu\, \tau, k = N_1, N_2, N_3$
- ☑ Possibly independent, 3 neutrino widths: $\Gamma_{N_1}, \Gamma_{N_2}, \Gamma_{N_3}$
- ☑ Majorana vs. Dirac particle: $\xi_\nu = \dfrac{1}{2}$ vs. $\xi_\nu = 1$
- ☑ UFO model HeavyN

Same-sign LNV searches at LHC

from arXiv:2011.02547





- Single production quadratic in mixing angle:

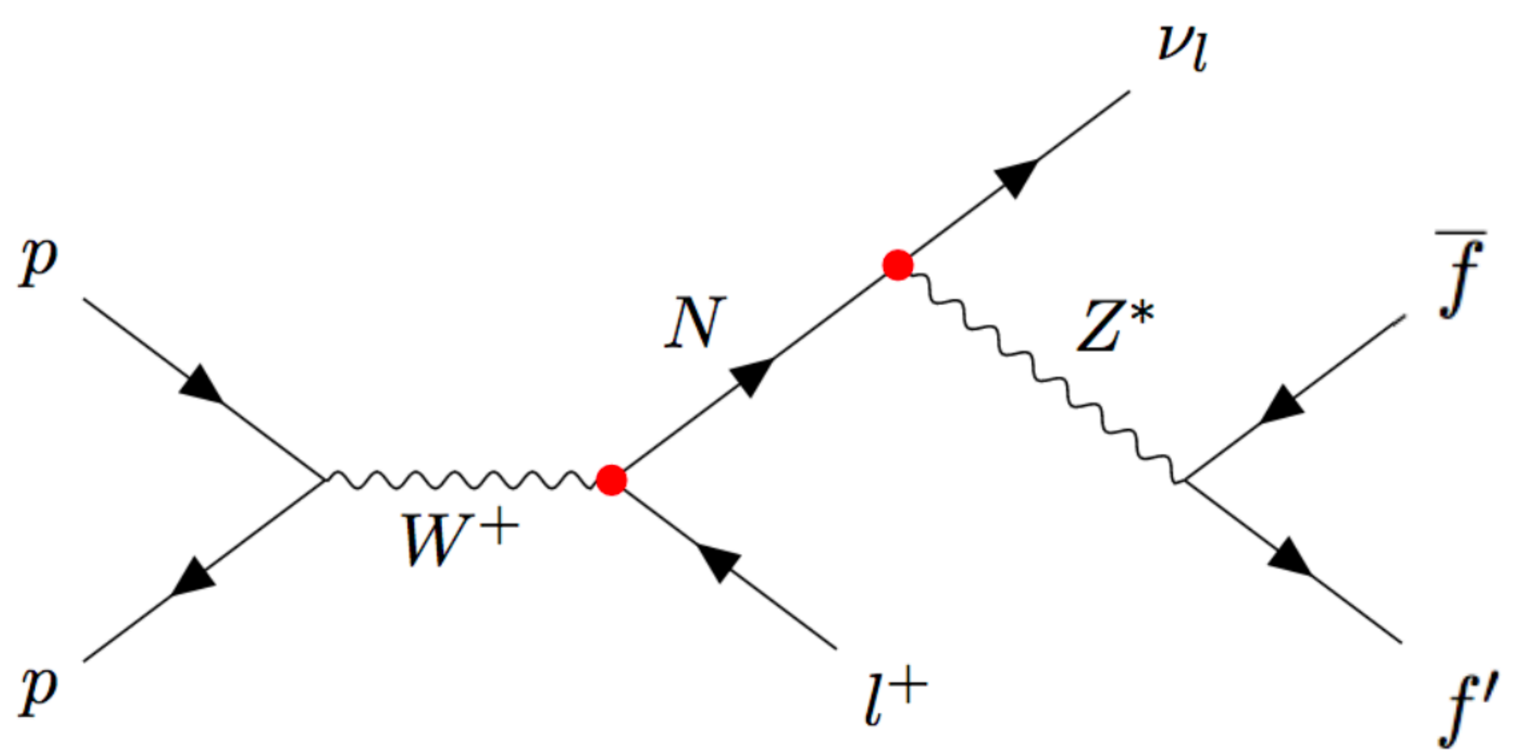
$$\sigma(pp \to N\ell^{\pm} + X) \equiv |V_{\ell N}|^2 \times \sigma_0(pp \to N\ell^{\pm} + X).$$

- Pair production/*t*-channel exchange quartic in mixing angle:

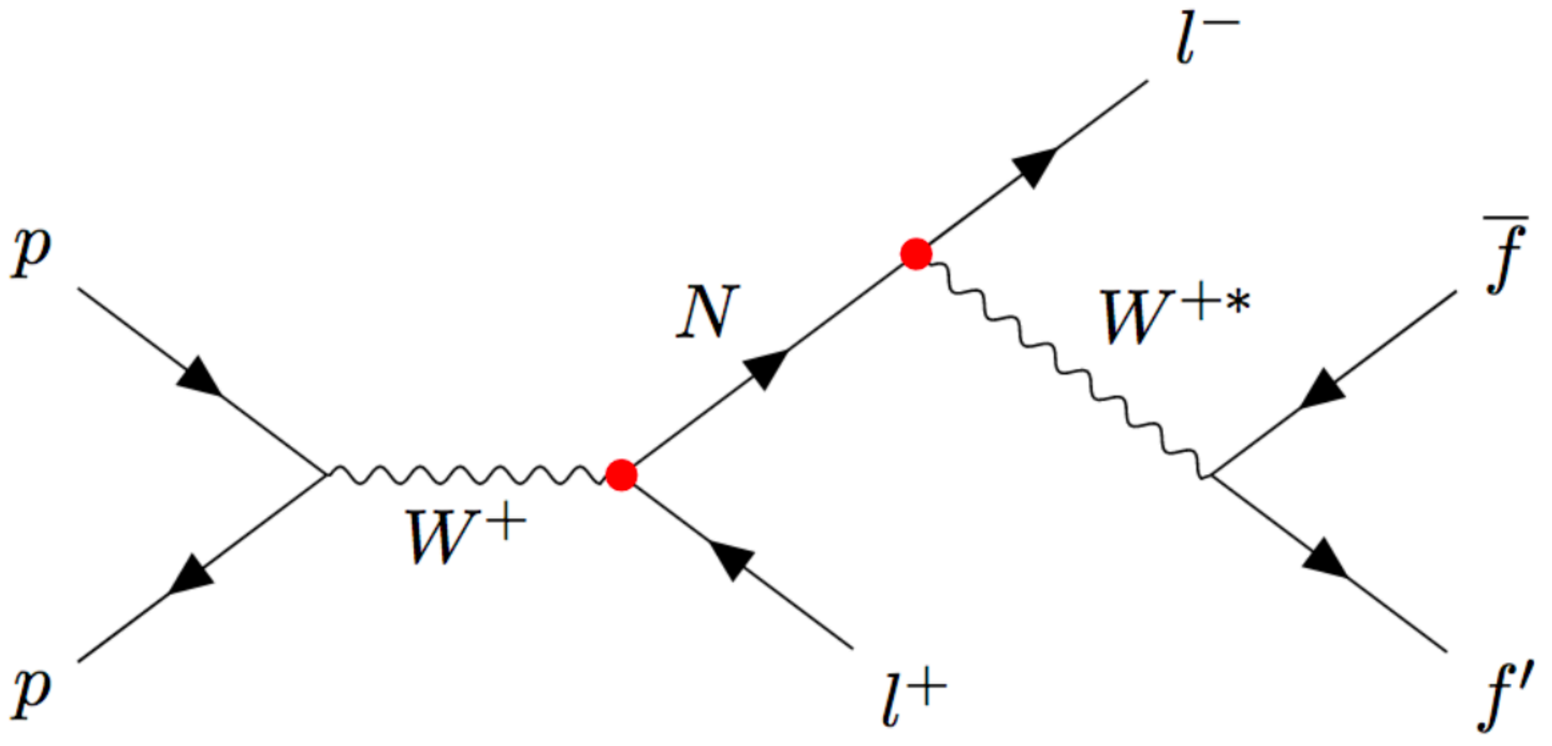
$$\sigma(pp \to \ell_i^{\pm}\ell_j^{\pm} + X) \equiv |V_{\ell_i N} V_{\ell_j N}|^2 \times \sigma_0(pp \to \ell_i^{\pm}\ell_j^{\pm} + X).$$

- Gigantically smaller background for LNV pair production process
- Two cases of hadron collider superiority: rate at *W,Z* decays, same-sign processes
- Might be motivation for e^-e^- running (or μTRISTAN, $\mu^+e^+, \mu^+\mu^+$)

Displaced vertex searches at (HL-)LHC



Neutral current decay



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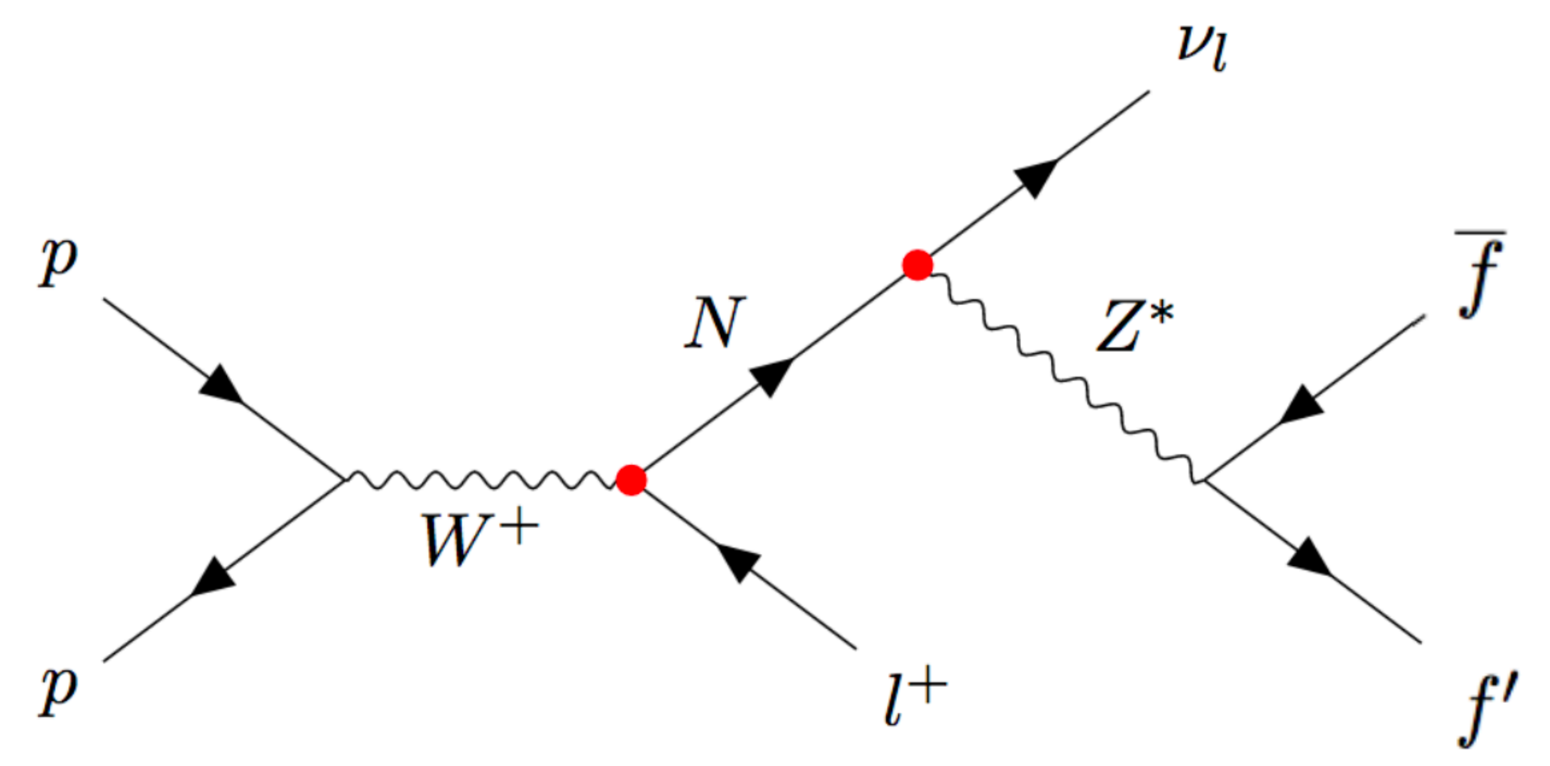

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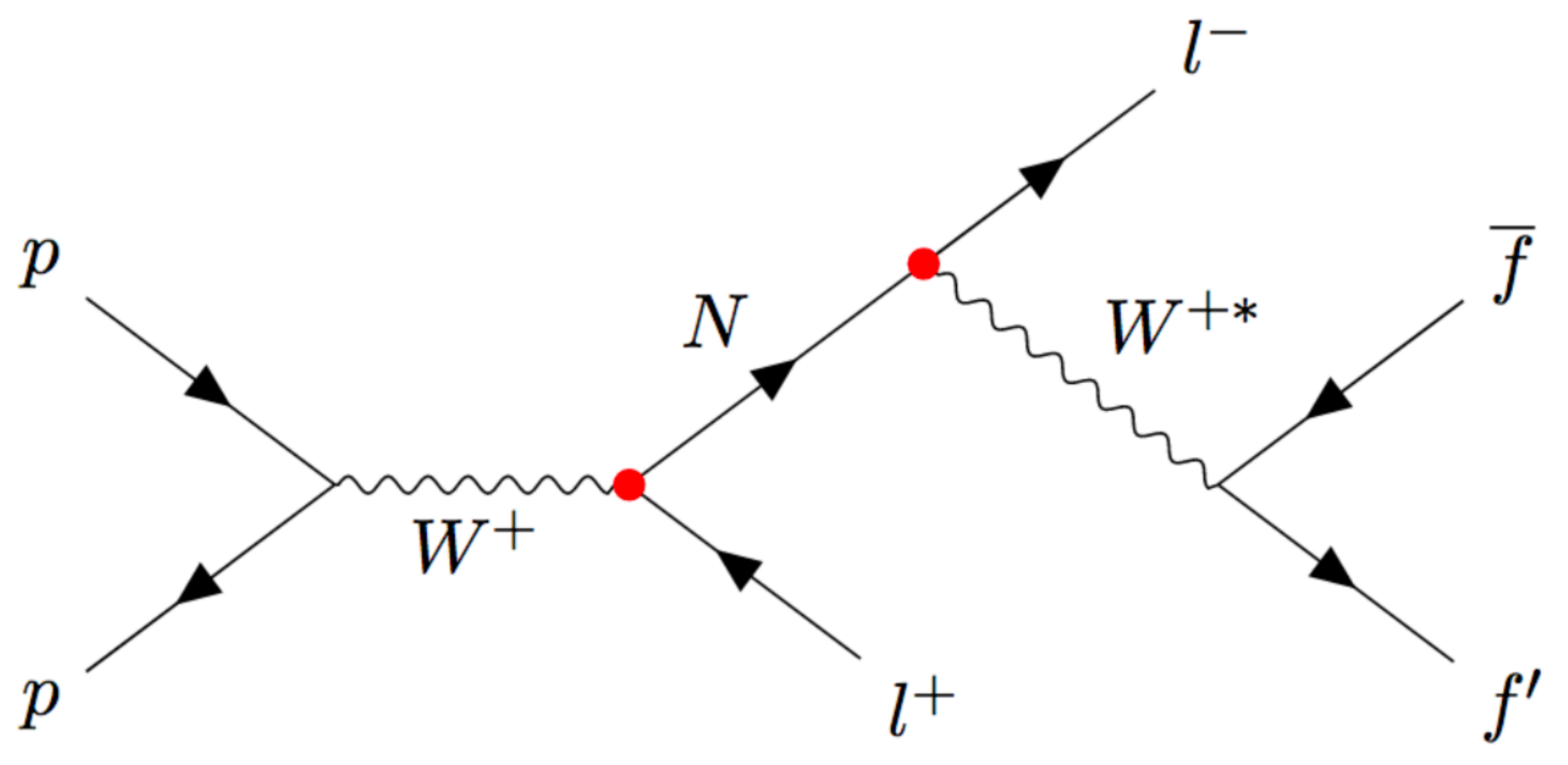

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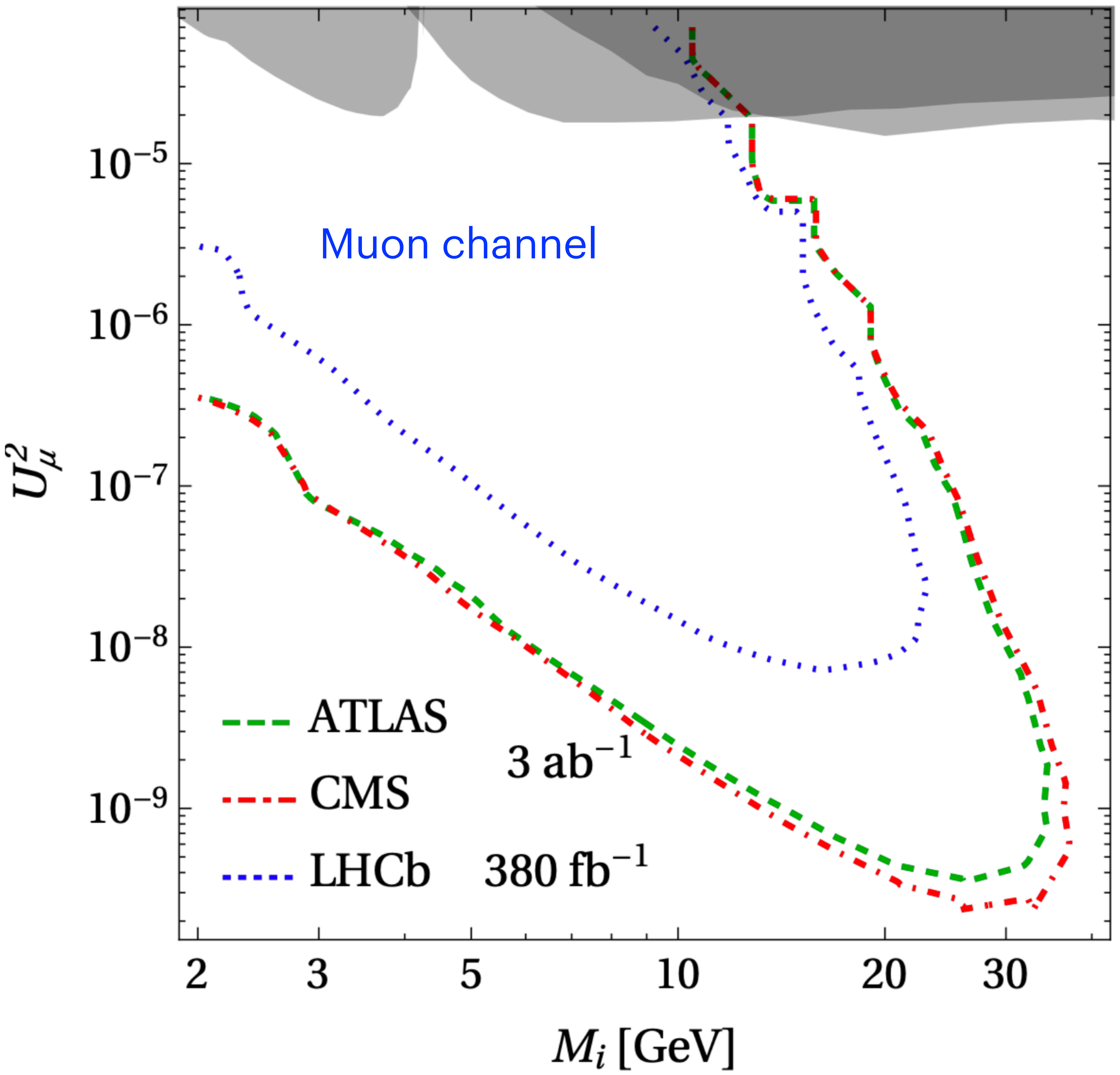

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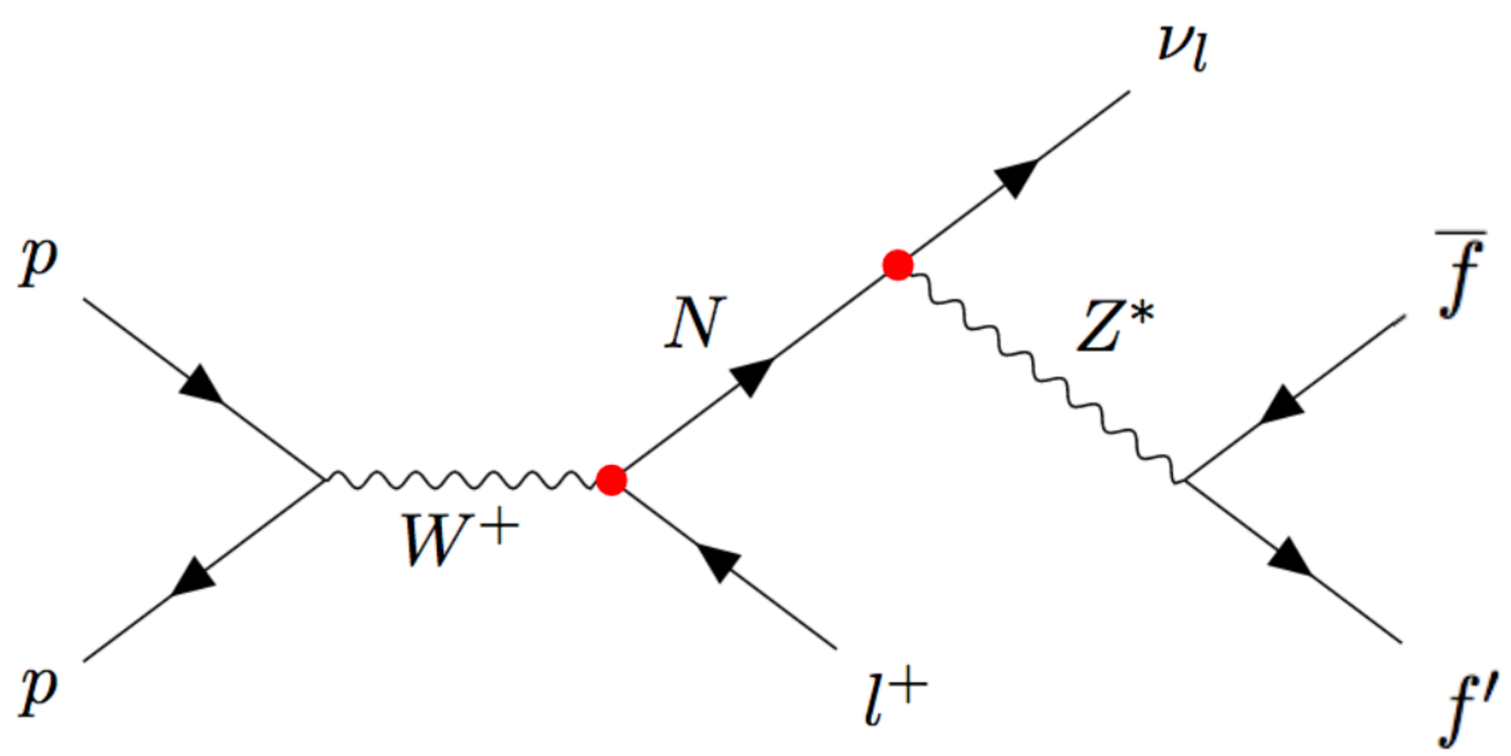
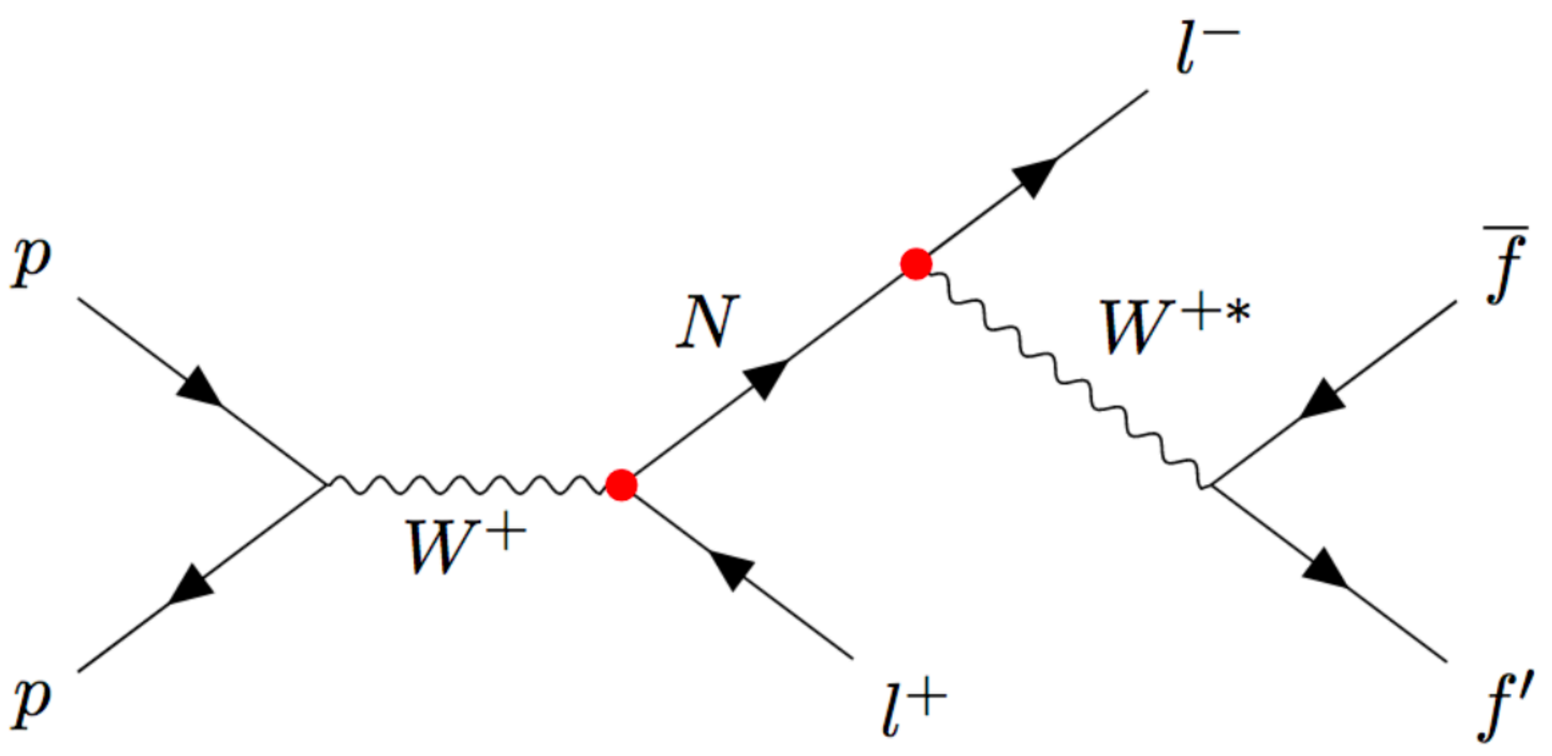
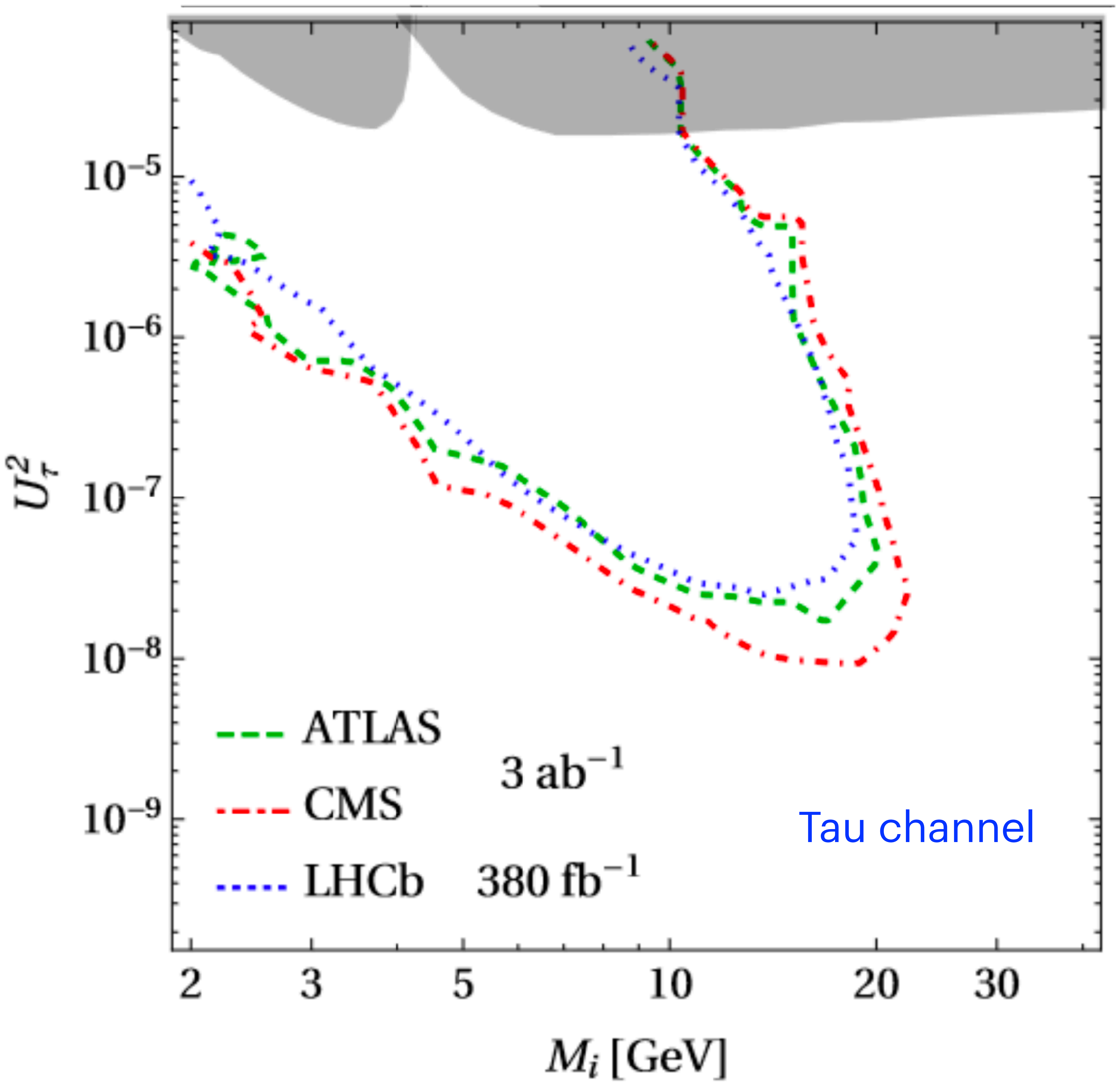


Neutral current decay



Charged current decay



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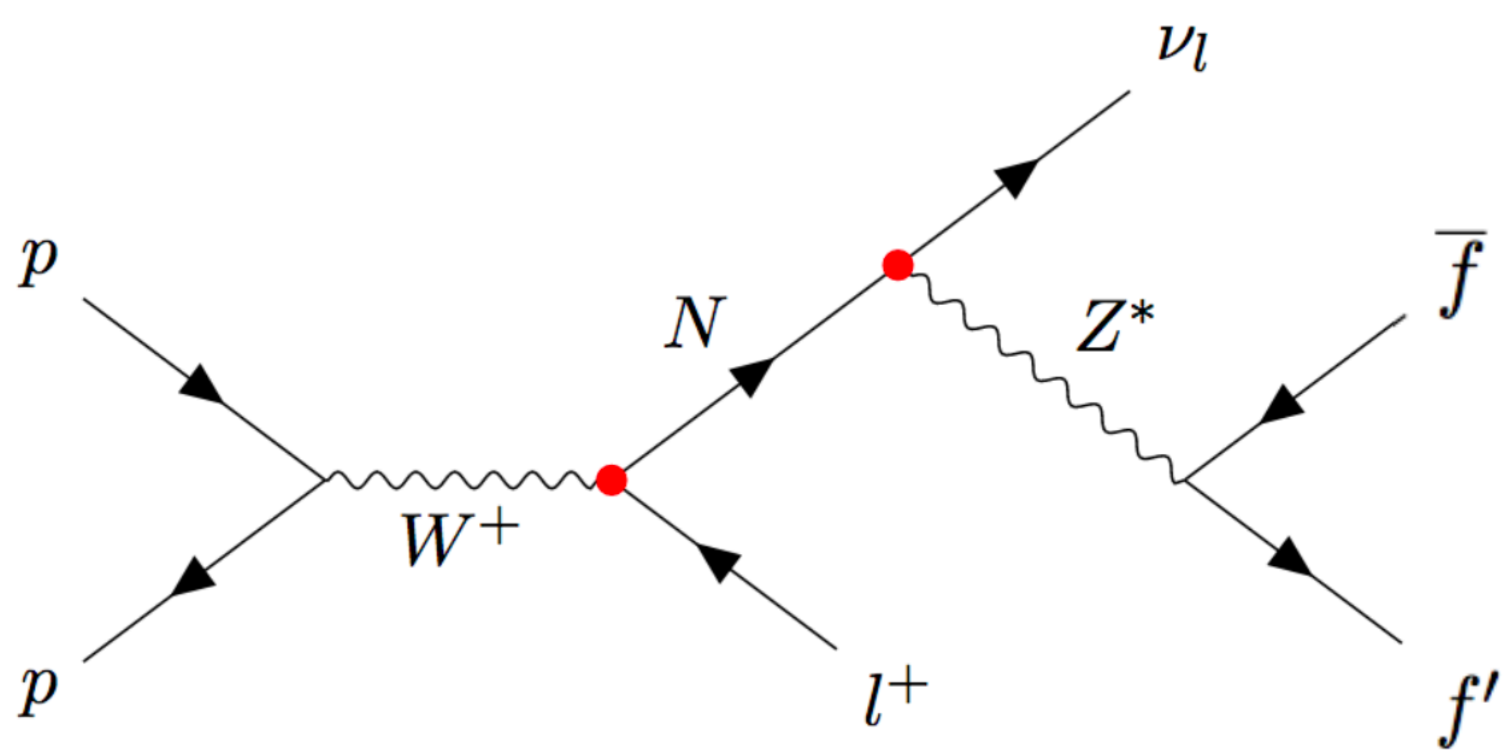

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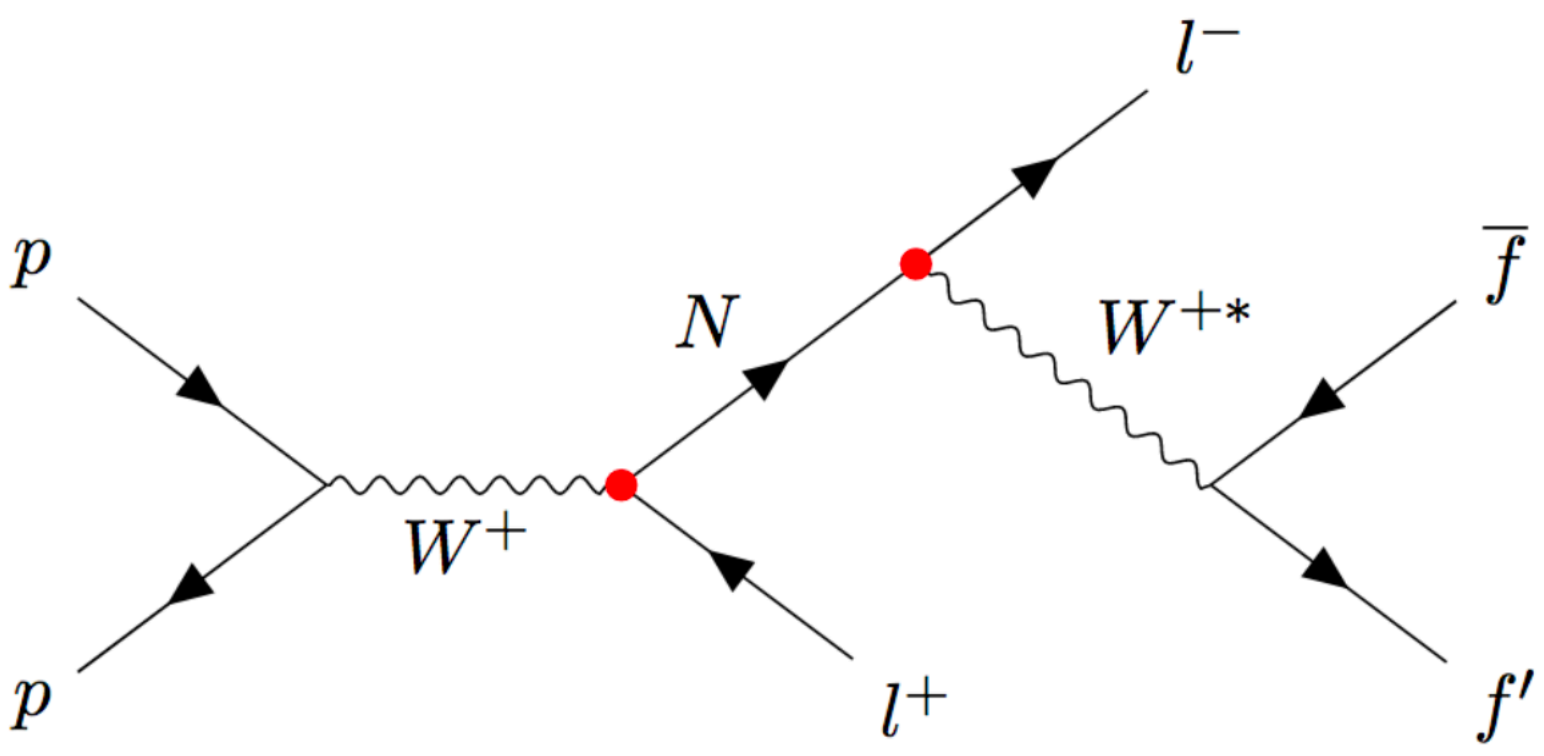
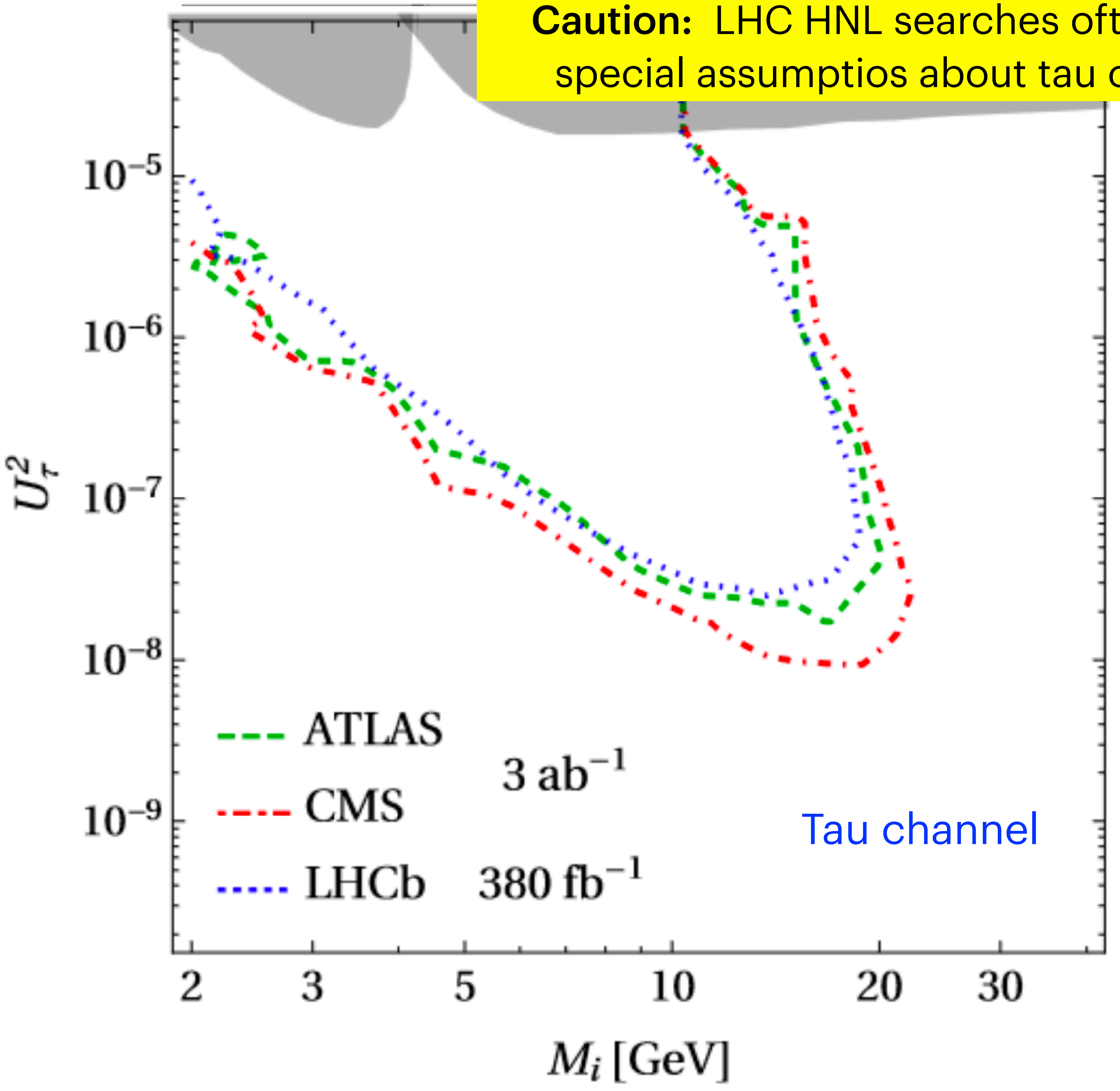
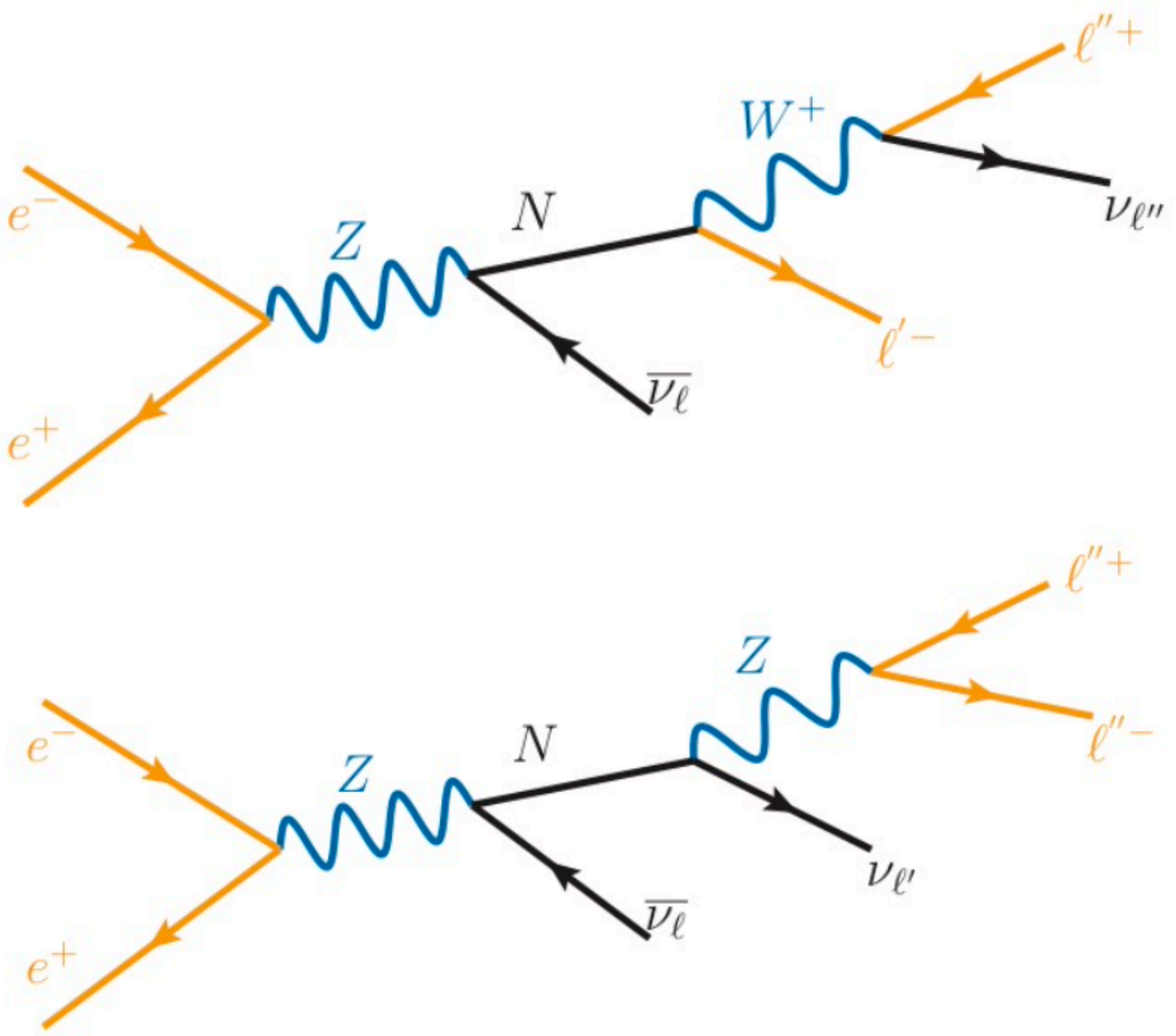


Charged current decay

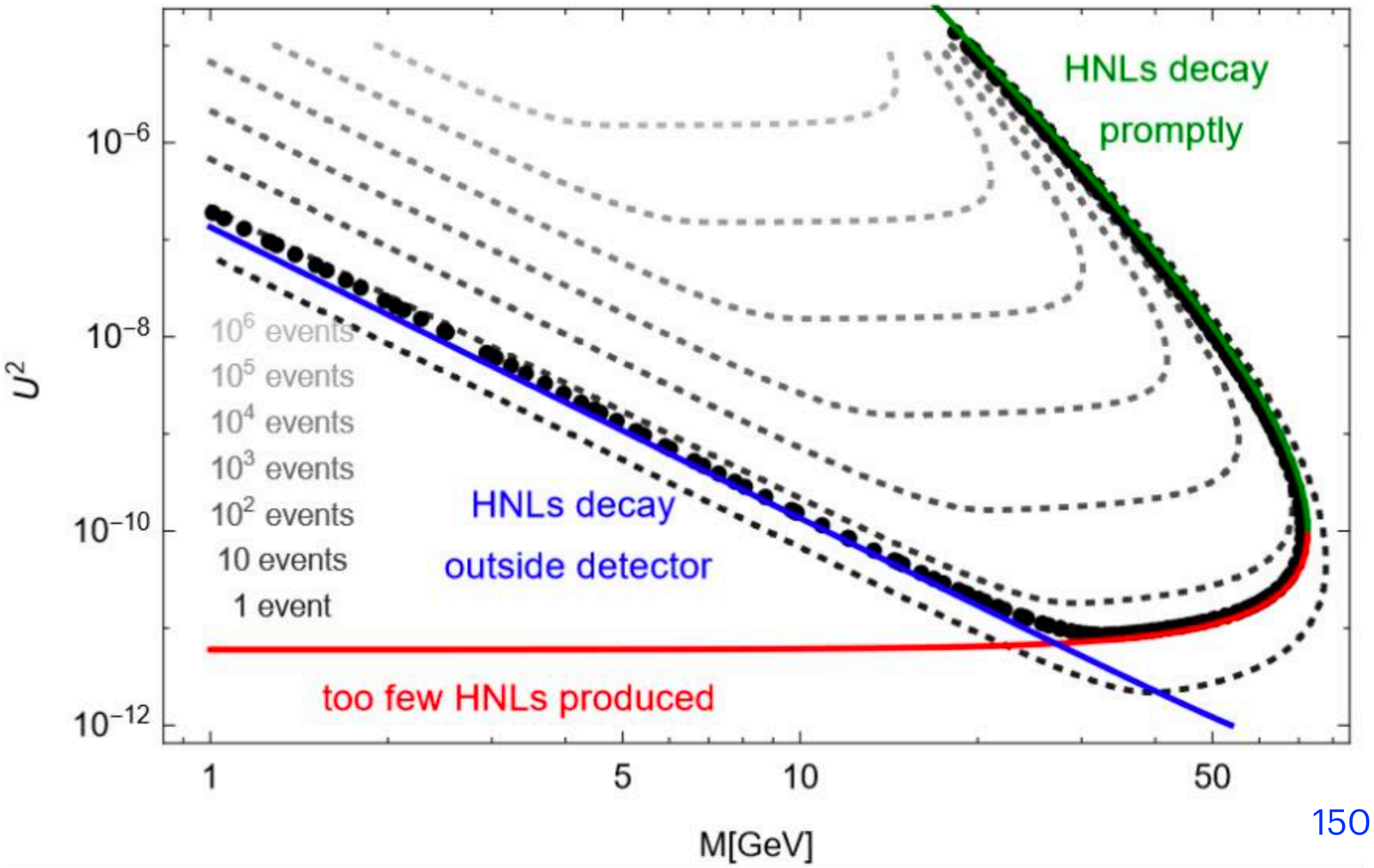
Caution: LHC HNL searches often make special assumptios about tau channel



"Light HNL:" Displaced vertex searches at the Z pole



$$\Delta\lambda_N = \frac{\beta\gamma}{\Gamma_N} \sim \frac{3.2\xi_\nu}{V_{\ell N}^2}\left(\frac{M_N}{\text{GeV}}\right)^6 \cdot \left[1 - \frac{M_N^2}{M_Z^2}\right] \ [\text{cm}]$$



150 ab^{-1}

Blondel et al., 1411.5230, 2203.05502

Drewes et al., 2210.17110

Signatures at e^+e^- colliders beyond the Z pole

- At lepton colliders, single production work much better than at LHC:
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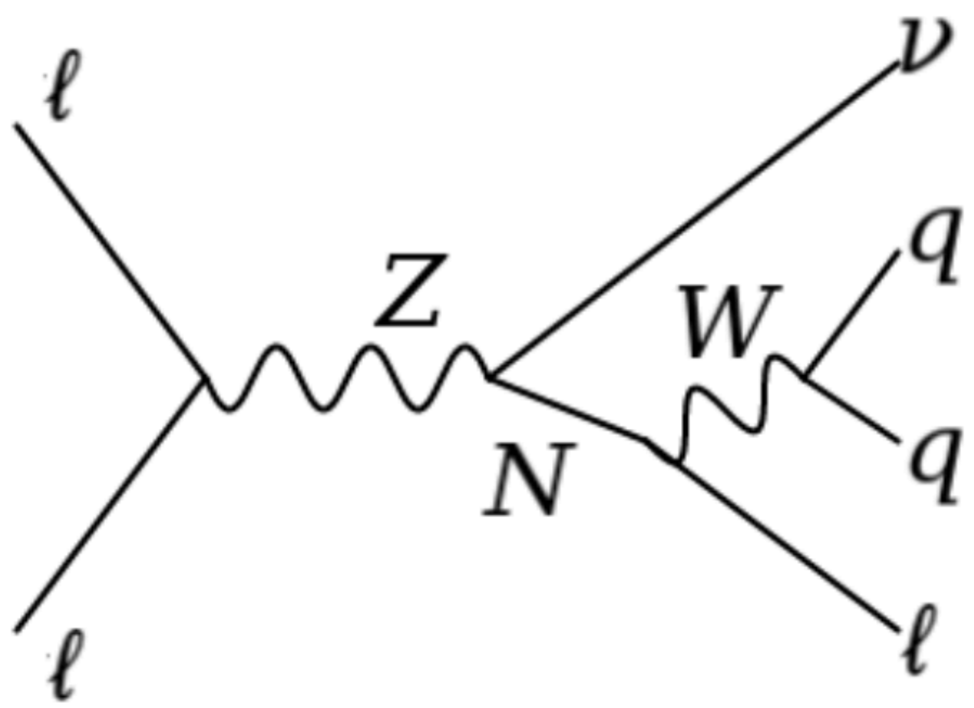

Equivalent to LHC (NC/CC) Drell-Yan production: for heavy HNL propagator-suppressed

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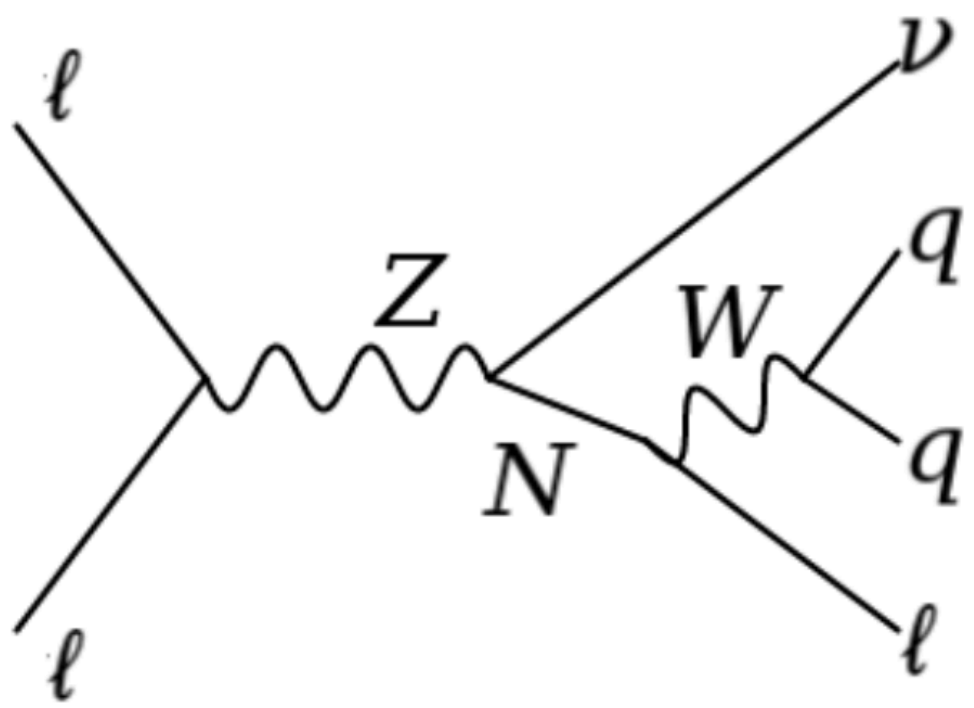

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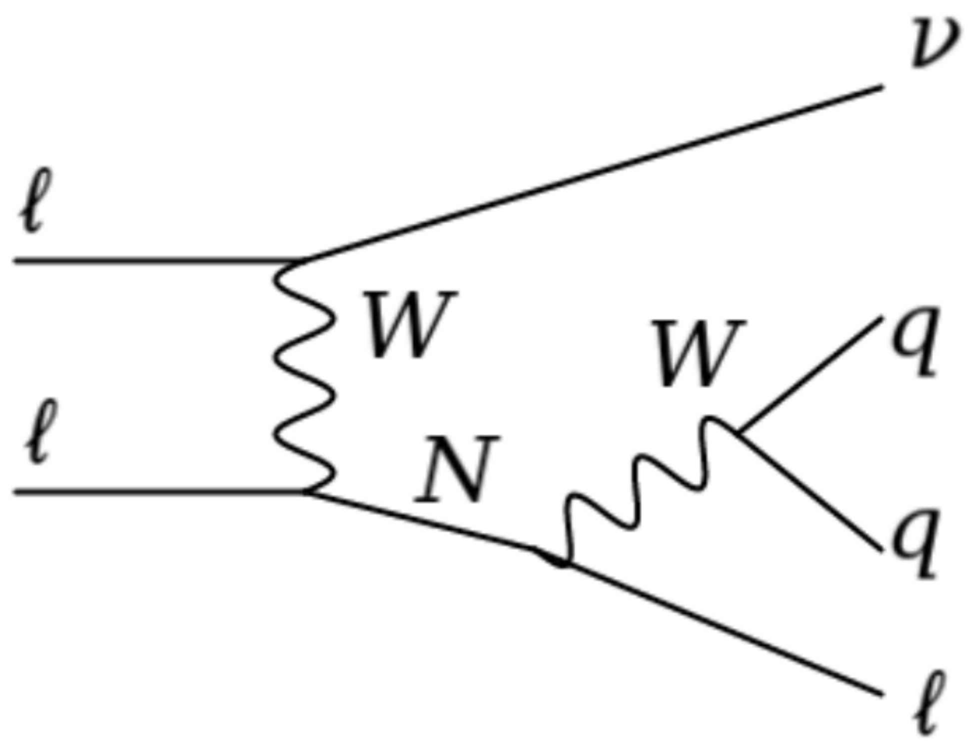

absent at LHC!
By far dominant process
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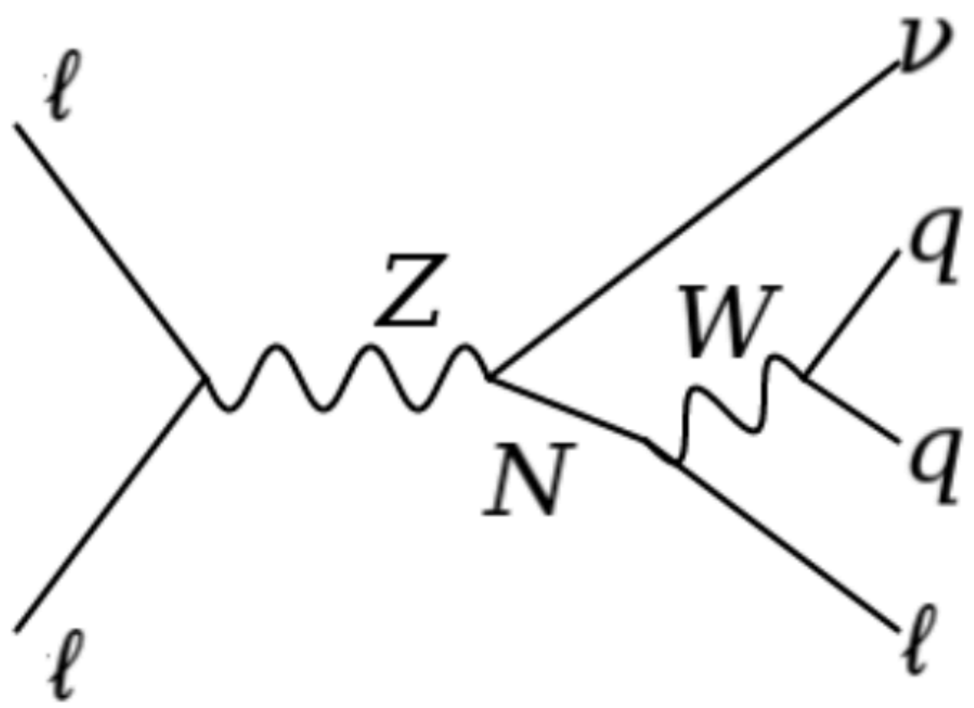

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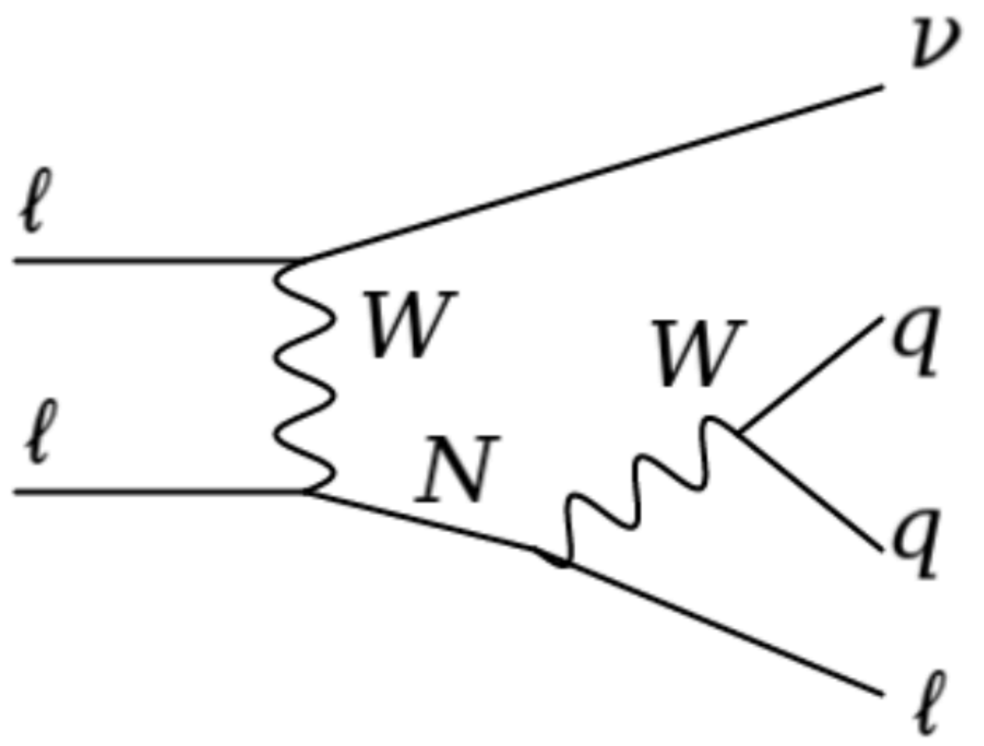

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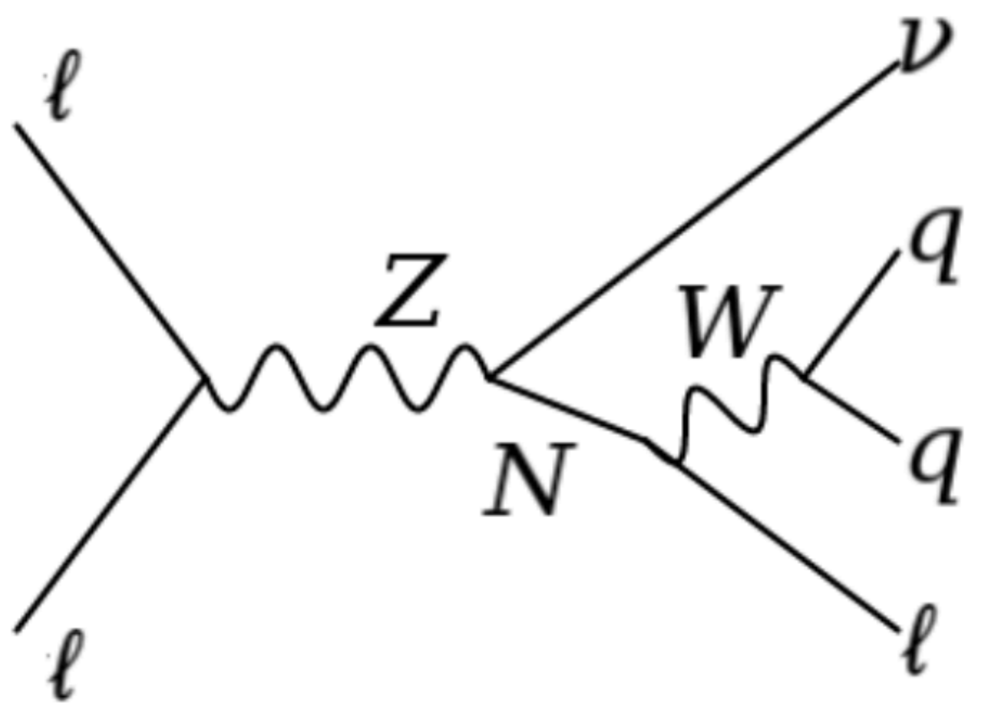

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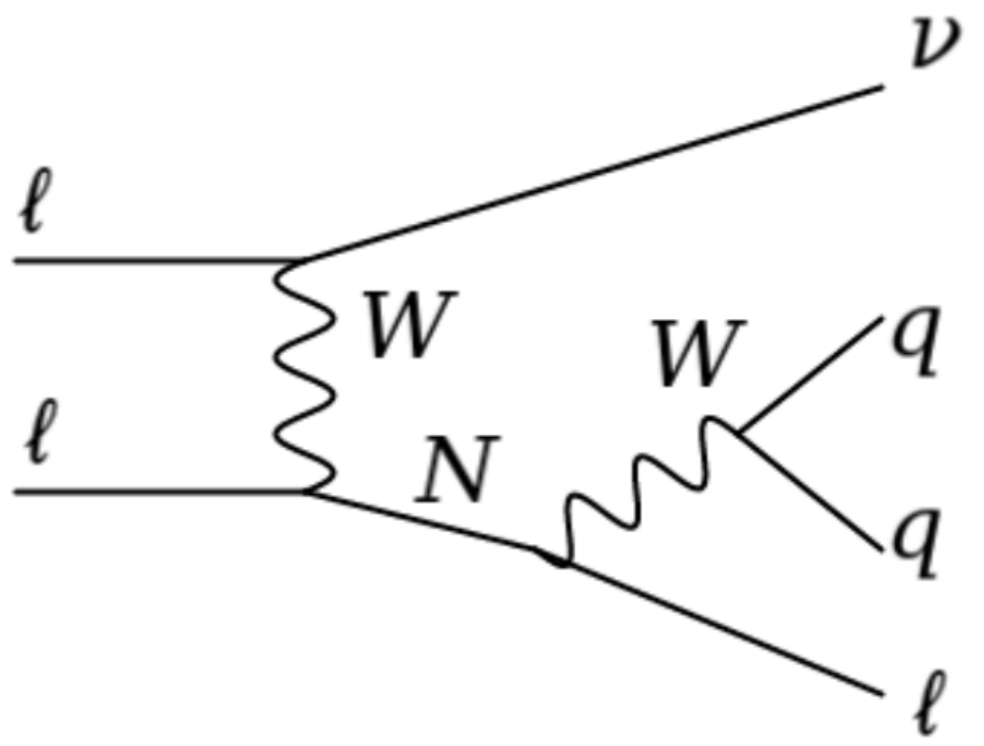
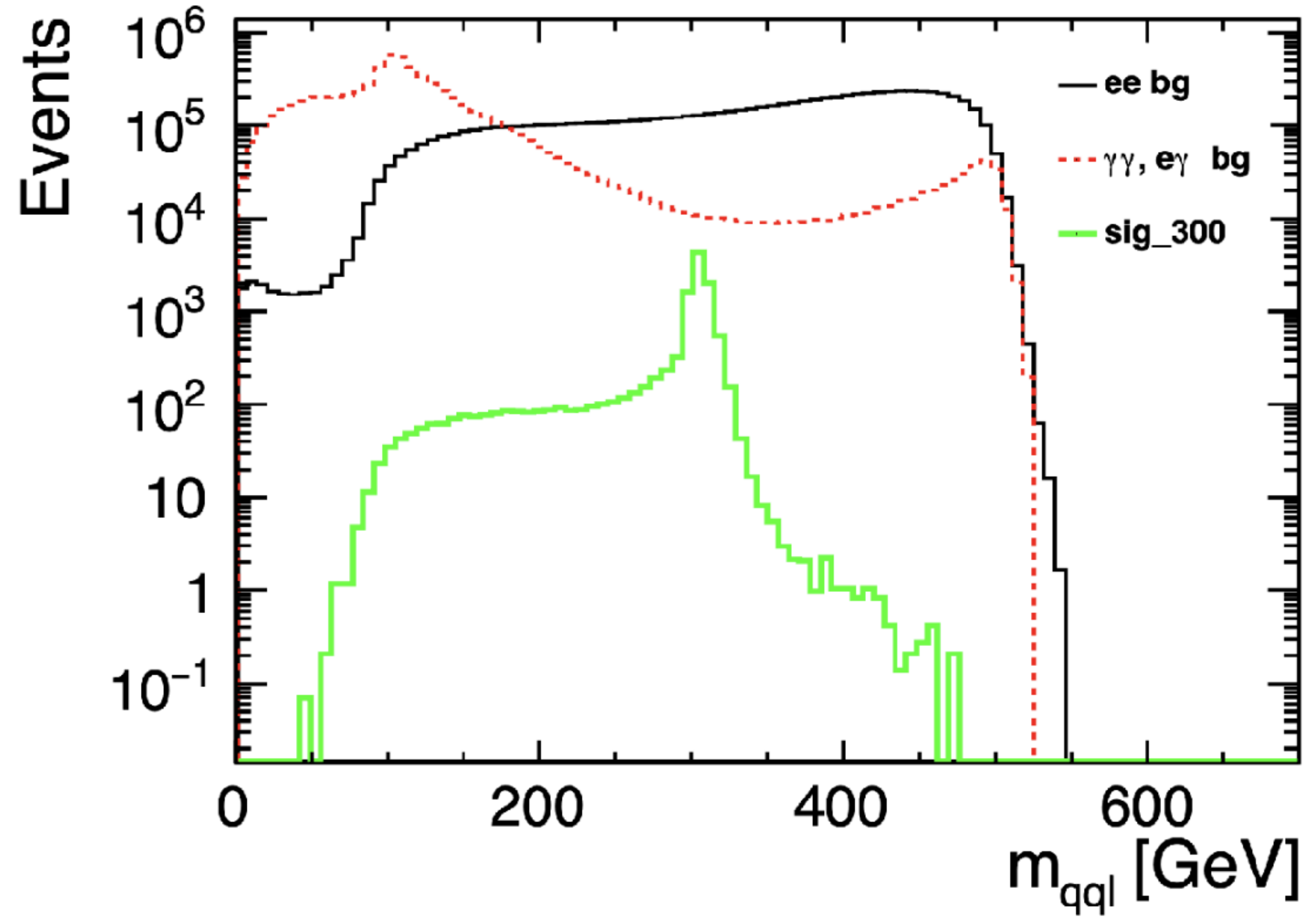


absent at LHC! By far dominant process for heavy HNL!

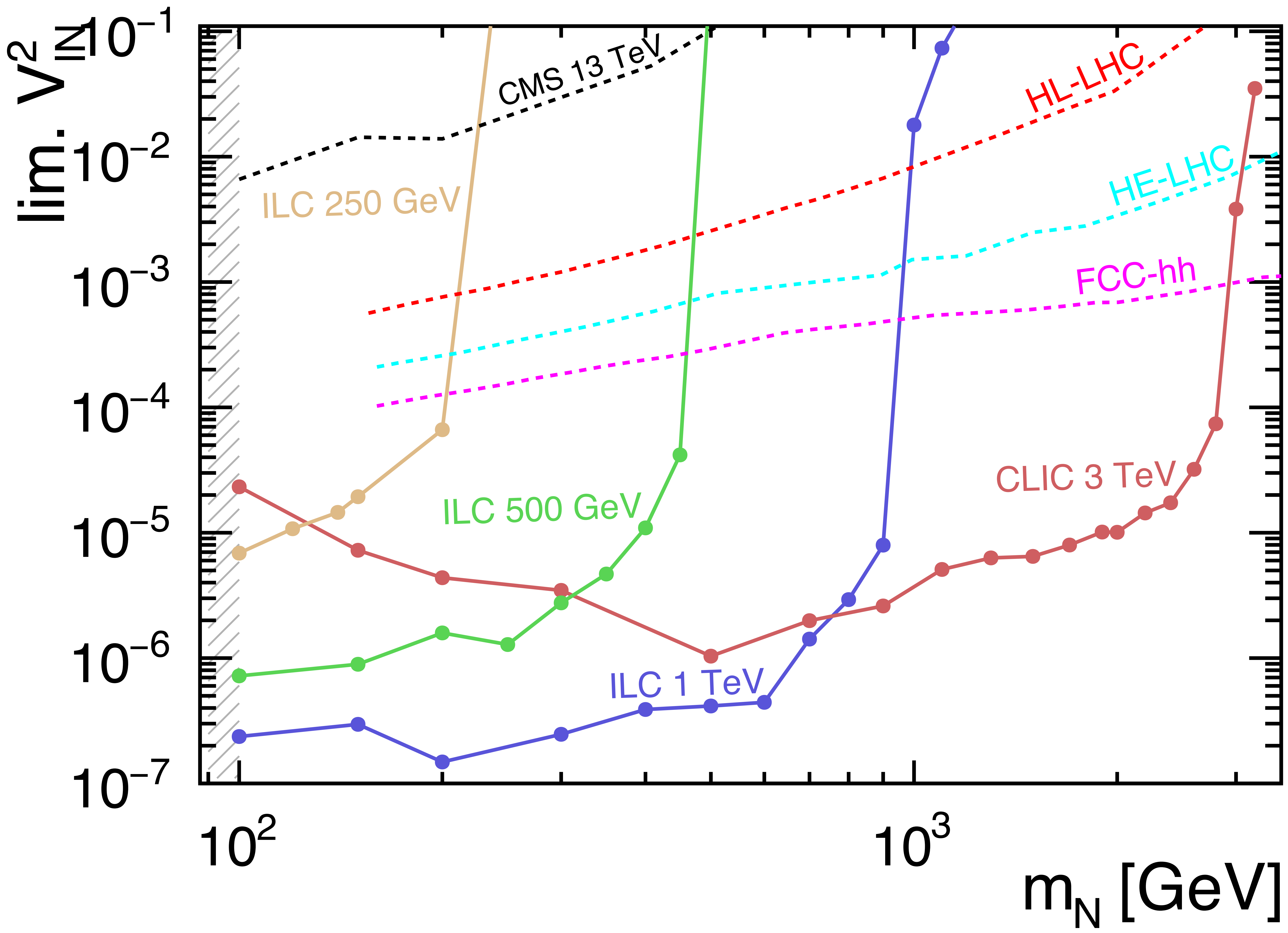
- At lepton colliders: optimal single channel is $\ell^+\ell^- \to N\nu \to \ell^\pm jj\nu$
- HNL mass reconstructable as resonance peak
- Major backgrounds: $\ell^+\ell^- \to jj\ell^\pm\nu,\ ,\ \ell\ell\ell'\ell',\ \{jj, jjjj\}\ell\ell,\ jj\ell^+\nu\ell^-\bar{\nu}$
- Off-shell processes extend sensitivity beyond collider energy!



ILC 500 GeV, (-80%, +30%), $m_N = 300$ GeV

Reach for HNLs

K. Mękała/JRR/A.F. Żarnecki, 2301.02602



LHC analysis [1812.08750],
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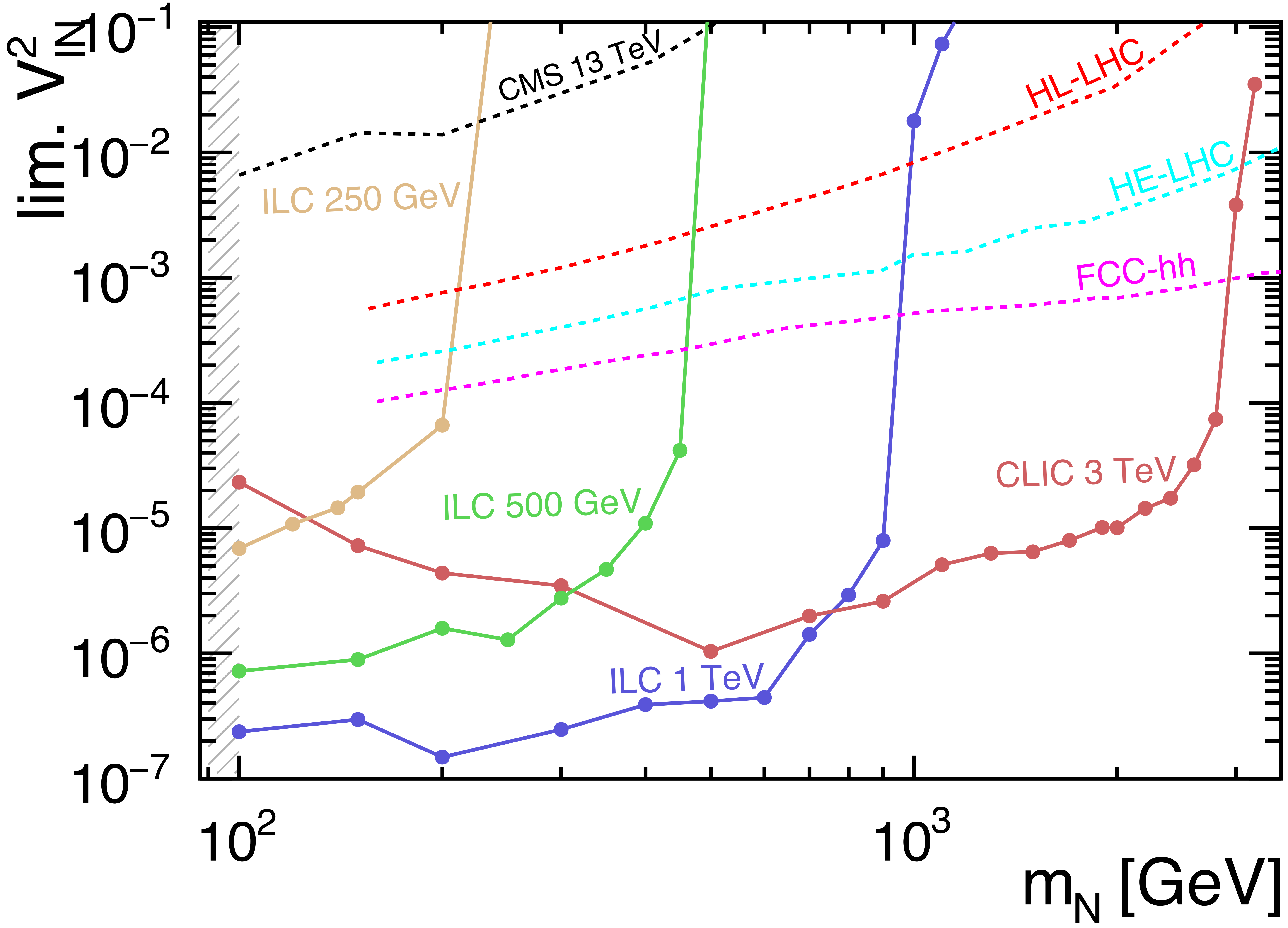

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High-energy lepton colliders outperform
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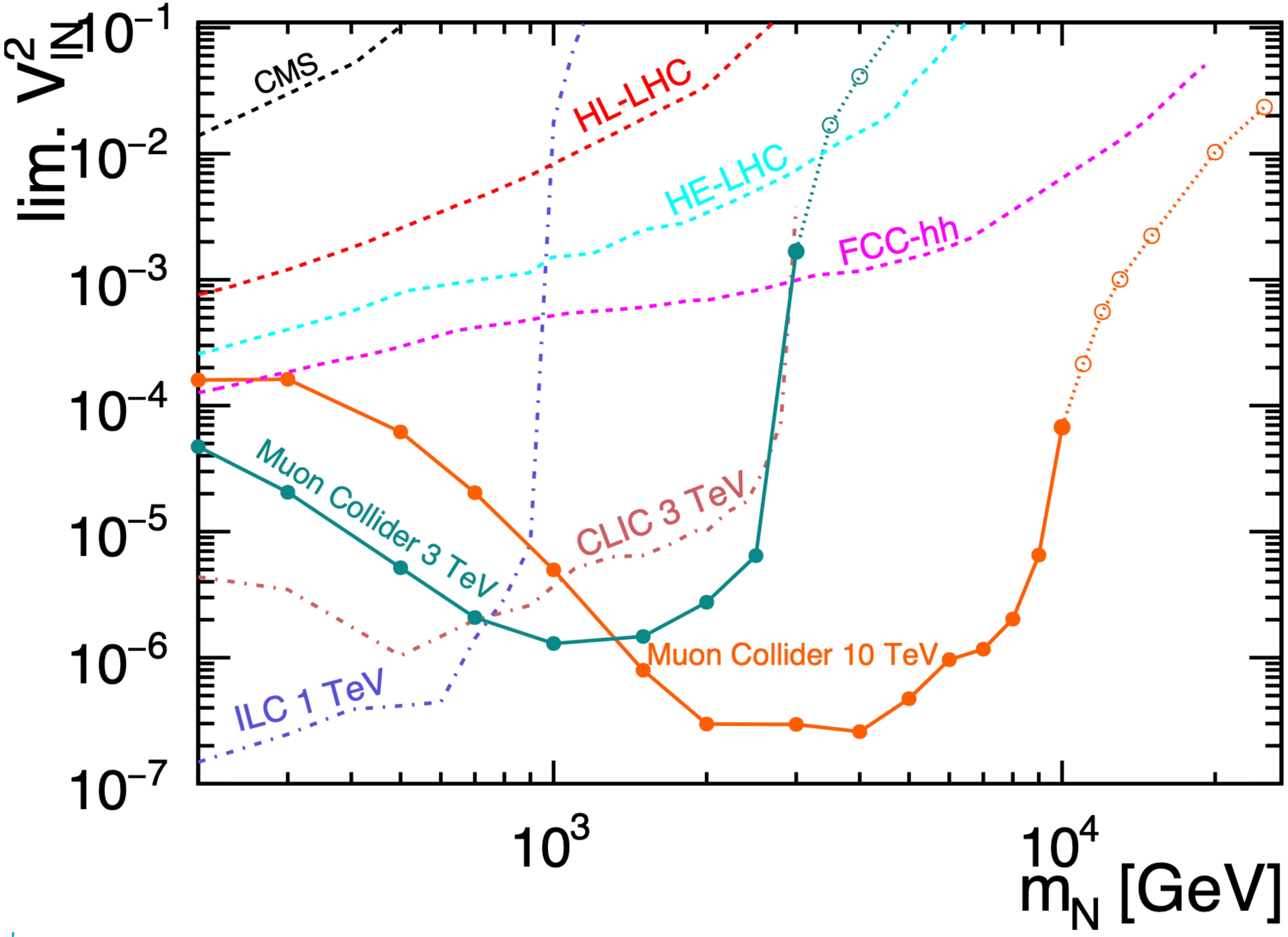

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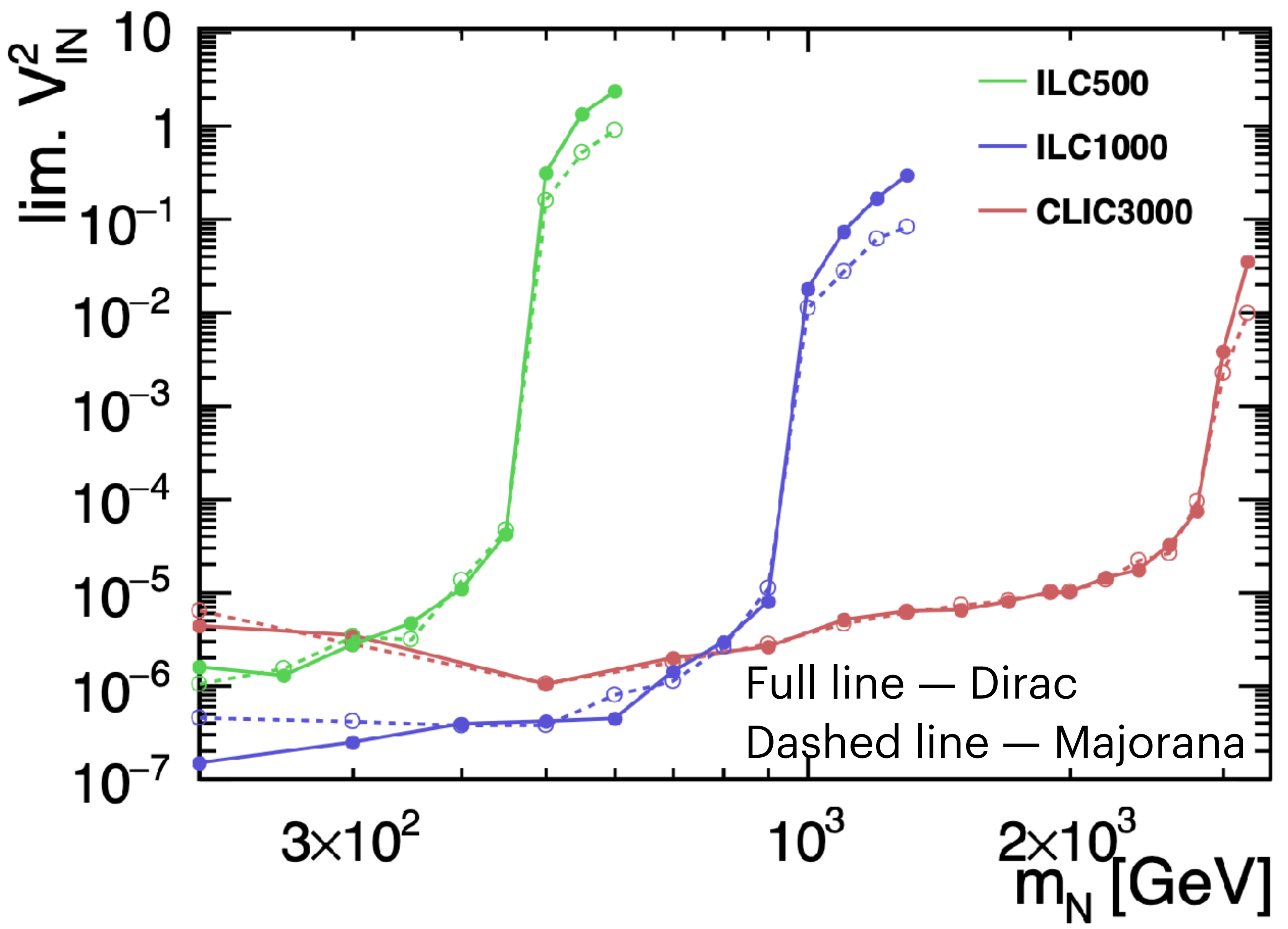
Discrimination of Dirac vs. Majorana

- Exclusion limit very similar for Dirac & Majorana neutrino (except: off-shell production)
- Possible discriminant: lepton emission angle in *N* rest frame



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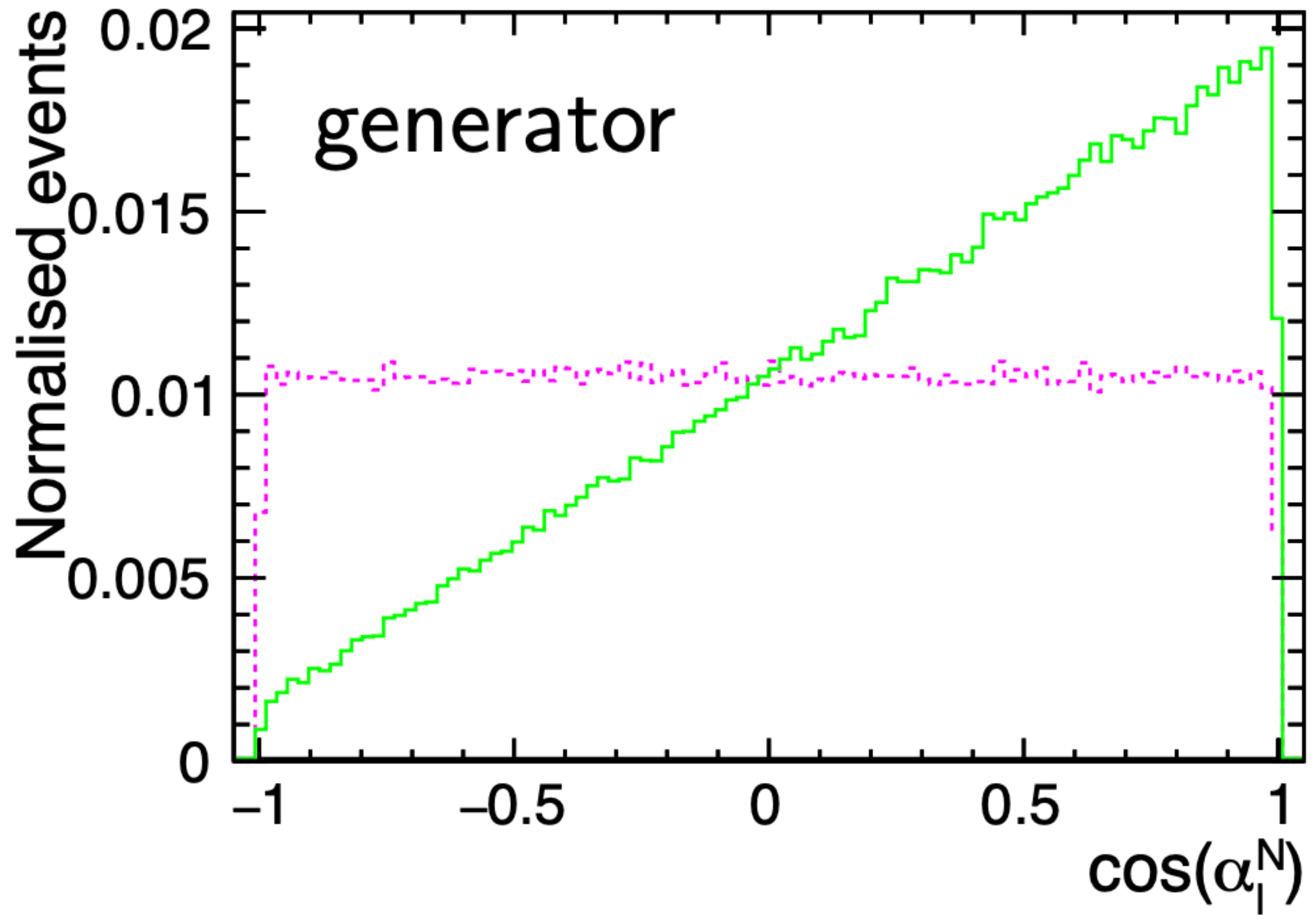

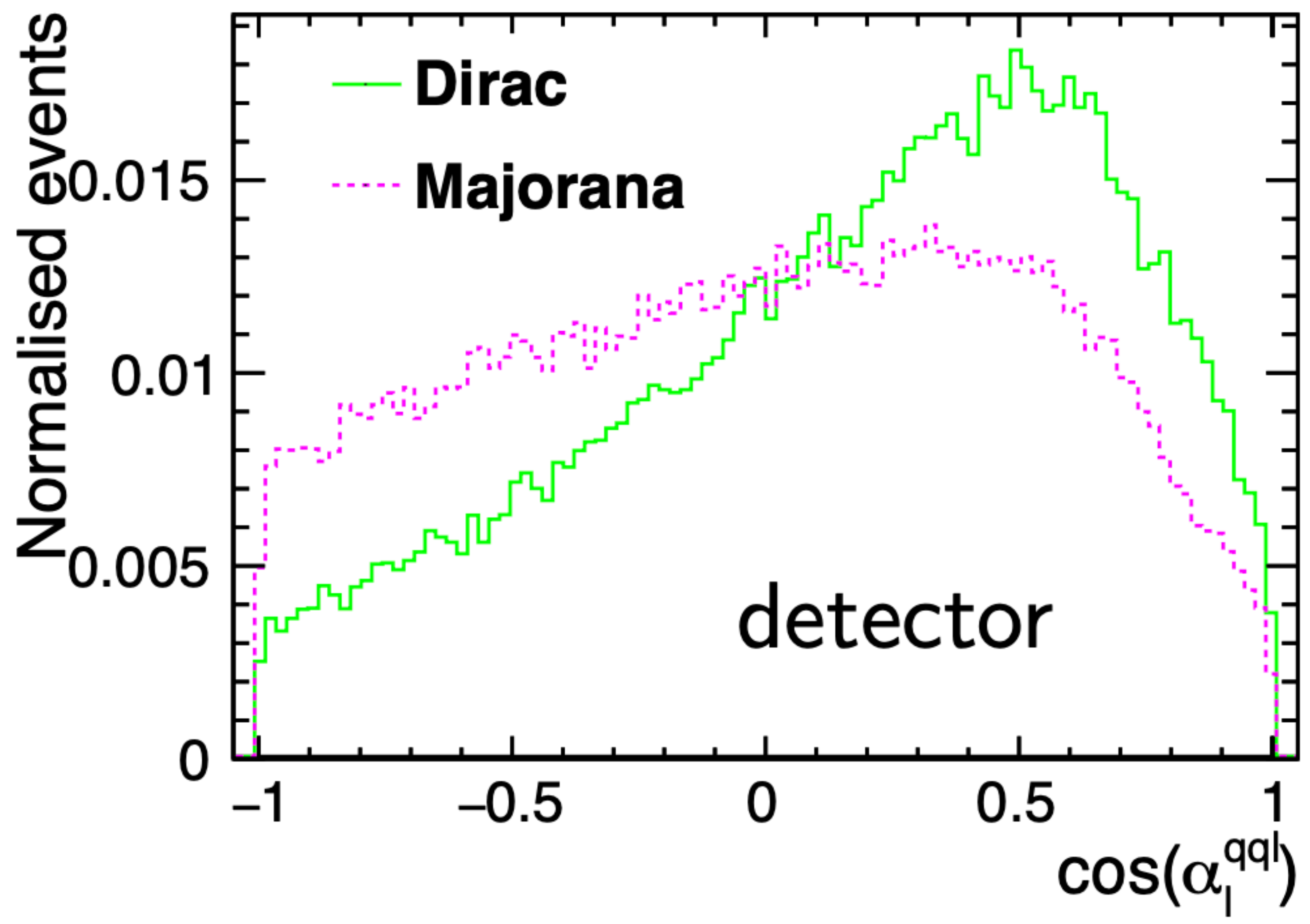

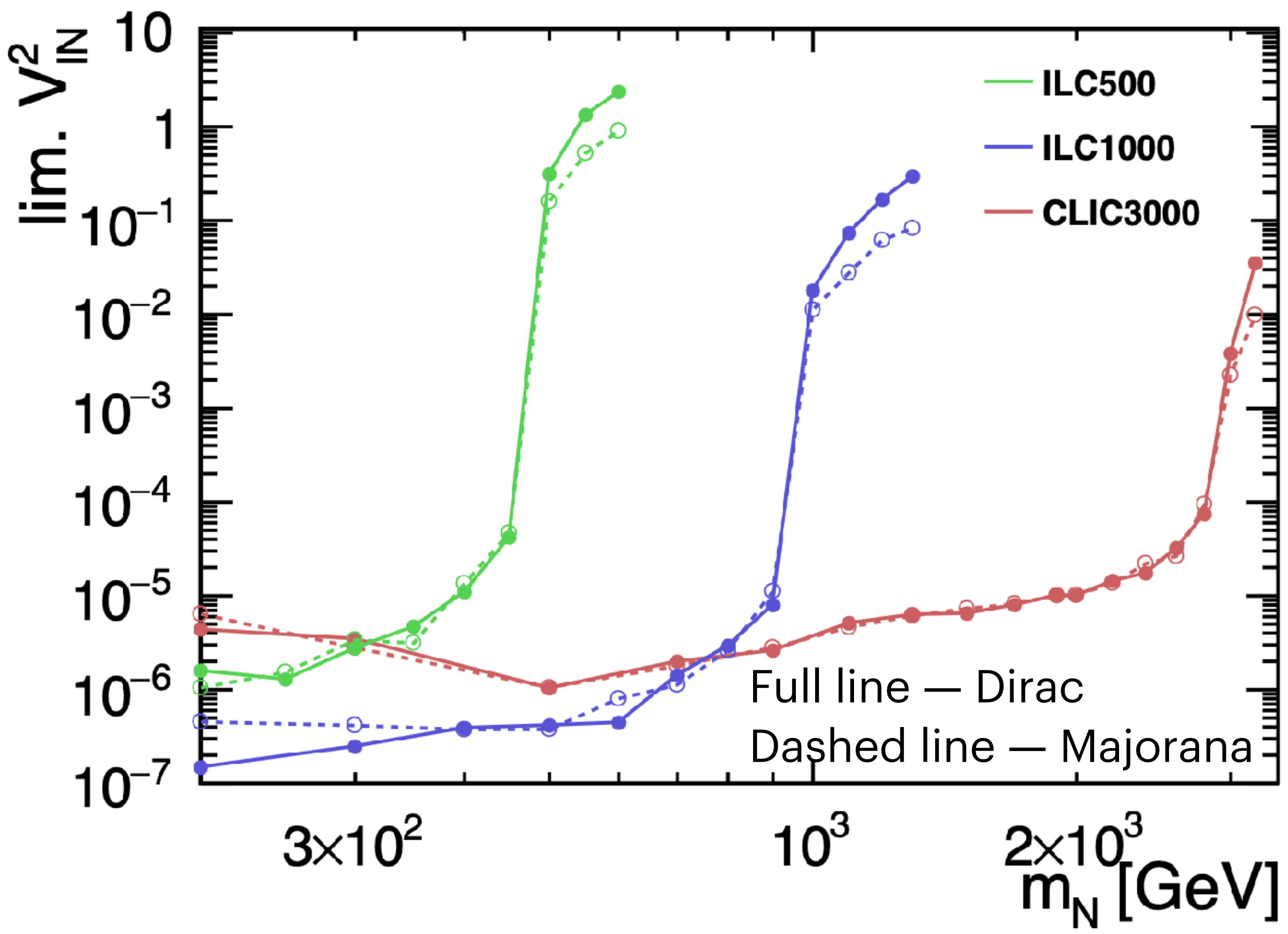

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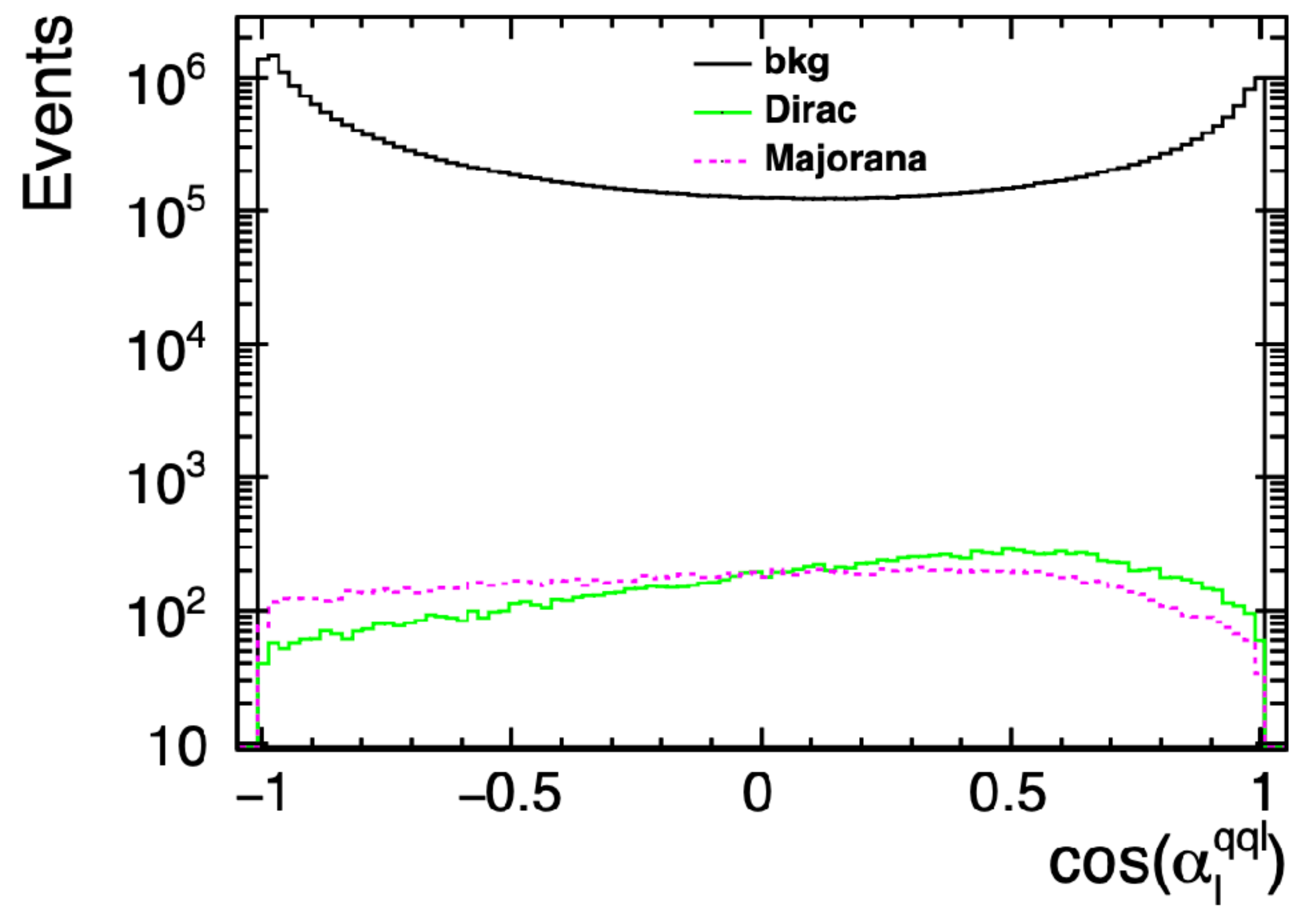

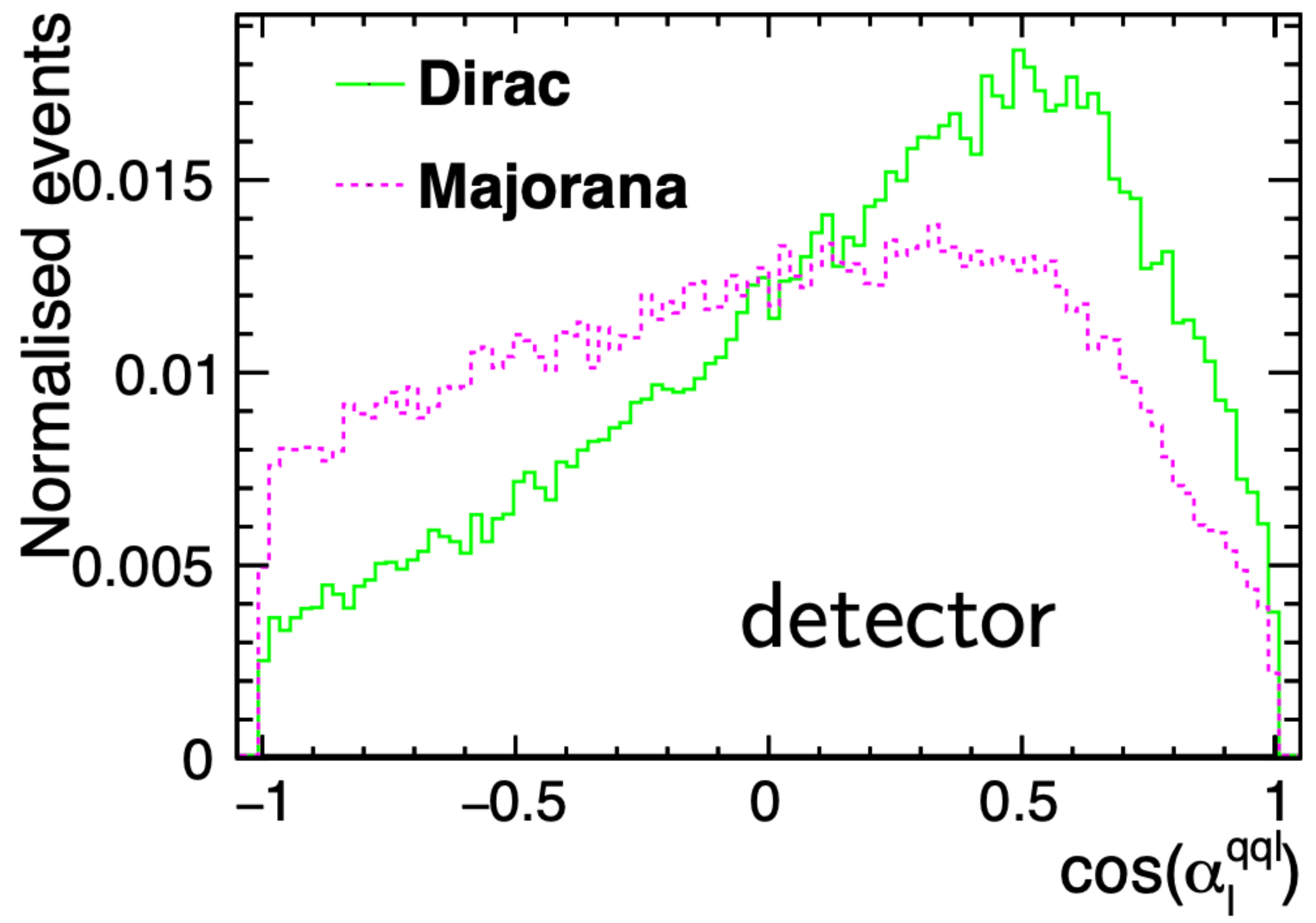

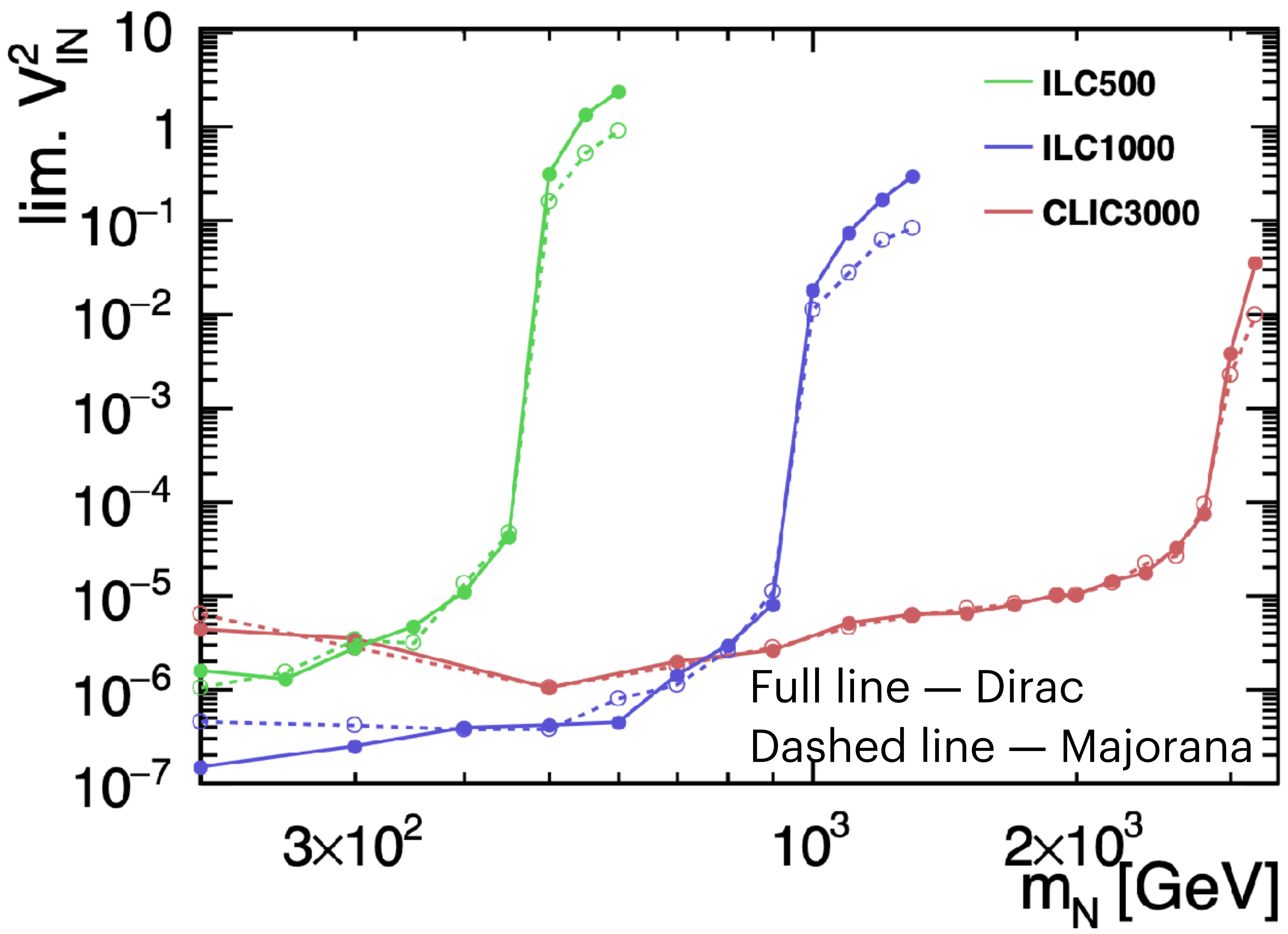

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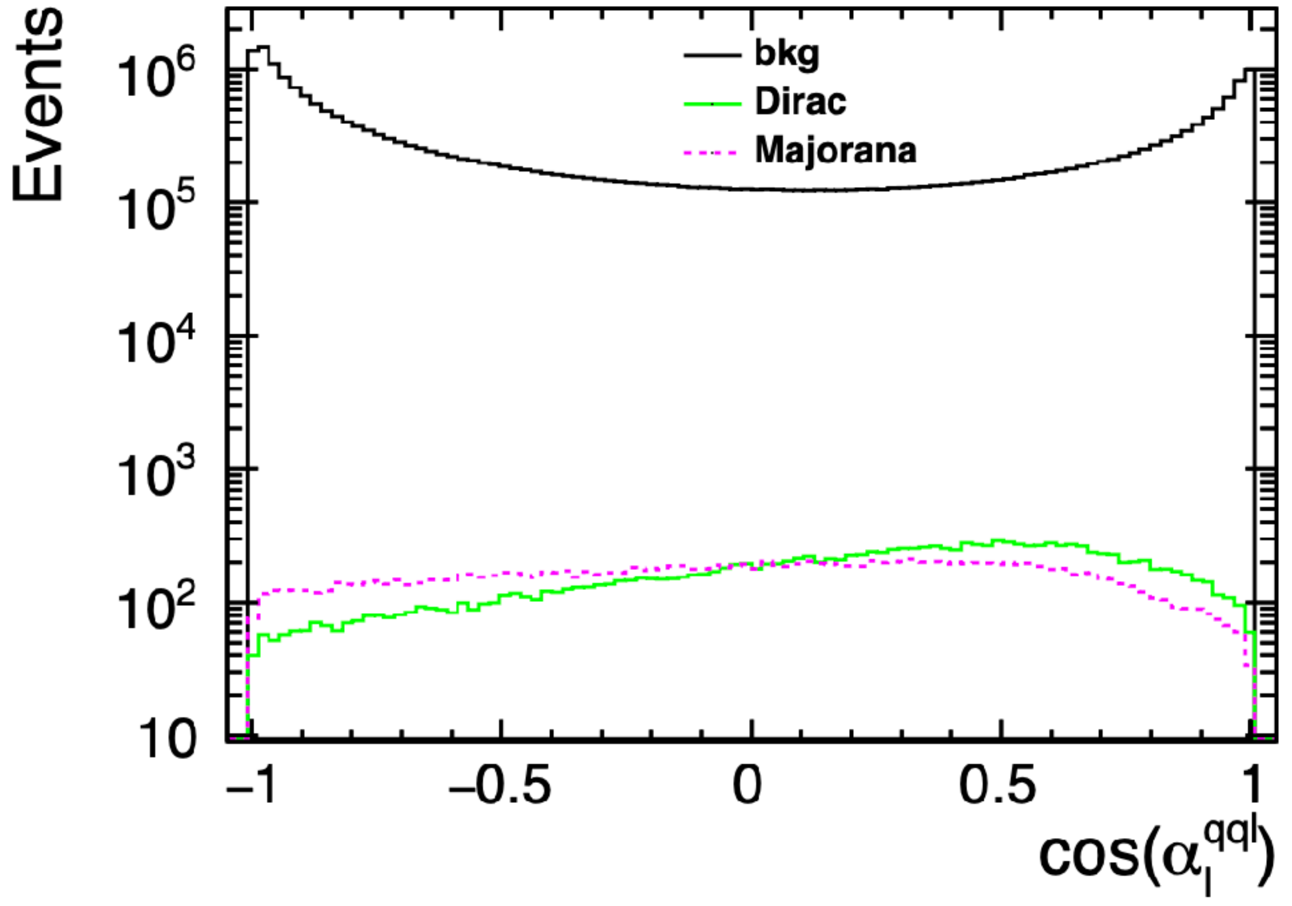
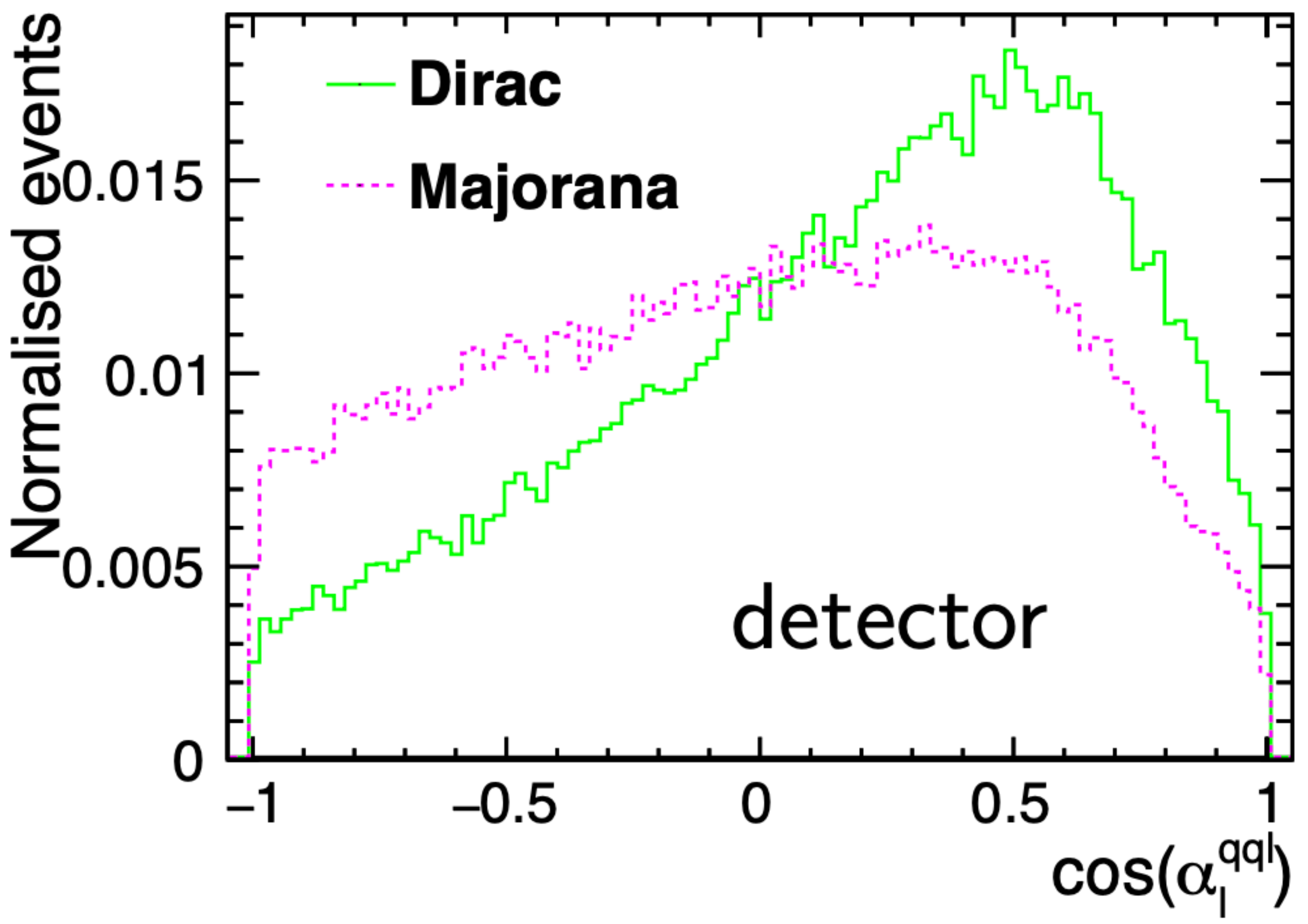
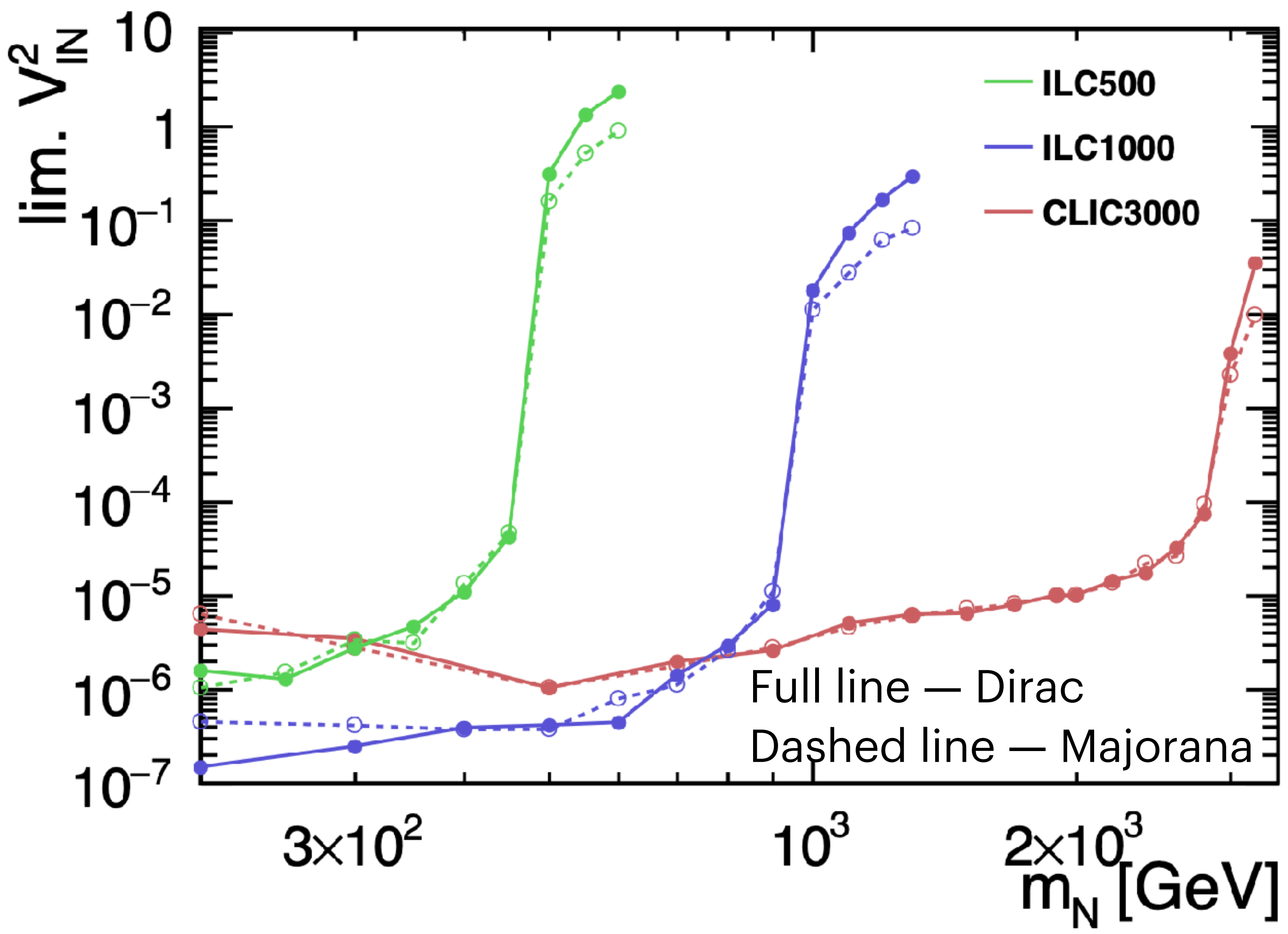
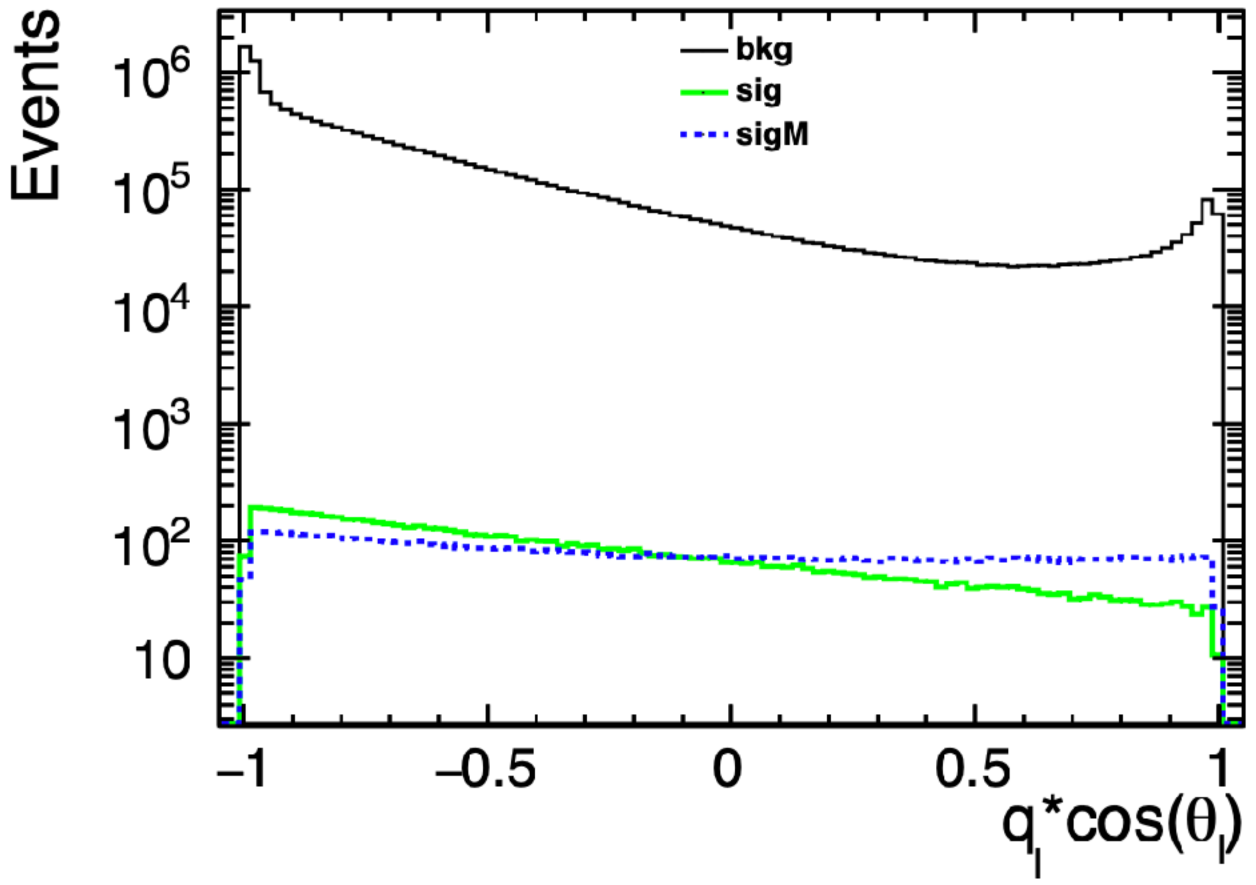


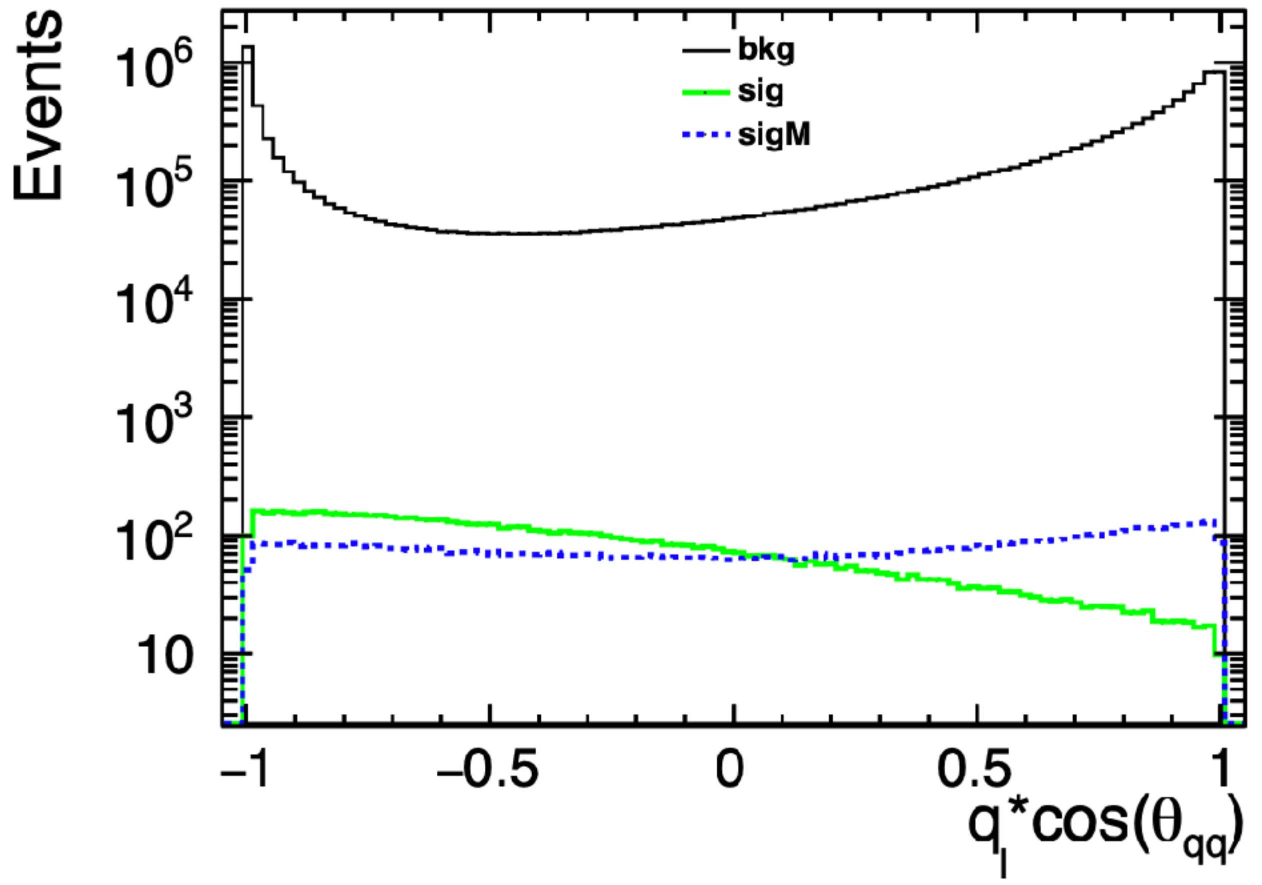




- More sophisticated variable: lepton and dijet angles relative to beam weighted by the lepton charge q_ℓ

ILC 250 GeV, $m_N = 150$ GeV





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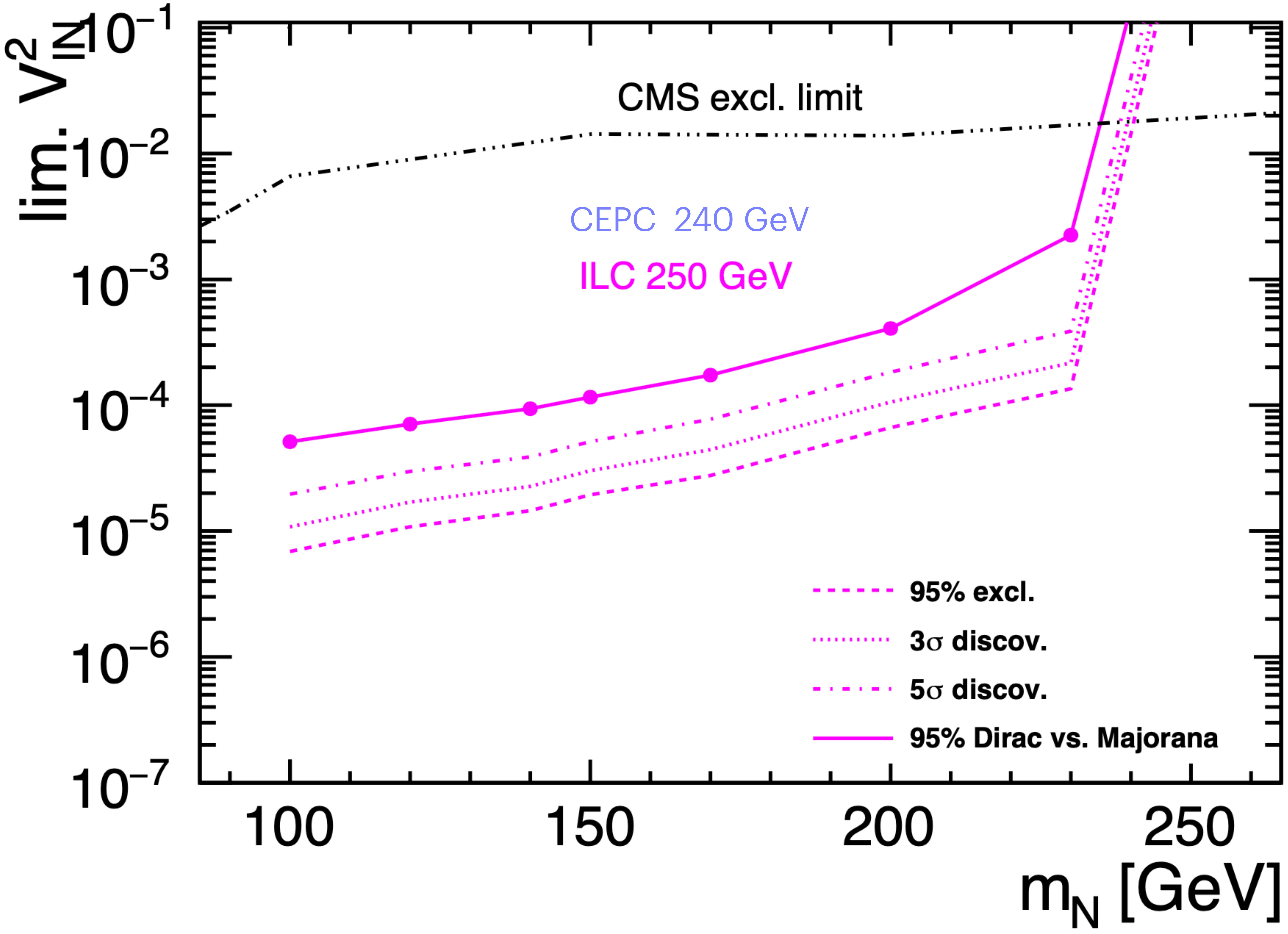

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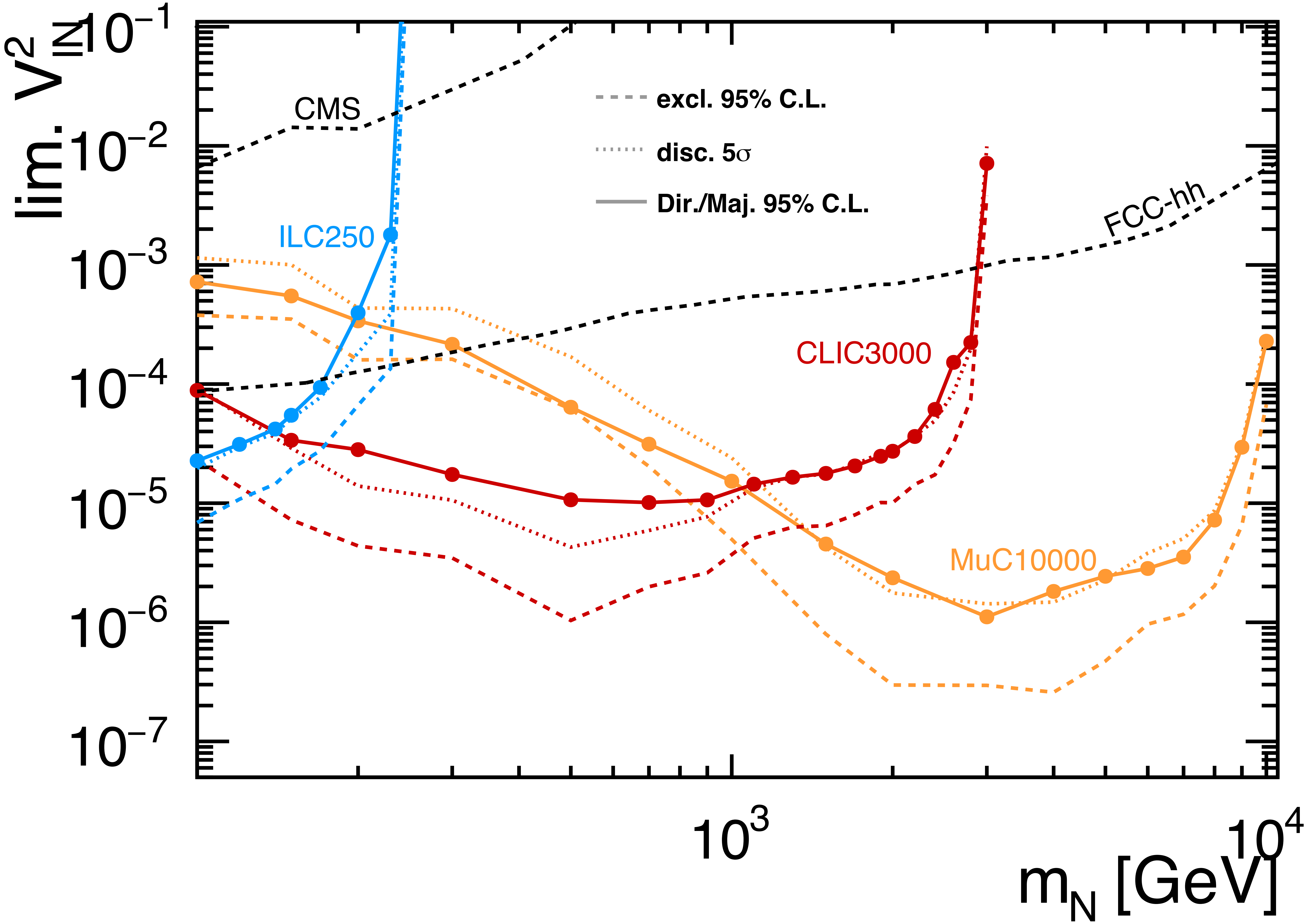

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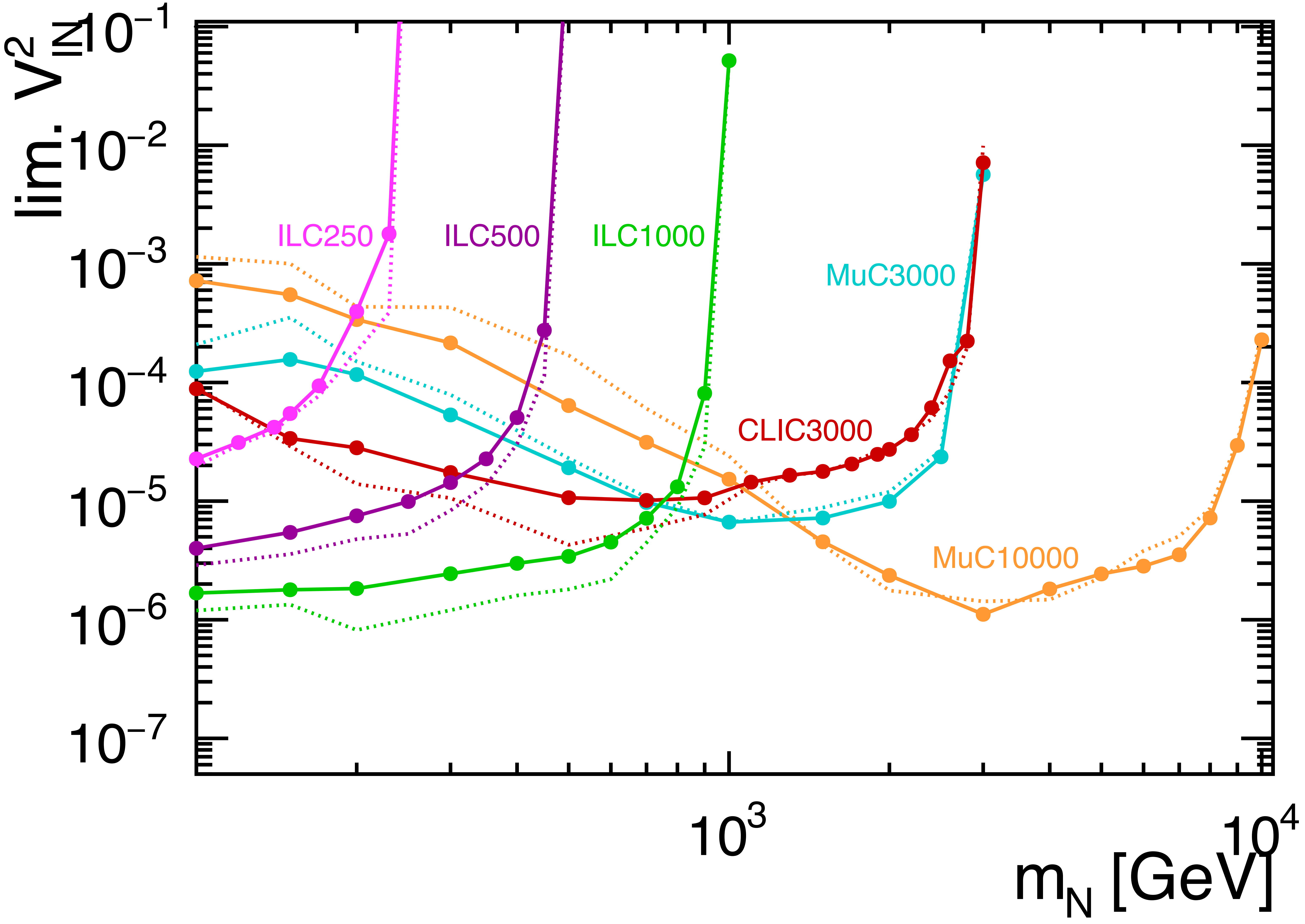

Almost immediately with a discovery a Majorana vs. Dirac discrimnation possible!

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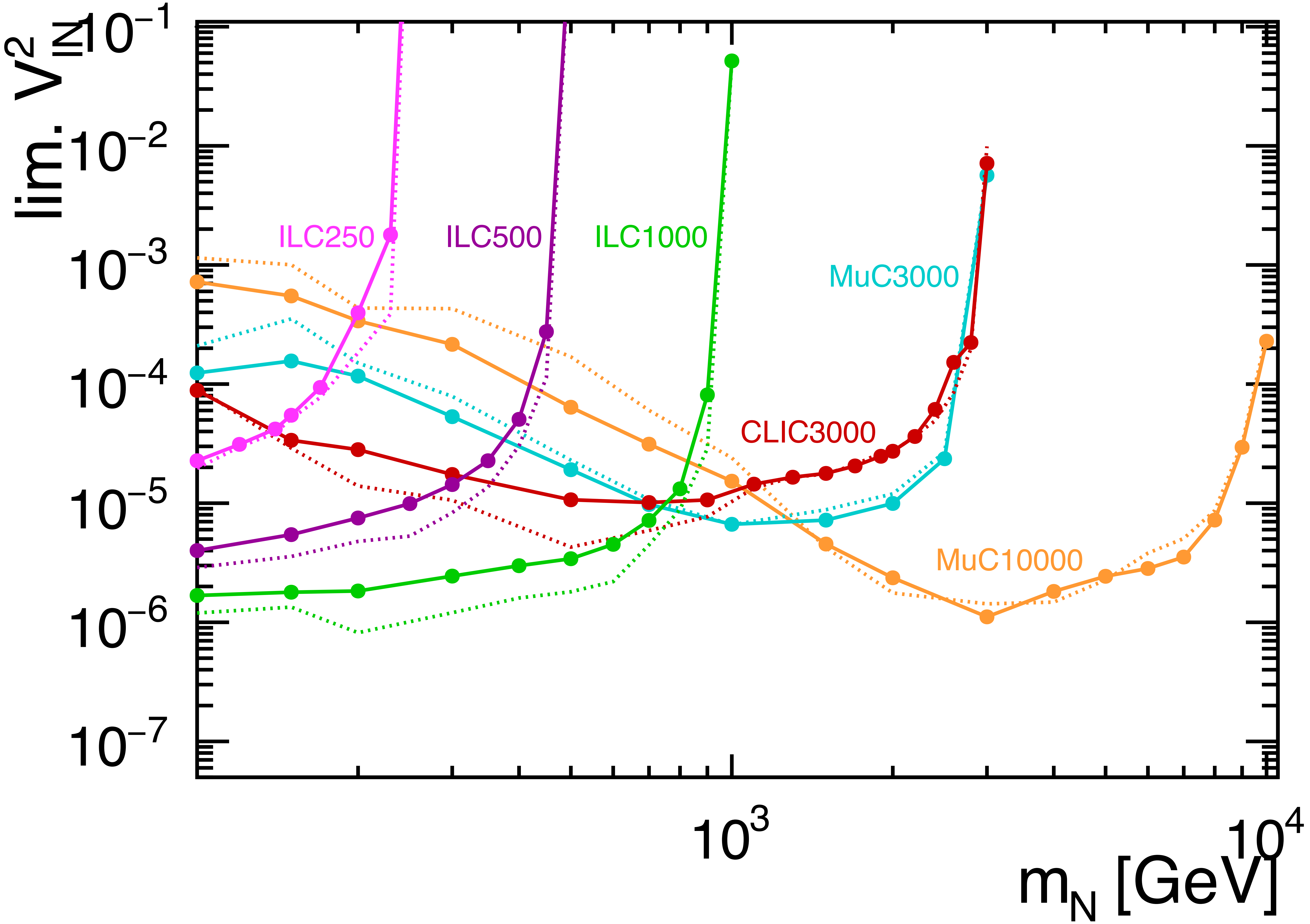

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More difficult, but possible for off-shell case!

Dirac vs. Majorana vs. pseudo-Dirac

Antusch/Hajer/Oliveira: 2308.07297, 2408.01389

- Heavy neutrinos can be Dirac, Majorana or a mixture of both ("pseudo-Dirac")
- HHNL: Lepton collider discriminant: combine CP information (charge + lepton decay angle)
- LHNL: LHC separation of LNC and LNV dilepton events by ratio of SS / OS: $R_{\ell\ell} = \#(\ell^\pm\ell^\pm)/\#(\ell^+\ell^-)$

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$$N_\ell = \frac{1}{\sqrt{2}}(N_+ - iN_-)$$

$$N_{\bar{\ell}} = \frac{1}{\sqrt{2}}(N_+ + iN_-)$$

Interaction eigenstates   Mass eigenstates

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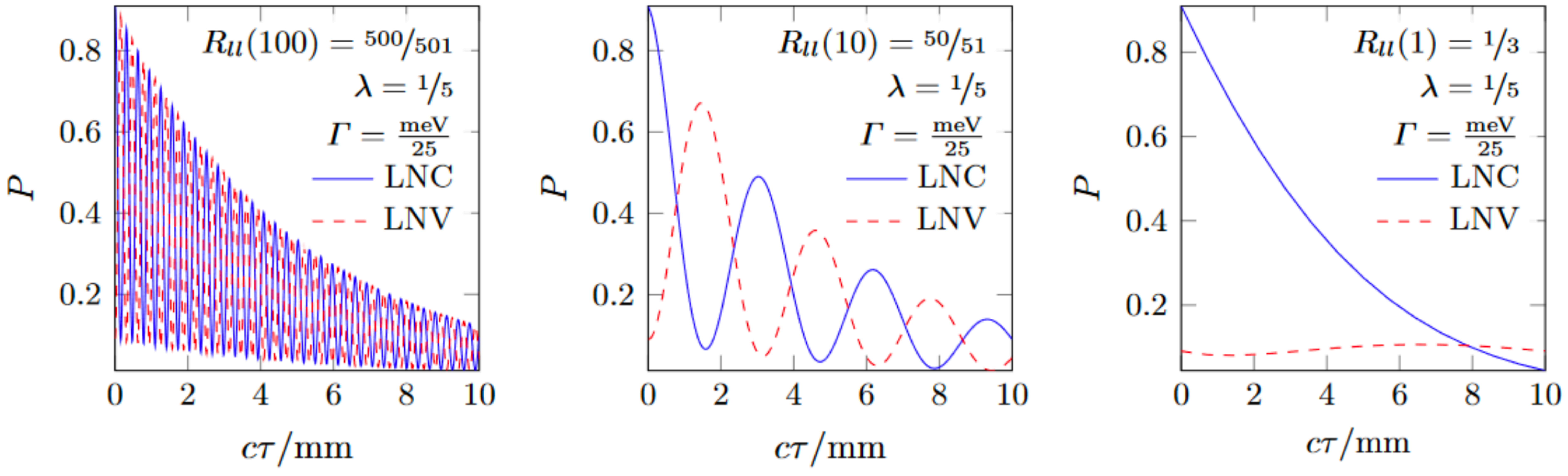

Conclusions & Outlook

- ☑ Heavy Neutrinos Leptons: connections to BAU (?), dark matter (?), flavor symmetries (?)
- ☑ Tiny neutrino masses: (1) scale suppression, (2) small parameters ("tuned"), (3) symmetry
- ☑ Without more experimental guidance (e.g. DUNE): beware of model prejudices
- ☑ Hadron colliders do cover same-sign LNV-/ ν-less double beta decay signatures
- ☑ Lepton collider LHNL: long-lived particles / displaced vertices (Z pole luminosity rules)
- ☑ Lepton collider HHNL: superior due to t-channel enhancement (W-lepton fusion)
- ☑ Mass peak of HHNL reconstructable in hadronic final states at lepton colliders
- ☑ Lepton collider clean environments allow Majorana/Dirac discrimination
- ☑ Interesting flavor complementarities between hadron, ee and $\mu\mu$ colliders

Heavy Duty Neutrino

Neutrino Trash Bags (100 Count) 8-12 Gallon Liner - Heavy Duty Drawstring Plastic Garbage Bags - Compatible with Simple Human Code J Trash Cans

BACKUP

Flavor complementarity of *ee* vs. *μμ* colliders

- Dominant *t*-channel production (*W* exchange):
- On-shell production
- Off-shell more difficult: need to scan each parameter point

$$\boxed{\sigma \propto \frac{|V_{\ell_{in}N}|^2 \cdot |V_{\ell_{out}N}|^2}{|V_{eN}|^2 + |V_{\mu N}|^2}}$$

cf. also talk by Krzysztof Mękała

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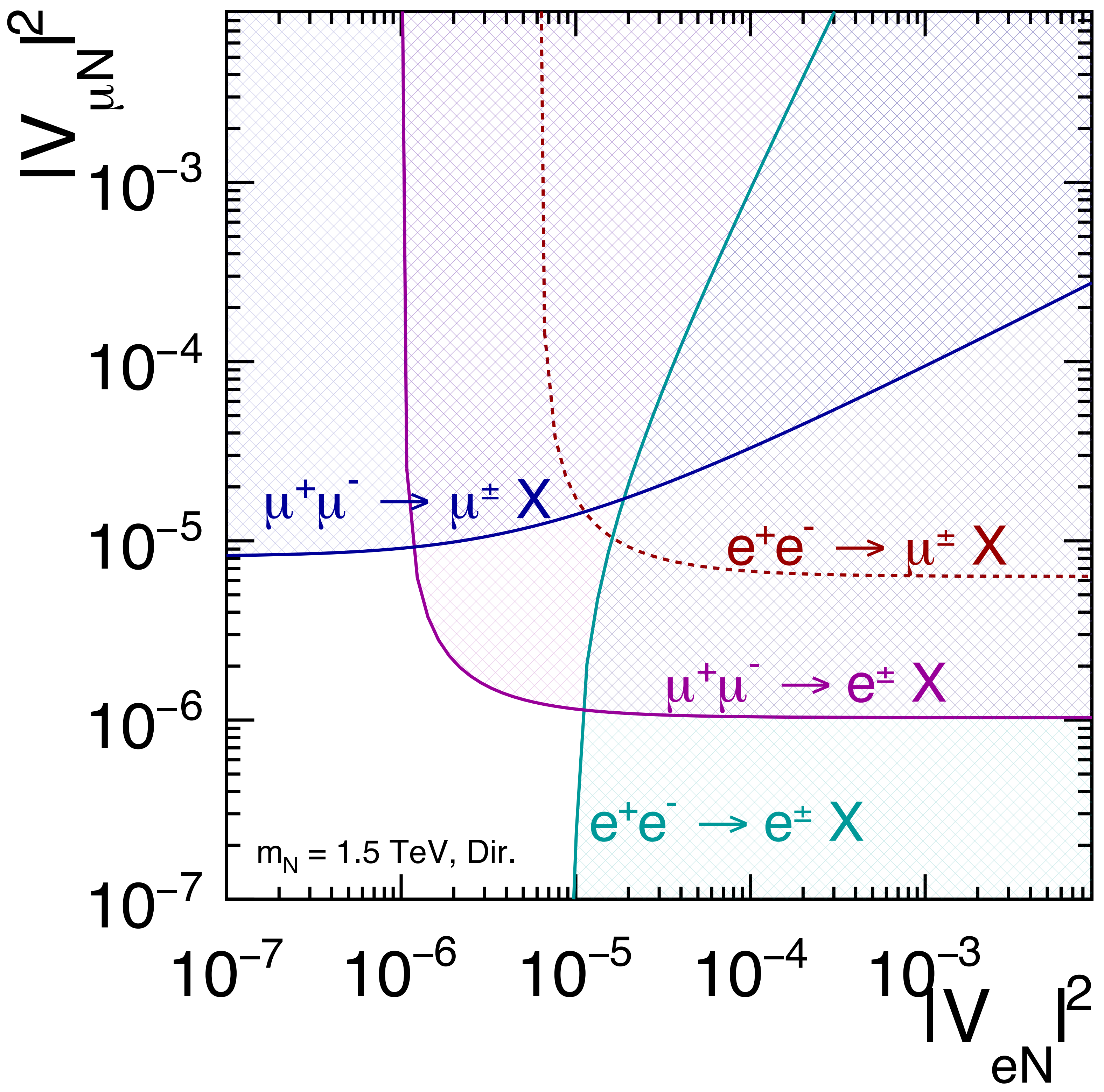

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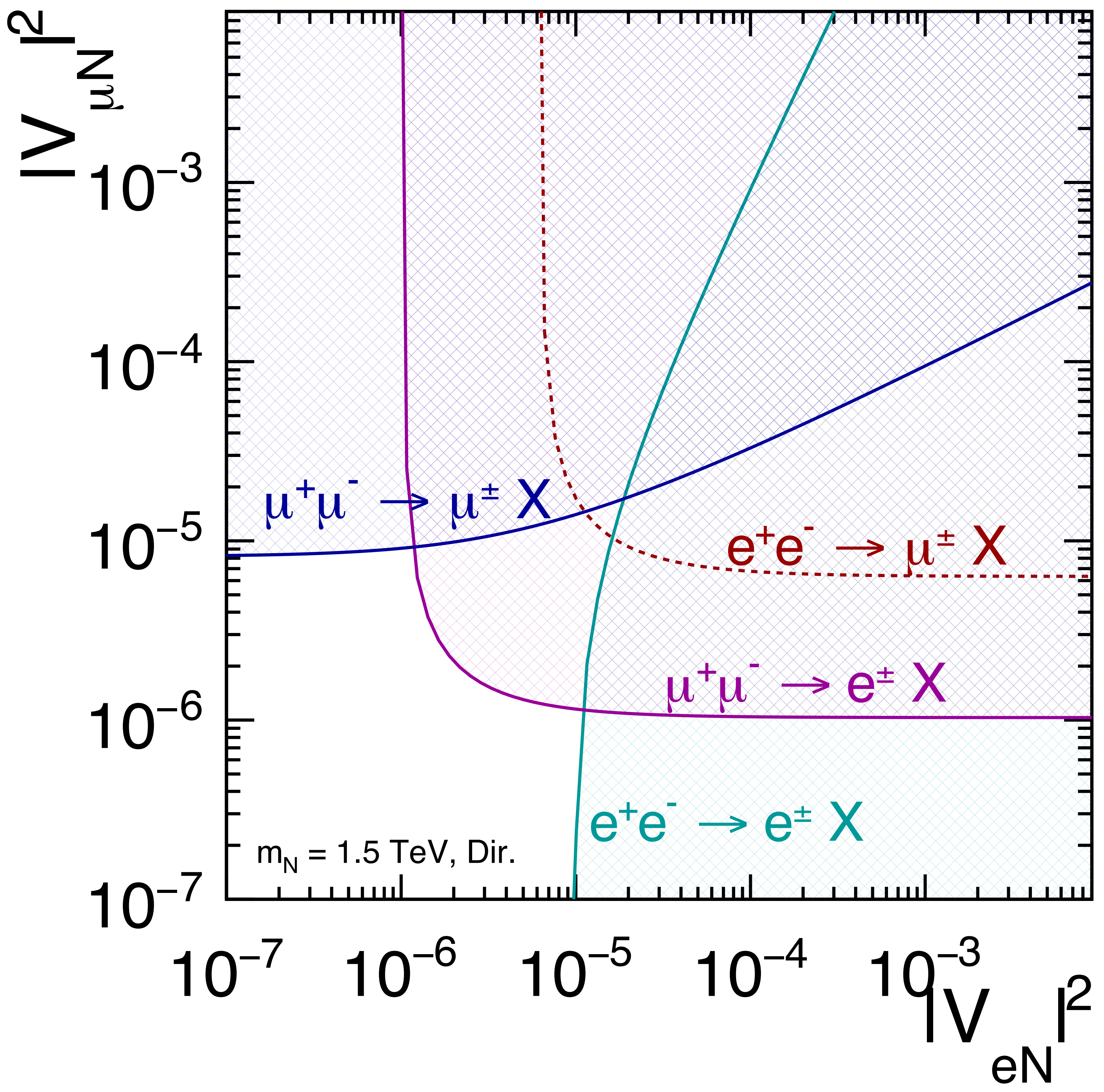

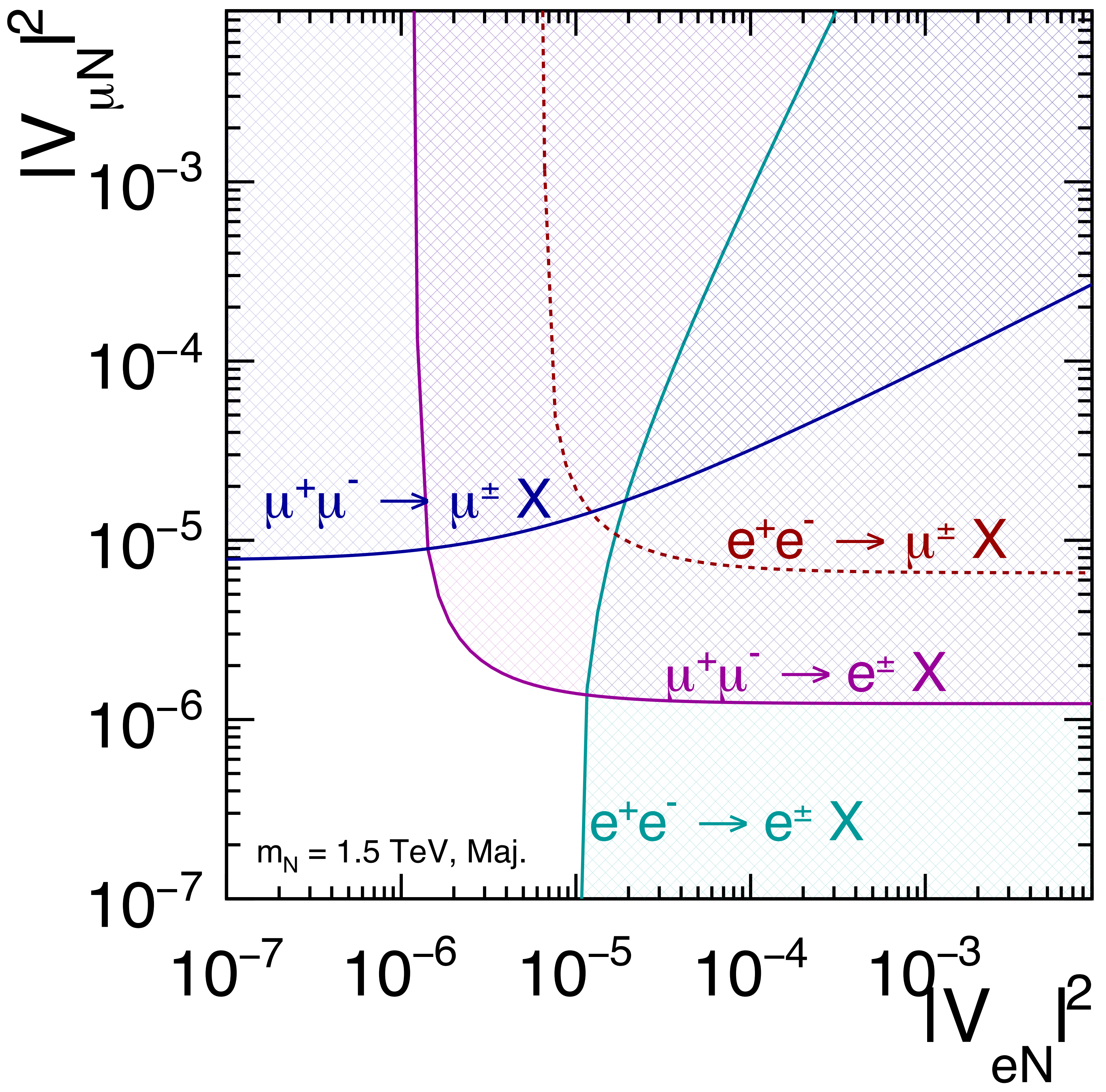

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