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Analytic Formulae for the Sensitivity Region of DV Searches for HNLs at Lepton Colliders

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LLP12 Workshop

Heavy Neutral Leptons (HNLs)

Common phenomenological description:

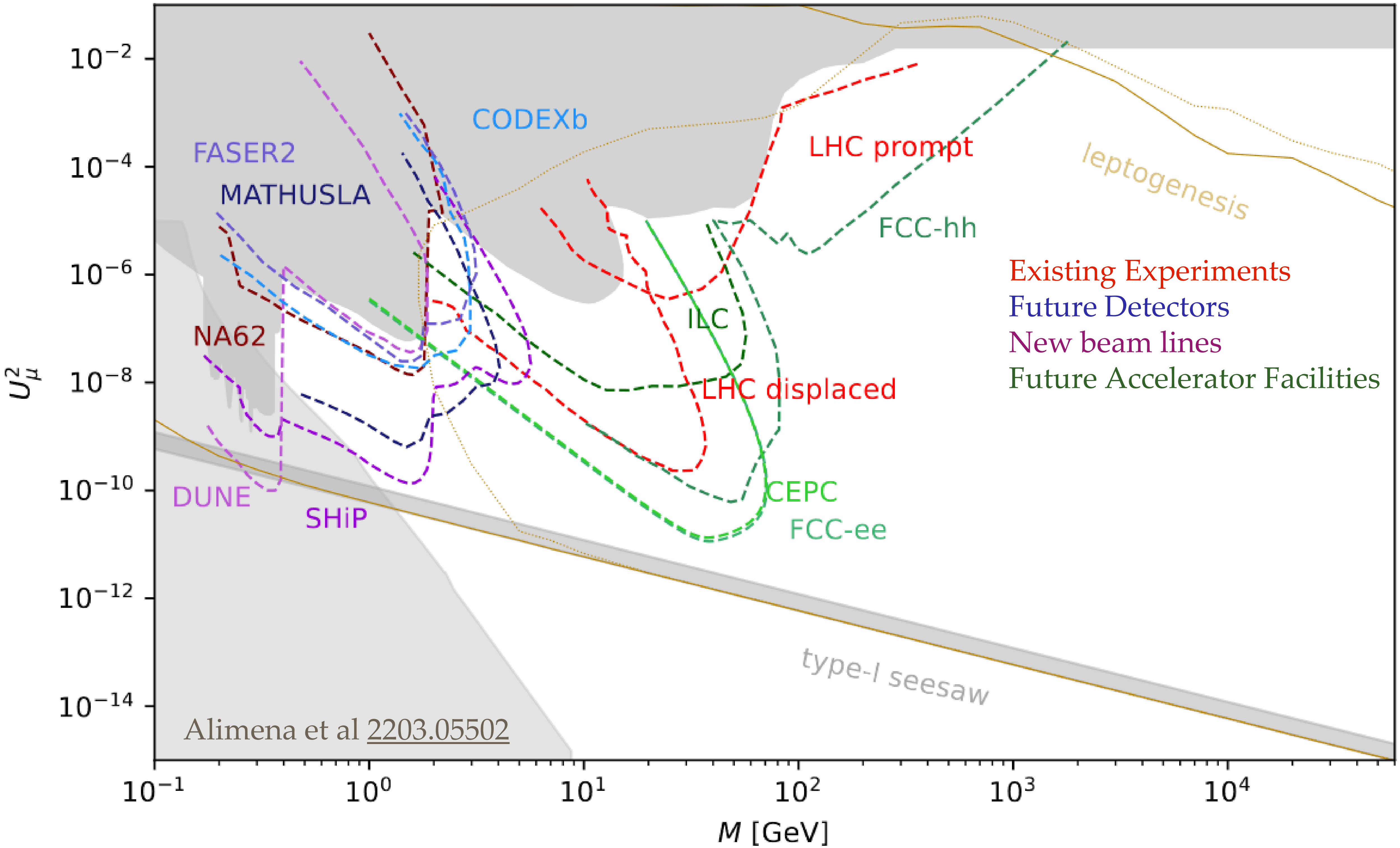
$$\mathcal{L} \supset -\frac{m_W}{v}\overline{N}\theta^*_\alpha\gamma^\mu e_{L\alpha}W^+_\mu - \frac{m_Z}{\sqrt{2}v}\overline{N}\theta^*_\alpha\gamma^\mu\nu_{L\alpha}Z_\mu - \frac{M}{v}\theta_\alpha h\overline{\nu_{L\alpha}}N + \text{h.c.}$$

- One flavour of HNLs *N*
- Couples to SM only through mixing θ_a with SM neutrinos, where a = e, μ, τ
- Model with five parameters : M, θ_e, θ_μ, θ_τ, and R_{ll}.
- **R_{ll} is ratio of lepton number violating (LNV) to lepton number conserving (LNC) *N* decays; $R_{ll} = 1$ for Majorana *N* and $R_{ll} = 0$ for Dirac *N*.**

- This is not a realistic model of neutrino mass, but can effectively capture the pheno of realistic models with suitable choices of : M, θ_e, θ_μ, θ_τ, R_{ll}.
- Technical naturalness and leptogenesis predict mass-degenerate HNLs, e.g. realised in vMSM, inverse seesaw, linear seesaw…
- For LLP searches: need **two more parameters describing the relation between production rate and lifetime** for an HNL pair with mass splitting ΔM

	c_{prod}	c_{dec}	R_{ll}	appearance
$\Delta M > \delta M_{\text{exp}} \gg \Gamma_N$	1	1	1	two Majorana HNLs with mixing U^2 each
$\delta M_{\text{exp}} > \Delta M \gg \Gamma_N$	2	1	1	one HNL, mixing $2U^2$, lifetime as Dirac, R_{ll} as Majorana
$\delta M_{\text{exp}} > \Gamma_N \gg \Delta M$	2	1	0	one Dirac HNL with mixing $2U^2$

HNL Searches at Lepton Colliders

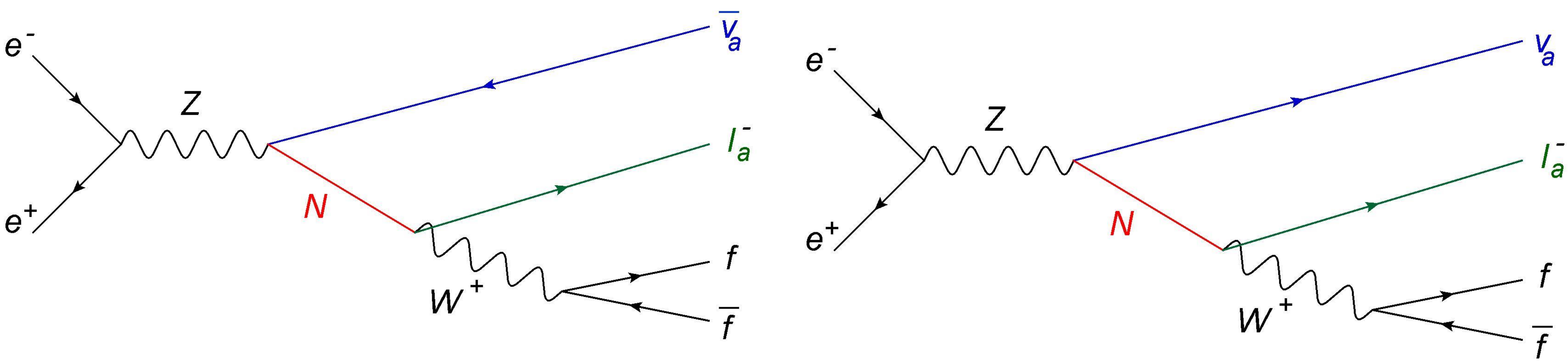


DV searches at the Z-Pole

- Semi-analytic approach even works reasonably well for proton collisions…

  Bondarenko et al 1902.06240 MaD et al 1905.09828

- Here: Two-body decay of particle at rest…



- There must be a simple way of doing this?

Number of Events

Number of produced HNLs:

$$N_{\mathrm{HNL}\alpha} \simeq 2\mathsf{u}_\alpha^2 U^2 c_{\mathrm{prod}} N_Z N_{\mathrm{IP}} \mathrm{B}_\alpha \Pi$$

for flavour mixing pattern $\mathsf{u}_\alpha^2 = \frac{U_\alpha^2}{U^2}$ with $\mathrm{B}_\alpha = \mathrm{BR}(Z \to \nu_\alpha \overline{\nu}_\alpha) = \frac{1}{5}\frac{1}{3}$

HNL momentum and phase space:

$$\mathrm{p}_N = \frac{m_Z}{2}\left(1 - (M/m_Z)^2\right) \qquad \Pi = \left(\frac{2\mathrm{p}_N}{m_Z}\right)^2 \left(1 + \frac{(M/m_Z)^2}{2}\right)$$

Number of observed decays:

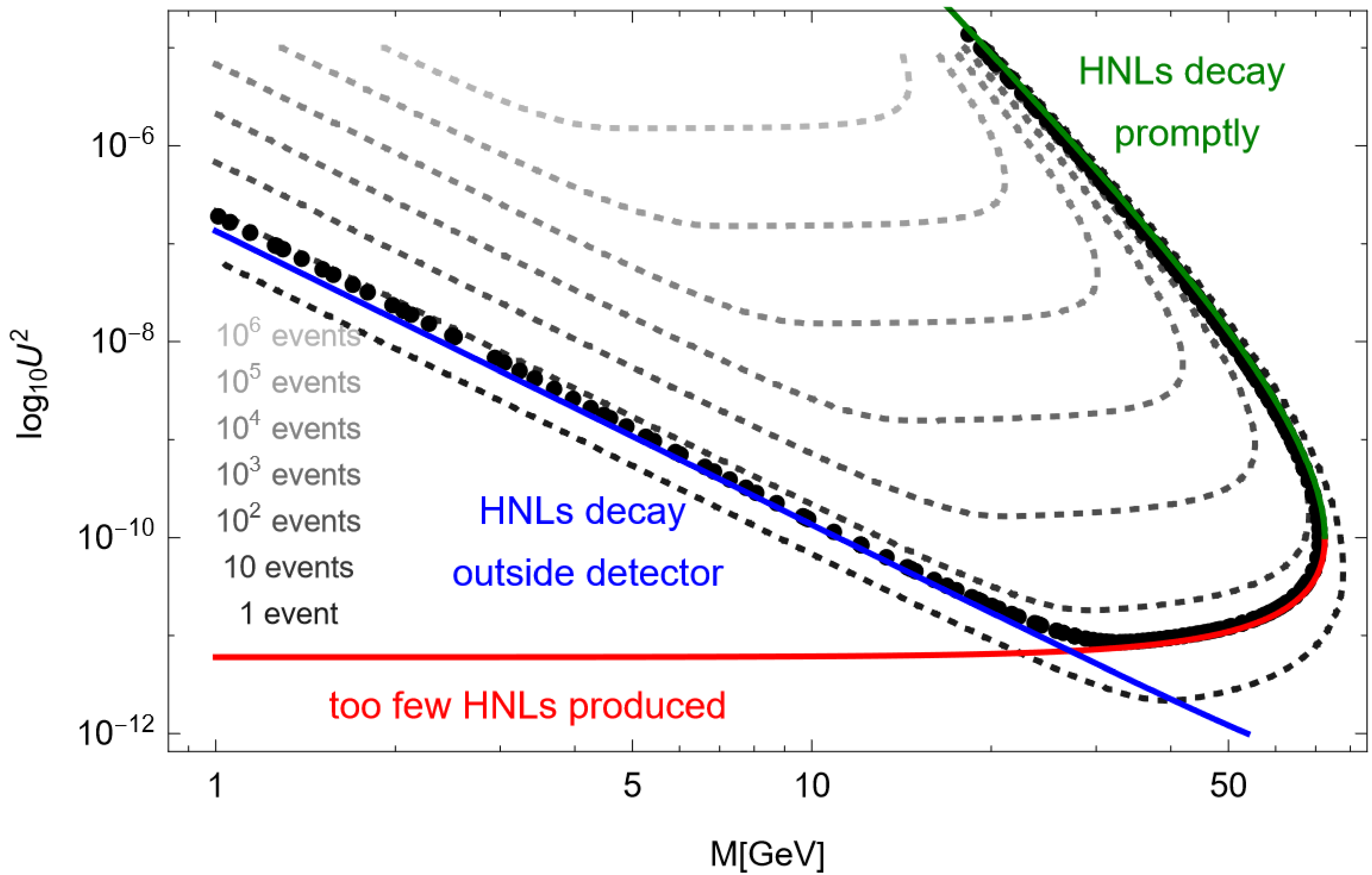
$$N_{\mathrm{obs}} \simeq \mathsf{u}_\beta^2 N_{\mathrm{HNL}\alpha} \left[\exp(-l_0/\lambda_N) - \exp(-l_1/\lambda_N)\right] \epsilon_{\alpha\beta}.$$

Decay length in lab: $\lambda_N = \frac{\beta\gamma}{\Gamma_N} \simeq \frac{1.6}{U^2 c_{\mathrm{dec}}} \left(\frac{M}{\mathrm{GeV}}\right)^6 \left(1 - (M/m_Z)^2\right) \mathrm{cm}$

for cylindrical detector: {“equivalent volume”) $l_1 = \frac{1}{2}(3/2)^{1/3} d_{\mathrm{cyl}}^{2/3} l_{\mathrm{cyl}}^{1/3}$

MaD 2210.17110

Sensitivity Region

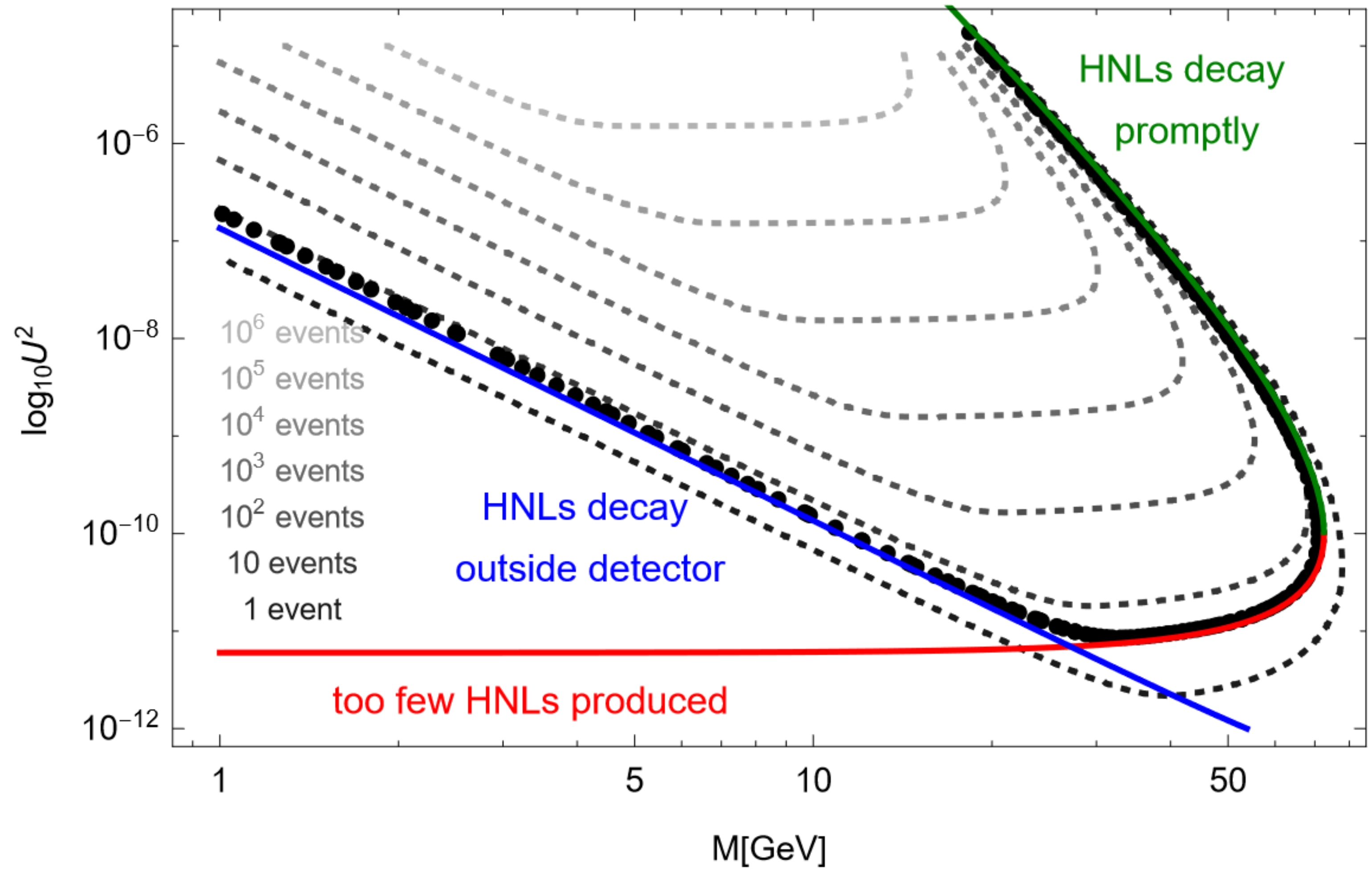


MaD 2210.17110

Sensitivity Region

$$U^2_{\rm max} = \frac{W_{-1}\left(XY\right)}{X} \simeq \frac{\log\left(XY\right)}{X}$$

$$U^2_{\rm min} = \frac{W_{0}\left(XY\right)}{X} \simeq Y$$



$$U^2_{\rm min} = \frac{2^{1/6}3^{1/3}8\pi^{3/2}(\mathrm{p}_N Y)^{1/2}}{(a c_{\rm dec})^{1/2} G_F M^3 d_{\rm cyl}^{1/3} l_{\rm cyl}^{1/6}} \simeq \sqrt{\frac{N_{\rm obs}}{\mathrm{u}_\alpha^2 \mathrm{u}_\beta^2}}\frac{57}{G_F M^3}\sqrt{\mathrm{p}_N} d_{\rm cyl}^{-1/3} l_{\rm cyl}^{-1/6}\left(\epsilon_{\alpha\beta} N_Z N_{\rm IP} a c_{\rm dec} c_{\rm prod} \Pi\right)^{-1/2}$$

$$Y = \frac{U^2 N_{\rm obs}/\mathrm{u}_\beta^2}{\epsilon_{\alpha\beta} N_{\rm HNL\alpha}} = \frac{N_{\rm obs}/(\mathrm{u}_\alpha^2 \mathrm{u}_\beta^2)}{2\epsilon_{\alpha\beta}\mathrm{B}_\alpha c_{\rm prod} N_{\rm IP}\Pi N_Z} \qquad X = \frac{l_0}{U_\beta^2 \lambda_N} = -\frac{a G_F^2 l_0 M^6 c_{\rm dec}}{96 \mathrm{p}_N \pi^3}$$

MaD 2210.17110

Conclusions

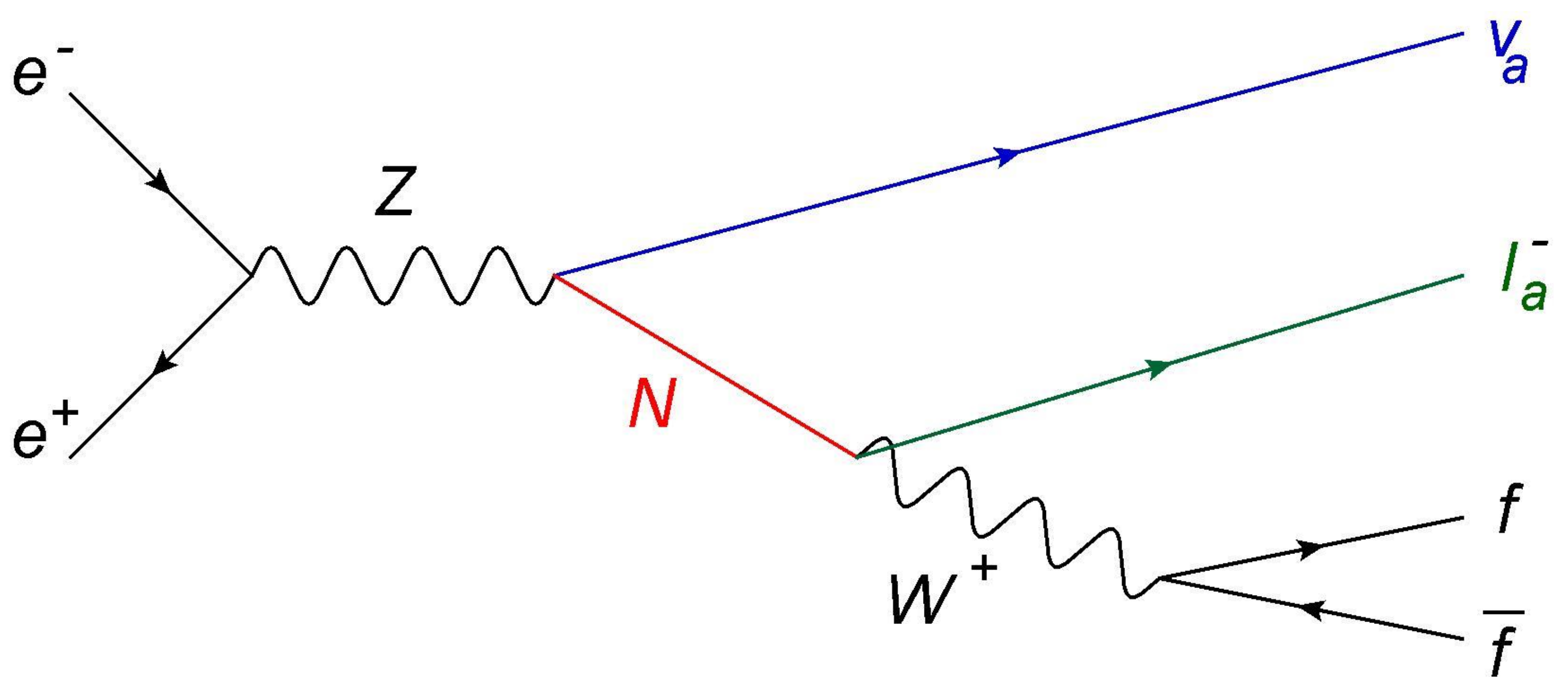
- HNLs at FCC-ee, CEPC are predominantly produced during Z-pole run
- Very simple process (Z are at rest, HNL produced in two body decay) makes analytic estimates for decay length, number of events, and sensitivity region very accurate
- Permits to estimate impact of detector geometry, extra detectors, number of IP, integrated luminosity without need for simulations!
- Approach should also work for other LLPs with two-body kinematics

Backup Slides

Majorana nature of HNLs: Can LNV decay be observed?

B-L symmetry: destructive interference amongst different HNL flavours

But: B-L is broken to generate neutrino mass. Is this enough???
long-lived HNLs:
HNL oscillations in detector can destroy coherence and make LNV observable!



- **Crucial quantity: relation between decay length and oscillation length**

  e.g. Anamiati et al 1607.05641

$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

- **Quasi-degenerate HNLs kinematically indistinguishable, behave like one particle with non-integer *Rll***

cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367, 2012.05763

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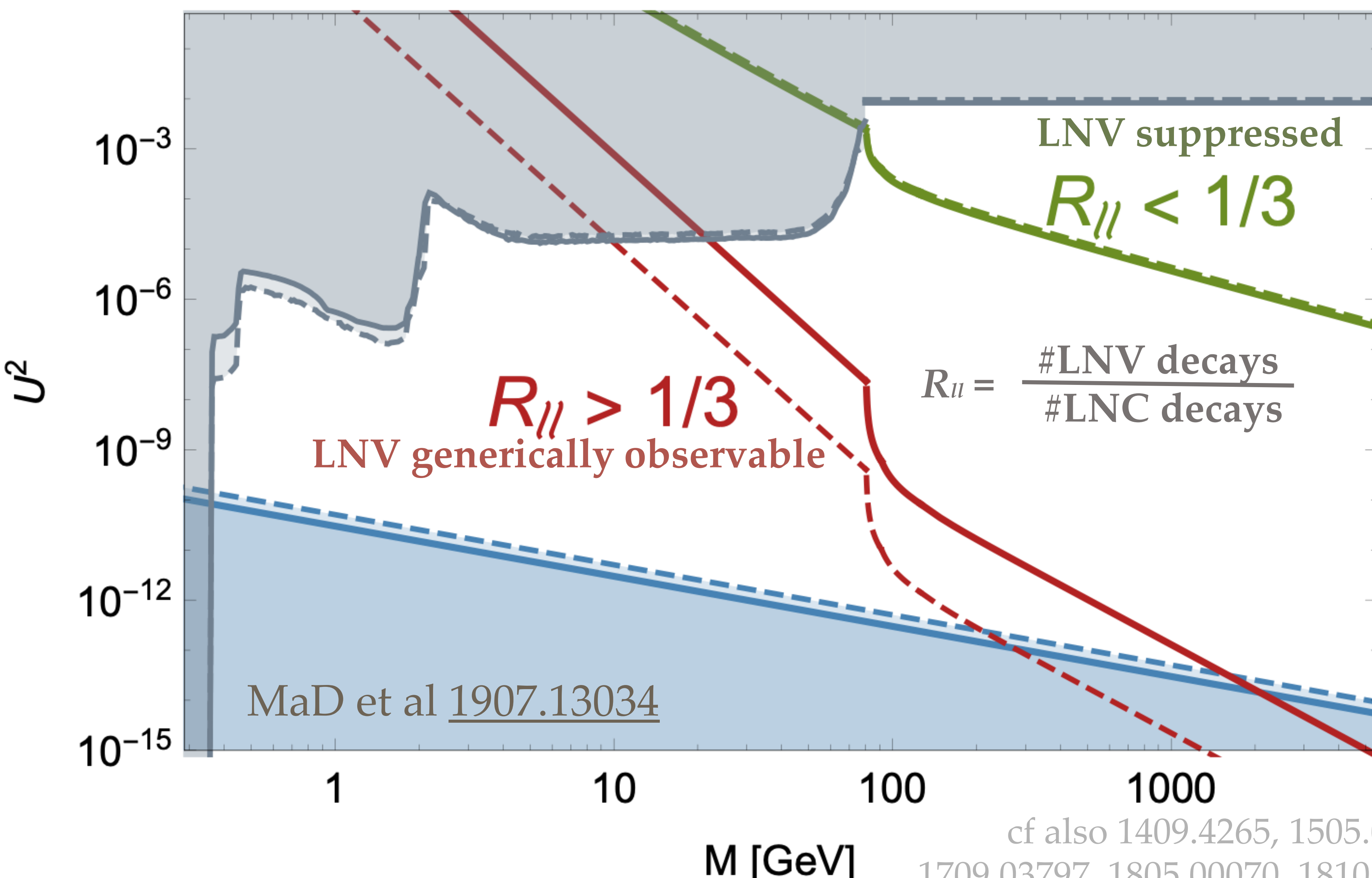

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$$\mathcal{R}_{\ell\ell} = \frac{\Delta M^2_{\rm phys}}{2\Gamma_N^2 + \Delta M^2_{\rm phys}}$$

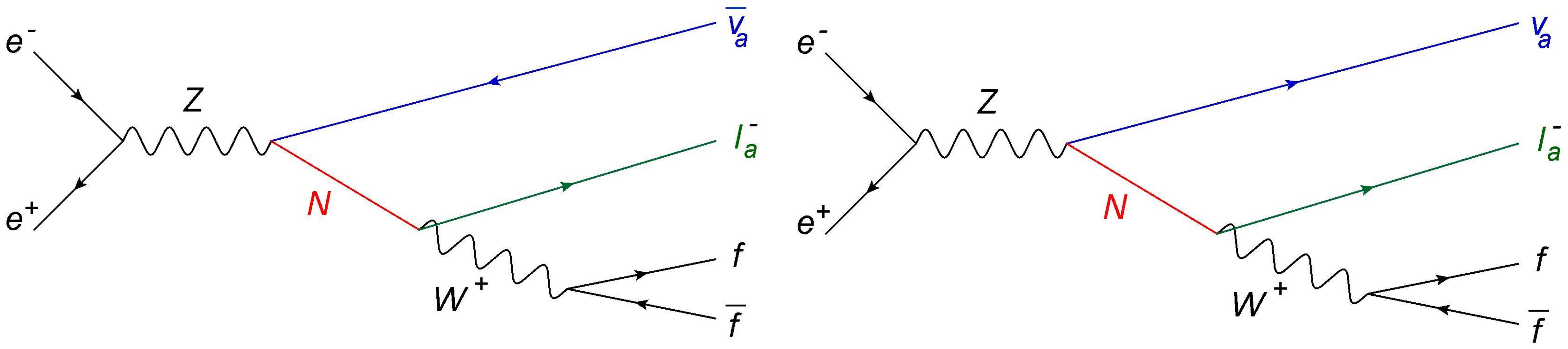
- **Does neutrino osc. data allow to see LNV this without fine tuning?**

  It depends

  MaD/Klaric/Klose 1907.13034

cf also 1409.4265, 1505.04749, 1605.01123, 1709.06553, 1703.01934, 1709.03797, 1805.00070, 1810.07210, 1905.03097, 1904.05367, 2012.05763

LNV at Lepton Colliders



- Largest event numbers: displaced vertices in *Z*-pole run
- Neutrino in final state unobservable
- Rely on indirect methods 2) – 4)
- 4-momentum of *N* can still be fully reconstructed

Blondel et al 1411.5230

Blondel et al 2105.06576 Alimena et al 2203.05502

How to practically distinguish Dirac from Majorana *N*?

1) Direct observation of LNV in fully reconstructed final state
2) Angular distribution of final state particles
3) Polarisation of final state particles
4) Lifetime of N