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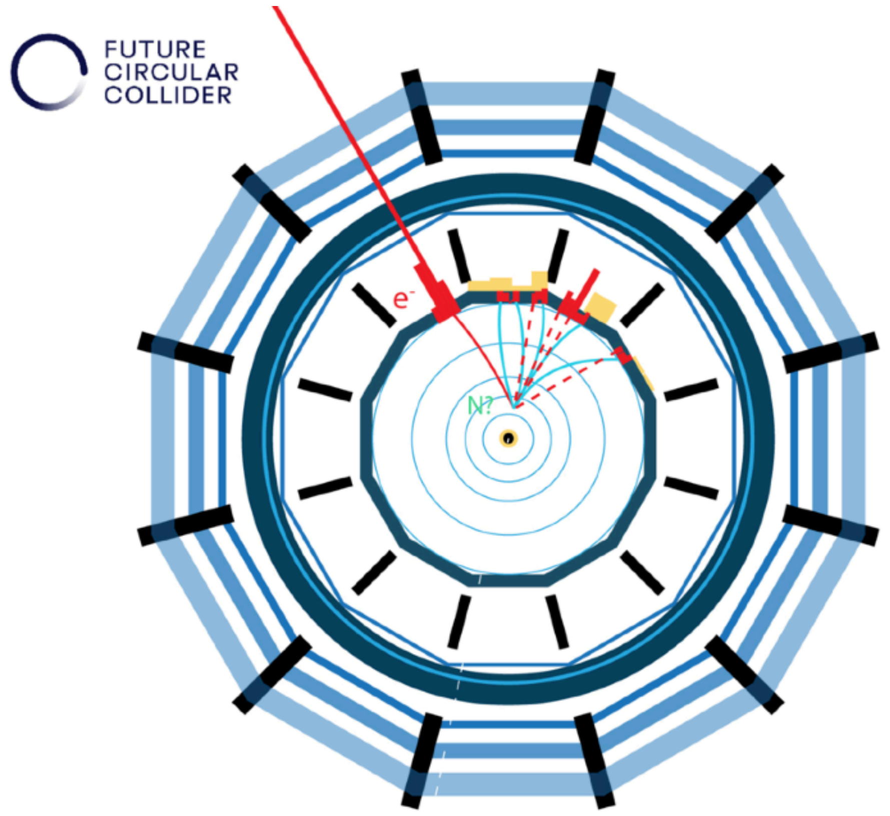
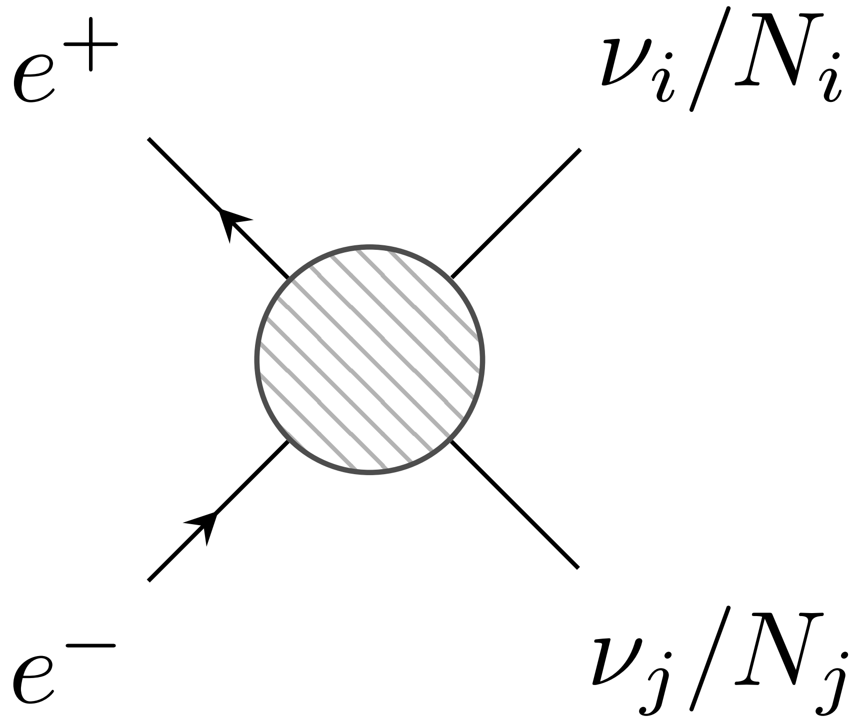




Constraining the SMEFT extended with sterile neutrinos at FCC-ee

Patrick Bolton (Jožef Stefan Institute)

In collaboration with: Frank Deppisch (UCL), Suchita Kulkarni (NAWI Graz),
Chayan Majumdar (UCL), Wenna Pei (UCL/Eötvös Loránd U.)

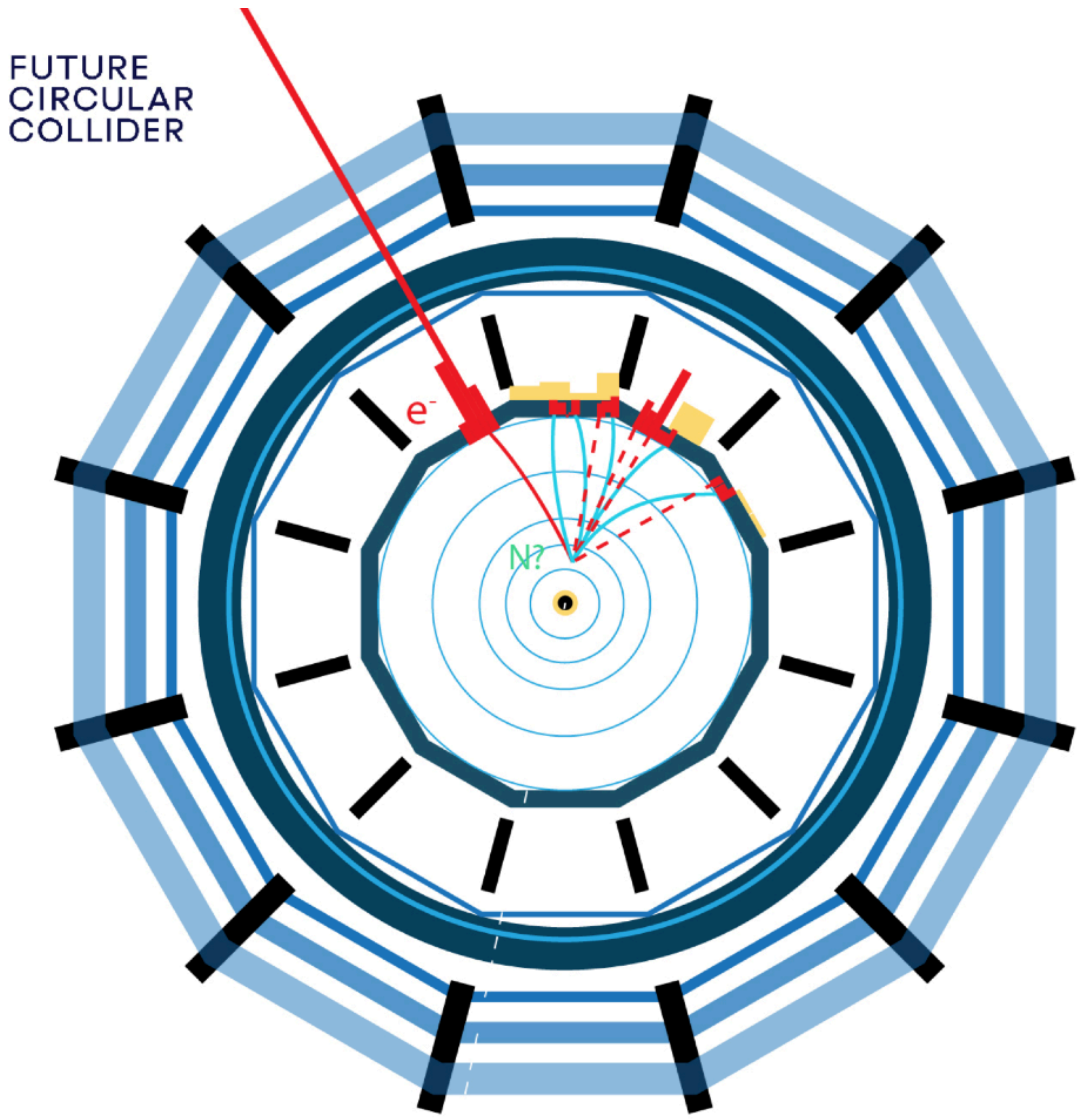
To appear soon on arXiv

Future Circular e^+e^- Collider (FCC-ee)

FUTURE CIRCULAR COLLIDER

Searches for Majorana/Dirac Heavy Neutral Leptons (HNLs) can be conducted at FCC-ee

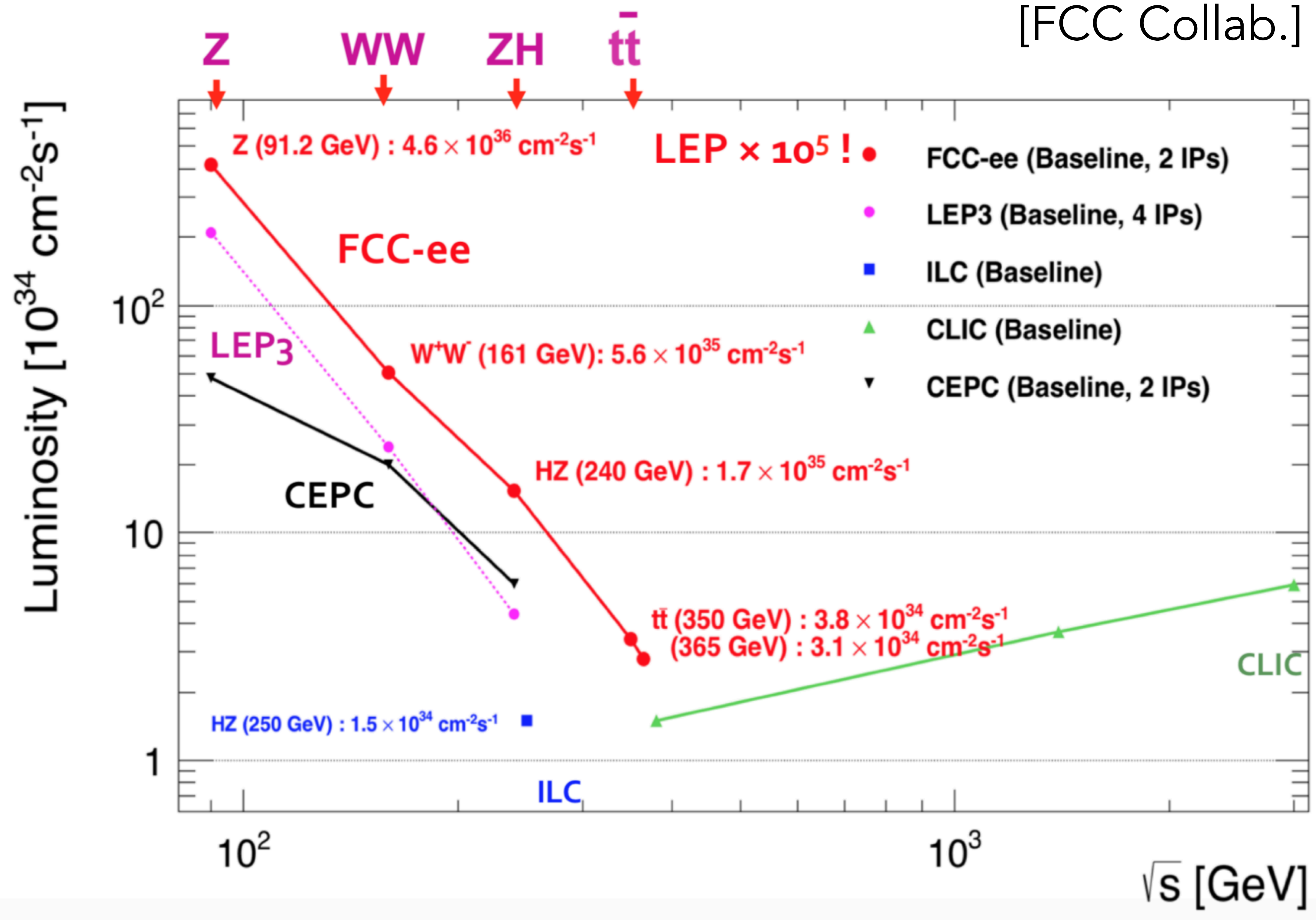
$$-Y_\nu \bar{L} N_R \tilde{H} - \frac{1}{2} M_R \bar{N}_R^c N_R + \text{h.c.}$$



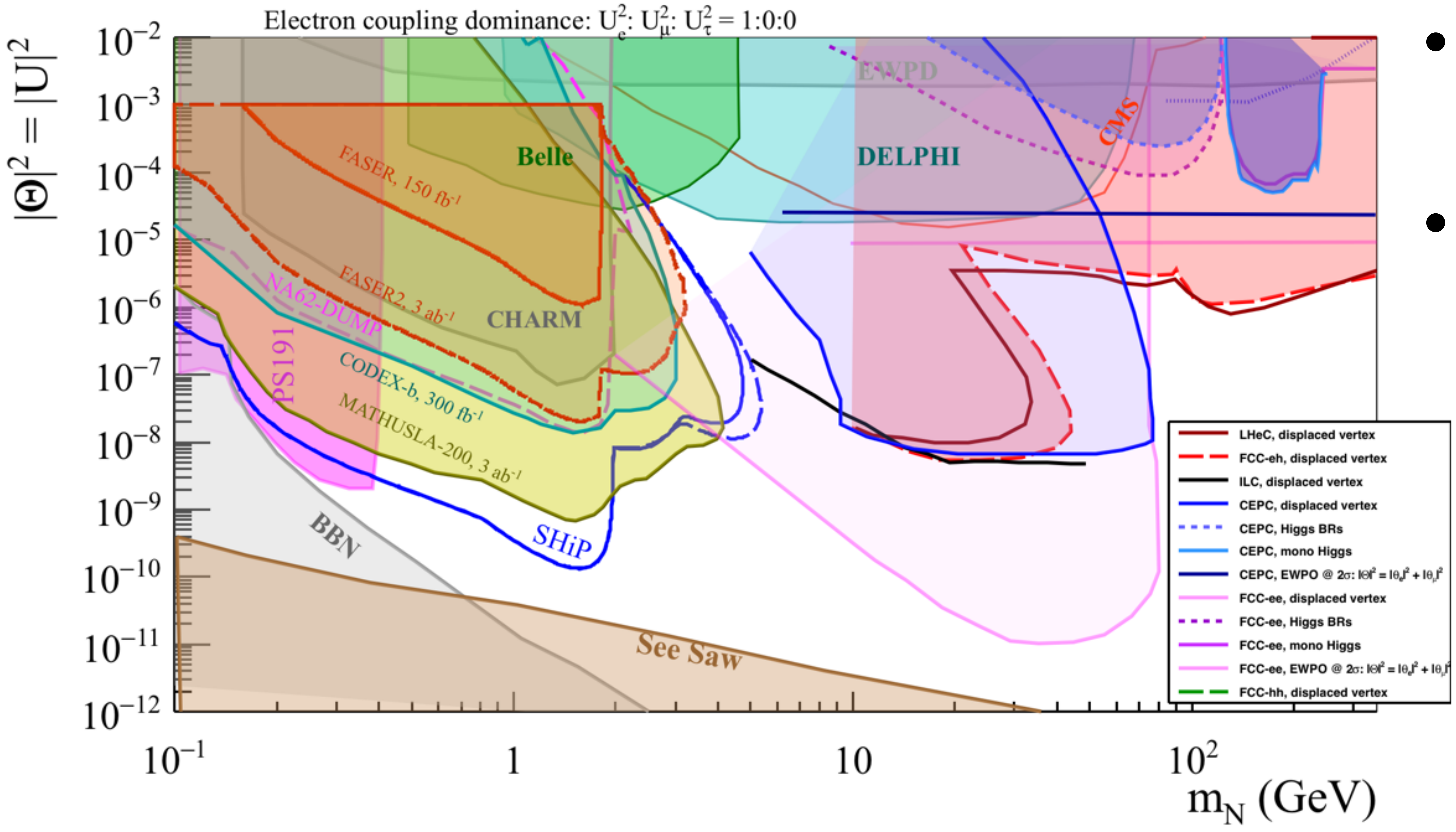
FCC-ee:

- Post-LHC accelerator following priorities set by the '2020 Update of the European Strategy for Particle Physics'
- 2025: Completion of the FCC Feasibility Study
- 15 year run at four centre of mass energies
  - → $\sqrt{s} = 91.2$ GeV, $\mathscr{L} = 100 - 150$ ab^{-1}
    'Tera-Z run', 5×10^{12} Z bosons
  - → $\sqrt{s} = 240$ GeV, $\mathscr{L} = 5$ ab^{-1}
    'ZH run', 2×10^6 Zh events

[FCC Collab.]



Future Circular e^+e^- Collider (FCC-ee)



[European Strategy for Particle Physics Preparatory Group, Update 2020]

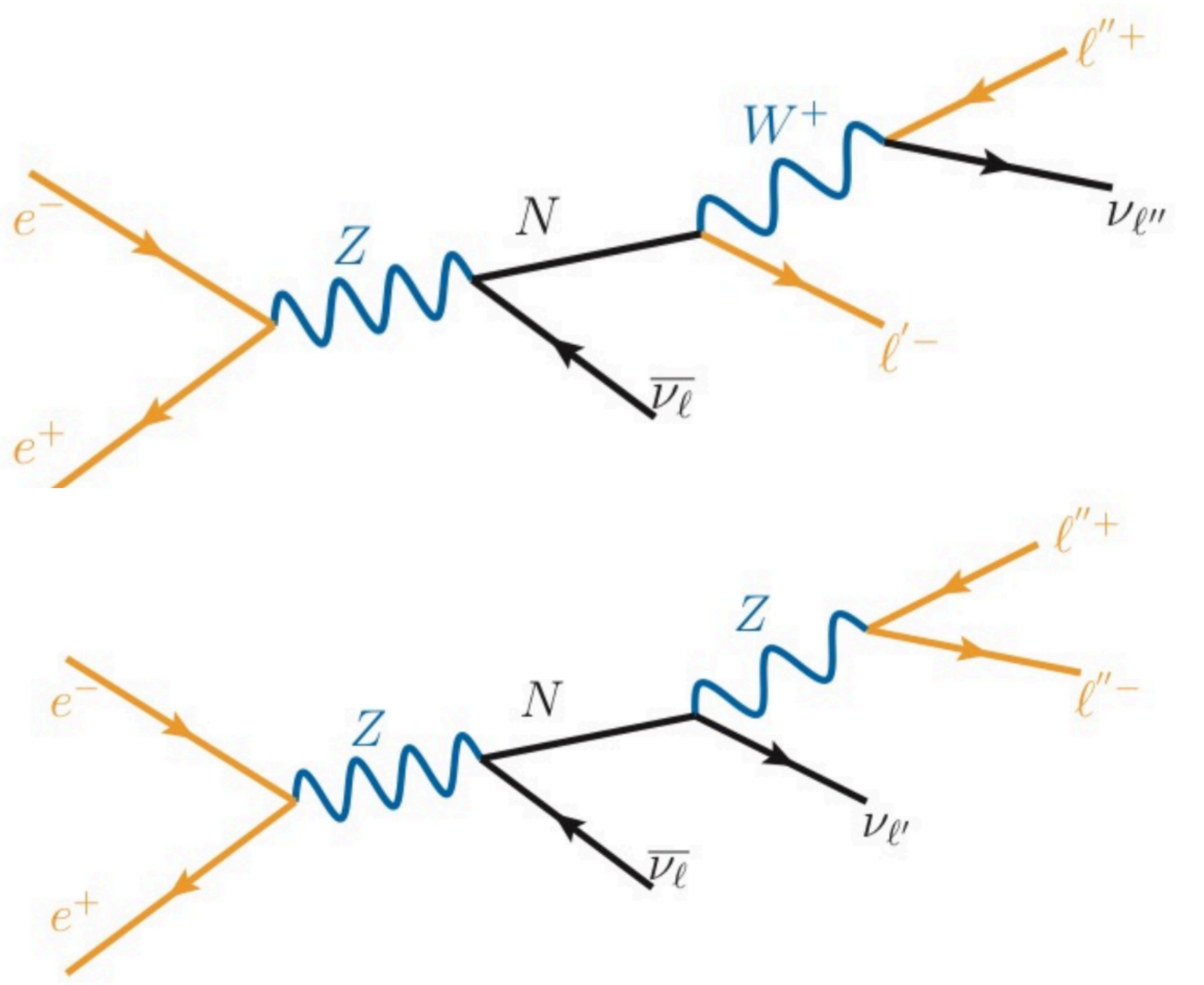
HNL production and decay via $V_{\ell N}$

- HNLs are long-lived (LLPs)
- Displaced vertex search $N \to \ell W^* \to \ell jj$

  [Blondel, Graverini, Serra, Shaposhnikov, 14]

- Displaced vertex search $N \to \nu\ell\ell$

  [Alimena et al., 22]



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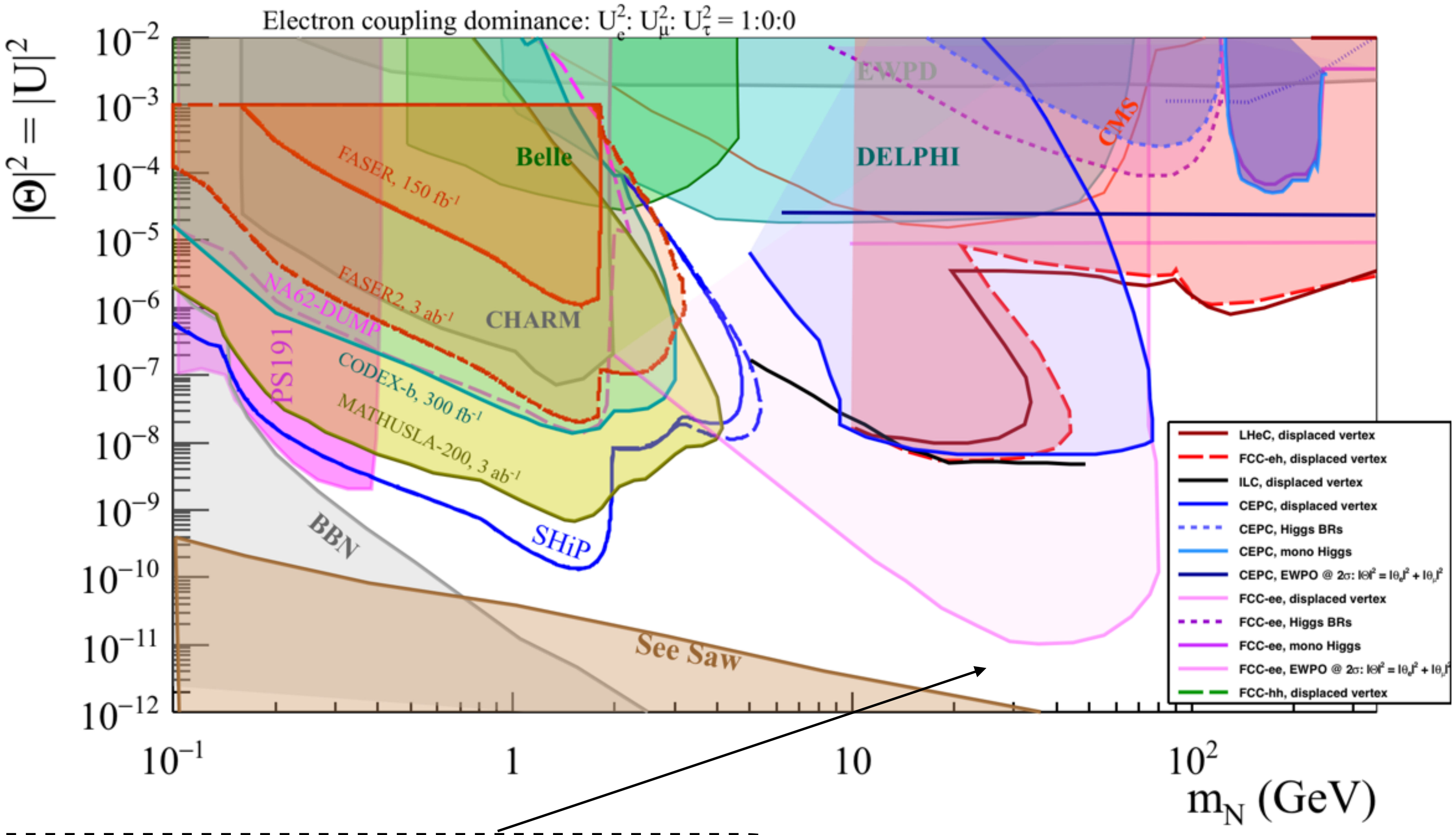
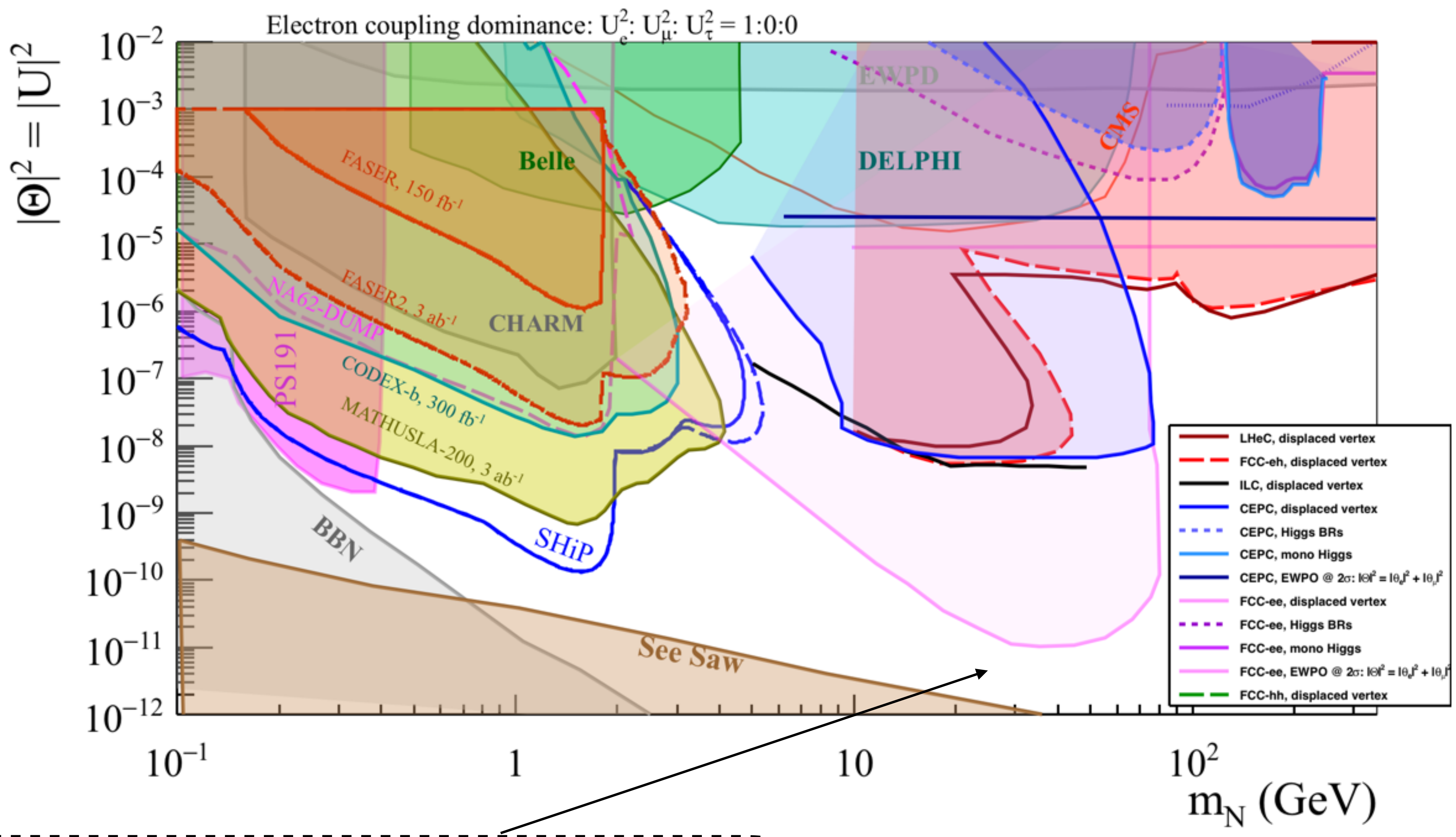


Active-sterile mixing (electroweak production of HNLs) could be below reach of FCC-ee

Future Circular e^+e^- Collider (FCC-ee)



Active-sterile mixing (electroweak production of HNLs) could be below reach of FCC-ee

Could heavy new physics instead mediate HNL interactions observable to FCC-ee?

νSMEFT at FCC-ee: four-fermion operators

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}+N_R} + \sum_i C_i^{(d)} \mathcal{O}_i^{(d)}$$

$$C_i^{(d)} \propto \Lambda^{4-d}$$

$d = 6$

$C_i = \dfrac{1}{\Lambda^2}$

$\Delta L = 0$

ψ^4	
$\mathcal{O}_{ll}$	$(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$
$\mathcal{O}_{le}$	$(\bar{L}\gamma_\mu L)(\bar{e}_R\gamma^\mu e_R)$
$\mathcal{O}_{lNle}$	$\epsilon_{ij}(\bar{L}^i N_R)(\bar{L}^j e_R)$
$\mathcal{O}_{lN}$	$(\bar{L}\gamma_\mu L)(\bar{N}_R\gamma^\mu N_R)$
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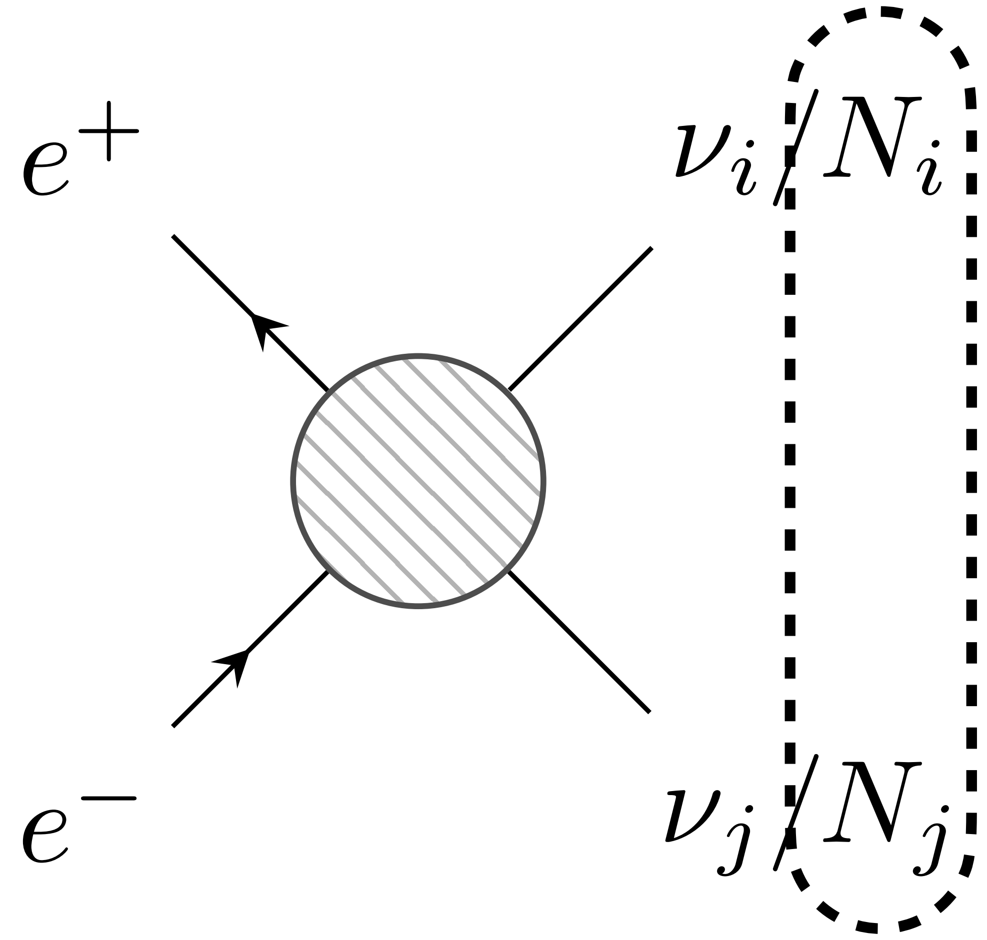

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$\Delta L = \pm 2$

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$\mathcal{O}_{lNlH}$	$\epsilon_{ij}(\bar{L}\gamma_\mu L)(\bar{N}_R^c\gamma^\mu L^i)H^j$
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$\mathcal{O}_{elNH}$	$H^\dagger(\bar{e}_R L)(\bar{N}_R^c N_R)$

Vector: $C_{Ne}^{V,RR}(\bar{N}_R\gamma_\mu N_R)(\bar{e}_R\gamma^\mu e_R)$ $\quad C_{Ne}^{V,RL}(\bar{N}_R\gamma_\mu N_R)(\bar{e}_L\gamma^\mu e_L)$

Scalar: $C_{Ne}^{S,RR}(\bar{N}_R^c N_R)(\bar{e}_L e_R)$ $\quad C_{Ne}^{S,RL}(\bar{N}_R^c N_R)(\bar{e}_R e_L)$

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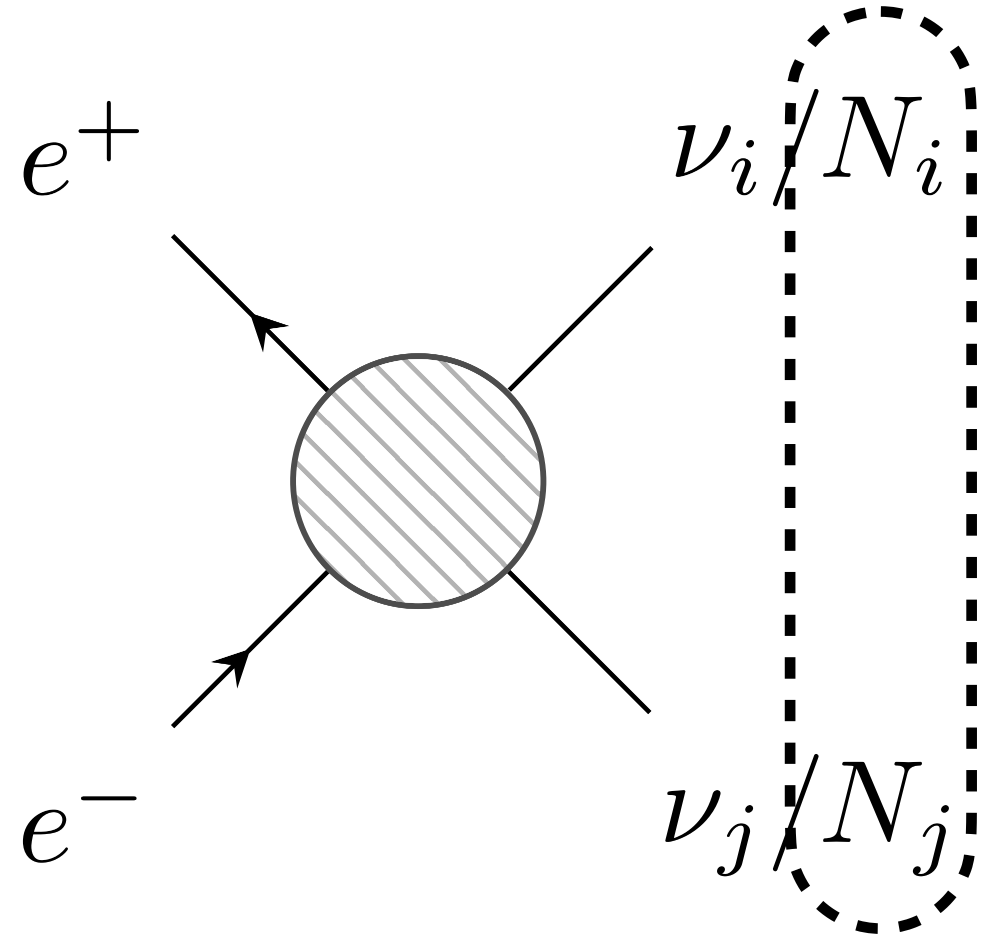

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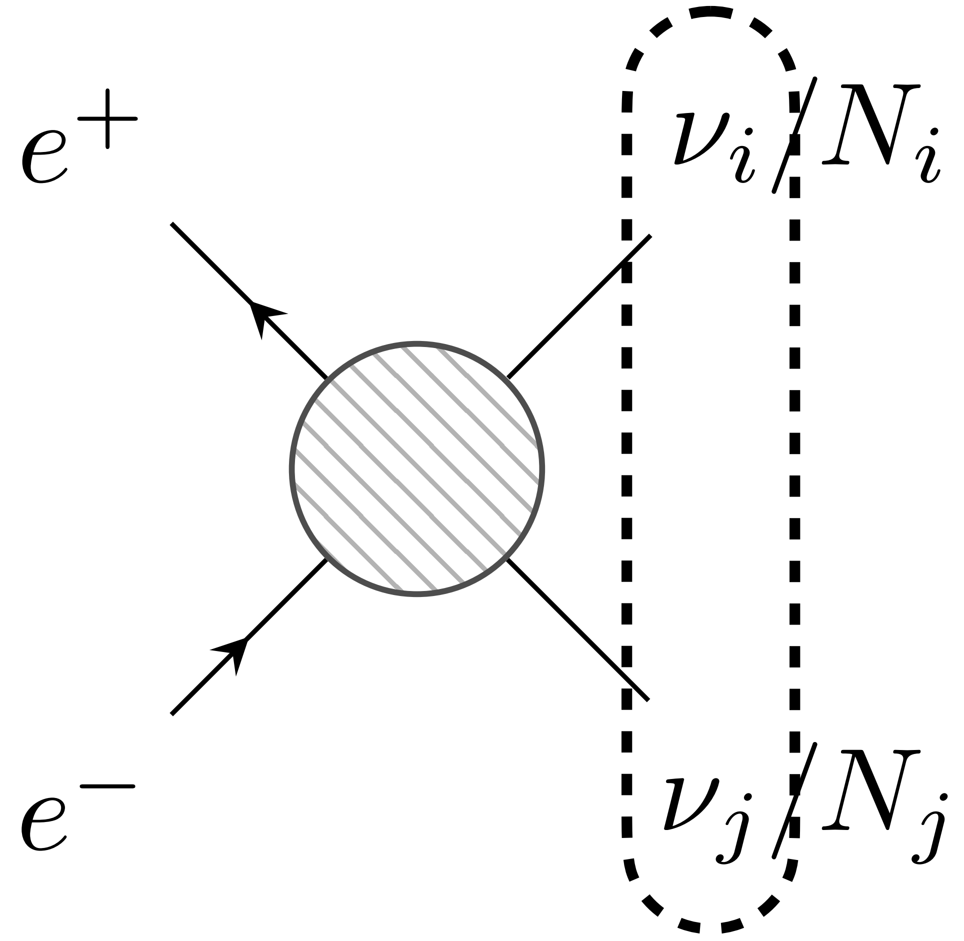
Constrained by **cLFV** processes:
$\mu \to eee$ ($\Lambda \gtrsim 150$ TeV, SINDRUM),
$\tau \to eee$, $\tau \to \mu ee$ ($\Lambda \gtrsim 10$ TeV, Belle)



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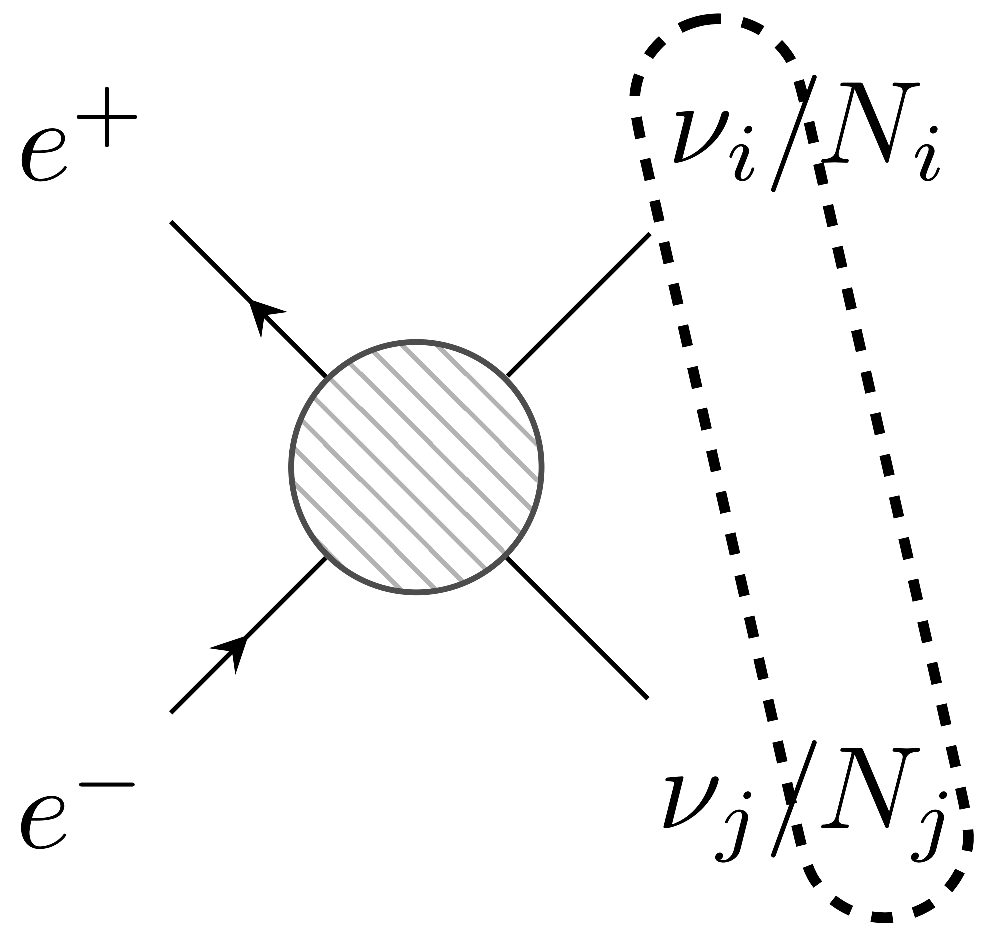

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Tensor: $C_{\nu Ne}^{T,RR}(\bar{\nu}_L\sigma_{\mu\nu}N_R)(\bar{e}_L\sigma^{\mu\nu}e_R)$

Note: Weak basis EFT operators → mass basis

No mixing between $\nu\nu$, νN, NN operators for $V_{\ell N} \to 0$

νSMEFT at FCC-ee: effective neutral- and charged-currents

$d = 6$

$C_i = \dfrac{1}{\Lambda^2}$

$\Delta L = 0$

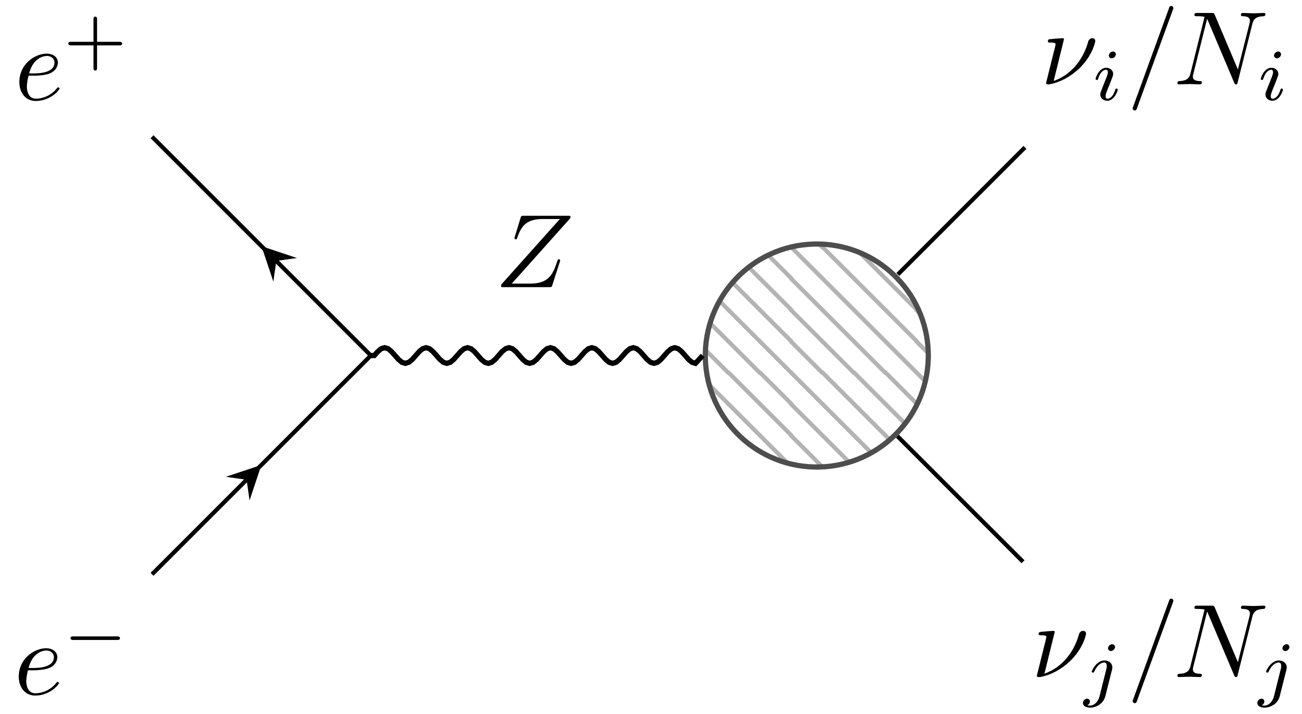
$\psi^2 H^2 D$	
$\mathcal{O}_{Hl}^{(1)}$	$(\bar{L}\gamma_\mu L)(H^\dagger i \overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{Hl}^{(3)}$	$(\bar{L}\gamma_\mu \tau^I L)(H^\dagger i \overleftrightarrow{D}^{I\mu} H)$
$\mathcal{O}_{HN}$	$(\bar{N}_R\gamma_\mu N_R)(H^\dagger i \overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{HNe}$	$(\bar{N}_R\gamma_\mu e_R)(\tilde{H}^\dagger i \overleftrightarrow{D}^\mu H)$

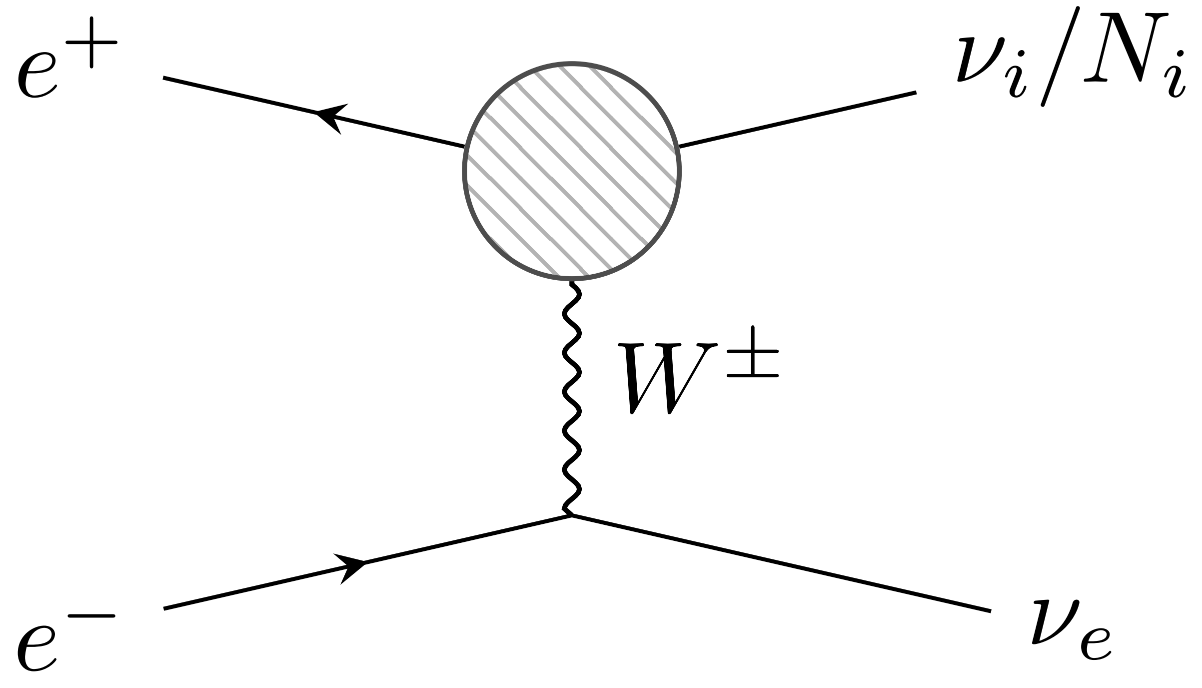
$d = 7$

$C_i = \dfrac{1}{\Lambda^3}$

$\Delta L = \pm 2$

$\psi^2 H^3 D$	
$\mathcal{O}_{Nl1}$	$\epsilon_{ij}(\bar{N}_R^c\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
$\mathcal{O}_{Nl2}$	$\epsilon_{ij}(\bar{N}_R^c\gamma_\mu L^i)H^j(H^\dagger i \overleftrightarrow{D}^\mu H)$
$\mathcal{O}_{leHD}$	$\epsilon_{ij}\epsilon_{mn}(\bar{L}^{ic}\gamma_\mu e_R)H^j H^m D^\mu H^n$





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Constrained by Electroweak Precision Data (EWPD)

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$\Delta L = \pm 2$

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$\mathcal{O}_{Nl1}$	$\epsilon_{ij}(\bar{N}_R^c\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
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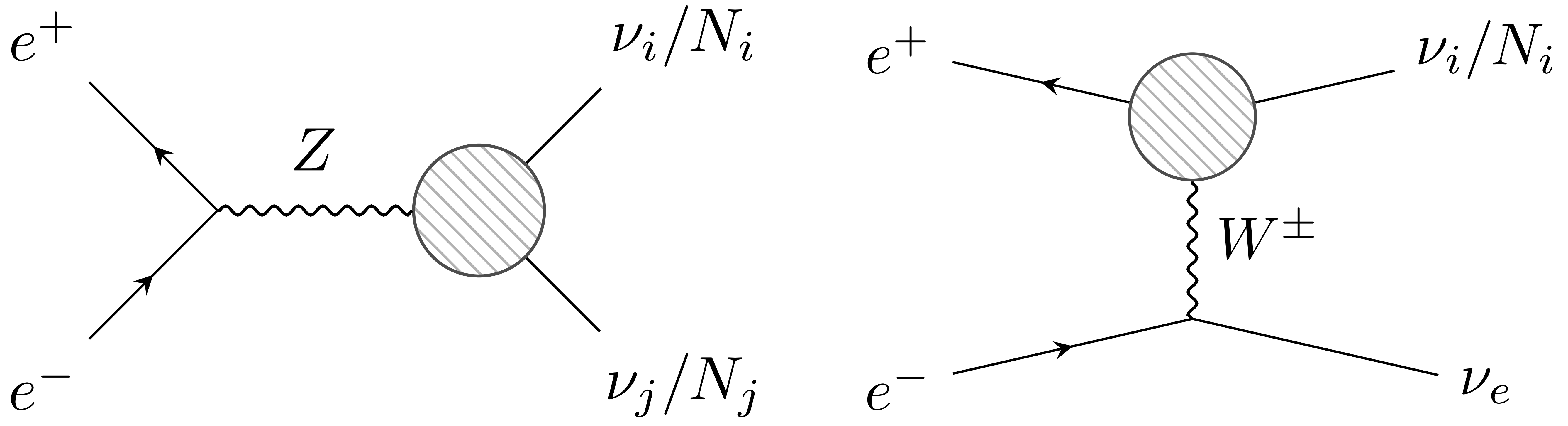
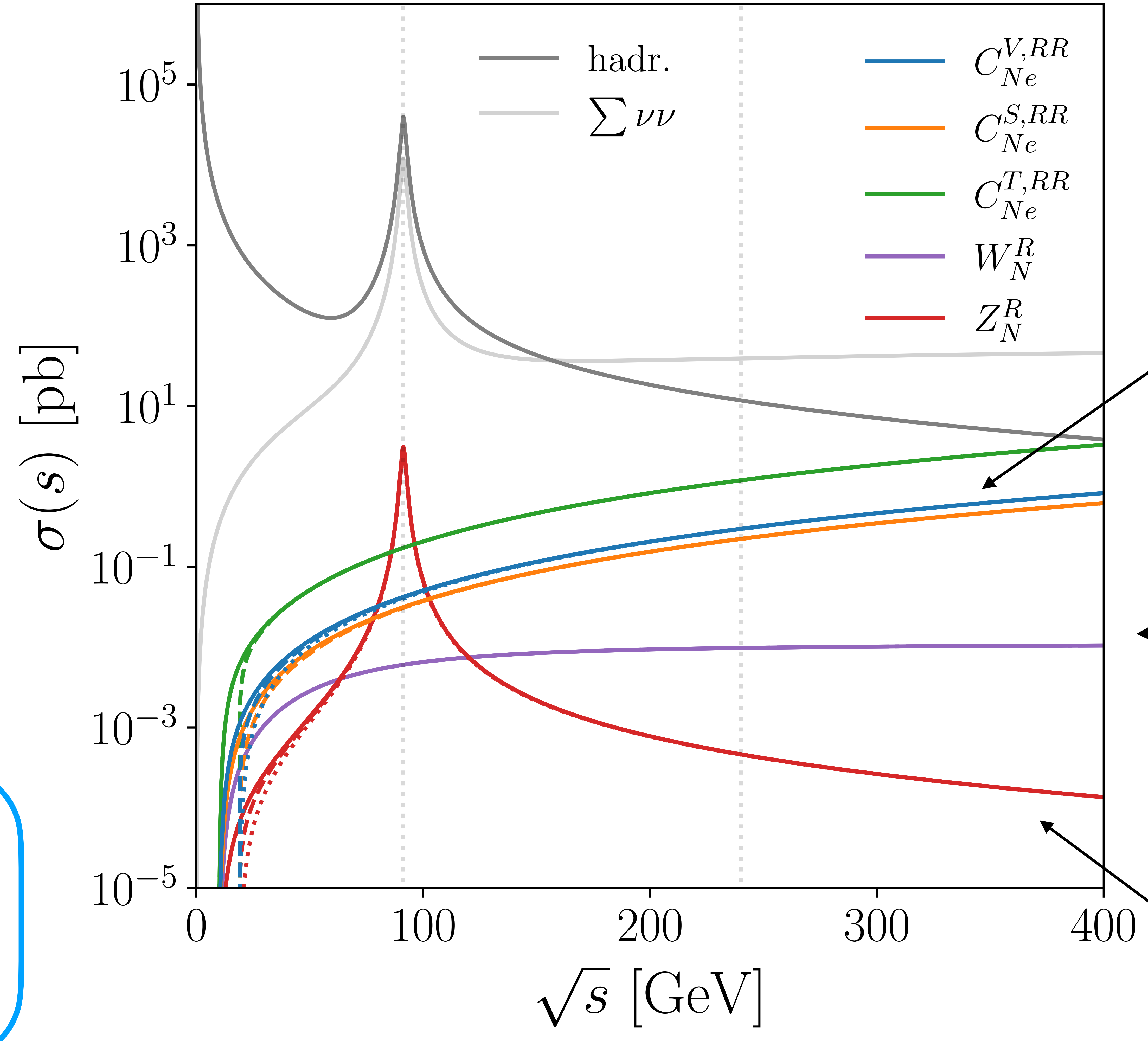


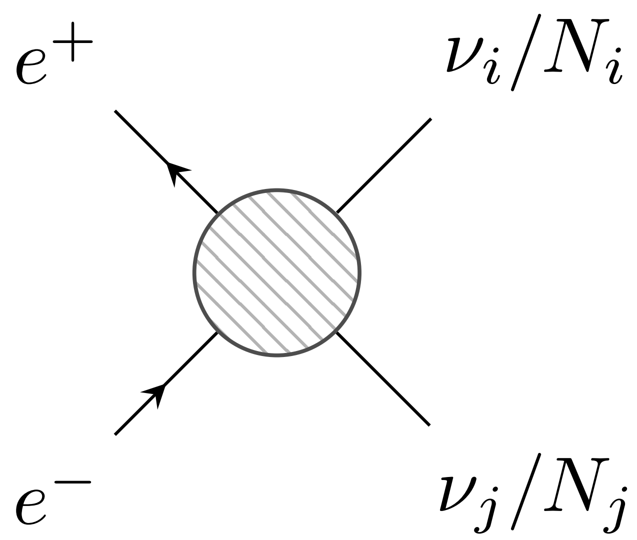
HNL production cross sections

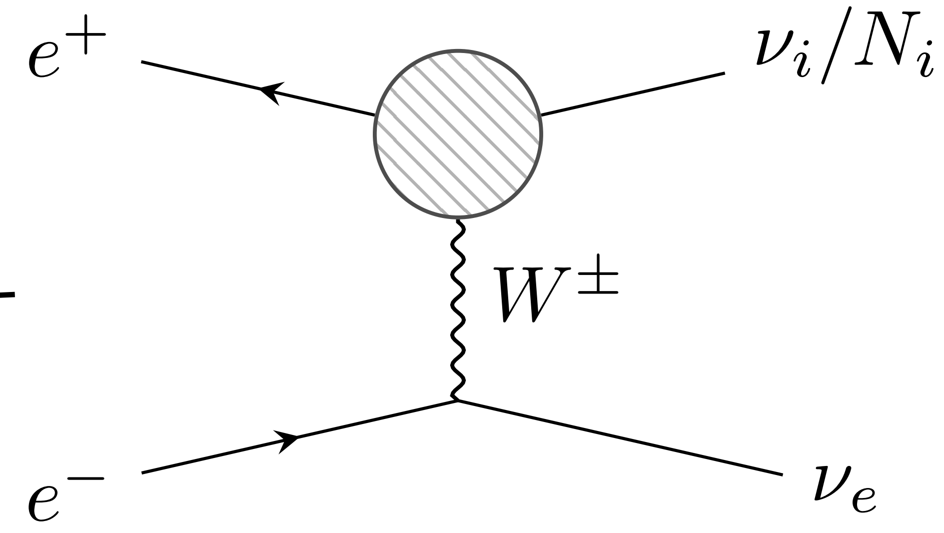
$$\sigma(s) = \int_{-1}^{1} \frac{d\sigma}{dc_\theta} dc_\theta$$

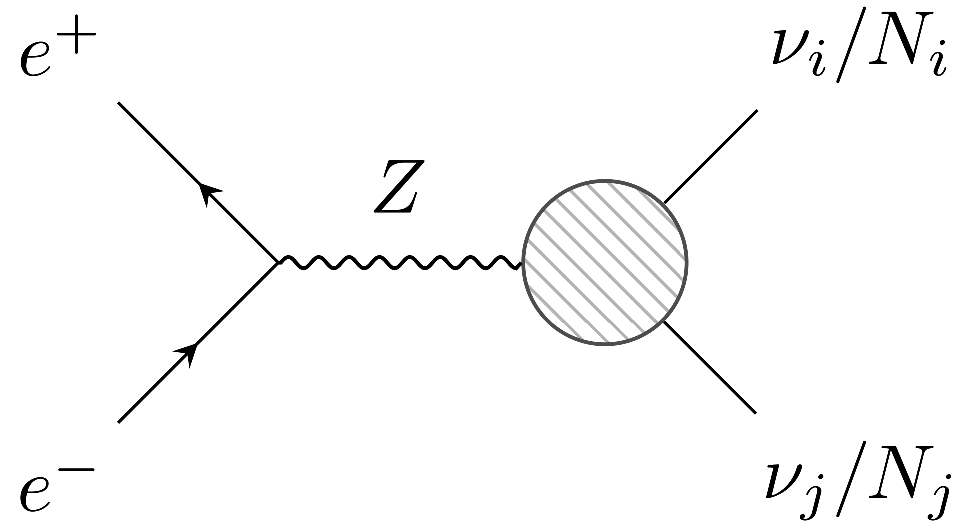
Calculated at LO, including all interference terms, neglecting m_e

For cut-based analysis, EFT operators implemented in `Feynrules` and simulated in `MadGraph_aMC@NLO`





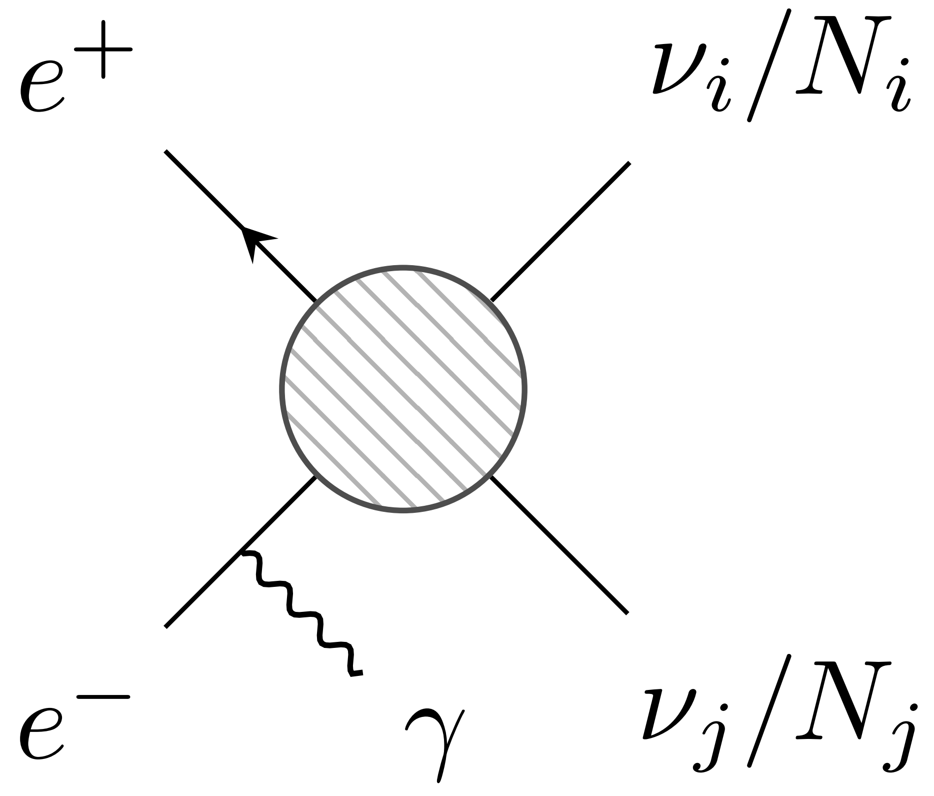




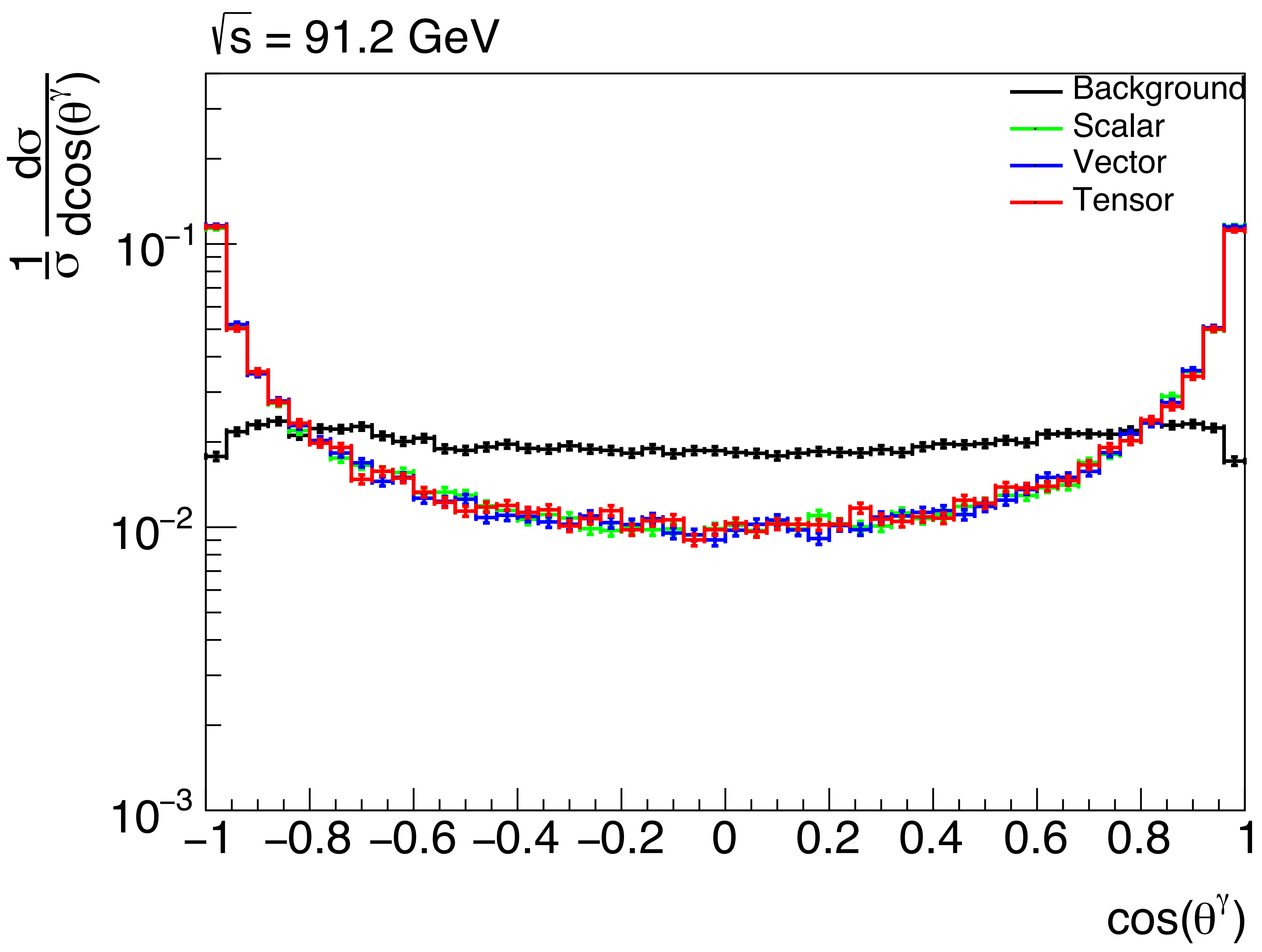
Monophoton analysis

HNLs produced and decay via EFT operators:

- HNLs long-lived and decay outside detector, monophoton plus $E_{\rm miss}$ signal
- Can be used to constrain νSMEFT operator coefficients C_i
- Apply cuts to minimise SM background ($e^+e^- \to \nu\bar{\nu}\gamma$)
- Require HNL *not* to decay inside detector ($\beta\gamma c\tau > 5$ m)



$$\delta = \frac{m_{N_2} - m_{N_1}}{m_{N_2}}$$



$\sqrt{s}$	Cuts
91.2	$\lvert\cos(\theta)\rvert < 0.4$ and $\lvert\cos(\theta)\rvert > 0.8$
240	$\lvert\cos(\theta)\rvert < 0.95$ $E_\gamma < 40$ GeV

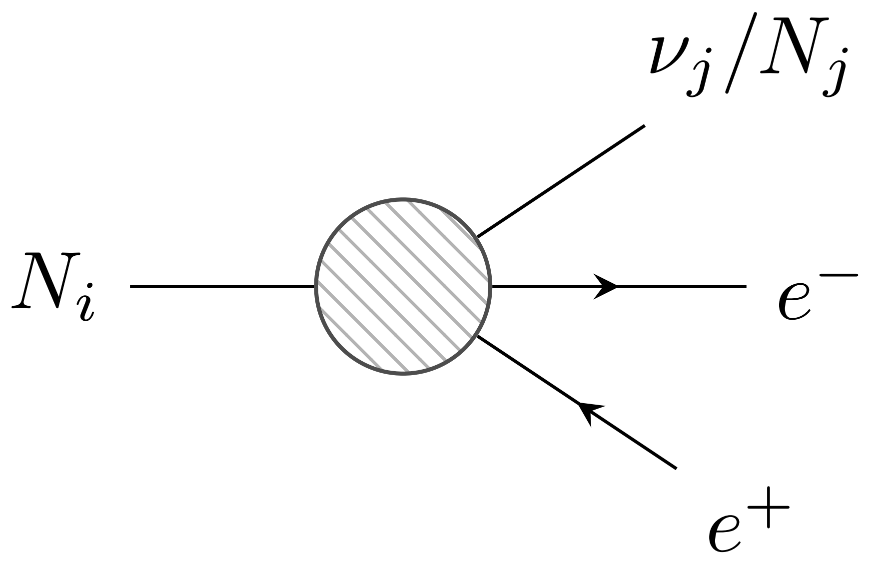
Consider bounds on 'diagonal' and 'off-diagonal' couplings

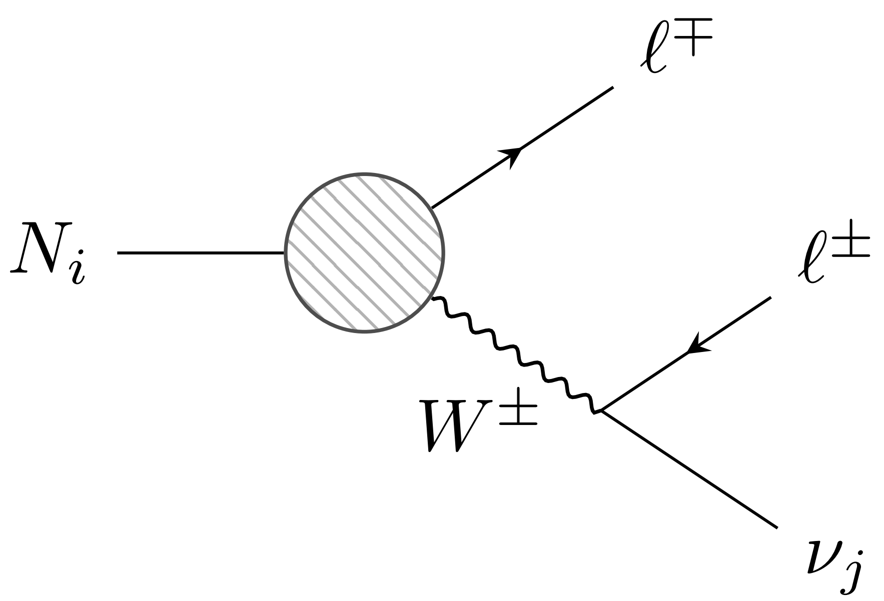
$$N_{\rm sig} = \mathcal{L}\cdot\sigma(s)\cdot\epsilon_{\rm cuts}\cdot\epsilon_{\rm decay} \qquad \mathcal{S} \approx \frac{N_{\rm sig}}{\sqrt{N_{\rm bkg}}}$$

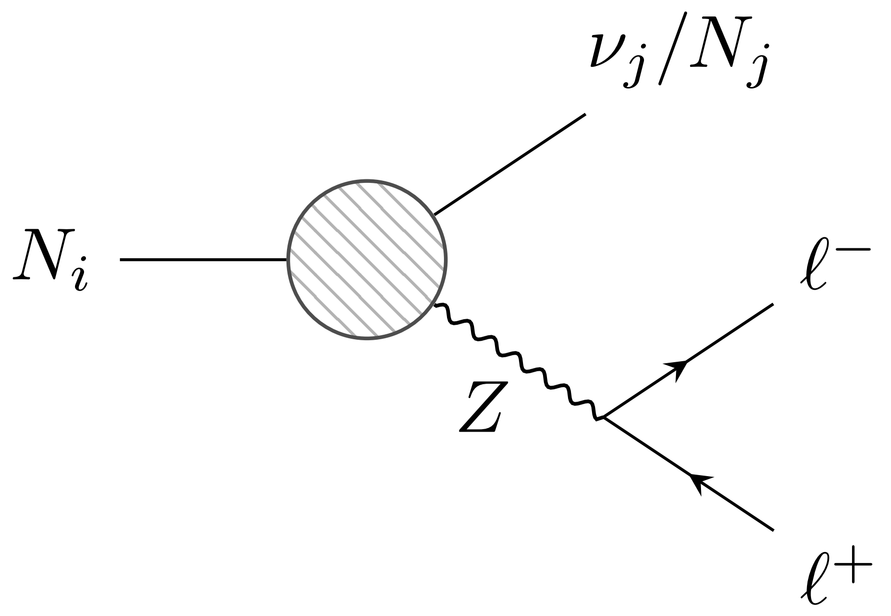
Displaced vertex analysis

If the HNLs are produced and decay via EFT operators:

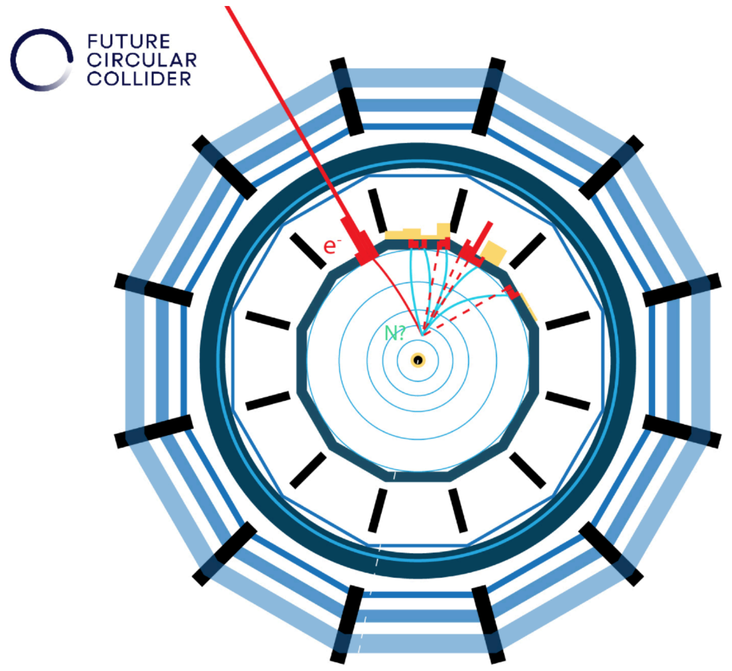
- HNLs long-lived and decay inside detector, displaced vertex (DV) signal
- Complimentary constraint on νSMEFT operator coefficients C_i
- Decays considered: $N_2 \to N_1 e^- e^+$ and $N_2 \to \nu e^- e^+$
- Cuts on $e^\pm$ track transverse impact parameter $|d_0|$ minimise SM backgrounds

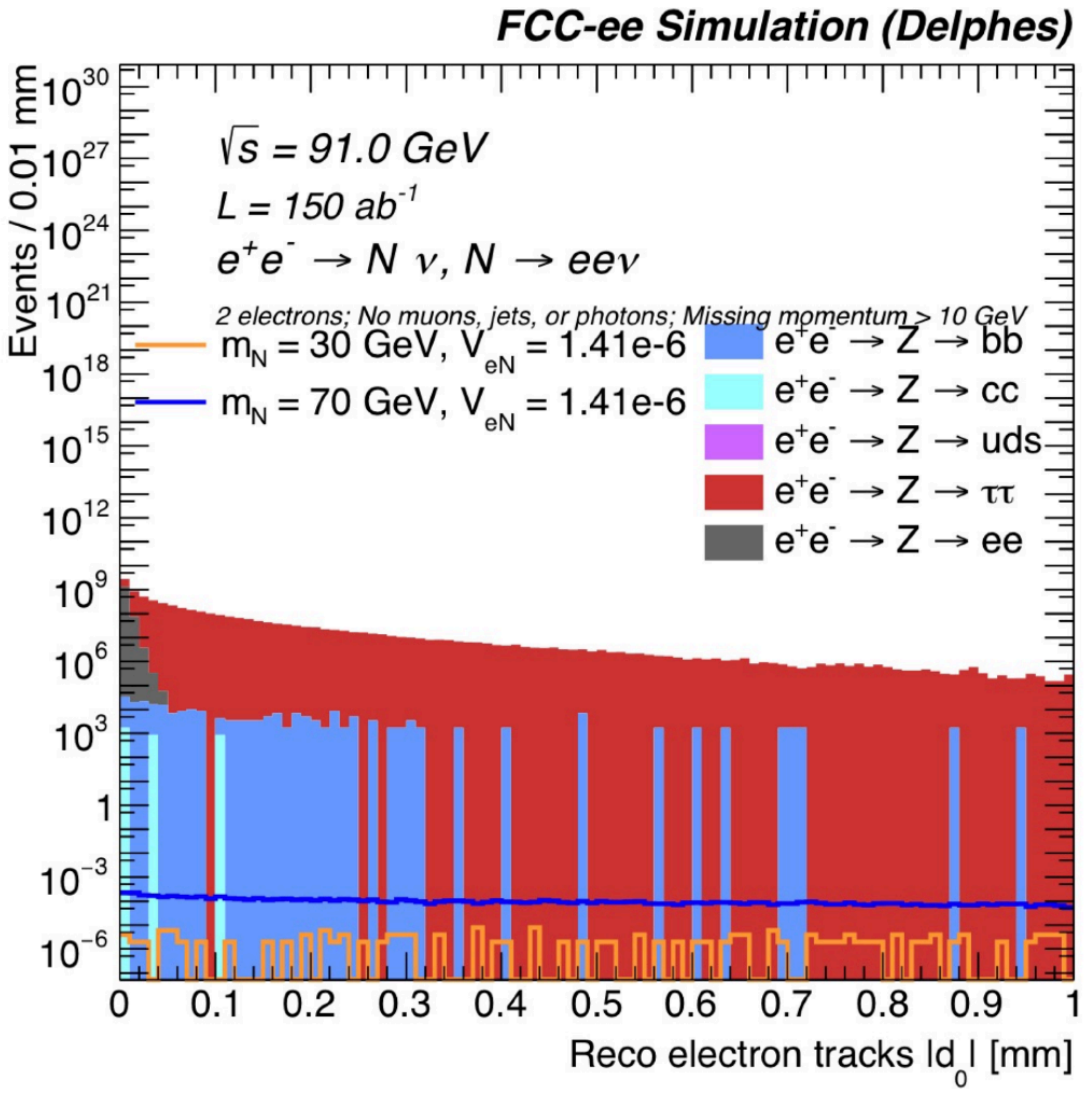


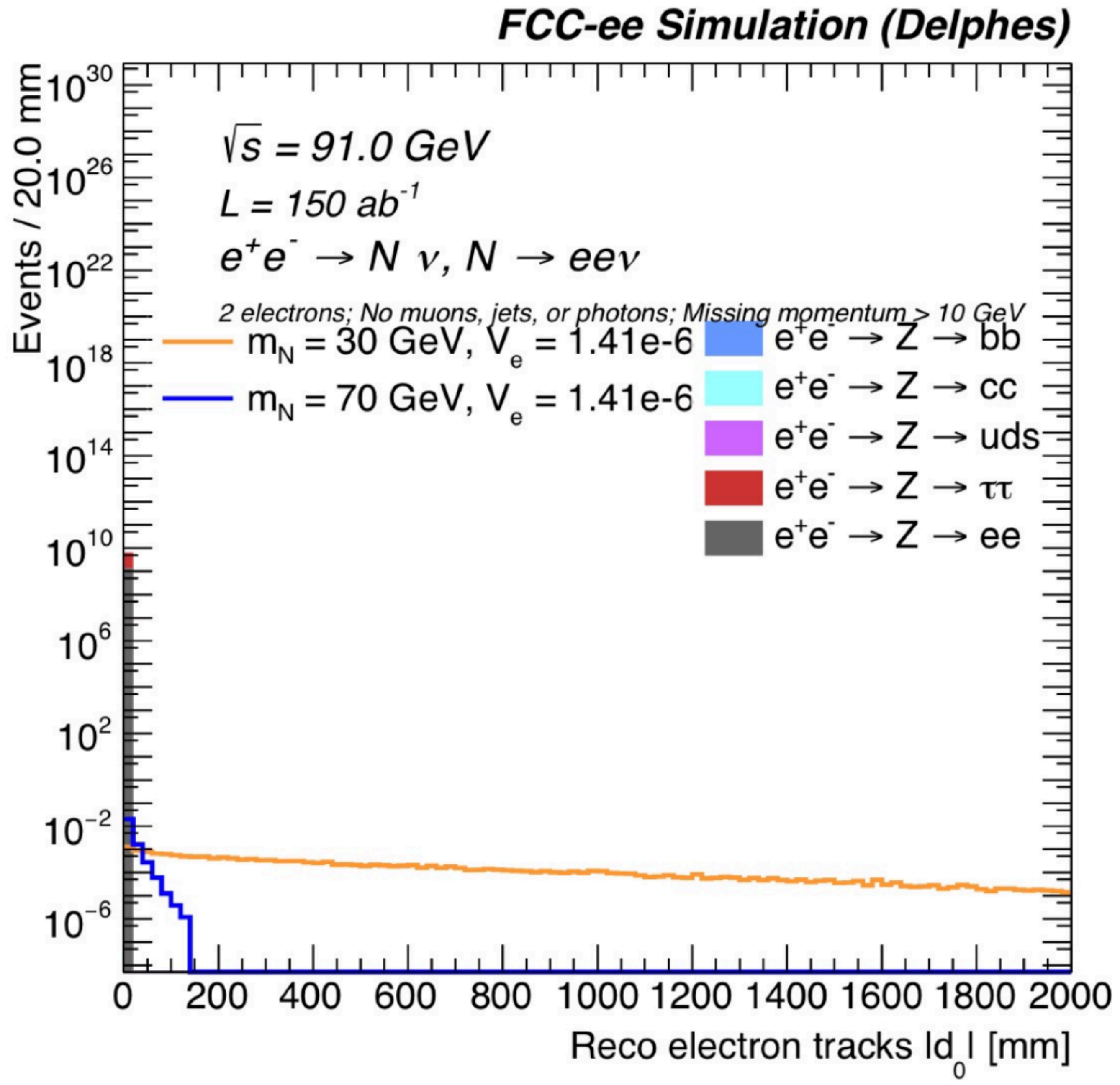




$$N_{\rm sig} = \mathcal{L} \cdot \sigma(s) \cdot {\rm Br}(N_2 \to N_1 e^- e^+) \cdot \epsilon_{\rm cuts} \cdot P_{\rm decay}$$



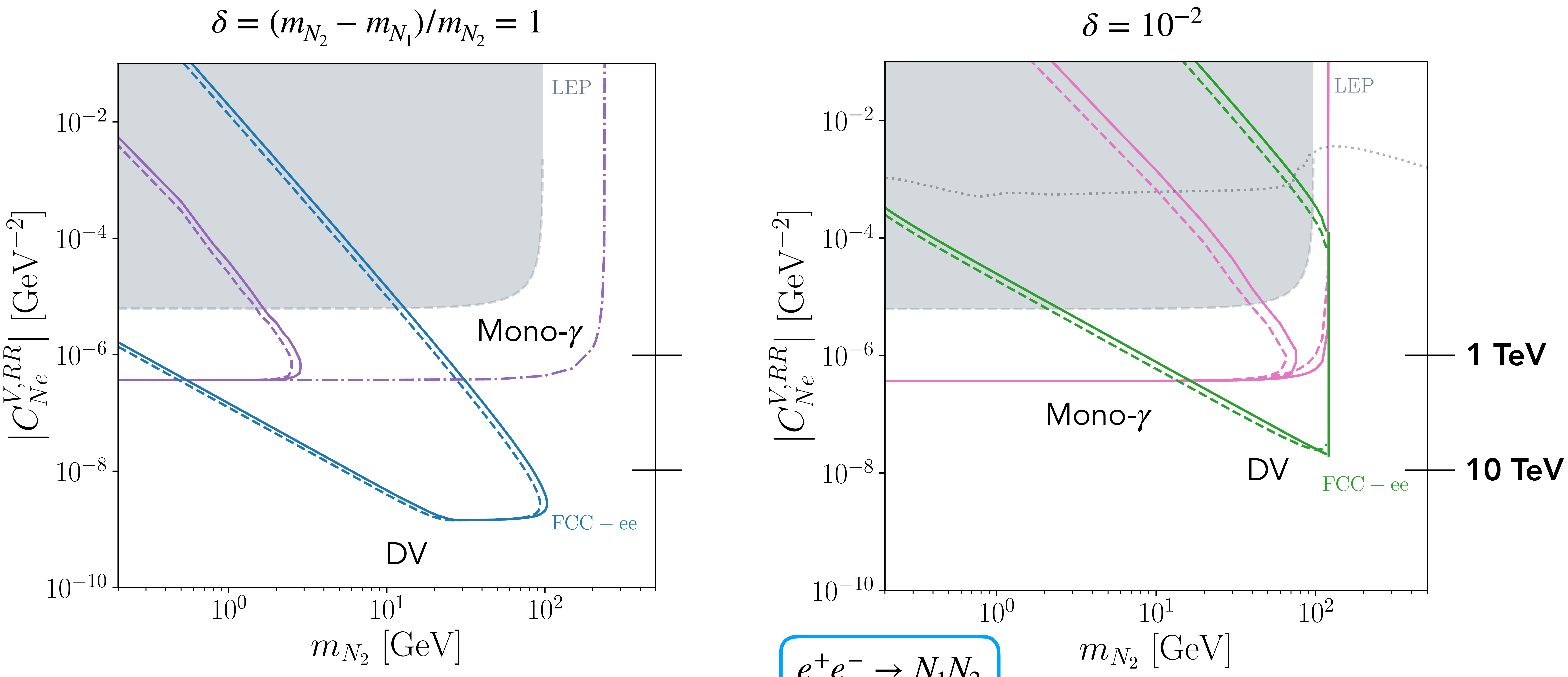




[Alimena et al., 22]

Constraints: four-fermion operators

$\mathcal{O}_{eN} = (\bar{e}_R\gamma_\mu e_R)(\bar{N}_R\gamma^\mu N_R)$ $C_{Ne}^{V,RR} = C_{eN} = \frac{1}{\Lambda^2}$



$e^+e^- \to N_1N_2$
$N_2 \to N_1e^-e^+$

[PDB, Deppisch, Kulkarni, Majumdar, Pei, 24]

Constraints: four-fermion operators

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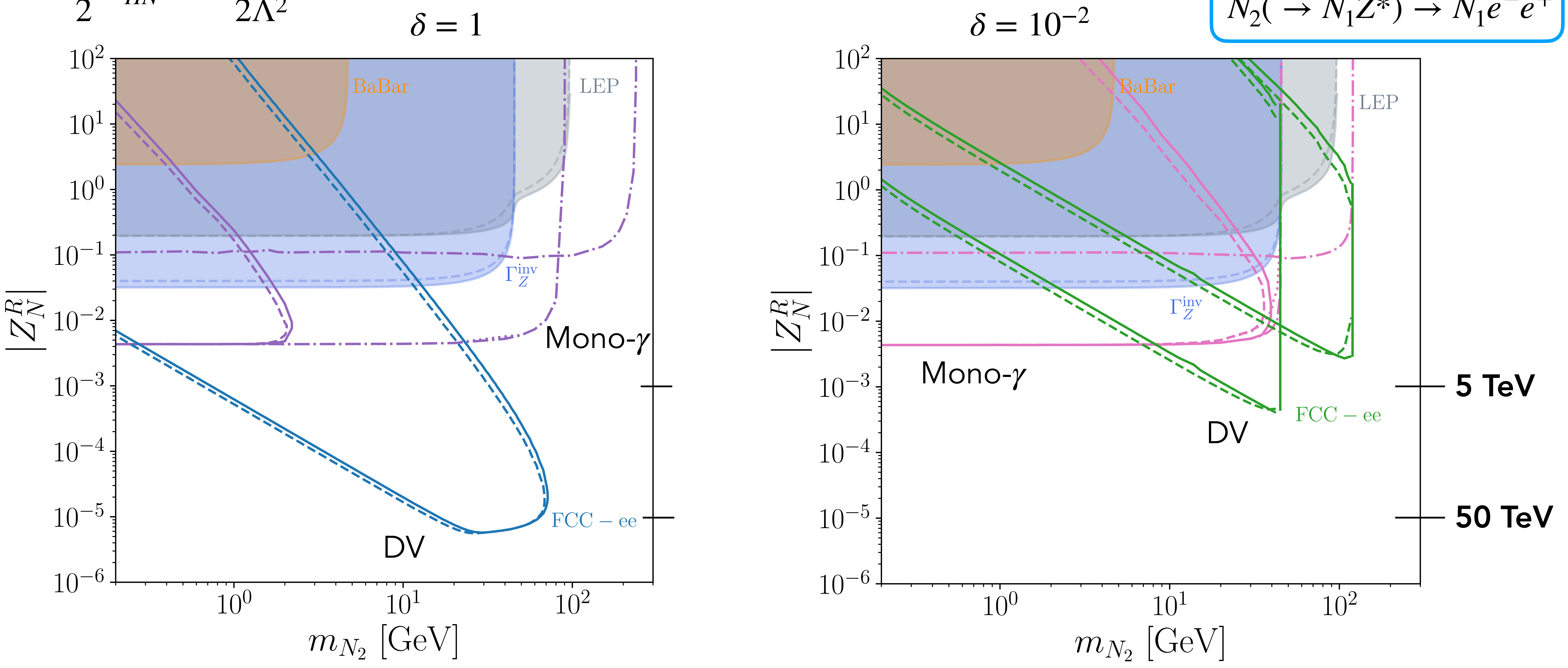
$e^+e^- \to N_1 N_2$
$N_2 \to N_1 e^- e^+$

[PDB, Deppisch, Kulkarni, Majumdar, Pei, 24]

Constraints: effective neutral-current $\mathcal{O}_{HN} = (\bar{N}_R \gamma_\mu N_R)(H^\dagger i \overleftrightarrow{D}^\mu H)$

$$Z_N^R = -\frac{v^2}{2} C_{HN} = -\frac{v^2}{2\Lambda^2}$$

$$e^+e^-(\to Z) \to N_1 N_2$$
$$N_2(\to N_1 Z^*) \to N_1 e^- e^+$$



[PDB, Deppisch, Kulkarni, Majumdar, Pei, 24]

Summary and conclusions

We consider the production and decay of Dirac/Majorana HNLs via EFT operators at FCC-ee

- Possible if active-sterile mixing is suppressed in the relevant HNL mass range
- $d = 6$ and $d = 7$ νSMEFT operators with possible tree-level UV completions are considered

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For long-lived HNLs, two interesting signatures:

- Monophoton plus E_{miss} signature ($e^+e^- \to \nu\nu\gamma$, $e^+e^- \to \nu N\gamma$ and $e^+e^- \to NN\gamma$)
- Displaced vertex ($e^+e^- \to \nu N\gamma$ and $e^+e^- \to NN'\gamma$ followed by $N \to N'e^-e^+$ or $N \to \nu e^-e^+$)

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The two analyses provide complimentary constraints in the (m_N, C_i) parameter space:

- Monophoton constraints generally weaker, but applicable for $m_N \to 0$
- Displaced vertex stronger in a specific mass range

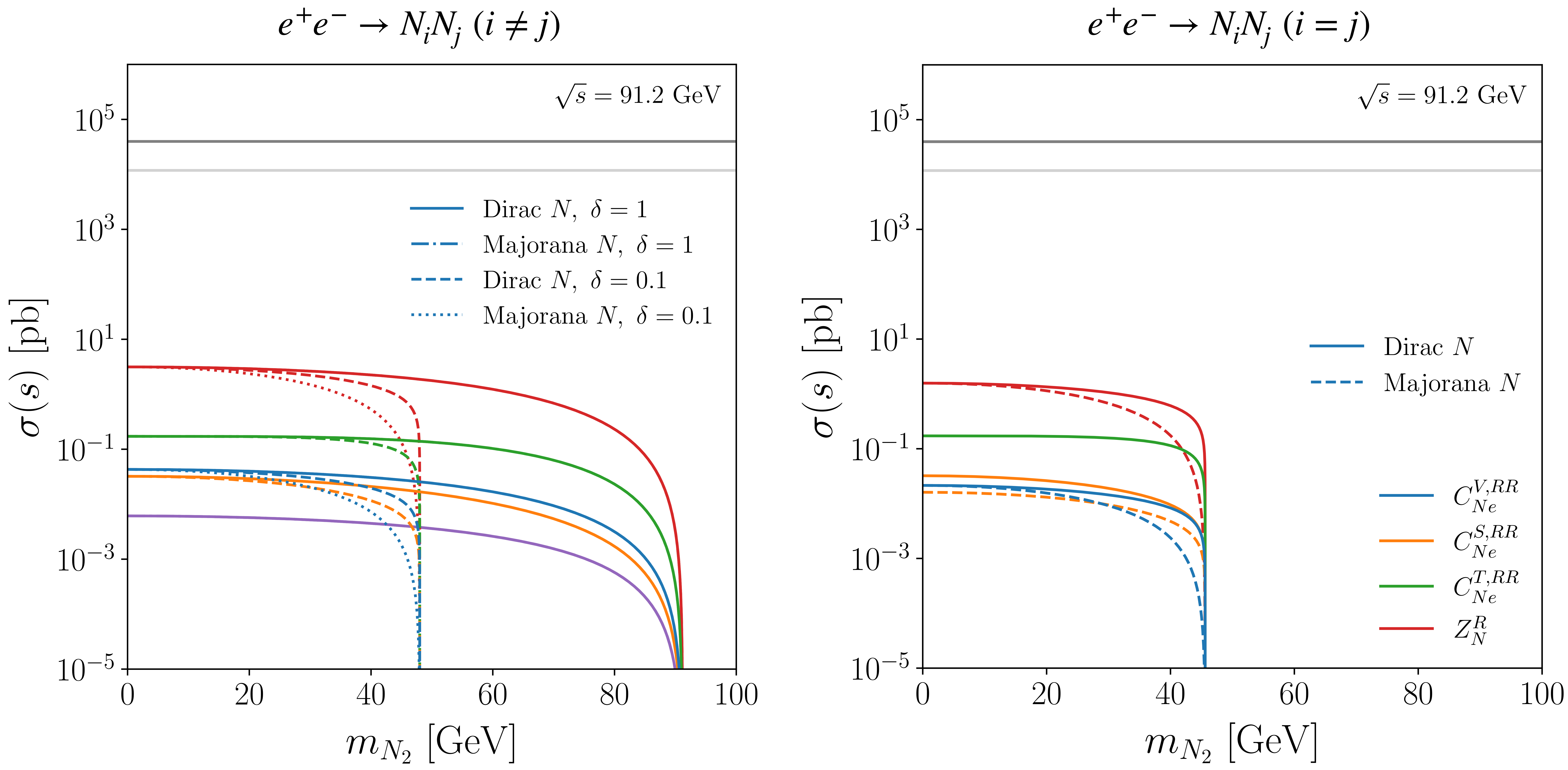
Conclusion: FCC-ee can considerably constrain νSMEFT operators involving HNLs in small $V_{\ell N}$ scenario

Going forwards, combine with other probes to constrain NP

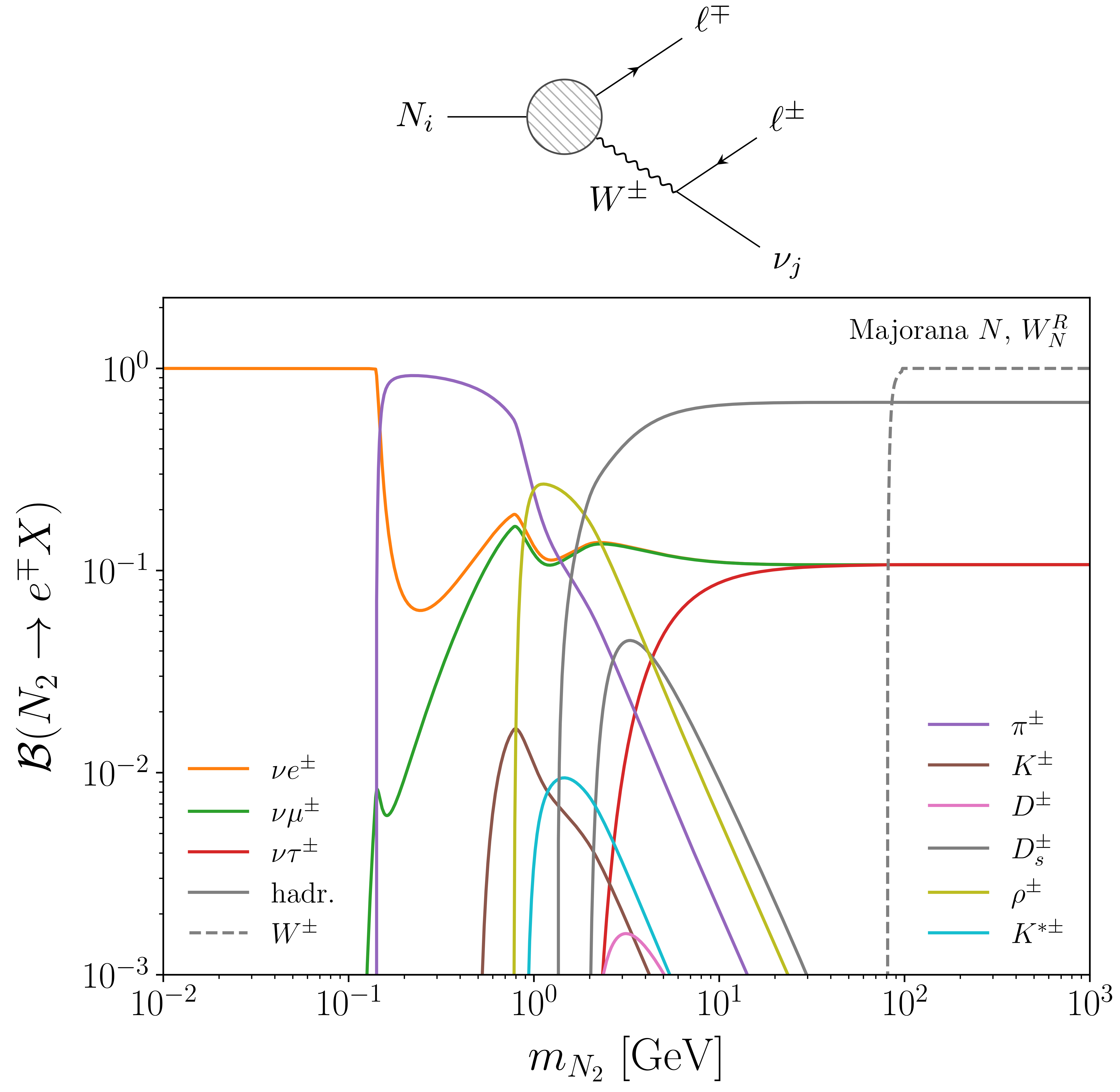
Thank you for your attention!

Bonus slides

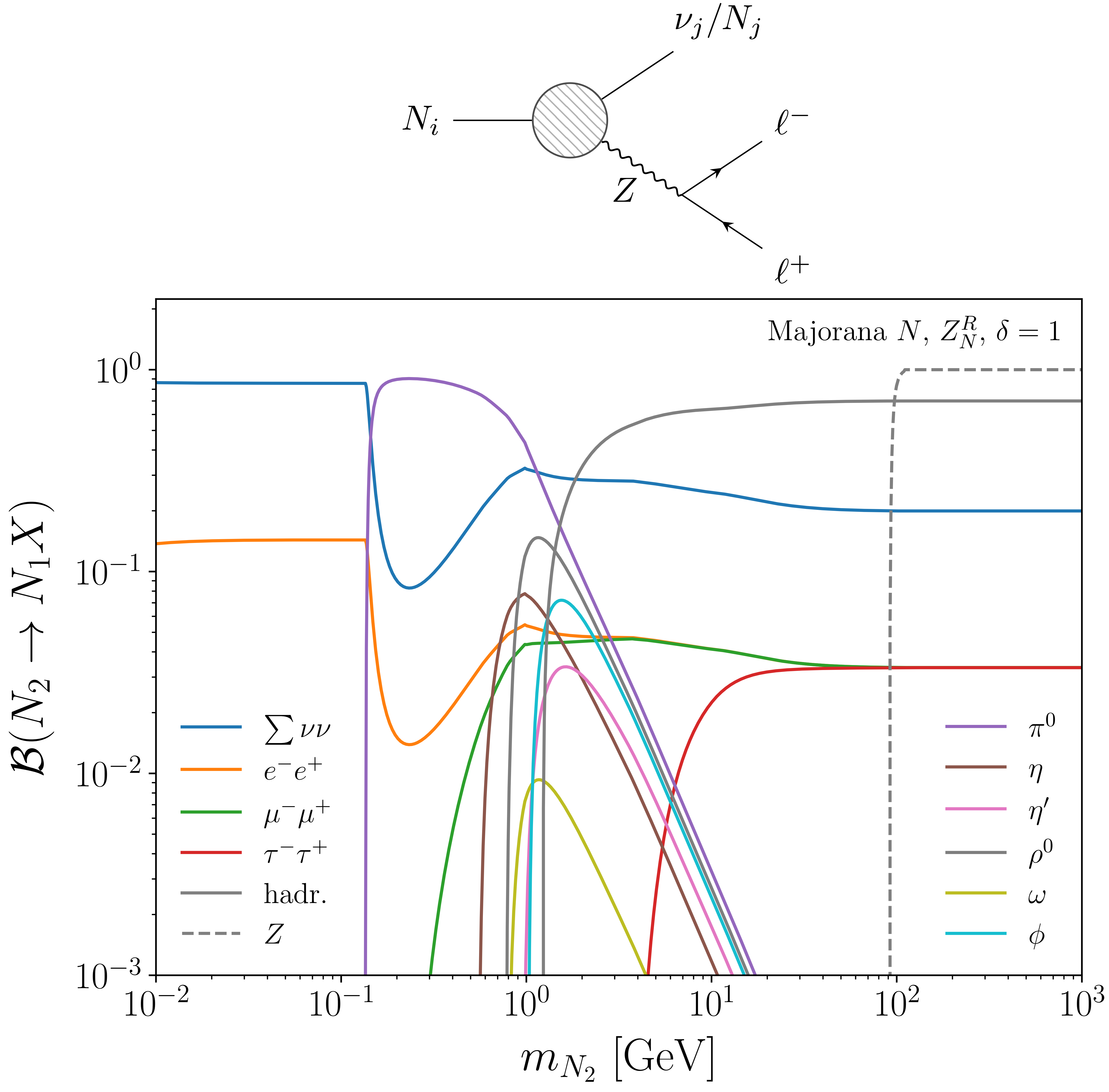
HNL production cross sections



HNL decays



N_i
$\ell^\mp$
$\ell^\pm$
$W^\pm$
ν_j
Majorana N, W_N^R
$\mathcal{B}(N_2 \to e^\mp X)$
m_{N_2} [GeV]
$\nu e^\pm$
$\nu\mu^\pm$
$\nu\tau^\pm$
hadr.
$W^\pm$
$\pi^\pm$
$K^\pm$
$D^\pm$
$D_s^\pm$
$\rho^\pm$
$K^{*\pm}$

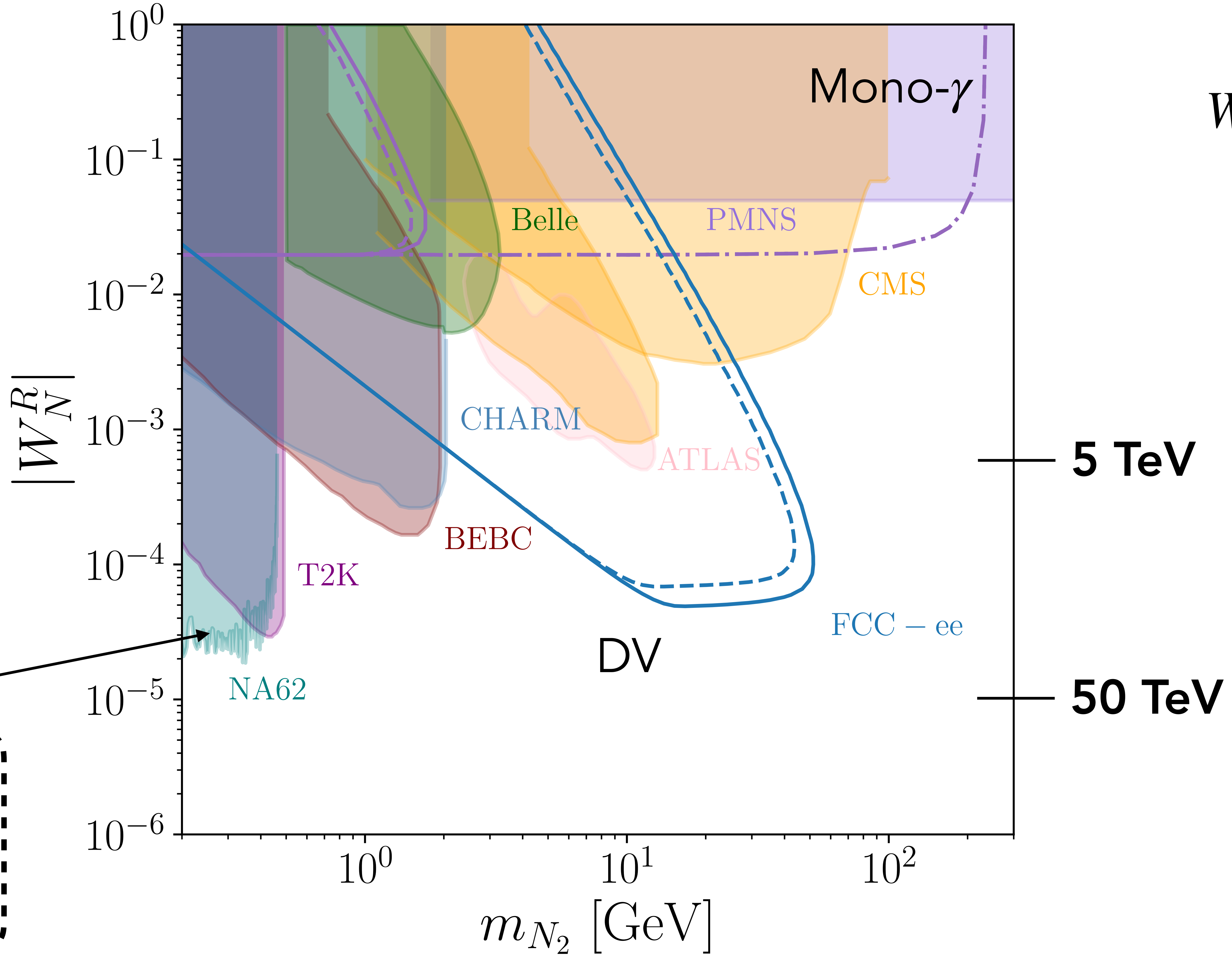


N_i
ν_j/N_j
ℓ^-
ℓ^+
Z
Majorana N, Z_N^R, $\delta = 1$
$\mathcal{B}(N_2 \to N_1 X)$
m_{N_2} [GeV]
$\sum \nu\nu$
e^-e^+
$\mu^-\mu^+$
$\tau^-\tau^+$
hadr.
Z
π^0
η
η'
ρ^0
ω
ϕ

Constraints: effective charged-current

$\mathcal{O}_{HNe} = (\bar{N}_R \gamma_\mu e_R)(\tilde{H}^\dagger i \overleftrightarrow{D}^\mu H)$

$e^+e^- \to \nu_e N_2$
$N_2(\to e^\mp W^\pm) \to \nu_e e^- e^+$



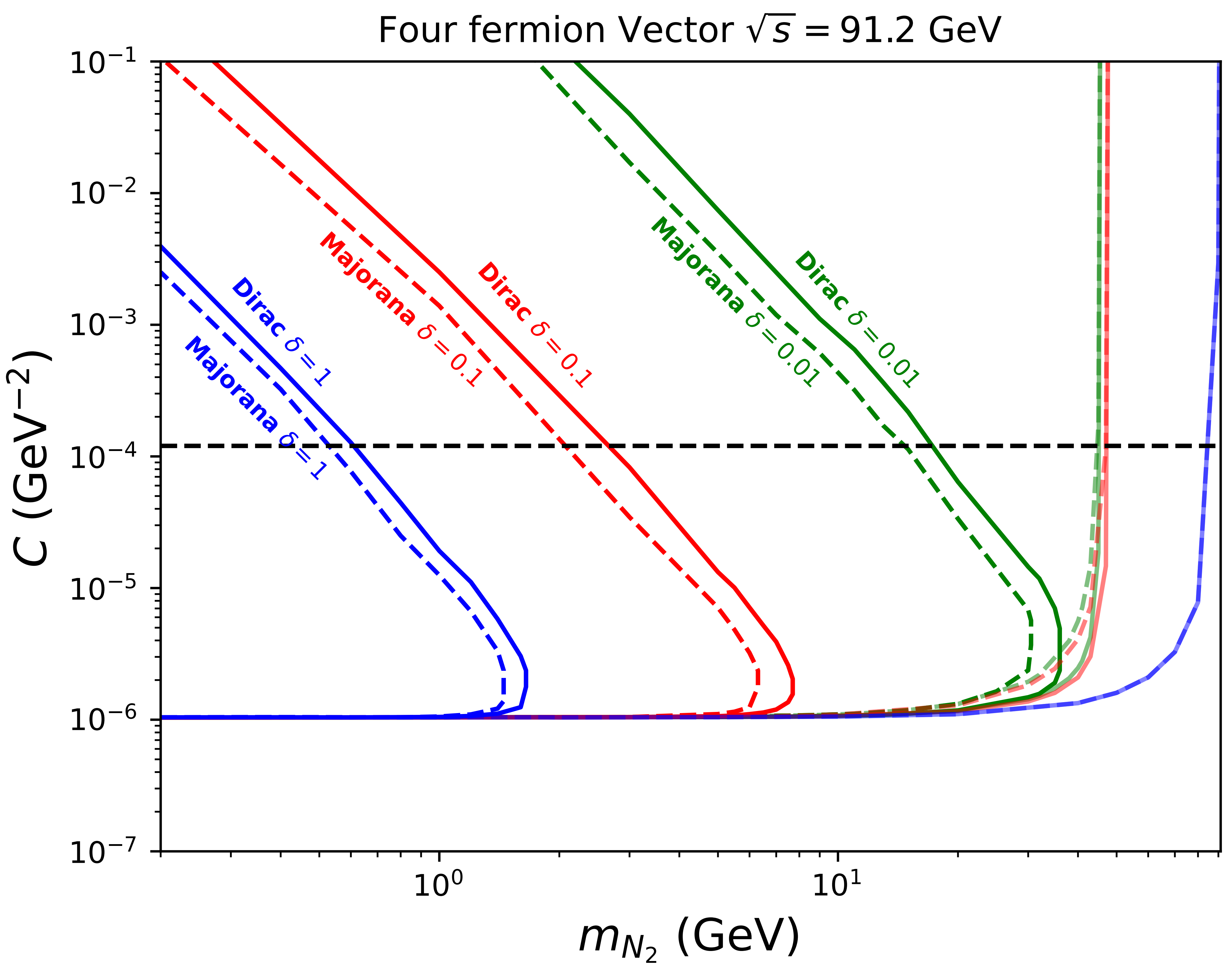
$$W_N^R = -\frac{v^2}{2} C_{HNe} = -\frac{v^2}{2\Lambda^2}$$

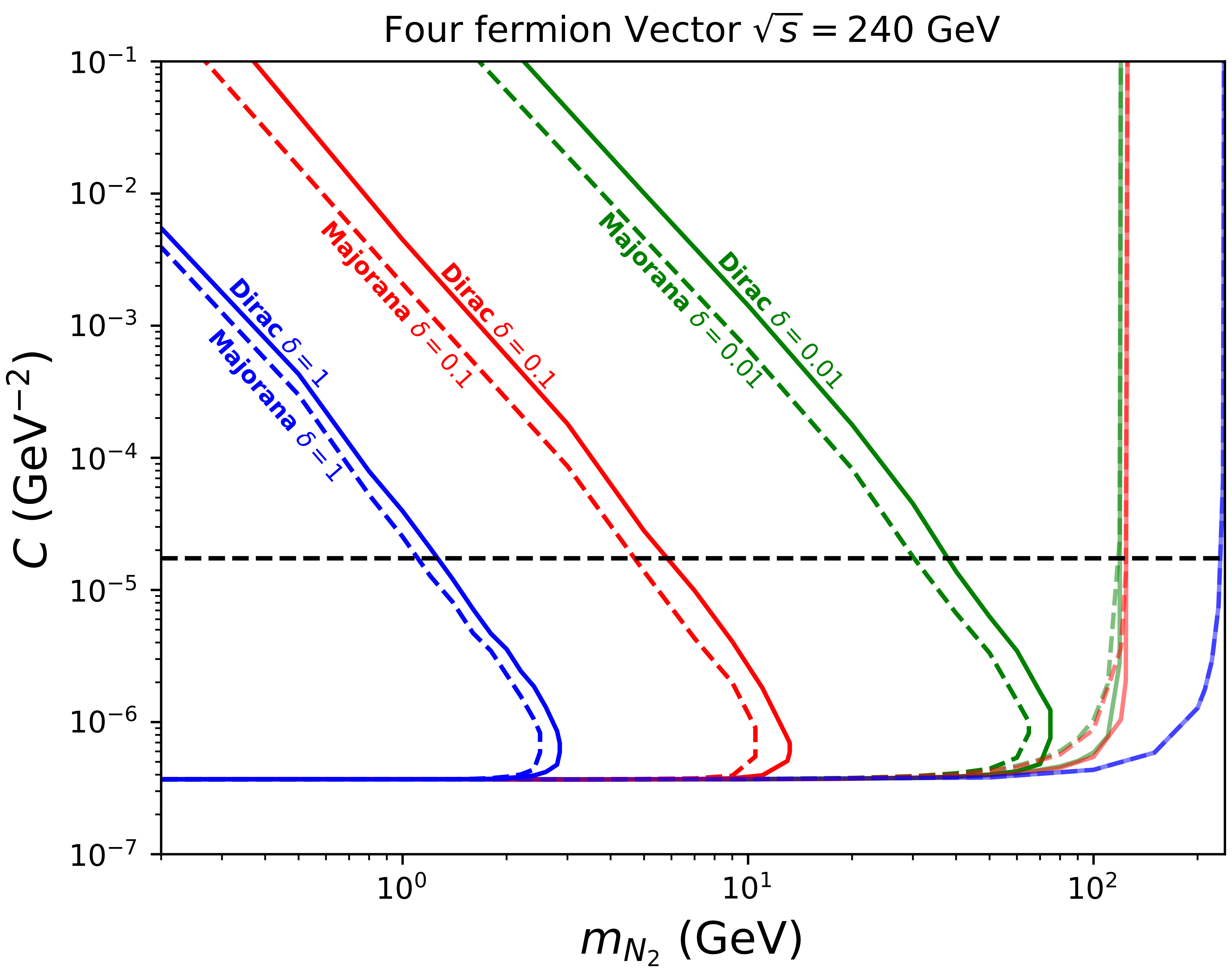
Recasted from $V_{\ell N}$ bounds involving CC production and decays of HNLs

[Fernández-Martínez et al., 23]

[PDB, Deppisch, Kulkarni, Majumdar, Pei, 24]

Monophoton constraints - Splitting dependence



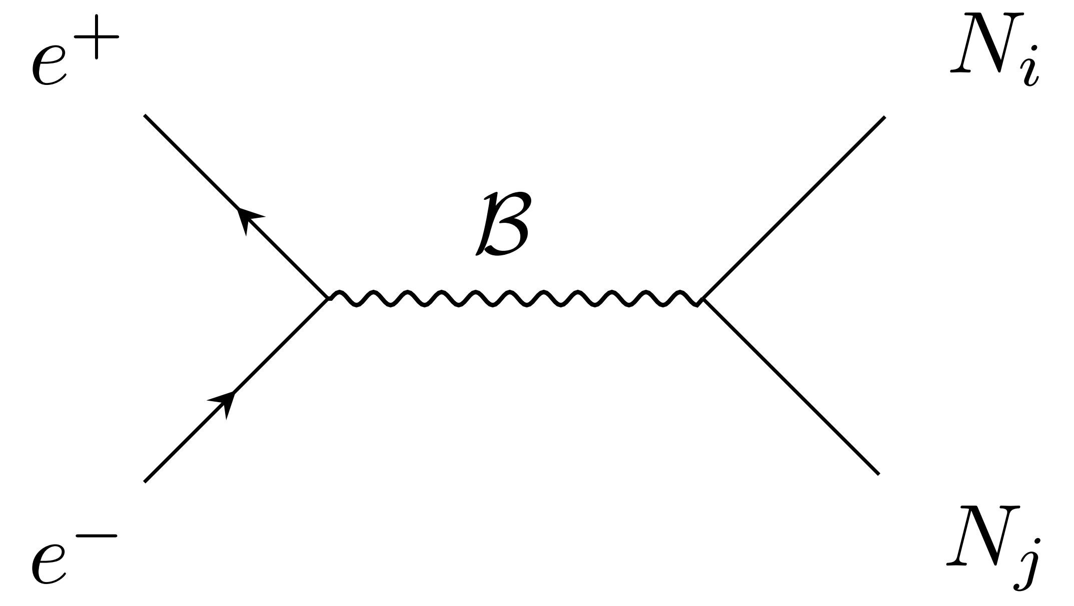


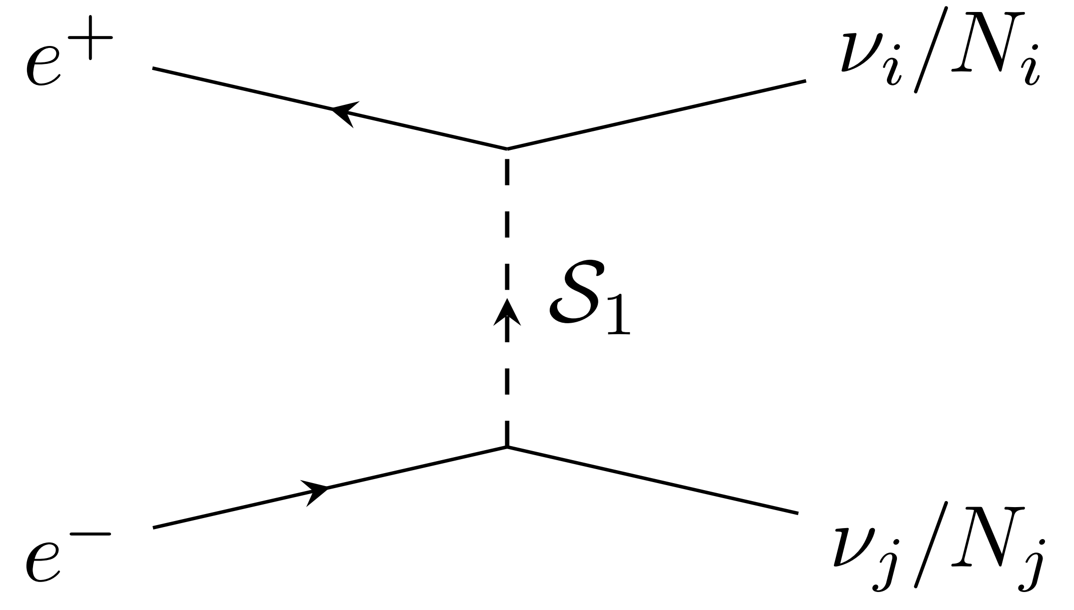
Tree-level UV complete scenarios

Scalar	$\mathcal{S}$	$\mathcal{S}_1$	φ	Ξ	Ξ_1
Irrep.	$(1,1)_0$	$(1,1)_1$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$

Fermion	$\mathcal{N}$	E	Δ_1	Δ_3	Σ	Σ_1
Irrep.	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$

Vector	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{L}_1$	$\mathcal{L}_3$
Irrep.	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(1,2)_{\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$





$\psi^2 H^2$	
$\mathcal{O}_5$	Ξ_1, $\mathcal{N}$, Σ
$\mathcal{O}_N$	$\mathcal{S}$, Δ_1

$\psi^2 H^3$	
$\mathcal{O}_{lNH}$	φ, E, Δ_1, Σ, Σ_1, $(\mathcal{S},\mathcal{N})$
$\psi^2 H^2 D$	
$\mathcal{O}_{Hl}^{(1),(3)}$	$\mathcal{N}$, E, Σ, Σ_1
$\mathcal{O}_{HN}$	Δ_1, $\mathcal{B}$
$\mathcal{O}_{HNe}$	Δ_1, $\mathcal{B}_1$

ψ^4	
$\mathcal{O}_{ll}$	$\mathcal{S}_1$, Ξ_1, $\mathcal{B}$, $\mathcal{W}$
$\mathcal{O}_{le}$	φ, $\mathcal{B}$, $\mathcal{L}_1$, $\mathcal{L}_3$
$\mathcal{O}_{lNle}$	$\mathcal{S}_1$, φ
$\mathcal{O}_{lN}$	φ, $\mathcal{B}$, $\mathcal{L}_1$
$\mathcal{O}_{eN}$	$\mathcal{S}_1$, $\mathcal{B}$, $\mathcal{B}_1$

$\psi^2 H^4$	
$\mathcal{O}_{lH}$	Ξ_1, $\mathcal{N}$, Σ
$\mathcal{O}_{NH}$	$\mathcal{S}$, (φ,Δ_1), (Ξ,Δ_1), (Ξ,Σ), (Ξ_1,Δ_1), (Ξ_1,Σ_1), $(\mathcal{N},\Delta_1)$, (Δ_1,Σ), (Δ_1,Σ_1)
$\psi^2 H^3 D$	
$\mathcal{O}_{Nl1(2)}$	$(\mathcal{S},\mathcal{N})$, $(\mathcal{S},\Delta_1)$, $(\mathcal{S},\mathcal{L}_1)$, (Ξ,Δ_1), (Ξ,Σ), $(\Xi,\mathcal{L}_1)$, (Ξ_1,Δ_1), (Ξ_1,Σ_1), $(\Xi_1,\mathcal{L}_1)$, $(\mathcal{N},\Delta_1)$, $(\mathcal{N},\mathcal{B})$, (Δ_1,Σ), (Δ_1,Σ_1), $(\Delta_1,\mathcal{B})$, $(\Delta_1,\mathcal{B}_1)$, $(\Delta_1,\mathcal{W})$, $(\Delta_1,\mathcal{W}_1)$, $(\Sigma,\mathcal{W})$, $(\Sigma_1,\mathcal{W}_1)$
$\mathcal{O}_{leHD}$	$\mathcal{N}$, Σ, (Ξ_1,Δ_1), $(\Delta_1,\mathcal{B}_1)$, $(\mathcal{B}_1,\mathcal{L}_3)$

$\psi^4 H$	
$\mathcal{O}_{llleH}$	$\mathcal{N}$, Σ, $(\mathcal{S}_1,\varphi)$, $(\mathcal{S}_1,\Delta_3)$, (φ,Ξ_1), (Ξ_1,Δ_3)
$\mathcal{O}_{lNlH}$	$(\mathcal{S}_1,\varphi)$, $(\mathcal{S}_1,E)$, $(\mathcal{S}_1,\Delta_1)$, (φ,Ξ_1), $(\varphi,\mathcal{N})$, (φ,Σ), (Ξ_1,Δ_1), (Ξ_1,Σ_1), $(\mathcal{N},\mathcal{B})$, $(\mathcal{N},\mathcal{L}_1)$, $(E,\mathcal{L}_1)$, $(\Delta_1,\mathcal{B})$, $(\Delta_1,\mathcal{W})$, $(\Sigma,\mathcal{W})$, $(\Sigma,\mathcal{L}_1)$, $(\Sigma_1,\mathcal{L}_1)$
$\mathcal{O}_{eNlH}$	$(\mathcal{S}_1,\varphi)$, $(\mathcal{S}_1,\mathcal{N})$, $(\mathcal{S}_1,\Delta_3)$, (φ,Δ_1), $(\mathcal{N},\mathcal{B})$, $(\mathcal{N},\mathcal{B}_1)$, $(\Delta_1,\mathcal{B})$, $(\Delta_1,\mathcal{B}_1)$, $(\Delta_1,\mathcal{L}_1)$, $(\Delta_1,\mathcal{L}_3)$, $(\Delta_3,\mathcal{L}_1)$, $(\Delta_3,\mathcal{L}_3)$
$\mathcal{O}_{lNeH}$	$(\mathcal{S},\varphi)$, $(\mathcal{S},E)$, $(\mathcal{S},\Delta_1)$, $(\mathcal{S}_1,\varphi)$, $(\mathcal{S}_1,E)$, $(\mathcal{S}_1,\Delta_1)$, (φ,Δ_1)
$\mathcal{O}_{elNH}$	$(\mathcal{S},\varphi)$, $(\mathcal{S},\Delta_1)$, (φ,Δ_1), $(\mathcal{S}_1,E)$, $(E,\mathcal{B}_1)$, $(\Delta_1,\mathcal{B}_1)$, $(\Delta_1,\mathcal{L}_1)$