Neutrino dipole portal at colliders

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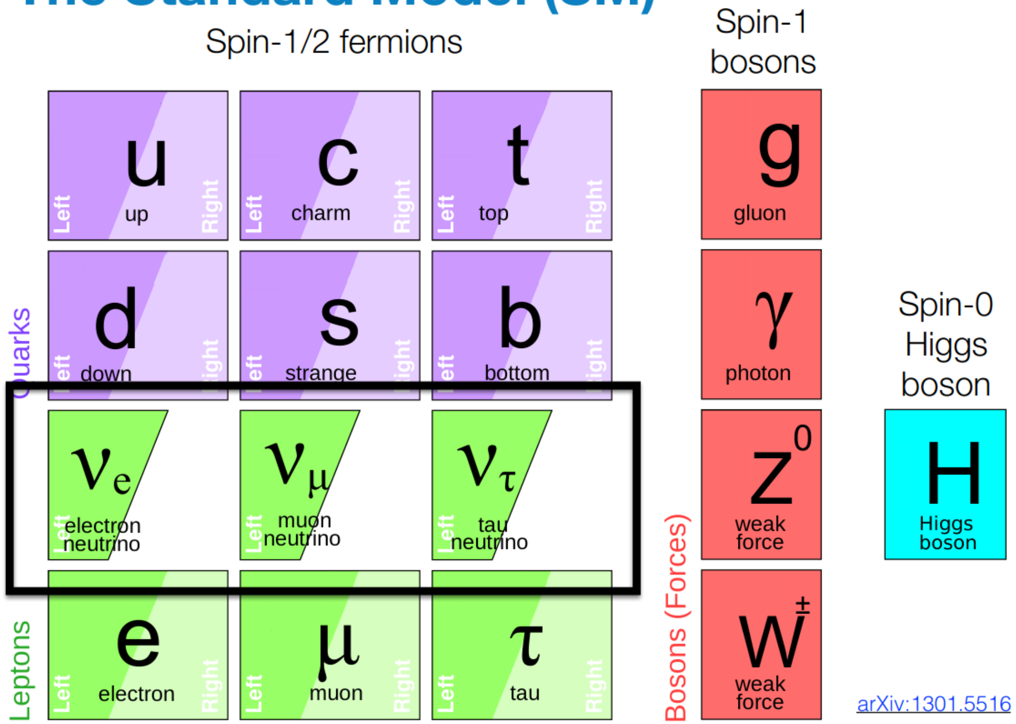
based on arXiv:2204.07802, arXiv:2301.06050, arXiv:2302.02081

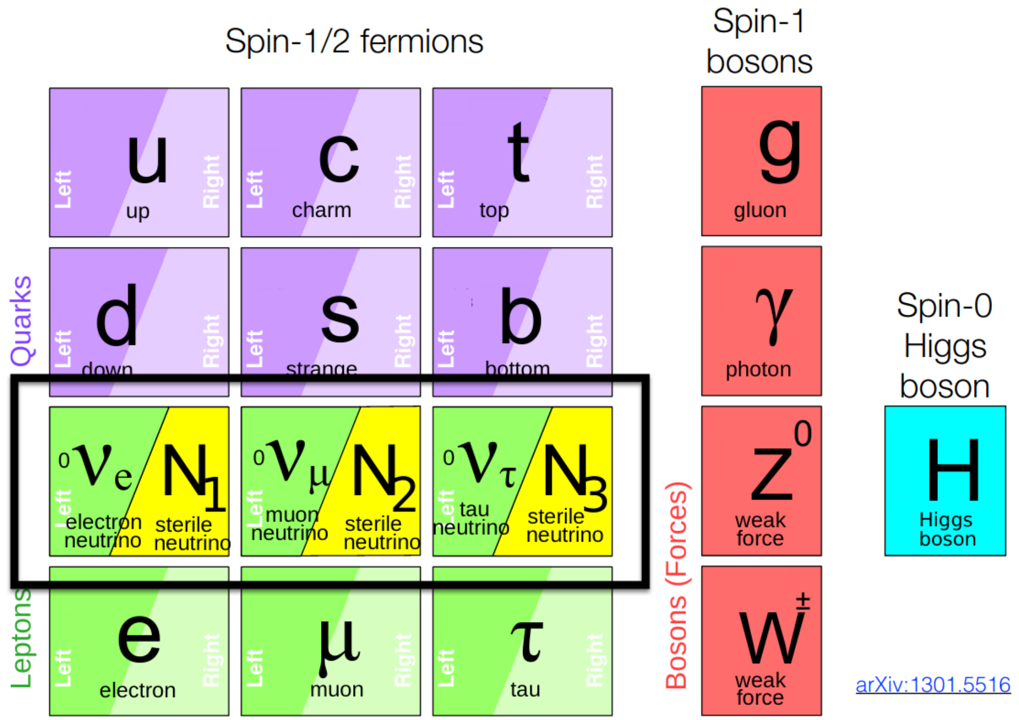
Mini-workshop in Theory, IAS & HKUST, 15/02/2023

Heavy Neutral Leptons

The Standard Model (SM)



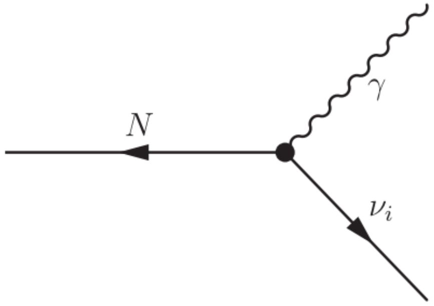
SM Extension with 3 HNLs



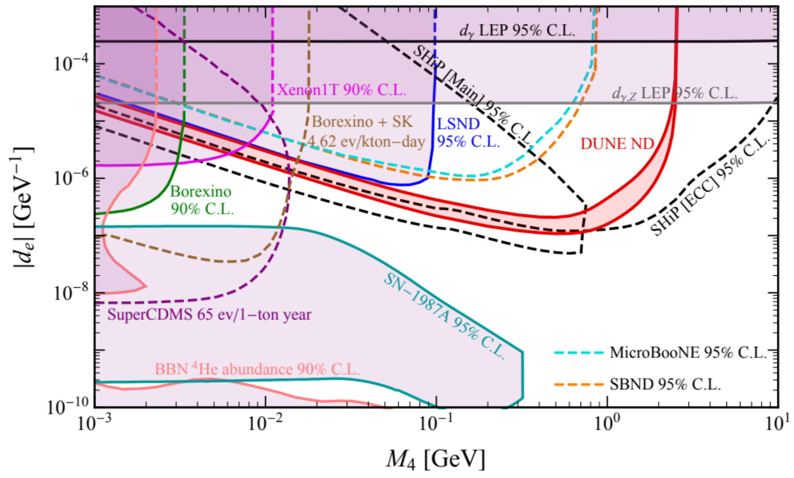
- Best-known description of fundamental particles and their interactions (expect gravity)
- Neutrino oscillations suggest $m_\nu > 0$
- Non-zero neutrino mass is not included in SM

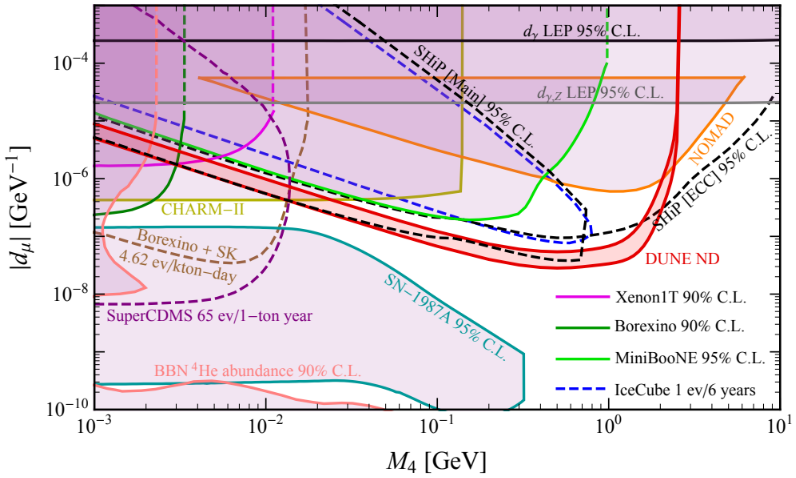
- Introduce right-handed states known as heavy neutral leptons (HNLs)
- Seesaw mechanism explains light neutrino masses

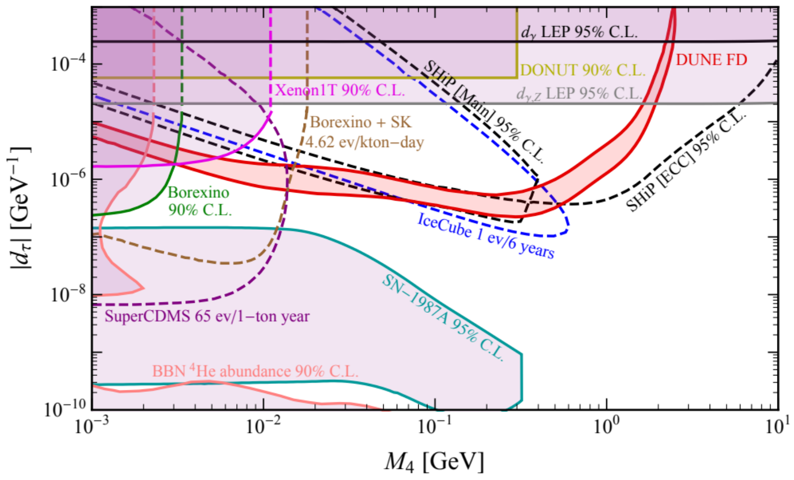
Neutrino dipole portal



$$\mathcal{L} \supset d_k \bar{\nu}_L^k \sigma_{\mu\nu} F^{\mu\nu} N + \text{H.c.},$$







arXiv: 2105.09699

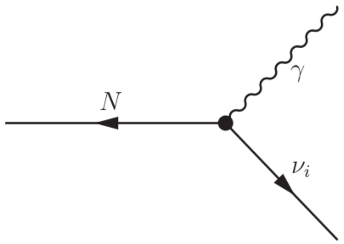
- Collider searches
- Beam-dump experiments
- Neutrino telescope searches
- Dark matter detection
- Astrophysical
- ……

Neutrino dipole portal

$$\mathcal{L} \supset \bar{L}(d_{\mathcal{W}} \mathcal{W}^a_{\mu\nu} \tau^a + d_B B_{\mu\nu}) \tilde{H} \sigma_{\mu\nu} N_D + \text{H.c.}$$

SSB

$$\mathcal{L} \supset d_W(\bar{\ell}_L W^-_{\mu\nu} \sigma^{\mu\nu} N_D) + \bar{\nu}_L [d_\gamma F_{\mu\nu} - d_Z Z_{\mu\nu}] \sigma^{\mu\nu} N_D + \text{H.c.}$$



$$\mathcal{L} \supset d_k \bar{\nu}^k_L \sigma_{\mu\nu} F^{\mu\nu} N + \text{H.c.},$$

$$d_\gamma = \frac{v}{\sqrt{2}} \left(d_B \cos\theta_w + \frac{d_{\mathcal{W}}}{2} \sin\theta_w \right)$$

$$d_Z = \frac{v}{\sqrt{2}} \left(\frac{d_{\mathcal{W}}}{2} \cos\theta_w - d_B \sin\theta_w \right)$$

$$d_W = \frac{v}{\sqrt{2}} \frac{d_{\mathcal{W}}}{2} \sqrt{2}.$$

$$\{m_N, d_{\mathcal{W}}, d_B\}$$

$$d_{\mathcal{W}} = a \times d_B$$

$$d_Z = \frac{d_\gamma (a \cos\theta_w - 2 \sin\theta_w)}{2 \cos\theta_w + a \sin\theta_w}$$

$$d_W = \frac{\sqrt{2} a d_\gamma}{2 \cos\theta_w + a \sin\theta_w}.$$

$$\{m_N, d_\gamma, a\}$$

$$a = -2 \cot\theta_w$$

HNL Decays

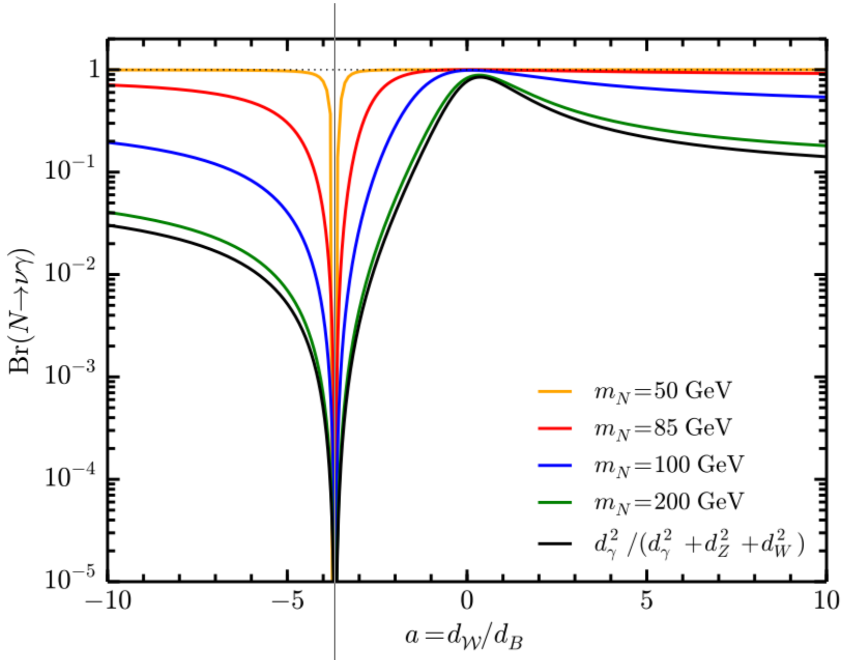
$$\Gamma_{N\to\nu\gamma} = \frac{d_\gamma^2 m_N^3}{4\pi},$$

$$\Gamma_{N\to\nu Z} = \frac{d_Z^2 (m_N^2 - M_Z^2)^2 (2m_N^2 + M_Z^2)}{8\pi m_N^3}\Theta(m_N > M_Z),$$

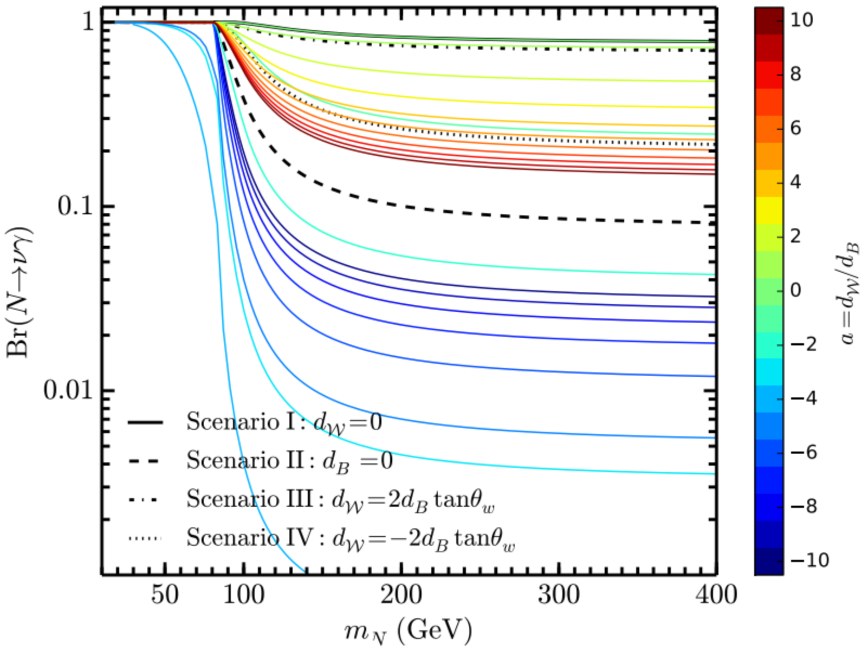
$$\Gamma_{N\to W\ell} = \frac{d_W^2}{8\pi m_N^3}\sqrt{(m_N^2 - (M_W - m_\ell)^2)(m_N^2 + (M_W - m_\ell)^2)}$$
$$\times \left(2m_\ell^2(2m_\ell^2 - 4m_N^2 - M_W^2) + (m_N^2 - M_W^2)(2m_N^2 + M_W^2)\right)\Theta(m_N > M_W + m_\ell).$$

$$N \to \nu Z^* \to \nu f \bar{f}$$

$$N \to W^* \ell \to \ell + f f'$$



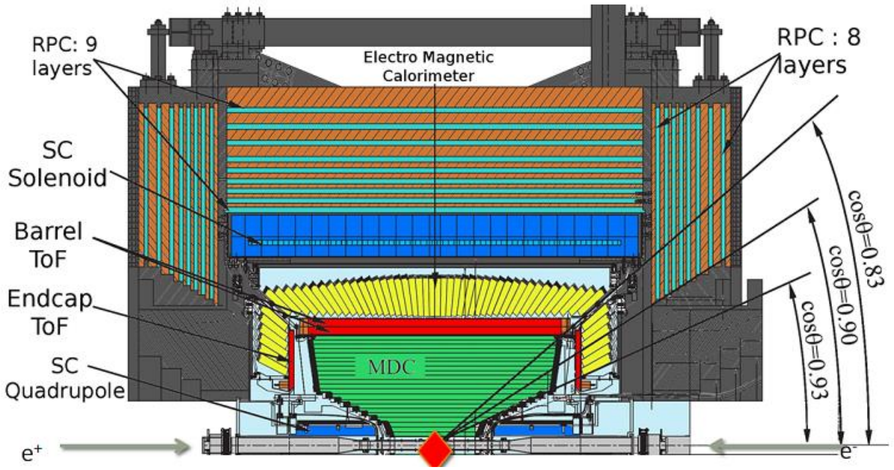
$a = -2\cot\theta_w$

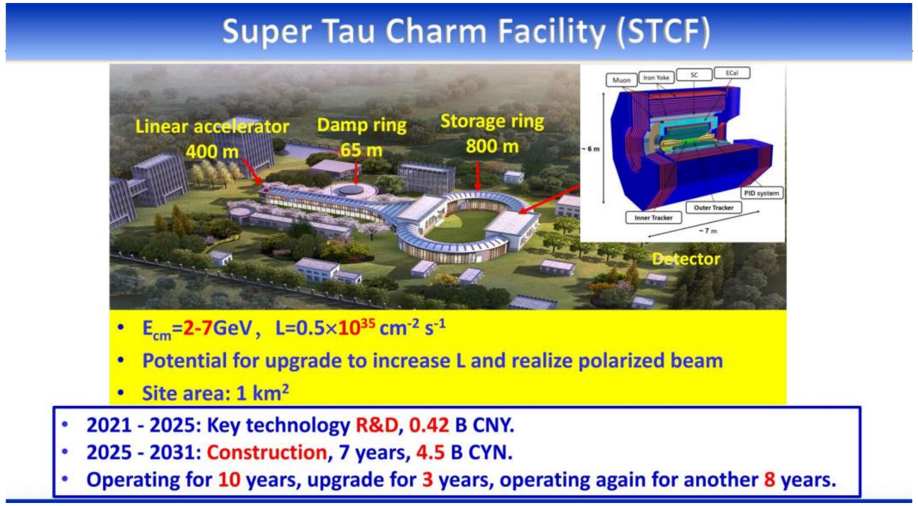


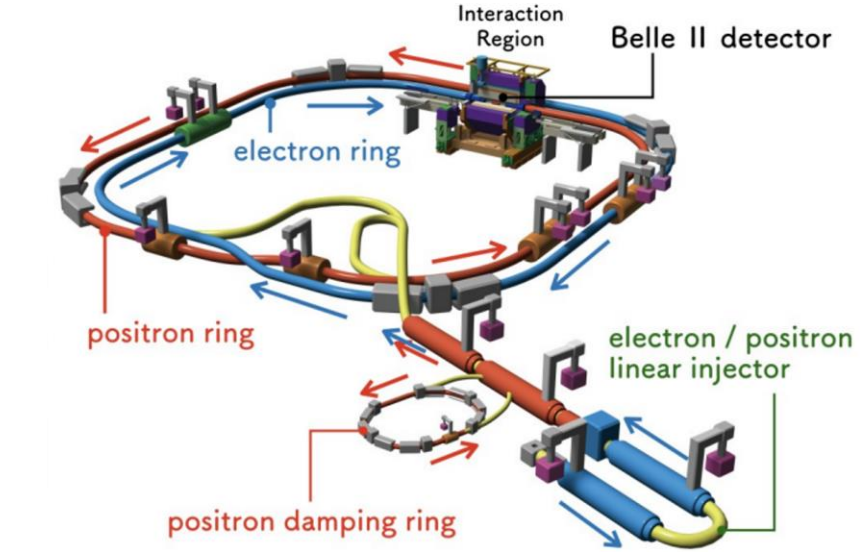
$$\mathrm{Br}(N\to\nu\gamma) \equiv \frac{\Gamma_{N\to\nu\gamma}}{\Gamma_{N\to\nu\gamma} + \Gamma_{N\to\nu Z} + \Gamma_{N\to W\ell} + \Gamma_{N\to\text{3-body}}}$$

e⁺ e⁻ colliders

BESIII detector

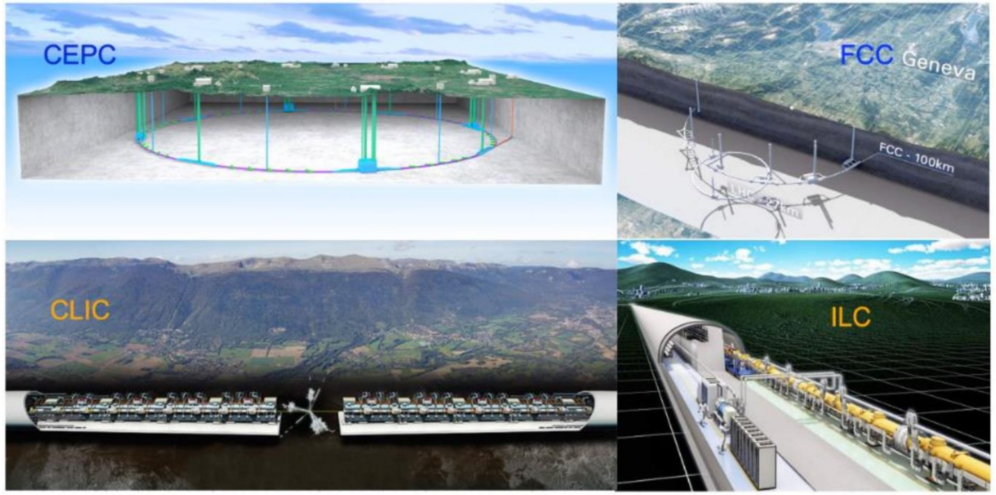




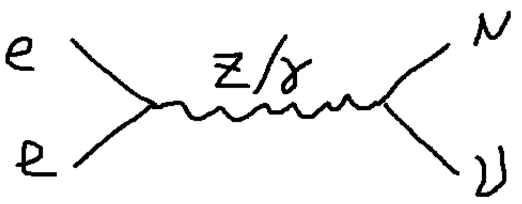


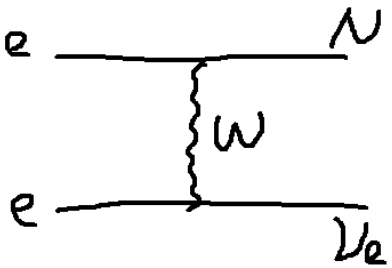
$$\sqrt{s} \ll M_Z$$

$$\sqrt{s} \geq M_Z$$



Production at electron colliders



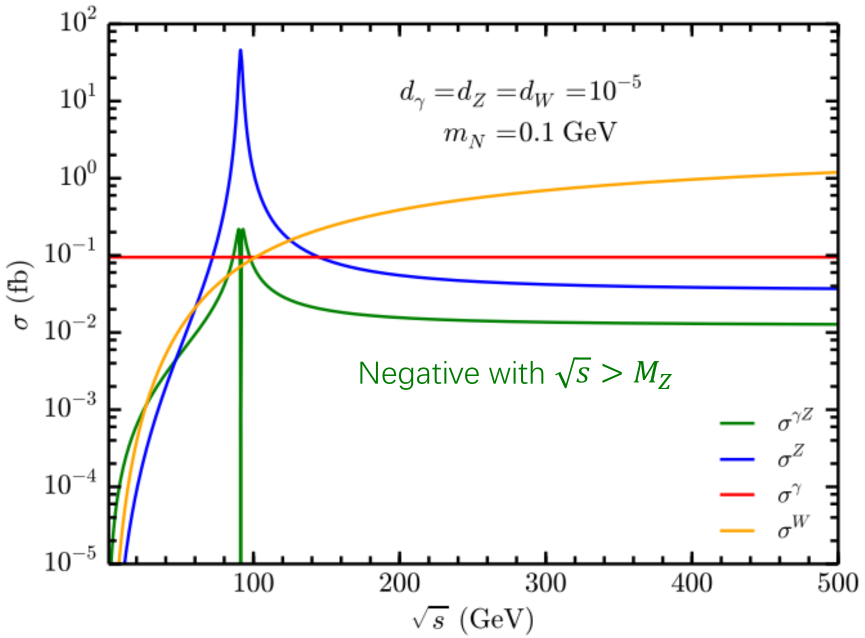


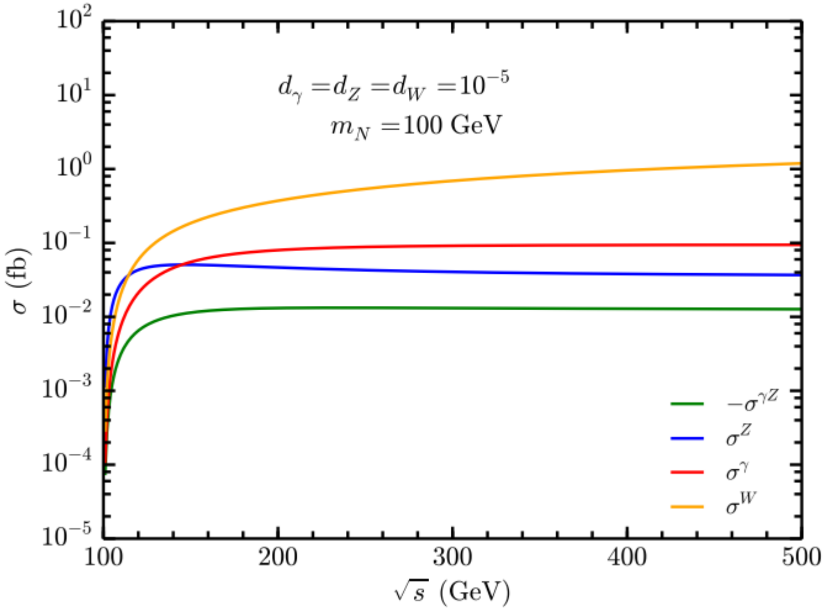
$$\sigma^{\gamma}(e^+e^-\to N\bar{\nu}) = \frac{\alpha d_\gamma^2 (s-m_N^2)^2(s+2m_N^2)}{3s^3},$$

$$\sigma^{Z}(e^+e^-\to N\bar{\nu}) = \frac{\alpha d_Z^2 (s-m_N^2)^2(s+2m_N^2)}{24 c_w^2 s_w^2 s\left(\Gamma_Z^2 M_Z^2 + (M_Z^2-s)^2\right)}\left[\left(8s_w^2-4s_w+1\right)\right],$$

$$\sigma^{\gamma Z}(e^+e^-\to N\bar{\nu}) = \frac{\alpha d_\gamma d_Z (s-m_N^2)^2(s+2m_N^2)}{6 c_w s_w s^2\left(\Gamma_Z^2 M_Z^2 + (M_Z^2-s)^2\right)}\left[(-4s_w+1)\left(M_Z^2-s\right)\right],$$

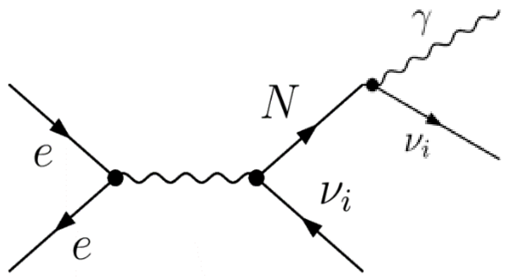
$$\sigma^{W}(e^+e^-\to N\bar{\nu}_e) = \frac{\alpha (d_W^e)^2}{2s_w^2 s}\left[-2s-\left(2M_W^2+s\right)\log\left(\frac{M_W^2}{-m_N^2+M_W^2+s}\right) + m_N^2\left(\frac{M_W^2}{-m_N^2+M_W^2+s}+1\right)\right],$$

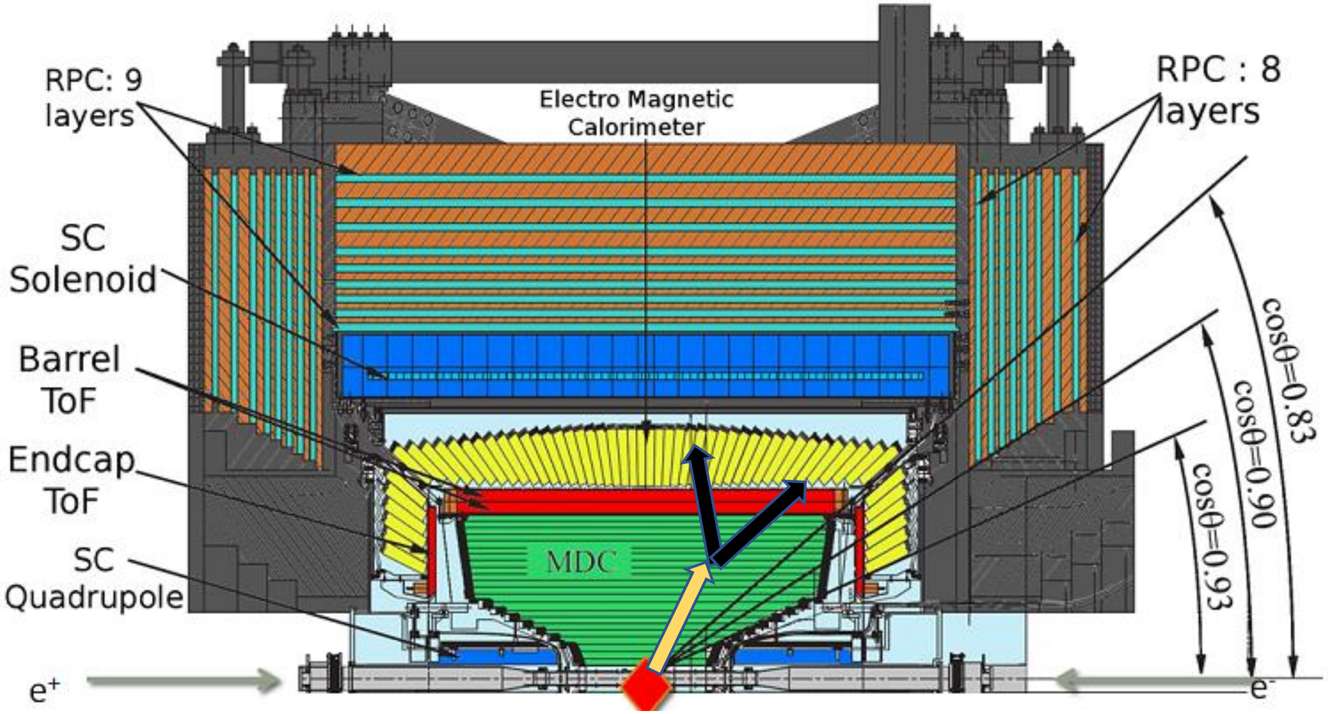




- With $\sqrt{s} \ll M_Z$ the contribution from Z or W can be neglected comparing with γ.
- σ^{γ} has little to do with the CM energy when $m_N \ll \sqrt{s}$.
- σ^{W} dominants when $\sqrt{s} \gg M_Z$ while can be ignored around Z-pole

Decay Length





$$\Gamma_{N\to\nu\gamma} = \frac{|d|^2 m_N^3}{4\pi}$$

$$l_{dec} = c\tau\beta\gamma = \frac{4\pi}{|d|^2 m_N^4}\sqrt{E_N^2 - m_N^2},$$

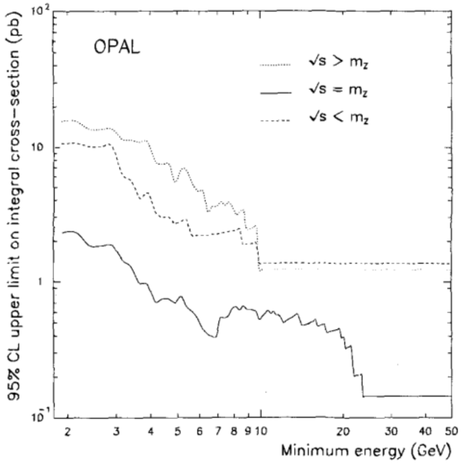
$$P_{dec}(l) = (1 - e^{-l/l_{dec}})\mathrm{Br}(N \to \nu\gamma).$$

$$N_s = L\sigma(e^+e^- \to N\nu)\mathrm{Br}(N \to \nu\gamma)\epsilon_{cuts}\epsilon_{det}P_{dec}(l_D)$$

Searches at LEP

OPAL collaboration, Z. Phys. C 65 (1995) 47

LEP1



scan-points. The 95 % CL upper limit on the cross-section at the Z^0 peak for production of a single photon with energy exceeding 23 GeV is found to be 0.15 pb. For models in

DELPHI collaboration, Eur. Phys. J. C 38 (2005) 395

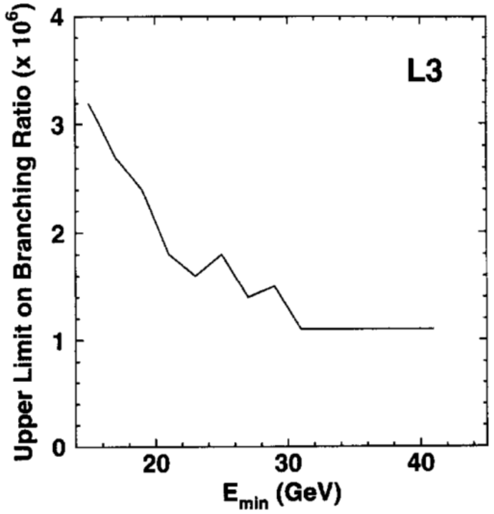
LEP2

	$\sqrt{s}$	200–209 GeV
	$< \sqrt{s} >$	205.4 GeV
	$N_{\rm observed}$	190
HPC	$N_{\rm background}$	0.1
$0.06 < x_\gamma < 1.1$	$N_{e^+e^- \to \nu\bar{\nu}\gamma}$	198.1±2.0
$45^\circ < \theta_\gamma < 135^\circ$	$\sigma_{\rm meas}$ (pb)	1.50±0.11
	$\sigma_{\nu\bar{\nu}\gamma(\gamma)}$ (pb)	1.61
	N_ν	2.71±0.30

$$\chi^2 = \left(\frac{\sigma^{\rm SM} + \sigma^{N\nu} - \sigma^{\rm exp}}{\delta\sigma^{\rm exp}}\right)^2$$

$Z \to \gamma + {\rm invisible}$

L3 collaboration, Phys. Lett. B 412 (1997) 201



95% C.L. upper limit of 3.2×10^{-6} with $E_\gamma > 15$ GeV

$Z \to {\rm invisible}$

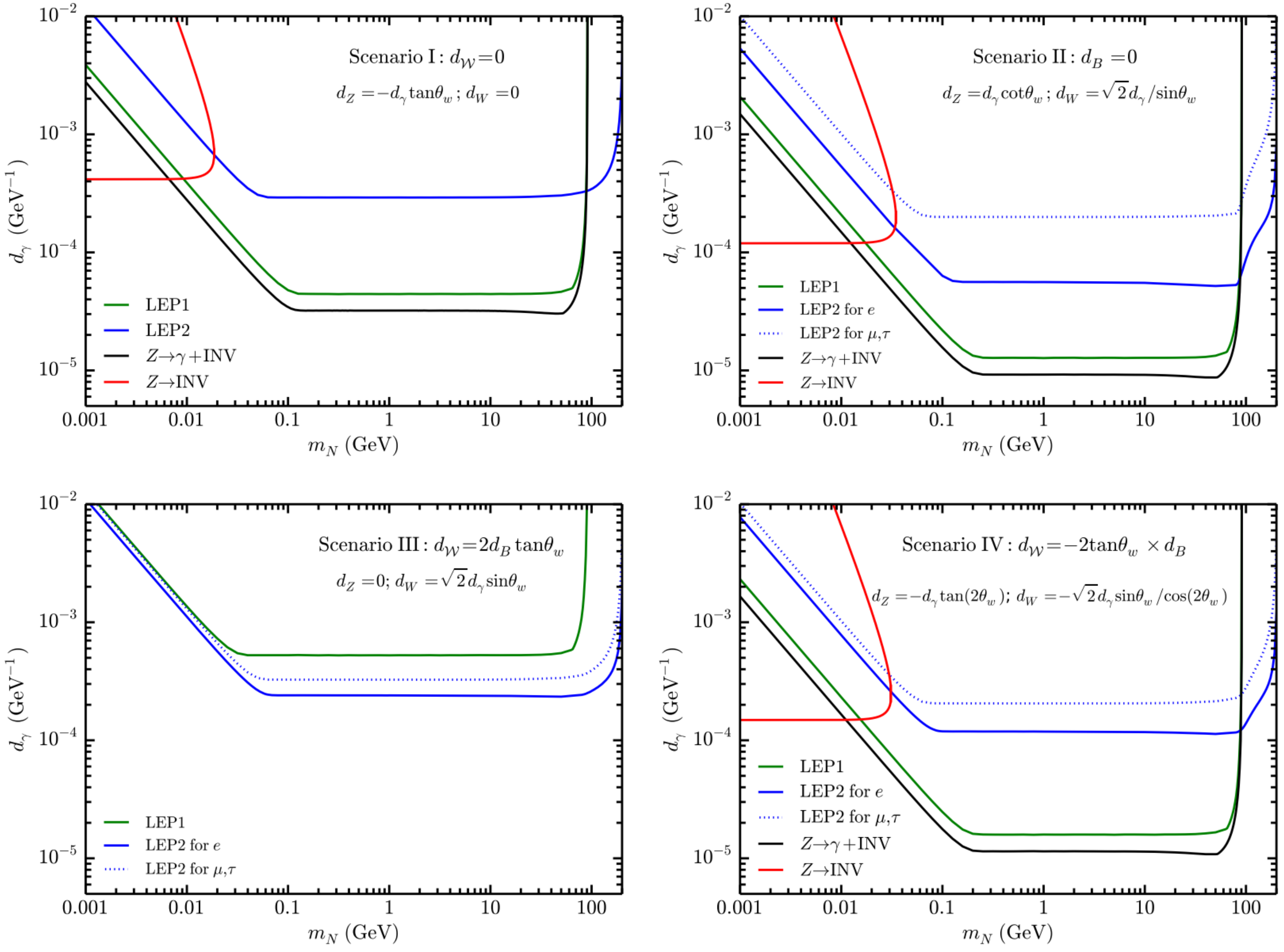
Phys.Rept. 427 (2006) 257

new physics contributions $\Gamma^{\rm NP}_{Z \to {\rm invisible}} < 2.0$ MeV at 95% C.L.

Four typical scenarios

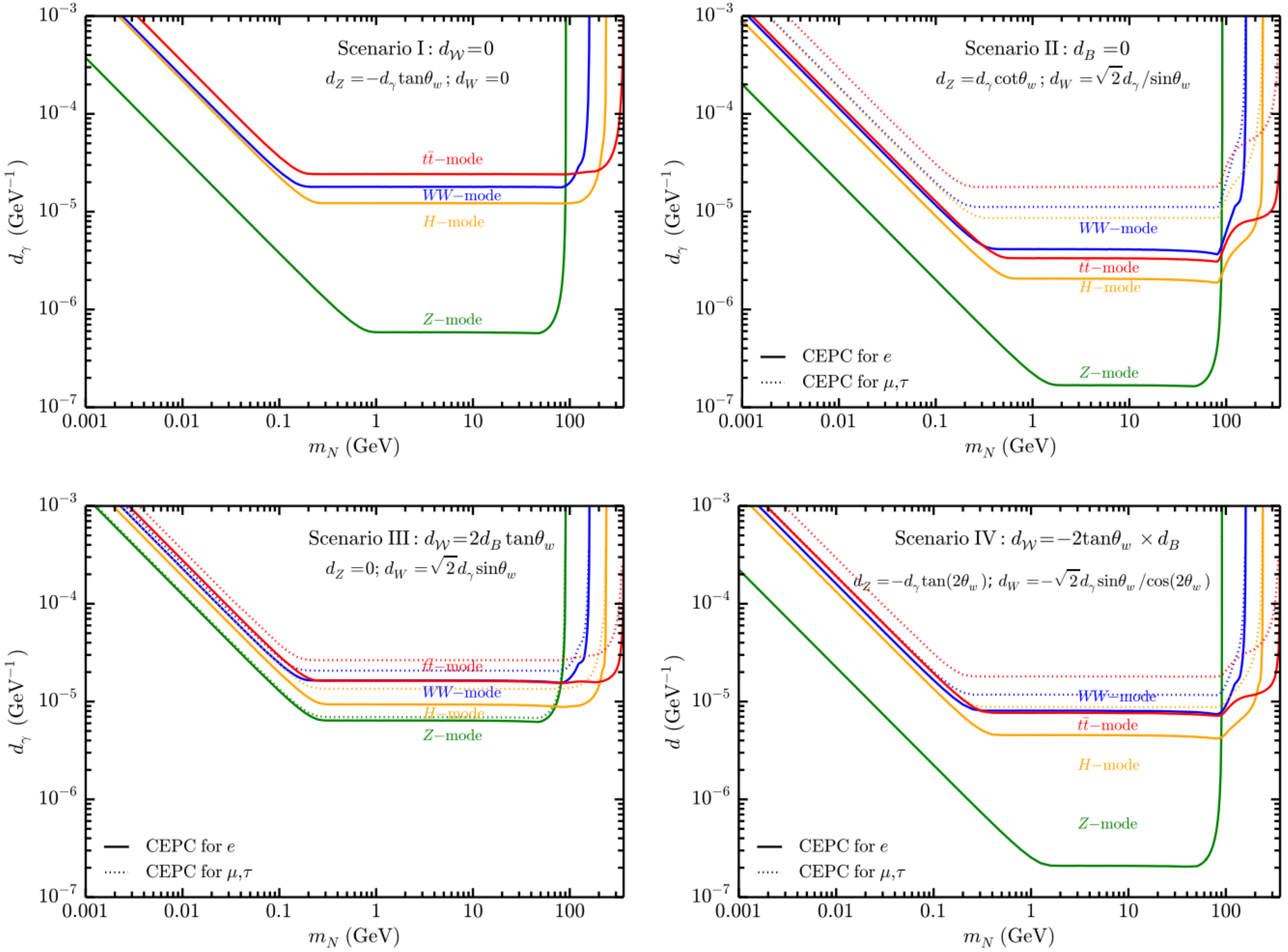
Scenario	Assumptions	Relations
I	$d_{\mathcal{W}} = 0$	$d_Z = -d_\gamma \tan\theta_w;\ d_W = 0$
II	$d_B = 0$	$d_Z = d_\gamma \cot\theta_w;\ d_W = \sqrt{2} d_\gamma / \sin\theta_w$
III	$d_{\mathcal{W}} = 2\tan\theta_w \times d_B$	$d_Z = 0;\ d_W = \sqrt{2} d_\gamma \sin\theta_w$
IV	$d_{\mathcal{W}} = -2\tan\theta_w \times d_B$	$d_Z = -d_\gamma \tan(2\theta_w);\ d_W = -\sqrt{2} d_\gamma \sin\theta_w / \cos(2\theta_w)$

Results at LEP



- A characteristic “U” shape.
- The measurements of Z decay will derive same sensitivity for all the three lepton flavors, so almost do the monophoton searches at LEP1.
- the constraints on electron will be stricter than mu or tau from monophoton searches at LEP2.
- The constraints from the measurement of the branching ratio for Z → γ + invisible are always found to be most stringent.

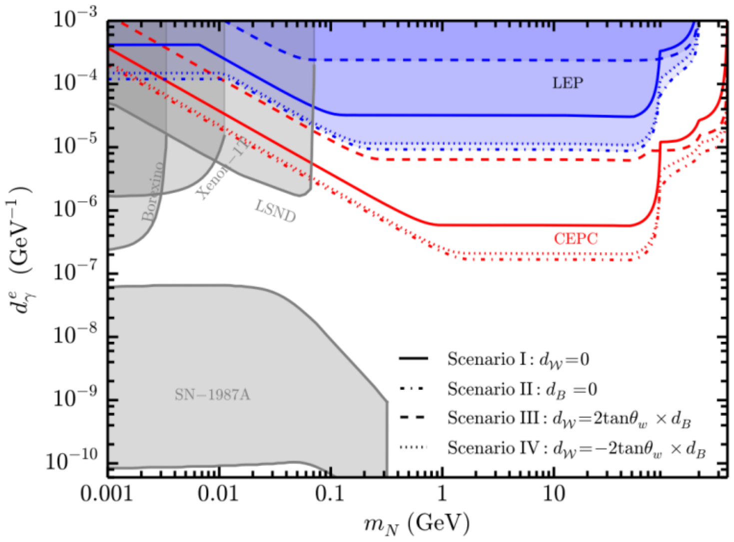
Results at CEPC

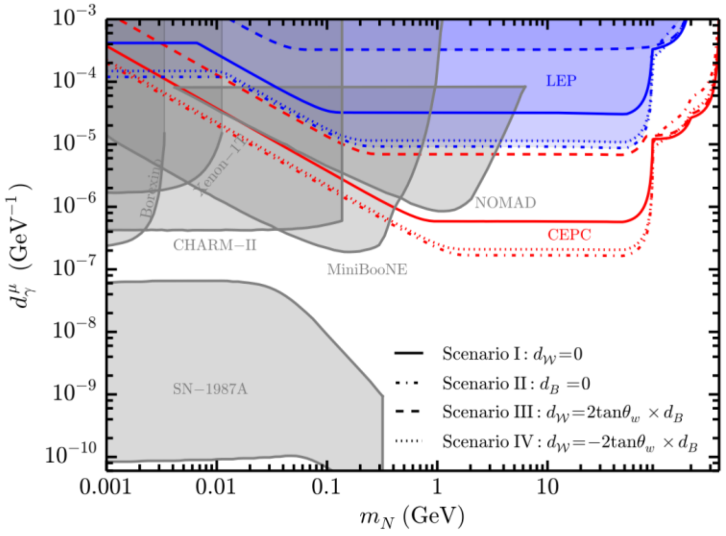


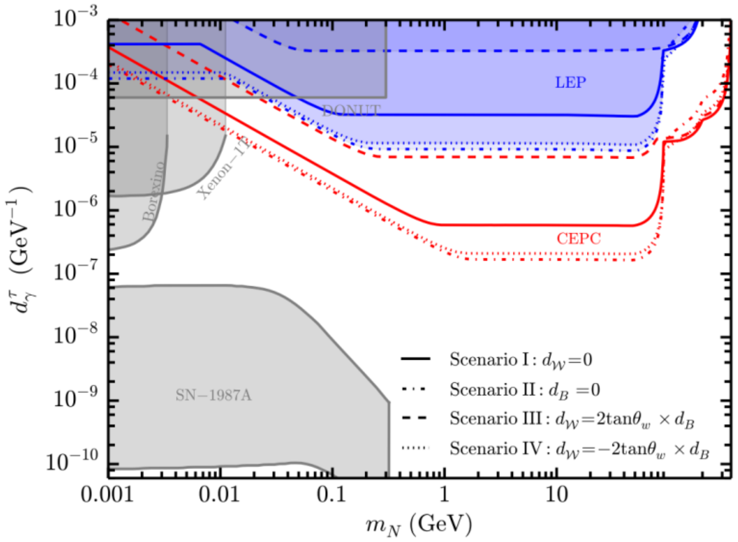
Operation mode	Z factory	WW threshold	Higgs factory	$t\bar{t}$
$\sqrt{s}$ (GeV)	91.2	160	240	360
Run time (year)	2	1	10	5
Instantaneous luminosity ($10^{34} cm^{-2} s^{-1}$, per IP)	191.7	26.6	8.3	0.83
Integrated luminosity (ab^{-1}, 2 IPs)	100	6	20	1
Event yields	3×10^{12}	1×10^{8}	4×10^{6}	5×10^{5}

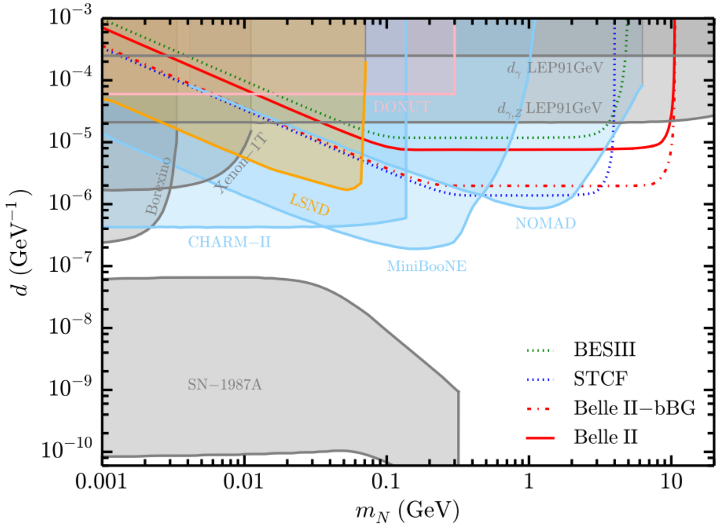
- Z-mode has the best sensitivity in all four scenarios for the HNL with small mass.
- Z-mode can give about two orders of magnitude of improvement over the other three running modes at CEPC in the sensitivity on d_mu/tau.

Results at electron colliders





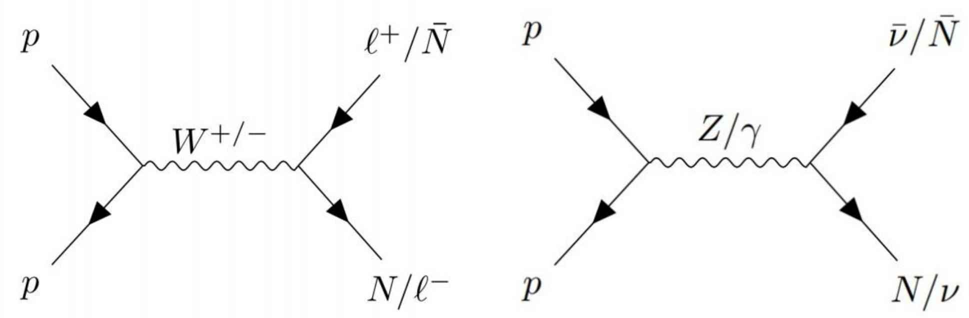




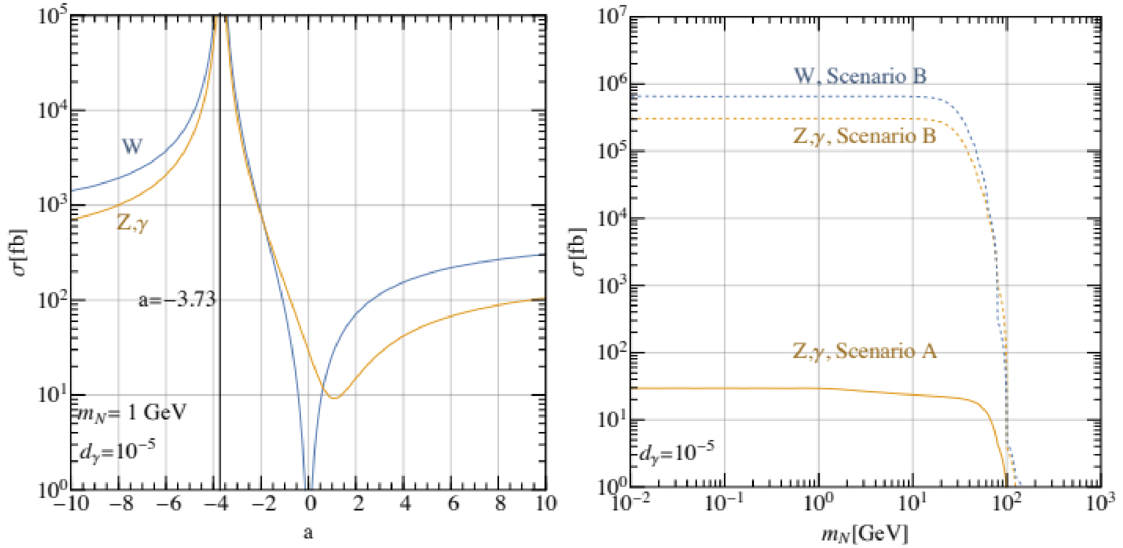
- The current constraints basically do not dependent on the ratio a, since the typical scattering energies are far less than the electroweak scale.

- Gray regions for all 3 lepton flavors
- Orange regions only for electron-neutrino (d_e)
- Skyblue regions only for muon-neutrino (d_μ)
- Pink regions only for tau-neutrino (d_τ)

Production at LHC

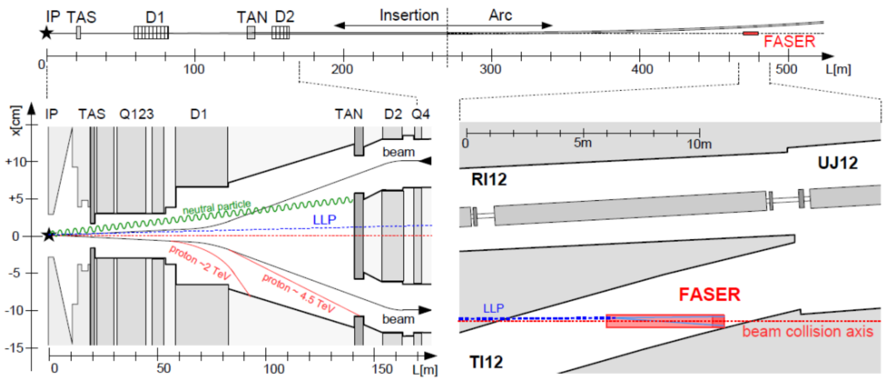


Scenario	Assumptions	Relations
A	$d_{\mathcal{W}} = 0$	$d_Z = -d_\gamma \tan\theta_w;\ d_W = 0$
B	$d_{\mathcal{W}} = -3.73 \times d_B$	$d_Z \approx 139.55 \times d_\gamma;\ d_W \approx 173.52 \times d_\gamma$

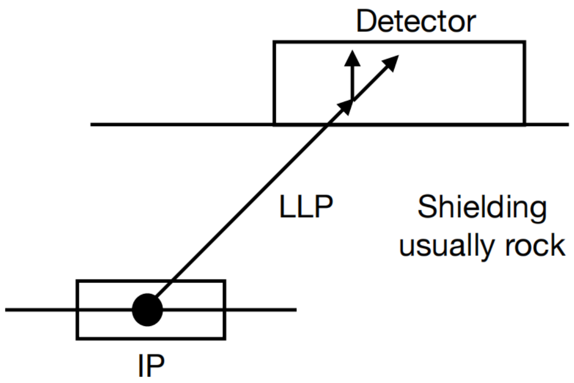


LLP detectors at LHC

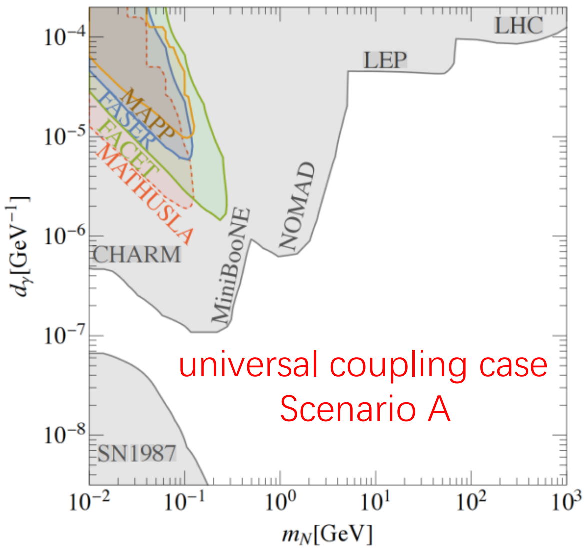
Detectors	L_x [m]	L_y [m]	L_{xy} [m]	L_z [m]	Luminosity [fb^{-1}]
FASER-2	–	–	$[0, 1]$	$[475, 480]$	3000
MAPP-2	$[3, 6]$	$[-2, 1]$	–	$[48, 61]$	300
FACET	-	-	$[0.18,\ 0.5]$	$[101, 119]$	3000
MATHUSLA	$[100, 120]$	$[-100, 100]$	-	[100,300]	3000

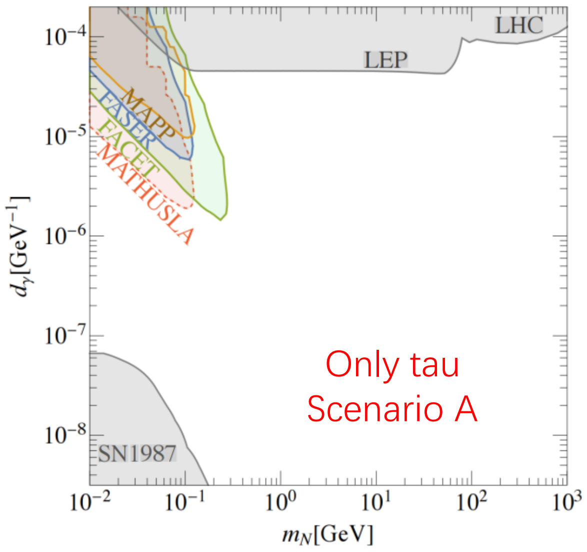


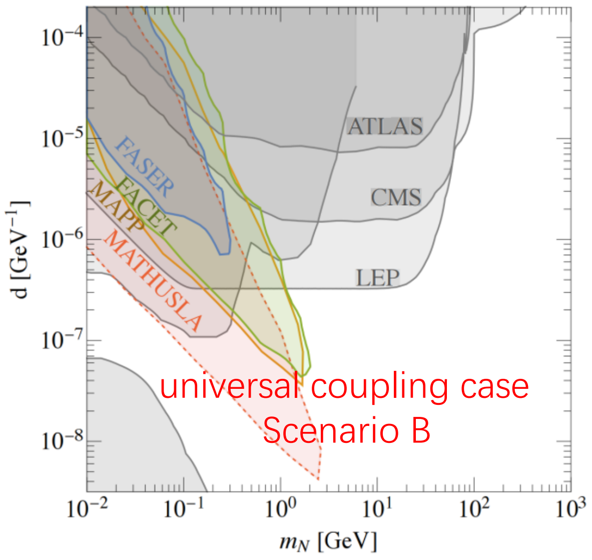
Approved experiment

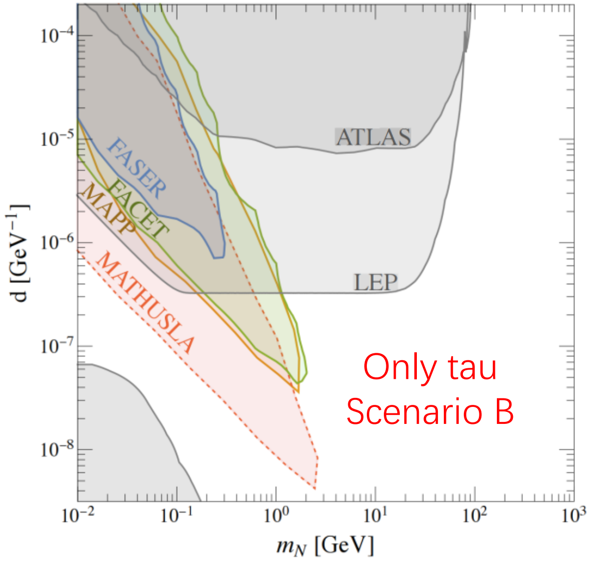


Results at LHC









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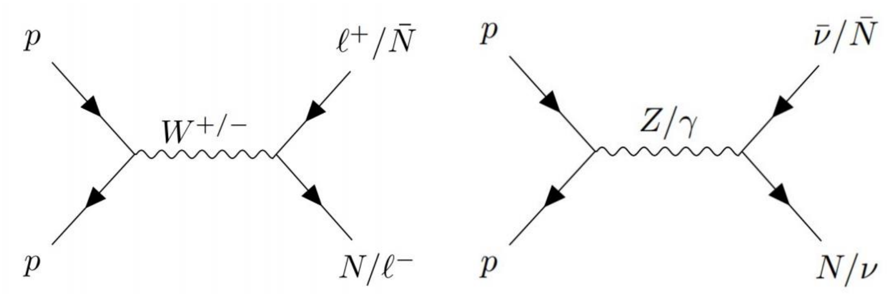

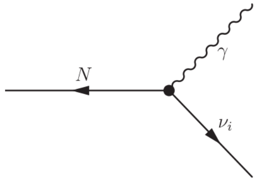

Summary

- The more general dipole couplings to HNL which respect the full gauge symmetries of the SM are considering.

- We present the constraints on various electron colliders and LHC by Long-lived Particle Detectors.

- The constraints on active-sterile neutrino transition magnetic moments dependent on the model at high energy colliders.

- The current constraints basically do not dependent on the ratio a, since the typical scattering energies are far less than the electroweak scale.

谢谢观看

Thank you!

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