The effective theory of RHν

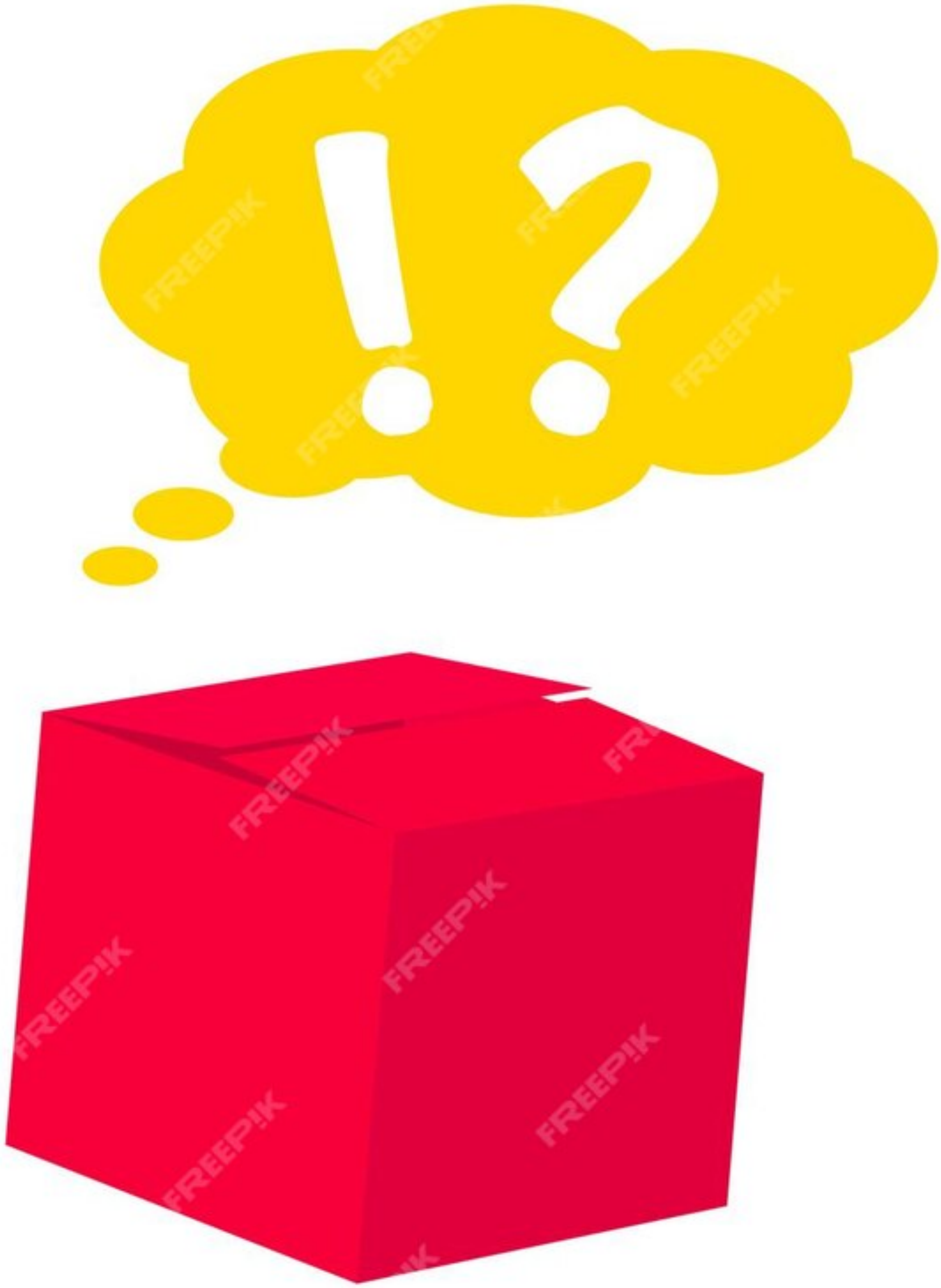
d=5 operators @ future colliders

Daniele Barducci

Bled 2024 - International workshop on LNV


FINEST HERBAL EXTRACTS
Cockta
Original


BLED
Beautiful Lake Et D=5
FINEST HERBAL EXTRACTS
Cockta
Original



Neutrinos have masses!!!

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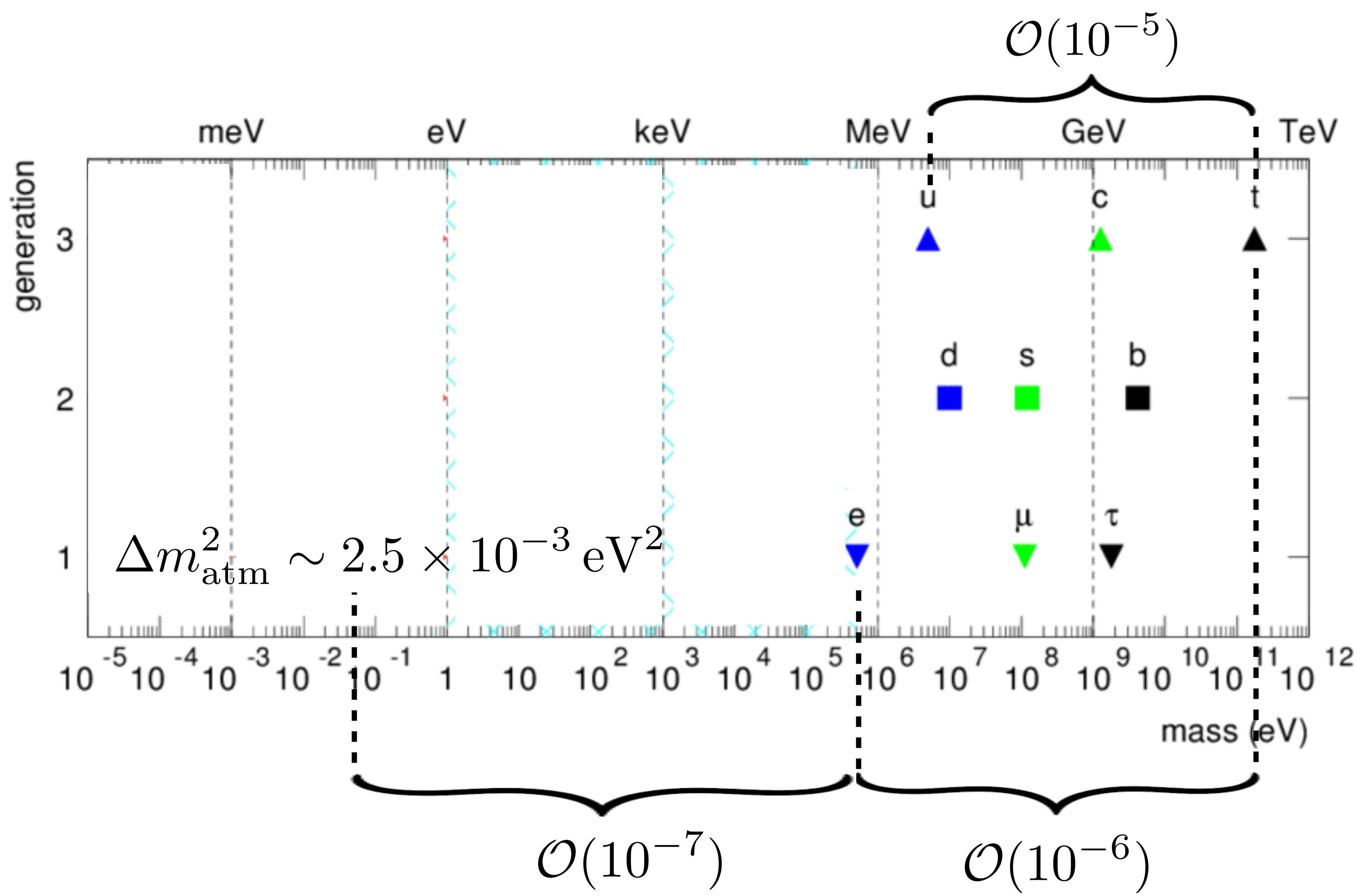
Neutrinos oscillate!!!

Neutrino masses

- Perhaps not too much a surprise, all the known fermions have mass…
- Also their lightness might not be an issue…



Neutrino oscillation

- Neutrino flavor mix, but again this is not new…
- Quark flavor mixes too, even though quark oscillations are not visible

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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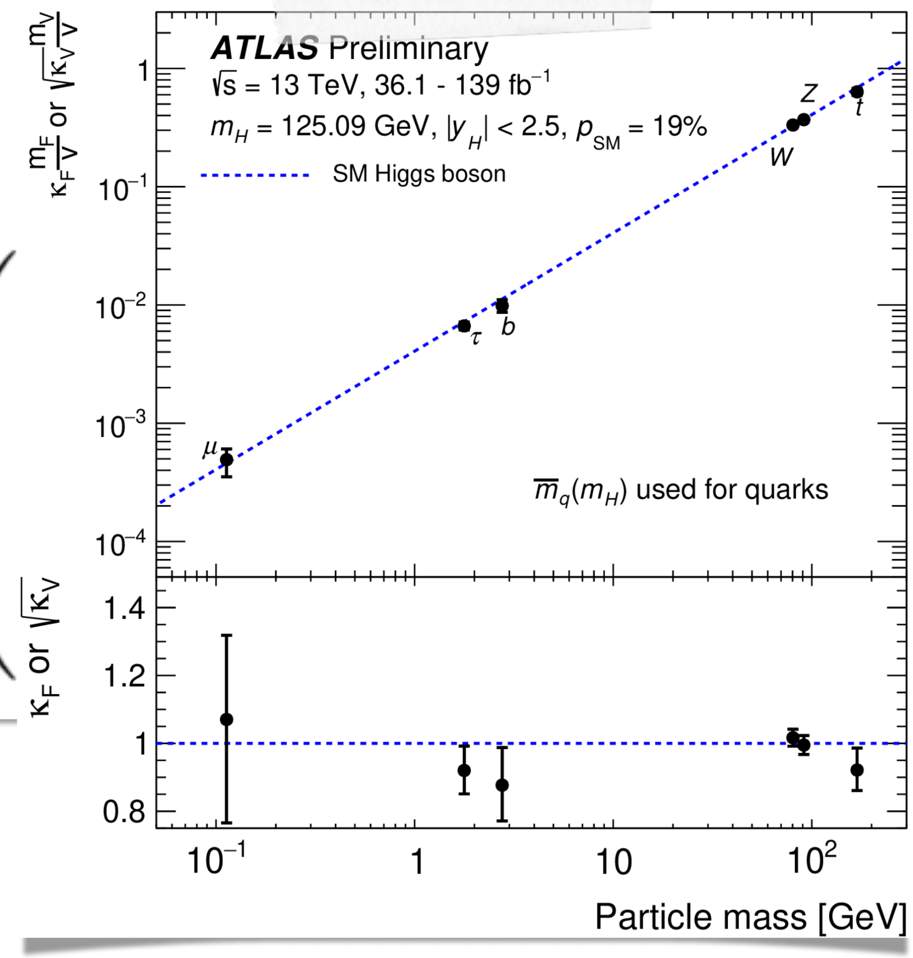
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \Big(\quad \cdots \quad V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

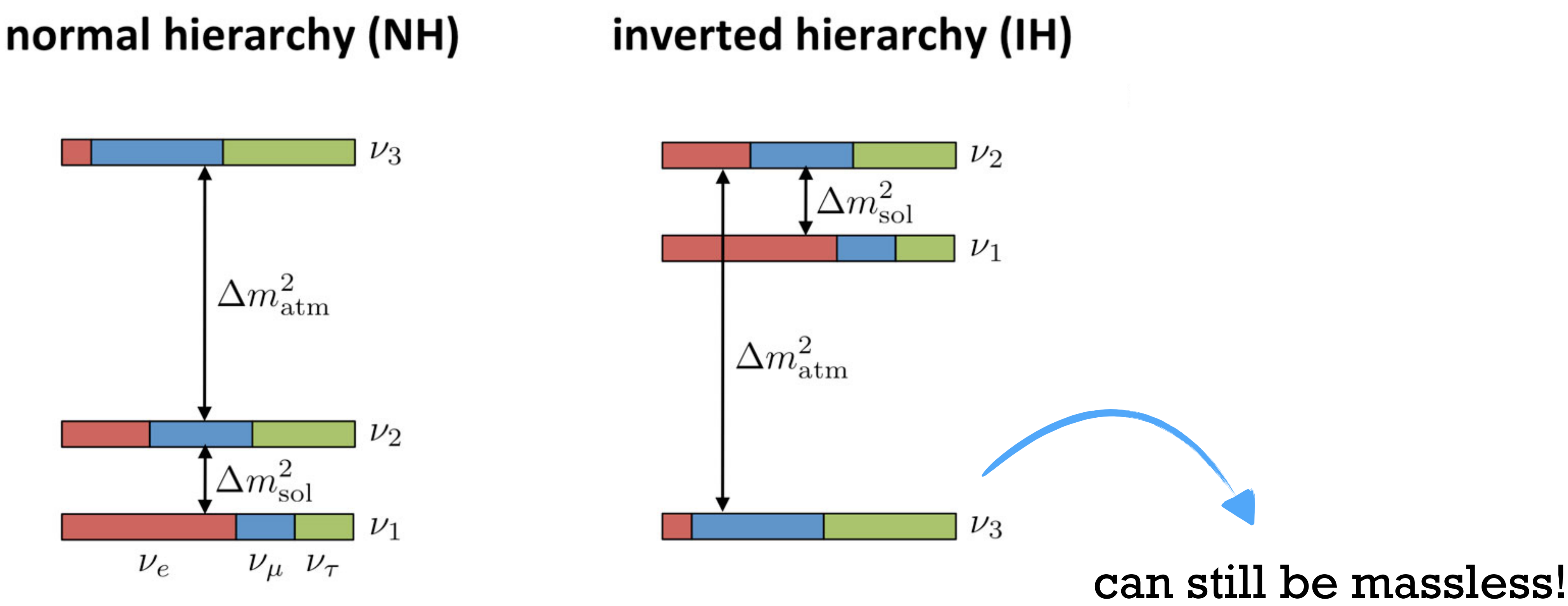


- CKM comes from the Yukawa sector, from which we believe fermions get mass
- We do not know if neutrinos get mass from the Higgs VEV, but we do not have direct evidence for e, u, d, s, c either…

So… what's the big deal?

- Neutrino oscillations only require two out of three neutrino to have a mass

$$\Delta m^2_{\rm atm} \sim 2.5 \times 10^{-3}\,{\rm eV}^2 \qquad \Delta m^2_{\rm sol} \sim 7.5 \times 10^{-5}\,{\rm eV}^2$$

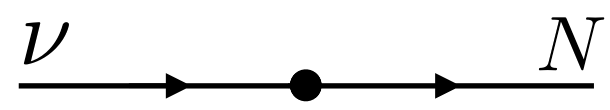


Still do not know what nature has chosen

- Neutrino masses can arise in a completely different way…

- Neutrino can get Dirac masses in the usual way via Yukawa interactions

$$-\mathcal{L} = Y_\nu L H N + h.c.$$

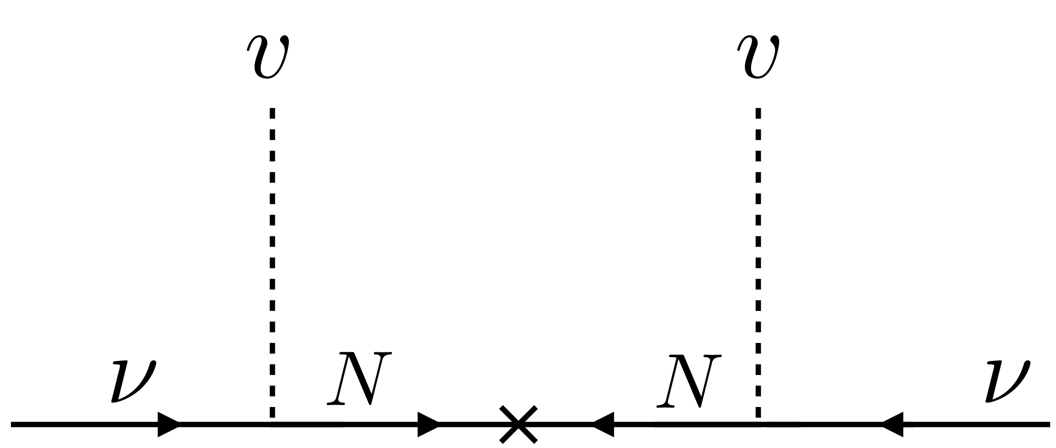


$$m_\nu \sim Y_\nu v$$

- A fermion singlet under the SM group can also have a Majorana mass

$$-\mathcal{L} = Y_\nu L H N + \frac{M_N}{2} N^2 + h.c.$$

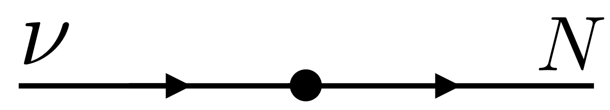
- Neutrinos acquire Majorana masses too



$$\begin{cases} m_N \sim M_N \\ m_\nu \sim \dfrac{Y_\nu^2 v^2}{M_N} \end{cases}$$

- Neutrino can get Dirac masses in the usual way via Yukawa interactions

$$-\mathcal{L} = Y_\nu L H N + h.c.$$

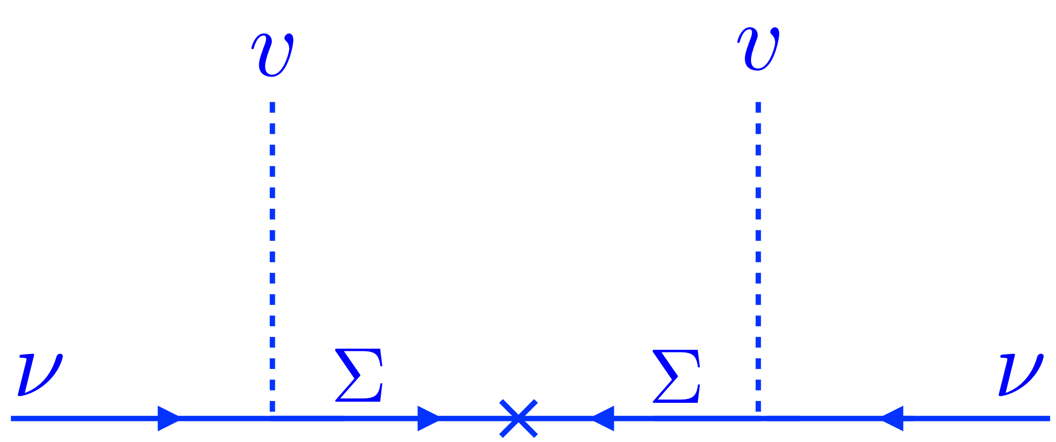


$$m_\nu \sim Y_\nu v$$

- Works also for $SU(2)_L$ triplets, since they are real irreps

$$-\mathcal{L} = Y_\nu L H \Sigma + \frac{M_\Sigma}{2}\Sigma^2 + h.c.$$

- Neutrinos acquire Majorana masses too

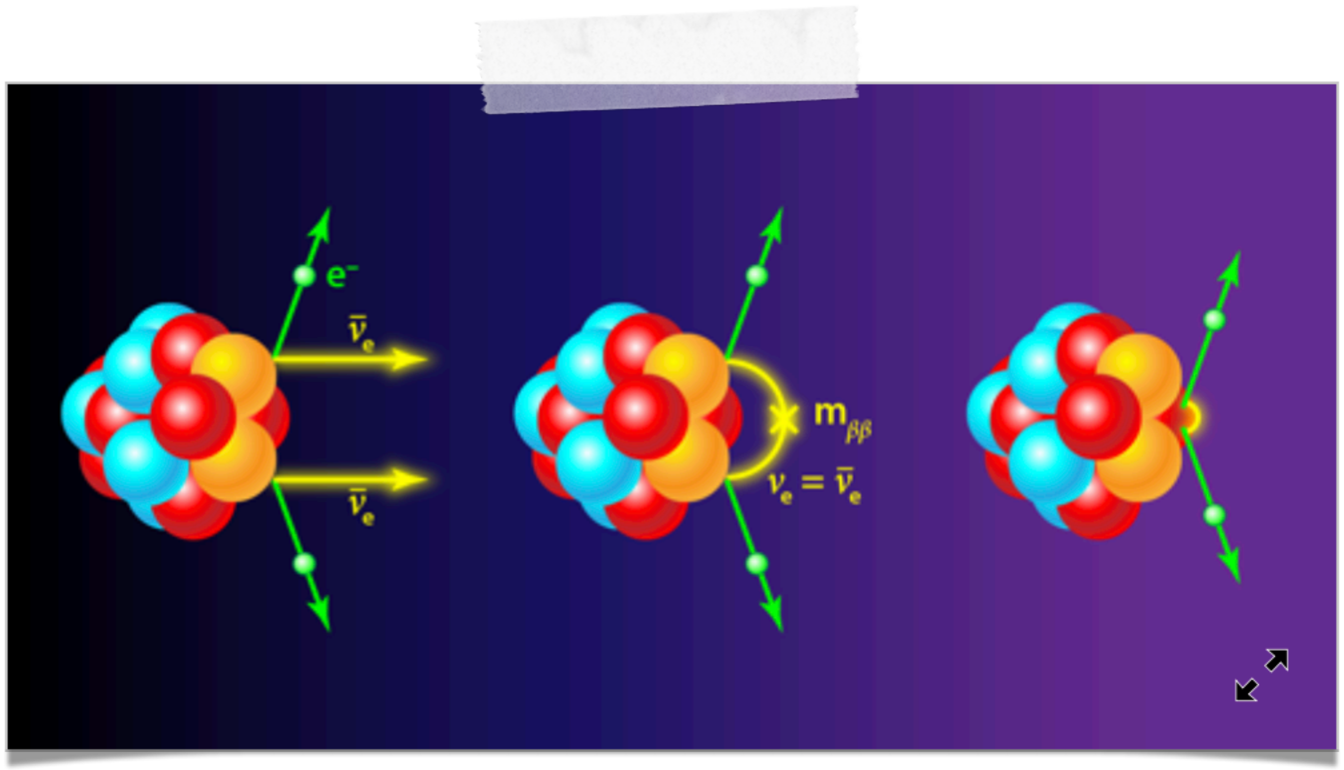


$$\begin{cases} m_N \sim M_\Sigma \\ m_\nu \sim \dfrac{Y_\nu^2 v^2}{M_\Sigma} \end{cases}$$

- In both cases lepton number is violated by two units

$$\Delta L = 2$$

- Accidental symmetry of the SM, no need to be a symmetry of a final theory
- Most striking evidence could be neutrinoless double beta decay



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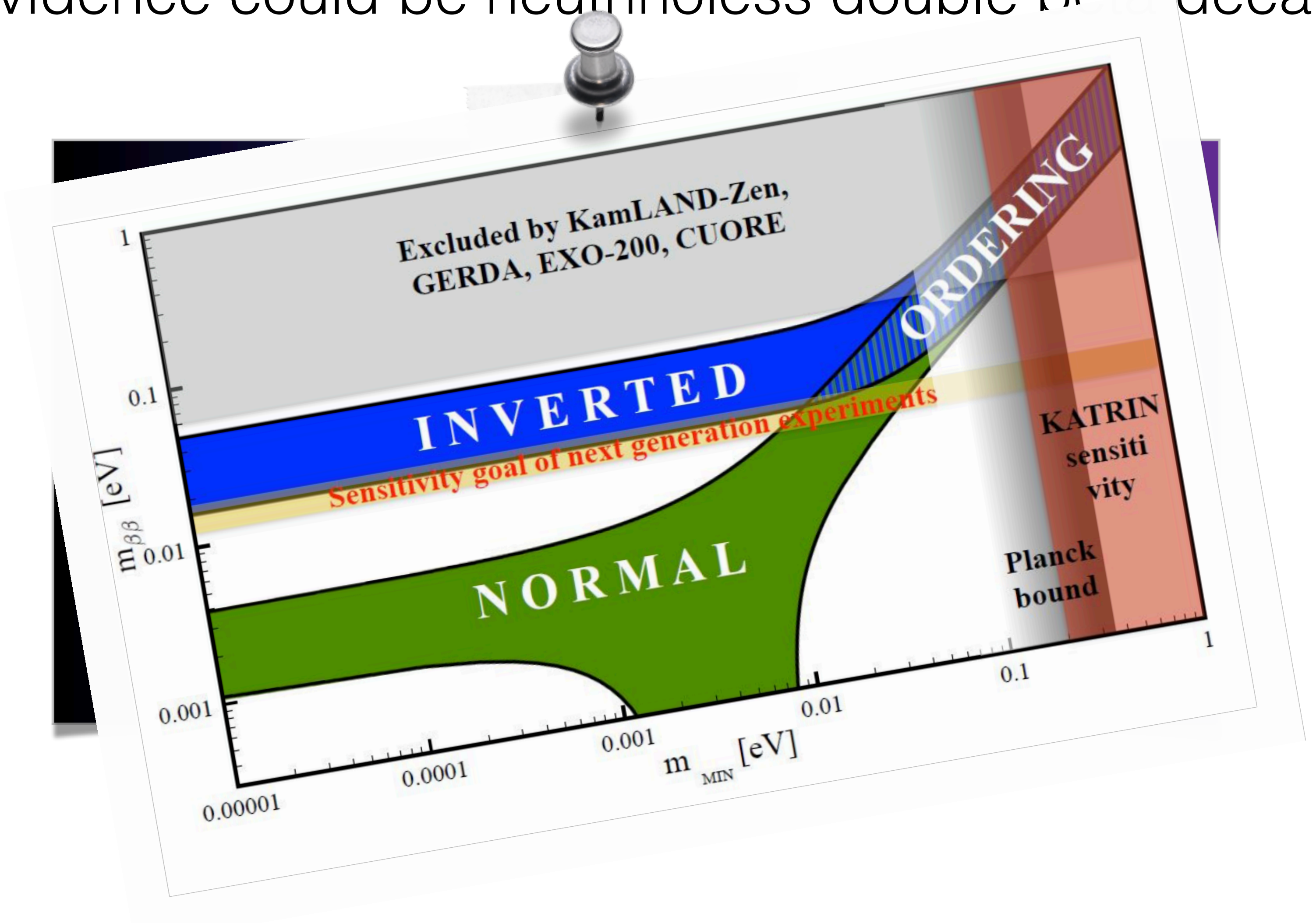

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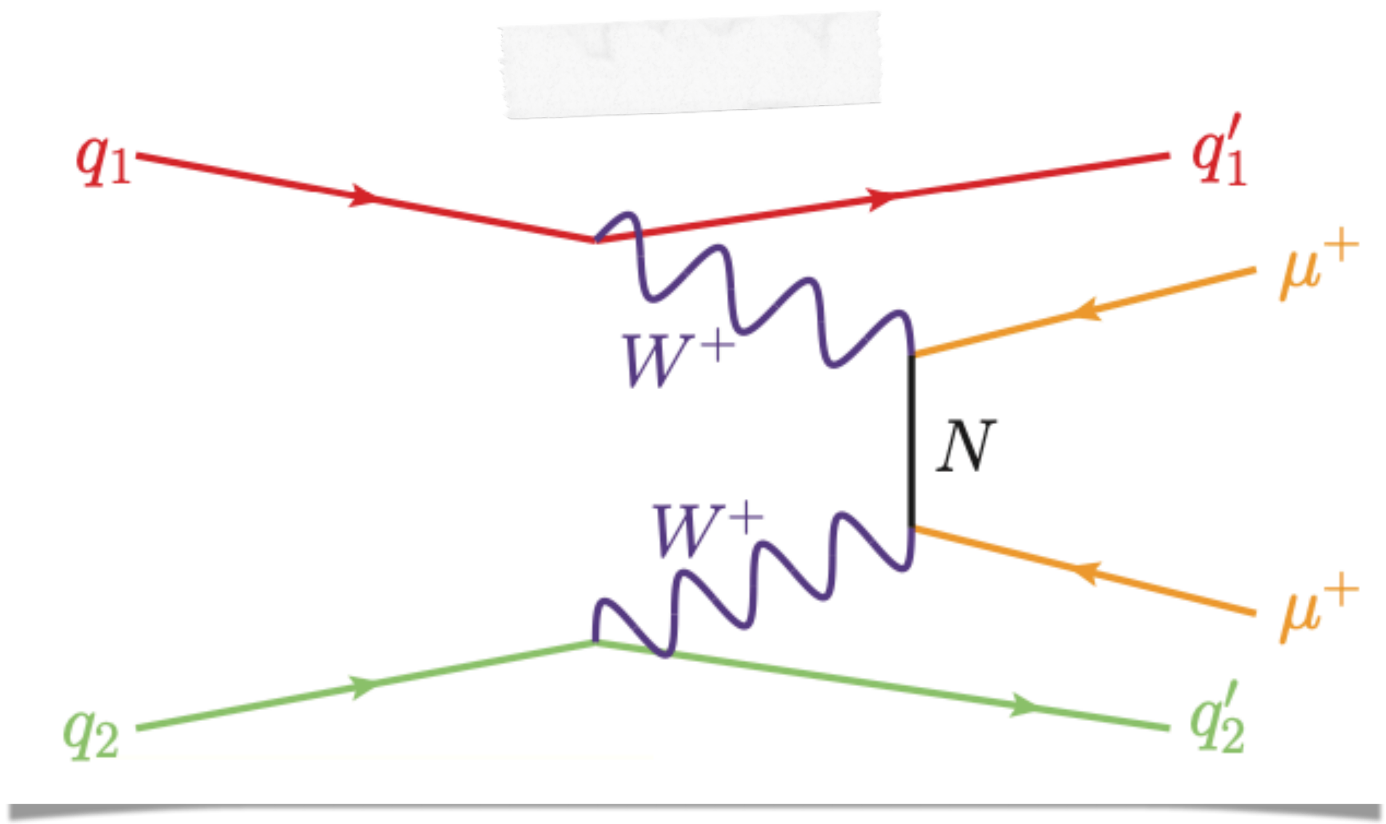

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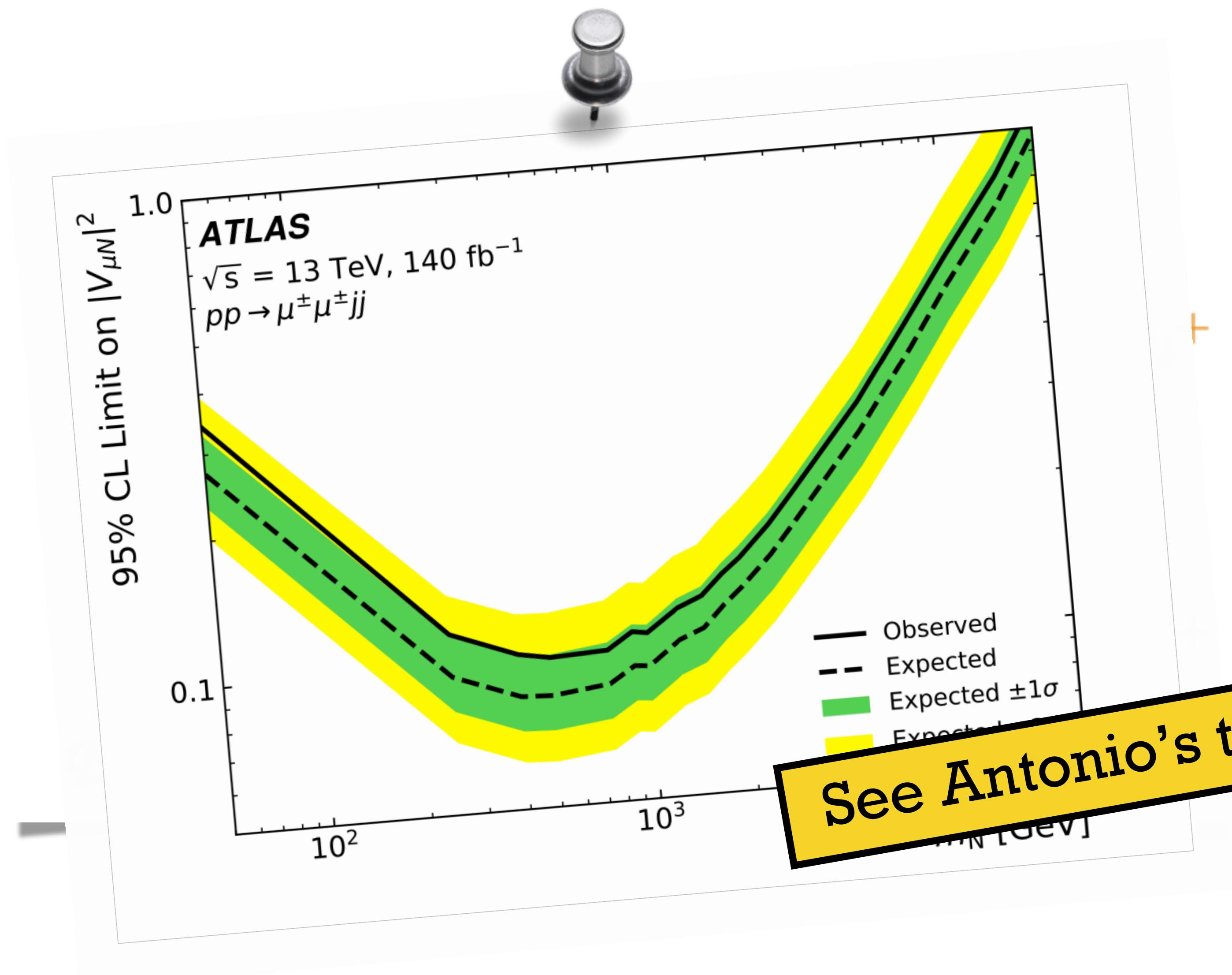
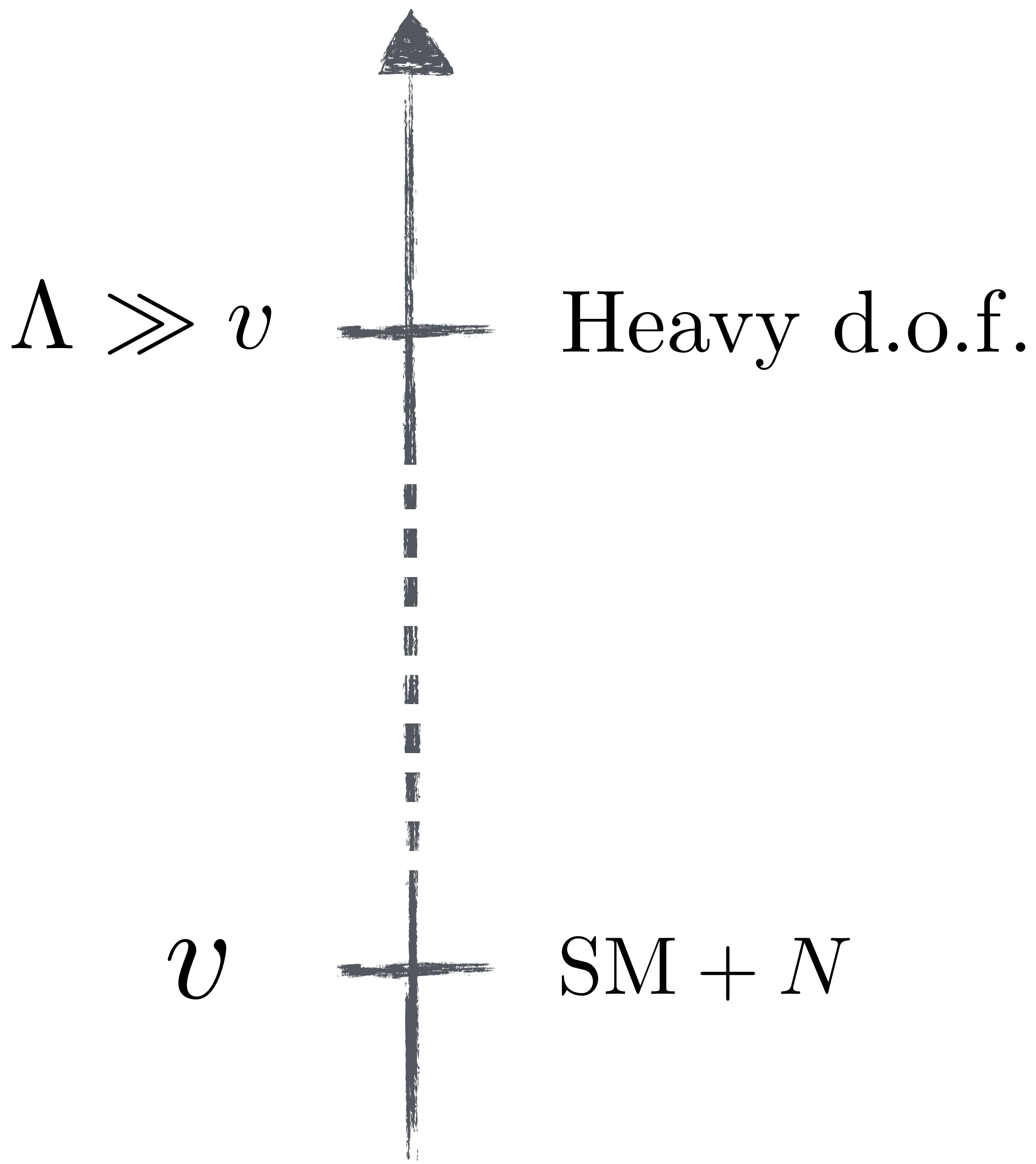
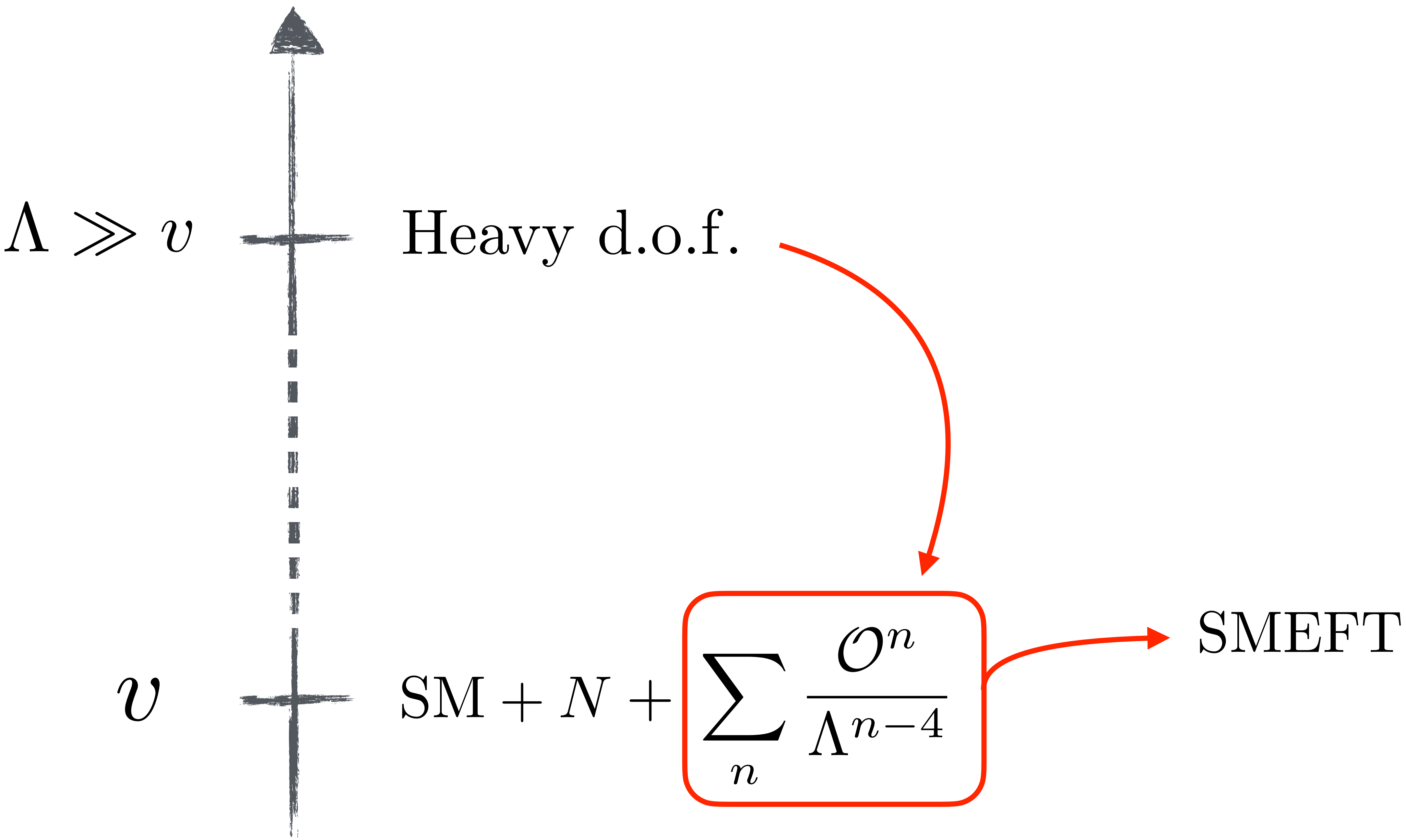


See Antonio's talk

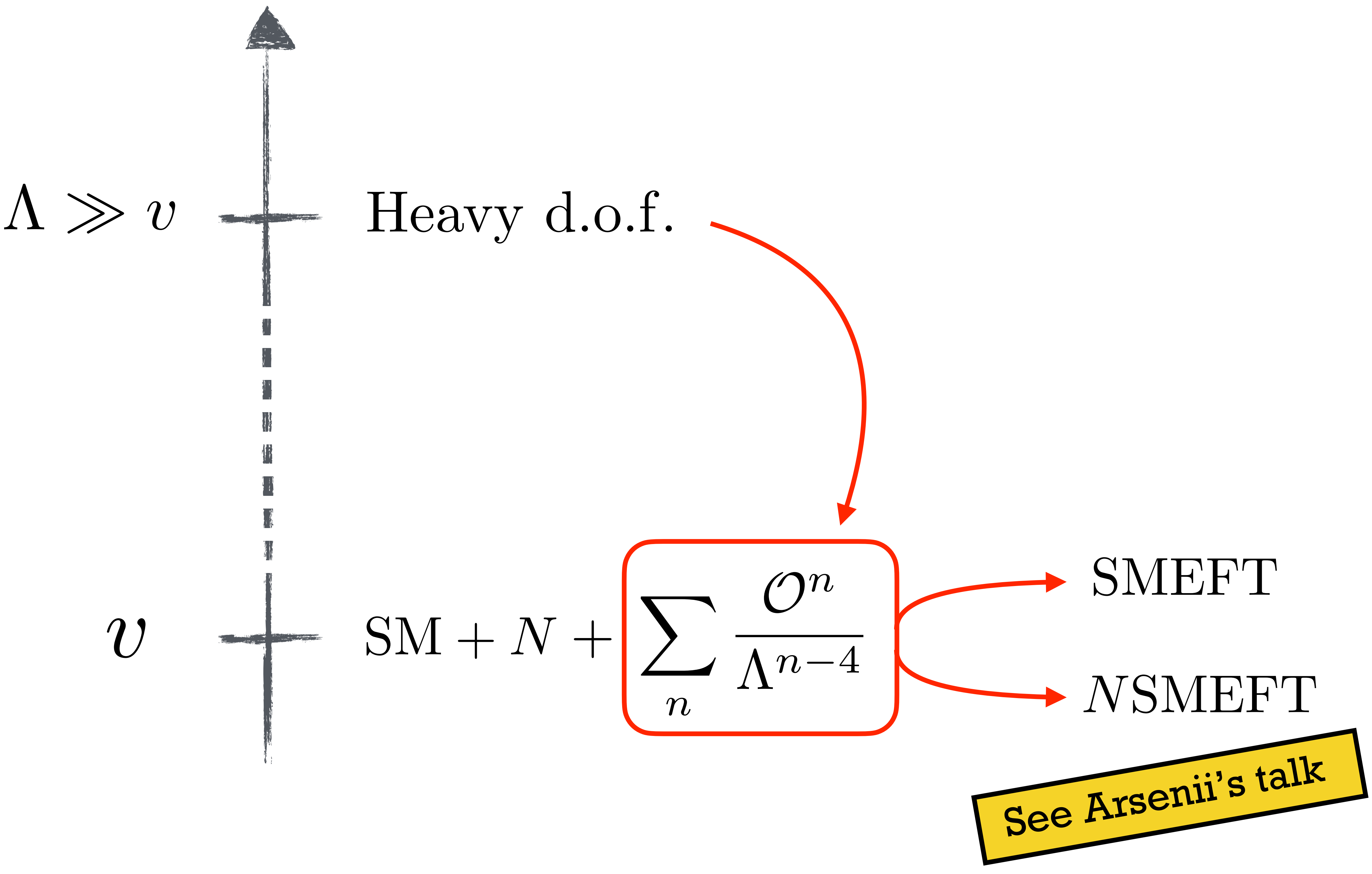
Beyond naive see-saw



Beyond naive see-saw



Beyond naive see-saw



- Non redundant basis has been worked out up to $d = 7$ [Liao, Ma 1612.04527]
- At $d = 5$ only two new operators exist [Graesser 0704.0438, Aparici+ 0904.3244]

$$\mathcal{O}_{NH} = |H|^2 N^2$$

$$\mathcal{O}_{NB} = N\sigma^{\mu\nu} N B_{\mu\nu}$$

Adds extra contributions to the neutrino mass matrix

Vanishes with a single right-handed neutrino

Pheno consequences?

Higgs operator

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N}\partial\!\!\!/ N - \bar{L}_L Y_\nu \tilde{H} N - \frac{1}{2} M_N \bar{N}^c N + \alpha_{NH} (\bar{N}^c N)(H^\dagger H) + h.c.$$

EWSB

$$-\frac{1}{2}\bar{n}^c \mathcal{M} n + h.c. = -\frac{1}{2}\bar{n}^c \begin{pmatrix} 0 & Y_\nu v \\ Y_\nu^T v & M_N - 2\alpha_{NH}\frac{v^2}{\Lambda} \end{pmatrix} n + h.c. \qquad n = (\nu_L, N^c)$$

neglect it, see later…

- Standard see-saw mass relation

$$m_\nu \simeq v^2 Y_\nu \frac{1}{M_N} Y_\nu^T = U^* m_\nu^{(d)} U^\dagger$$

- For single RH neutrino 1-to-1 correspondence between heavy mass and mixing

$$\theta \sim \frac{yv}{M_N} \sim \sqrt{\frac{m_\nu}{M_N}} \sim 7.2 \times 10^{-6} \left(\frac{1 \text{ GeV}}{m_N}\right)^{1/2}$$

- With additional RH states extra freedom, best seen in the Casas-Ibarra formalism

$$m_\nu \simeq v^2 Y_\nu \frac{1}{M_N} Y_\nu^T = U^* m_\nu^{(d)} U^\dagger$$

solved with

$$Y_\nu \simeq \frac{1}{v} U^* \sqrt{\mu} \sqrt{M_N}$$

$$\sqrt{\mu} \sqrt{\mu}^T = m_\nu^{(d)}$$

- Write $\sqrt{\mu} = \sqrt{m}\mathcal{R}$ with
  - $\sqrt{m}$ matrix containing physical neutrino masses
  - $\mathcal{R}$ complex orthogonal matrix

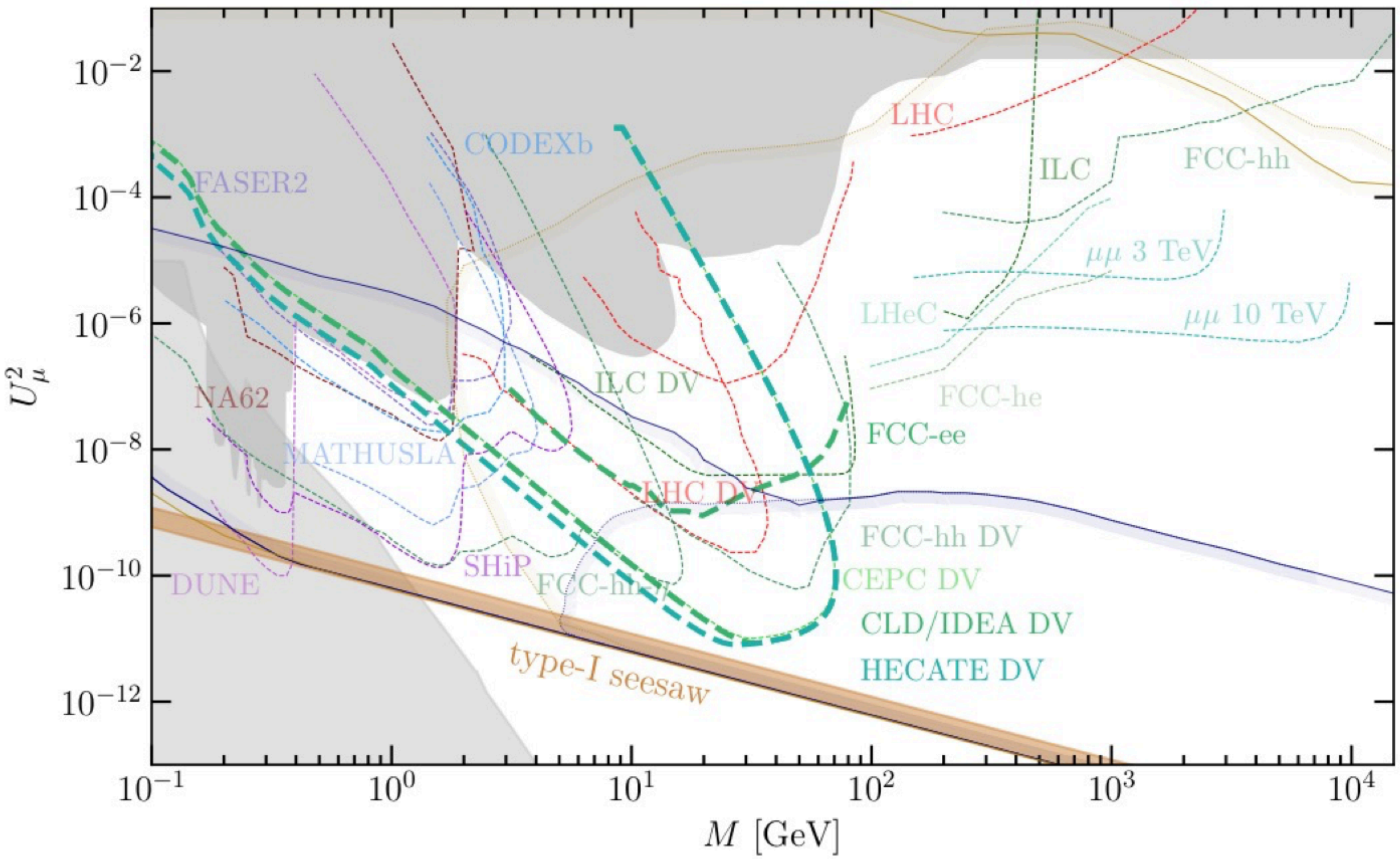
- For example, with 2 RH neutrinos

$$\sqrt{m_{NH}} = \begin{pmatrix} 0 & 0 \\ 0 & \sqrt{m_2} \\ \sqrt{m_3} & 0 \end{pmatrix} \qquad \mathcal{R} = \begin{pmatrix} \cos z & \pm \sin z \\ -\sin z & \pm \cos z \end{pmatrix} \qquad z = \beta + i\gamma$$

- Complex angle in $\mathcal{R}$ gives an exponential enhancement of the mixing

$$\theta \sim 7.2 \times 10^{-6}\, e^{\gamma - i\beta} \left(\frac{1\ \mathrm{GeV}}{m_N}\right)^{1/2}$$

- m_N and θ can be taken almost as independent parameters - **back here**



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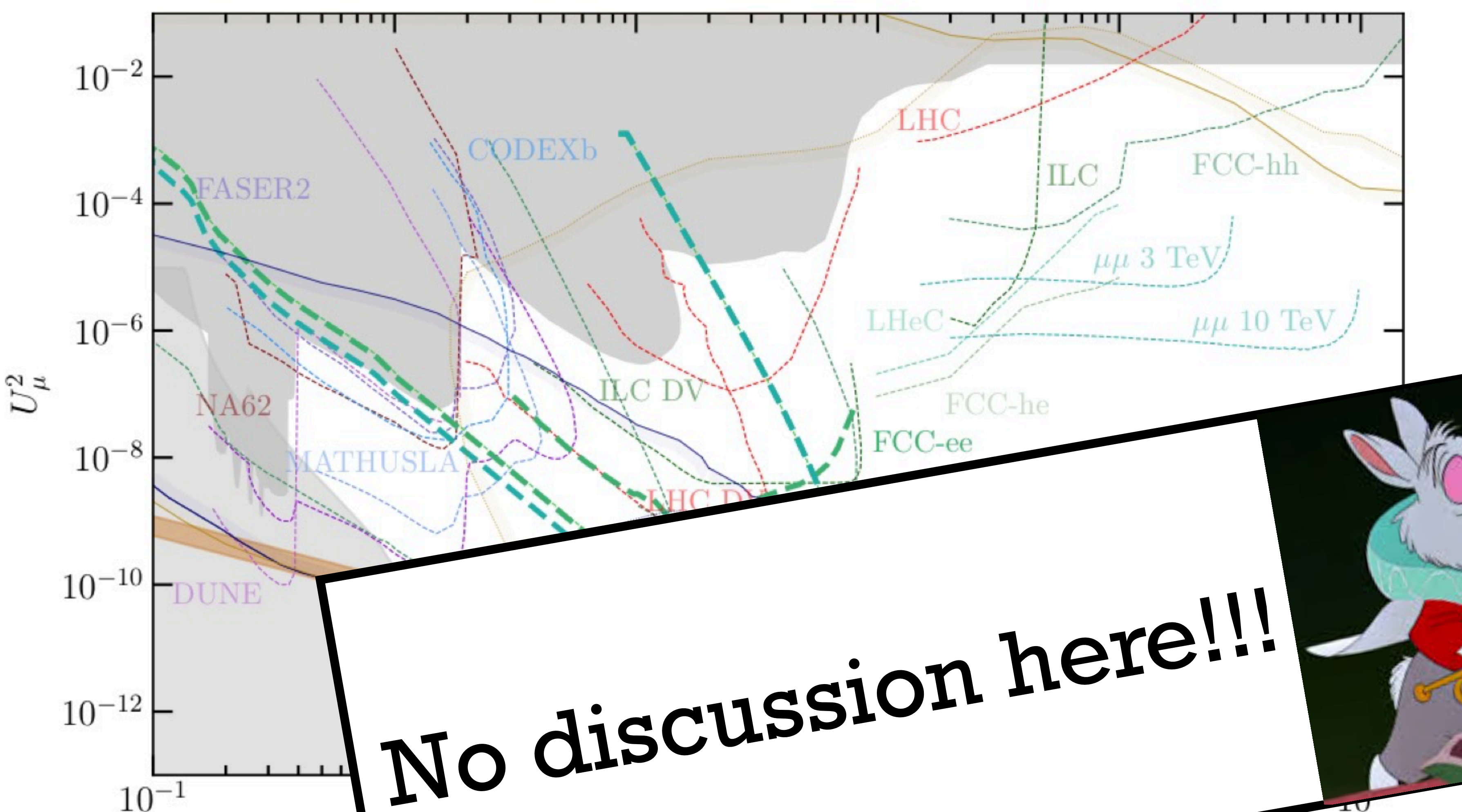
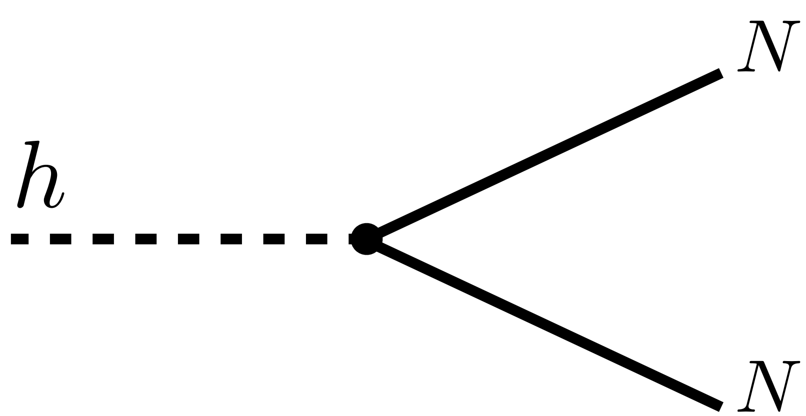


No discussion here!!!

- After EWSB the $|H|^2 N^2$ operator triggers new decay mode for light N

$$\frac{1}{\Lambda}|H|^2 N^2 \xrightarrow{\text{EWSB}} \frac{v}{\Lambda} h N^2$$



$$\Gamma = \frac{1}{2\pi}\frac{v^2}{\Lambda^2} m_H \left(1 - \frac{4m_N^2}{m_H^2}\right)^{3/2}$$

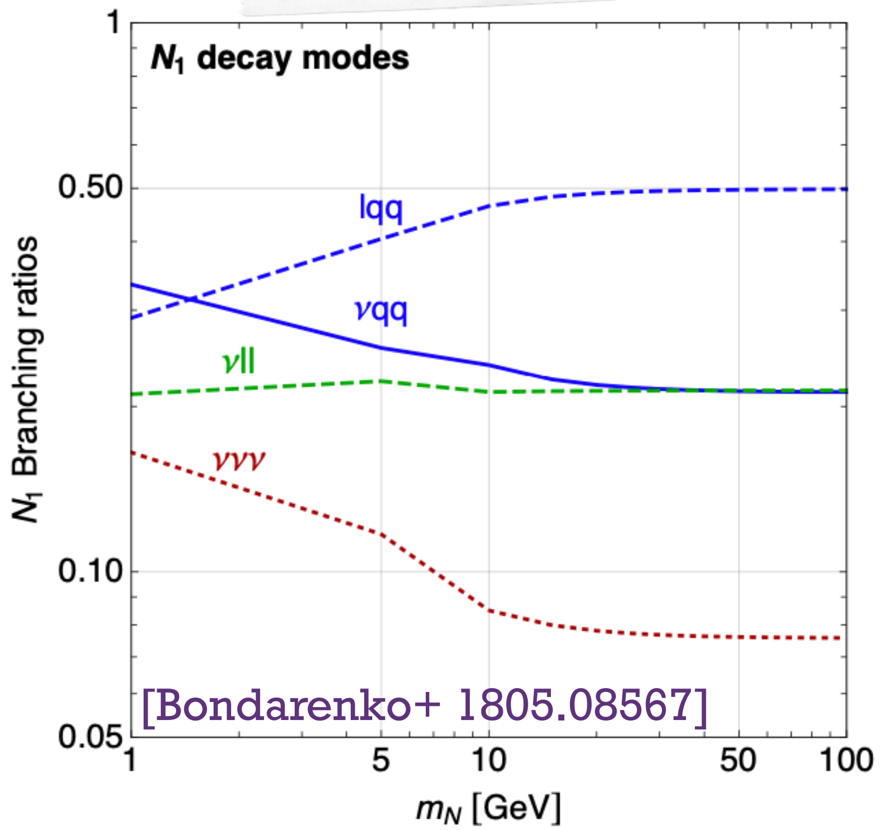
See Fabrizio's talk

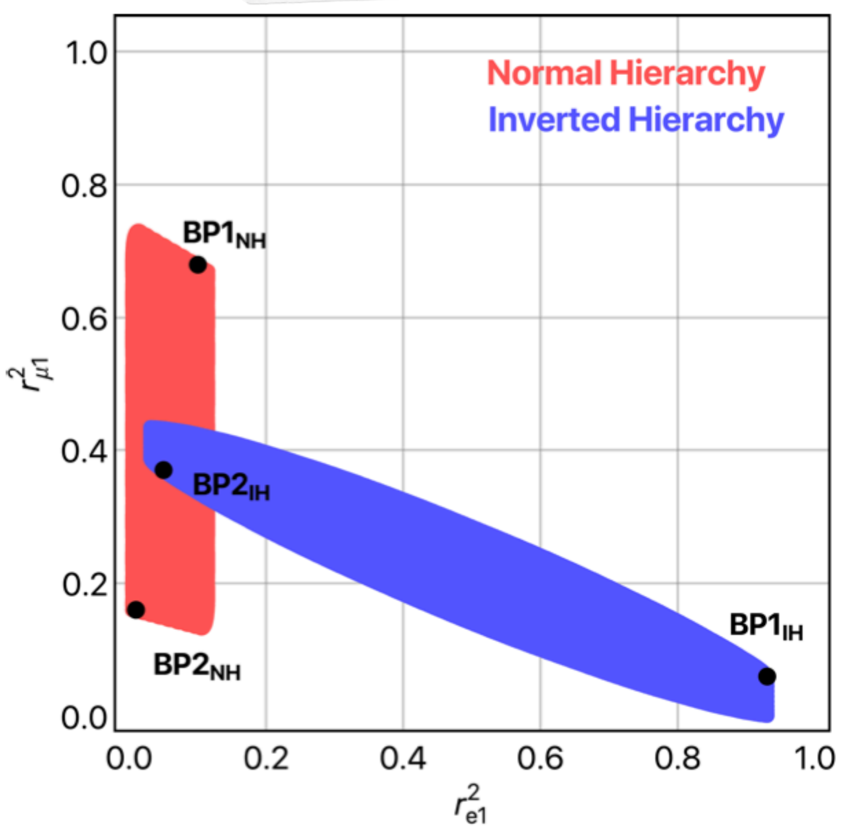
Pheno predictions

- Untagged / invisible Higgs decay if N is detector stable
- Distinctive signatures, either prompt or displaced from N decay

Sterile neutrino decay modes

Final state	Channel	Mediator
$\ell' q \bar{q}$	$\ell'_\alpha q_i \bar{q}_j$	W
$\nu q \bar{q}$	$\nu_\alpha q_i \bar{q}_j$	Z
$\nu \ell' \ell'$	$\ell'_\alpha \ell'_\beta \nu_\beta$, $\alpha \neq \beta$	W
	$\nu_\alpha \ell'_\beta \ell'_\beta$, $\alpha \neq \beta$	Z
	$\nu_\alpha \ell'_\beta \ell'_\beta$, $\alpha = \beta$	W and Z
$\nu\nu\nu$	$\nu_\alpha \nu_\beta \nu_\beta$	Z





	Channel	SS
Fully-leptonic	$4\ell\ \not{E}_T$	✓
	$2\ell\ \not{E}_T$	
Semi-leptonic	$3\ell\ 2q\ \not{E}_T$	✓
	$2\ell\ 4q$	✓
	$2\ell\ 2q\ \not{E}_T$	
	$\ell\ 4q\ \not{E}_T$	
	$\ell\ 2q\ \not{E}_T$	
Fully-hadronic	$4q\ \not{E}_T$	
	$2q\ \not{E}_T$	
Invisible	$\not{E}_T$	

	Channel	SS
Fully-leptonic	$3\ell\ \tau\ \not{E}_T$	✓
	$2\ell\ 2\tau\ \not{E}_T$	
	$\ell\ \tau\ \not{E}_T$	
	$\ell\ 3\tau\ \not{E}_T$	
	$4\tau\ \not{E}_T$	
	$2\tau\ \not{E}_T$	
Semi-leptonic	$2\ell\ \tau\ 2q\ \not{E}_T$	
	$\ell\ 2\tau\ 2q\ \not{E}_T$	
	$\ell\ \tau\ 4q$	
	$\ell\ \tau\ 2q\ \not{E}_T$	

	Channel	SS
Semi-leptonic	$3\tau\ 2q\ \not{E}_T$	
	$2\tau\ 4q$	
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	$\tau\ 2q\ \not{E}_T$	
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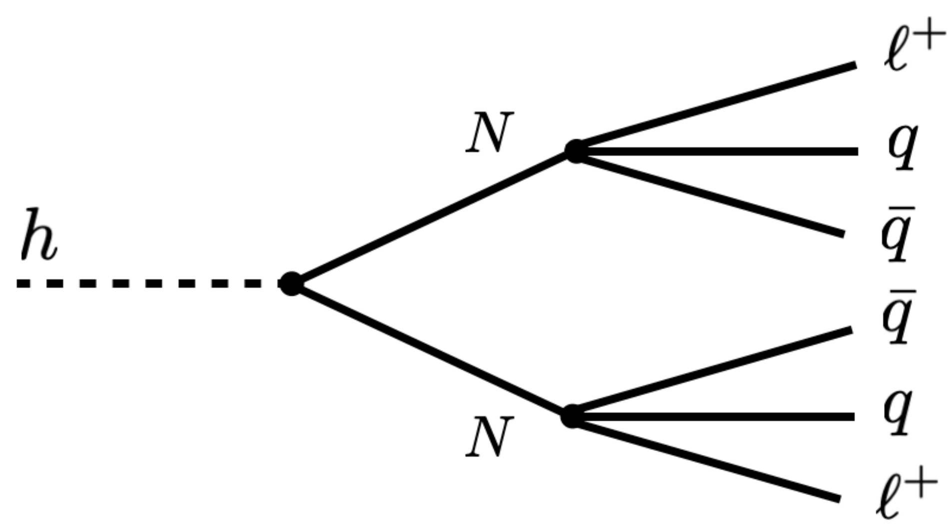
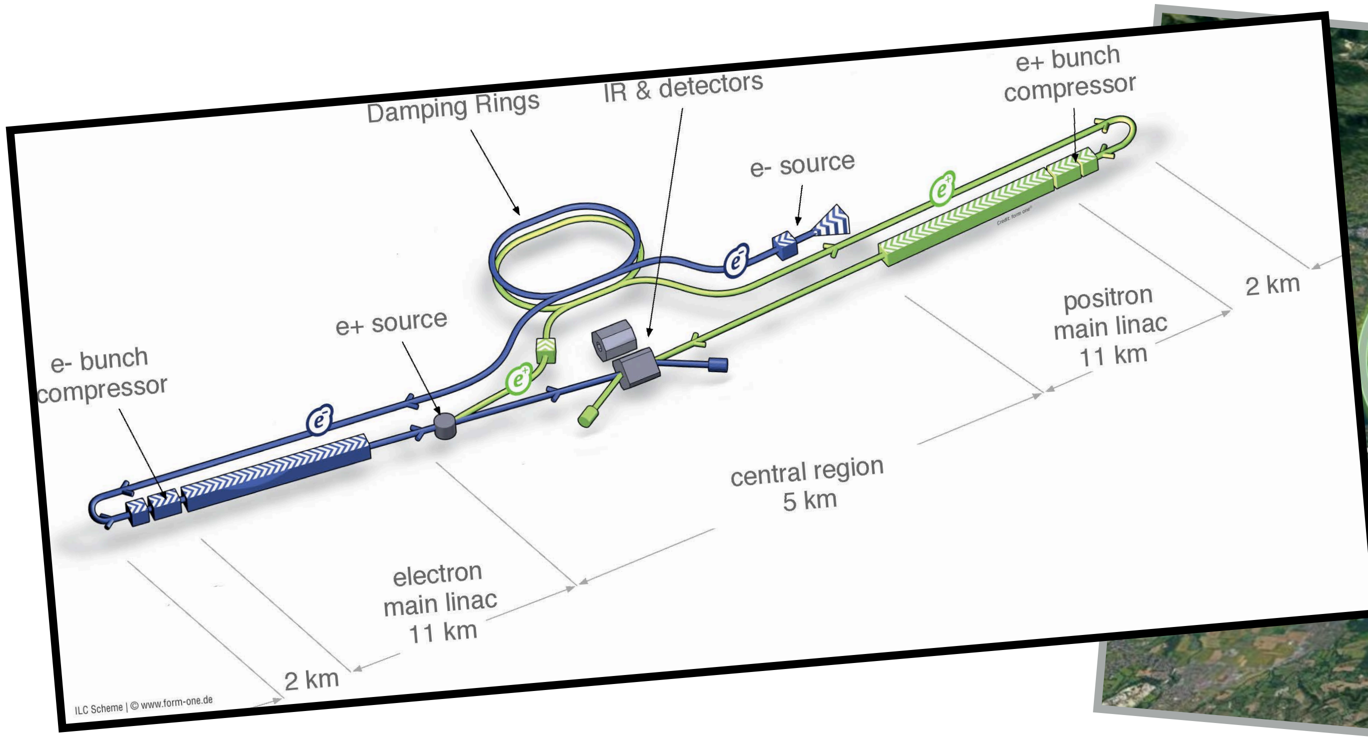


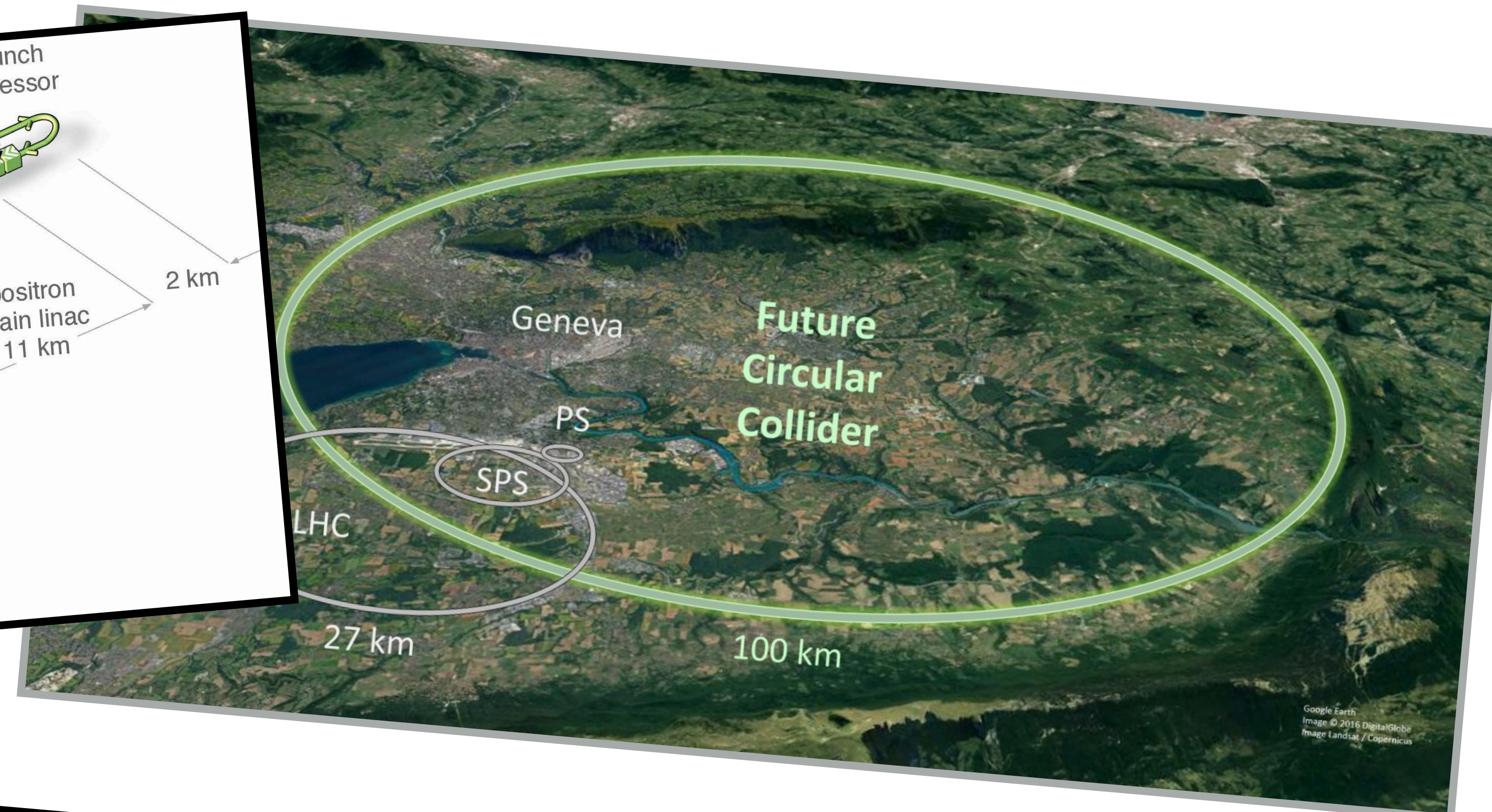
LNV highest rate channel

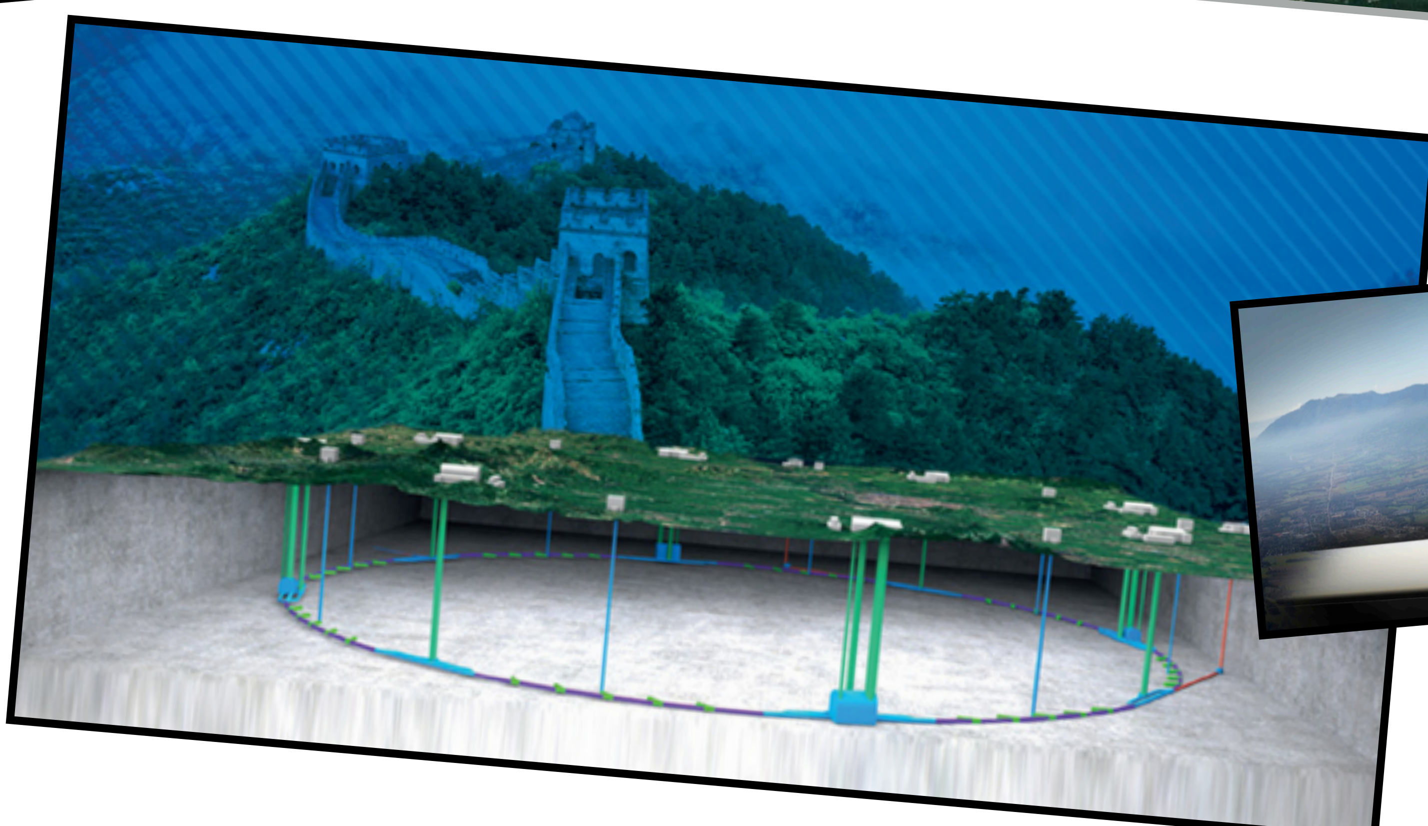
- Total width, hence lifetime, free-parameter - depends on θ { Prompt / Displaced / Stable }

Future Higgs / Z factories

- Heavy neutral leptons ideal target for future Higgs factories







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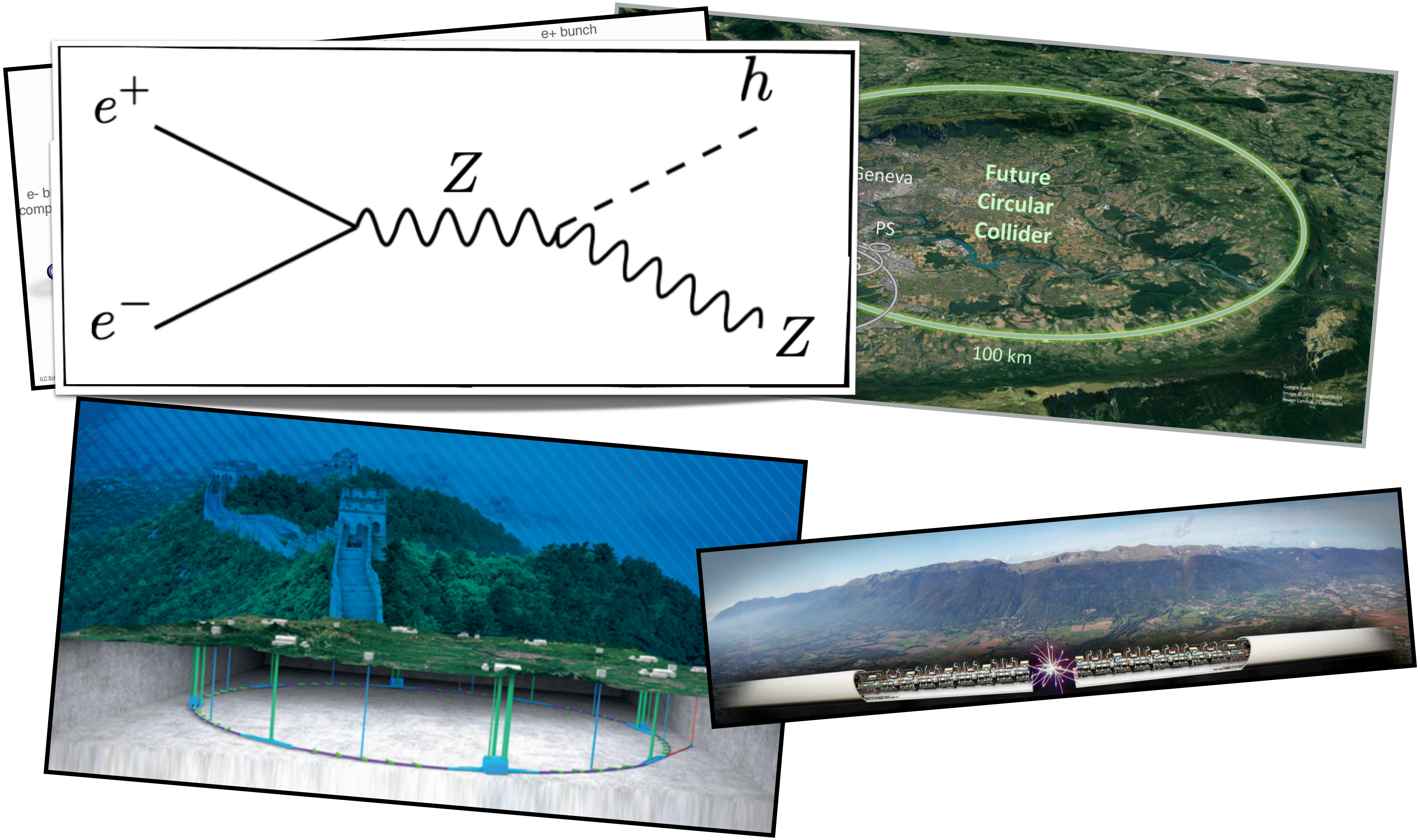

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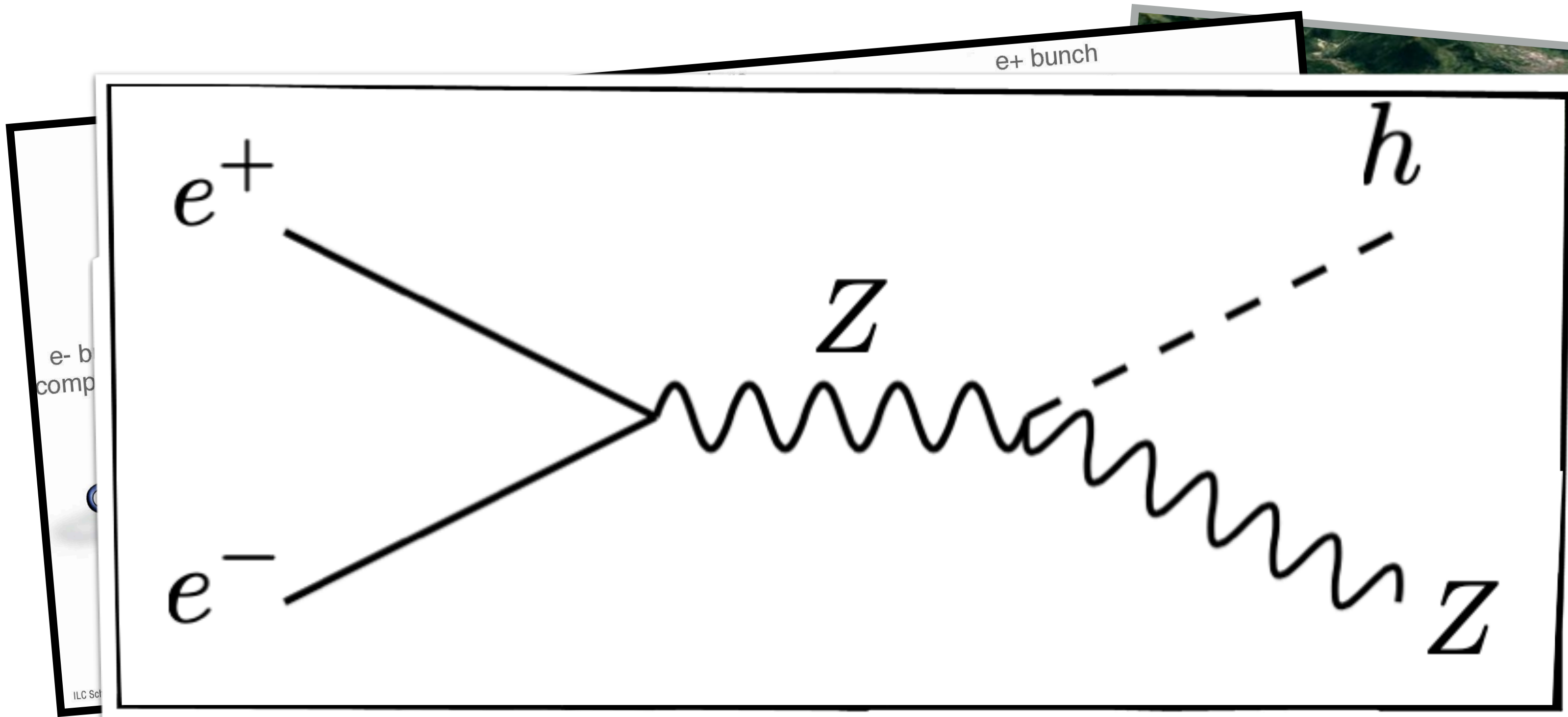
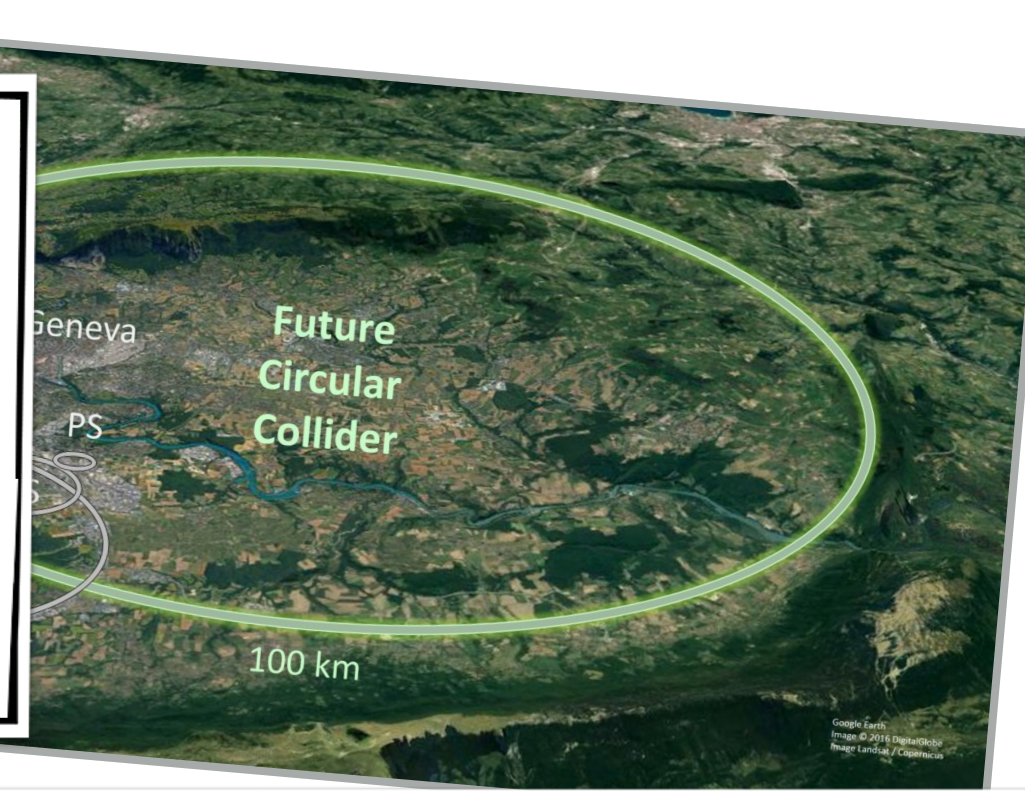
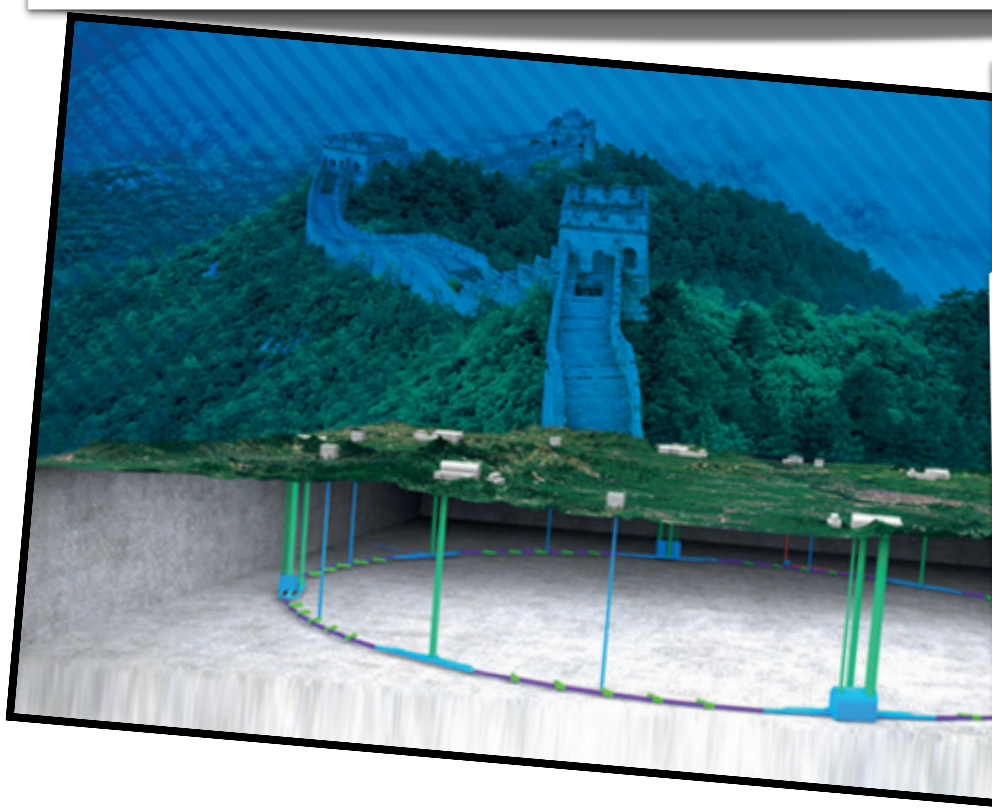




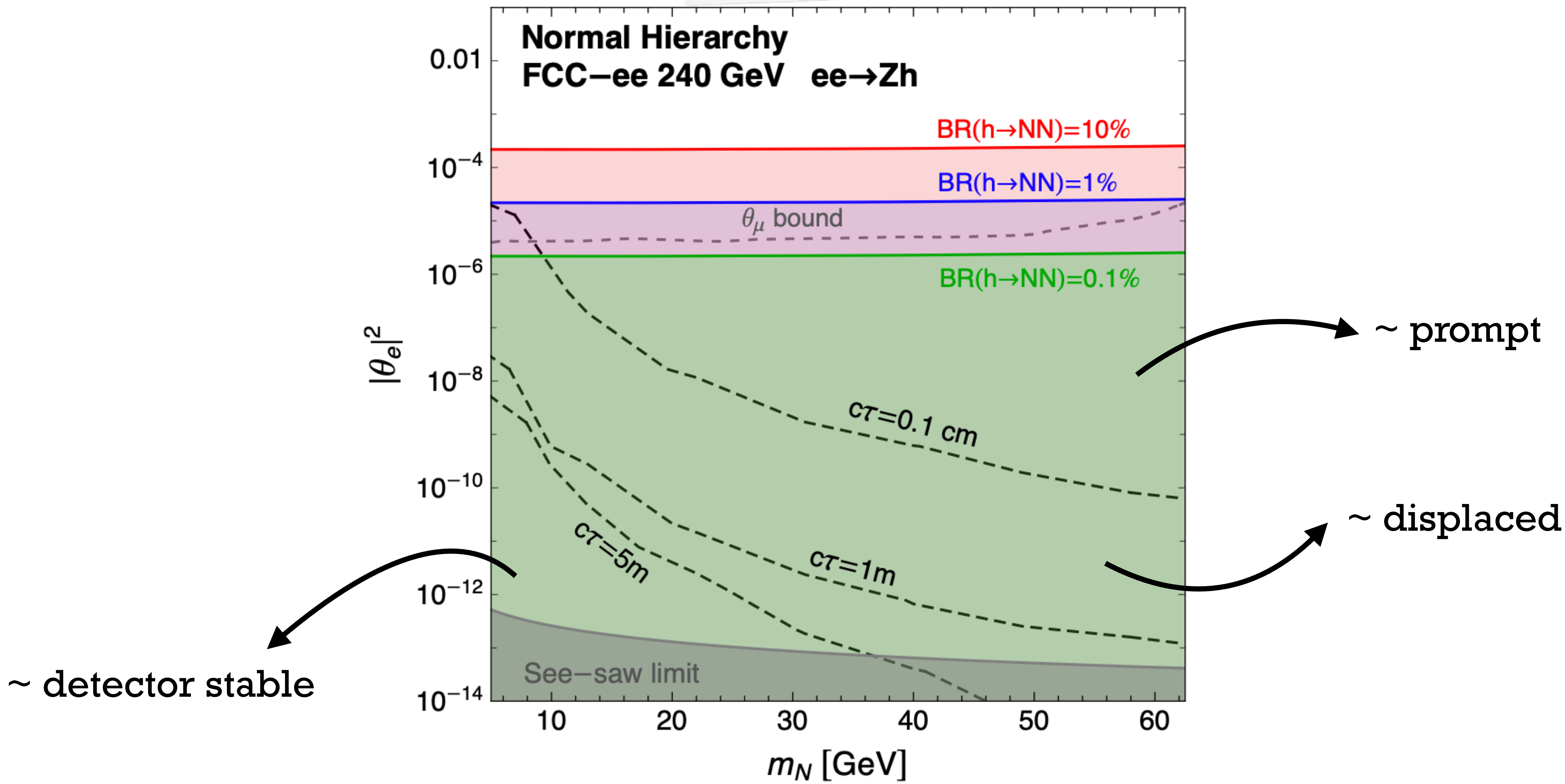


Higgs run

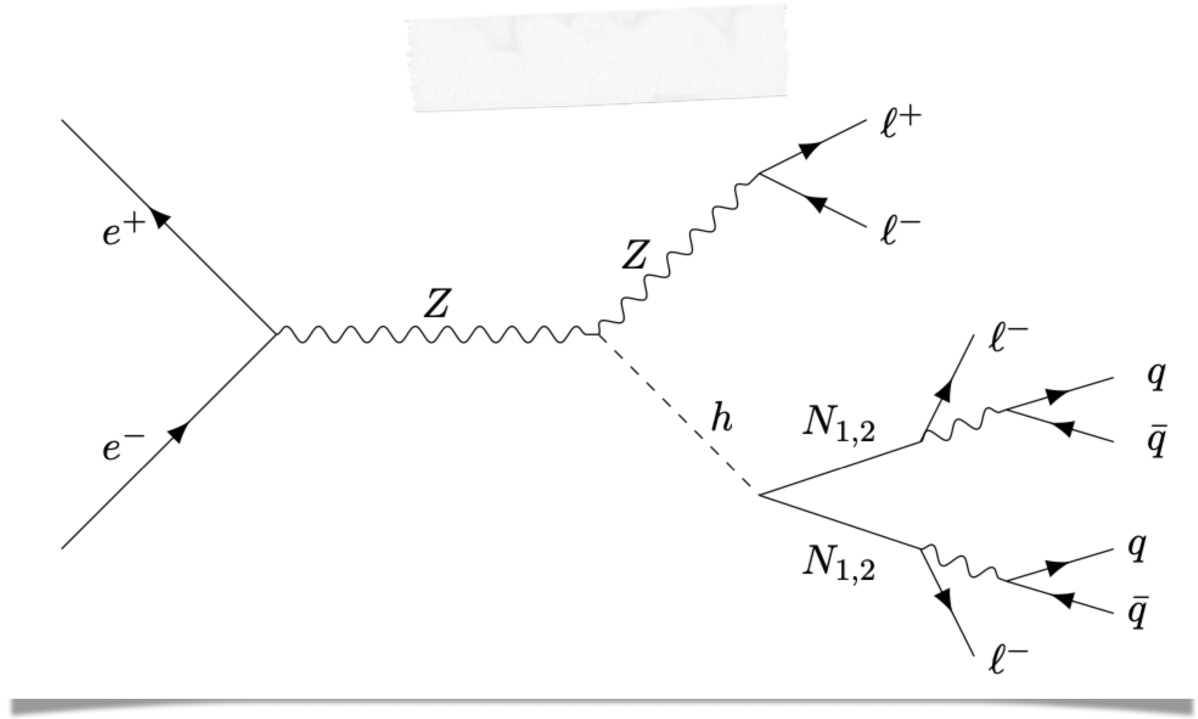
Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	σ_{Zh} [fb]
FCC-ee	240	5	193
ILC	250	2 (pol)	297
CLIC-380	380	1 (pol)	133
CEPC	240	5.6	193

Prompt decay

- Need largish mixing, constrained by direct searches
- Can Higgs decay be the dominant production channel? Yes



- Consider final state with the largest BR, LNV $\ell^\pm\ell^\pm 4j$



- Ask for a pair of SS leptons, Higgs-strahlung topology and leptonic Z

$$p_T^\ell > 2.5\,\mathrm{GeV} \qquad p_T^j > 5\,\mathrm{GeV} \qquad |\eta^{\ell,j}| < 2.44 \qquad \Delta R(\ell\ell, \ell j) > 0.15$$

$$|m_{\ell^+\ell^-} - m_Z| < 10\,\mathrm{GeV} \qquad |s - 2\sqrt{s}E_{\ell^+\ell^-} + m^2_{\ell^+\ell^-} - m_H| < 10\,\mathrm{GeV}$$

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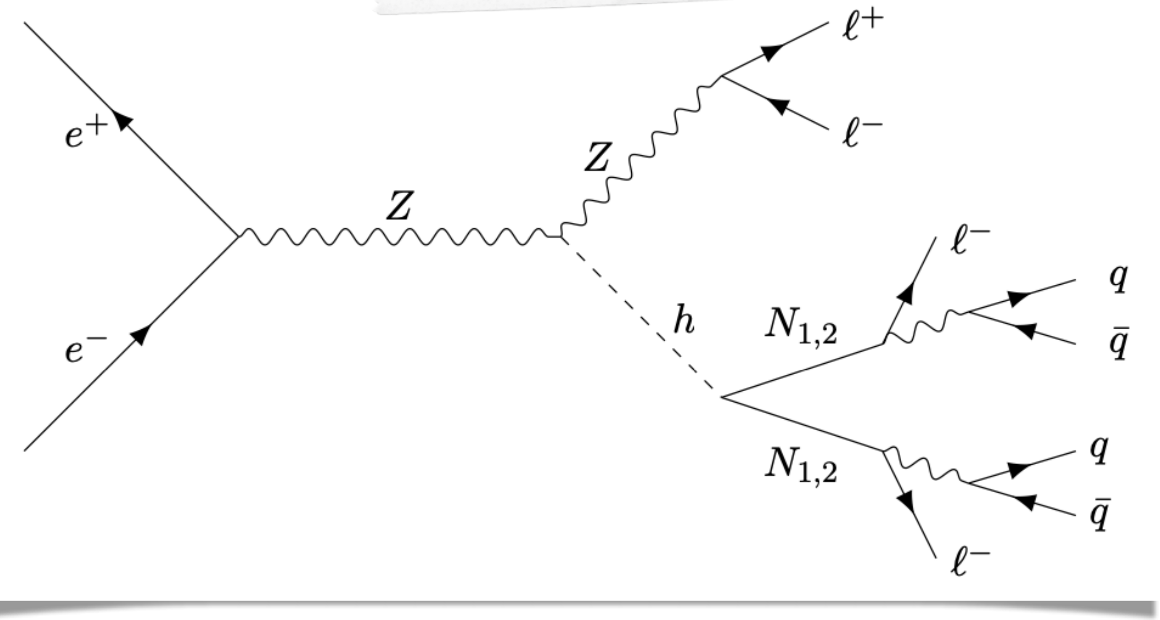

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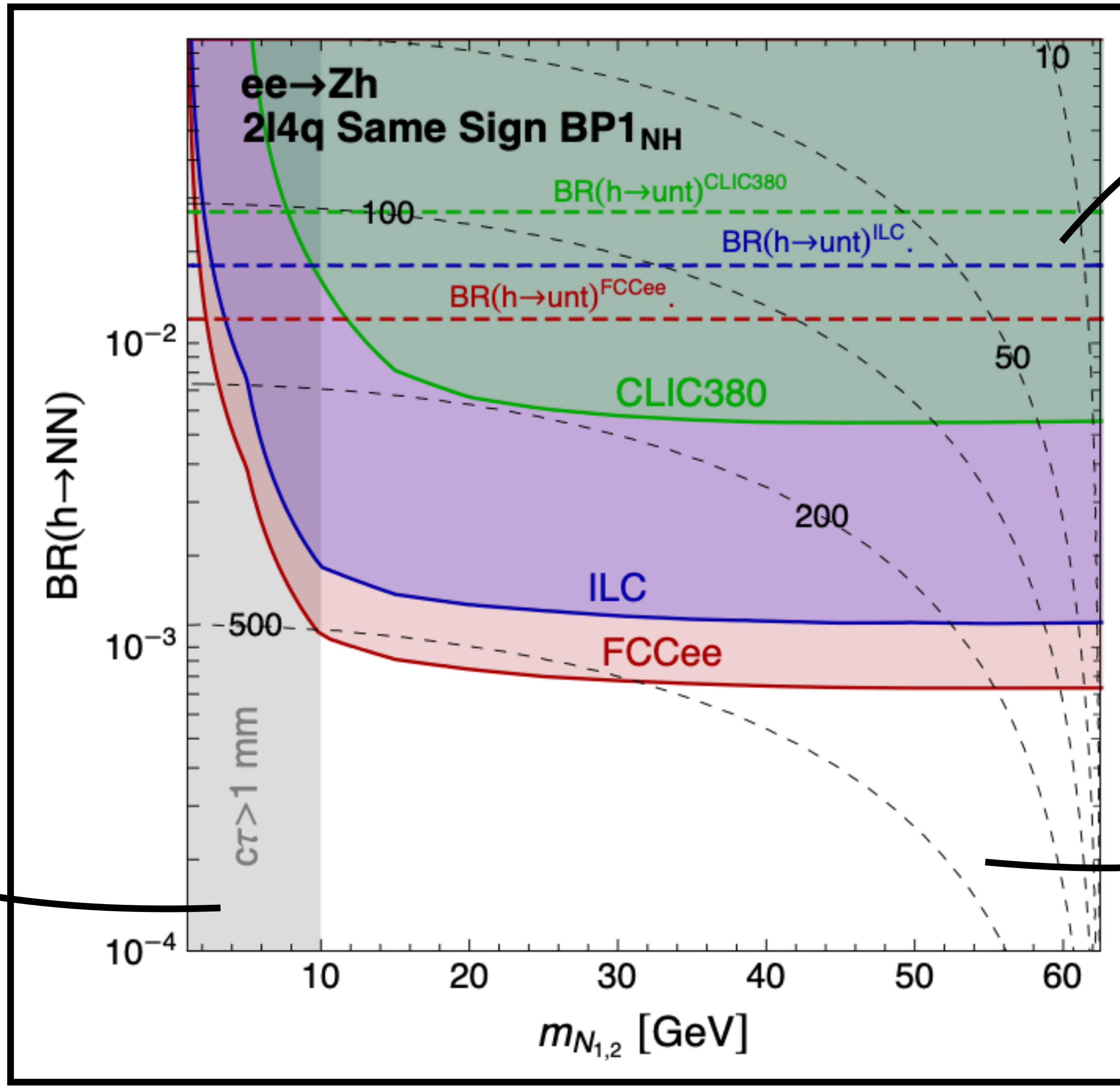
Irreducible background - any process giving $(Z \to \ell^+_\alpha \ell^-_\alpha)(h \to \ell^+_\beta \ell^+_\gamma + \ldots)$

$L\,\&\,Q_{\text{em}}$ are conserved, need $2\nu 4q \ldots$ $(Z \to \ell^+_\alpha \ell^-_\alpha)(h \to \ell^+_\beta \nu_\beta \ell^+_\gamma \nu_\gamma \bar{u} d \bar{u} d)$ **negligible**

- Assume backgrounds from e.g. mis-ID to be negligible and work with zero bkg

[Strong assumption, but probably not too bad given the signal characteristics, potential accuracy of particle-flow reconstruction and improved analysis techniques…]



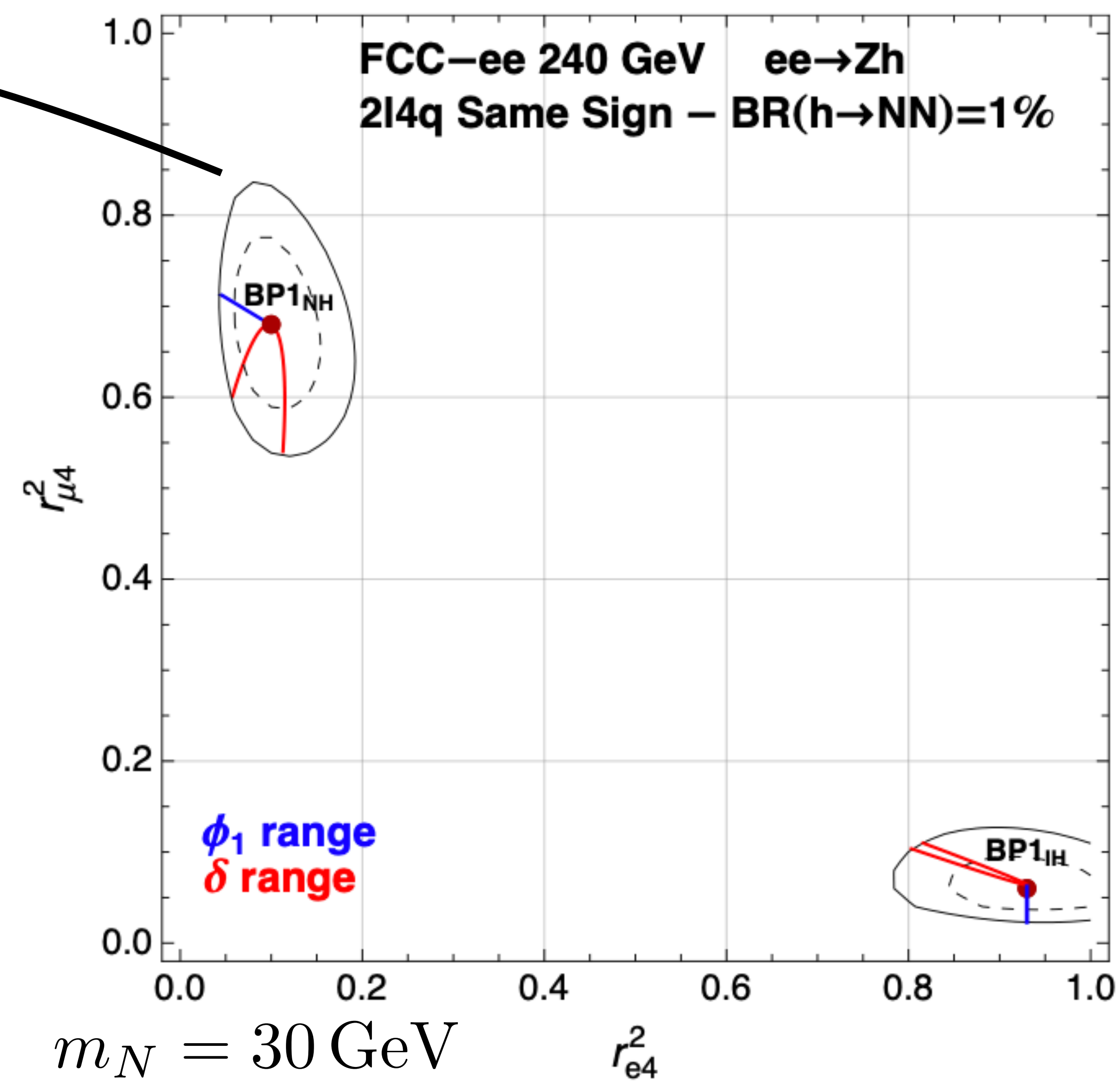
Untagged Higgs decay

Too large mixing
if prompt, excluded

Λ isocontours [TeV]

- What can we learn if we observe a signal? Can we determine the flavor structure?
- Build $p(n_{\rm obs}|n_{\rm th}) = \frac{1}{n_{\rm obs}!} e^{-n_{\rm th}} n_{\rm th}^{n_{\rm obs}}$ injecting a signal
  - Determine normalized mixing up to 10%

	$\mathrm{BR}(h \to NN) = 1\%$
$\mathbf{BP1_{NH}}$	$3.69 \leq \phi_1 \leq 5.57$ $0.78 \leq \delta \leq 1.85 \cup 4.47 \leq \delta \leq 5.55$

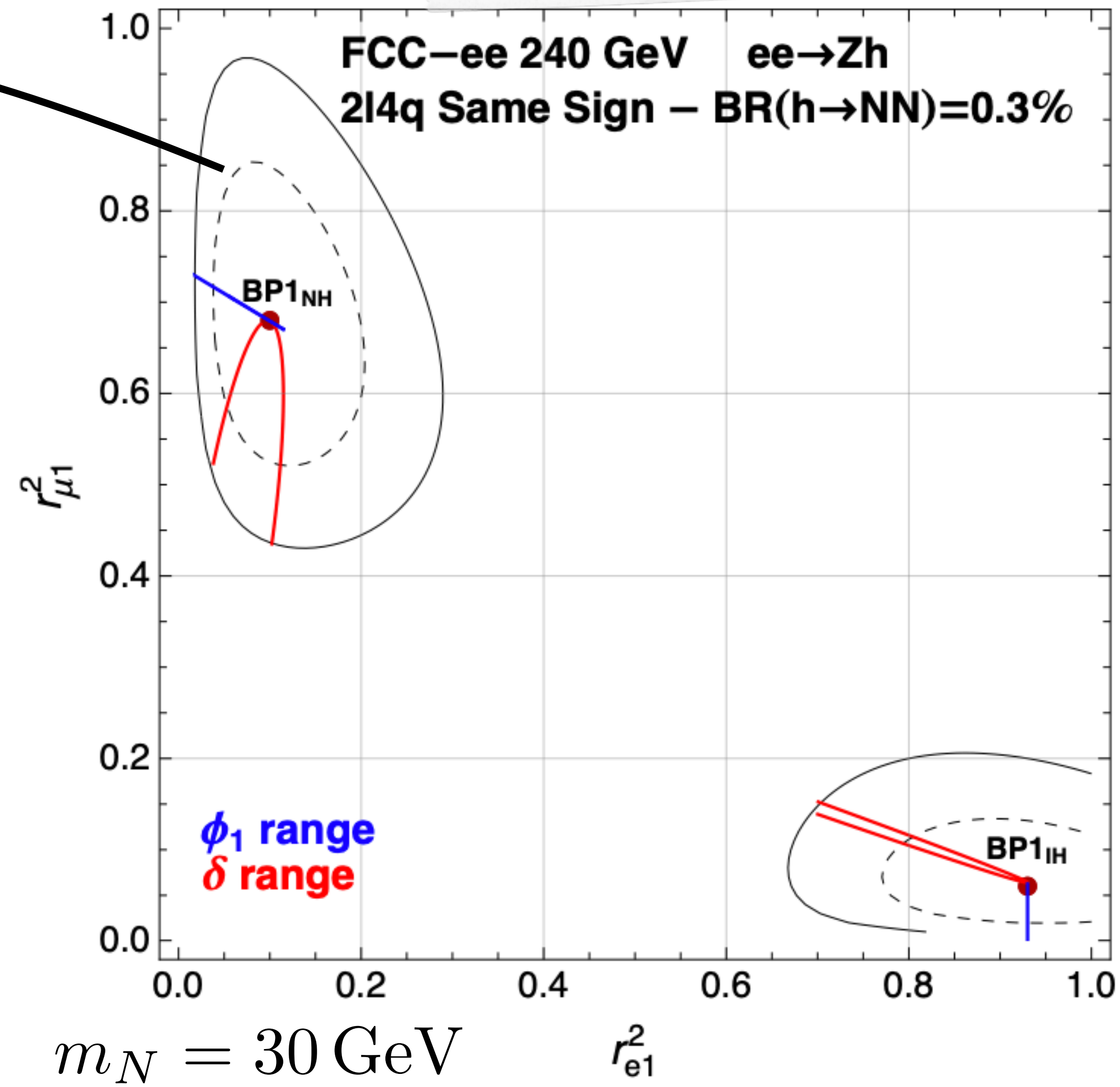


$m_N = 30\,\mathrm{GeV}$

- What can we learn if we observe a signal? Can we determine the flavor structure?
- Build $p(n_{\rm obs}|n_{\rm th}) = \frac{1}{n_{\rm obs}!} e^{-n_{\rm th}} n_{\rm th}^{n_{\rm obs}}$ injecting a signal

  - Determine normalized mixing up to 30%

	$\mathrm{BR}(h \to NN) = 0.3\%$
$\mathbf{BP1_{NH}}$	$0.037 \leq \phi_1 \leq 5.95$ $0 \leq \delta \leq 2.53 \cup 3.80 \leq \delta \leq 2\pi$



$m_N = 30\,\mathrm{GeV}$

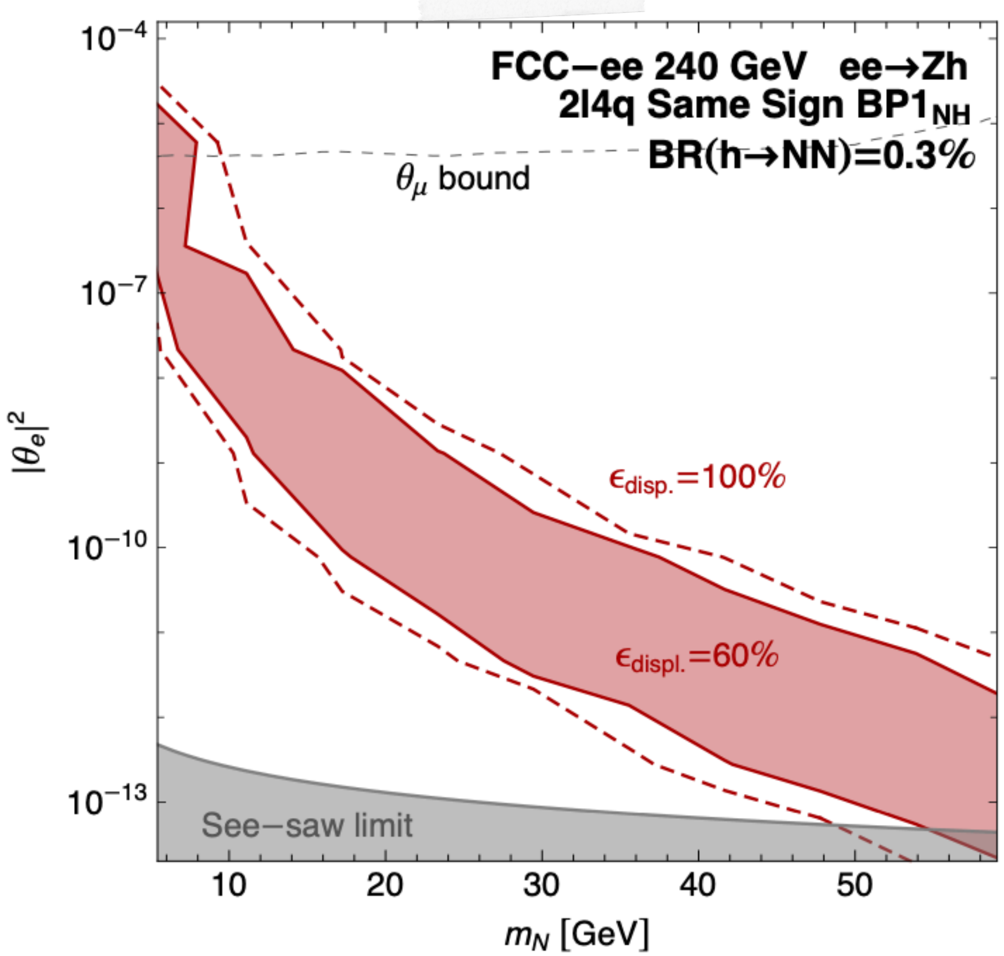
Displaced decay

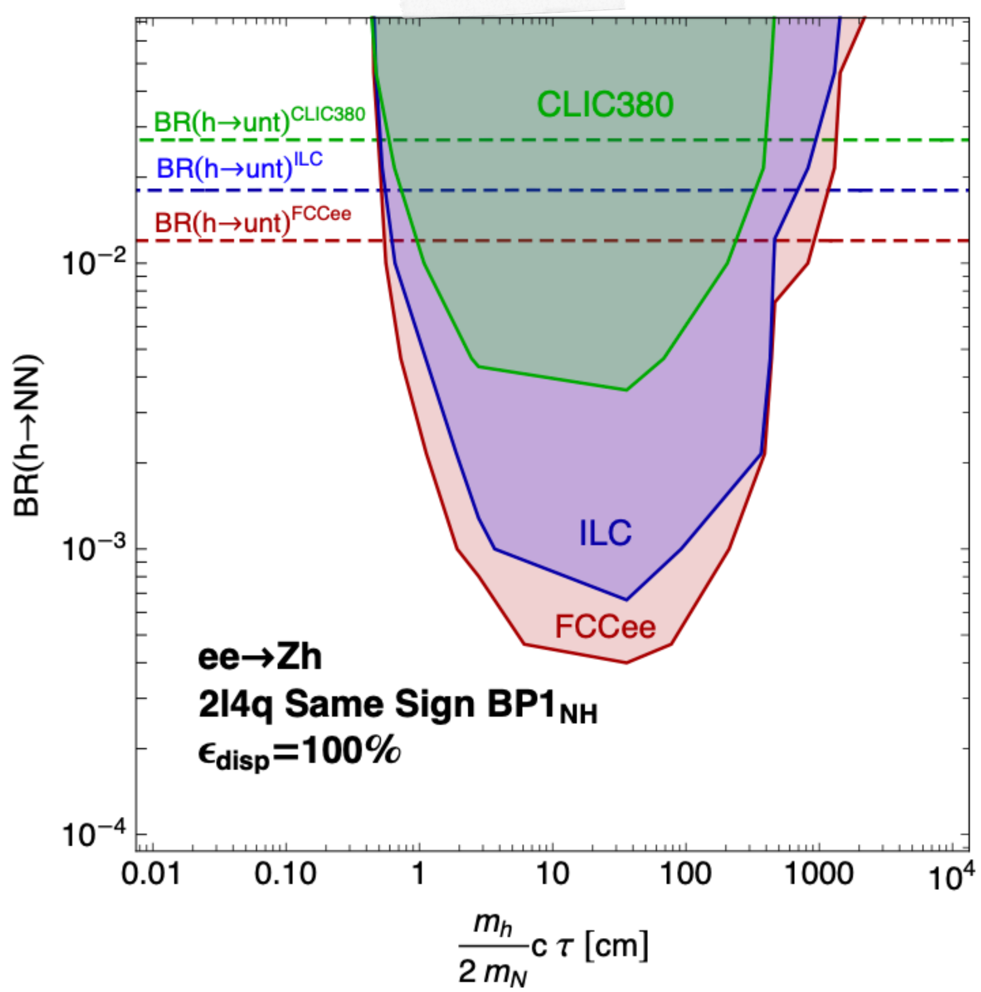
- Consider displaced a decay within $1\,\mathrm{cm} < L_{\mathrm{dec}} < 1\,\mathrm{m}$ and spherical detector
- Consider again the $2\ell 4j$ final state, with the higher rate. Both SS and OS

$$N_s = \sigma_{Zh} \times \mathrm{BR}(Z \to \ell^+\ell^-) \times \mathrm{BR}(h \to NN) \times \mathrm{BR}(NN \to 2\ell 4q) \times \epsilon_{Zh} \times \epsilon^2_{P_{\Delta L}} \times \epsilon^2_{\mathrm{disp.}} \times \mathcal{L}$$

Probability for both neutrino to decay within [1cm, 1m]

$$\mathcal{P}(x_i, x_f) = e^{-\frac{x_i}{\beta\gamma c\tau}} - e^{-\frac{x_f}{\beta\gamma c\tau}}$$ on event by event basis





[c.f.r. 1E-2/1E-3 @ LHC, Caputo+ 1704.08721]

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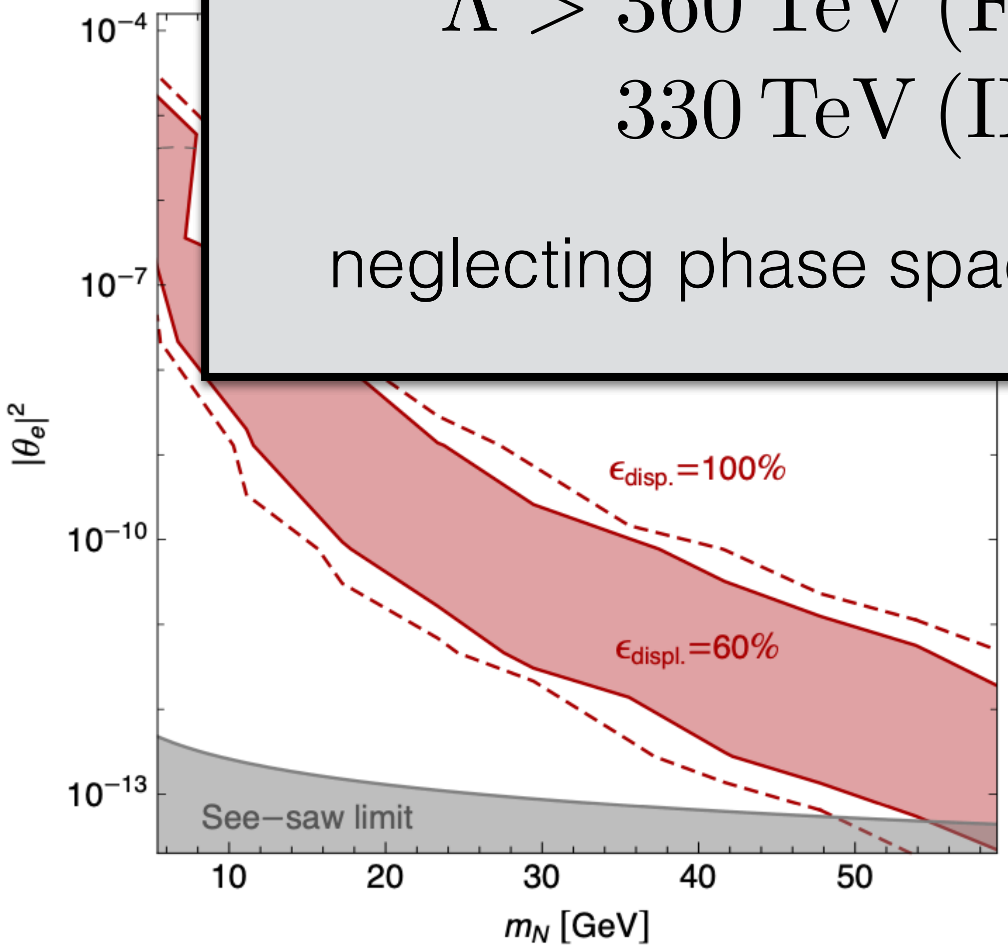
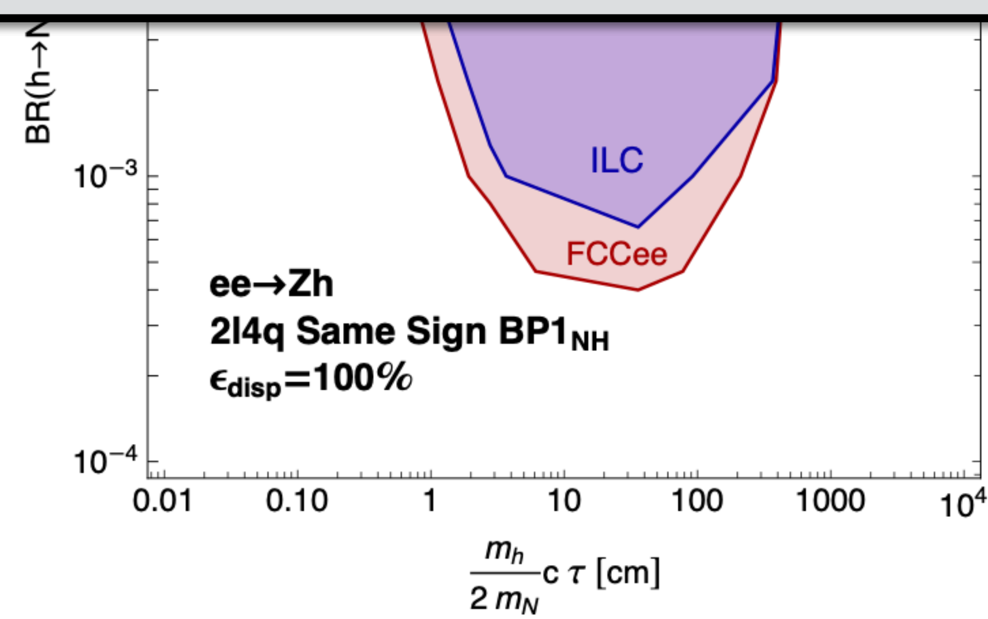
Detector stable

- Bounds from invisible Higgs decay, mappable in Λ

$$\Lambda > 360\,\mathrm{TeV}\,(\mathrm{FCC-ee}),\ 320\,\mathrm{TeV}\,(\mathrm{CEPC})$$
$$330\,\mathrm{TeV}\,(\mathrm{ILC}),\ 210\,\mathrm{TeV}\,(\mathrm{CLIC})$$

neglecting phase space



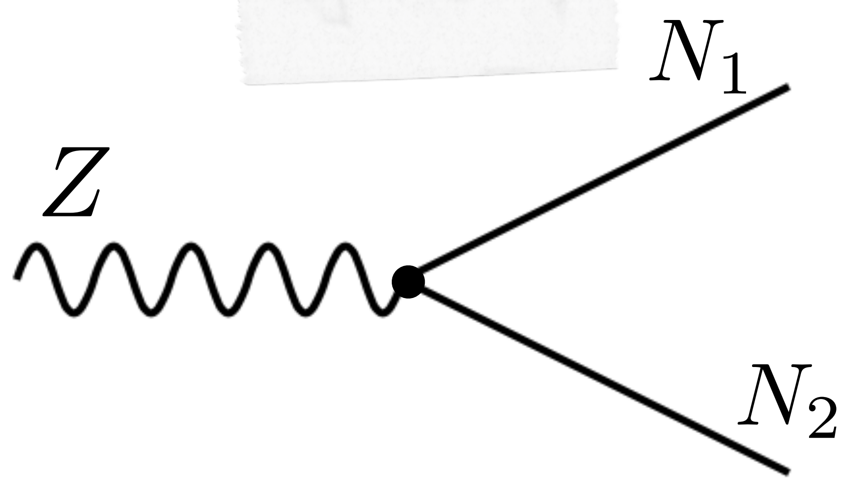


[c.f.r. 1E-2/1E-3 @ LHC, Caputo+ 1704.08721]

Dipole operator

$$\mathcal{O}_{NB} = \frac{\alpha_{NB}}{\Lambda} N\sigma^{\mu\nu} N B_{\mu\nu}$$

- Antisymmetry of $\sigma^{\mu\nu}$, need two flavors of RH neutrino
- After EWSB generate a dipole with the Z boson and γ



$$\Gamma_{Z\to N_1 N_2} = \frac{2}{3\pi}\frac{|\alpha_{NB}^{12}|^2}{\Lambda^2}\frac{s_w^2}{m_Z^3}\lambda^{1/2}(m_Z^2, m_{N_1}^2, m_{N_2}^2)\zeta(m_Z, m_{N_1}, m_{N_2})$$

$$\zeta(m_Z, m_{N_1}, m_{N_2}) = m_Z^2(m_Z^2 + m_{N_1}^2 + m_{N_2}^2 - 6 m_{N_1} m_{N_2}\cos 2\phi_{12}) - 2(m_{N_1}^2 - m_{N_2}^2)^2$$

$$\phi_{12} = \arg[\alpha_{NB}^{12}]$$

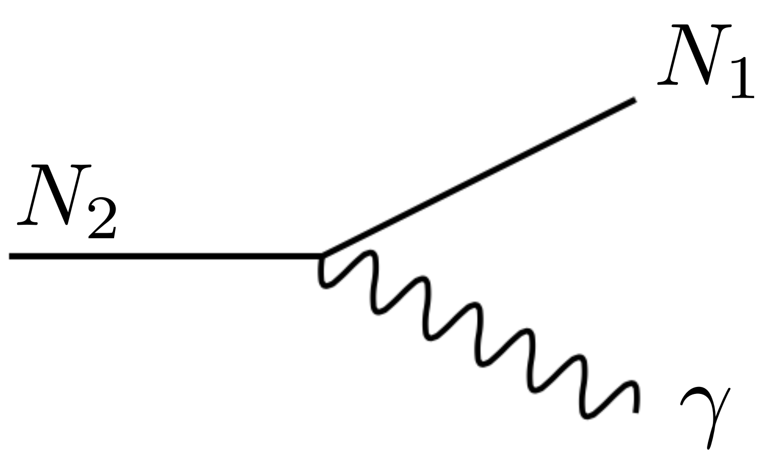
- Future colliders can produce huge numbers of Z bosons

Z pole run

Collider	$\sqrt{s}$ [GeV]	$\int \mathcal{L}$ [ab^{-1}]	N_Z
FCC-ee	m_Z	150	6.5×10^{12}
CEPC	m_Z	16	6.9×10^{11}

What about the N decay?

- Differently from $\mathcal{O}_{NH}$ this operator can trigger N decay via the photon dipole

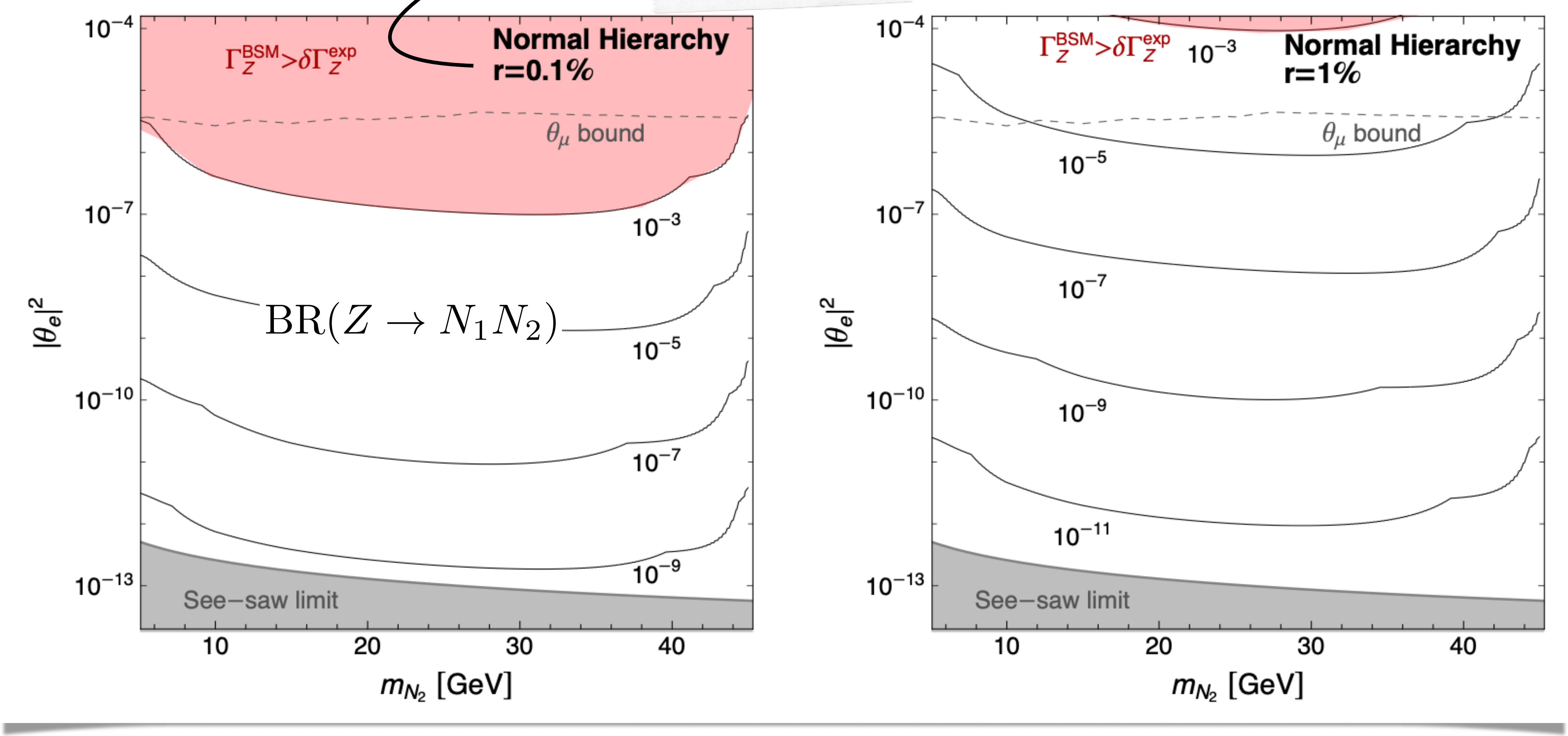


$$\Gamma(N_2 \to N_1 \gamma) = \frac{2}{\pi} c_w^2 \frac{|\alpha_{NB}|^2}{\Lambda^2} m_{N_2}^3 \left(1 - \frac{m_{N_1}^2}{m_{N_2}^2}\right)^3$$

- Whether N_2 decays via mixing or via $\mathcal{O}_{NB}$ also depends on $m_{N_2} - m_{N_1}$

- Above the lines the decay via mixing dominates for the given $\mathrm{BR}(Z \to N_1 N_2)$ which fixes Λ

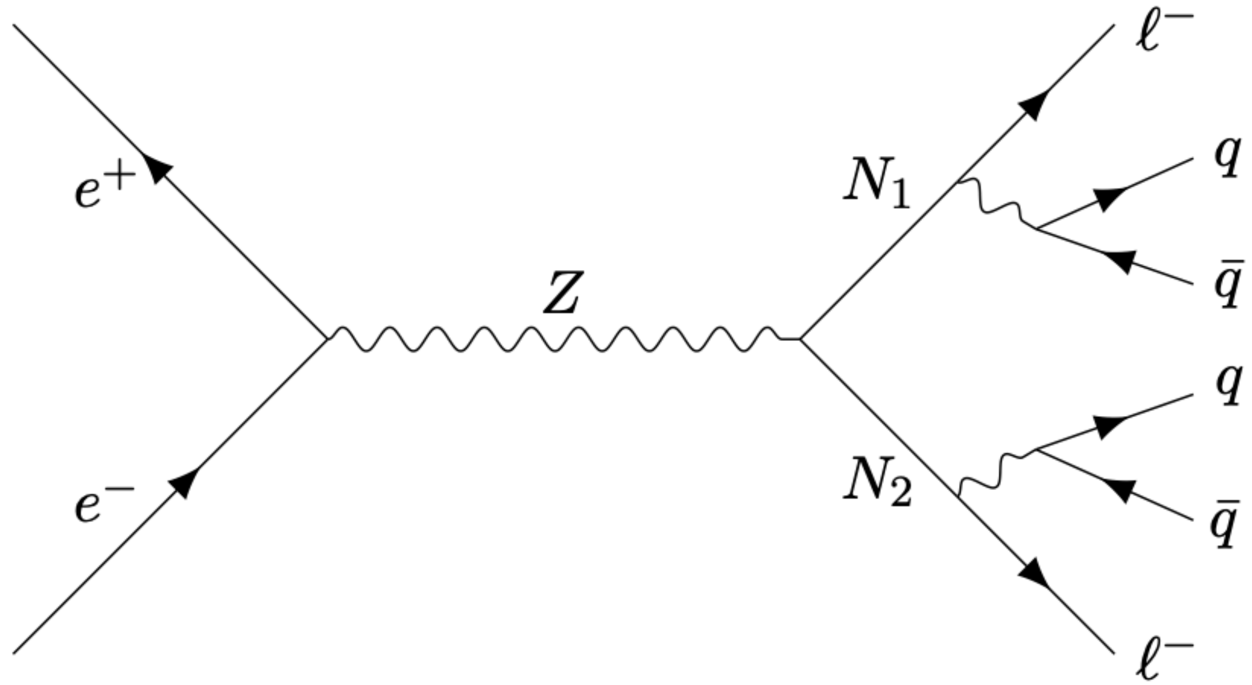
$$r = \frac{m_{N_2} - m_{N_1}}{m_{N_1}}$$



- Region exists where decay is induced by the mixing and production via Z decay

Prompt decay

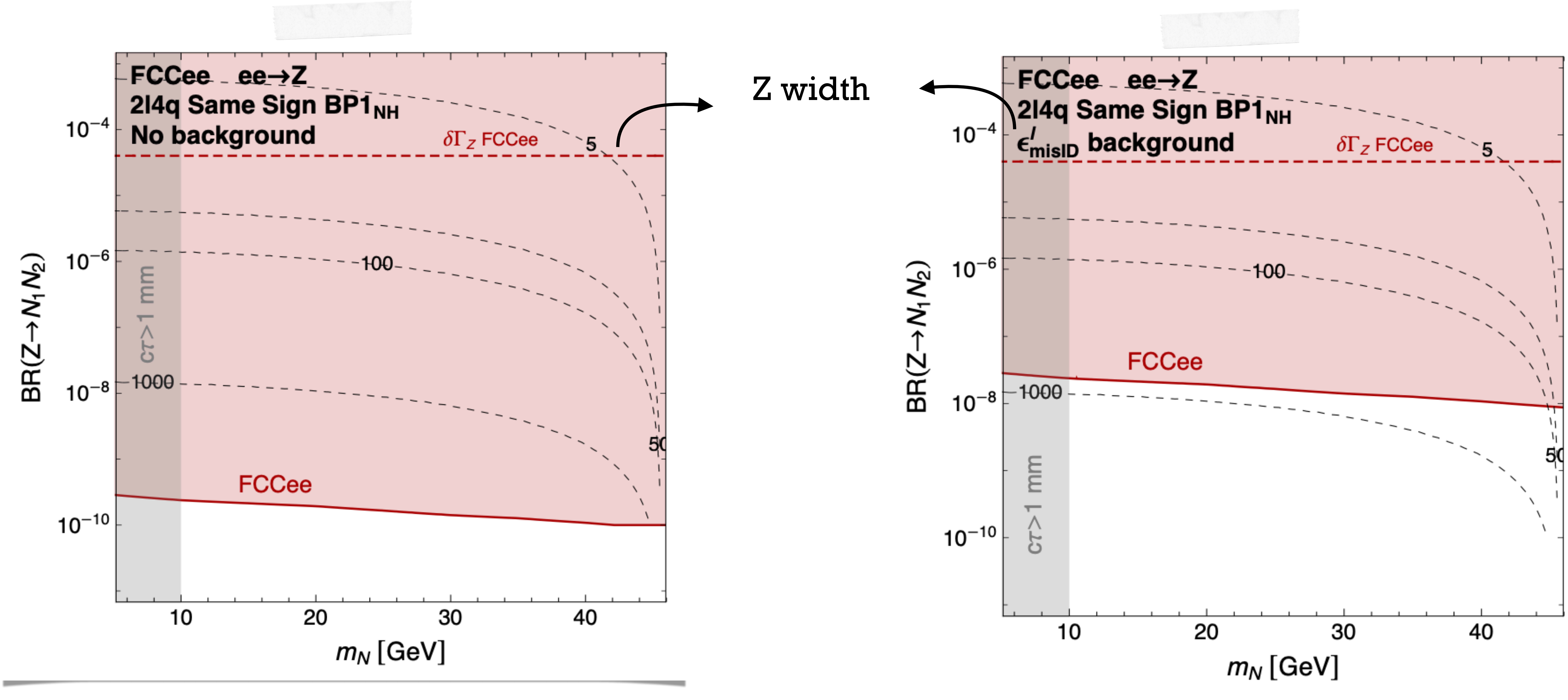
- Still use the dominant LNV $2\ell 4j$ final state



- Basic selections on $p_T, |\eta|$ and isolations

- Consider the reducible $\ell^+\ell^- 4j$ background with flat charge mis-ID of 10^{-3}

$$\sigma_{\ell^+\ell^- 4q} \times 2 \times \epsilon^{\ell}_{\rm misID}(1 - \epsilon^{\ell}_{\rm misID}) \simeq 130 \text{ fb} \times \epsilon^{\ell}_{\rm misID}(1 - \epsilon^{\ell}_{\rm misID}) \simeq 0.26 \text{ fb},$$



- In the mis-ID bkg scenario can probe $10^3\ \mathrm{TeV}$

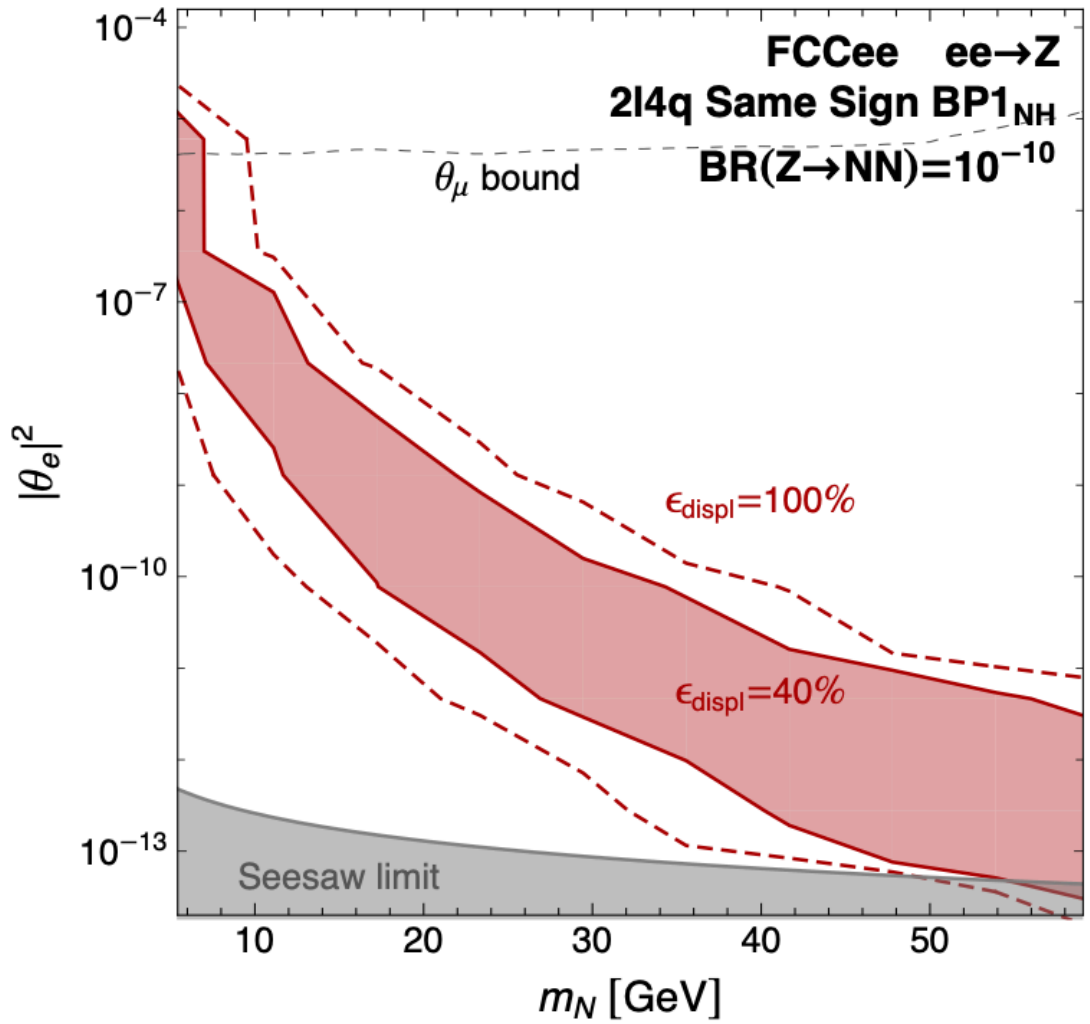
Caveat

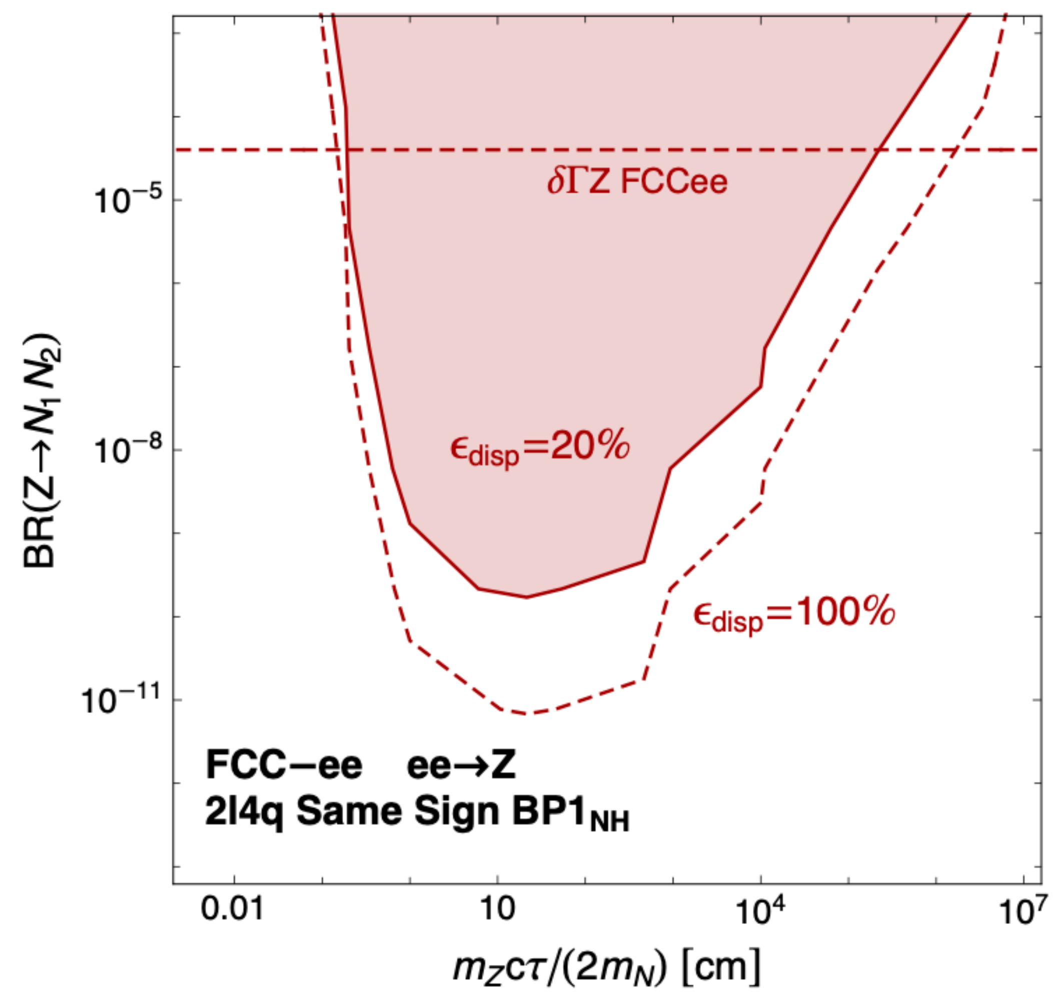
- Dipole operator can only be generated at loop level in a weakly coupled UV completion with only spin 0,1/2, 1 states [Craig+ 2001.00017]

1000 TeV ⟶ 10 TeV… 

Displaced decay

- Similar strategy than the $\mathcal{O}_{NH}$ operator





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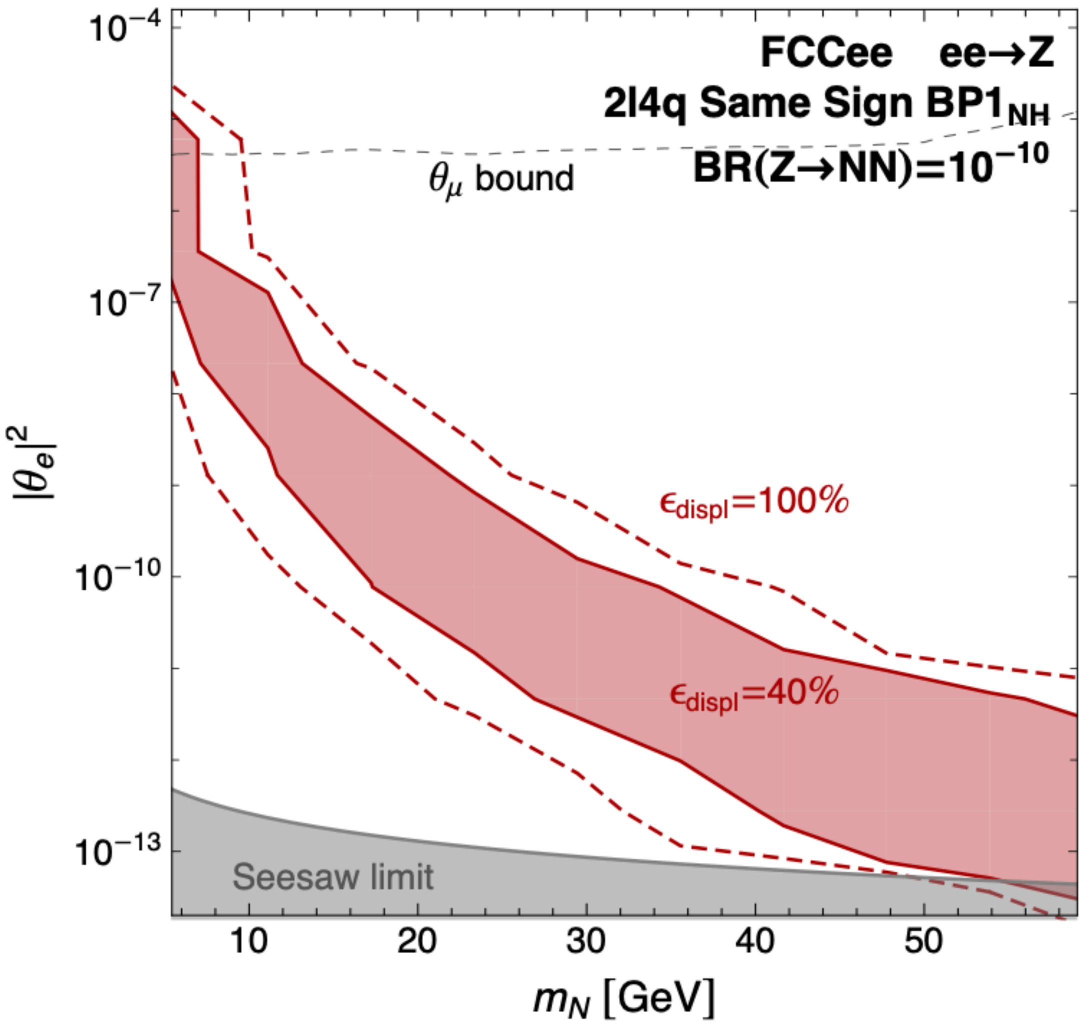
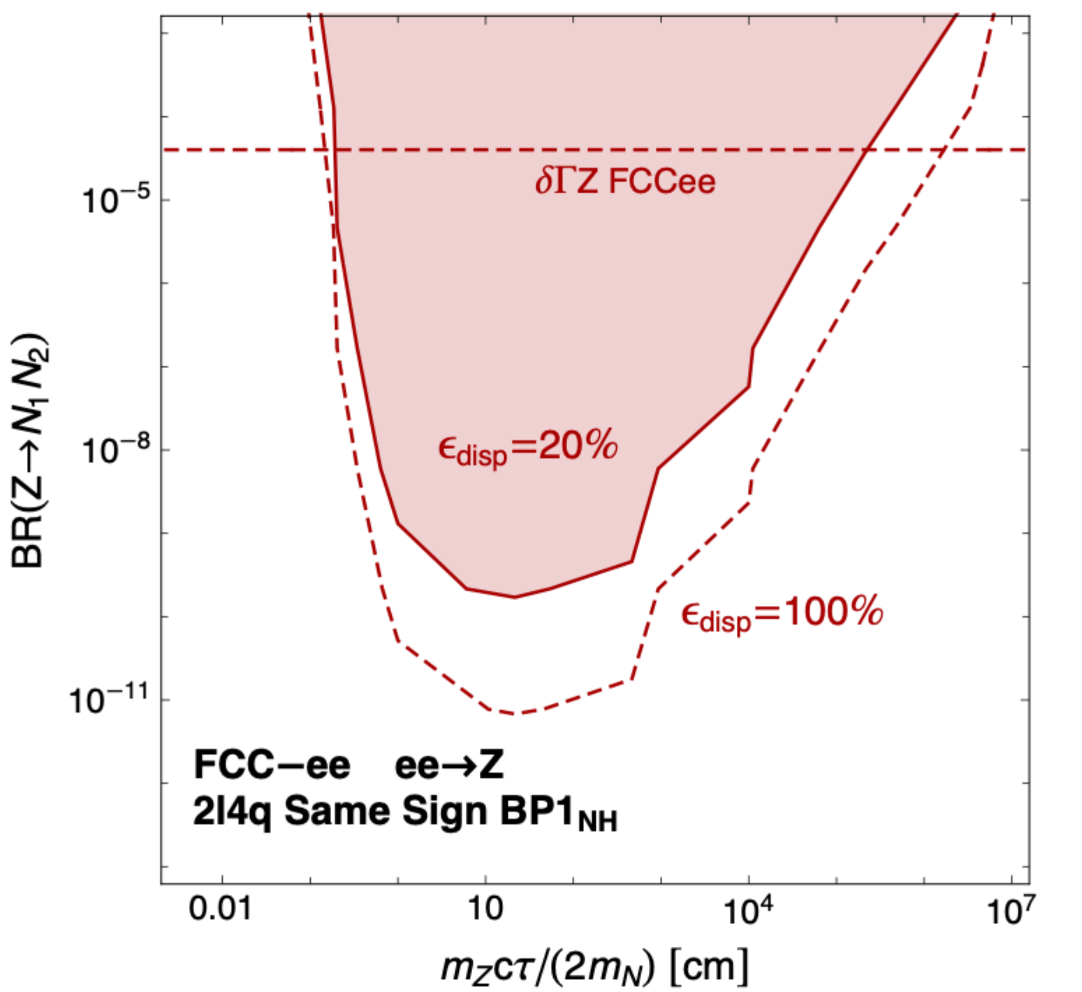




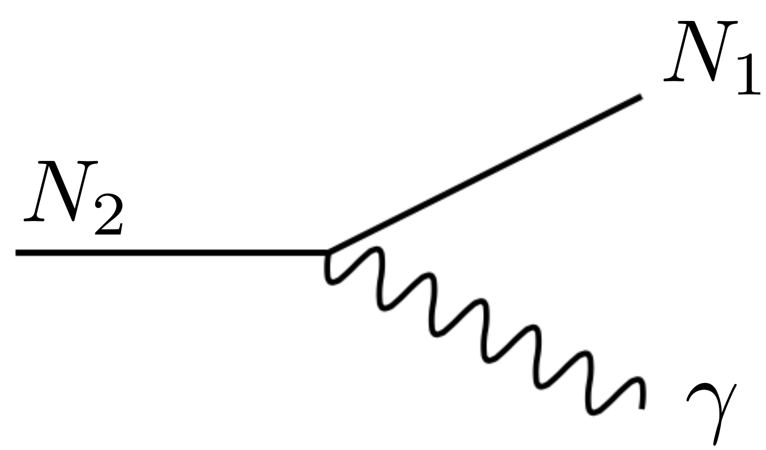
Detector stable

- FCC-ee will measure $R_\nu = \Gamma_{Z\to \text{inv}}/\Gamma_{Z\to\ell\ell}$ 0.3×10^{-3}
  corresspondinq to $\delta\Gamma_Z \sim 100\,\text{KeV}$

$$\Lambda \gtrsim 20\,\text{TeV}$$

Photon dipole

- If the mixing is negligible small, the heaviest N can decay via the photon dipole



- Depending on the masses and suppression scale one can have $\lambda_{N_2} \gg L_{\rm dec}$
- Many experiment can be sensitive to RHN with macroscopic decay lengths…

Photon dipole

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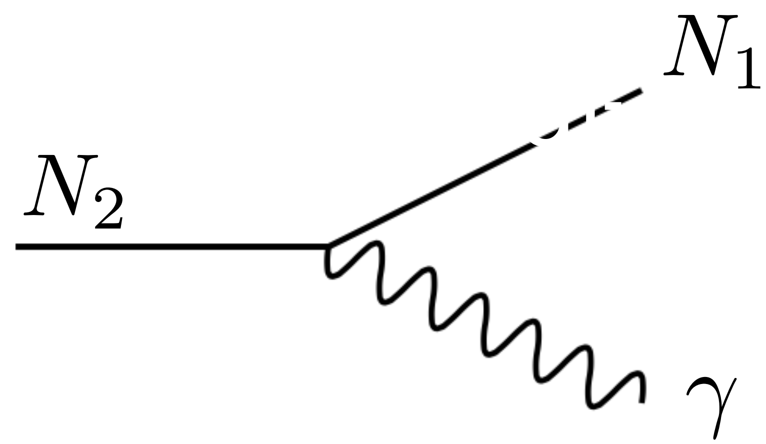

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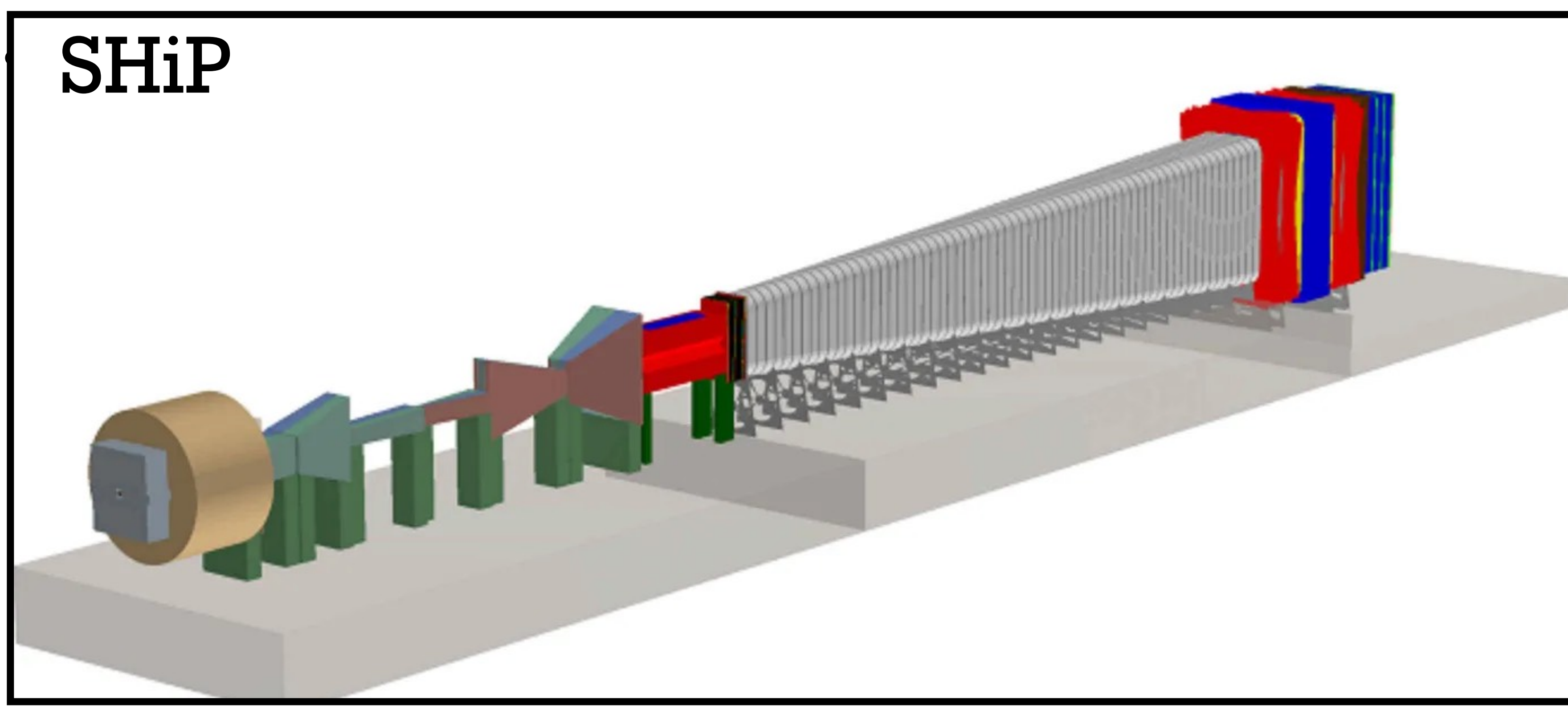

Photon dipole

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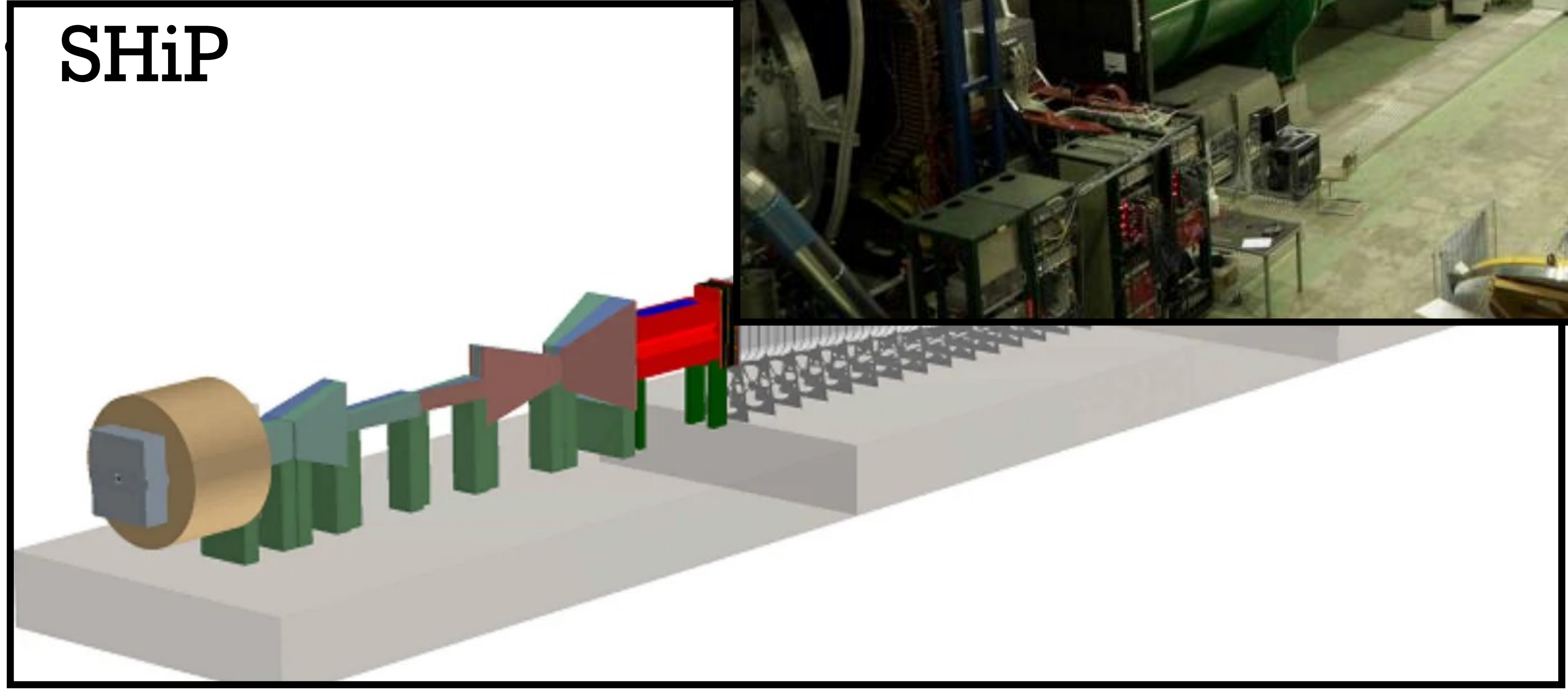
N

- Depending on the masse



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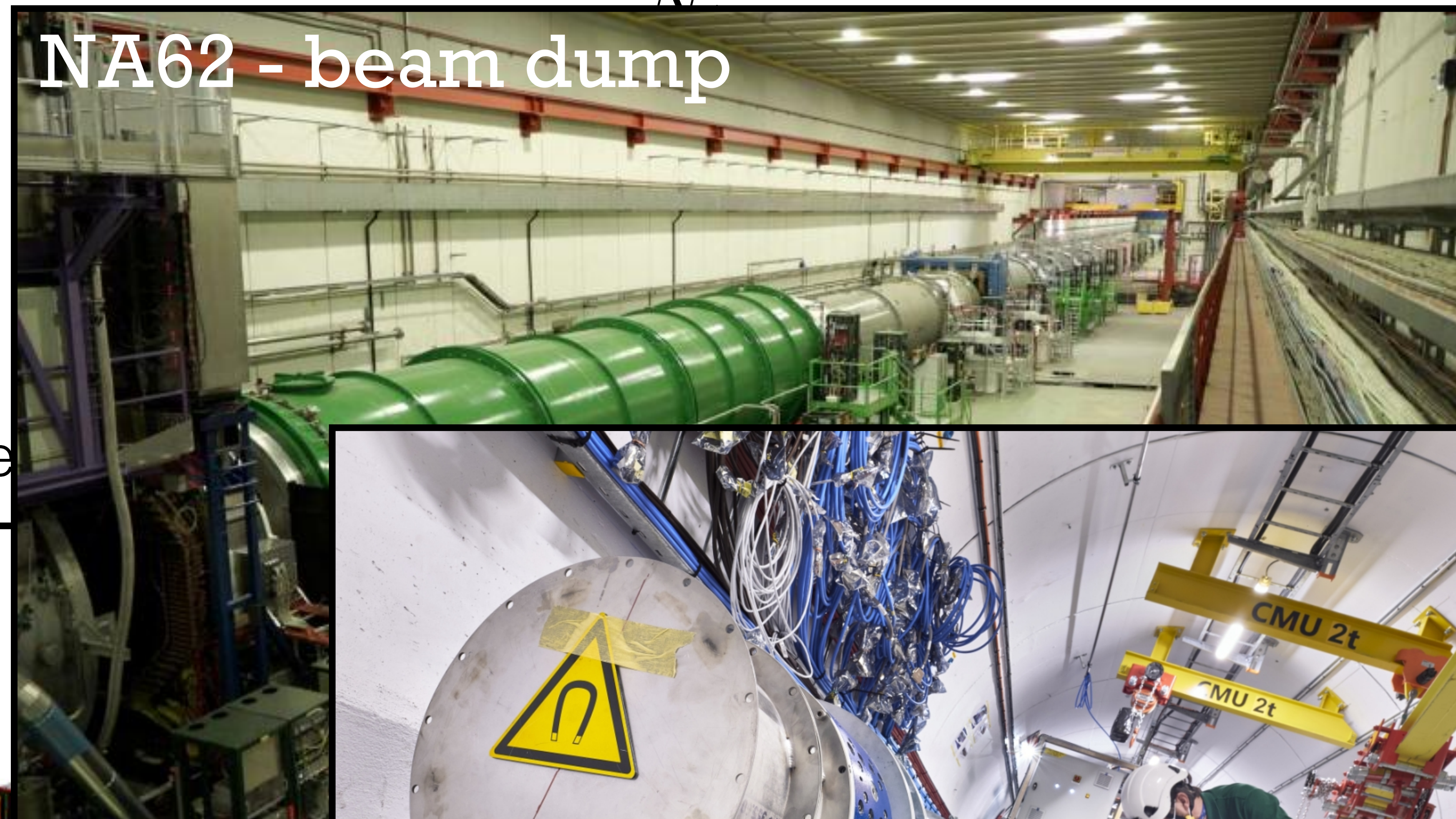
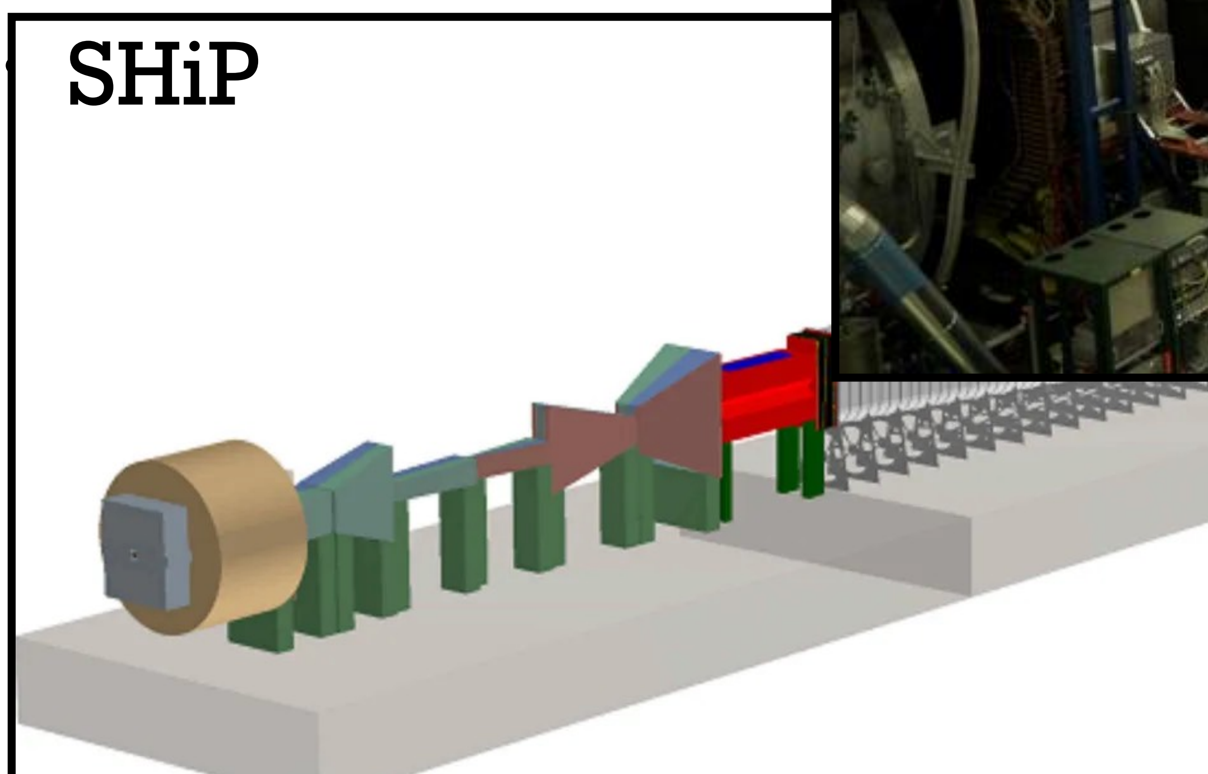
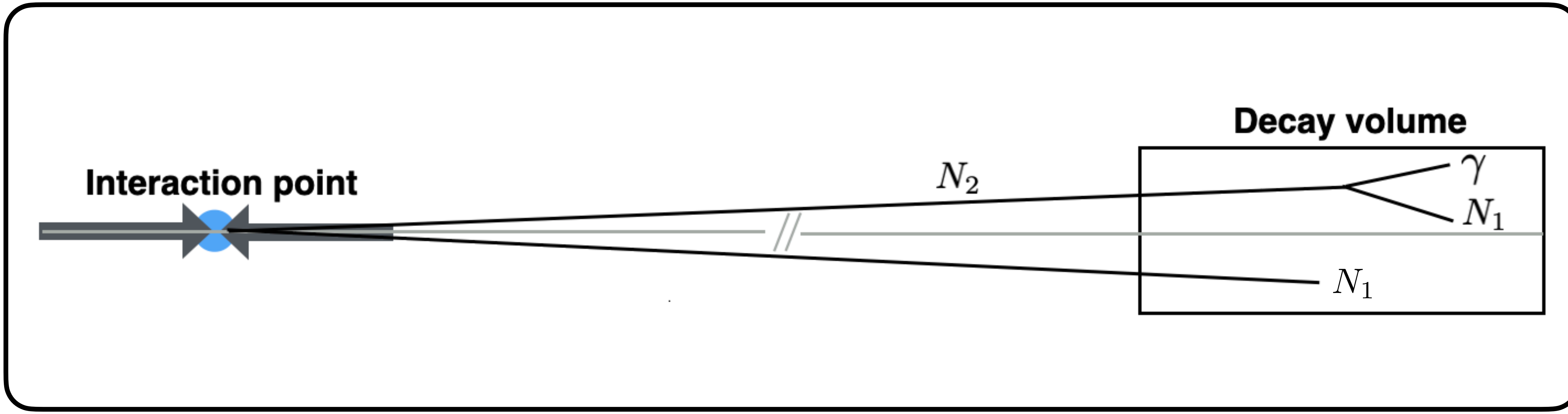






- The signal in the decay volume is a single photon
- In the N_2 rest frame

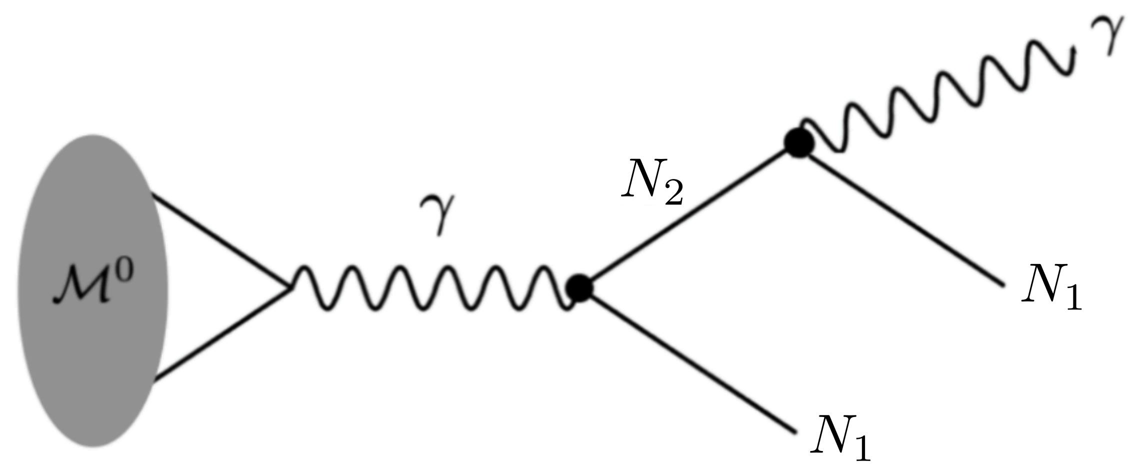
$$E_\gamma = m_{N_2} \frac{\delta}{2} \frac{2+\delta}{(1+\delta)^2} \qquad \delta = \frac{m_{N_2} - m_{N_1}}{m_{N_1}}$$

- Boosting in the laboratory frame

$$E_\gamma^{\text{lab}} = \left(P_{N_2} + \sqrt{m_{N_2}^2 + P_{N_2}^2}\right) \frac{\delta}{2} \frac{2+\delta}{(1+\delta)^2} \simeq 2 P_{N_2} \delta$$

Smaller δ implies longer lifetime but softer photons…

- The dipole mediates $N_1 N_2$ production via meson decay, either in fixed target experiments **[SHiP, NA62-dump]** or in pp collisions [**FASER**]



Beam-dump experiment

$$N_{\rm prod} = \sum_M N_{\rm POT}\, N_M\, {\rm BR}(M \to N_1 N_2),$$

LHC collisions

$$N_{\rm prod} = \sum_M \sigma_{\rm ine}\, \mathcal{L}\, N_M\, {\rm BR}(M \to N_1 N_2)$$

$$\sigma_{\rm ine} = 79.5\,{\rm mb}$$

$$f_{\rm dec} = e^{-L_{\rm entry}/L_{N_2}} - e^{-L_{\rm exit}/L_{N_2}}$$

$$N_{\rm signal} = N_{\rm prod}\, \langle\, f_{\rm dec}\, \epsilon_{\rm det}\, \rangle$$

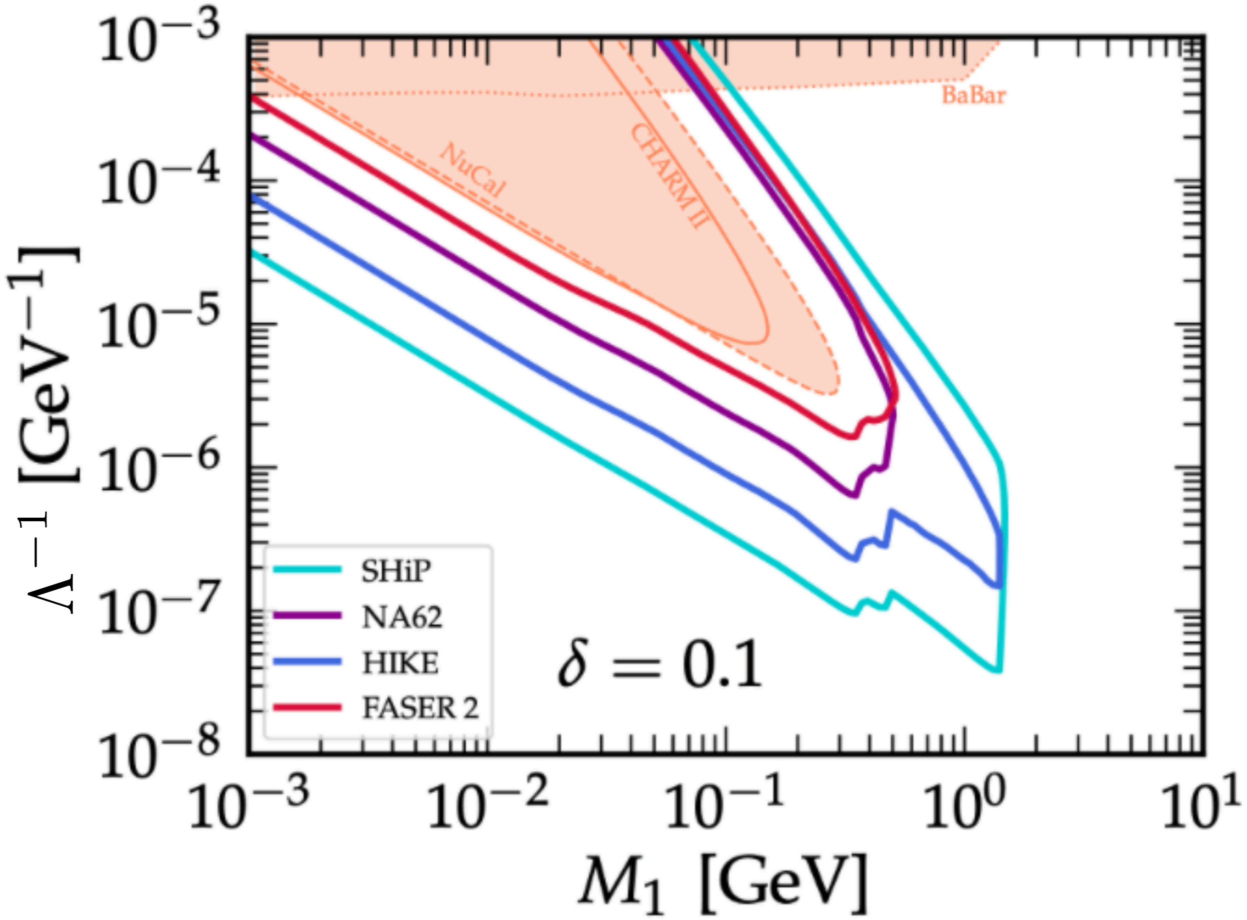
- Meson multiplicities estimated with **PYTHIA, FORESEE and SENSCalc**

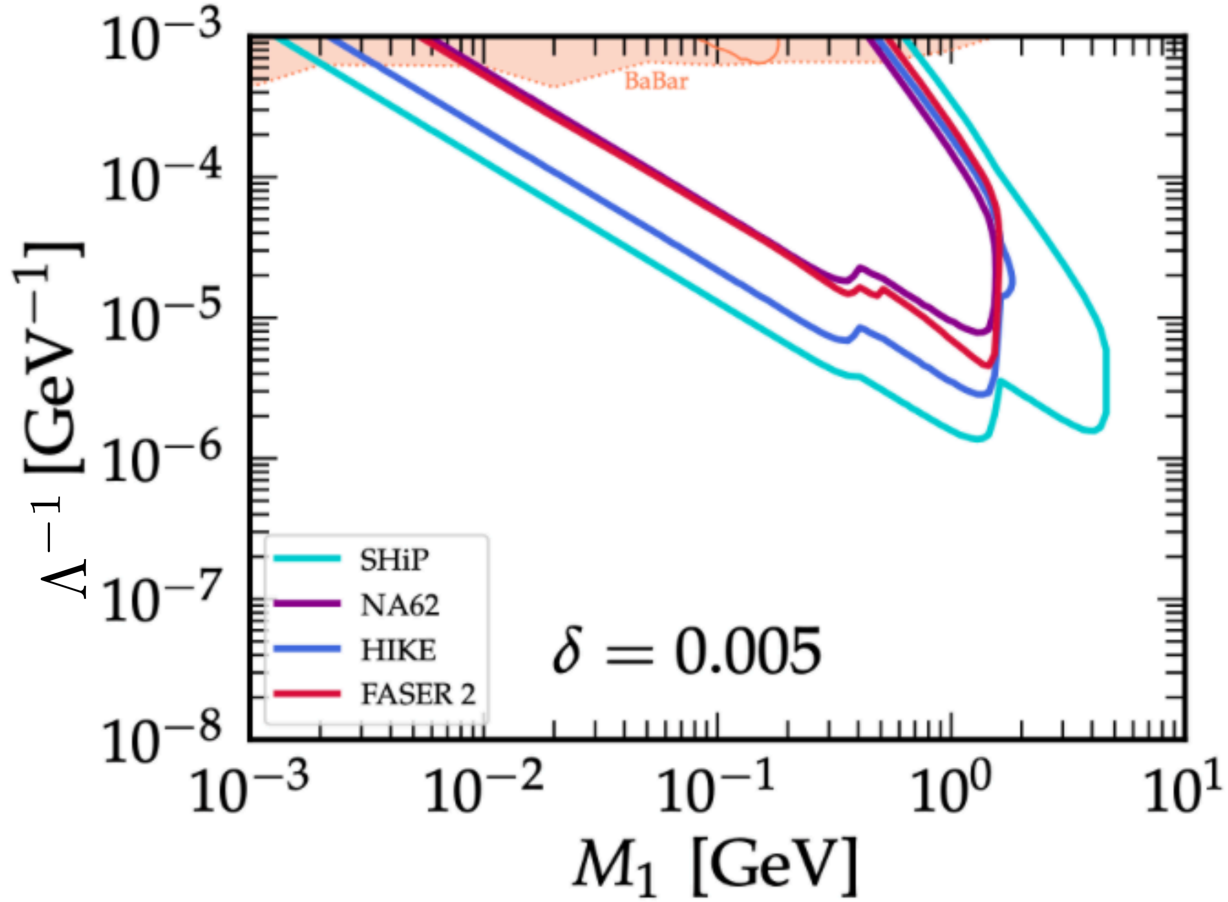
NA62 dump - $N_{\rm POT} = 10^{18}$
HIKE - $N_{\rm POT} = 5 \times 10^{19}$
SHiP - $N_{\rm POT} = 6 \times 10^{20}$

N_{π^0}	N_η	$N_{\eta'}$	N_ρ
4.3	0.049	0.055	0.58

N_ω	N_ϕ	$N_{J/\Psi}$	N_Υ
0.57	0.021	4.7×10^{-6}	2.2×10^{-9}

- Cut on $E_\gamma > 1\,{\rm GeV}$ - isocontours of $N = 3$ signal events





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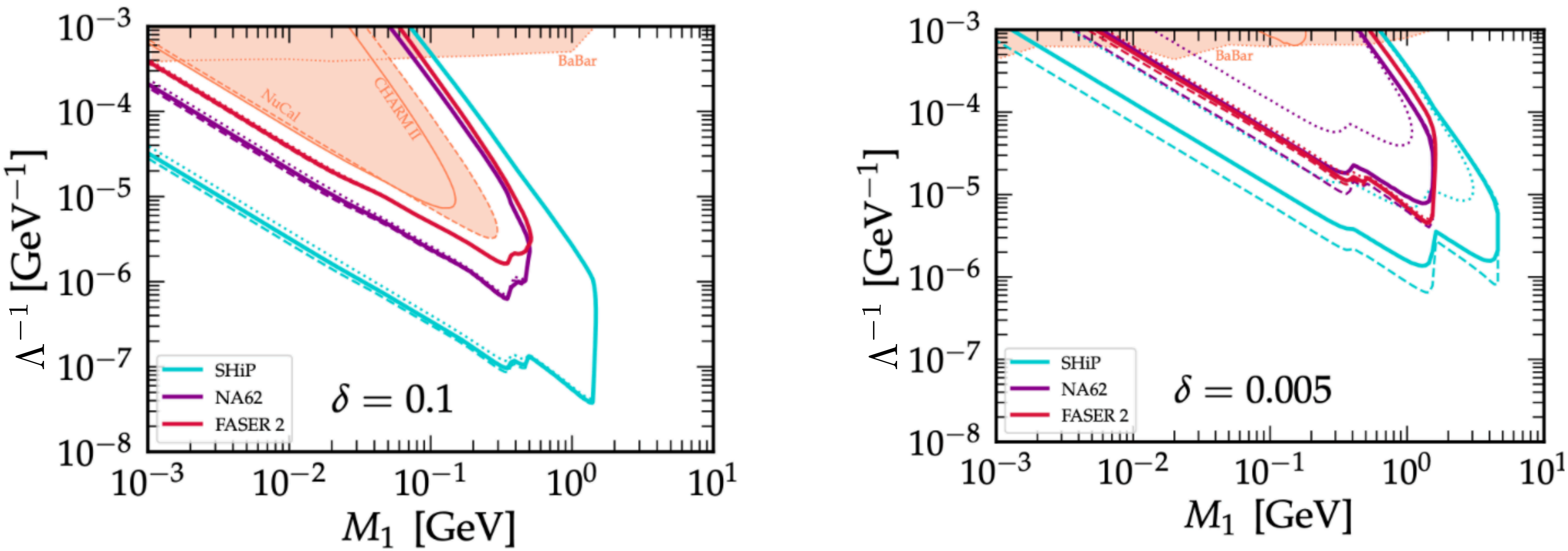
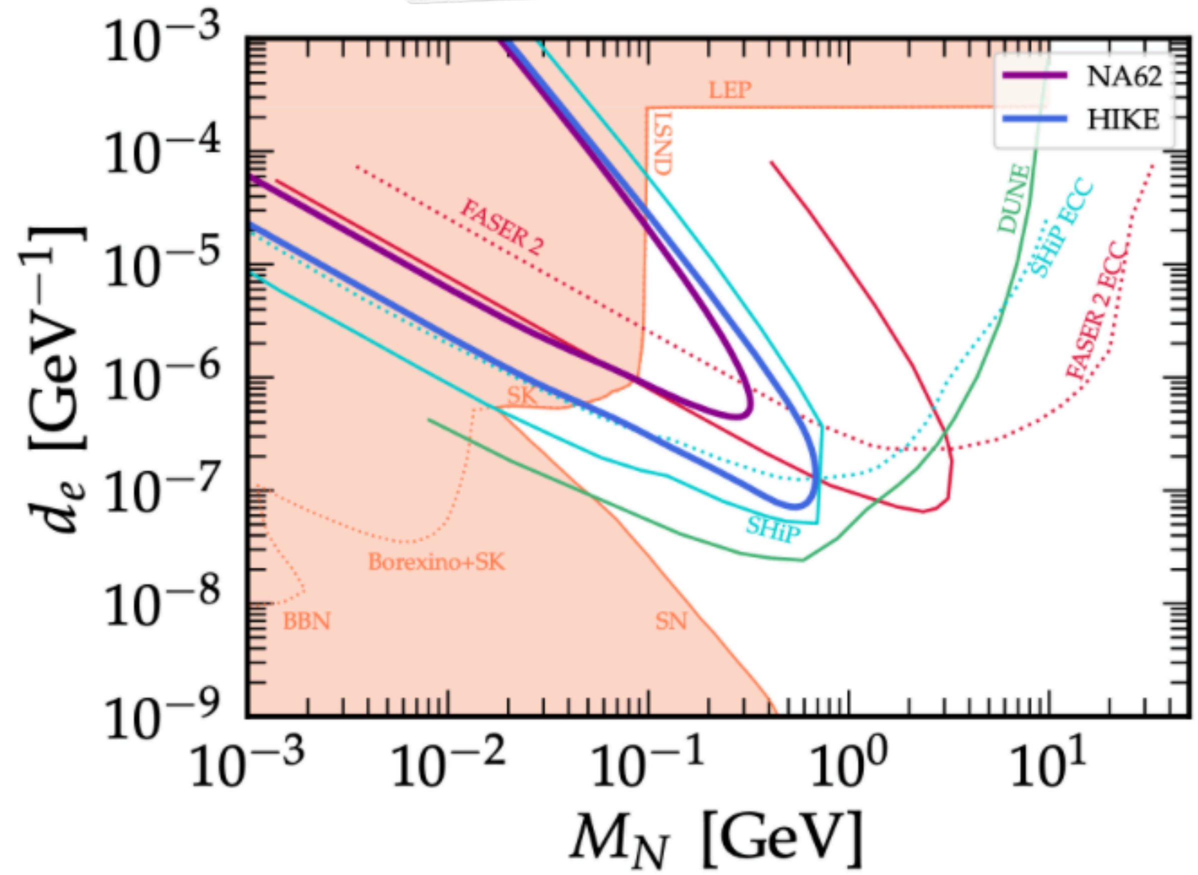
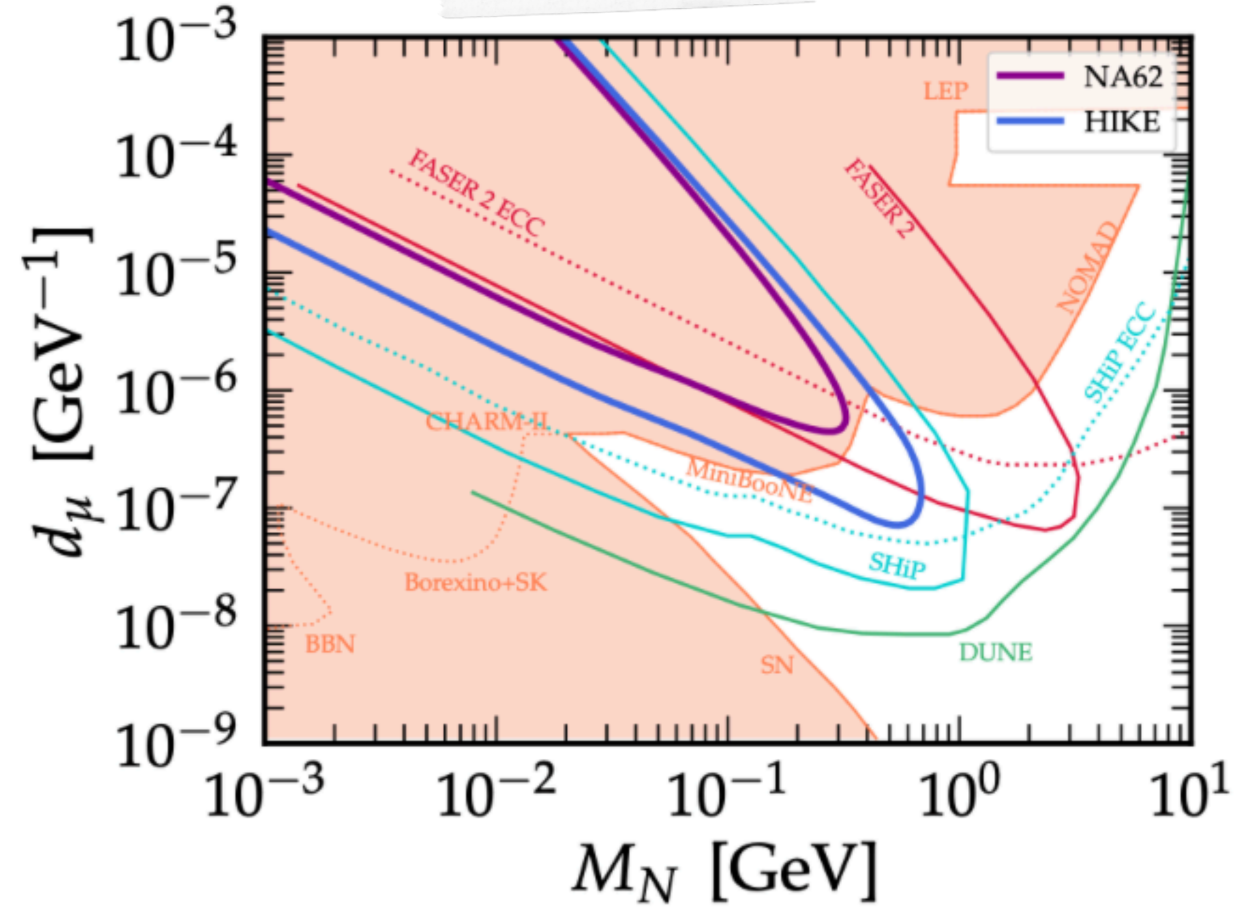
Modifying the photon energy threshold: 0.5 GeV, 2 GeV



- Similar strategy applicable to active-sterile dipole

$$\mathcal{O} = d^i_\nu \bar{N} \sigma^{\mu\nu} \nu_i F_{\mu\nu}$$





Thank you

BACKUP

Benchmark point choices

$$\mathbf{BP1_{NH}}: \quad r_{e4}^2 : r_{\mu4}^2 : r_{\tau4}^2 = 0.10 : 0.68 : 0.22$$

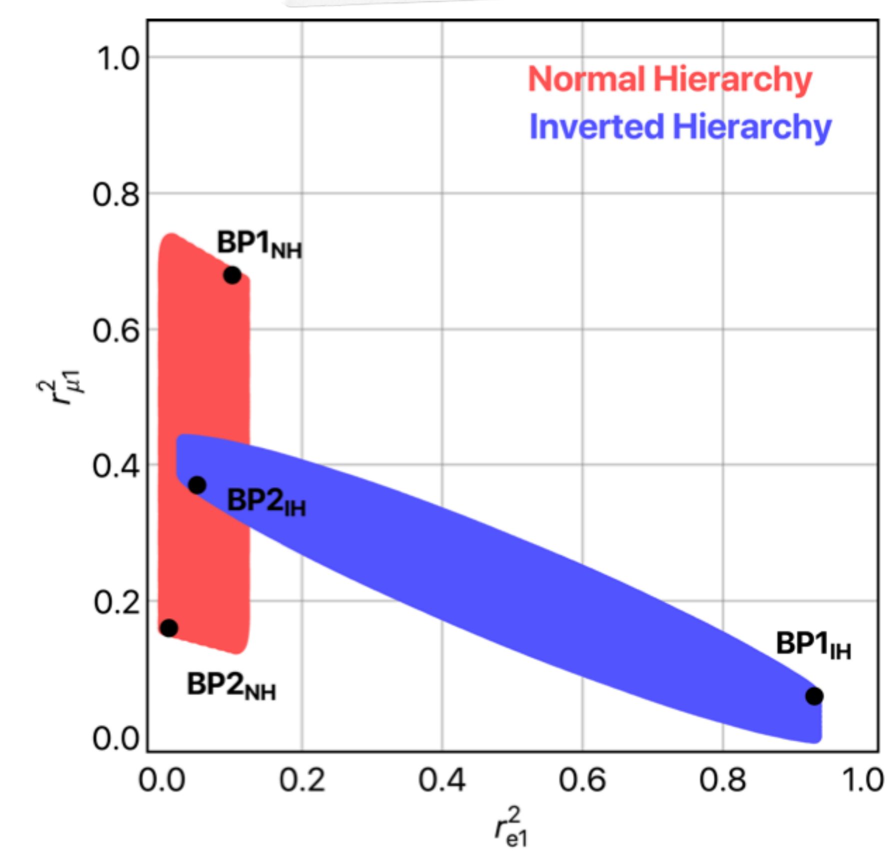
$$\mathbf{BP2_{NH}}: \quad r_{e4}^2 : r_{\mu4}^2 : r_{\tau4}^2 = 0.01 : 0.16 : 0.83$$

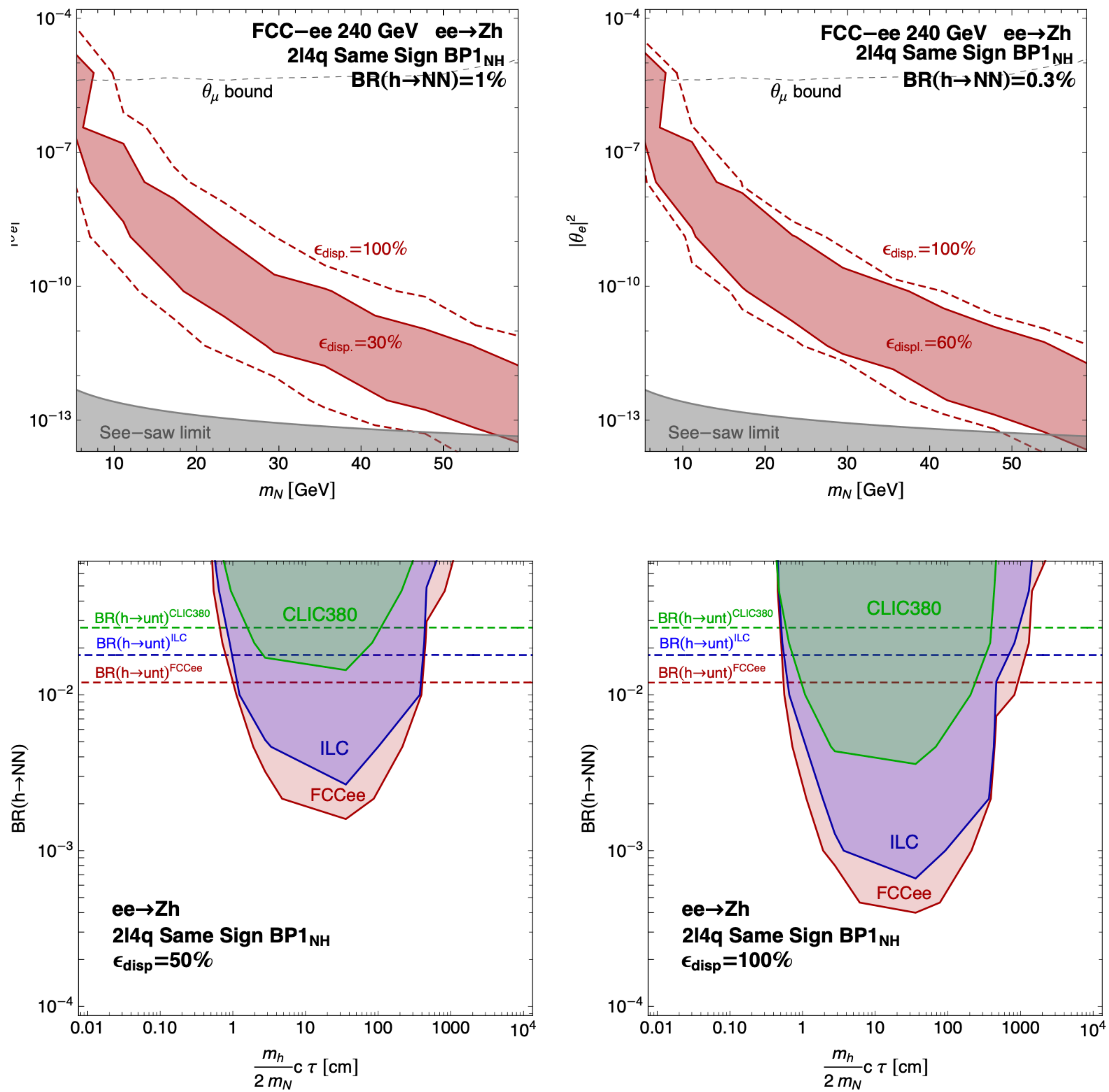
BR	Channel	SS	BR	Channel	SS	BR	Channel	SS	BR	Channel	SS
0.16	$2\ell\ 4q$	✓	0.01	$3\ell\ \tau\ \not{E}_T$		0.13	$2\tau\ 4q$		0.01	$2\tau\ 2q\ \not{E}_T$	✓
0.09	$\ell\ 4q\ \not{E}_T$		0.01	$2\ell\ 2\tau\ \not{E}_T$		0.09	$\tau\ 4q\ \not{E}_T$		0.01	$2\ell\ 4q$	
0.05	$4q\ \not{E}_T$		0.01	$2\ell\ \not{E}_T$		0.06	$4q\ \not{E}_T$		0.01	$\ell\ 2q\ \not{E}_T$	
0.05	$2\ell\ \tau\ 2q\ \not{E}_T$		0.01	$2\tau\ 4q$		0.06	$\ell\ 2\tau\ 2q\ \not{E}_T$		0.01	$\not{E}_T$	
0.04	$3\ell\ 2q\ \not{E}_T$	✓	0.01	$\ell\ \tau\ \not{E}_T$		0.04	$\ell\ \tau\ 2q\ \not{E}_T$		0.01	$2\ell\ 2q\ \not{E}_T$	
0.03	$\ell\ 4q\ \tau$		0.01	$\tau\ 2q\ \not{E}_T$		0.03	$\ell\ \tau\ 4q$		0.01	$\ell\ 3\tau\ \not{E}_T$	
0.03	$\ell\ 2q\ \not{E}_T$		0.01	$\not{E}_T$		0.03	$\tau\ 2q\ \not{E}_T$		0.	$3\ell\ \tau\ \not{E}_T$	
0.02	$2\ell\ 2q\ \not{E}_T$		0.	$2\tau\ 2q\ \not{E}_T$		0.02	$\ell\ 4q\ \not{E}_T$		0.	$2\tau\ \not{E}_T$	
0.02	$\ell\ \tau\ 2q\ \not{E}_T$		0.	$\ell\ 3\tau\ \not{E}_T$		0.02	$2\ell\ 2\tau\ \not{E}_T$		0.	$3\ell\ 2q\ \not{E}_T$	✓
0.02	$\tau\ 4q\ \not{E}_T$		0.	$3\tau\ 2q\ \not{E}_T$		0.02	$2\ell\ \tau\ 2q\ \not{E}_T$		0.	$2\ell\ \not{E}_T$	
0.02	$2q\ \not{E}_T$		0.	$2\tau\ \not{E}_T$		0.02	$2q\ \not{E}_T$		0.	$4\tau\ \not{E}_T$	
0.01	$\ell\ 2\tau\ 2q\ \not{E}_T$		0.	$4\tau\ \not{E}_T$		0.01	$3\tau\ 2q\ \not{E}_T$		0.	$4\ell\ \not{E}_T$	✓
0.01	$4\ell\ \not{E}_T$	✓				0.01	$\ell\ \tau\ \not{E}_T$				

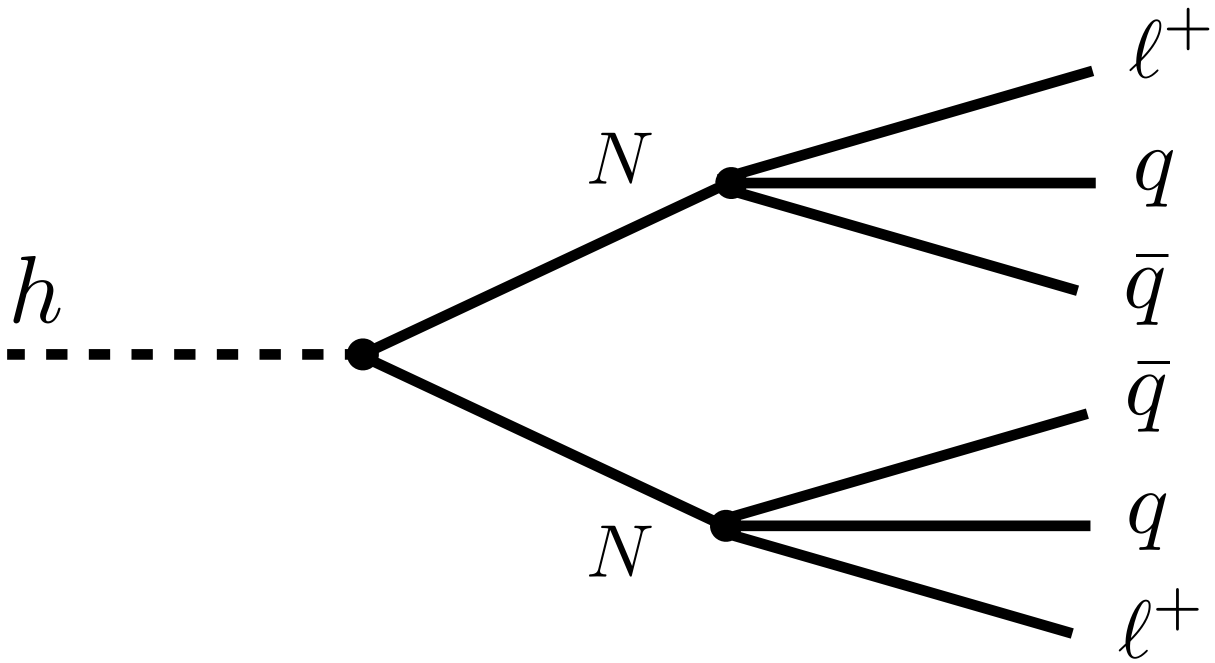
$$\mathbf{BP1_{IH}}: \quad r_{e4}^2 : r_{\mu4}^2 : r_{\tau4}^2 = 0.93 : 0.06 : 0.01$$

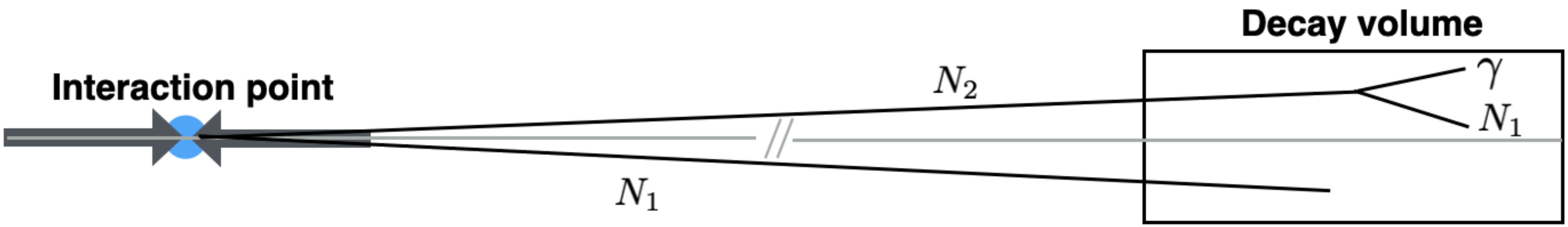
$$\mathbf{BP2_{IH}}: \quad r_{e4}^2 : r_{\mu4}^2 : r_{\tau4}^2 = 0.05 : 0.37 : 0.58$$

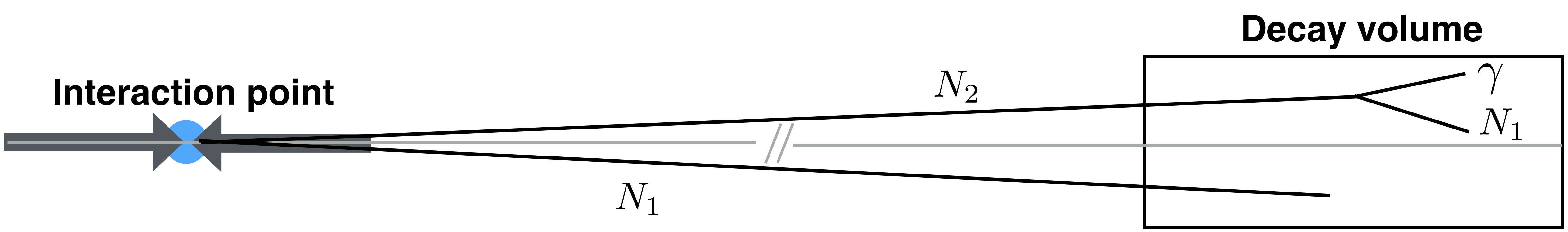
BR	Channel	SS	BR	Channel	SS	BR	Channel	SS	BR	Channel	SS
0.24	$2\ell\ 4q$	✓	0.01	$\ell\ \tau\ \not{E}_T$		0.06	$2\tau\ 4q$		0.01	$2\ell\ 2q\ \not{E}_T$	
0.11	$\ell\ 4q\ \not{E}_T$		0.01	$2\ell\ 2\tau\ \not{E}_T$		0.06	$\tau\ 4q\ \not{E}_T$		0.01	$3\ell\ 2q\ \not{E}_T$	✓
0.07	$3\ell\ 2q\ \not{E}_T$	✓	0.	$\ell\ \tau\ 4q$		0.06	$4q\ \not{E}_T$		0.01	$\ell\ \tau\ \not{E}_T$	
0.05	$4q\ \not{E}_T$		0.	$\tau\ 4q\ \not{E}_T$		0.05	$\ell\ \tau\ 4q$		0.01	$3\ell\ \tau\ \not{E}_T$	
0.04	$\ell\ 2q\ \not{E}_T$		0.	$\ell\ 2\tau\ 2q\ \not{E}_T$		0.05	$\ell\ 4q\ \not{E}_T$		0.01	$\not{E}_T$	
0.04	$2\ell\ \tau\ 2q\ \not{E}_T$		0.	$\tau\ 2q\ \not{E}_T$		0.05	$2\ell\ 4q$	✓	0.01	$3\tau\ 2q\ \not{E}_T$	
0.03	$2\ell\ 2q\ \not{E}_T$		0.	$2\tau\ 2q\ \not{E}_T$		0.04	$2\ell\ 2\tau\ 2q\ \not{E}_T$		0.01	$2\tau\ 2q\ \not{E}_T$	
0.02	$4\ell\ \not{E}_T$	✓	0.	$2\tau\ \not{E}_T$		0.04	$\ell\ 2\tau\ 2q\ \not{E}_T$		0.01	$2\ell\ \not{E}_T$	
0.02	$2q\ \not{E}_T$		0.	$\ell\ 3\tau\ \not{E}_T$		0.03	$\ell\ \tau\ 2q\ \not{E}_T$		0	$4\ell\ \not{E}_T$	✓
0.02	$\ell\ \tau\ 2q\ \not{E}_T$		0.	$2\tau\ 4q$		0.02	$2q\ \tau\ \not{E}_T$		0	$\ell\ 3\tau\ \not{E}_T$	
0.01	$2\ell\ \not{E}_T$		0.	$3\tau\ 2q\ \not{E}_T$		0.02	$2q\ \not{E}_T$		0	$2\tau\ \not{E}_T$	
0.01	$3\ell\ \tau\ \not{E}_T$		0.	$4\tau\ \not{E}_T$		0.02	$\ell\ 2q\ \not{E}_T$		0	$4\tau\ \not{E}_T$	
0.01	$\not{E}_T$					0.02	$2\ell\ 2\ \tau\ \not{E}_T$				




FCC−ee 240 GeV ee→Zh
2l4q Same Sign BP1$_{NH}$
BR(h→NN)=1%
θ_μ bound
$\epsilon_{disp.}$=100%
$\epsilon_{disp.}$=30%
See−saw limit
m_N [GeV]
FCC−ee 240 GeV ee→Zh
2l4q Same Sign BP1$_{NH}$
BR(h→NN)=0.3%
$|\theta_e|^2$
θ_μ bound
$\epsilon_{disp.}$=100%
$\epsilon_{displ.}$=60%
See−saw limit
m_N [GeV]
BR(h→NN)
BR(h→unt)^{CLIC380}
BR(h→unt)^{ILC}
BR(h→unt)^{FCCee}
CLIC380
ILC
FCCee
ee→Zh
2l4q Same Sign BP1$_{NH}$
ϵ_{disp}=50%
$\frac{m_h}{2\,m_N} c\,\tau$ [cm]
BR(h→NN)
BR(h→unt)^{CLIC380}
BR(h→unt)^{ILC}
BR(h→unt)^{FCCee}
CLIC380
ILC
FCCee
ee→Zh
2l4q Same Sign BP1$_{NH}$
ϵ_{disp}=100%
$\frac{m_h}{2\,m_N} c\,\tau$ [cm]


h
N
N
ℓ^+
q
$\bar{q}$
$\bar{q}$
q
ℓ^+


Decay volume
Interaction point
N_2
γ
N_1
N_1


Decay volume
Interaction point
N_2
γ
N_1
N_1