Collider Probes of Neutrino Magnetic Moment

Samiur R. Mir
Oklahoma State University

In collaboration with
Vedran Brdar, Ying-Ying Li, Yilin Wang

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Neutrino magnetic moment: theory

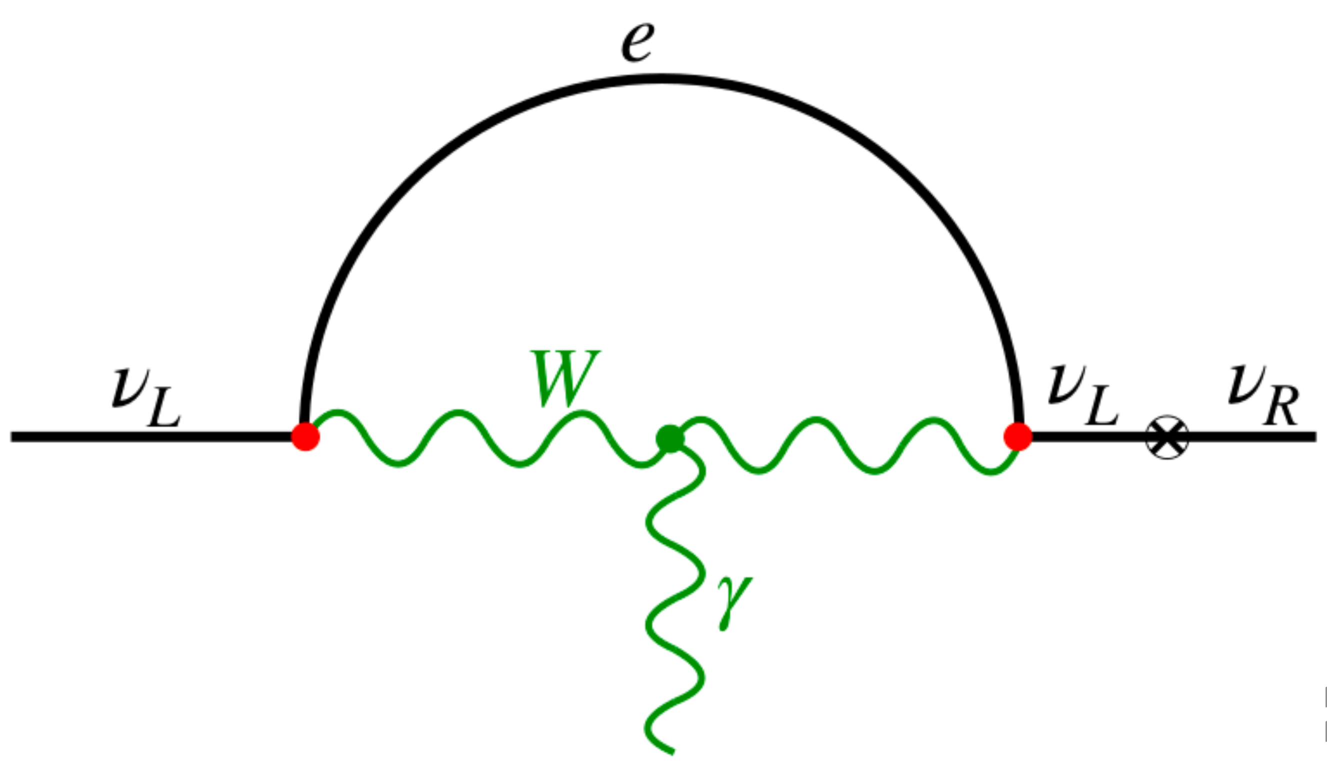
- Neutrino oscillation indicates that neutrinos have mass
- Addition of right-handed neutrino ν_R ensures a nonzero magnetic moment

neutrino magnetic moment interaction,

$$\mathscr{L}_{\nu}^{mag} \supset \frac{1}{2}\mu_{\nu}^{\alpha\beta}\bar{\nu}_L^{\alpha}\sigma^{\mu\nu}\nu_R^{\beta}F_{\mu\nu}$$

- Adding ν_R to SM can generate tiny magnetic moment,

$$\mu_\nu \sim 10^{-20}\mu_B\left(\frac{m_\nu}{0.1\,eV}\right) \sim 10^{-17}\left(\frac{m_\nu}{0.1\,eV}\right)GeV^{-1}$$



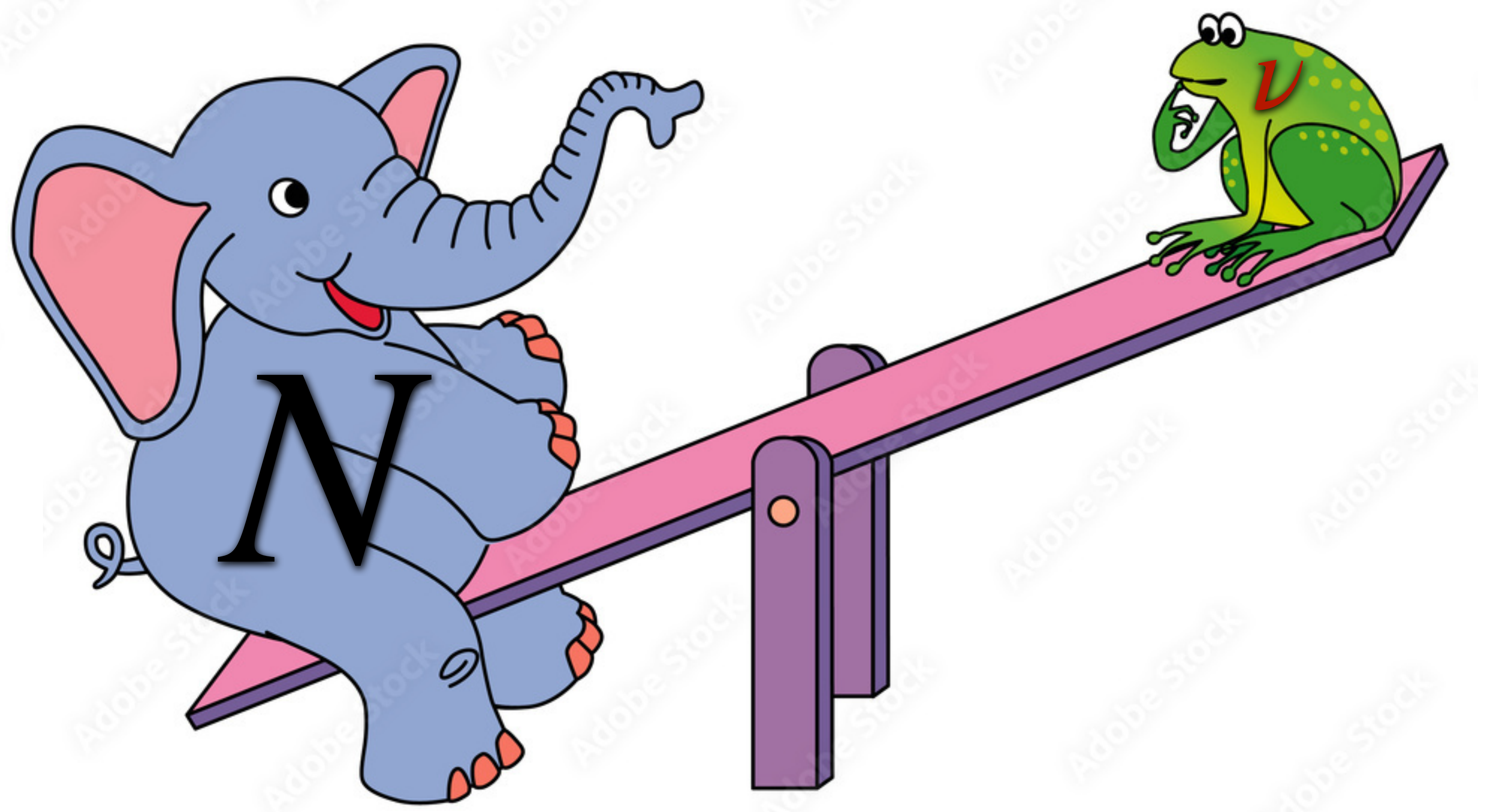
Neutrino magnetic moment: theory

- In the framework of well-motivated

  Seesaw mechanism, mass generation

  involves heavy N_R ,

  i.e., heavy neutral lepton (HNL)



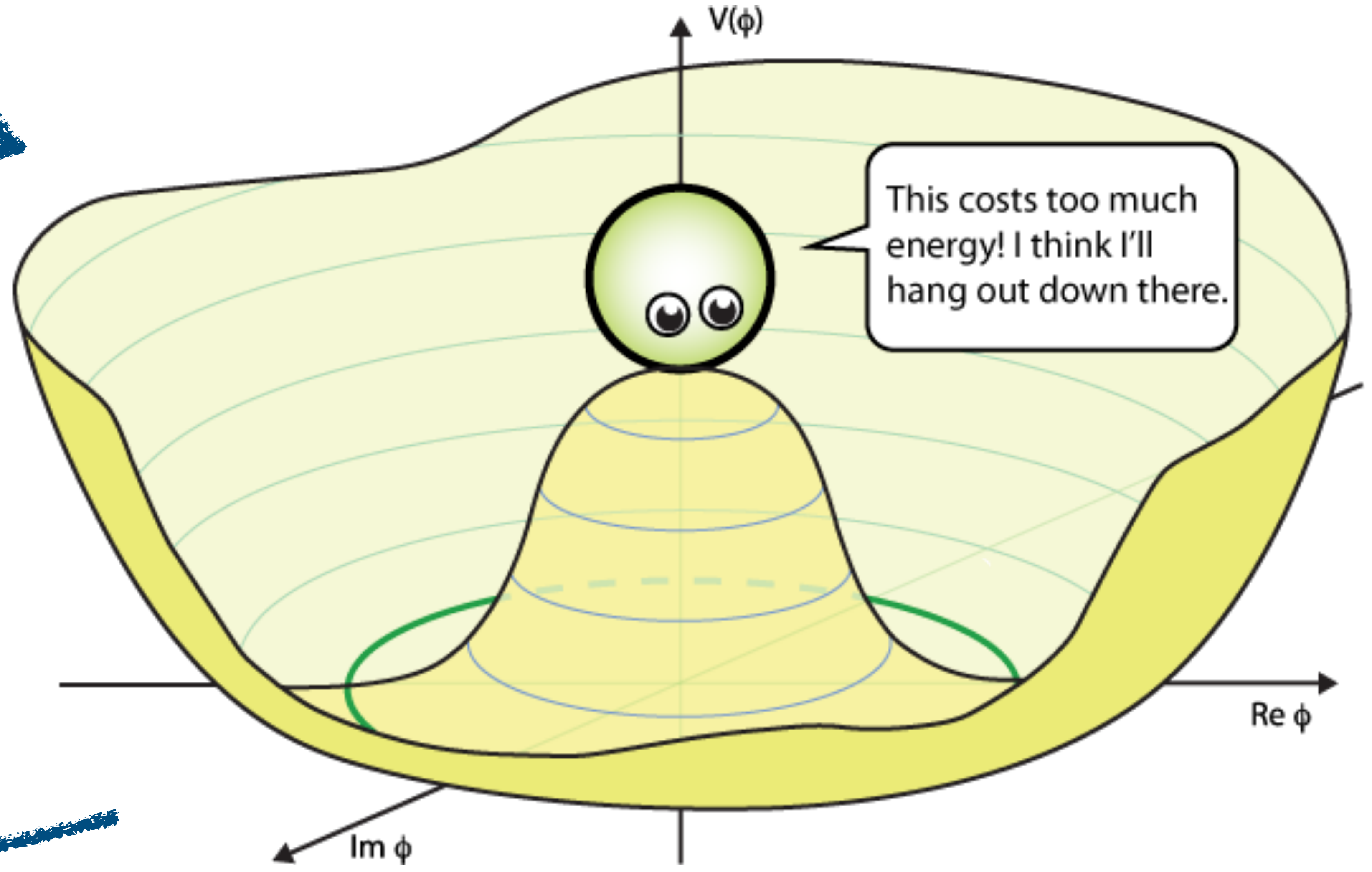
$$\mathscr{L}_\nu^{mag} \supset \frac{1}{2}\mu_\nu^{\alpha\beta}\bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R^\beta F_{\mu\nu}$$

- μ_ν can be **enhanced** in BSM theories considering the **dipole portal** between active ν_L and sterile N_R , leading to “transition magnetic moment”

Active-sterile neutrino transition magnetic moment

We consider 6-dim EFT Lagrangian with electroweak symmetry,

$$\mathscr{L} \supset \frac{c_B}{\Lambda^2} g' B_{\mu\nu} \bar{L}_L \tilde{H} \sigma^{\mu\nu} N_R + \frac{c_W}{\Lambda^2} g W^a_{\mu\nu} \sigma^a \bar{L}_L \tilde{H} \sigma^{\mu\nu} N_R$$



$$\mathscr{L} \supset \frac{c_W}{\Lambda^2} g W^-_{\mu\nu} \frac{v}{\sqrt{2}} \bar{l}_L \sigma^{\mu\nu} N_R$$

$$+ \left(\frac{c_B}{\Lambda^2} g' \cos\theta_w + \frac{c_w}{\Lambda^2} g \sin\theta_w \right) F_{\mu\nu} \frac{v}{\sqrt{2}} \bar{\nu}_L \sigma^{\mu\nu} N_R$$

$$+ \left(-\frac{c_B}{\Lambda^2} g' \sin\theta_w + \frac{c_W}{\Lambda^2} g \cos\theta_w \right) Z_{\mu\nu} \frac{v}{\sqrt{2}} \sigma^{\mu\nu} N_R$$

Constraints on neutrino magnetic moment and prospects of collider exp.

Collider Probes of Neutrino Magnetic Moment…

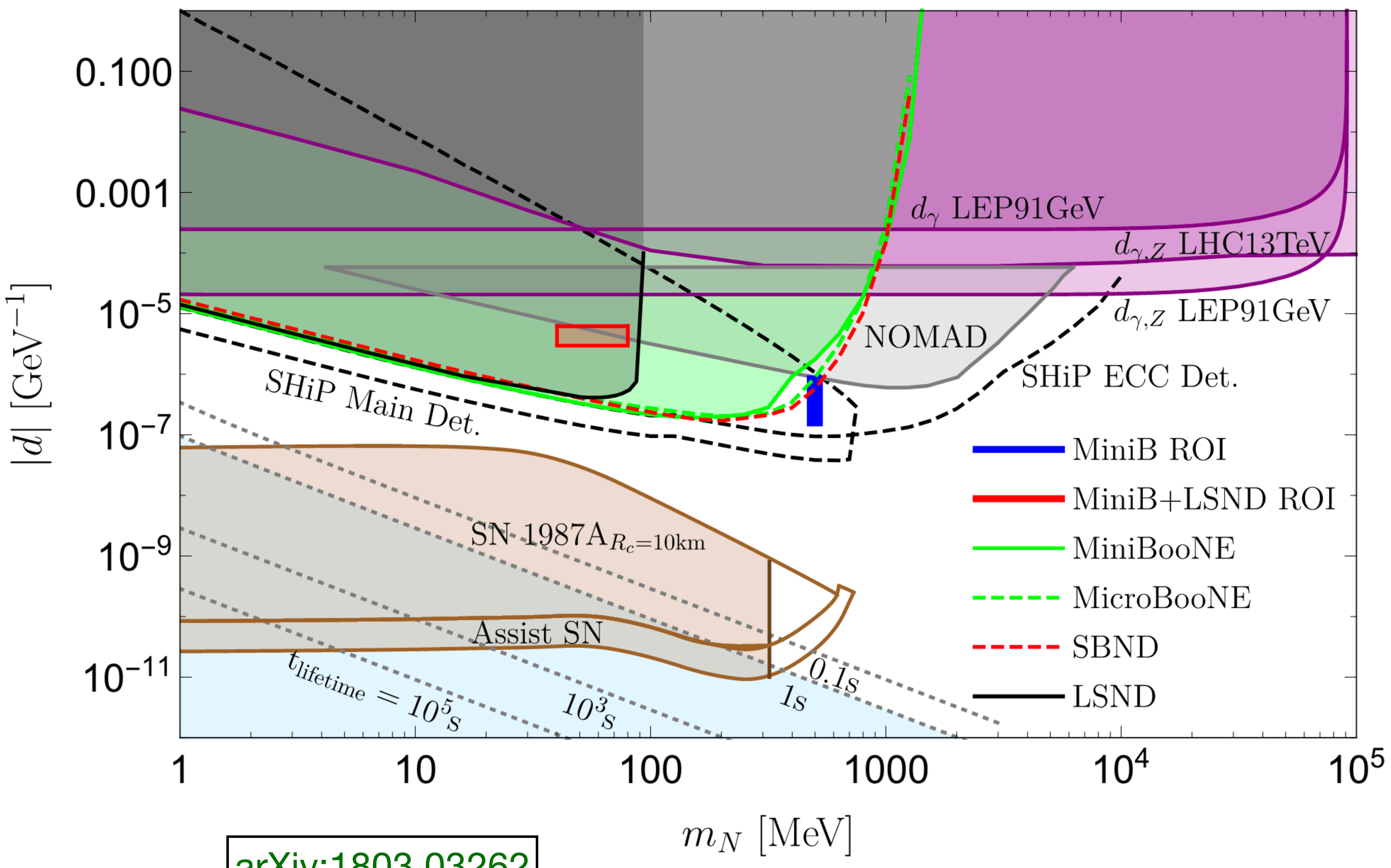
Higher energy $\sqrt{s}$ can

- produce and thus probe larger HNL mass m_N

While…

Higher luminosity $\mathscr{L}$ allows to

- test the sensitivity on d_γ more precisely since sensitivity reach, $d_\gamma \propto \mathscr{L}^{-1/4}$



arXiv:1803.03262

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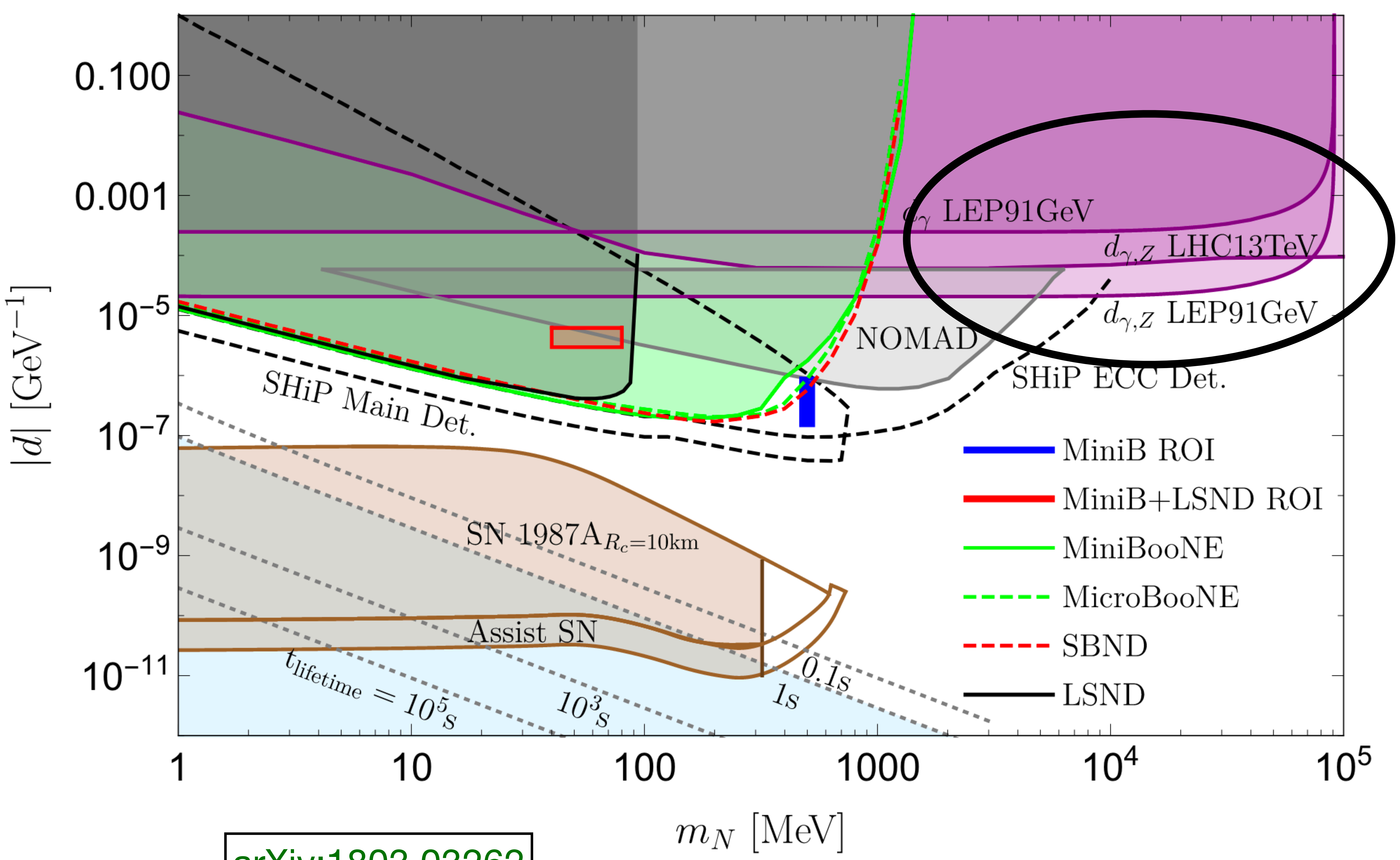

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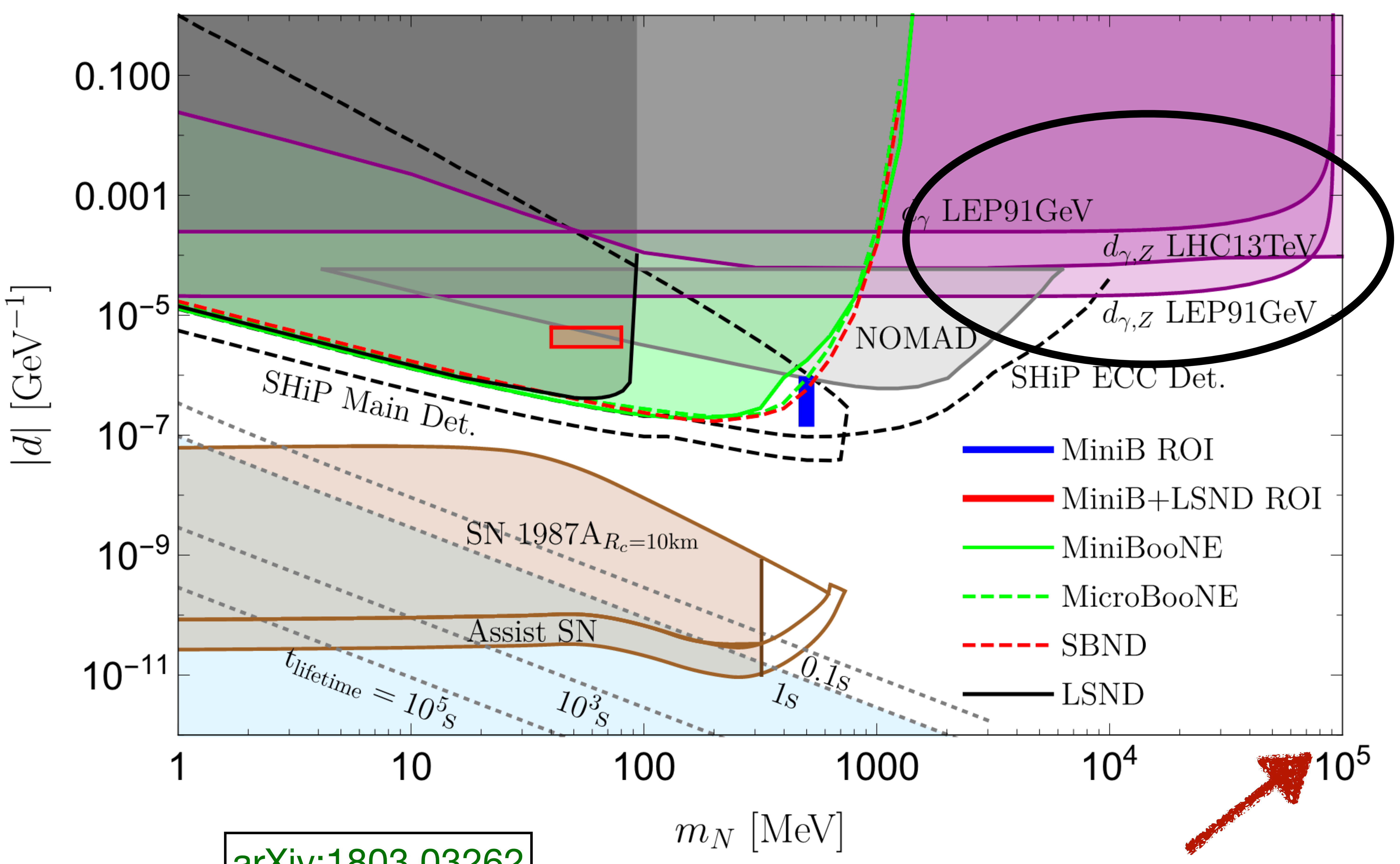

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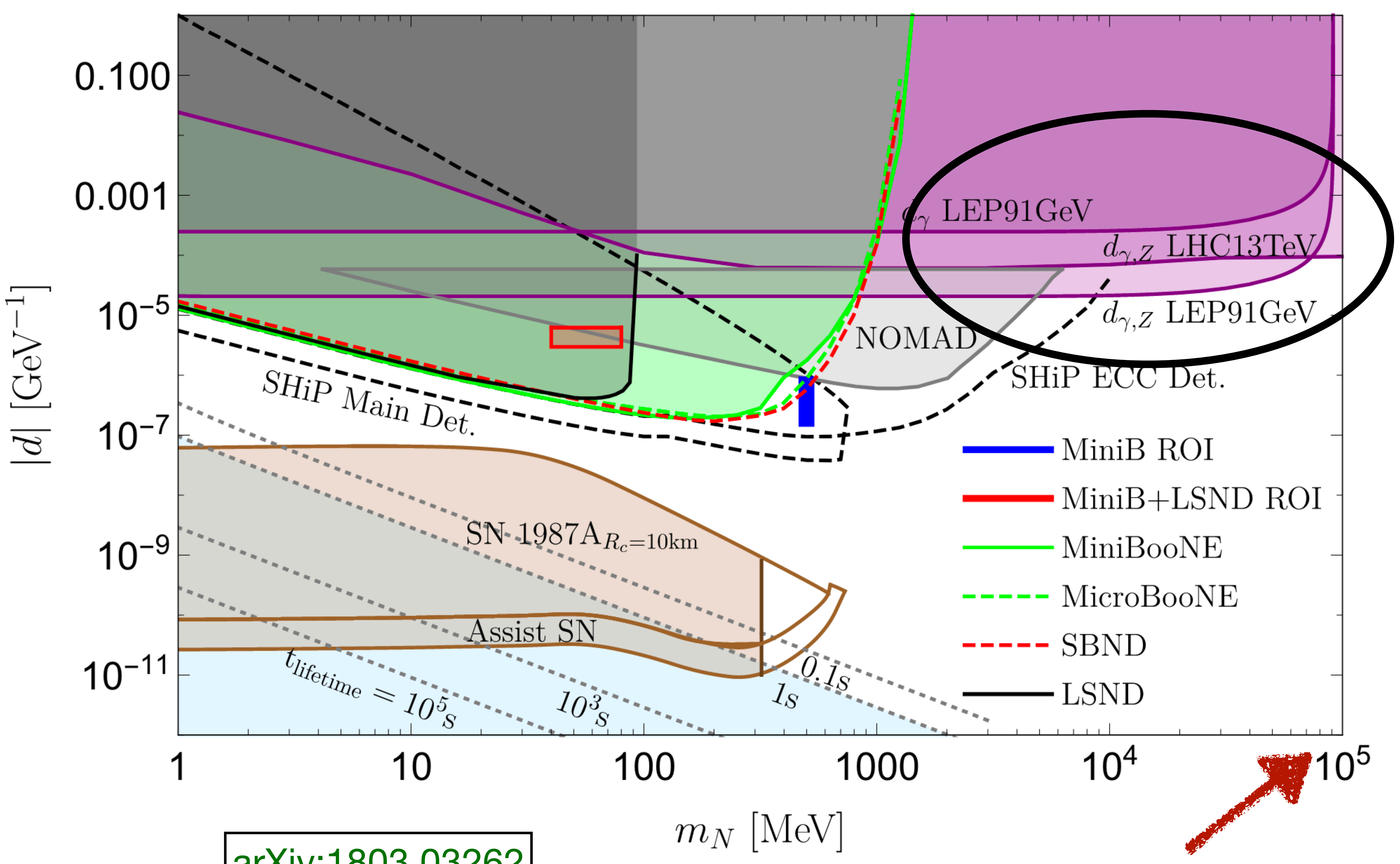
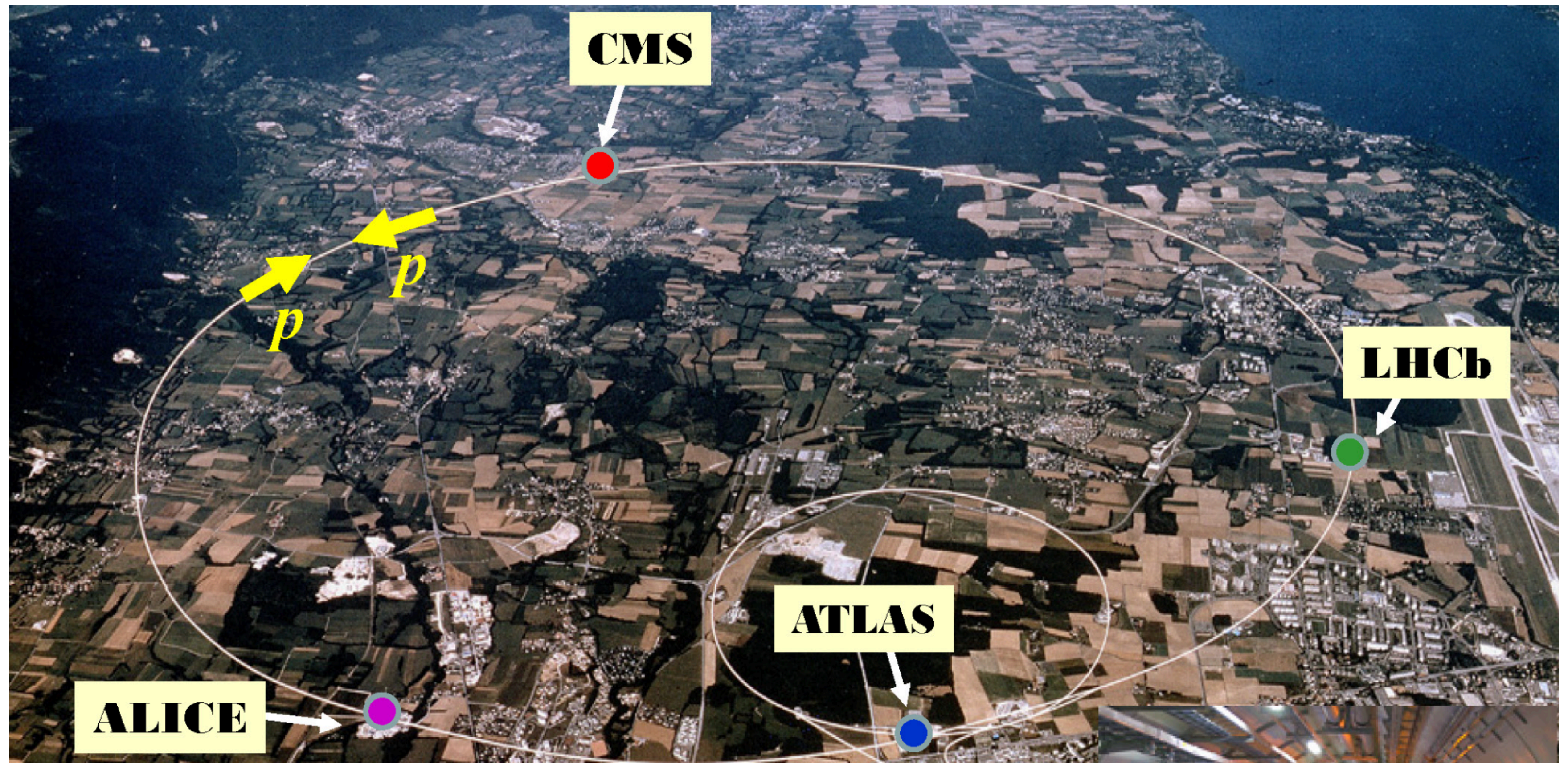


arXiv:1803.03262

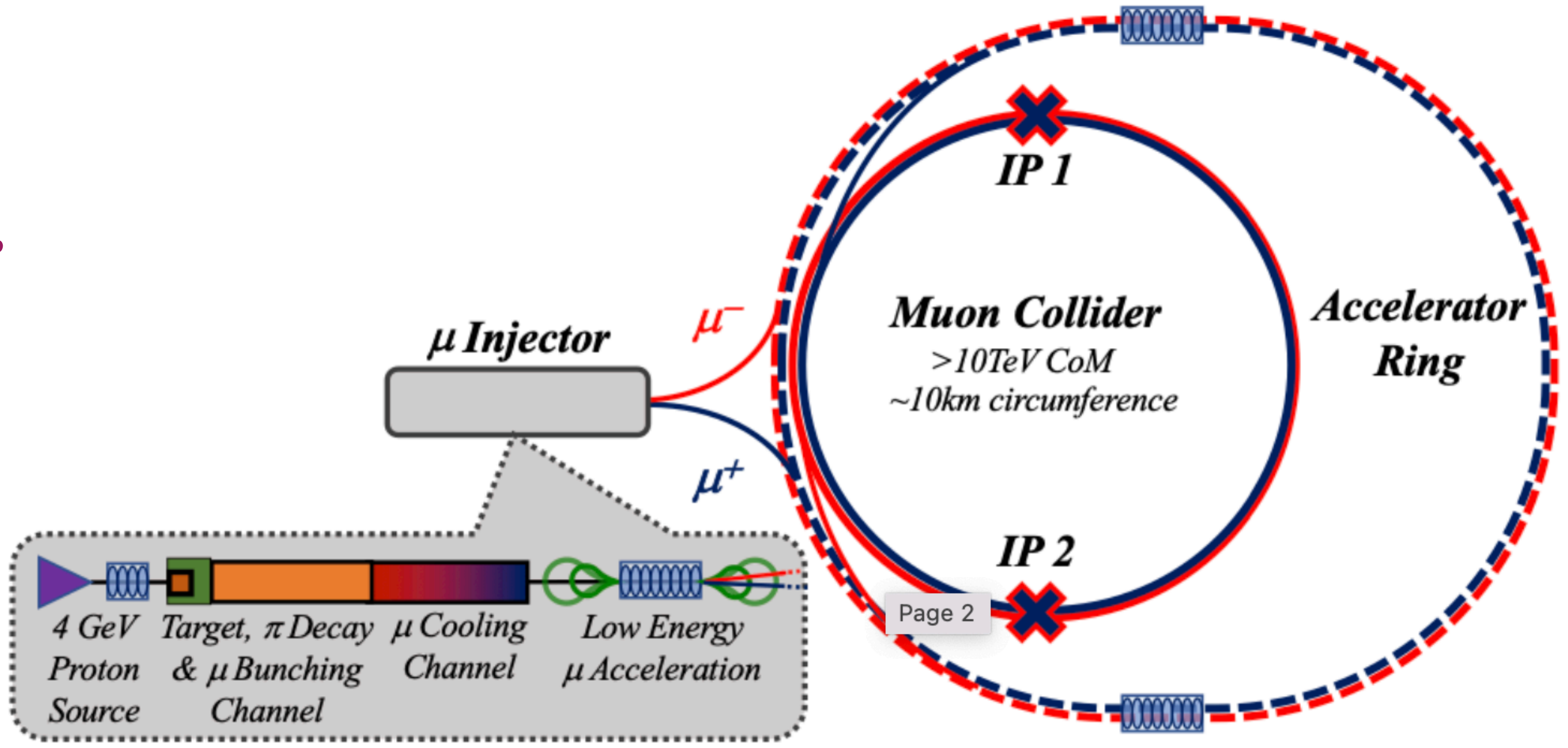
Only up to 100 GeV

Prospects of future experiments

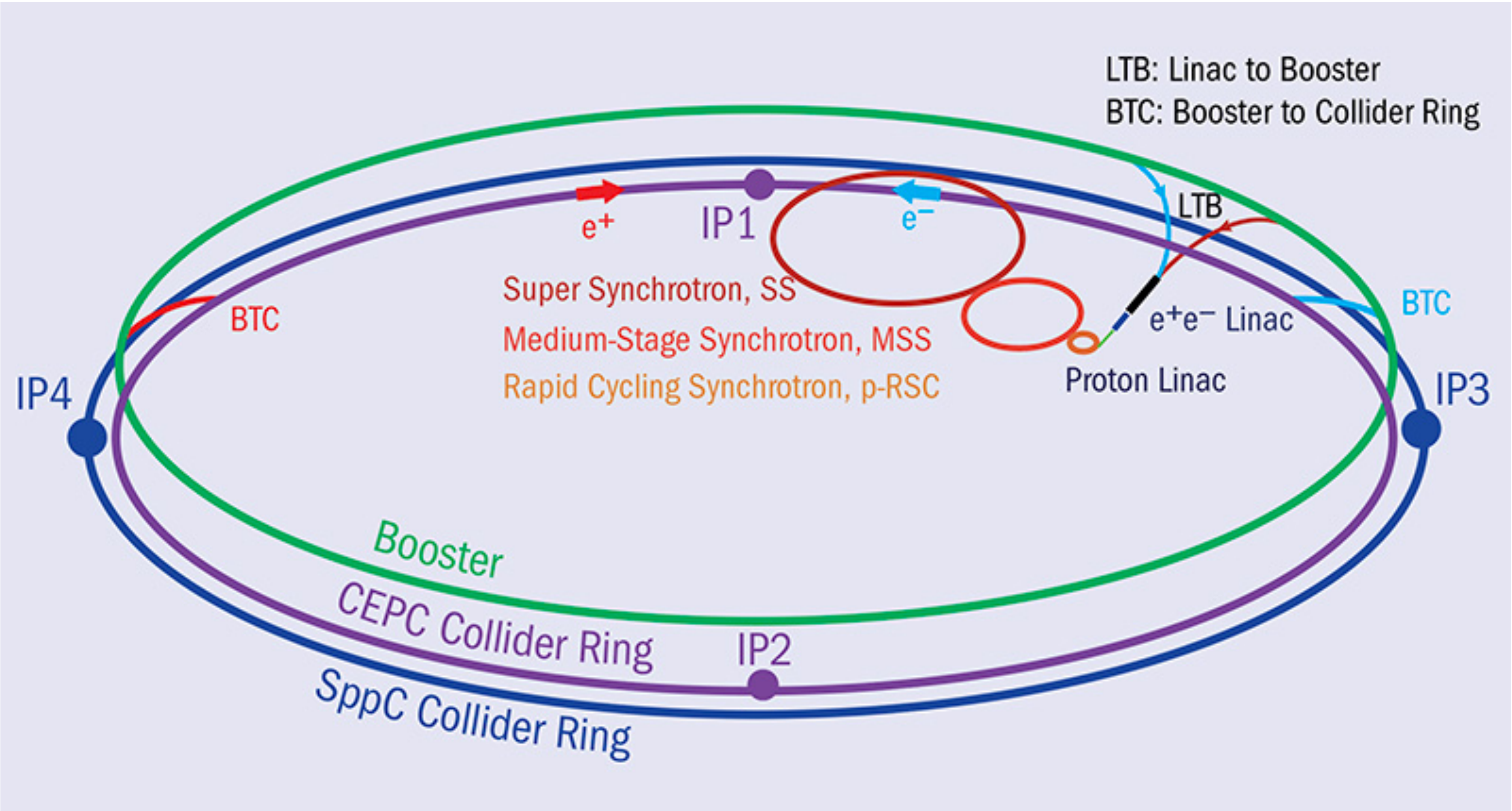
High Lumi LHC
$\sqrt{s} = 14$ TeV,
$\mathscr{L} = 3\ ab^{-1}$
Operational by 2029



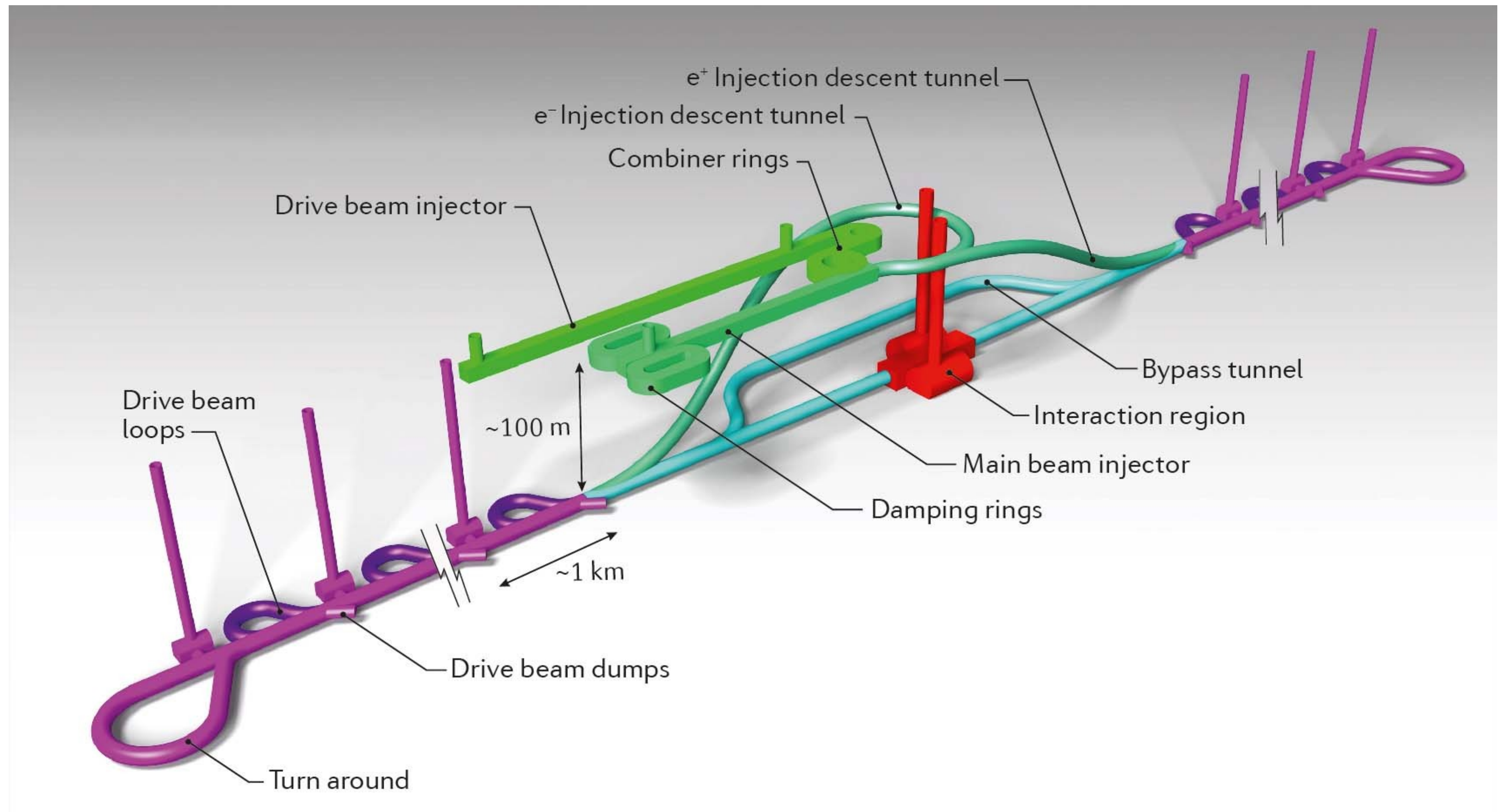
Muon Collider
$\sqrt{s} = 10$ TeV,
$\mathscr{L} = 10\ ab^{-1}$



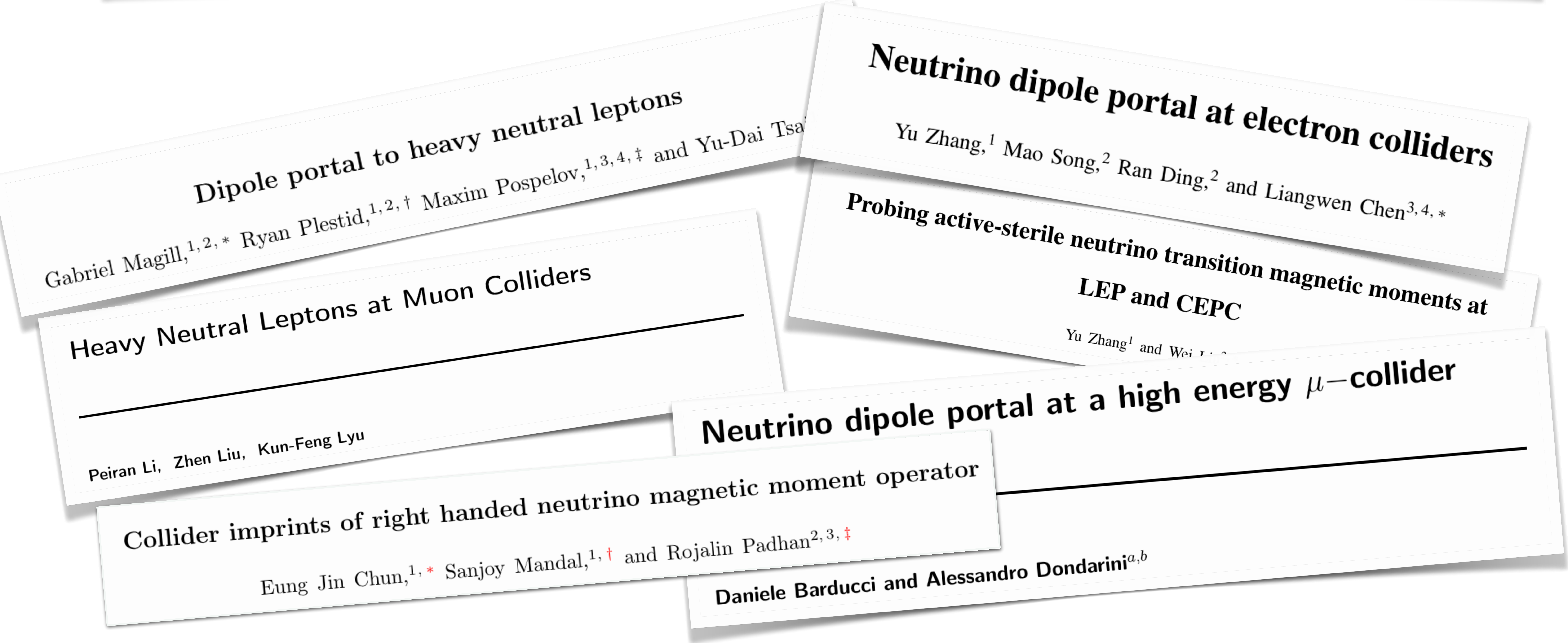
Circular e^-e^+ Collider (CEPC)
$\sqrt{s} = 240$ GeV,
$\mathscr{L} = 20\ ab^{-1}$



Compact Linear Collider (CLIC)
$\sqrt{s} = 3$ TeV,
$\mathscr{L} = 3\ ab^{-1}$



Previously on ν-dipole portal at colliders



Dipole portal to heavy neutral leptons

Gabriel Magill,[1,2,*] Ryan Plestid,[1,2,†] Maxim Pospelov,[1,3,4,‡] and Yu-Dai Tsa

Neutrino dipole portal at electron colliders

Yu Zhang,[1] Mao Song,[2] Ran Ding,[2] and Liangwen Chen[3,4,*]

Probing active-sterile neutrino transition magnetic moments at LEP and CEPC

Yu Zhang[1] and Wei L

Heavy Neutral Leptons at Muon Colliders

Peiran Li, Zhen Liu, Kun-Feng Lyu

Neutrino dipole portal at a high energy $\mu-$collider

Daniele Barducci and Alessandro Dondarini[a,b]

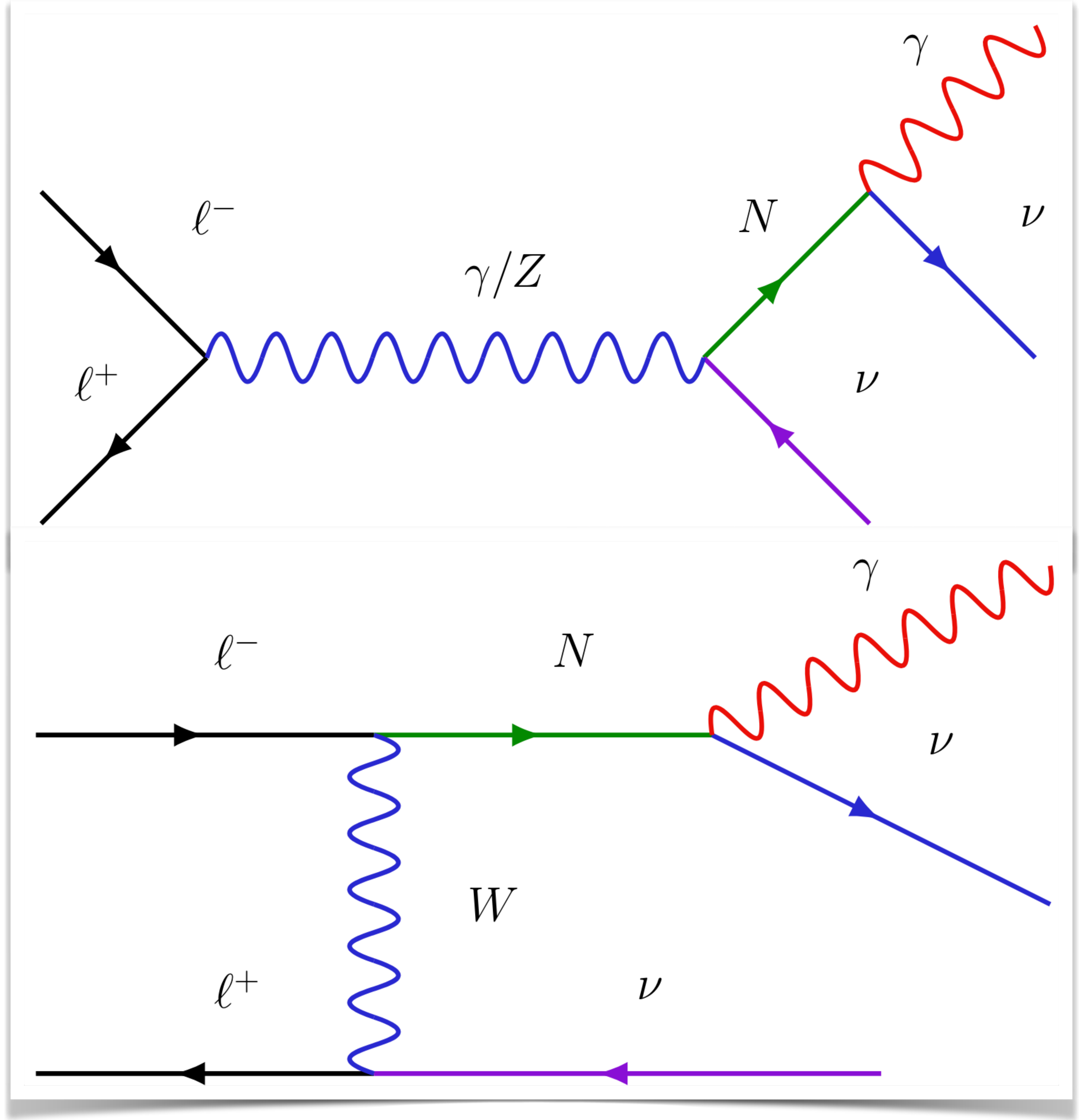
Collider imprints of right handed neutrino magnetic moment operator

Eung Jin Chun,[1,*] Sanjoy Mandal,[1,†] and Rojalin Padhan[2,3,‡]

Mono-photon signal and its background

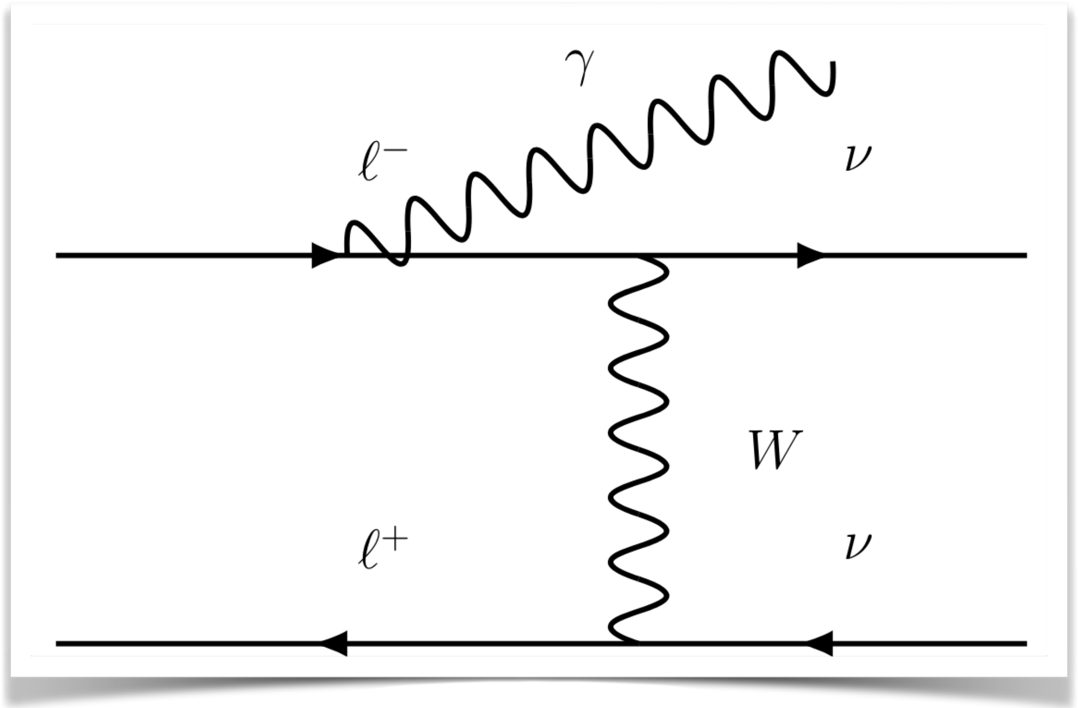
Signal: $\ell^+\ell^- \to \bar{\nu}N$ (on-shell)

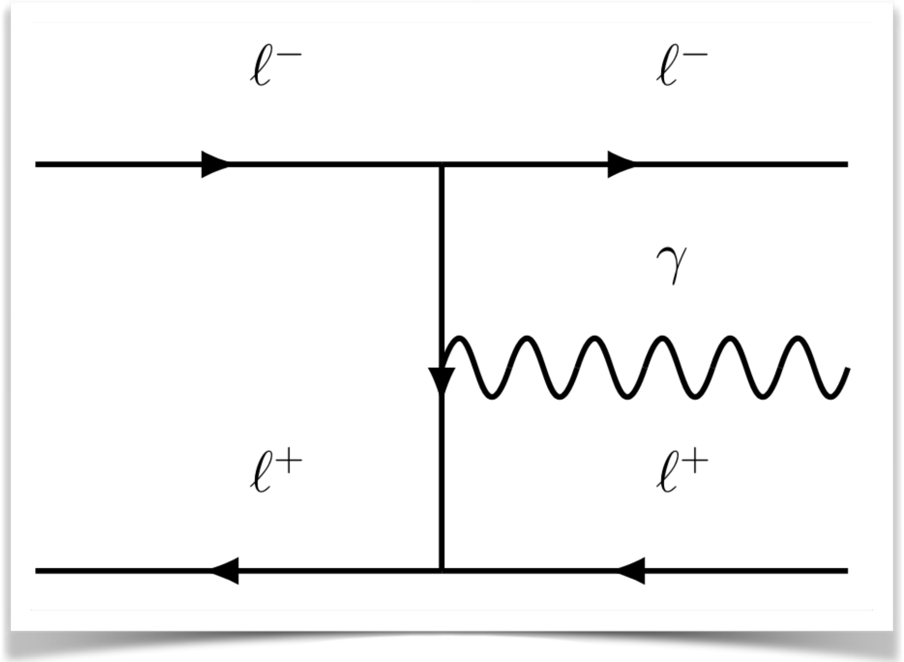
and N decays to a photon: $N \to \nu\gamma$

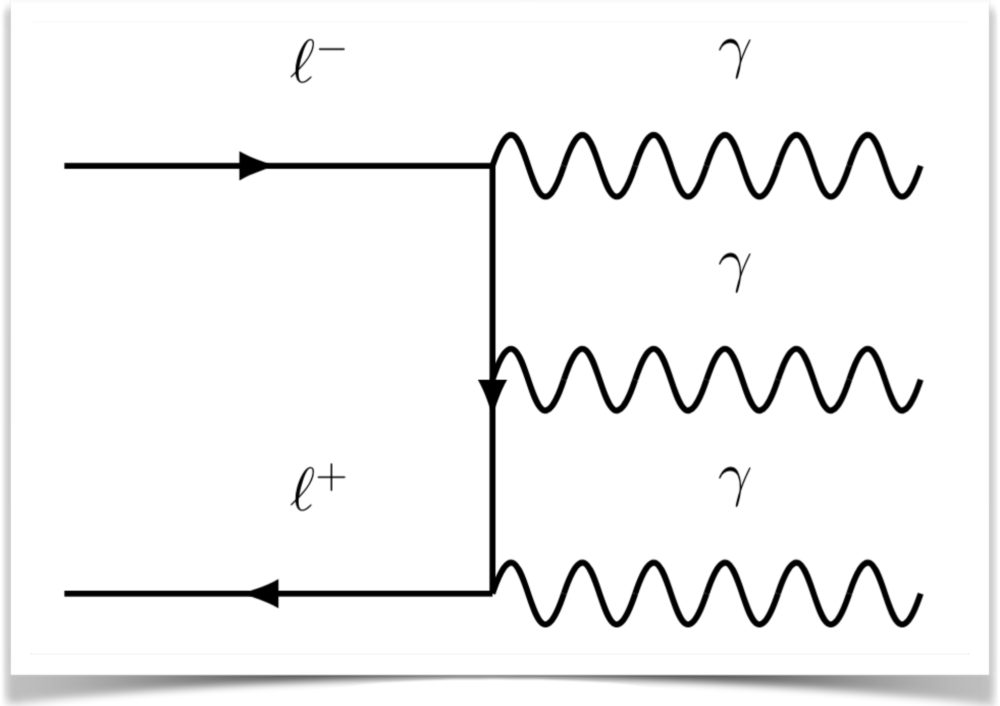


Background

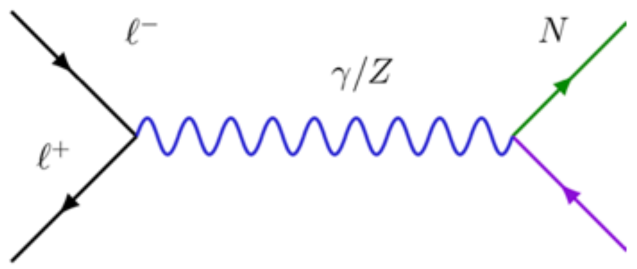
$\ell^+\ell^- \to \nu\bar{\nu}\gamma, \quad \ell^+\ell^- \to \ell^+\ell^-\gamma, \quad \ell^+\ell^- \to \gamma\gamma\gamma$

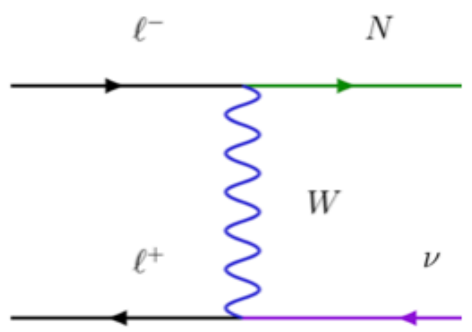






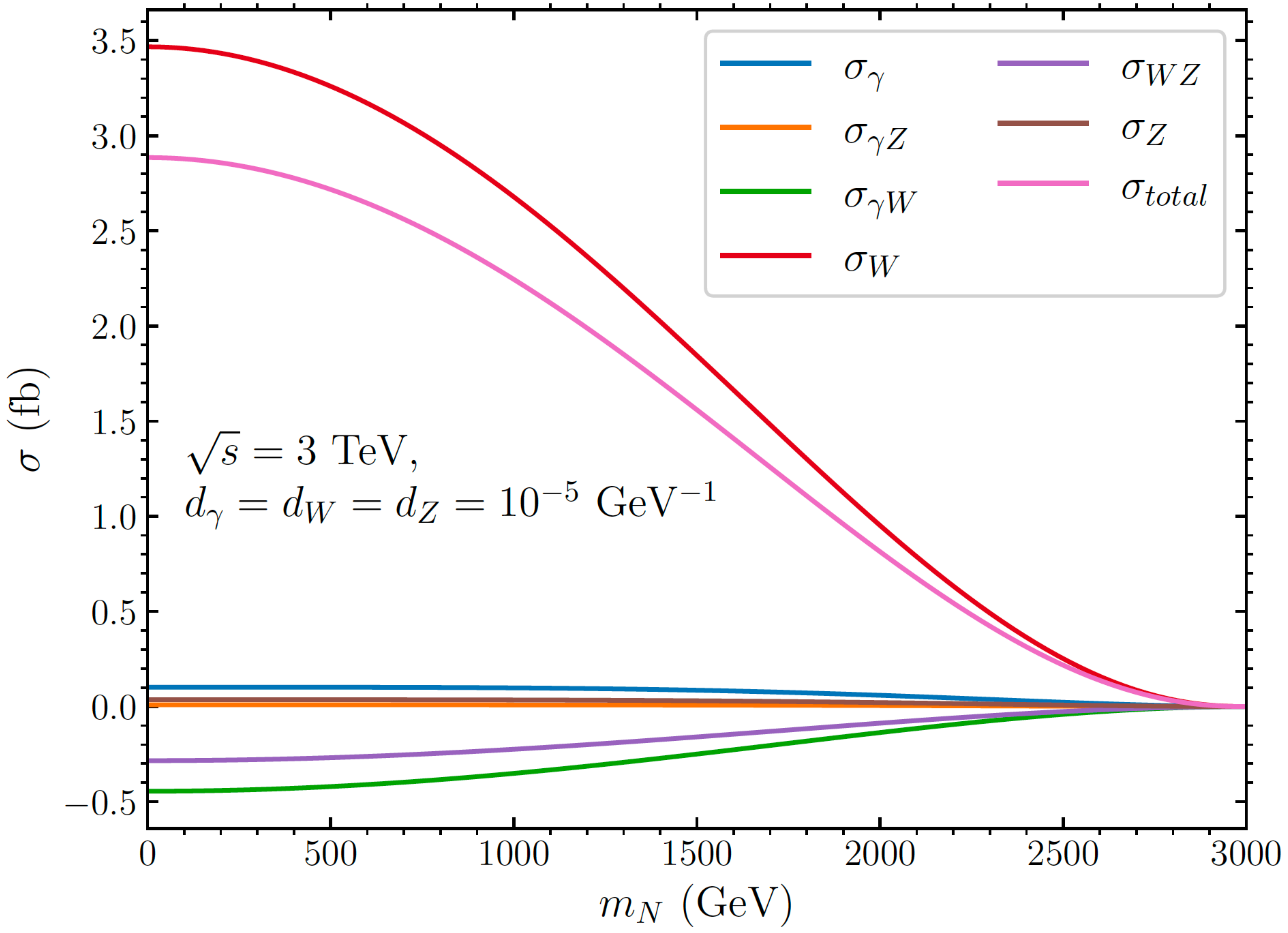
Cross-section $\sigma(\ell^+\ell^- \to \nu N)$

$\mathscr{M} =$ 

$+$ 

$$= \mathscr{M}_\gamma + \mathscr{M}_Z + \mathscr{M}_W$$

$$\sigma_{tot} = \overbrace{\sigma_\gamma + \sigma_Z + \sigma_W}^{\text{squared terms}} + \underbrace{\sigma_{\gamma Z} + \sigma_{\gamma W} + \sigma_{WZ}}_{\text{interference terms}}$$



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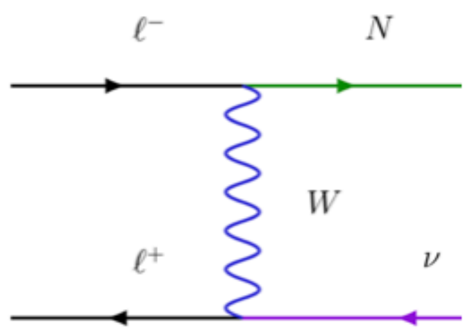
$\mathscr{M} =$  $+$ 

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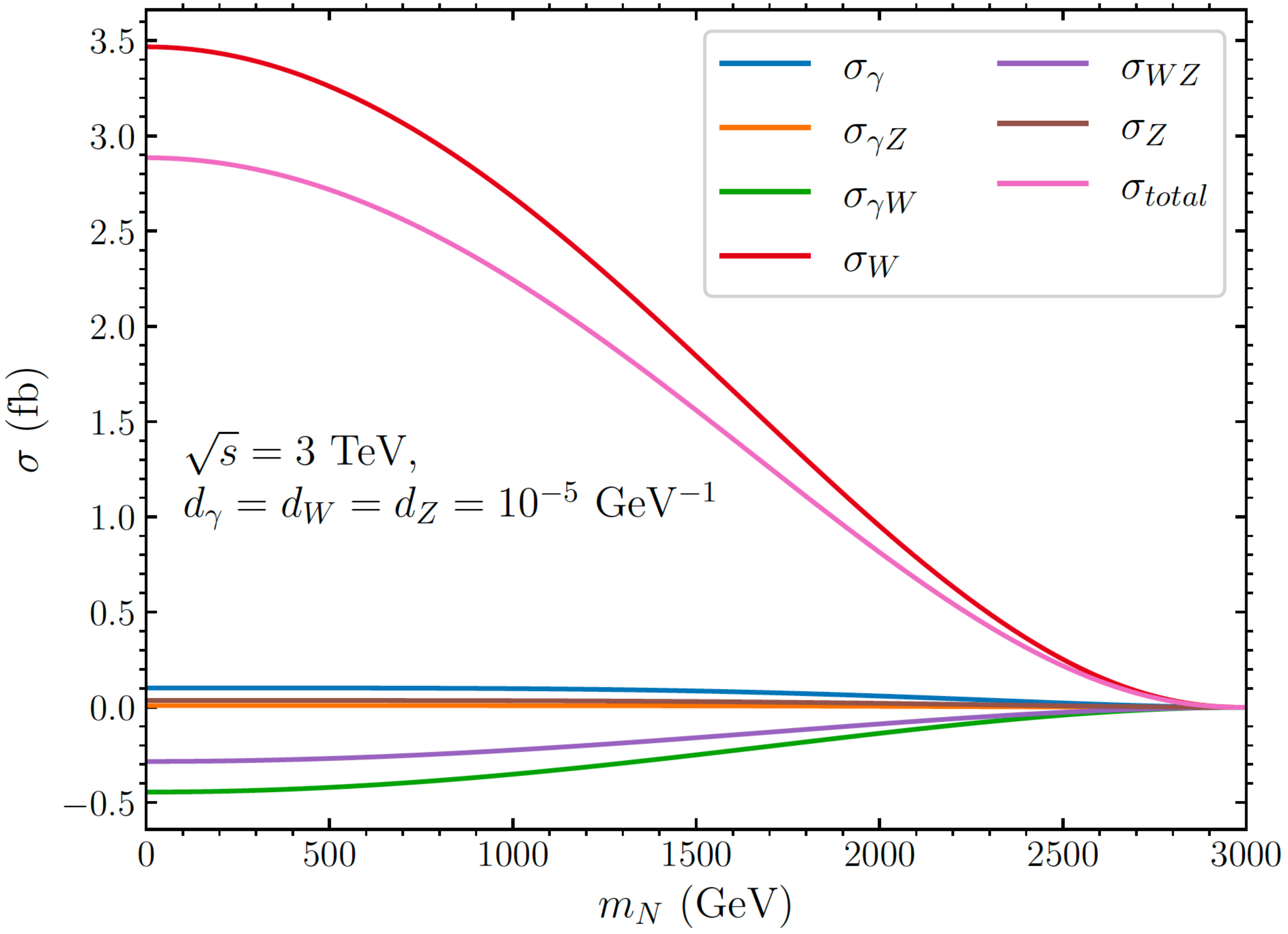

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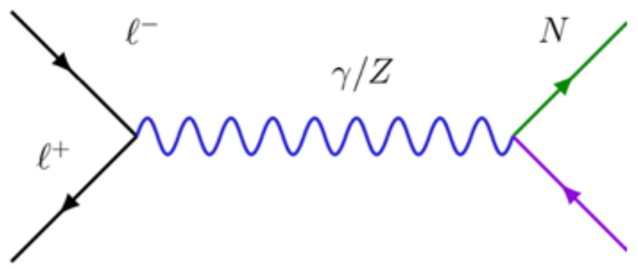
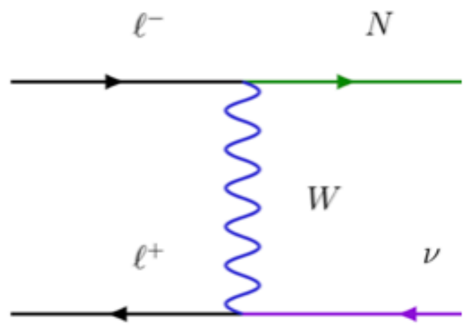
$\mathscr{M} =$  $+$ 

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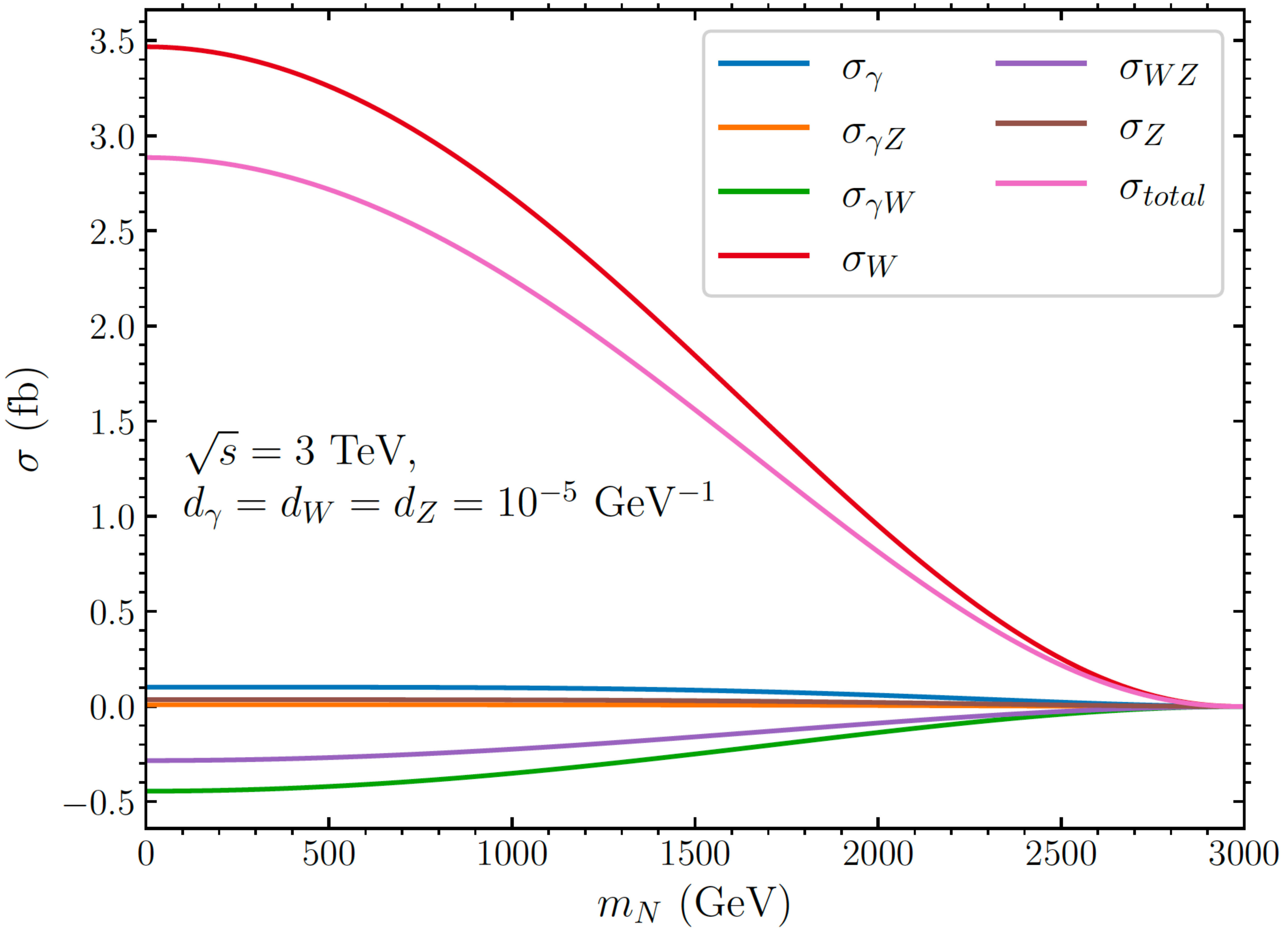

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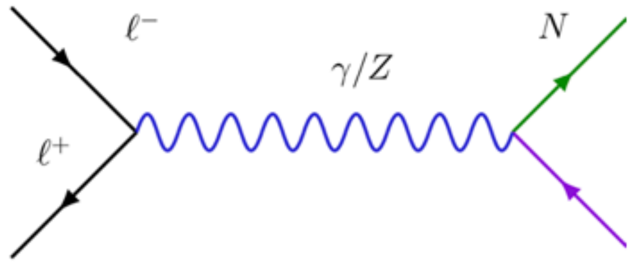
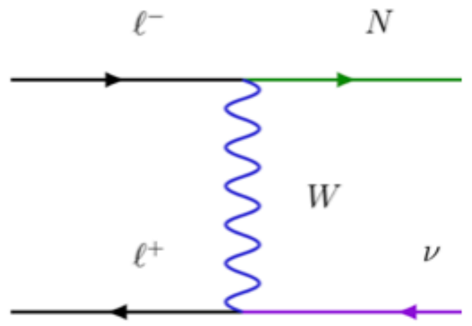
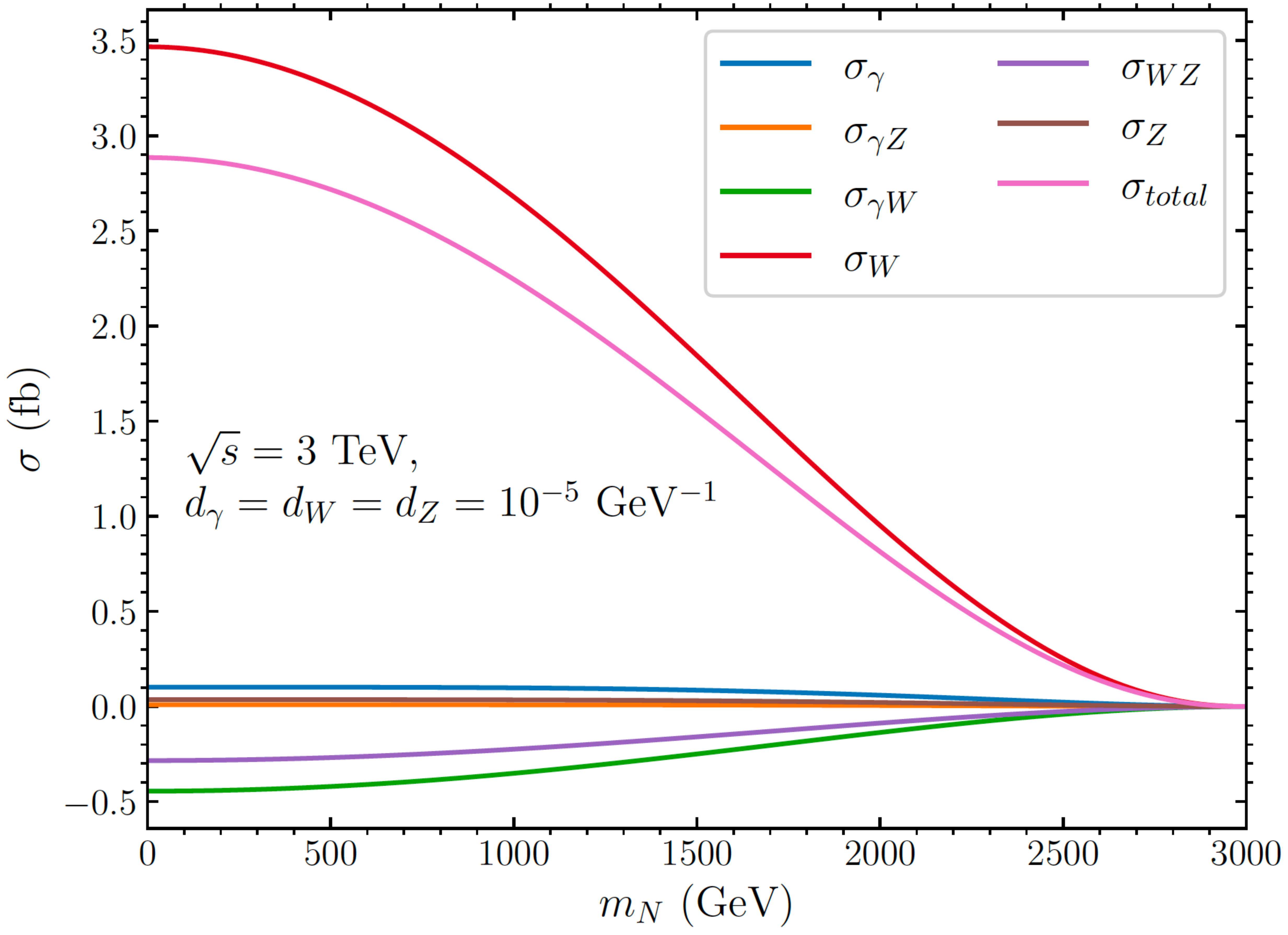
$\mathcal{M} =$ 

$+$ 

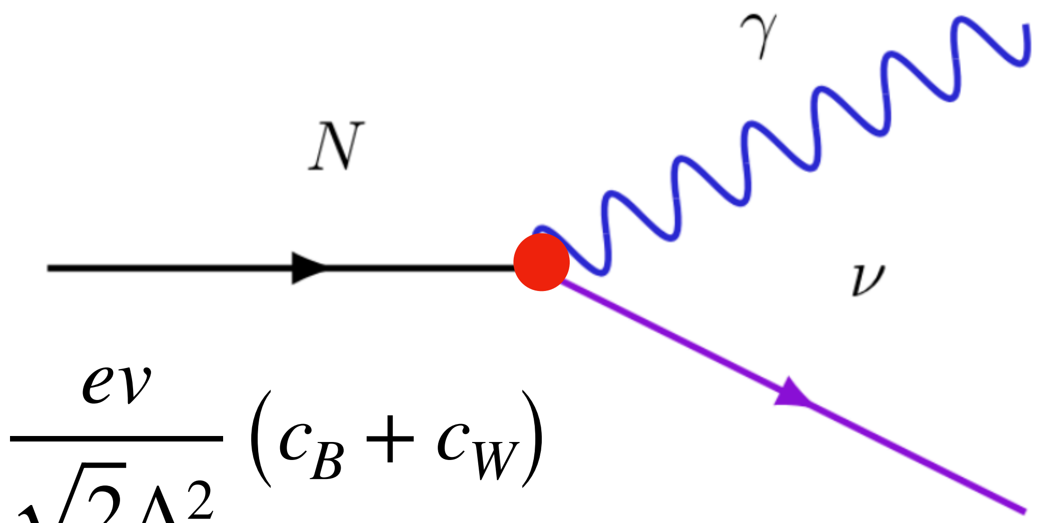
$$= \mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_W$$

$$\sigma_{tot} = \overbrace{\sigma_\gamma + \sigma_Z + \sigma_W}^{\text{squared terms}} + \underbrace{\sigma_{\gamma Z} + \boxed{\sigma_{\gamma W} + \sigma_{WZ}}}_{\text{interference terms}}$$

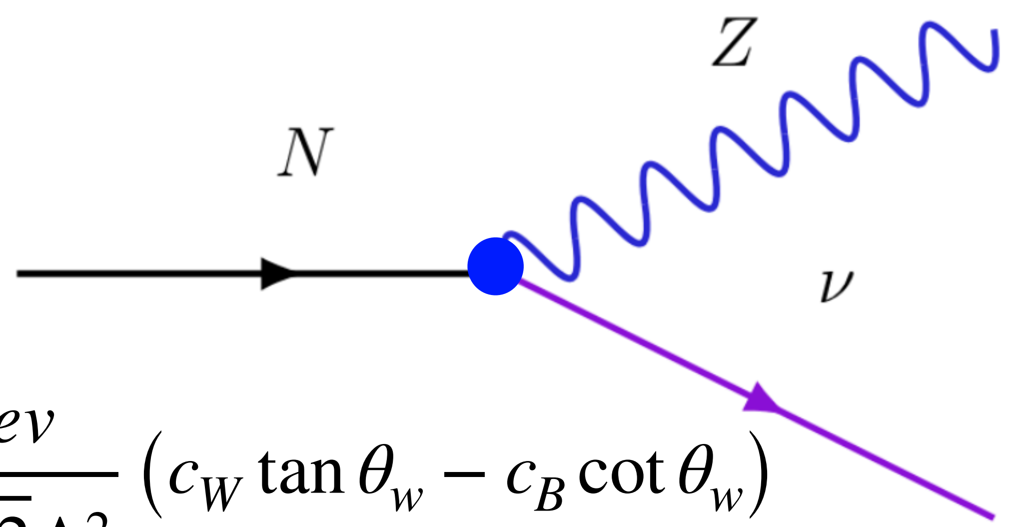
We found them to be non-vanishing in contrast to a previous study (arXiv:2301.06050)



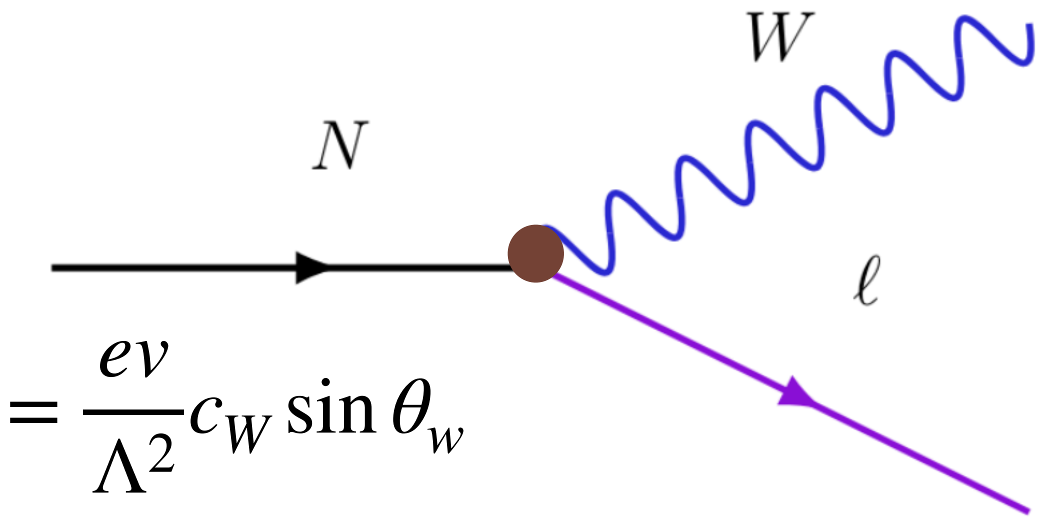
Dipole couplings and decay widths



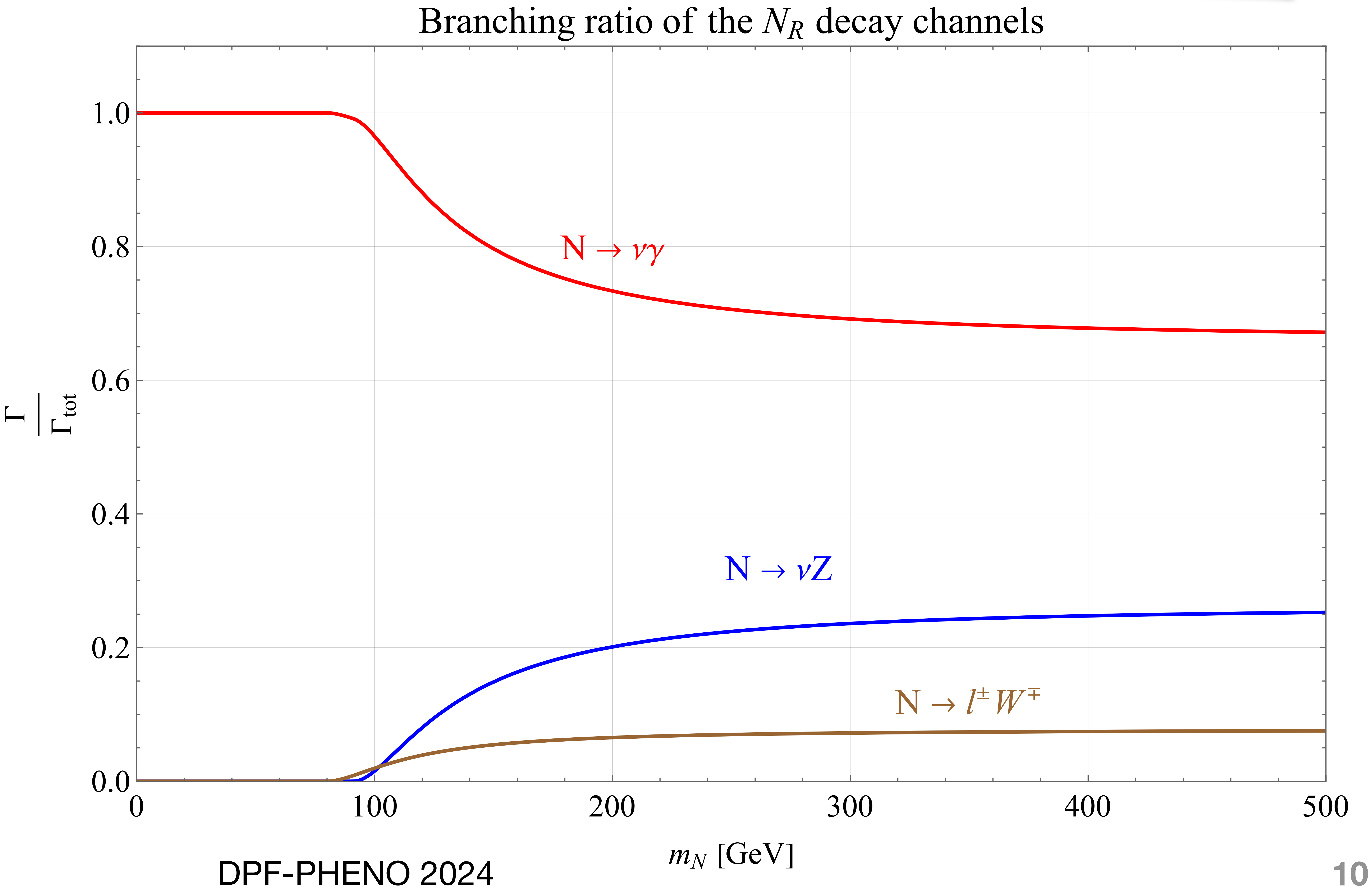
$$d_\gamma = \frac{ev}{\sqrt{2}\Lambda^2}\left(c_B + c_W\right)$$



$$d_Z = \frac{ev}{\sqrt{2}\Lambda^2}\left(c_W \tan\theta_w - c_B \cot\theta_w\right)$$



$$d_W = \frac{ev}{\Lambda^2} c_W \sin\theta_w$$



Analysis

- Goal is to probe $d_\gamma \propto (c_B + c_W)$

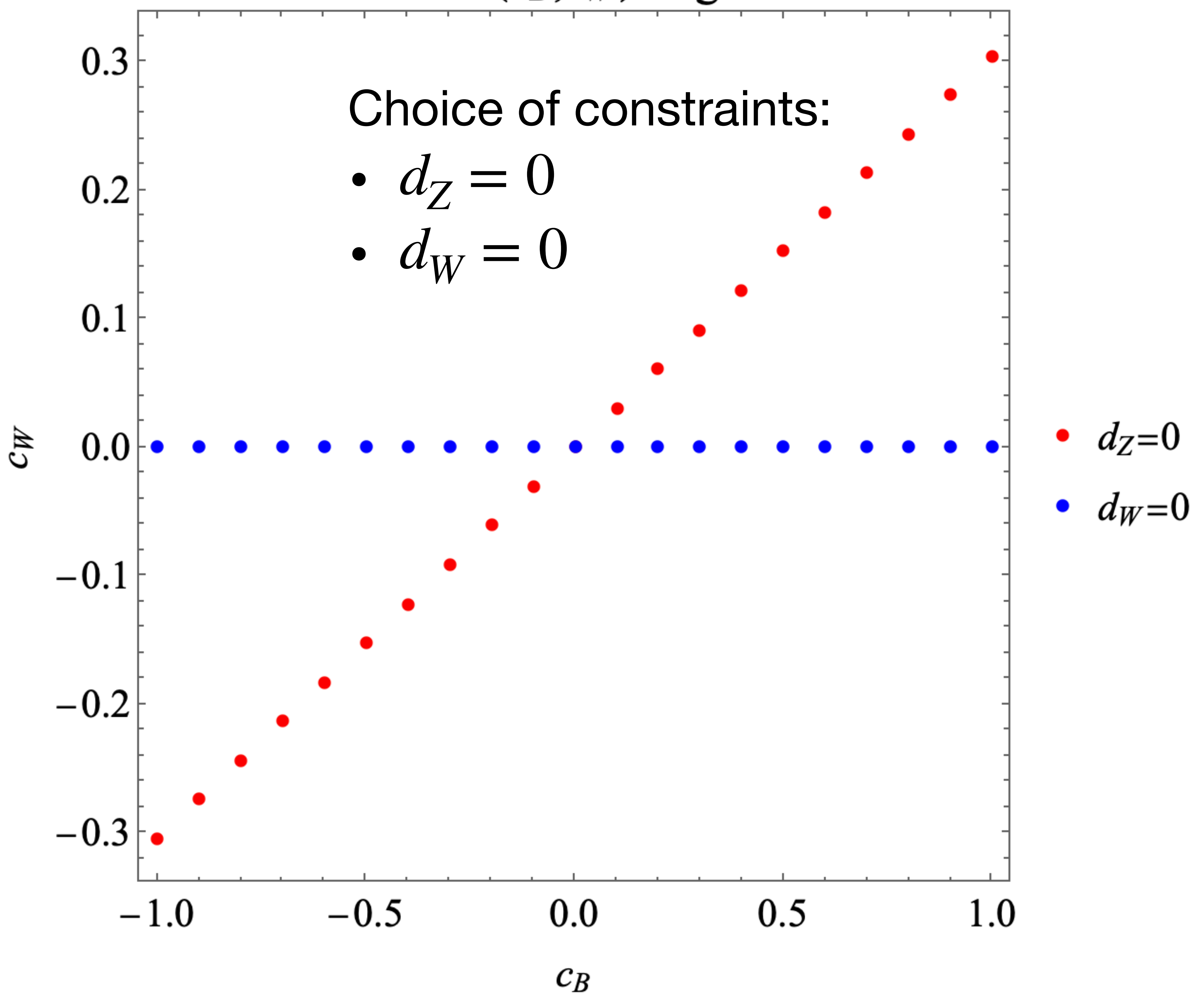
- Note that (d_γ, d_Z, d_W) are correlated, we can impose *constraints* on them to evaluate exclusion limit on d_γ

- We generate Monte Carlo events scanning (c_B, c_W) parameter space

$2 \to 3$

$(c_B, c_W) \to (d_\gamma, d_Z, d_W)$

Parameter Points (c_B, c_W) to generate events



Analysis

With choices of constraints (e.g. $d_W = 0, d_Z = 0$)…

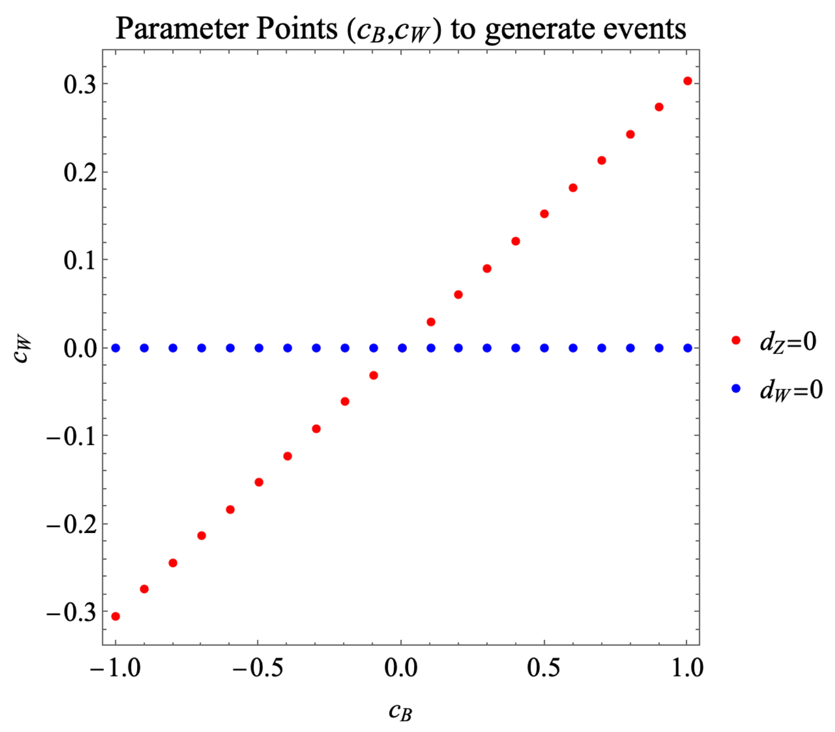
Generating MC events for monophoton signal scanning (c_B, c_W) parameter space

→

Applying conservative cuts on the events i.e. $N \rightarrow N_{cut}$

→

Implement $N_{cut}(c_B, c_W)$ and find optimal (d_γ, m_N)



Important cuts:

- photon: $p_{T,\gamma} > 20$ GeV, $|\eta_\gamma| < 2.5$
- Veto lepton
- Veto Z-resonance

Our results

With the constraint

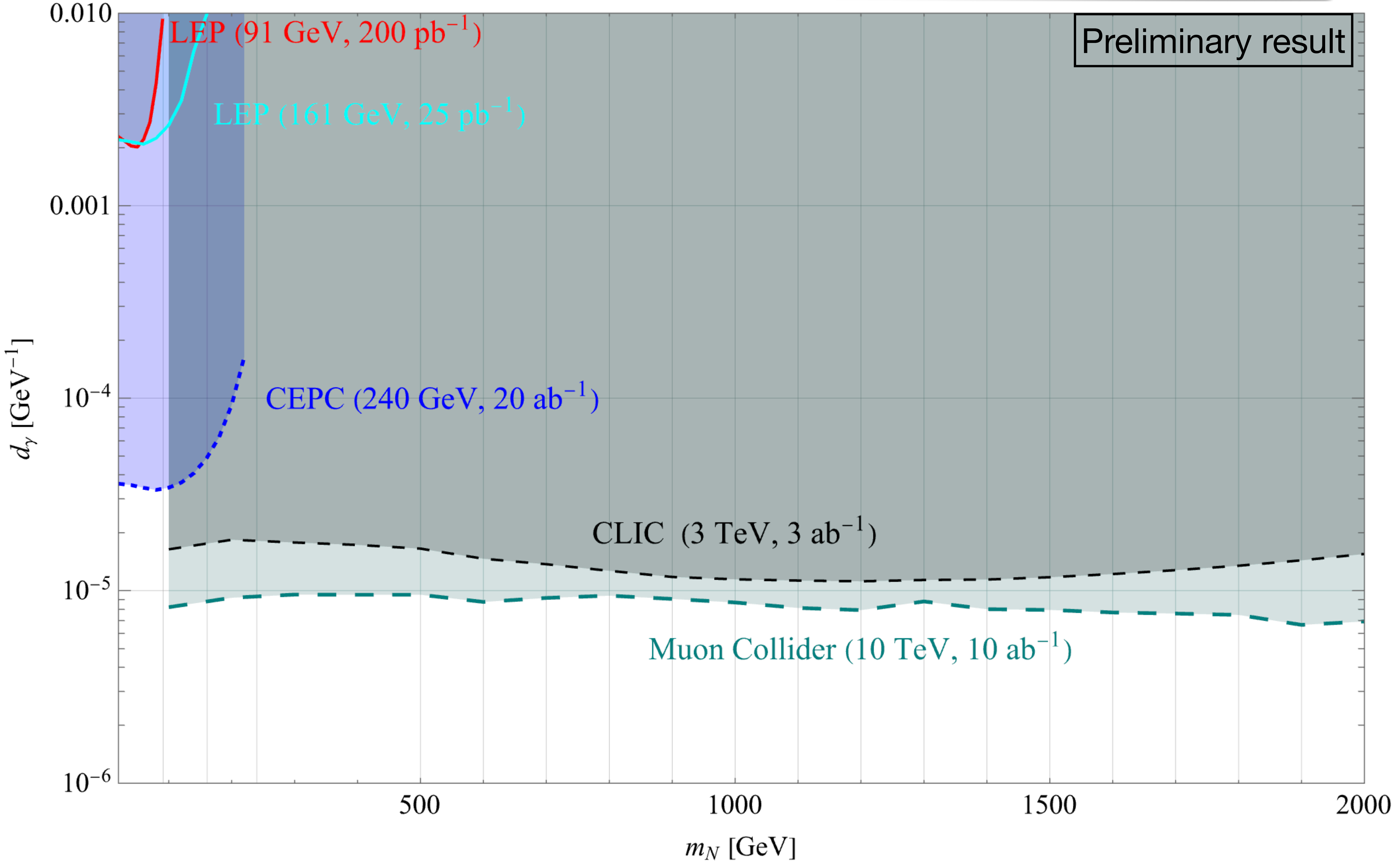
$d_Z = 0$,

high **energy** and

luminosity

increase the sensitivity to probe the parameters

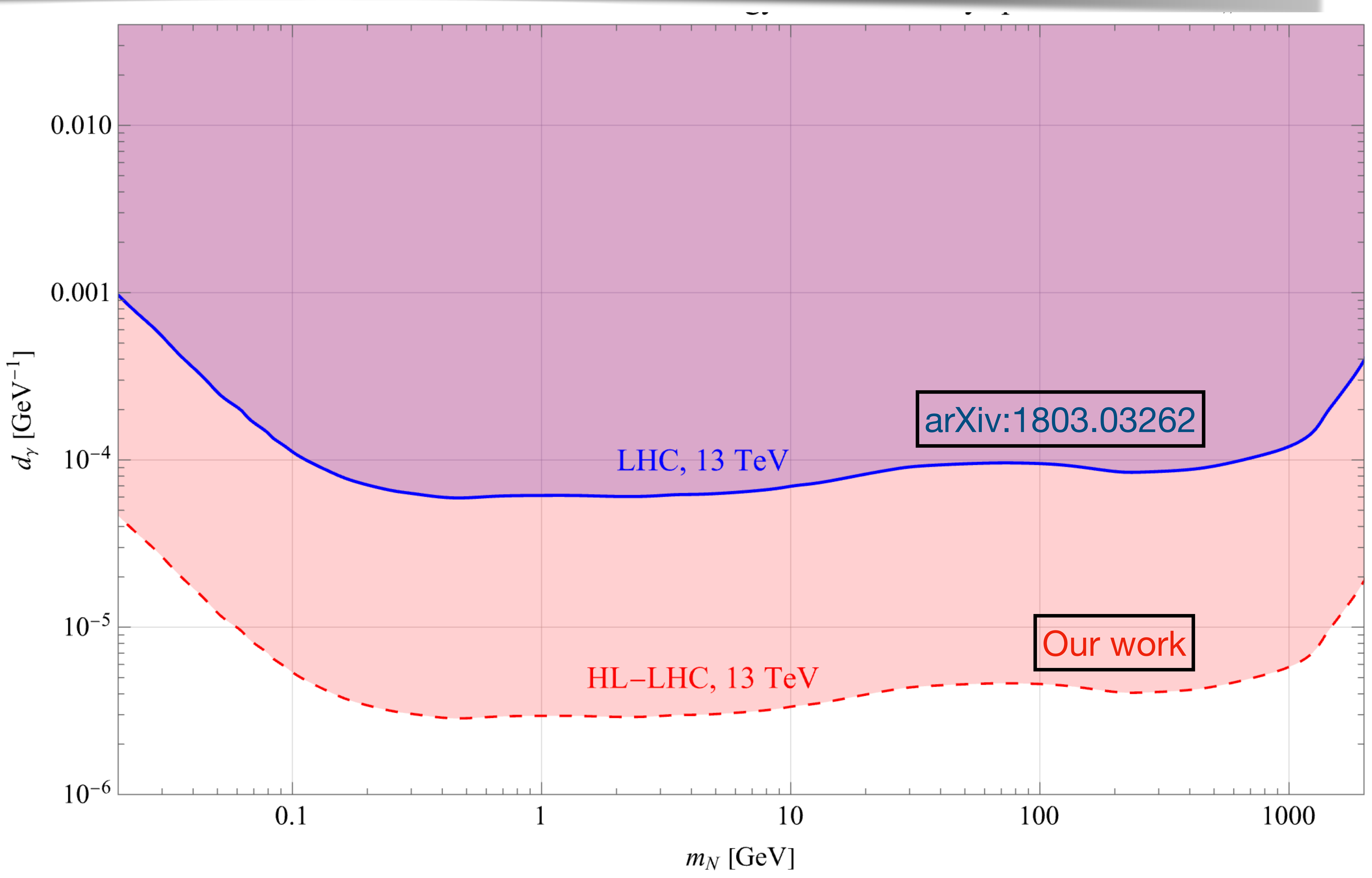
d_γ and m_N



Our results

- We can also explore the parameter space at the hadron collider

- With the constraint $d_W = 0$, high luminosity $(36.1\, fb^{-1} \to 3000\, fb^{-1})$ improves the sensitivity by an order of magnitude



Summary

- Calculated HNL production cross-section and decay widths analytically
- Evaluated sensitivity reach on d_γ (and m_N) obtained from mono-photon signal events
- Plan to extend our investigation to other unique signals of HNL
- With the projected sensitivity on d_γ and m_N, unconstrained region in the parameter space (d_γ, m_N) can be tested at the proposed future colliders

Backup…

Intensity and d_γ

Derivation

$$S(B) = \sigma_{S(B)} \mathscr{L} \epsilon, \quad \sigma_S \propto d_\gamma^2$$

$$\frac{S}{\sqrt{B}} = \text{const} \times d_\gamma^2 \mathscr{L}^{1/2}$$

$$\frac{S}{\sqrt{B}} = 2.71 \quad (95\,\%\ CL)$$

$$\therefore d_\gamma^{\ 2} \propto \mathscr{L}^{-1/2}$$

High intensity allows to

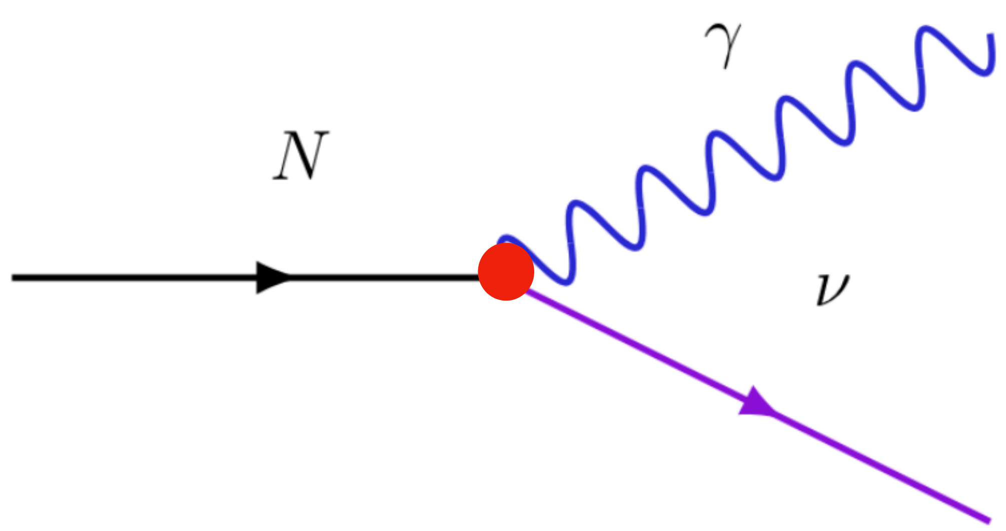
- access the "d_γ-well" deeper since limit for $d_\gamma \propto \mathscr{L}^{-1/4}$

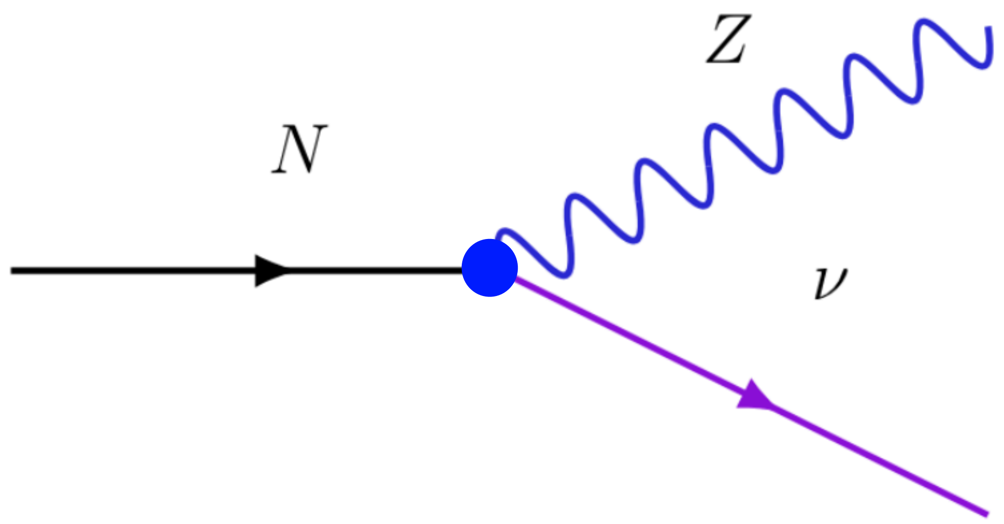
Analysis

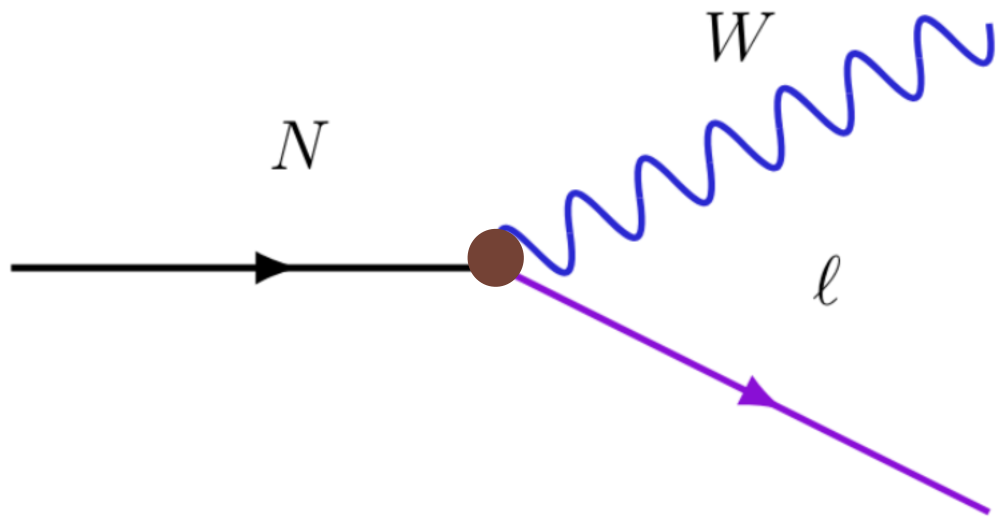
- Cuts applied on the future experiments:
  - # of photons = 1
  - # of leptons = 0
  - $E_\gamma \notin [E_{z\gamma} \pm 5]$ (removes on-shell $Z + \gamma$ background) $\left(E_{z\gamma} = \dfrac{s - m_Z^2}{2\sqrt{s}} \right)$
  - $E_\gamma > E_{\gamma,max}$ where $E_{\gamma,max} = \dfrac{\sqrt{s}}{1 + \sin\theta_\gamma / \sin\theta_b}$ is the maximum photon energy in individual event in SM

- Definition of visible particles:
  - Visible photon: $p_{T,\gamma} > 20$ GeV, $|\eta_\gamma| < 2.5$
  - Visible lepton: $p_{T,\ell} > 20$ GeV, $|\eta_\ell| < 2.5$

Dipole couplings and decay widths







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$$d_Z = \frac{ev}{\sqrt{2}\Lambda^2}\left(c_W \tan\theta_w - c_B \cot\theta_w\right)$$

$$d_W = \frac{ev}{\Lambda^2} c_W \sin\theta_w$$

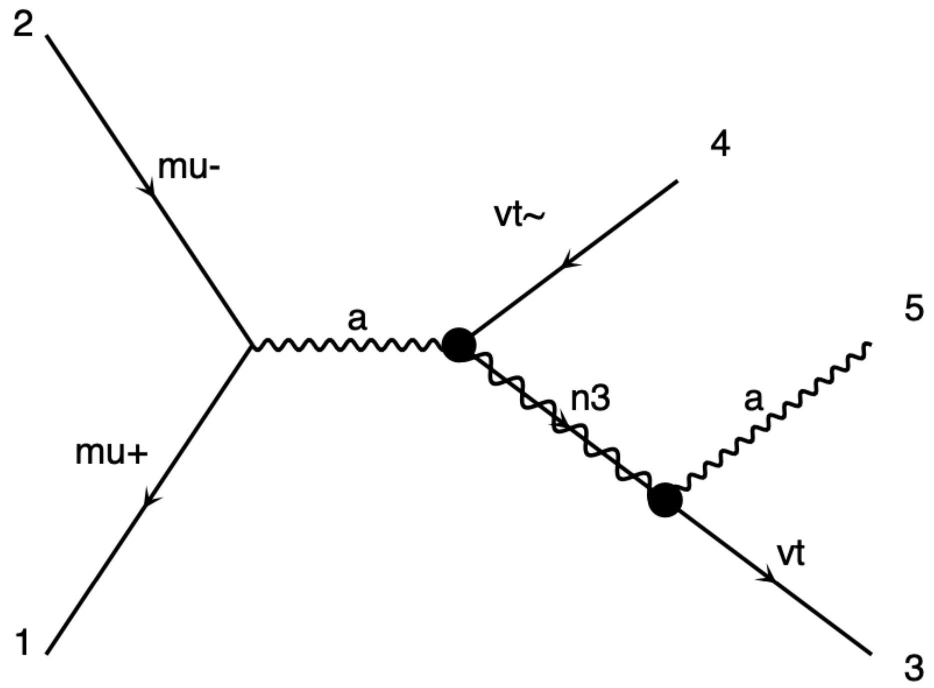
$$\Gamma_{N\to\nu\gamma} = \frac{d_\gamma^2 m_N^3}{2\pi}$$

$$\Gamma_{N\to\nu Z} = \frac{d_Z^2\left(m_N^2 - M_Z^2\right)\left(2m_N^2 + M_Z^2\right)}{4\pi m_N^3}$$

$$\Gamma_{N\to Wl} = \frac{d_W^2}{4\pi m_N^3}\sqrt{\left(\left(m_l - M_W\right)^2 - m_N^2\right)} \times \sqrt{\left(\left(m_l + M_W\right)^2 - m_N^2\right)} \times \left[2\left(m_l^2 - m_N^2\right)^2 - M_W^2\left(m_l^2 + m_N^2\right) - M_W^4\right]$$

Analytic results for the signal

Analytic expression for cross-section $\sigma(\mu^+\mu^- \to \nu N)$



$$
\begin{aligned}
\sigma_\gamma &= \frac{\alpha d_\gamma^2 \left(m^2 - s\right)^2 \left(2m^2 + s\right)}{3s^3} \\
\sigma_{\gamma Z} &= \frac{\alpha d_\gamma d_Z \left(c_w^2 - 3s_w^2\right)\left(m^2 - s\right)^2 \left(2m_N^2 + s\right)\left(s - M_Z^2\right)}{6 c_w s_w s^2 \left[\left(s - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2\right]} \\
\sigma_{\gamma W} &= \frac{\alpha d_\gamma d_W}{\sqrt{2} s_w s^2}\left[2W^2\left(-m^2 + s + W^2\right)\log\frac{-m_N^2 + s + M_W^2}{M_W^2}\right. \\
&\quad \left. - \left(m_N^2 - s\right)\left(m_N^2 - s - 2M_W^2\right)\right] \\
\sigma_W &= -\frac{\alpha d_W^2 \left(m_N^2 - s\right)}{2 s_w^2 s^2}\left[2\left(m_N^2 - s\right) - \left(m_N^2 - s - 2M_W^2\right)\log\frac{-m_N^2 + s + M_W^2}{M_W^2}\right] \\
\sigma_{WZ} &= -\frac{\alpha d_W d_Z \left(c_w^2 - s_w^2\right)\left(s - M_Z^2\right)}{2\sqrt{2} c_w s_w^2 s \left[\left(s - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2\right]}\left[\left(m_N^2 - s\right)\left(m_N^2 - s - 2M_W^2\right)\right. \\
&\quad \left. - 2M_W^2\left(-m_N^2 + s + M_W^2\right)\log\frac{-m_N^2 + s + M_W^2}{M_W^2}\right] \\
\sigma_Z &= \frac{\alpha d_Z^2 \left(c_w^4 - 2c_w^2 s_w^2 + 5s_w^4\right)\left(m_N^2 - s\right)^2\left(2m_N^2 + s\right)\left(s - M_Z^2\right)}{24 c_w^2 s_w^2 s \left[\left(s - M_Z^2\right)^2 + \Gamma_Z^2 M_Z^2\right]}
\end{aligned}
$$