Probing the Dirac-Majorana nature of neutrinos

based on arXiv: 25xx.xxxxx (in prep.)

in collaboration with
Bhupal Dev, Raj Gandhi, André de Gouvêa, and Kevin Kelly

Takuya Okawa (SISSA)

Dirac neutrino vs Majorana neutrino

The question of whether neutrinos are Dirac or Majorana remains open

- Dirac neutrino: $\nu \neq \bar{\nu}$
- Majorana neutrino: $\nu = \bar{\nu}$

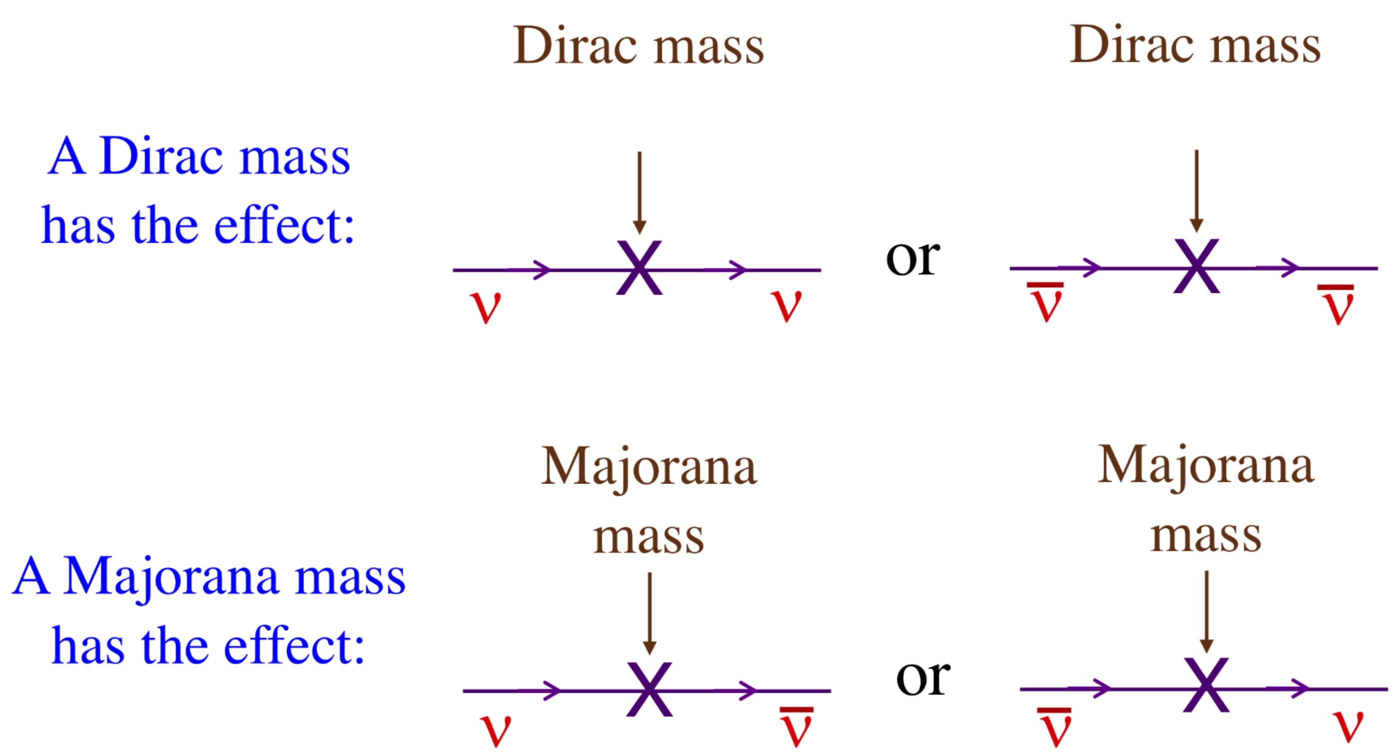


image credit: Balantekin & Kayser, 1805.00922

Main reasons:

- Relevant processes are extremely rare
- Nearly all accessible neutrinos are ultra-relativistic
- Observable differences are small

Dirac vs Majorana: rare relevant processes

Relevant processes are extremely rare

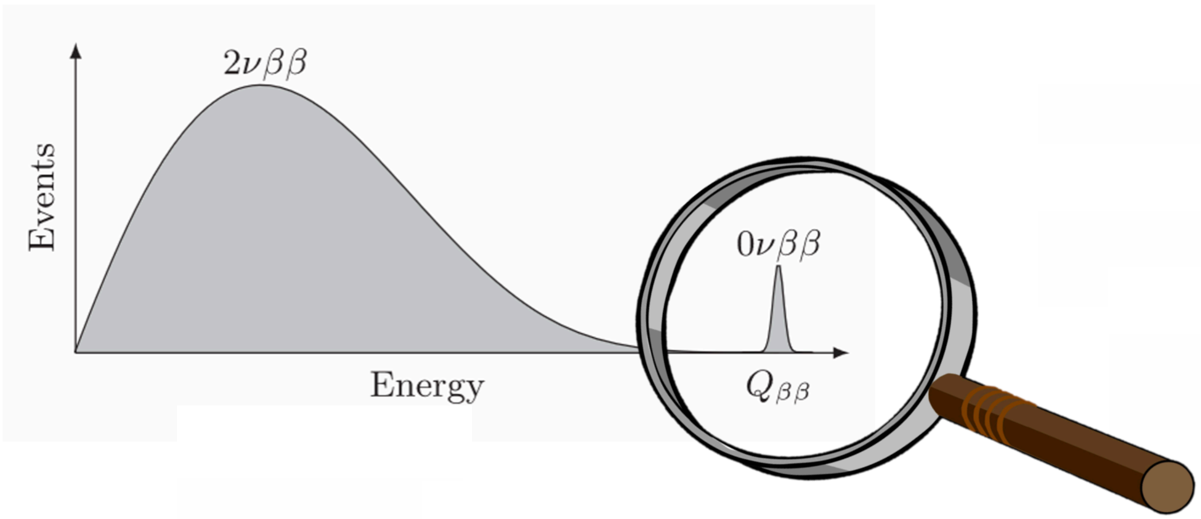
The $0\nu\beta\beta$-decay half-life:

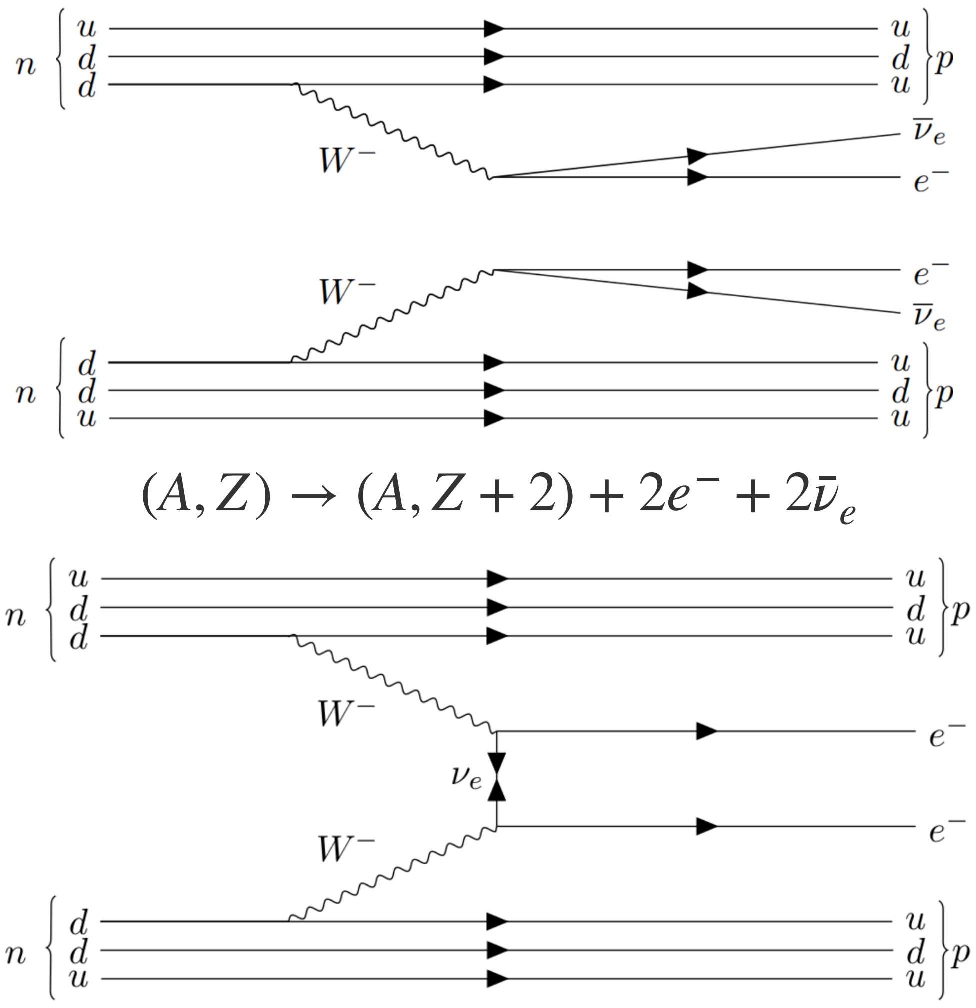
$$T_{1/2}^{0\nu} = \left(G|\mathcal{M}|^2\langle m_{\beta\beta}\rangle^2\right)^{-1} \simeq 10^{27-28}\left(\frac{0.01\ \mathrm{eV}}{\langle m_{\beta\beta}\rangle}\right)^2\ \mathrm{yr}$$

Haven't been observed → upper bound:

$$m_{\beta\beta} = |\sum_i U_{ei}^2 m_i| \lesssim 0.1\ \mathrm{eV}$$

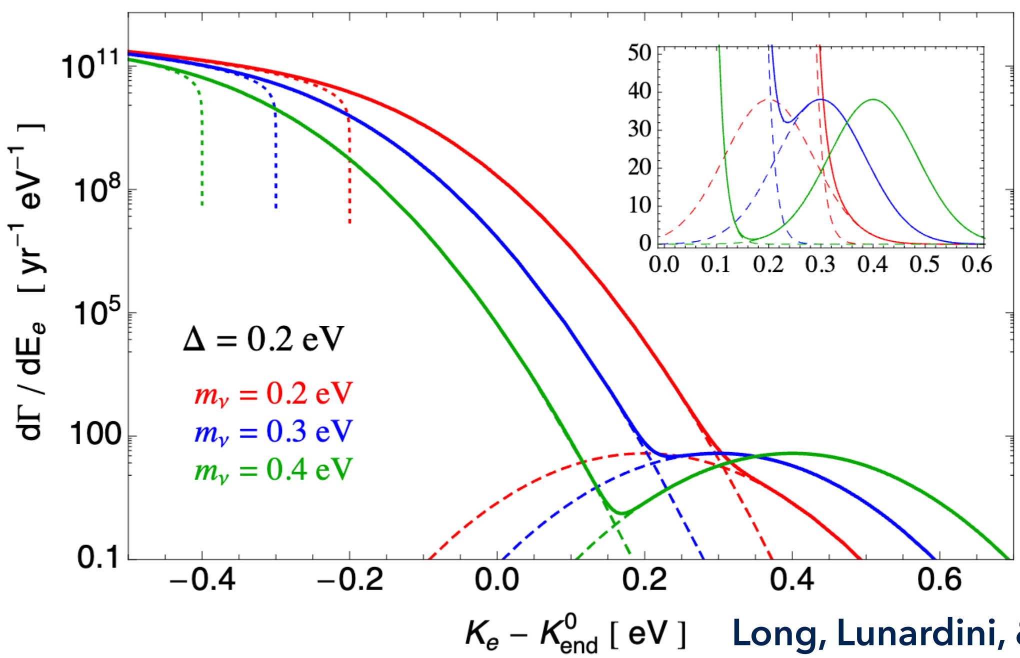
Dolinski, Poon, & Rodejohann 1902.04097





Dirac vs Majorana: rare relevant processes

Relevant processes are extremely rare

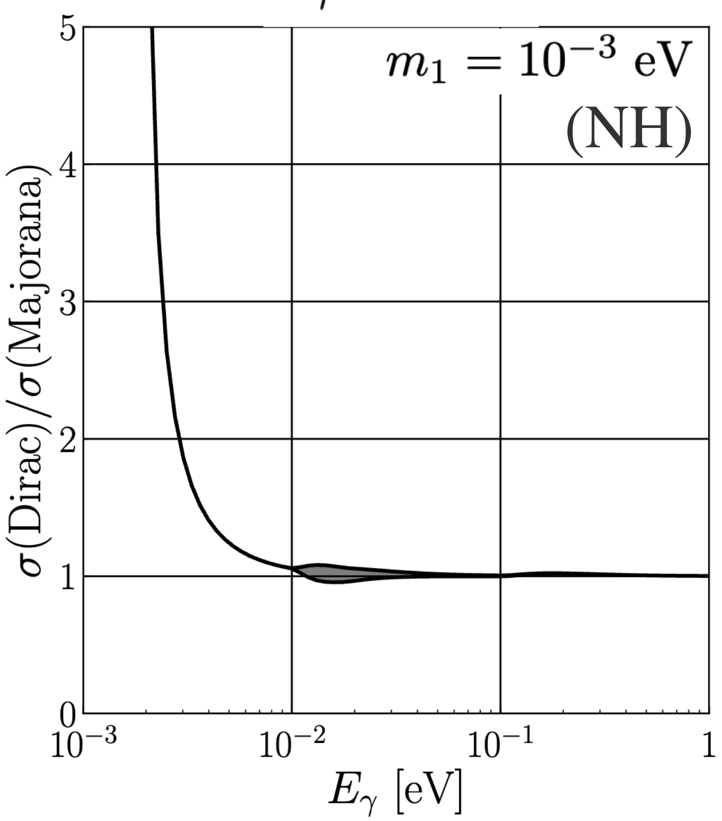


$\nu + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$

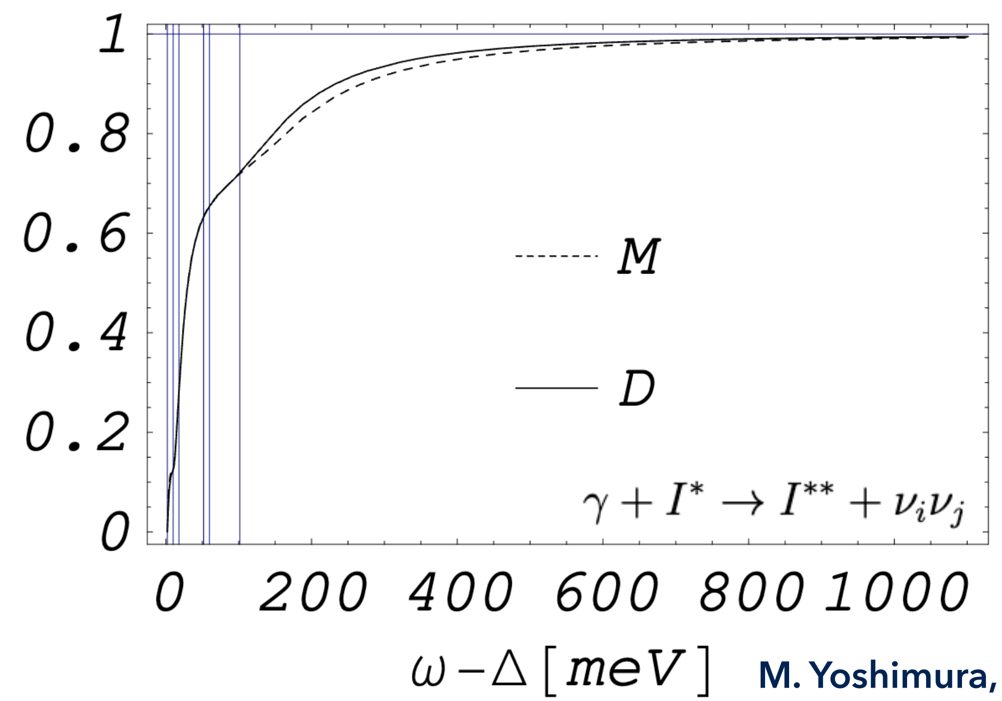
$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} = 2\,\Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}}$

Long, Lunardini, & Sabancilar, 1405.7654

$e\gamma \to e\nu\bar{\nu}$



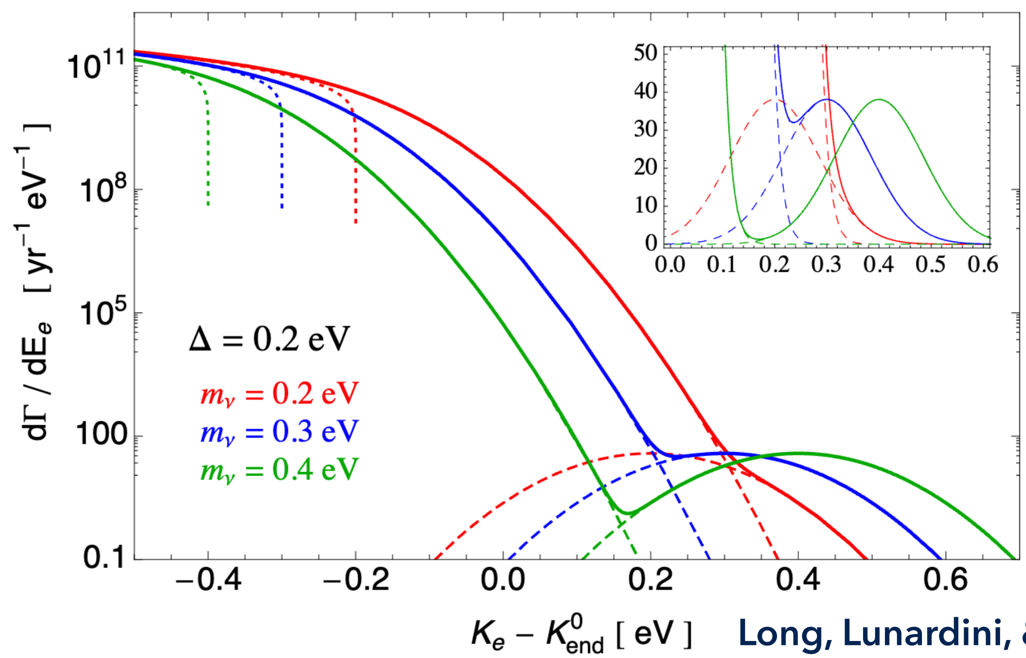
Berryman, de Gouvêa, Kelly, & Schmitt 1805.10294



M. Yoshimura, 0611362

Dirac vs Majorana: rare relevant processes

Relevant processes are extremely rare



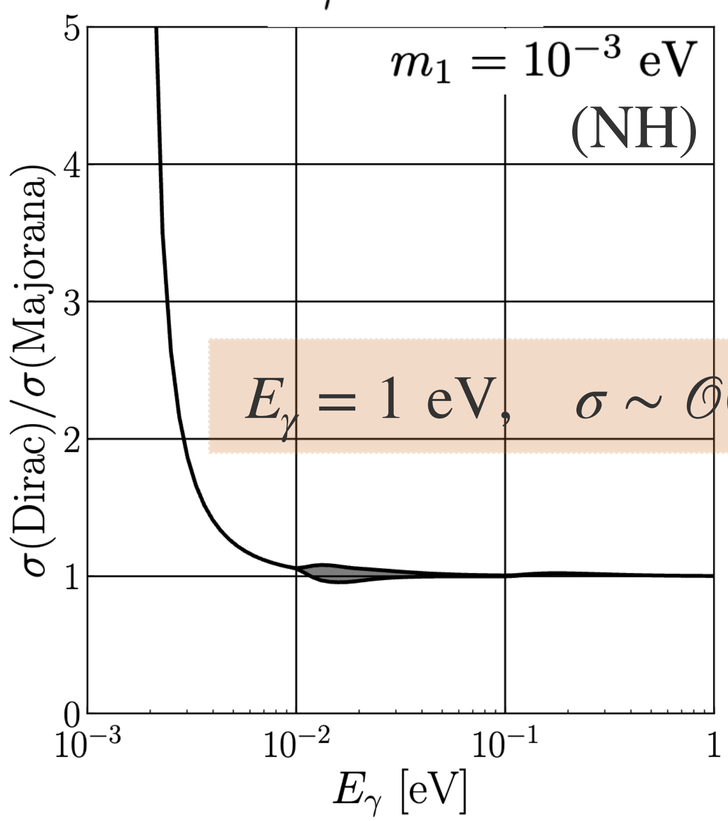
Long, Lunardini, & Sabancilar, 1405.7654

$$\Gamma^{D}_{C\nu B} \approx 4.06\ \mathrm{yr}^{-1}$$
$$\Gamma^{M}_{C\nu B} \approx 8.12\ \mathrm{yr}^{-1}$$
(100g target)

$$\nu + {}^3\mathrm{H} \to {}^3\mathrm{He} + e^-$$

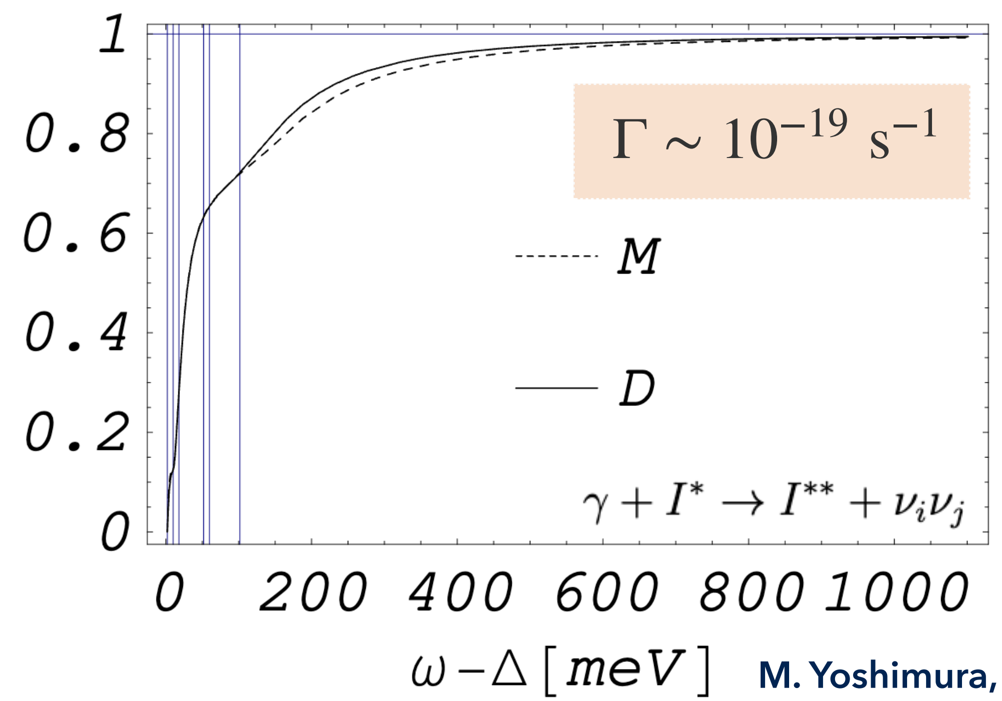
$$\Gamma^{M}_{C\nu B} = 2\,\Gamma^{D}_{C\nu B}$$

$$e\gamma \to e\nu\bar{\nu}$$



$E_\gamma = 1$ eV, $\sigma \sim \mathcal{O}(10^{-47})$ b

Berryman, de Gouvêa, Kelly, & Schmitt 1805.10294

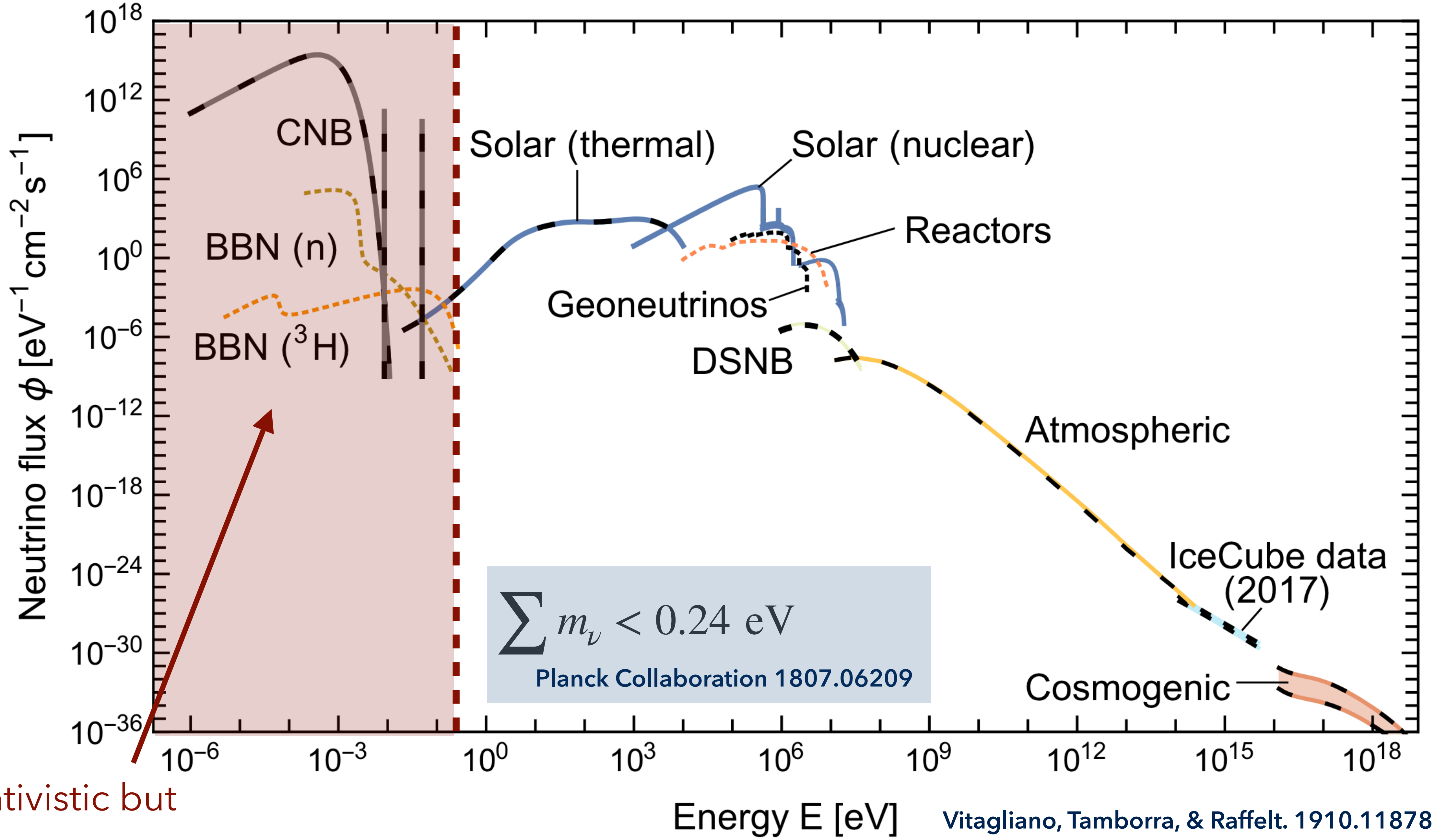


$\Gamma \sim 10^{-19}\ \mathrm{s}^{-1}$

M. Yoshimura, 0611362

Dirac vs Majorana: ultra-relativistic neutrinos

Nearly all accessible neutrinos are ultra-relativistic



not relativistic but haven't been detected

smaller cross section σ

Dirac vs Majorana: ultra-relativistic neutrinos

Nearly all accessible neutrinos are ultra-relativistic

→ helicity roles as the lepton number L, making L conserved in either case due to the structure of weak interaction

e.g.) $W^+ \to e^+ + \nu_e$, $\nu_e + N \xrightarrow{\text{CC}} e + X$ **see also: Balantekin & Kayser, 1805.00922**

$$\mathscr{L}_{cc} \supset -\frac{g}{\sqrt{2}}\bar{e}\gamma^\lambda \frac{1-\gamma_5}{2}\nu W_\lambda^-, -\frac{g}{\sqrt{2}}\bar{\nu}\gamma^\lambda \frac{1-\gamma_5}{2} e W_\lambda^+,$$

Recall that…

create an anti-fermion

$$\psi(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\vec{p}}}} \sum_s \left[a_{\vec{p},s}\, u(\vec{p},s)\, e^{-ip\cdot x} + b^\dagger_{\vec{p},s}\, v(\vec{p},s)\, e^{+ip\cdot x} \right]$$

annihilate a fermion

Dirac vs Majorana: ultra-relativistic neutrinos

Nearly all accessible neutrinos are ultra-relativistic

$\rightarrow$ helicity roles as the lepton number L, making L conserved in either case due to the structure of weak interaction

e.g.) $W^+ \rightarrow e^+ + \nu_e$, $\nu_e + N \xrightarrow{\text{CC}} e + X$ **see also: Balantekin & Kayser, 1805.00922**

Dirac	create: $e^-, \bar{\nu}_e$ absorb: e^+, ν_e	create: e^+, ν_e absorb: $e^-, \bar{\nu}_e$

$$\mathscr{L}_{cc} \supset -\frac{g}{\sqrt{2}} \boxed{\bar{e}} \gamma^\lambda \frac{1-\gamma_5}{2} \boxed{\nu} W_\lambda^-, \; -\frac{g}{\sqrt{2}} \boxed{\bar{\nu}} \gamma^\lambda \frac{1-\gamma_5}{2} \boxed{e} W_\lambda^+,$$

Majorana	create: $e^-, \nu_e, \bar{\nu}_e$ absorb: $e^+, \nu_e, \bar{\nu}_e$	create: $e^+, \nu_e, \bar{\nu}_e$ absorb: $e^-, \nu_e, \bar{\nu}_e$

Dirac: $W^+ \rightarrow e^+ + \nu_e$, $\nu_e + N \xrightarrow{\text{CC}} e^- + X$

Majorana: $W^+ \rightarrow e^+ + \nu_e$, $\nu_e + N \xrightarrow{\text{CC}} e^\pm + X$ (L may be violated)

Dirac vs Majorana: ultra-relativistic neutrinos

Nearly all accessible neutrinos are ultra-relativistic

→ helicity roles as the lepton number L, making L conserved in either case due to the structure of weak interaction

e.g.) $W^+ \to e^+ + \nu_e,\ \nu_e + N \xrightarrow{\text{CC}} e + X$ **see also: Balantekin & Kayser, 1805.00922**

Dirac

create: $e^-, \bar{\nu}_e$ create: e^+, ν_e

absorb: e^+, ν_e absorb: $e^-, \bar{\nu}_e$

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Majorana

create: $e^-, \nu_e, \bar{\nu}_e$ create: $e^+, \nu_e, \bar{\nu}_e$

absorb: $e^+, \nu_e, \bar{\nu}_e$ absorb: $e^-, \nu_e, \bar{\nu}_e$

Dirac: $W^+ \to e^+ + \nu_e,\ \nu_e + N \xrightarrow{\text{CC}} e^- + X$

Majorana: $W^+ \to e^+ + \nu_e,\ \nu_e + N \xrightarrow{\text{CC}} e^\pm + X$

if ν_e is ultra-relativistic,

e^- is predominantly produced

→ no difference between Dirac and Majorana

Dirac vs Majorana: small observable differences

Observable differences are small

Difference between $|\mathscr{M}|^2$ is suppressed by a neutrino mass (in the SM processes)

$$|\mathscr{M}^D|^2 - |\mathscr{M}^M|^2 \propto m_\nu^2$$

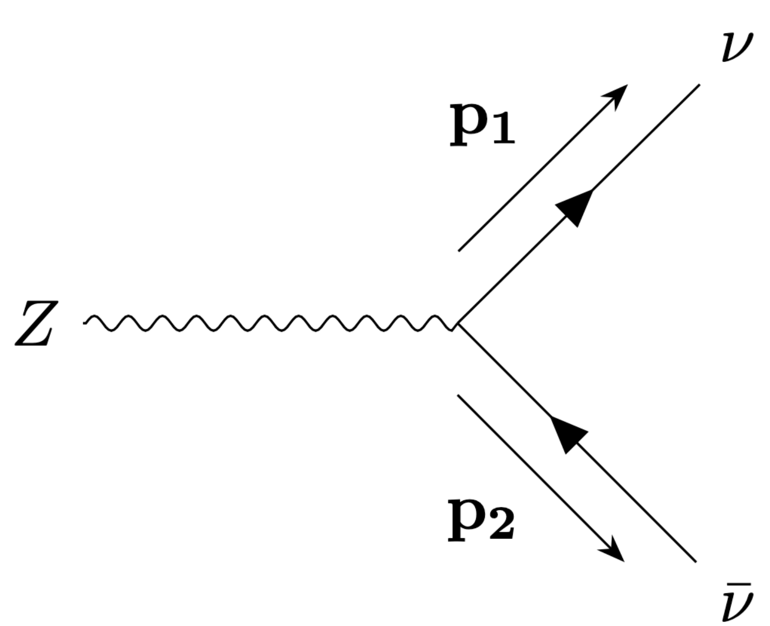
e.g.) $Z \to \nu\bar{\nu}$ R. E. Shrock, eConf C8206282

$$\mathscr{L} \supset \frac{g_Z}{2}\bar{\nu}_i Z^\mu \gamma_\mu P_L \nu_i$$

$$\mathscr{M}^D = -\frac{ig_Z}{2}\varepsilon_\alpha(p)\bar{u}(p_1)\gamma^\alpha \frac{1-\gamma^5}{2} v(p_2) \equiv \mathscr{M}(p_1, p_2)$$

$$\mathscr{M}^M = \frac{1}{\sqrt{2}}\left(\mathscr{M}(p_1,p_2) - \mathscr{M}(p_2,p_1)\right)$$

$$\to \left|\mathscr{M}^D\right|^2 - \left|\mathscr{M}^M\right|^2 \propto m_\nu^2$$



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$$\to \left|\mathscr{M}^D\right|^2 - \left|\mathscr{M}^M\right|^2 = \frac{g_Z^2 m_\nu^2}{2}$$

Confirmed in many processes:

- $Z \to \nu\bar{\nu}$ Shrock, eConf C8206282
- $\gamma^\star \to \nu\bar{\nu}$ Kayser, PRD 26 (1982) 1662
- $e^+e^- \to \nu\bar{\nu}$ Ma & Pantaleone, PRD 40 (1989) 2172
- $K^+ \to \pi^+\nu\bar{\nu}$ Nieves & Pal, PRD 32 (1985) 1849
- $e^+e^- \to \nu\bar{\nu}\gamma$ Chhabra & Babu, PRD 46 (1992) 903
- $e^-\gamma \to e^-\nu\bar{\nu}$ Berryman, de Gouvêa, Kelly, & Schmitt 1805.10294
- $B^0 \to \mu^+\mu^-\nu_\mu\bar{\nu}_\mu$ (?)

$\ldots$ C. S. Kim, 2307.05654
Akhmedov & Trautner, 2402.05172
Bigaran, Parke, & Pasquini. 2507.07180

Heavy neutral lepton decay

Heavy neutral lepton N offers higher chance to distinguish Dirac from Majorana

- Relevant processes are extremely rare   **see, e.g., Kayser 1805.07523, Balantekin, A. de Gouvêa, and Kayser 1808.10518**
- Nearly all accessible neutrinos are ultra-relativistic
- Observable differences are small

Angular distribution of decay products might shed light on the nature of neutrinos

e.g.) $N_1 \to N_2 + \gamma$

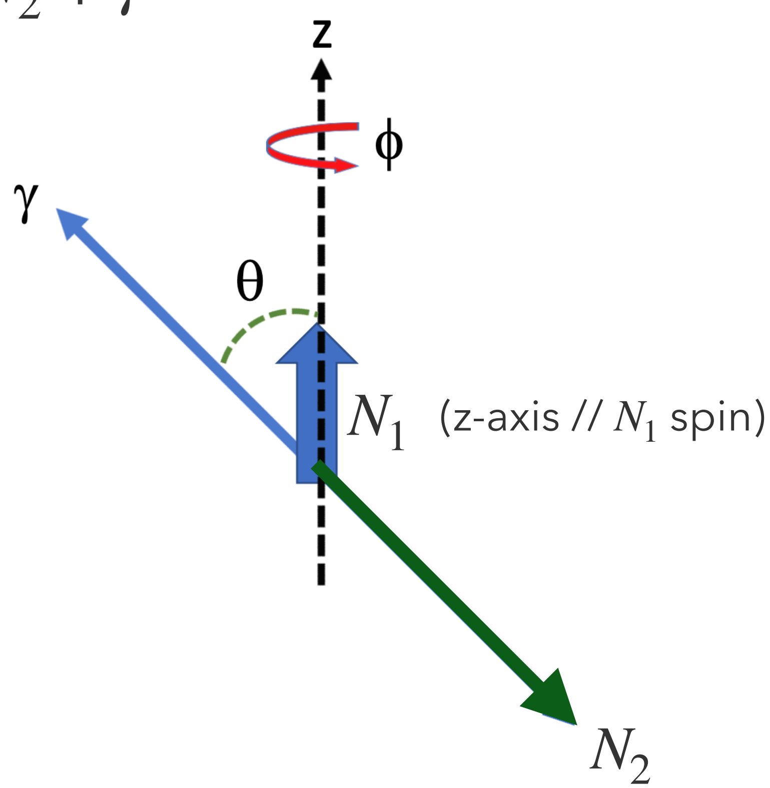


figure: A. B. Balantekin & B. Kayser, 1805.00922

Majorana N_1 and N_2 → must be isotropic

(in the rest frame of N_1)

Dirac N_1 and N_2 → may be anisotropic

Angular distribution of decay products

Consider the decay process $N_1 \to N_2 + X$ (X: self-conjugate $\bar{X} = X$)

$$\frac{d\Gamma(N_1 \to N_2 + X)}{d(\cos\theta)} = \frac{\Gamma}{2}(1 + \alpha\cos\theta)$$

$$\frac{d\Gamma(\bar{N}_1 \to \bar{N}_2 + X)}{d(\cos\theta)} = \frac{\bar{\Gamma}}{2}(1 + \bar{\alpha}\cos\theta)$$

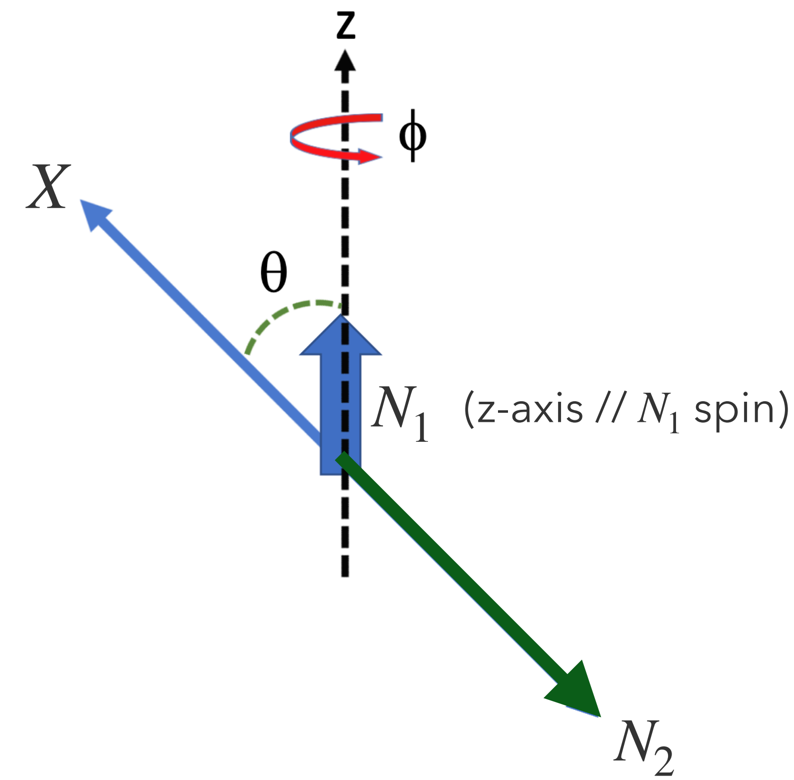


figure: A. B. Balantekin & B. Kayser, 1805.00922

If neutrinos are Majorana, CPT invariance requires

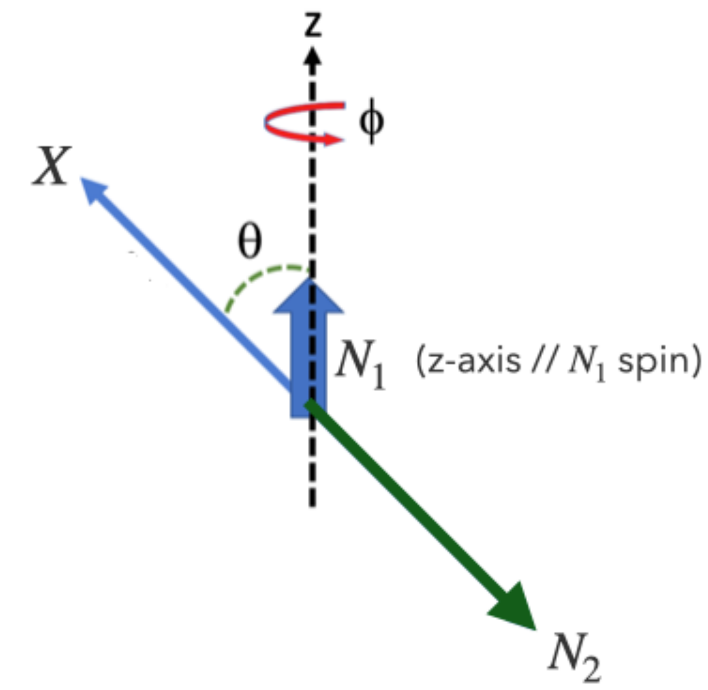
$$\Gamma = \bar{\Gamma},\ \alpha = -\bar{\alpha}$$

in the lowest order of perturbations

$\to \alpha = 0$ for Majorana neutrino

(for Dirac, $\alpha \in [-1,1]$)

Angular distribution of decay products



Two types of scenarios studied

1. $N \to \nu_i + X$

$$\frac{d\Gamma(N \to \nu + X)}{d(\cos\theta)} = \frac{\Gamma_0}{2}(1 + \alpha\cos\theta)$$

X	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im m(\mu d^*)}{\lvert\mu\rvert^2+\lvert d\rvert^2}$	1	$\frac{m_N^2-2m_\rho^2}{m_N^2+2m_\rho^2}$	$\frac{m_N^2-2m_Z^2}{m_N^2+2m_Z^2}$	1

(for Majorana, $\alpha = 0$)

B. Kayser 1805.07523

2. $N \to \nu_i + X,\ X = l_\alpha^- + l_\beta^+ \quad (\alpha \neq \beta)$ A. de Gouvêa et al., 2104.05719

   The flat spectrum will be observed if a detector is charge-blind

$$\frac{d\Gamma}{d\cos\theta} \equiv \frac{d\Gamma(N \to \nu X)}{d\cos\theta} + \frac{d\Gamma(N \to \nu \bar{X})}{d\cos\theta}$$ doesn't depend on $\cos\theta$

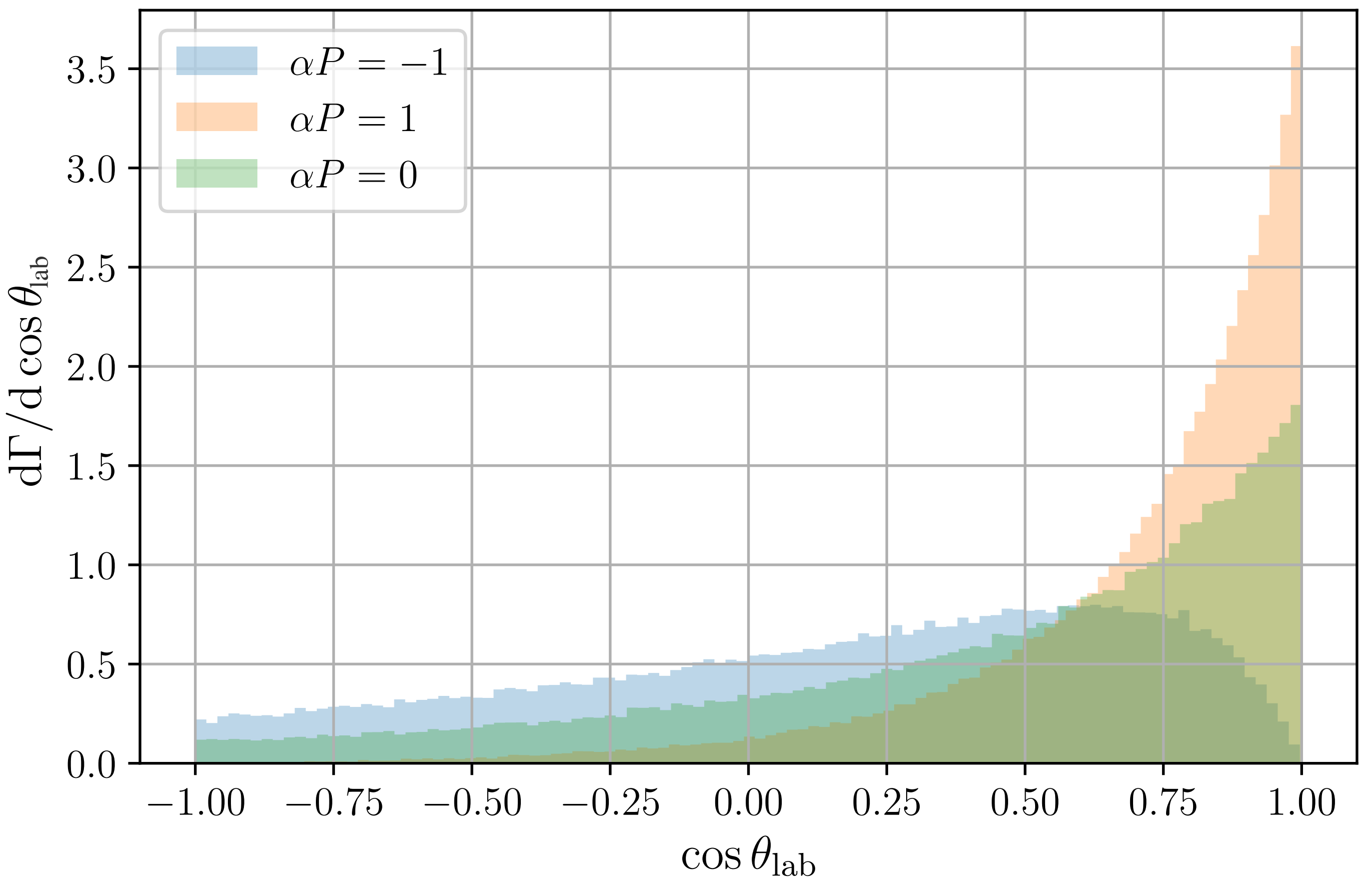
Angular distribution of decay products

Lab frame angular distribution depends on…

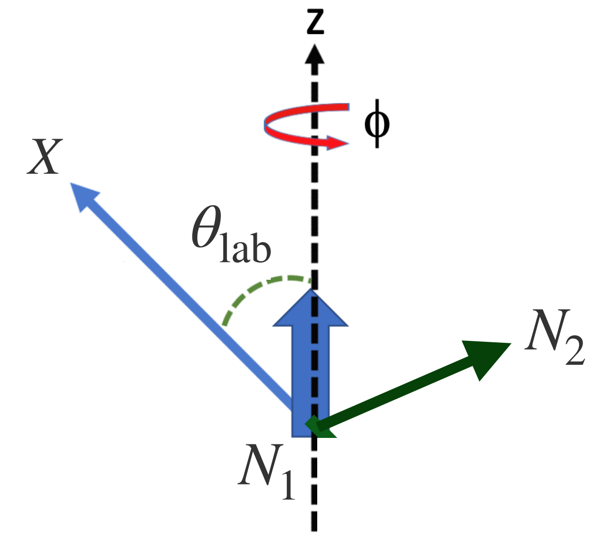
- α: decay asymmetry parameter
- P: polarization of the N sample; $P = (N_+ - N_-)/(N_+ + N_-) \in [-1,1]$

  $N_+(N_-)$: number of parent particles whose spins align(oppositely align) with momenta

Angular distribution of X in the boosted frame ($\gamma = 1.2$)



$$\frac{d\Gamma(N \to \nu + X)}{d(\cos\theta)} = \frac{\Gamma_0}{2}(1 + \alpha\cos\theta)$$

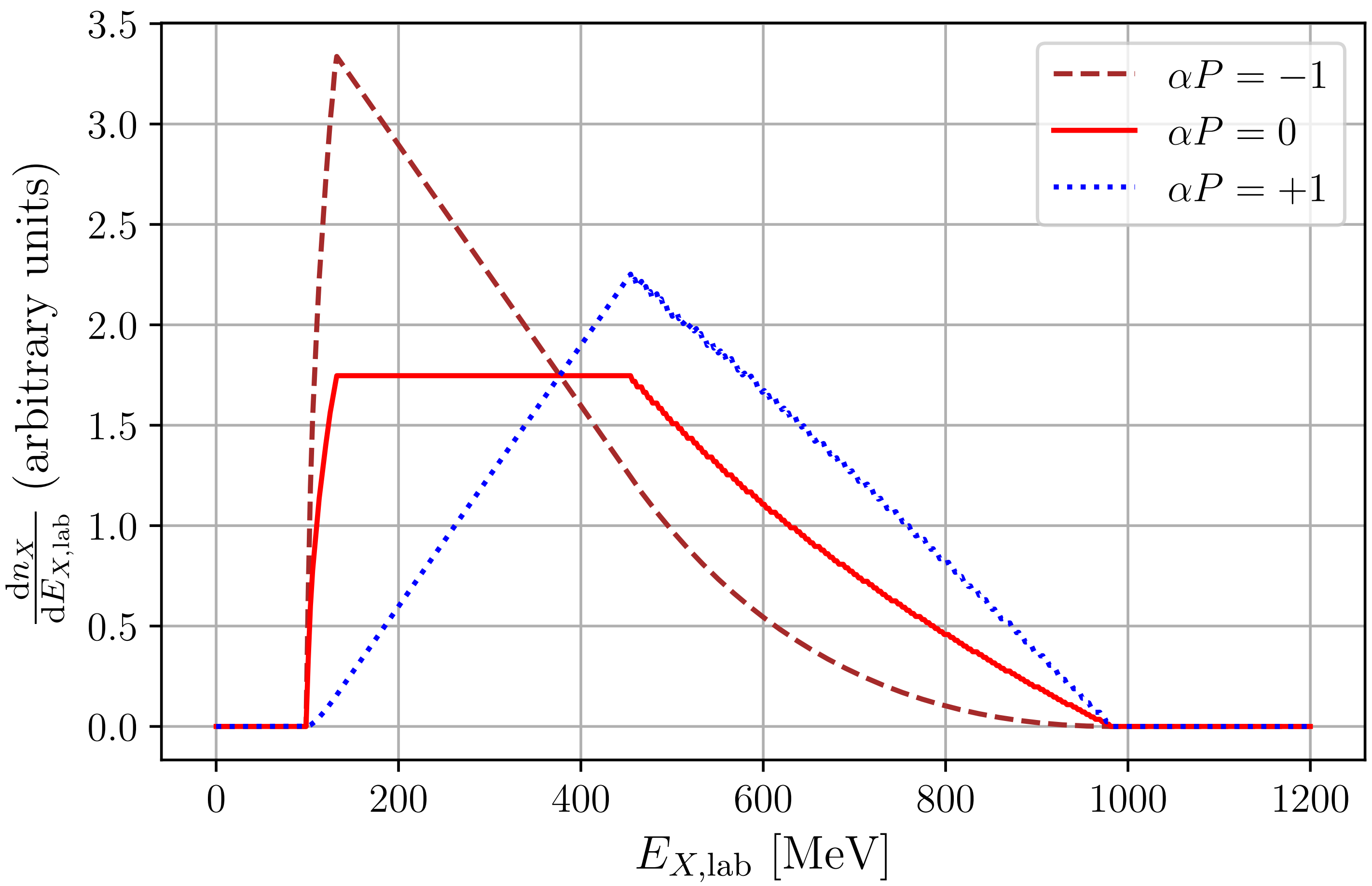


Energy distribution of decay products

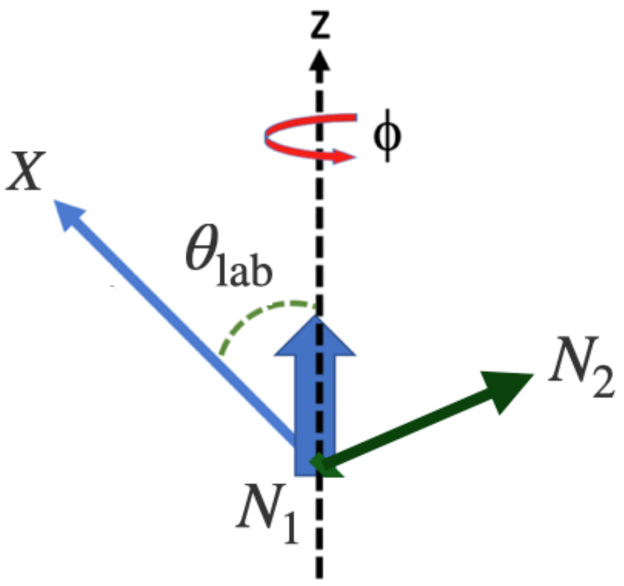
Energy distribution of decay products in the lab frame might also be helpful

Lab frame energy distribution also depends on…

- α: decay asymmetry parameter
- P: polarization of the N sample; $P = \dfrac{N_+ - N_-}{N_+ + N_-}$



credit: Balantekin, A. de Gouvêa, and Kayser 1808.10518

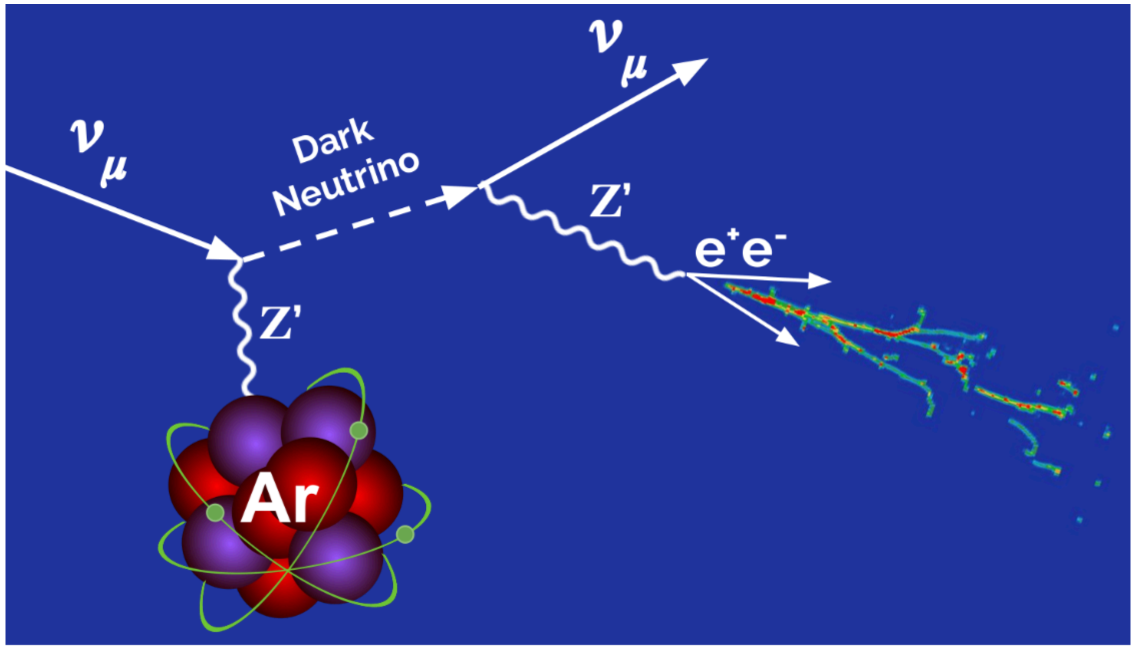


$$m_N = 300\ \text{MeV},\ m_X = 100\ \text{MeV}$$

$$f(E_{N,\mathrm{lab}}) = \Theta(E_{N,\mathrm{lab}} - 500\ \text{MeV}) \times \Theta(1000\ \text{MeV} - E_{N,\mathrm{lab}})$$

Asymmetry in dark neutrino decay

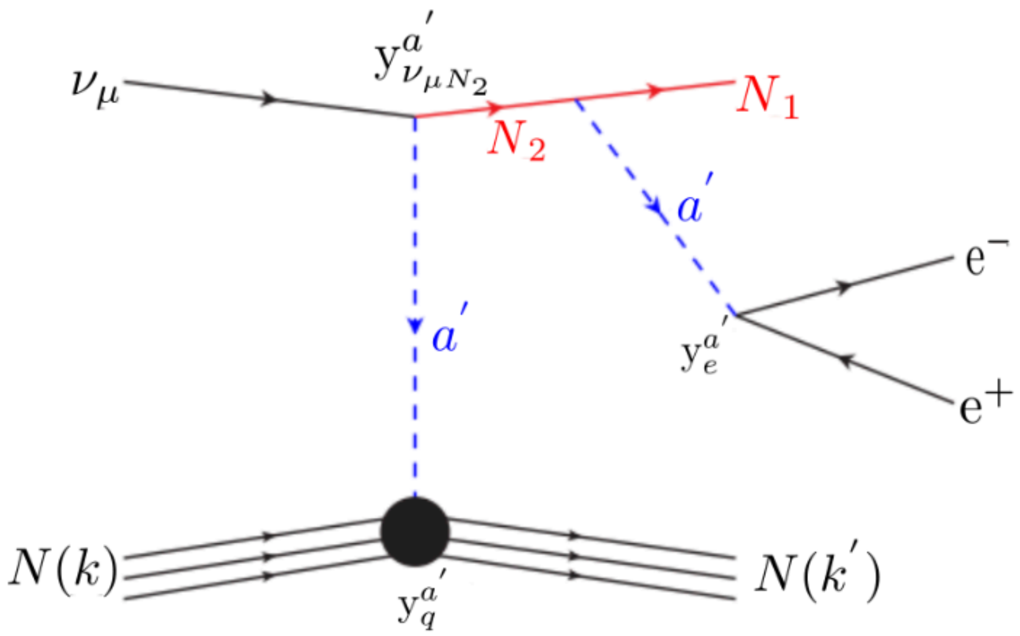
Consider a dark neutrino coupled to neutrinos and a dark scalar ϕ or vector Z'



MicroBooNE Collaboration, 2502.10900

see also: Doojin & Raj's talks

MiniBooNE excess might be explained by a dark sector particle decaying into a e^+e^- pair (* disfavored by MicroBooNE)



Abdallah et al., 2406.07643

Extend to 2HDM + 3HNL model. Explains LSND and MiniBooNE anomalies (possibly ATOMKI anomaly as well)

Asymmetry in dark neutrino decay

Consider a dark neutrino coupled to neutrinos and a dark scalar ϕ or vector Z',

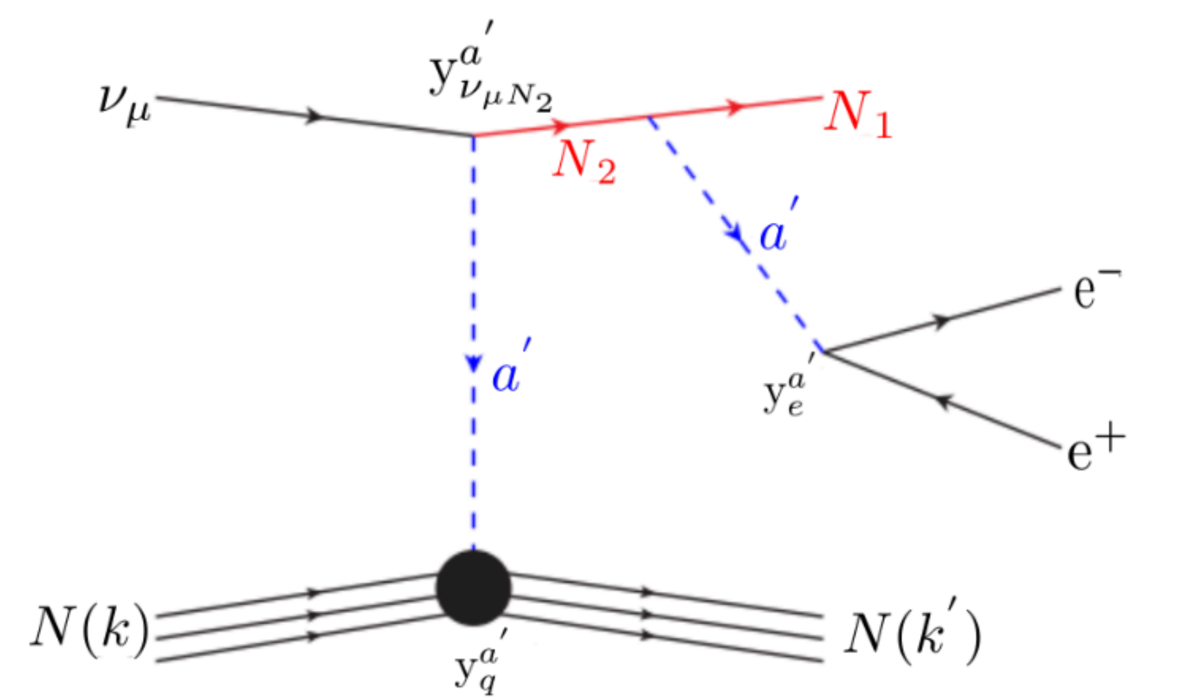
and its decay $N_2 \to N_1 + \phi$ (or Z')

$$\mathscr{L}_{\text{int}} \supset \sum_{i,j}^{3+n} \phi\, \bar{\nu}_j \left(g^S_{ij} + i\gamma^5 g^P_{ij} \right) \nu_i \qquad \mathscr{L}_{\text{int}} \supset \sum_{i,j}^{3+n} Z'_\mu \gamma^\mu \bar{\nu}_j (g^V_{ij} - g^A_{ij}\gamma^5)\nu_i$$

($+\mathscr{L}_{\text{int}}$ which let ϕ or Z' decay to observable particles)

Goals:

- Study the asymmetry of angular/energy distributions of ϕ/Z' by varying parameters $\{m, g, f_{E_{N_2}}\}$
- Estimate the sensitivity of MicroBooNE experiment to the Dirac-Majorana nature of HNLs (ongoing)



$$m_{N_2} = 120 \text{ MeV}, m_{N_1} = 70 \text{ MeV}, m_{a'} = 17 \text{ MeV}$$
$$y^{a'}_{\nu_\mu N_2} = 3.15 \times 10^{-2}, \lambda^{a'}_{N_1 N_2} = 0.1$$

Spin-0 case

$$\mathscr{L}_{\text{int}} \supset \sum_{i,j}^{3+n} \phi\, \bar{\nu}_j \left(g_{ij}^S + i\gamma^5 g_{ij}^P \right) \nu_i$$

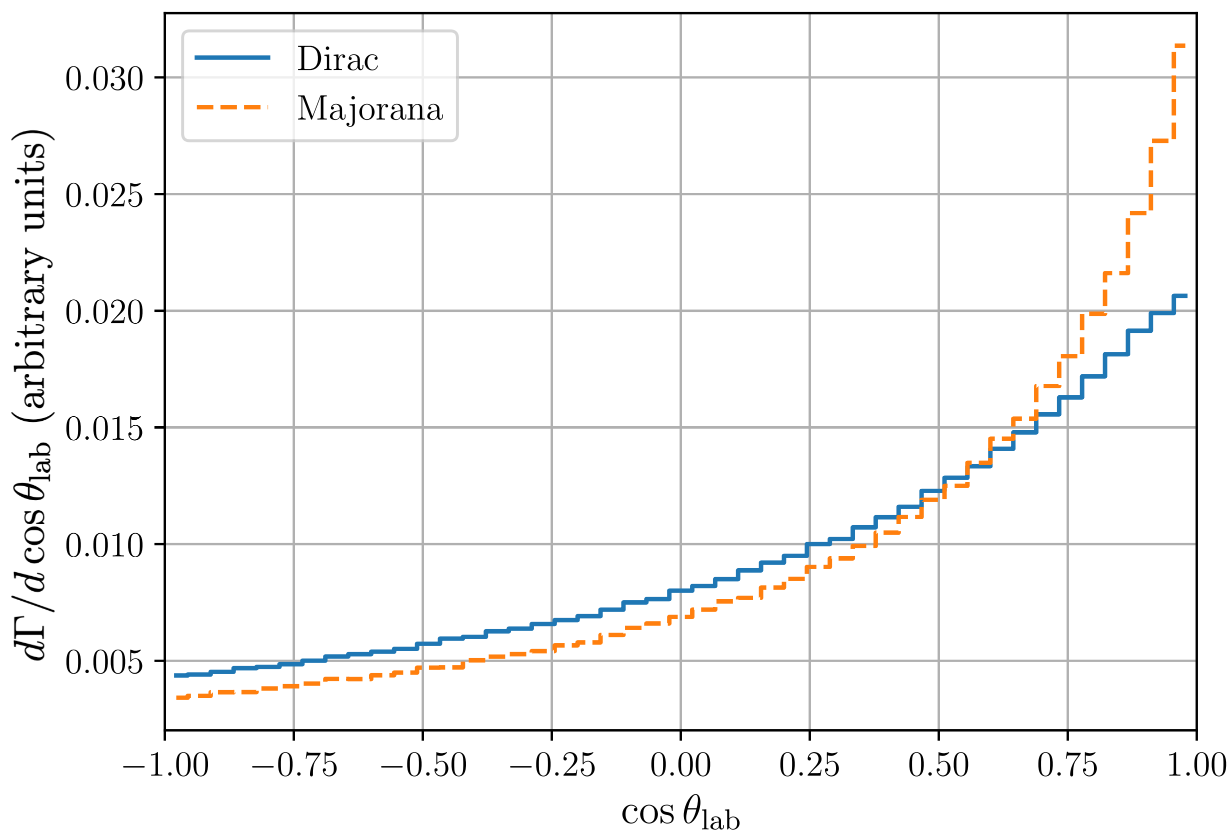
$$\frac{d\Gamma(N \to \nu + X)}{d(\cos\theta)} = \frac{\Gamma_0}{2}(1 + \alpha\cos\theta)$$

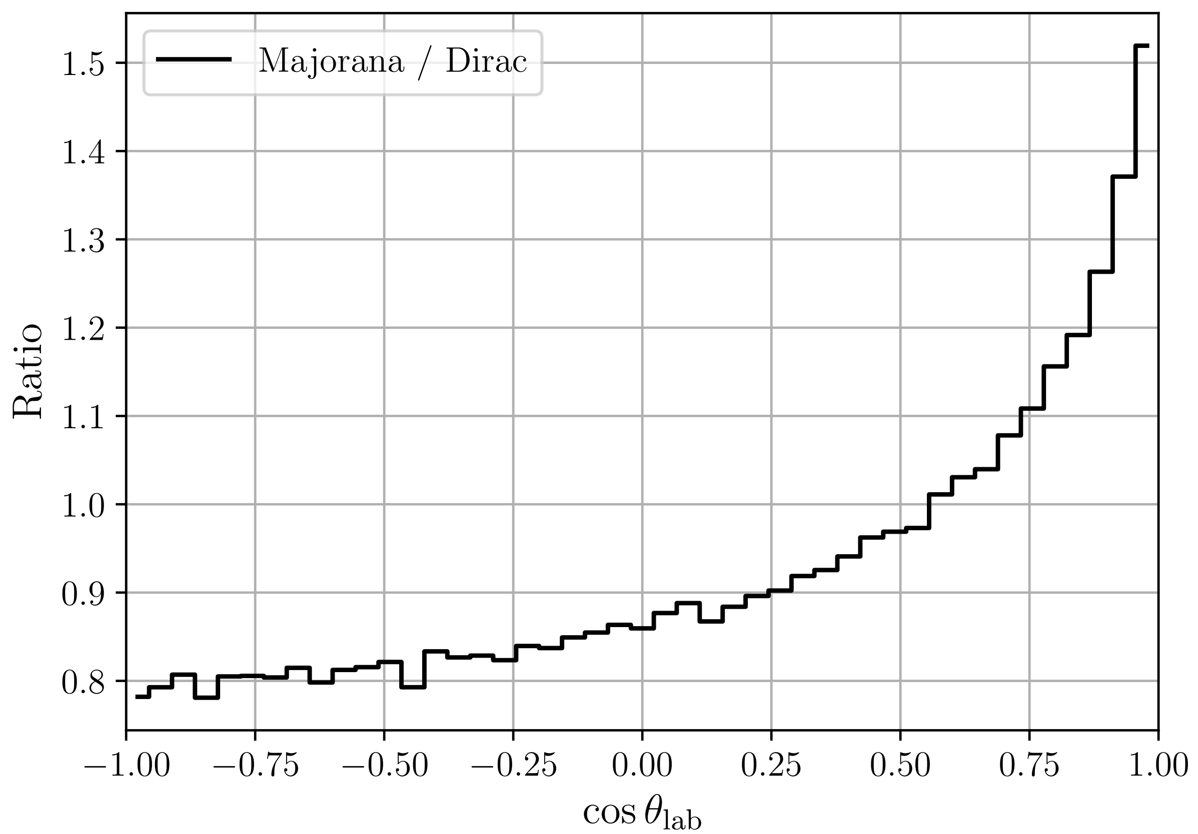
Benchmark model:

$$m_{N_2} = 120 \text{ MeV}, m_{N_1} = 70 \text{ MeV}, m_{a'} = 17 \text{ MeV}$$
$$g_S = 1,\ g_P = i$$
$$\to \alpha = 0.66$$

$$f_{N_2} \propto \exp\left(-\frac{(E_{N_2} - \mu)^2}{2\sigma^2} \right) \qquad \mu = 350 \text{ MeV} \quad \sigma = 100 \text{ MeV}$$

Angular distribution (left) and Majorana-to-Dirac ratio (right)





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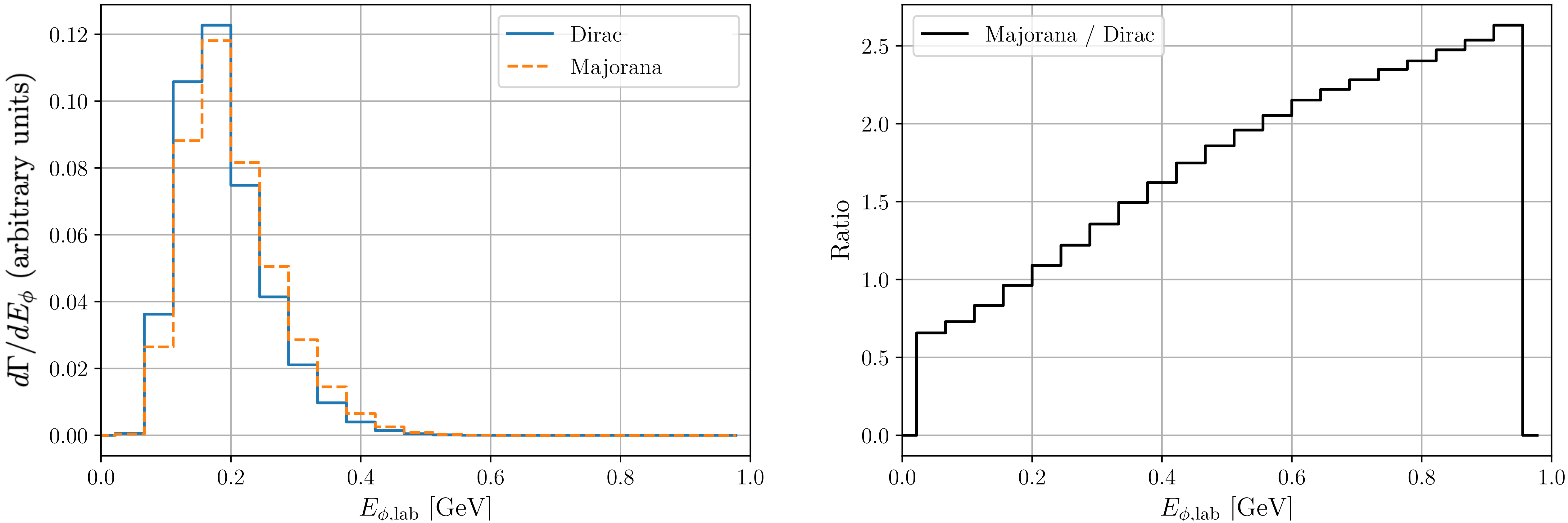
Energy distribution (left) and Majorana-to-Dirac ratio (right)



Spin-1 case

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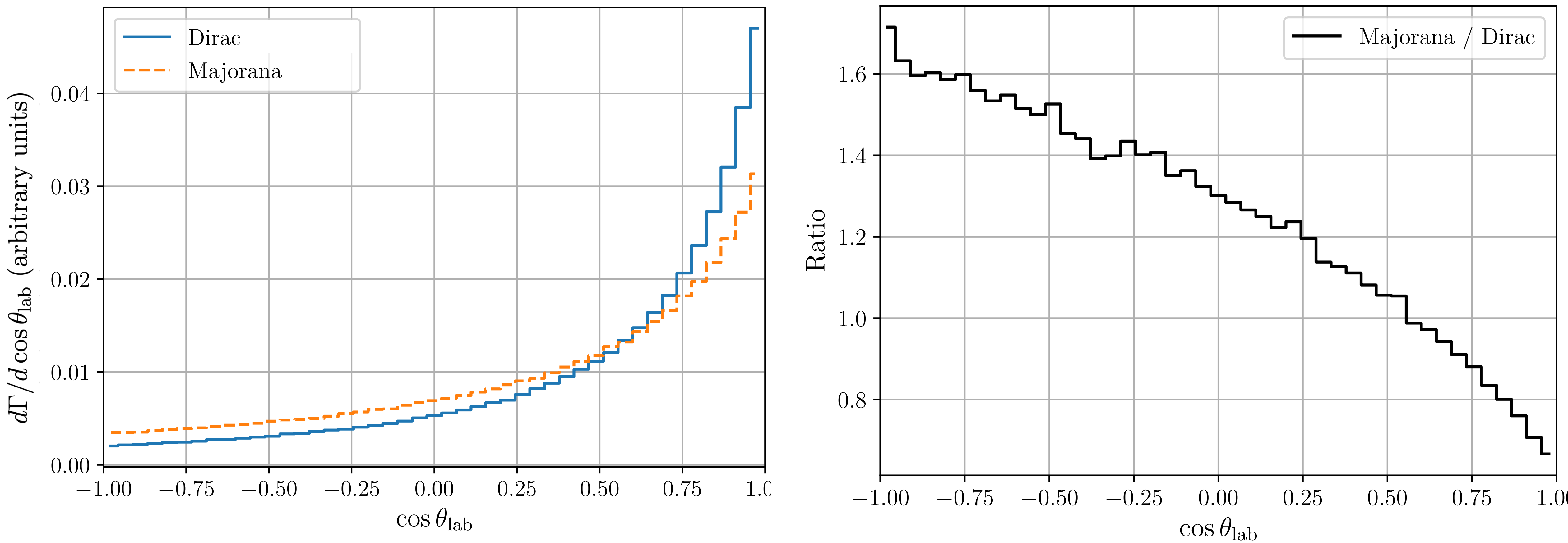
$$g_V = g_A = 1$$
$$\to \alpha = -0.98$$

$$f_{N_2} \propto \exp\left(-\frac{(E_{N_2} - \mu)^2}{2\sigma^2}\right) \quad \mu = 350 \text{ MeV} \quad \sigma = 100 \text{ MeV}$$

Angular distribution (left) and Majorana-to-Dirac ratio (right)



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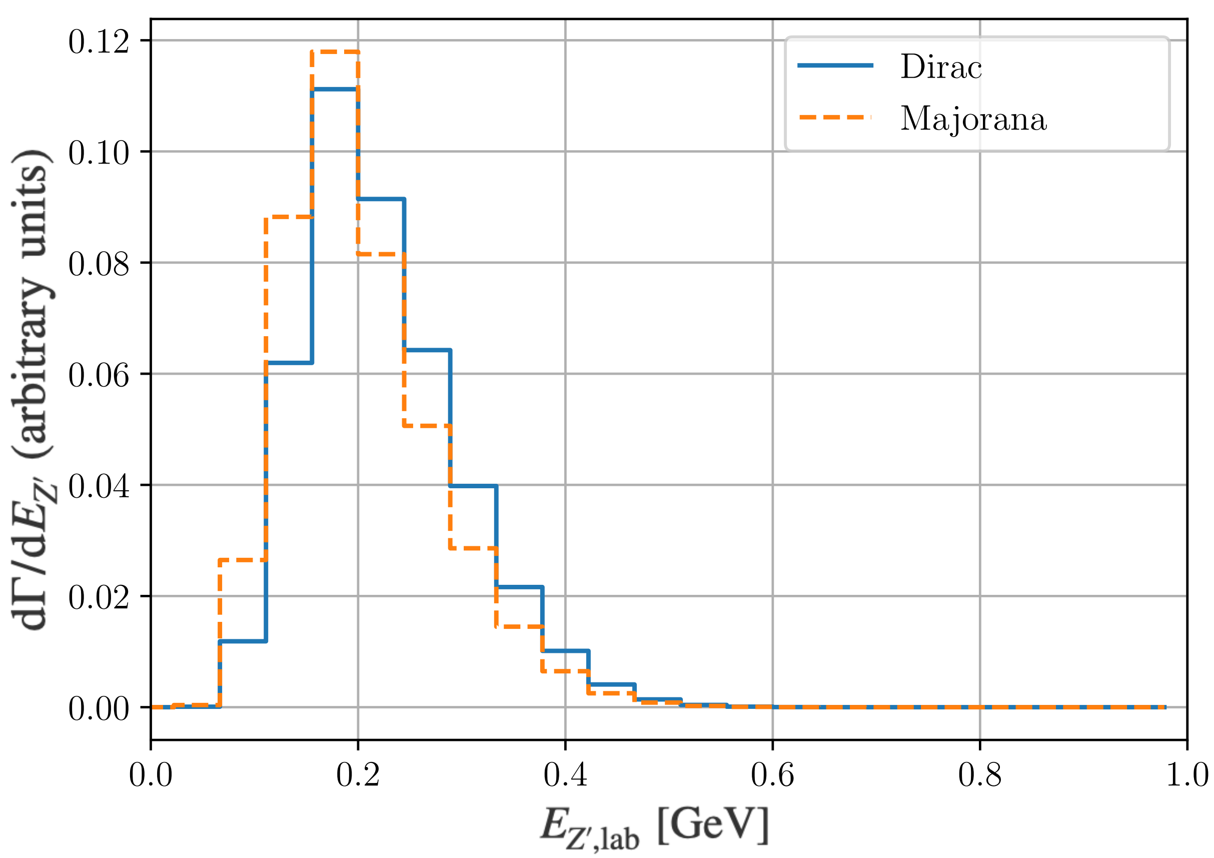
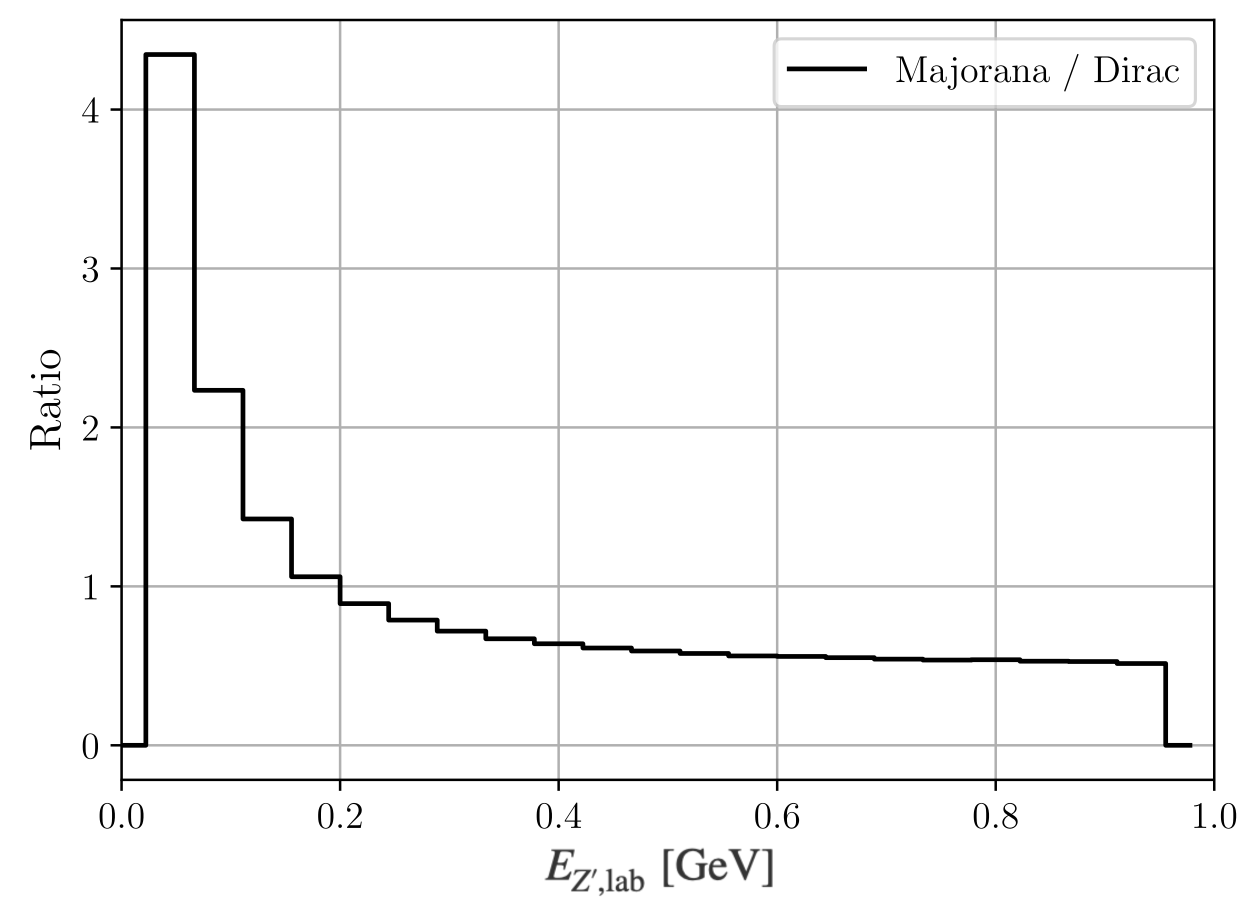
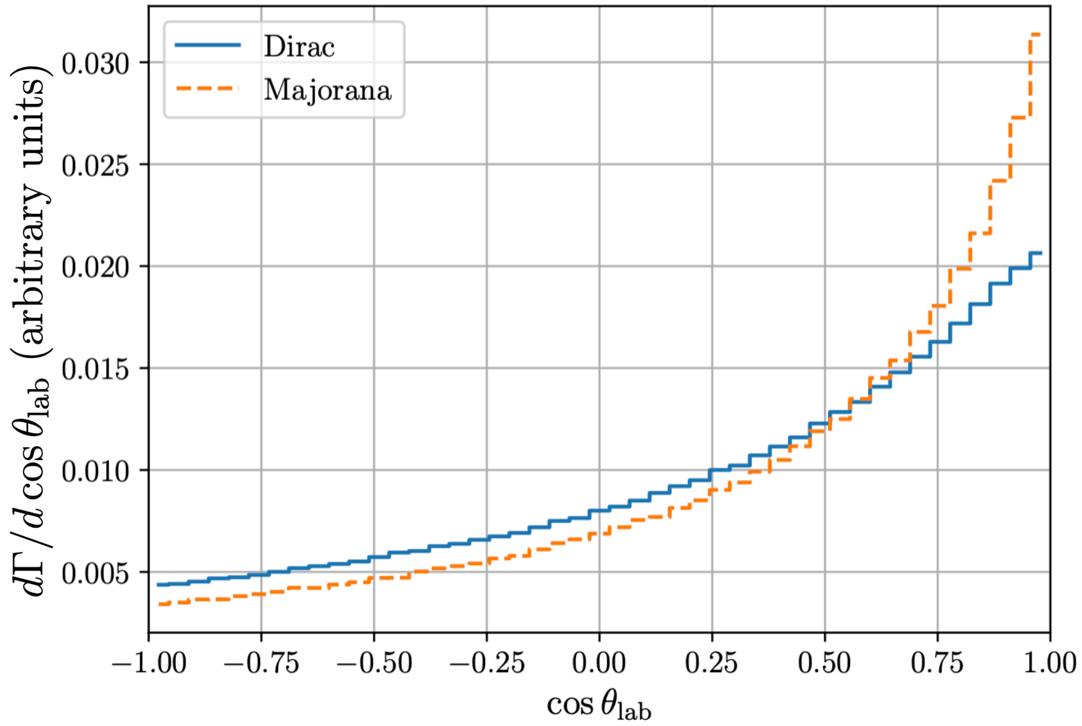


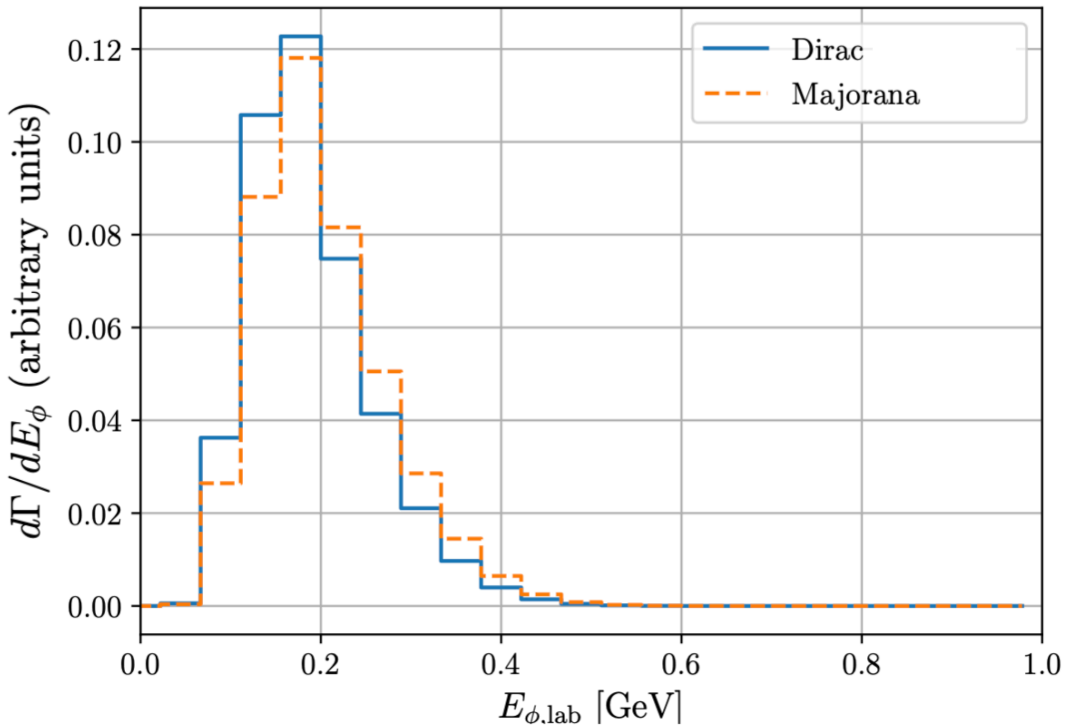


Asymmetry in angular/energy distribution

- For positive/negative α, (if N_2 has left-handed chirality)
  - angular distribution is shifted backward/forward
  - energy distribution is red-shifted/blue-shifted

e.g.) $\alpha > 0$ case





- For the benchmark model ($\alpha \gtrsim 0.6,\ \langle\gamma\rangle \sim 3$), $\mathcal{O}(10\%)$ difference in the angular distribution and $\mathcal{O}(100\%)$ difference in the energy distribution are expected

Decay asymmetry parameter α

- Both parity-preserving and violating interaction terms are necessary
  – otherwise $\alpha = 0$ for Dirac. No difference in angular and energy distributions

$$\alpha \propto \mathrm{Im}(g_{ij}^S g_{ij}^{P*}) \text{ (spin-0)}, \quad \mathrm{Re}(g_{ij}^V g_{ij}^{A*}) \text{ (spin-1)}$$

see also: de Gouvêa, Fox, Kayser, & Kelly 2104.05719

- Depends only on g_S/g_P or g_V/g_A

$$\alpha = -\frac{4m_{\nu_i}\mathrm{Im}(g_{ij}^S g_{ij}^{P*})\sqrt{\left(\frac{m_{\nu_i}^2 + m_{\nu_j}^2 - m_\phi^2}{2m_{\nu_i}}\right)^2 - m_{\nu_j}^2}}{\left(|g_{ij}^S|^2 + |g_{ij}^P|^2\right)\left(m_{\nu_i}^2 + m_{\nu_j}^2 - m_\phi^2\right) + 2\left(|g_{ij}^S|^2 - |g_{ij}^P|^2\right)m_{\nu_i}m_{\nu_j}} \quad \text{(spin-0)}$$

$$\alpha = \frac{2m_{\nu_i}\mathrm{Re}(g_{ij}^V g_{ij}^{A*})\sqrt{\left(\frac{m_{\nu_i}^2 + m_{\nu_j}^2 - m_{Z'}^2}{2m_{\nu_i}}\right)^2 - m_{\nu_j}^2}\left(1 - \frac{m_{\nu_i}^2 - m_{\nu_j}^2 - m_{Z'}^2}{m_{Z'}^2}\right)}{\left(|g_{ij}^V|^2 + |g_{ij}^A|^2\right)\left\{\frac{m_{\nu_i}^2 + m_{\nu_j}^2 - m_{Z'}^2}{2} + \frac{m_{\nu_i}^2 - m_{\nu_j}^2 + m_{Z'}^2}{2}\cdot\frac{m_{\nu_i}^2 - m_{\nu_j}^2 - m_{Z'}^2}{m_{Z'}^2}\right\} - 3m_{\nu_i}m_{\nu_j}\left(|g_{ij}^V|^2 - |g_{ij}^A|^2\right)} \quad \text{(spin-1)}$$

Decay asymmetry parameter α

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$$\alpha \propto \mathrm{Im}(g^S_{ij} g^{P*}_{ij}) \text{ (spin-0)}, \quad \mathrm{Re}(g^V_{ij} g^{A*}_{ij}) \text{ (spin-1)}$$

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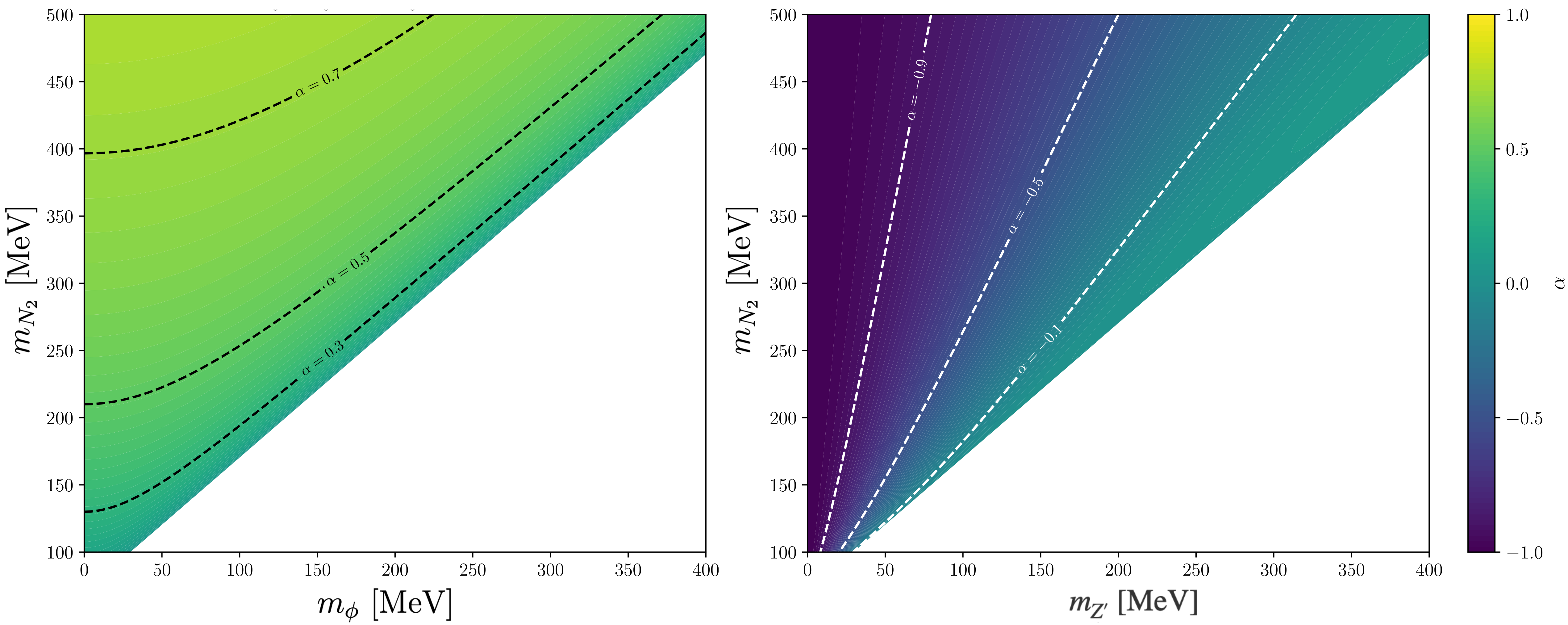

$(m_{N_1} = 70 \text{ MeV},\ g_S = 1,\ g_P = i,\ g_V = g_A = 1)$

Decay asymmetry parameter α

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$$\alpha \propto \mathrm{Im}(g^S_{ij} g^{P*}_{ij}) \text{ (spin-0)}, \quad \mathrm{Re}(g^V_{ij} g^{A*}_{ij}) \text{ (spin-1)}$$

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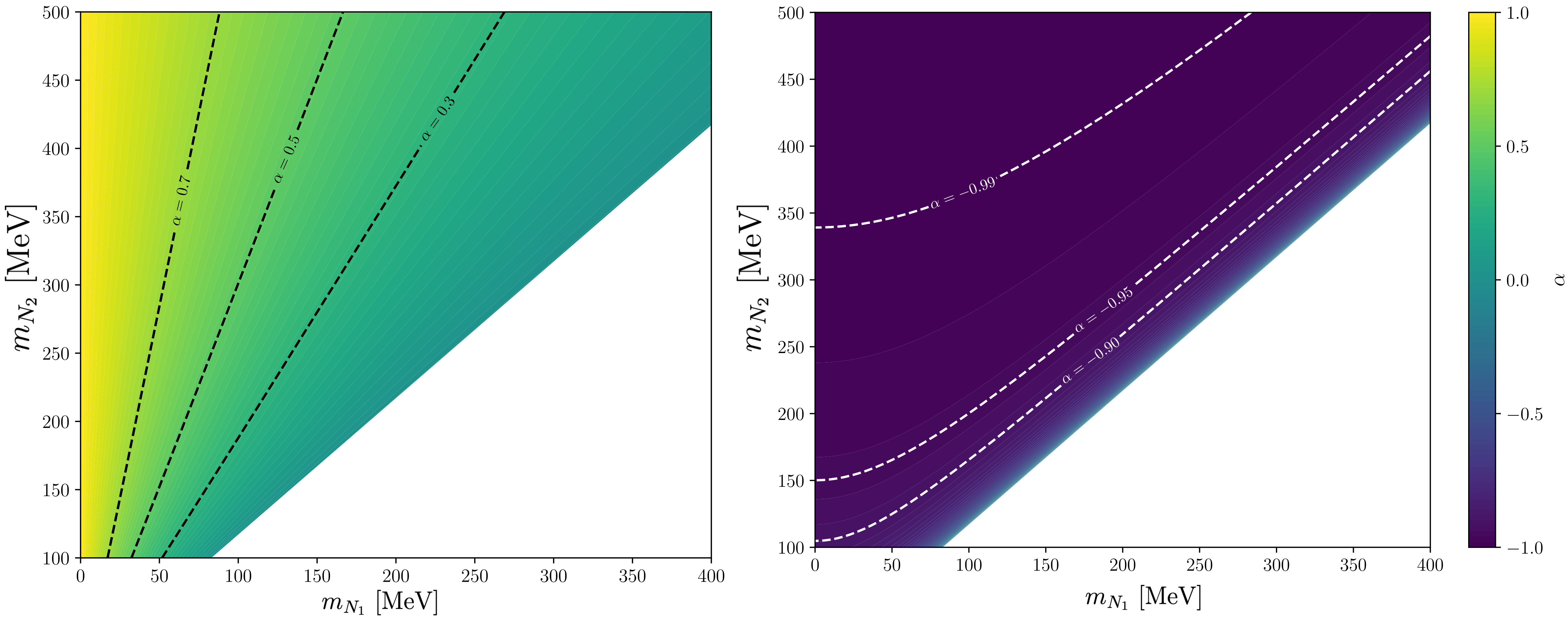

$(m_{\phi/Z'} = 17 \text{ MeV},\ g_S = 1,\ g_P = i,\ g_V = g_A = 1)$

Decay asymmetry parameter α

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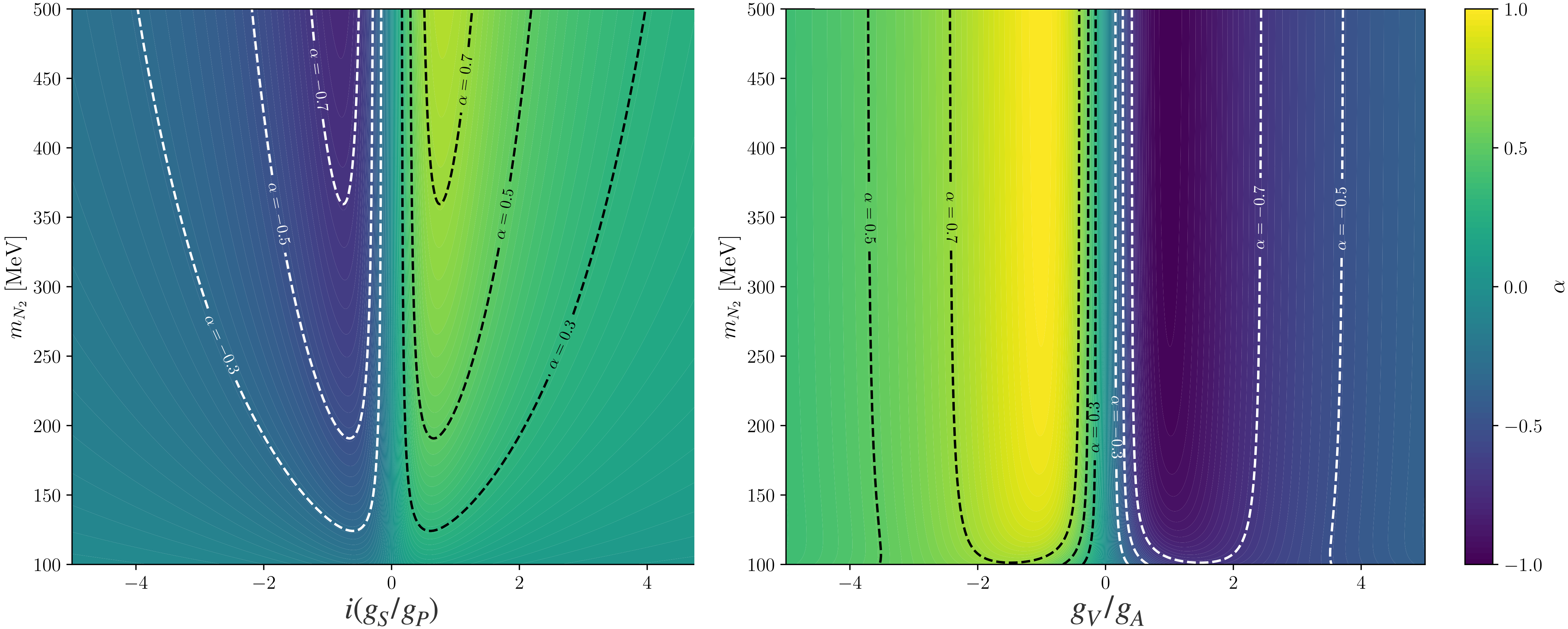
  – otherwise $\alpha = 0$ for Dirac. No difference in angular and energy distributions

$$\alpha \propto \mathrm{Im}(g^S_{ij} g^{P*}_{ij}) \text{ (spin-0)}, \quad \mathrm{Re}(g^V_{ij} g^{A*}_{ij}) \text{ (spin-1)}$$

see also: de Gouvêa, Fox, Kayser, & Kelly 2104.05719

- Depends only on g_S/g_P or g_V/g_A

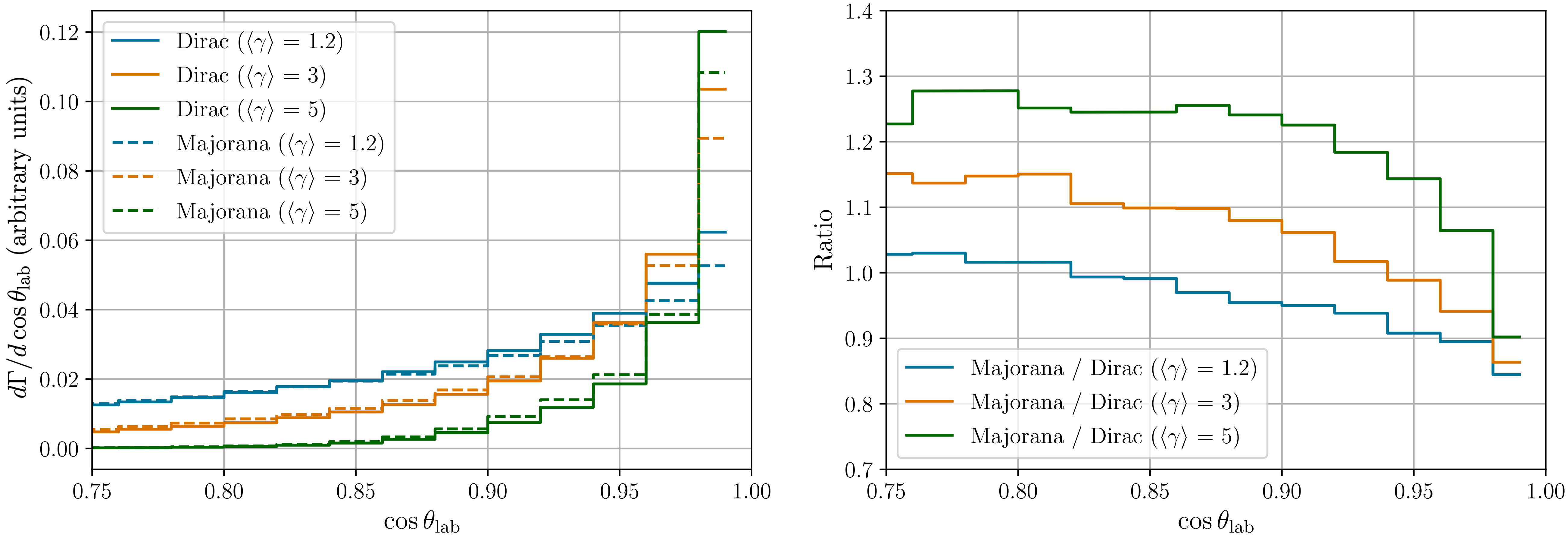


$(m_{N_2} = 120$ MeV, $m_{N_1} = 70$ MeV, $m_{\phi/Z'} = 17$ MeV$)$

Parent particles' boost and polarization

Parent Dirac neutrinos are more polarized if they are boosted more

$$P = \frac{N_+ - N_-}{N_+ + N_-}, \qquad N_+ \propto \frac{1}{2}\left(1 - \sqrt{1 - \frac{m_{N_2}^2}{E_{N_2}^2}}\right), \qquad N_- \propto \frac{1}{2}\left(1 + \sqrt{1 - \frac{m_{N_2}^2}{E_{N_2}^2}}\right)$$



Polarization of neutrinos

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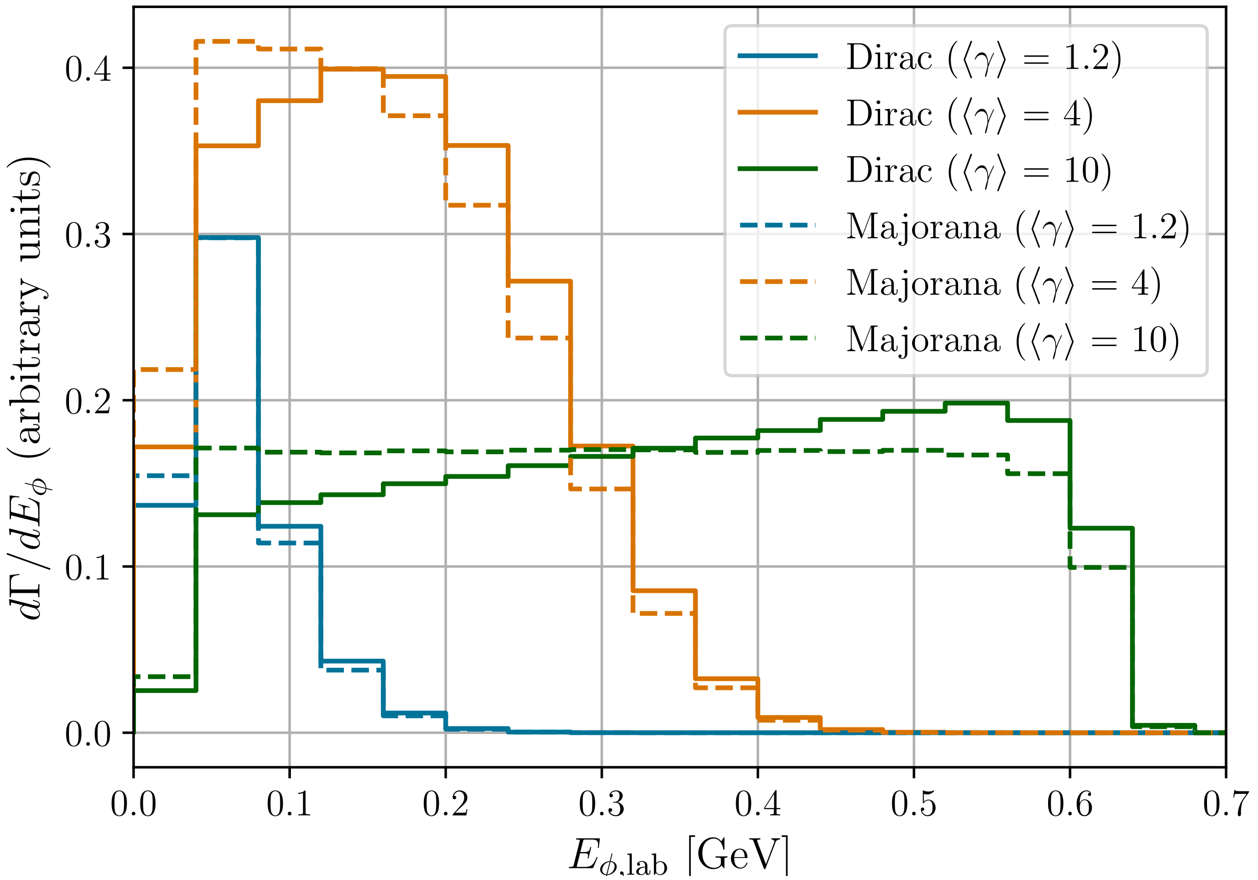
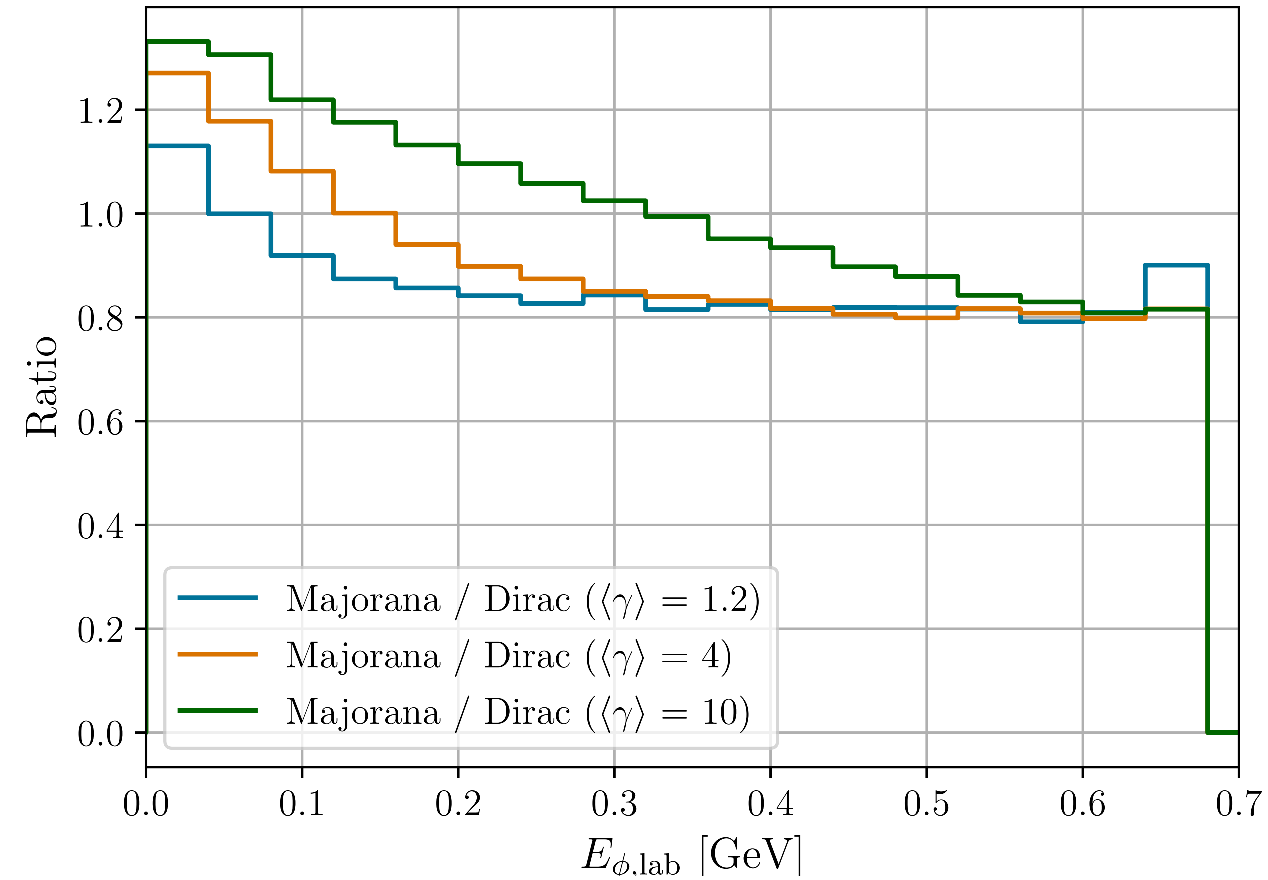




($m_{N_2} = 120$ MeV, $m_{N_1} = 70$ MeV, $m_\phi = 17$ MeV, $g_P = i$, $g_A = 1$, $\sigma = 100$ MeV are assumed)

Asymmetry in angular/energy distribution

Lab frame angular/energy distribution is characterized by α and boost of N_2

Large decay asymmetry parameter $|\alpha|$ is realized when…

- Parent particle mass m_{N_2} is large
- $g_S/g_P \simeq i$ or $g_V/g_A \simeq 1$
- Daughter particle mass m_ϕ, m_{N_1} are small

Larger boost results in…

- Larger polarization P of parent neutrinos 🙂
- More collimated decay particles 😕
  – if too collimated, the detector might not be able to resolve the difference

Summary

- The question of whether neutrinos are Dirac or Majorana remains open
- Angular and energy distribution of decay products might be useful

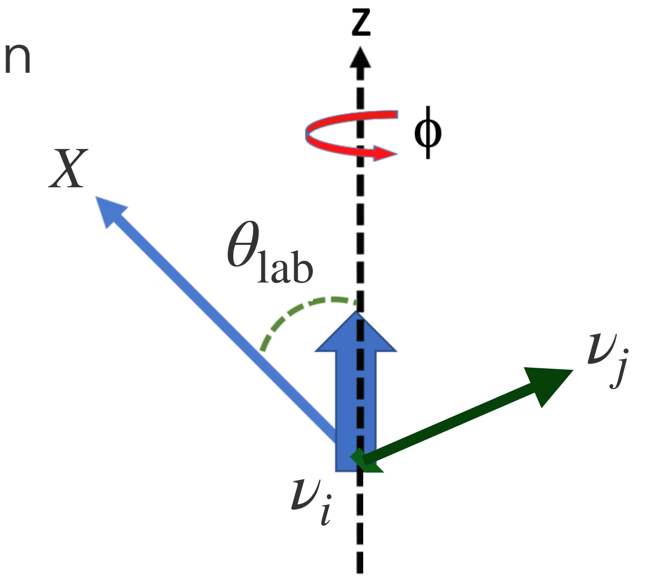
  – In a neutrino decay process $N_2 \to N_1 + X$, the angular distribution of decay products has to be isotropic in the rest frame of N_2 if neutrinos are Majorana
- Large asymmetry favors
  - large parent mass m_{N_2}
  - small daughter mass $m_{N_1}, m_{\phi/Z'}$
  - equally strong parity-conserving and violating interactions ($g_S/g_P \simeq i$ or $g_V/g_A \simeq 1$)
  - highly boosted parent particles (pros and cons)
- $\mathcal{O}(10\%)$ difference in the angular/energy distribution doesn't sound crazy

Backup

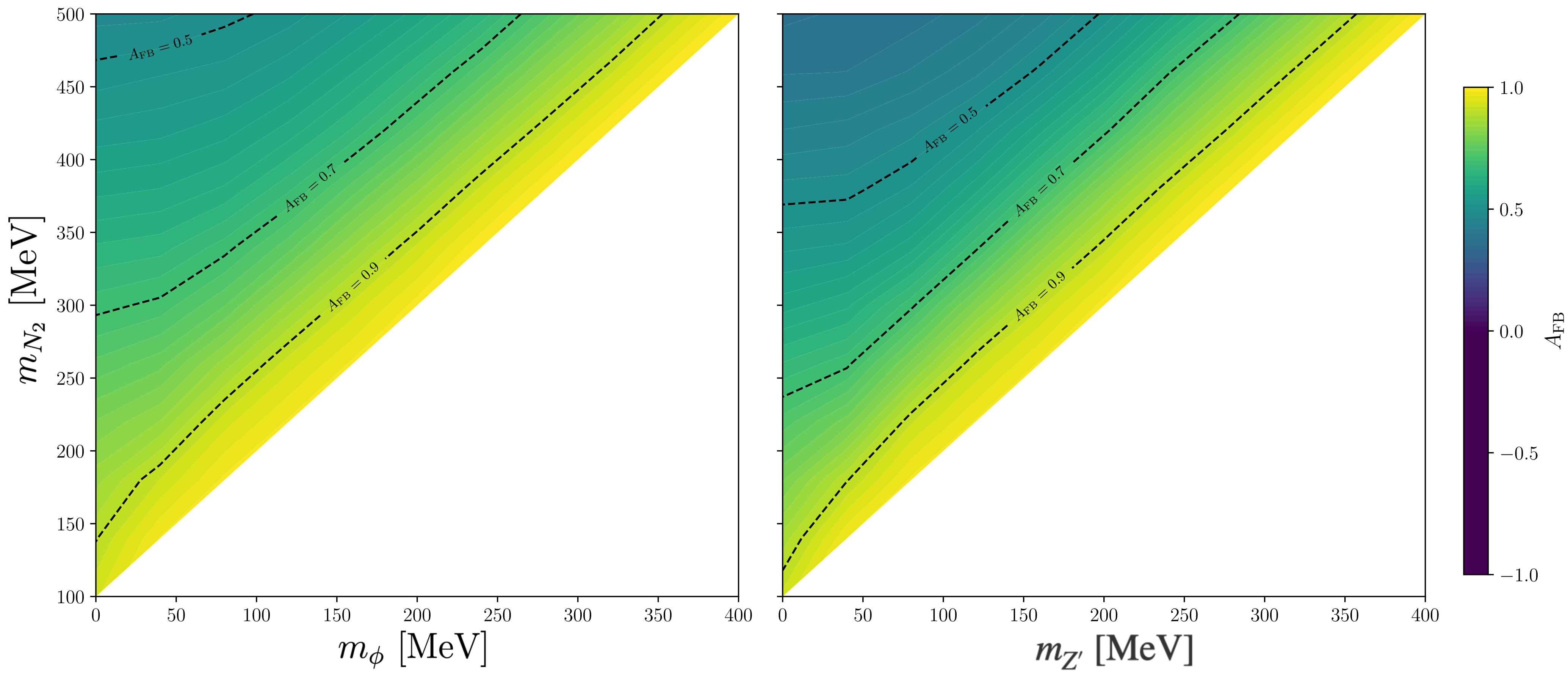
The forward-backward asymmetry

A_{FB} quantifies the asymmetry between forward and backward emission

$$A_{\mathrm{FB}} \equiv \frac{\displaystyle\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}} - \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}}}{\displaystyle\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}} + \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}}}$$



m_{N_2} vs m_ϕ

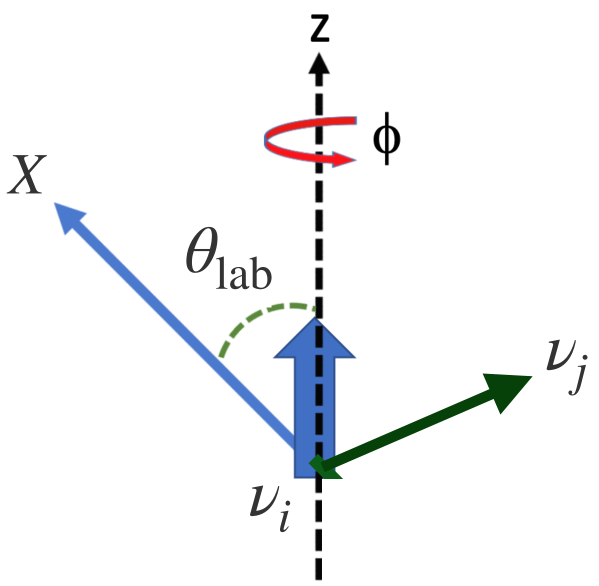


$(m_{N_1} = 70$ MeV, $g_S = 1,\ g_P = i,\ g_V = g_A = 1)$

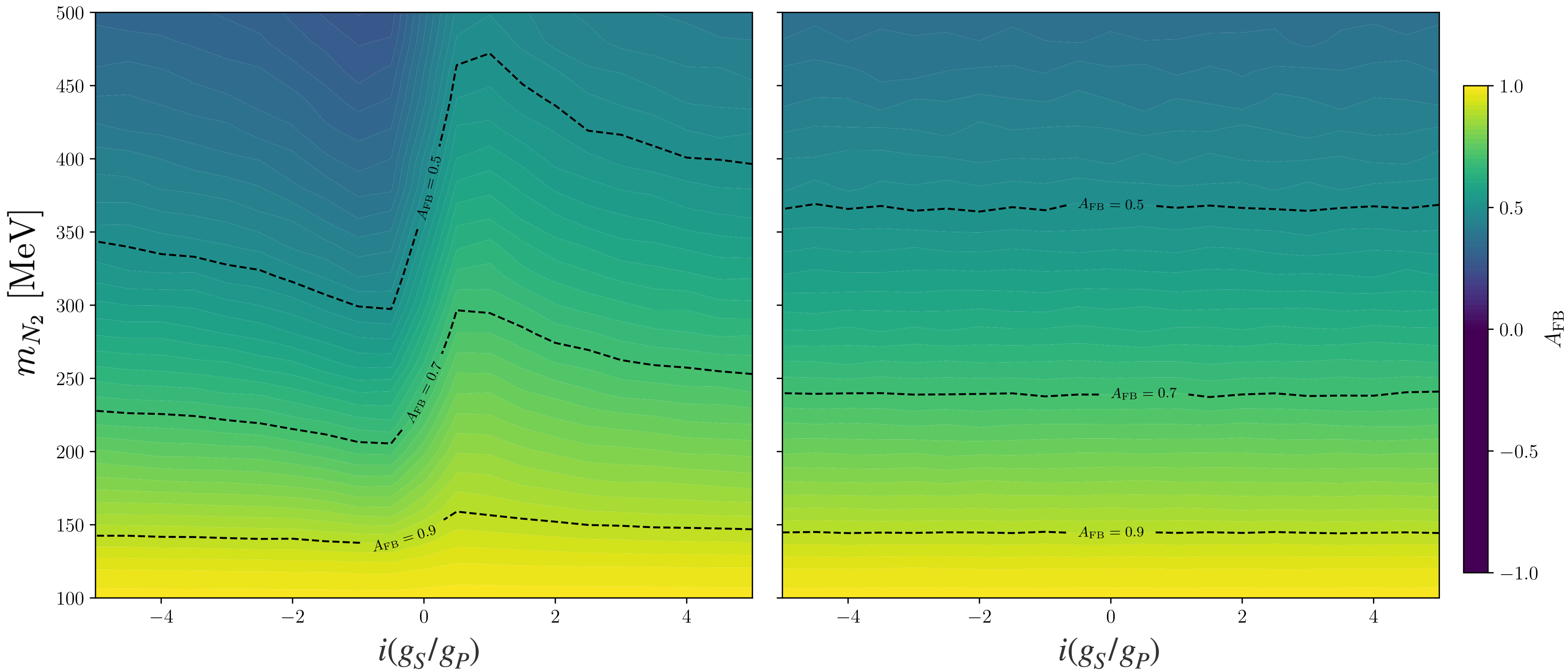
The forward-backward asymmetry

A_{FB} quantifies the asymmetry between forward and backward emission

$$A_{\mathrm{FB}} \equiv \frac{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}} - \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}}}{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}} + \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\mathrm{lab}}}\,\mathrm{d}\cos\theta_{\mathrm{lab}}}$$



m_{N_2} vs g_S

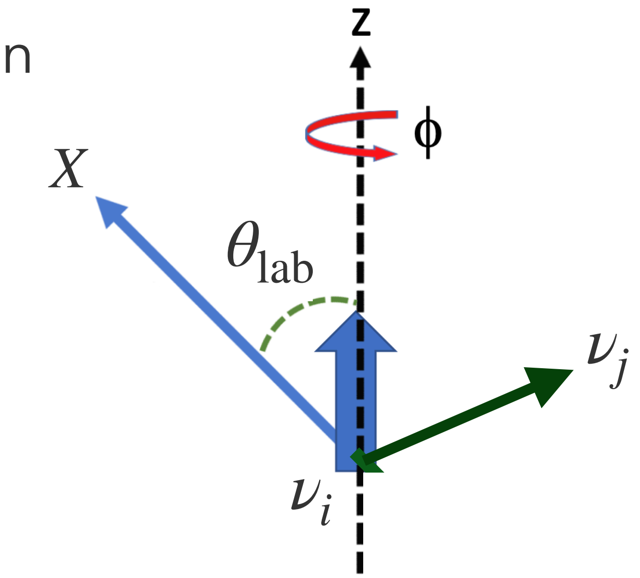


($m_{N_1} = 70$ MeV, $m_{\phi/Z'} = 17$ MeV)

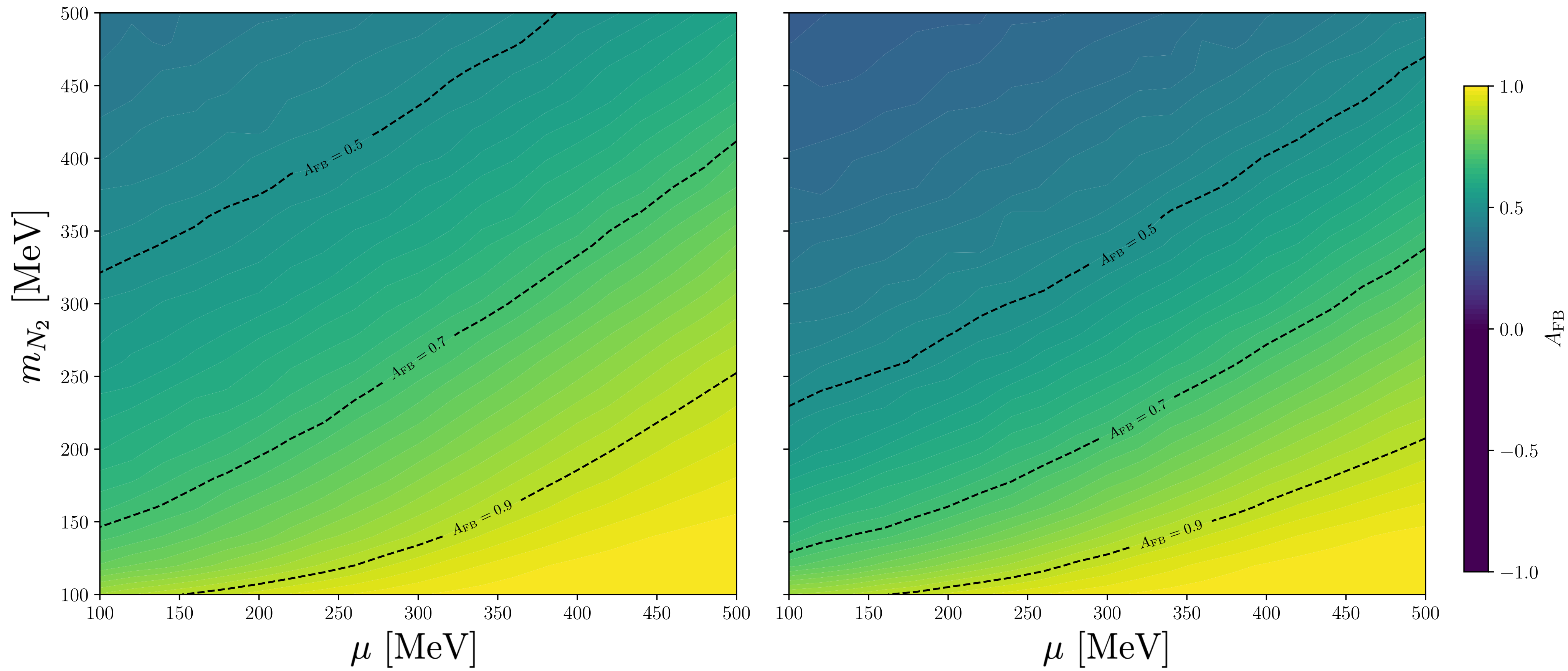
The forward-backward asymmetry

$A_{\rm FB}$ quantifies the asymmetry between forward and backward emission

$$A_{\rm FB} \equiv \frac{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\rm lab}}\,\mathrm{d}\cos\theta_{\rm lab} - \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\rm lab}}\,\mathrm{d}\cos\theta_{\rm lab}}{\int_0^1 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\rm lab}}\,\mathrm{d}\cos\theta_{\rm lab} + \int_{-1}^0 \frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta_{\rm lab}}\,\mathrm{d}\cos\theta_{\rm lab}}$$



m_{N_2} vs μ



$(m_{N_1} = 70$ MeV, $m_{\phi/Z'} = 17$ MeV, $g_S = 1,\ g_P = i,\ g_V = g_A = 1)$