



On the asymmetric distribution of decay products of heavy fermions

based on arXiv:25xx.xxxxx

with Bhupal Dev, Raj Gandhi, and Kevin Kelly

Takuya Okawa (WashU in St. Louis → SISSA (from Fall 2025))

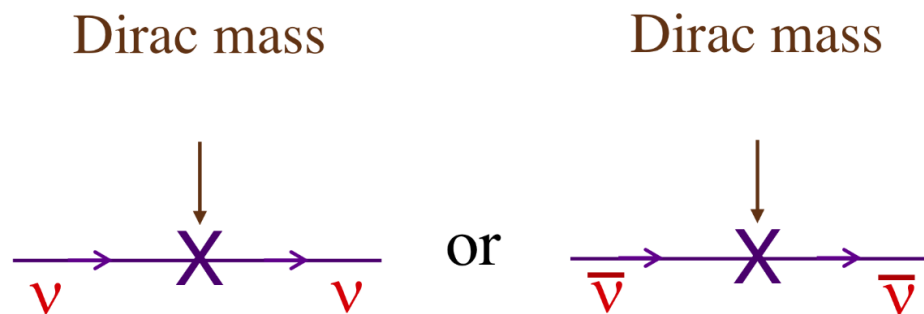
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Dirac neutrino vs Majorana neutrino

The question of whether neutrinos are Dirac or Majorana remains open

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

A Dirac mass
has the effect:



A Majorana mass
has the effect:

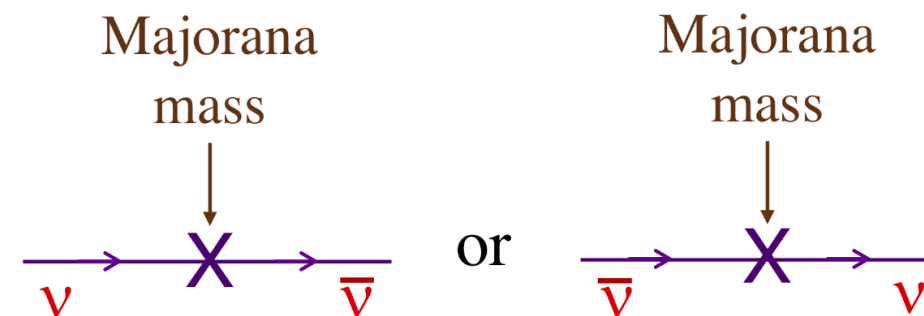


image credit: Balantekin & Kayser, 1805.00922

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

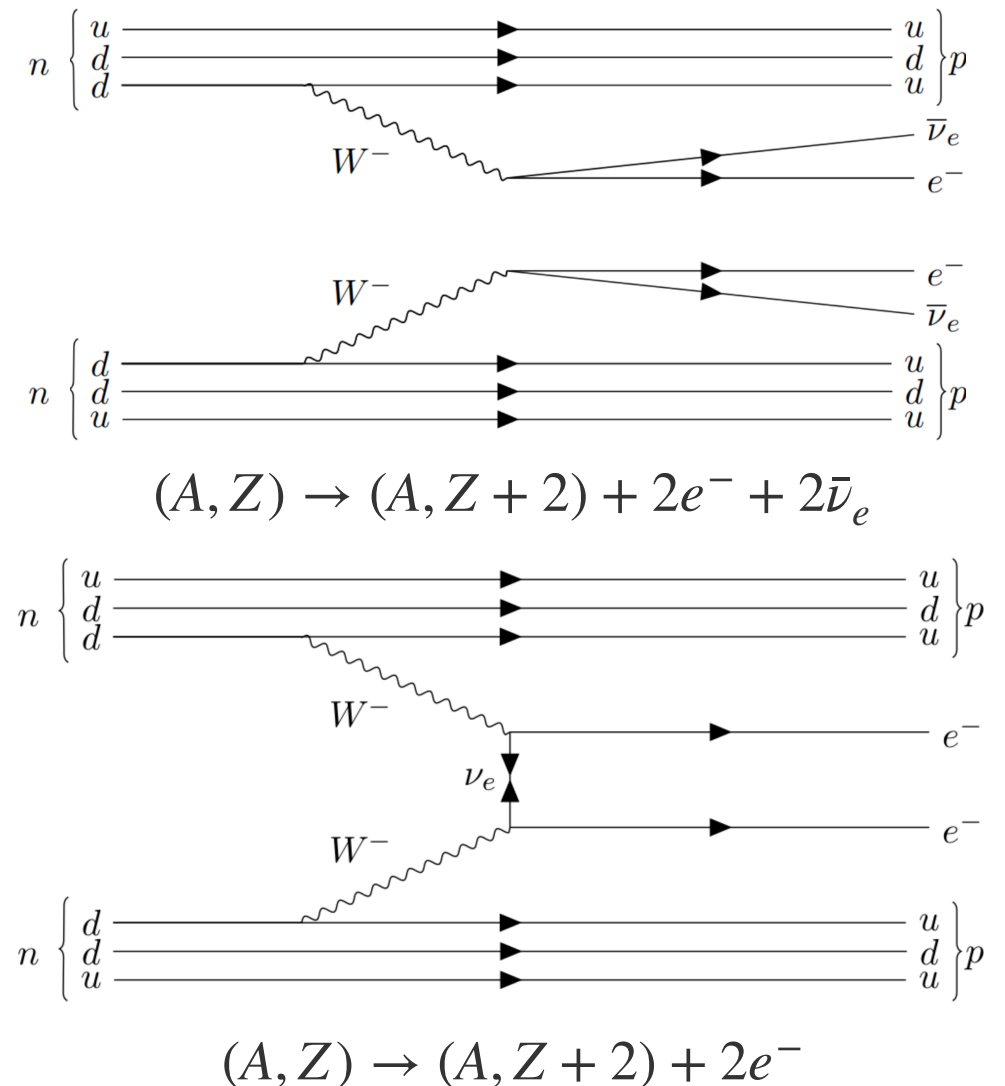
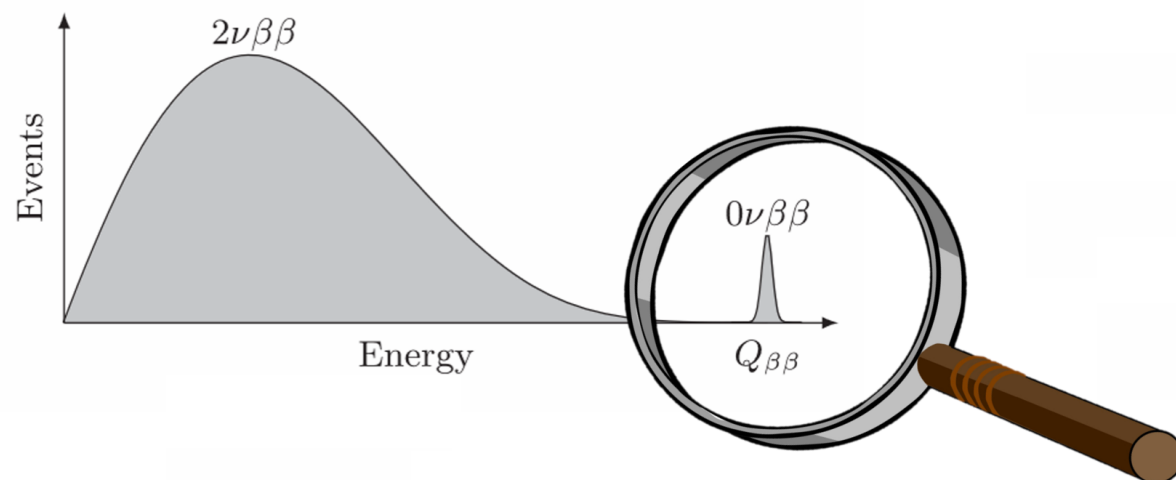
The $0\nu\beta\beta$ -decay half-life:

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

Haven't been observed $\rightarrow$ upper bound:

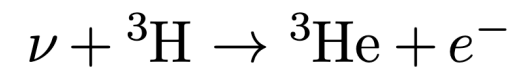
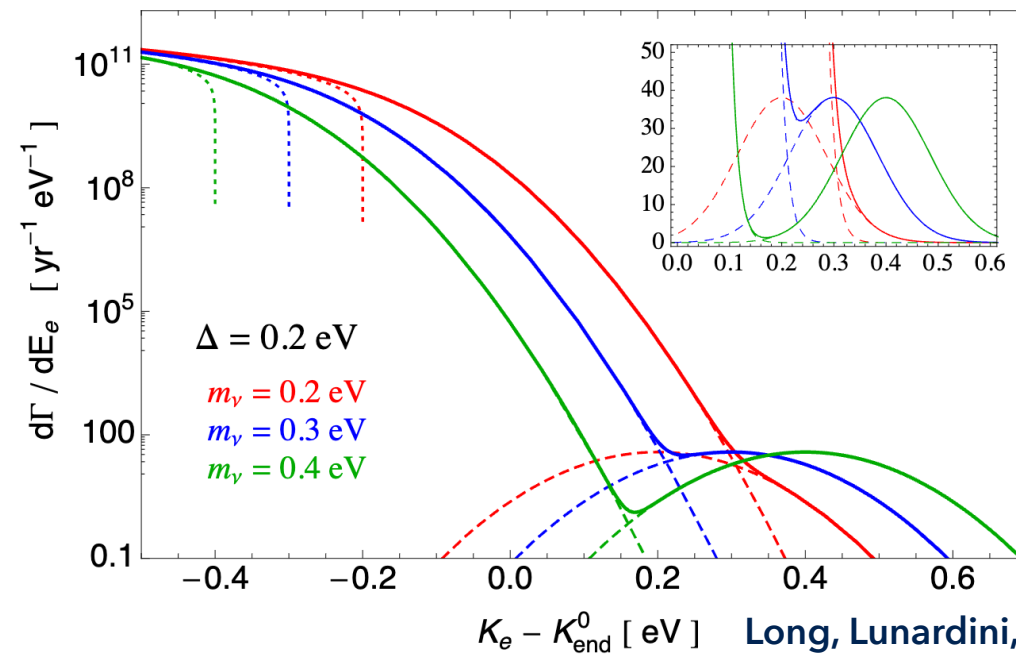
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \lesssim 0.1 \text{ eV}$$

Dolinski, Poon, & Rodejohann 1902.04097



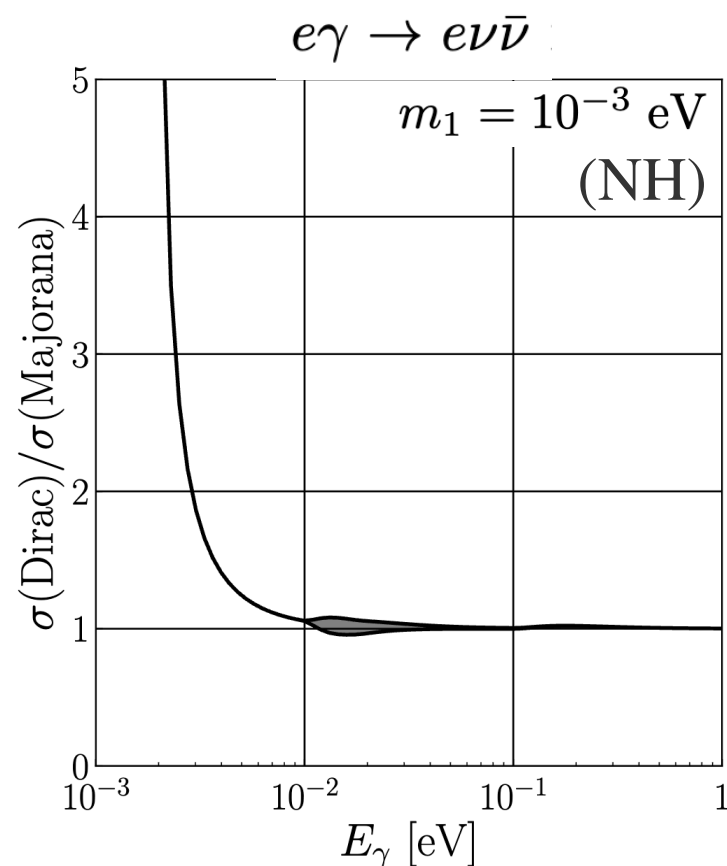
Dirac vs Majorana: rare relevant processes

Relevant processes are extremely rare

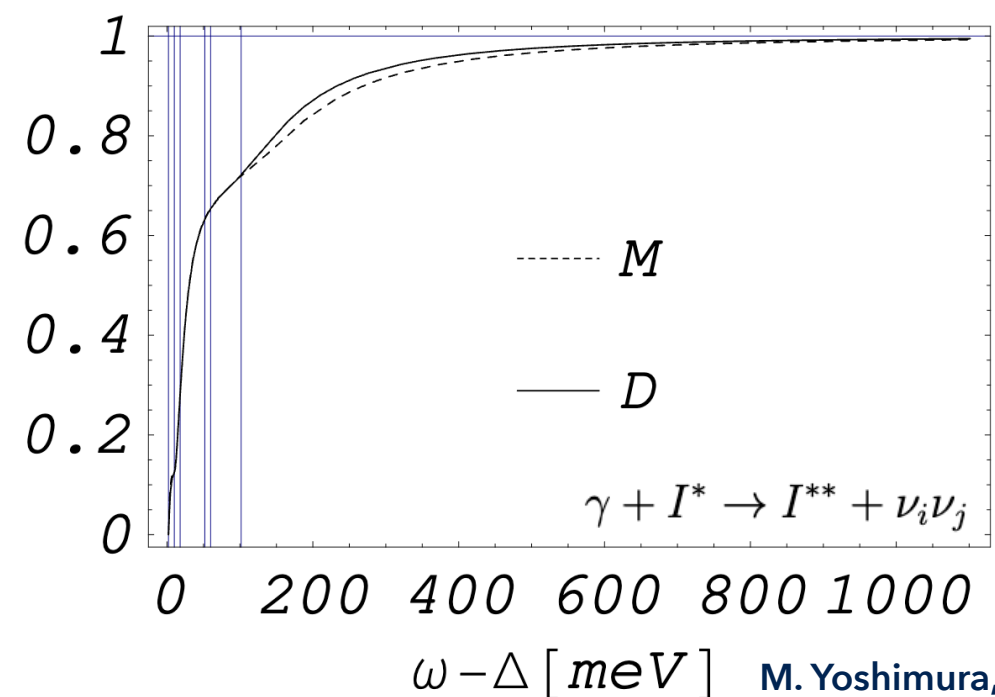


$$\Gamma_{\text{C}\nu\text{B}}^{\text{M}} = 2\Gamma_{\text{C}\nu\text{B}}^{\text{D}}$$

Long, Lunardini, & Sabancilar, 1405.7654



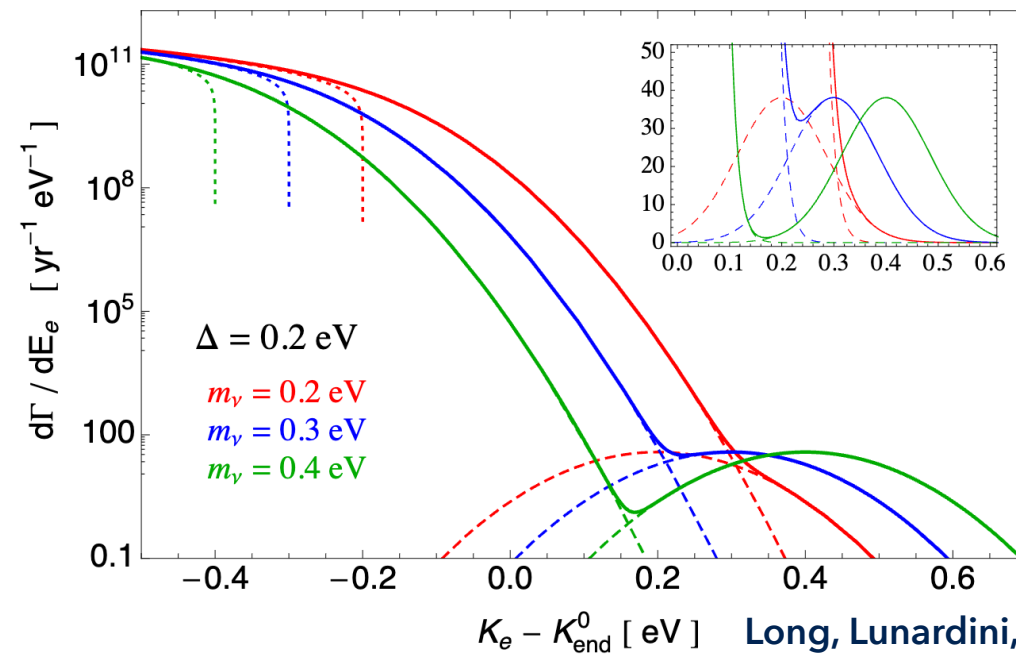
Berryman, de Gouvêa, Kelly, & Schmitt 1805.10294



M. Yoshimura, 0611362

Dirac vs Majorana: rare relevant processes

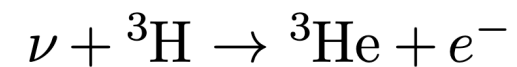
Relevant processes are extremely rare



$$\Gamma_{\text{C}\nu\text{B}}^{\text{D}} \approx 4.06 \text{ yr}^{-1}$$

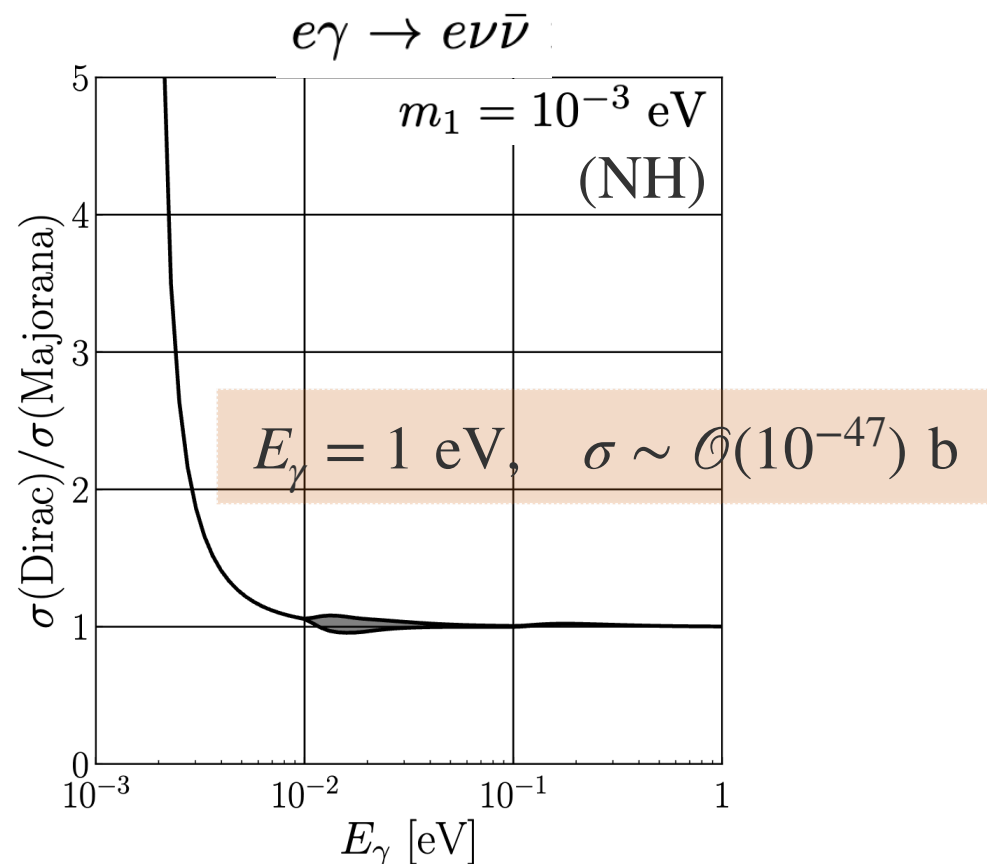
$$\Gamma_{\text{C}\nu\text{B}}^{\text{M}} \approx 8.12 \text{ yr}^{-1}$$

(100g target)

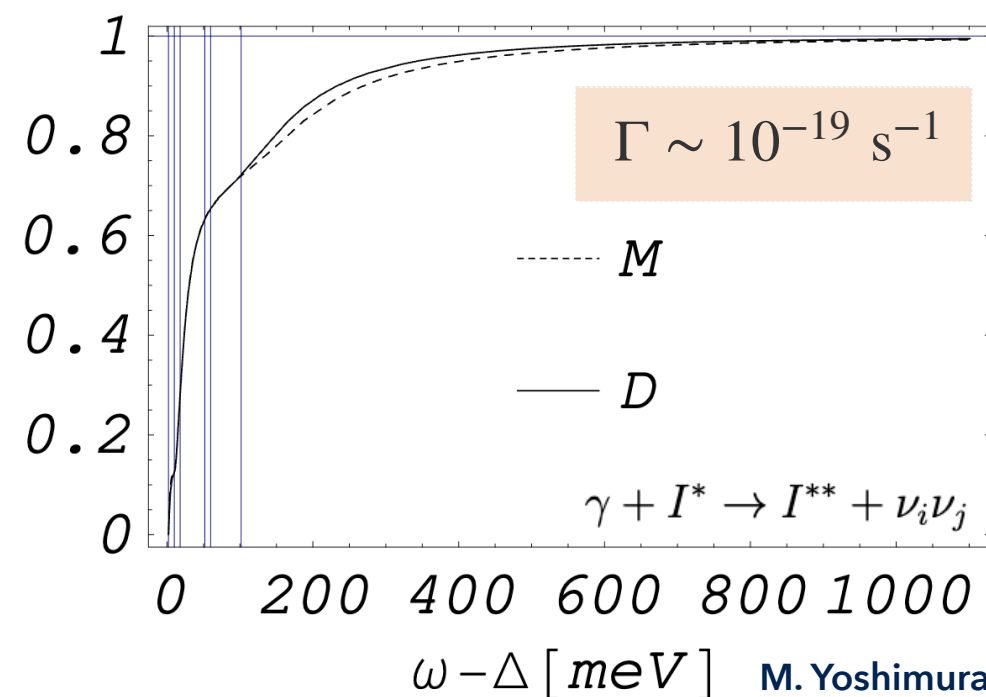


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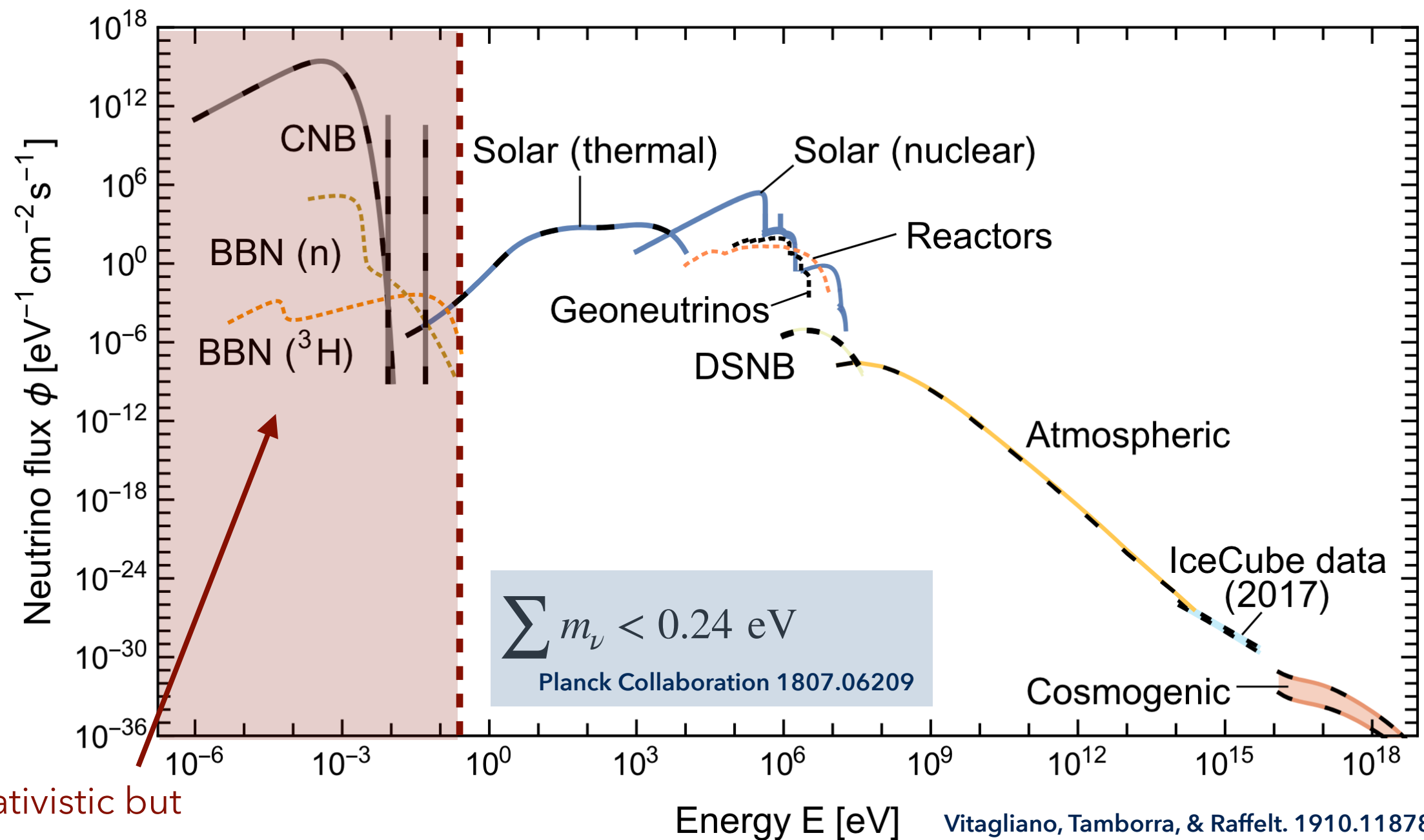
Berryman, de Gouvêa, Kelly, & Schmitt 1805.10294



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

Vitagliano, Tamborra, & Raffelt. 1910.11878

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

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

Recall that...

$$\psi(x) = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\vec{p}}}} \sum_s \left[\underbrace{a_{\vec{p},s}}_{\text{annihilate a fermion}} u(\vec{p}, s) e^{-ip \cdot x} + \underbrace{b_{\vec{p},s}^\dagger}_{\text{create an anti-fermion}} v(\vec{p}, s) e^{+ip \cdot x} \right]$$

Dirac vs Majorana: ultra-relativistic neutrinos

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

	create: $e^-, \bar{\nu}_e$	create: e^+, ν_e
Dirac	absorb: e^+, ν_e	absorb: $e^-, \bar{\nu}_e$
	$\mathcal{L}_{cc} \supset -\frac{g}{\sqrt{2}} \bar{e} \gamma^\lambda \frac{1-\gamma_5}{2} \nu W_\lambda^- - \frac{g}{\sqrt{2}} \bar{\nu} \gamma^\lambda \frac{1-\gamma_5}{2} e W_\lambda^+,$	
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: $W^+ \rightarrow e^+ + \nu_e, \nu_e + N \xrightarrow{\text{CC}} e^- + X$

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

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

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

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

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

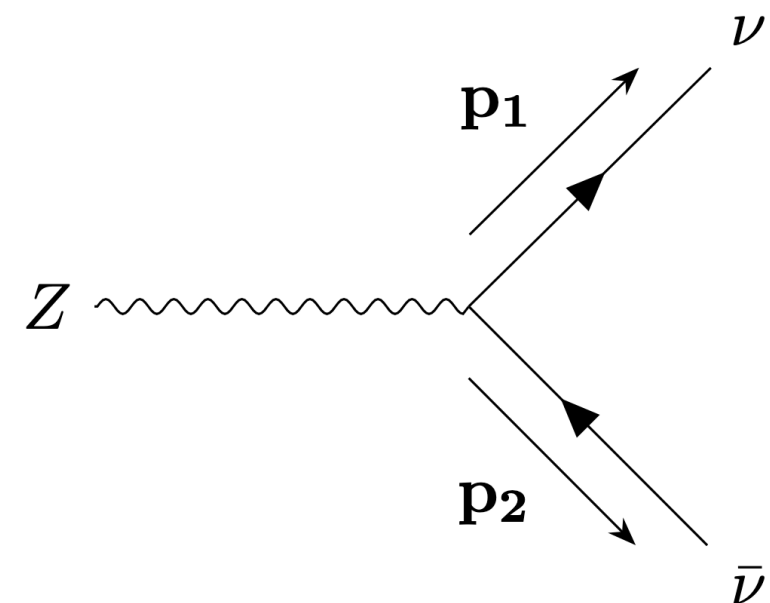
e.g.) $Z \rightarrow \nu \bar{\nu}$ R. E. Shrock, eConf C8206282

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

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

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

$$\rightarrow |\mathcal{M}^D|^2 - |\mathcal{M}^M|^2 = \frac{g_Z^2 m_\nu^2}{2}$$



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Confirmed in many processes:

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

...

C. S. Kim, 2307.05654

Akhmedov & Trautner, 2402.05172

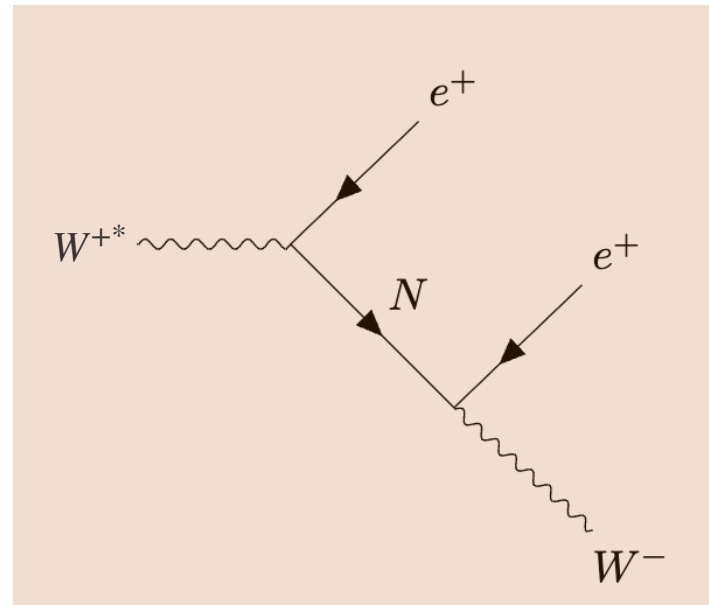
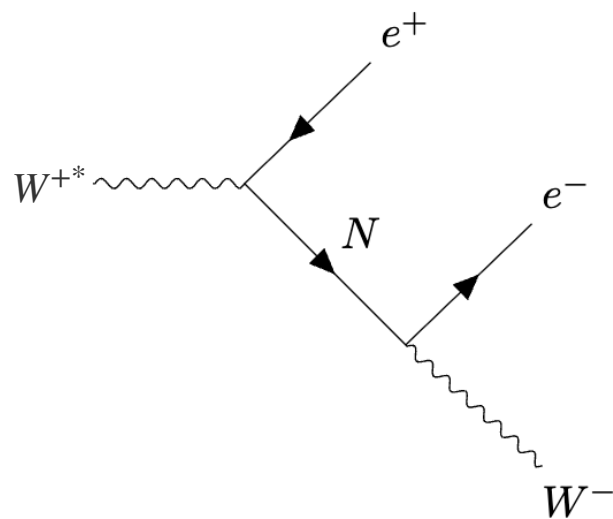
Bigaran, Parke, & Pasquini. 2507.xxxx

Heavy neutral lepton decay

Heavy neutral lepton N is more likely produced as a non-relativistic particle,
→ offers higher chance to distinguish Dirac from Majorana

- lepton number violating interaction

e.g.) $W^{+*} \rightarrow e^+ + N, N \rightarrow e + W, \dots$



this process is
possible only
if N is Majorana

→ difficult to detect because the detector might be insensitive to charge

- Angular distribution of decay products
- Lab frame energy distribution of decay products

Angular distribution of decay products

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

see, e.g., Kayser 1805.07523, Balantekin, A. de Gouvêa, and Kayser 1808.10518

e.g.) $\nu_1 \rightarrow \nu_2 + \gamma$

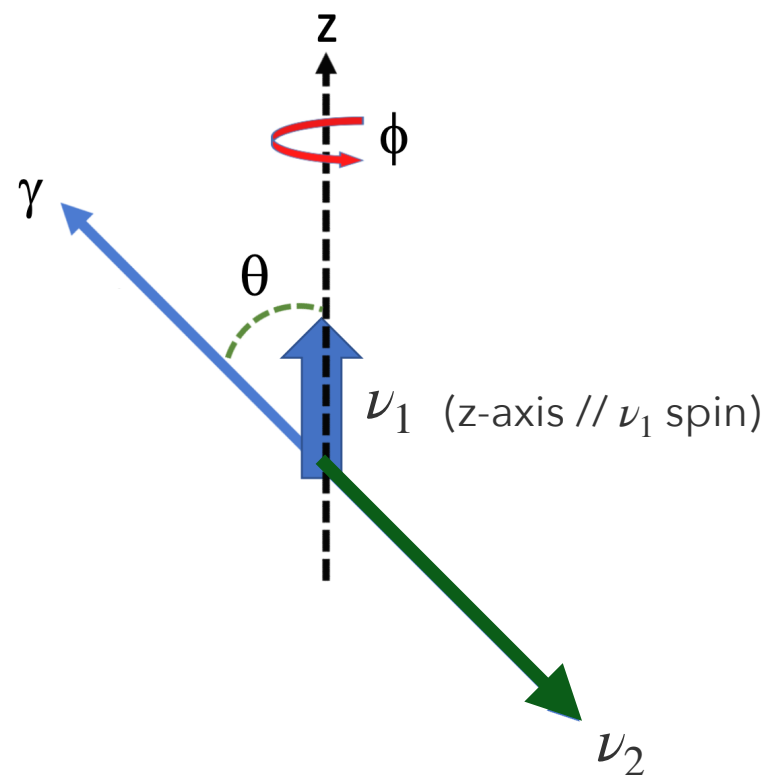


figure: A. B. Balantekin & B. Kayser, 1805.00922

Neutrinos are Majorana $\rightarrow$ isotropic distribution of ν_1 in the rest frame of ν_2

Neutrinos are Dirac $\rightarrow$ anisotropic distribution, forward/backward direction is preferred
depending on a helicity of ν_2

Angular distribution of decay products

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

see, e.g., Kayser 1805.07523, Balantekin, A. de Gouvêa, and Kayser 1808.10518

Consider the decay process $\nu_i \rightarrow \nu_j + X$ (X : self-conjugate $\bar{X} = X$)

$$\frac{d\Gamma(\nu_i \rightarrow \nu_j + X)}{d(\cos \theta)} = \frac{\Gamma}{2}(1 + \alpha \cos \theta)$$

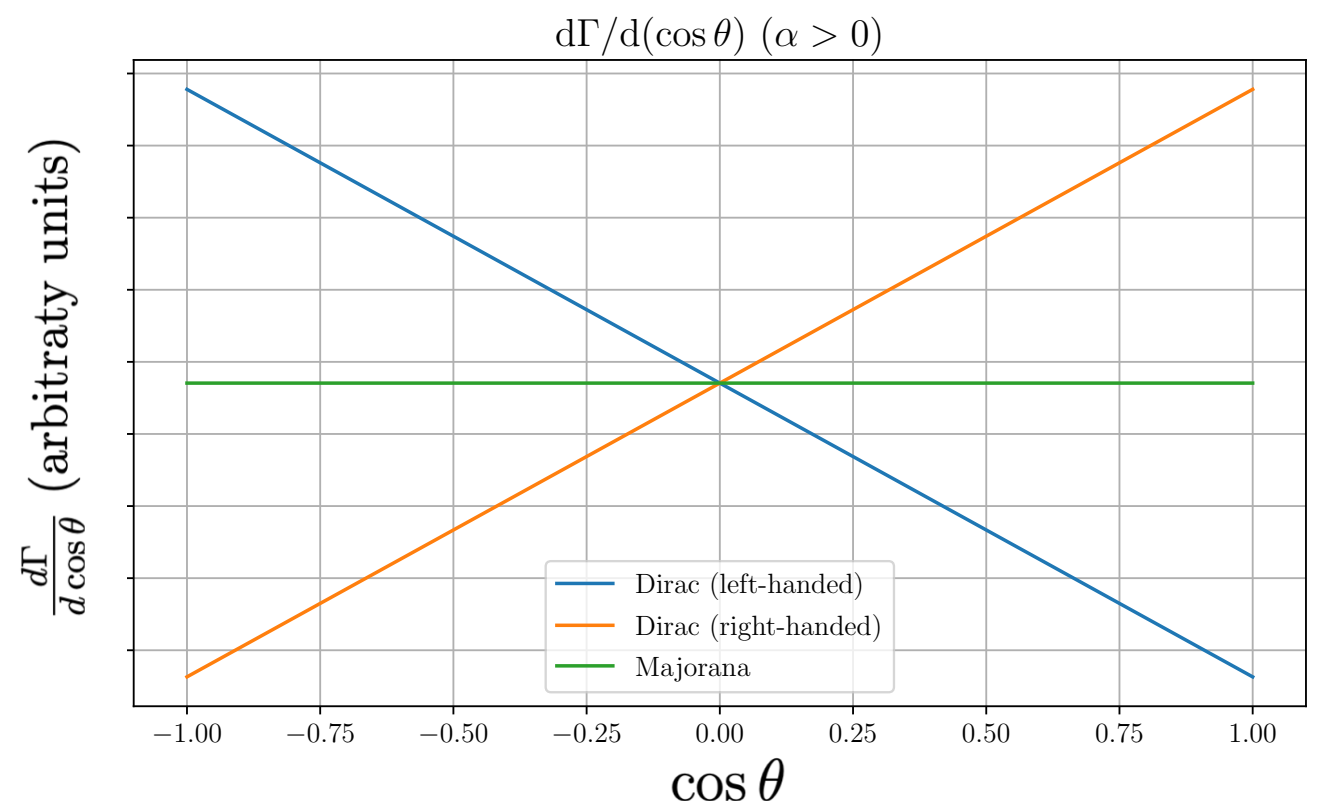
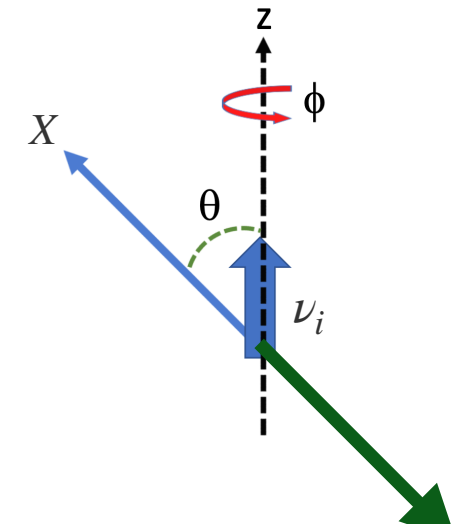
$$\frac{d\Gamma(\bar{\nu}_i \rightarrow \bar{\nu}_j + X)}{d(\cos \theta)} = \frac{\bar{\Gamma}}{2}(1 + \bar{\alpha} \cos \theta)$$

CPT invariance requires

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

in the lowest order of perturbations
(if neutrinos are Majorana)

$\rightarrow \alpha = 0$ if neutrinos are Majorana



Angular distribution of decay products

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

see, e.g., Kayser 1805.07523, Balantekin, A. de Gouvêa, and Kayser 1808.10518

Two types of scenarios studied

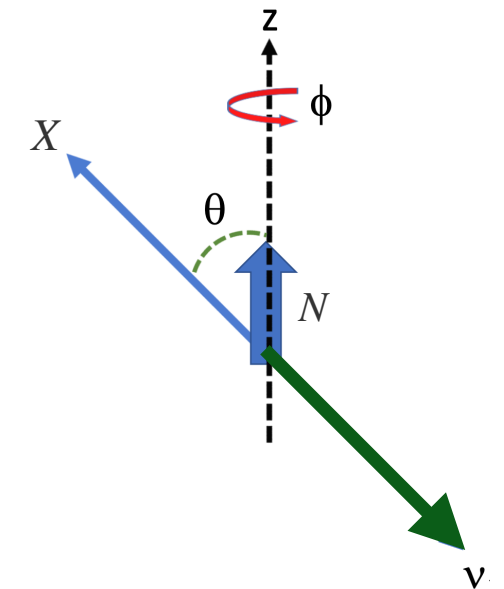
1. $N \rightarrow \nu_i + X$

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

X	γ	π^0	ρ^0	Z^0	H^0
α	$\frac{2\Im m(\mu d^*)}{ \mu ^2 + d ^2}$	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. $N \rightarrow \nu_i + X$, $X = l_\alpha^- + l_\beta^+$ ($\alpha \neq \beta$) A. de Gouvêa et al., 2104.05719

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

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

Angular distribution of decay products

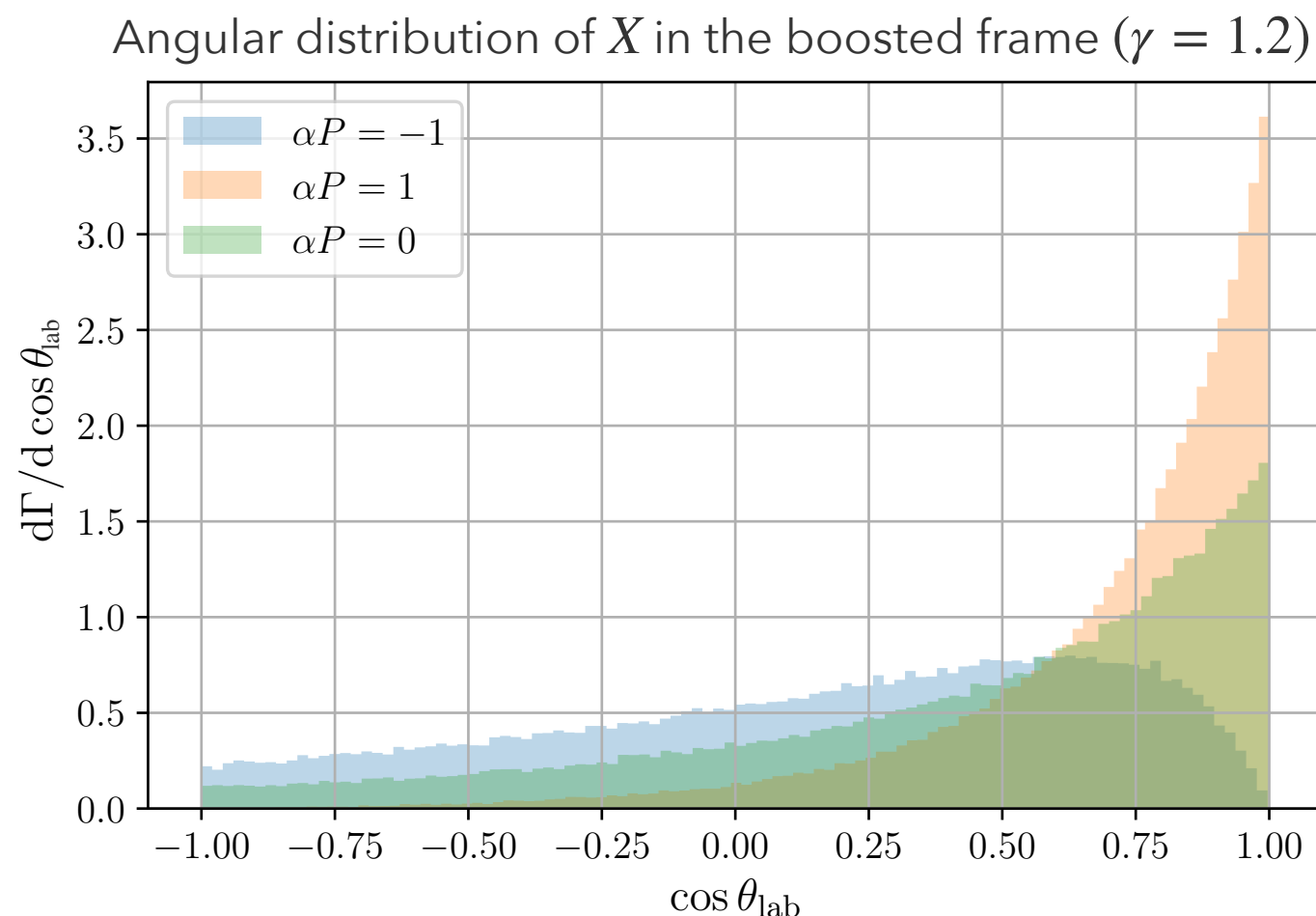
Angular distribution of decay products might shed light on the nature of neutrinos

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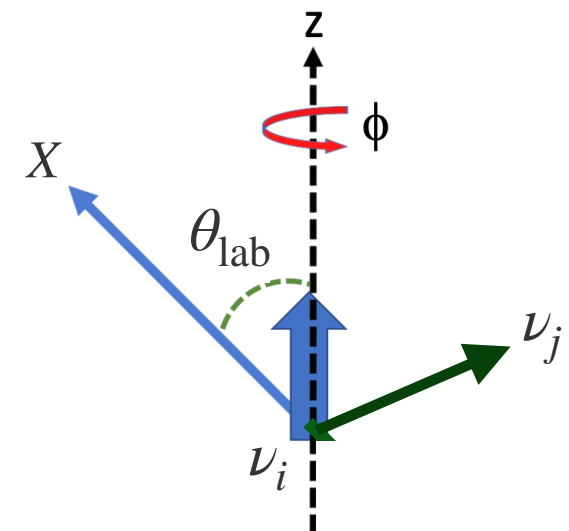
Lab frame angular distribution depends on...

- α : decay asymmetry parameter ($\alpha = 0$ for Majorana, $\alpha \in [-1, 1]$ for Dirac)
- 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



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

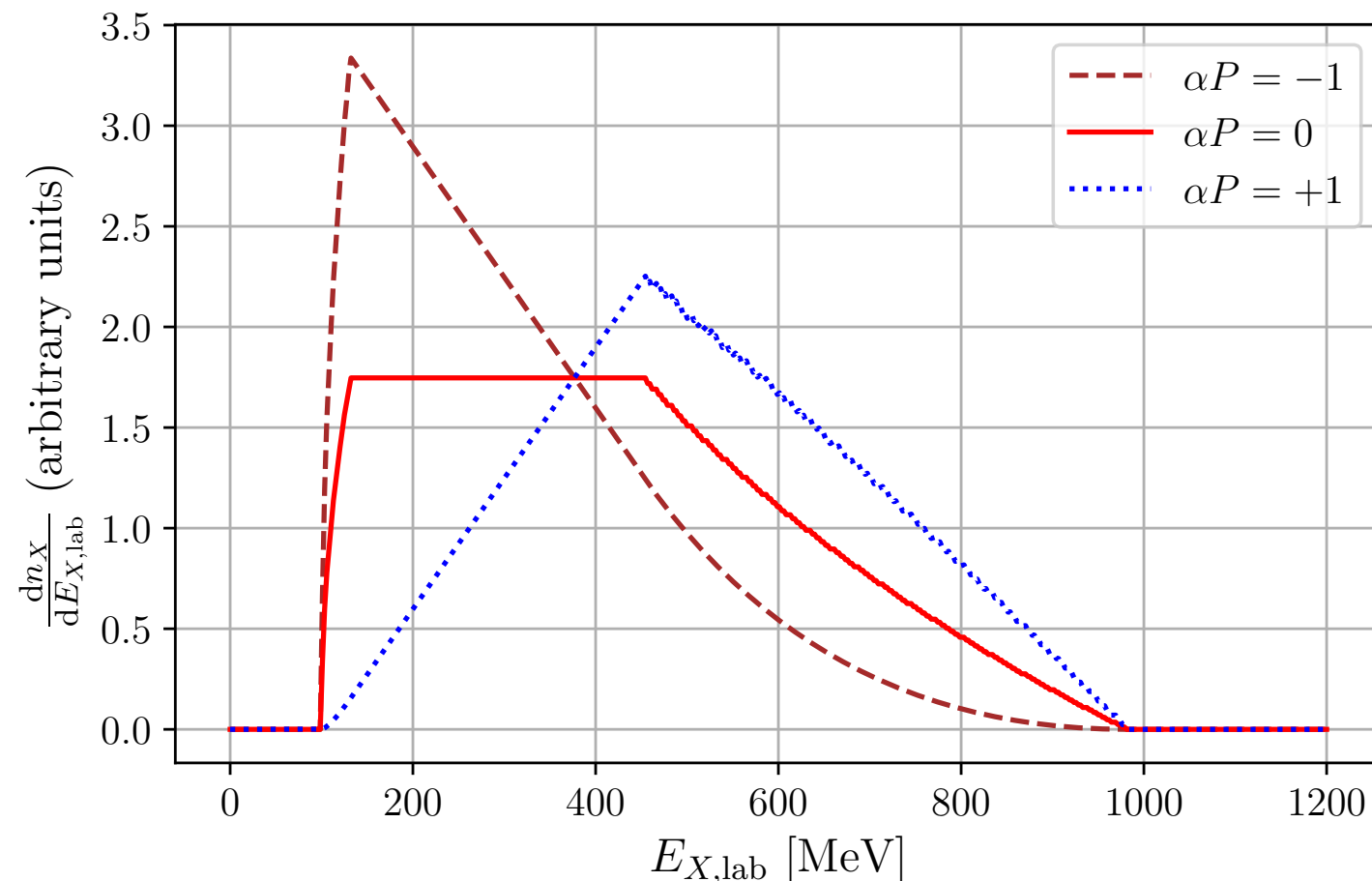


Energy distribution of decay products

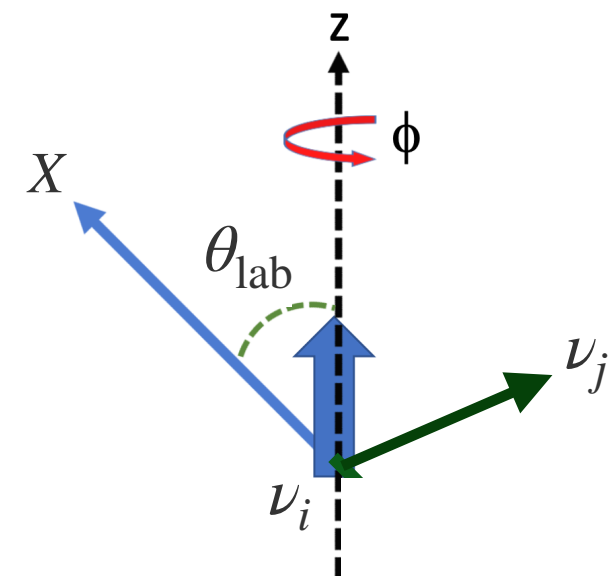
Energy distribution of decay products in the lab frame might also be helpful

Lab frame energy distribution also depends on...

- α : decay asymmetry parameter ($\alpha = 0$ for Majorana, $\alpha \in [-1, 1]$ for Dirac)
- P : polarization of the N sample; $P = \frac{N_+ - N_-}{N_+ + N_-}$



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



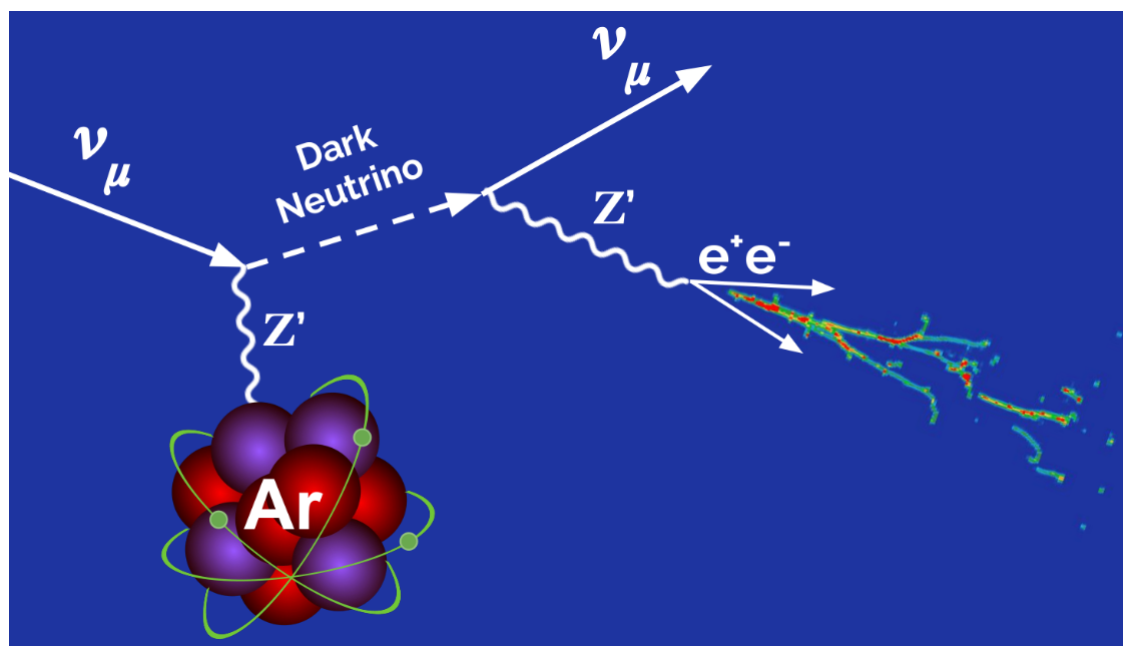
$$m_N = 300 \text{ MeV}, m_X = 100 \text{ MeV}$$

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

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

Asymmetry in dark neutrino decay

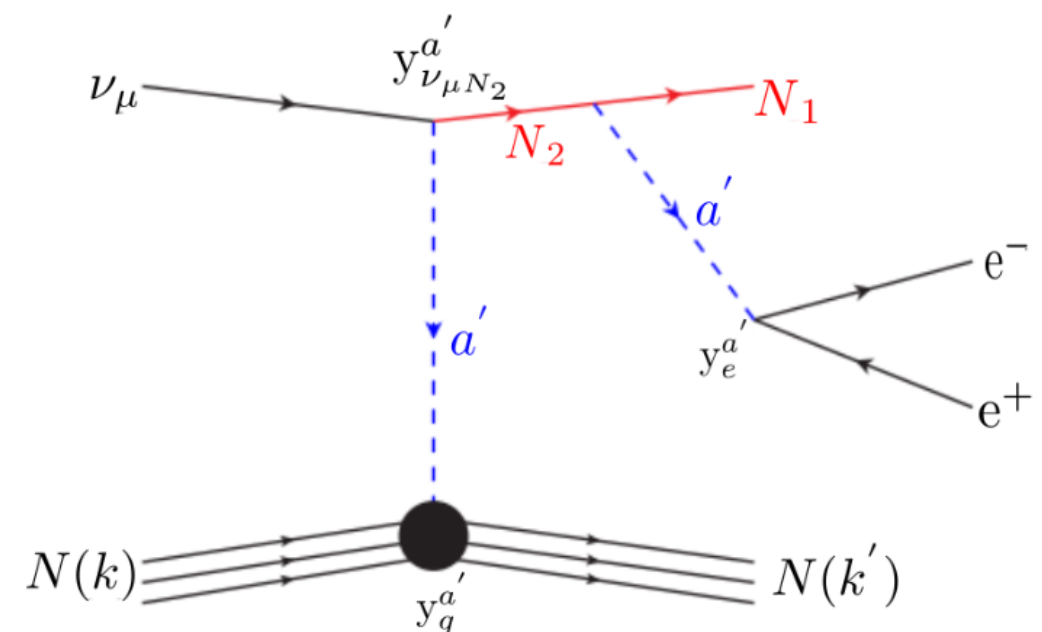
Consider a dark neutrino coupled to neutrinos and a dark scalar ϕ or vector Z'



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, MiniBooNE, and ATOMKI anomalies

Asymmetry in dark neutrino decay

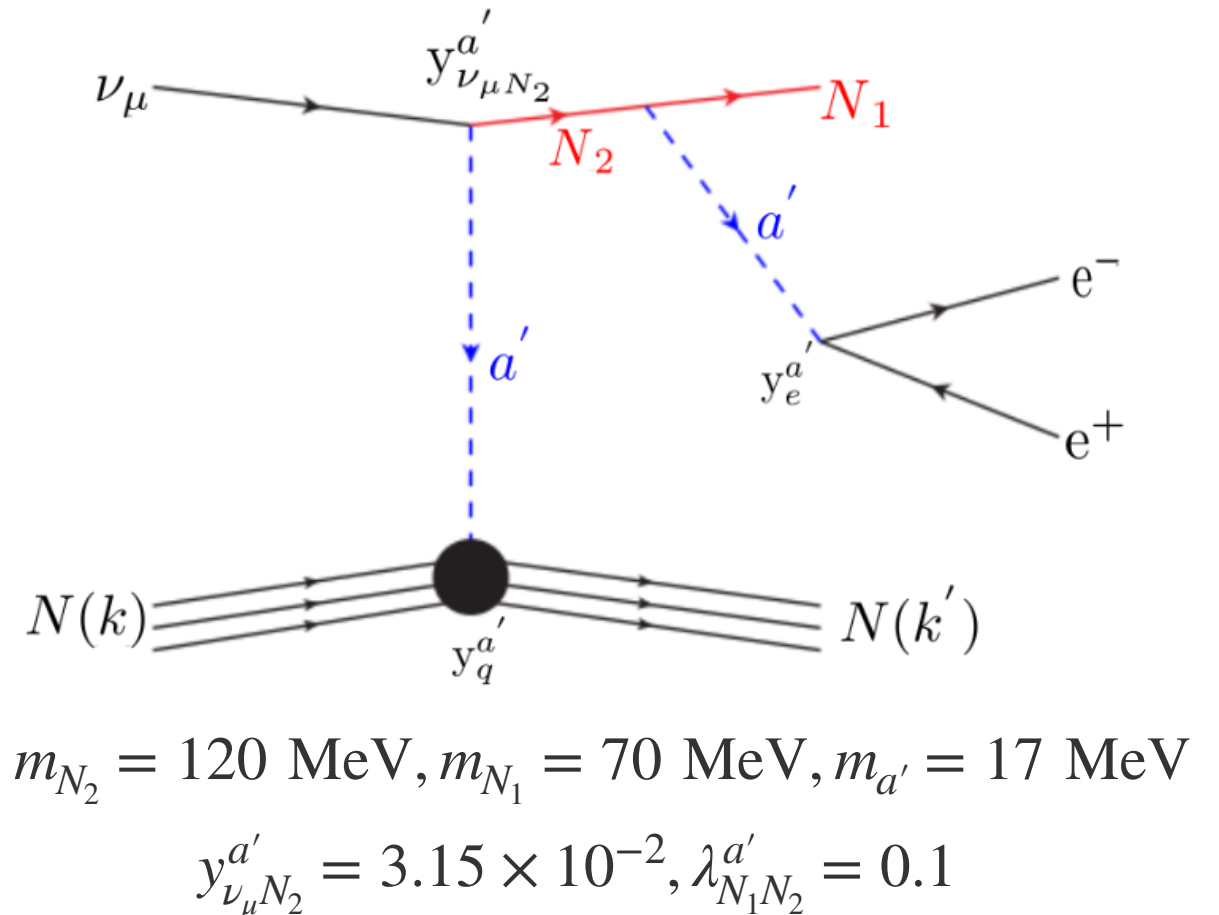
Consider a dark neutrino coupled to neutrinos and a dark scalar ϕ or vector Z' , and its decay $N_2 \rightarrow N_1 + \phi$ (or Z')

$$\mathcal{L}_{\text{int}} \supset \sum_{i,j}^{3+n} \phi \bar{\nu}_j \left(g_{ij}^S + i\gamma^5 g_{ij}^P \right) \nu_i \quad \mathcal{L}_{\text{int}} \supset \sum_{i,j}^{3+n} Z'_\mu \gamma^\mu \bar{\nu}_j (g_{ij}^V - g_{ij}^A \gamma^5) \nu_i$$

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

Goals:

- Study the asymmetry of angular/energy distributions of ϕ/Z' by varying parameters (mass, coupling, energy distribution of parent particles)
- Using the model in 2406.07643 as a benchmark model, check whether short baseline experiments can distinguish Dirac and Majorana neutrinos



Spin-0 case

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

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

Benchmark model:

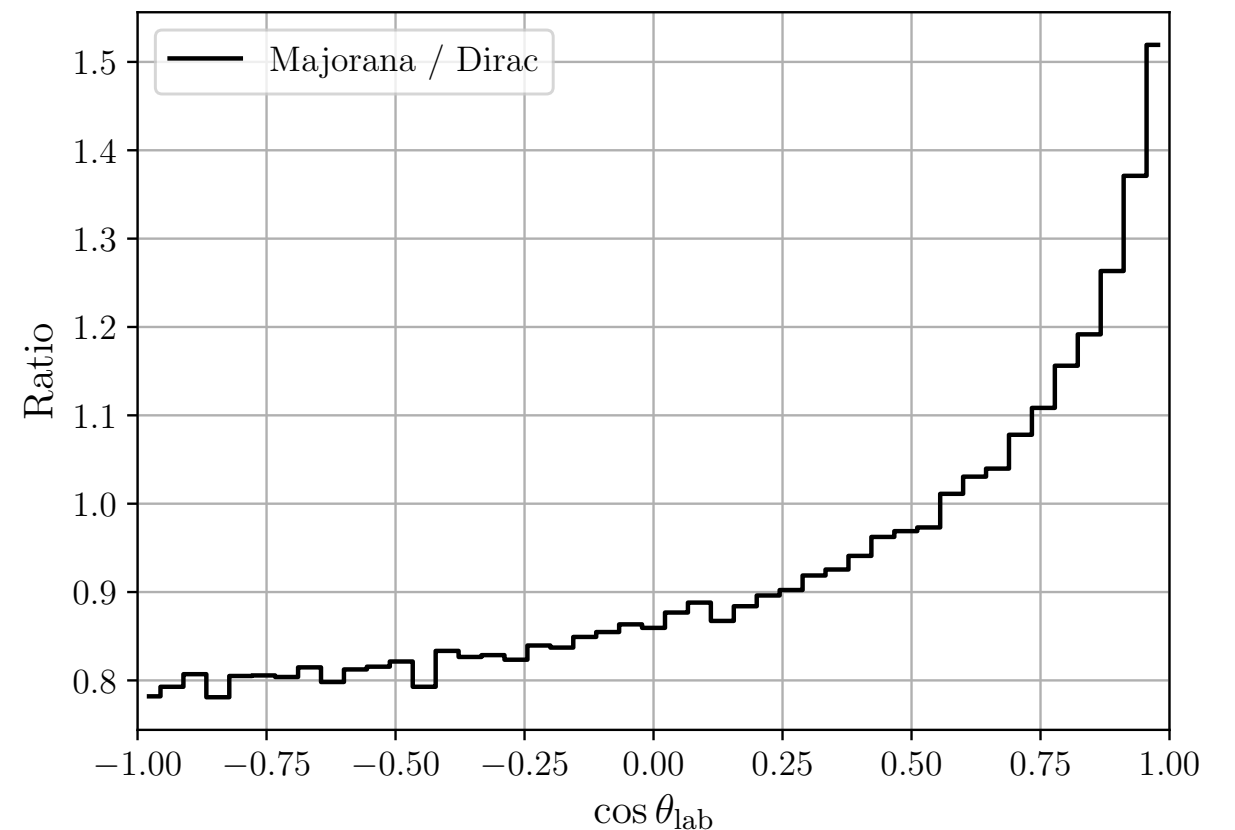
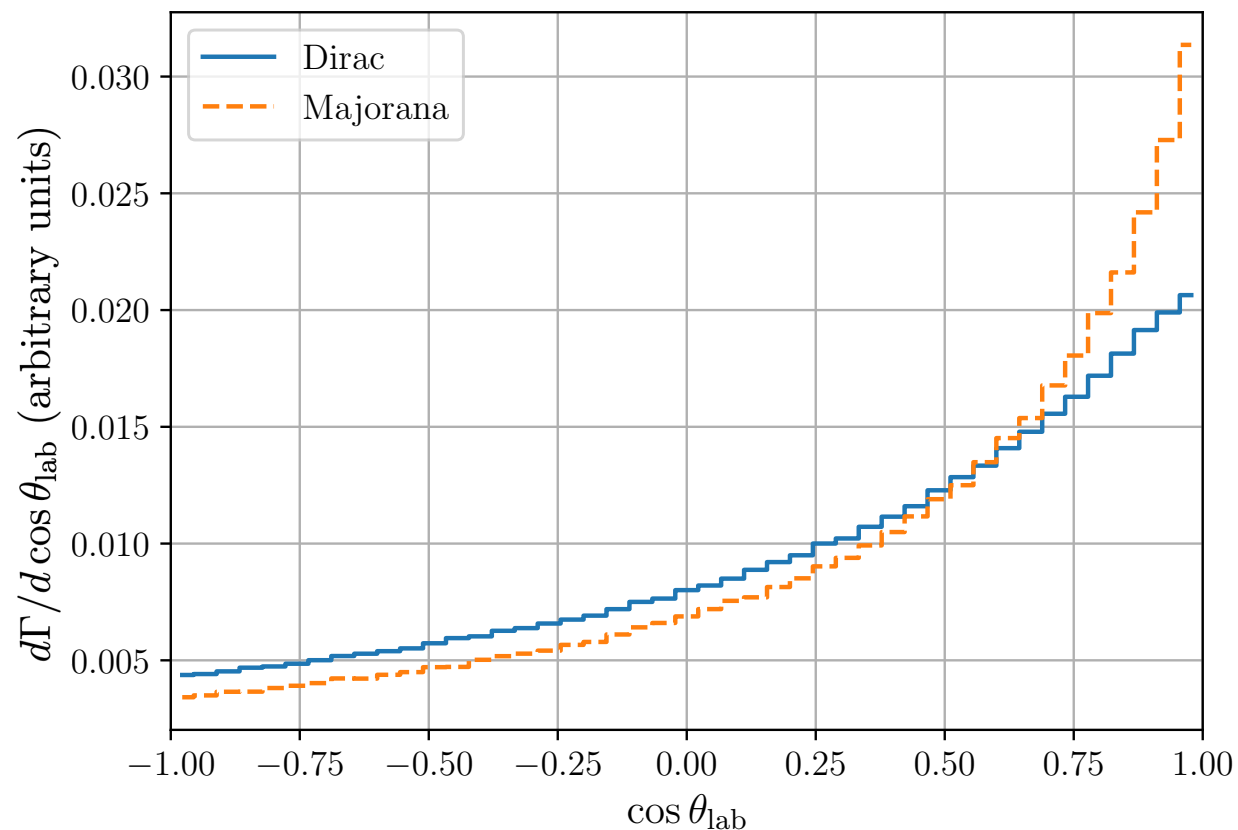
$$m_{N_2} = 120 \text{ MeV}, m_{N_1} = 70 \text{ MeV}, m_{a'} = 17 \text{ MeV}$$

$$g_S = 1, g_P = i$$

$$\rightarrow \alpha = 0.66$$

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

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



Spin-0 case

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

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Benchmark model:

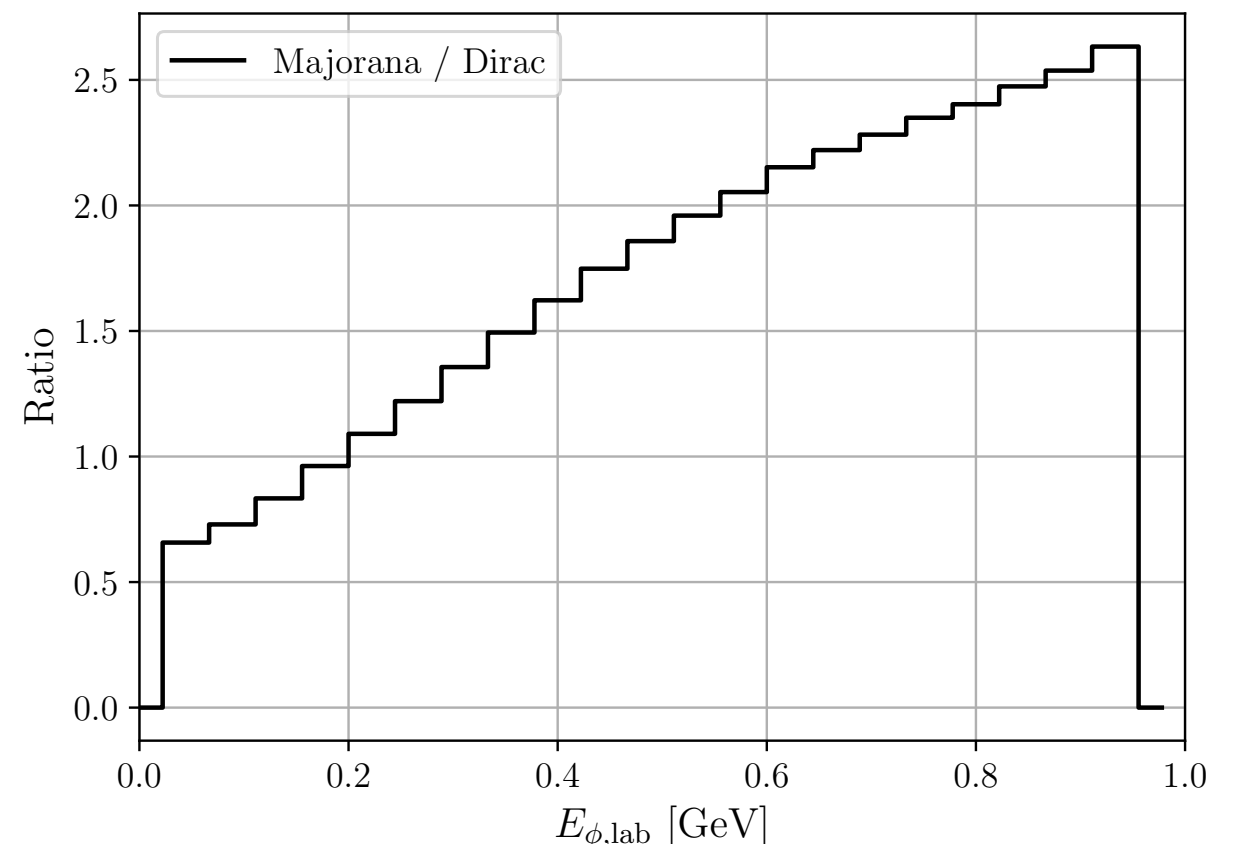
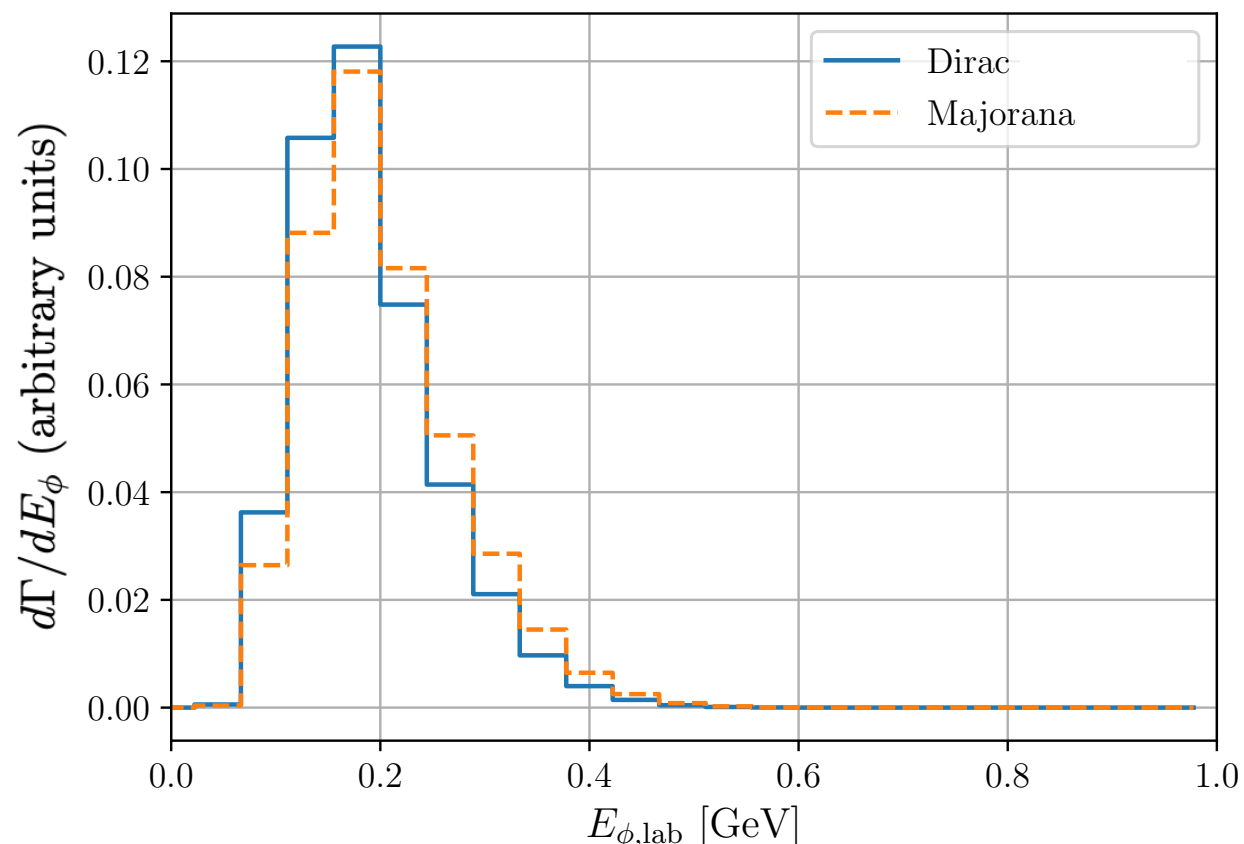
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Energy distribution (left) and Majorana-to-Dirac ratio (right)



Spin-1 case

$$\mathcal{L}_{\text{int}} \supset \sum_{i,j}^{3+n} Z'_\mu \gamma^\mu \bar{\nu}_j (g_{ij}^V - g_{ij}^A \gamma^5) \nu_i$$

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

Benchmark model:

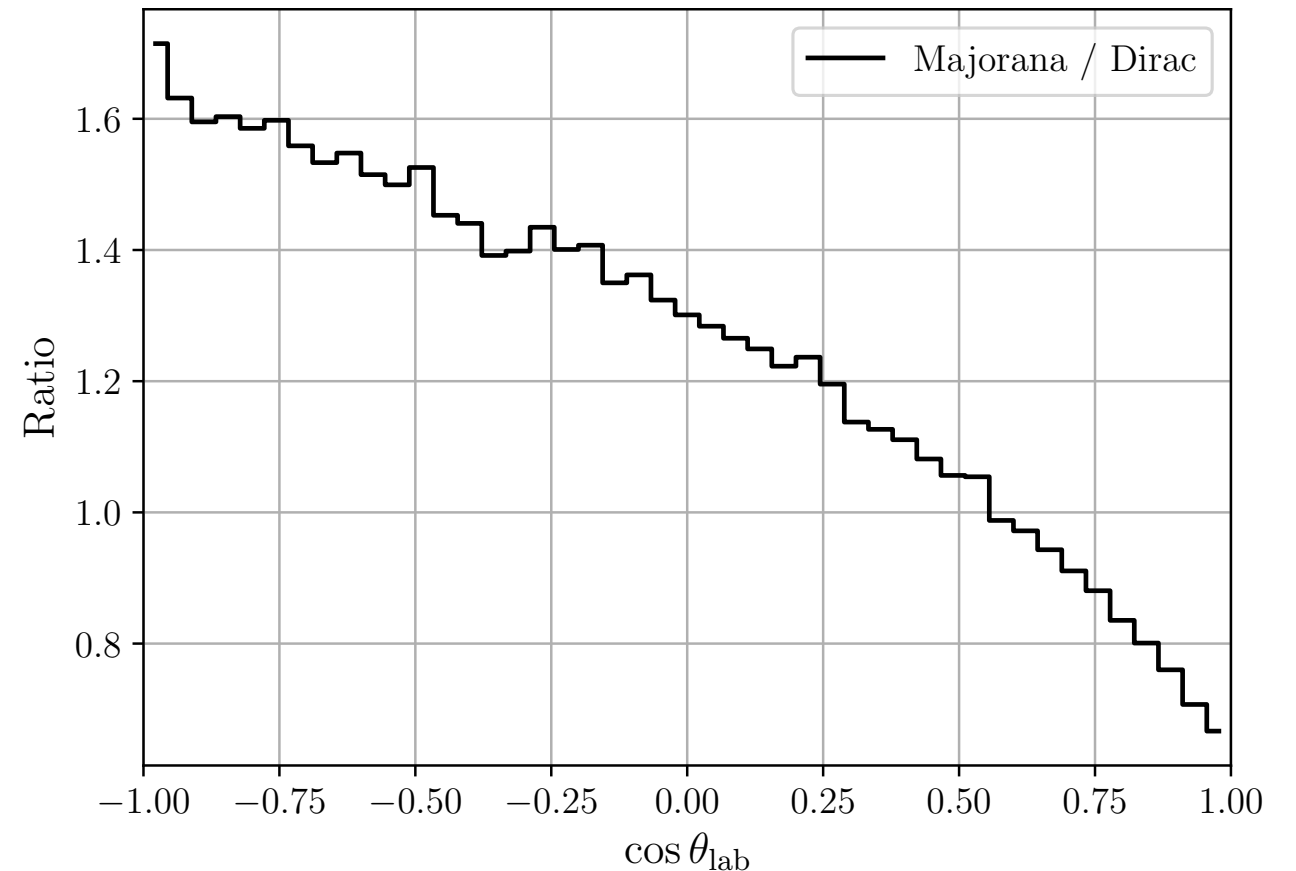
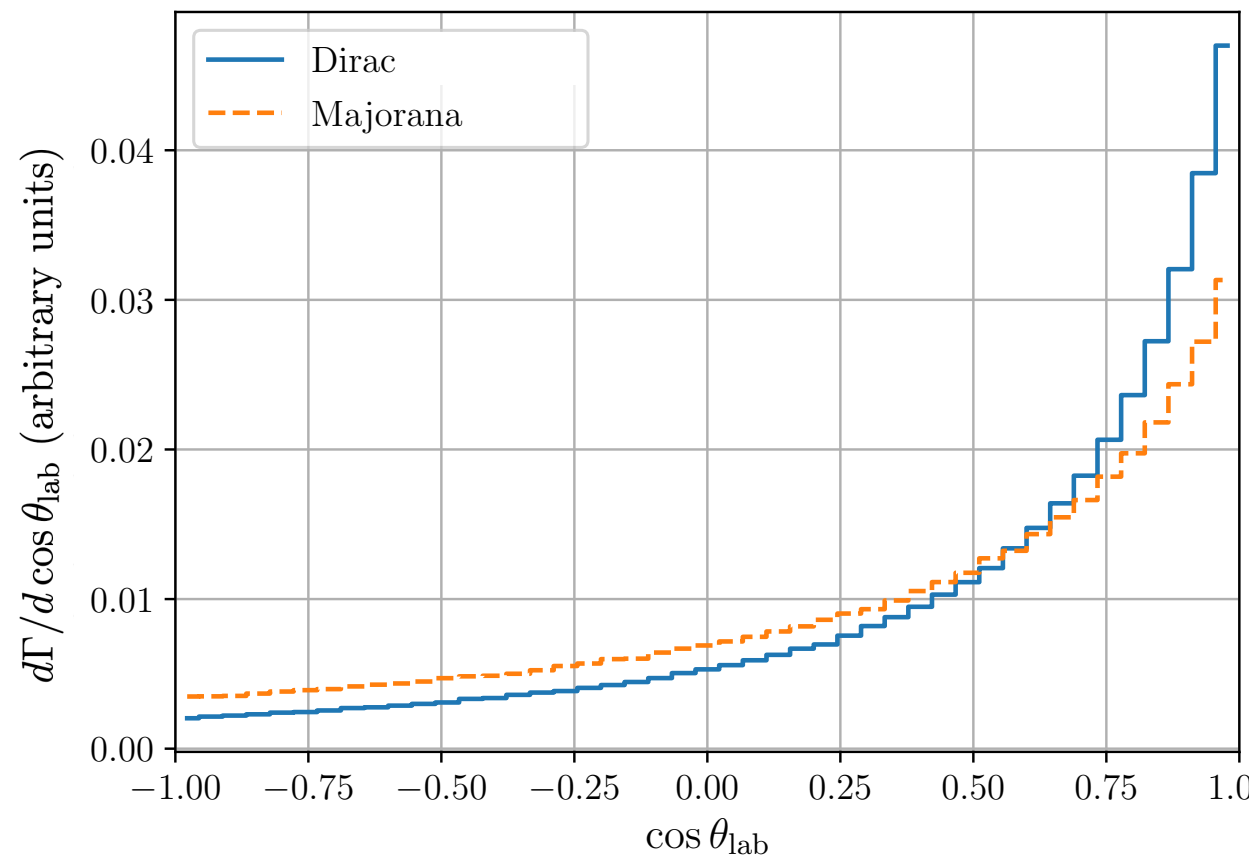
$$m_{N_2} = 120 \text{ MeV}, m_{N_1} = 70 \text{ MeV}, m_{a'} = 17 \text{ MeV}$$

$$g_V = g_A = 1$$

$$\rightarrow \alpha = -0.98$$

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

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



Spin-1 case

$$\mathcal{L}_{\text{int}} \supset \sum_{i,j}^{3+n} Z'_\mu \gamma^\mu \bar{\nu}_j (g_{ij}^V - g_{ij}^A \gamma^5) \nu_i$$

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

Benchmark model:

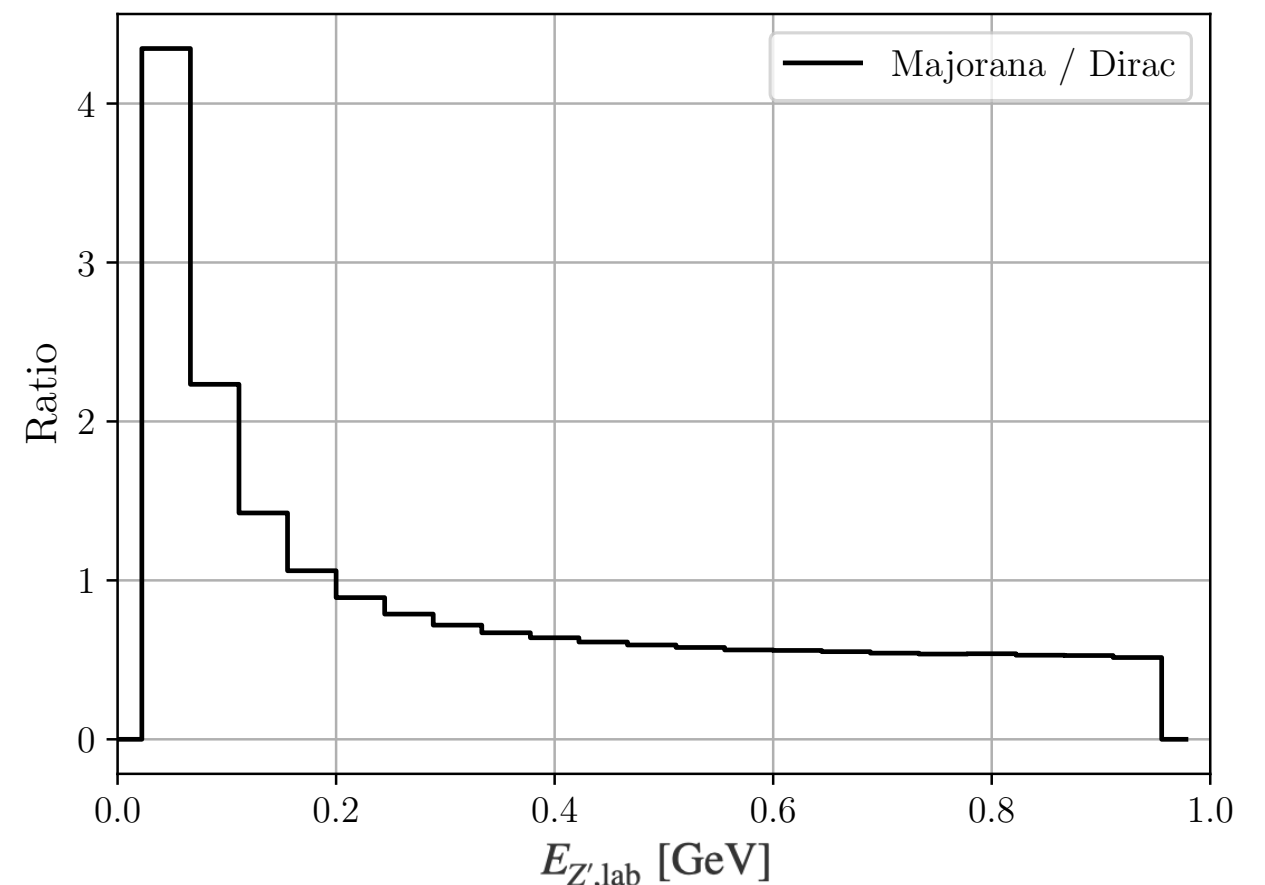
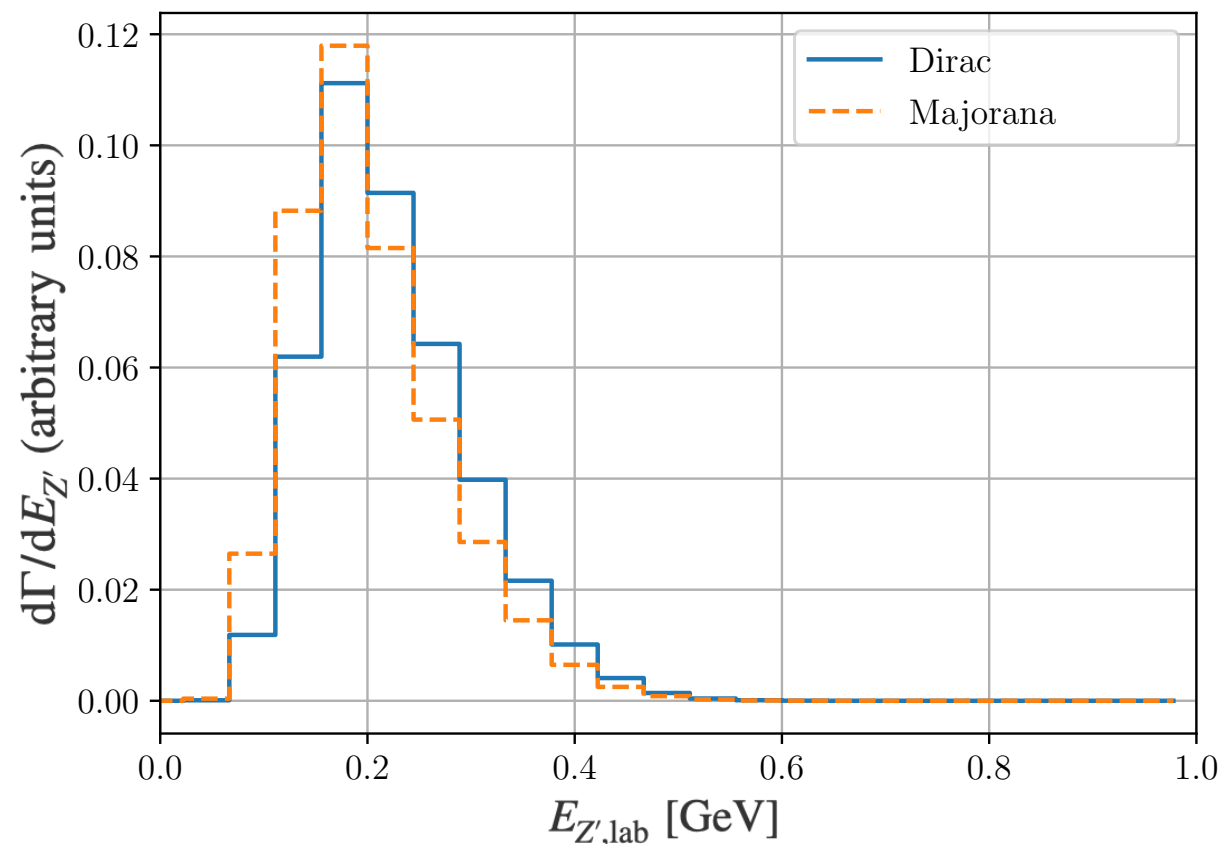
$$m_{N_2} = 120 \text{ MeV}, m_{N_1} = 70 \text{ MeV}, m_{a'} = 17 \text{ MeV}$$

$$g_V = g_A = 1$$

$$\rightarrow \alpha = -0.98$$

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

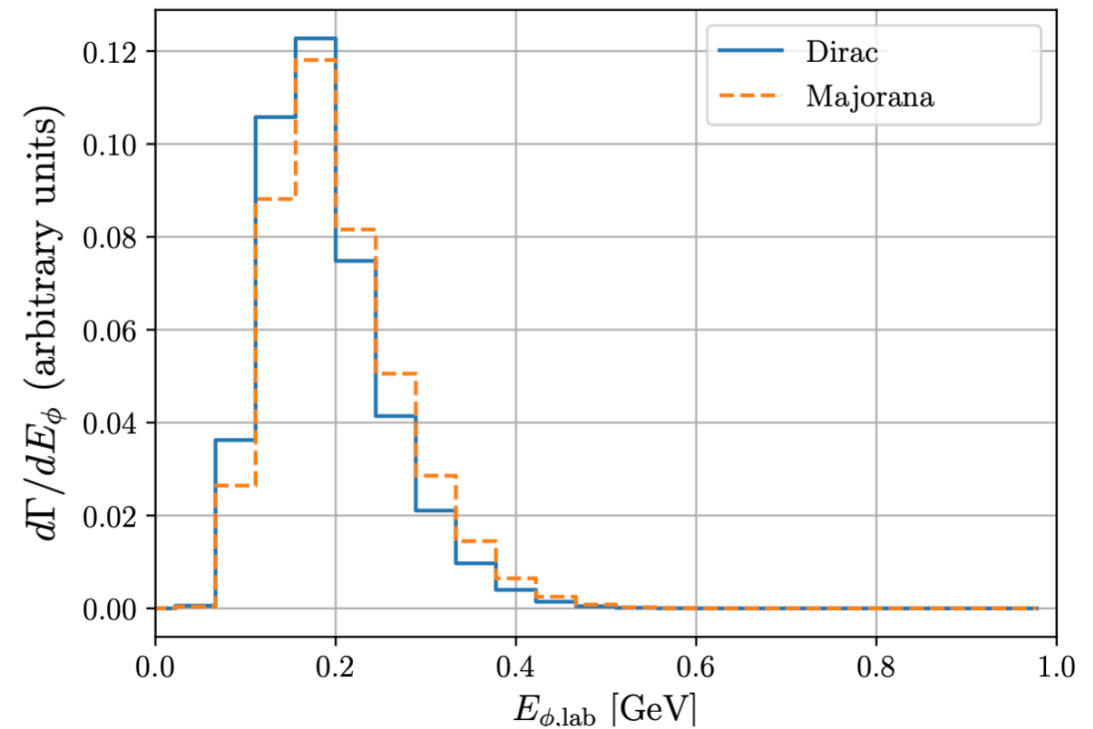
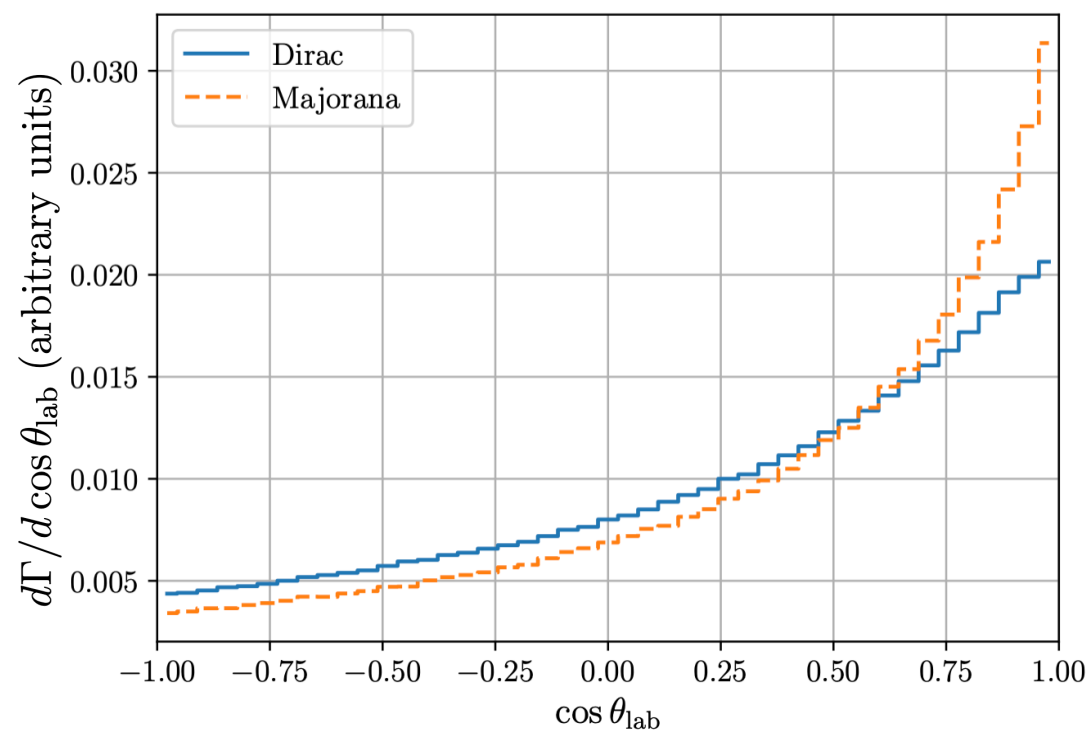
Energy distribution (left) and Majorana-to-Dirac ratio (right)



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

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

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

- Depends only on g_S/g_P or g_V/g_A

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

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

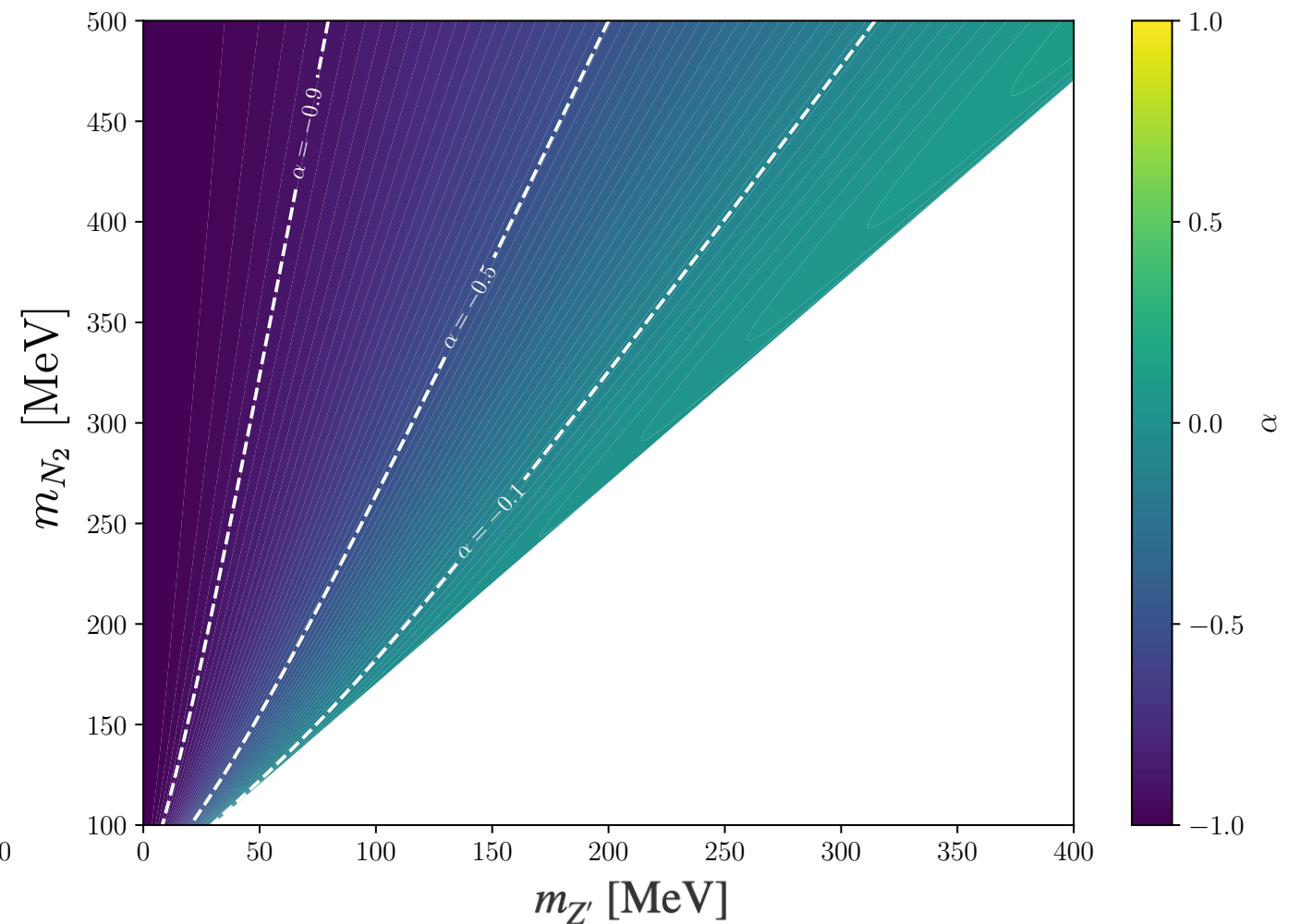
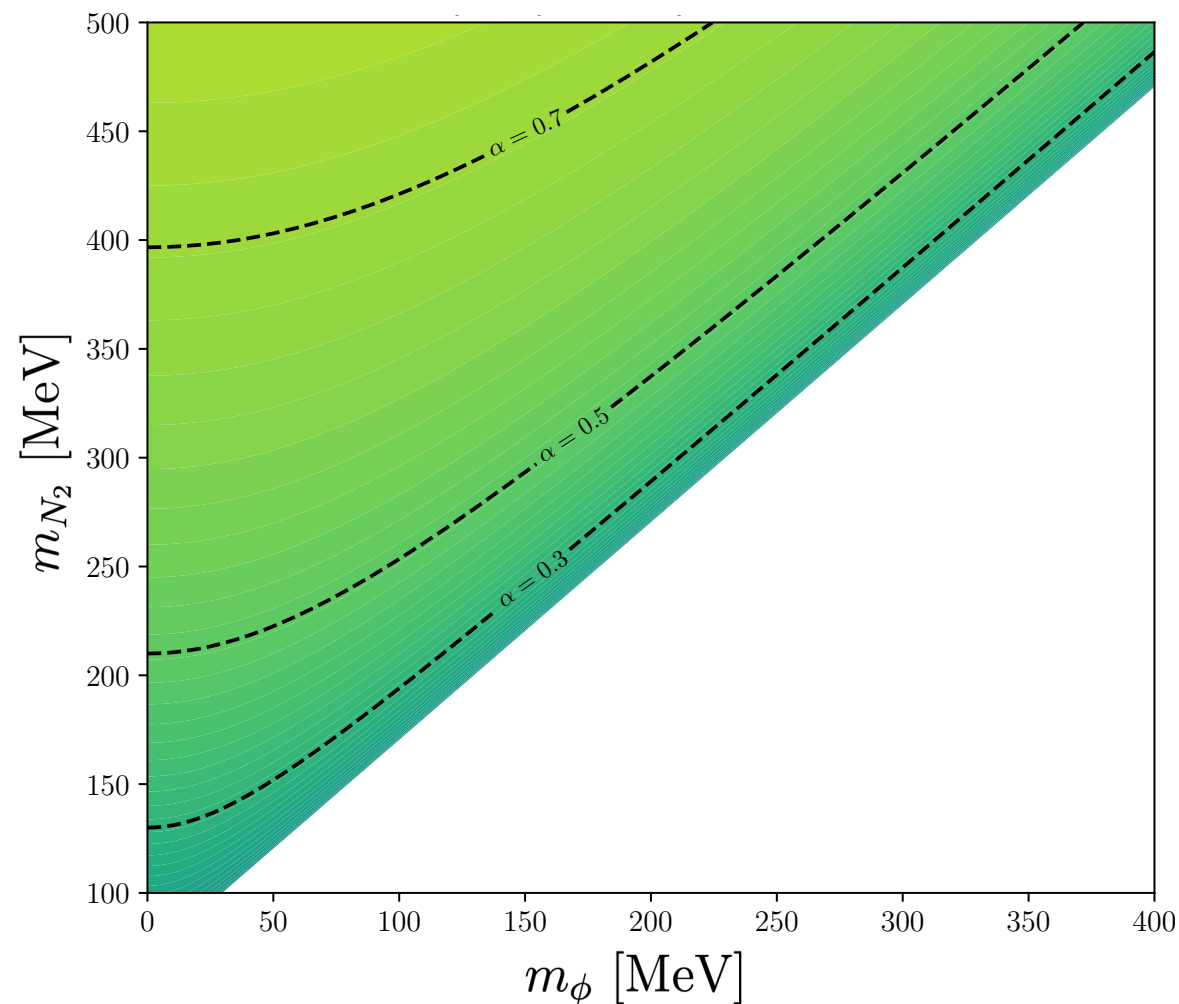
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- Depends only on g_S/g_P or g_V/g_A



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

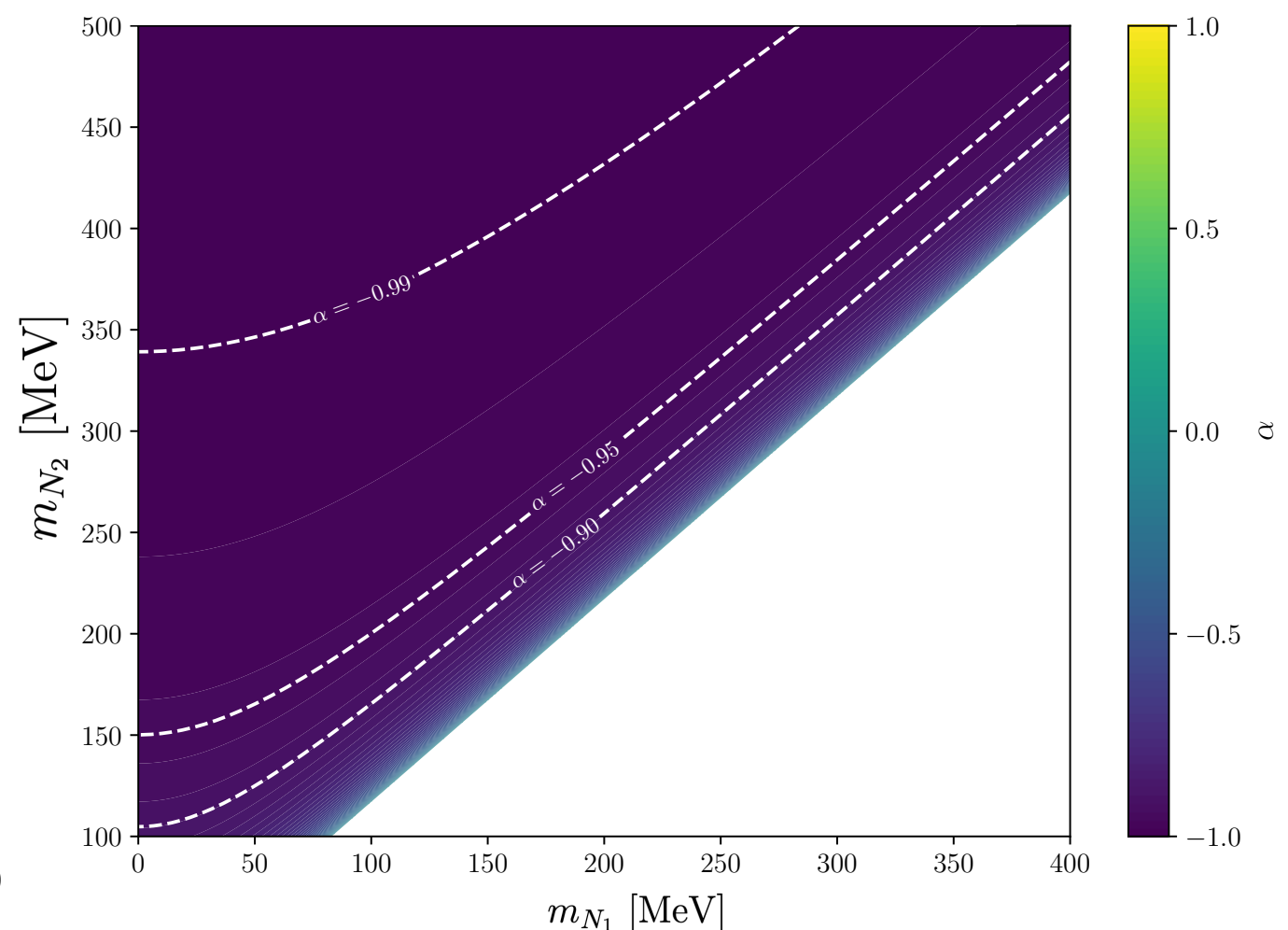
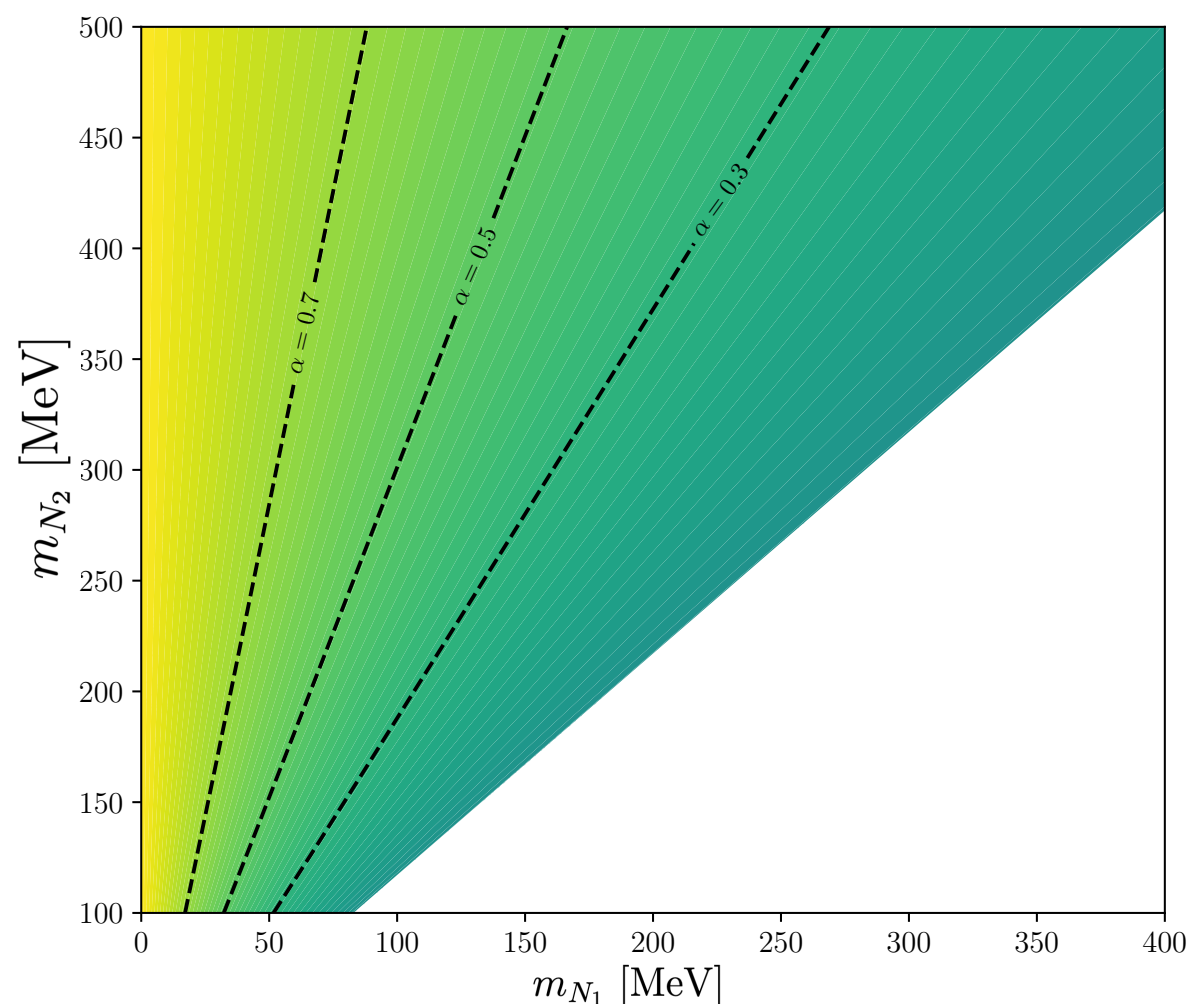
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- Depends only on g_S/g_P or g_V/g_A



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

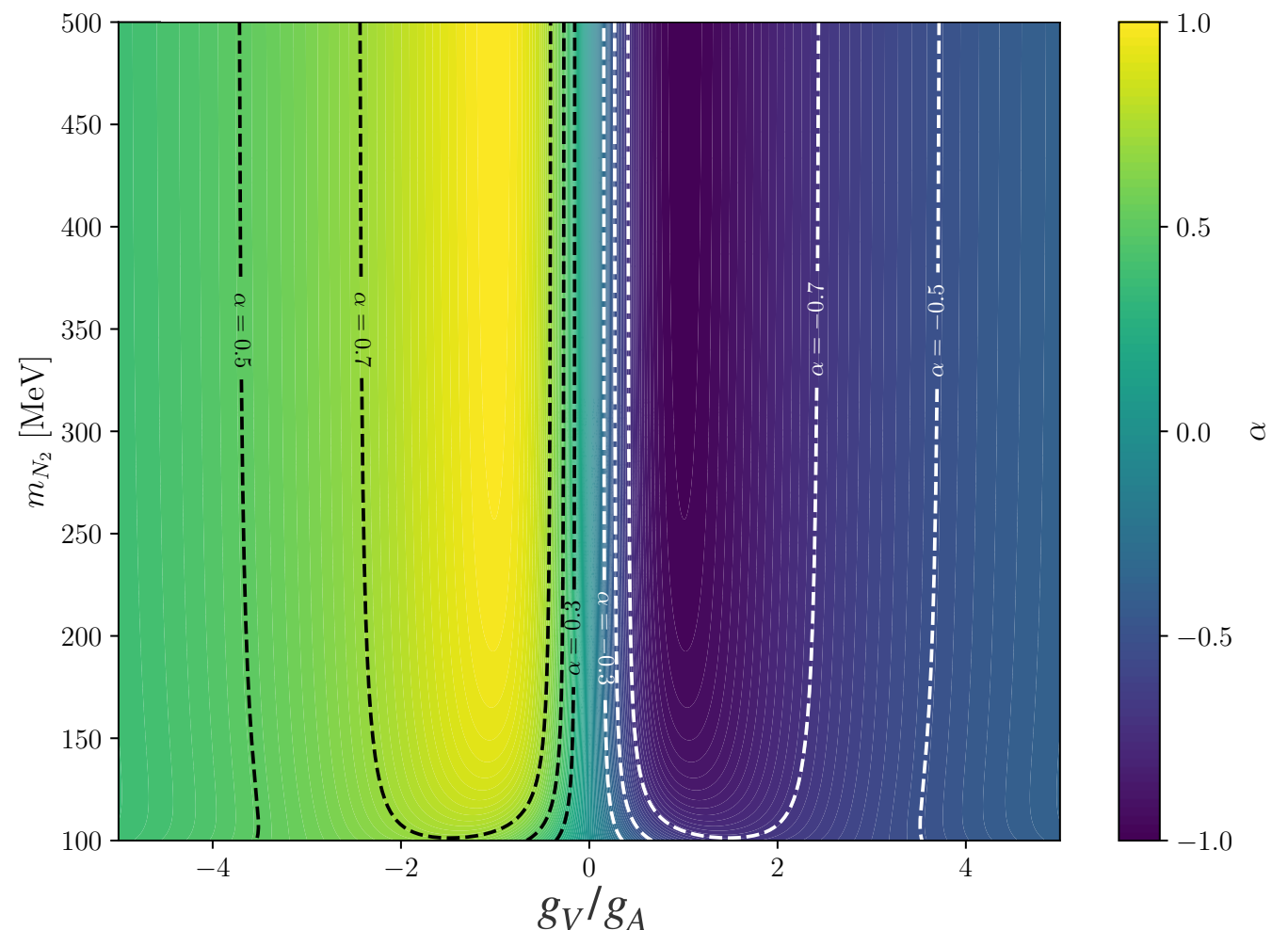
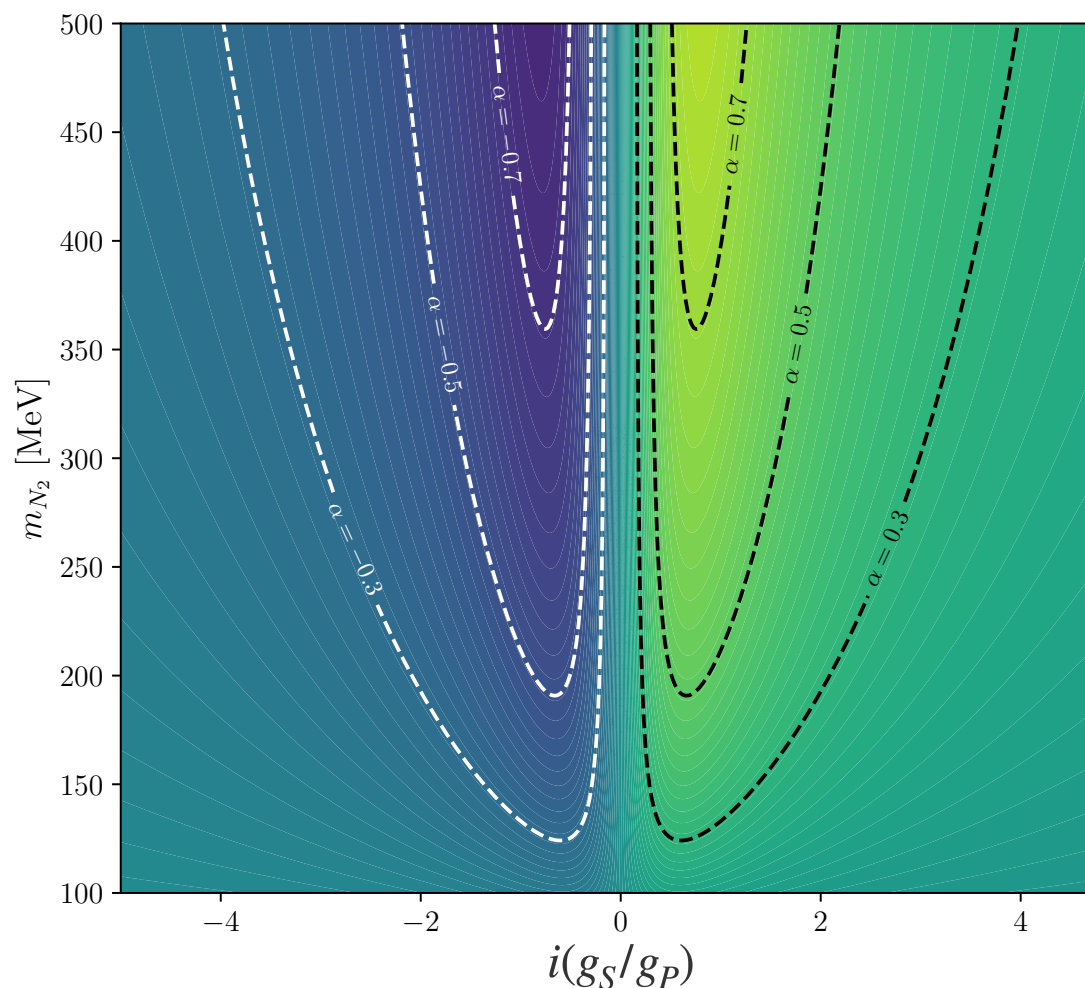
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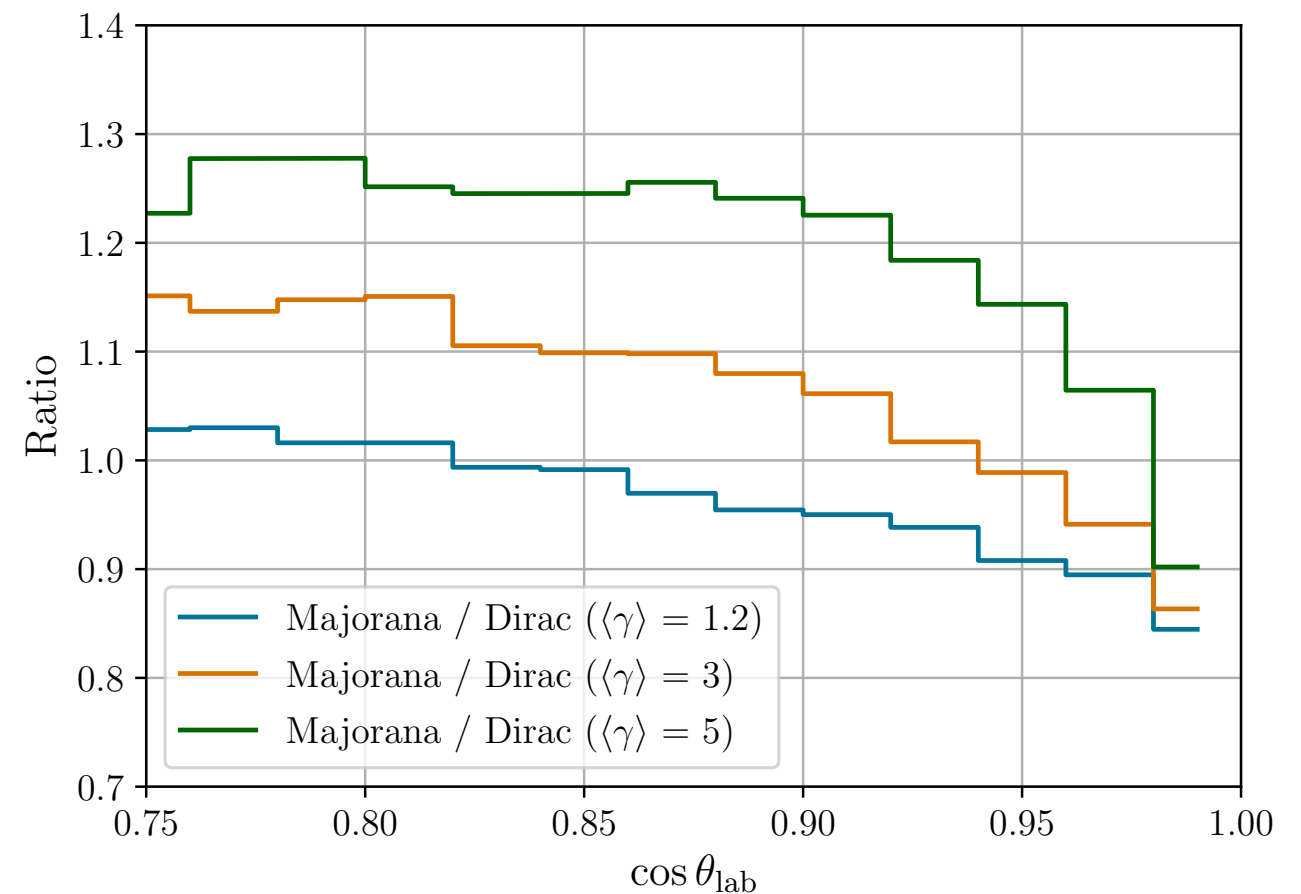
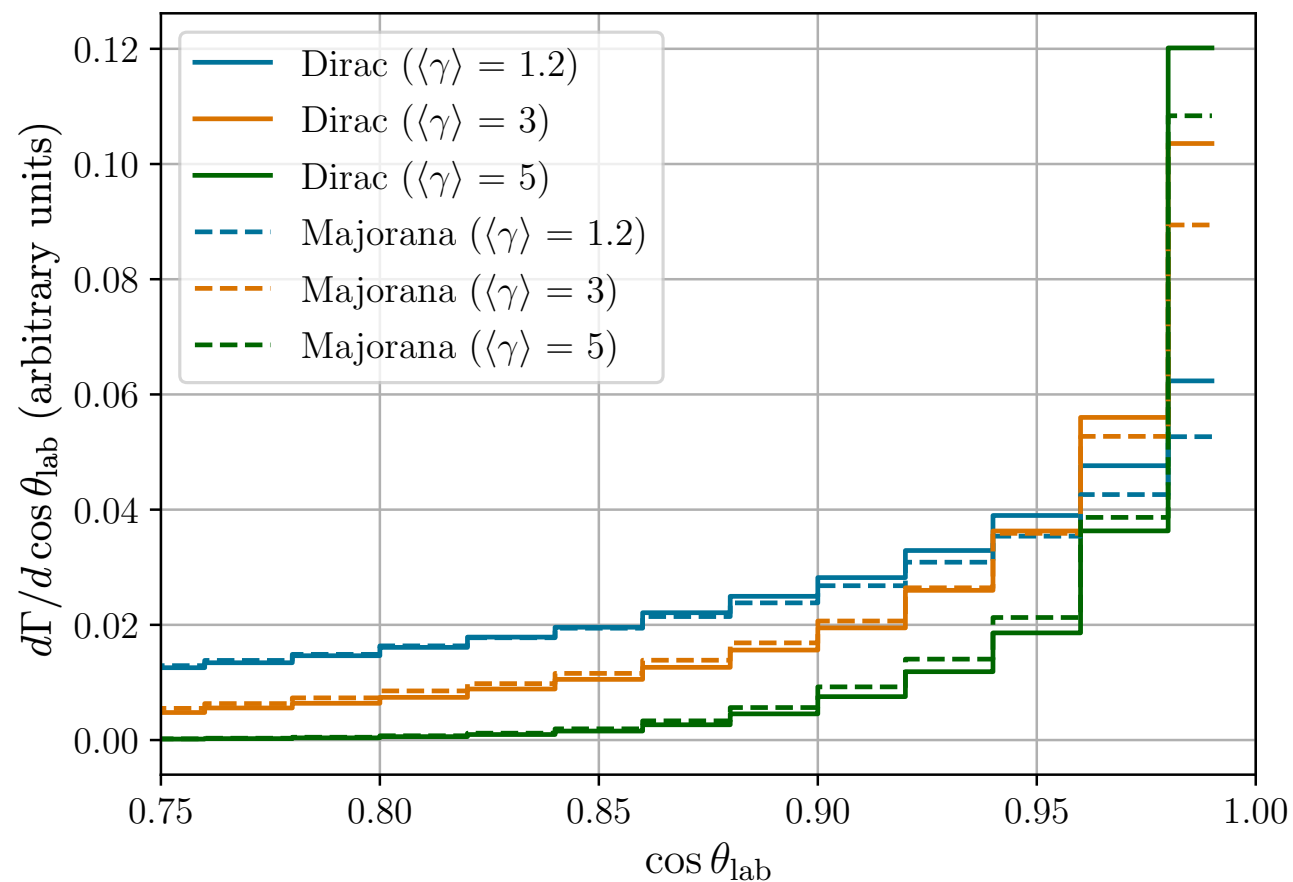


$(m_{N_2} = 120 \text{ MeV}, m_{N_1} = 70 \text{ MeV}, m_{\phi/Z'} = 17 \text{ MeV})$

Parent particles' boost and polarization

Parent Dirac neutrinos are more polarized if they are boosted more

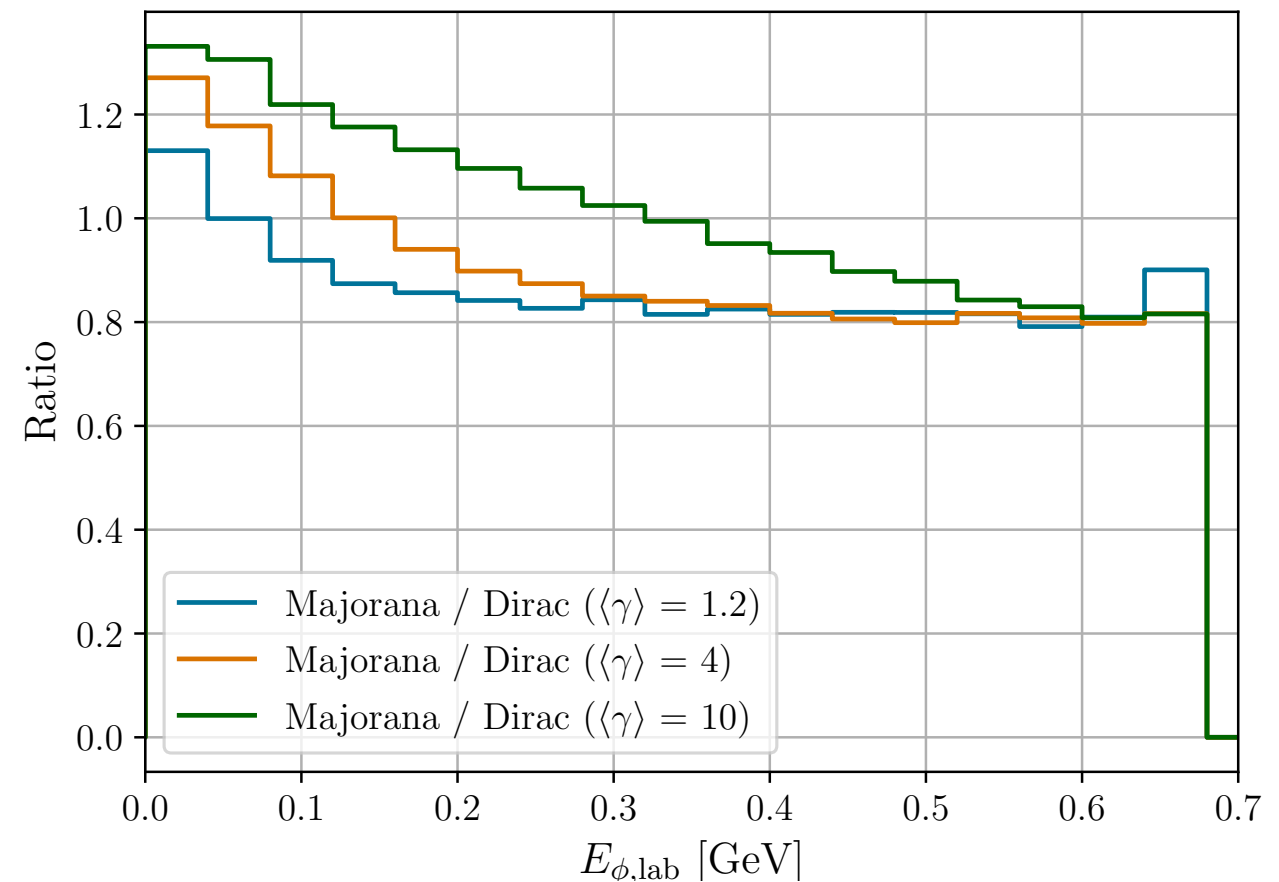
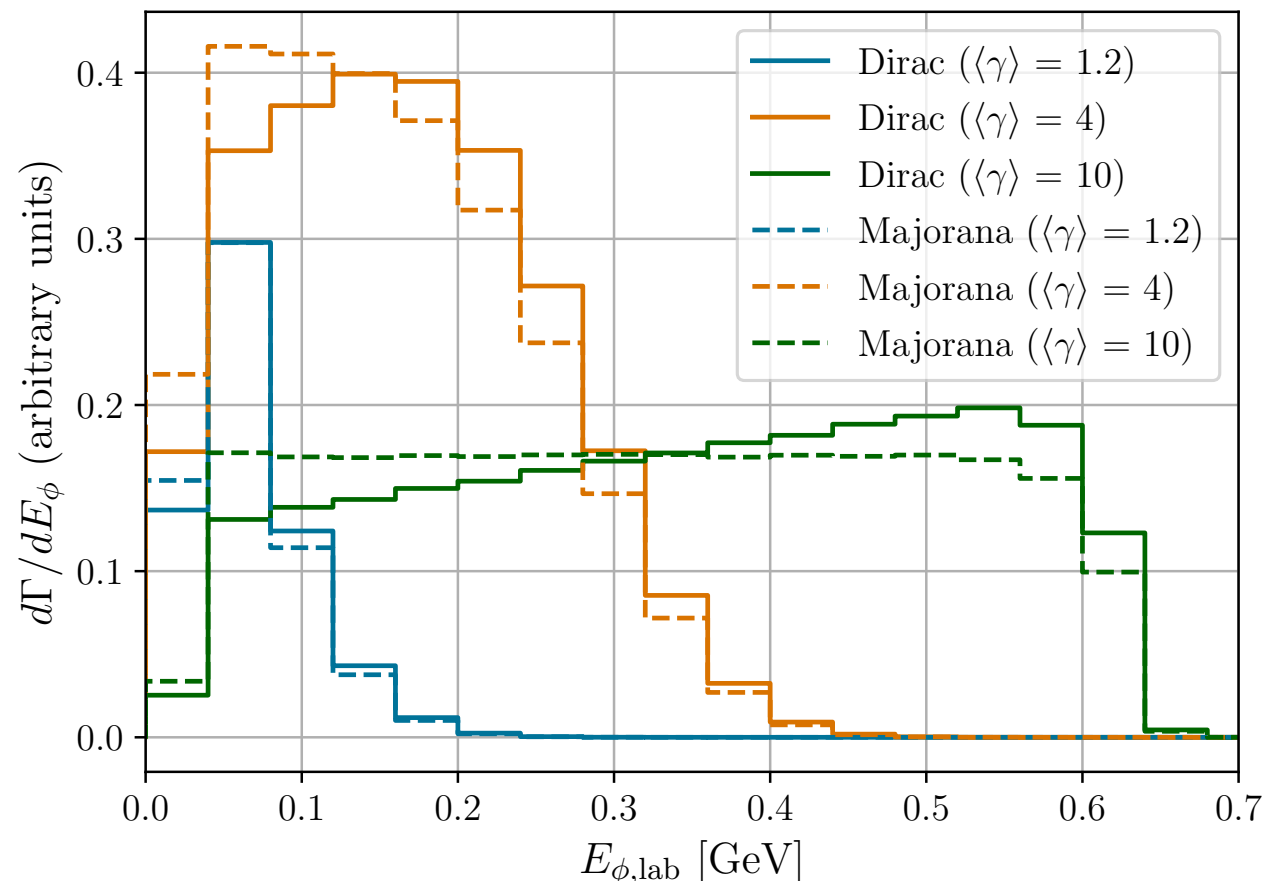
$$P = \frac{N_+ - N_-}{N_+ + N_-}, \quad N_+ \propto \frac{1}{2} \left(1 - \sqrt{1 - \frac{m_{N_2}^2}{E_{N_2}^2}} \right), \quad N_- \propto \frac{1}{2} \left(1 + \sqrt{1 - \frac{m_{N_2}^2}{E_{N_2}^2}} \right)$$



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

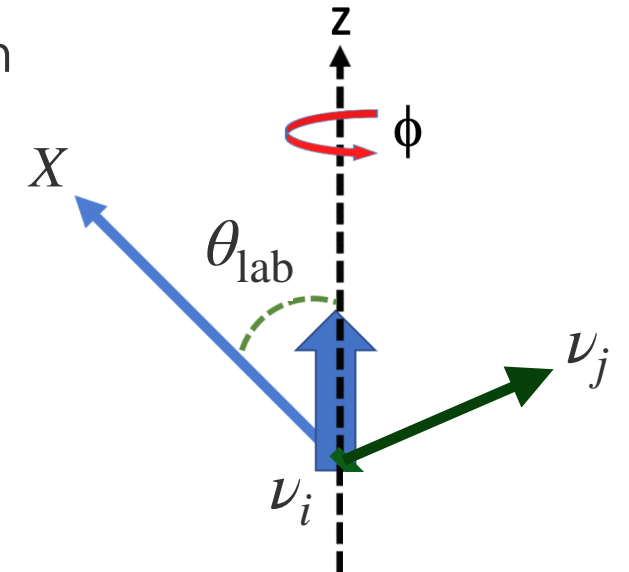
Larger boost results in...

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

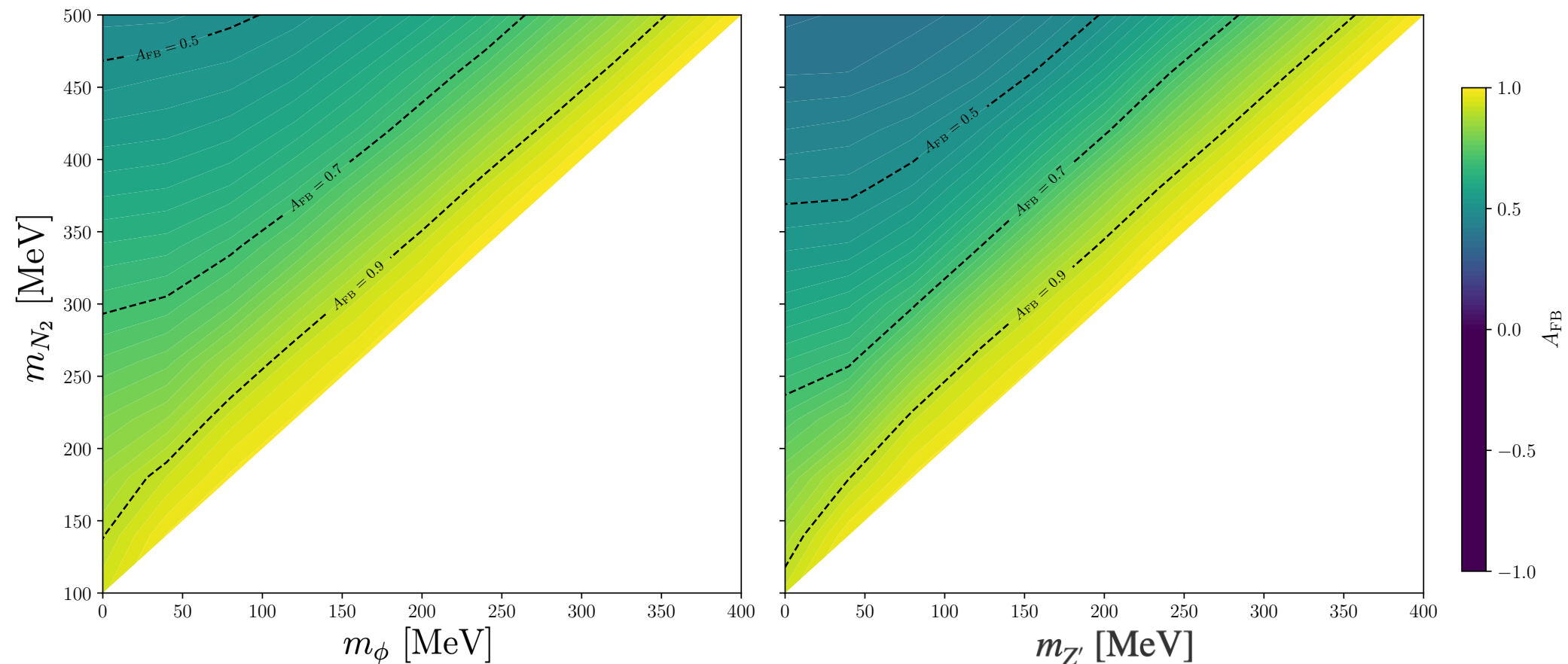
The forward-backward asymmetry

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

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



m_{N_2} vs m_ϕ

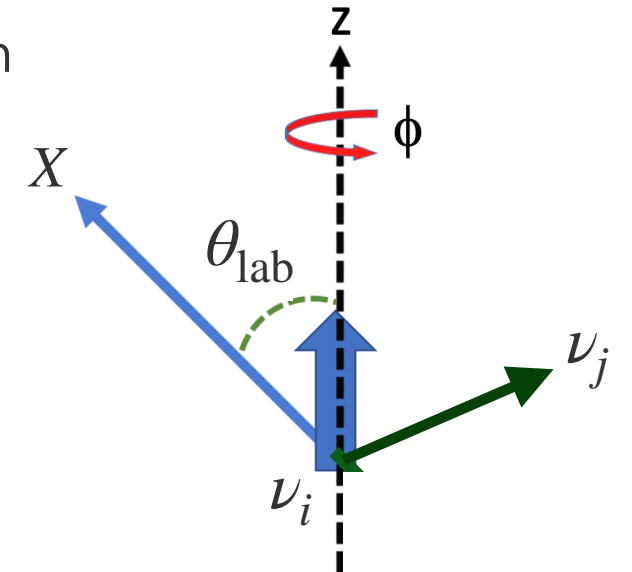


$(m_{N_1} = 70 \text{ MeV}, g_S = 1, g_P = i, g_V = g_A = 1)$

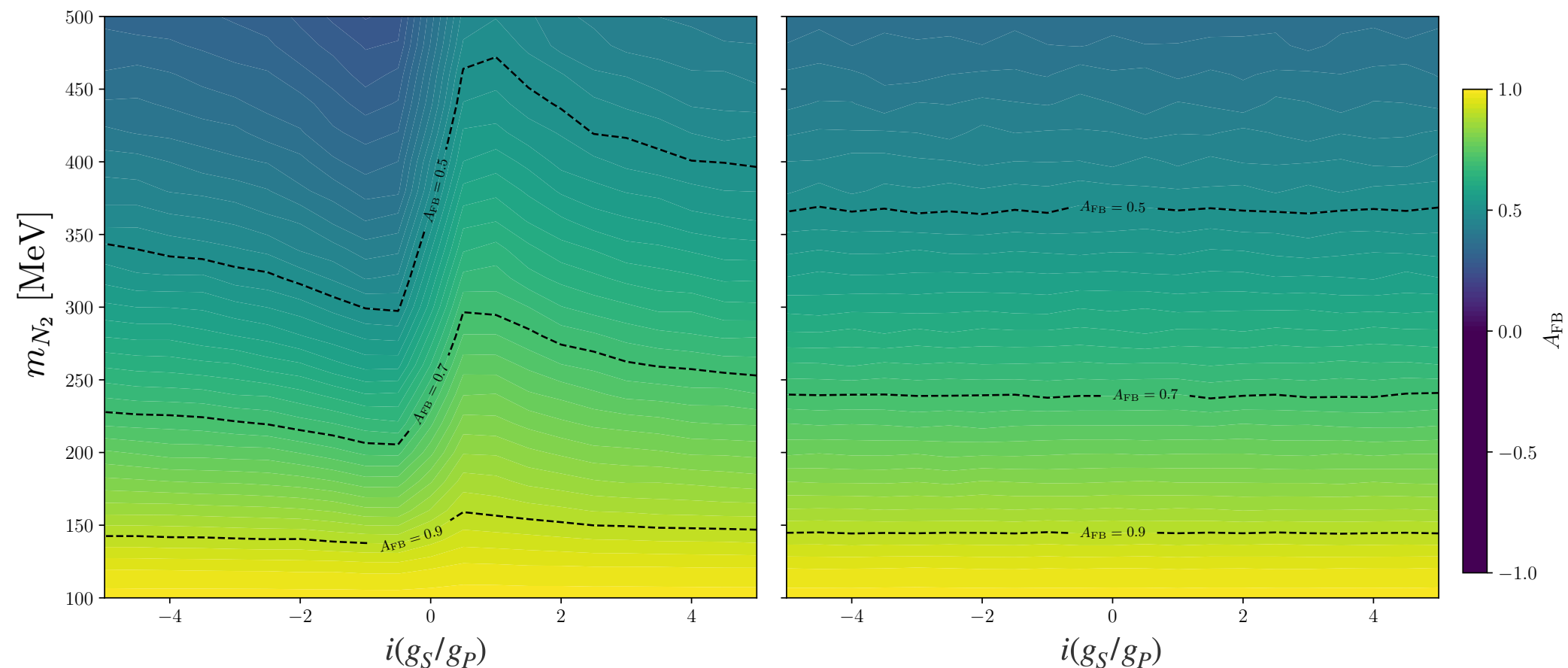
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m_{N_2} vs g_S

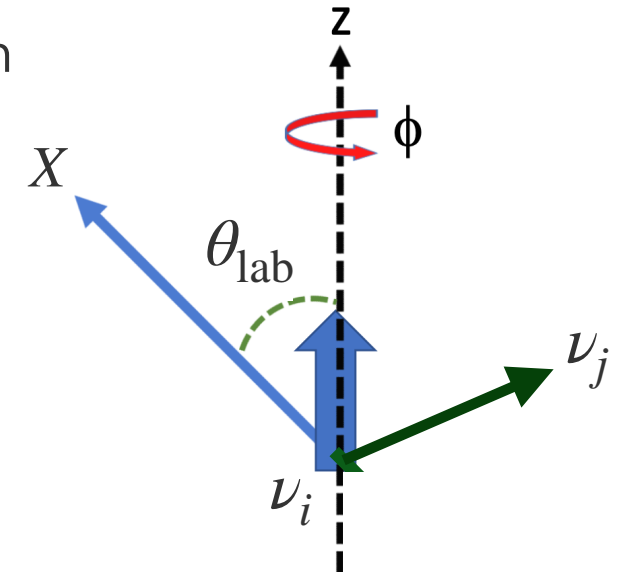


$(m_{N_1} = 70 \text{ MeV}, m_{\phi/Z'} = 17 \text{ MeV})$

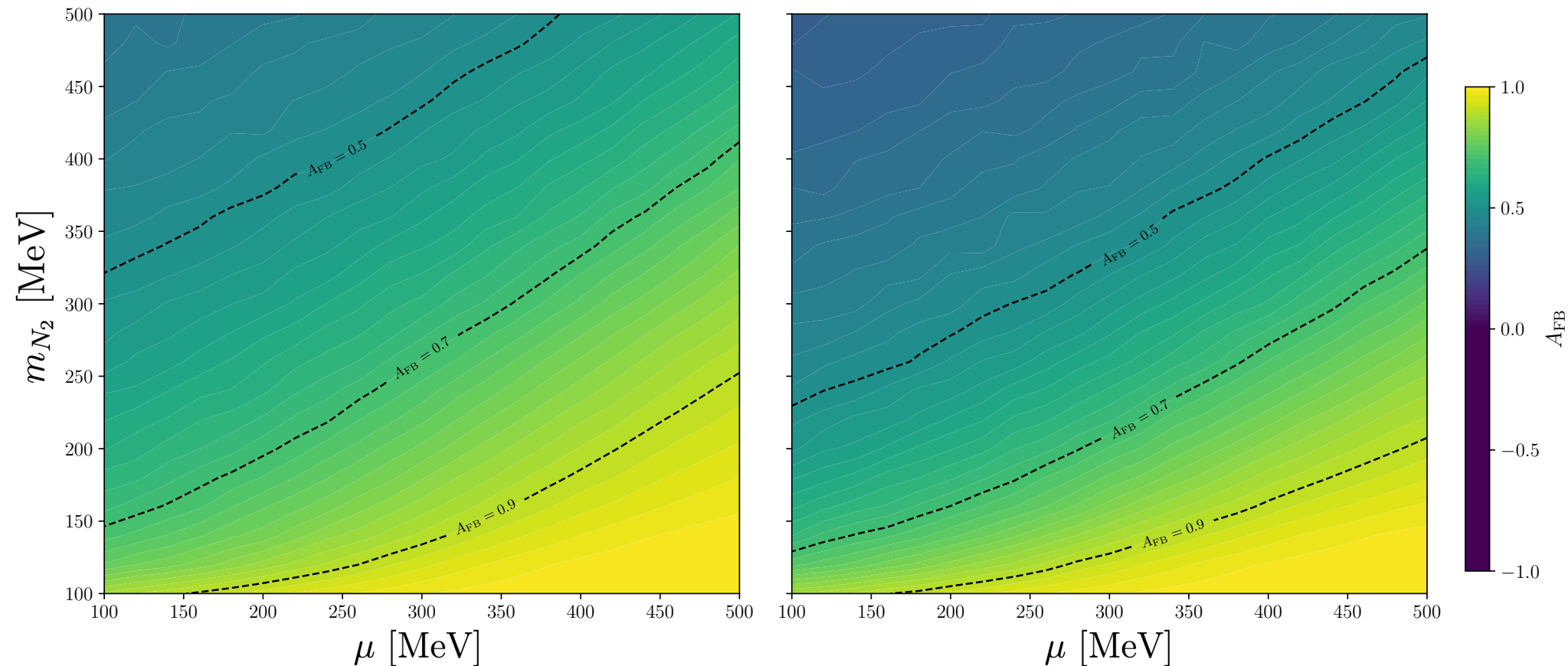
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m_{N_2} vs μ



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

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 $N_2 \rightarrow N_1 + X$, 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