Light
Searching for ~~Dark~~ Gauge Bosons in Next-Generation ν Experiments
: New Interference Features

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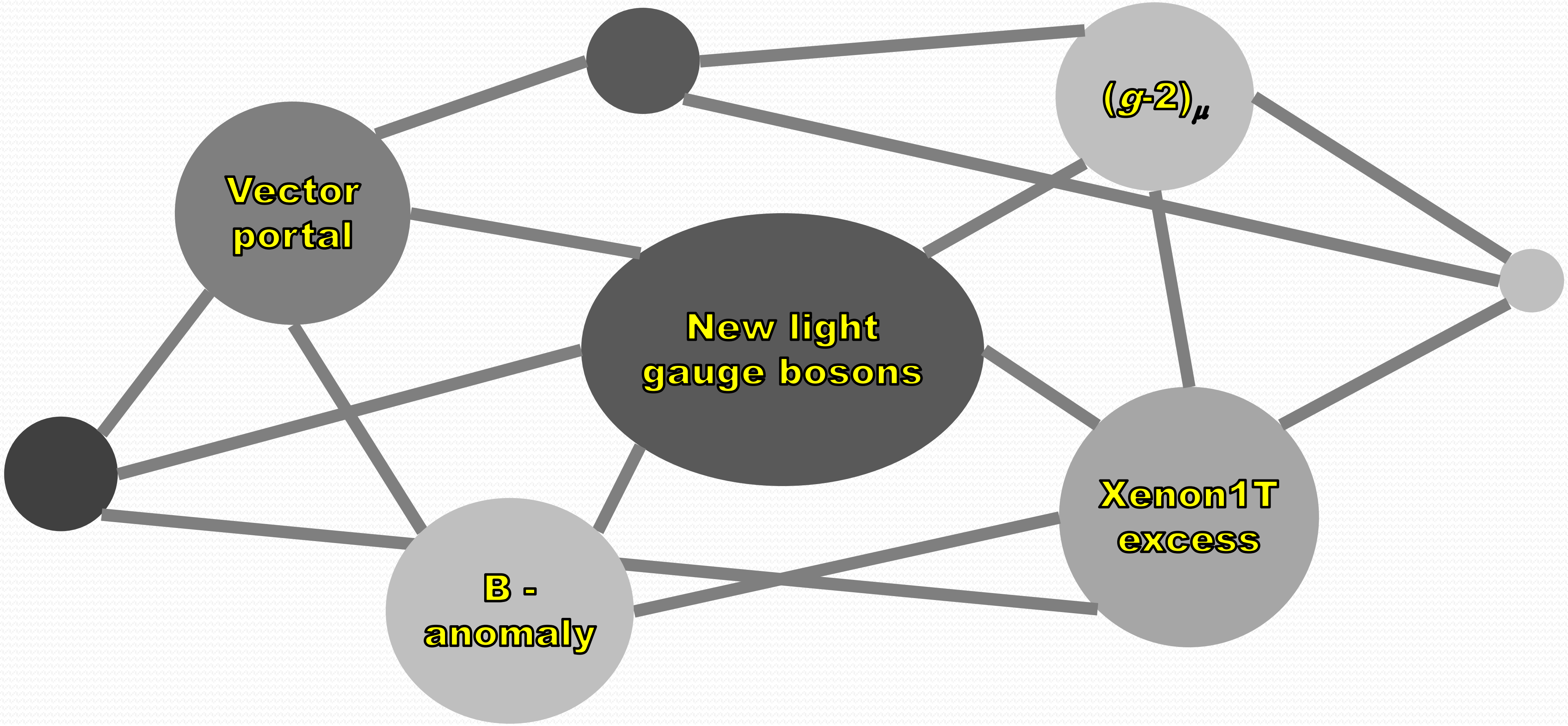
In collaboration with Bhupal Dev, Kuver Sinha, and Yongchao Zhang, arXiv:2105.09309

New (Light) Gauge Bosons: Motivations



Lepto-philic Gauge Bosons in Neutrino Experiments

- ✓ $\boldsymbol{B-L}$
- ✓ $\boldsymbol{L_\mu - L_e}$
- ✓ $L_\tau - L_\mu$
- ✓ $L_\tau - L_e$
- ✓ L
- ✓ …

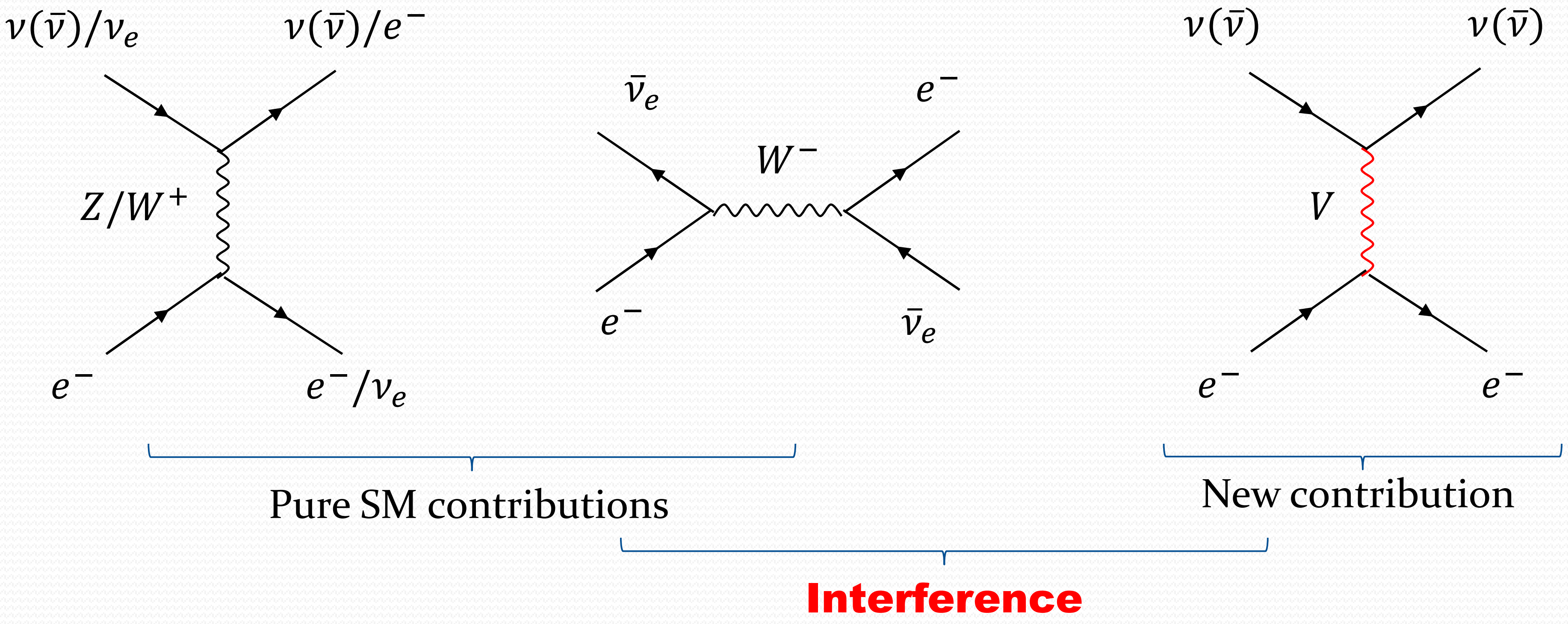
"Friendly" to neutrinos

❑ Search channels

- ✓ Through their decay [Berryman et al, arXiv:1912.07622; Dev et al, arXiv:2104.07681; Bauer et al, arXiv:1803.05466; Ariga et al, arXiv:1811.12522, etc]
- ✓ **Through neutrino scattering** [Bilmis et al, arXiv:1512.07763; Lindner et al, arXiv:1803.00060; Ballet et al, arXiv:1902.08579, etc]

Models and Signal Processes

$$-\mathcal{L} \supset g_V Q_\ell V_\mu \bar{\ell}\gamma^\mu \ell + g_V Q_{\nu_\ell} V_\mu \bar{\nu}_\ell \gamma^\mu \nu_\ell$$



[Bilmis et al, arXiv:1512.07763; Lindner et al, arXiv:1803.00060; Ballet et al, arXiv:1902.08579; Amaral et al, arXiv:2006.11225]

Scattering Cross-Sections: Destructive/Constructive Interference

$$\frac{d\sigma}{dE_e} = \frac{d\sigma_{\rm SM}}{dE_e} + \frac{d\sigma_V}{dE_e} + \frac{d\sigma_{\rm int}}{dE_e}$$

$$\frac{d\sigma_{\rm SM}}{dE_e} = \frac{2G_F^2 m_e}{\pi E_\nu^2}\left\{c_1^2 E_\nu^2 + c_2^2(E_\nu - E_e)^2 - c_1 c_2 m_e E_e\right\},$$

$$\frac{d\sigma_V}{dE_e} = \frac{Q_{\nu_\ell}^2 Q_e^2 g_V^4 m_e}{4\pi E_\nu^2}\frac{\{2(E_\nu - E_e)E_\nu + (E_e - m_e)E_e\}}{(2m_e E_e + m_V^2)^2},$$

$$\frac{d\sigma_{\rm int}}{dE_e} = \frac{Q_{\nu_\ell} Q_e g_V^2 G_F m_e}{2\sqrt{2}E_\nu^2 \pi (2m_e E_e + m_V^2)} \times \left\{c_3(2E_\nu^2 - m_e E_e) + c_4 2(2E_\nu - E_e)E_e + 4s_W^2\left[2(E_\nu - E_e)E_\nu + (E_e - m_e)E_e\right]\right\},$$

Flavor	c_1	c_2	c_3	c_4
ν_e	$s_W^2 + \frac{1}{2}$	s_W^2	$+1$	0
$\bar{\nu}_e$	s_W^2	$s_W^2 + \frac{1}{2}$	$+1$	-1
ν_μ, ν_τ	$s_W^2 - \frac{1}{2}$	s_W^2	-1	0
$\bar{\nu}_\mu, \bar{\nu}_\tau$	s_W^2	$s_W^2 - \frac{1}{2}$	-1	$+1$

$s_W^2 \approx 0.25$ ⟹

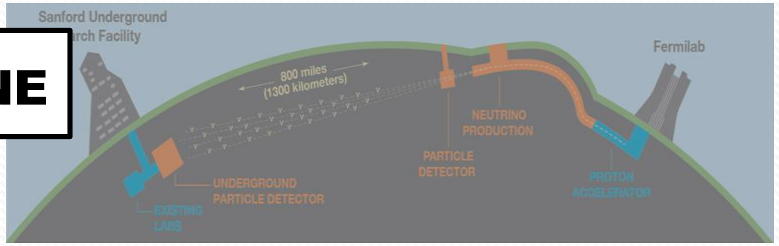
$$\left(\frac{d\sigma_{\rm int}}{dE_e}\right)_{\nu_\mu} \propto -Q_{\nu_\mu} Q_e (2E_{\nu_\mu} - E_e),$$

$$\left(\frac{d\sigma_{\rm int}}{dE_e}\right)_{\bar{\nu}_\mu} \propto Q_{\nu_\mu} Q_e (2E_{\nu_\mu} - E_e),$$

- If muon-flavor ν's (and/or tau-flavor ν's) dominate, **interference effects** (destructive or constructive) **can be significant** [see also Ballet et al, arXiv:1902.08579],
- the **sign depends on Q_{ν_μ} relative to Q_e**, and
- ***new interference features*** (see slides 9 and 10) are prominent in flavor-selective ν experiments!

Benchmark Experiments: DUNE and JSNS²

DUNE

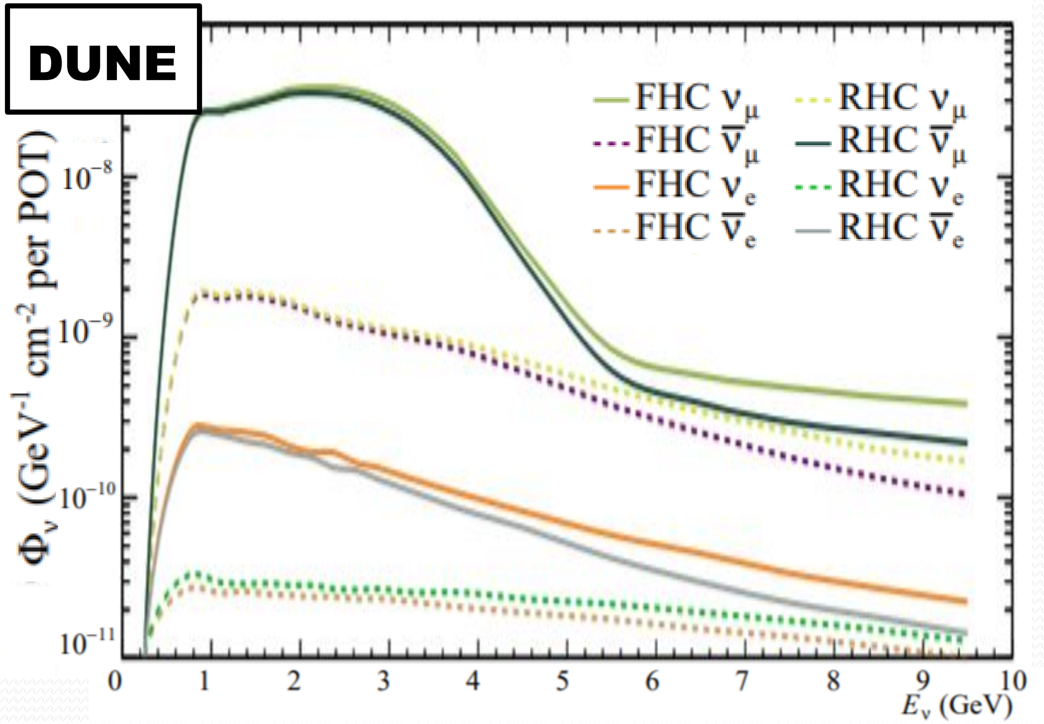


JSNS²

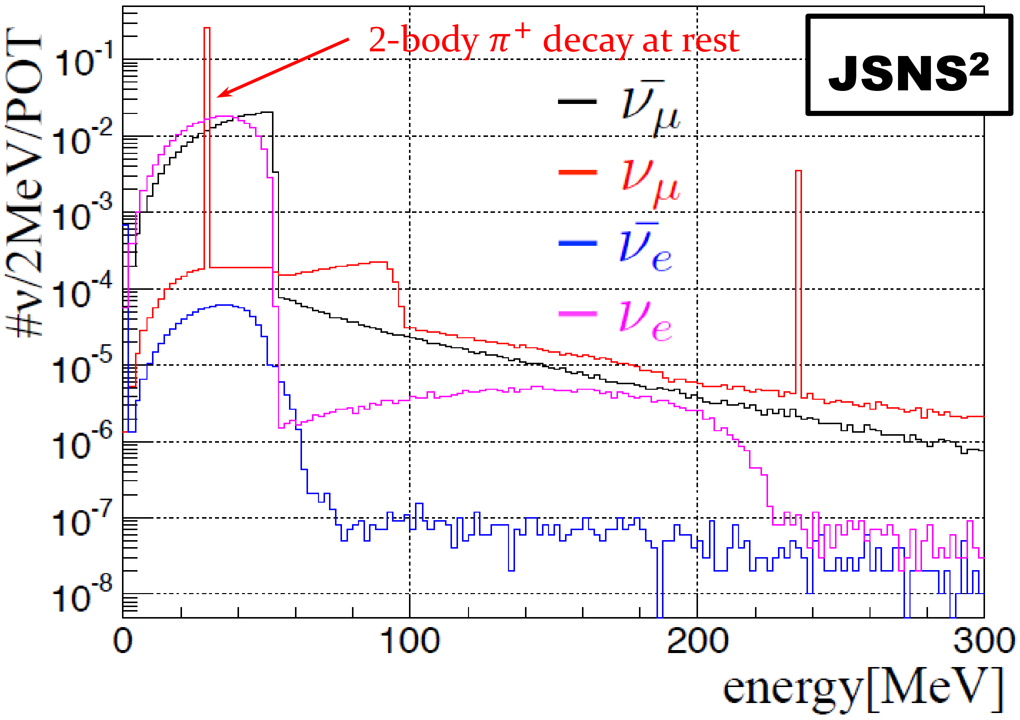
Data taking	~ 5 years	Operational since late 2020
Beam spec.	120 GeV, 1.2 MW	3 GeV, 1 MW
POTs/yr	1.1×10^{21}	3.8×10^{22}
Detector	**67.5 t** (fid. Vol.) LArTPC, **574 m** from target	**17 t** (fid. vol.) Gd-dopped LS, **24 m** from target
ν sources	$\pi^{\pm}, \mu^{\pm}, K^{\pm}$ (decay in flight)	**Stopped** $\pi^{\pm}, \mu^{\pm}, K^{\pm}$ (decay at rest)
Beam focusing	Yes, **flavor selective**	No, **flavor NOT selective**

LArTPC = liquid argon time projection chamber, LS = liquid scintillator

Neutrino Fluxes



[DUNE collaboration, arXiv:2002.03005]

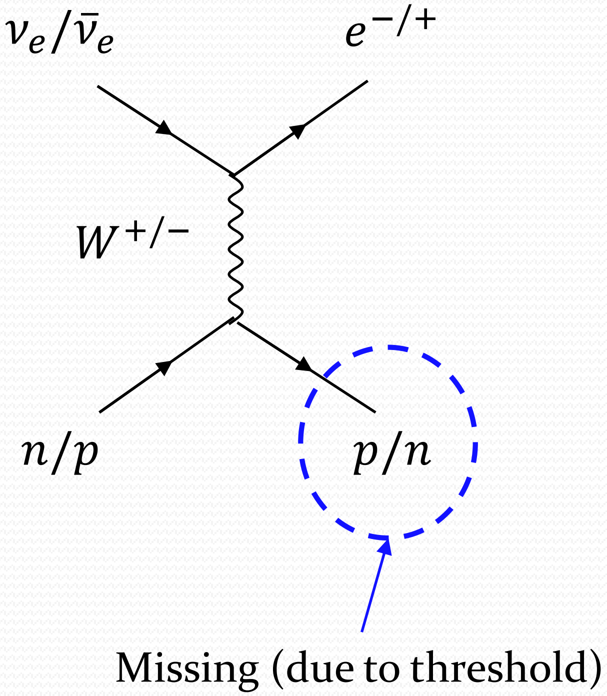


[JSNS^2 collaboration, arXiv:1705.08629]

ν_μ ($\bar{\nu}_\mu$) dominates over the other flavors in the FHC = ν (RHC = $\bar{\nu}$) mode at the **flavor-selective DUNE**, while **comparable amounts of ν_μ and $\bar{\nu}_\mu$** reach the detector at the **non-flavor-selective JSNS^2**.

Background Considerations

CCQE events



- ✓ For DUNE, $E_e\theta_e^2$ cut to reject CCQE events while keeping signal events [see e.g., MINERνA collaboration, arXiv:1512.07699]
- ✓ For JSNS^2, not enough neutrino energy to create CCQE events

⇒ We assume backgrounds are **negligible**.

Sensitivity Calculation

- Exposure
  - ✓ DUNE: 7 years (1.2 MW for first 6 years + 2.4 MW for last year [DUNE collaboration, arXiv:2006.16043]) = 3.5 years in the neutrino mode + 3.5 years in the antineutrino mode [DUNE collaboration, arXiv:2008.12769]
  - ✓ $JSNS^2$: 5 years [$JSNS^2$ collaboration, arXiv:1705.08629]

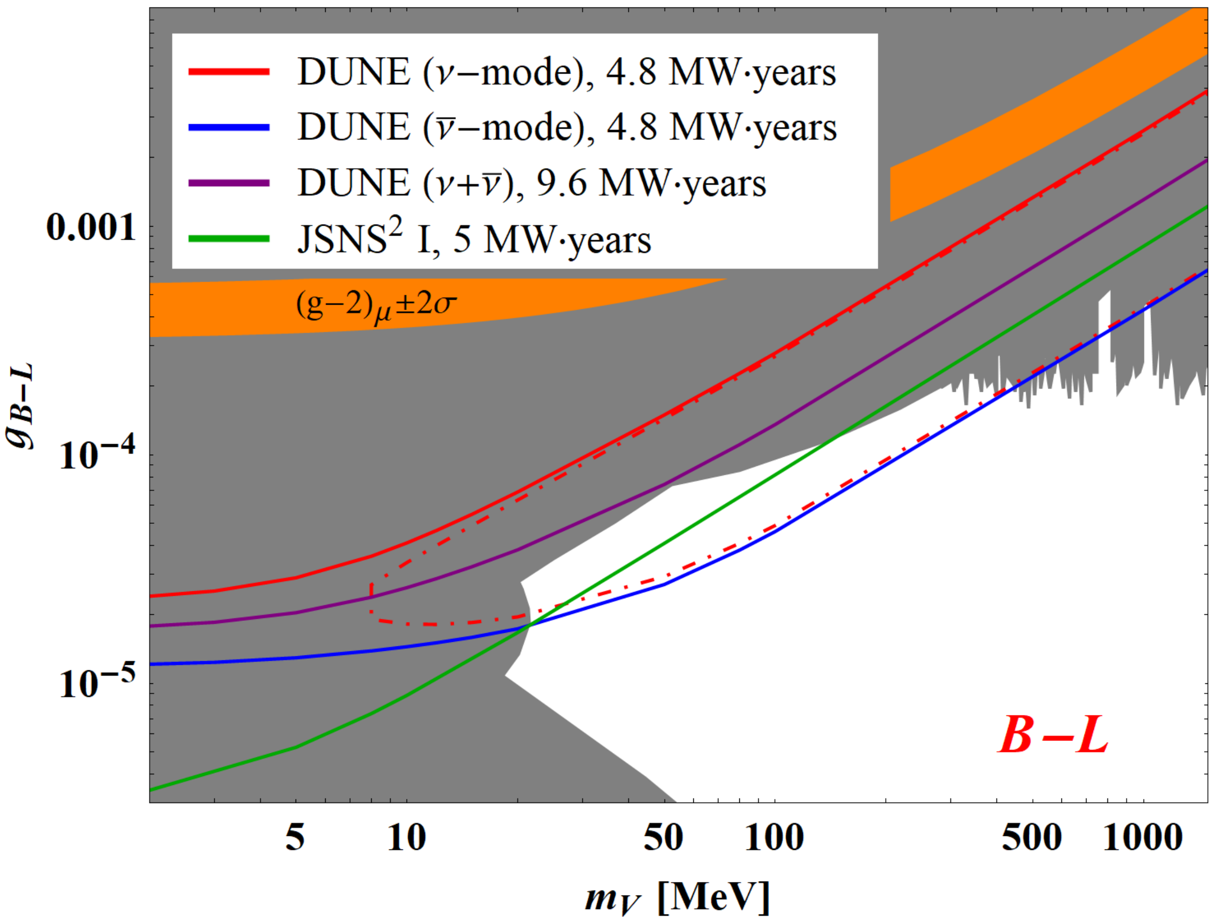
- Sensitivity estimate

$$\chi^2 = \min_{\alpha} \left\{ \frac{[N_{\mathrm{SM}+V+\mathrm{int}} - (1+\alpha) N_{\mathrm{SM}}]^2}{N_{\mathrm{SM}+V+\mathrm{int}}} + \left(\frac{\alpha}{\sigma_{\mathrm{norm}}} \right)^2 \right\}$$

N_{SM}:
- DUNE: Dedicated study available [Marshall et al, arXiv:1910.10996]
- $JSNS^2$: Theoretical calculation performed

σ_{norm}:
- 5% for DUNE, no info. available for $JSNS^2$

Result: $B-L$ Gauge Boson



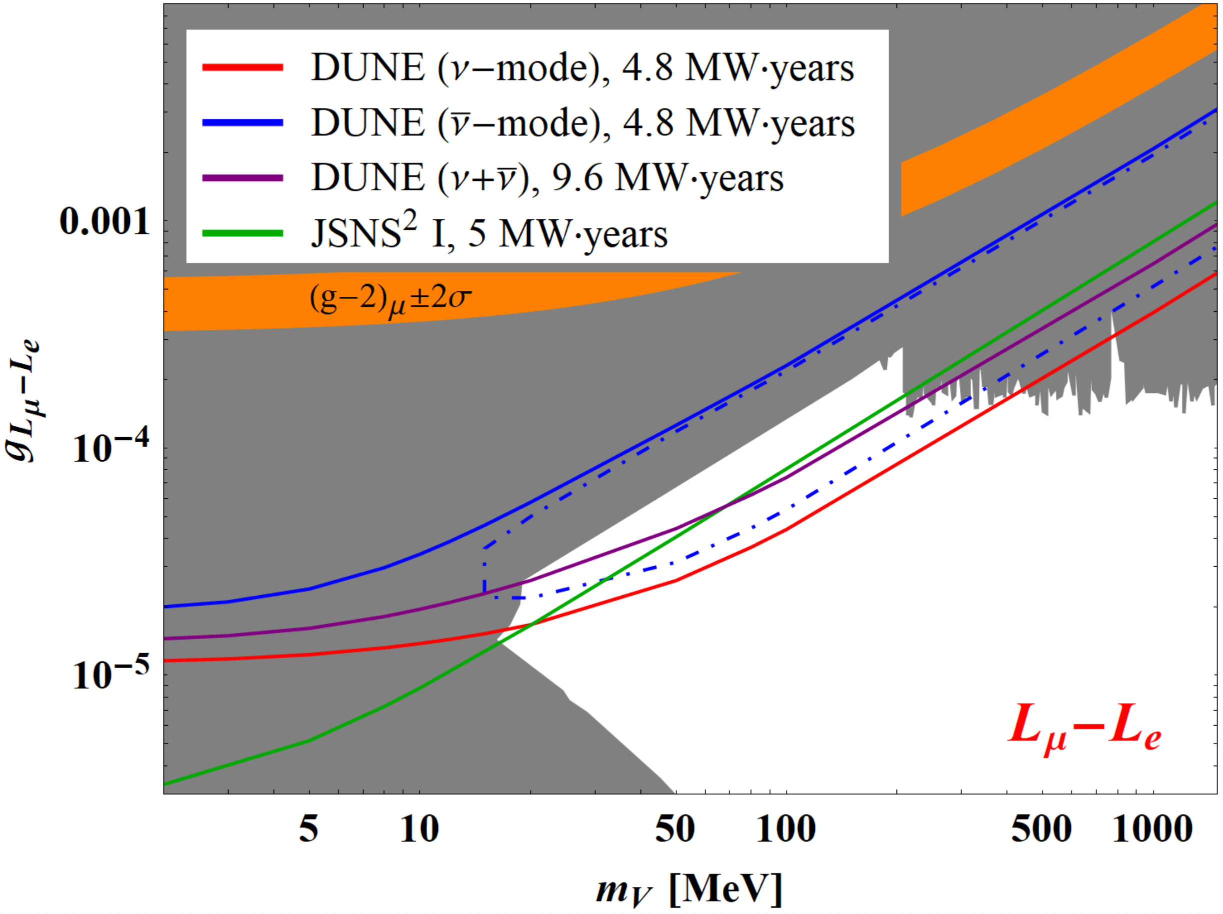
DUNE

- ✓ Sensitivity by a deficit in the ν mode (region surrounded by a red dot-dashed line)
- ✓ Combined analysis vs individual analyses
- ✓ Similar sensitivity reaches in both modes

JSNS²

- ✓ Individual analyses unavailable
- ✓ Ongoing experiment with a higher beam intensity ⇒ Competitive sensitivity reaches in a nearer future

Result: $L_\mu - L_e$ Gauge Boson



DUNE

- ✓ Sensitivity by a deficit in the anti-ν mode (region surrounded by a blue dot-dashed line)
- ✓ Combined analysis vs individual analyses
- ✓ Similar sensitivity reaches in both modes

JSNS²

- ✓ Individual analyses unavailable
- ✓ Ongoing experiment with a higher beam intensity ⇒ Competitive sensitivity reaches in a nearer future

Conclusions

- ❑ It is promising to search for light (lepto-philic) gauge bosons at neutrino experiments.
- ❑ <u>New interference feature</u>
  - ✓ Destructive interference can allow flavor-selective neutrino experiments to be sensitive to gauge boson signals by a deficit.
  - ✓ Individual analyses can lead to sensitivity reaches superior to the combined analysis in flavor-selective neutrino experiments.

Thank you!