

2026 IAS Program on
Fundamental Physics (FP2026)



東南大學
SOUTHEAST UNIVERSITY

Probing dark particles
in neutrino scattering experiments

Ruofei Feng, Shao-Feng Ge, Yongchao Zhang

2026-01-12

HKUST

Probing dark particles in neutrino scattering experiments

Part 1

Motivation

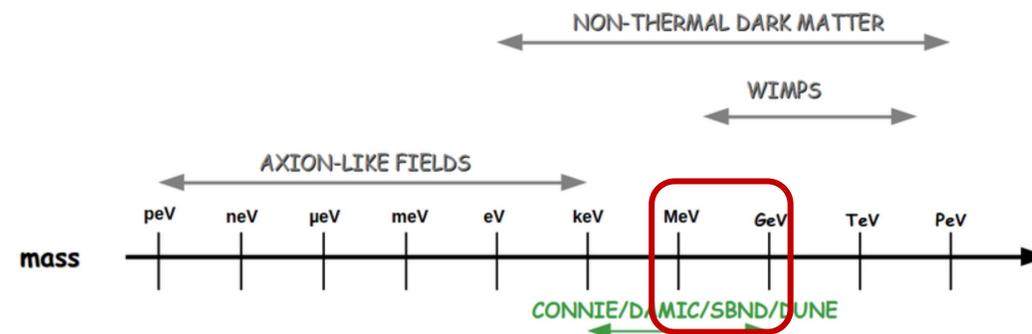
Why neutrino scattering experiments?

Why dark particle?

Why experiments matters?

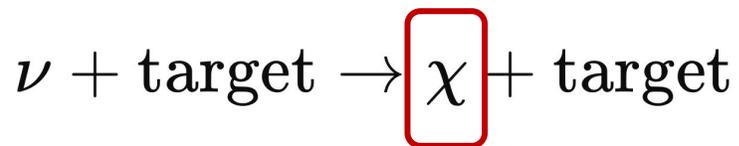
Why neutrino scattering?

- large fluxes with MeV–GeV energy range
 - low-background and well-understood kinematics
 - Neutrinos can probe weakly interacting new physics
- new physics models
complementary to colliders and cosmology/astrophysics



What is the dark particle?

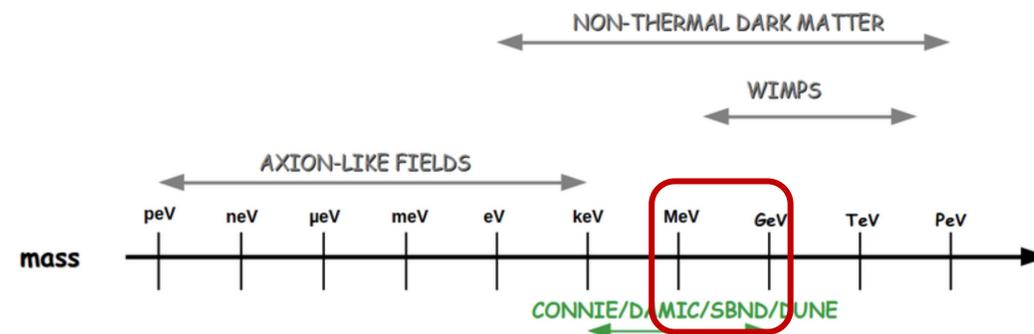
model-independent traditional dark matter \longrightarrow a generic light **dark sector particle**
sterile neutrinos, dark fermions, portal states



$$\begin{aligned} \nu_\alpha(\bar{\nu}_\alpha) + e^- &\rightarrow \chi(\bar{\chi}) + e^- \\ \nu_\alpha(\bar{\nu}_\alpha) + \mathcal{N} &\rightarrow \chi(\bar{\chi}) + \mathcal{N} \end{aligned}$$

Why neutrino scattering?

- large fluxes with MeV–GeV energy range
 - low-background and well-understood kinematics
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complementary to colliders and cosmology/astrophysics



What is the dark particle?

The sensitivity strongly depends on:

energy thresholds, recoil energy distributions
detector acceptance, background rejection

➔ DUNE
COHERENT
CONUS+



Probing dark particles in neutrino scattering experiments

Part 2

Theoretical Framework

EFT Set-up

Kinematics: threshold & dark particle mass

Dark particle Decay

Signal process: Neutrino up-scattering into a dark particle

$$\nu_\alpha(\bar{\nu}_\alpha) + e^- \rightarrow \chi(\bar{\chi}) + e^-$$

$$\nu_\alpha(\bar{\nu}_\alpha) + \mathcal{N} \rightarrow \chi(\bar{\chi}) + \mathcal{N}$$

Heavy mediator \rightarrow EFT approach
Four-fermion interaction

$$\mathcal{L}_{\text{eff}} = \sum_{i,\alpha,f} \frac{1}{\Lambda_{i,\alpha f}^2} (\bar{\chi} \Gamma^i P_L \nu_\alpha) (\bar{f} \Gamma_i f) + \text{H.c.}$$

effective cutoff scale smaller $\Lambda \rightarrow$ stronger coupling

$$f = e, \mathcal{N}$$

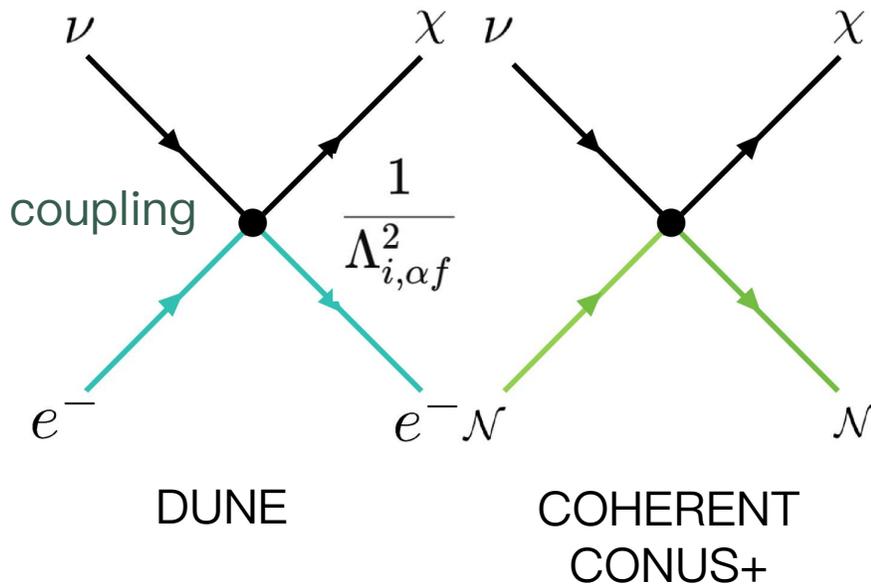
$$\Gamma^i \equiv \{I, i\gamma^5, \gamma^\mu, \gamma^\mu\gamma^5, \sigma^{\mu\nu}\}$$

$$i = S, P, V, A, T$$

$$(\bar{q}\Gamma^i q)(\chi\Gamma_i P_L \nu_\alpha) \quad \text{SM quarks}$$

gluons at the 1-loop or 2-loop order

\rightarrow more fundamental interactions



Signal process: Neutrino up-scattering into a dark particle

$$\nu_\alpha(\bar{\nu}_\alpha) + e^- \rightarrow \chi(\bar{\chi}) + e^-$$

$$\nu_\alpha(\bar{\nu}_\alpha) + \mathcal{N} \rightarrow \chi(\bar{\chi}) + \mathcal{N}$$

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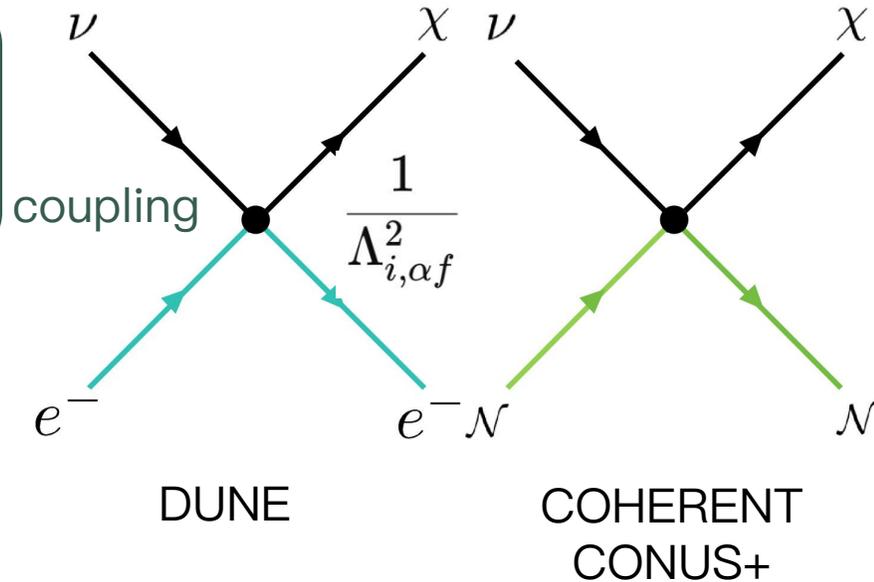
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$$i = S, P, V, A, T$$

$$(\bar{q}\Gamma^i q)(\chi\Gamma_i P_L \nu_\alpha) \quad \text{SM quarks}$$

gluons at the 1-loop or 2-loop order

\rightarrow more fundamental interactions



nucleon-level coupling

$\nu + f \rightarrow \chi + f$ massive dark particle requires a minimum neutrino energy

- Inelastic threshold (given recoil energy T):

minimum neutrino energy to produce a detectable recoil

$$E_{\nu}^{\min}(m_{\chi}, T) = \frac{1}{2} \left(T + \sqrt{2mT + T^2} \right) \left(1 + \frac{m_{\chi}^2}{2mT} \right)$$

\downarrow
dark particle mass
 \downarrow
target mass

- for a fixed neutrino energy:

$$T_{\max}(m_{\chi}, E_{\nu}) = \frac{2mE_{\nu}^2 - m_{\chi}^2(E_{\nu} + m) + E_{\nu}\sqrt{\Delta}}{2m(2E_{\nu} + m)}$$

$$T_{\min}(m_{\chi}, E_{\nu}) = \frac{2mE_{\nu}^2 - m_{\chi}^2(E_{\nu} + m) - E_{\nu}\sqrt{\Delta}}{2m(2E_{\nu} + m)}$$

- dark particle mass range:

$$(k + p)^2 \geq (m_{\chi} + m_f)^2$$

$$m_{\chi} \lesssim \sqrt{m(m + 2E_{\nu})} - m$$

$$m_{\chi}^{\max} = \sqrt{m_f(m_f + 2E_{\nu})} - m_f$$

- electron target (DUNE): $m_f = m_e \ll E_{\nu} \Rightarrow m_{\chi}^{\max} \approx \sqrt{2m_e E_{\nu}} \sim \mathcal{O}(100 \text{ MeV})$
- nuclei target (COHERENT, CONUS+): $m_f = m_N \gg E_{\nu} \Rightarrow m_{\chi}^{\max} \approx E_{\nu} \lesssim 50 \text{ MeV}$

determined by kinematics

experiment	DUNE(ν -e)	COHERENT(ν -N)	CONUS+(ν -N)
$m_{\chi, \max}$	$\sim 100\text{MeV}$	$\sim 50\text{MeV}$	$\sim 10\text{MeV}$

➡ complementary

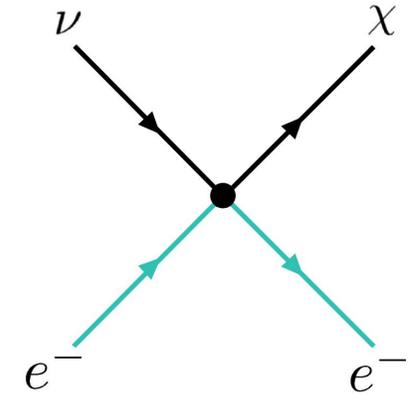
- electron-positron pair

$$\chi \rightarrow \nu_\alpha + e^+ + e^-$$

tree-level decay

$$\Gamma(\chi \rightarrow \nu_\alpha e^+ e^-) \simeq \frac{m_\chi^5}{192\pi^3 \Lambda_{i,e}^4} \left(1 - \frac{4m_e^2}{m_\chi^2}\right)^{3/2}$$

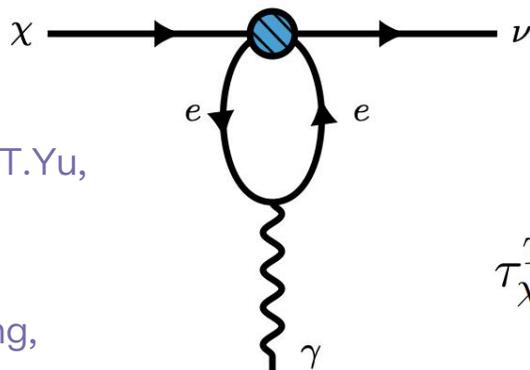
$$\tau_\chi \simeq \underline{5 \times 10^8 \text{ cm}} \left(\frac{m_\chi}{30 \text{ MeV}}\right)^{-5} \left(\frac{\Lambda_{i,e}}{1 \text{ TeV}}\right)^4$$



- invisible decay

$$\chi \rightarrow \nu_\alpha \gamma, \quad \chi \rightarrow \nu_\alpha \gamma \gamma, \quad \chi \rightarrow \nu_\alpha \gamma \gamma \gamma, \quad \chi \rightarrow \nu_\alpha \nu \bar{\nu}$$

one-loop



$$\Gamma^T(\chi \rightarrow \nu_\alpha \gamma) = \frac{\alpha m_e^2 m_\chi^3}{16\pi^4 \Lambda_{T,e}^4} \log^2 \left(\frac{\Lambda_{T,e}^2}{m_e^2} \right)$$

$$\tau_\chi^{T,e} \simeq \underline{6 \times 10^{11} \text{ cm}} \left(\frac{m_\chi}{30 \text{ MeV}}\right)^{-3} \left(\frac{\Lambda_{T,e}}{1 \text{ TeV}}\right)^4 \left(\frac{\log^2(\Lambda_{T,e}^2/m_e^2)}{1000}\right)$$

J.A.Dror, G.Elor,
R.McGehee and T.T.Yu,
2011.01940

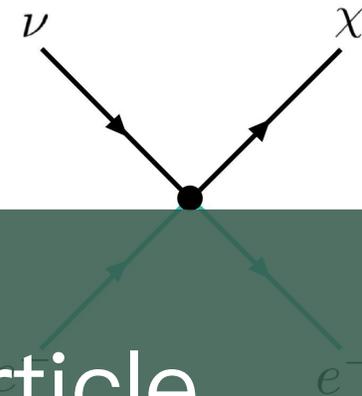
S.F.Ge, X.G.He,
X.D.Ma and J.Sheng,
2201.11497

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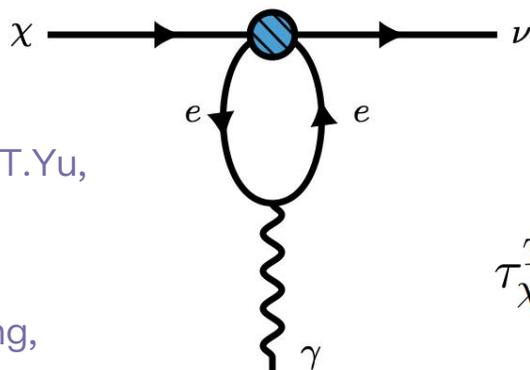
$$\tau_\chi \simeq \underline{5 \times 10^8 \text{ cm}} \left(\frac{m_\chi}{30 \text{ MeV}}\right)^{-5} \left(\frac{\Lambda_{i,e}}{1 \text{ TeV}}\right)^4$$

the dark particle is a long-lived particle

- invisible decay

$$\chi \rightarrow \nu_\alpha \gamma, \quad \chi \rightarrow \nu_\alpha \gamma \gamma, \quad \chi \rightarrow \nu_\alpha \gamma \gamma \gamma, \quad \chi \rightarrow \nu_\alpha \nu \bar{\nu}$$

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J.A.Dror, G.Elor,
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2011.01940

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2201.11497

Probing dark particles in neutrino scattering experiments

Part 3

ν -e Scattering

DUNE Set up

Signal & observable

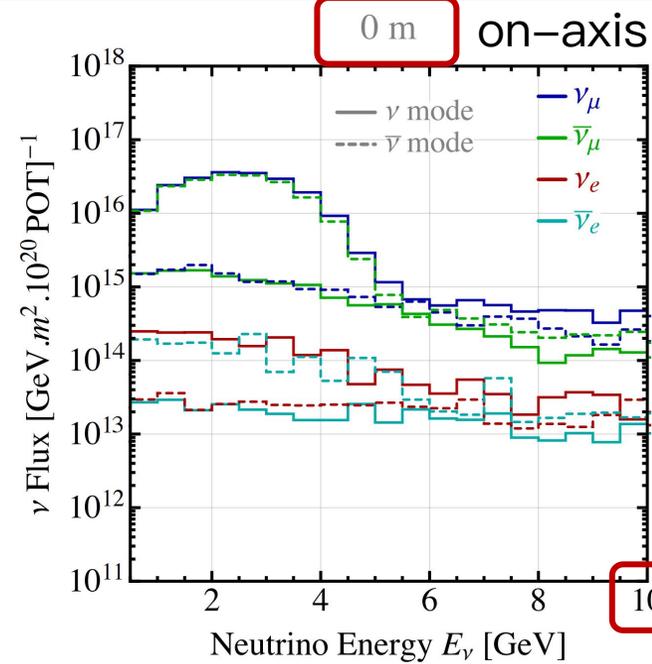
Sensitivity

DUNE ν -e scattering



NEUTRINO BEAM

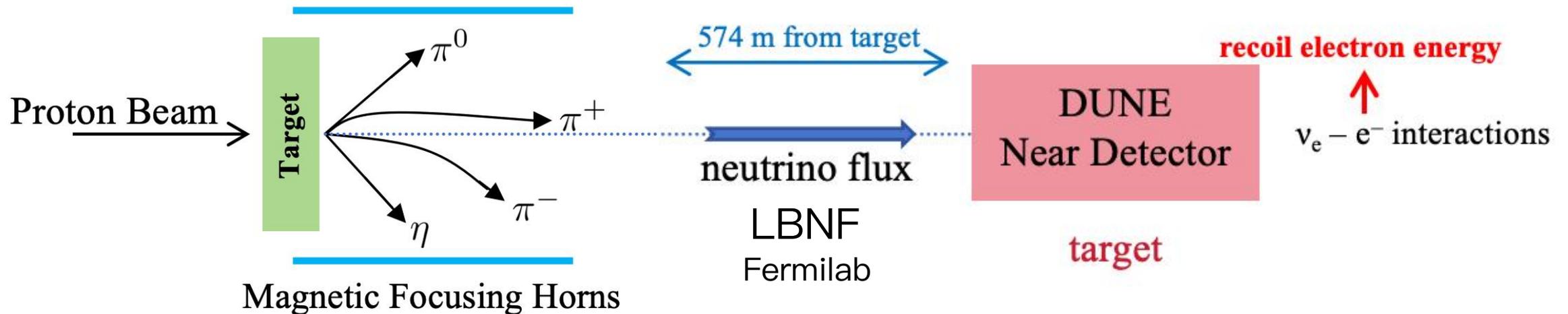
- POT: $1.1 \cdot 10^{21}$
- energy: ~ 10 GeV
- type: $\nu_\mu \bar{\nu}_\mu \nu_e \bar{\nu}_e$
- on-axis, two modes



V.Mathur, I.M.Shoemaker and Z.Tabrizi, 2111.14884

DETECTOR

- target: LAr
- fiducial mass ~ 67 tons
- threshold: $T_{e^{\text{min}}} \sim 30$ MeV

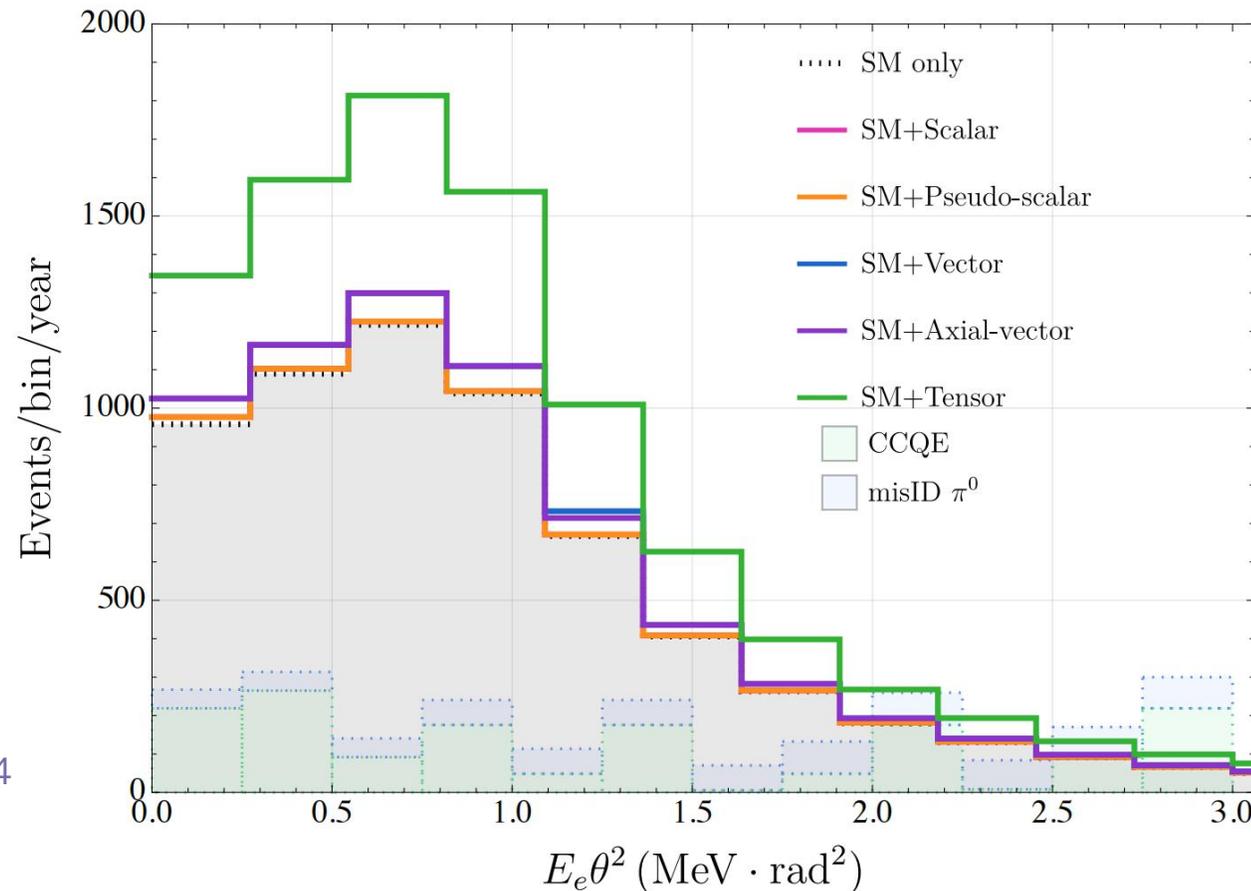


DUNE Near Detector

- signal: $\nu_\alpha(\bar{\nu}_\alpha) + e^- \rightarrow \chi(\bar{\chi}) + e^-$
- background:
 - SM ν - e scattering
 - CCQE (the charged-current quasi-elastic neutrino scattering)
 - misidentified π^0 events

V.Mathur, I.M.Shoemaker and Z.Tabrizi, 2111.14884

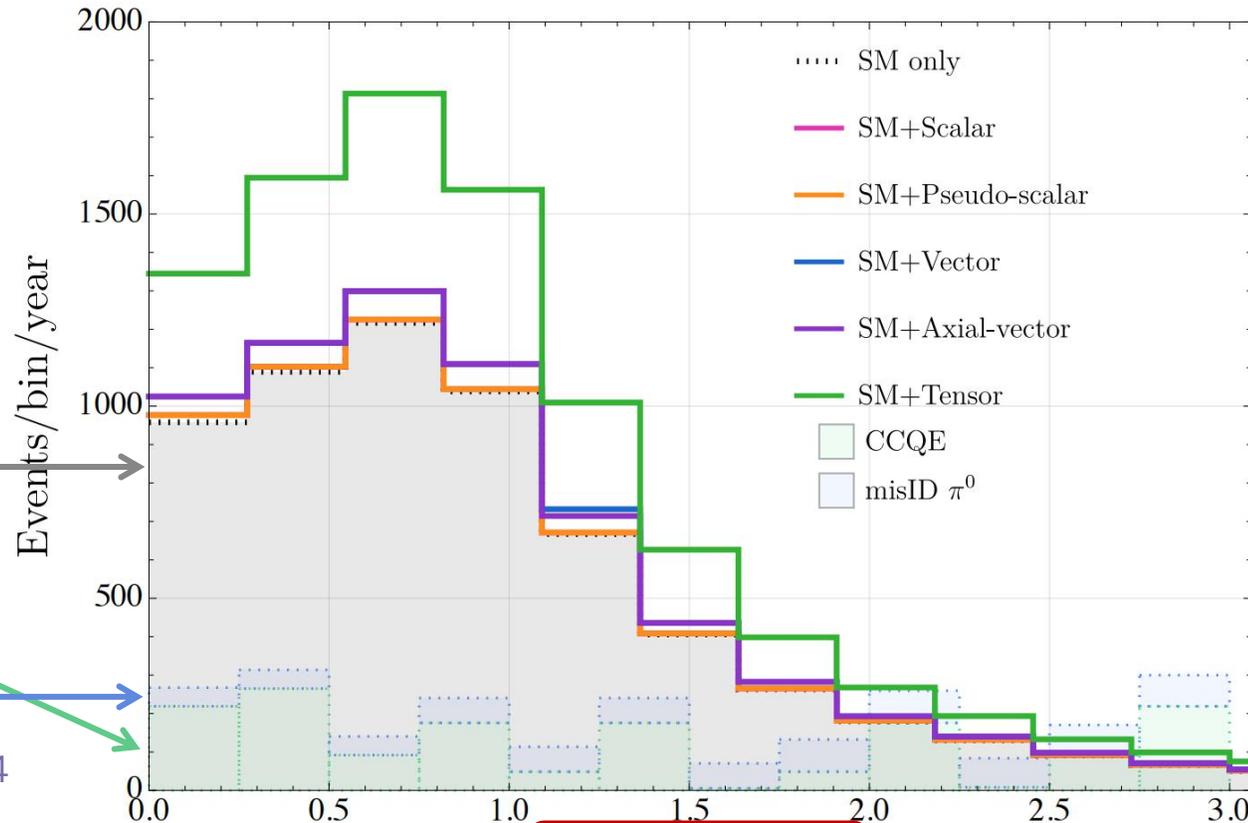
$\Lambda = 650 \text{ GeV}$, $m_\chi = 10 \text{ MeV}$
 $\nu - \text{mode}$



$\Lambda = 650 \text{ GeV}, m_\chi = 10 \text{ MeV}$
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DUNE Near Detector

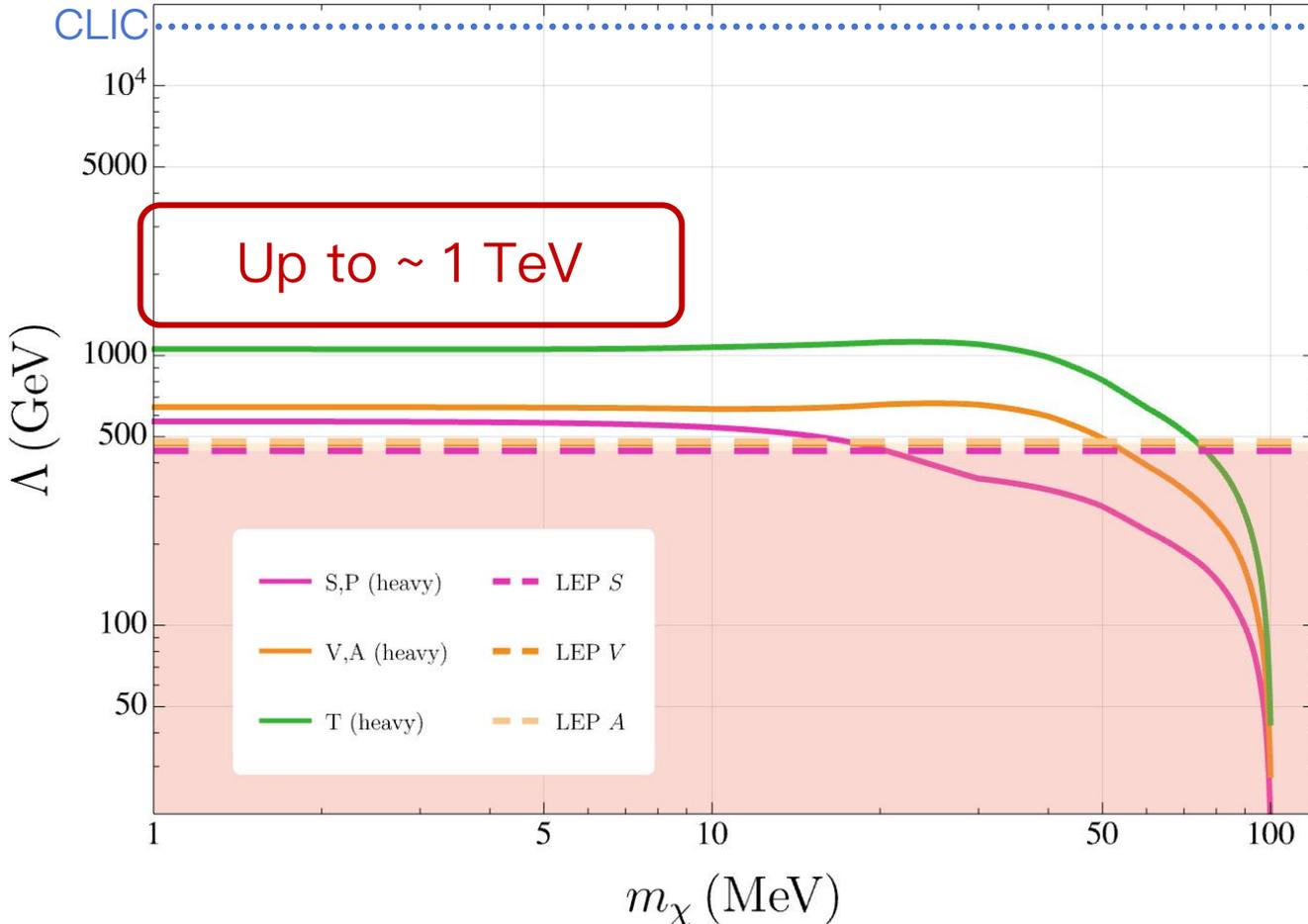
- signal: $\nu_\alpha(\bar{\nu}_\alpha) + e^- \rightarrow \chi(\bar{\chi}) + e^-$
 - background:
 - SM $\nu - e$ scattering
 - CCQE (the charged-current quasi-elastic neutrino scattering)
 - misidentified π^0 events
- V.Mathur, I.M.Shoemaker and Z.Tabrizi, 2111.14884



CCQE & misID π^0 are effectively suppressed by the cut on the variable $E_e \theta^2 \text{ (MeV} \cdot \text{rad}^2\text{)}$

- performing a χ^2 analysis using 12 bins
$$\chi^2 = 2 \sum_{i=1}^{12} \left[\mathcal{N}_i^{\text{th}} - \mathcal{N}_i^{\text{exp}} + \mathcal{N}_i^{\text{exp}} \log \left(\frac{\mathcal{N}_i^{\text{exp}}}{\mathcal{N}_i^{\text{th}}} \right) \right] + \left(\frac{\alpha_1}{\sigma_{\alpha_1}} \right)^2 + \left(\frac{\alpha_2}{\sigma_{\alpha_2}} \right)^2$$

DUNE-ND Sensitivity (heavy/light) + LEP exclusion



- EFT ~ heavy mediator limit (our work) Solid lines

Interaction Type	m_χ^{\max} [MeV]	Λ_i ($m_\chi = 1$ MeV) [GeV]
Scalar (S)	~ 100	562
Pseudoscalar (P)	~ 100	560
Vector (V)	~ 100	650
Axial-vector (A)	~ 100	640
Tensor (T)	~ 100	1070

- LEP ~ the same effective operator existing limits Dashed lines

P.J.Fox, R.Harnik, J.Kopp and Y.Tsai, 1103.0240

- Future lepton colliders (CEPC, ILC, CLIC) ~ the same effective operator Dotted lines

S.F.Ge, K.Ma, X.D.Ma and J.Sheng, 2306.00657

Probing dark particles in neutrino scattering experiments

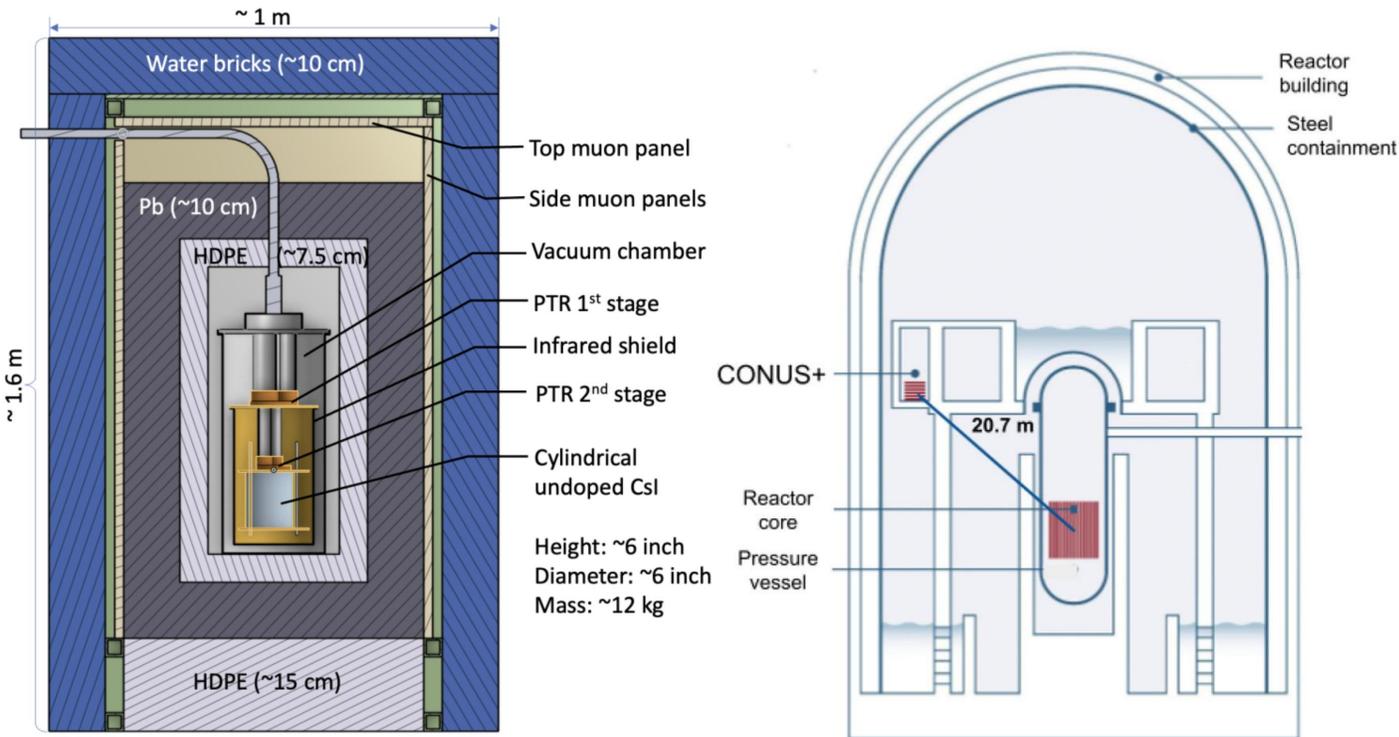
Part 4

ν -N Scattering

COHERENT & CONUS+ Set up

Result & discussions

CEvNS – Coherent Elastic Neutrino–Nucleus Scattering



	COHERENT	CONUS+
ν source	SNS (DAR ν)	reactor ν
ν energy	~ 50 MeV	~10 MeV
target	CsI	Ge

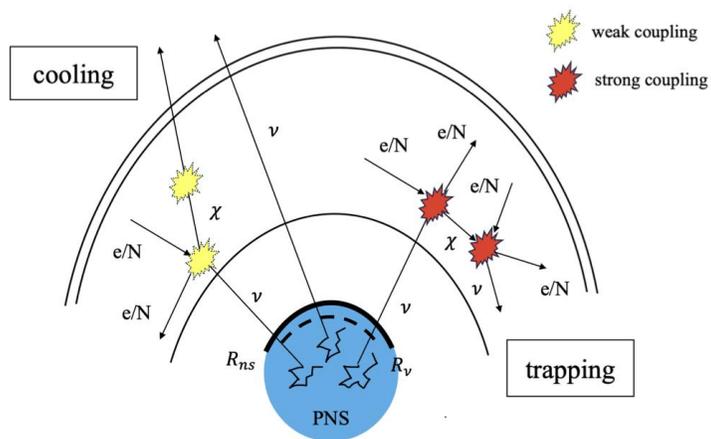
CryoCsI design

ν -N Scattering



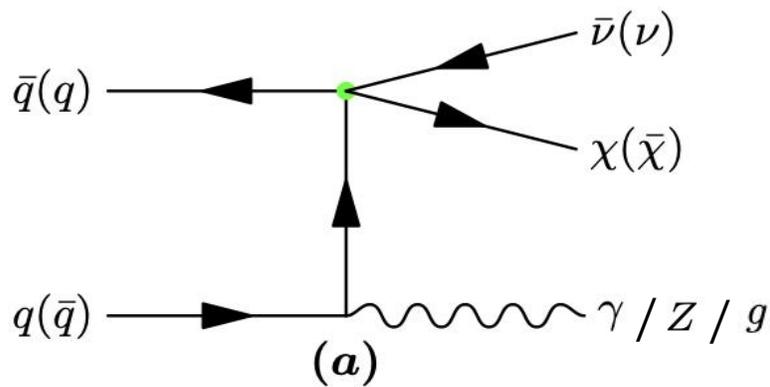
$\Lambda_i (m_\chi = 1 \text{ MeV}) [\text{GeV}]$

int.	COHERENT CONUS+		SN1987A	LHC			meson decay	
				mono-jet	mono- γ	mono-Z/W	B	K
S	450	692	—	4491	2728	8848	—	—
P	8	6	—	5767	3519	11361	—	—
V	IC	388	[1500, 60000]	4526	2525	7322	467	646
	IV	200	—	—	—	—	—	—
A	44	38	—	1829	1017	2959	304	—
T	25	18	—	2519	1083	3770	—	—



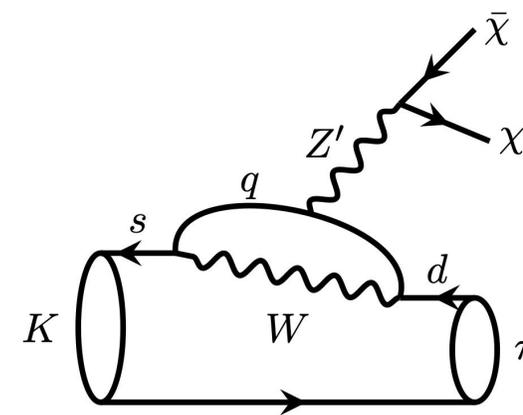
Y.Lin, C.T.Lu and N.Song, 2507.22124

Ruofei FENG (SEU)



K.Ma, S.F.Ge, L.Y.He and N.Zhou, 2405.16878

Probing Dark Particles in neutrino scattering experiments

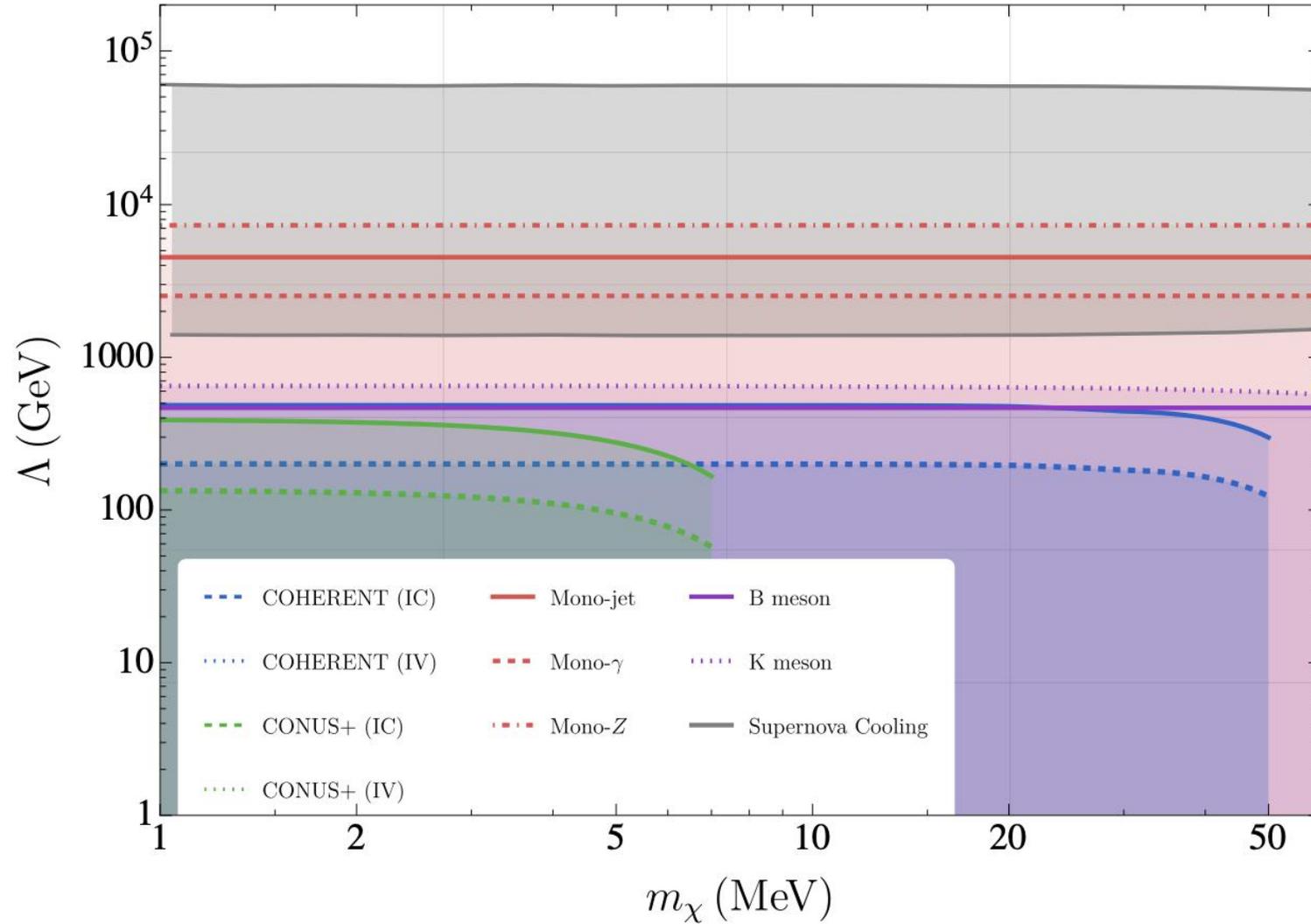


Z.K.Liu, Y.Li, B.F.Hou and Q.Chang, 2512.21191

Example



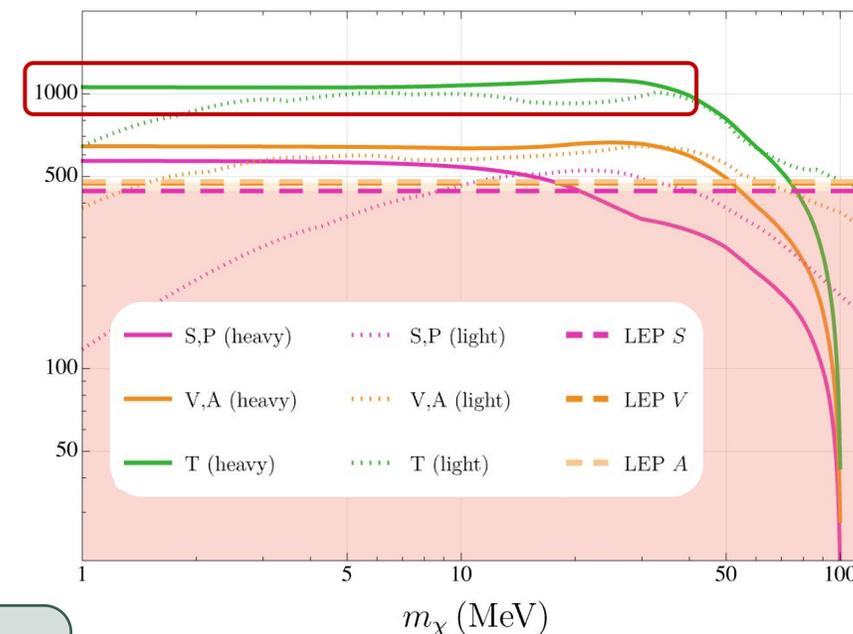
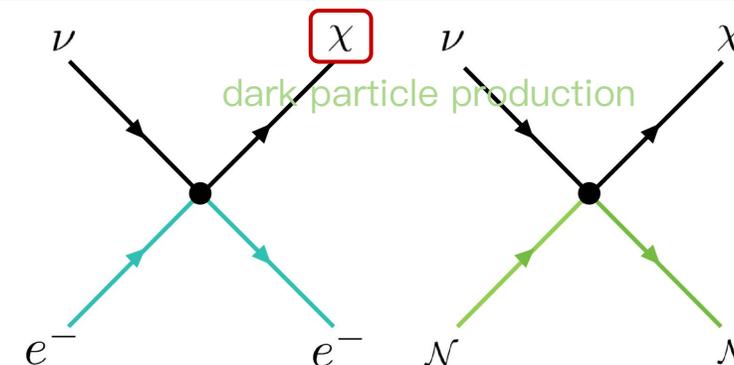
V-type: COHERENT, CONUS+ exclusion + LHC exclusion + Rare Meson Decay



Summary



1. We studied neutrino up-scattering into a generic dark particle in a **model-independent EFT** framework.
2. Neutrino scattering experiments provide a **clean and controlled** probe of weakly coupled dark sector particles in the MeV–GeV mass range.
3. DUNE–ND can probe dark particle masses up to $\mathcal{O}(100 \text{ MeV})$ with sensitivity to EFT cutoff scales reaching the **TeV level**, depending on the Lorentz structure.
4. Low-energy experiments such as COHERENT and CONUS+ probe **complementary mass ranges**, with their reach largely determined by kinematics.



THANK YOU!

backup-cross section (v-e)



- For the **electron target**, it is straightforward to calculate the **differential cross sections**, with respect to the recoil energy T_e of electron:

$$\frac{d\sigma_e^S}{dT_e} = \frac{m_e}{4\pi\Lambda_{S,e}^4} \left(1 + \frac{T_e}{2m_e}\right) \left(\frac{m_e T_e}{E_\nu^2} + \frac{m_\chi^2}{2E_\nu^2}\right),$$

$$\frac{d\sigma_e^P}{dT_e} = \frac{m_e}{4\pi\Lambda_{P,e}^4} \frac{T_e}{2m_e} \left(\frac{m_e T_e}{E_\nu^2} + \frac{m_\chi^2}{2E_\nu^2}\right),$$

$$\frac{d\sigma_e^V}{dT_e} = \frac{m_e}{2\pi\Lambda_{V,e}^4} \left[\left(1 - \frac{m_e T_e}{2E_\nu^2} - \frac{T_e}{E_\nu} + \frac{T_e^2}{2E_\nu^2}\right) - \frac{m_\chi^2}{4E_\nu^2} \left(1 + \frac{2E_\nu}{m_e} - \frac{T_e}{m_e}\right) \right],$$

$$\frac{d\sigma_e^A}{dT_e} = \frac{m_e}{2\pi\Lambda_{A,e}^4} \left[\left(1 + \frac{m_e T_e}{2E_\nu^2} - \frac{T_e}{E_\nu} + \frac{T_e^2}{2E_\nu^2}\right) + \frac{m_\chi^2}{4E_\nu^2} \left(1 - \frac{2E_\nu}{m_e} + \frac{T_e}{m_e}\right) \right],$$

$$\frac{d\sigma_e^T}{dT_e} = \frac{4m_e}{\pi\Lambda_{T,e}^4} \left[\left(1 - \frac{m_e T_e}{4E_\nu^2} - \frac{T_e}{E_\nu} + \frac{T_e^2}{4E_\nu^2}\right) - \frac{m_\chi^2}{4E_\nu^2} \left(\frac{1}{2} + \frac{2E_\nu}{m_e} - \frac{T_e}{2m_e}\right) \right].$$

- For the scattering of neutrinos with **nuclei**, the differential cross section can be written as, with respect to the recoil energy T_N of nuclei

$$\frac{d\sigma_N^S}{dT_N} = \frac{A^2 m_N}{4\pi \Lambda_{S,N}^4} F_W^2(|\mathbf{q}|^2) \left(1 + \frac{T_N}{2m_N}\right) \left(\frac{m_N T_N}{E_\nu^2} + \frac{m_\chi^2}{2E_\nu^2}\right),$$

$$\frac{d\sigma_N^P}{dT_N} = \frac{A^2 m_N}{4\pi \Lambda_{P,N}^4} F_W^2(|\mathbf{q}|^2) \frac{T_N}{2m_N} \left(\frac{m_N T_N}{E_\nu^2} + \frac{m_\chi^2}{2E_\nu^2}\right),$$

$$\frac{d\sigma_N^V}{dT_N} = \frac{C_V^2 m_N}{2\pi \Lambda_{V,N}^4} F_W^2(|\mathbf{q}|^2) \left[\left(1 - \frac{m_N T_N}{2E_\nu^2} - \frac{T_N}{E_\nu} + \frac{T_N^2}{2E_\nu^2}\right) - \frac{m_\chi^2}{4E_\nu^2} \left(1 + \frac{2E_\nu}{m_N} - \frac{T_N}{m_N}\right) \right],$$

$$C_V = \begin{cases} Z + N = A, & \Lambda_{V,p} = \Lambda_{V,n} \quad (\text{isospin conserving}), \\ Z - N, & \Lambda_{V,p} = -\Lambda_{V,n} \quad (\text{isospin violating}). \end{cases}$$

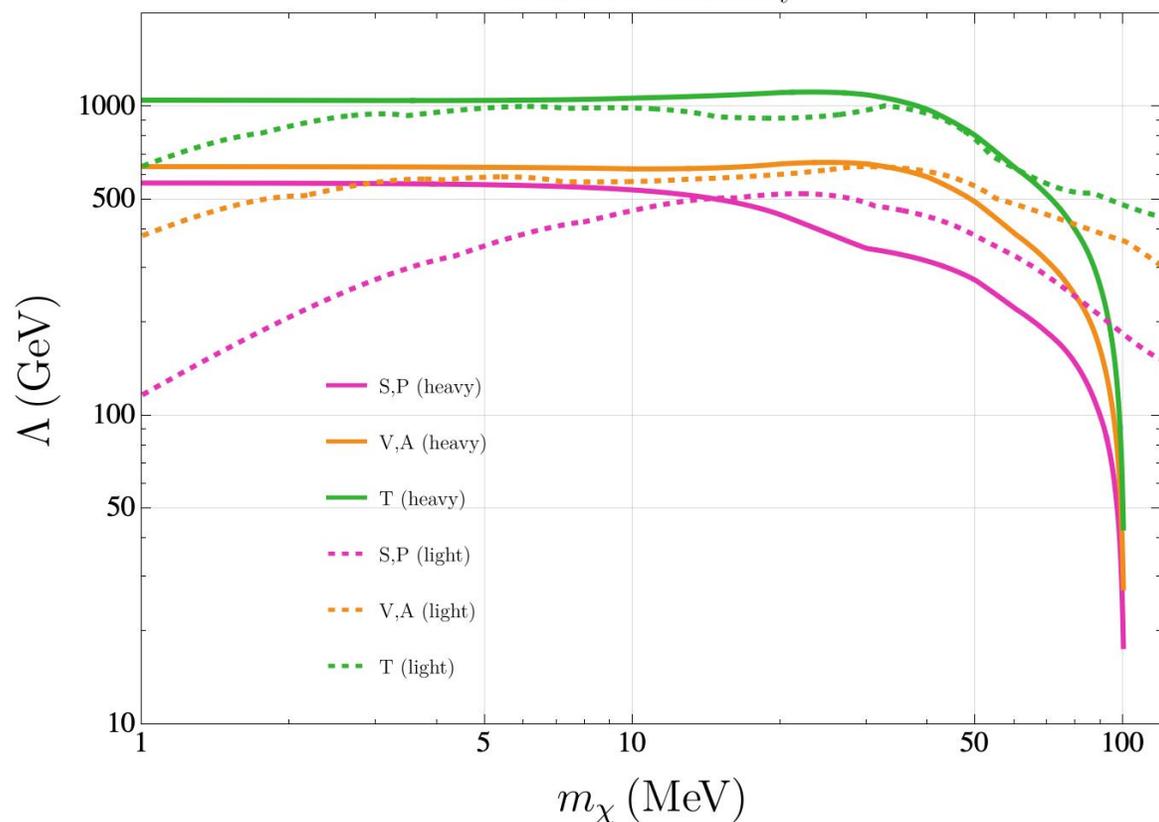
- For the scattering of neutrinos with **nuclei**, the differential cross section can be written as, with respect to the recoil energy T_N of nuclei

$$\begin{aligned} \frac{d\sigma_N^A}{dT_N} = & \frac{2m_N}{(2J+1)\Lambda_{A,N}^4} \left\{ \left[\left(2 + \frac{m_N T_N}{E_\nu^2} - \frac{2T_N}{E_\nu} - \frac{T_N}{m_N} + \frac{T_N^2}{2E_\nu^2} + \frac{T_N^2}{m_N E_\nu} \right) \right. \right. \\ & \left. \left. - \frac{m_\chi^2}{2E_\nu^2} \left(1 + \frac{3E_\nu}{m_N} + \frac{m_\chi^2}{m_N T_N} - \frac{T_N}{2m_N} \right) \right] \tilde{S}^{\mathcal{T}}(|\mathbf{q}|^2) \right. \\ & \left. + 2 \left[\frac{T_N}{E_\nu} \left(\frac{E_\nu}{m_N} - \frac{T_N}{2E_\nu} - \frac{T_N}{m_N} \right) + \frac{m_\chi^2}{2E_\nu^2} \left(2 + \frac{3E_\nu}{m_N} + \frac{m_\chi^2}{m_N T_N} - \frac{T_N}{2m_N} \right) \right] \tilde{S}^{\mathcal{L}}(|\mathbf{q}|^2) \right\}, \end{aligned}$$

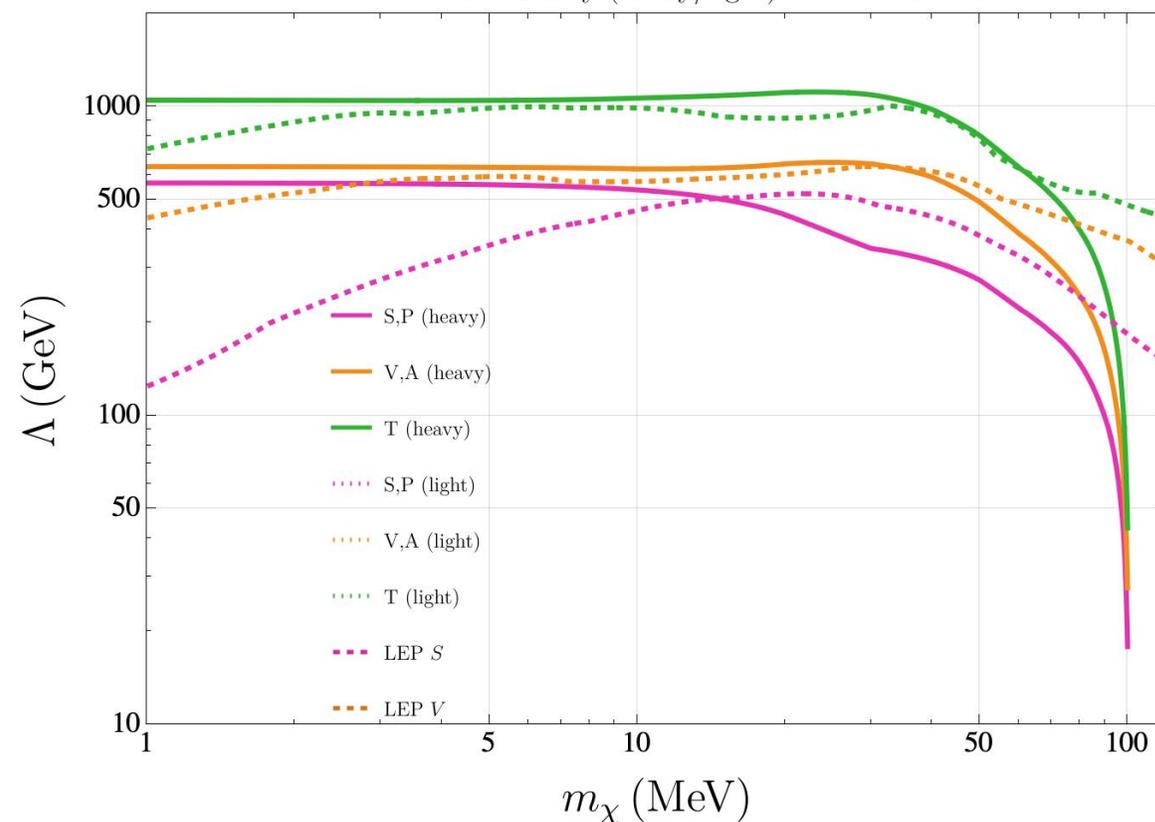
$$\begin{aligned} \frac{d\sigma_N^T}{dT_N} = & \frac{m_N}{(2J+1)\Lambda_{T,N}^4} \left\{ \left[\left(2 - \frac{m_N T_N}{E_\nu^2} - \frac{2T_N}{E_\nu} + \frac{T_N}{m_N} - \frac{T_N^2}{m_N E_\nu} - \frac{T_N^2}{E_\nu^2} \right) \right. \right. \\ & \left. \left. + \frac{m_\chi^2}{2E_\nu^2} \left(1 + \frac{3E_\nu}{m_N} - \frac{T_N}{m_N} + \frac{m_\chi^2}{m_N T_N} \right) \right] \tilde{S}^{\mathcal{T}}(|\mathbf{q}|^2) \right. \\ & \left. + \left[\left(1 - \frac{T_N}{E_\nu} - \frac{T_N}{2m_N} + \frac{T_N^2}{2E_\nu^2} + \frac{T_N^2}{2m_N E_\nu} \right) \right. \right. \\ & \left. \left. - \frac{m_\chi^2}{2E_\nu^2} \left(1 + \frac{3E_\nu}{2m_N} - \frac{T_N}{2m_N} + \frac{m_\chi^2}{2m_N T_N} \right) \right] \tilde{S}^{\mathcal{L}}(|\mathbf{q}|^2) \right\}, \end{aligned}$$

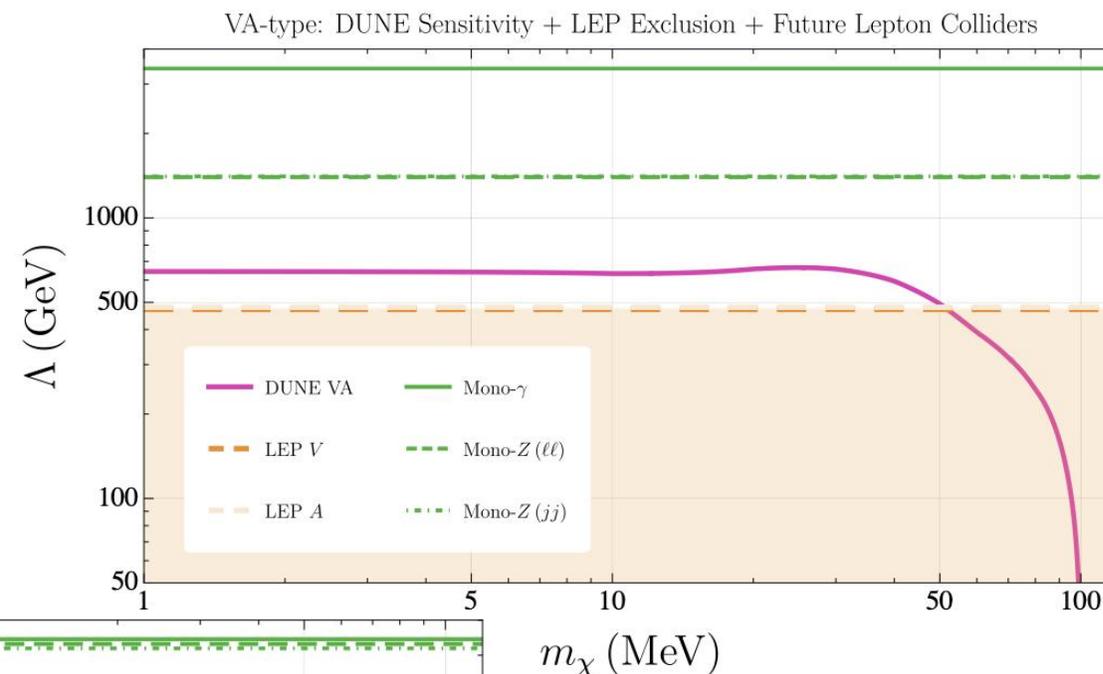
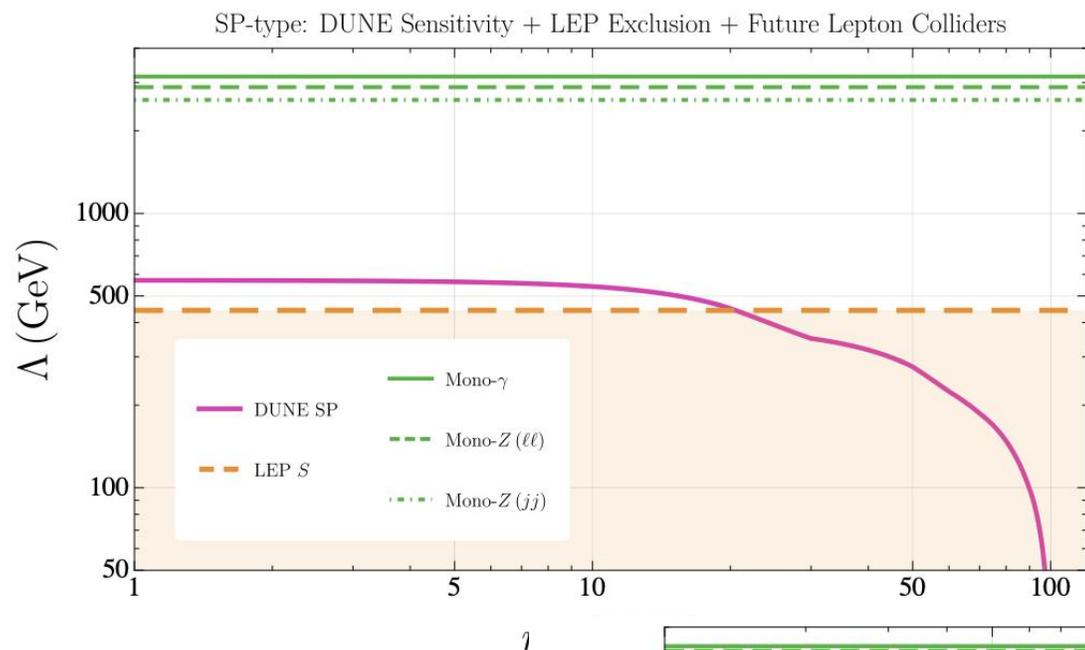
Heavy mediator vs. light mediator (sensitivity to momentum transfer)

DUNE-ND Sensitivity

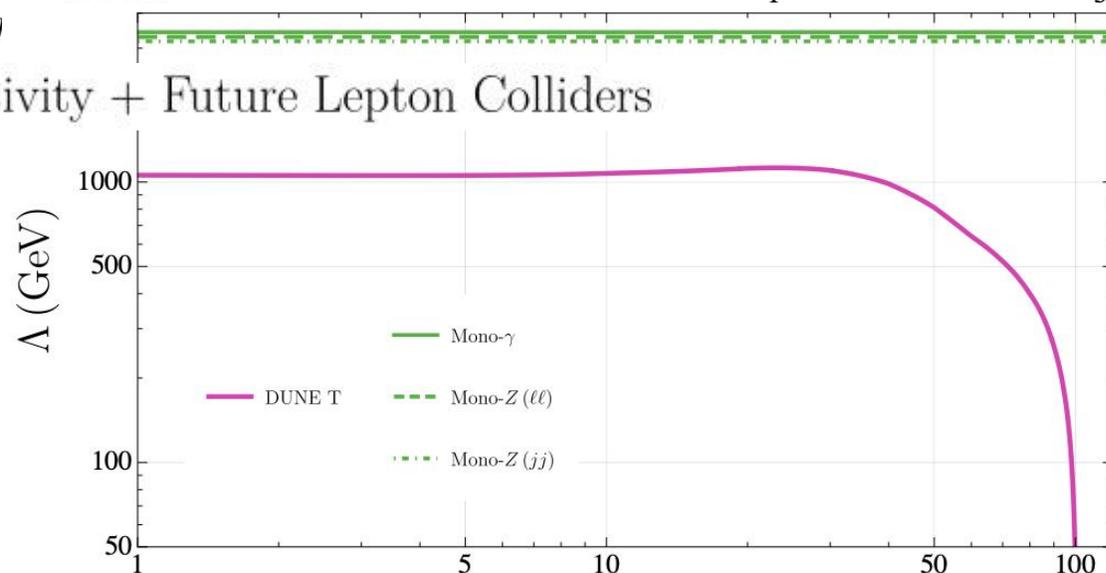


DUNE-ND Sensitivity (heavy/light) + LEP reference

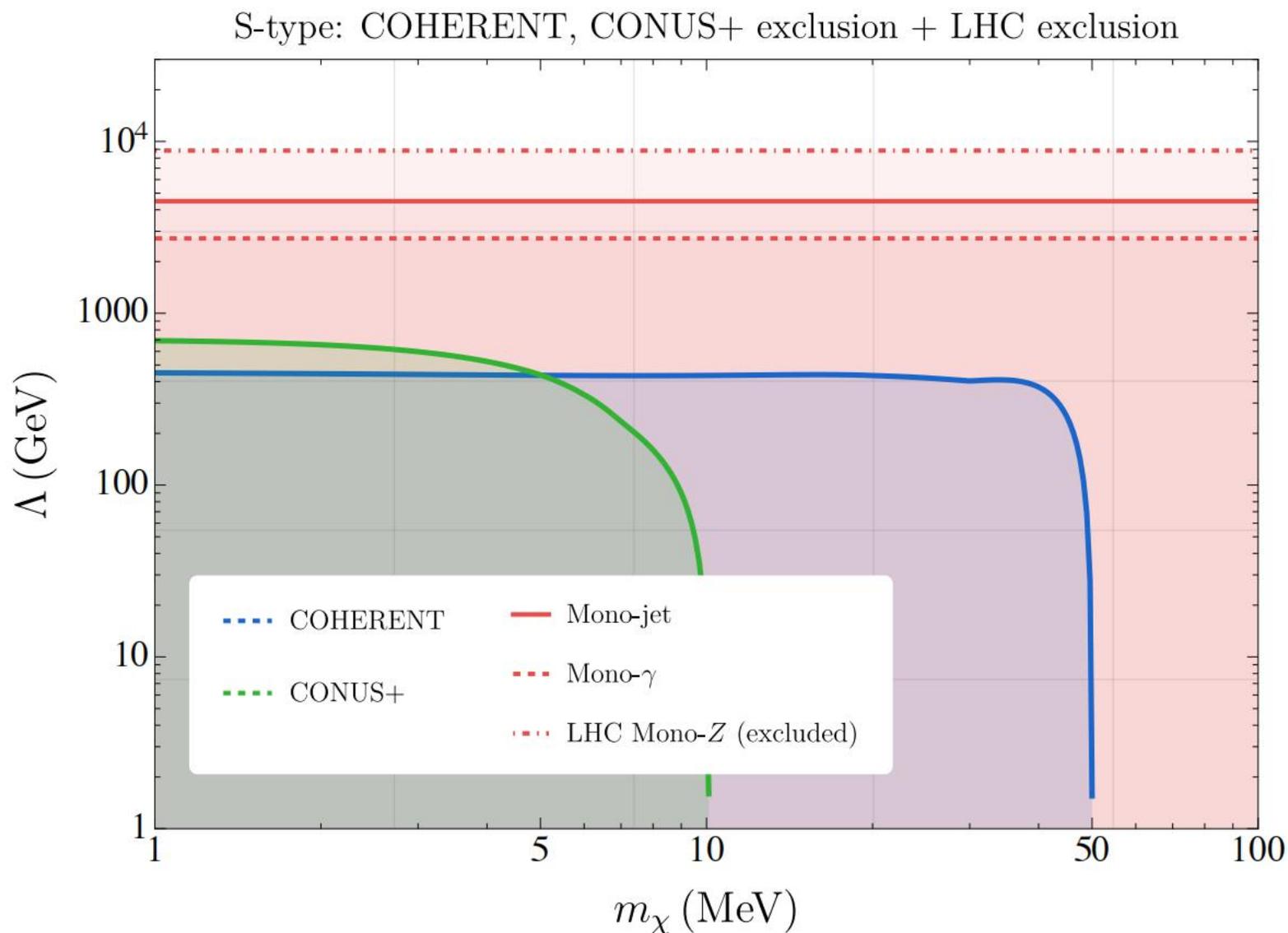




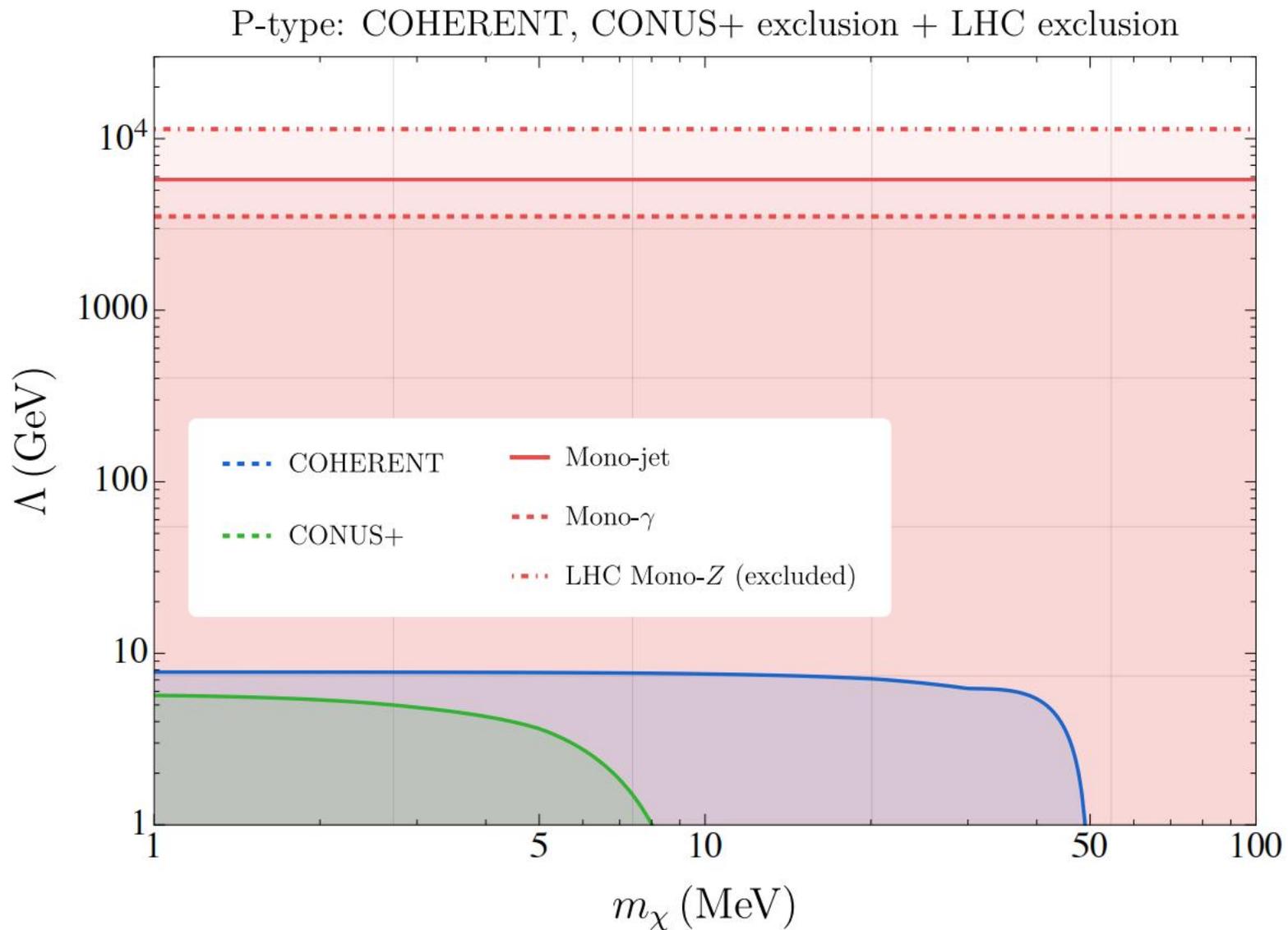
T-type: DUNE Sensitivity + Future Lepton Colliders



ν -N constrains (Scalar)



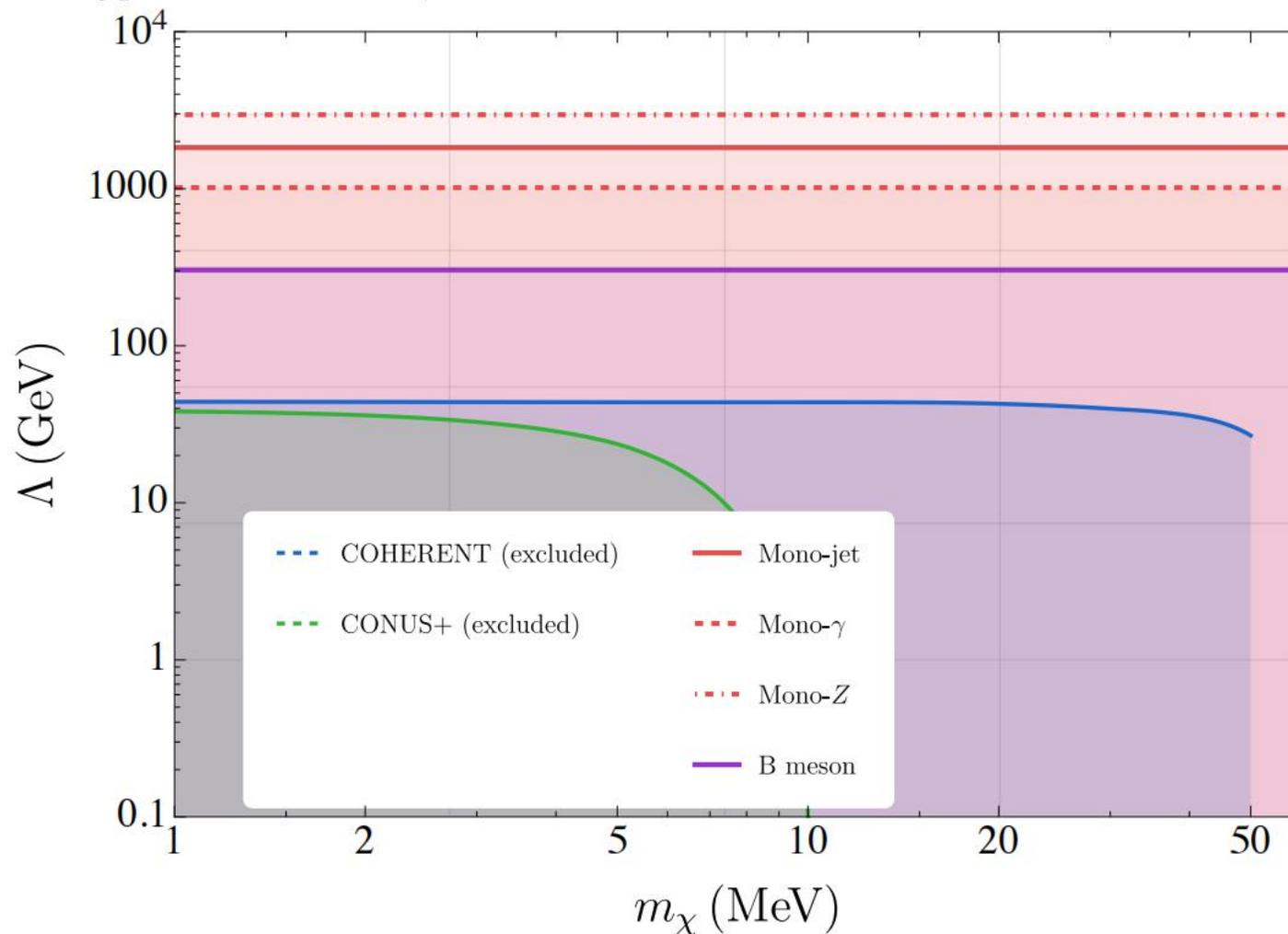
ν -N constrains (Pseudo-Scalar)



ν -N constrains (Axial-vector)



A-type: COHERENT, CONUS+ exclusion + LHC exclusion + B Meson Decay



ν -N constrains (Tensor)

