Coherent Elastic Neutrino-Nucleus Scattering as a Probe of Z'

James Dent

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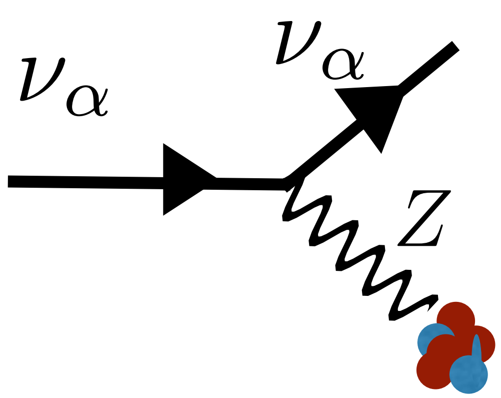
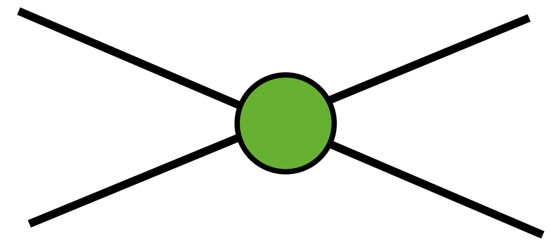
M.Abdullah, JBD, B. Dutta, G.L. Kane, S. Liao, and L. Strigari PRD 2018, 1803.01224

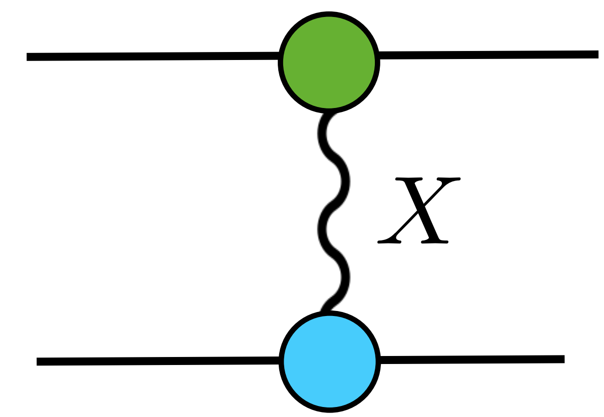
Outline

Coherent Scattering



NSI





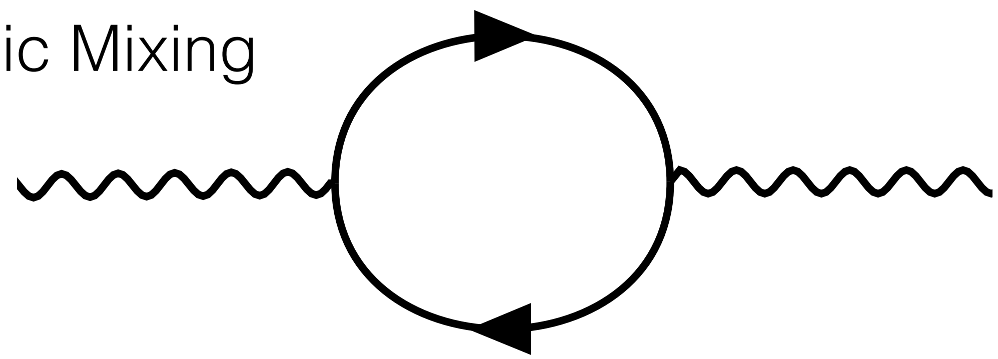
Experimental Programs

COHERENT

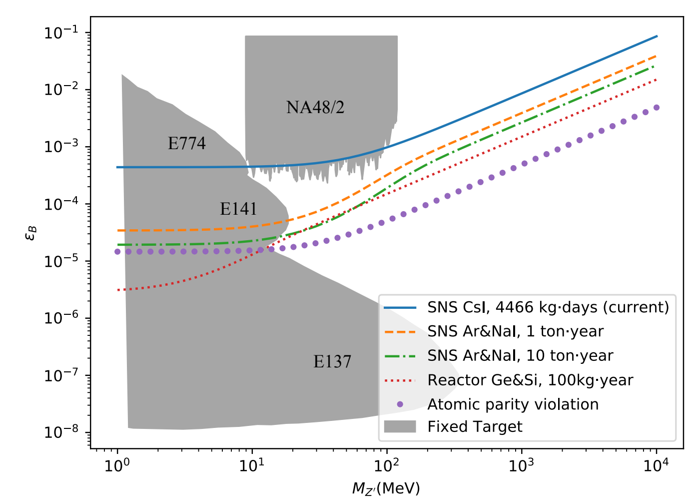
CONUS

MINER

Kinetic Mixing

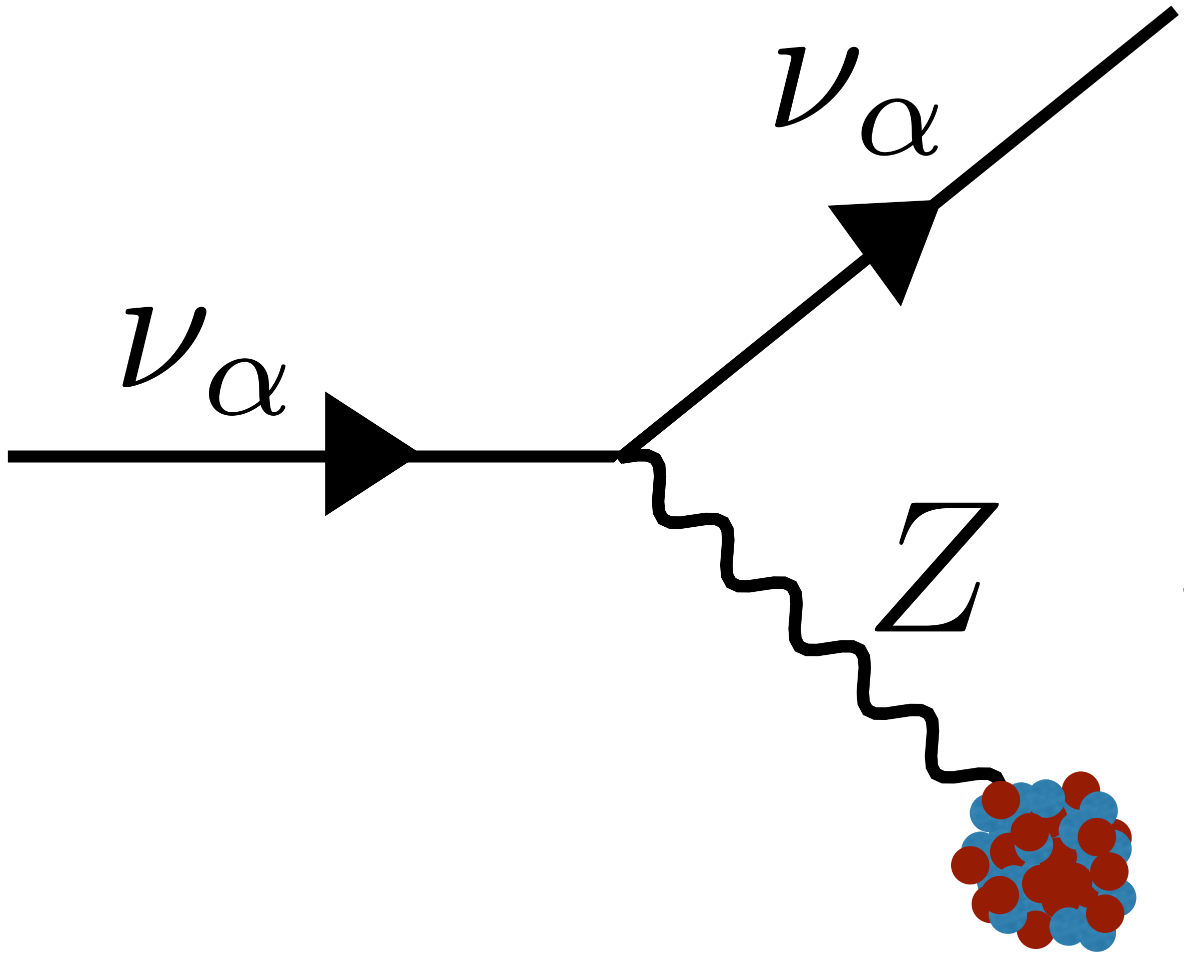


Models and Bounds



Coherent Elastic Neutrino-Nucleus Scattering: Standard Model Process

Basics of Coherent Elastic Neutrino-Nucleus Scattering



Coherency is obtained when

$$q \lesssim \frac{1}{R_{\rm nuc}} = \frac{160\,{\rm MeV}}{A_T^{1/3}}$$

This translates to energies below 50MeV for typical nuclear targets

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E_R}{E_\nu^2}\right) + \left(1 - \frac{E_R}{E_\nu}\right)^2\right) F(q^2)$$

$$Q_V^2 = (Z g_V^p + N g_V^n)^2 \qquad g_V^p = 1/2 - 2\sin^2\theta_W \text{ and } g_n^V = -1/2$$

The Standard Model coupling values show that the scattering goes roughly ~N^2

D.Z.Freedman, PRD 1974 V.B.Kopeliovich and L.L.Frankfurt, JETP Lett. 1974

Kinematics

The key elements are the exchanged momentum and the recoil energy

$$q = \sqrt{2mE_R} \qquad\qquad E_R = \frac{2mE_\nu^2\cos^2\theta}{(m+E_\nu)^2 - E_\nu^2\cos^2\theta}$$

An obstacle in detecting this process lies with the low recoil energy

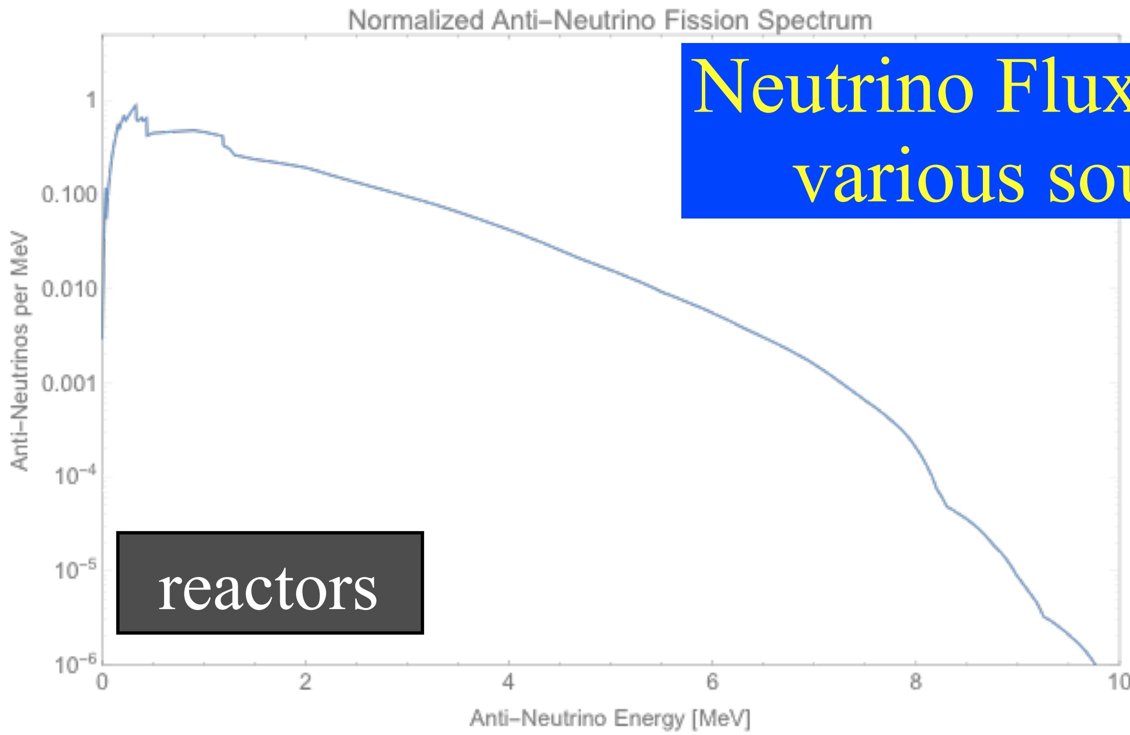
$$E_{R,\mathrm{max}} = \frac{2E_\nu^2}{m+2E_\nu}$$

A 5 MeV neutrino will elicit a ~1keV recoil in an A = 50 atom.

A 30 MeV neutrino gives a ~14-15keV recoil to Cs or I.

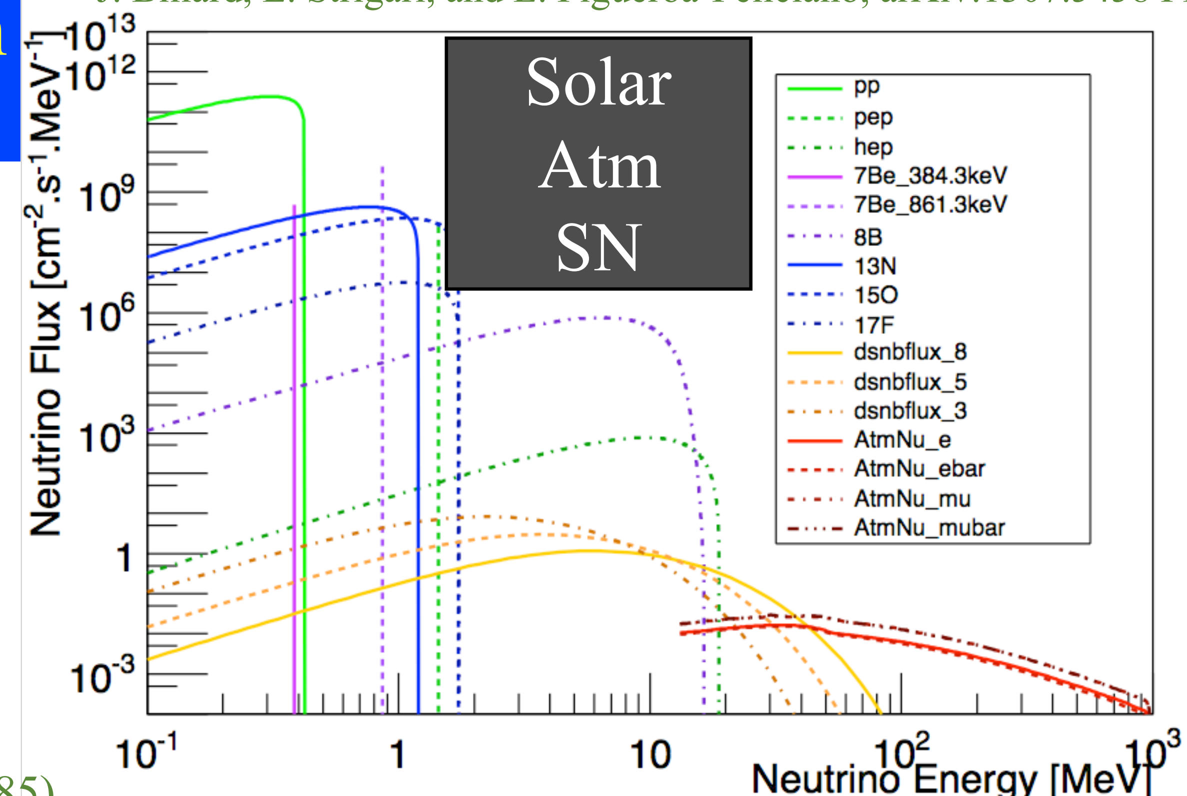
Low threshold detectors are needed.

Neutrino Fluxes from various sources



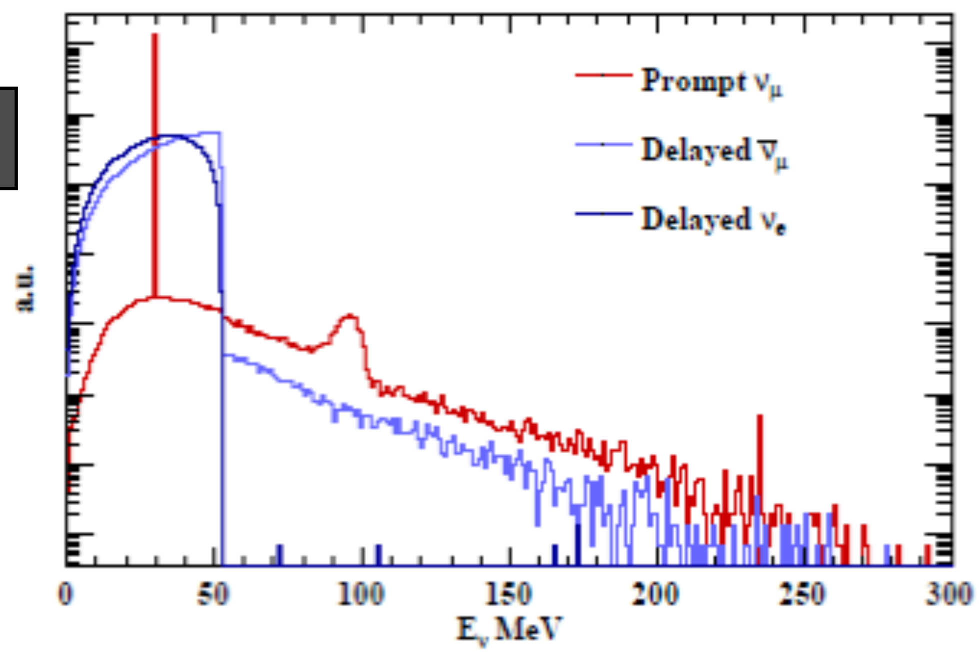
V.I. Kopeikin (2012)
K. Schreckenbah, G. Colvin, W. Gelletly, and F. Von Feilitzsch, PLB (1985)
B. Dutta, R. Mahapatra, L.E. Strigari, and J.W. Walker, 1508.07981 PRD

J. Billard, L. Strigari, and E. Figueroa-Feliciano, arXiv:1307.5458 PRD

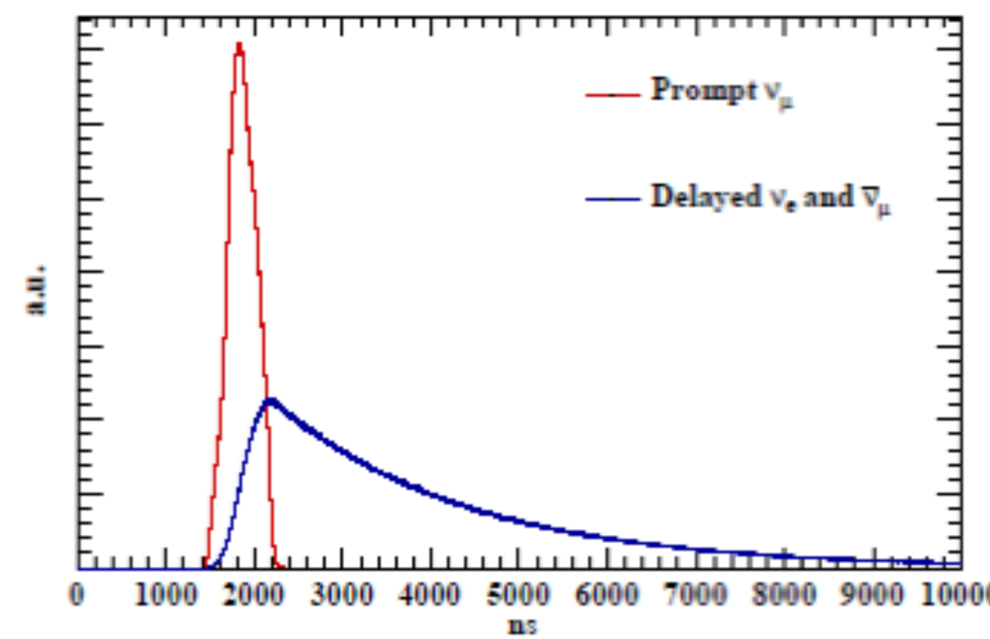


SPS

COHERENT Collaboration
1509.08702



(a)SNS neutrino energy spectrum



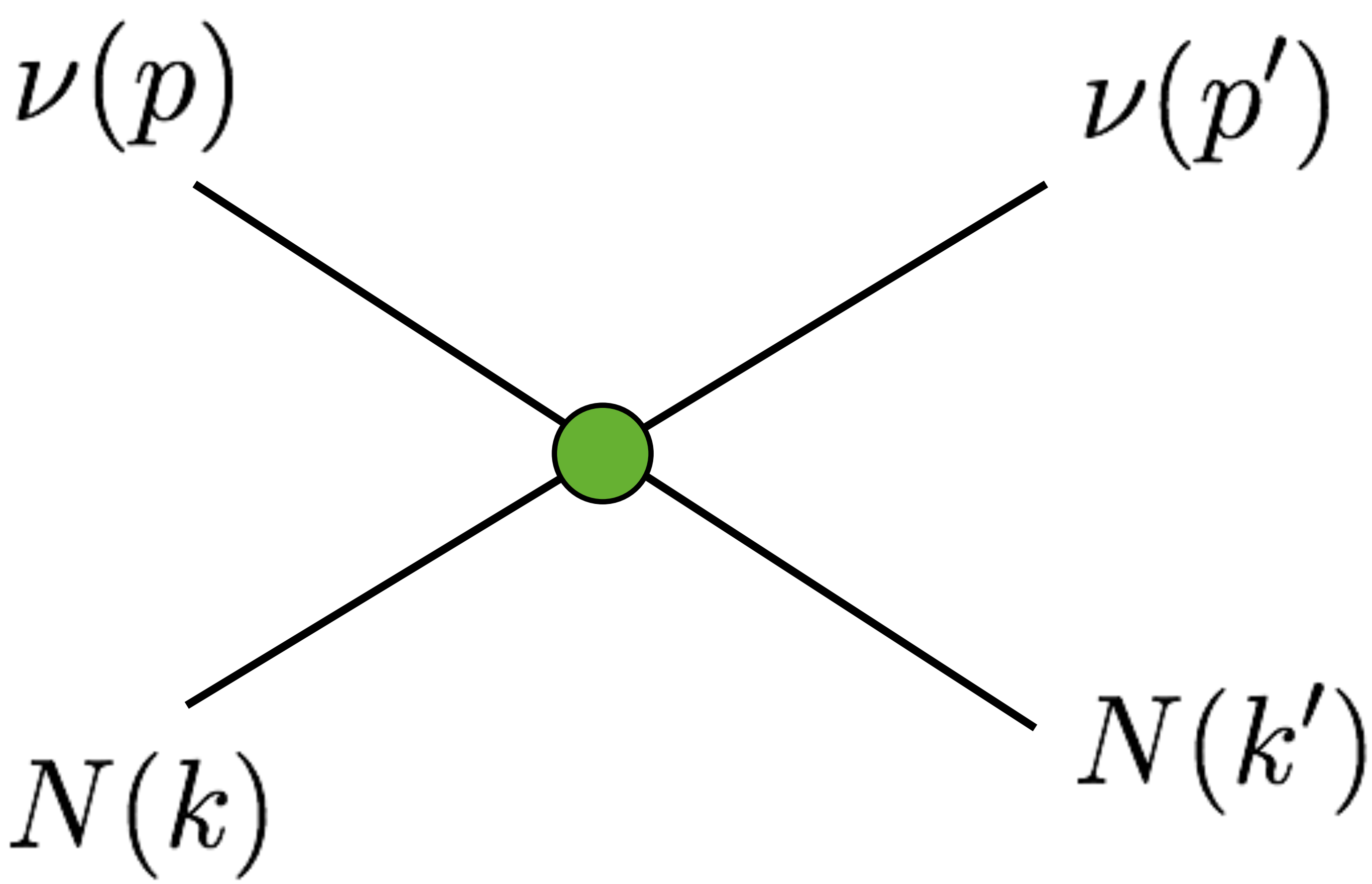
(b)SNS neutrino timing distribution

Non-Standard Interactions

Non-Standard Interactions (NSI)

$$\mathcal{L}_{NSI} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f} \bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L}\left(\epsilon^{fL}_{\alpha\beta}\bar{f}_L\gamma_{\mu}f_L + \epsilon^{fR}_{\alpha\beta}\bar{f}_R\gamma_{\mu}f_R\right)$$

Four-Fermi style interaction in units of G_F



$$\epsilon^{fV}_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

$$\epsilon^{fA}_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} - \epsilon^{fR}_{\alpha\beta}$$

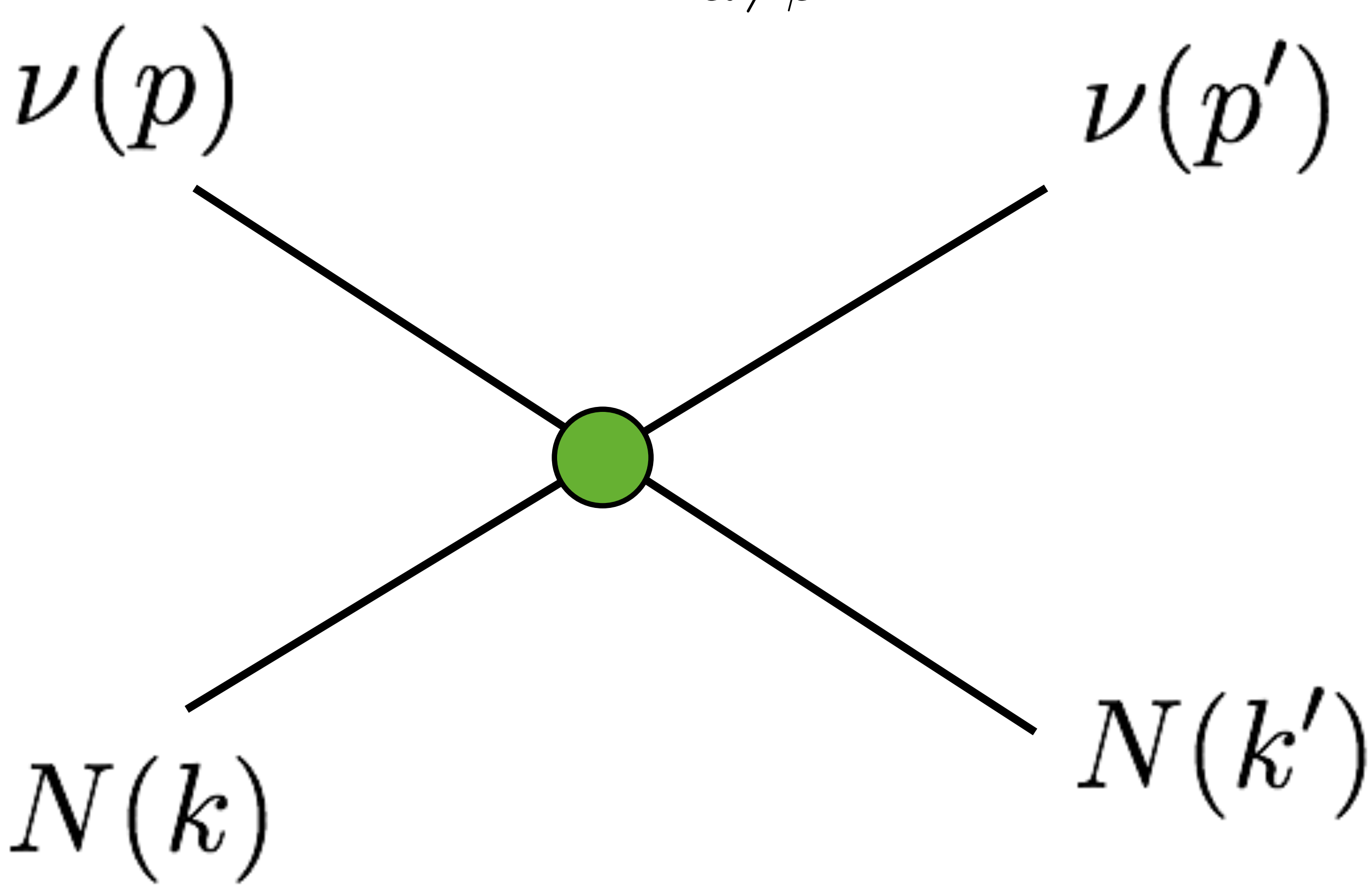
$$\alpha = e, \mu, \tau$$

$$f = e, u, d$$

Non-Standard Interactions (NSI) for CENNS

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 Q_V^2}{2\pi} m_N \left(1 - \left(\frac{m_N E_R}{E_\nu^2}\right) + \left(1 - \frac{E_R}{E_\nu}\right)^2\right) F(q^2)$$

$$\begin{aligned} Q_V^2 \ &\equiv \ \left[Z(g_p^V + 2\epsilon_{\alpha\alpha}^{uV} + \epsilon_{\alpha\alpha}^{d}) + N(g_n^V + \epsilon_{\alpha\alpha}^{uV} + 2\epsilon_{\alpha\alpha}^{d})\right]^2 \\ &+ \ \sum_{\alpha\neq\beta}\left[Z(2\epsilon_{\alpha\beta}^{uV} + \epsilon_{\alpha\beta}^{d}V) + N(\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV})\right]^2 \end{aligned}$$



$$\alpha = e, \mu, \tau$$

$$f = e, u, d$$

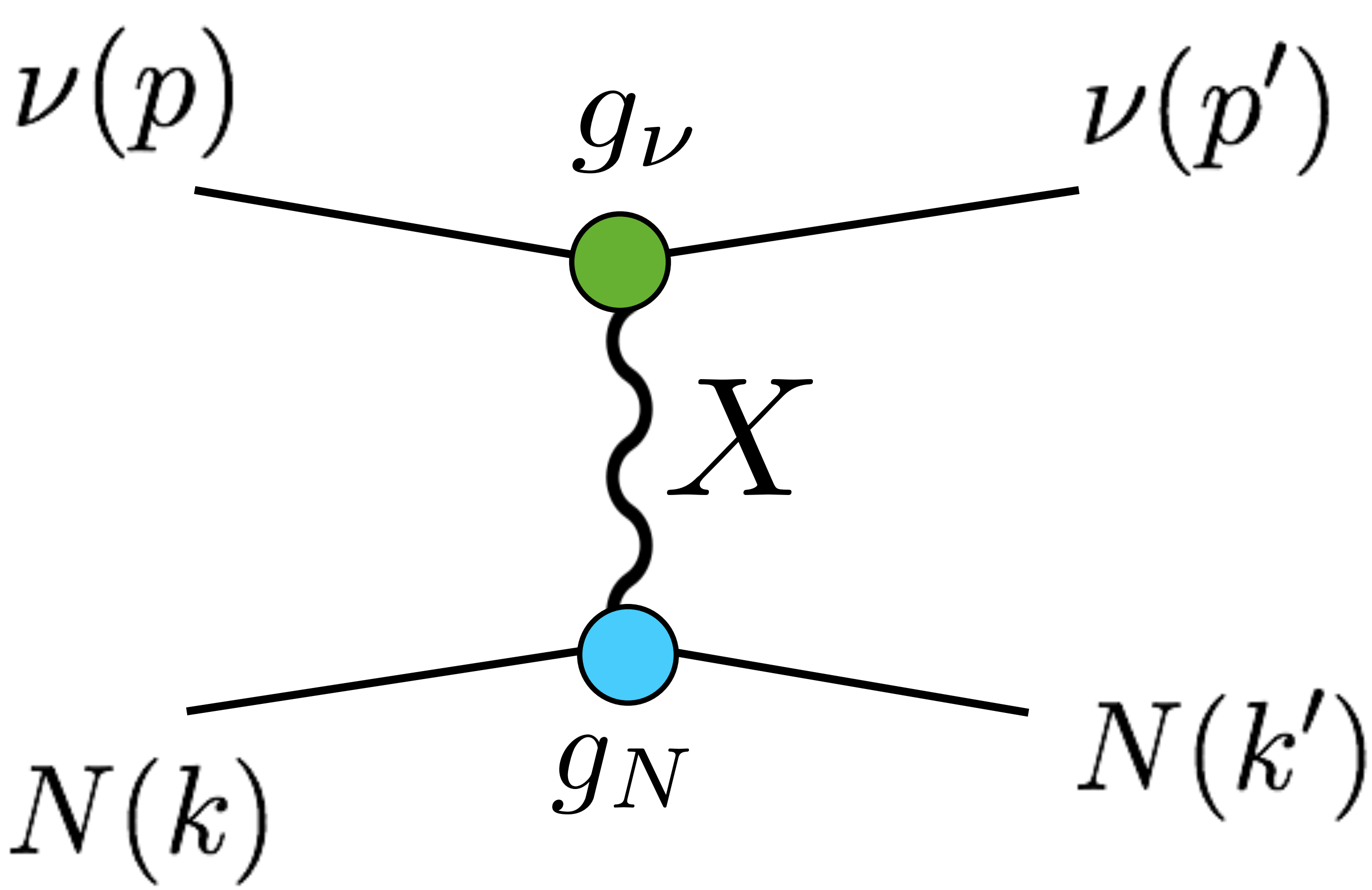
	90% C.L. range	origin
		NSI with quarks
ϵ_{ee}^{dL}	$[-0.3, 0.3]$	CHARM
ϵ_{ee}^{dR}	$[-0.6, 0.5]$	CHARM
$\epsilon_{\mu\mu}^{dV}$	$[-0.042, 0.042]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{uV}$	$[-0.044, 0.044]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{dA}$	$[-0.072, 0.057]$	atmospheric + accelerator
$\epsilon_{\mu\mu}^{uA}$	$[-0.094, 0.14]$	atmospheric + accelerator
$\epsilon_{\tau\tau}^{dV}$	$[-0.075, 0.33]$	oscillation data + COHERENT
$\epsilon_{\tau\tau}^{uV}$	$[-0.09, 0.38]$	oscillation data + COHERENT
$\epsilon_{\tau\tau}^{qV}$	$[-0.037, 0.037]$	atmospheric
		NSI with electrons
ϵ_{ee}^{eL}	$[-0.021, 0.052]$	solar + KamLAND
ϵ_{ee}^{eR}	$[-0.07, 0.08]$	TEXONO
$\epsilon_{\mu\mu}^{eL}$, $\epsilon_{\mu\mu}^{eR}$	$[-0.03, 0.03]$	reactor + accelerator
$\epsilon_{\tau\tau}^{eL}$	$[-0.12, 0.06]$	solar + KamLAND
$\epsilon_{\tau\tau}^{eR}$	$[-0.98, 0.23]$ [-0.25, 0.43]	solar + KamLAND and Borexino reactor + accelerator
$\epsilon_{\tau\tau}^{eV}$	$[-0.11, 0.11]$	atmospheric

	90% C.L. range	origin
	NSI with quarks	
$\epsilon_{e\mu}^{qL}$	$[-0.023, 0.023]$	accelerator
$\epsilon_{e\mu}^{qR}$	$[-0.036, 0.036]$	accelerator
$\epsilon_{e\mu}^{uV}$	$[-0.073, 0.044]$	oscillation data + COHERENT
$\epsilon_{e\mu}^{dV}$	$[-0.07, 0.04]$	oscillation data + COHERENT
$\epsilon_{e\tau}^{qL}$, $\epsilon_{e\tau}^{qR}$	$[-0.5, 0.5]$	CHARM
$\epsilon_{e\tau}^{uV}$	$[-0.15, 0.13]$	oscillation data + COHERENT
$\epsilon_{e\tau}^{dV}$	$[-0.13, 0.12]$	oscillation data + COHERENT
$\epsilon_{\mu\tau}^{qL}$	$[-0.023, 0.023]$	accelerator
$\epsilon_{\mu\tau}^{qR}$	$[-0.036, 0.036]$	accelerator
$\epsilon_{\mu\tau}^{qV}$	$[-0.006, 0.0054]$	IceCube
$\epsilon_{\mu\tau}^{qA}$	$[-0.039, 0.039]$	atmospheric + accelerator
	NSI with electrons	
$\epsilon_{e\mu}^{eL}$, $\epsilon_{e\mu}^{eR}$	$[-0.13, 0.13]$	reactor + accelerator
$\epsilon_{e\tau}^{eL}$	$[-0.33, 0.33]$	reactor + accelerator
$\epsilon_{e\tau}^{eR}$	$[-0.28, -0.05]$ & $[0.05, 0.28]$ [-0.19, 0.19]	reactor + accelerator TEXONO
$\epsilon_{\mu\tau}^{eL}$, $\epsilon_{\mu\tau}^{eR}$	$[-0.10, 0.10]$	reactor + accelerator
$\epsilon_{\mu\tau}^{eV}$	$[-0.018, 0.016]$	IceCube

Y.Farzan and M.Tortola, Front.In Phys. 2018, 1710.09360

Non-Standard Interactions (NSI): light mediators

$$\mathcal{M} \propto \frac{g_X^2}{q^2 - M_X^2}$$

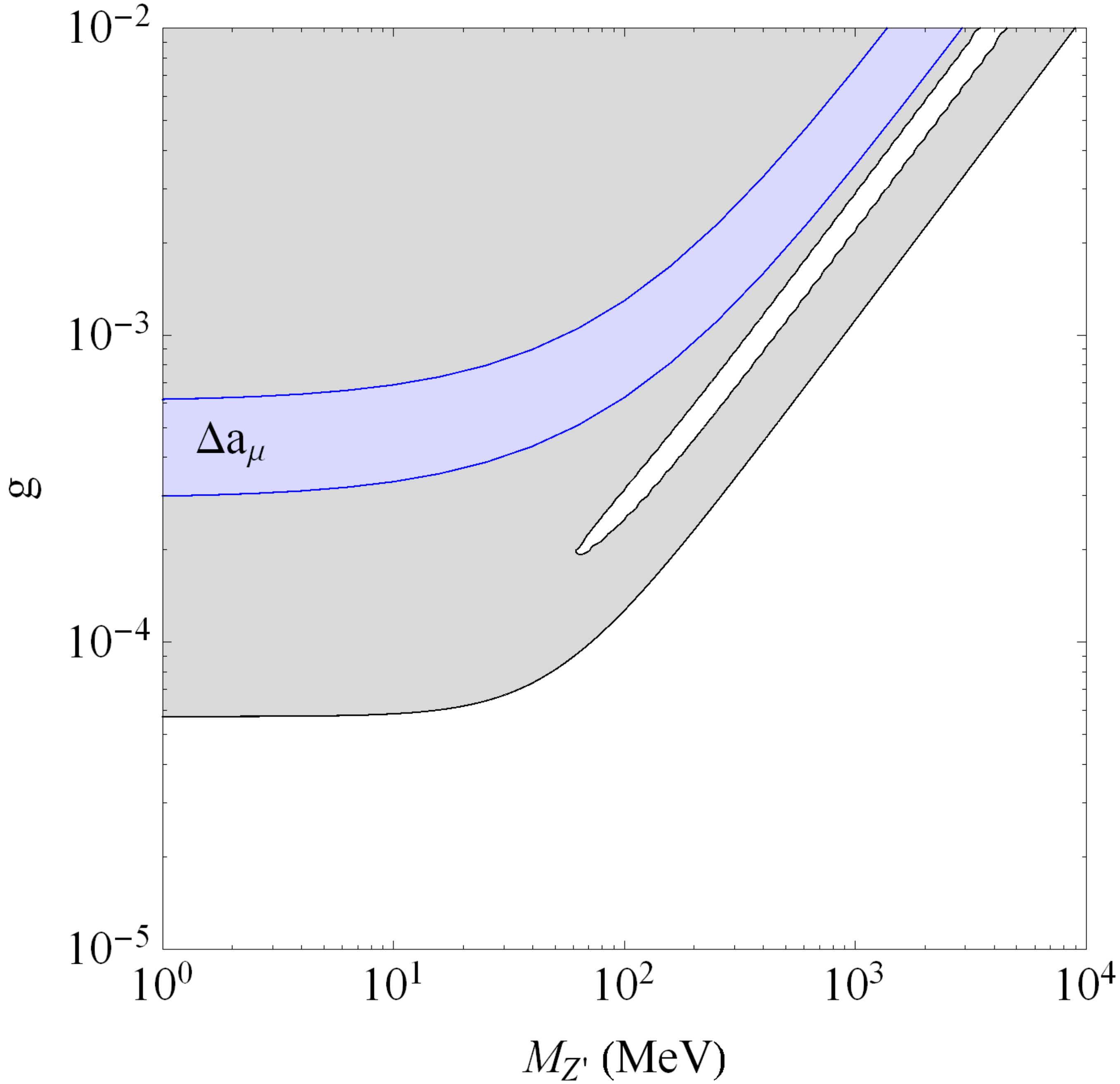


When the mediator mass is

$$M_X^2 \ll q^2 \Longrightarrow \frac{g_X^2}{q^2}$$

there is a momentum-dependent interaction which produce increased rates at low energy

Direct interactions or via mixing



An example of a light mediator with universal flavor-conserving couplings to first-generation quarks, the muon, and neutrinos.

Constraints in the coupling-mass plane after COHERENT

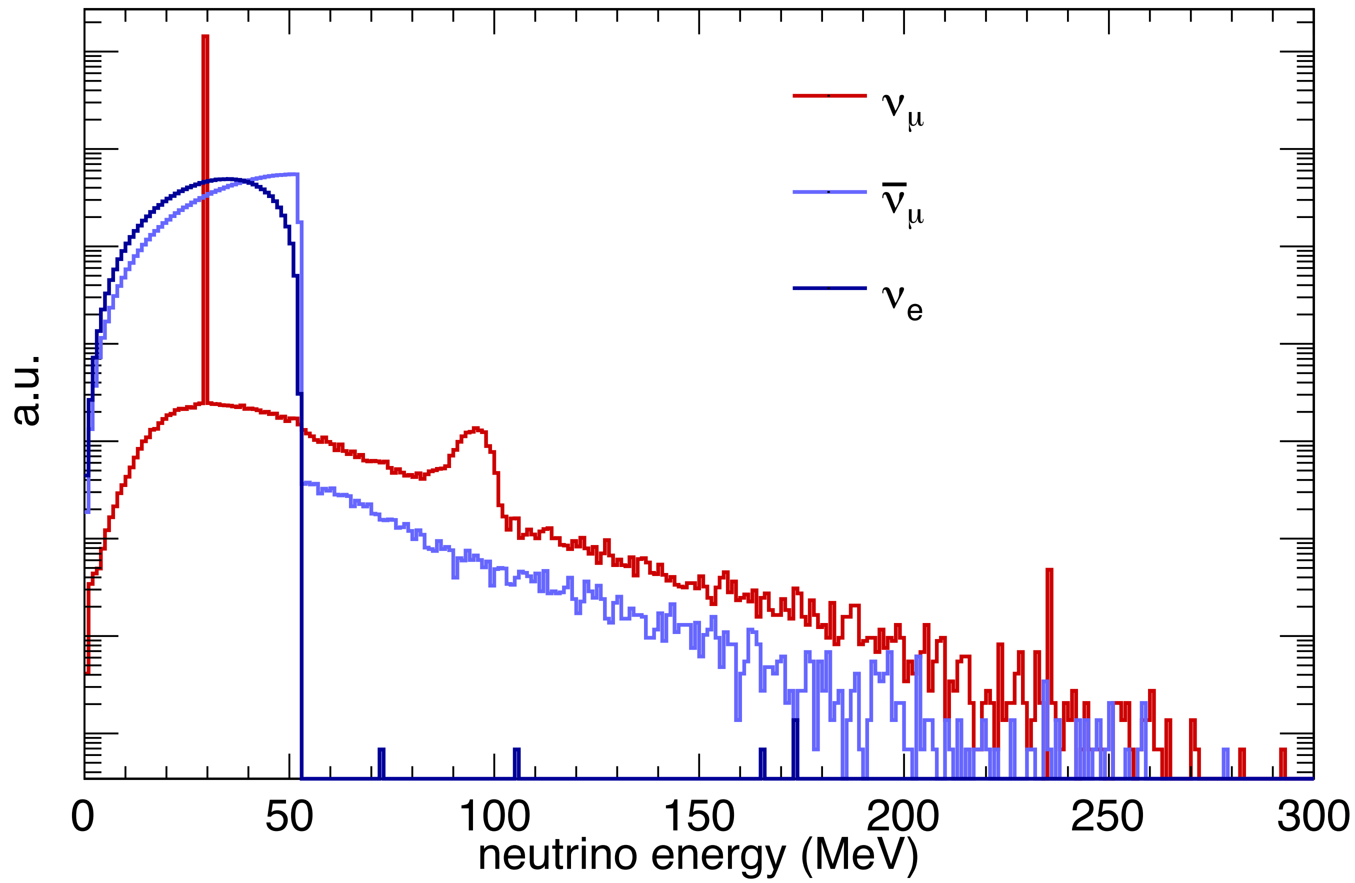
$$Q^2_{\alpha,\mathrm{NSI}} = \left[Z\left(g_p^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)} \right) + N\left(g_n^V + \frac{3g^2}{2\sqrt{2}G_F(Q^2 + M_{Z'}^2)} \right) \right]^2$$

J.Liao and D. Marfatia, PLB (2017) 1708.04255

Experimental Programs

ORNL Knoxville, TN, USA

Stopped pion source



prompt

$$\pi^+ \to \nu_\mu + \mu^+$$

delayed

$$\mu^+ \to \bar{\nu}_\mu + e^+ + \nu_e$$

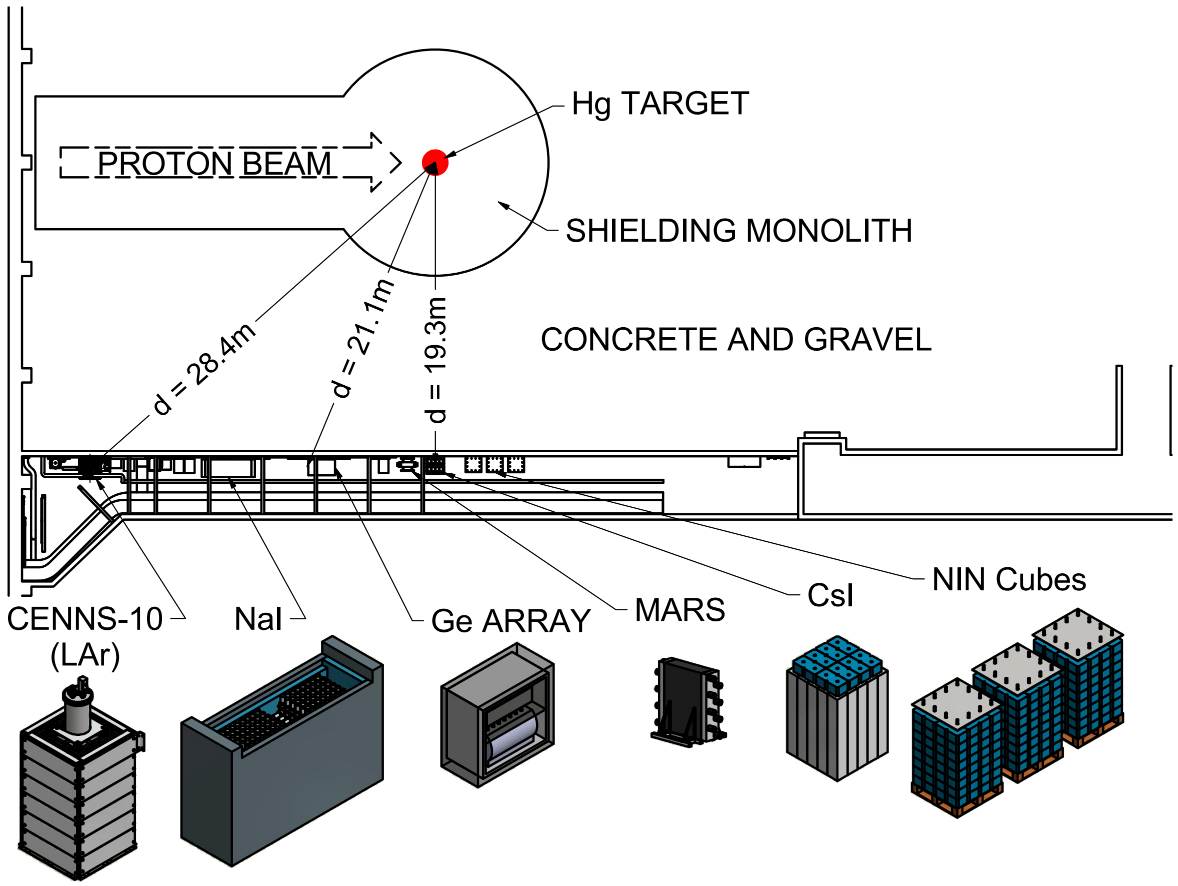
$$4.3 \times 10^7\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

at 20m

Nuclear target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVnr)
CsI[Na]	Scintillating crystal	14.6	19.3	6.5
Ge	HPGe PPC	10	22	5
LAr	Single-phase	22	29	20
NaI[Tl]	Scintillating crystal	185*/2000	28	13

Akimov *et al.* 1803.09183

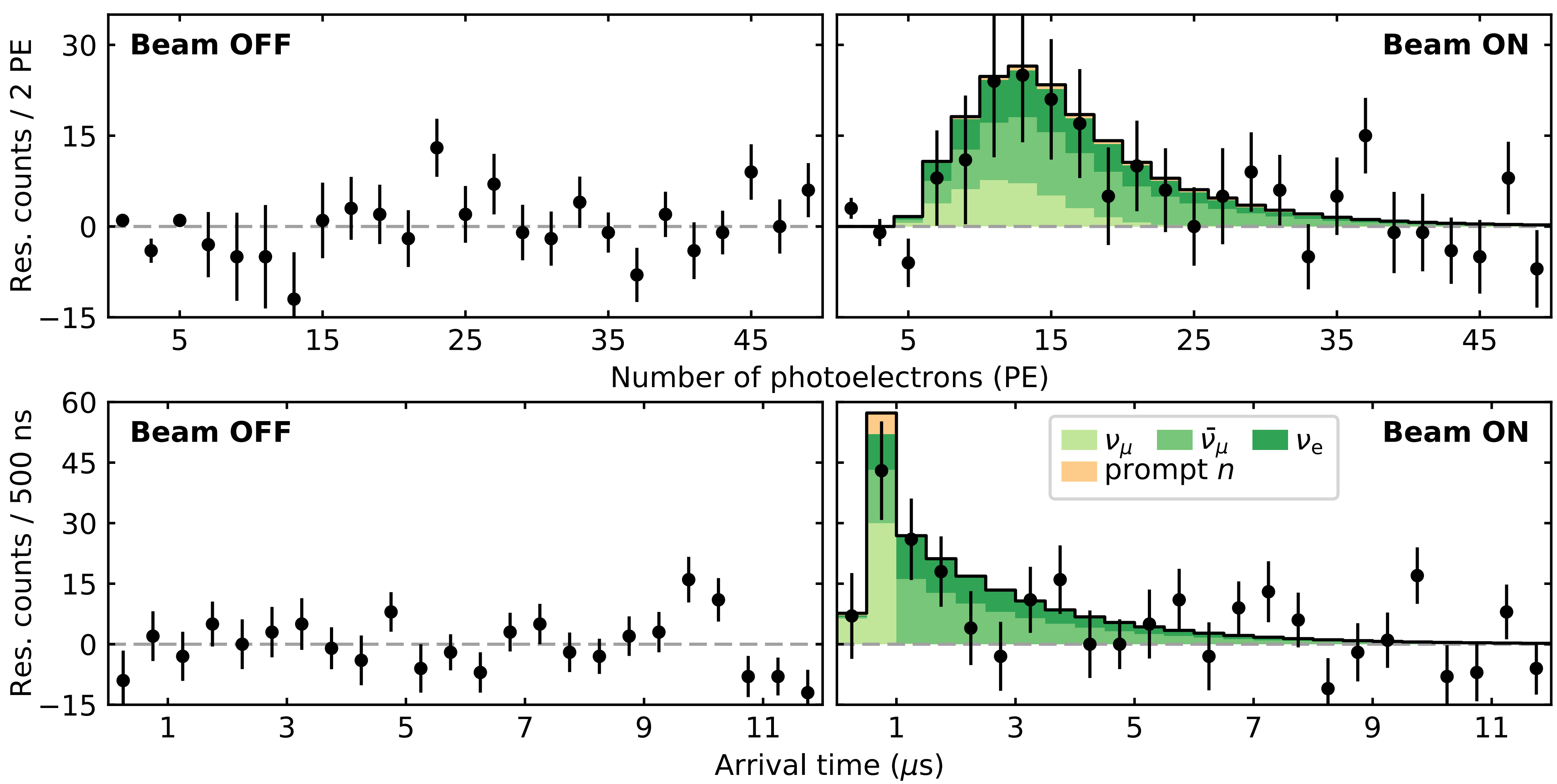
Akimov *et al*. Science (2017) 1708.01294

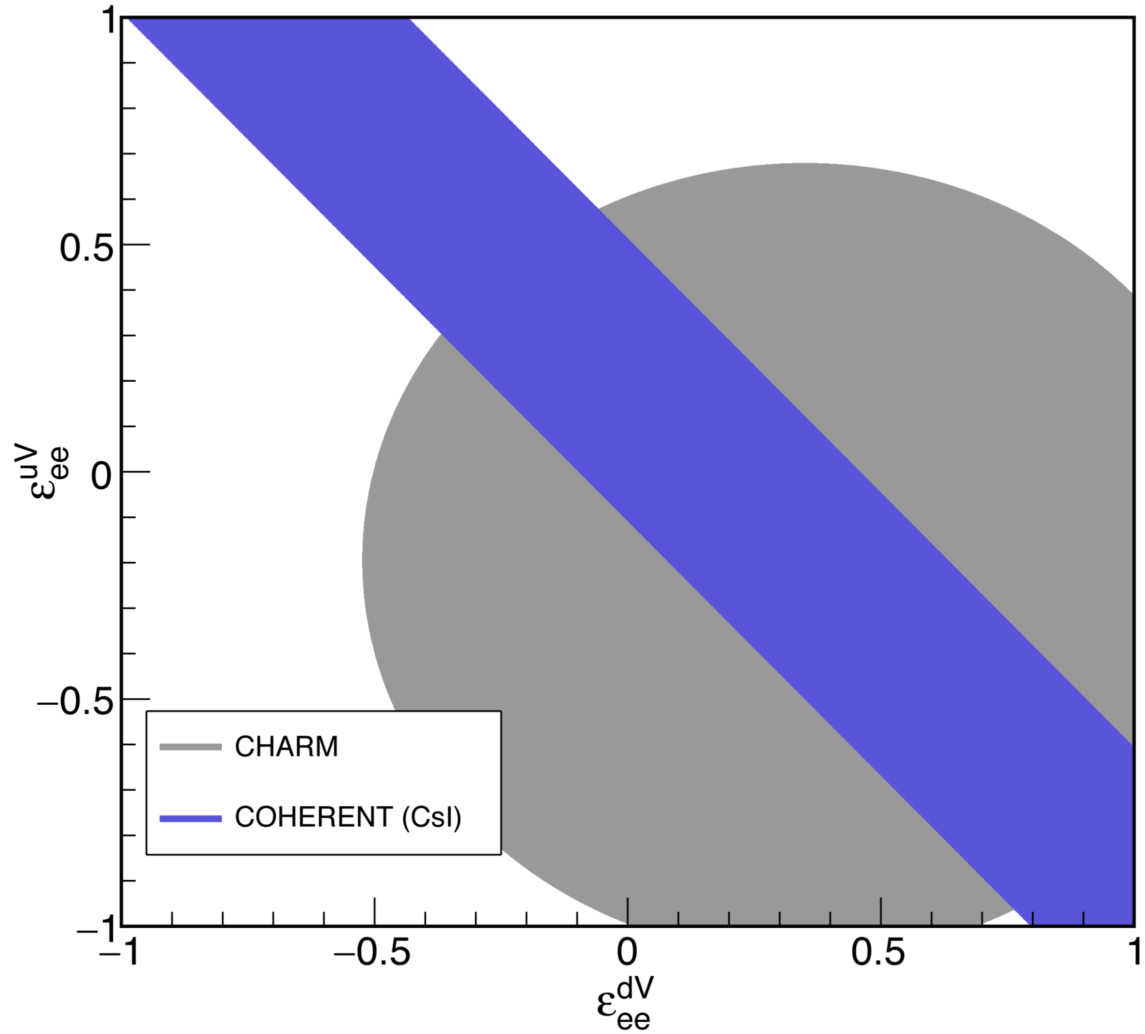


134 ± 22 measured

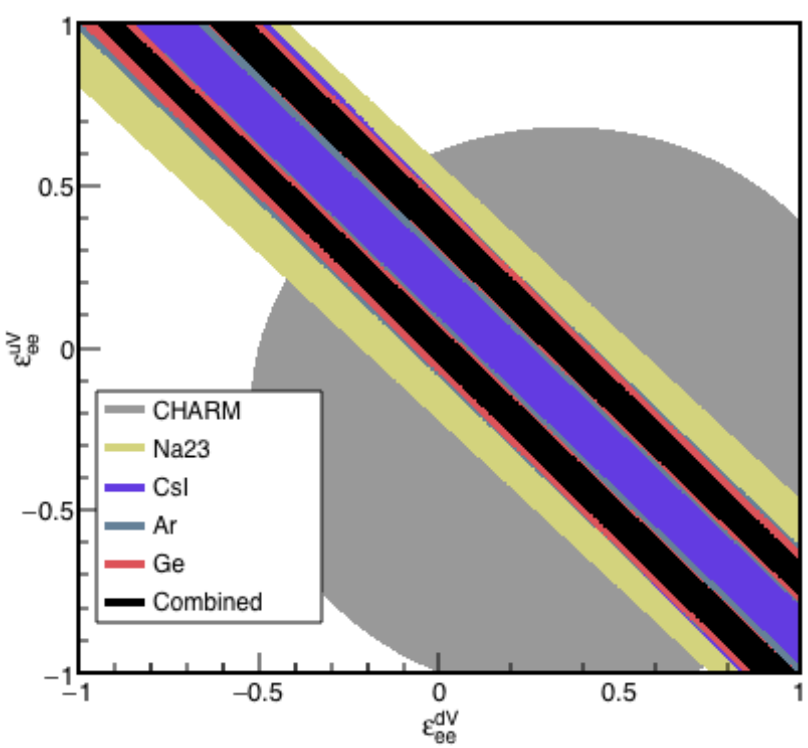
173 ± 48 SM

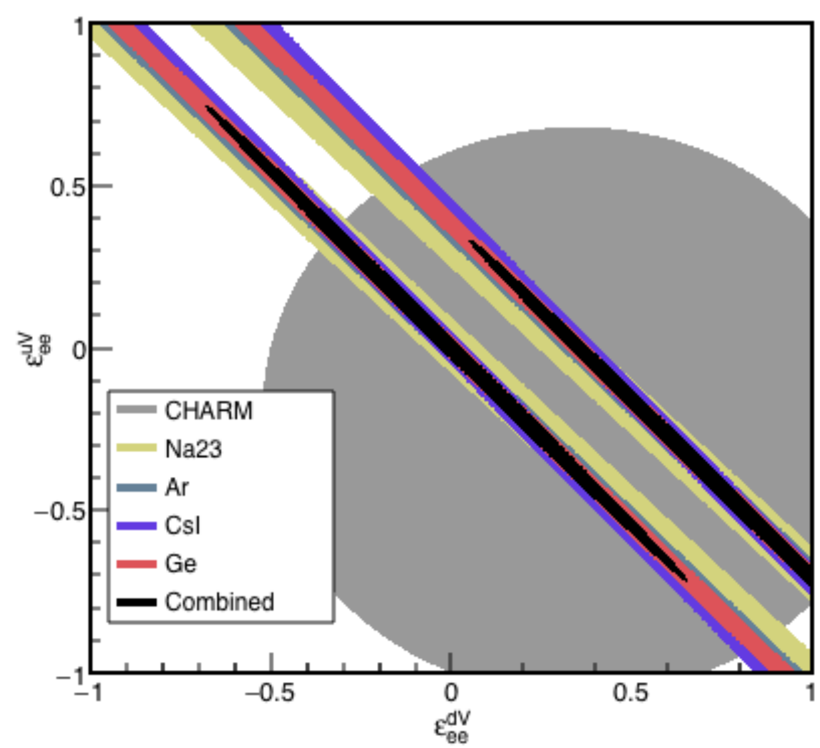
6.7σ Rejection of background only





Current NSI bounds

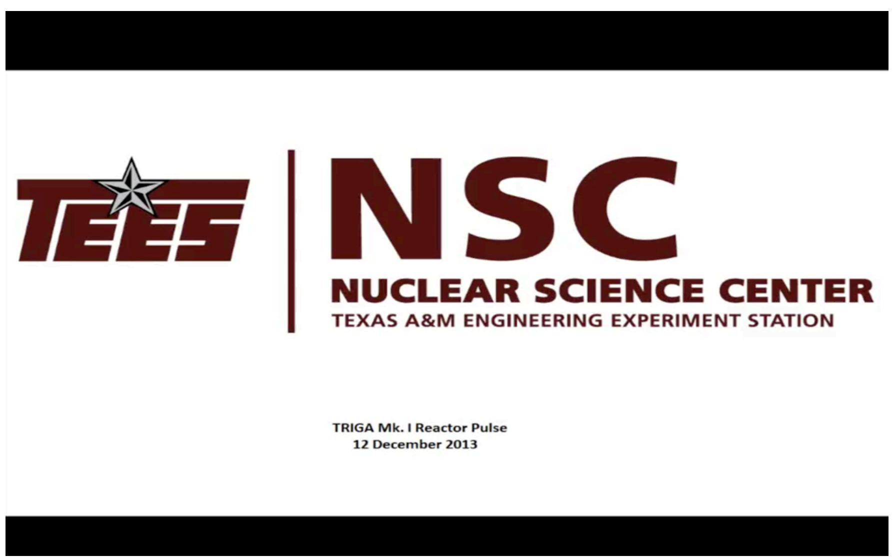




Projected NSI bounds

Akimov *et al.* 1803.09183

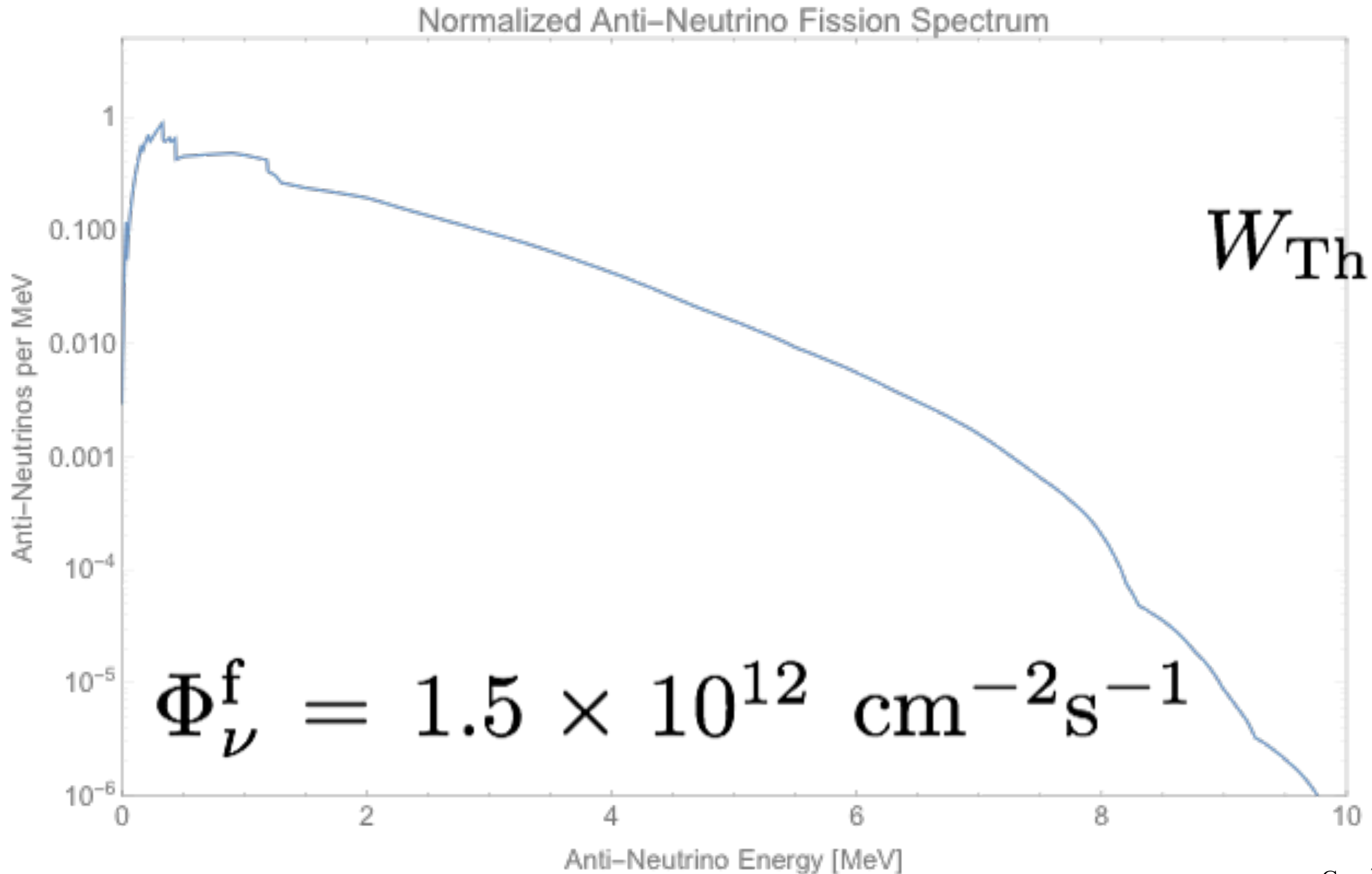
Mitchell Institute Neutrino Experiment at Reactor



Very low threshold SuperCDMS style germanium and silicon detectors fabricated at Texas A&M sited near at 4.5-5.5m from a moveable nuclear reactor core

TAMU reactor

$$W_{\mathrm{Th}} = 1.00 \pm 0.02 \ \mathrm{MW}$$

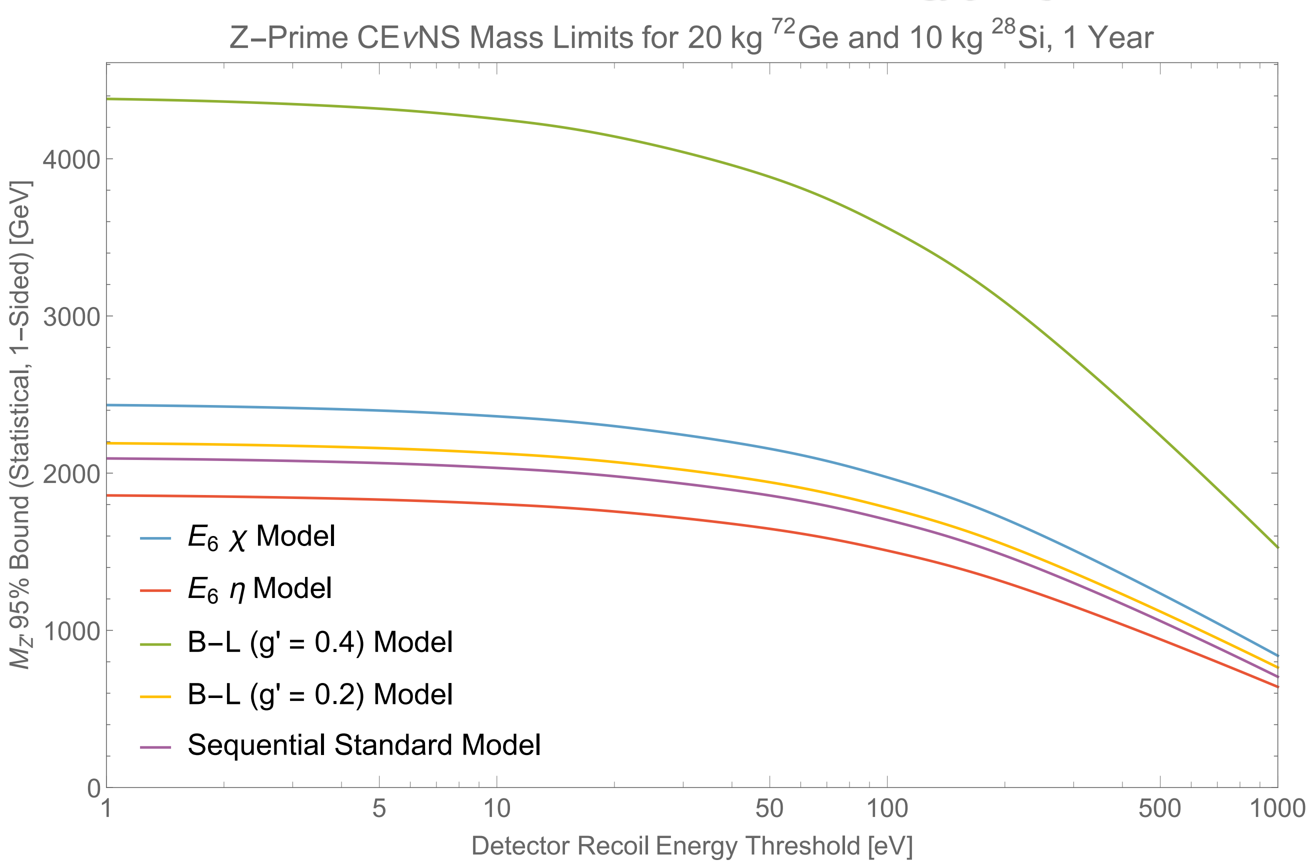


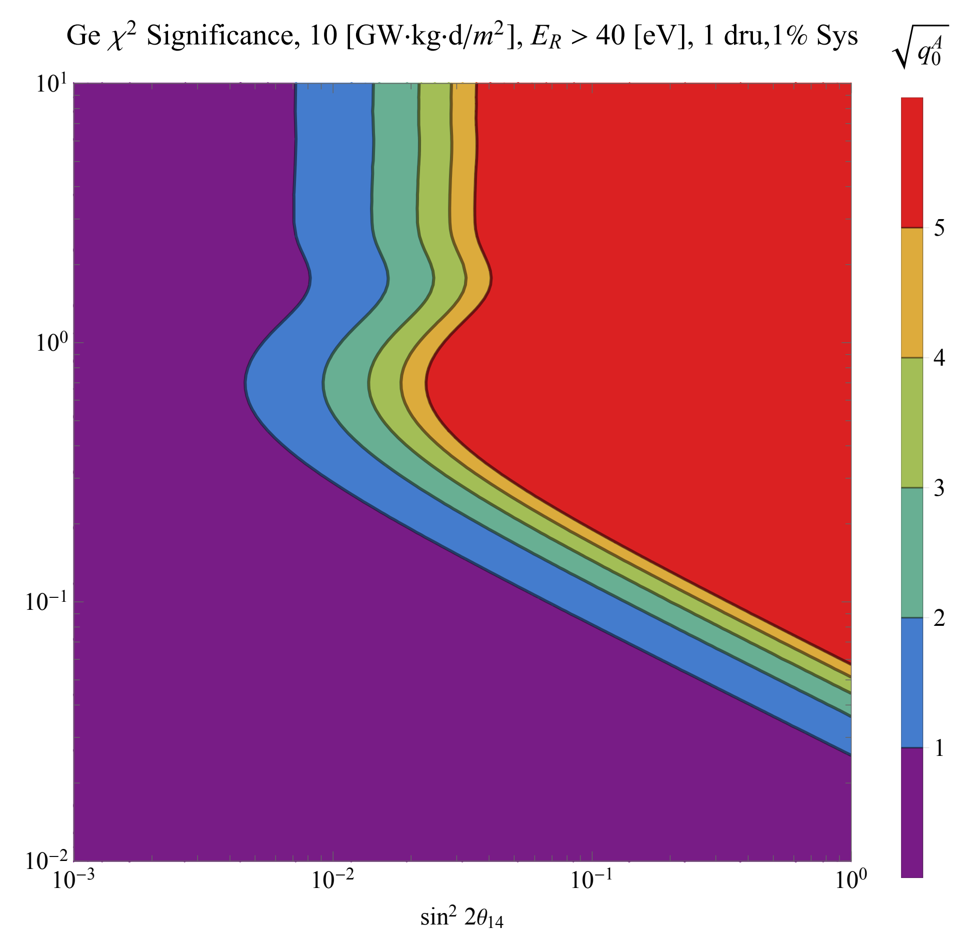
$$\Phi_{\nu}^{\mathrm{f}} = 1.5 \times 10^{12} \ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

B. Dutta, R. Mahapatra, L.E. Strigari, and J.W. Walker, PRD (2016) arXiv:1508.07981

B. Dutta, Y. Gao, R. Mahapatra, N. Mirabolfathi, L.E. Strigari, and J.W. Walker, arXiv:1511.02834

MINER Collaboration, 1609.02066





From CONUS collaboration slides at Neutrino 2018, Werner Maneschg presenter

3.9GW reactor in Brokdorf, Germany

$2.4 \times 10^{13}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 17m

3.85kg active mass Germanium detector with a <300 eVee threshold

	counts	counts/(d·kg) (*)
reactor OFF (114 kg*d)	582	
reactor ON (112 kg*d)	653	
ON-OFF (exposure corr.)	84	0.94
Significance	**2.4 σ**	2.3 σ

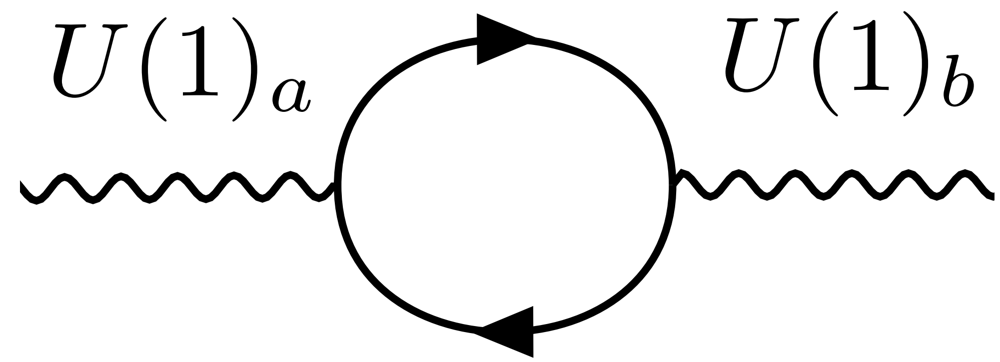
(*) Including stat. uncertainty and above efficiencies

Some systematics still under study

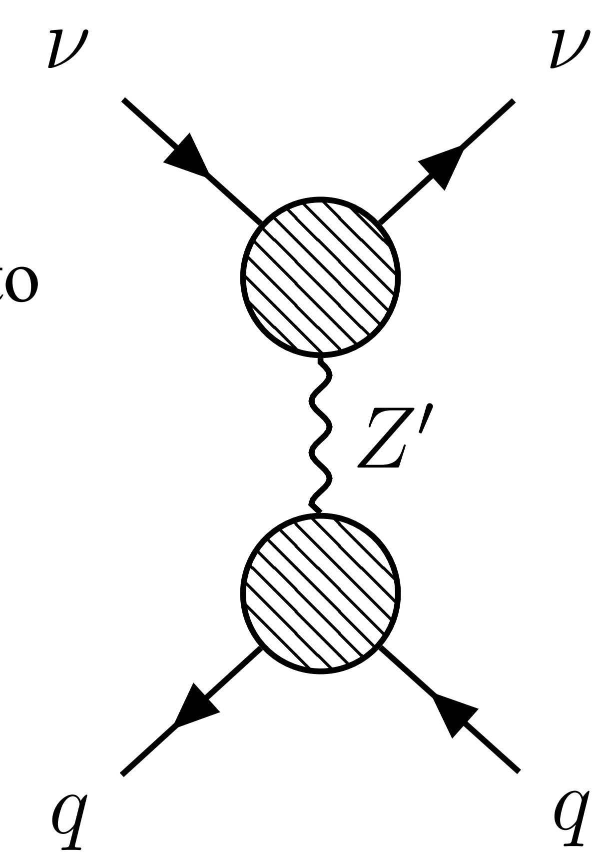
NSI: Mixing Effects with a Light Mediator

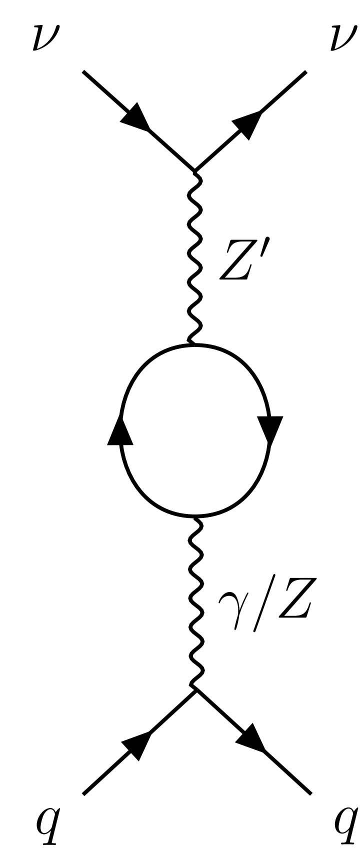
Kinetic Mixing Portal

Extend the SM by an extra $U(1)$ which introduces a new field



We will examine the cases where the new field has only loop induced couplings to SM fields, as well as tree level couplings with neutrinos.





The new gauge group induces a kinetic mixing term in the Lagrangian

$$L_{gauge} = -\frac{1}{4}F_a^{\mu\nu}F_{a\mu\nu} - \frac{1}{4}F_b^{\mu\nu}F_{b\mu\nu} - \frac{\epsilon}{2}F_a^{\mu\nu}F_{b\mu\nu}$$

ϵ Parameterizes the mixing between the hypercharge and new group

Bounds are placed in the coupling-mass plane

For some models there also exist direct couplings to SM fields

$$\mathcal{L} \supset Z'_\mu(g'_\nu \bar{\nu}_L \gamma^\mu \nu_L + g'_{f,v}\bar{f}\gamma^\mu f + g'_{f,a}\bar{f}\gamma^\mu\gamma^5 f)$$

After a field redefinition

$$B_\mu \to B_\mu - \epsilon X_\mu$$

Canonical kinetic terms are recovered

$$L_{gauge} = -\frac{1}{4} F_a^{\mu\nu} F_{a\mu\nu} - \frac{1}{4} F_b^{\mu\nu} F_{b\mu\nu}$$

$Z' \bar{f} f$ couplings arise from the covariant derivative term:

$$i\bar{\psi}\gamma^\mu D_\mu \psi = i\bar{\psi}\left(\partial_\mu + igT^3 W_\mu^3 + ig' Q_Y B_\mu + i(g_X Q_X - g'\epsilon Q_Y) X_\mu\right)\psi$$

S. Gopalakrishna, S.Jung, and J.D. Wells, PRD (2008), 0801.3456
M. Lindner, F.S. Queiroz, W. Rodejohann, and Xun-Jie Xu, JHEP (2018), 1803.00060
…many others

Rotate to the mass basis

$$\begin{pmatrix} B_\mu \\ W^3_\mu \\ X_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_w & -\epsilon\,\sin\alpha - \sin\theta_w\cos\alpha & \sin\theta_w\sin\alpha - \epsilon\,\cos\alpha \\ \sin\theta_w & \cos\theta_w\cos\alpha & -\cos\theta_w\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} A_\mu \\ Z_\mu \\ Z'_\mu \end{pmatrix}$$

One finds the $Z'\bar{f}f$ coupling term:

$$\frac{-ig}{\cos\theta_w}\left[\cos\alpha(\tan\alpha - \epsilon\,\sin\theta_w)\right]\left[T^3_L - \frac{(\tan\alpha - \epsilon\,/\sin\theta_w)}{\tan\alpha - \epsilon\,\sin\theta_w}\sin^2\theta_w Q\right]$$

Given in terms of the *Z-Z'* mixing angle α

A few cases of interest:

$\boxed{\text{Dark Hypercharge:}}$ small mixing α with the definition:

$$\epsilon_B \equiv \cos\alpha(\tan\alpha - \epsilon\,\sin\theta_w)$$

$Z'\bar{f}f$ coupling term: $$ig\tan\theta_w\,(Y_f/2)\,\epsilon_B$$

$\boxed{\text{Dark } Z\text{:}}$ $\epsilon = 0$

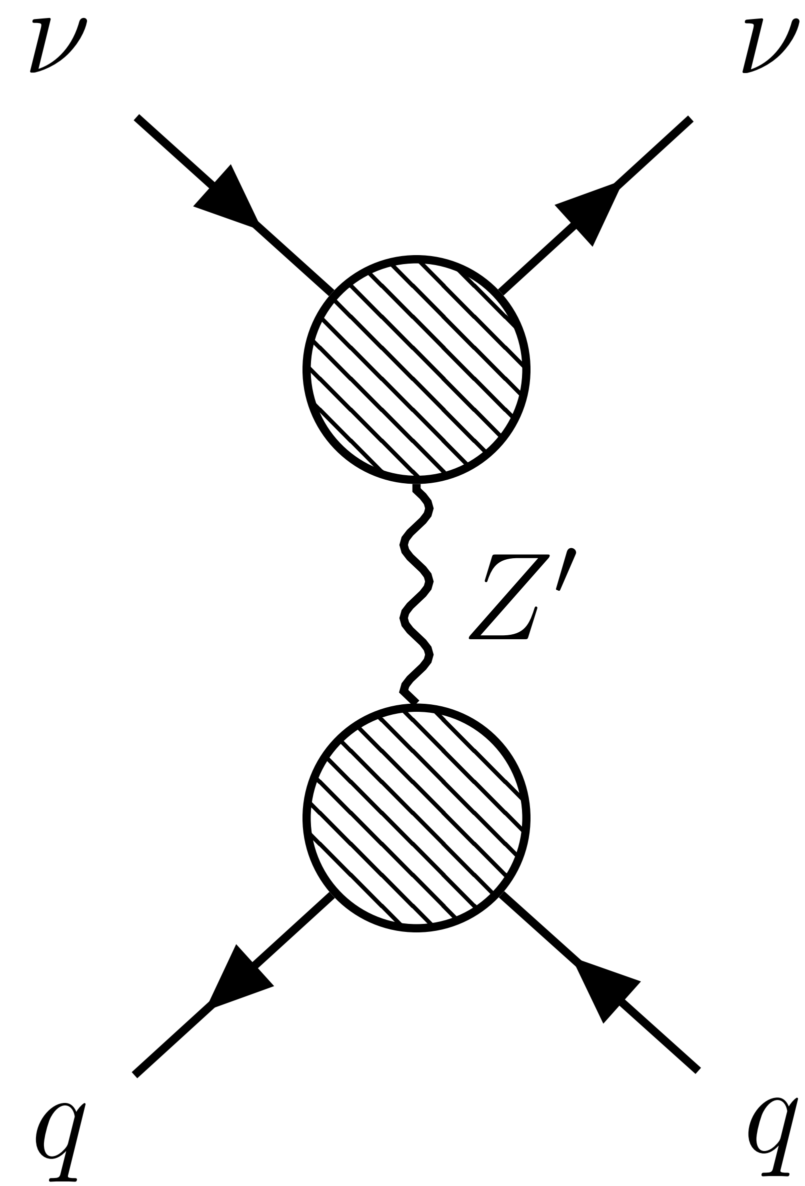
$$\epsilon_z \equiv \sin\alpha$$

$Z'\bar{f}f$ coupling term: $$\frac{-ig}{\cos\theta_w}\,\epsilon_z\,\left[T_L^3 - \sin\theta_w^2 Q\right]$$

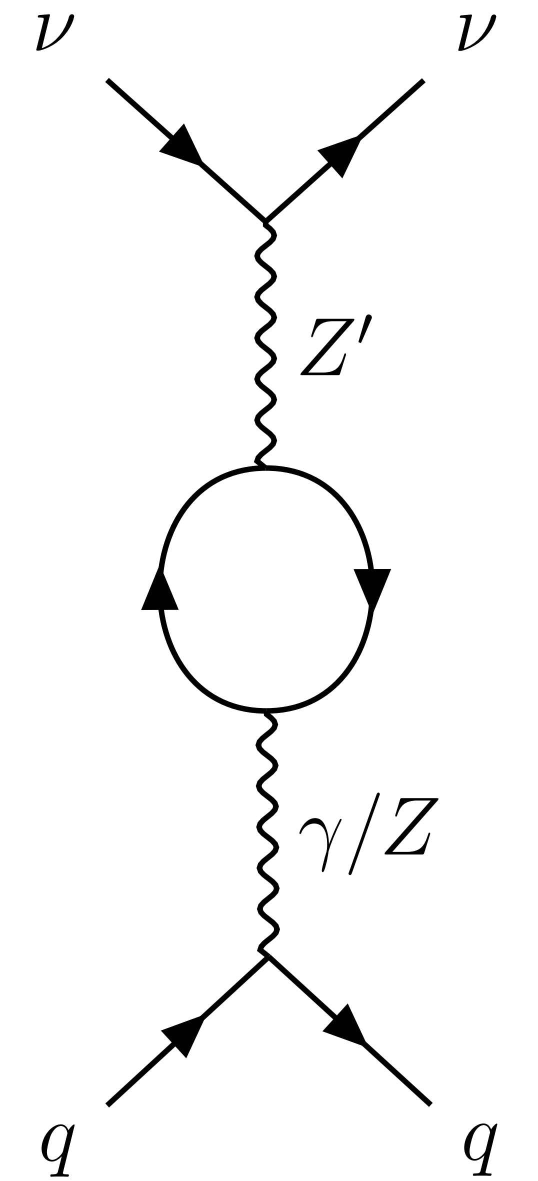
$\boxed{U(1)_{L_\mu - L_\tau}}$ (g-2)$_\mu$, B decay anomalies, HEν, DM

X.G.He, G.C.Joshi, J.H.Lew, and R.R.Volkas, PRD (1991)

$$\mathcal{L}_{int} \supset g_{Z'}Q_{\alpha\beta}(\bar{l}_\alpha\gamma^\mu l_\beta + \bar{\nu}_{L\alpha}\gamma^\mu\nu_{L\beta})Z'_\mu$$



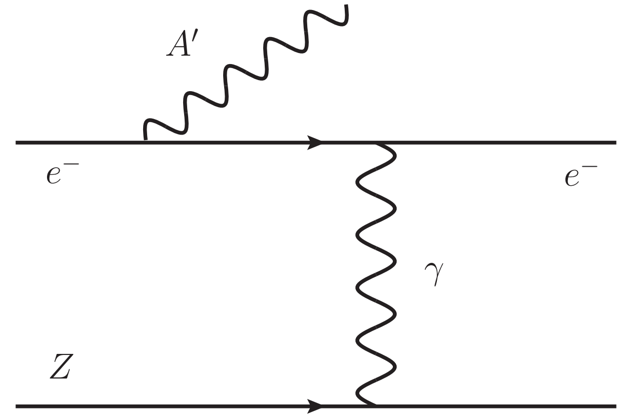
Dark Z and dark hypercharge



$U(1)_{L_\mu - L_\tau}$

Bounds

Fixed Target Experiments
E137, E141, E774, NA48/2



Dark Z and
dark hypercharge

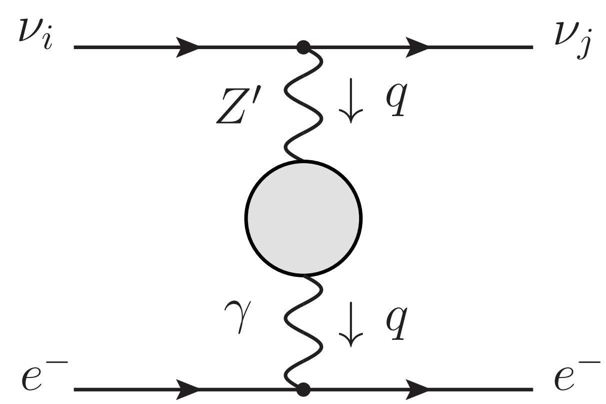
Bjorken, Essig, Schuster, and Toro, PRD 2009, 0906.0580

Atomic Parity Violation

Dark Z and
dark hypercharge

^{133}Cs transitions (S.G.Porsev, K.Beloy, and A.Derevianko, PRD 2010, 1006.4193, H. Davoudiasl, H.-S. Lee, and W.J. Marciano, PRD 2012, 1203.2947)

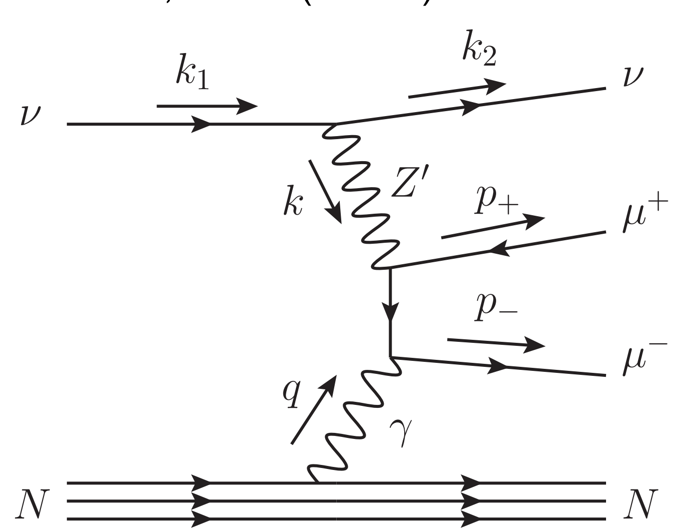
Borexino



$U(1)_{L_\mu - L_\tau}$

M. Agostini et al. (Borexino) (2017), 1707.09279
T.Araki, S.Hoshino, T.Ota, J.Sato, and T.Shimomura, PRD (2017) 1702.01497,

Neutrino Trident



$U(1)_{L_\mu - L_\tau}$

W.Altmannshofer, S.Gori, M.Pospelov, and I.Yavin, PRL (2014) 1406.2332

Numerical Approach

$$\chi^2 = \sum_{\text{bins,detectors}} \frac{\left(N_{exp} - (1+\beta)\, N_{pred}\right)^2}{N_{bg} + N_{exp}} + \left(\frac{\beta}{\sigma_\beta}\right)^2$$

N_{exp}	Number of expected (SM) events
N_{pred}	Number of predicted (BSM) events
β	Nuisance parameter
σ_β	Fractional systematic uncertainty (0.1)

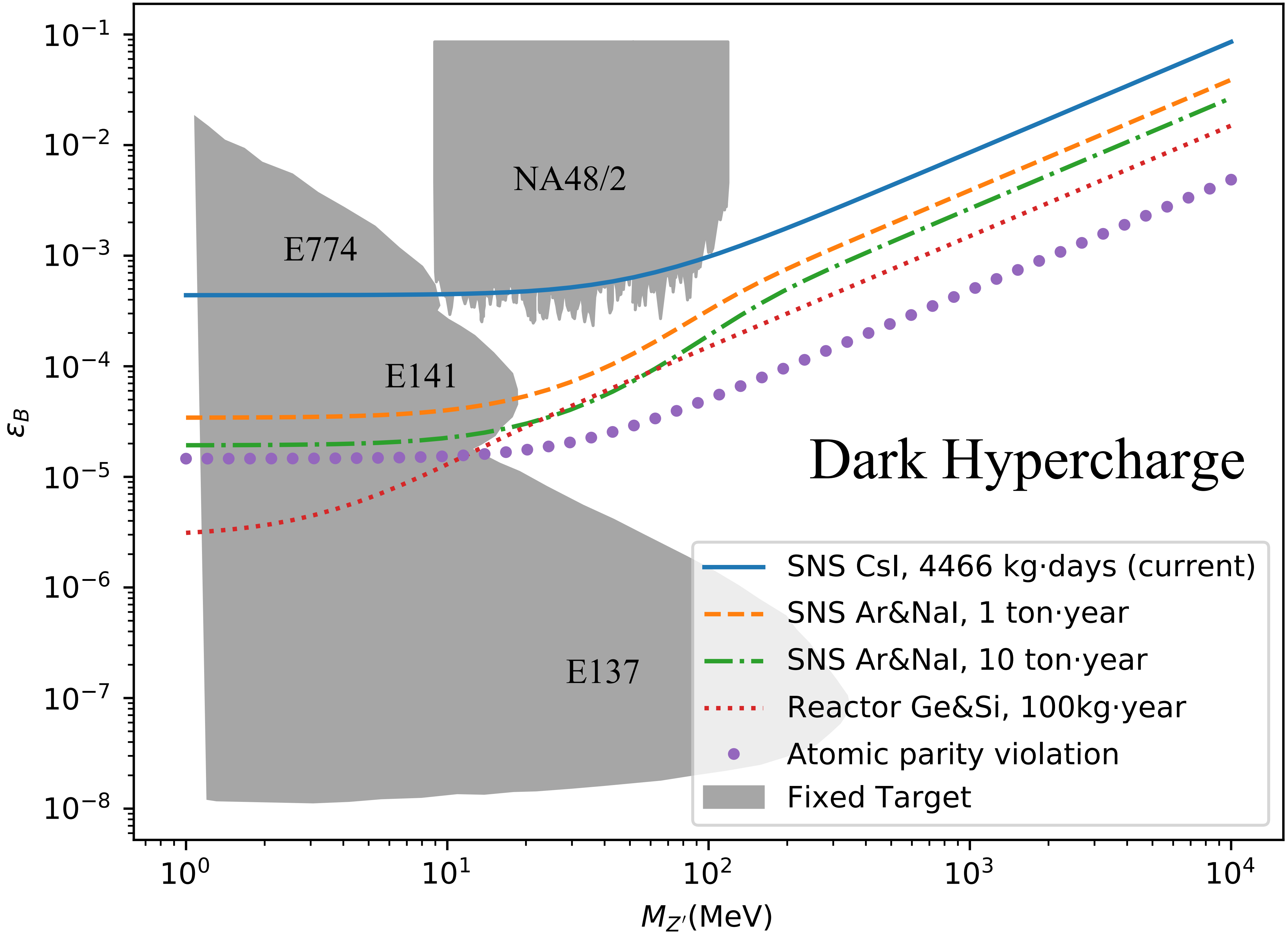
2σ or discovery sensitivity at 95% probability

Numerical Approach

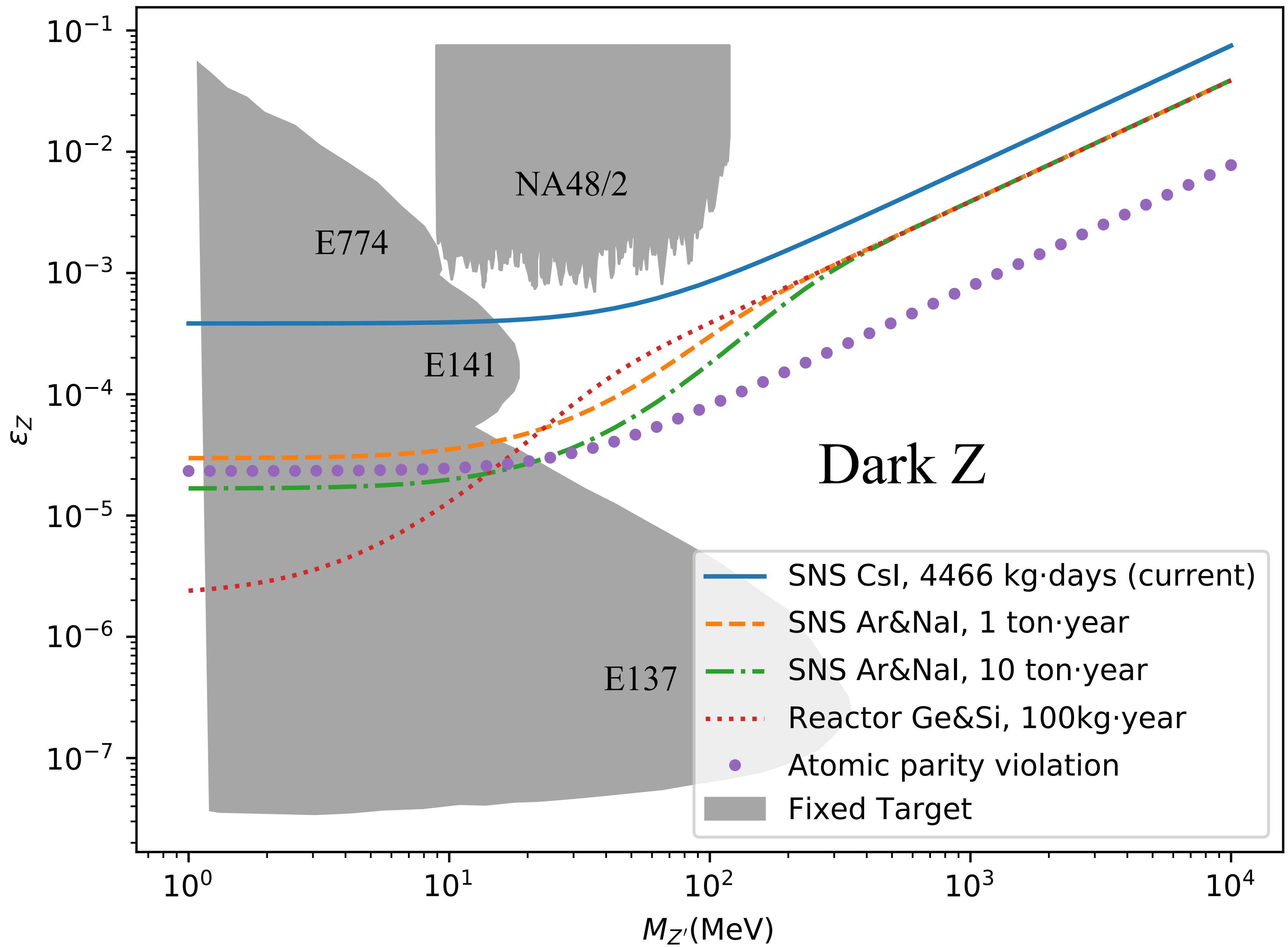
Bounds are made using the current COHERENT data with 14.6 kg of CsI crystals with 4.25 keV thresholds.

Projections for the SNS are made using 1 ton of LAr and 1 ton of NaI with a 2 keV threshold for each target.

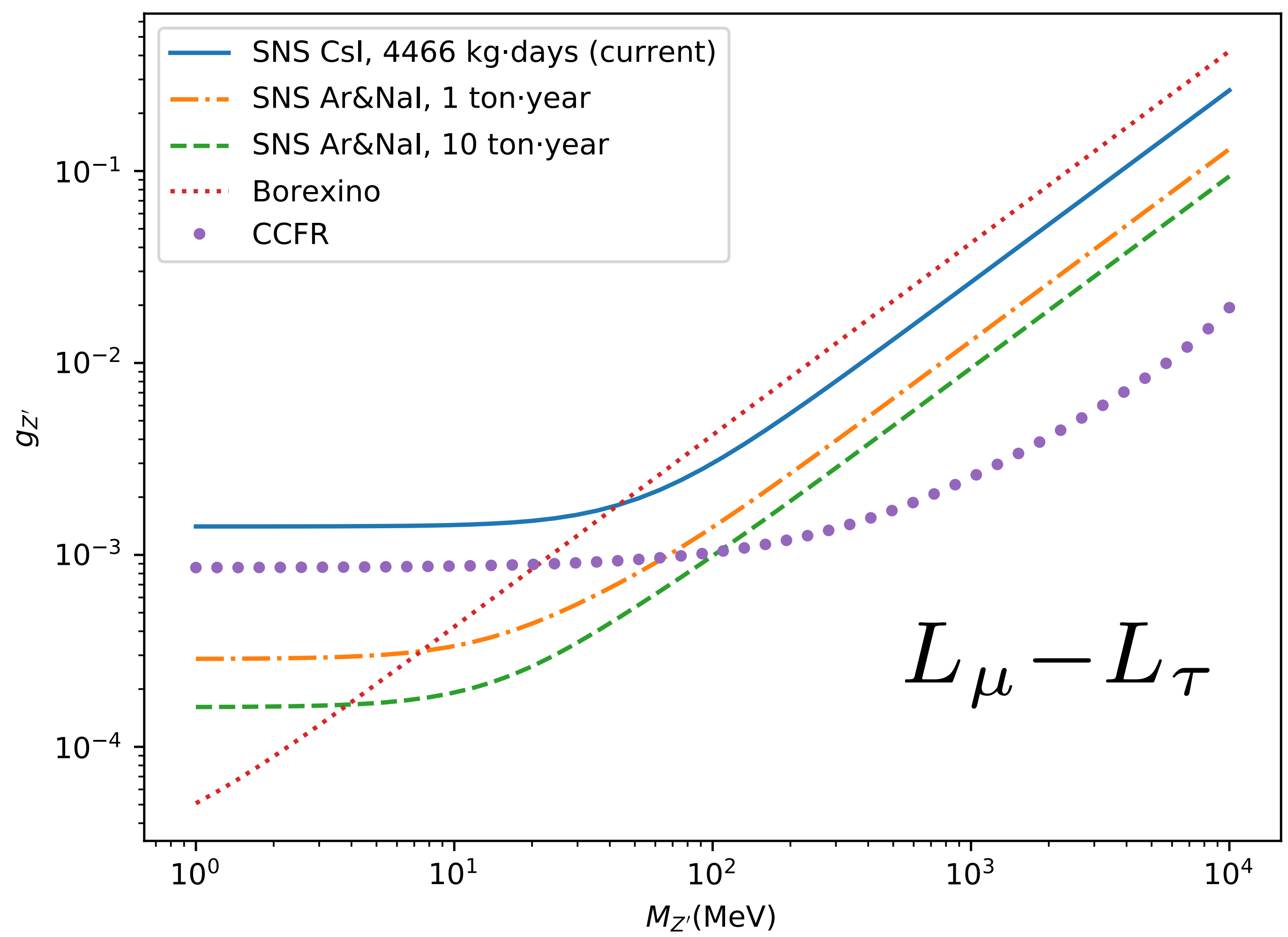
Projections for reactor are made using a 1 MW at 1m (or 1 GW at 30 m) with 100 eVnr thresholds for cryogenic Ge and Si detectors.



Beam dump experiments: E137 (20GeV) E141 (9GeV) E774 (275GeV) (Bjorken et al. PRD 1988, Riordan et al. PRL 1987, Bross et al. PRL 1991)
Neutral pion decay: NA48/2 (Batley et al. PLB 2015, 1504.00607, Ilten, Soreq, Williams, and Xue 1801.04847, Bjorken, Essig, Schuster, and Toro, PRD 2009, 0906.0580, Harnik, Kopp, and Machado, JCAP 2012, 1202.6073)
Atomic Parity Violation: ^{133}Cs transitions (S.G.Porsev, K.Beloy, and A.Derevianko, PRD 2010, 1006.4193, H. Davoudiasl, H.-S. Lee, and W.J. Marciano, PRD 2012, 1203.2947)



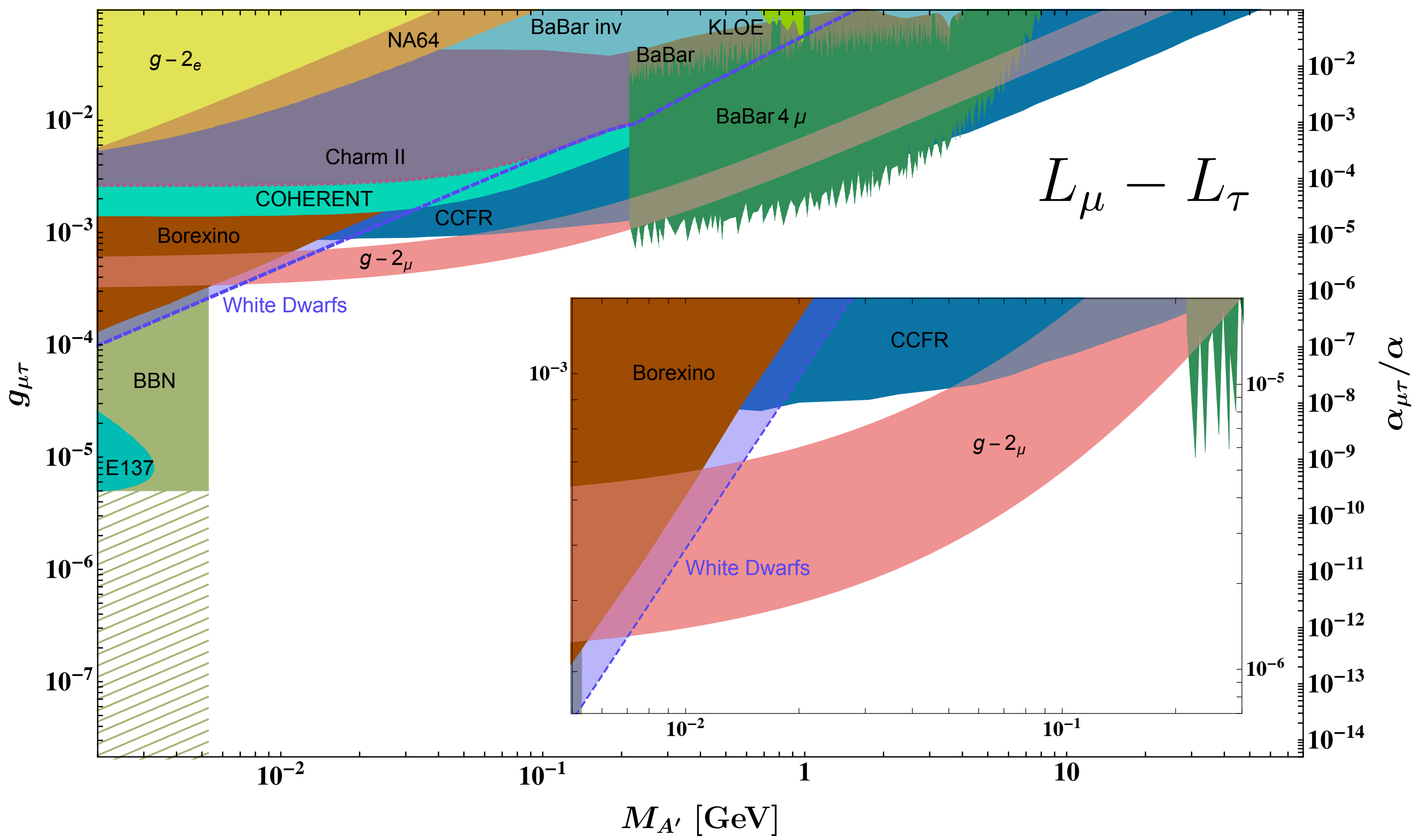
NA48/2
E774
E141
E137
Dark Z
SNS CsI, 4466 kg·days (current)
SNS Ar&NaI, 1 ton·year
SNS Ar&NaI, 10 ton·year
Reactor Ge&Si, 100kg·year
Atomic parity violation
Fixed Target
ε_Z
$M_{Z'}$(MeV)
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}



Solar neutrino measurements from Borexino, M. Agostini et al. (Borexino) (2017), 1707.09279

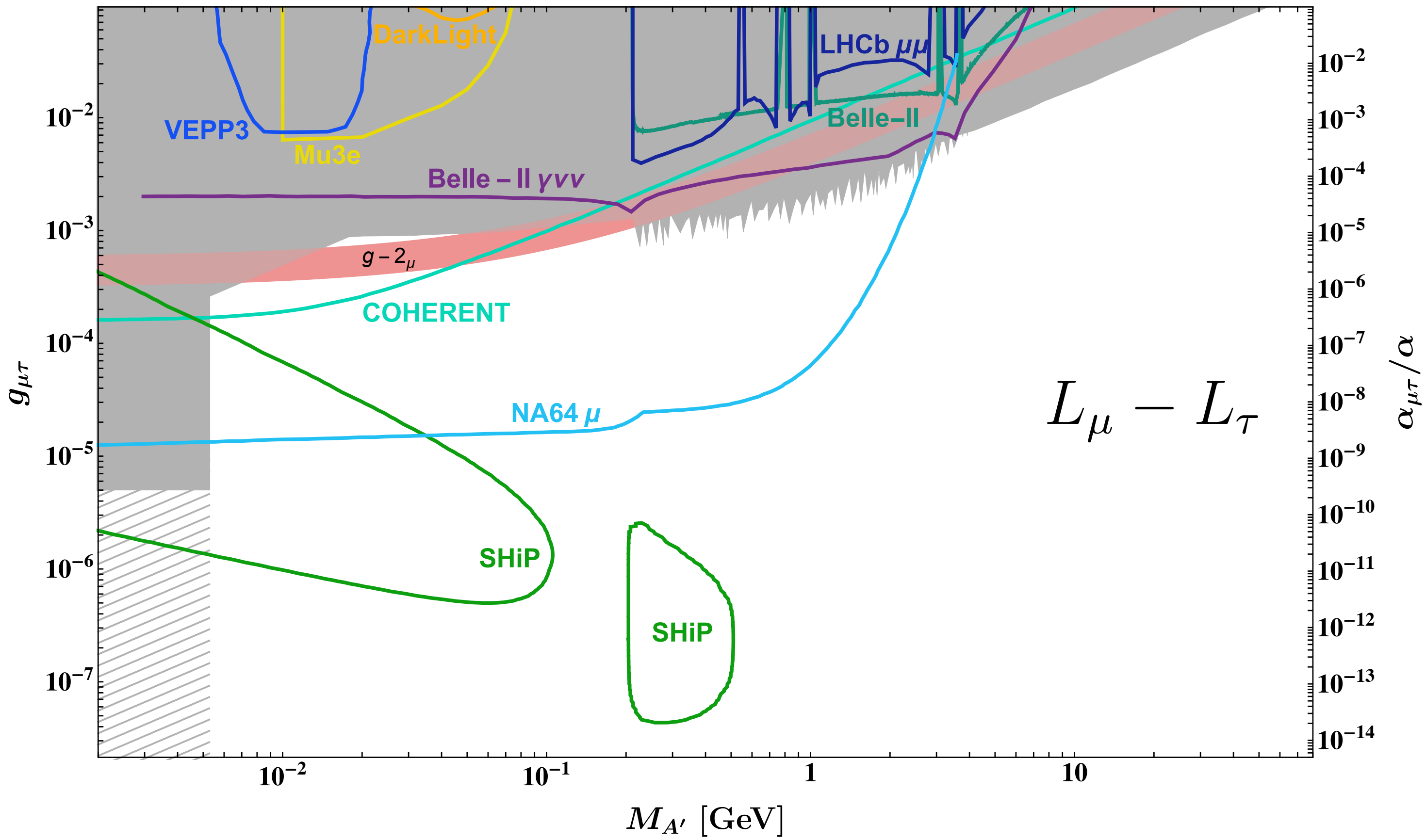
Neutrino Trident measurements from CHARM-II (Geiregat et al. PLB 1990) and CCFR (Mishra et al. (CCFR) PRL 1991)
Theory limits from Altmannshofer, Gori, Pospelov, and Yavin, PRD 2014, 1403.1269 and PRL 2014, 1406.2332

Additional Bounds (current)



M.Bauer, P.Foldenhauer, and J.Jaeckel, JHEP (2018), 1803.05466

Additional Bounds (future)



M.Bauer, P.Foldenhauer, and J.Jaeckel, JHEP (2018), 1803.05466

Summary

Coherent Elastic Neutrino-Nucleus Scattering is already able to set interesting limits on BSM physics.

Complementarity from stopped-pion sources and reactors, as well as a variety of target materials will be able to provide coverage in numerous models.

There is great potential in the near future for significantly increasing the reach of the coherent scattering experiments and new theoretical explorations.