利用中微子与原子核的弹性相干散射探测新物理

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Outline

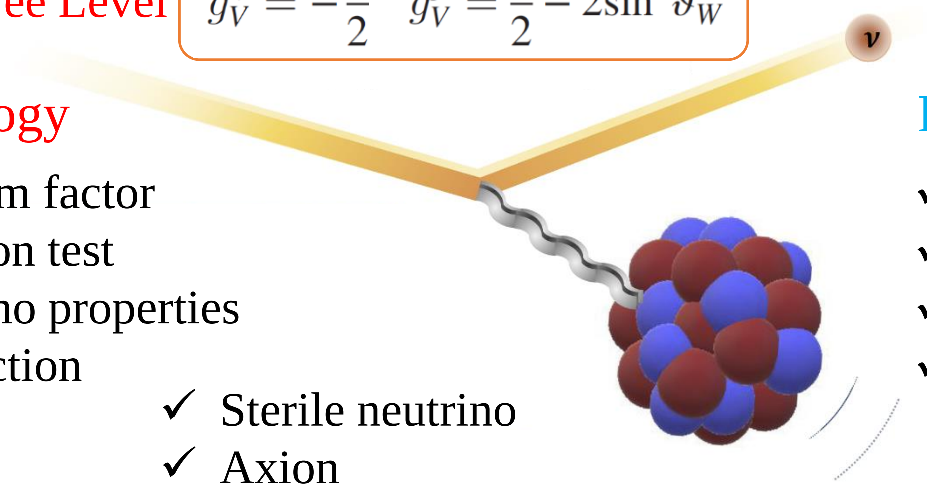
- Coherent Elastic Neutrino-Nucleus Scattering
- COHERENT experiment
- Constraints on light mediators
- Summary

Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for $|\vec{q}|R \ll 1$
- Frist observed in 2017
- Taking into account interactions with both neutrons and protons:

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(q^2) + g_V^p Z F_Z(q^2)\right]^2$$

Tree Level $\boxed{g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W}$



Phenomenology

- ✓ Nuclear form factor
- ✓ EW precision test
- ✓ New neutrino properties
- ✓ New interaction
  - ✓ Sterile neutrino
  - ✓ Axion
  - ✓ Dark matter
  - ✓ Supernova

Experiment

- ✓ Stopped-pion neutrino
- ✓ Reactor neutrino
- ✓ DM observatories
- ✓ Solar neutrino

Coherent Elastic Neutrino-Nucleus Scattering

- Predicted in 1974 for $|\vec{q}|R \ll 1$ [Freedman, Physical Review D, 1974, 9(5): 1389]
- Taking into account interactions with both neutrons and protons [P.A. Zyla et al., Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)]

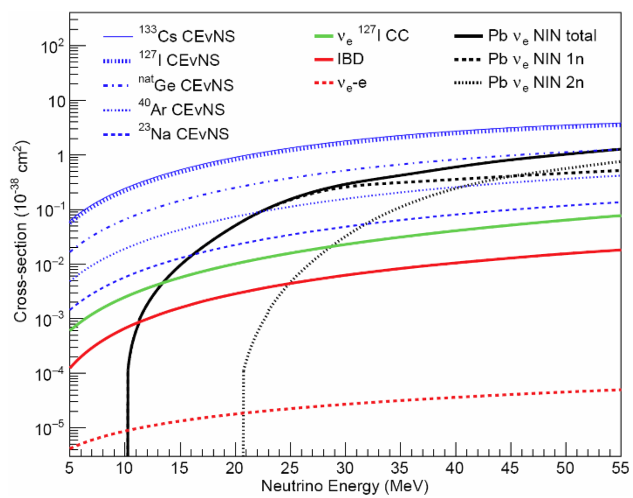
$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right)\left[g_V^n N F_N(q^2) + g_V^p Z F_Z(q^2)\right]^2$$

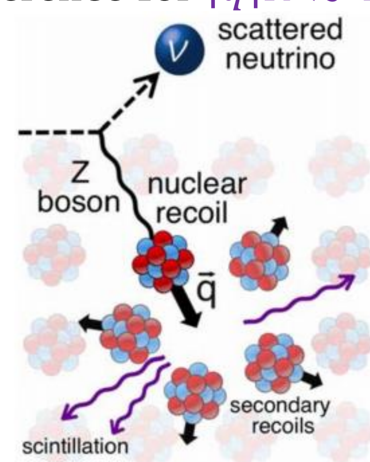
Tree Level $\boxed{g_V^n = -\frac{1}{2} \quad g_V^p = \frac{1}{2} - 2\sin^2\vartheta_W}$

The neutron contribution is dominant! $\Rightarrow$ $\frac{d\sigma}{dT} \sim N^2 F_N^2(q^2)$

- The form factors $F_N(|\vec{q}|^2)$ and $F_Z(|\vec{q}|^2)$ describe the loss of coherence for $|\vec{q}|R \gtrsim 1$.

$T \simeq |\vec{q}|^2/2M$
$M \sim 100$ GeV, $R \sim 5$ fm
$\rightarrow T \lesssim 10$ keV





COHERENT experiment

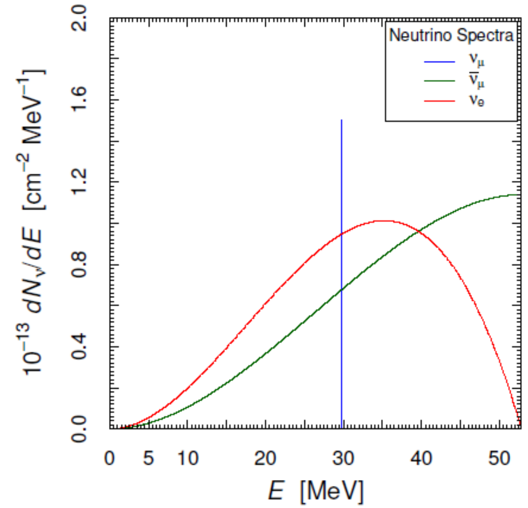
- 14.6 kg CsI(2017) and 24 kg LAr(2020).
- Prompt monochromatic ν_μ :

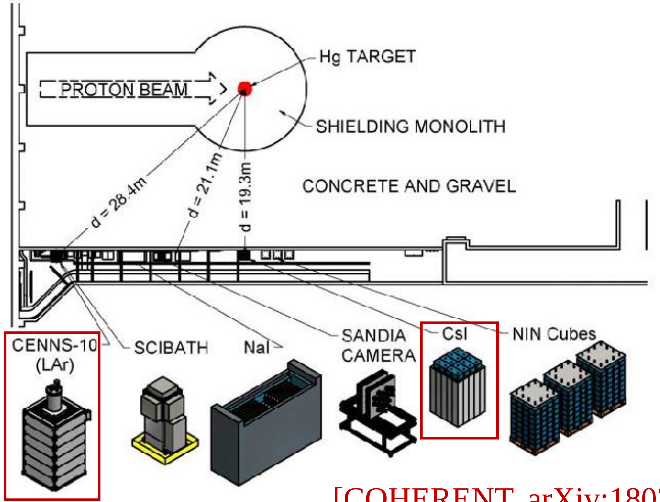
$$\pi^+ \to \mu^+ + \nu_\mu$$

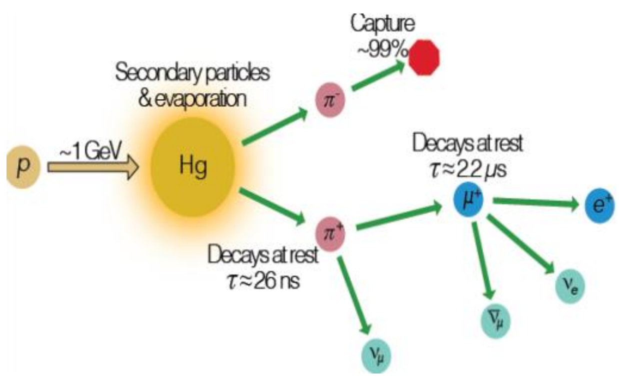
- Delayed $\bar{\nu}_\mu$, ν_e :

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

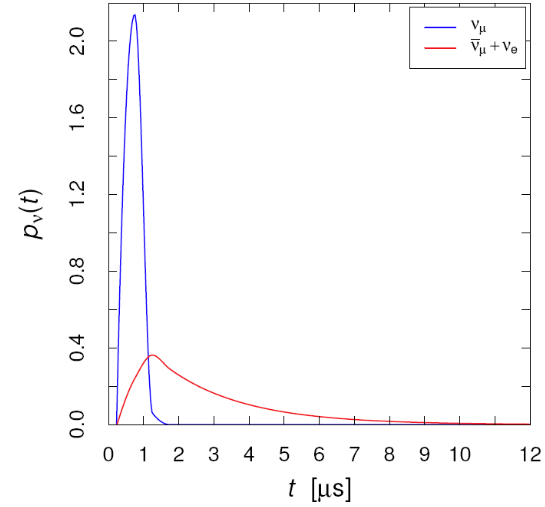
- The COHERENT energy and time information allow us to distinguish the interactions of ν_e, ν_μ and $\bar{\nu}_\mu$







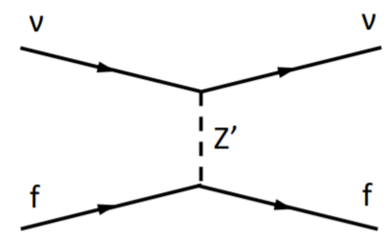
[COHERENT, arXiv:1803.09183]



Constraints on light vector mediators Z'

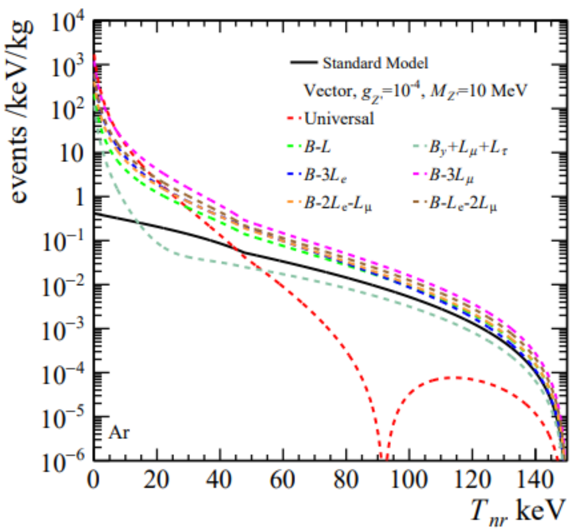
The generic Lagrangian that describes the interaction of Z' with neutrinos and quarks is

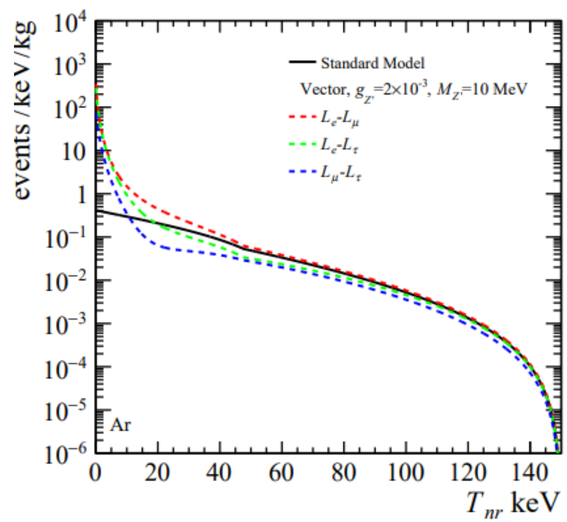
$$\mathcal{L}_{Z'}^{V} = -Z'_{\mu}\left[\sum_{\ell=e,\mu,\tau} g_{Z'}^{\nu_\ell V}\,\overline{\nu_{\ell L}}\gamma^{\mu}\nu_{\ell L} + \sum_{q=u,d} g_{Z'}^{qV}\,\overline{q}\gamma^{\mu}q\right], \qquad g_{Z'}^{qV} = g_{Z'}Q'_q, \quad g_{Z'}^{\nu_\ell V} = g_{Z'}Q'_{\ell}$$



$$Q_\ell^2 = \left[\left(g_V^p(\nu_\ell) + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) ZF_Z(|\vec{q}|^2) + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) NF_N(|\vec{q}|^2)\right]^2$$

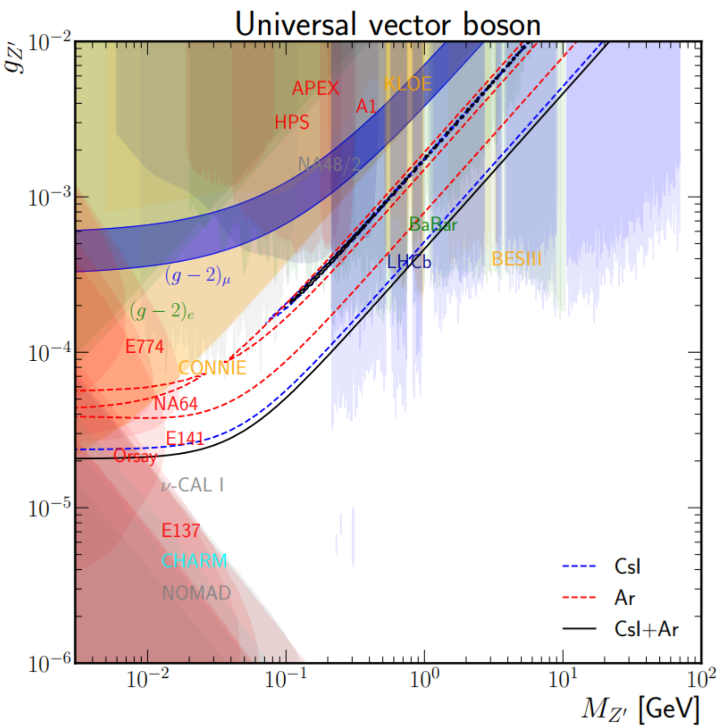
$$\epsilon_{\ell\ell}^{fV} = \frac{g_{Z'}^2\, Q'_\ell Q'_f}{\sqrt{2}G_F\,(|\vec{q}|^2 + M_{Z'}^2)},$$

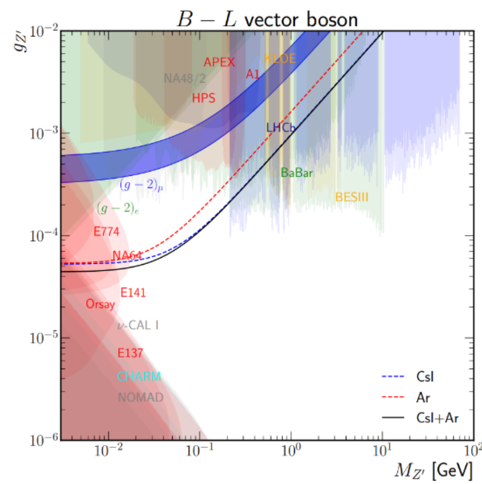


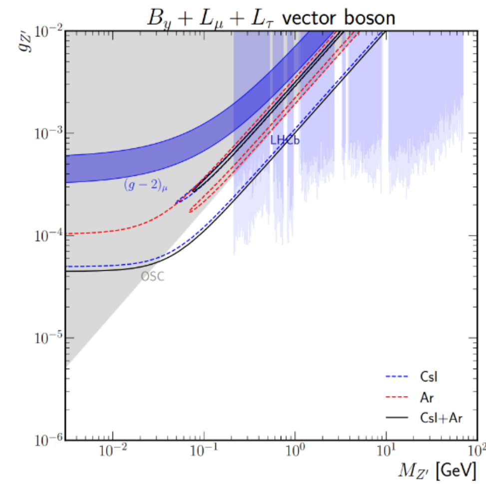


Model	Q'_u	Q'_d	Q'_e	Q'_μ	Q'_τ
universal	1	1	1	1	1
$B-L$	1/3	1/3	-1	-1	-1
$B-3L_e$	1/3	1/3	-3	0	0
$B-3L_\mu$	1/3	1/3	0	-3	0
$B-2L_e-L_\mu$	1/3	1/3	-2	-1	0
$B-L_e-2L_\mu$	1/3	1/3	-1	-2	0
$B_y+L_\mu+L_\tau$	1/3	1/3	0	1	1
L_e-L_μ	0	0	1	-1	0
L_e-L_τ	0	0	1	0	-1
$L_\mu-L_\tau$	0	0	0	1	-1

Constraints on light vector mediators Z'







The thin allowed strip

$$Q^V_{\ell,\mathrm{SM+V}} \simeq -Q^V_{\mathrm{SM}}$$

$$(g_{Z'}^{\mathrm{univ}})_{\mathrm{strip}} \simeq \sqrt{\frac{N}{A}\frac{\sqrt{2}G_F M_{Z'}^2}{3}} \simeq 1.8\times10^{-3}\,\frac{M_{Z'}}{\mathrm{GeV}},$$

We compare with other experiment

- visible dark photon decays in beam dump：E141, E137, E774, KEK, Orsay, ν-CAL I, CHARM , NOMAD , and PS191,
- fixed target: A1 and APEX,
- Collider: BaBar, KLOE, LHCb
- rare-meson-decay: NA48/2
- invisible dark photons decays in the NA64 and BaBar

We also compare the constraints with the excluded regions obtained from the global analysis of oscillation data (OSC)

Constraints on light vector mediators Z'

model	CsI+Ar	
	$g_{Z'}$(low $M_{Z'}$)	$\frac{g_{Z'}}{M_{Z'}}$(high $M_{Z'}$)
universal	2.07×10^{-5}	0.48×10^{-3}
$B - L$	4.42×10^{-5}	0.99×10^{-3}
$B_y + L_\mu + L_\tau$	4.47×10^{-5}	1.04×10^{-3}
$B - 3L_e$	4.34×10^{-5}	0.95×10^{-3}
$B - 3L_\mu$	2.76×10^{-5}	0.63×10^{-3}
$B - 2L_e - L_\mu$	3.95×10^{-5}	0.88×10^{-3}
$B - L_e - 2L_\mu$	3.26×10^{-5}	0.74×10^{-3}

- $\boldsymbol{B - 3L_e}$

  $$B - 3w_e L_e - 3(1 - w_e)L_\tau$$

- $\boldsymbol{B - 3L_\mu}$

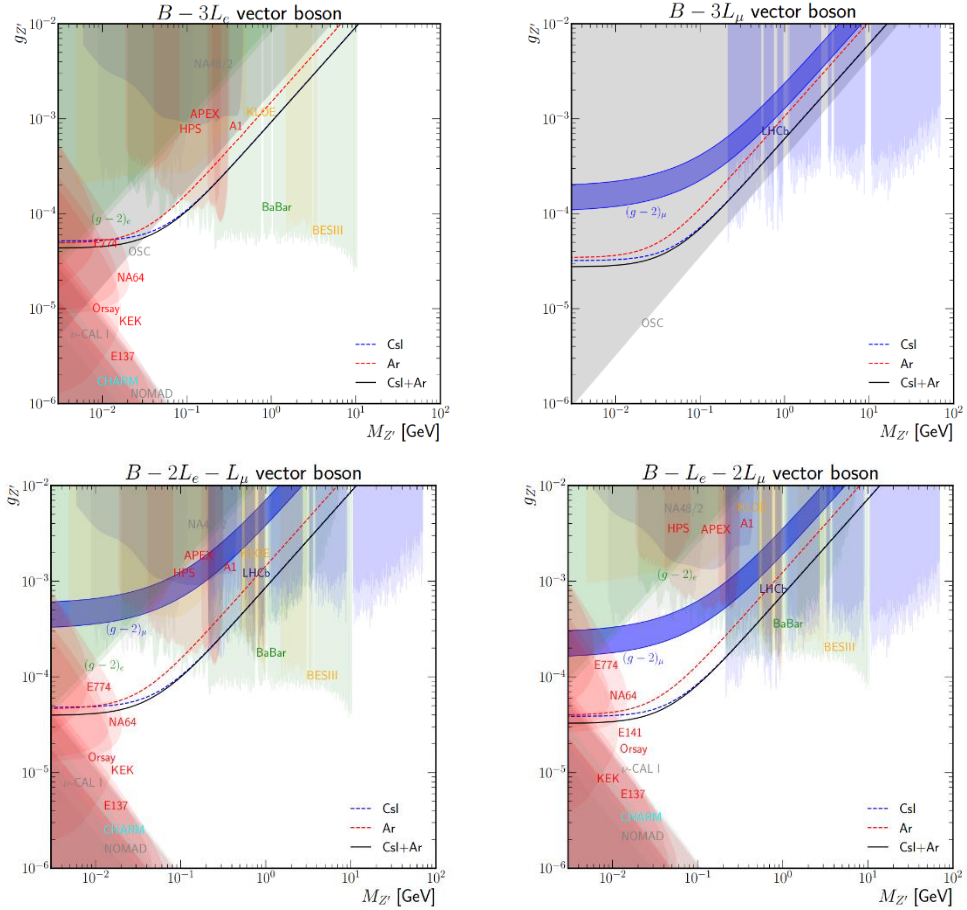
  $$B - 3w_\mu L_\mu - 3(1 - w_\mu)L_\tau$$

- $\boldsymbol{B - 2L_e - L_\mu}$

  $$B - 2w_1 L_e - w_1 L_\mu - 3(1 - w_1)L_\tau$$

- $\boldsymbol{B - L_e - 2L_\mu}$

  $$B - w_2 L_e - 2w_2 L_\mu - 3(1 - w_2)L_\tau$$

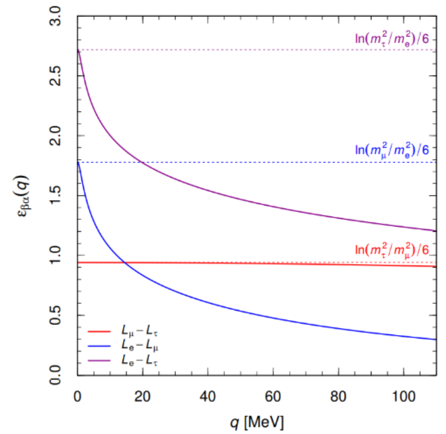


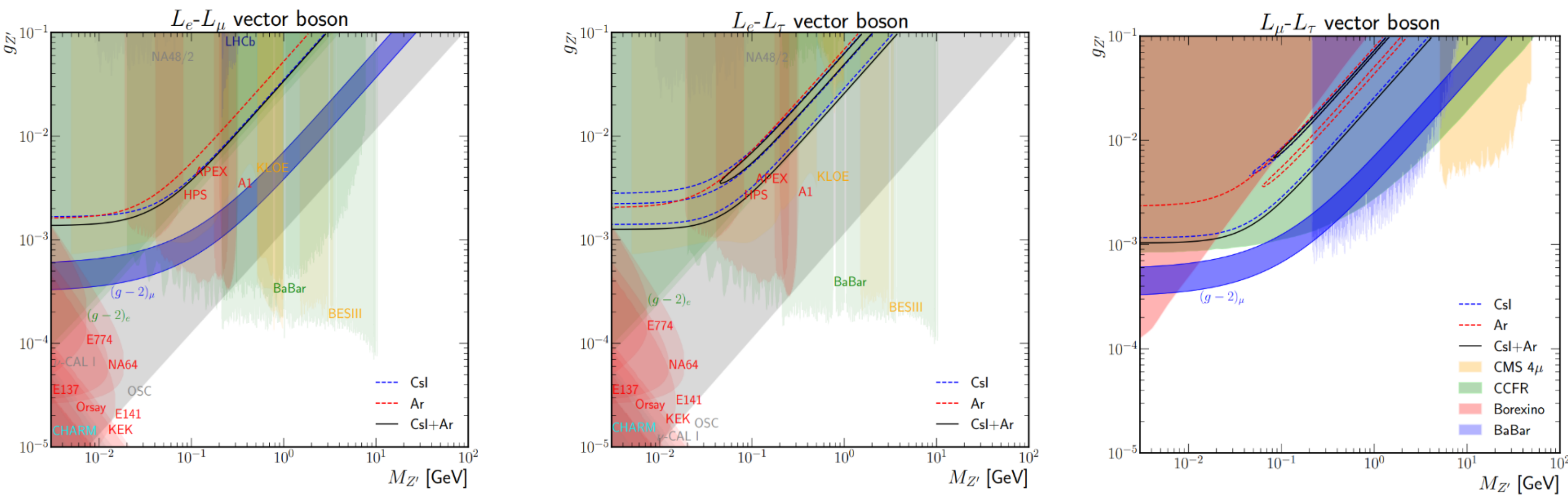
Constraints on light vector mediators Z'

$$\left(\frac{d\sigma}{dT_{\rm nr}}\right)^{\nu_\ell-\mathcal{N}}_{L_\alpha-L_\beta}(E,T_{\rm nr}) = \frac{G_F^2 M}{\pi}\left(1-\frac{M T_{\rm nr}}{2E^2}\right)$$
$$\times\left\{\left[g_V^p(\nu_\ell)+\frac{\sqrt{2}\alpha_{\rm EM} g_{Z'}^2\left(\delta_{\ell\alpha}\varepsilon_{\beta\alpha}(|\vec{q}|)+\delta_{\ell\beta}\varepsilon_{\alpha\beta}(|\vec{q}|)\right)}{\pi G_F\left(|\vec{q}|^2+M_{Z'}^2\right)}\right] Z F_Z(|\vec{q}|^2)+g_V^n N F_N(|\vec{q}|^2)\right\}^2 ,$$

one-loop kinetic mixing coupling

$$\varepsilon_{\beta\alpha}(|\vec{q}|) = \int_0^1 x(1-x)\ln\left(\frac{m_\beta^2+x(1-x)|\vec{q}|^2}{m_\alpha^2+x(1-x)|\vec{q}|^2}\right)dx\,,$$

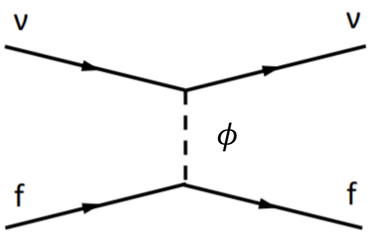




Constraints on light scalar mediators

The generic Lagrangian that describes the interaction of ϕ with neutrinos and quarks is

$$\mathcal{L}_\phi^S = -\phi \left[\sum_{\ell=e,\mu,\tau} g_\phi^{\nu_\ell}\, \overline{\nu_\ell}\, \nu_\ell + \sum_{q=u,d} g_\phi^q\, \overline{q}\, q \right],$$

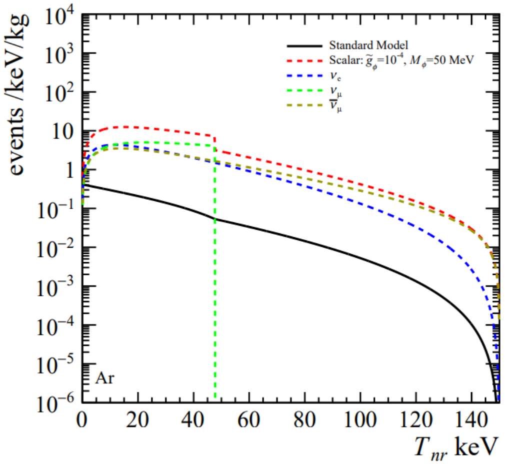


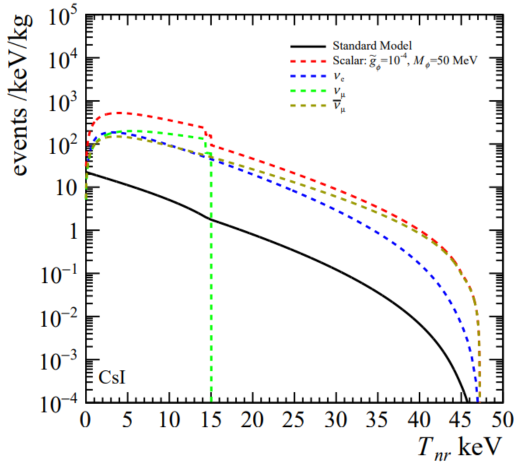
CEνNS cross section

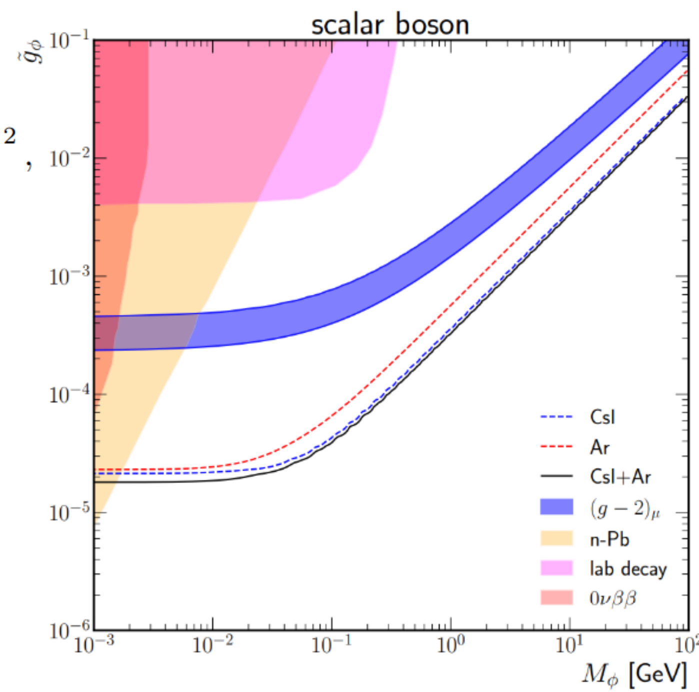
$$\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}} = \left(\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}\right)_{\mathrm{SM}} + \left(\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}\right)_{\mathrm{scalar}},$$

$$\left(\frac{d\sigma_{\nu_\ell\text{-}\mathcal{N}}}{dT_{\mathrm{nr}}}\right)_{\mathrm{scalar}} = \frac{M^2 T_{\mathrm{nr}}}{4\pi E^2} \frac{(g_\phi^{\nu_\ell})^2 \mathcal{Q}_\phi^2}{(|\vec{q}|^2 + M_\phi^2)^2},$$

$$\frac{M^2 T_{\mathrm{nr}}}{4\pi E^2} \frac{\tilde{g}_\phi^4}{(|\vec{q}|^2 + M_\phi^2)^2} \left(\frac{\sigma_{\pi N}}{\overline{m}_{ud}}\right)^2_{\mathrm{ref}} \left[Z F_Z(|\vec{q}|^2) + N F_N(|\vec{q}|^2)\right]^2,$$







Summary

- CEνNS: unique process to explore the nonstandard interaction of neutrinos.
- The combined fit of the COHERENT CsI and Ar: improvement of constraints on the nonstandard interaction of neutrinos.
- We presented the results obtained from the separate analyses of the CsI and Ar data and those obtained from the combined analysis of the two datasets.
- We considered several models with a light vector boson Z', which couples directly to quarks and leptons or indirectly to nucleons at the one-loop level.
- We compared with several non-CEνNS experiments.
- CEνNS data allow us to extend the excluded regions.
- We obtained the strong constraints on a light scalar boson and rejects the explanation of the $(g-2)_\mu$ anomaly in this model

Thanks