LUND UNIVERSITY

CEvNS light Z'

Johan Rathsman

Prospects for finding light Z' from CEvNS at ESS

Johan Rathsman
Work in progress with:
Joakim Cederkäll, Yaşar Hiçyılmaz, Else Lytken, Stefano Moretti

FPNP@ESS, 2025-01-17

Light Z′ models

- Assume extra $U(1)$ gauge symmetry giving additional Z′ gauge boson
- B-L well known example

$$\mathcal{L}_{\rm NC}^{\rm Z'} = -\sum_f \bar{\psi}_f(\gamma^\mu C_V^f + \gamma^\mu\gamma^5 C_A^f)\psi_f Z'_\mu$$

In B-L models $C_V^f = g_{Z'} Q'_f$ with $Q'_u = Q'_d = 1/3$ and $Q'_{\nu_\ell} = -1$.

- here we assume fermion charges only constrained by anomaly conditions
- possible to explain so called Atomki anomaly with a 17 MeV Z′ (X17)
- would modify normalisation and shape of nuclear recoil spectrum in CEvNS

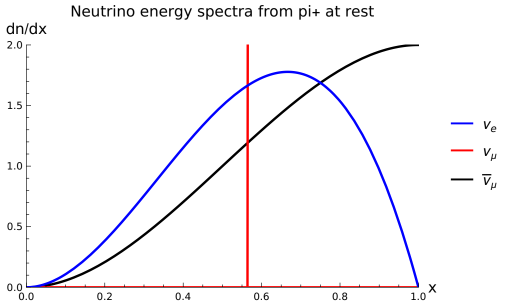
Benmark models allowed by current constraints

Parameter	BM111	BM222	BM333	BM444	BM666
g'	2.51×10^{-5}	3.48×10^{-5}	1.57×10^{-5}	1.81×10^{-5}	1.88×10^{-5}
$m_{Z'}$ [GeV]	0.0175	0.0174	0.0175	0.0166	0.0171
C_V^u	-2.49×10^{-4}	-2.55×10^{-4}	-2.48×10^{-4}	-2.49×10^{-4}	-2.54×10^{-4}
C_V^d	1.43×10^{-4}	1.46×10^{-4}	1.39×10^{-4}	1.09×10^{-4}	1.12×10^{-4}
$C_V^{\nu_e}$	1.38×10^{-5}	1.39×10^{-5}	1.10×10^{-5}	-1.18×10^{-5}	-1.13×10^{-5}
$C_V^{\nu_\mu}$	2.01×10^{-5}	1.74×10^{-5}	1.25×10^{-5}	-1.27×10^{-5}	-1.13×10^{-5}

Neutrino flux from π^+ decay at rest

$$\frac{d\Phi_{\nu_e}}{dx} = \frac{rN_{\mathrm{POT}}}{4\pi L^2} 12x^2(1-x)$$
$$\frac{d\Phi_{\bar{\nu}_\mu}}{dx} = \frac{rN_{\mathrm{POT}}}{4\pi L^2} 2x^2(3-2x)$$
$$\frac{d\Phi_{\nu_\mu}}{dx} = \frac{rN_{\mathrm{POT}}}{4\pi L^2} \delta\left(x-x_0\right)$$

- $x = \dfrac{2E_\nu}{m_\mu}$, $0 < x < 1$
- r nr of π^+ per proton,
- N_{POT} nr of protons on target,
- L distance



$$x_0 = \frac{m_{\pi^+}^2 - m_\mu^2}{m_\mu m_{\pi^+}} \approx 0.564\,.$$

Nuclear recoil energy spectrum for CEvNS

$$\frac{dN}{dy} = \frac{rN_{\rm POT}}{4\pi L^2}\frac{G_F^2 m_\mu^2}{4\pi}\sum_{\nu_\ell}\left[\frac{dn_{\nu_\ell}}{dy}_V (Q_V^{\nu_\ell})^2\right]$$

- $y = \dfrac{2ME_{\rm nr}}{m_\mu^2}$, $0 < y < 1$
- M nucleus mass.
- $E_{\rm nr}$ nuclear recoil energy

$$\frac{dn_{\nu_e}}{dy}_V = \frac{1}{2} - 3y + 4y^{3/2} - \frac{3}{2}y^2$$

$$\frac{dn_{\nu_\mu}}{dy}_V = \frac{1}{2} - 2y + 2y^{3/2} - \frac{1}{2}y^2 + \left(\frac{1}{2} - \frac{y}{2x_0^2}\right)\Theta\left(1 - \frac{y}{x_0^2}\right)$$

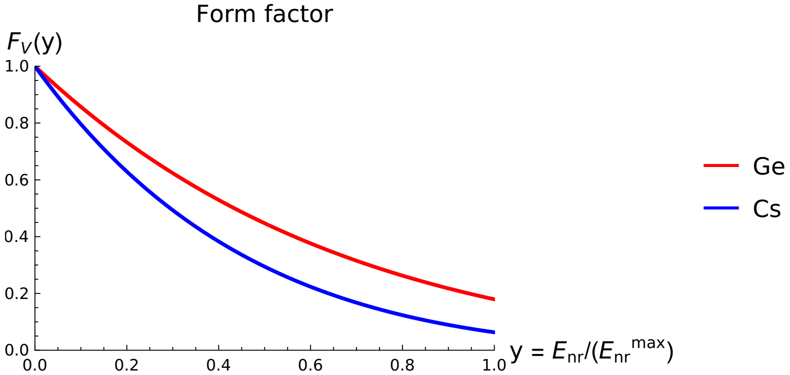
$$Q_V^{\nu_\ell} = g_V^{p,\nu_\ell}\, Z\, F_{V,Z}(y) + g_V^{n,\nu_\ell}\, N\, F_{V,N}(y)$$

Klein Nystrand nuclear form factor

$F_{V,Z}(y)$ and $F_{V,N}(y)$ nuclear form factors for protons and neutrons

$$F_{V,Z}(Q^2) = F_{V,N}(Q^2) = \frac{3}{(QR_A)^3}\left[\sin(QR_A) - QR_A\cos(QR_A)\right]\frac{1}{1+Q^2}$$

$Q^2 = 2ME_{\mathrm{nr}} = ym_\mu^2$, $R_A = 1.2A^{1/3}$ fm, and $a = 0.7$ fm.



Vector couplings

Vector couplings of neutrinos to protons and neutrons modified by Z' exchange

$$
\begin{aligned}
g_V^{p,\nu_\ell} &= g_{V,\mathrm{SM}}^{p} + \frac{\sqrt{2}C_V^{\nu_\ell}(2C_V^u + C_V^d)}{G_F(ym_\mu^2 + m_{Z'}^2)} \\
g_V^{n,\nu_\ell} &= g_{V,\mathrm{SM}}^{n} + \frac{\sqrt{2}C_V^{\nu_\ell}(C_V^u + 2C_V^d)}{G_F(ym_\mu^2 + m_{Z'}^2)}
\end{aligned}
$$

for the SM we use the LO values

$$
\begin{aligned}
g_{V,\mathrm{SM}}^{p} &= (1 - 4\sin^2\theta_W) \\
g_{V,\mathrm{SM}}^{n} &= -1
\end{aligned}
$$

with $sin^2\theta_W = 0.24$

Z' signal ratio compared to SM

Using $F_{V,Z}(y) = F_{V,N}(y)$ the signal ratio compared to the SM becomes

$$\left[\sum_{\nu_\ell} \frac{dn_{\nu_\ell}}{dy}_V \left(-1 + \frac{\sqrt{2}C_V^{\nu_\ell}[N(C_V^u + 2C_V^d) + Z(2C_V^u + C_V^d)]}{[N - (1 - 4\sin^2\theta_W)Z]G_F m_\mu^2 (y + m_{Z'}^2/m_\mu^2)}\right)^2\right] \Big/ \left[\sum_{\nu_\ell} \frac{dn_{\nu_\ell}}{dy}_V\right]$$

for $B - L$ model this reduces to

$$\left(1 + \frac{\sqrt{2}g_{Z'}^2(N + Z)}{[N - (1 - 4\sin^2\theta_W)Z]G_F m_\mu^2 (y + m_{Z'}^2/m_\mu^2)}\right)^2$$

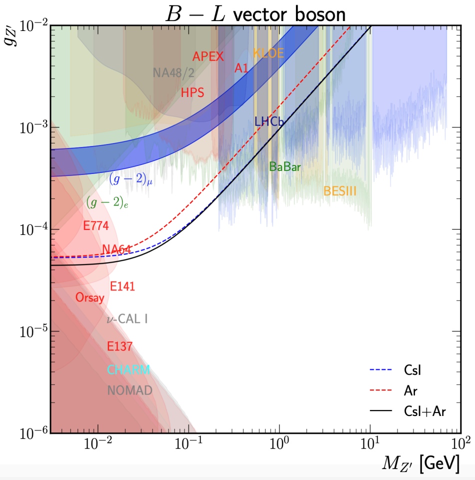
CEvNS light Z′

Johan Rathsman

Current limits on B-L model from Atzori Corona et al (2202.11002):

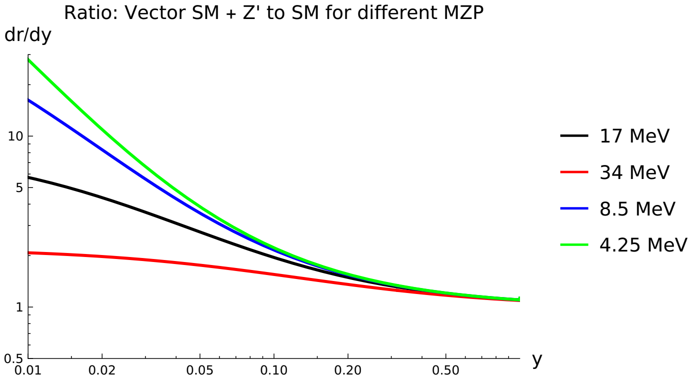
$g_{Z'} < 5 \times 10^{-5}$ for $m_{Z'} = 0.017$ GeV

- will use this a reference model/parameter value



The propagator $\dfrac{1}{y + m_{Z'}^2/m_\mu^2}$ affects the shape of the spectrum

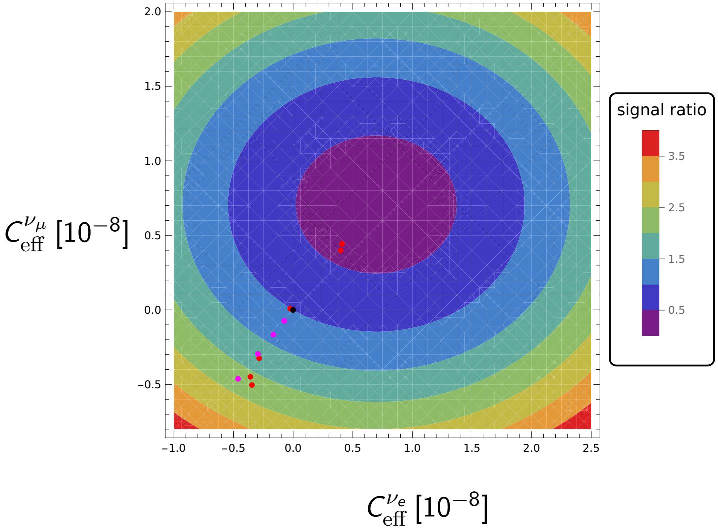
Ex: B-L model with $g_{Z'} = 5 \times 10^{-5}$ for $m_{Z'} = 4.25, 8.5, 17, 34$ MeV



note: independent of nuclear mass

Signal ratio when integrating over $0.01 < y < 0.31$

Effective couplings: $C_{\text{eff}}^{\nu_\ell} = \dfrac{C_V^{\nu_\ell}[N(C_V^u + 2C_V^d) + Z(2C_V^u + C_V^d)]}{[N - (1 - 4\sin^2\theta_W)Z]}$



black: SM

magenta: B-L

$g_{Z'} = 2, 3, 4, 5 \times 10^{-5}$

red: X17 BMs

CEvNS light Z'

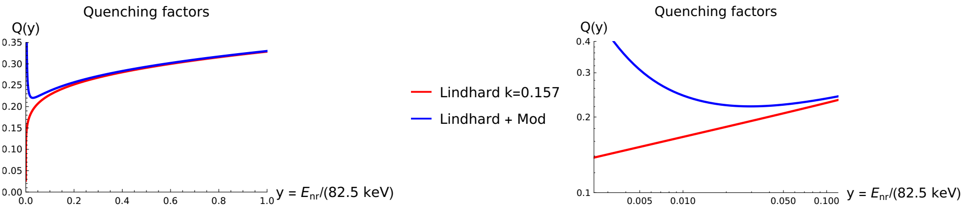
Johan Rathsman

Detector considerations

Germanium detector as an example (inspired by Dreden-II exp)

Quenching factor: conversion of nuclear recoil to ionisation signal

$$y_{\text{ion}} = Q(y)y$$



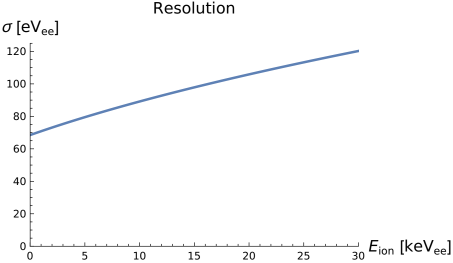
Modifications added to span uncertainties at small recoil energies

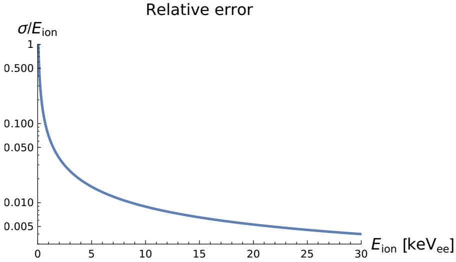
Threshold $\sim$ 800 eV $\Rightarrow y \gtrsim 0.01$

Detector considerations, cont'd

The detector resolution

$$R(y_{\rm rec}, y_{\rm ion}) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(y_{\rm rec}-y_{\rm ion})^2}{2\sigma^2}\right]$$





Threshold: $y_{\rm rec} > \dfrac{0.200\,\mathrm{keV}}{82.5\,\mathrm{keV}} = 0.0024$

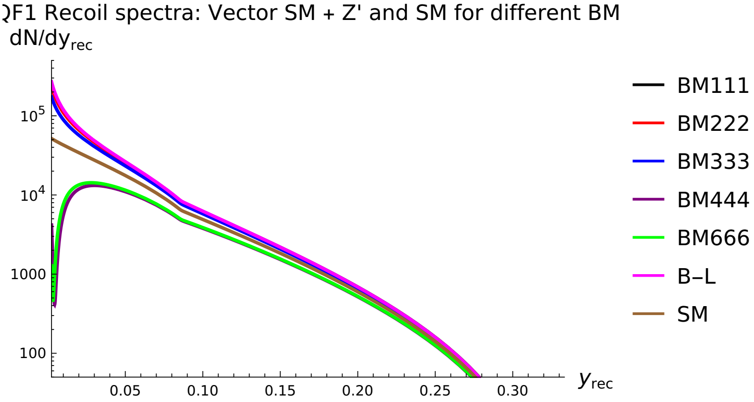
Statistics

Flux factor $\frac{rN_{\mathrm{POT}}}{4\pi L^2}$ assuming 5000 hours per year of beam on target

	Far, L=25 m		
Parameter	Low	Med	High
Beam energy [GeV]	0.84	0.84	2.0
Yeild r	0.08	0.08	0.3
Power [MW]	0.80	2.0	5.0
N_{POT} [year^{-1}]	1.1×10^{23}	2.7×10^{23}	2.7×10^{23}
Time in years	1	3	3
Flux factor [GeV^2]	4.3×10^{-14}	3.2×10^{-13}	1.2×10^{-12}

Also assuming $m_{\mathrm{target}} = 20$ kg

Number of events in HighFar scenario



CEvNS light Z'

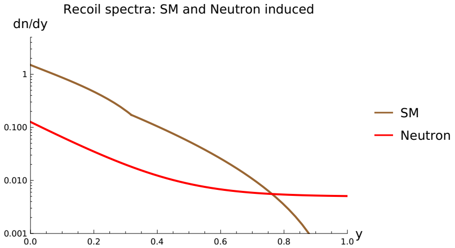
Johan Rathsman

Backgrounds and systematics

Backgrounds

- Reducible: neutron induced nuclear recoils
  - prompt
  - ambient - here the duty factor helps
- Irreducible
  - Standard Model

Neutron background at $L = 25$ m with 50 cm polyethylene neutron moderator

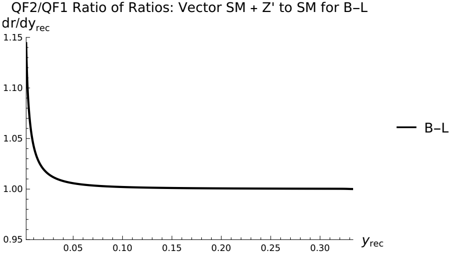


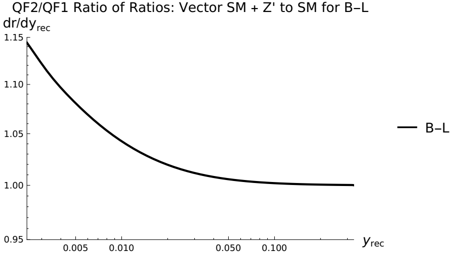
Based on C. M. Lewis (PhD thesis U Chicago) (rescaled CsI to Ge)

Backgrounds and systematics, cont'd

Systematic uncertainties

- neutrino flux - uncertainties in r - assume 10 %
- quenching factor





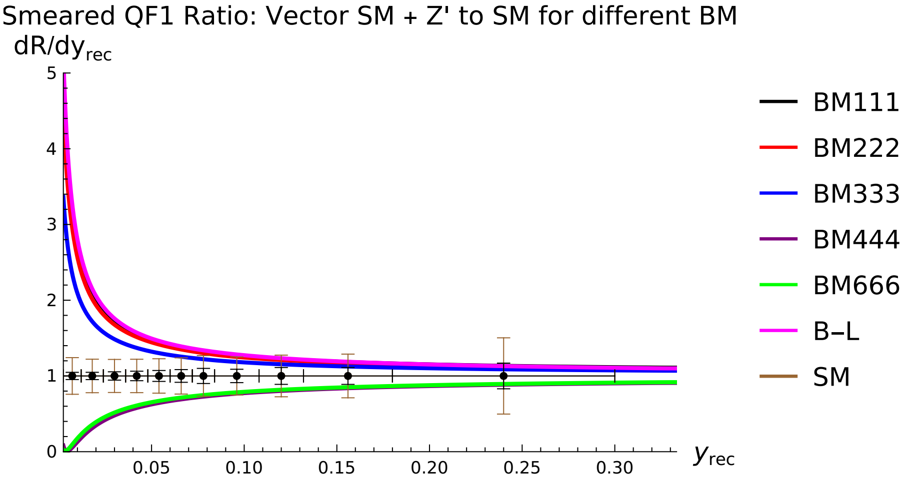
- small for $y_{\rm rec} > 0.02$
- up to 15 % at threshold $y_{\rm rec} = 0.0024$ (0.200 keV$_{\rm ee}$)

LUND UNIVERSITY

CEvNS light Z′

Johan Rathsman

Resulting ratio to SM



statistical error (in black) $1/\sqrt{N_{\rm SM}} \sim 5$ %

systematic errors: $R_{\rm QF} + R_{\rm flux} + R_{\rm neutron}$

CEvNS light Z′

Johan Rathsman

Light Z′ models

Neutrino flux from π^+ decay at rest

CEvNS

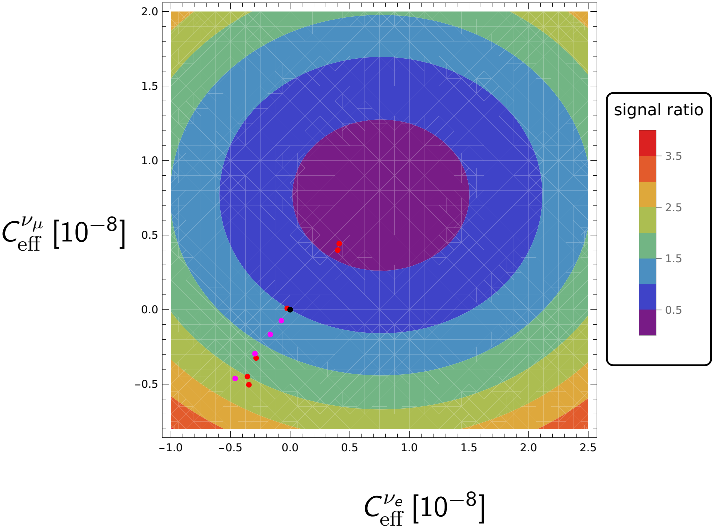
Detector considerations

Statistics

Backgrounds and systematics

Summary and conclusions

Integrating over $0.0024 < y_{\rm rec} < 0.1$ gives overall signal strength



black: SM

magenta: B-L

$g_{Z'} = 2, 3, 4, 5 \times 10^{-5}$

red: X17 BMs

Summary and conclusions

- CEvNS very promising for finding light Z′ gauge boson
- For $m_{Z'} \sim 20$ MeV the shape could also be used
- Current limits allow for a factor 2 up or down compared to SM cross-section
- Currently systematics limiting factor
- few percent statistical uncertainty possible to reach with 5 MW