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Probing the X_{17} using Coherent Elastic Neutrino Nucleus Scattering

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Based on arXiv:2509.15128 and arXiv:2603.15246 with:
Joakim Cederkäll, Yaşar Hiçyılmaz, Else Lytken, Stefano Moretti

The X17 particle, status and new ideas 2026, Trento, 25/03-26

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Outline:

- Coherent elastic neutrino nucleus scattering
- Neutrino Sources
- Detector effects
- Analysis of data
- Interpretation in minimal Z' model for the X_{17}
- Conclusions

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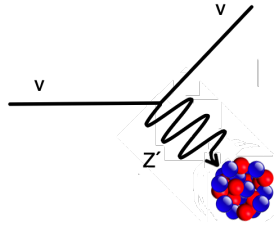
Coherent Elastic Neutrino Nucleus Scattering (CEνNS)

- Coherent elastic scattering off the whole nucleus
- $[N-(1-4\sin^2\theta_W)Z]^2$ enhancement in SM cross-section (N neutrons, Z protons)
- Tabletop detector possible – $\mathcal{O}(10)$ kg
- High sensitivity also to BSM physics - such as the X_{17}
- Nuclear recoil energies down to $\sim$1 keV
- Requires extremely low threshold to be sensitive
- current best threshold corresponds to 5 electron-hole pairs in Germanium



Cross-section for CEνNS with Z'

Dominated by vector coupling of nucleus (axial vector coupling $\propto$ nucleus spin)

$$\frac{d\sigma^{\nu_{e/\mu}N}}{dy} = \frac{[N-(1-4\sin^2\theta_W)Z]^2\,[F_V(y)]^2}{4\pi m_\mu^2}\left(1-\frac{y}{x^2}\right) \times\left(\frac{G_F m_\mu^2}{\sqrt{2}}-\frac{C_{\rm eff}^{\nu_{e/\mu}}}{y+m_{Z'}^2/m_\mu^2}\right)^2$$

where $G_F m_\mu^2/\sqrt{2}=9.3\times10^{-8}$, $m_{X_{17}}^2/m_\mu^2=0.026$ and

$$x = \frac{2E_\nu}{m_\mu},\ 0<x<1$$

$$y = E_{\rm nr}/E_{\rm nr}^{\rm max},\ 0<y<1,\ E_{\rm nr}^{\rm max}=m_\mu^2/(2M)$$

$$C_{\rm eff}^{\nu_{e/\mu}} = C_V^{\nu_{e/\mu}}\frac{N(C_V^u+2C_V^d)+Z(2C_V^u+C_V^d)}{N-(1-4\sin^2\theta_W)Z}$$

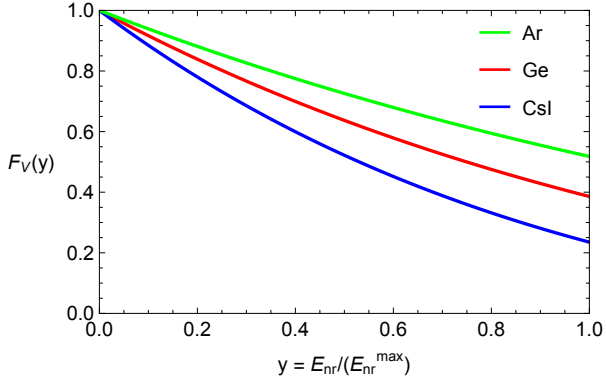
C_V^f vector coupling to Z'

Klein Nystrand nuclear form factor

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

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

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



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Neutrino Sources

Spallation sources

- pulsed proton beam producing neutrons and π^+
- π^+ stopped in target before decay, $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$
- $\tau_{\pi^+} = 26$ns, $\tau_\mu = 2200$ns

Nuclear reactors

- continues flux of anti-neutrinos $\overline{\nu}_e$ from fission products

Nuclear recoil spectrum

$$\frac{dN_r}{dy} = \frac{m_{\rm det} N_{\rm A}}{M_{\rm A}} \int_{\sqrt{y}}^{1} \frac{d\sigma^{\nu N}}{dy} \frac{d\Phi_\nu}{dx} dx$$

kinematics gives $x > \sqrt{y}$ (head-on collision)

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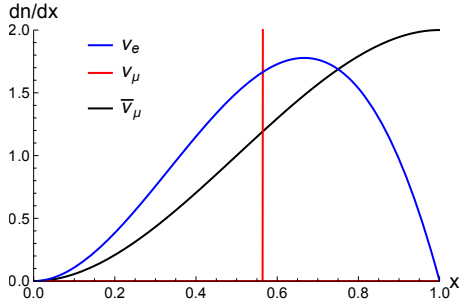
Neutrino flux from $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$ decay at rest

$$\frac{d\Phi_{\nu_e}}{dx} = \frac{rN_{\rm POT}}{4\pi L^2}\,12x^2(1-x)$$

$$\frac{d\Phi_{\bar{\nu}_\mu}}{dx} = \frac{rN_{\rm POT}}{4\pi L^2}\,2x^2(3-2x)$$

$$\frac{d\Phi_{\nu_\mu}}{dx} = \frac{rN_{\rm POT}}{4\pi L^2}\,\delta(x-x_0)$$



- $x = \dfrac{2E_\nu}{m_\mu}$, $0 < x < 1$
- r nr of π^+ per proton
  r =0.08(0.3)@0.8(5)MW
- $N_{\rm POT}$ nr of protons on target
- L distance

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

Neutrino flux from reactors

$$\frac{d\Phi_{\overline{\nu}_e}}{dx} = \frac{\Phi t_{\rm exp}}{N_{\overline{\nu}_e}} \left[x e^{a_2+b_2x+c_2x^2} + \right.$$
$$\left. + e^{a_1+b_1x+c_1x^2+d_1x^3+e_1x^4+f_1x^5} \right]$$

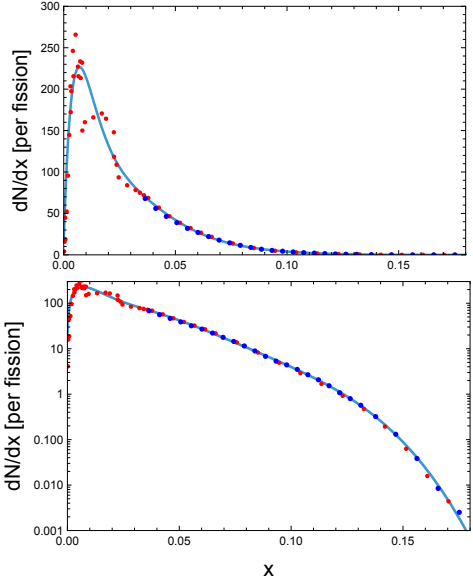
Fitted to data from DayaBay (blue) and calculation by Kopeikin (red), $N_{\overline{\nu}_e} = 6.8$

Total fluxes for experiments

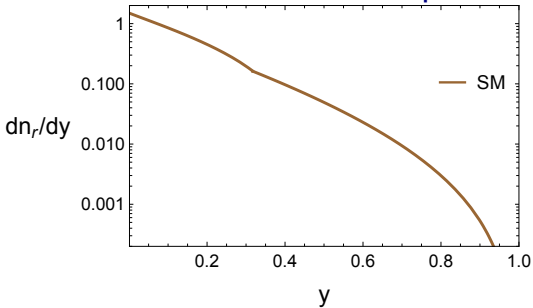
- $\Phi_{\rm Dresden-II} = 4.8 \times 10^{13}$ cm^2/s
- $\Phi_{\rm CONUS+} = 1.5 \times 10^{13}$ cm^2/s

Much lower energy than π^+-DAR

$\Rightarrow$ (Much lower)^2 nuclear recoil energy

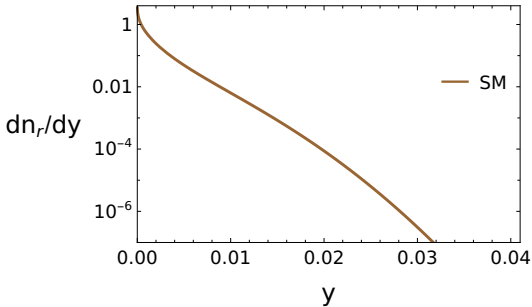


Theoretical nuclear recoil spectra



$$\frac{dn_r}{dy} = \int_{\sqrt{y}}^{1} \frac{d\sigma^{\nu N}}{dy} \frac{d\Phi_\nu}{dx} dx$$

π^+ DAR



reactors

Quenching factor for Germanium

Ionisation energy smaller than nuclear recoil energy

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

Described by the Lindhard model

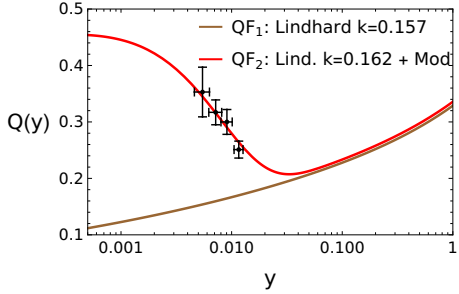
$$Q_{\rm Lind}(y) = \frac{kg(y)}{1+kg(y)}$$

$$g(y) = 3(C_Z y)^{0.15} + 0.7(C_Z y)^{0.60} + C_Z y$$

$$C_Z = E_{\rm nr}^{\rm max} \times 11.5/Z^{7/3}$$

$E_{\rm nr}^{\rm max} = 82.5$keV for Ge

uncertainty at small recoil energies



$$\begin{aligned} {\rm QF}_1 &= Q_{\rm Lind}(k=0.157), \\ {\rm QF}_2 &= Q_{\rm Lind}(k=0.162) + Q_{\rm Mod} \end{aligned}$$

with $Q_{\rm Mod}(y) = 0.36\exp(-120y)$

detector threshold $\Leftrightarrow y \gtrsim 0.01$

Detector resolution

Finite detector resolution gives smearing

$$\frac{dN_r}{dy_{\rm rec}} = \int_{y_{\rm min}}^{1} \frac{2}{1+{\rm Erf}\left(\frac{Q(y)y}{\sqrt{2}\sigma}\right)} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(y_{\rm rec}-Q(y)y)^2}{2\sigma^2}\right] \frac{dN_r}{dy} dy$$

minimal fractional recoil energy $y_{\rm min} = 0.00034$

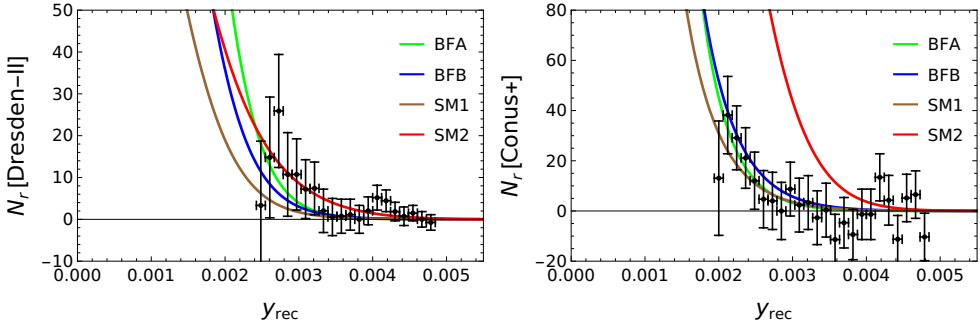
$\sigma = \sigma_E/E_{\rm nr}^{\rm max}$ is a dimensionless width with

$$\sigma_E^2 = \sigma_n^2 + E_{\rm ion}\eta F,$$

where $\eta = 2.96$ eV$_{\rm ee}$, the Fano factor $F = 0.11$ and σ_n is the intrinsic resolution of the detector

$$\begin{aligned} \sigma_n^{\rm Dresden-II} &= 68.5\,{\rm eV_{ee}}, \\ \sigma_n^{\rm CONUS+} &= 20.0\,{\rm eV_{ee}}. \end{aligned}$$

Detected recoil spectra for reactors compared to SM



not possible to construct quenching factor that describes both data sets

Y. Li, G. Herrera and P. Huber, JHEP **11** (2025), 022

use QF_1 since overall in better agreement with data

adding a X_{17} (BFA and BFA) able to describe both datasets

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Statistical analysis of data

$$\chi^2 = \sum_i \left(\frac{(1+\rho)x_i - \mu_i}{\sigma_i} \right)^2 + \left(\frac{\rho}{\sigma_{\rm sys}} \right)^2 ,$$

x_i model predictions for number of events

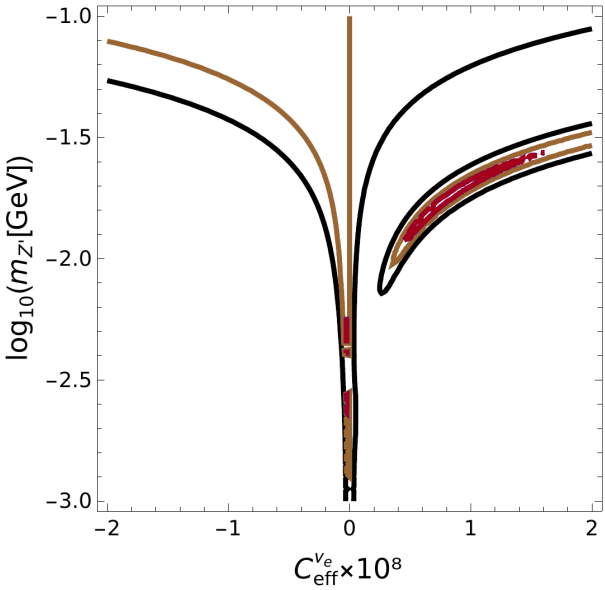
μ_i number of observed events

σ_i corresponding errors

ρ overall scale factor, determined from minimising χ^2

$\sigma_{\rm sys}$ overall systematic uncertainty, use $\sigma_{\rm sys} = 0.17$ (CONUS+)

χ^2 contours for arbitrary mass Z'



Brown = SM

Black = SM+6

Red = SM−2

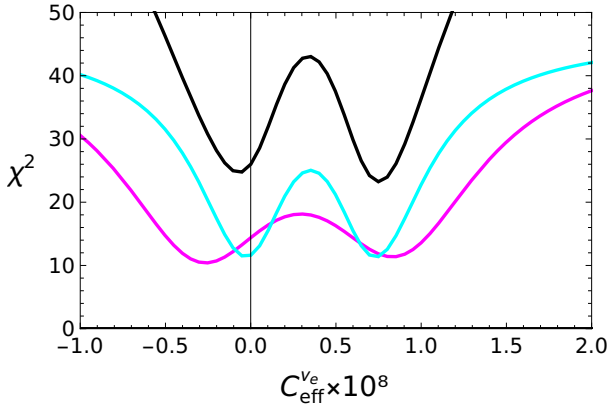
Preferred region:

$m_{Z'} \approx [13, 25]$ MeV and

$C_{\rm eff}^{\nu_e} \approx [0.5, 1.5] \cdot 10^{-8}$

$C_{\rm eff}^{\nu_e}$ positive $\Leftrightarrow$ negative interference with SM

χ^2 curve for X_{17}



magenta = Dresden-II

cyan = CONUS+

combined=black

Preferred values:

BFA: $C_{\rm eff}^{\nu_e} \approx 0.75 \cdot 10^{-8}$

BFB: $C_{\rm eff}^{\nu_e} \approx -0.10 \cdot 10^{-8}$

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Adding in Ar, Ge and CsI data from COHERENT

Approximate nuclear dependence of effective charges

$$C_{\rm eff}^{\nu_{e/\mu}} = C_V^{\nu_{e/\mu}} \frac{N(C_V^u + 2C_V^d) + Z(2C_V^u + C_V^d)}{N - (1 - 4\sin^2\theta_W)Z}$$

by average of effect on C_V^d and C_V^u

$$C_{\rm eff}^{\nu_{e/\mu}}({\rm Ar}) = 1.020\, C_{\rm eff}^{\nu_{e/\mu}}({\rm Ge})$$
$$C_{\rm eff}^{\nu_{e/\mu}}({\rm CsI}) = 0.953\, C_{\rm eff}^{\nu_{e/\mu}}({\rm Ge}),$$

Systematic scale uncertainties:

$$\sigma_{\rm sys}^{\rm Ar} = 0.13 \text{ (Argon)},$$
$$\sigma_{\rm sys}^{\rm CsI} = 0.12 \text{ (Caesium Iodine)},$$
$$\sigma_{\rm sys}^{\rm Ge} = 0.103 \text{ (Germanium)}.$$

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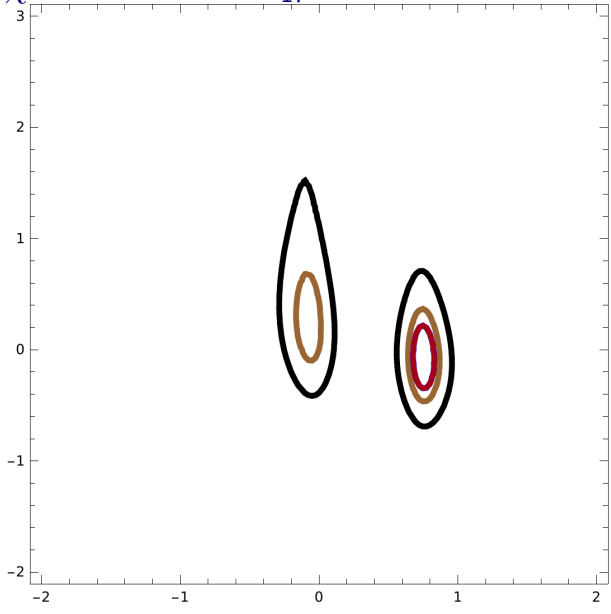
χ^2 contours for X_{17}



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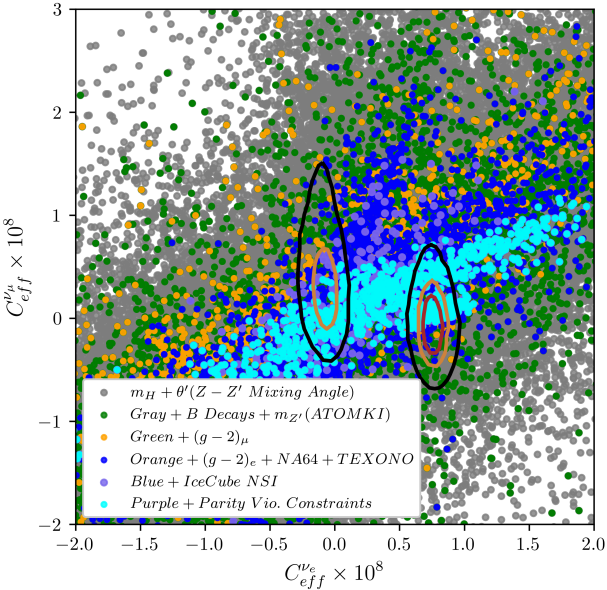
Two distinct best fit regions

BFA: $C_{\rm eff}^{\nu_e} = 0.75 \times 10^{-8}$, $C_{\rm eff}^{\nu_\mu} = -0.05 \times 10^{-8}$

BFB: $C_{\rm eff}^{\nu_e} = -0.10 \times 10^{-8}$, $C_{\rm eff}^{\nu_\mu} = 0.35 \times 10^{-8}$

.

χ^2 contours for X_{17}



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Two distinct best fit regions

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Points show result of scan in minimal Z' model for the X_{17}

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A minimal Z' model for the X_{17}

Gauge sector:

- additional $U(1)'$ field which has kinetic mixing with the SM $U(1)_Y$
- there is also mass mixing between the Z and the Z'

Higgs sector:

- additional complex scalar χ which mixes with the SM Higgs field H

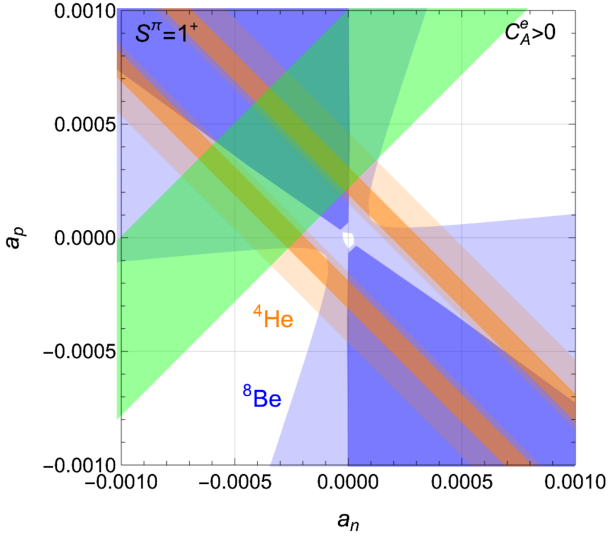
Fermion sector:

- SM fermions + three right handed neutrinos
- first two generations get masses from higher dim. operators with χ and H
- $U(1)'$ charges respect anomaly equations

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

axial vector couplings C_A^f constrained to explain X_{17} data

Barducci and Toni, JHEP **07** (2023), 168



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Fermion vector and axial vector couplings

Given by $U(1)'$ charges as

$$C_V^f \simeq \tilde{g}\cos^2\theta_W Q_f + g'[Q'_H(T_f^3 - 2\sin^2\theta_W Q_f) + (Q'_{f,R} + Q'_{f,L})/2]$$
$$C_A^f \simeq g'[-Q'_H T_f^3 + (Q'_{f,R} - Q'_{f,L})/2]$$

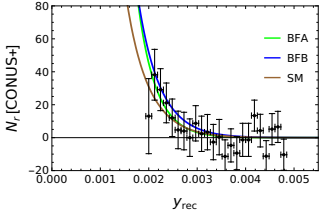
where the gauge couplings are

$$\mathcal{D}_\mu = \partial_\mu + \cdots + ig_1 Y B_\mu + i(\tilde{g}Y + g'Q')B'_\mu$$

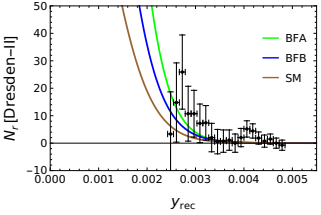
with $\tilde{g} = -\eta g_1/\sqrt{1-\eta^2}$ and η gives the kinetic mixing

$$\mathcal{L}_{\rm Kin}^{U(1)'} = -\frac{1}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \frac{1}{4}\hat{F}'_{\mu\nu}\hat{F}'^{\mu\nu} - \frac{\eta}{2}\hat{F}'_{\mu\nu}\hat{F}^{\mu\nu}$$

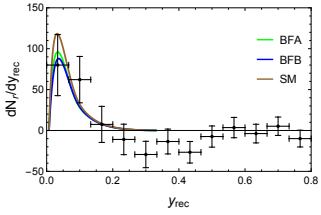
Comparison of X17 model to all data



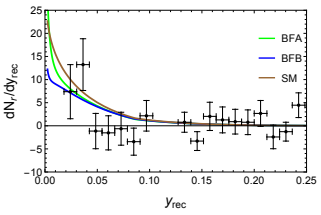
CONUS+



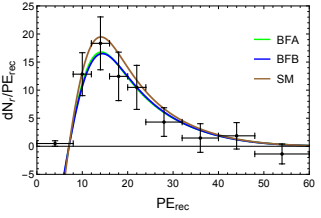
Dresden-II



COHERENT-Ar

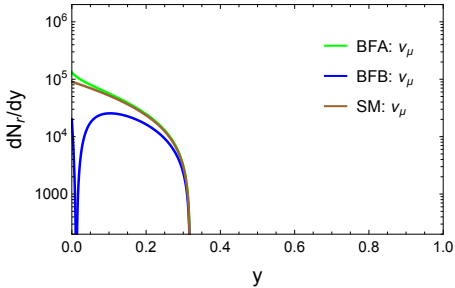


COHERENT-Ge

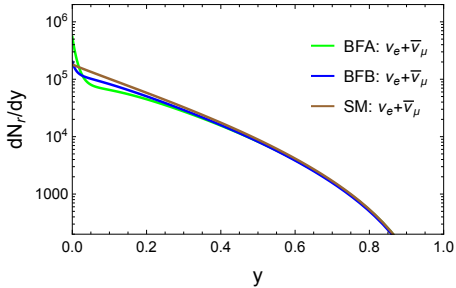


COHERENT-CsI

Timing information to distinguish coupling combinations?



prompt π^+ decay



delayed μ decay

Also need to lower detector threshold

CONUS+: 160 eV_{ee}

Dresden-II: 200 eV_{ee}

COHERENT-Ge: 1500 $eV_{ee} \Leftrightarrow y \approx 0.1$ (last week 500 eV_{ee})

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Conclusions and outlook

CEνNS at reactors and spallation sources and X_{17}:

- can search for light Z' such as the X_{17}
- fit to available data prefers an X_{17} compared to the SM, requires flavour non-universality
- minimal model with Z' as the X_{17} can describe data

Experimental challenges for CEνNS

- quenching factor at low nuclear recoil energies
- neutron background at spallation sources
- need to measure absolute neutrino flux (uncertainty on r)

Other CEνNS possibilities – Solar ^{8}B neutrinos:

- First evidence seen in dark matter experiments XENONnT and PandaX-4T
- ν_e, ν_μ, and ν_τ all contribute
- "neutrino floor" can be turned from DM background to BSM signal

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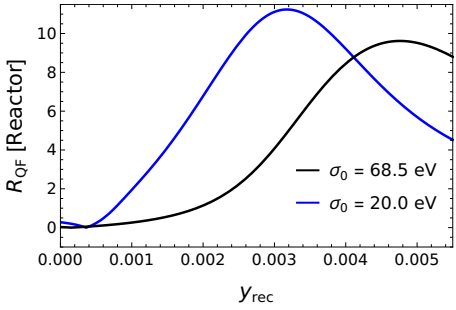
Questions

Question 1: would be very beneficial to have experimental analysis and theoretical calculations for more general states: mix of scalar and pseudo-scalar as well as vector and axial-vector

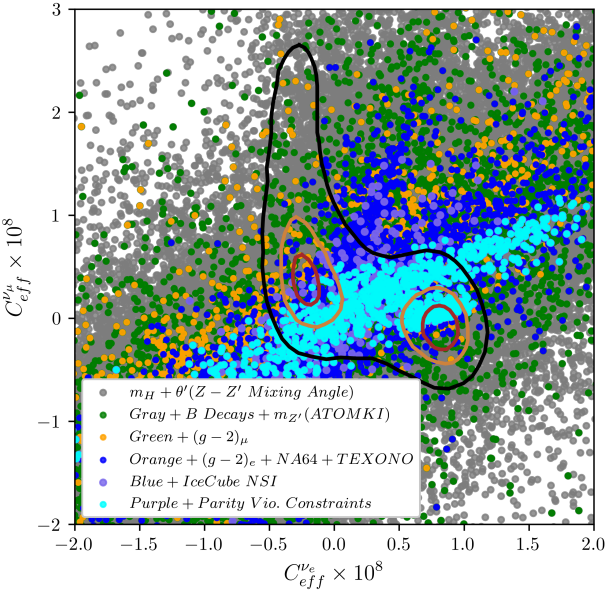
Question 2: would the "invisible" decay width to neutrinos be interesting for further analysis

Backup – quenching factor uncertainty



$$R_{\rm QF} = \left| \frac{\left.\frac{dN_r}{dy_{\rm rec}}\right|_{\rm QF2} - \left.\frac{dN_r}{dy_{\rm rec}}\right|_{\rm QF1}}{\left.\frac{dN_r}{dy_{\rm rec}}\right|_{\rm QF1}} \right|$$

χ^2 contours for X_{17} with quenching factor uncertainty



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Red = SM−2

Small effect on best fit regions

BFA: $C^{\nu_e}_{\rm eff} = 0.75 \times 10^{-8}$, $C^{\nu_\mu}_{\rm eff} = -0.05 \times 10^{-8}$

BFB: $C^{\nu_e}_{\rm eff} = -0.10 \times 10^{-8}$, $C^{\nu_\mu}_{\rm eff} = 0.35 \times 10^{-8}$

Allowed region substantially larger