Coherent Elastic neutrino-Nucleus Scattering with directional (νBDX-DRIFT) detectors

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νBDX-DRIFT collaboration:

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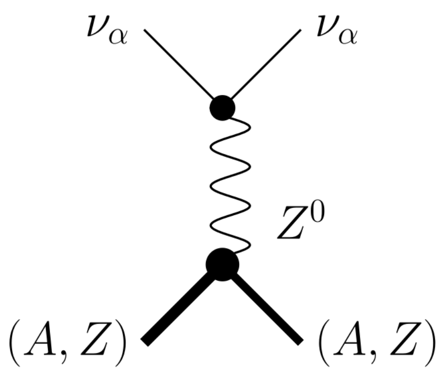
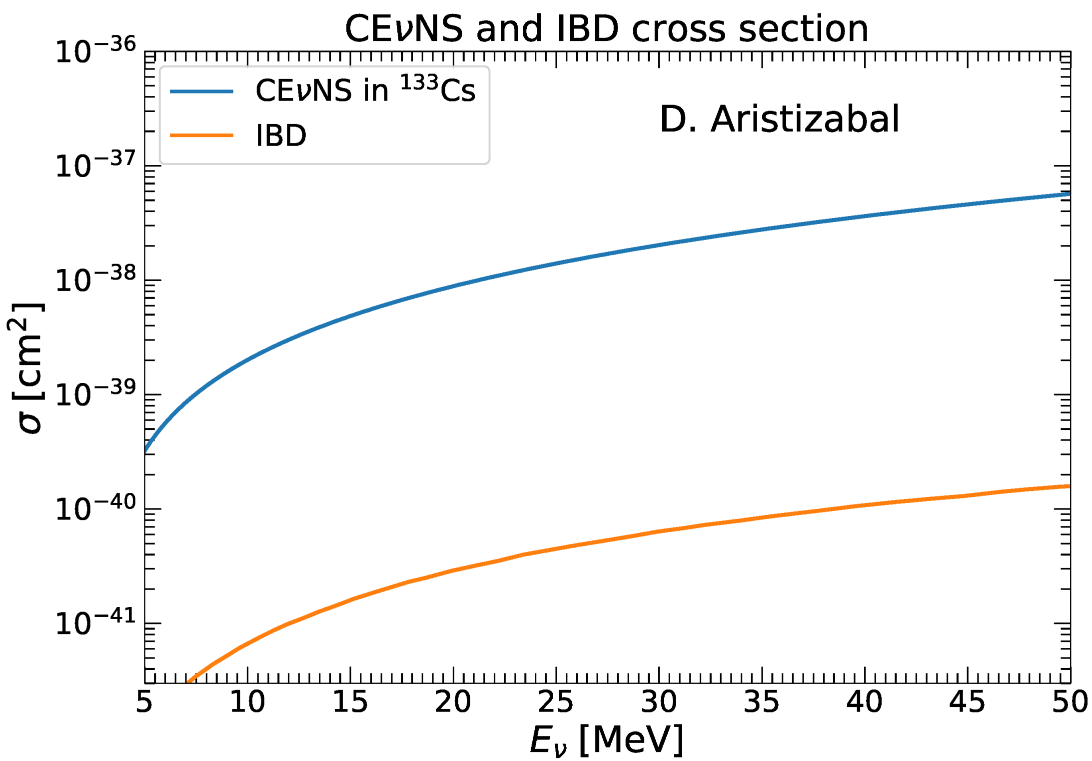
What is Coherent Elastic neutrino-Nucleus Scattering?



$$|\nu_\alpha + (A, Z)\rangle \rightarrow |\nu_\alpha + (A, Z)\rangle$$

Possible when E_ν sufficiently small



CEνNS in more detail

CEνNS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently $\Rightarrow$ cross section enhancement

$$\lambda \gtrsim R_N \;\Rightarrow\; q \lesssim 200\ \text{MeV}$$

$$E_R = q^2/2m_N \;\Rightarrow\; E_\nu \simeq \sqrt{E_R^{\text{max}} m_N/2}$$

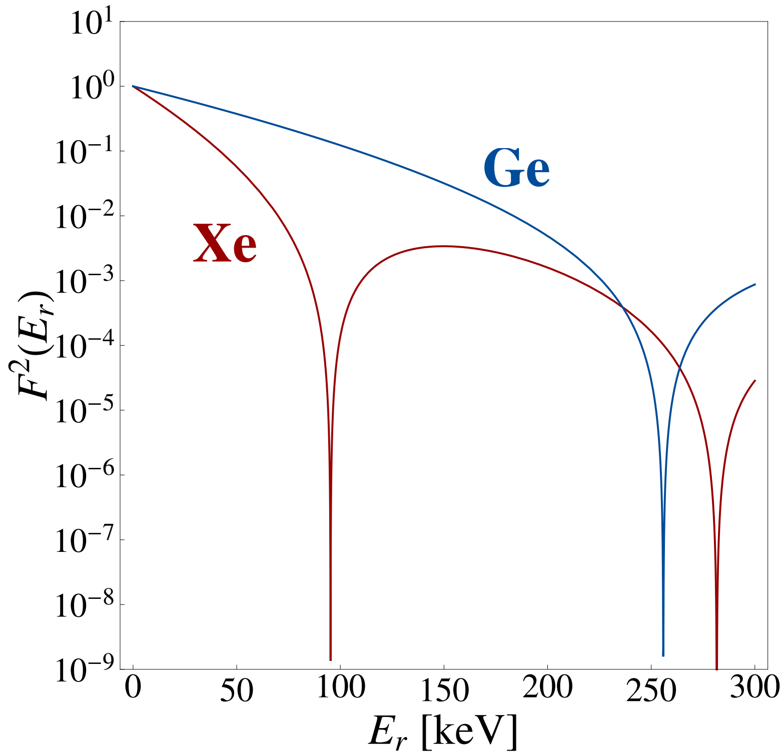
$$E_\nu \lesssim 200\ \text{MeV}$$

Freedman, 1974; Drukier & Stodolsky, 1984

$$\frac{d\sigma_\nu}{dE_R} = \frac{G_F^2}{4\pi} Q_{\text{SM}}^2 m_N \left(1 - \frac{E_r m_N}{2E_\nu^2}\right) \underbrace{F^2(E_r)}_{\text{Form factor}}$$

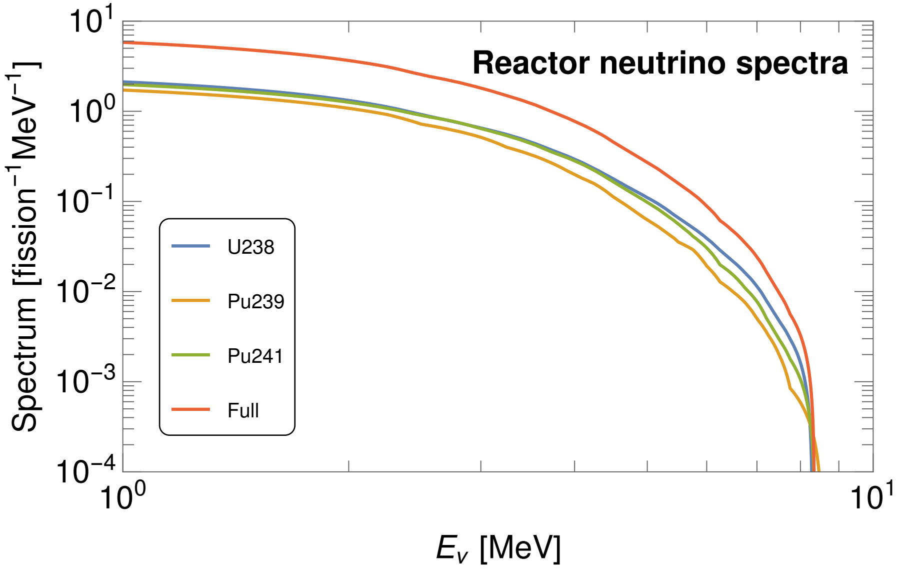
$$Q_{\text{SM}}^2 = [N - (1 - s_W^2)Z]^2 \simeq N^2$$

Helm, 1956

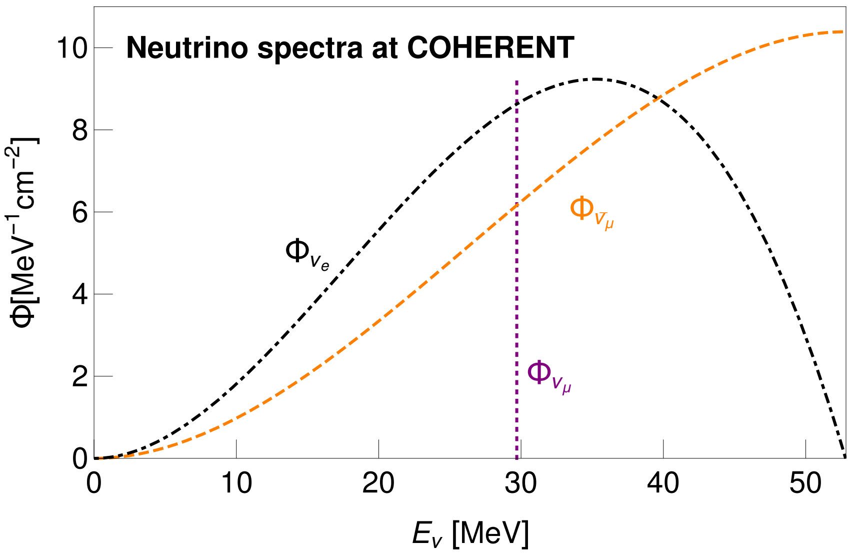


CEvNS environments

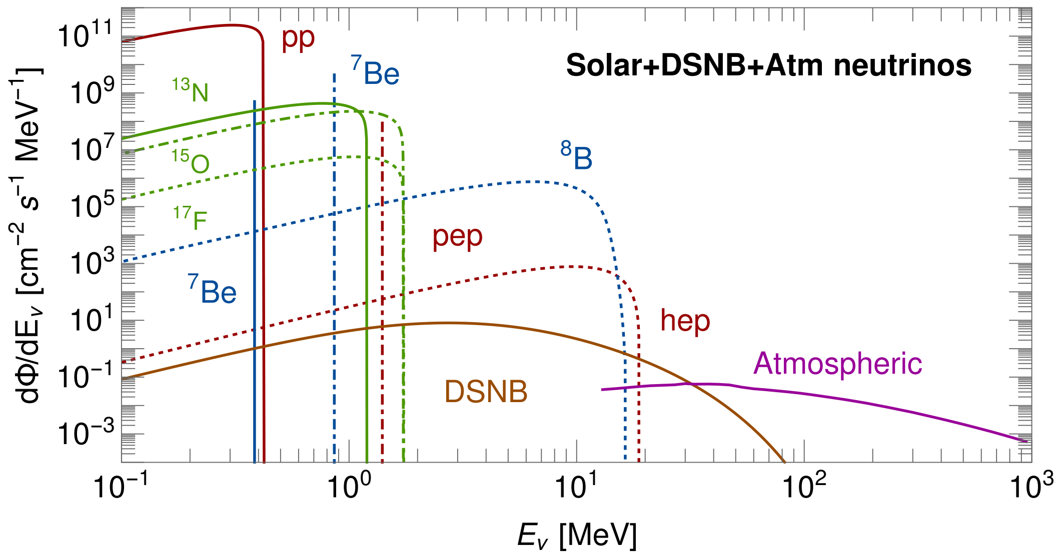
Reactor (CONUS, NUCLEUS, RICOCHET...)



Fixed target neutrinos (COHERENT)



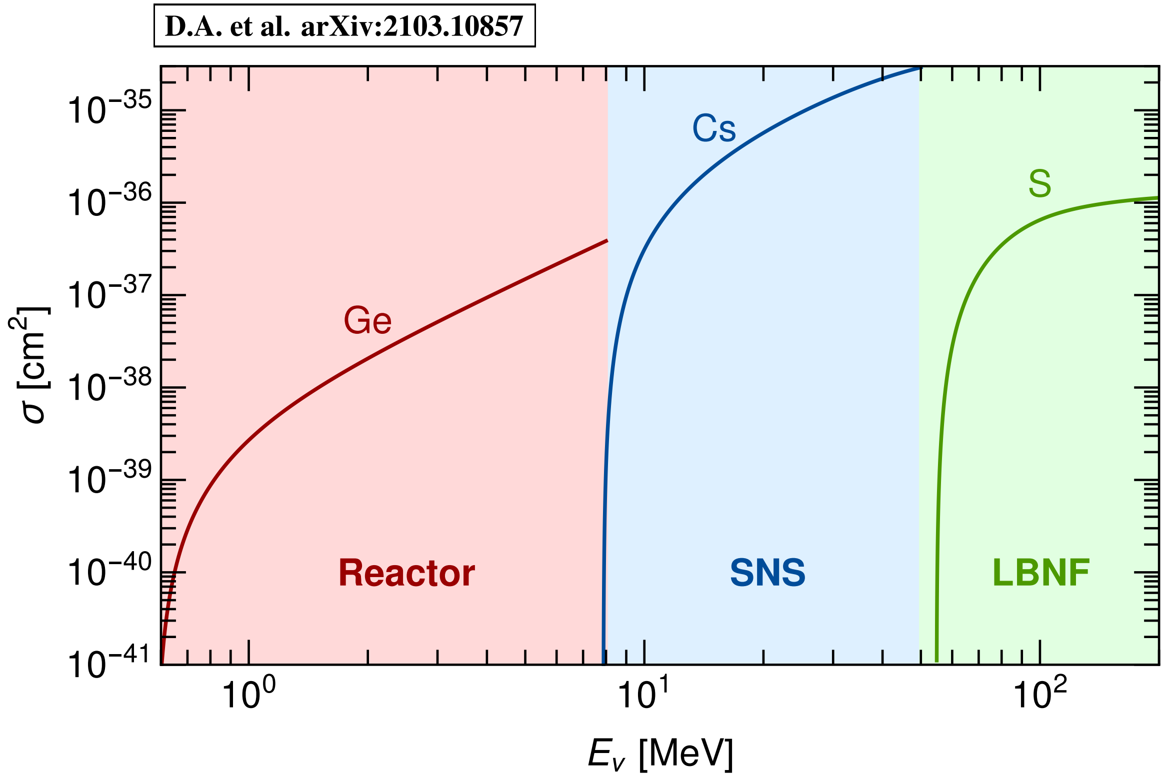
Solar+DSNB+Atm (DM detectors)



Neutrino sources and CEvNS “regimes”

Decay-in-flight neutrinos sources can as well be used

NuMI and LBNF

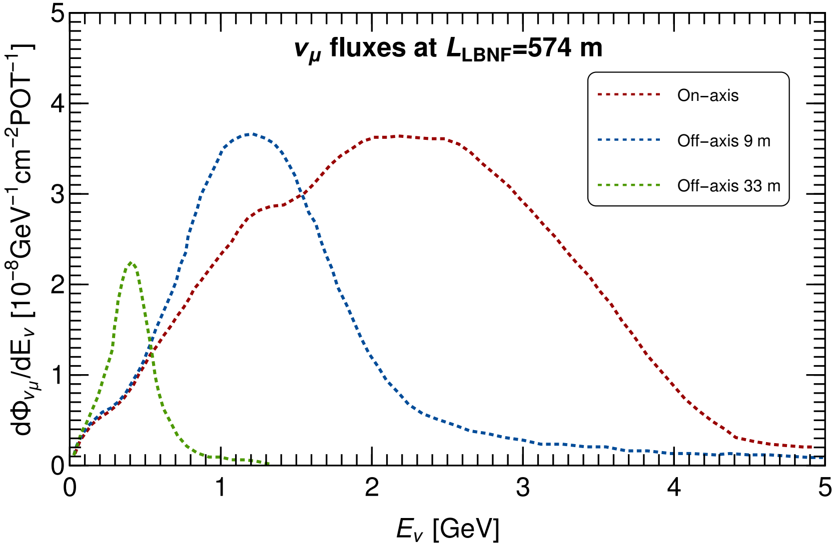


Entering the “high-energy” window requires a substantial amount of ν’s in the low-enery tail

LBNF provides that!

LBNF neutrino beamline low-energy tail

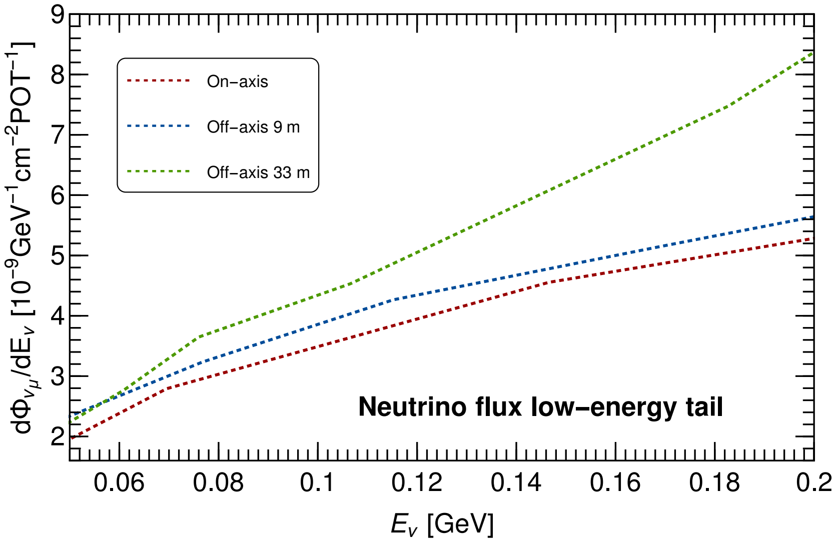
arXiv:2002.03005



Full spectrum $\Rightarrow n_\nu \simeq 10^{14}$/year/cm^2

Available e.g for $\nu - e$ scattering

arXiv:2002.03005



Low-energy tail: $n_\nu \simeq 10^{12}$/year/cm^2

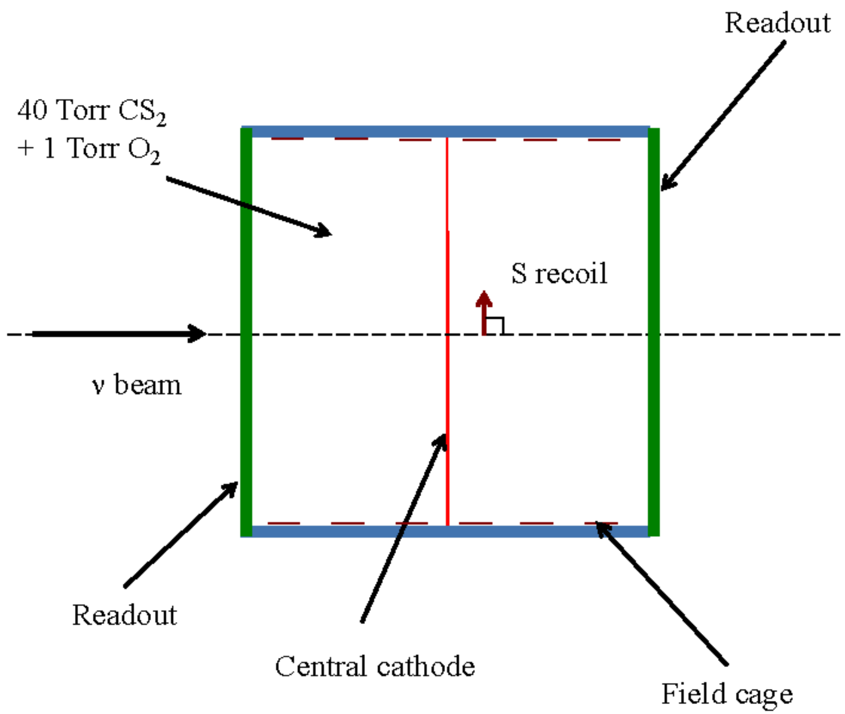
$\sigma_{\text{CEvNS}} \sim N^2$

Sizable number of events!

νBDX-DRIFT: Basics

➪ Directional low pressure TPC detector

➪ Operates with CS_2 (other gases possible CF_4, $C_8H_{20}Pb$...)

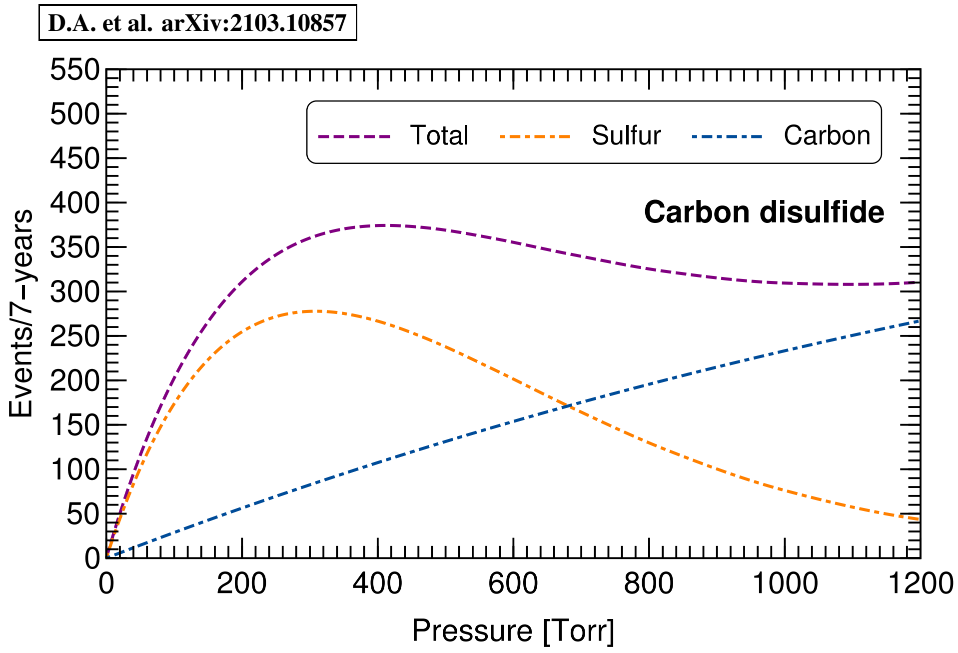


➪ NRs mainly in sulfur induce ionization

➪ CS_2^- ions used to transport the ionization to the readout planes (MWPCs)

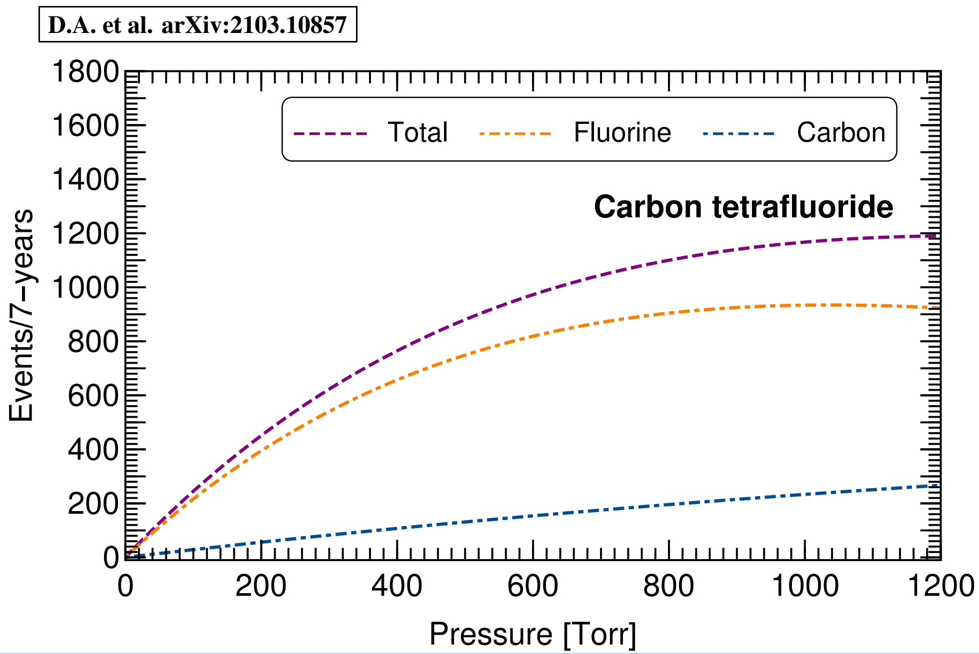
CEvNS signals

Signals in CS_2 and CF_4



Signal peaks at 400 Torr

Expected signal: 370 events



100% filled with CF_4

Expected signal: 880 events

SM and BSM studies

Measurements of R_n via CEvNS

$$F_W(q^2) = \frac{1}{Q_W}\left[Z\, g_V^p\, F_V^p(q^2) + (A-Z)\, g_V^n\, F_V^n(q^2)\right]$$

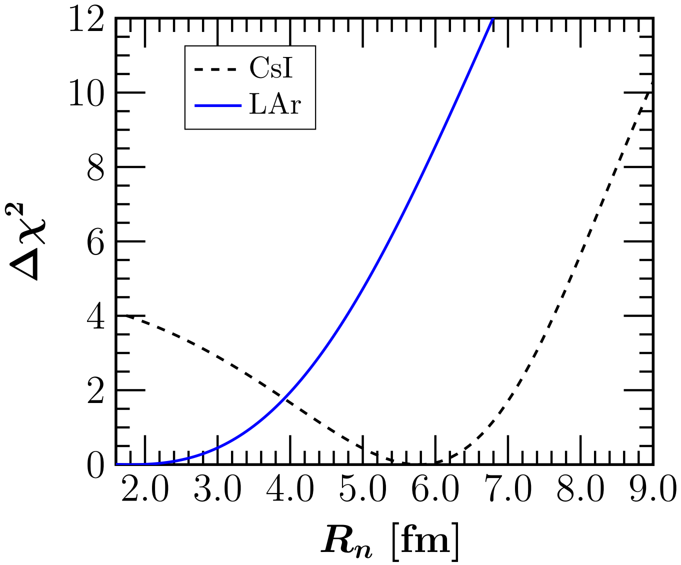
⇒ F_V^p: Depends on $R_p \Rightarrow$ known at 0.1% level ($e^- - N$ scattering)

⇒ F_V^n: Depends on $R_n \Rightarrow$ poorly known (hadron experiments)

$$N_{\text{CEvNS}} = N_{\text{CEvNS}}(R_n)$$

$$N_{\text{CEvNS}}^{\text{Exp}} \Rightarrow R_n$$

Miranda et al, JHEP 05 (2020)



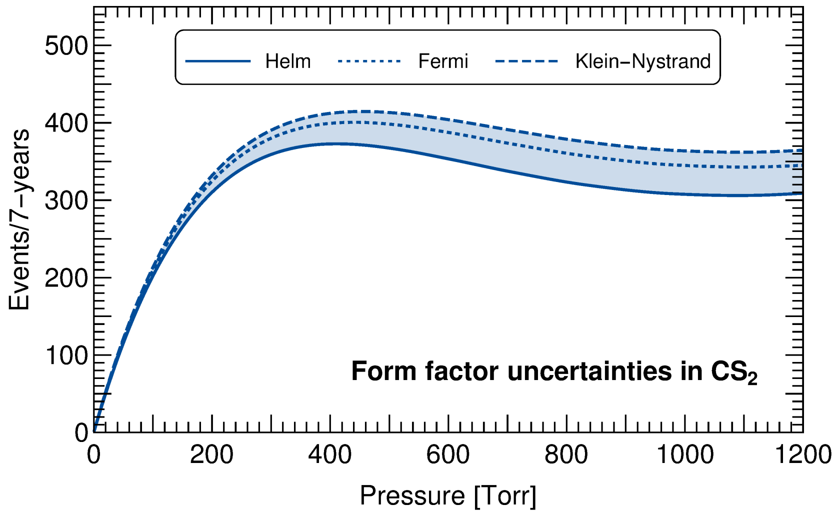
COHERENT 90% CL limits

CsI: $R_n^{\text{Cs}} = R_n^{\text{I}}$: $R_n \subset [3.4, 7.2]$ fm

Ar: $R_n < 4.33$ fm

Neutron density distributions: Results

D.A. et al. PRD, 104 (2021)

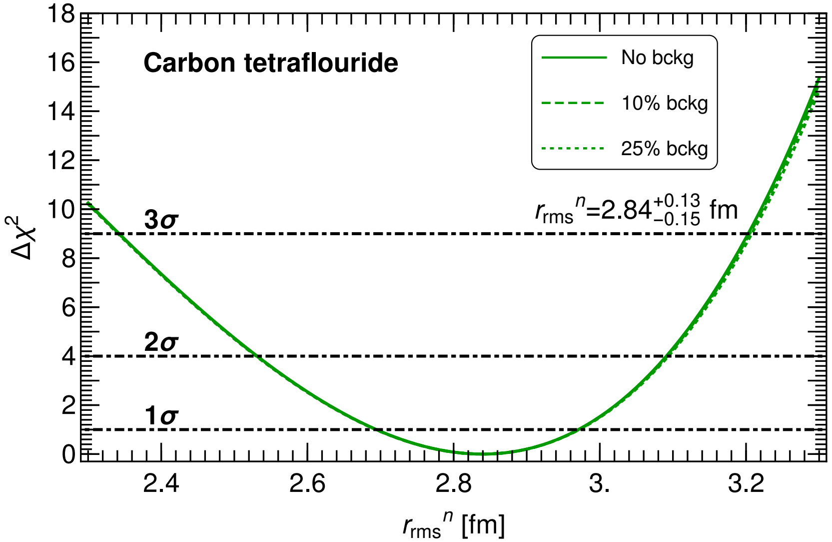


High-energy nature of the flux

⇒ Moderate dependence on the FF

⇒ Accounted for in signal uncertainty $\sim 10\%$

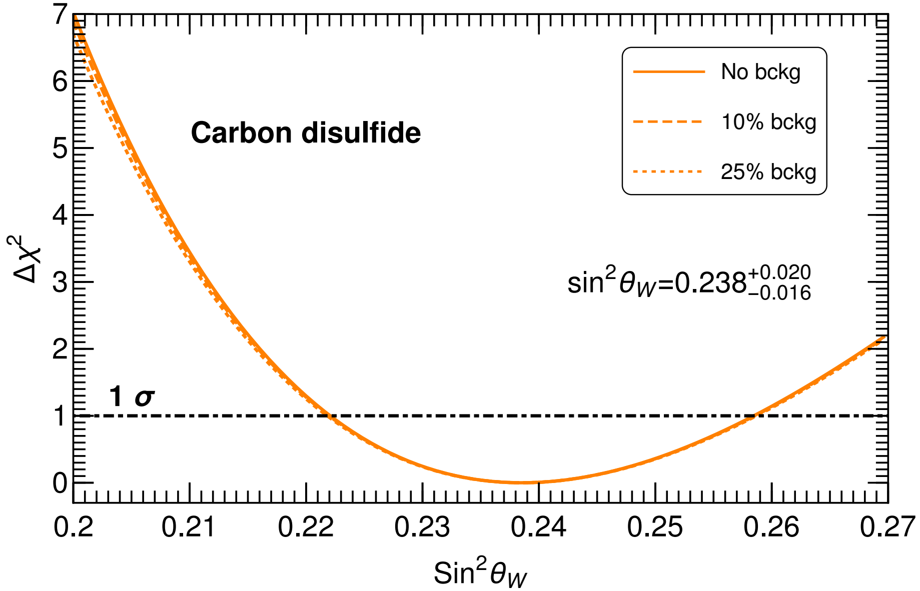
D.A. et al. PRD, 104 (2021)



Approximation: $r^n_{\rm rms}|_{\rm C} = r^n_{\rm rms}|_{\rm F}$

C and F determined with a 3% accuracy

Weak mixing angle at νBDX-DRIFT



$$\mathrm{CS}_2:\ \sin^2\theta_W = 0.238^{+0.020}_{-0.016}$$

$$\mathrm{CF}_4:\ \sin^2\theta_W = 0.238^{+0.021}_{-0.017}$$

$\sim 8\%$ level in NR channel

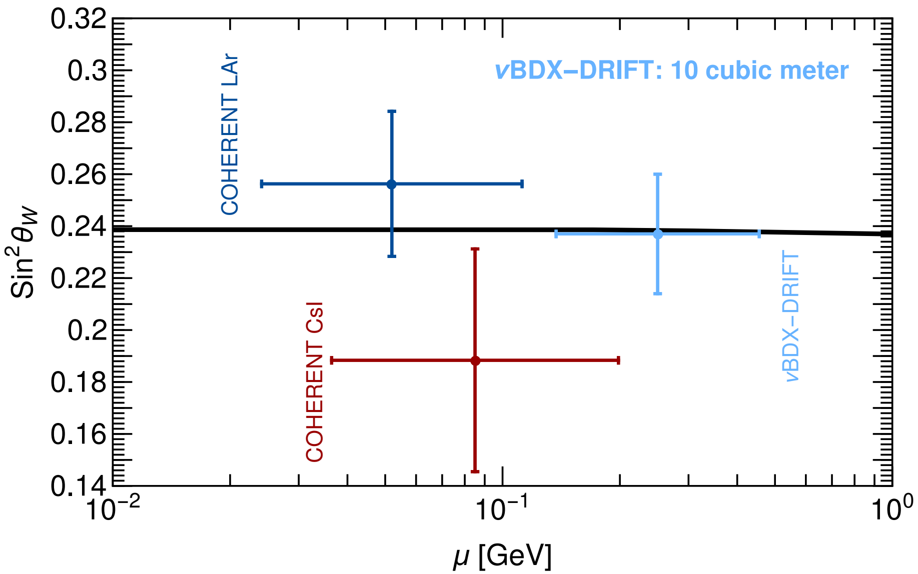
DUNE in e-channel 3%

How this compares with COHERENT?

LAr: $q \subset [35, 68]$ MeV

CsI: $q \subset [38, 78]$ MeV

νBDX-DRIFT: $q \subset [78, 397]$ MeV

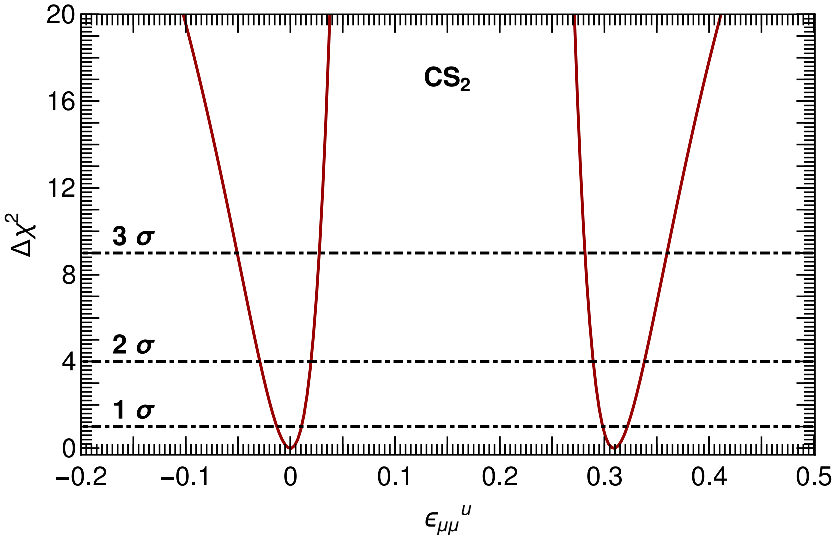


Neutrino NSI

$$\mathcal{L}_{\text{NSI}} \sim G_F \bar{\nu}_a \gamma_\mu (1-\gamma_5)\nu_b \, q\gamma^\mu \epsilon^q_{ab} q$$

Initial state flavor, ν_μ: Only $\epsilon_{\mu b}$ parameters are testable

D.A. et al, PRD 104 (2021)



Region I: Deviations are small, $\epsilon^u_{\mu\mu} \to 0$

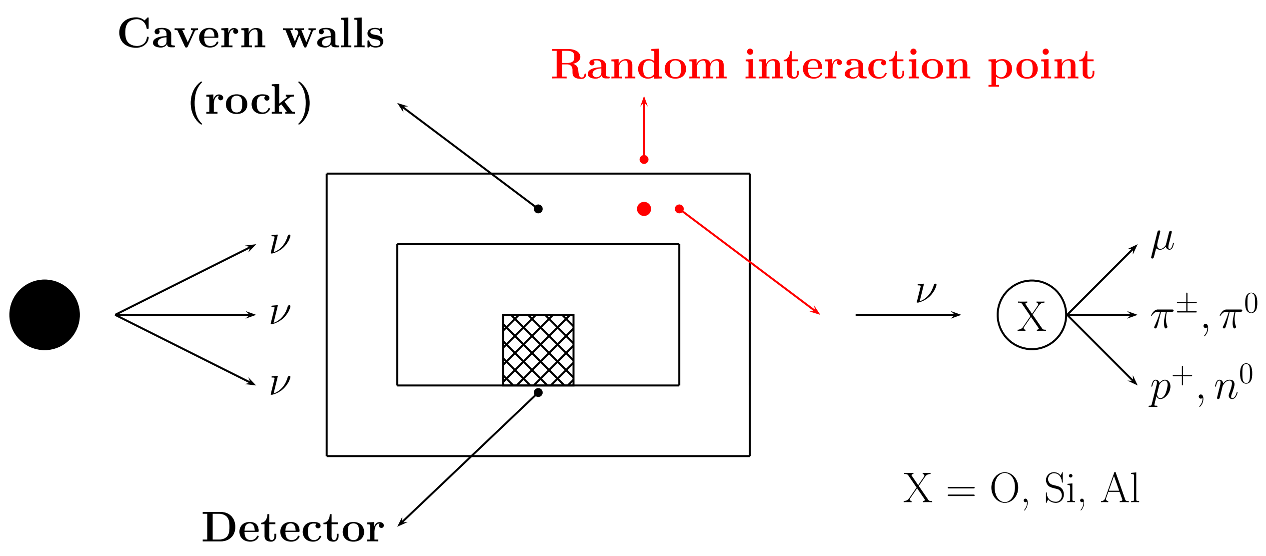
Region II: NSI exceeds SM by ~ 2

$\Rightarrow$ Destructive interference

νBDX-DRIFT CS$_2$ (7-years)		**COHERENT CsI** (1-year)	
$\epsilon^u_{\mu\mu}$	$[-0.013, 0.011] \oplus [0.30, 0.32]$	$\epsilon^u_{\mu\mu}$	$[-0.06, 0.03] \oplus [0.37, 0.44]$
$\epsilon^u_{e\mu}$	$[-0.064, 0.064]$	$\epsilon^u_{e\mu}$	$[-0.13, 0.13]$

A few comments on rock neutron bckg

Assessing rock neutrons



Stage-I

✎ Use GENIE to generate final-state particles energy spectra

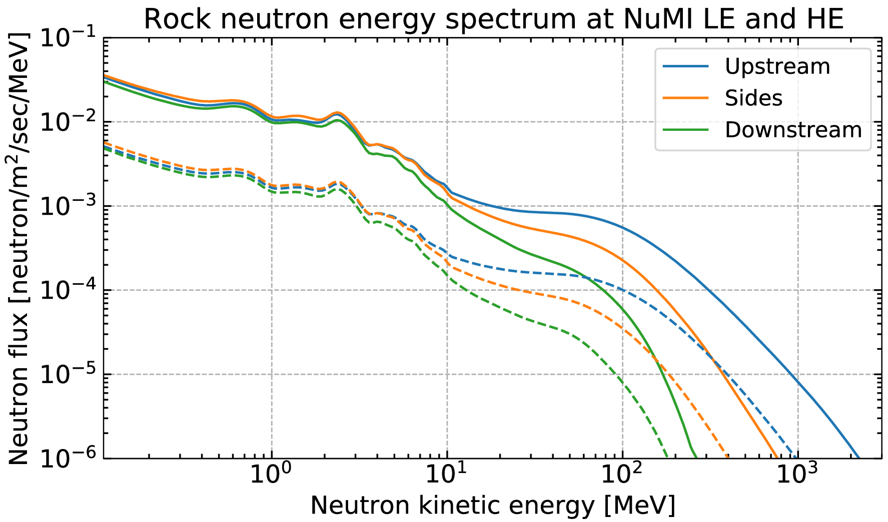
✎ Sample (randomly) (x, y, z) and propagate with the aid of GEANT4 $\Rightarrow n^0$ from the walls.

Stage-II

✎ Fire n^0 from the wall and use GEANT4 to record energy deposited in in veto and fiducial volume

Neutron spectra

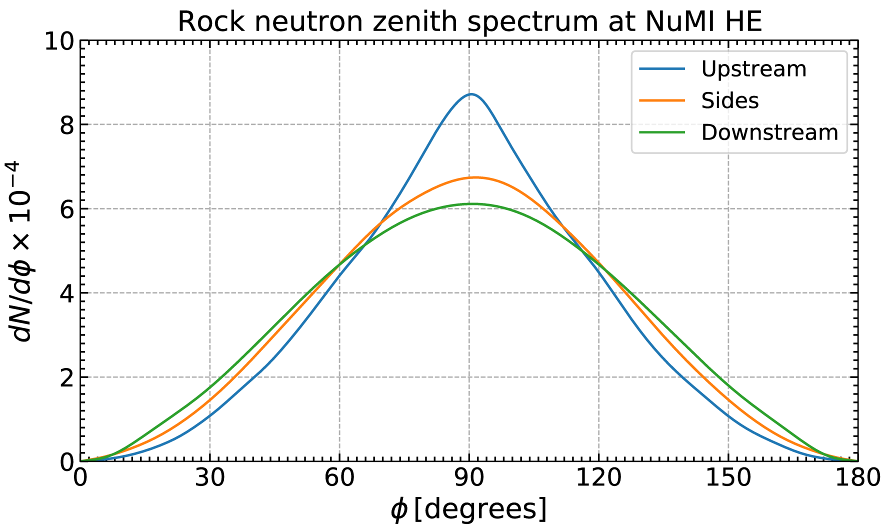
D.A.S. et al. arXiv:2210.08612



Calculation done for two NuMI modes:

Low-Energy and High-Energy

D.A.S. et al. arXiv:2210.08612

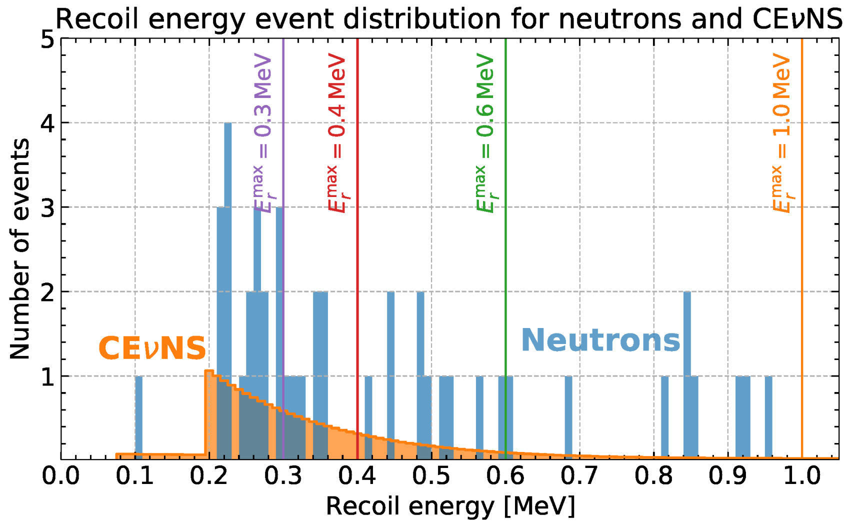


Neutrons (tend to) pile up

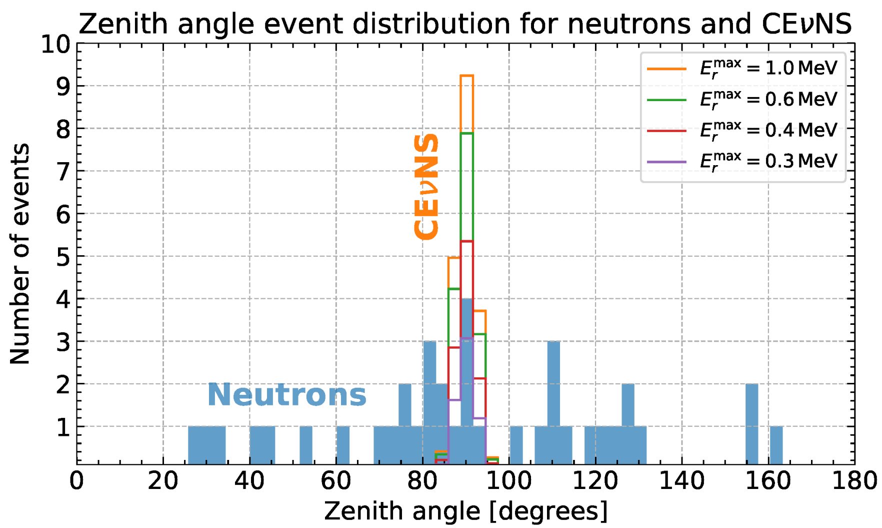
along the direction of the beam

Rock neutron bckg vs signal

D.A.S. et al. arXiv:2210.08612



D.A.S. et al. arXiv:2210.08612



NuMI Low Energy (LE) mode

Exposure $10\,m^3$ – year

Events pile up at 90°

Signal-to-noise ratio: 2.5

Final remarks

Conclusions

✍ νBDX-DRIFT combined with a high-energy neutrino beam (e.g. LBNF) is suitable for CEvNS measurements in CS_2, CF_4, $C_8H_{20}Pb$...

✍ Rock neutron background is likely to be the most challenging background
Directionality allows background rejection

✍ Offers a rich neutrino program, complementary to other CEvNS related agendas: ν-cleus, CONUS, CONNIE, COHERENT (SNS)...

✍ SM measurements include: Weak mixing angle at $\langle Q \rangle \simeq 0.1$ GeV
neutron density distributions of C, F, S, Pb with sensitivities of order 3-8%

✍ BSM searches include: Neutrino NSI, NGI and light vector and scalar mediators
Sensitivities for NSI: $\mathcal{O} \sim 10^{-2}$ couplings can be tested

✍ Directional signatures of LDM

Thanks!