Neutrino and light dark matter physics with directional detectors

Diego Aristizabal

USM

νBDX-DRIFT collaboration:

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Why directionality

● Why directionality
Why Coherent Elastic ν-nucleus Scattering (CEvNS)?
CEvNS: Cross section, environments and measurements
CEvNS with LBNF and a directional detector
Neutron backgrounds and directionality
LDM (very preliminary results)
Final remarks

Detectors used in DM direct searches or CEvNS measurements rely mainly in energy deposition measurements

Directionality adds a new observable!

- ⇨ Measure CEvNS in targets not yet used at energies not yet explored
- ⇨ Measurements with higher background discrimination
- ⇨ Study up-scattering processes ⇒ Provides info on nature of up-scattered d.o.f
- ⇨ Analysis of $2 \to 3$ processes with invisible final state ⇒ Hard to identify using RS alone
- ⇨ Searches for LDM produced in e.g. neutral meson decays with an extra observable
- ⇨ Identification of the DM spin through angular distribution measurements

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Why Coherent Elastic ν-nucleus Scattering (CEvNS)?
- Neutrino processes at different energy scales
- Intermediate regime
- A few comments on theoretical uncertainties
- Low-energy regime

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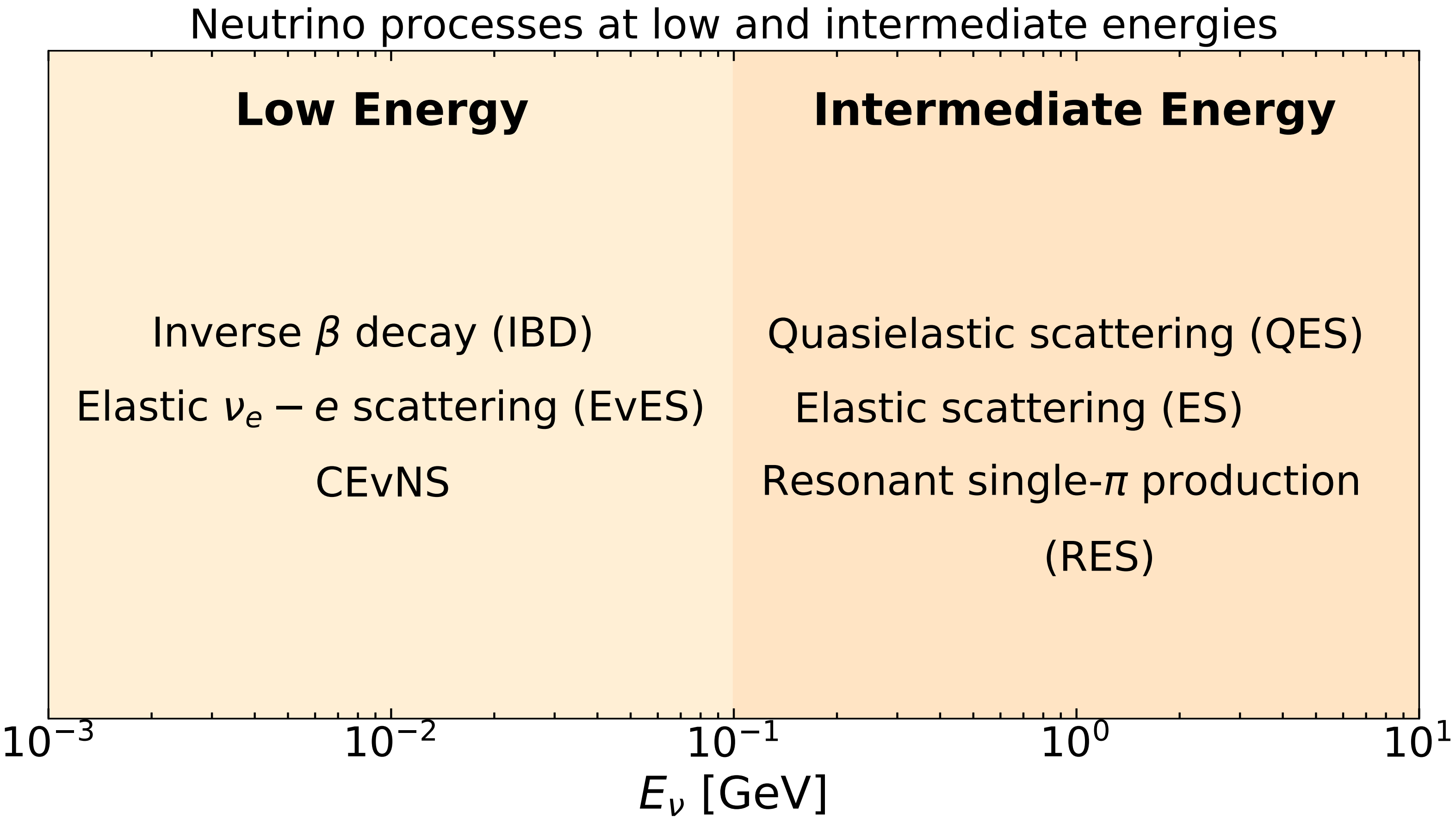
Neutrino processes at different energy scales



Neutrino processes at low and intermediate energies

Low Energy

Inverse β decay (IBD)

Elastic $\nu_e - e$ scattering (EvES)

CEvNS

Intermediate Energy

Quasielastic scattering (QES)

Elastic scattering (ES)

Resonant single-π production (RES)

Intermediate regime

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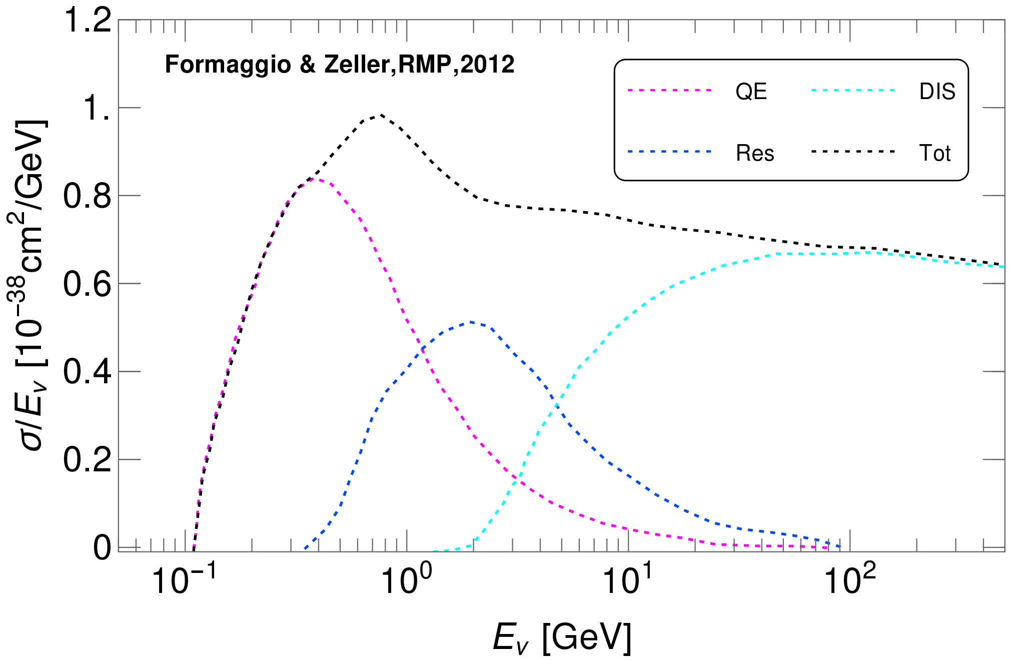
QES (CC)	ES (NC)	RES (NC & CC)
$\nu_\mu + n \to \mu^- + p$	$\nu + p \to \nu + p \quad \overline{\nu} + p \to \overline{\nu} + p$	$\nu_\mu N \to \mu^- N^* \to \mu^- \pi N'$
$\overline{\nu}_\mu + p \to \mu^+ + n$	$\nu + n \to \nu + n \quad \overline{\nu} + n \to \overline{\nu} + n$	$\nu_\mu N \to \nu_\mu N^* \to \nu_\mu \pi N'$



QES:	MINERvA, 2013 (FNAL)
	MINERvA, 2020
ES:	MiniBooNE, 2010 (FNAL)
RES:	K2K, 2008 (JPARC)
	T2K, 2017
	MINERvA, 2017

Theoretically calculations are challenging
Theoretical uncertainties are large!

A few comments on theoretical uncertainties

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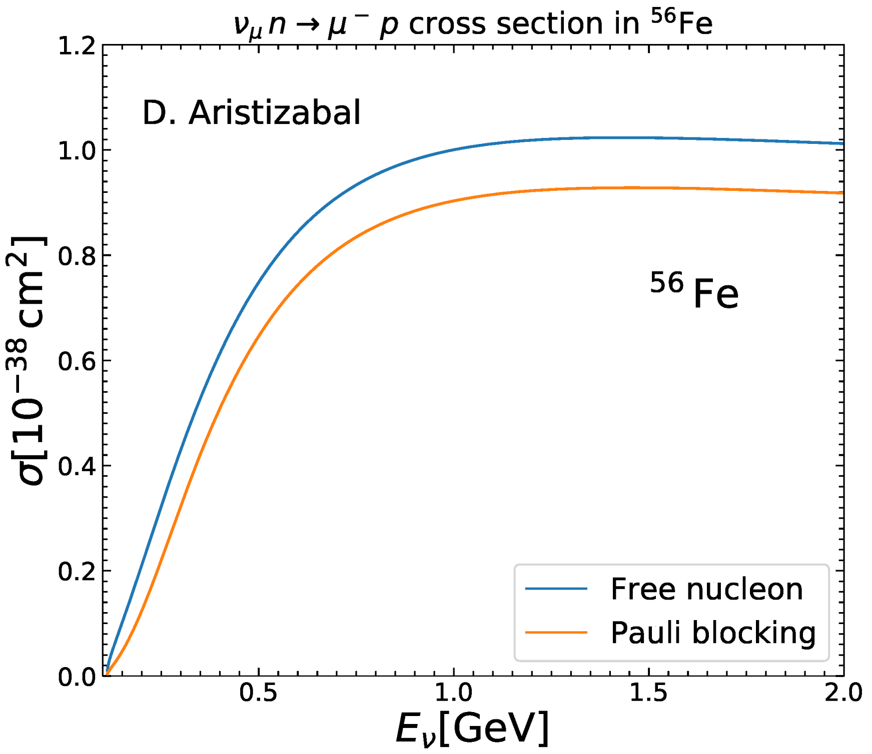
Dominant effects

Pauli blocking: Final-state fermion states must be assured an unoccupied quantum state.

Fermi motion: Nucleons in the nuclear environment are not at rest.

Reinteractions: The recoiling nucleon can reinteract in the nuclear medium



Environmental effects are $\sim 30\% - 20\%$

Nuclear effects are relevant

Effects in MC generators:

`GENNIE` & `NuWro` Differences $\sim 10\%$

Low-energy regime

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Inverse beta decay (IBD)

$$\boxed{\overline{\nu}_e + p \to e^+ + n}$$

Used in reactor neutrino detection. Daya Bay, 2015

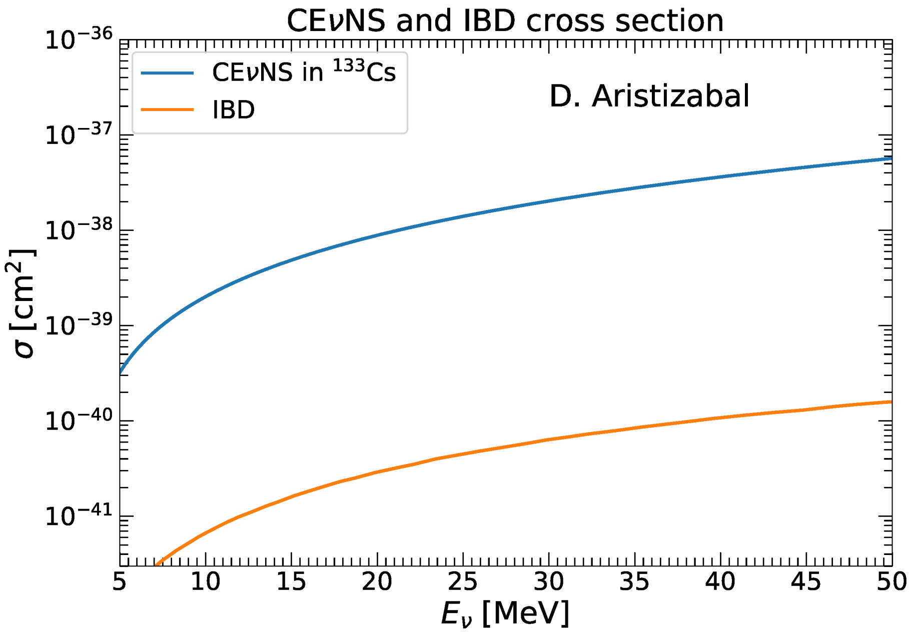
Uncertainties of $\sim 1\%$ (τ_n)

CEvNS

$$\boxed{\nu + (A,Z) \to \nu + (A,Z)}$$

Measured at the SNS, 2017 (first ever)

Uncertainties of $\sim 1-5\%$ (rms of n^0 distribution)



Environmental effects are absent

Nuclear effects are subdominant

Clean processes!

In neutrino standards

CEvNS cross section is “huge”

- Why directionality

Why Coherent Elastic ν-nucleus Scattering (CEvNS)?

CEvNS: Cross section, environments and measurements

- CEνNS cross section
- CEvNS environments
- Neutrino sources and CEvNS "regimes"
- Ongoing projects worldwide

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CEνNS cross section

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

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

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

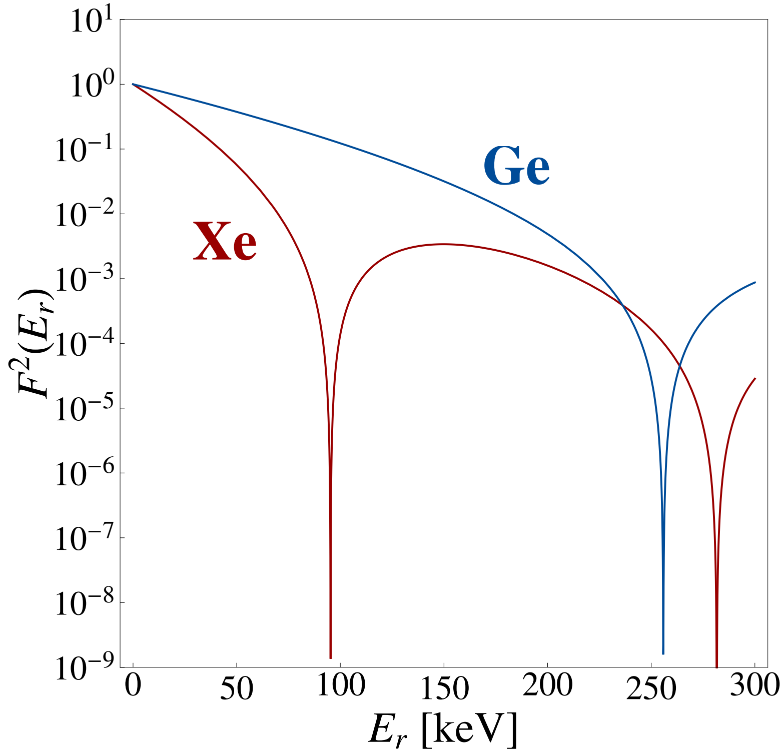
$$E_\nu \lesssim 200\ \text{MeV}$$

Freedman, 1974; Drukier & Stodolsky, 1984

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

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

Helm, 1956



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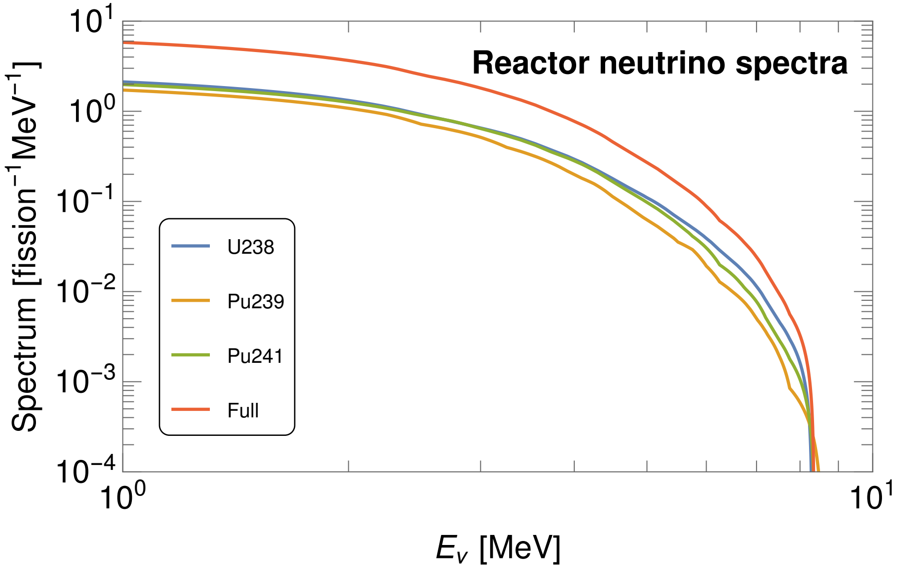
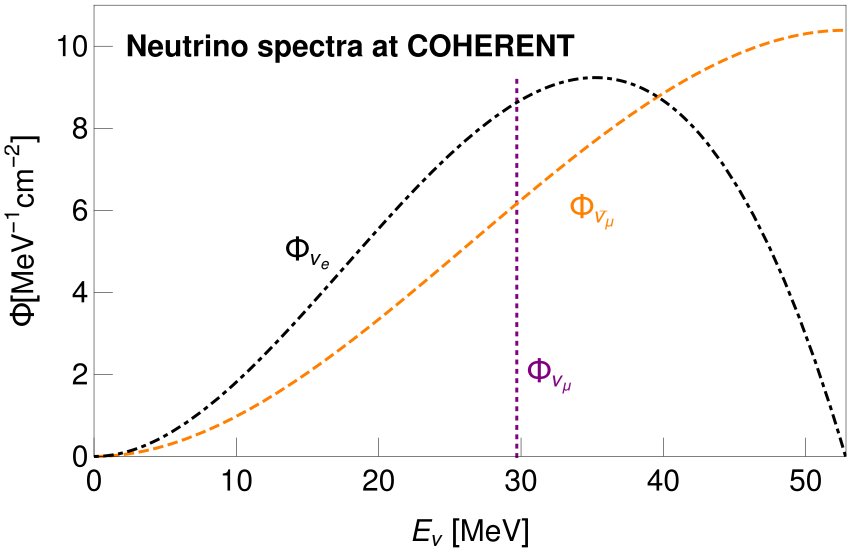
CEvNS environments

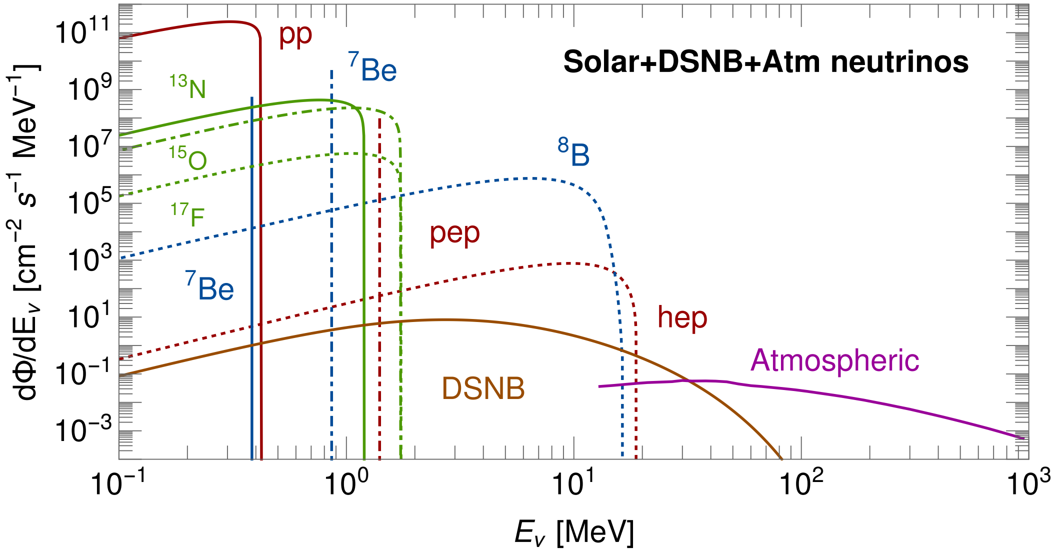
Reactor (CONUS, NUCLEUS, RICOCHET...)



Fixed target neutrinos (COHERENT)



Solar+DSNB+Atm (DM detectors)



Neutrino sources and CEvNS “regimes”

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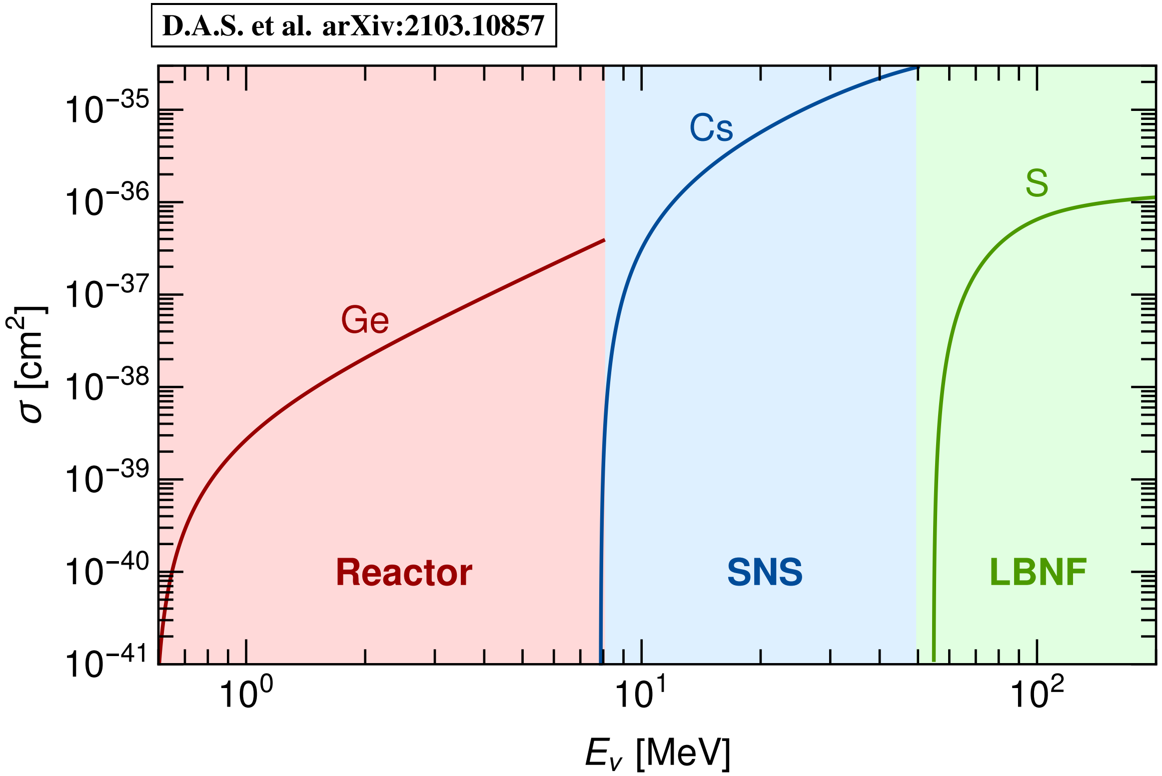
Decay-in-flight neutrinos sources can as well be used

NuMI and LBNF


D.A.S. et al. arXiv:2103.10857

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

LBNF provides that!

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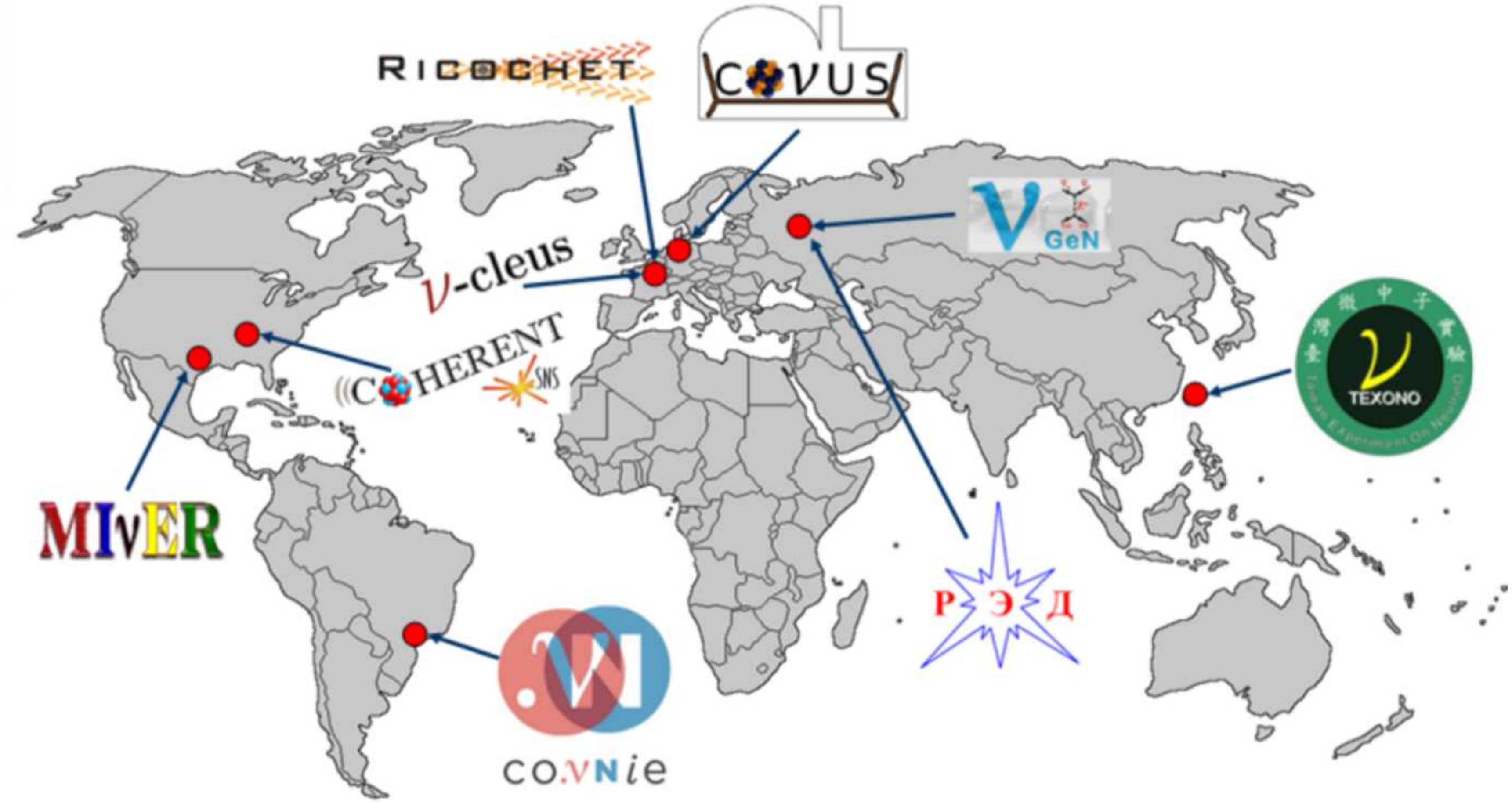
Ongoing projects worldwide



● Argentina	νIOLETA (Neutrino Interaction Observation with a Low Energy Threshold Array)
● Mexico	SBC (Scintillating Bubble Chamber)
● Belgium	SoLid (Search for oscillations with Lithium 6 detector)
● South Korea	NEON (Neutrino Elastic-scattering Observation experiment with NaI[Tl] crystal)

- Why directionality

Why Coherent Elastic ν-nucleus Scattering (CEvNS)?

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CEvNS with LBNF and a directional detector

- νBDX-DRIFT: Basics
- Signals in CS_2 and CF_4
- Measurements of R_n via CEvNS
- Neutron density distributions: Results
- Neutrino Nonstandard Interactions (NSI)

Neutron backgrounds and directionality

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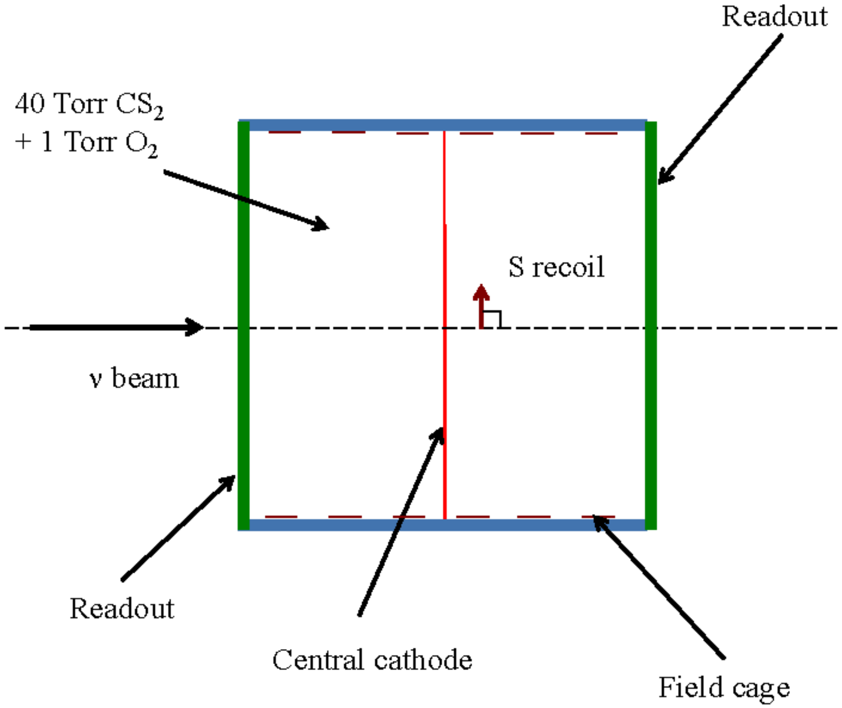
νBDX-DRIFT: Basics

- 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)

Signals in CS_2 and CF_4

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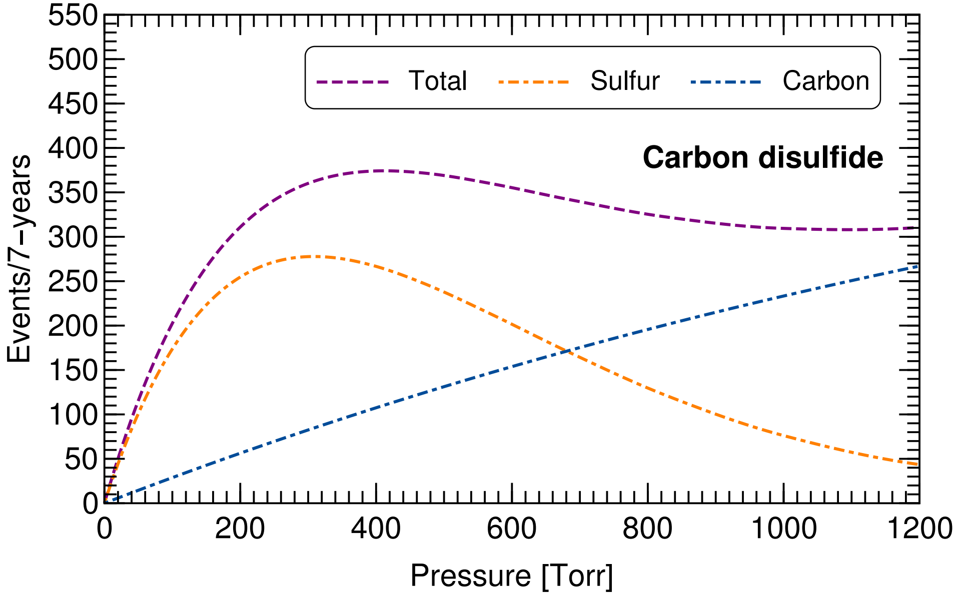
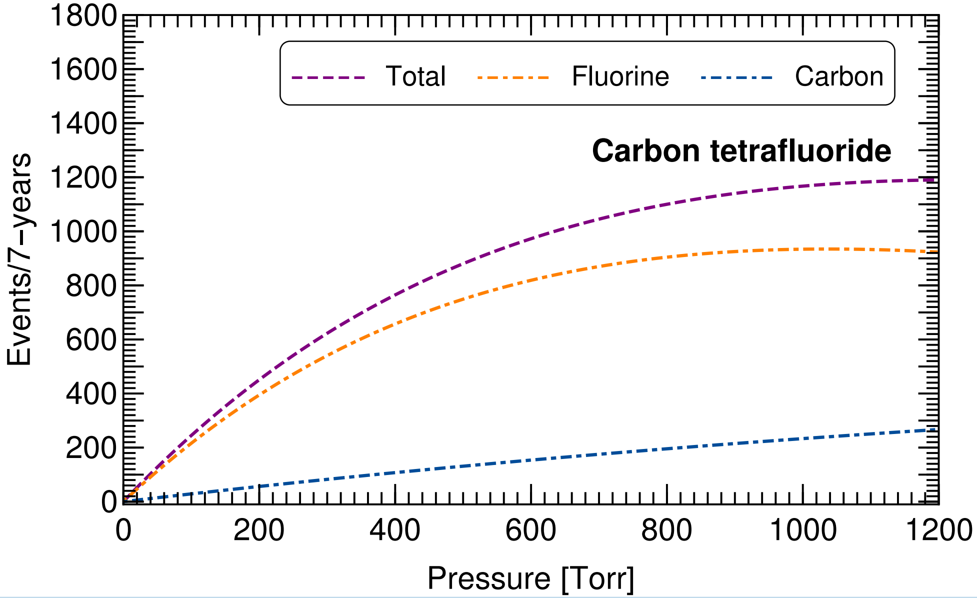
D.A.S. et al. arXiv:2103.10857



Signal peaks at 400 Torr

Expected signal: 370 events

D.A.S. et al. arXiv:2103.10857



100% filled with CF_4

Expected signal: 880 events

Measurements of R_n via CEvNS

- Why directionality

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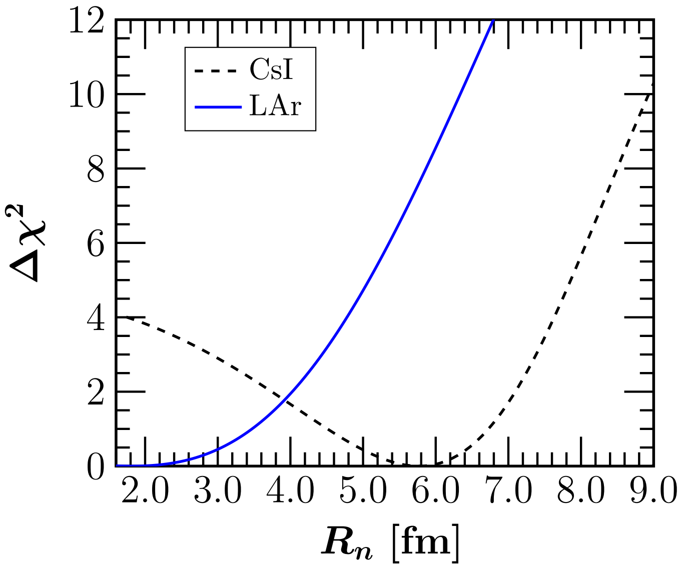
$$\boxed{F_W(q^2) = \frac{1}{Q_W}\left[Z\, g_V^p\, F_V^p(q^2) + (A-Z)\, g_V^n\, F_V^n(q^2)\right]}$$

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

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

$$\boxed{N_{\text{CEvNS}} = N_{\text{CEvNS}}(R_n)} \qquad \boxed{N_{\text{CEvNS}}^{\text{Exp}} \Rightarrow R_n}$$

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

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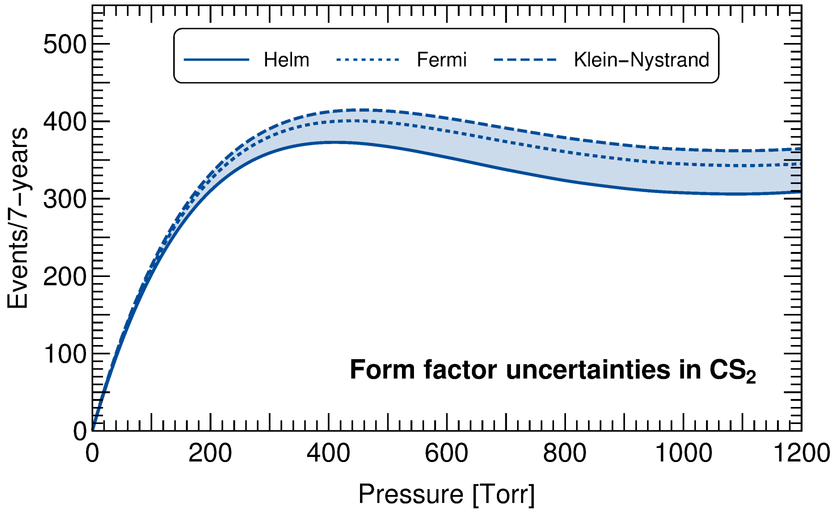
D.A.S. et al. PRD, 104 (2021)

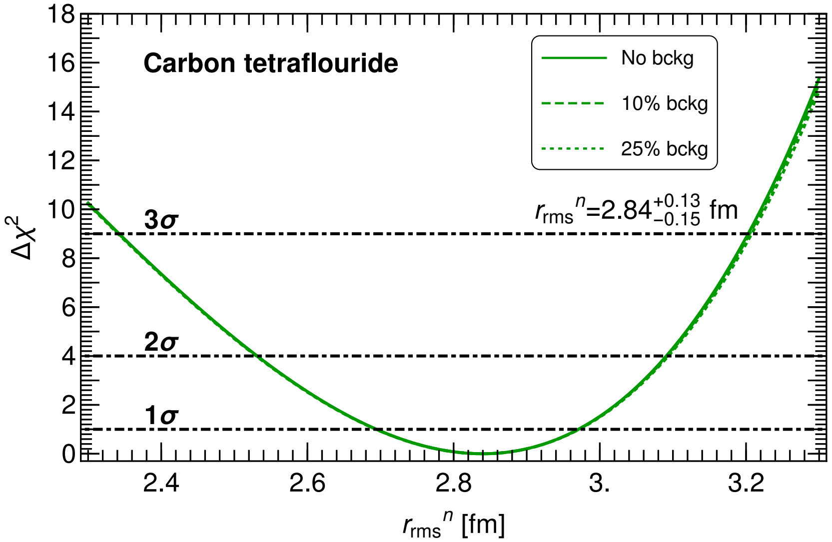


High-energy nature of the flux

⇒ Moderate dependence on the FF

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

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



Approximation: $r^n_{\text{rms}}|_C = r^n_{\text{rms}}|_F$

C and F determined with a 3% accuracy

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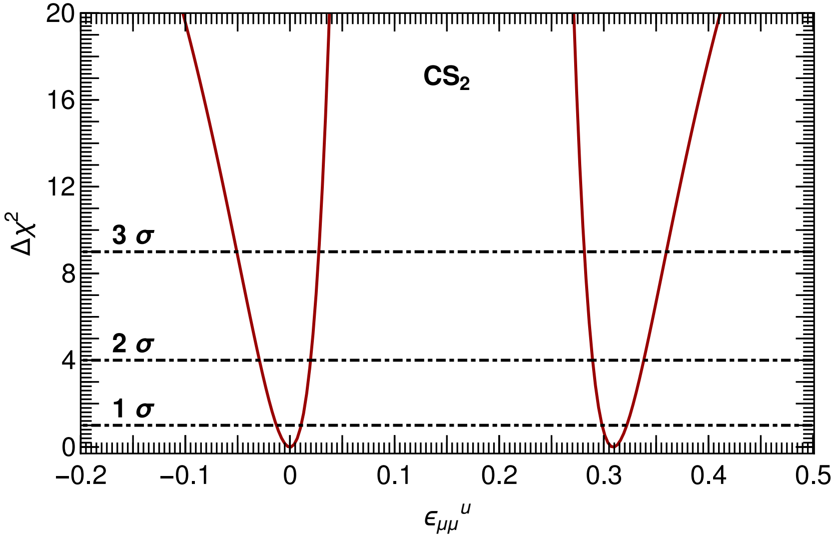
Neutrino Nonstandard Interactions (NSI)

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

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

D.A.S. 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)	
$\epsilon^u_{\mu\mu}$	$[-0.013, 0.011] \oplus [0.30, 0.32]$	$\epsilon^u_{\mu\mu}$	$[-0.06, 0.03] \oplus [0.37, 0.44]$
$\epsilon^u_{e\mu}$	$[-0.064, 0.064]$	$\epsilon^u_{e\mu}$	$[-0.13, 0.13]$

- ● Why directionality

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Neutron backgrounds and directionality
- ● Assessing rock neutrons
- ● Rock neutron bckg vs signal

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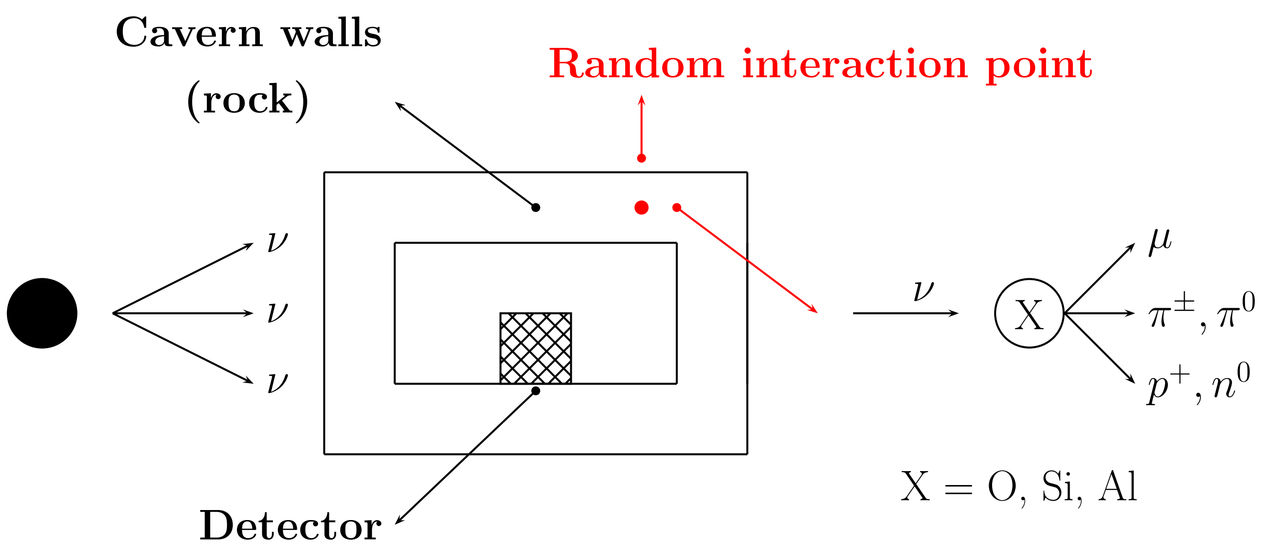
Neutron backgrounds and directionality

Assessing rock neutrons



Stage-I

✎ Use `GENIE` to generate final-state particles energy spectra

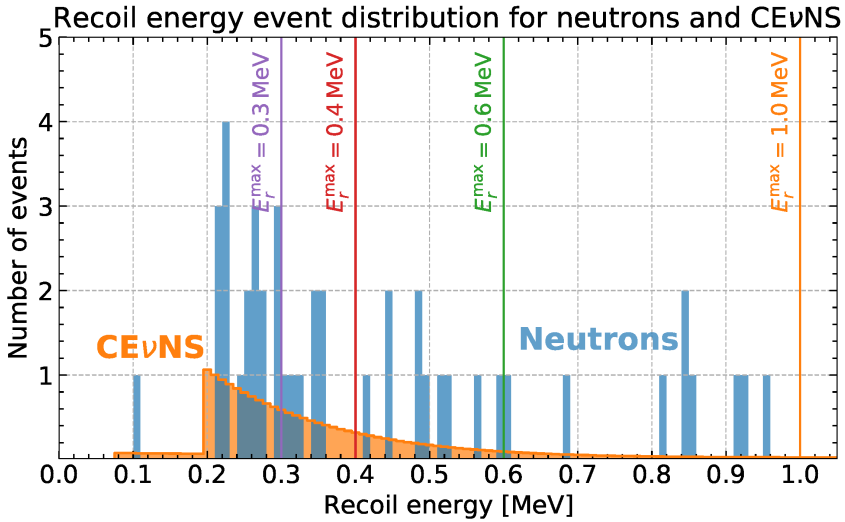
✎ Sample (randomly) (x, y, z) and propagate with the aid of `GEANT4` $\Rightarrow n^0$ from the walls.

Stage-II

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

Rock neutron bckg vs signal

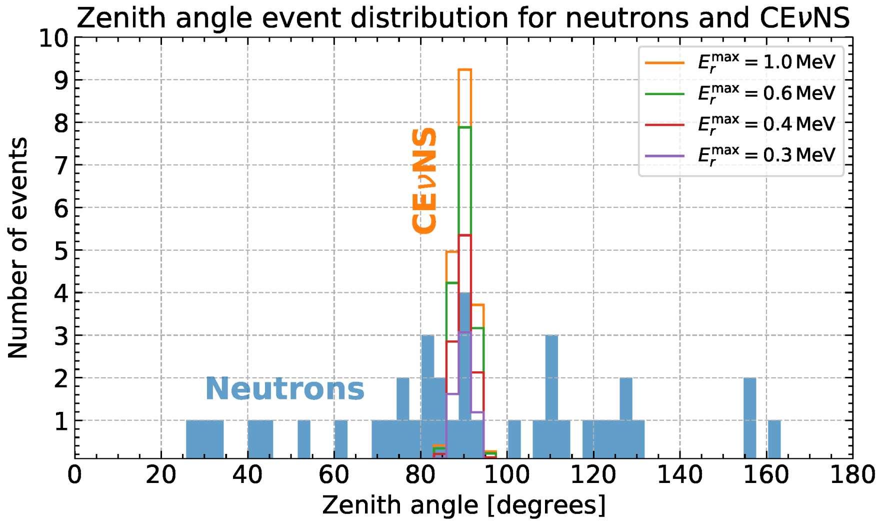
D.A.S. et al. arXiv:2209.08612



NuMI Low Energy (LE) mode

Exposure 10 m^3 – year

D.A.S. et al. arXiv:2209.08612



Events pile up at 90°

Signal-to-noise ratio: 2.5

- Why directionality

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LDM (very preliminary results)
- Production
- LDM fluxes
- π^0 flux
- Double differential BR
- Dalitz plot and on-shell/off-shell A_D^μ
- Doble differential BR in lab frame
- Technical implementation
- Fluxes at production

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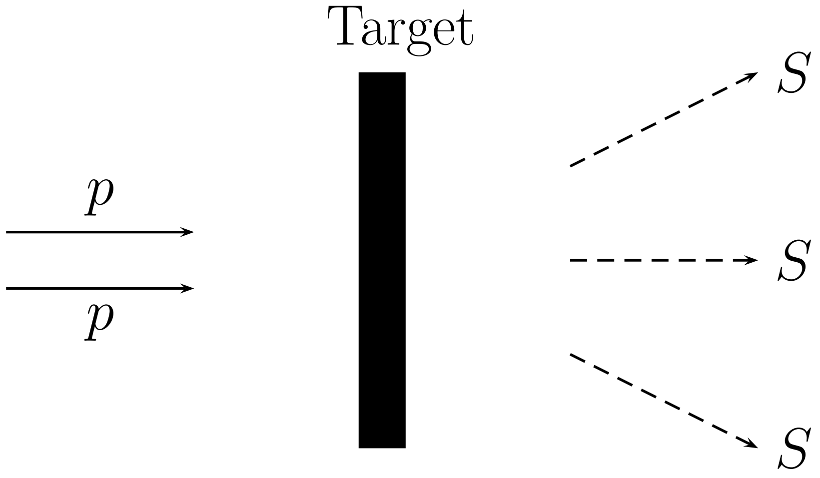
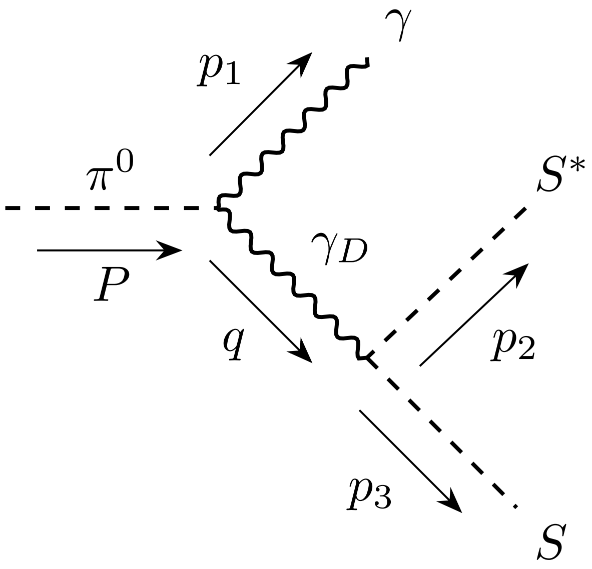
Production

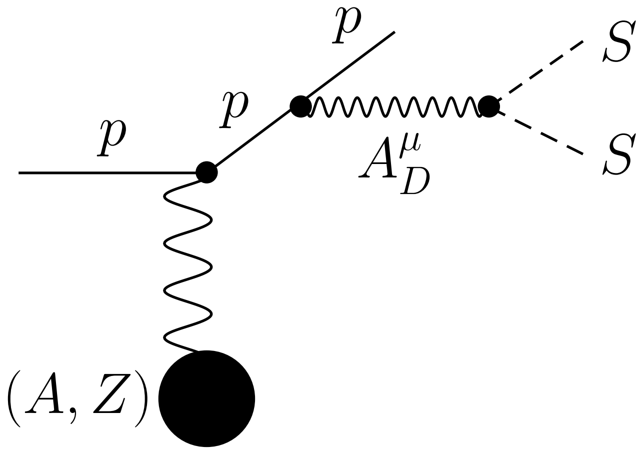
Same technology used in neutrino detection can be used for LDM searches

Personal view: Literature is plenty of analyses... But, poorly documented

Understand from “scratch” ⇒ **Write your own code!**







LDM fluxes

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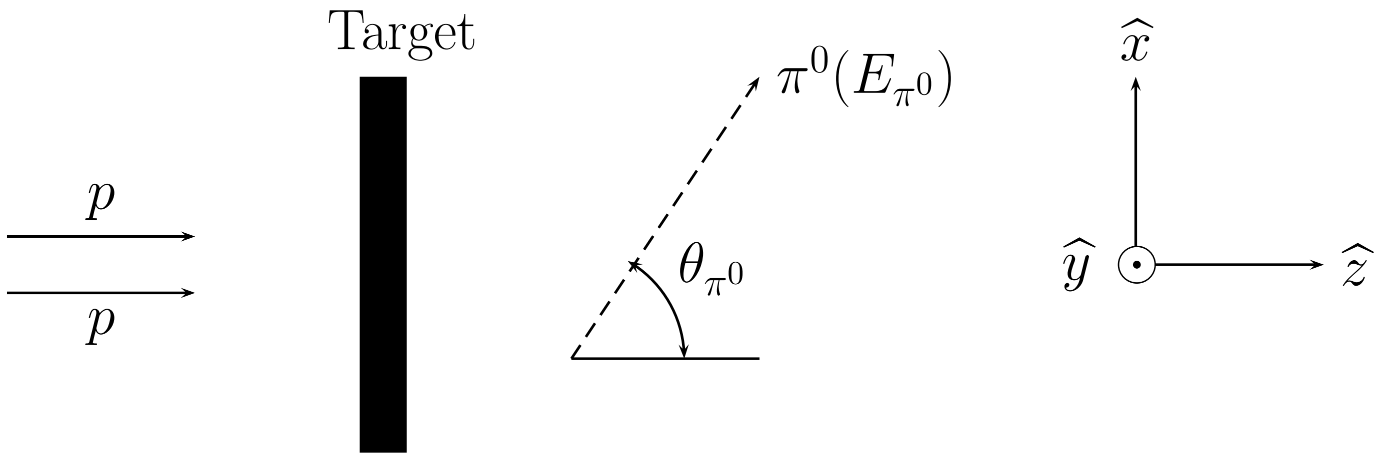
Benchmark (validate) code with existent COHERENT data/analysis

⇒ Focus in π^0 decays

A fraction of the π^0 produce an spectrum given by

$$\frac{d^2N_X}{dE_3^{\text{Lab}}\,d\cos\theta_3^{\text{Lab}}} = \int \overbrace{\frac{d^2N_{\pi^0}}{dE_{\pi^0}\,d\cos\theta_{\pi^0}}}^{\pi^0\text{flux}} \underbrace{\frac{d^2\text{Br}(\pi^0\to\gamma+X+X)}{dE_3^{\text{Lab}}\,d\cos\theta_3^{\text{Lab}}}}_{\text{Lab frame}}\, dE_{\pi^0}\,d\cos\theta_{\pi^0}$$

⇒ DM distribution is azimuth-symmetric w.r.t. proton beam ($\hat{z}$) $[s(\pi^0)=0]$



π^0 flux

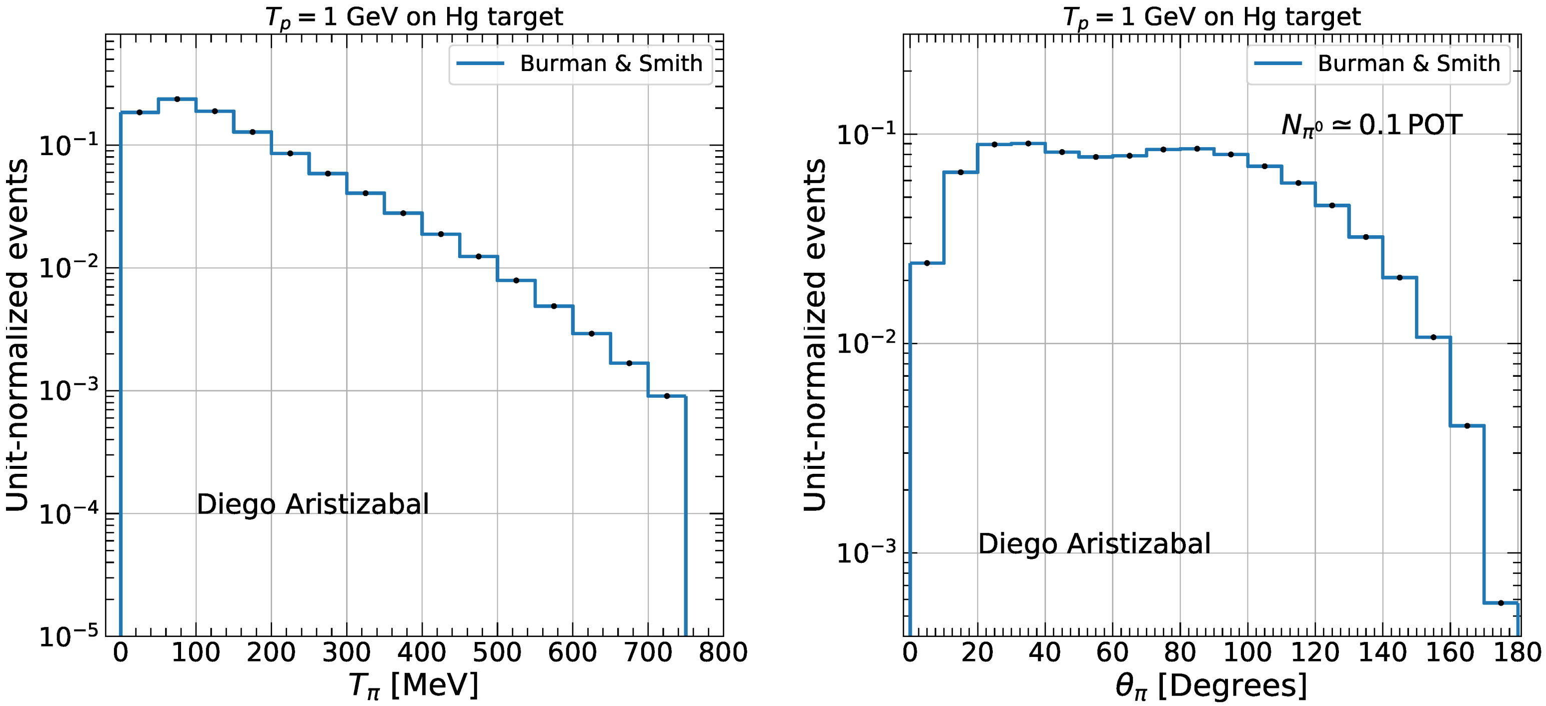
Two paths can be followed:

Ideally, run a `GEANT4` simulation

Approximation: use $\pi^\pm$ fluxes parametrizations

⇒ For $T_p \lesssim 1$ GeV: Burman and Smith parametrization for π^+ (π^- get absorbed by nuclei)

⇒ For $1\,$GeV $\lesssim T_p \lesssim 10\,$GeV: Sanford & Wang parametrization for $\pi^\pm$



Double differential BR

Analytical integration of three-body phase space in terms of invariant masses

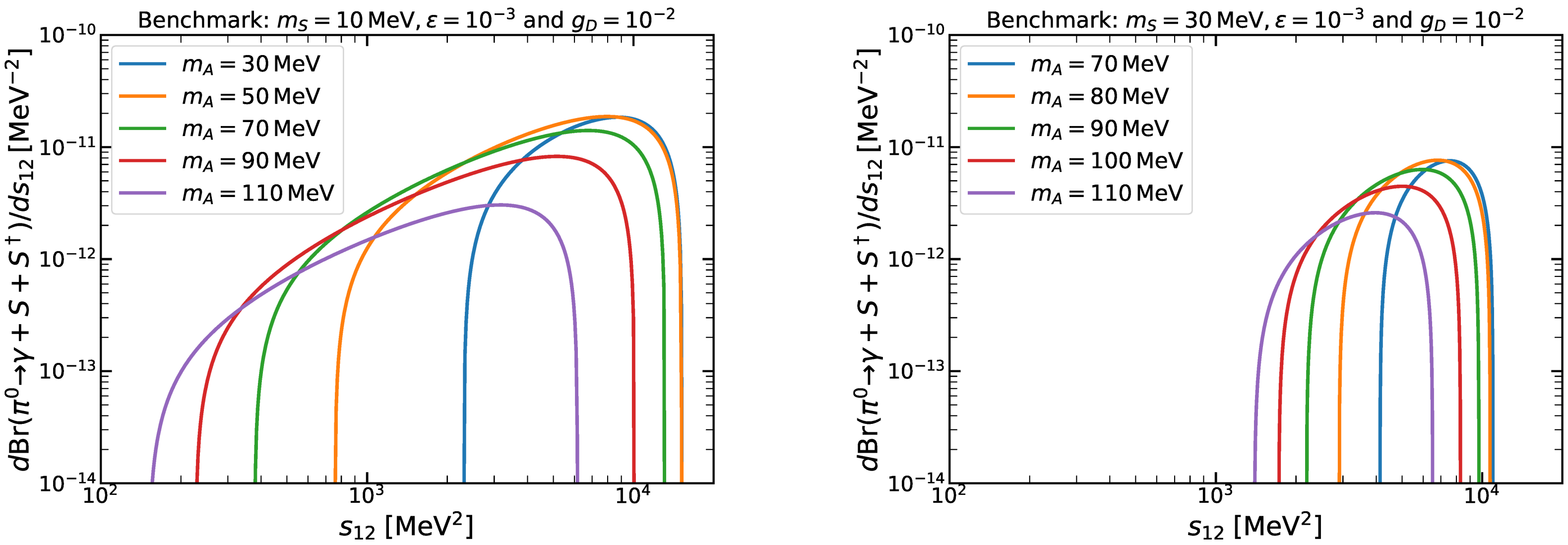
⇒ Go to the π^0 rest frame

⇒ Boost the result to the Lab frame

$$\boxed{d^2\Gamma = \frac{1}{(2\pi)^3}\frac{1}{2^5 m_\pi^3}|\mathcal{M}|^2 ds_{12}ds_{23}}$$

$$|\mathcal{M}|^2_{\text{Num}} = -m_S^2 m_\pi + s_{23}[m_\pi^2 m_S^2 + s_{12}(m_\pi^2 + m_S^2) - s_{12}^2 - m_S^4] - s_{12}s_{23}^2$$

Integration over s_{23} can be done analytically!



Dalitz plot and on-shell/off-shell A_D^μ

- Why directionality

Why Coherent Elastic ν-nucleus Scattering (CEvNS)?

CEvNS: Cross section, environments and measurements

CEvNS with LBNF and a directional detector

Neutron backgrounds and directionality

LDM (very preliminary results)
- Production
- LDM fluxes
- π^0 flux
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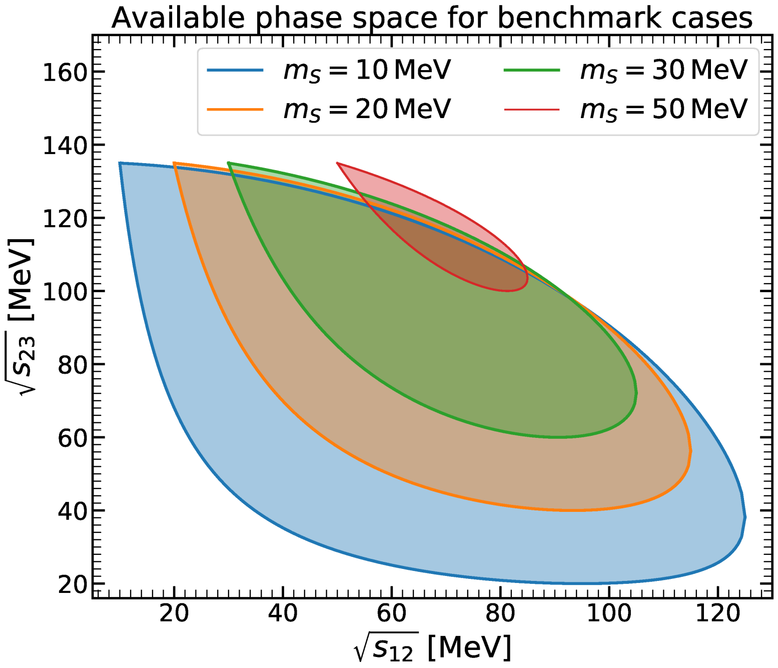
Final remarks

First check: Dalitz interpretation and on-shell/off-shell BRs

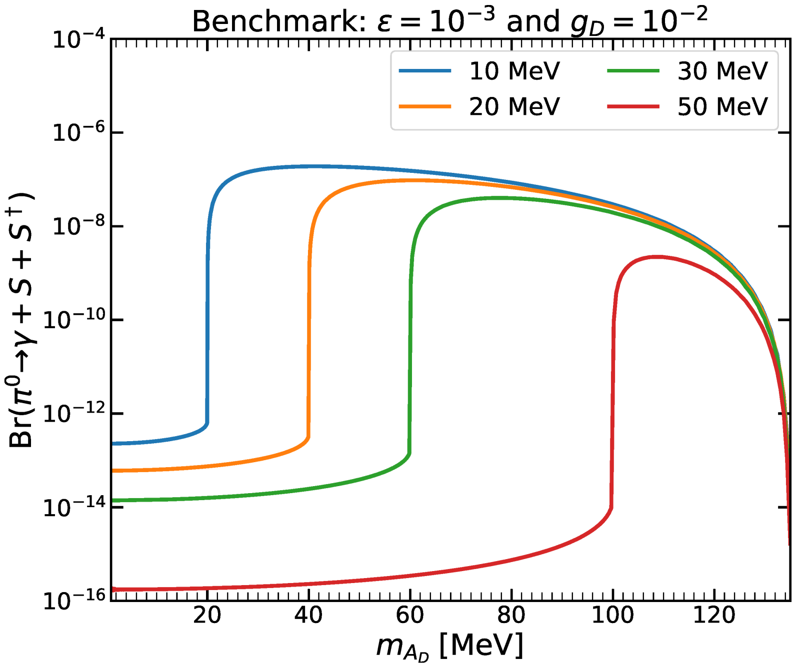


Range of s_{12} determined by

phase space area

Off-shell A_D^μ have suppressed BRs

Focus on on-shell A_D^μ!



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Doble differential BR in lab frame

π^0 rest frame

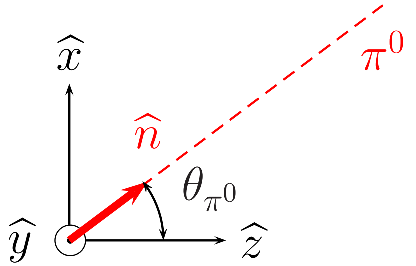
$$\boxed{s_{12} = m_\pi^2 + m_S^2 - 2m_\pi E_3^*}$$

$$\boxed{\frac{d\Gamma}{dE_3^*} = 2m_\pi \frac{d\Gamma(E_3^*)}{ds_{12}}}$$

Laboratory frame

$$\beta = \sqrt{E_\pi^2 - m_\pi^2}/E_\pi$$

$$\gamma = E_\pi/m_\pi$$



$$E_3^{\text{Lab}} = \gamma(E_3^* + p_{3x}^* + p_{3z}^*)$$

$$\tan\theta_3^{\text{Lab}} = p_{3x}^*/p_{3z}^*$$

$$\boxed{\frac{d^2\Gamma}{dE_3^{\text{Lab}}\, d\cos\theta_3^{\text{Lab}}} = 2m_\pi \frac{d\Gamma}{ds_{12}} J(E_3^{\text{Lab}}, \theta_3^{\text{Lab}}, E_\pi, \theta_\pi)}$$

Technical implementation

- Why directionality

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The parameter space dependence can be split in two independent data sets

Set 1: Kinematics parameters

$$\{E_\pi, \theta_\pi, E_3^*, \theta_3^*\}$$

Set 2: Model parameters

$$\{m_S, m_{A_D}, \epsilon, g_D\}$$

The problem is—in general—very CPU expensive

Strategy

- ⇨ Grid over set 2 and run Monte Carlo over set 1
- ⇨ For fixed set 2, generate a random uniform set 1
- ⇨ Bin E_3^{Lab} and sum at each bin over all other variables

Fluxes at production

- Why directionality

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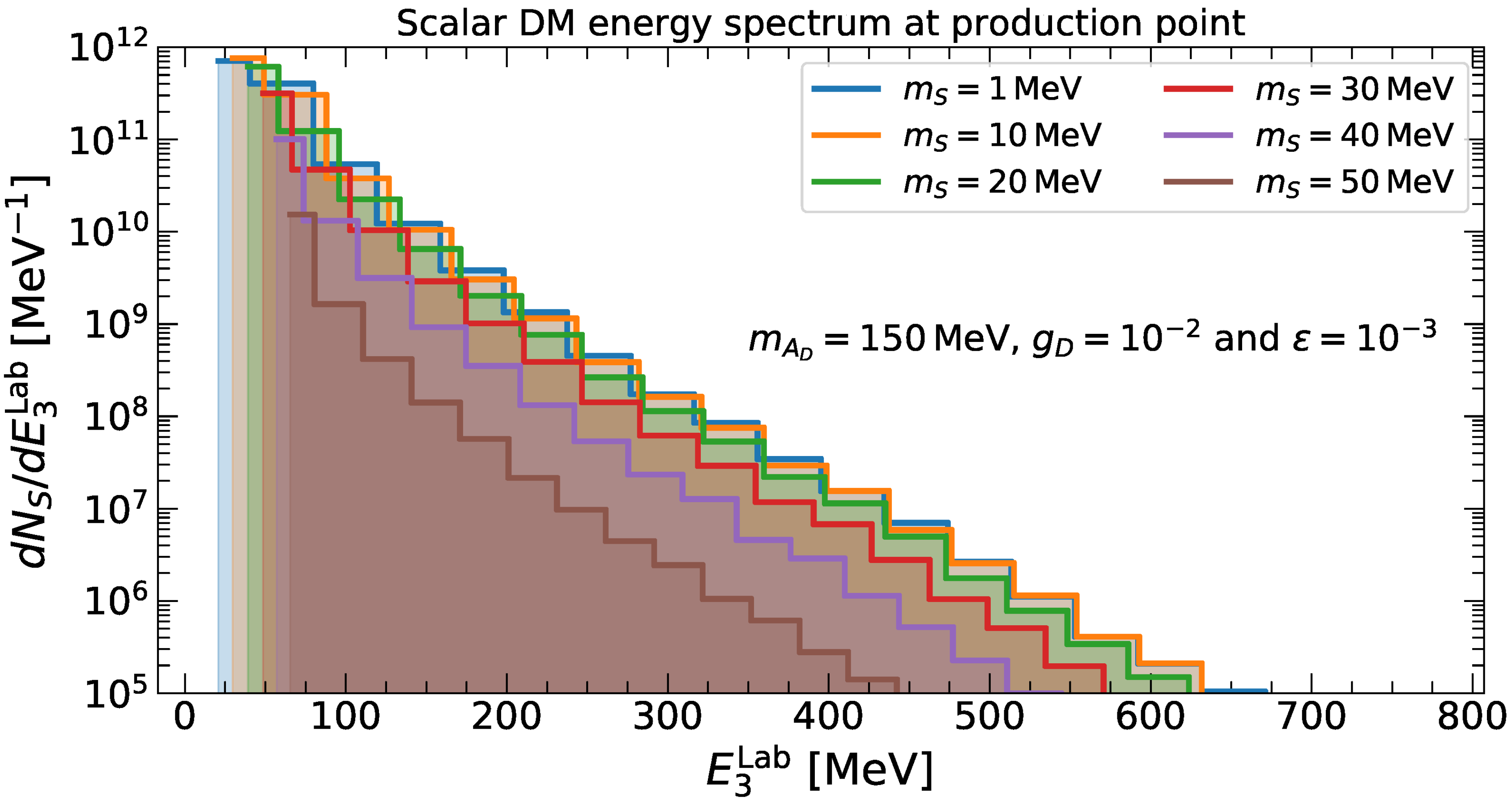

● Why directionality

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LDM (very preliminary results)

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● Conclusions

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%.
Searches for NSI and BSM physics possible

✍ Work to test feasibility for LDM searches underway
Directionality might offer a new avenue not yet explored