Neutrino theory overview

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A few theoretical aspects of neutrino phenomenology

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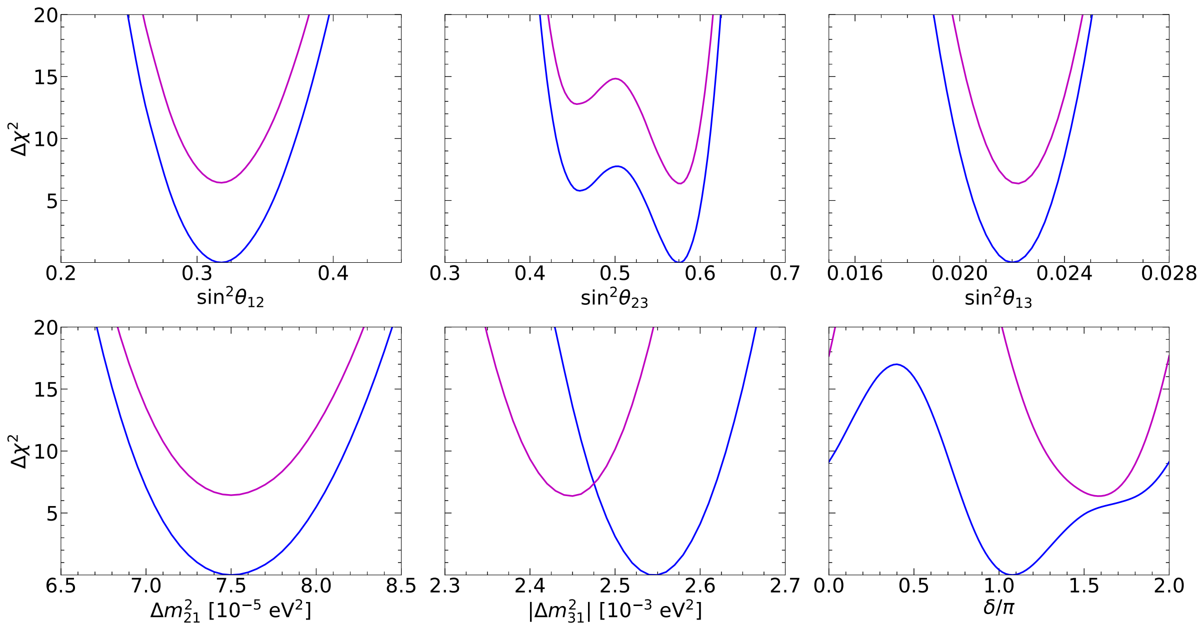
What we know so far

Neutrino masses

Water Cherenkov, reactor, long-baseline experiments (SK, T2K, DayaBay, KamLAND, NOνA...) provide a wealth of data

Forero, Tortola, Valle et al. (2006.11237)



Other constraints

Neutrino-less-double-β decay

EXO (2019), GERDA (2020)

$\langle m_\nu \rangle \lesssim (79 - 180)$ meV

Kinematic experiments

Mainz, Troitsk, KATRIN (2022)

$m_\beta < 0.8$ eV

Cosmological limits

PLANCK (2018) lensing+BAO

$\sum_i m_{\nu_i} < 0.12$ eV

See talk by Forero

... What is left?

An incomplete list...

⇒ Is **CP** a good symmetry of the lepton sector? If not, δ?
NOνA, DUNE, Hyper-K

⇒ Do neutrinos follow a NH or IH mass spectrum?
DUNE, JUNO and Hyper-K

⇒ Are neutrinos **Dirac** or **Majorana** fermions?

⇒ If **Majorana**, at what scale is L broken?
Origin of neutrino masses
LEGEND (^{76}Ge), **DARWIN** (^{135}Xe), **LHC**

⇒ Do neutrinos (mass mechanism) are related with DM?
LHC

⇒ Do neutrinos (mass mechanism) have something to do with ΔB?

⇒ Do neutrino interactions involve some sort of BSM?
If so, what can we learn from neutrino scattering experiments?

How relevant these questions are?

Ask an average **“hardcore” BSM** folk:

Neutrino physics is done, these questions are marginal (irrelevant), in the best case

Ask an average **“hardcore” neutrino** folk

These questions are of the upmost relevance in particle physics (physics)

For what is worth... **My personal take**:

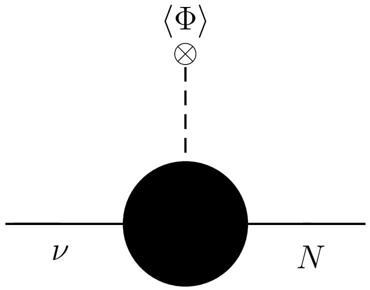
Try to be as general as possible

Derive measurable predictions

Construct testable scenarios

Origin of neutrino masses

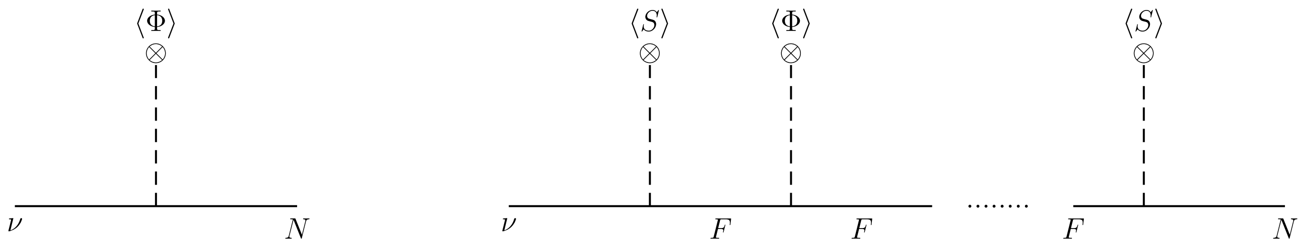
Dirac neutrino masses



$$m_\nu = y_{\text{Eff}} \langle \Phi \rangle$$

$$m_\nu \sim 0.1 \text{ eV} \quad \Rightarrow \quad y_{\text{Eff}} \sim 10^{-12}$$

Completions



$$y_{\text{Eff}} \sim 10^{-12}$$

$$y_{\text{Eff}} \sim y \left(\frac{\langle S \rangle}{M_F} \right)^n \langle \Phi \rangle \sim 10^{-12}$$

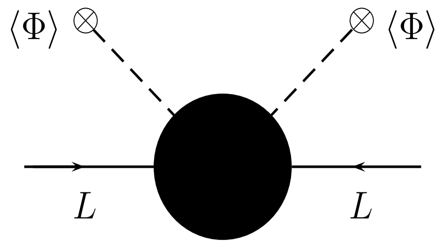
No experimental signal

Smallness “understood”

No testability possible!

Disproving Dirac neutrinos only possible via the observation of $\Delta L = 2$ processes ($0\nu\beta\beta$)

Majorana neutrino masses

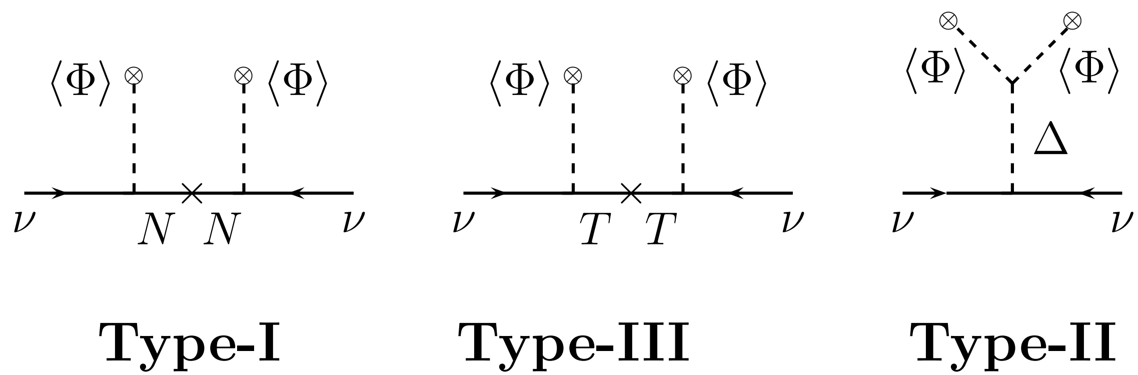


$$\left(M_\nu^{\text{eff}}\right)_{ij} \sim C_{ij}\frac{v^2}{\Lambda}$$

"Natural" couplings $\mathcal{O}(C_{ij}) \sim 1$ point towards a GUT lepton number-breaking scale $\Lambda \sim 10^{15}$ GeV

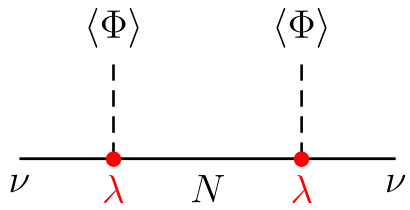
The high-energy picture

Tree level



High scale approaches

"Conventional wisdom": Neutrino acquire their masses via the standard seesaw



- $M_N \gg \Lambda_{\text{EW}} \quad \Rightarrow \quad \mathcal{O}(\lambda) \sim 1$ $\boxed{m_\nu \sim 0.1 \text{ eV}}$
- $N \to LH$ addresses $n_{\Delta B} \sim 10^{-10}$

$SO(10)$: **Fermions** $\subset$ **10** $\subset$ RHNs $\Rightarrow$ **Type-I seesaw**

No possible experimental proof

☞ No direct prove possible given the large scale involved $M_N \sim \Lambda_{\text{GUT}}$

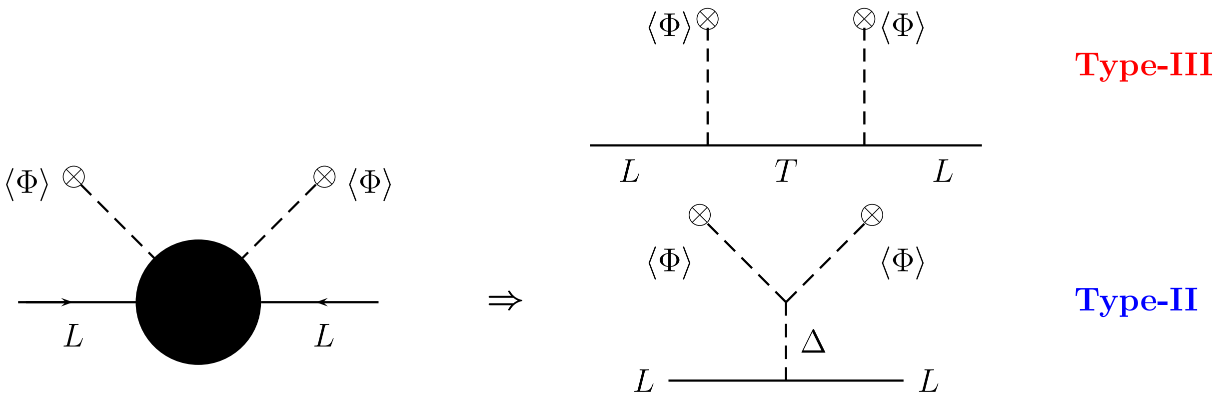
☞ No indirect test possible:

$\{9|\lambda_{ij}|, 6$ CP phases$, 3\ M_N\}$ versus $\{3\ \theta_{ij}, 3$ CP phases$, 3\ m_{\nu_i}, n_{\Delta B}\}$

Deconstruction of Lagrangian parameters not possible

"Standard" variations

Type-III as well as type-II seesaws are well motivated too



Motivation

Simplicity: Type-II and type-III seesaw's are as simple as type-I

(number of parameters, new d.o.f...)

Theoretical: In minimal $SU(5)$ GUT models:

Fermions: $\mathbf{5}^*_F$ $\mathbf{10}_F$ Higgs : $\mathbf{5}_S$ $\mathbf{45}_S$ ($b-\tau$ unification)

GUT breaking : $\mathbf{24}_S$ Neutrino masses : $\underbrace{\mathbf{24}_F}_{\text{Type-I + Type-III}}$ $\underbrace{\mathbf{15}_S}_{\text{Type-II}}$

Constructing potentially testable models

The neutrino mass matrix generated from an $n - loop$ and dimension d diagram

(Bonnet, Hirsch et. al. 2012)

$$m_\nu \sim \varepsilon \times \frac{Y^2 v^2}{\Lambda} \times \left(\frac{Y^2}{16\pi^2}\right)^n \times \left(\frac{v^2}{\Lambda}\right)^{d-5}$$

Lower scale models

$\Rightarrow$ The neutrino mass matrix arises from higher-order loop diagrams

$\Rightarrow$ The neutrino mass matrix arises from higher-order effective operators

$\Rightarrow$ The neutrino mass matrix involves small parameters

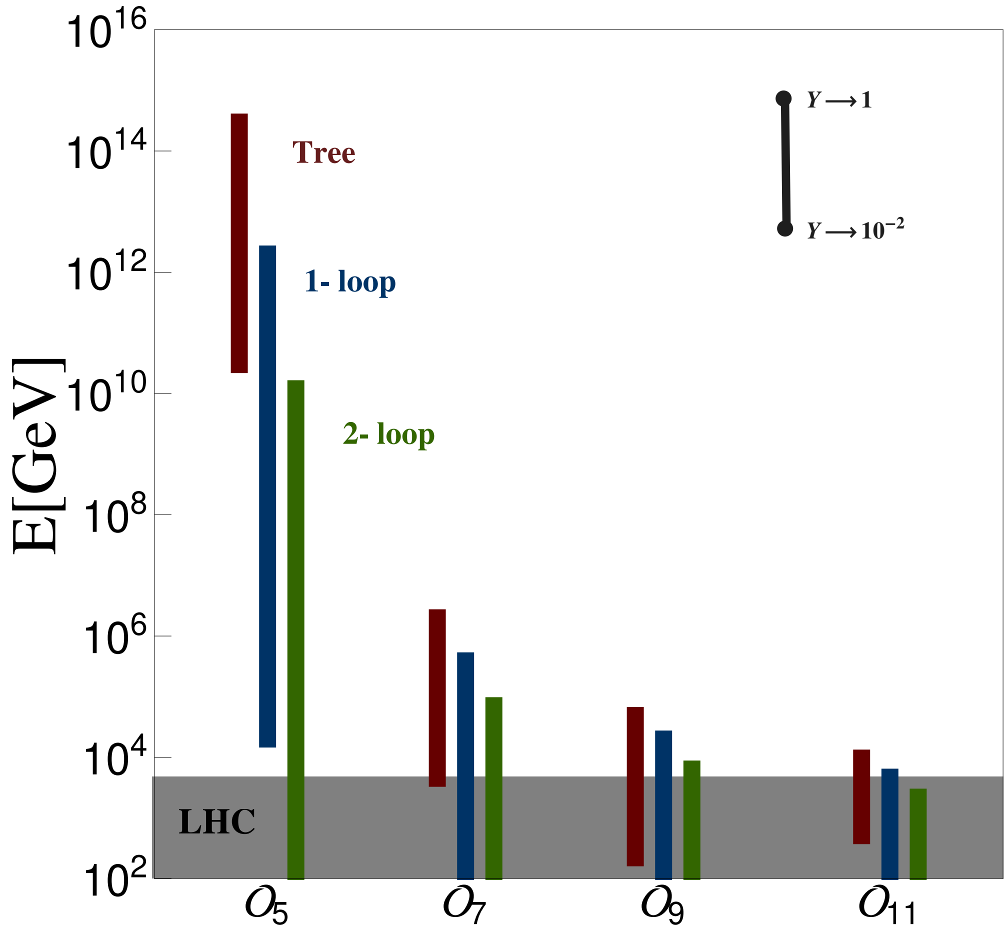
$\Rightarrow$ Combinations...

Allowing for Y couplings in the range $[10^{-2}, 1]$, some possibilties enable $\Lambda \sim \Lambda_{\text{EW}}$

Potential testabilty at LHC!

Testability: A “proof-of-principle”

Depending on the cutoff scale and the operator responsible for m_ν some scenarios might be ruled out



What has been done?

Model-dependent results

(An almost "infinite" list)

Loop-induced

Ext. scalar sectors: Babu-Zee (1988), Zee (1980)

Ext. scalar + fermion sector: Scotogenic (2006)

Hybrid tree+loop: A. Pilaftsis 1992

Higher operators

$d = 7$ (Babu et. al. 2009)

$d \geq 7$+1-loop (Kanemura & Ota, 2010)

Slightly broken L

Inverse seesaw (Valle & Mohapatra, 1986)

Hambye et. al, 2009

Pilaftsis & Dev 2012,2013

Complete picture only possible in model-independent approaches

Loop-induced

Eff. Op. approach

Babu & Leung (2001)

de Gouvea & Jenkins (2007)

Volkas et. al. 2012

Diagrammatic approach

1-loop: Hirsch et. al. 2012

Mixed: Pascoli et. al. 2012

2-loop: D.A.S et. al, 2014

3-loop: Cepedello et al, 2018

Higher order

Winter et. al. 2005 (Non-SUSY)

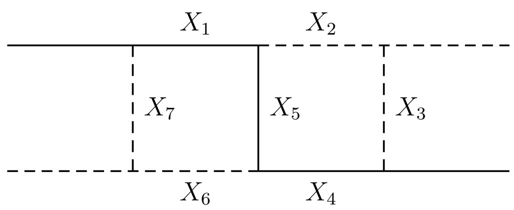
Winter et. al. 2011 (SUSY)

Hirsch et. al. 2017 (1-loop $d = 7$)

Systematization: An example

Tables with QNs for all genuine diagrams as well as results for all possible two-loop integrals in: **D.A.S, Dégee, Dorame and Hirsch, 2014**

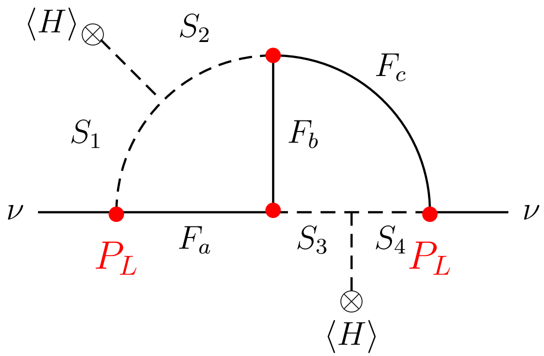
Using these results



$\boldsymbol{\alpha = 2}$ **and** $\boldsymbol{\beta = -3}$

X_2 \ X_1	1				
	X_5	X_7	X_6	X_3	X_4
1	1	2	1, 3	2	1
2	**2**	**2**	**1**, 3	**1**, 3	**2**
3	3	2	1, 3	2	1, 3

Y_1	Y_2	Y_3	Y_4	Y_5	Y_6	Y_7
$-1+\alpha$	$-1+\beta$	β	$-1+\beta$	$\alpha-\beta$	$-1+\alpha$	α



PTBM-3 model

FIELDS	F_a	F_b	F_c	S_1	S_2	S_3	S_4
$SU(2)_L$	1	2	2	2	1	2	1
$U(1)_Y$	1	5	-4	2	1	-4	-3

νMMs à la carte: Model construction becomes a computer algorithm exercise

Bottom line

⇒ Systematization possible even at 3-loop and at 1-loop with higher order operators

⇒ The number of possible models is huge

⇒ Systematic classification of possible signals is a complex task and likely to be of practical use...

⇒ **Can low-intensity rare processes observables be of some utility?**

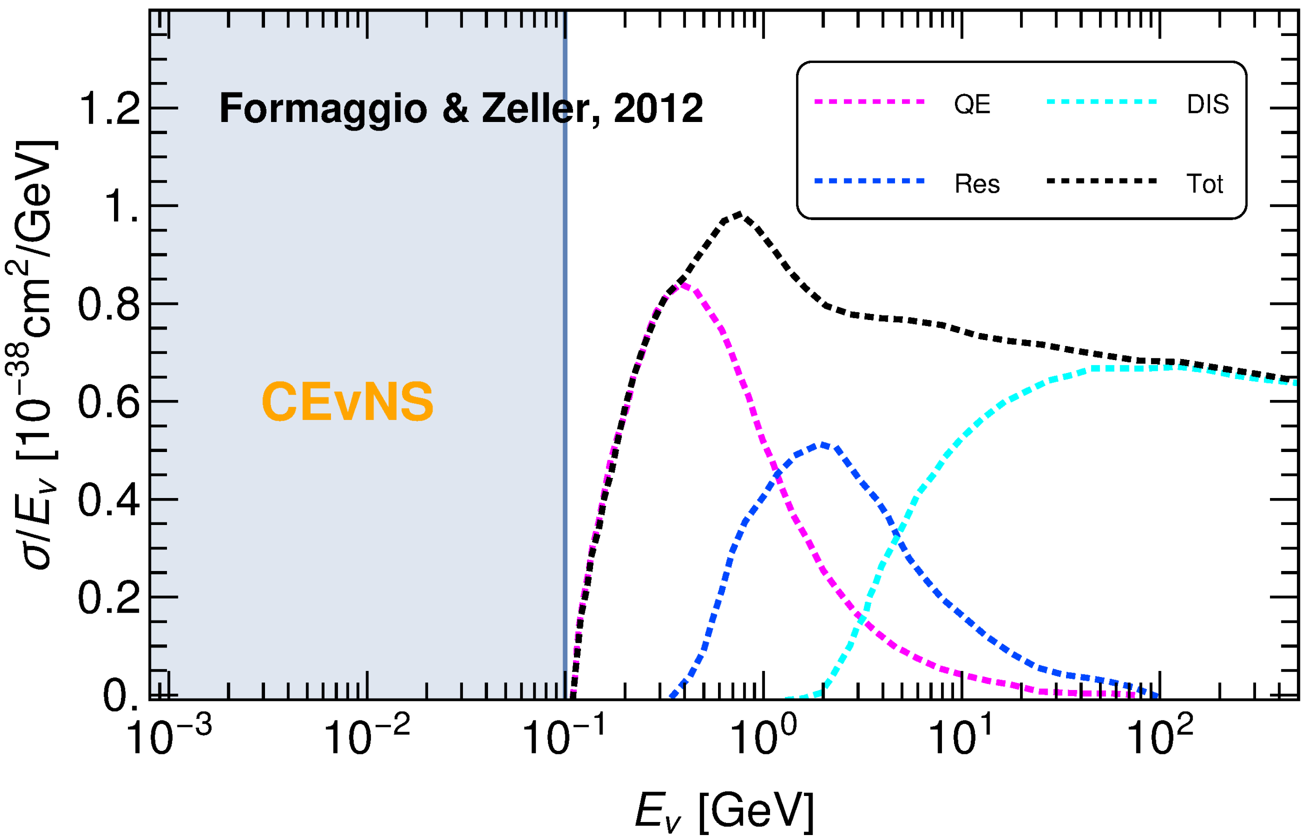
⇒ They do add, but do not change the overall picture

Collider and LFV low-energy observables cannot rule out $\Lambda_{\Delta L\neq 0} < \Lambda_{\text{GUT}}$

What can we learn from neutrino scattering?

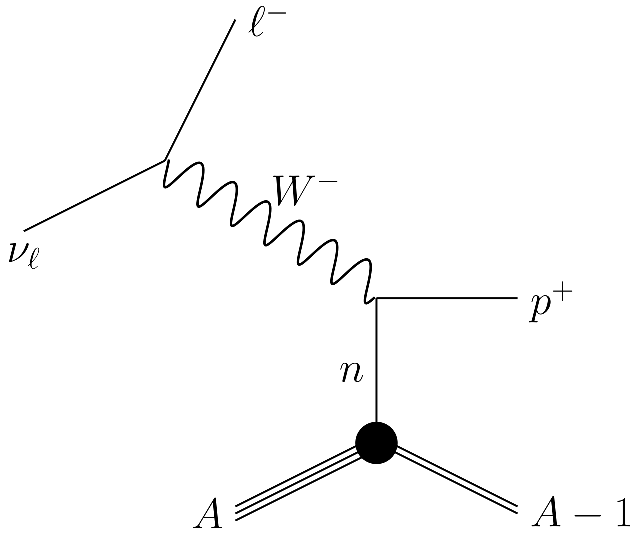
Energy domains

Neutrino cross sections switchoff or kick in as a function of incoming neutrino energy



Intermediate domain: QES and its NC counterpart

$$\nu_\ell + n \to \ell^- + p^+ \qquad \overline{\nu}_\ell + p^+ \to \ell^+ + n^0$$



Nuclear environmental effects matter!

Pauli blocking

Fermi motion

Nucleon reinteractions

Modern Monte Carlo generators include these effects

Differences among outputs $\sim 10\%$. Theoretical uncertainties are substantial

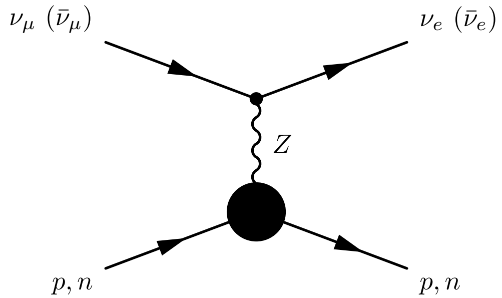
Measurements at MiniBOONE, μBooNE **Minerνa** and T2K $\sim 20\%$ uncertainty (syst.)

NP effects confronted with charged lepton limits. If present at all, NP effects are way below theoretical uncertainties

Look in the NC channel!

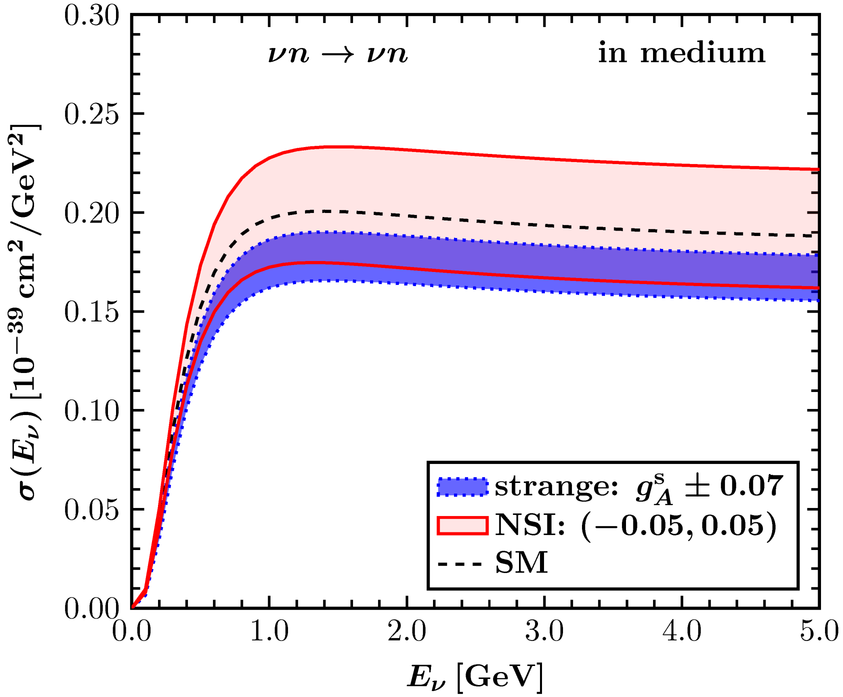
NSI in elastic NC

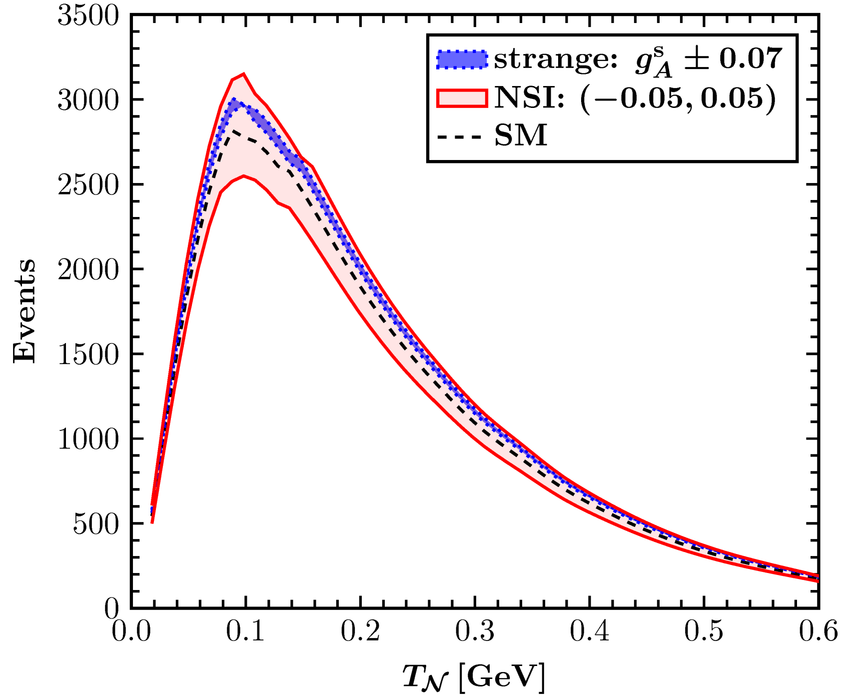
$$\mathcal{L} \sim G_F \overline{\nu}_a \gamma_\mu (1-\gamma_5)\nu_b q \gamma^\mu \epsilon^q_{ab} q$$



Limits on NSI (CHARM, COHERENT) allow for $\sim 30\%$ spread

Data can be used to test NSI **(Kosmas & Papoulias, 1611.05069)**





Low domain: Case for CEvNS

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

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

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

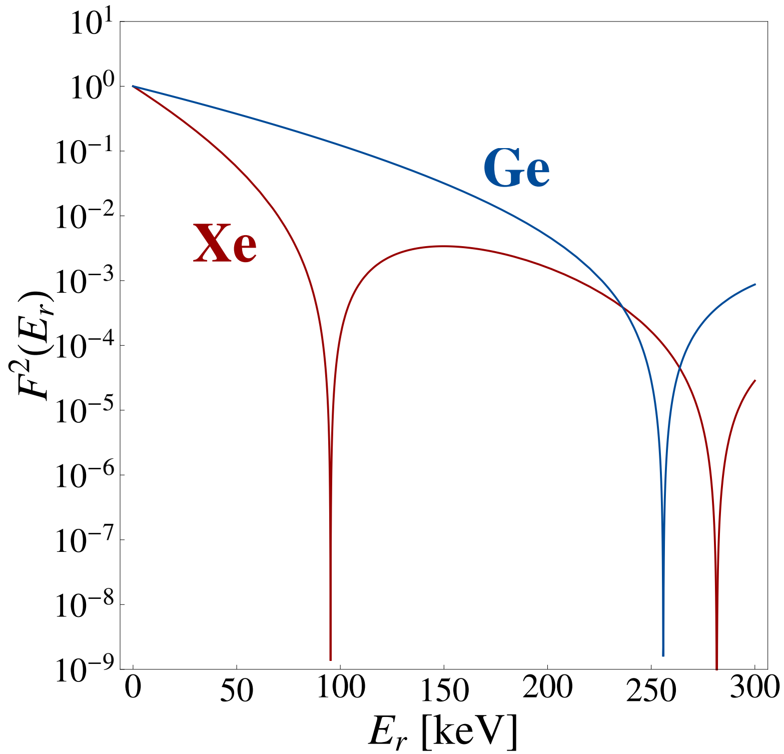
$$E_\nu \lesssim 200\ \text{MeV}$$

Freedman, 1974

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

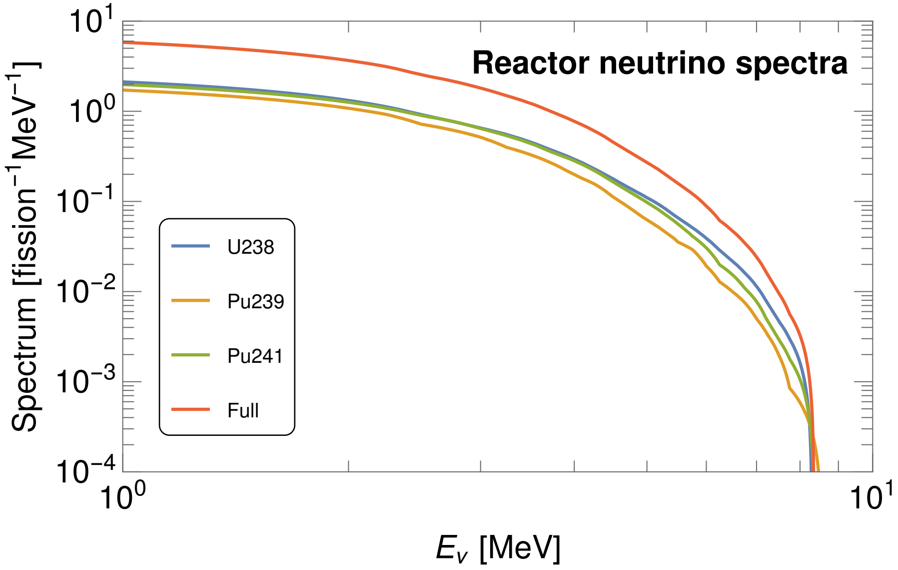
$$Q_{\text{SM}}^2 = [N - (1 - s_W^2)Z]^2 \simeq N^2$$

Helm, 1956

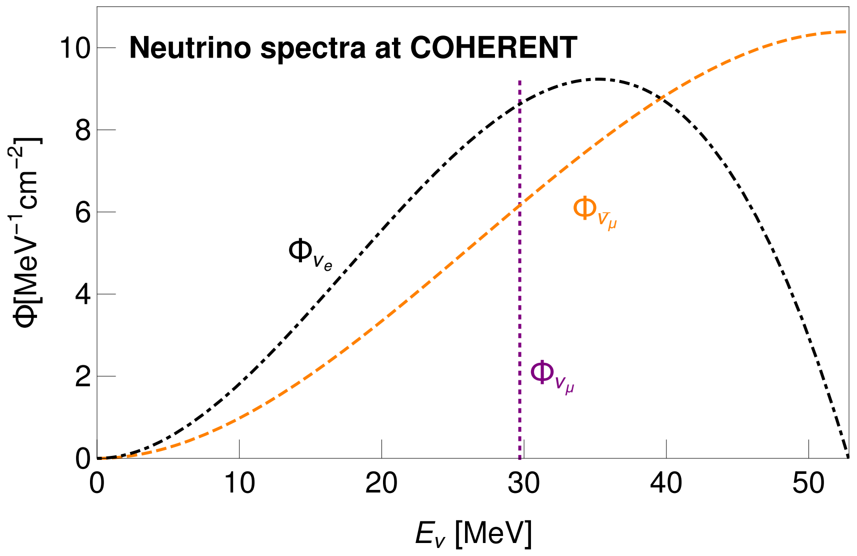


CEvNS environments

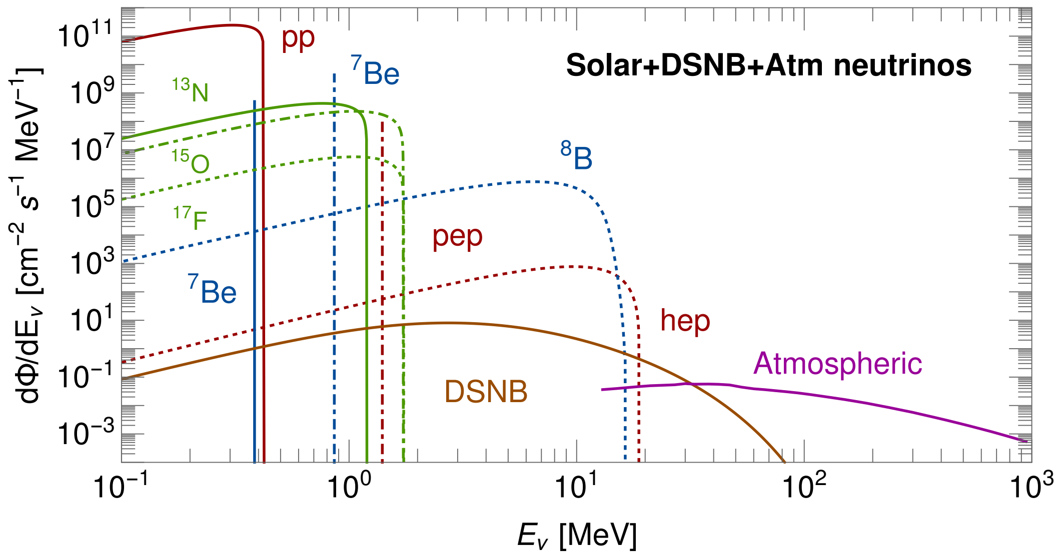
Reactor (NUCLEUS, Dresden-II, CONUS)



Fixed target neutrinos (COHERENT)



Solar+DSNB+Atm (DM detectors)

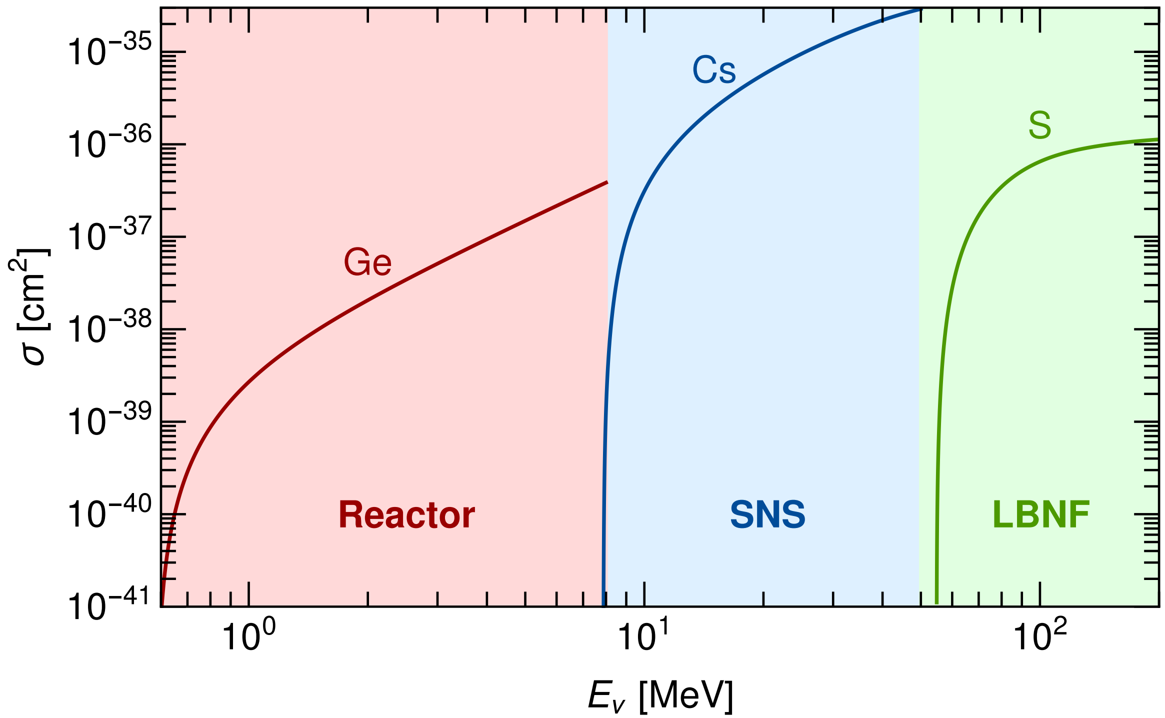


Neutrino sources and CEvNS "regimes"

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

NuMI and LBNF

D.A.S et al. arXiv:2103.10857

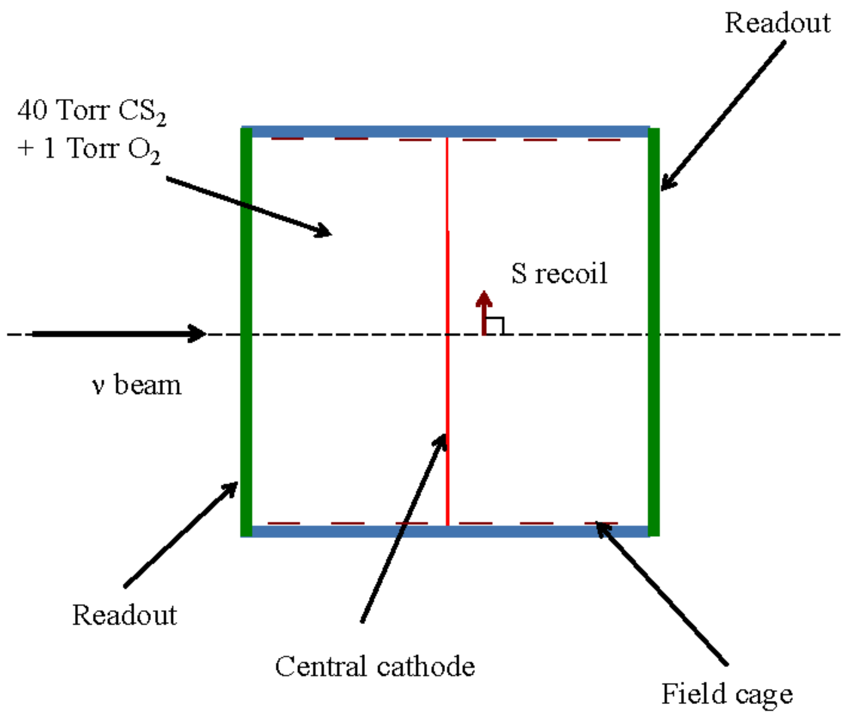


Entering the "high-energy" window requires a substantial amount of ν's in the low-enery tail

LBNF provides that!

The νBDX-DRIFT detector

- 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)

Physics program

The combination of the LBNF neutrino beamline
and the νBDX-DRIFT defines a neutrino program

CEvNS measurements

Measurements in CS_2, CF_4, $C_8H_{20}Pb$...

... Complementary to CONUS (Ge), CONNIE (Si), COHERENT (Ar, CsI, NaI)

SM measurements

Measurements of $\sin^2\theta_W$ at a new energy scale

... Complementary to DUNE measurements in electron channel

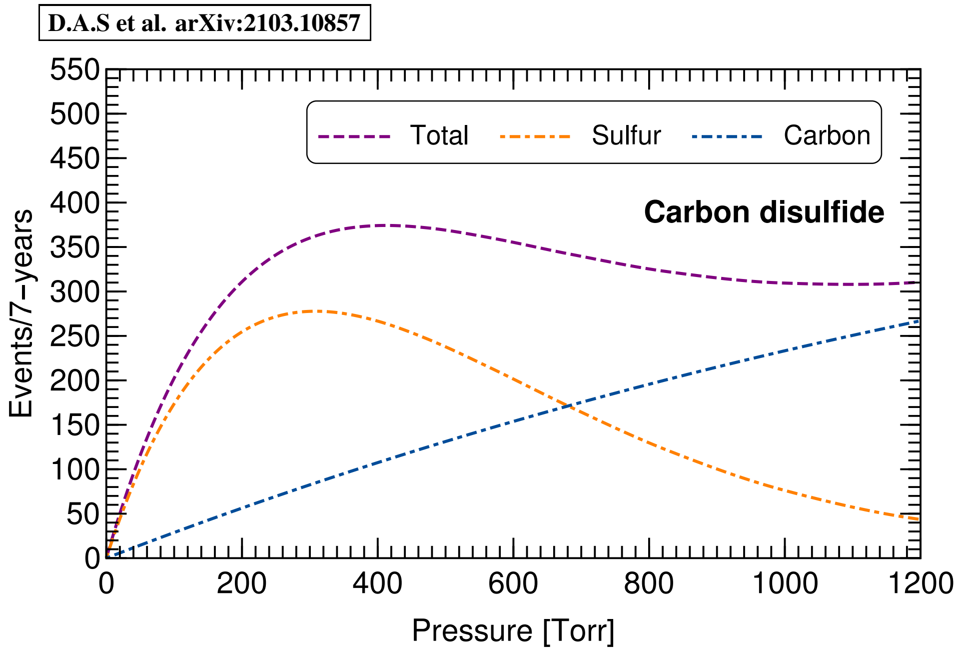
Measurements of neutron distributions in e.g. C, S, F, Pb...

Measurements of neutrino-nucleon elastic and QE scattering

BSM searches

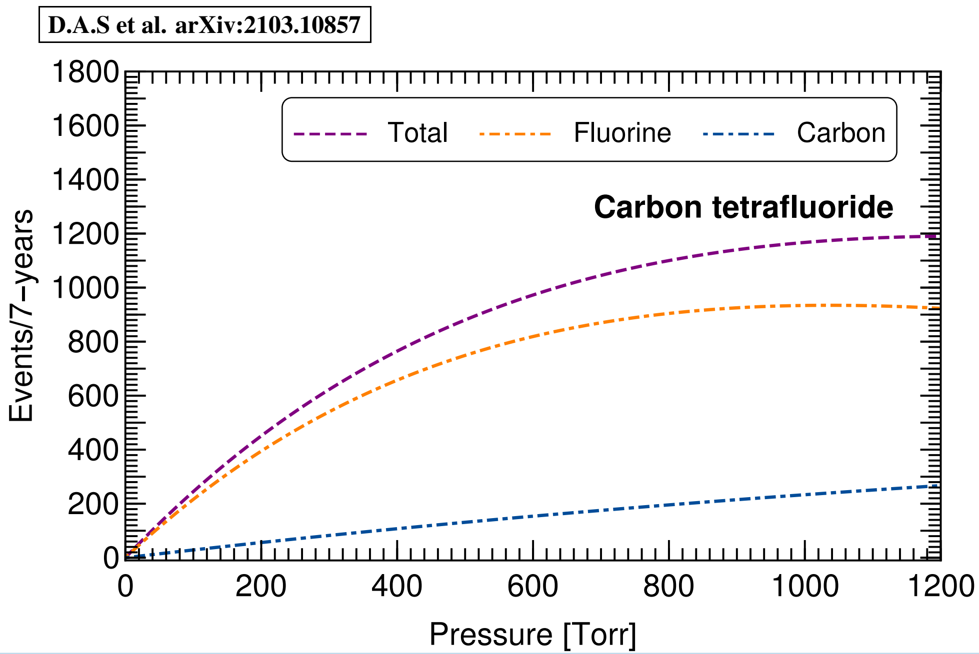
Neutrino NSI, NGI, Dark-neutrino interactions, dark sectors

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

Measurements of R_n via CEvNS

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

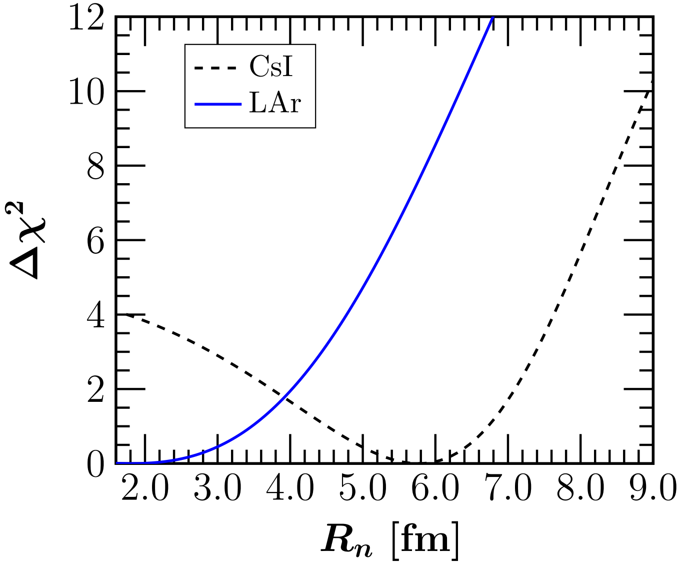
⇒ F_V^p: Depends on $R_p \Rightarrow$ known at 0.1% level ($e^- - N$ scattering)

⇒ 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)



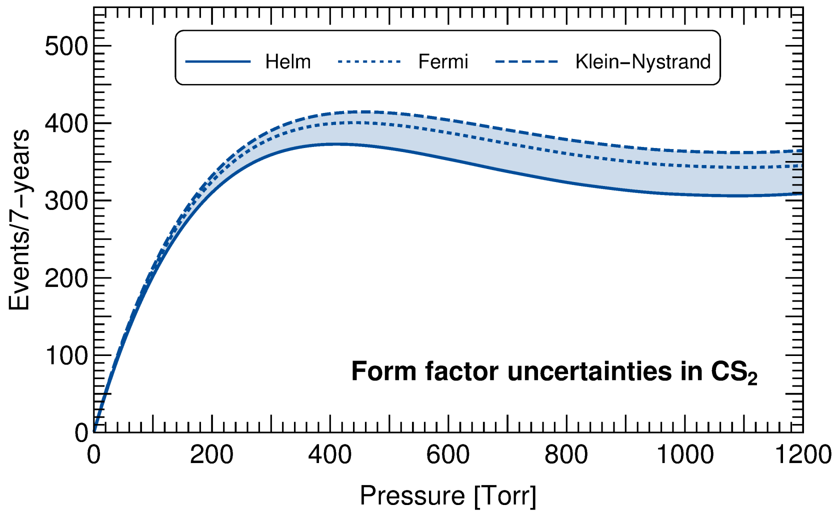
COHERENT 90% CL limits

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.S et al. PRD, 104 (2021)

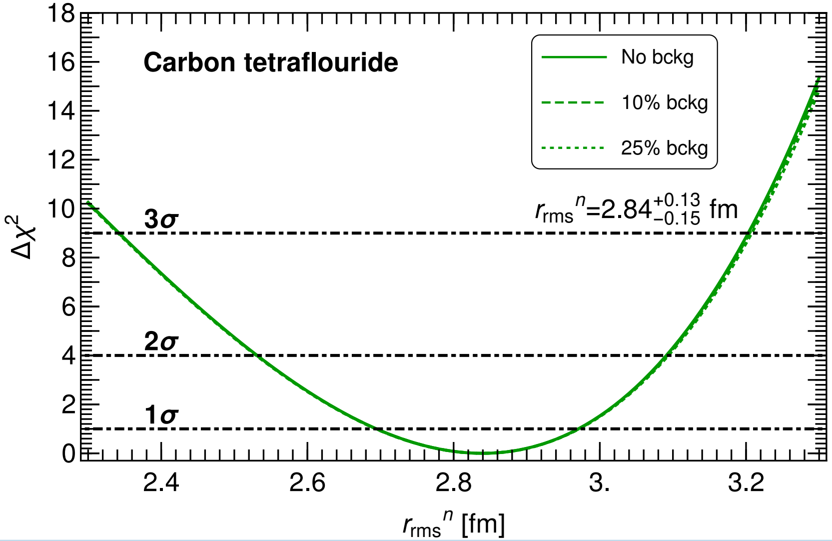


High-energy nature of the flux

$\Rightarrow$ Moderate dependence on the FF

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

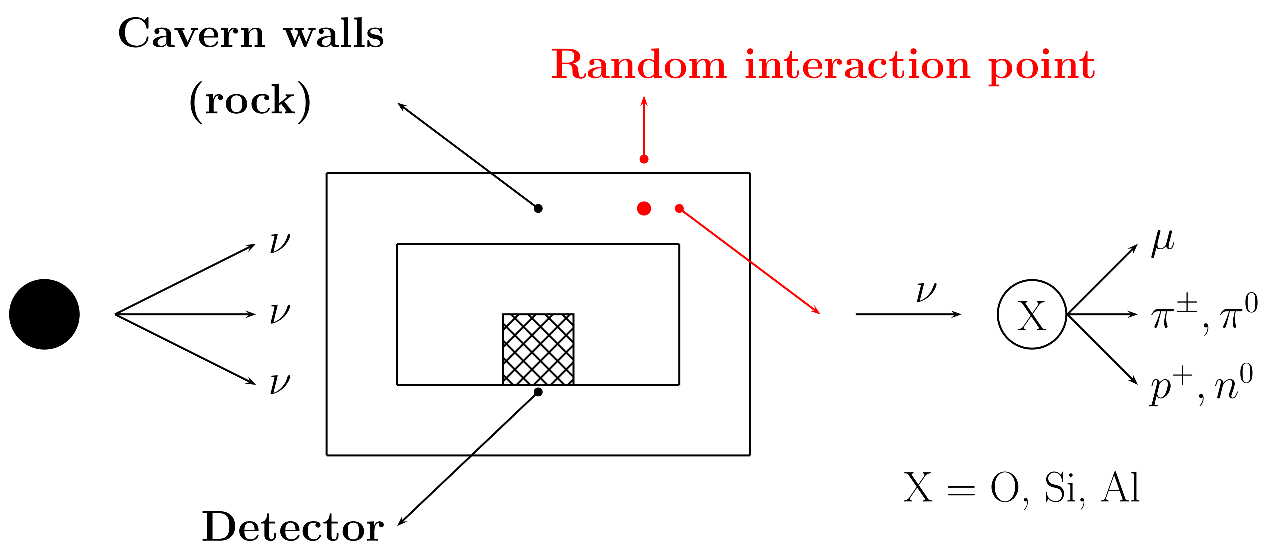
D.A.S et al. PRD, 104 (2021)



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

C and F determined with a 3% accuracy

Assessing rock neutrons



Stage-I

✎ Use GENIE to generate final-state particles energy spectra

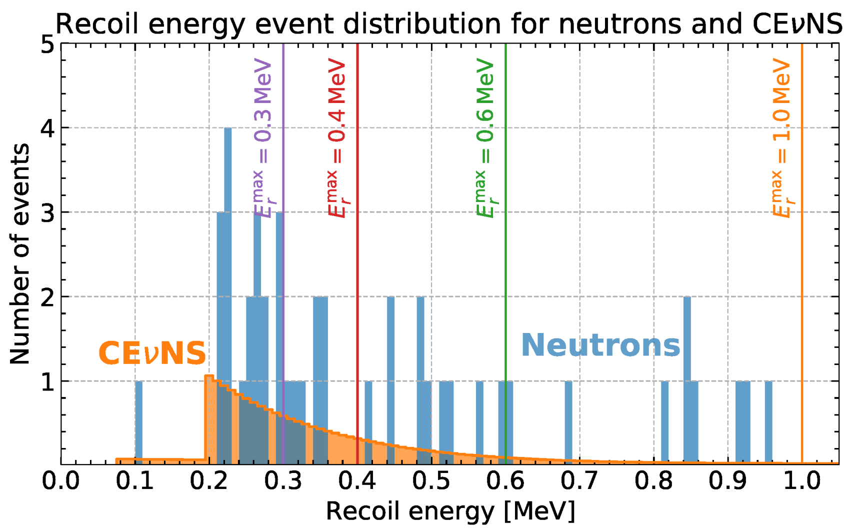
✎ Sample (randomly) (x, y, z) and propagate with the aid of GEANT4 $\Rightarrow n^0$ from the walls.

Stage-II

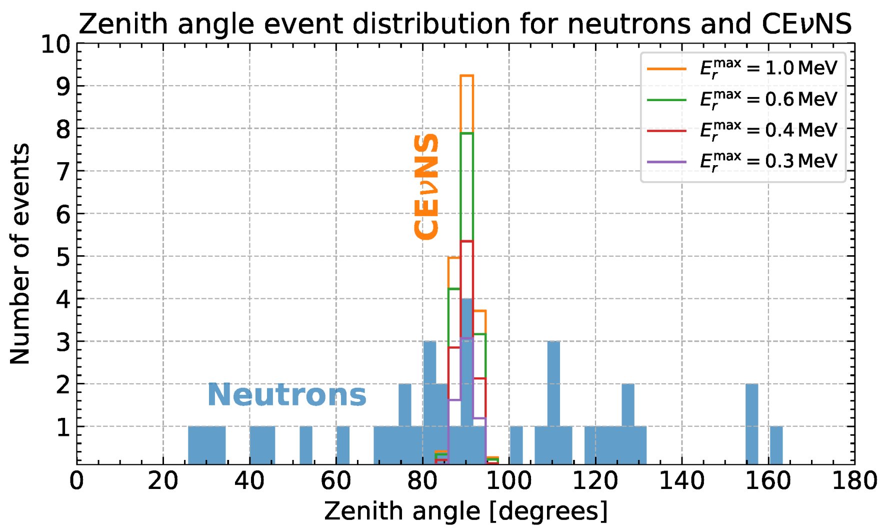
✎ Fire n^0 from the wall and use GEANT4 to record energy deposited in in veto and fiducial volume

Rock neutron bckg vs signal

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



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



NuMI Low Energy (LE) mode

Exposure $10\,\mathrm{m}^3$ – year

Events pile up at 90°

Signal-to-noise ratio: 2.5

Final remarks

Rèsumè

⇒ In the next 10 years a large number of next-generation neutrino experiments will provide a wealth of data

⇒ Some open questions will be certainly addressed (experimentally) others will perhaps remain open for quite a while

⇒ Neutrinos have always surprised us, it could be that they still can...