Neutrino cross sections

Open Symposium on the European Strategy for Particle Physics

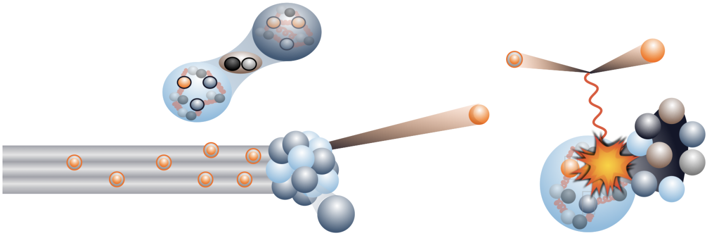


Figure from the University of Edinburgh: Particle Physics Experiment

Ivan Esteban

On behalf of the
Neutrinos and Cosmic Messengers WG

23rd June, 2025

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

Introduction

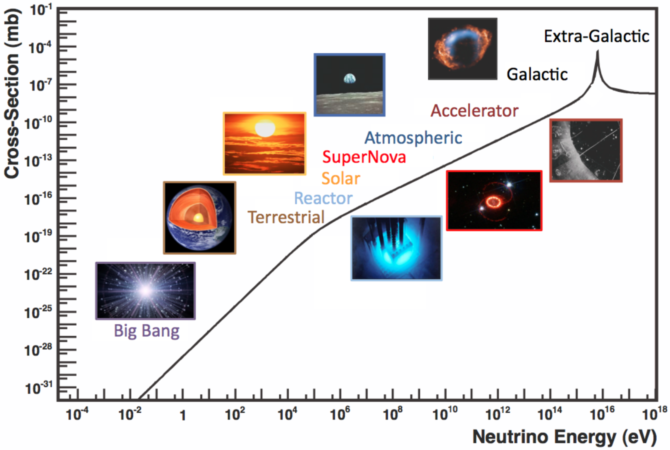
I must apologize that in this talk I have not done my duty. I have not really, in any sense, given you a summary talk of the conference; rather I have tried to discuss some of the main problems that can be settled in the future by using the high-energy neutrino beams. As it must be clear to all of you, much of the future of weak interactions lie in the study of the high-energy neutrino processes. These processes can, on the one hand, be used to study the basic properties of weak interactions, and, on the other hand, they enable us to probe the strong interactions through the measurements of the various matrix elements.

T. D. Lee, "Informal conference of experimental neutrino physics", 1965

Neutrinos only interact weakly,

- ⇒ Clean probes of weak interactions
- ⇒ Potential sensitivity to weaker-than-weak interactions
- ⇒ Unique probes of target structure
- ⇒ Abundantly produced in astro/cosmo: we need to know their interactions for SM and BSM!

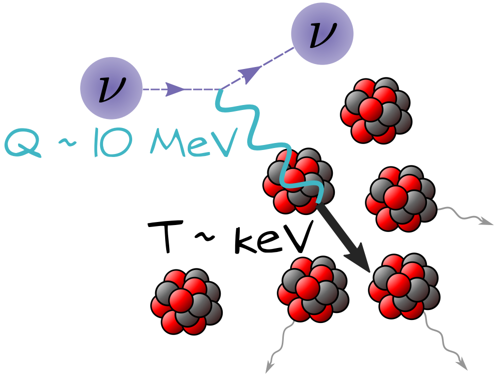
Introduction



Formaggio, Zeller; "From eV to EeV: Neutrino Cross-Sections Across Energy Scales", `arXiv:1305.7513`

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Big picture



Coherent **E**lastic $\boldsymbol{\nu}$eutrino **N**ucleus **S**cattering

$\sigma \propto N^2$, well-understood cross section

$$\frac{\mathrm{d}\sigma^{\mathrm{SM}}}{\mathrm{d}E_R} = \frac{G_F^2 M}{8\pi}\left[2 - \frac{M E_R}{E_\nu^2} - \frac{2 E_R}{E_\nu} + \left(\frac{E_R}{E_\nu}\right)^2\right] \mathcal{Q}_W^2 |F(Q^2)|^2$$

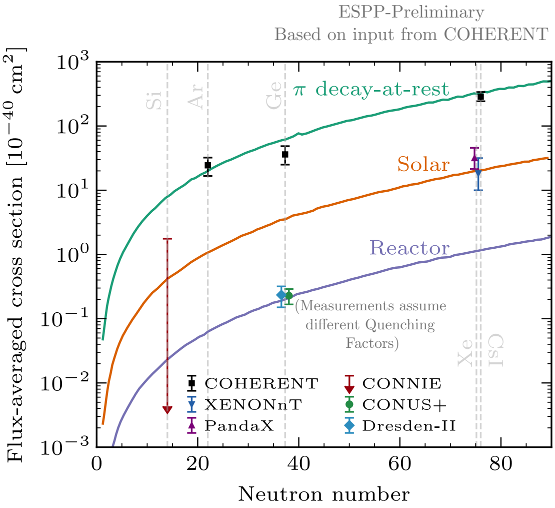
$$\mathcal{Q}_W \equiv N - (1 - 4\sin^2\theta_W) Z$$

But low E_ν ($\lesssim 50\,\mathrm{MeV}$) and low nuclear recoils ($\lesssim$ keV, the lower the better)

Low energies: CEνNS

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Physics program



Within the SM,

- Key process for supernova explosions
- Nuclear (*neutron*) structure
- Weak mixing angle
- Neutrino charge radius

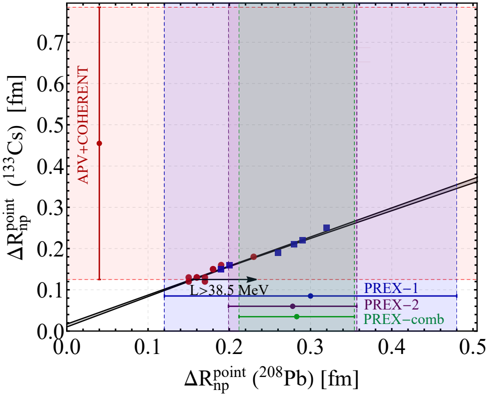
- Low-energy inelastic cross-sections for supernova detection elsewhere
- Supernova detection via NC
- Reactor monitoring
- ...

Plus a strong BSM program (NSI, light mediators, neutrino EM properties, dark sectors. . .) ⇒ Joachim's talk.

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Neutron distribution in nuclei

$$\frac{\mathrm{d}\sigma^{\mathrm{SM}}}{\mathrm{d}E_R} \propto |F(Q^2)|^2; \quad Q^2 = 2ME_R + \mathcal{O}(E_R/M)$$



Cadeddu et al; arXiv:2102.06153

Measurement only possible with neutrinos (Y axis) or parity-violating electron scattering (X axis). Dominated by statistics+energy reconstruction (*Quenching Factor*) uncertainties.

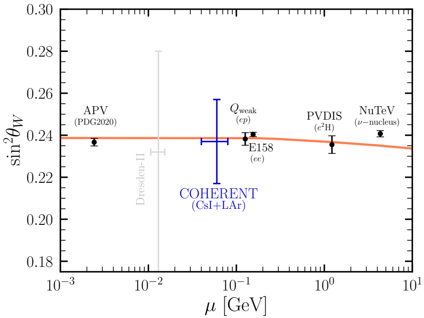
Beyond a test of first-principles calculations, it can be related to the energy of isospin-asymmetric matter, key for the equation of state of neutron-rich matter including neutron stars.

Low energies: CEνNS

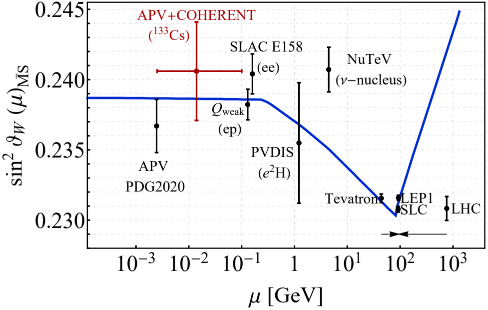
Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Weak mixing angle

$$\sigma^{\text{SM}} \propto [N - (1 - 4\sin^2\theta_W)Z]$$



De Romeri et al; arXiv:2211.11905



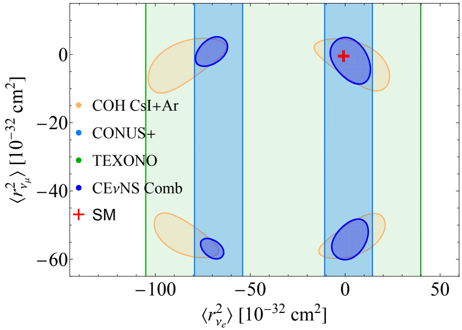
Cadeddu et al; arXiv:2102.06153

Future: competitive determinations of θ_W potentially possible with $\mathcal{O}(50kg)$ Ge (low threshold, "low" N/Z)

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Neutrino charge radius

$$\sin^2 2\theta_W \to \sin^2 2\theta_W \left(1 + \frac{1}{3} m_W^2 \langle r_\nu^2 \rangle\right)$$



Atzori Corona et al; arXiv:2501.18550

Future: measurement of θ_W potentially possible with $\mathcal{O}(50kg)$ Ge (low threshold, "low" N/Z)

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Future: "explosion" of proposals

Experiment	Neutrino source	Detector material	Deployed?	Reference
COHERENT	Pion-decay-at-rest	NaI, 3500 kg	3/7 modules deployed	COHERENT input
COHERENT	Pion-decay-at-rest	Liquid Ar, 750 kg	Cryostat under commissioning	COHERENT input
COHERENT	Pion-decay-at-rest	Cryogenic CsI, 10 kg (low threshold)	No	COHERENT input
COHERENT	Pion-decay-at-rest	Ne, 20 kg	No	COHERENT input
Captain Mills	Pion-decay-at-rest	Ar, 10 ton	Commissioning last year	arXiv:2105.14020
ESS	Pion-decay-at-rest	CsI, 22.5 kg; Si, 1 kg; Xe, 20 kg; Ge, 7 kg; Ar, 10 kg; C_3F_8, 10 kg (large ν flux)	No	arXiv:1911.00762
SuperCDMS	Solar	Si, 3.7 kg; Ge, 25 kg	Commissioning	Proceedings
RES_NOVA	Solar	Pb, 2.4 ton–465 ton	No	arXiv:2004.06936
CYGNUS	Solar	He+CF_4, 15 kg–1500 kg	No	arXiv:2404.03690
BULLKID	Solar	Si, ∼kg	Demonstrator commissioned	arXiv:2209.14806
CONUS100	Reactor	Ge, 100 kg	No	CONUS input
CONNIE upgrade	Reactor	Si, 1 kg–10 kg (low threshold)	No	CONNIE input
MINER	Reactor	Ge, 1.5 kg; Si, 10 g	Engineering runs done	arXiv:1609.02066
NEON	Reactor	NaI, 13.3 kg	Yes	arXiv:2204.06318
NUCLEUS	Reactor	Al_2O_3, $CaWO_4$; 10 g–1 kg (low threshold)	Yes	arXiv:2211.04189
Ricochet	Reactor	Ge, ∼kg (low threshold)	Yes	arXiv:2111.06745
SBC	Reactor	Ar, 10 kg	Prototype under construction	arXiv:2101.08785
NUXE	Reactor	Xe, 10 kg–100 kg	No	Ni et al, 2021
PALEOCCENE	Reactor	Different materials, 10 g–1 kg (exploits defect formation, low threshold)	No	arXiv:2203.05525

Low energies: CEνNS

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

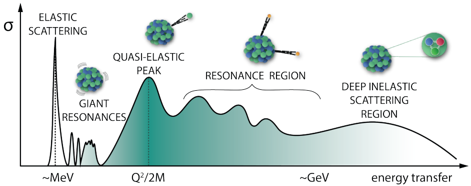
Challenges

Some measurements (e.g., absolute rate at pion-decay-at-rest sources) are already systematics-limited. On top of scaling,

- Can we reduce flux uncertainties in pion-decay-at-rest?
  [E.g., D_2O detector, `arXiv:2104.09605`]

- How can we reduce Quenching Factor and energy calibration uncertainties?
  [Converts nuclear recoil to observed energy, critical for interpreting reactor results. E.g., phonons, defect formation, calibration by radiative neutron capture CRAB]

- Can we reduce energy thresholds (stats+sensitivity to some physics)?
  [E.g., Si]



Neutrino Scattering Theory Experiment Collaboration, arXiv:2503.23556

Key systematic for oscillation measurements (Mark's talk): $N_{\mathrm{evt}} = \phi \times \sigma \times P_{\mathrm{osc}}$

But also rich in nuclear effects

- Nuclear initial state
- Multi-nucleon effects
- Final-state interactions
- Quark-hadron duality
- ...

Most of this program is explored with electrons, but neutrinos are complementary.

GeV energies

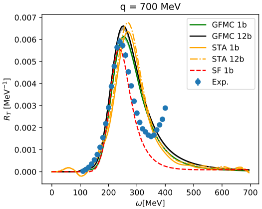
Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Nuclear physics

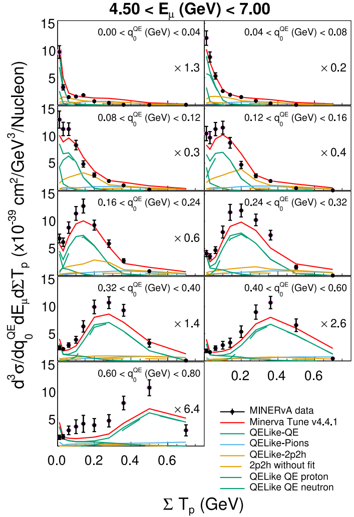
Clearly a lot to be learned about the nuclear initial state and final-state interactions!

Can we disentangle from, e.g., flux uncertainties and unknown neutrino energy? [Neutrino tagging? See Mark's talk for SBN@CERN/nuSCOPE]

Ultimately, how much can we link with ab-initio calculations?



Andreoli et al, arXiv:2108.10824

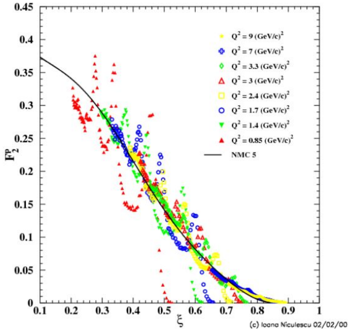


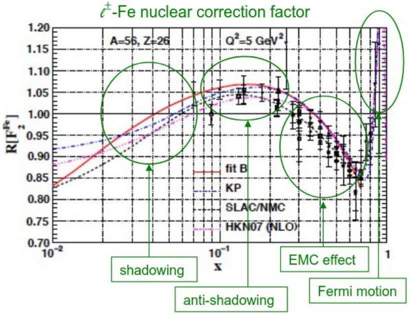
MINERvA, arXiv:2203.08022

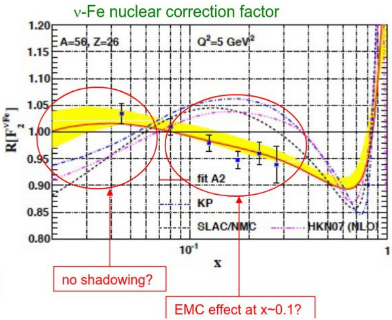
Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

Quark-hadron transition

Low-Q^2 corrections to DIS (quark-hadron duality).
Compared to electrons, neutrinos probe a different current.







T. Katori, talk in “Neutrino–Nucleus Interactions in the Standard Model and Beyond”

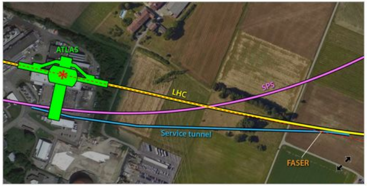
Collider neutrinos

The Dawn of Collider Neutrino Physics

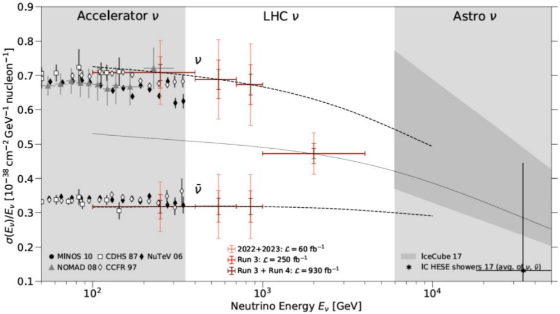
Elizabeth Worcester
Brookhaven National Laboratory, Upton, New York, US

July 19, 2023 • *Physics* 16, 113

The first observation of neutrinos produced at a particle collider opens a new field of study and offers ways to test the limits of the standard model.



Google Earth, imagery (c)2023 Maxar Technologies, map data (c)2023; CERN; adapted by APS/Alan Stonebraker



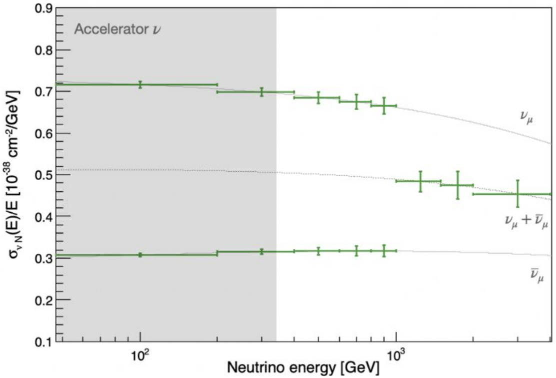
A rich physics program

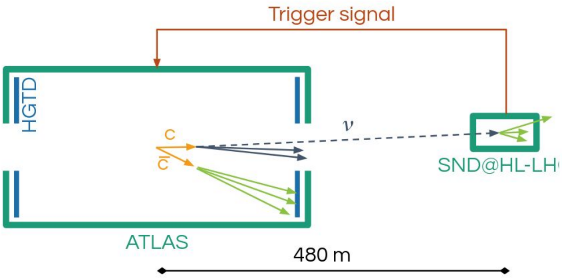
- *Unexplored energy regime*
- ν_τ, $\bar{\nu}_\tau$: lepton flavor universality, systematic for ν_τ **appearance searches in oscillation experiments**
- *QCD*: charm hadrons contribute significantly. Forward charm production can be measured, linked to **low-x PDFs** (relevant for, e.g., Higgs physics or to test QCD saturation) and **prompt atmospheric neutrinos** (relevant for, e.g., astrophysical neutrino searches).

  Similarly, forward strangeness can be measured, linked to the **muon puzzle** in cosmic-ray physics.

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

SND@HL-LHC



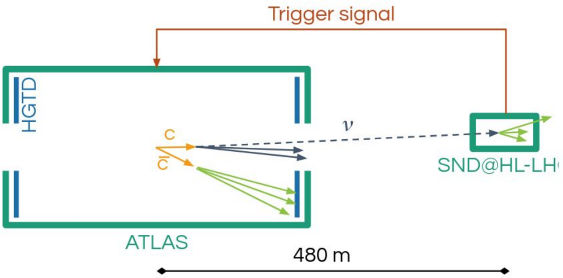


Measurement	Uncertainty Stat.	Sys.	Uncertainty Stat.	Sys.
Gluon PDF	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	$< 5\%$
ν_μ and $\overline{\nu}_\mu$ cross-section	-	-	1%	5%

TeV energies

SND@HL-LHC

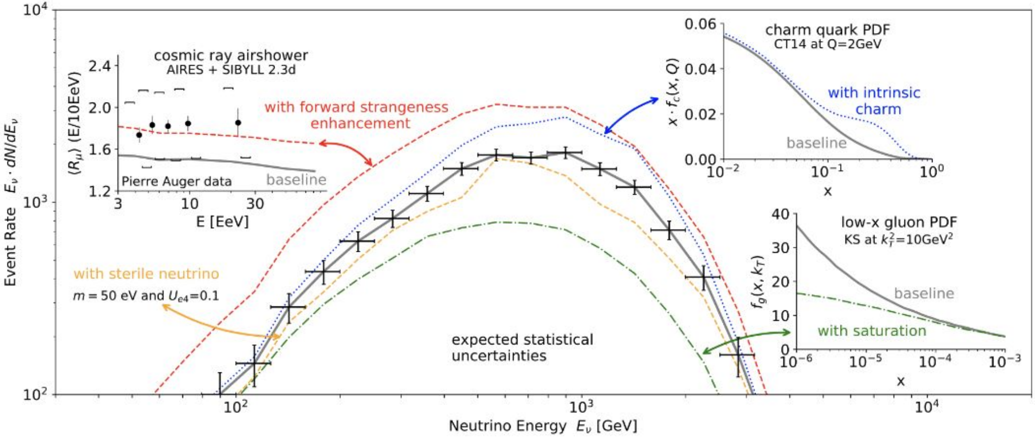
- All 6 flavors
- Tagged neutrino beam ($\mathcal{O}(600)$ events)
- PDFs at low Bjorken-x



Measurement	Uncertainty Stat.	Sys.	Uncertainty Stat.	Sys.
Gluon PDF	5%	35%	2%	5%
ν_e/ν_τ ratio for LFU test	30%	22%	6%	10%
ν_e/ν_μ ratio for LFU test	10%	10%	2%	5%
Charm-tagged ν_e/ν_μ ratio for LFU test	-	-	10%	$< 5\%$
ν_μ and $\bar{\nu}_\mu$ cross-section	-	-	1%	5%

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

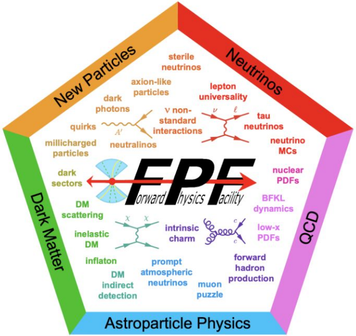
FASER upgrade

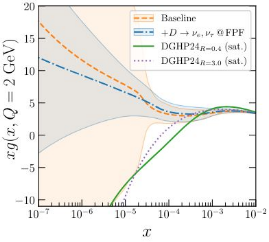


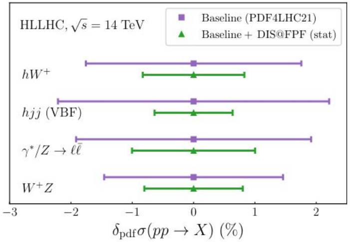
(Illustration plot)

TeV energies

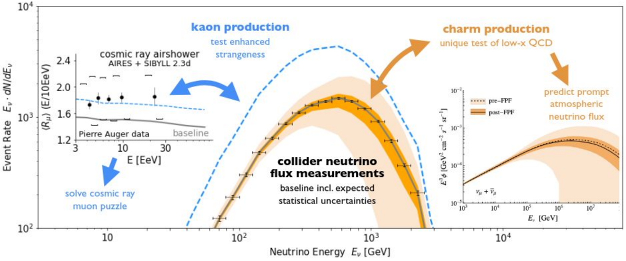
FPF





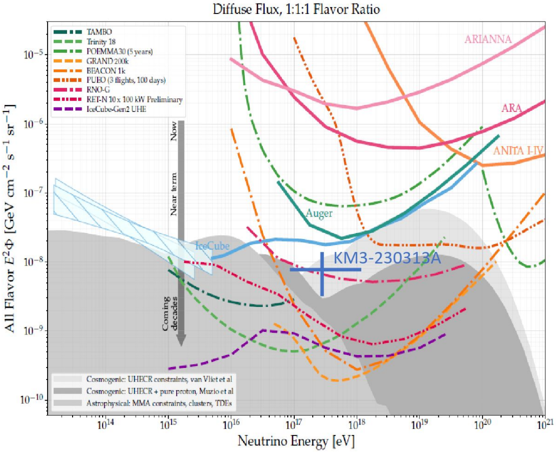


- FLArE: LAr TPC
- FASERv2: emulsion
- FASER2: multipurpose (tracker, cal, magnet, μ)
- FORMOSA: plastic scintillator for millicharged particles



(Ultra-)High Energy astrophysical neutrinos

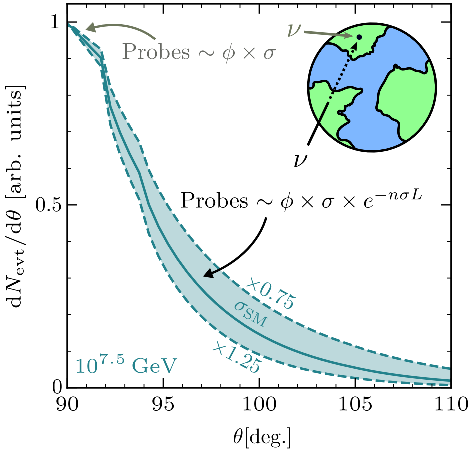
(See Aart's talk)

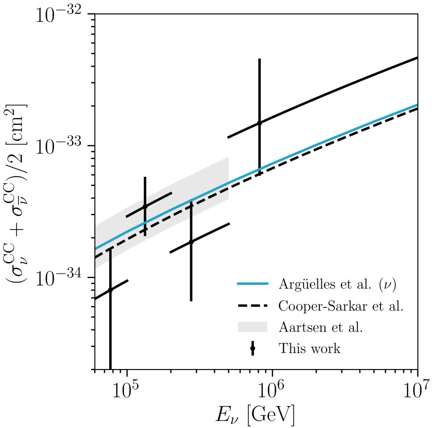


Beyond TeV energies

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

(Ultra-)High Energy astrophysical neutrinos





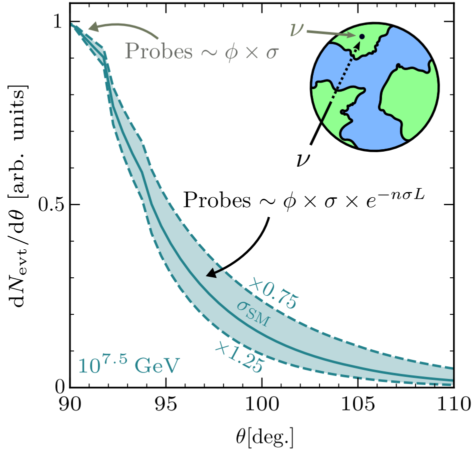
Earth absorption modifies angular distribution $\Rightarrow$ handle on cross section

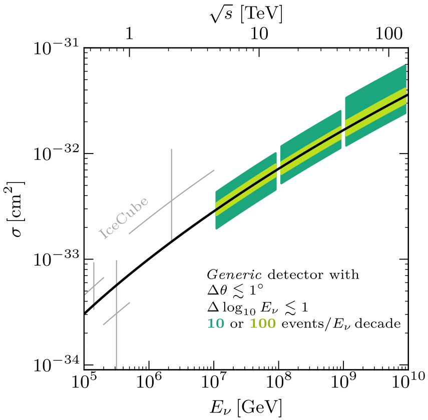
IceCube, arXiv:2011.03560

Beyond TeV energies

Ivan Esteban, University of the Basque Country
Neutrinos and Cosmic Messengers Working Group

(Ultra-)High Energy astrophysical neutrinos





Earth absorption modifies angular distribution ⇒ handle on cross section

IE, Prohira, Beacom; `arXiv:2205.09763`

Outlook

- Neutrino interactions offer a unique window
  - **MeV** (CEνNS): precision probe of weak interactions (and beyond) and nuclear structure
  - **GeV** (LBL): nuclear initial state, quark-hadron duality...
  - **TeV** (collider): connection to astroparticle physics, low-x QCD, saturation...
  - **PeV, EeV** (astrophysical): beyond laboratory reach
- And the future looks bright!
  - **MeV** (CEνNS): high-statistics, low-systematics proposals
  - **GeV** (LBL): Mark's talk!
  - **TeV** (collider): HL-LHC
  - **PeV, EeV** (astrophysical): Aart's talk!
- But there are challenges
  - **MeV** (CEνNS): e.g.,we have to reduce systematics
  - **GeV** (LBL): e.g., can we disentangle from flux and energy uncertainties?
  - **TeV** (collider): e.g., can we be ready for HL-LHC?
  - **PeV, EeV** (astrophysical): e.g., how many events?