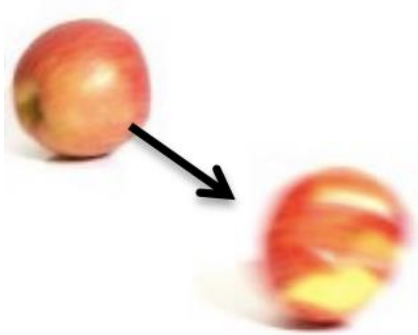
Neutrino interactions

Dan Pershey (Florida State University) – Jul 16, 2024

Second school on neutrino and dark matter detection
South American Institute for Fundamental Research

Neutrino-nucleus scattering across energy scales

keV



CEvNS: nuclei acquire small kinetic energy

MeV

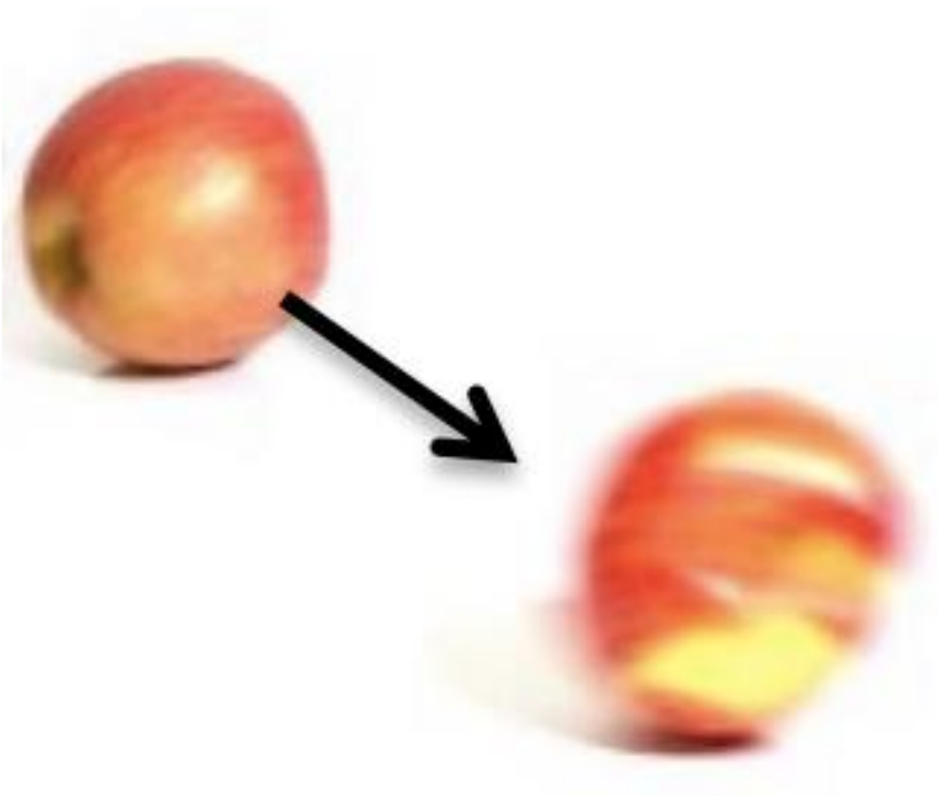
Transitions in nuclear shell state. Important for astrophysics!

GeV

Messy! QCD involved in multiple and complicated ways. Many oscillation experiments here

TeV

Scattering off quarks. Nucleus scattered, but easily modeled



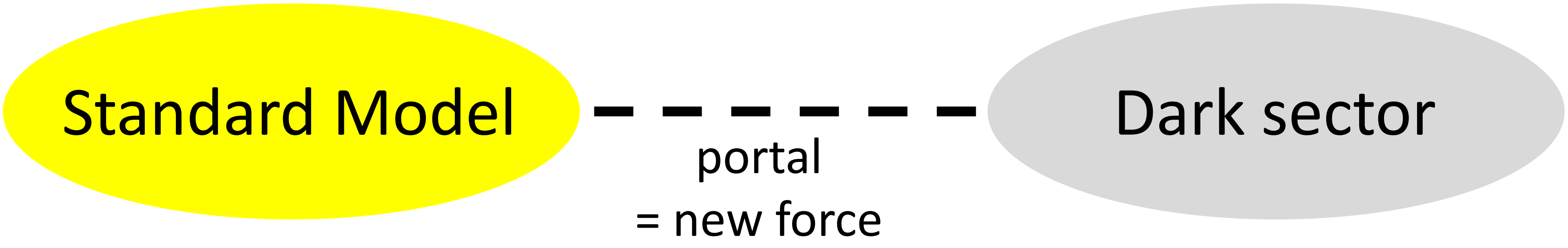
keV

The elastic regime

CEvNS

Neutrino interactions and fundamental physics

Discovery of the dark sector



Dark sectors particles:

1: electrically neutral

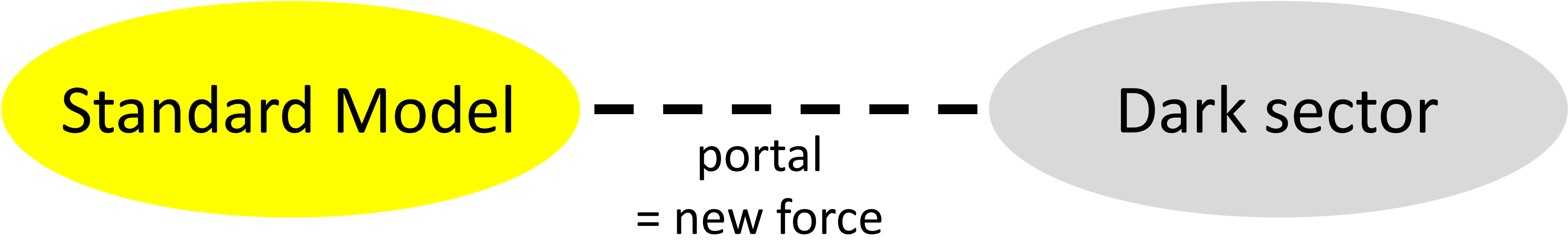
2: feeble interactions and light

3: interacts with the SM through a portal

$$\bar{p}\gamma^{\mu}(1-\gamma^{5})n\,\overline{e}\gamma^{\mu}(1-\gamma^{5})\,\nu$$

Neutrino interactions and fundamental physics

Discovery of the dark sector



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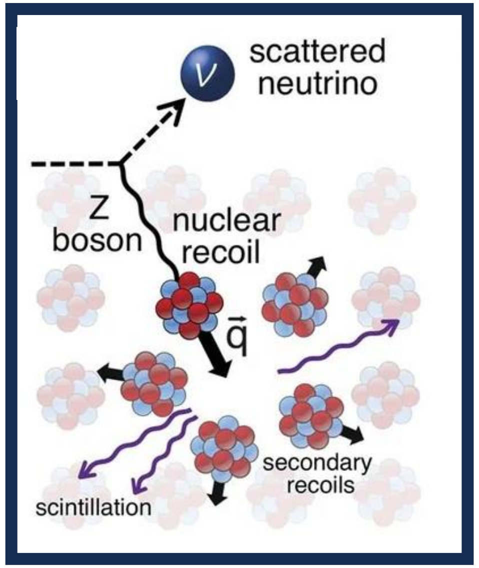
$$\boxed{\bar{p}\gamma^{\mu}(1-\gamma^{5})n\ \bar{e}\gamma^{\mu}(1-\gamma^{5})}\,\nu$$

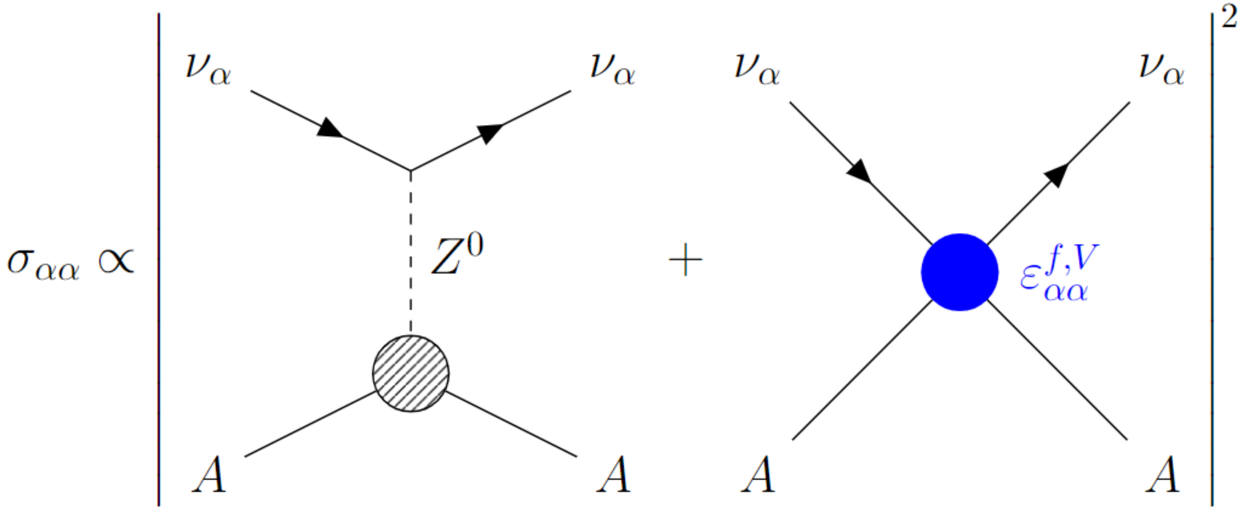
portal

The neutrino sector is the original dark sector!

Argument from Brian Batell

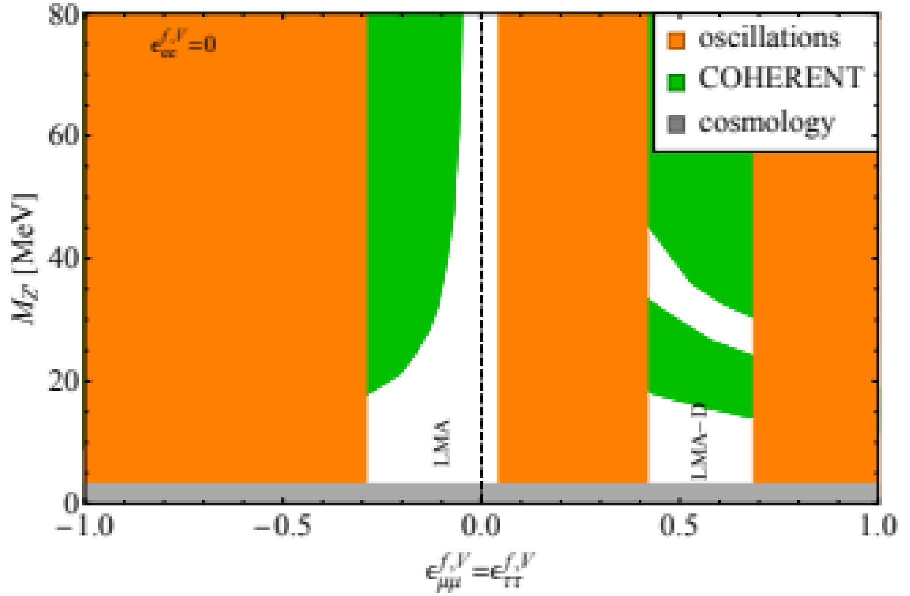
CEvNS connections: neutrino oscillations





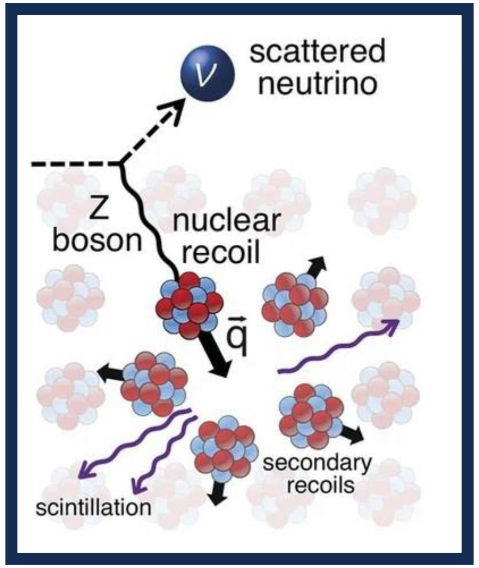
$$H = \frac{1}{2E}\left[U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + a \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right]$$

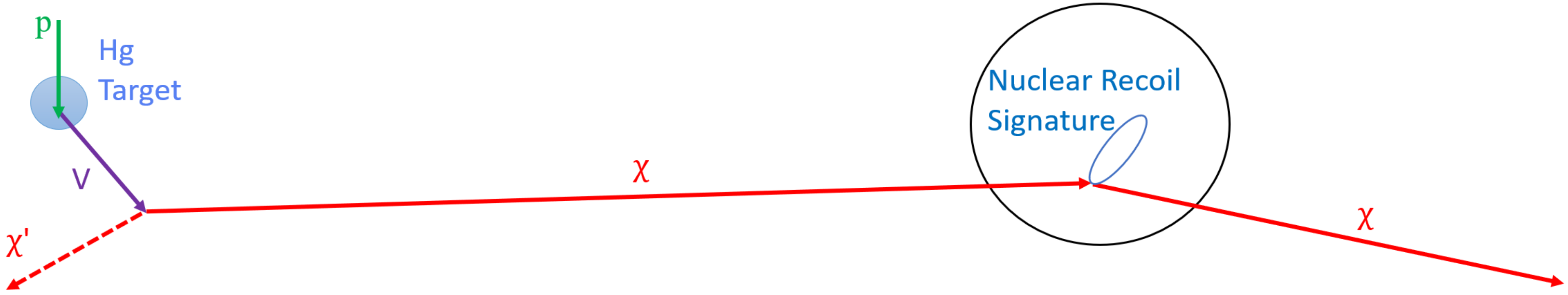
– Neutrino-quark interactions are poorly constrained
– Flavor-dependent non-standard interactions can adjust interaction potential for neutrinos traveling through matter
– **Oscillation ambiguity!** Distinguish between LMA and LMA-dark oscillation scenarios



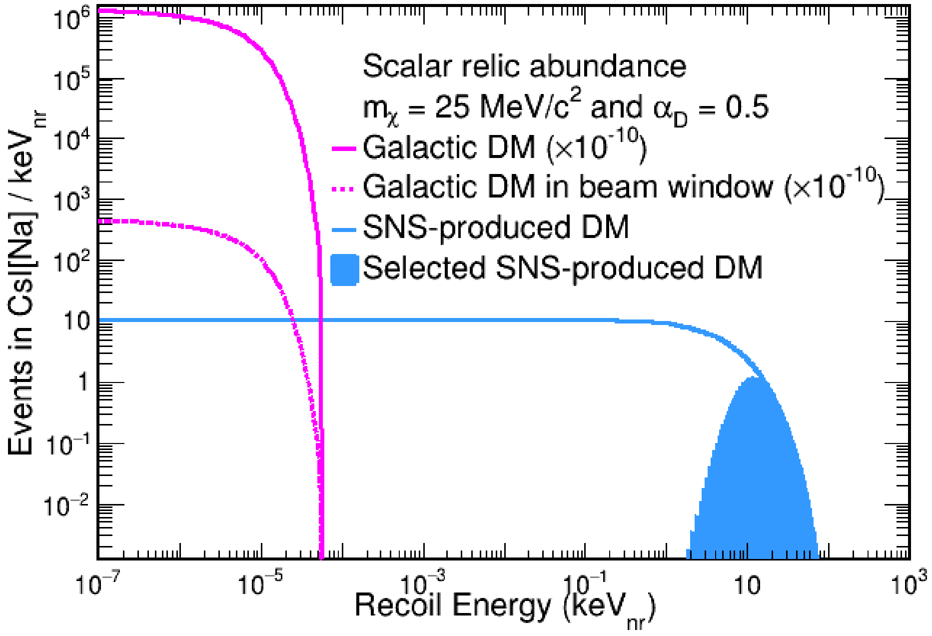
Denton and Gehrlein, *PRD* **106** 015022 (2022)

CEvNS connections: dark matter





[COHERENT, *PRL* **130** 051803 (2023)]



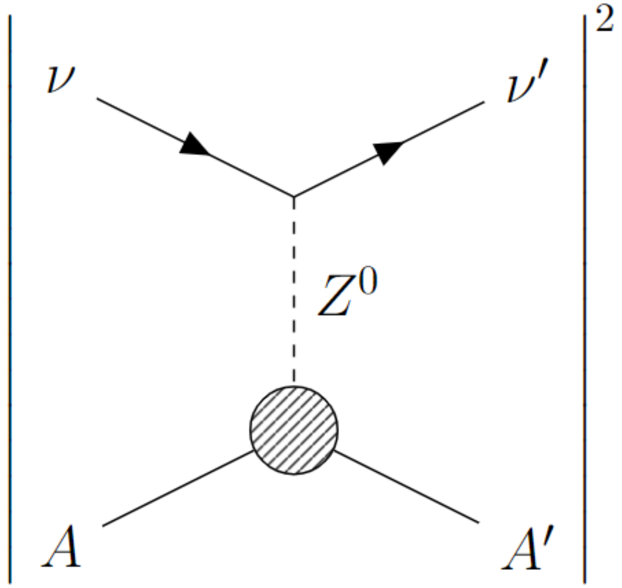
Portal to hidden-sector dark matter

$$\mathcal{L} = \mathcal{L}_\chi - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu - \underline{\frac{\kappa}{2}V^{\mu\nu}F_{\mu\nu}}$$

– Galactic dark matter is slow: β < few parts per mil
– Dark matter particles produced at accelerators are relativistic and make comparatively enormous recoils

Coherence in CEvNS

$$\sigma \propto |\mathcal{M}|^2 =$$



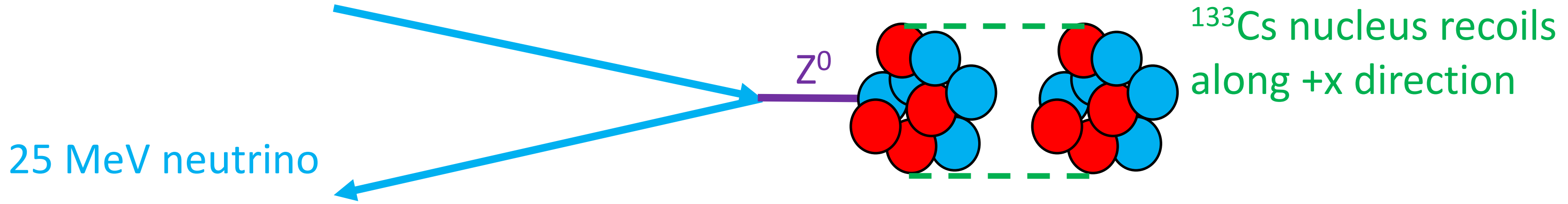
Quantum mechanics – charge of the nucleus is sum of charges of individual nucleons within. Probability to scatter is proportional to the square of the sum

Coherence: $\sigma \propto Q_W^2$

$$Q_W^2 = (g_p^V Z + g_n^V N)^2 = \left[(1 - 4\sin^2\theta_W)Z - N\right]^2$$

$$\frac{d\sigma}{dE_{\text{rec}}} = \frac{G_F^2}{4\pi} Q_W^2 \left(1 - \frac{E_{\text{rec}}}{E_{\text{rec,max}}}\right) |F(Q^2)|^2$$

Elastic scattering: Kinematics



Elastic neutrino-nucleus scattering

Momentum transfer: $$Q \equiv \sqrt{|\Delta \mathbf{p}_\nu|^2 - \Delta E_\nu^2} \approx |\Delta \mathbf{p}_\nu| \leq 2E_\nu$$

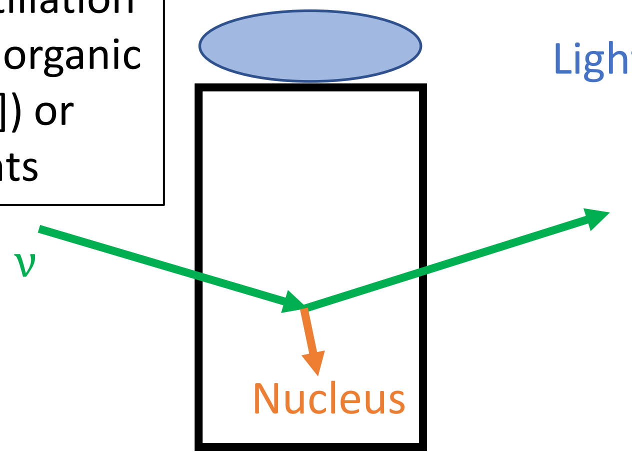
^{133}Cs kinetic energy: $$E_{\text{rec}} \approx \frac{p_{\text{Cs}}^2}{2m_{\text{Cs}}} = \frac{Q^2}{2m_{\text{Cs}}} \leq \frac{2E_\nu^2}{m_{\text{Cs}}} = 10.1\ \text{keV}$$

CEvNS energy scales:
$$\begin{cases} E_\nu \sim 25\ \text{MeV} \\ Q \sim 50\ \text{MeV} \\ E_{\text{rec}} \sim 10\ \text{keV} \end{cases}$$

$$\frac{d\sigma}{dE_{\text{rec}}} = \frac{G_F^2}{4\pi} Q_W^2 \left(1 - \frac{E_{\text{rec}}}{E_{\text{rec,max}}}\right) |F(Q^2)|^2$$

Challenge: detecting low levels of scintillation

General CEvNS scintillation detector – doped inorganic crystals (e.g. CsI[Na]) or liquid noble elements



Light detector – e.g. Photomultiplier tube (PMT)

Monitor scintillation activity in crystal with light detector, *but how many photons do we expect to collect?*

Initial recoil energy	10 keV	CEvNS interaction – neutrino kicks a nucleus giving it 10 keV of kinetic energy

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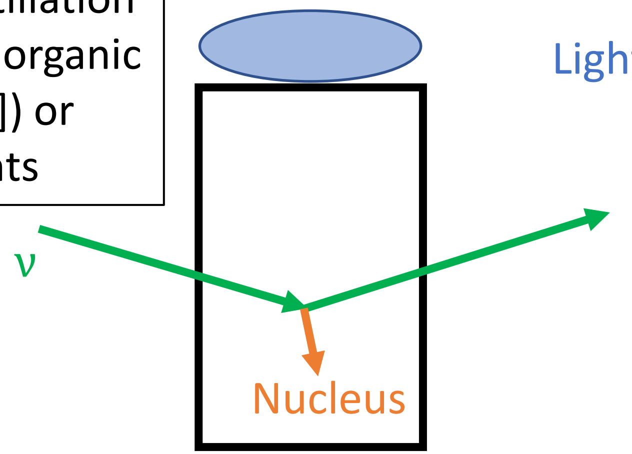

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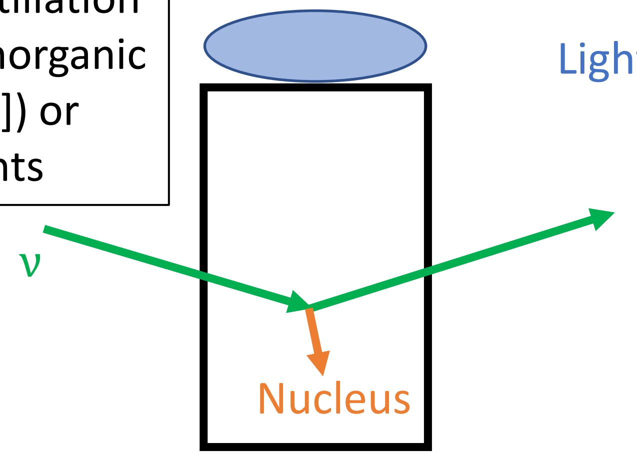

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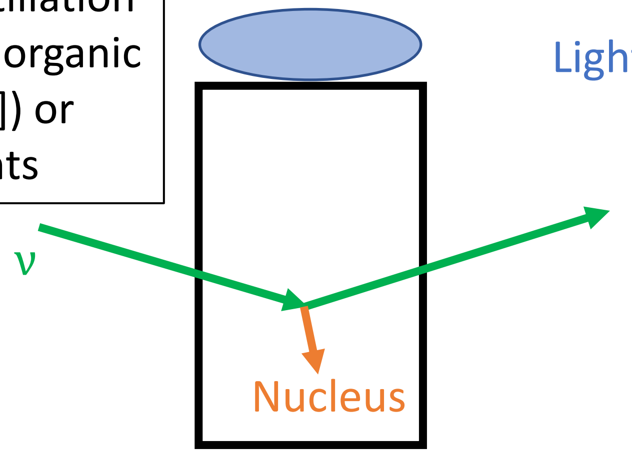

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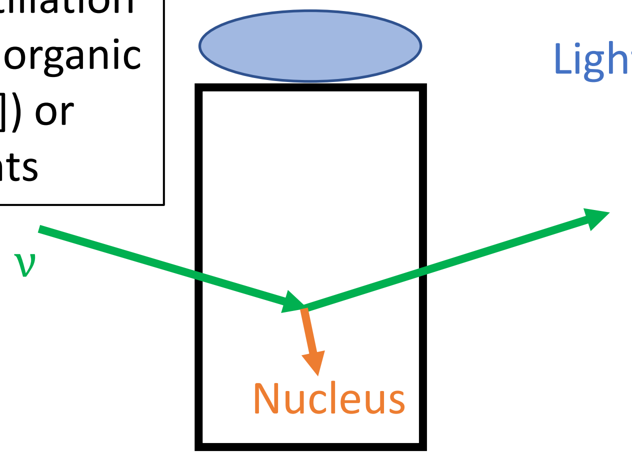

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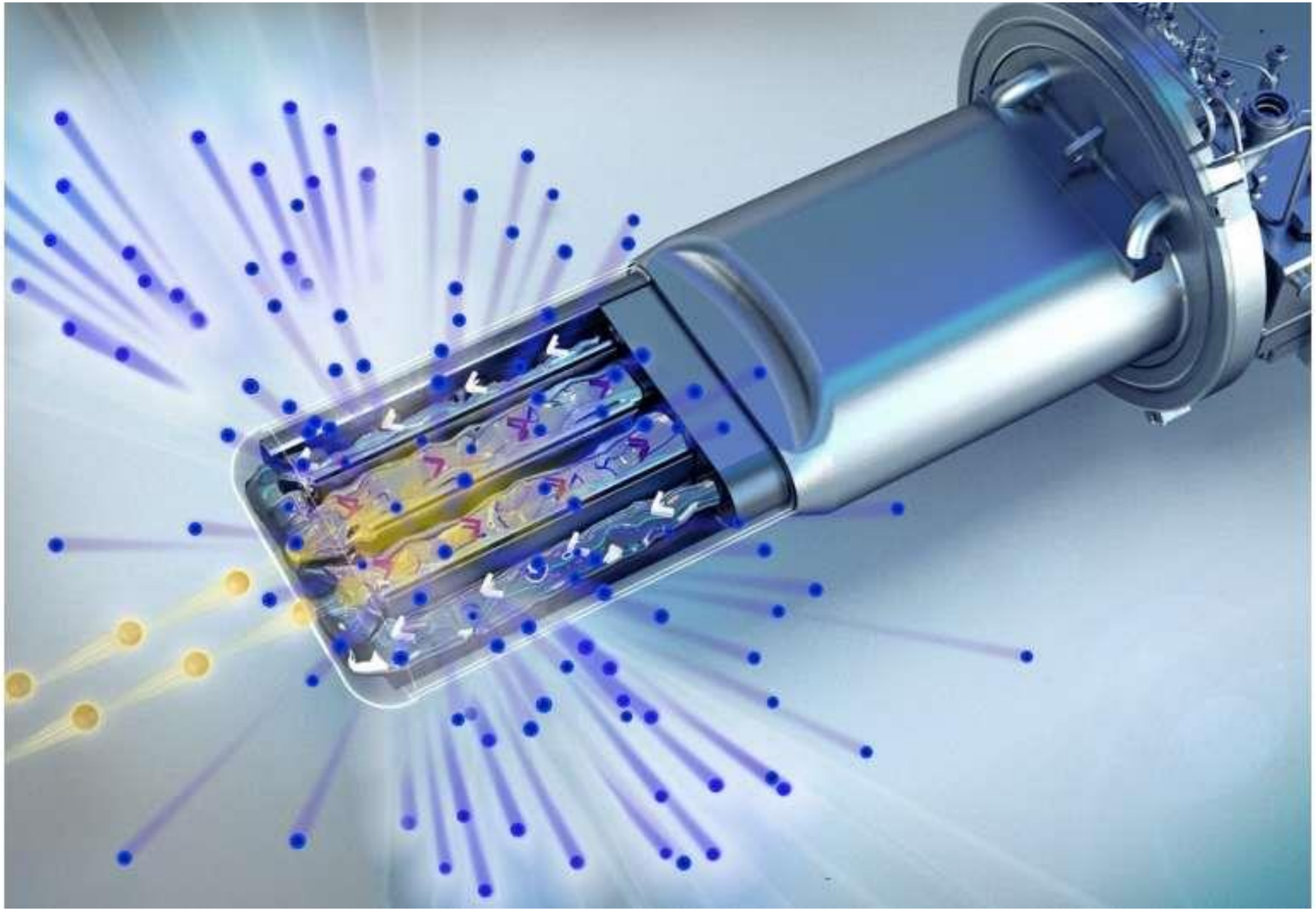
PMT quantum efficiency	10 γ	Light detectors have quantum efficiency for detecting photon. Depends on detector and scintillation wavelength

The Spallation Neutron Source (SNS)

Oak Ridge National Lab in Tennessee, USA
1.4 MW -> 2.1 MW (2027) of 1GeV protons at 60 Hz
Delivers pulses of neutrinos 350 ns FWHM

Liquid mercury as a target

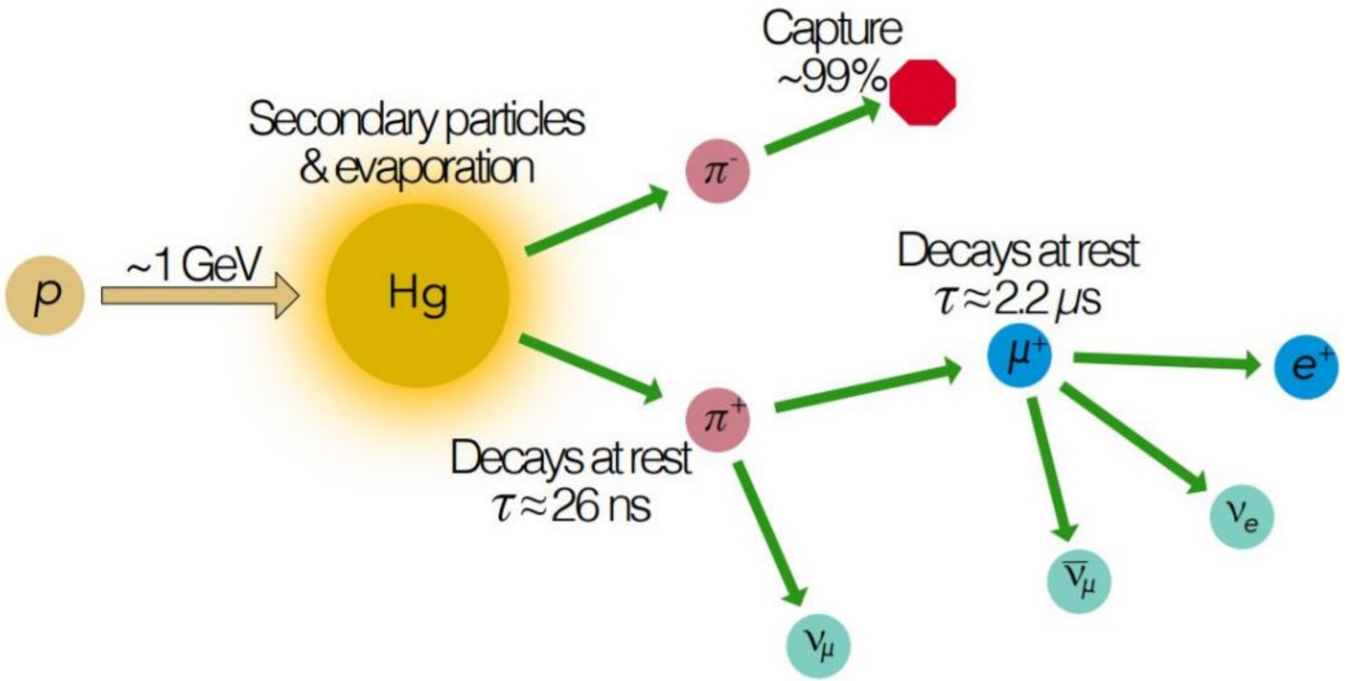


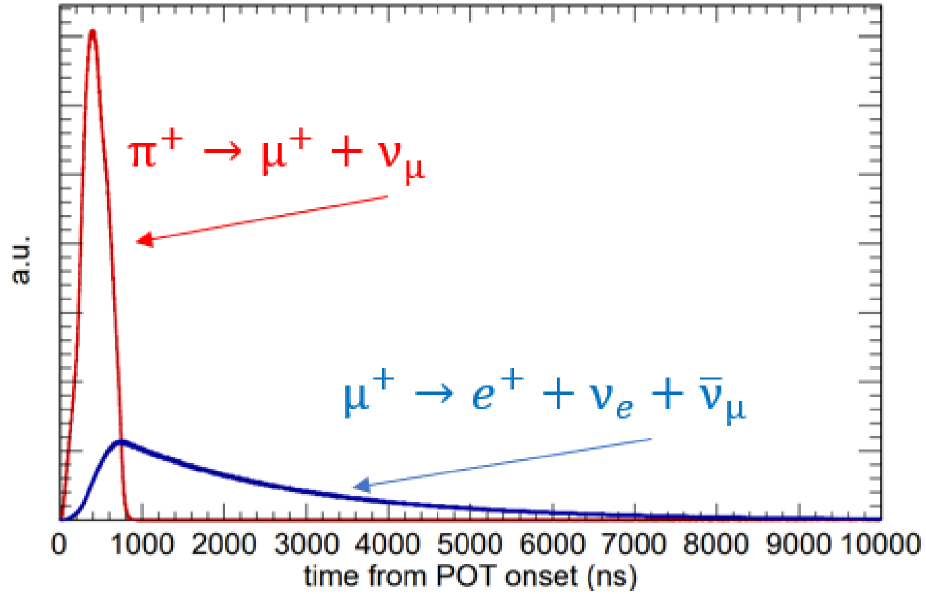
Concern for MW particle beams: cooling! SNS uses a liquid mercury target

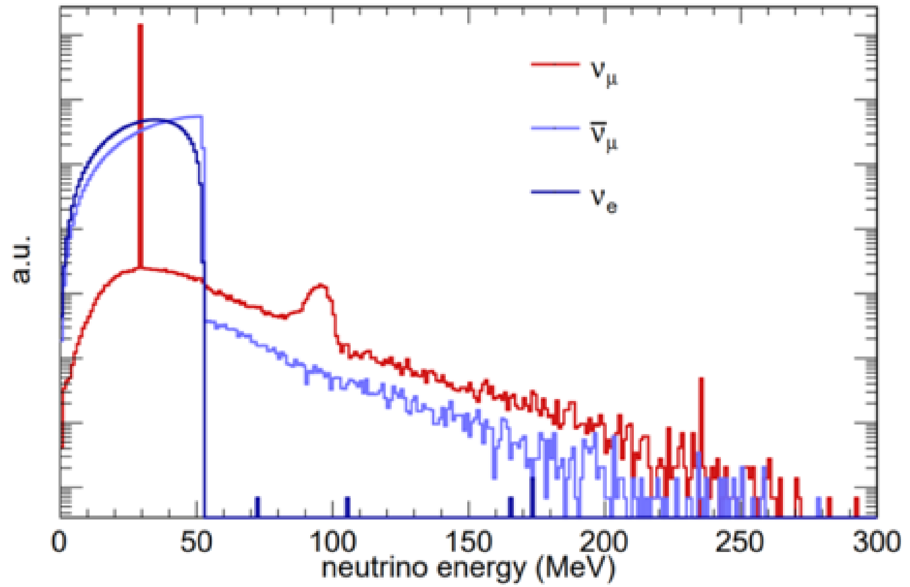
- Heavy nucleus in a liquid state -> can circulate and pass through a heat exchanger to cool

$\sim 0.1\ \pi^+$ / proton = 0.3 ν / proton

Neutrinos from pion decay





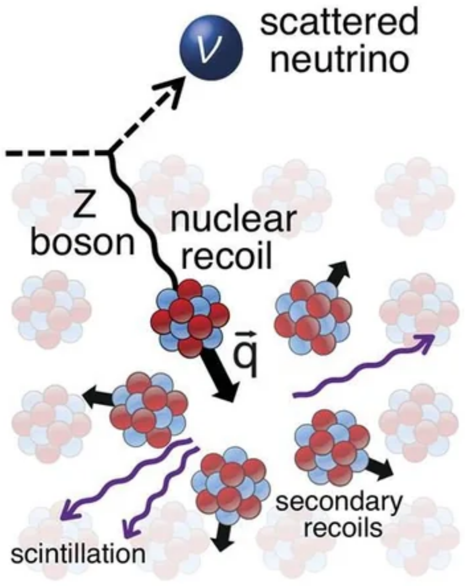


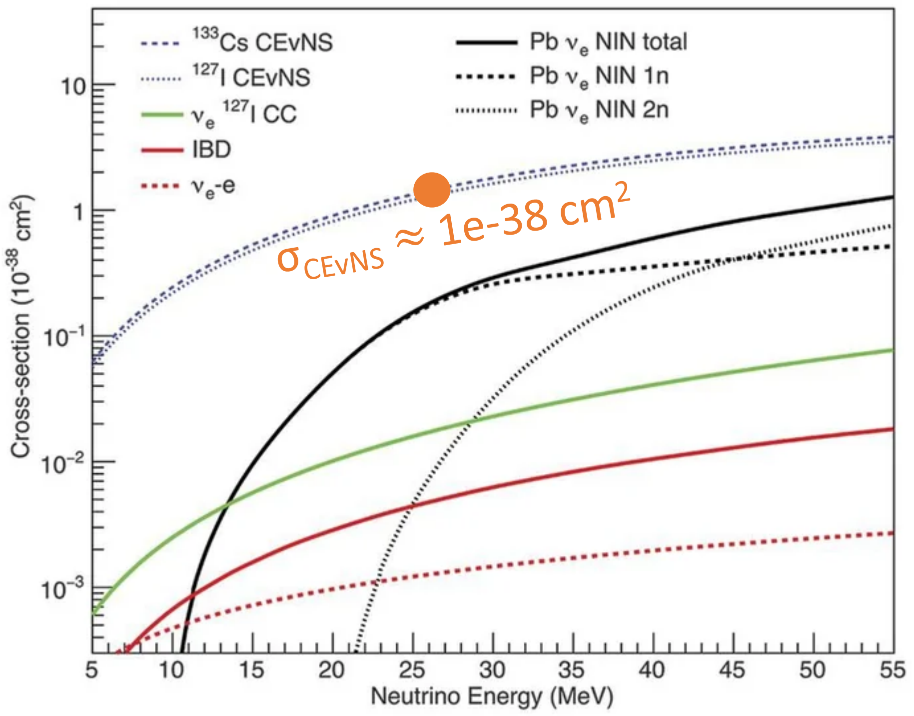
$$\pi^+ \to \mu^+ + \nu_\mu \quad : \; \tau = 26 \text{ ns}$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu \quad : \; \tau = 2200 \text{ ns}$$

Can we measure CEvNS at the SNS?

CEvNS was first seen by the COHERENT experiment at the SNS

How massive was the detector?





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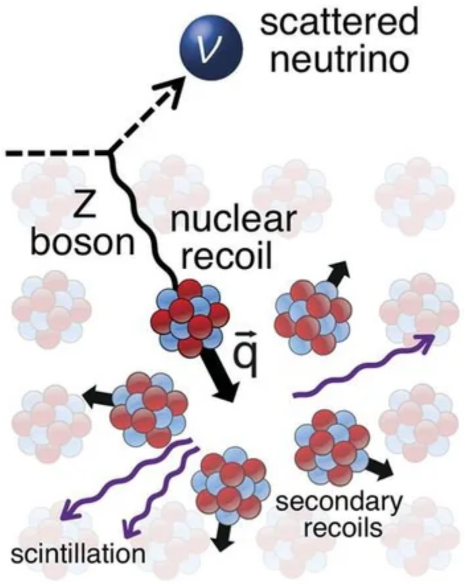
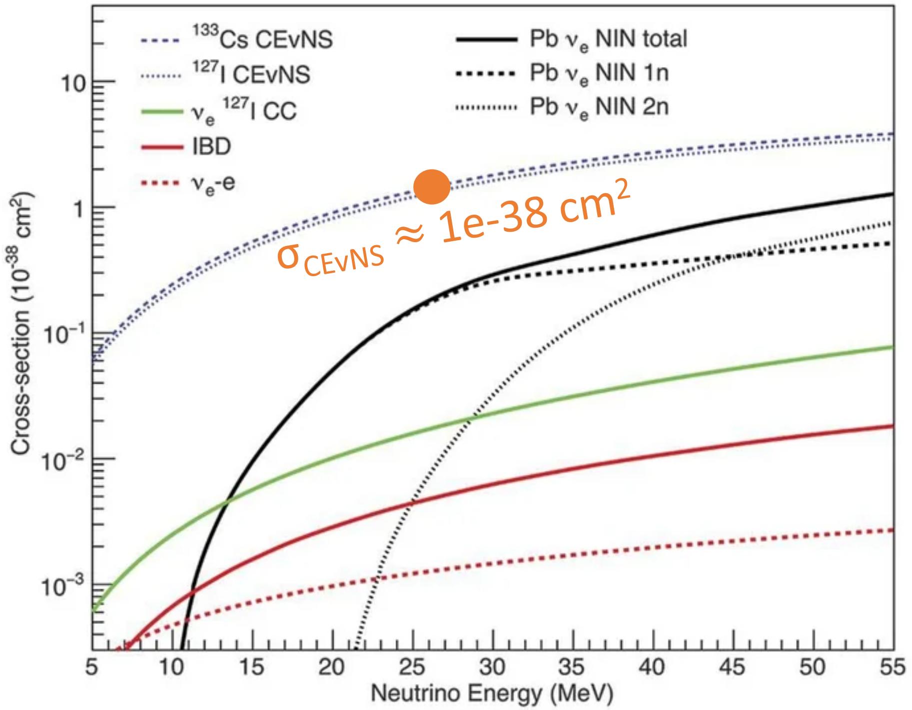
Let's say we want to build a detector that will record 1 CEvNS interaction each day 20 m from the SNS target





N_{proton} = 1.4 MW / (1 GeV) x 86400 s = 8e20

$N_{pi} = N_{proton}$ x 0.1 = 8e19

$N_{\nu} = 3\ N_{pi}$ = 2e20 →

ϕ_{ν} = 2e20 / [4pi(2000 cm)^2] = 5e-12 / cm^2

$N_{CEvNS} = N_{Cs/I} \times \sigma_{CEvNS} \times \phi_{\nu}$

$N_{Cs/I} = N_{CEvNS}/(\sigma_{CEvNS} \times \phi_{\nu})$ = 1/(1e-38 cm^2 x 5e-12/cm^2)

$N_{Cs/I}$ = 2e25 Cs/I atoms = 5 kg

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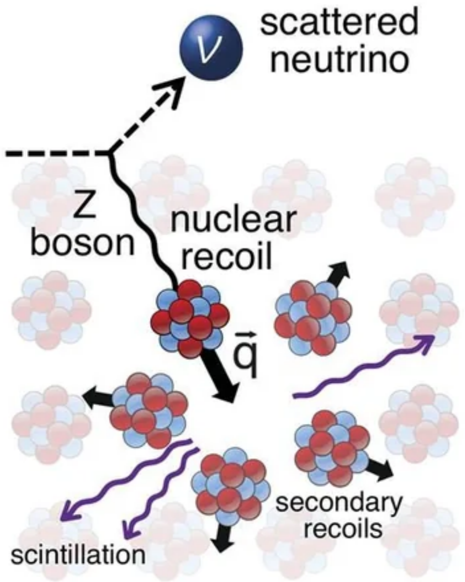

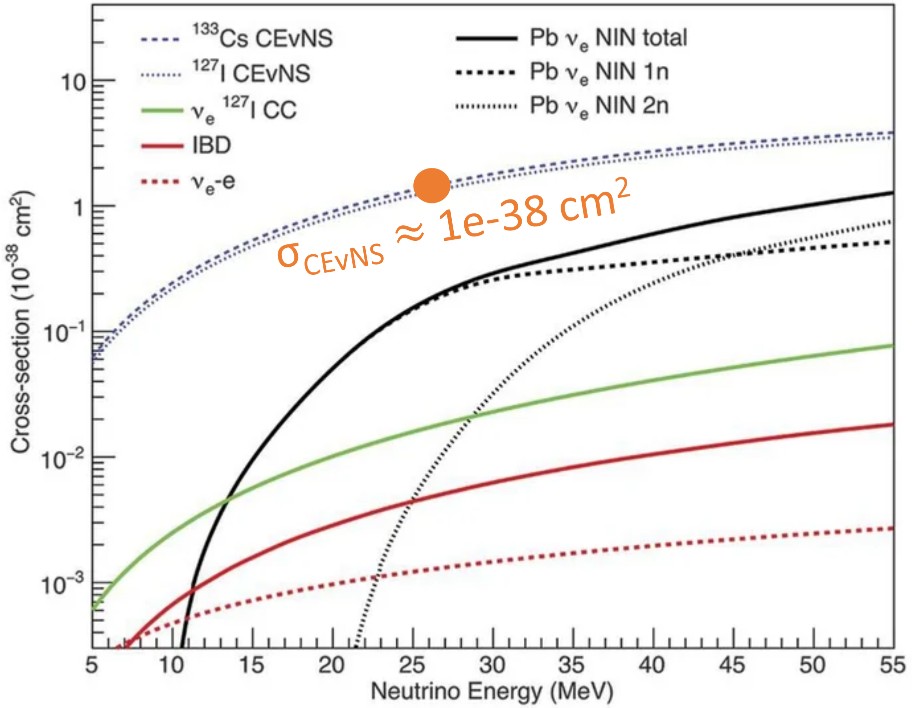

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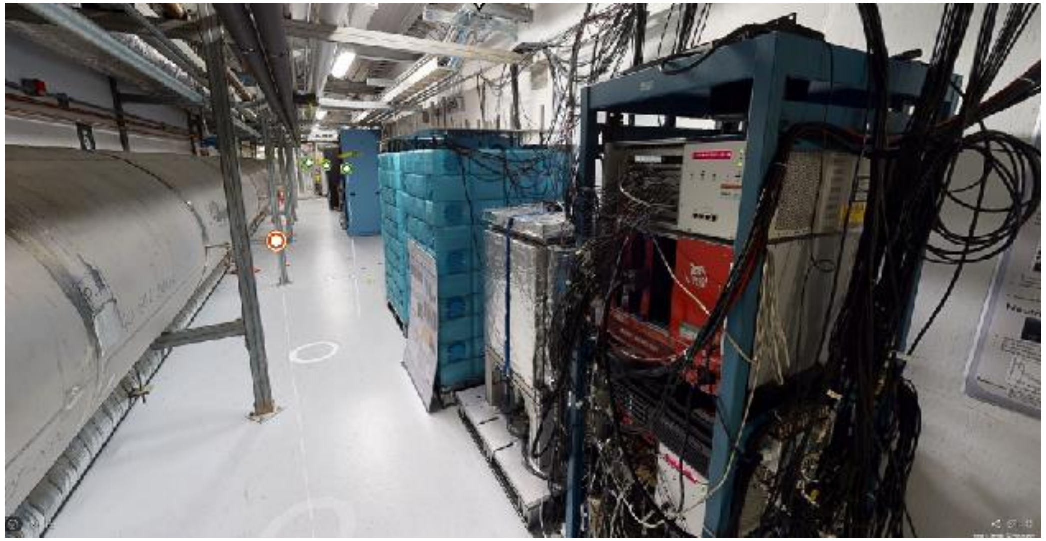
Answer: 14.6 kg

Hand-held detector

The COHERENT experiment at the SNS

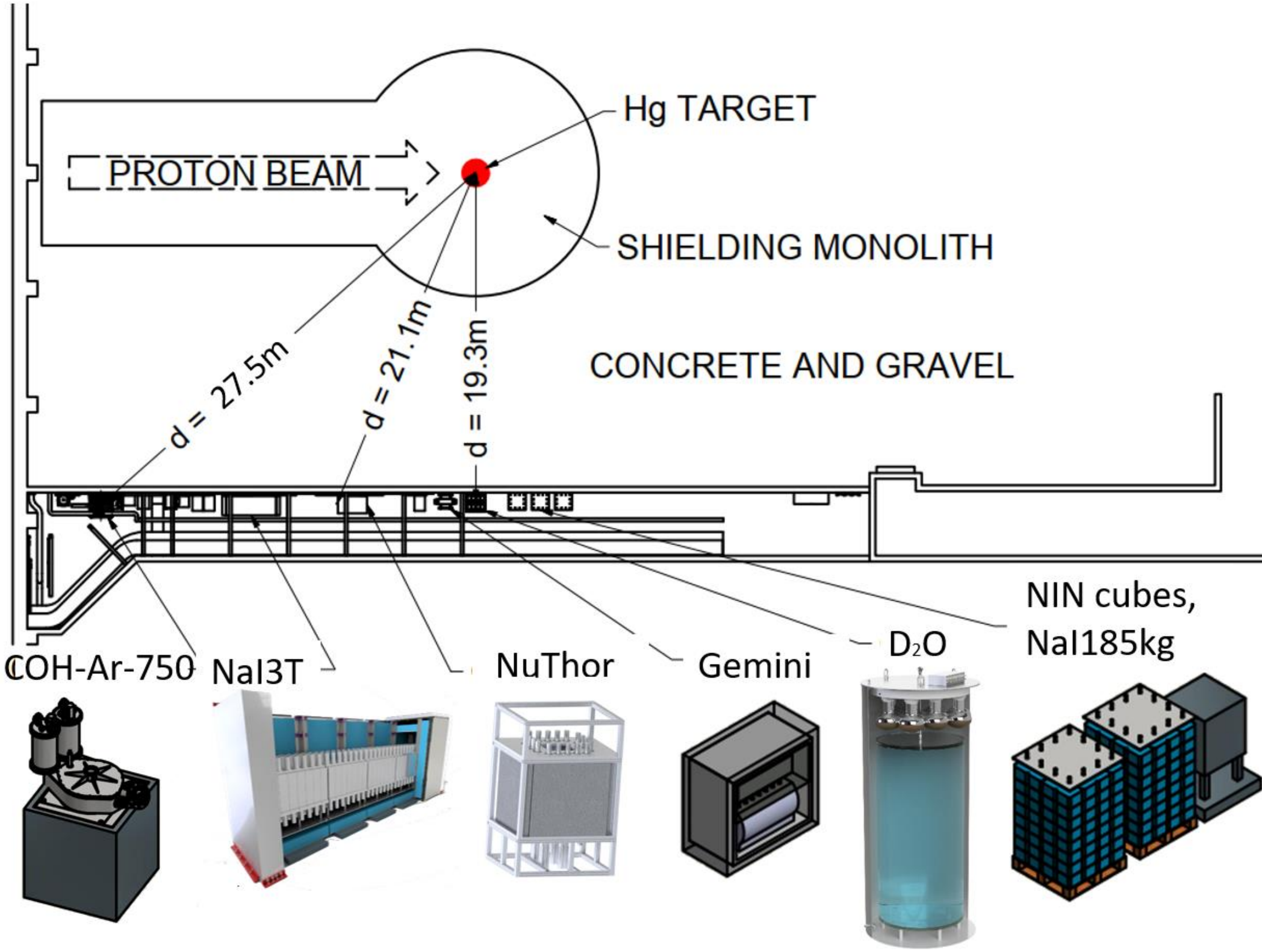
A suite of neutrino detectors in a cramped hallway



Goal: measure as many low-energy neutrino cross sections as possible

CEvNS:
Measured: CsI/Ar/Ge
Ongoing: Na

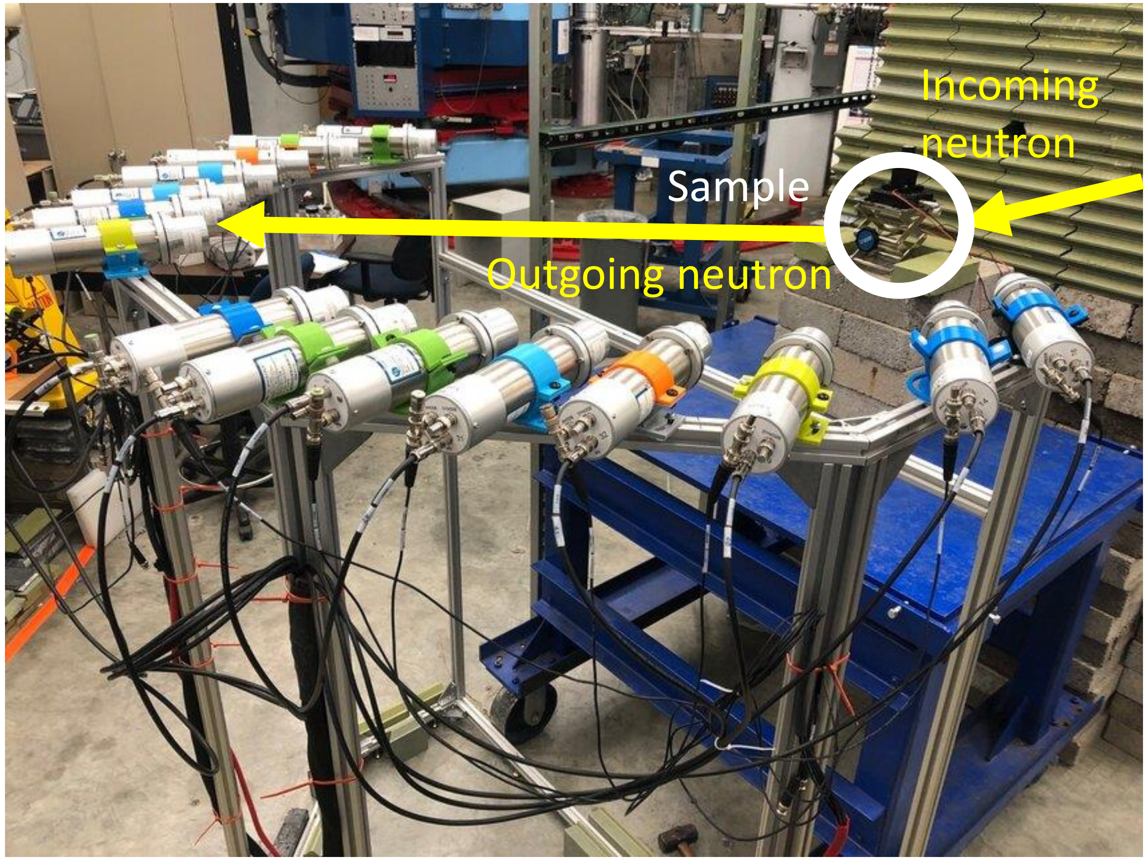
Inelastics:
Measured: Pb/I
Ongoing: Ar/D_2O/Th



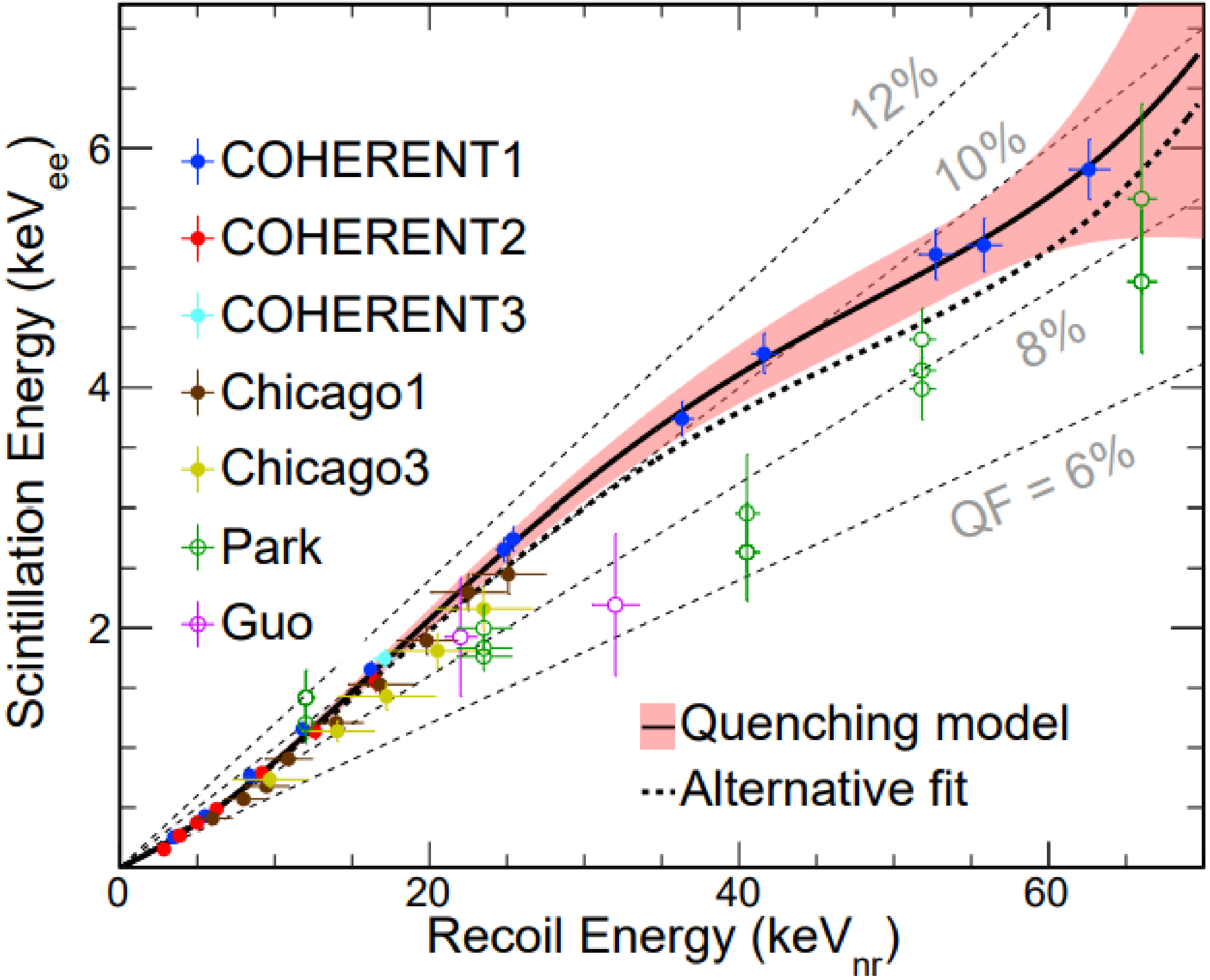
Take a VR tour here

CsI[Na] scintillation response to nuclear recoils

Only a fraction of nucleus's kinetic energy, E_{nr}, goes into scintillation energy, E_{ee}: Quenching



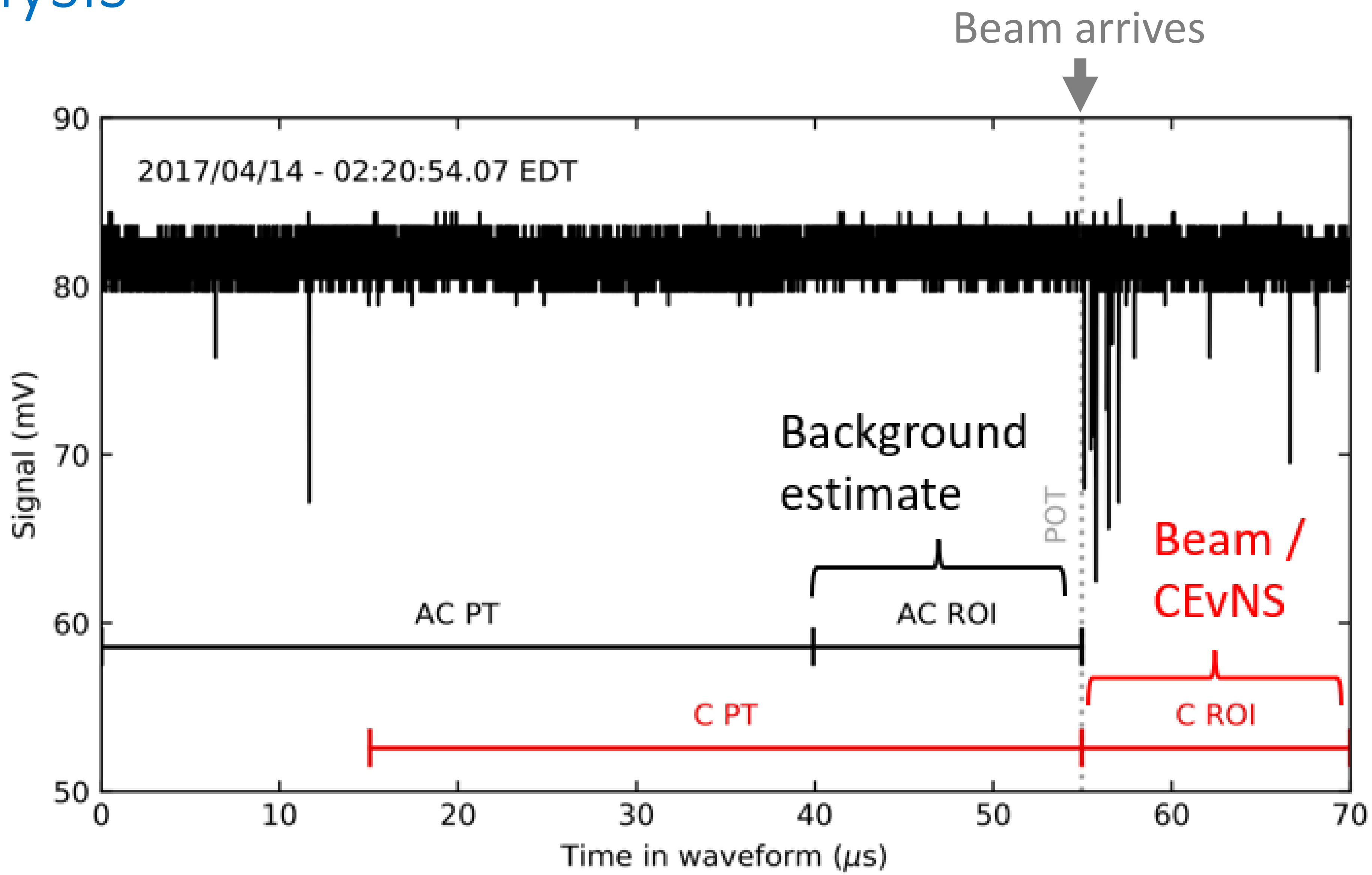
COHERENT, *JINST* **17** P10034, 2022



Waveform analysis

The accelerator is bunched in time:
350 ns @ 60 Hz

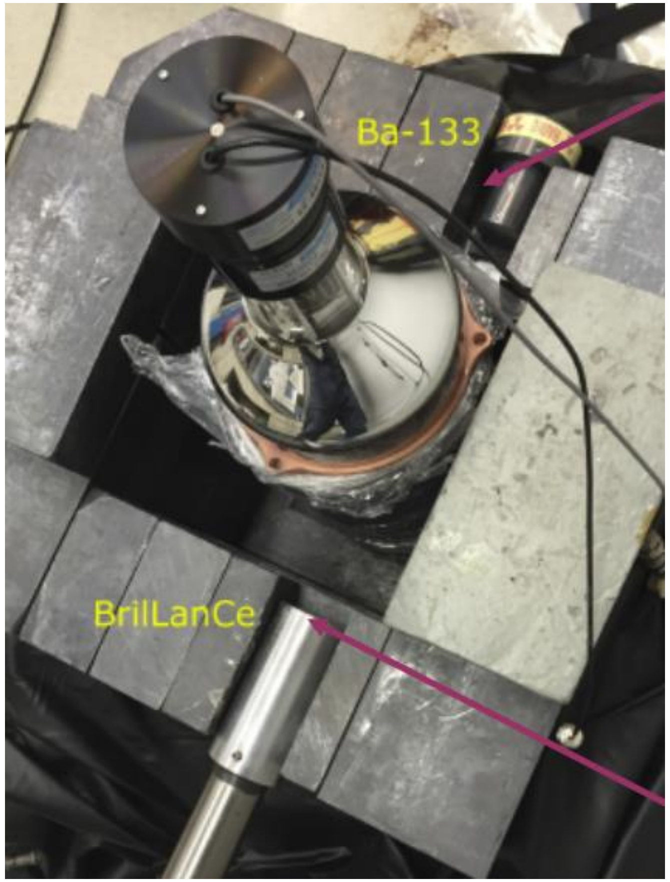
1: search for interacting beam neutrinos (C ROI)
2: estimate backgrounds in-situ (AC ROI)
3: monitor background scintillation in real-time with pre-trace (PT) to each ROI

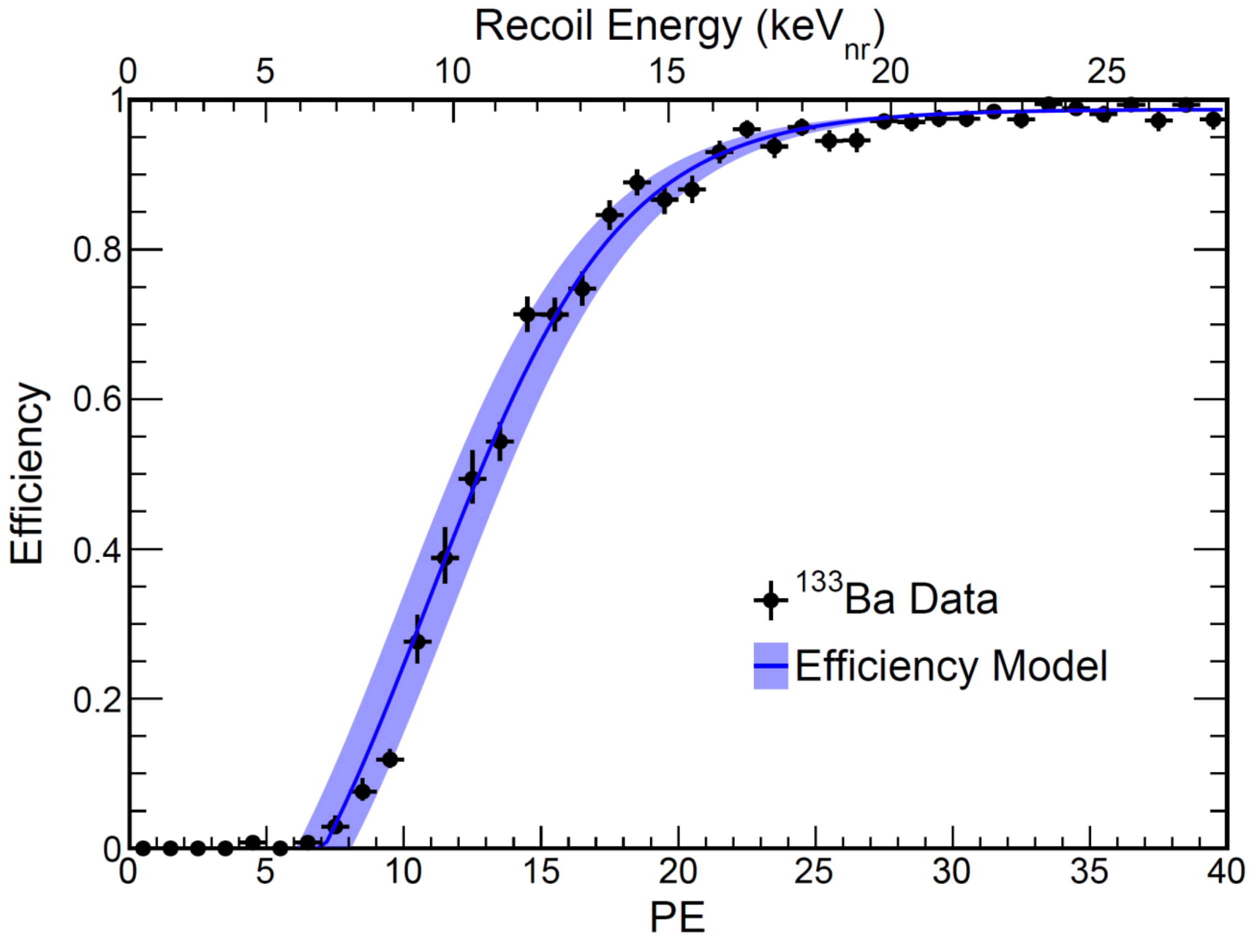


Efficiency for tagging nuclear recoils

Data-driven estimation of CEvNS selection efficiency

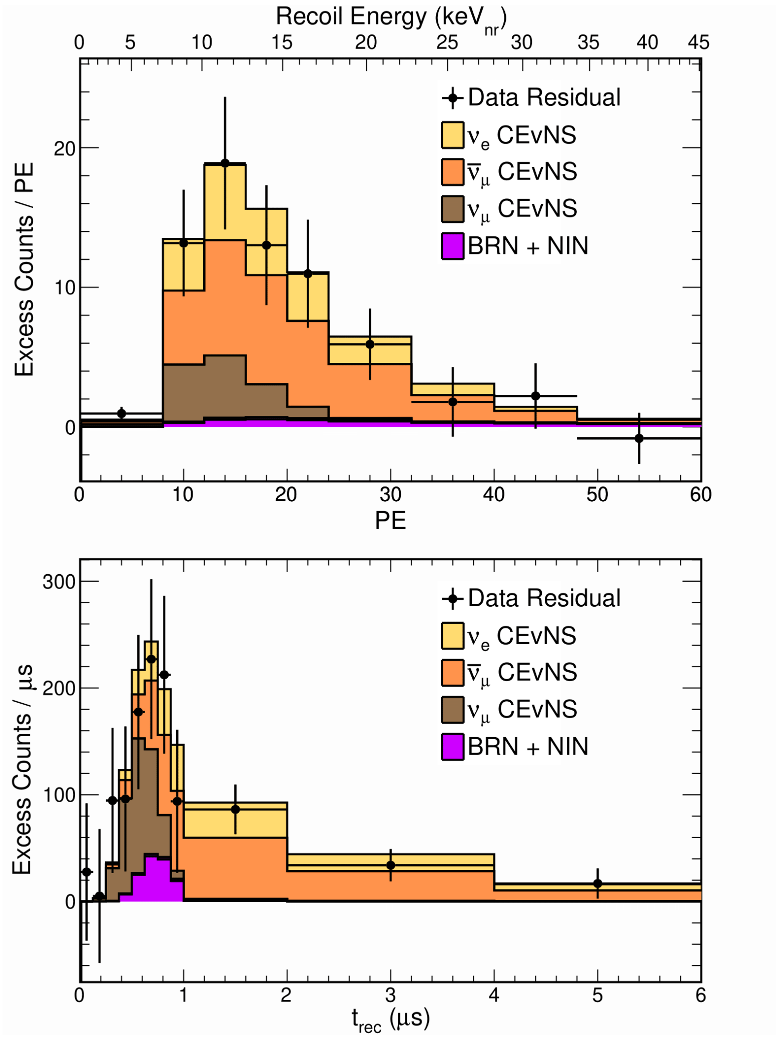
Coincidence measurement of collimated beam of photons from ^{133}Ba decay





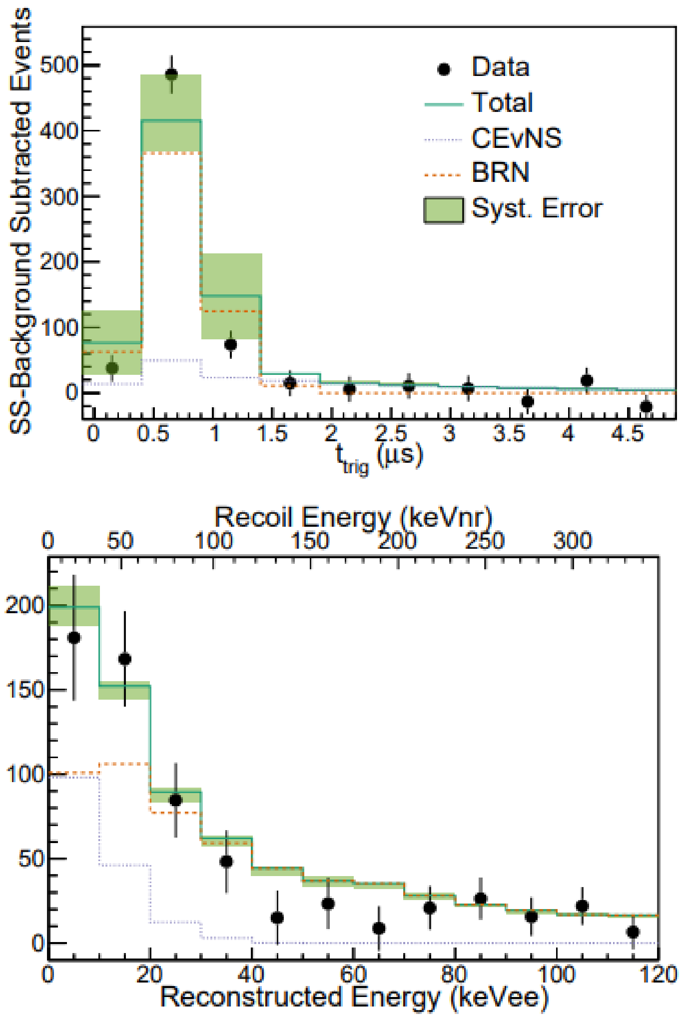
COHERENT CEvNS measurements

CsI – inorganic scintillator



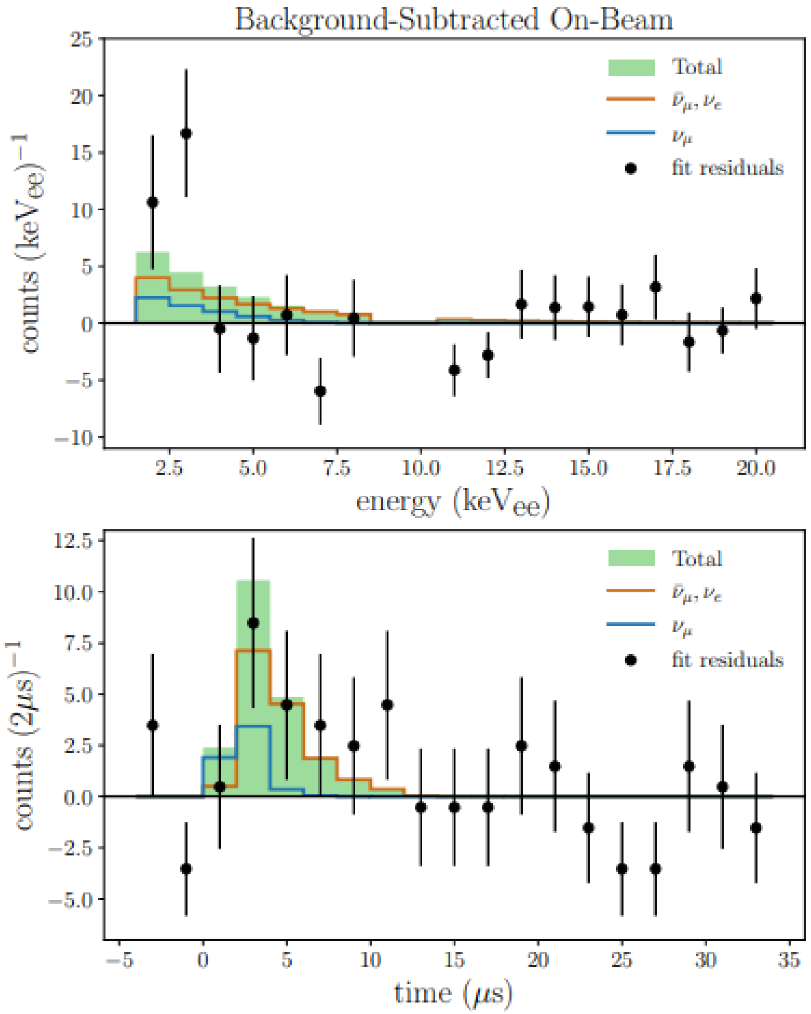
[COHERENT, PRL 129 081801 (2022)](#)

Argon scintillator



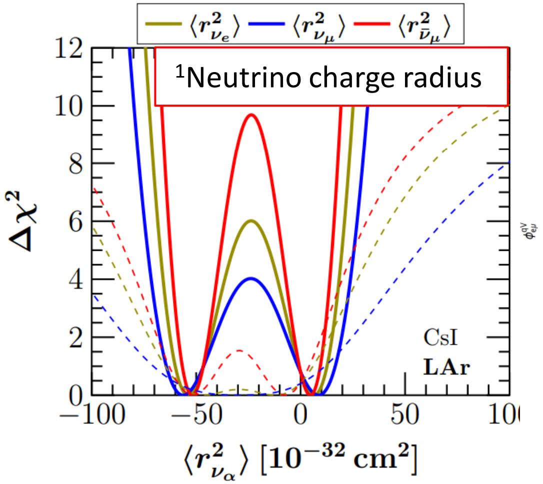
[COHERENT, PRL 126 012002 (2021)](#)

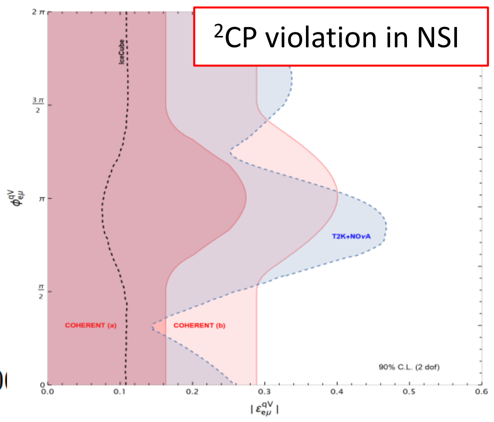
Germanium diode

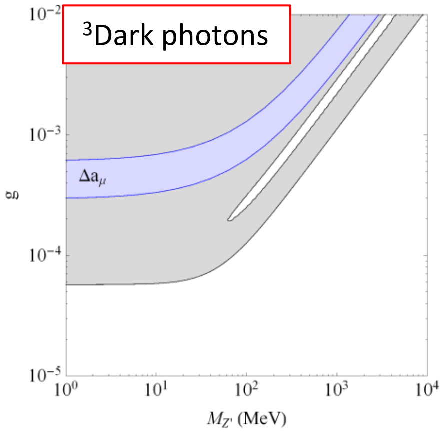


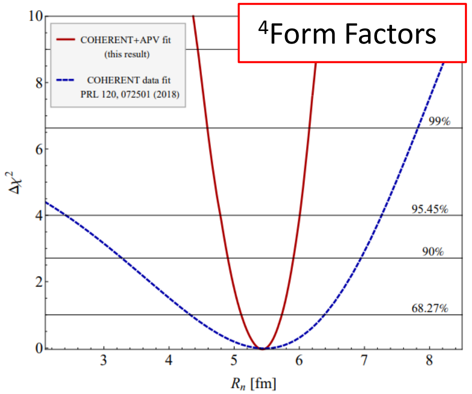
[COHERENT, arXiv:2406.13806 (2024)](#)

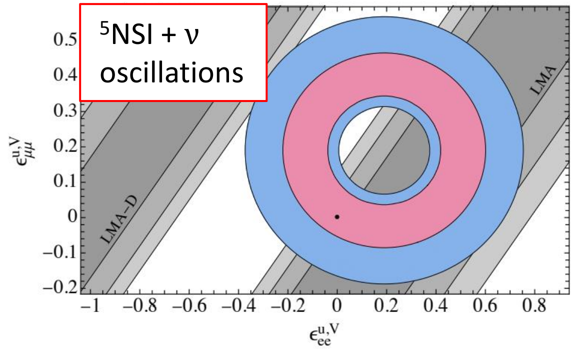
Physics with COHERENT

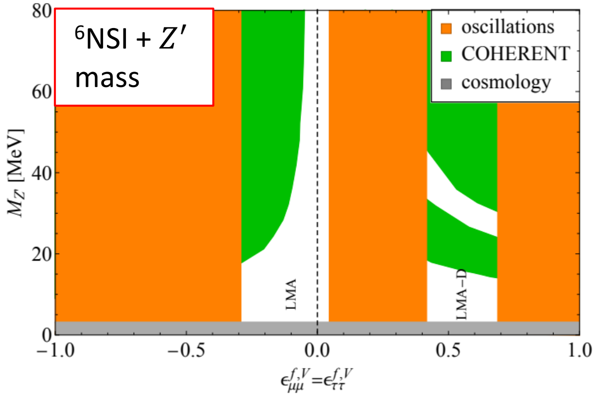


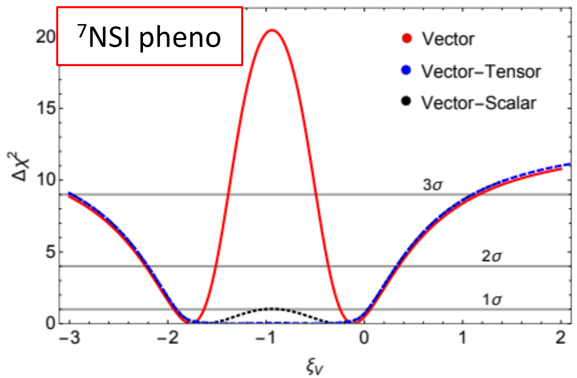


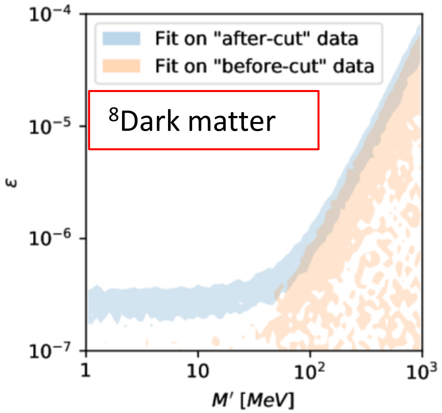


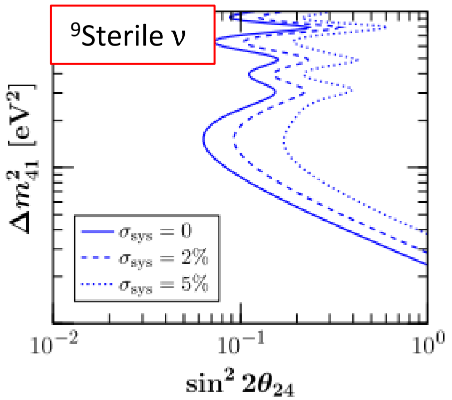


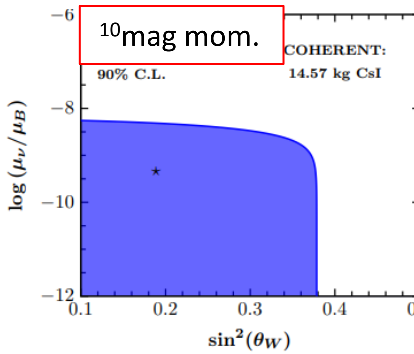






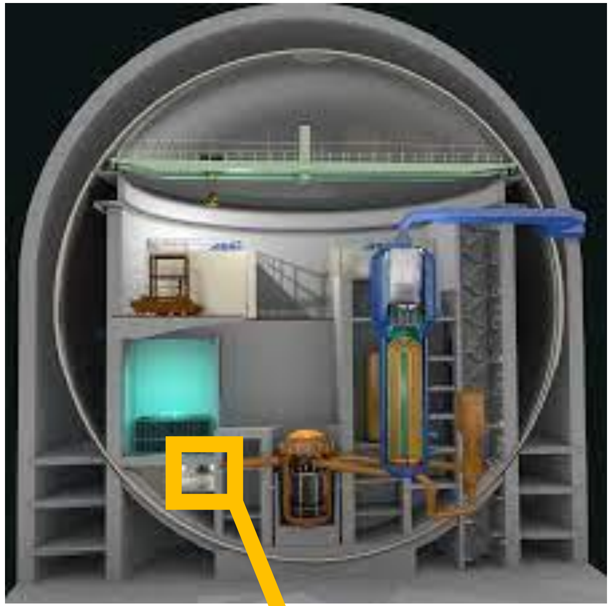




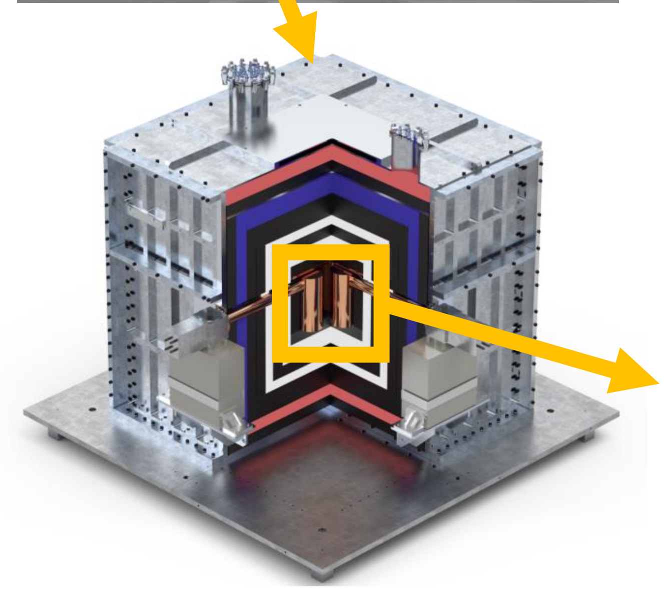


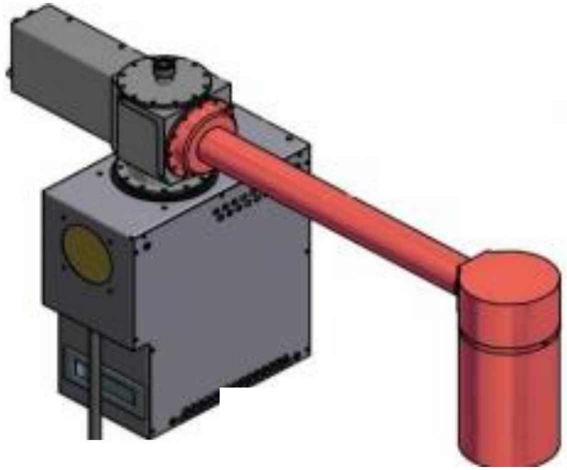
[1]Miranda et al., *JHEP* **05** 130 (2021)
[2]Khan et al., *PRD* **104** 015019 (2021)
[3]Liao/Marfatia, *PLB* **775** 54-57 (2017)
[4]Cadeddu/Dordei, *PRD* **99** 092003(2019)
[5]Coloma et al., *PRD* **96** 115007 (2017)
[6]Denton/Gehrlein, *PRD* **106** 015022 (2022)
[7]Sierra et al., *PRD* **98** 075018 (2018)
[8]Dutta et al., *PRL* **124** 121802 (2019)
[9]Miranda et al., *PRD* **102** 113014 (2020)
[10]Papoulias/Kosmas, *PRD* **97** 033003 (2017)

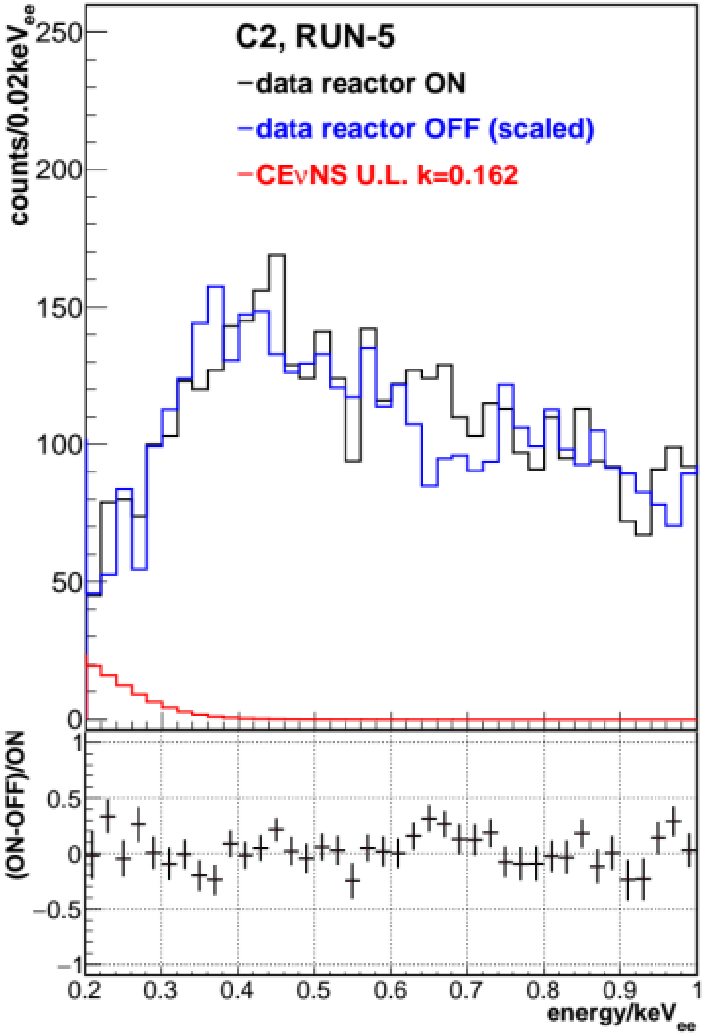
CEvNS at reactors – CONUS



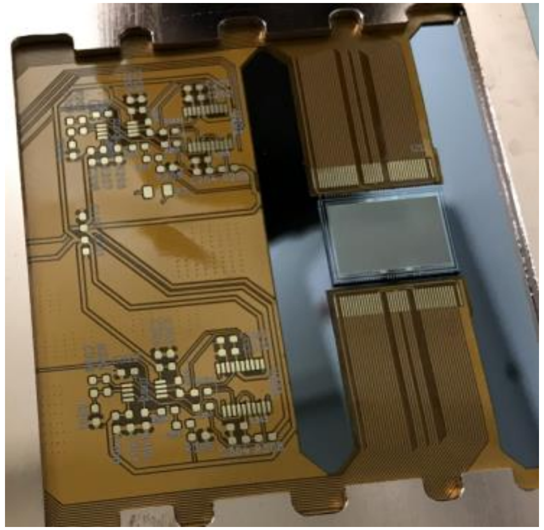
- Ge ionization detectors operated at Brokdorf nuclear reactor
- Strictest constraint of CEvNS cross section at a reactor – 2 x SM
- CONUS+: upgraded electronics pushed threshold 210 -> 150 keV, collected reactor-off data
- reactor CEvNS hopefully soon



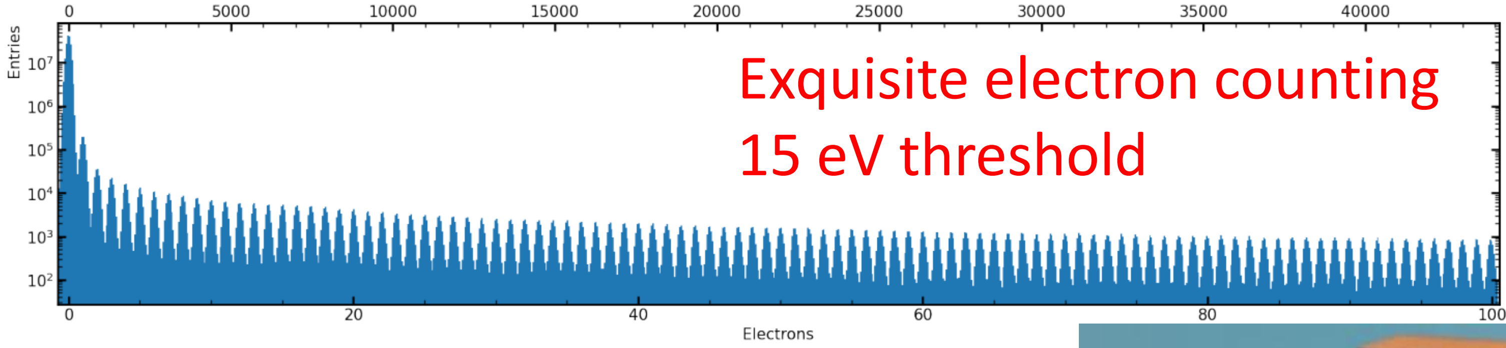




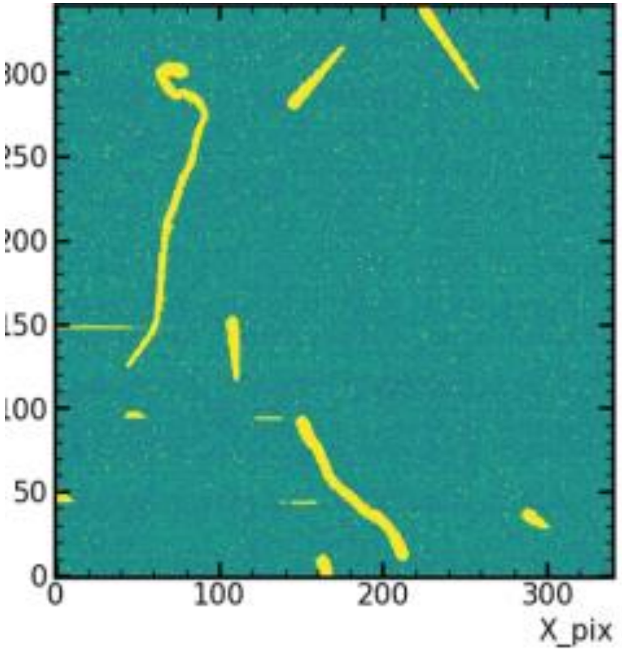
CEvNS at reactors – CONNIE

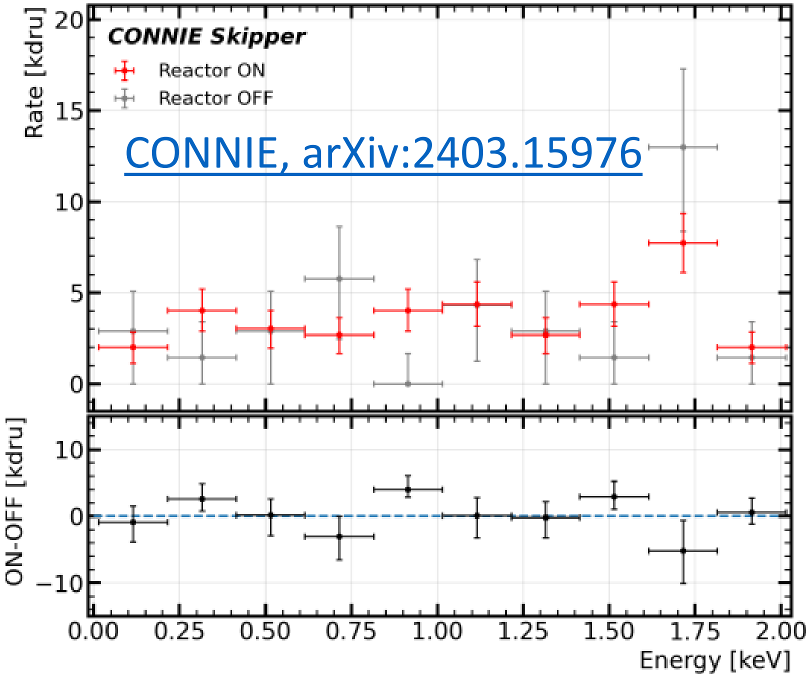


g-scale Si Skipper-CCD detectors at Angra reactor (Rio de Janeiro)



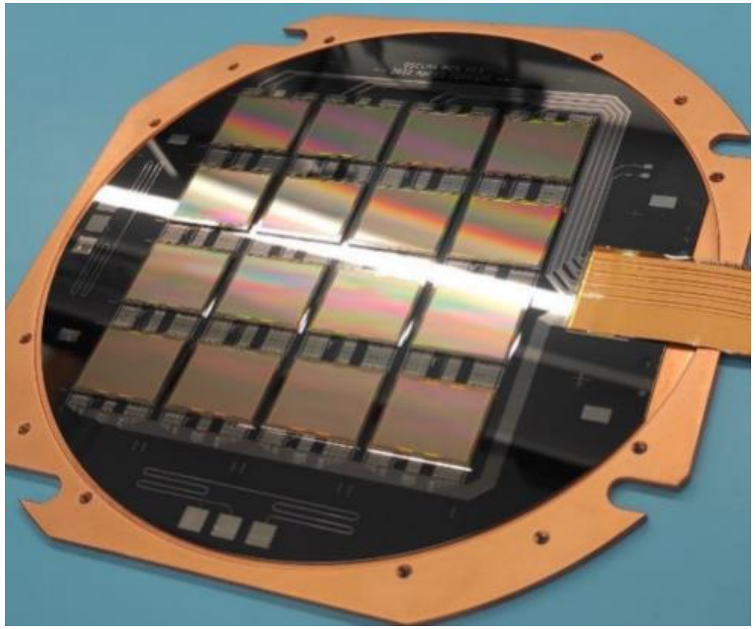
Exquisite electron counting
15 eV threshold





[CONNIE, arXiv:2403.15976](https://arxiv.org/abs/2403.15976)

Reactor cross section < 32 x SM



Multi-chip-module installed May 2024
32x active mass (8g)!

MeV

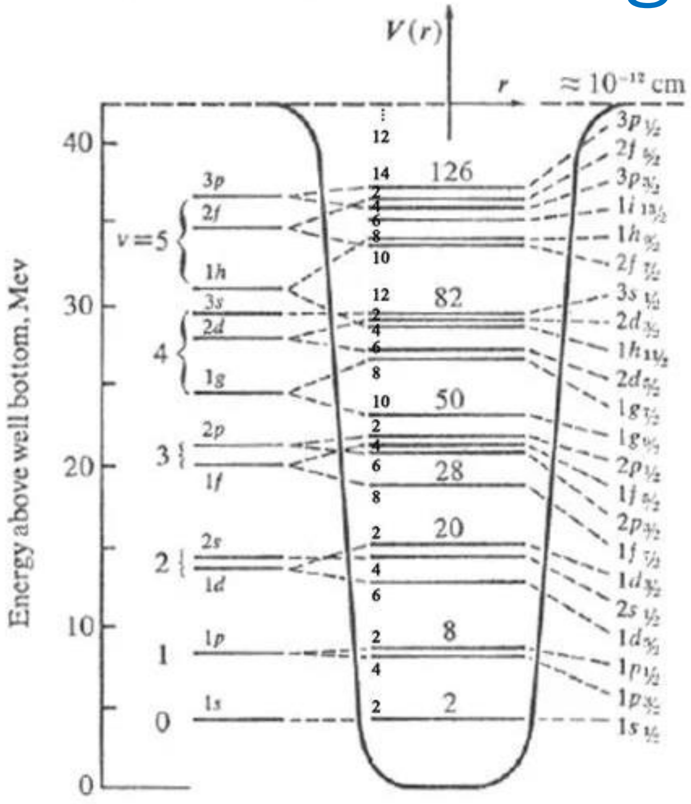
The inelastic regime

Inelastic scattering on nuclei

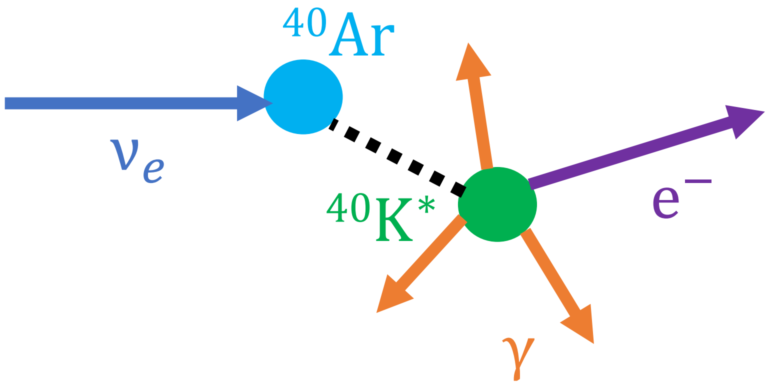
Inverse beta decay

ν-e elastic scattering

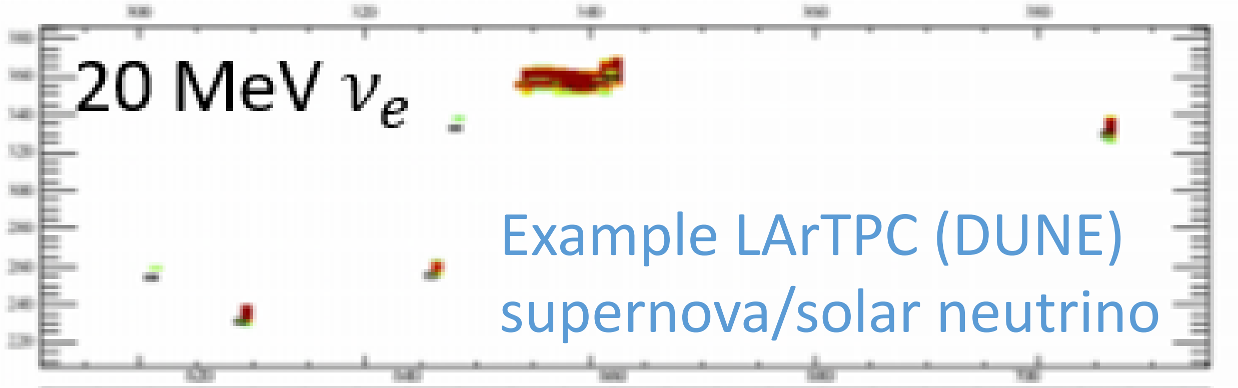
Inelastic scattering on nuclei – argon ν_e CC example



$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

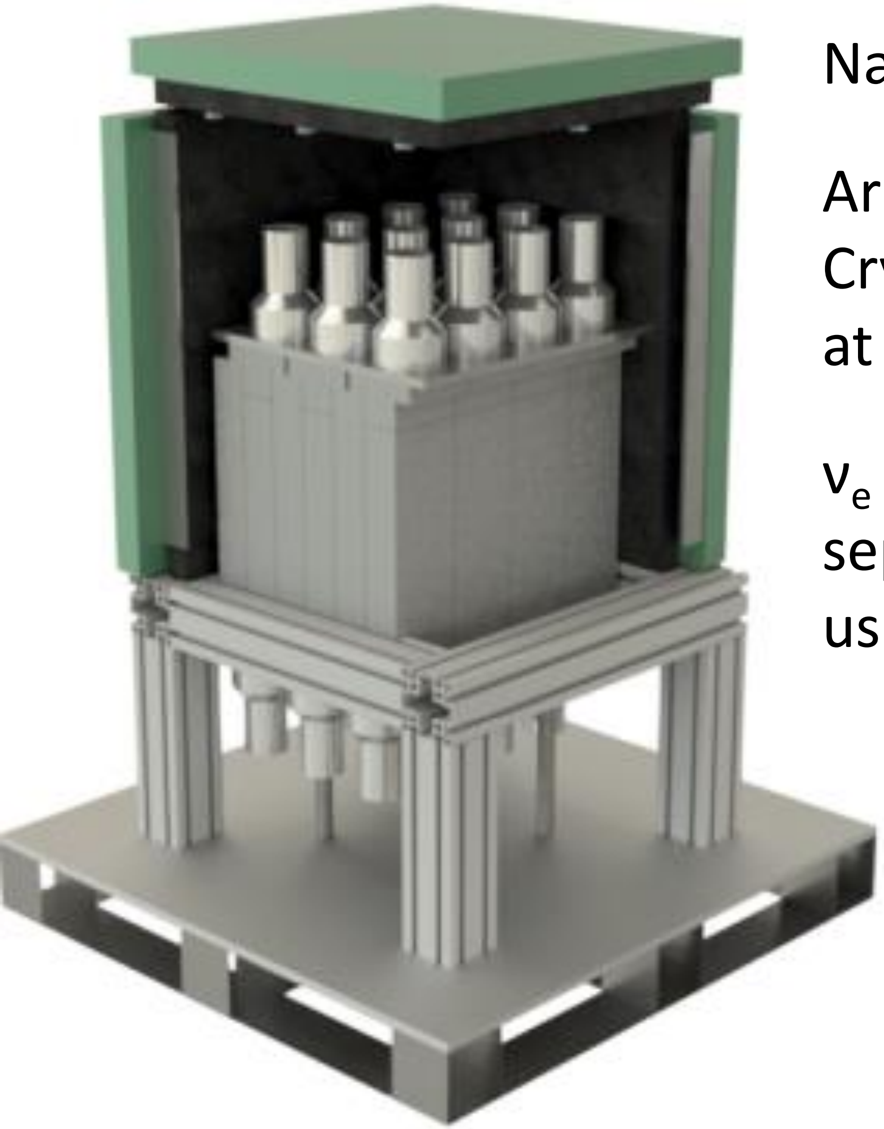


Visible energy: $E_\nu - (m_K + m_e - m_{Ar}) = E_\nu - 2.0$ MeV



– Bound scattering at MeV scale
– Like atomic electrons, protons and neutrons live in nuclear shells
– Neutrinos can bump up to an excited state

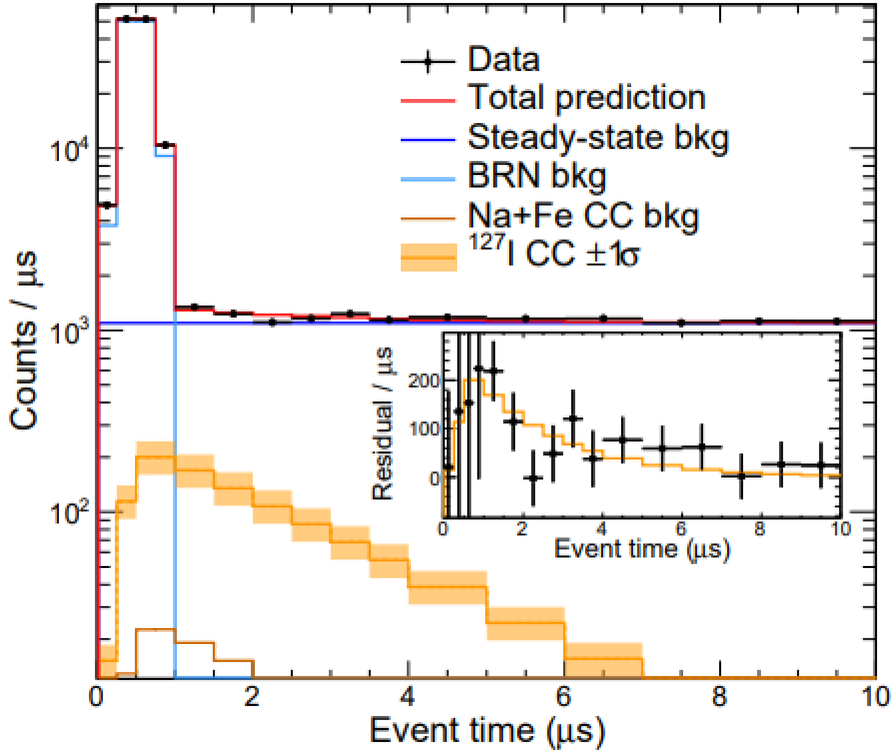
Measurement from COHERENT – iodine ν_e CC example



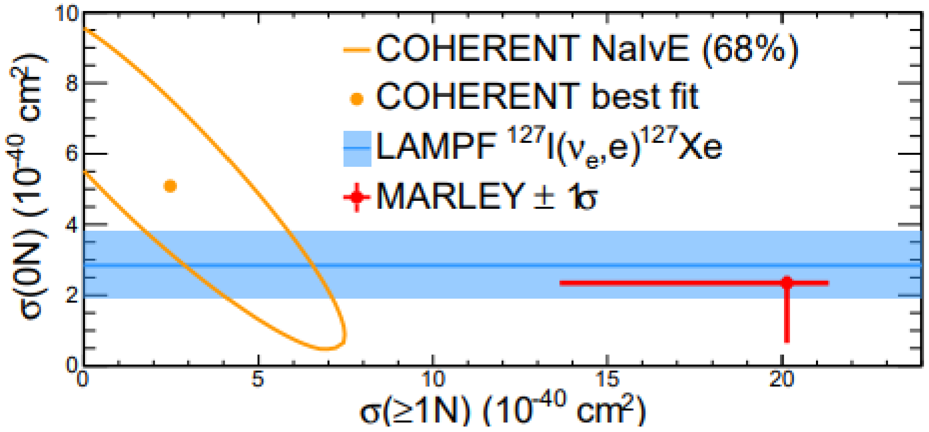
NaIvE COHERENT detector

Array of 24 7.7-kg NaI[Tl] Crystals in Neutrino alley at the SNS

ν_e CC signal on ^{127}I separated from background using timing information



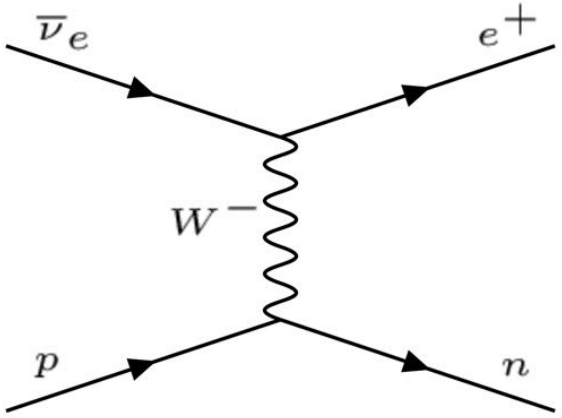
Distinguish between interactions that spit out a neutron using energy information



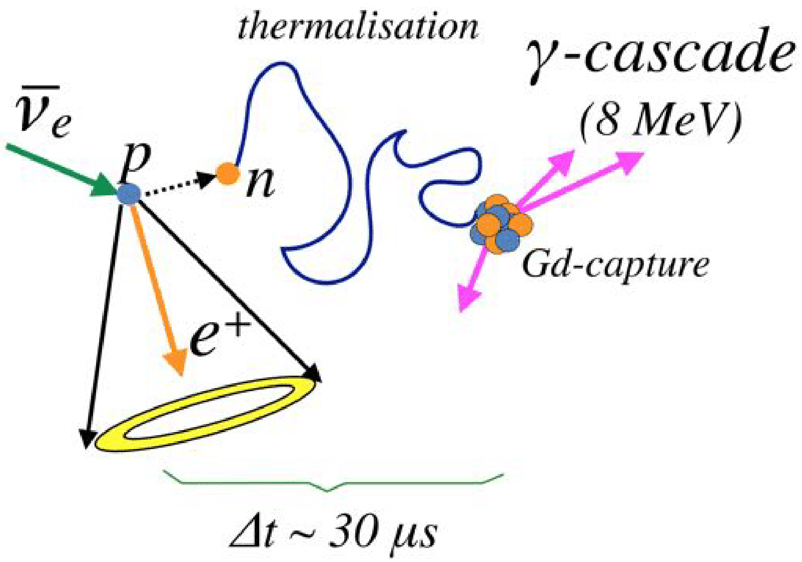
COHERENT *PRL* **131** 221801 (2023)

Inverse beta decay (IBD)

(anti)neutrino scattering



Inverse beta decay



Coincidence of two signals – background rejection!

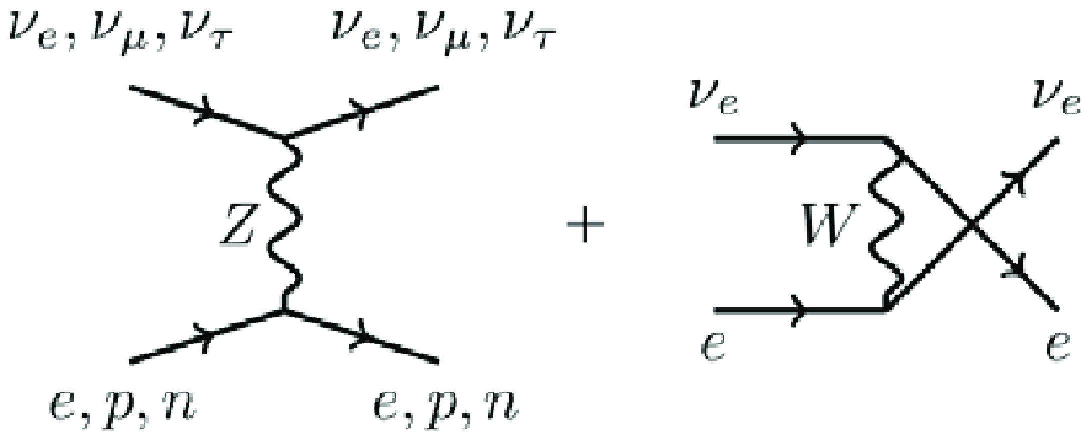
$\sigma \sim$ 1e-42 cm^2 @ 5 MeV

Pros:
Background rejection
Well-understood σ
Visible energy: E_ν – 1.8 MeV correlates with prompt energy

Cons:
Only sensitive to anti-ν
Must have free protons in scattering material

Common interaction channel for reactor and supernova anti-neutrinos

Neutrino-electron scattering (ES)



For $E_\nu \gg m_e$, outgoing electron almost parallel with neutrino

$\sigma \sim$ 5e-45 cm^2 @ 5 MeV (ν_e)
$\sigma \sim$ 2e-45 cm^2 @ 5 MeV ($\bar{\nu}_e$)
$\sigma \sim$ 0.6e-45 cm^2 @ 5 MeV (ν_x)

Pros:
Directional info
Well-understood σ
All detectors sensitive

Cons:
Tiny cross section
Poor energy estimates

GeV

The complicated regime

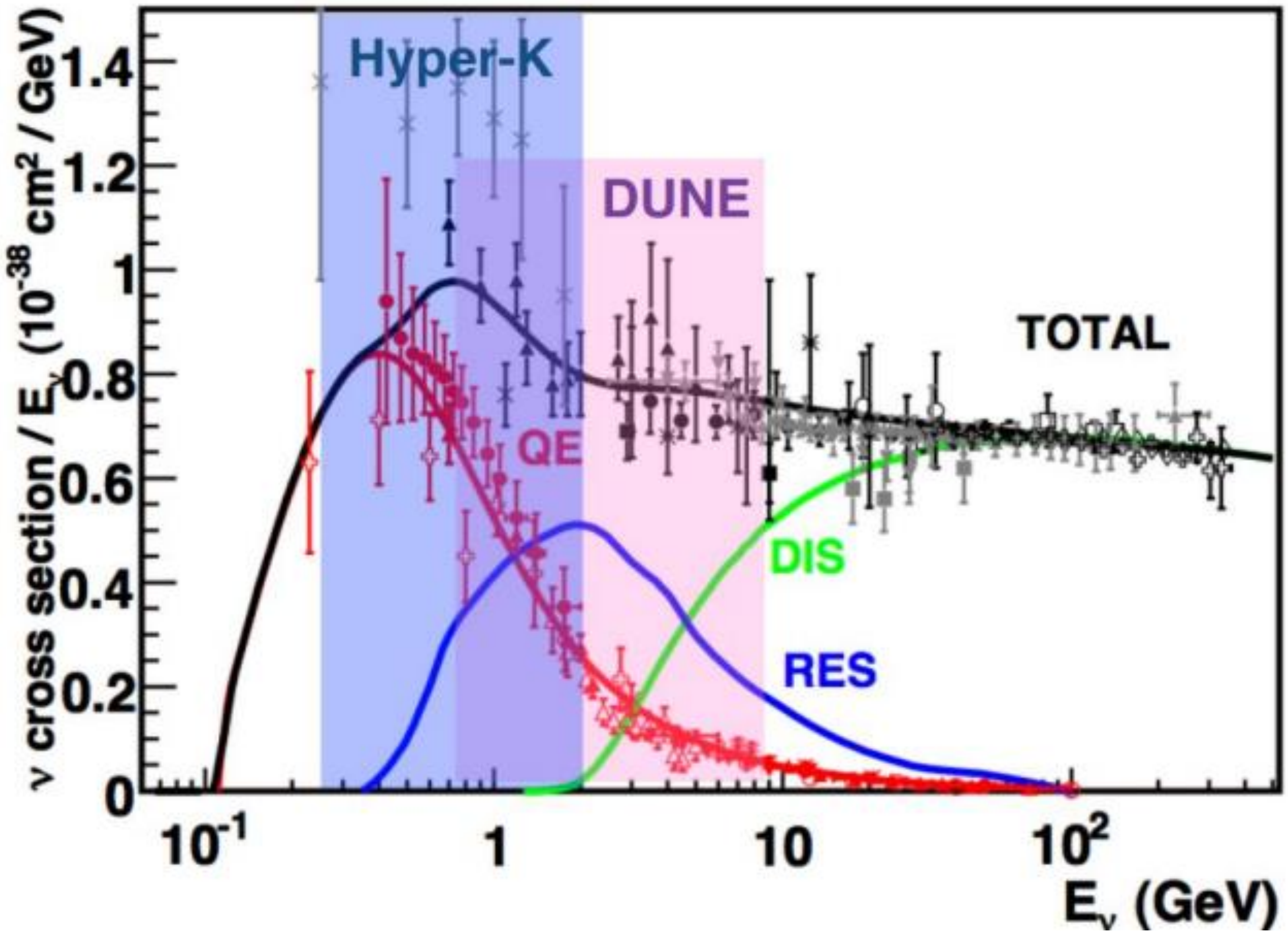
Quasi-elastic

Resonant production

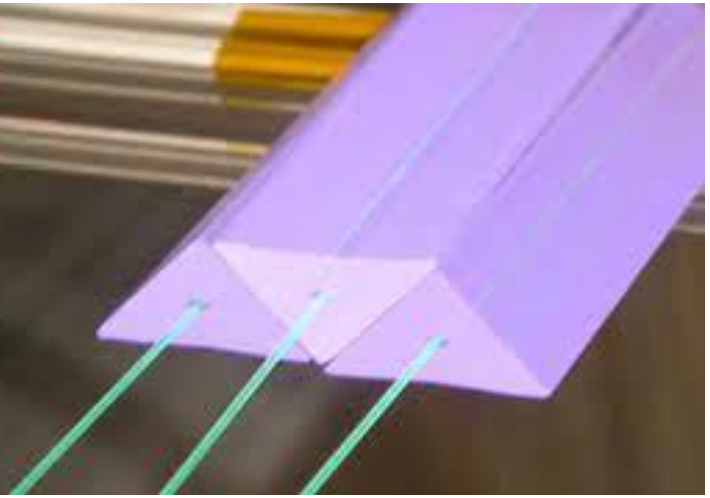
Deep inelastic scattering

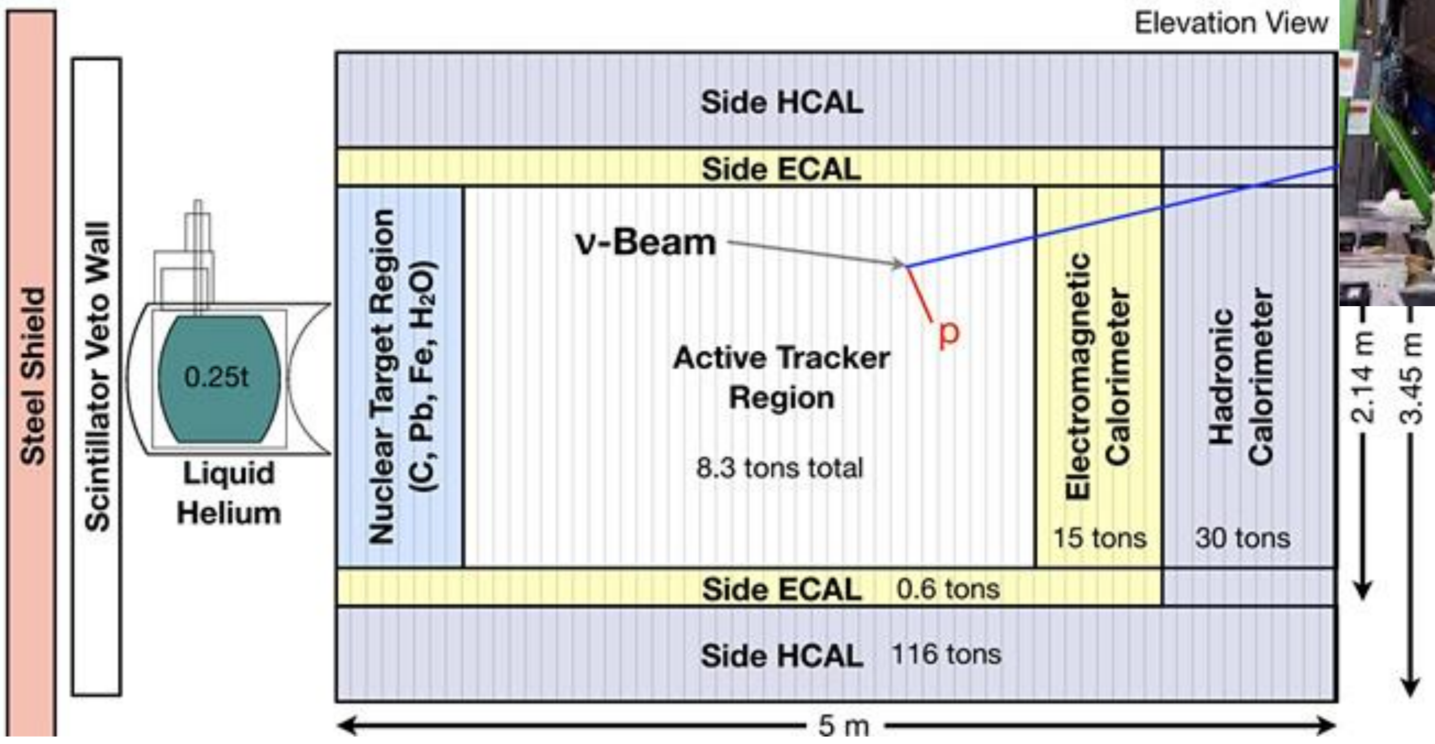
Neutrino interactions and oscillations

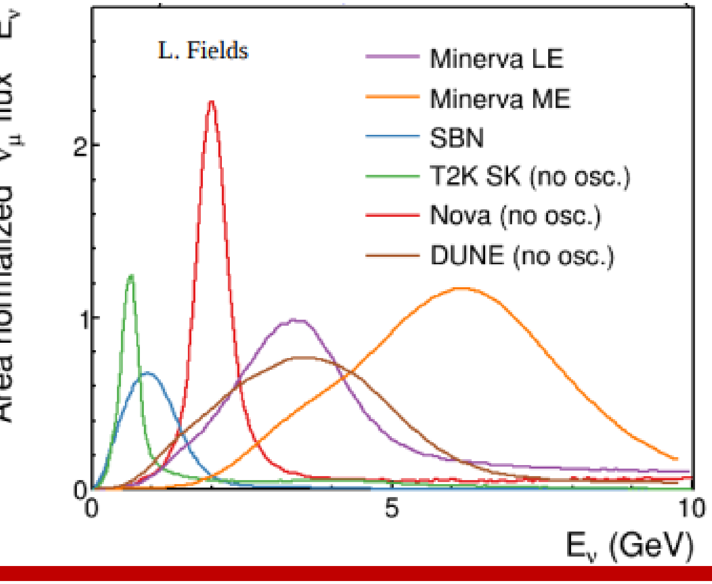
– Oscillation experiments occupy the most complicated regime
– An energy dependent phenomenon: *need to precisely understand particles produced and their kinematics*



The MINERvA experiment





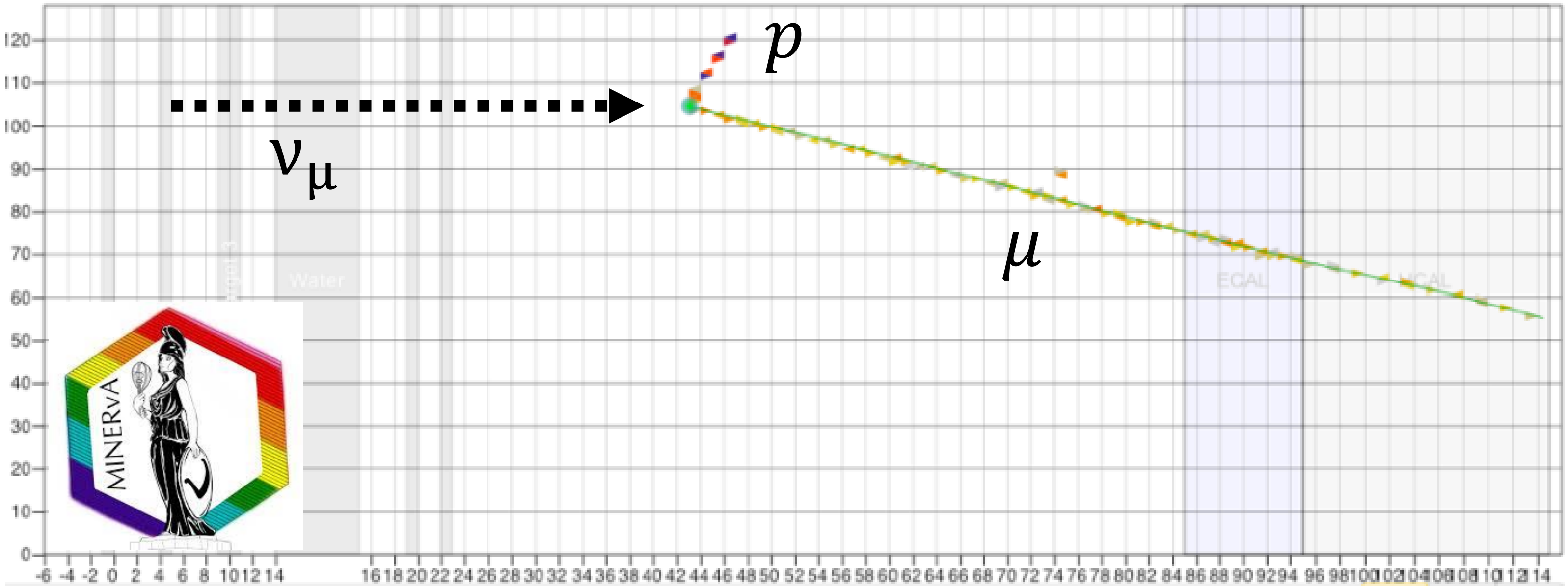


Plastic scintillator tracker at Fermilab to study ν–nucleus interactions
Neutrino flux overlaps with upcoming experiments like DUNE

Quasi-elastic interactions

$$\nu_\mu + n \rightarrow \mu^- + p$$

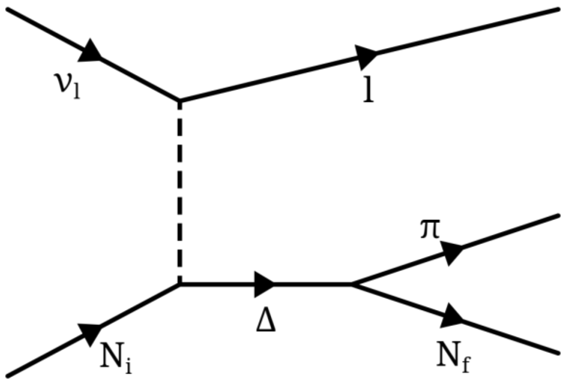
$$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$$



Two body scattering: only need to measure final-state variables to completely solve system
Muon energy and scattering angle

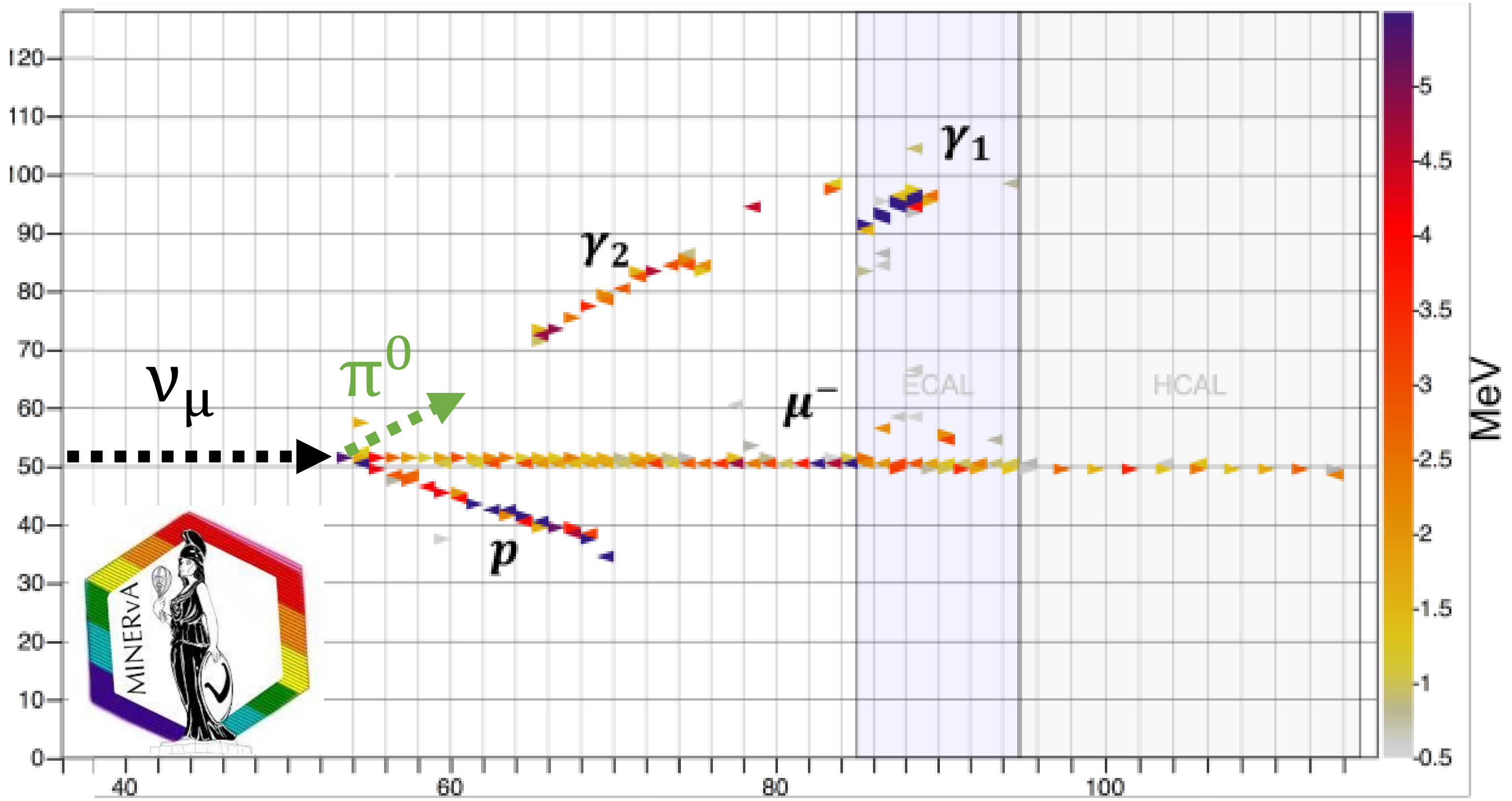
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu cos\,\theta_\mu)}$$

Resonant π production



$$\nu_\mu + n \rightarrow \mu^- + \Delta^+ \rightarrow \mu^- + p + \pi^0$$

$$\nu_\mu + p \rightarrow \mu^- + \Delta^{++} \rightarrow \mu^- + p + \pi^+$$



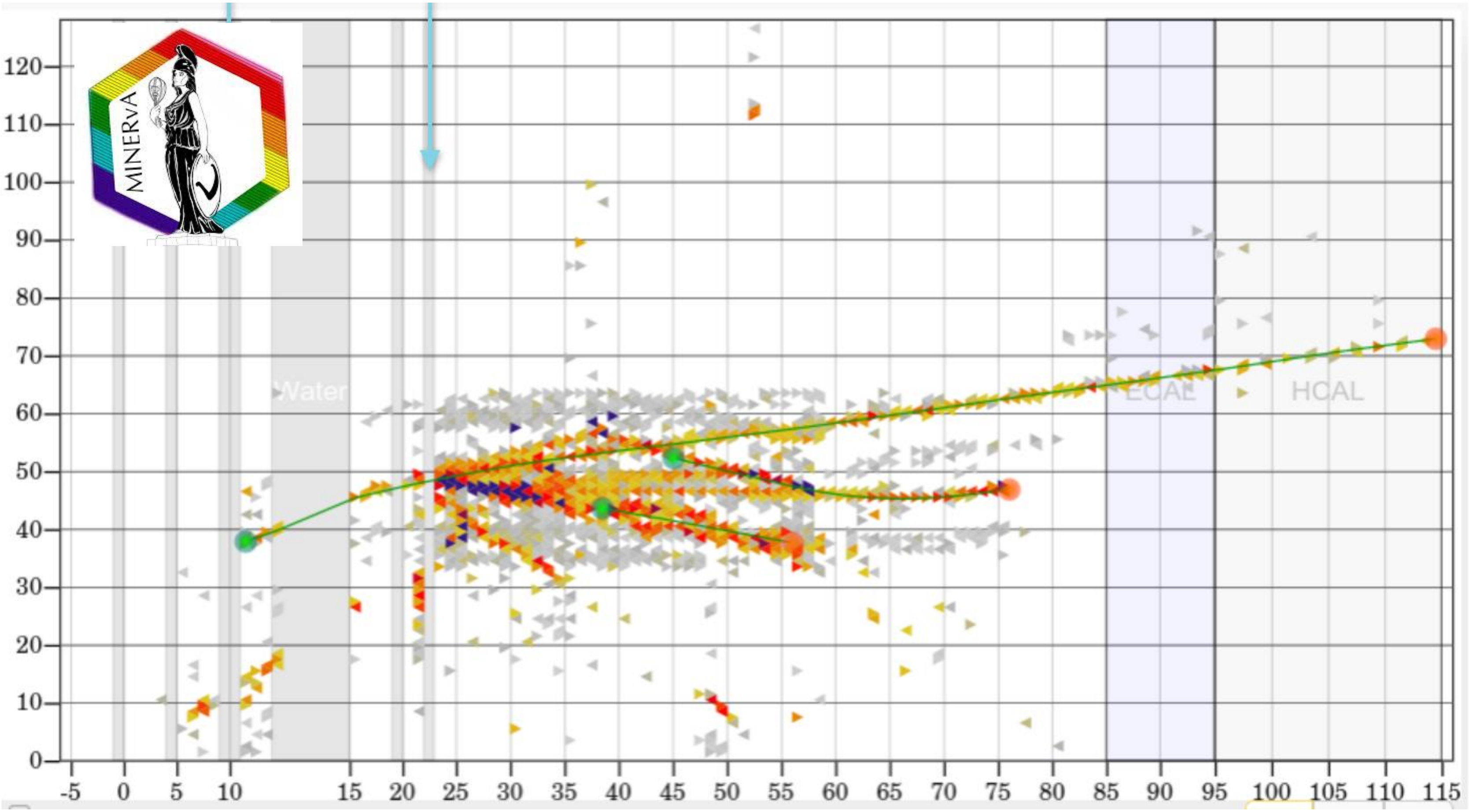
At slightly higher momentum transfer, the nucleon can be excited to a Δ_{1232} resonance
Produces a distinctive, *nucleon+pion decay topology* with invariant mass 1232 MeV

Charged pion decay can release invisible energy through neutrinos – energy resolution!

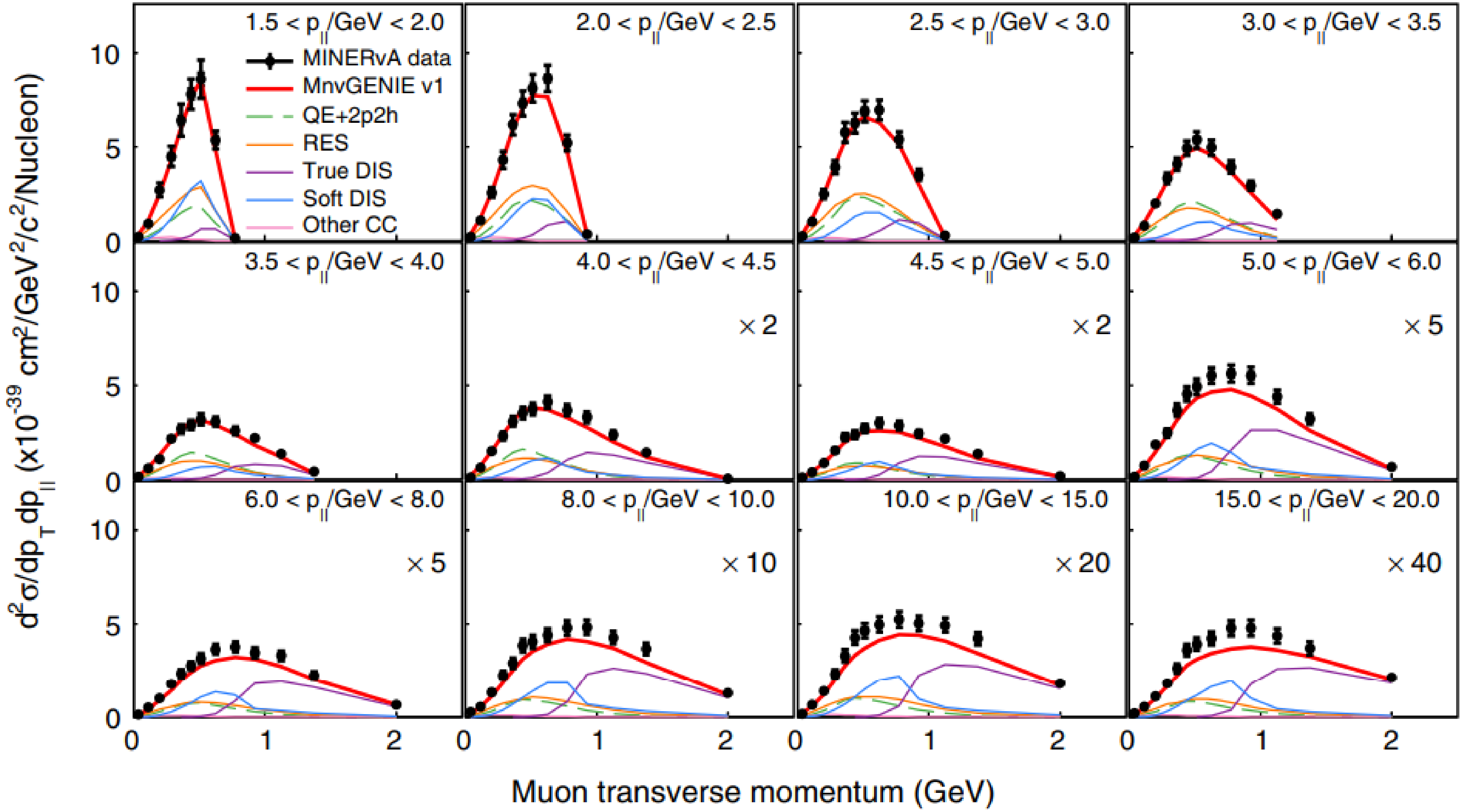
Deep inelastic scattering

$$\nu_\mu + q \to \mu^- + X$$

Scattering localized on the scale of the nucleus – structure unimportant for predicting kinematics

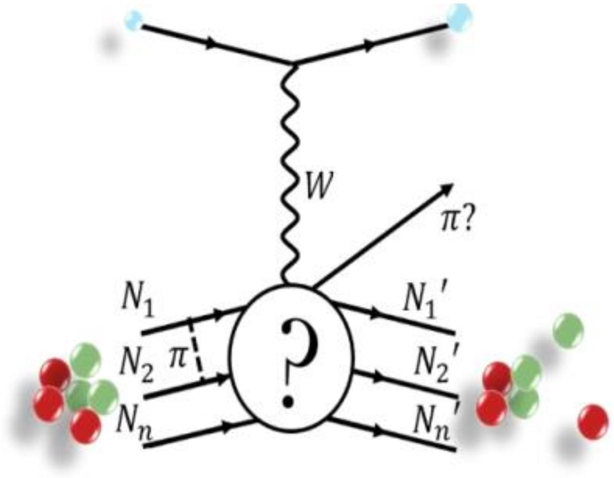


Recipe for predicting kinematics: neutrino interaction



MINERvA PRD 101 112007 (2020)

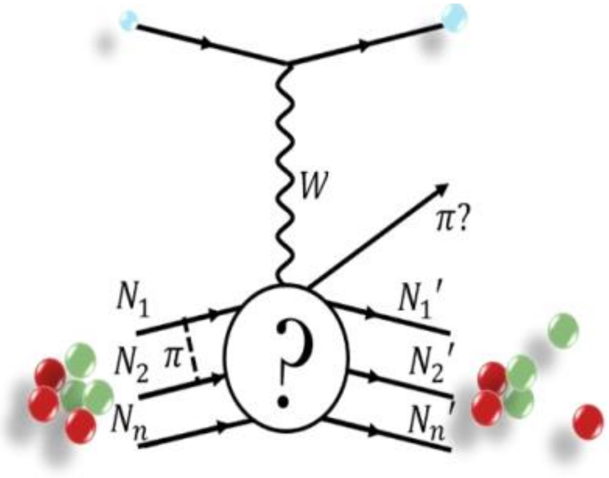
Recipe for predicting kinematics: nuclear motion



Back to nuclear shell model – the nucleus is a complex medium with each nucleon carrying momentum

This momentum will smear final-state particle kinematics

Recipe for predicting kinematics: nuclear motion



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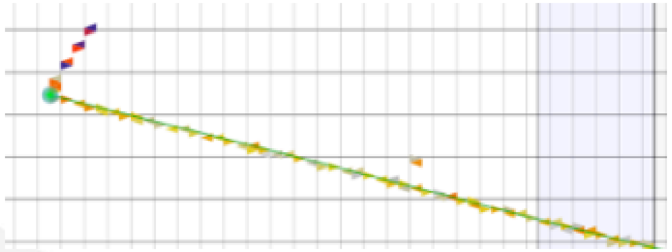
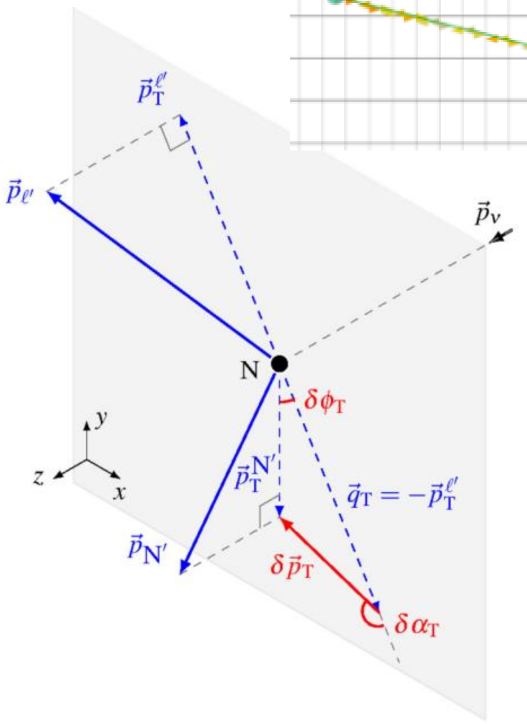
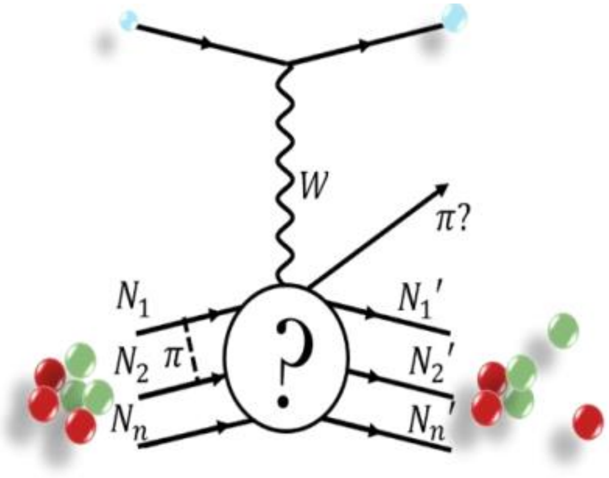




Quasi-elastic events can test this!
If you track both muon and proton you can reconstruct the initial nucleon momentum

Recipe for predicting kinematics: nuclear motion



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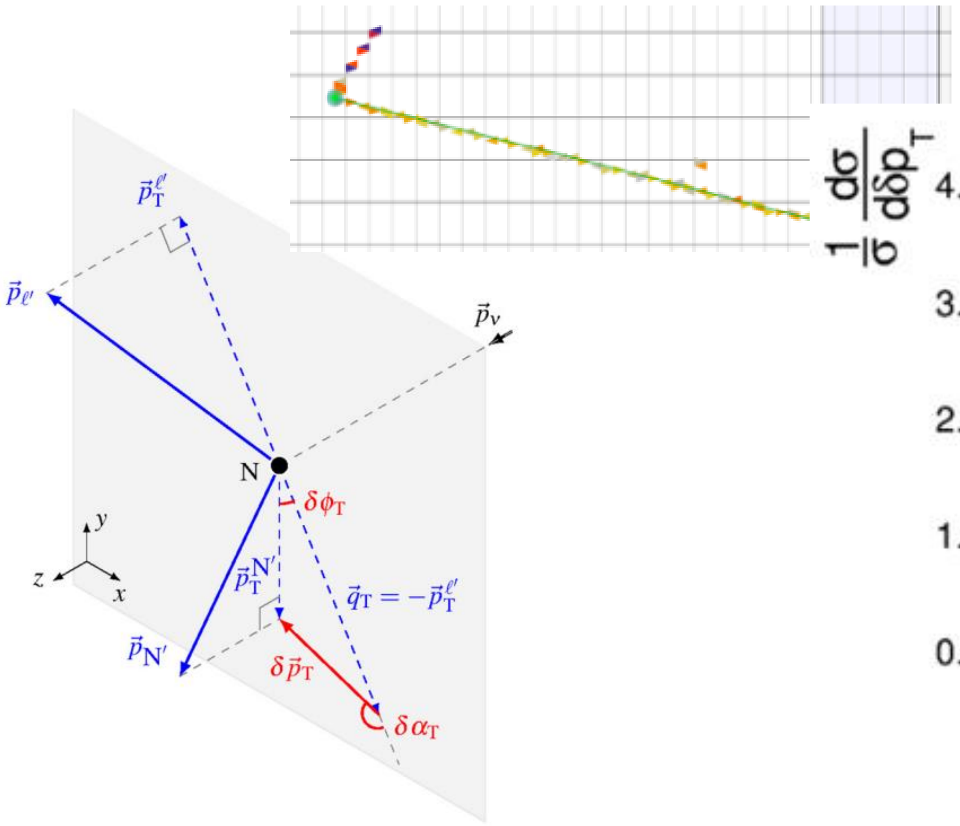
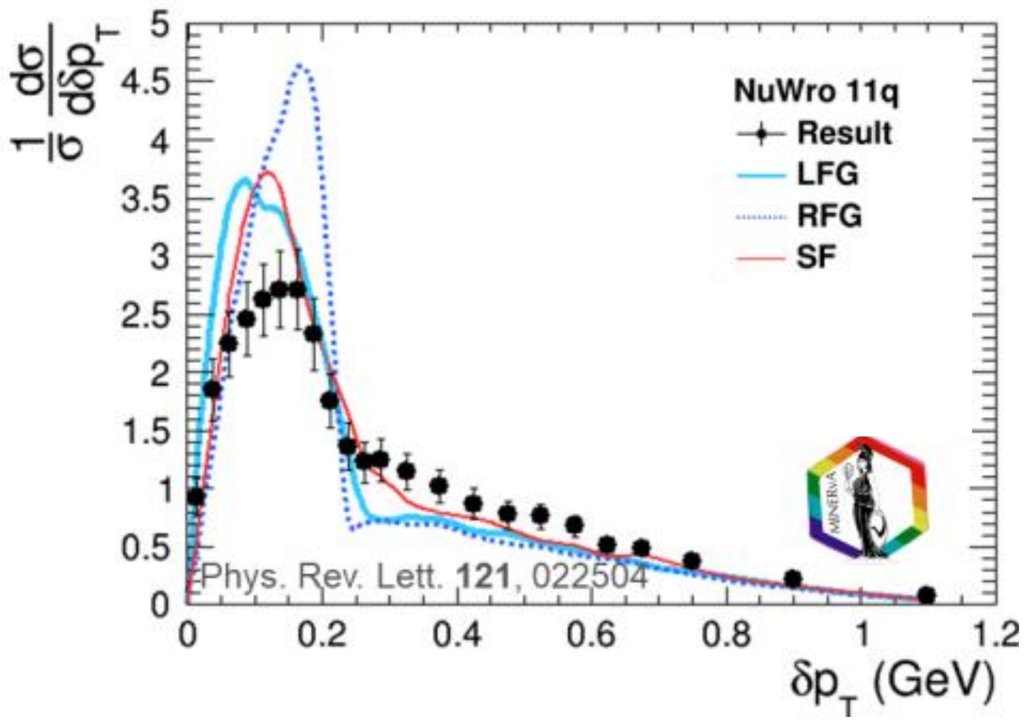
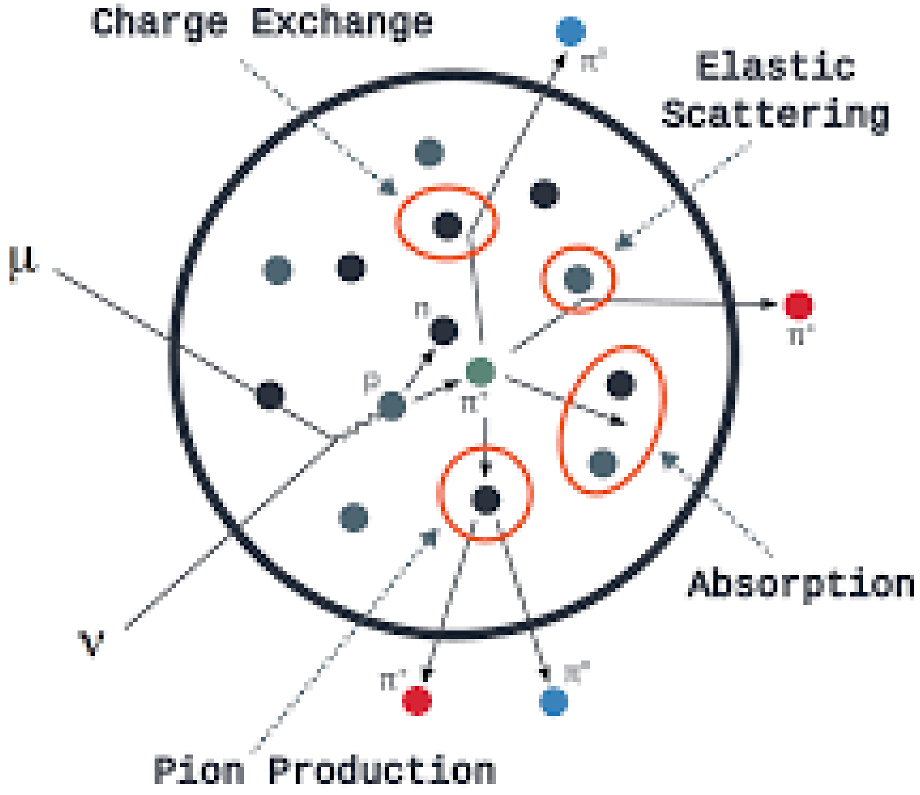
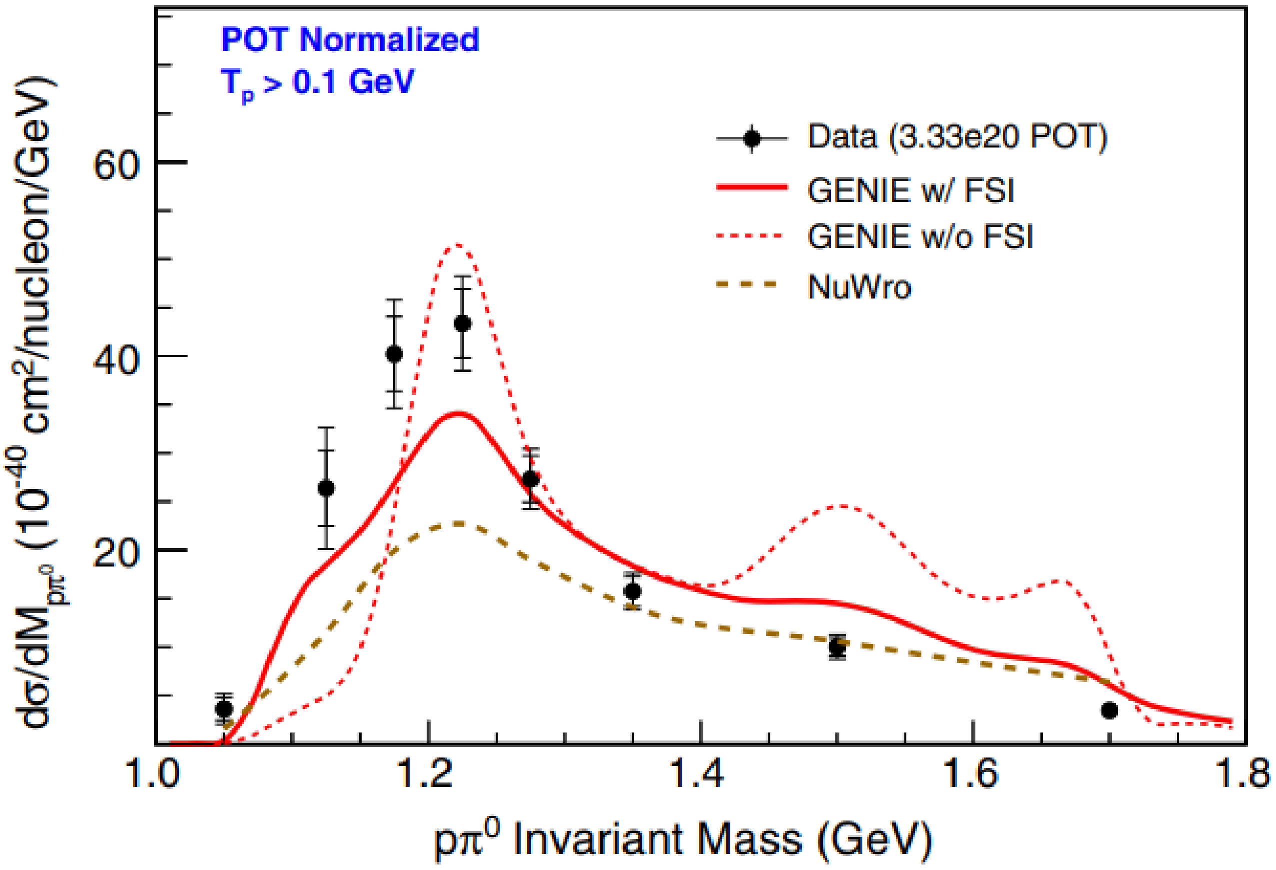




Recipe for predicting kinematics: final state interactions



[MINERvA *PRD* **96** 072003 (2017)]

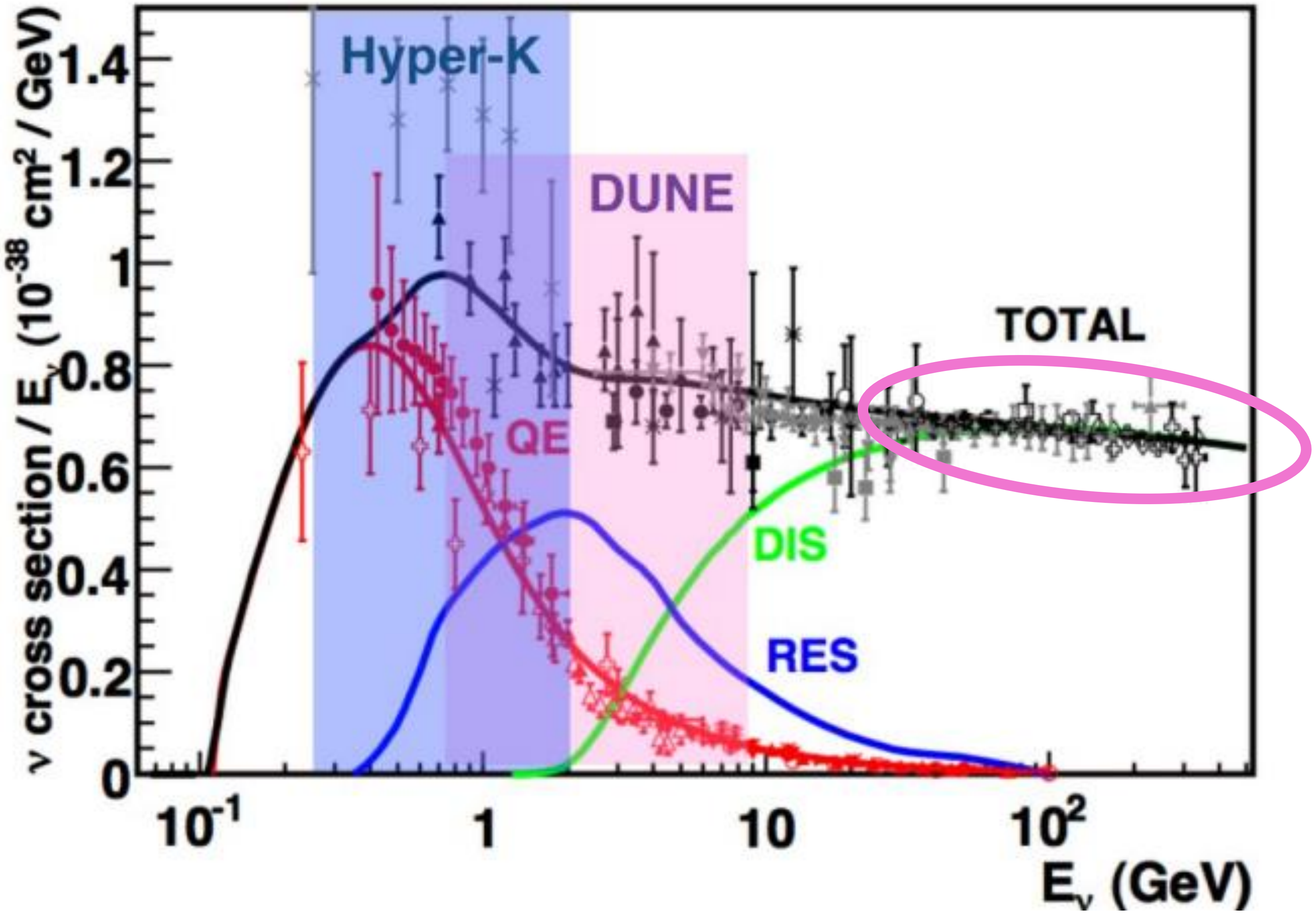


TeV

The obliteration regime

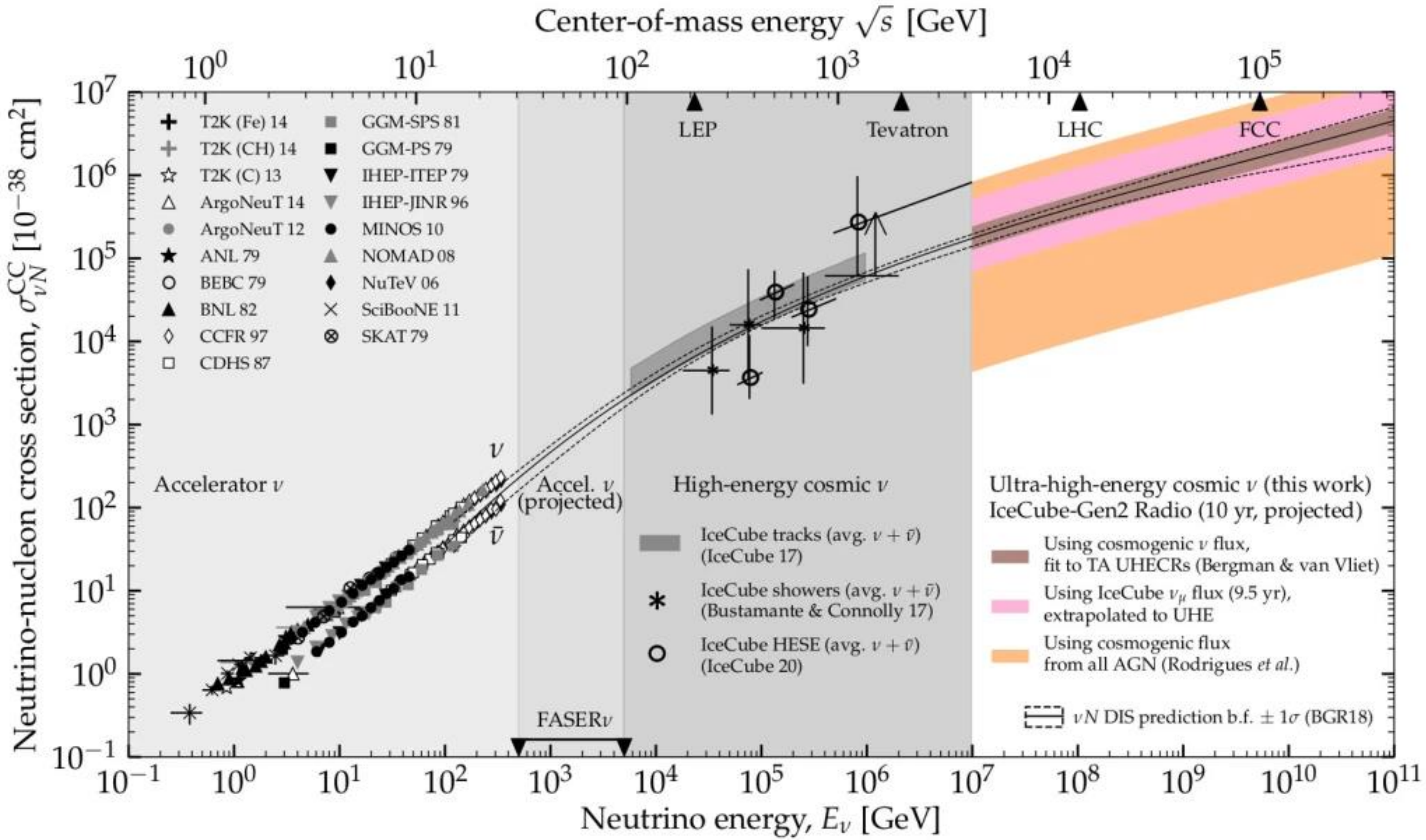
Deep inelastic scattering

Deep inelastic scattering

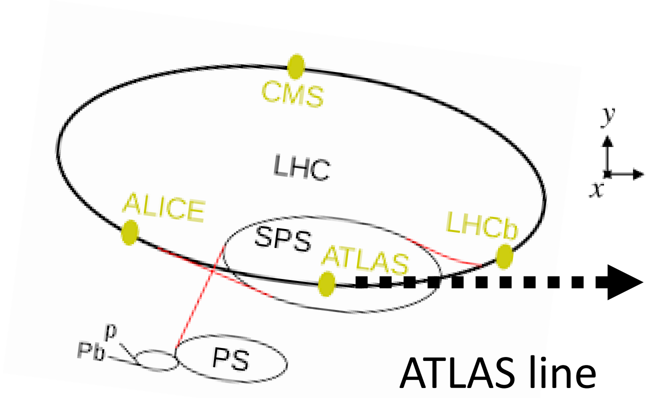


– Above 30 MeV, cross section dominated by the DIS channel
– Simplifies experimental concerns
– Scattering of quarks. Nuclear environment not important
– Easier to model

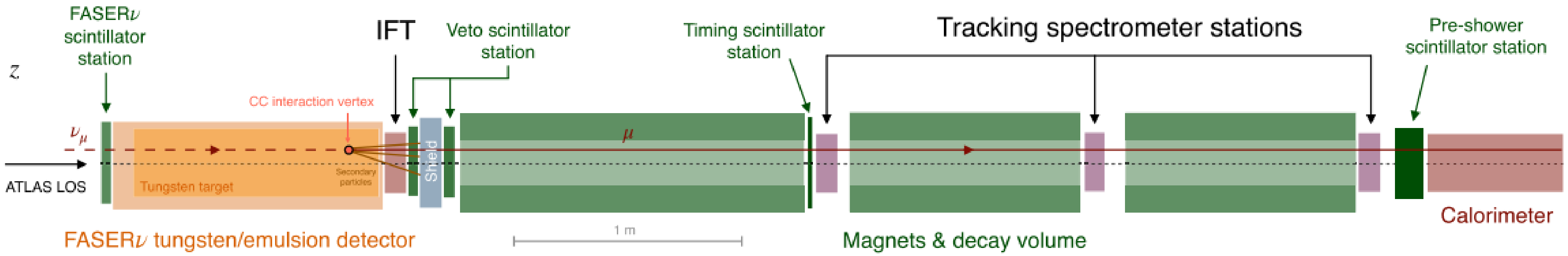
Measuring over all scales

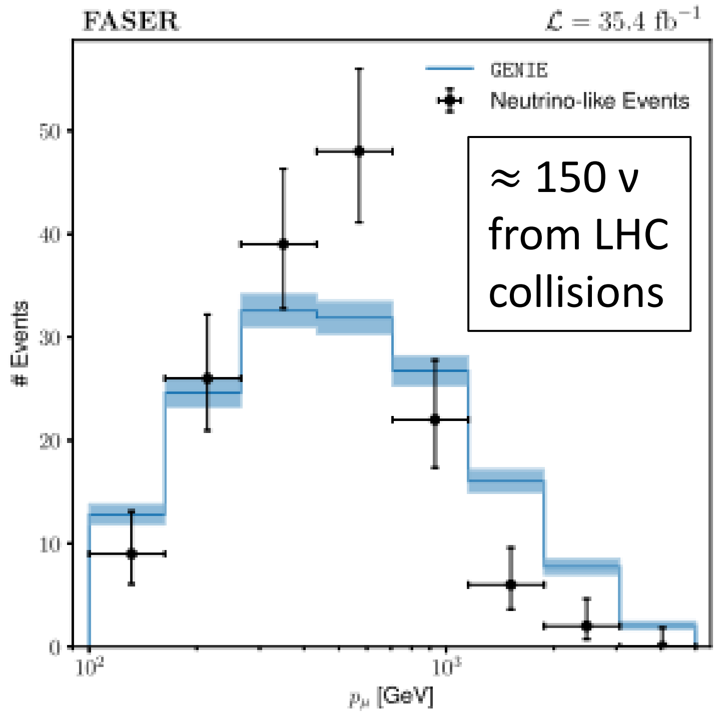


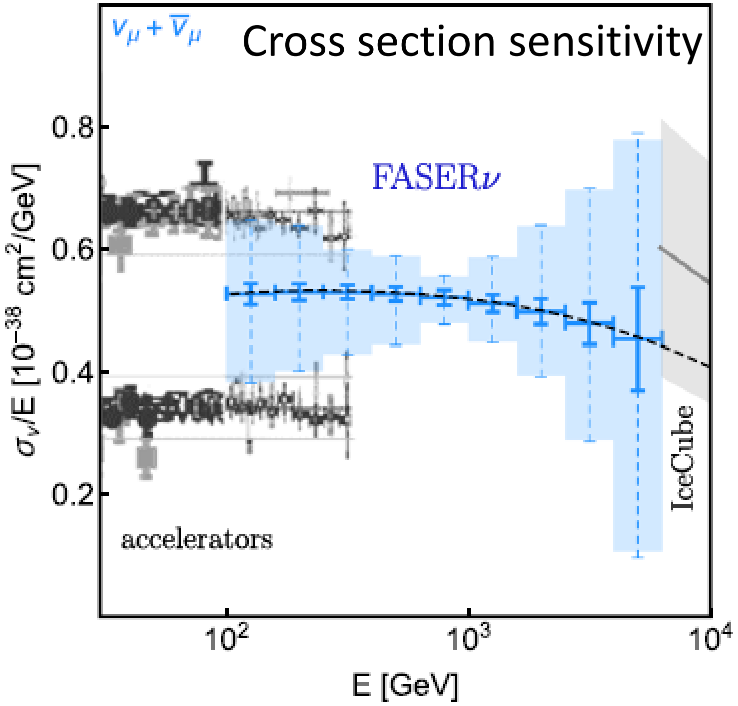
The FASERν project: closing the accelerator-cosmic gap



ATLAS line of sight







Look for the highest energy neutrinos made at accelerators: go to the LHC

Muon spectrometer on ATLAS line of sight

FASERν, *Eur Phys J C* **80** 61 (2020)
FASERν, PRL 131 031801 (2023)

Summary

– Study neutrino interactions from keV to TeV scale

– Fundamental scattering properties poorly known and precision measurements at low energies could be next clear indication of new physics

– Many uncertainties on scattering in the MeV-GeV regimes that must be resolved for astrophysics (tomorrow) and oscillations (Thursday)