Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Neutrino Physics

17th Hadron Collider Physics Summer School
Aug 15-26, 2022

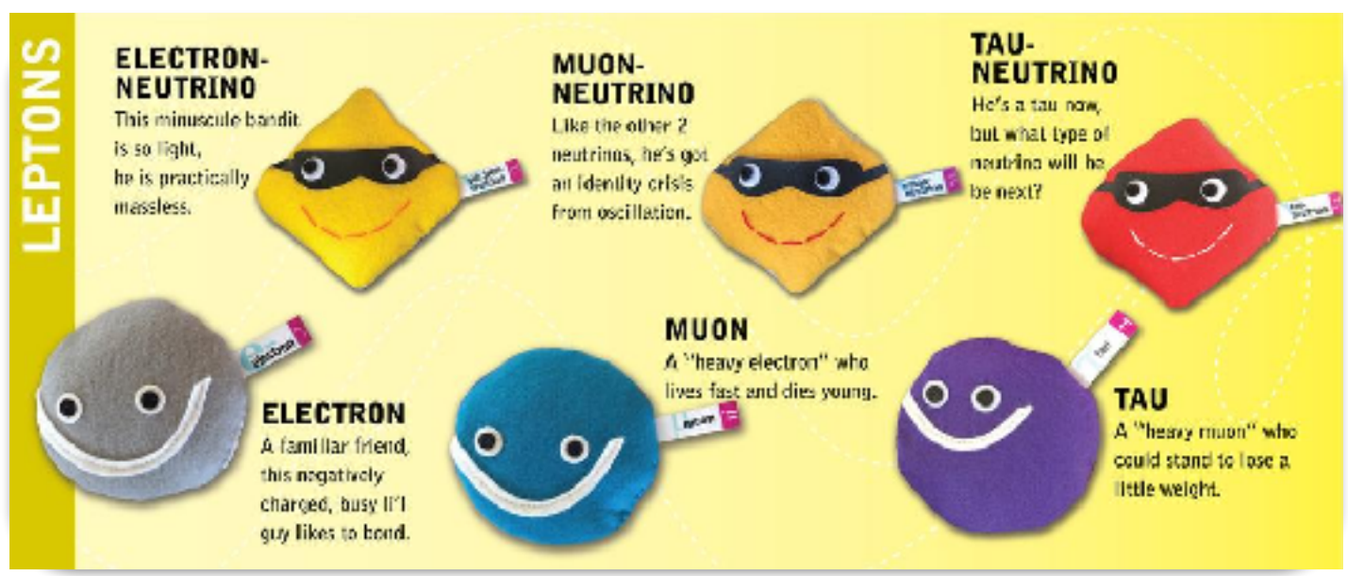
Noemi Rocco

Interesting facts about neutrinos

Neutrinos are very, very abundant: each second around 100 billions of neutrinos pass through our body, whether we are indoors or outdoors, and without our body noticing them, or them noticing our body.

"Neutrinos ... win the minimalist contest: zero charge, zero radius, and very possibly zero mass."

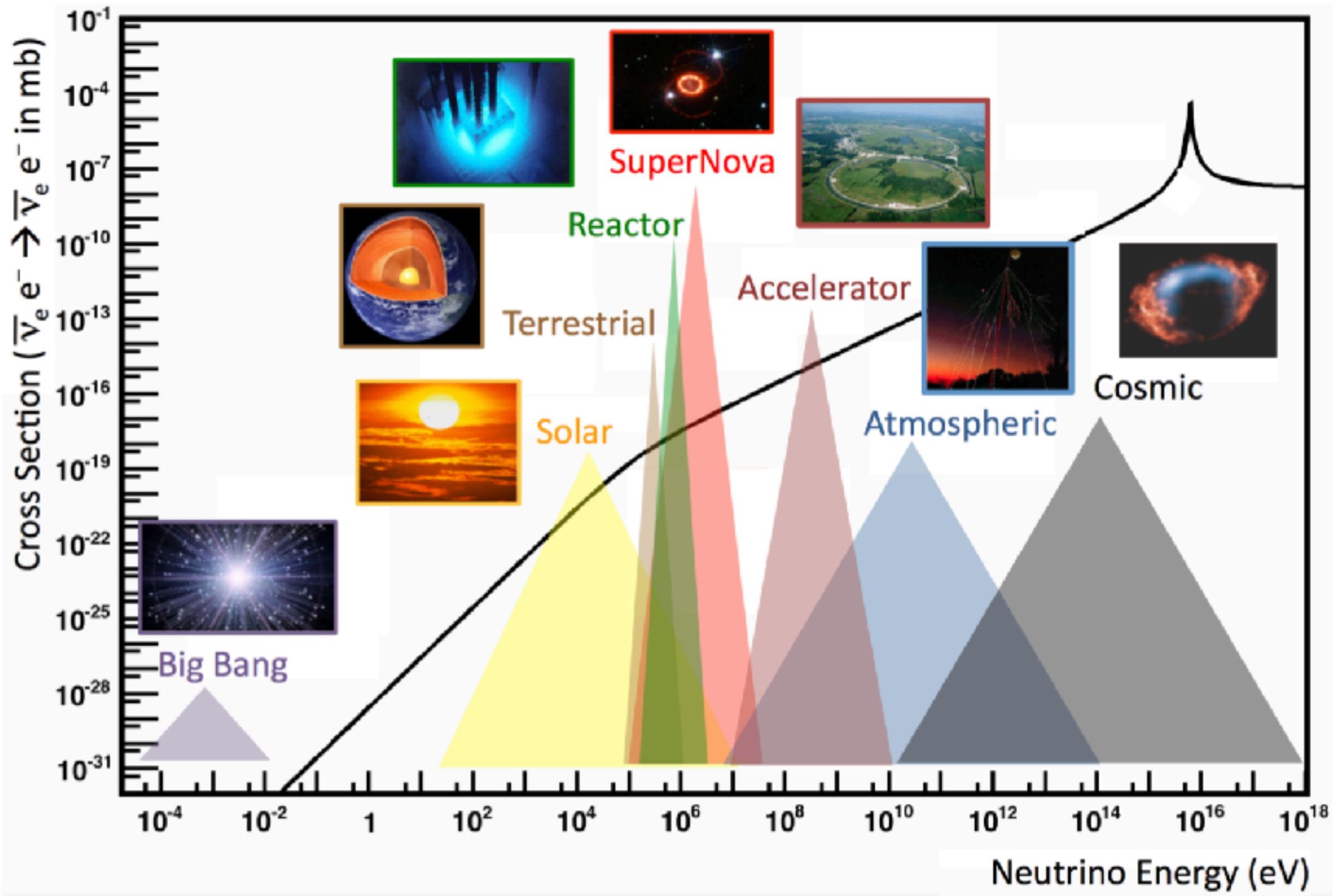
L. Lederman: 1988 nobel prize in Physics "for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"



✐ https://www.particlezoo.net

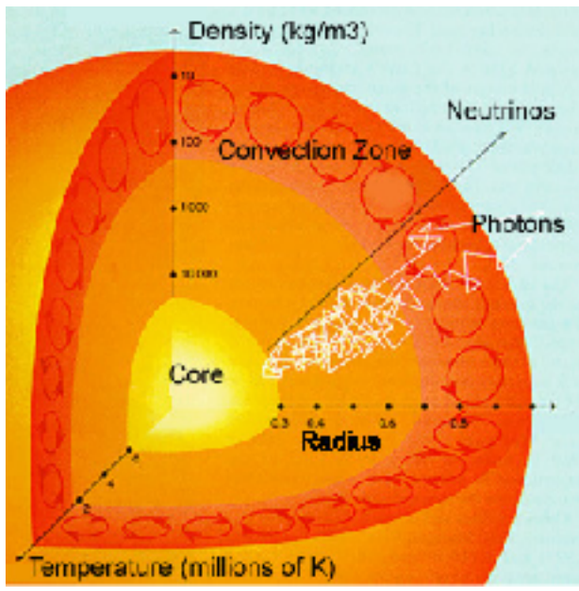
Many different sources of neutrinos

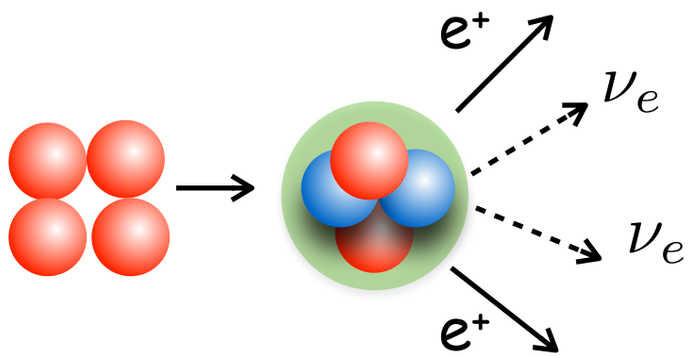
A number of different sources of neutrinos over different energies give us information about the universe and its formation



Solar neutrino anomaly

The **Homestake** experiment was aimed at collecting and counting electron neutrinos produced in the sun to test the **Solar Standard Model (SM).** The expected flux can be calculated based on our knowledge of the sun.

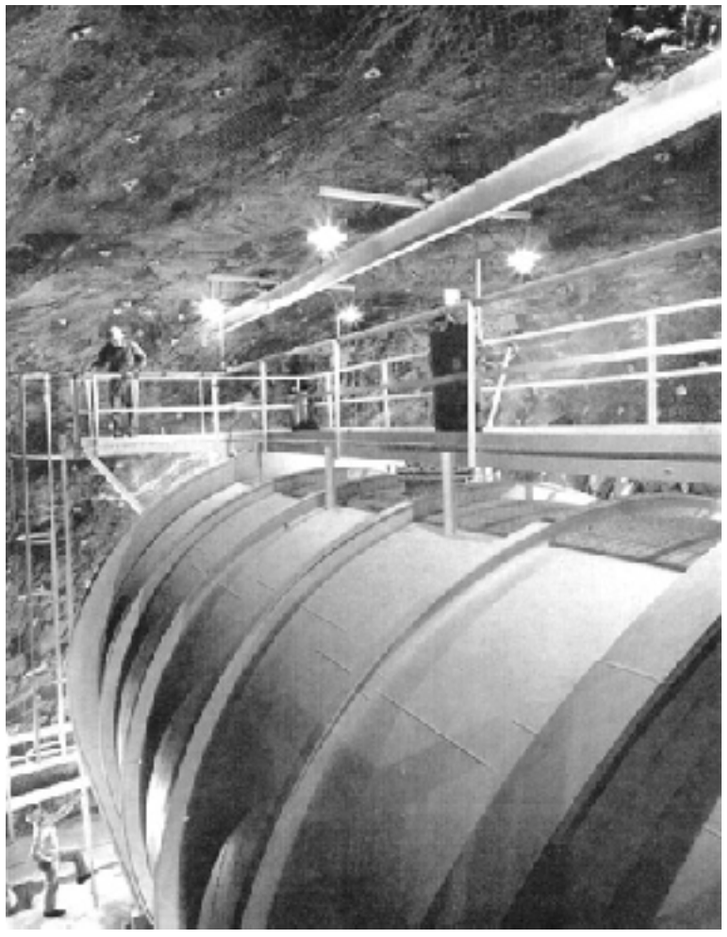




pp chain

The experiment was carried out in a deep-mine location to shield from cosmic rays

✐ 1968 Homestake, SD



The neutrino trap was a tank filled with 100K gallons of cleaning fluid (tetrachilene)

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

Puzzle: only **1/3 of the neutrinos** predicted by the solar SM were detected; this results was confirmed by other experiments

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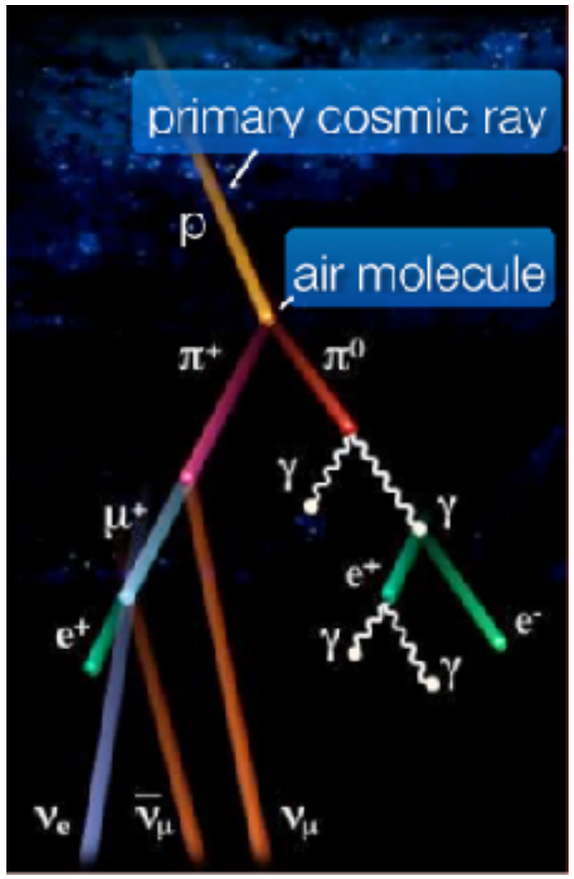
Atmospheric neutrino anomaly



The cosmic rays, upon interaction with the nuclei in the atmosphere, produce pions which decay into muons and muon neutrinos:

$$p + N \rightarrow \pi^{\pm} + X$$

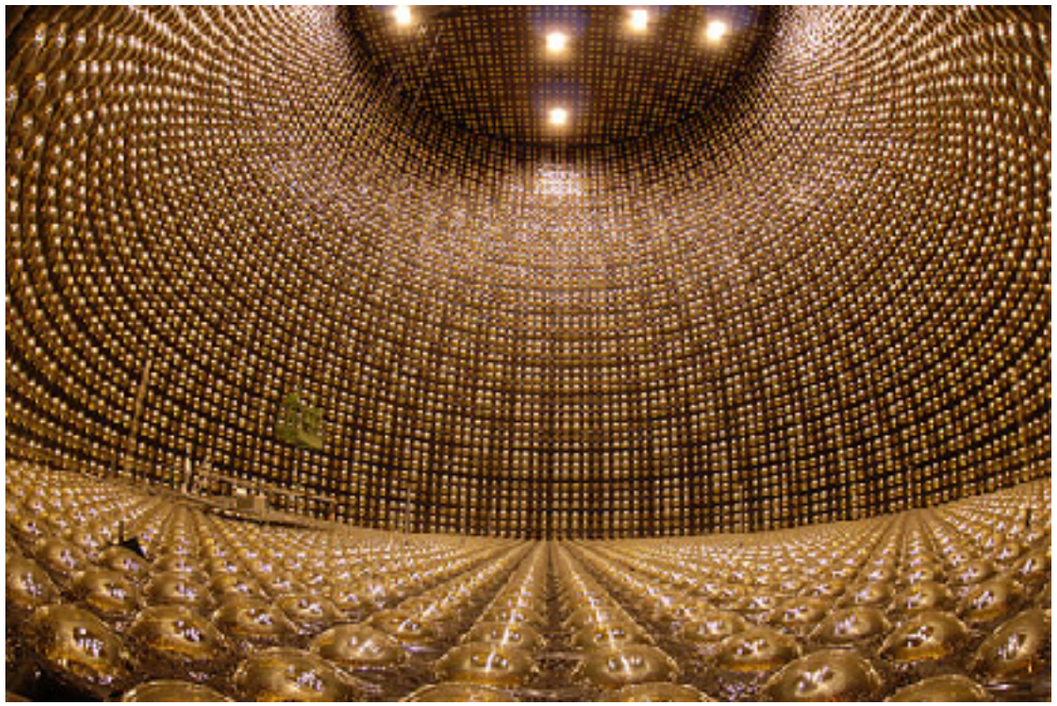
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\mu^{\pm} \rightarrow e^{\pm} + \nu_{e}(\bar{\nu}_{e}) + \nu_{\mu}(\bar{\nu}_{\mu})$$

Atmospheric neutrino should arrive in a ratio

$$R = (\nu_{\mu} + \bar{\nu}_{\mu})/(\nu_{e} + \bar{\nu}_{e}) \rightarrow 2$$

✐ Super-Kamiokande Collaboration PRL 81 (1998)



Super-Kamiokande Detector: 50 kton water, ~11000 photomultiplier tubes (PMT) placed 1000 m underground

First measurement of atmospheric neutrino anomaly: **depletion in the number of muon neutrino**

$R_{\mathrm{data}}/R_{\mathrm{MC}}$ ~ 0.6

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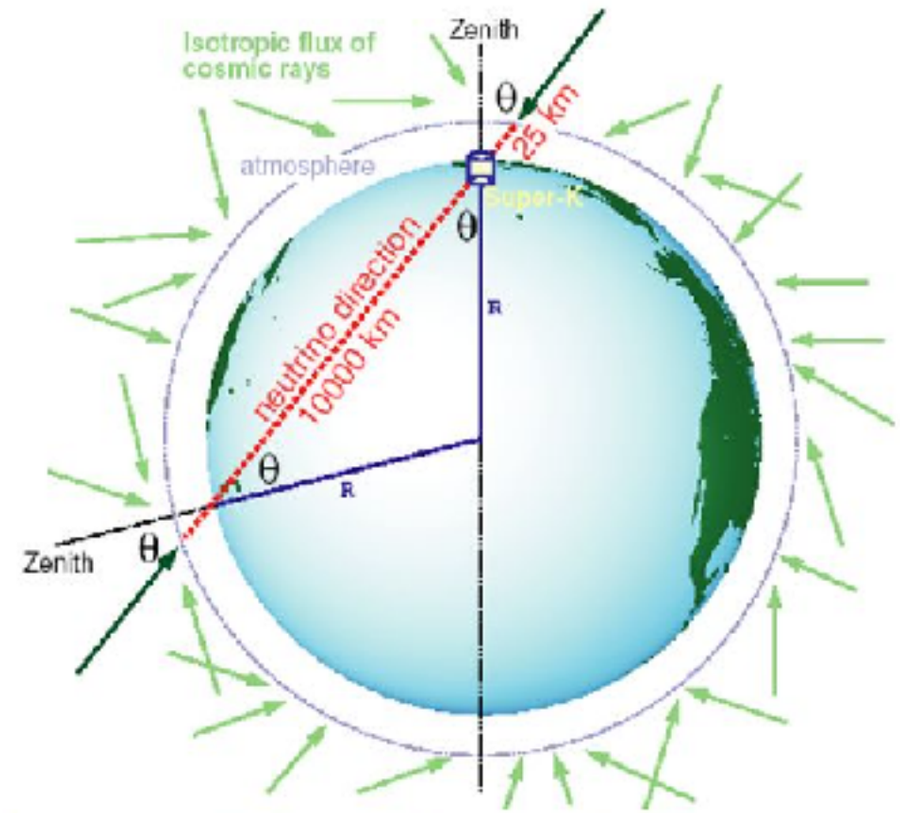
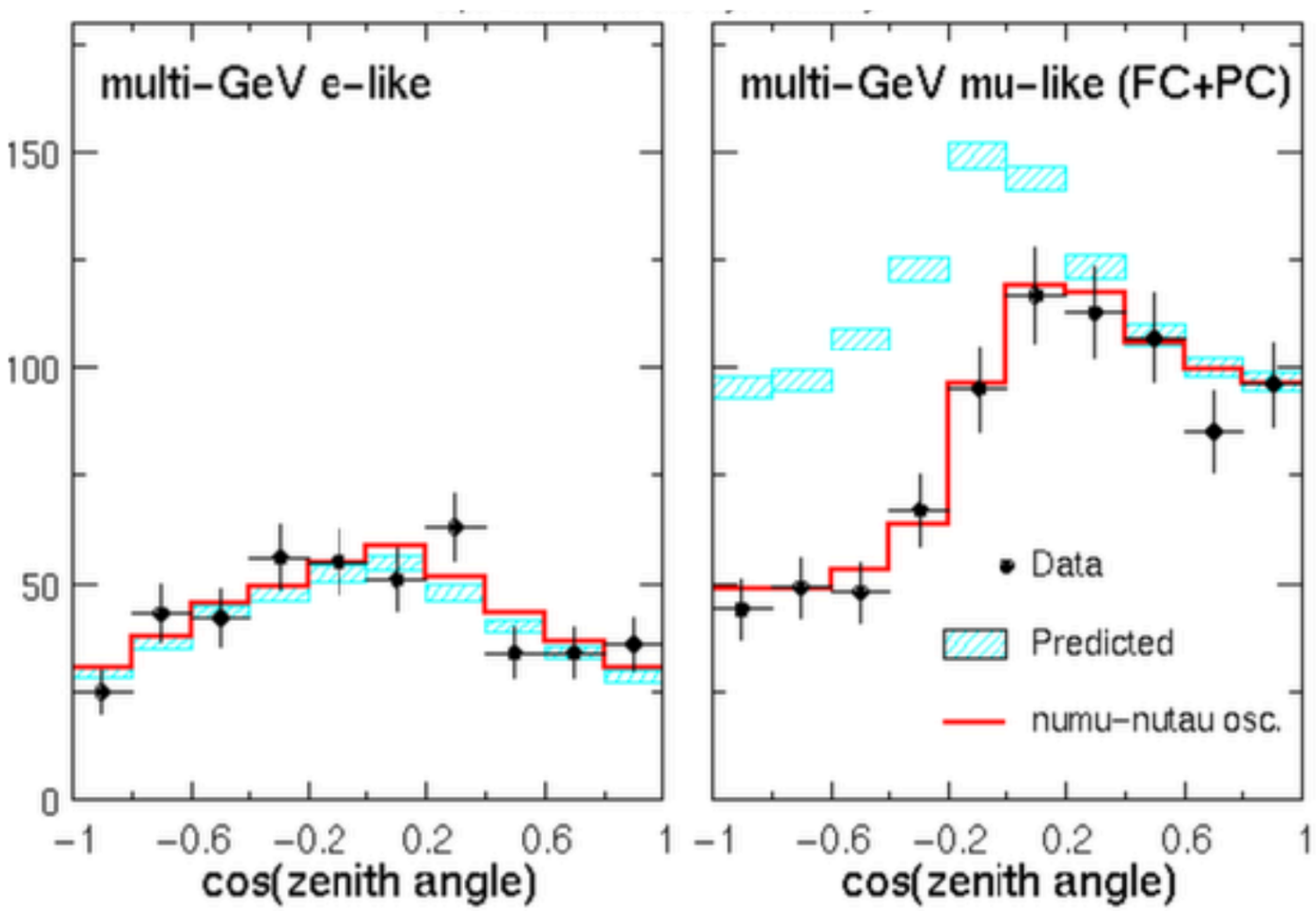
Atmospheric neutrino anomaly

Cosmic rays hit the earth isotropically. We would assume to measure the same number of up and down neutrinos: the **cosine distribution** of these neutrinos should be **symmetric**



✐ Super-Kamiokande Collaboration Phys.Lett.B 436 (1998)



Strong **deviation** from expectation in the shape of the μ-like event **zenith angle distribution.**

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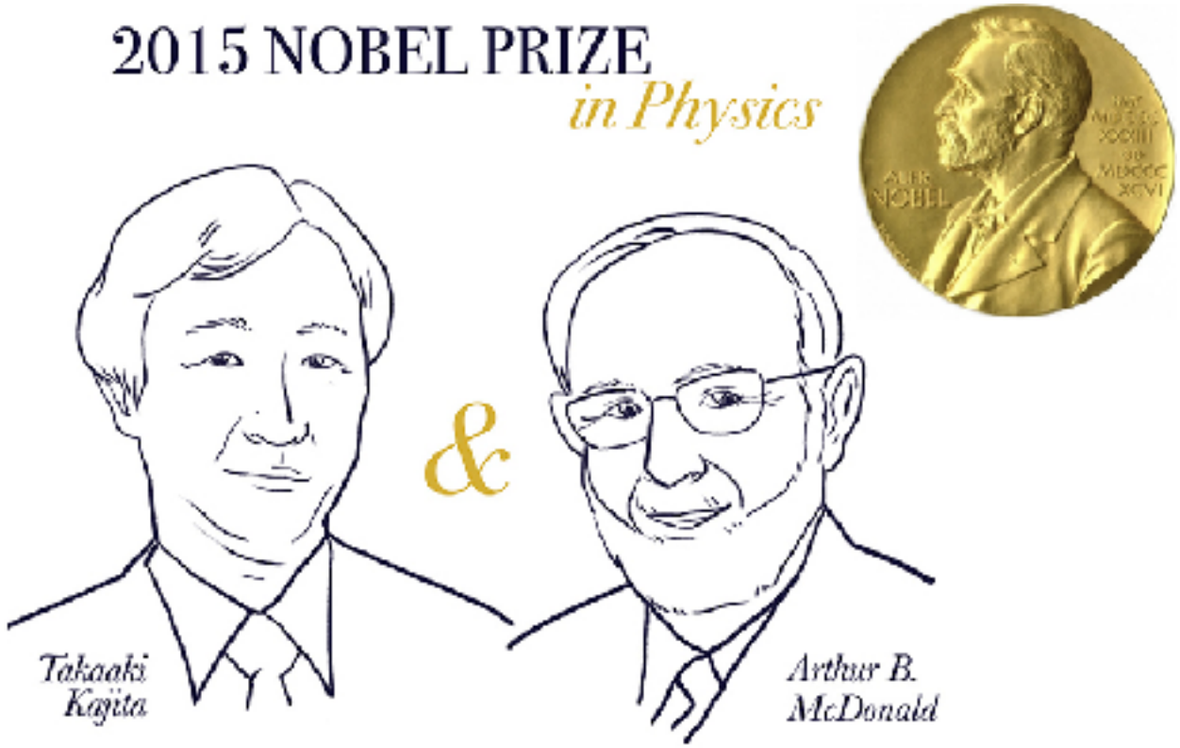
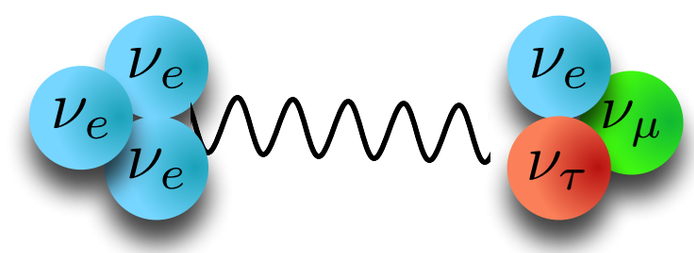
How do neutrino oscillate?



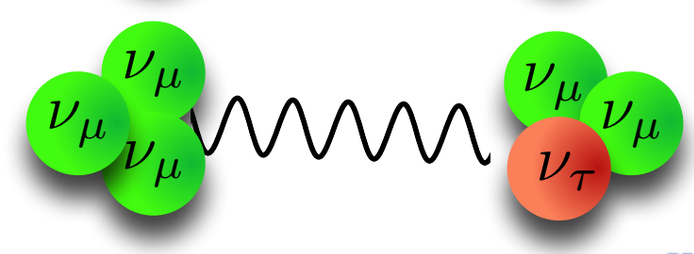
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino **change flavor** after propagating for a finite distance. The **rate** of change depends on the **neutrino energy** and on the traveled **distance**

✔ **Solar Neutrino Anomaly** is explained by oscillations



✔ **Atmospheric Neutrino Anomaly** is explained by oscillations



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Today's challenges in neutrino physics

There are some big questions that we are trying to answer:

- What is the absolute mass of the neutrinos?
- Are neutrinos their own anti-particles?

} β and ββ decay

- What are the parameters that characterize the oscillations?
- Are there only three neutrino flavors?
- Is there other BSM physics at play?

} Neutrino oscillation experiments

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How do neutrino oscillate?

Neutrino Flavor change arises because **neutrinos have masses**

Neutrinos with a given flavor:

$$|\nu_e\rangle\,,|\nu_\mu\rangle$$

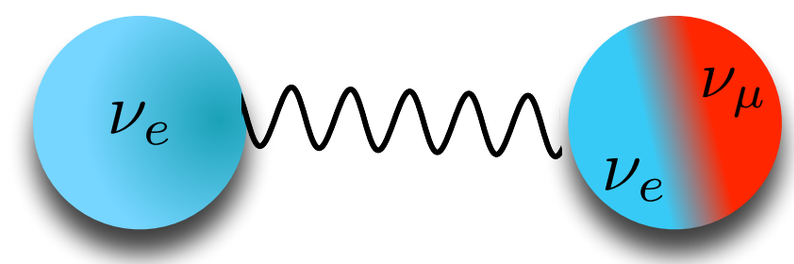
Neutrinos with a given mass:

$$|\nu_1\rangle\,,|\nu_2\rangle \qquad m_1\,,m_2$$

$$|\nu_i(t,\mathbf{x})\rangle = e^{-i(E_i t-\mathbf{p}\cdot\mathbf{x})}|\nu_i\rangle$$

- The neutrino flavor eigenstates can be written as a combination of the mass ones

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$
$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$



- The ν_e propagation in vacuum is written as

$$|\nu(t,\mathbf{x})\rangle = \cos\theta e^{-i(E_1 t-\mathbf{p}_1\cdot\mathbf{x})}|\nu_1\rangle + \sin\theta e^{-i(E_2 t-\mathbf{p}_2\cdot\mathbf{x})}|\nu_2\rangle$$

- The oscillation probability in the ultra relativistic limit ($t \simeq L$, $E_i - |p_i| \simeq m_i^2/2E_i$)

$$P_{e\mu}(L) = |\langle\nu_\mu|\nu(t,z=L)\rangle|^2 = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \longrightarrow P_{ee}(L) = 1 - P_{e\mu}(L)$$

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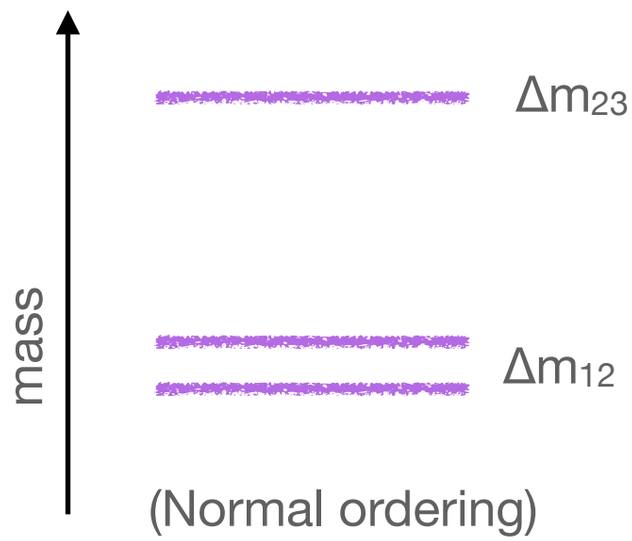
How do neutrino oscillate?

Flavor eigenstates ⟵

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

⟶ **Mass** eigenstates



PMNS matrix: 3x3 Unitary matrix:

- 3 mixing angles θ_{12} θ_{23} θ_{13}
- 1 complex phase δ_{CP}
- 3 masses and two independent splittings

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_j U_\alpha^* e^{-i\frac{\Delta^2 m_{1j}^2 L}{2E}} U_{\beta j} \right|^2$$

Atmospheric+ Accelerator	**Reactor+ Accelerator**	**Solar+ Reactor**
Δm^2_{23}	θ_{13}	Δm^2_{12}
θ_{23}	δ_{CP}	θ_{12}

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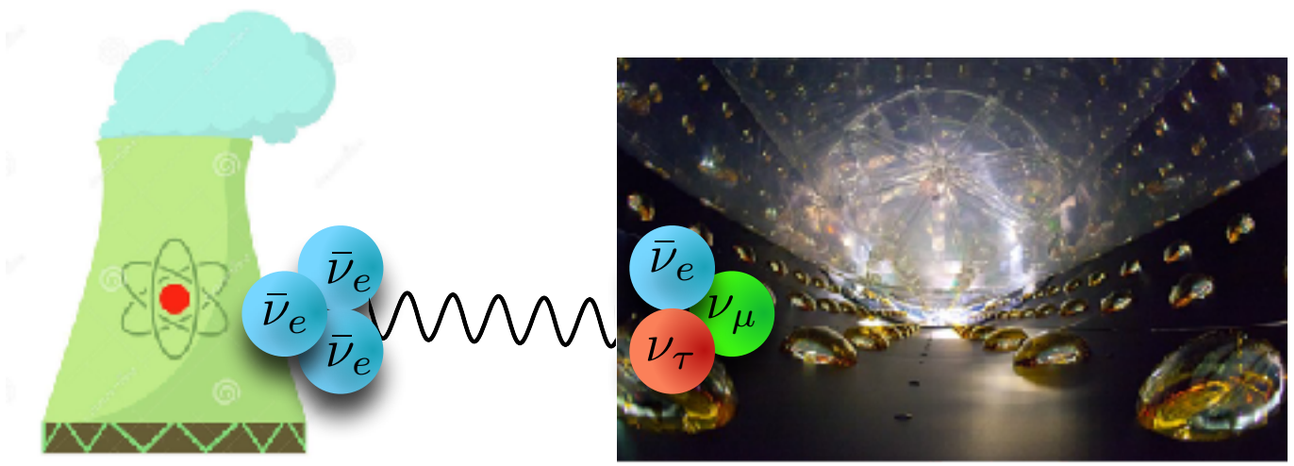
Measuring neutrino oscillation parameters

Reactor Experiments



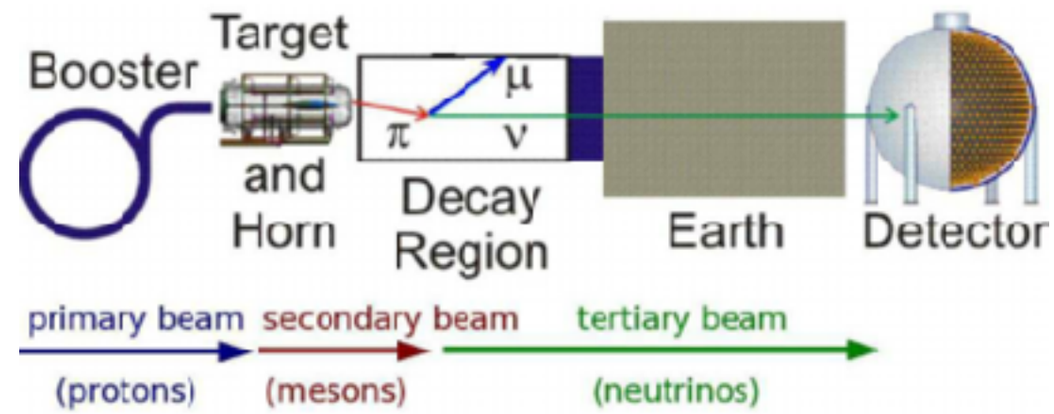
Energy: MeV

Baseline: 10 m - 100 km

$\bar{\nu}_e$ are produced in nuclear fission processes happening in the nuclear reactor

Detectors measure
$\bar{\nu}_e \not\rightarrow \bar{\nu}_e$ (disappearance)

Accelerator Experiments



Energy: GeV

Baseline: 30 m - 1500 km

Neutrino are produced as secondary decay products

Experiments measure $\nu_\mu \rightarrow \nu_e$ (appearance) and/or $\nu_\mu \not\rightarrow \nu_\mu$ (disappearance)

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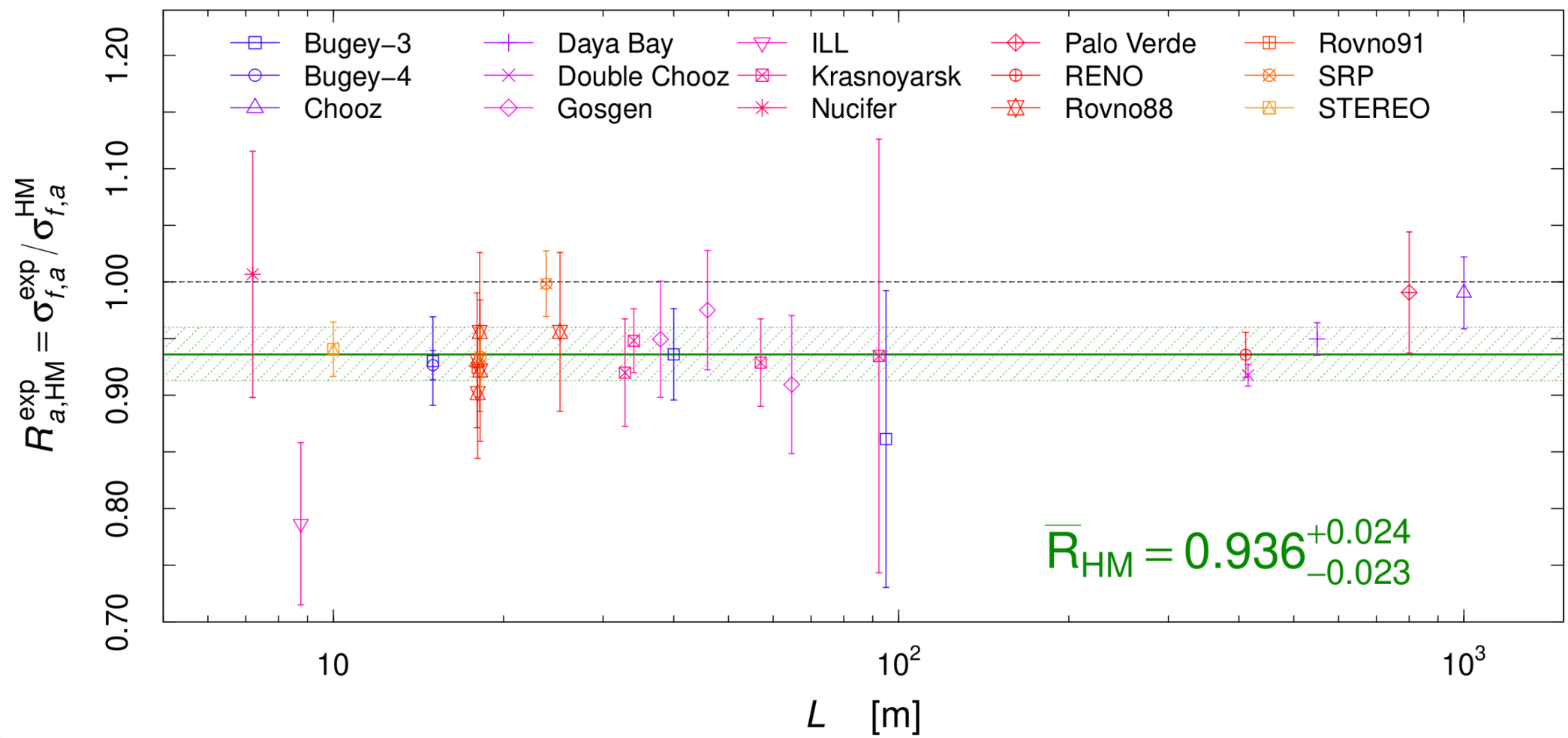
Short Baseline Anomalies: Reactor neutrino fluxes

Deficit of reactor $\bar{\nu}_e$ flux ~ 3.5 % (~ 3 σ) below predictions

$\bar{\nu}_e \rightarrow \boxed{?}$

L/E is too small for standard oscillation, deficit can be explained by neutrino oscillation with $\Delta m^2 > 0.5\ eV^2$



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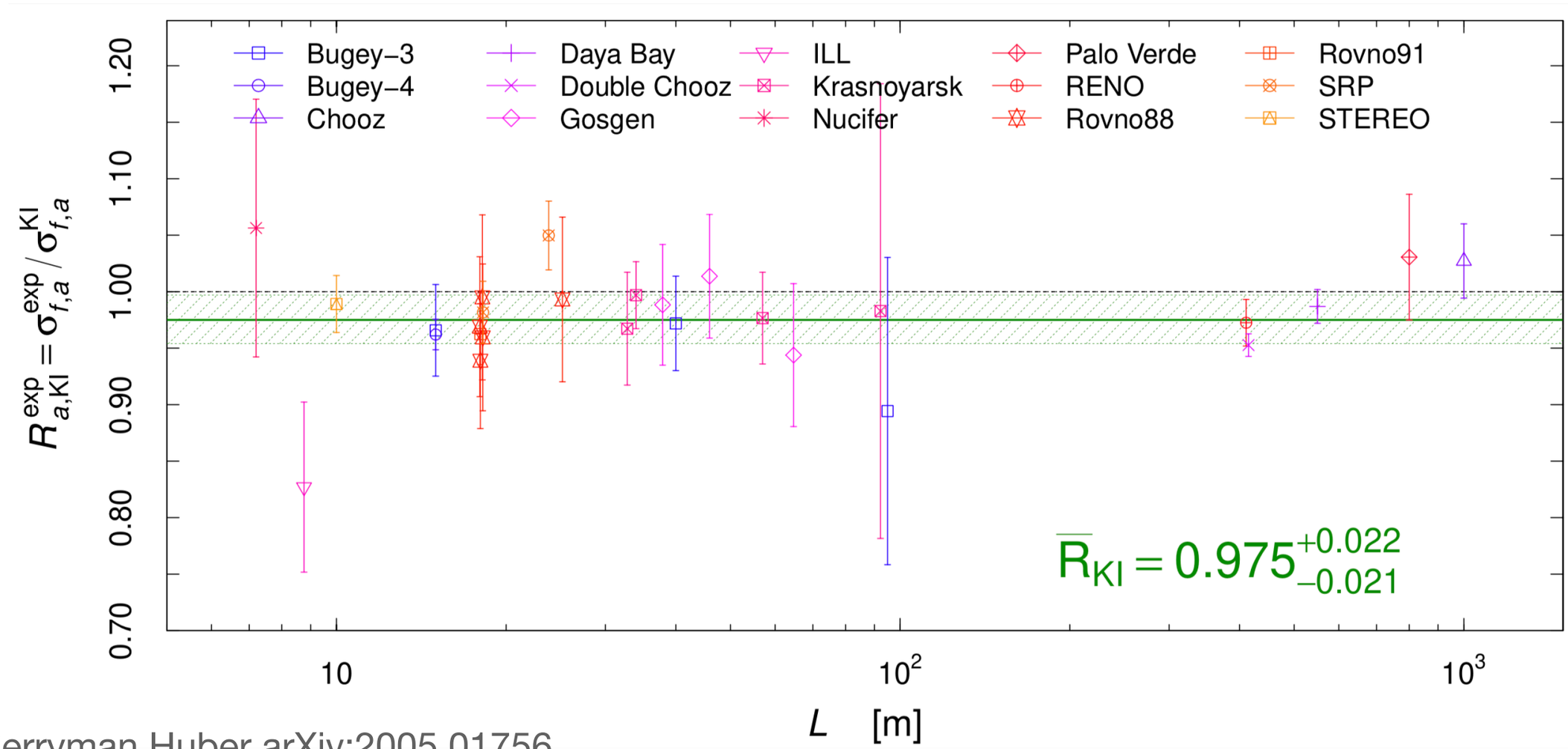
Short Baseline Anomalies: Reactor neutrino fluxes

Reactor flux comparison after new input data to flux calculation

(new ß spectra from ^{235}U fission)



Berryman Huber arXiv:2005.01756

Giunti Li Ternes Xin arXiv:2110.06820

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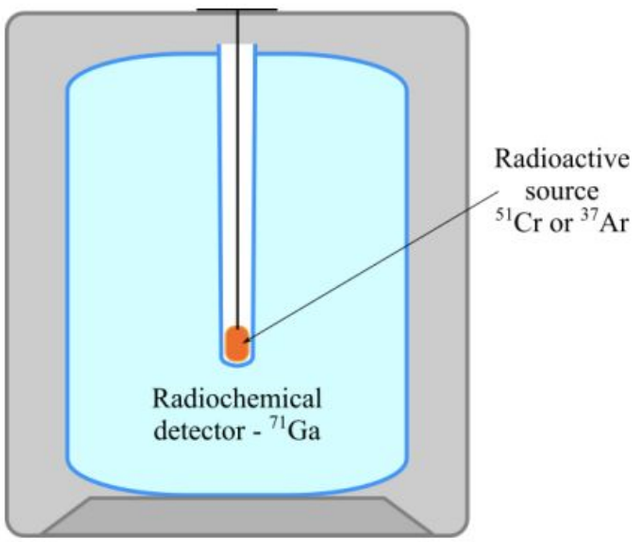
Short Baseline Anomalies: Gallium Anomaly

SAGE/GALLEX experiments used ^{51}Cr and ^{37}Ar radioactive sources (producing ν_e via electron capture) for calibration of their Gallium detectors



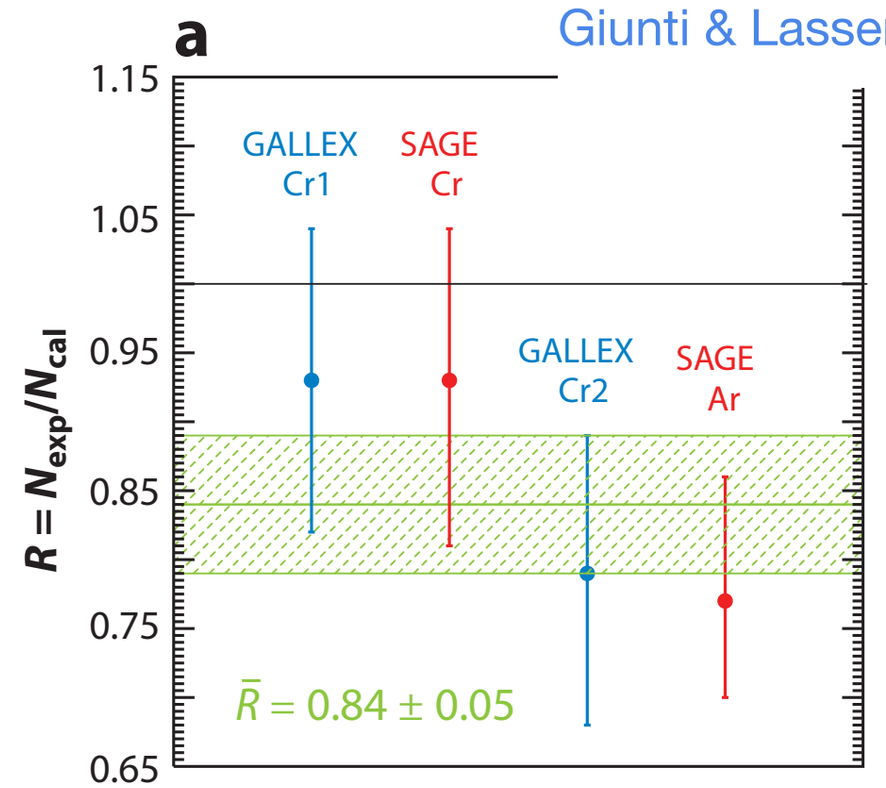
$$\nu_e \rightarrow \boxed{?}$$

- Neutrino Detection via:

$$^{71}\mathrm{Ga} + \nu_e \rightarrow ^{71}\mathrm{Ge} + e^-$$

3 σ deficit of radioactive ν_e event rate, $\Delta m^2 > 1$ eV^2

Giunti & Lasserre (2019)



New radioactive sources and detectors for improved direct tests of the Gallium Anomaly has been realized in the form of the BEST experiment which confirmed the anomaly at 4 σ .

BEST arXiv:2109.11482

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The MiniBooNE and LSND event excess

Anomalies observed in ν_e appearance experiments

LSND

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Energy: 20 - 55 MeV

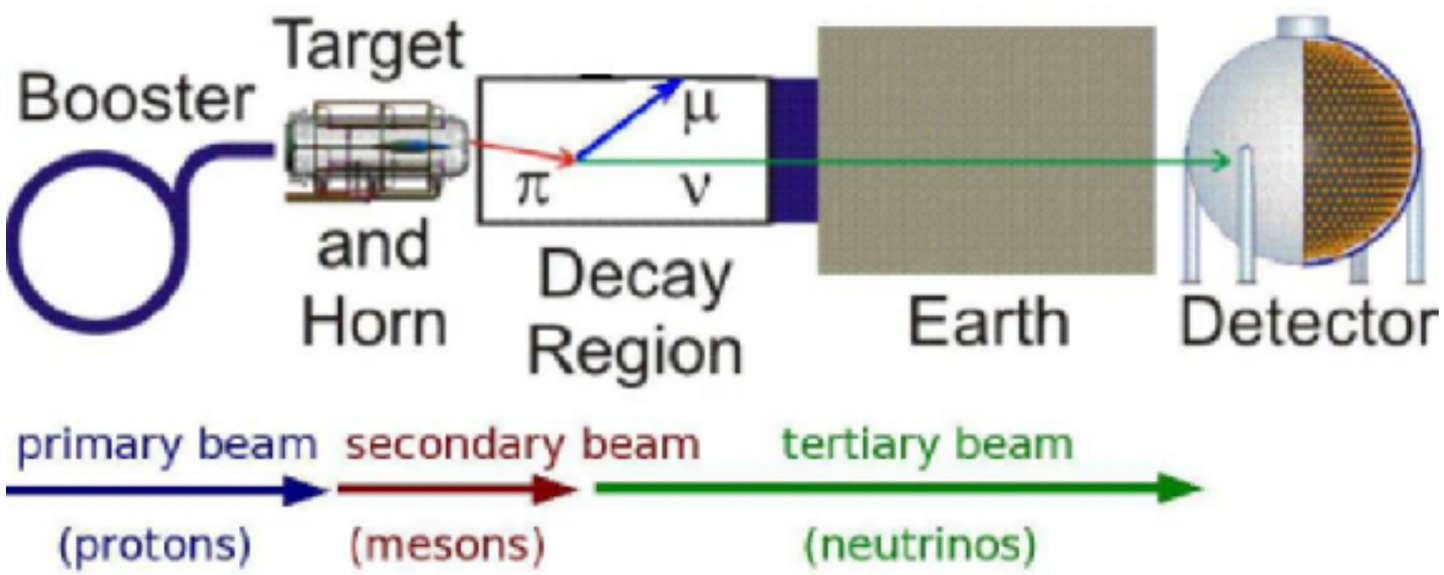
Baseline: 10 m - 100 km

MiniBooNE

$\nu_\mu \rightarrow \nu_e$

Energy: 800 MeV

Baseline: 540 km



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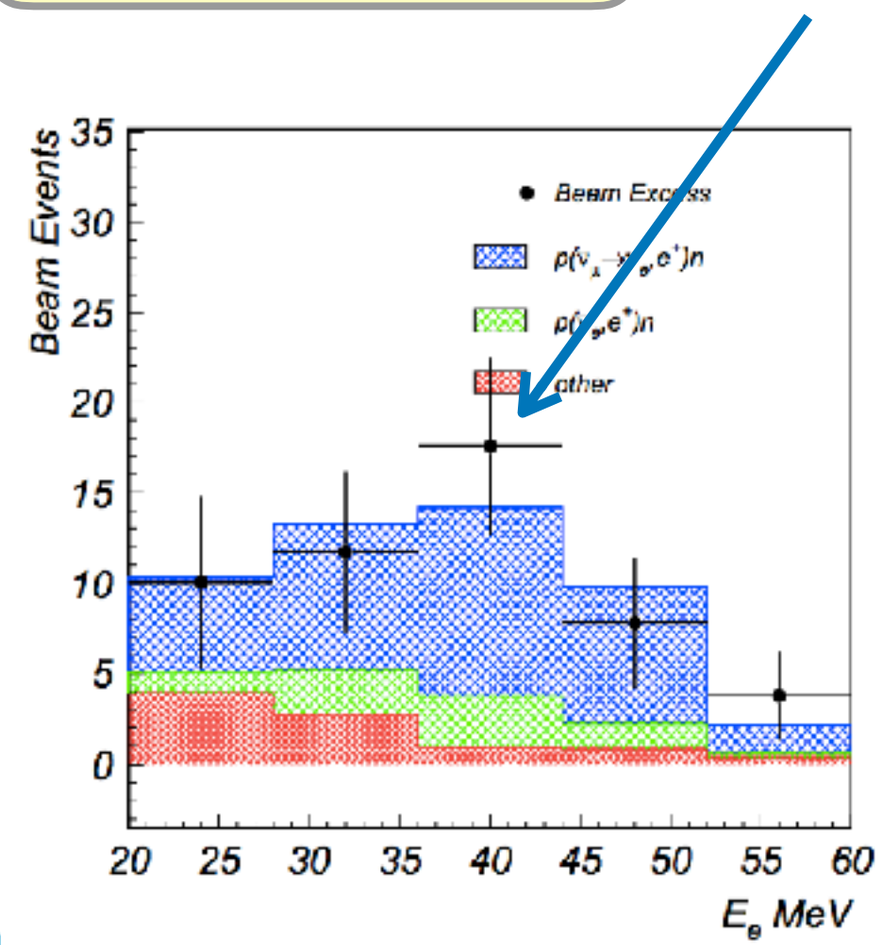
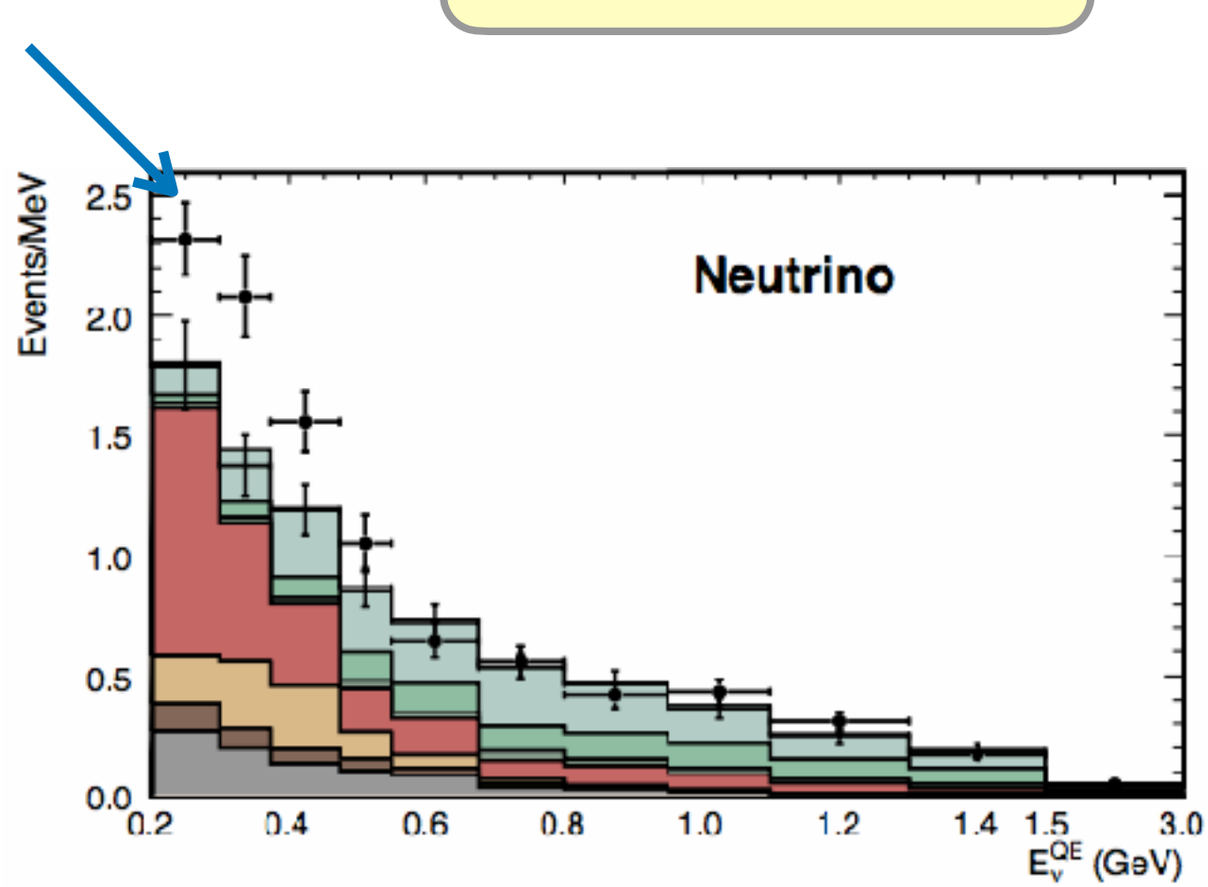
$\nu_\mu \rightarrow \nu_e$

Energy: 800 MeV

Baseline: 540 km

Excess of electromagnetic events on a scale of L/E ~ m/MeV





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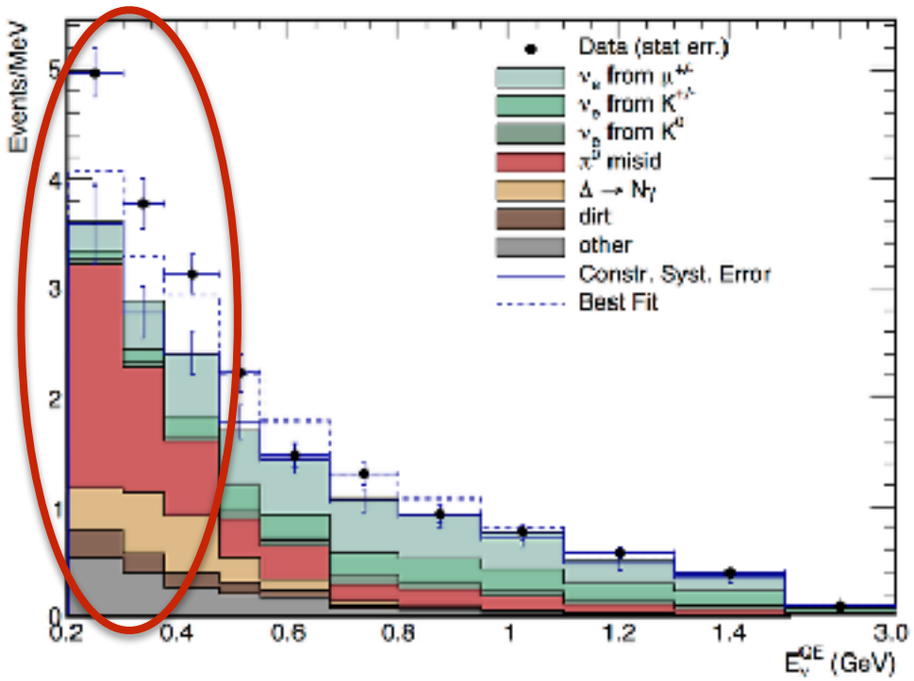
MiniBooNE anomaly

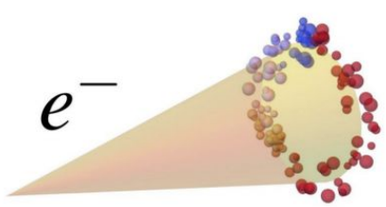


✐ MiniBooNE Collaboration PRL 110 101802 (2013)

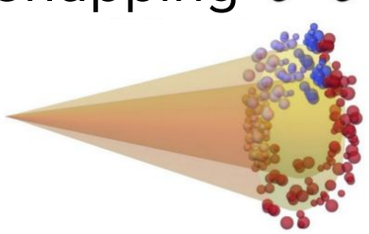
Updated results have been presented in 2018 by the MiniBooNE collaboration: doubled statistics in neutrino-mode running since the previous result

Excess of ν_e in a ν_μ beam confirmed (4.8 σ)

L/E is too small for standard oscillation (wrong Δm^2)



overlapping e^+e^-



<u>Standard Model explanation:</u> background γ produced by Δ→ N+γ

γ → e^++e^- are indistinguishable to MiniBooNE

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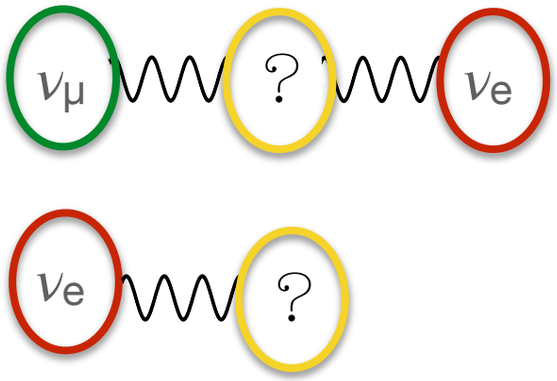
Common aspects shared by the four anomalies

Deviations from the expected electron neutrino event rate, from either electron- or muon-neutrino sources



L/E ~ 0.1-10 m/MeV incompatible with standard oscillations

Leading interpretation: Light sterile neutrino oscillations

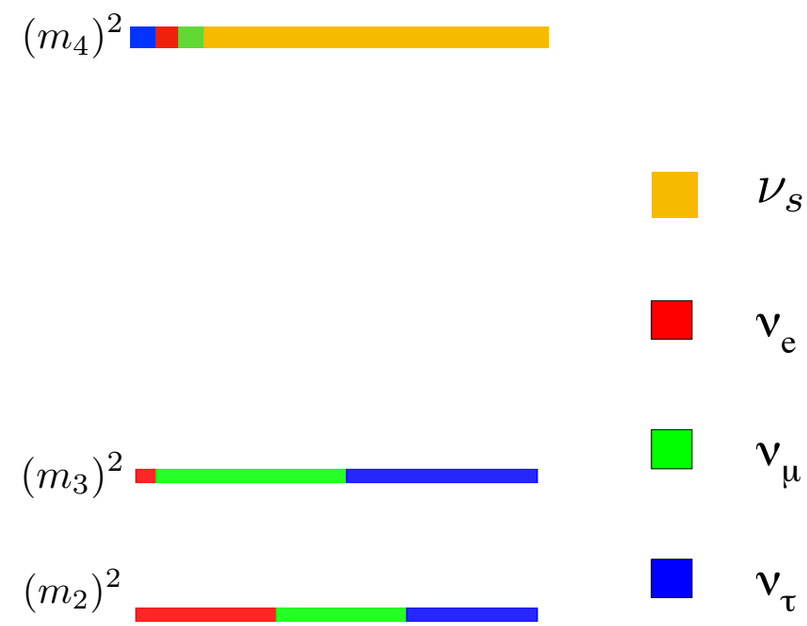
Add extra neutrino flavor, promote **mixing matrix 4x4**

Oscillation channels are related:

ν_e disappearance

ν_μ disappearance

$\nu_\mu \rightarrow \nu_e$ appearance



Probability amplitudes depends on ν_e and/or ν_μ flavor content(s) of ν_4

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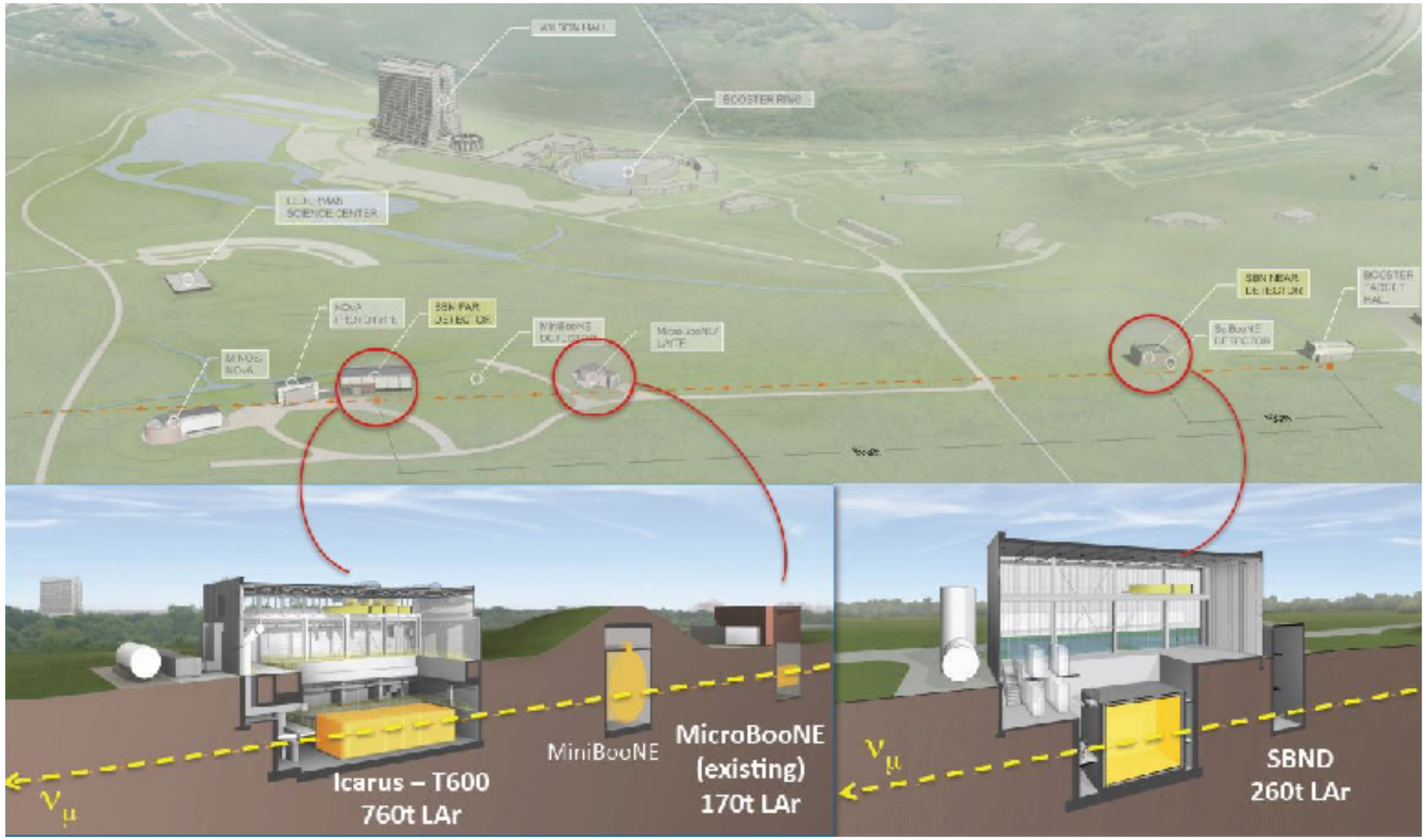
Short Baseline Neutrino Oscillation Searches



Multiple LAr-TPC detectors at different baselines along the Booster Neutrino Beam; capable of **multi-channel searches** with **enhanced sensitivity** to light sterile oscillations

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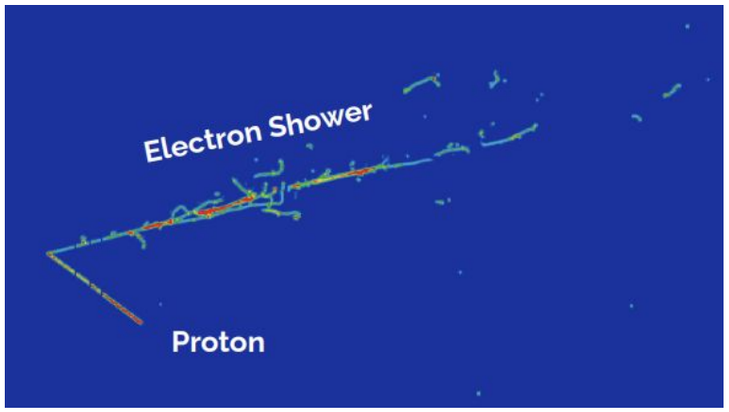
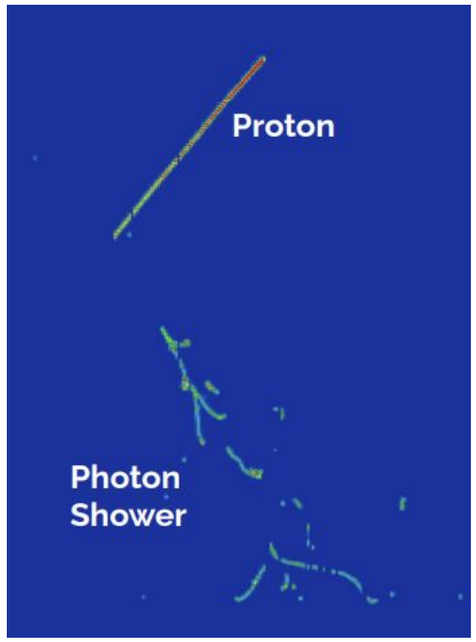
Sterile ν searches: (beyond) MicroBooNE

MicroBooNE: A direct test of the MiniBooNE anomaly:





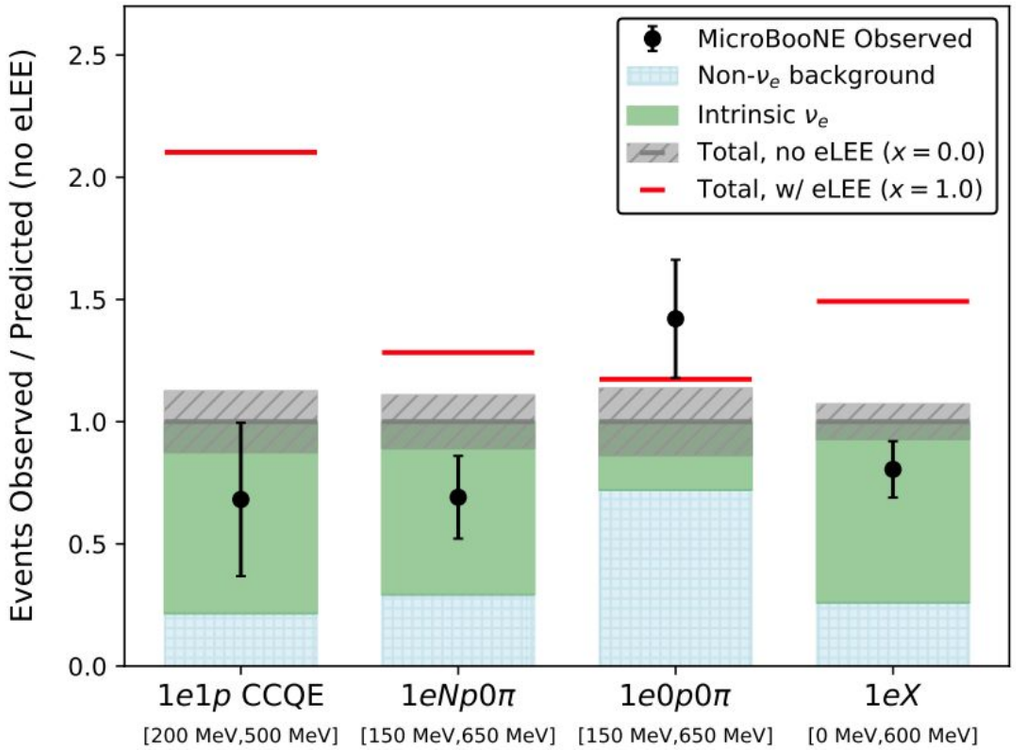
- MicroBooNE finds no hints of an electromagnetic event excess
- MicroBooNE's result does not rule out the existence of sterile neutrinos
- SBND + ICARUS will test the sterile neutrino hypothesis
  – can cover the parameter space favored by past anomalies with 5σ significance

LarTPC: high resolution tracking capable of identifying different species of particles

Can distinguish between **e** and **γ → e⁺+e⁻** : gap between the shower start point and neutrino vertex

First analysis searching for an excess of low-energy electromagnetic events in single electron and single photon final states

Phys.Rev.Lett. 128 (2022) 24, 241801



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Open Questions

Many fundamental questions are still open:

✔ $m_1^2 < m_2^2$

✔ $m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$

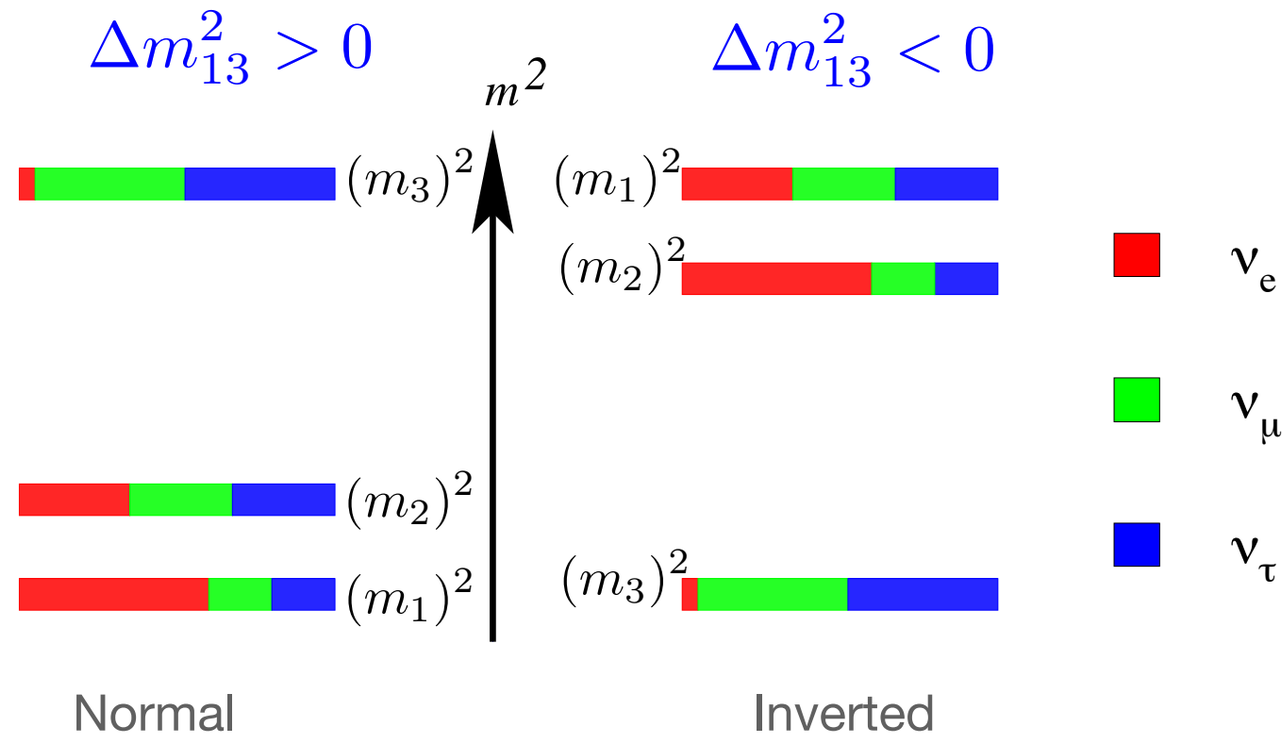
? What is the correct ordering, sign of Δm_{13}^2

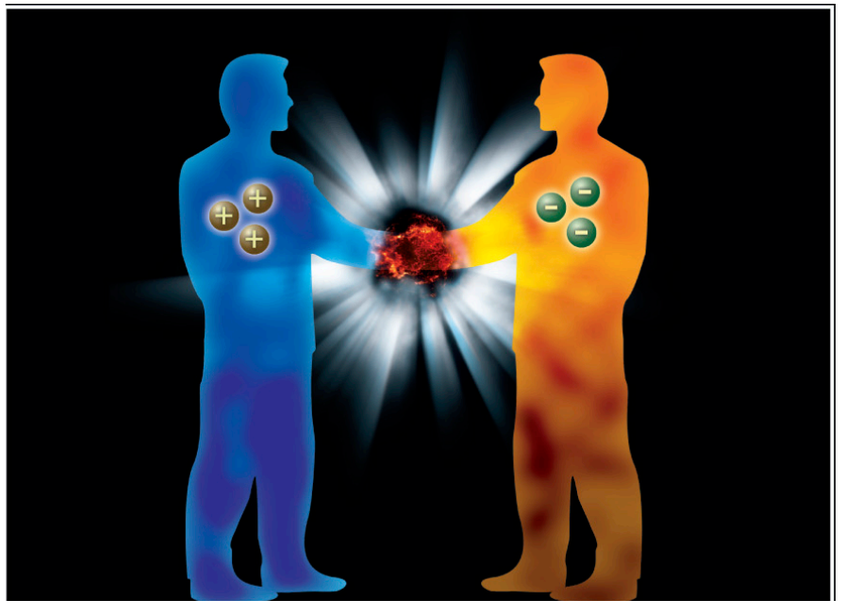
? Is θ_{23} maximal: is ν_3 mostly ν_μ or ν_τ

? Are there CP violations in the lepton sector

$$P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

Understanding matter-antimatter asymmetry





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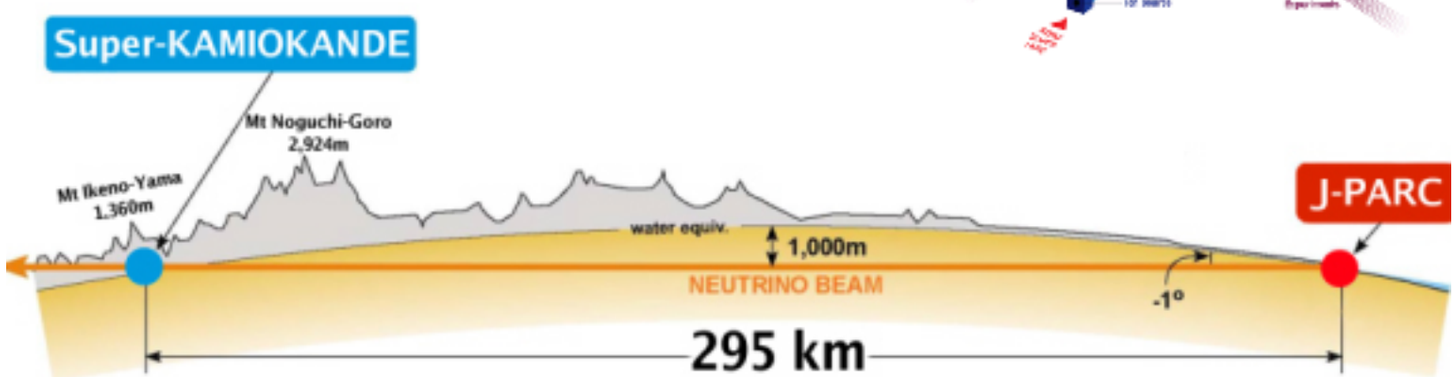
Long Baseline Neutrino experiments

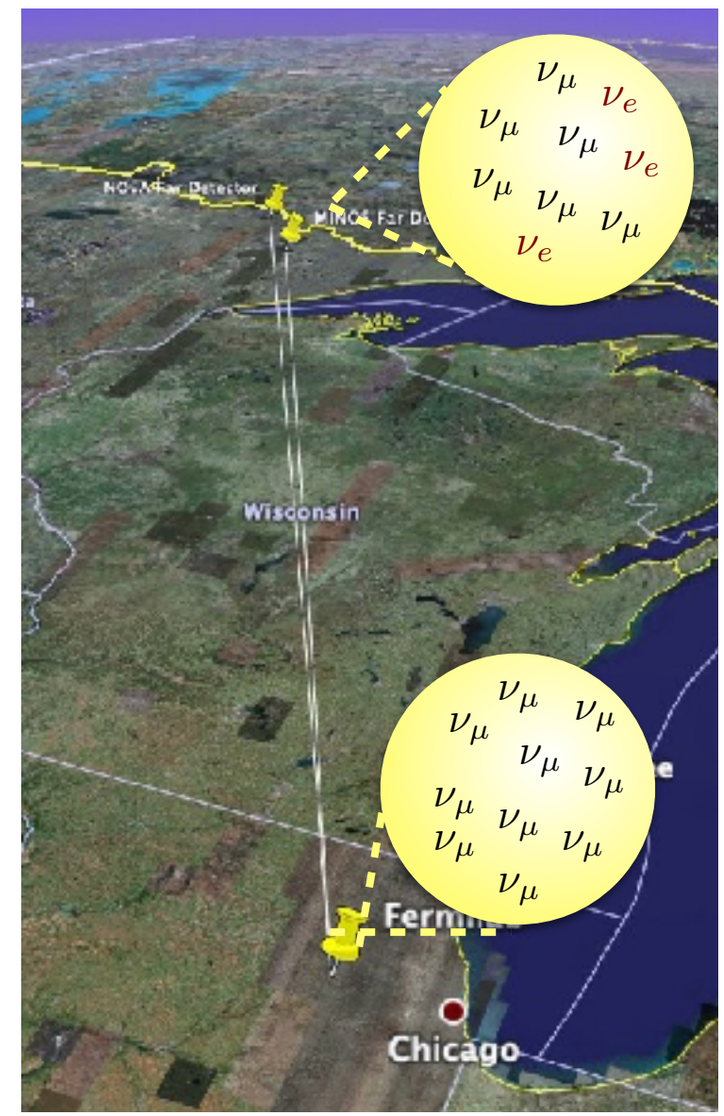
These questions are addressed **with Long Baseline** Neutrino Oscillation experiments

T2K: Tokai to Kamioka

295 km



NOvA: Fermilab to Ash River
810 km



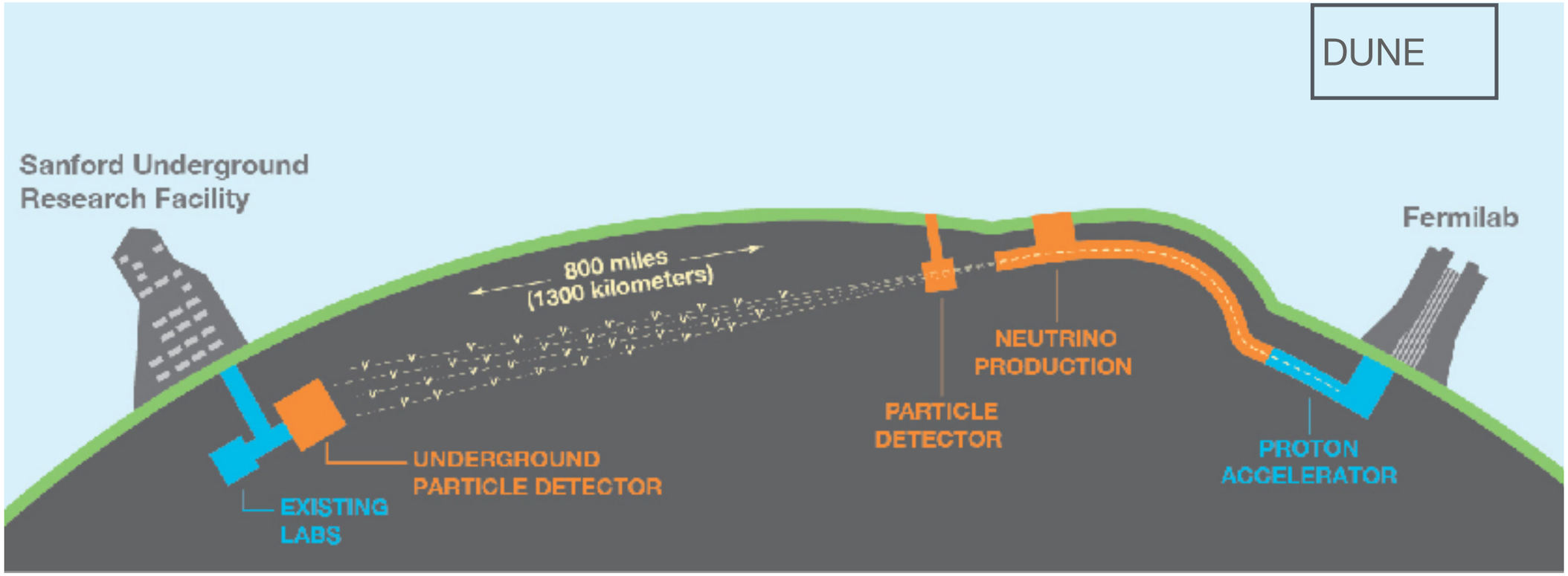
Currently measuring:

$P(\nu_\mu \not\to \nu_\mu)$ ν_μ disappearance

$P(\nu_\mu \to \nu_e)$ ν_e appearance

Noemi Rocco, nrocco@fnal.gov

Long Baseline Neutrino experiments



The scope of DUNE is to definitively answer these questions (mass ordering, CP violating phase and precision measurements of the oscillation parameters)

Highly energetic neutrino beam from Fermilab going 1300km to Homestake in South Dakota

More than 1000 scientists from 175 institutions and 32 countries

Not only oscillations but also: supernovae neutrinos, proton decay searches…

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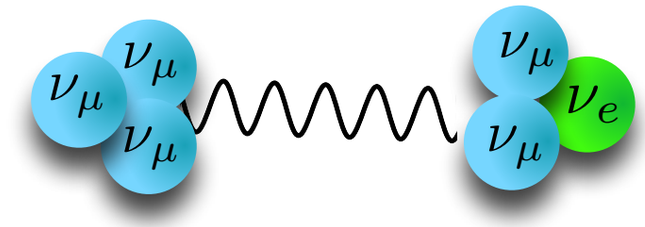
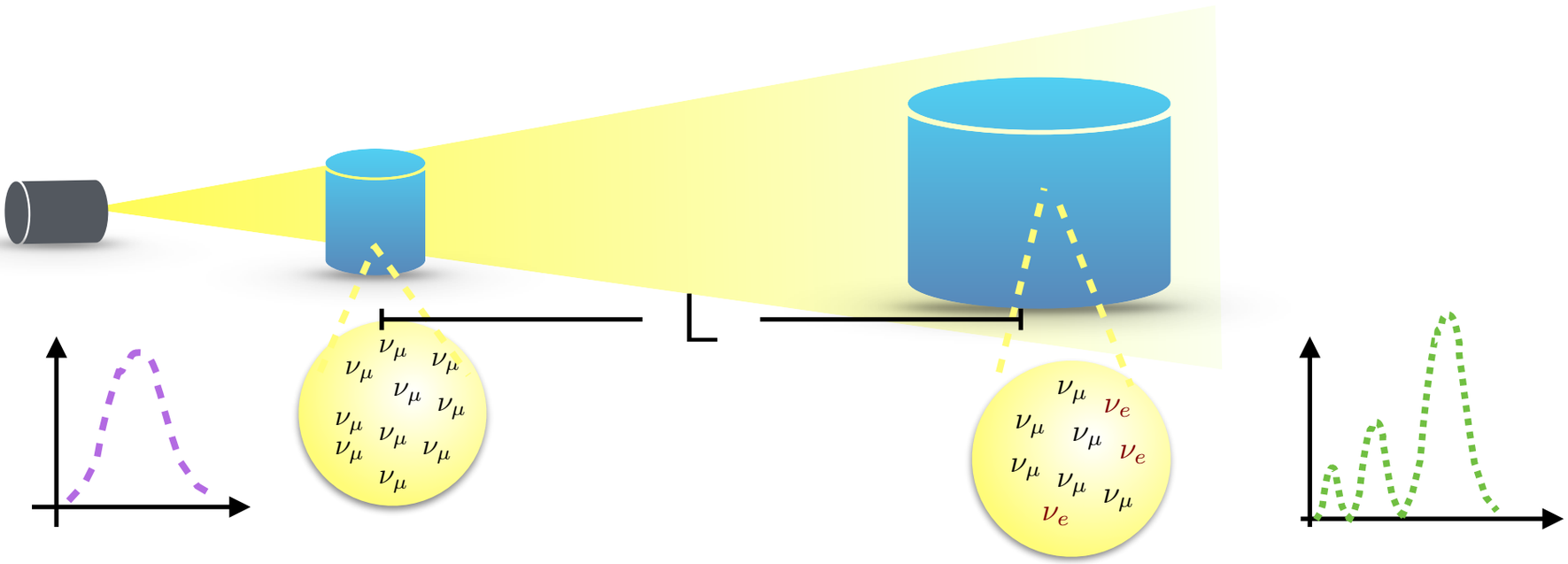
Addressing Neutrino-Oscillation Physics

$$P_{\nu_\mu \to \nu_e}(E, L) \sim \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right) \to \Phi_e(E, L)/\Phi_\mu(E, 0)$$





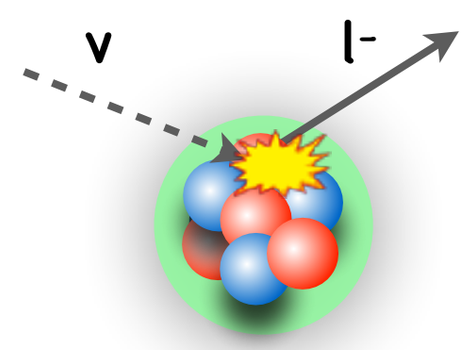
Detectors measure the **neutrino interaction rate:**

$$N_e(E_{\rm rec}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{\rm rec}) dE$$

Reconstructed ν energy

Cross Section

Smearing matrix



A precise determination of σ(E) is crucial to extract ν oscillation parameters

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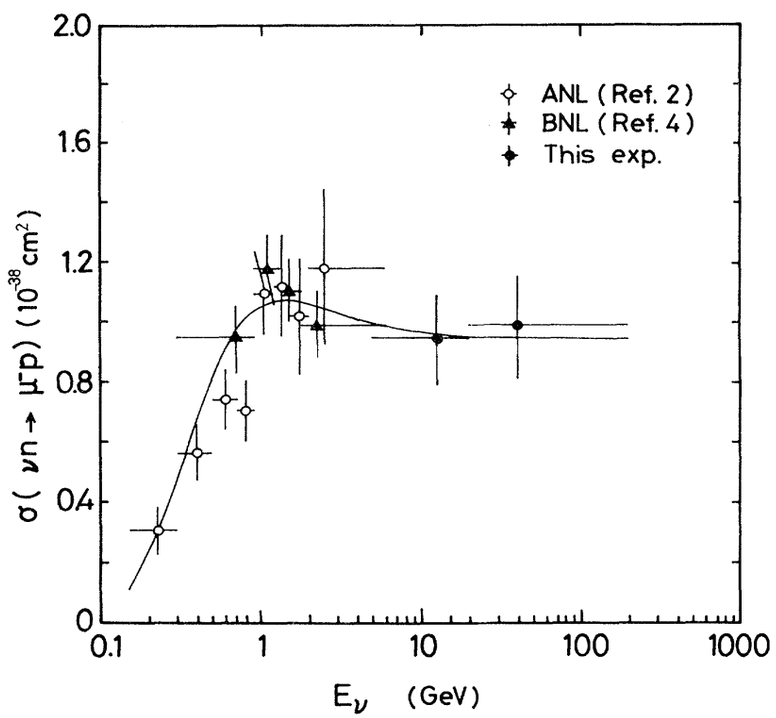
To study neutrinos we use nuclei



✐ T. Kitagaki et al, Phys. Rev. D 28, 436 (1983)

Neutrino scattering extensively studied 1970-90's using deuterium-filled **bubble chambers**

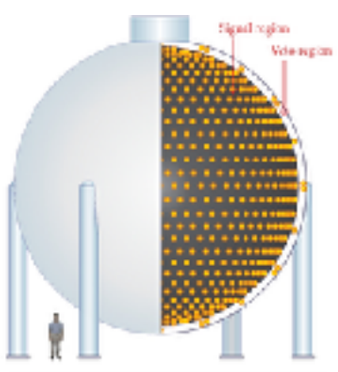
$$\mathcal{N}_{\text{hits}} = \sigma \times \Phi \times N$$

Targets

Bubble Chamber experiment at Fermilab

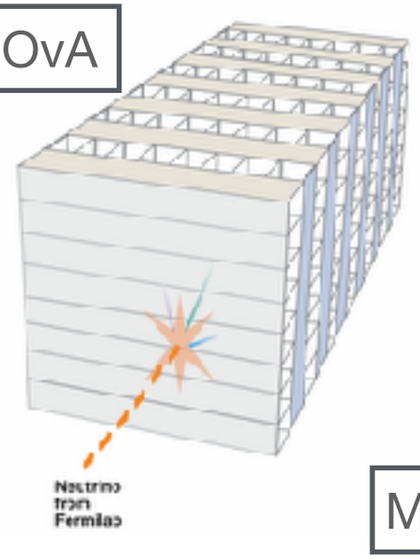
Utilize **heavy target** in neutrino detectors to maximize interactions→ understand **nuclear structure**

Carbon

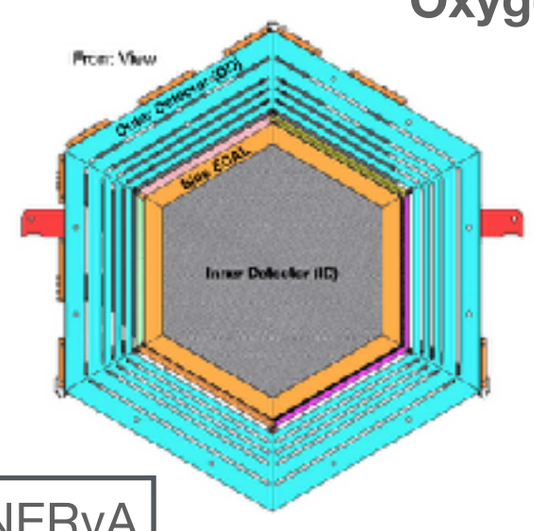


MiniBooNE

NOvA



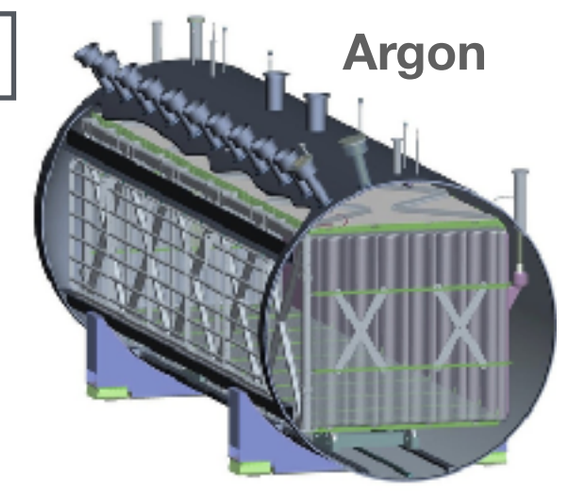
Oxygen



MINERvA

S-K

Argon



MicroBooNE

Fermilab

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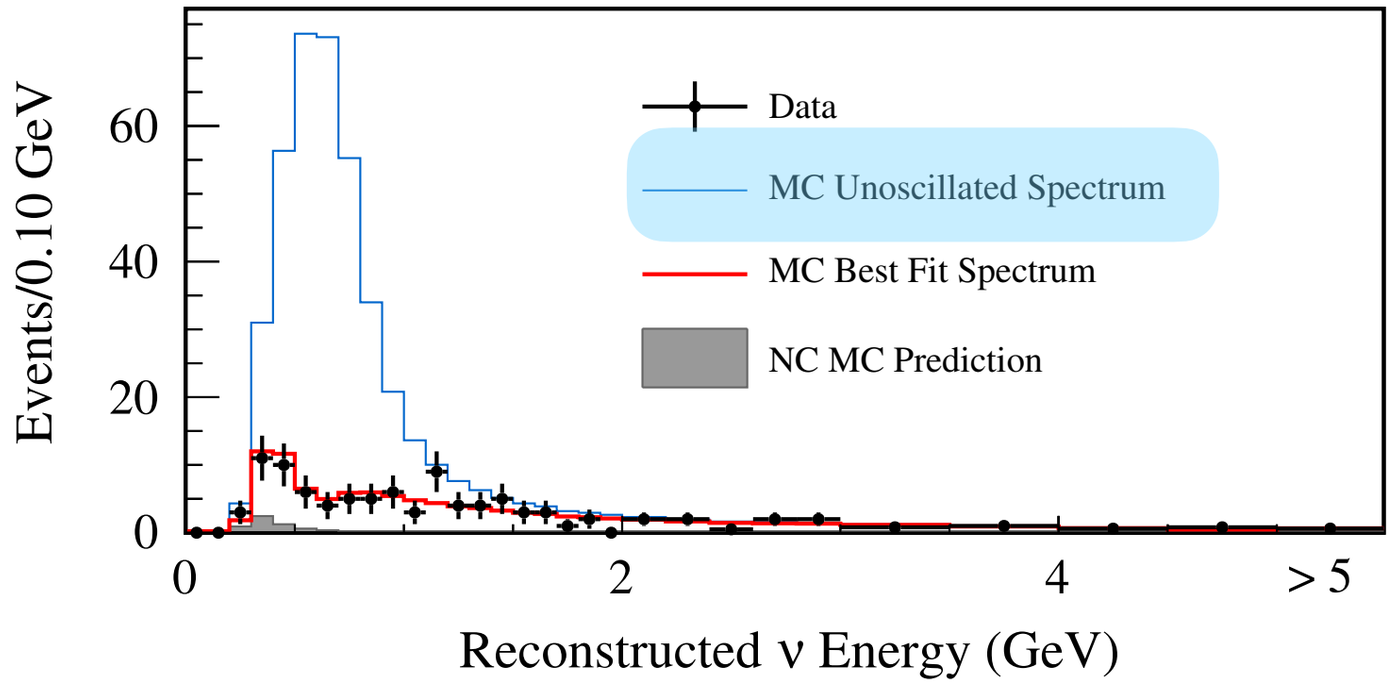
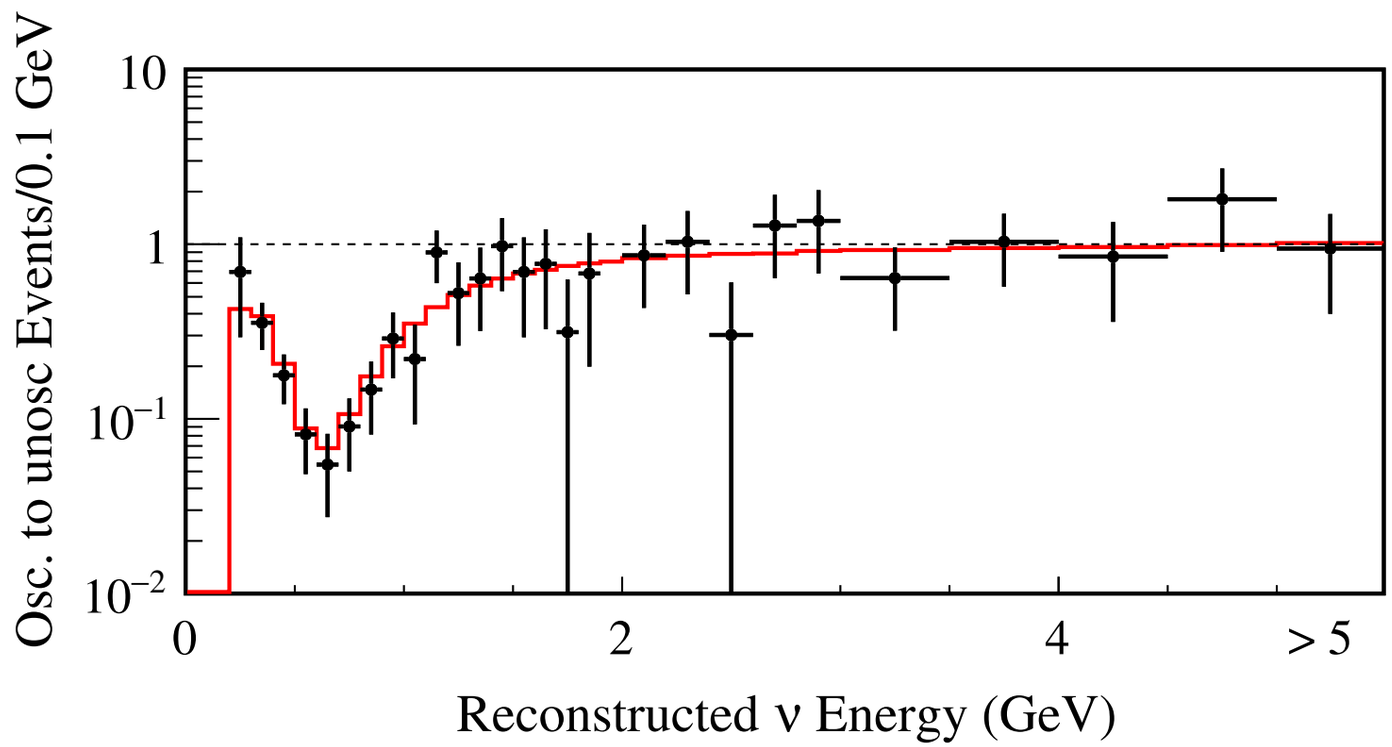
Oscillations Require E_ν reconstruction

T2K, Phys. Rev. D 91, 072010 (2015)





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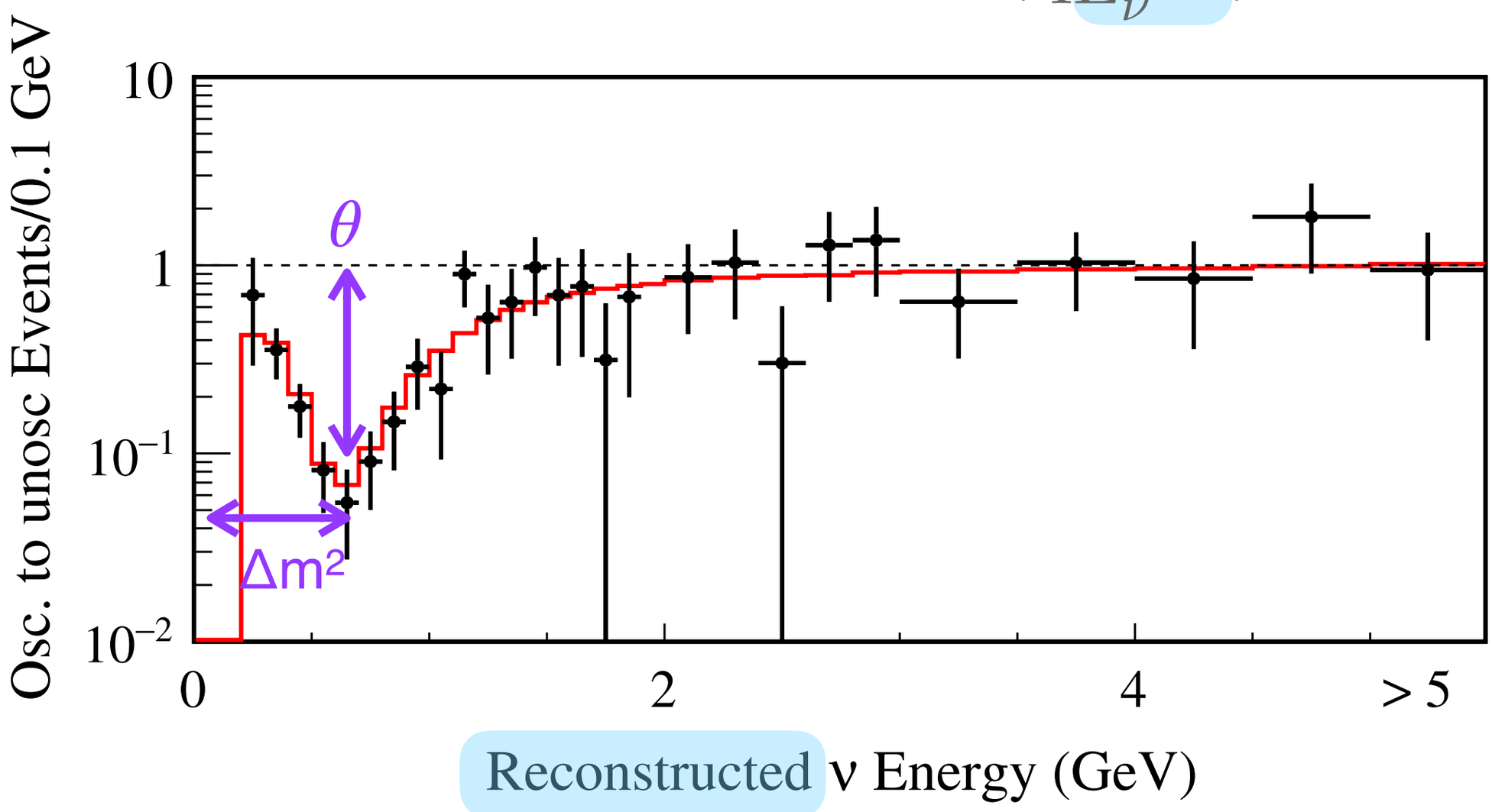
Oscillations Require E_ν reconstruction

T2K, Phys. Rev. D 91, 072010 (2015)

$$P(\nu_\mu \rightarrow \nu_x) \sim \sin^2 2\theta \, \sin^2\left(\frac{\Delta m^2 L}{4E_\nu^{true}}\right)$$



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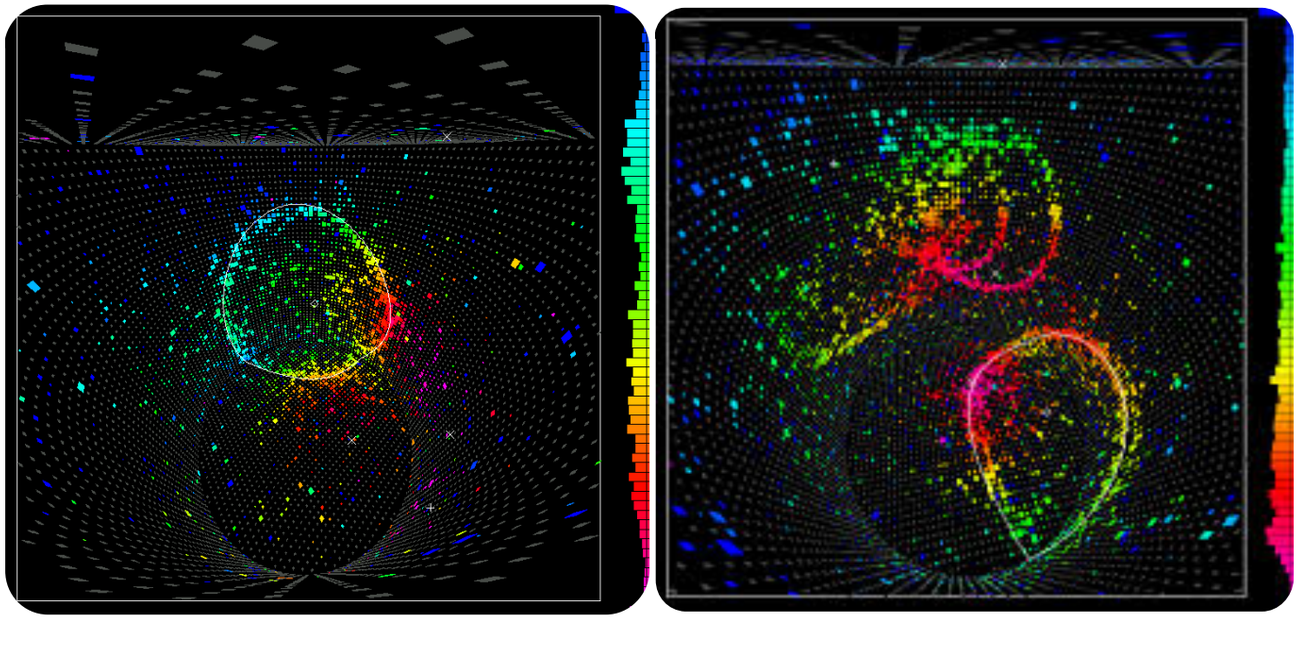
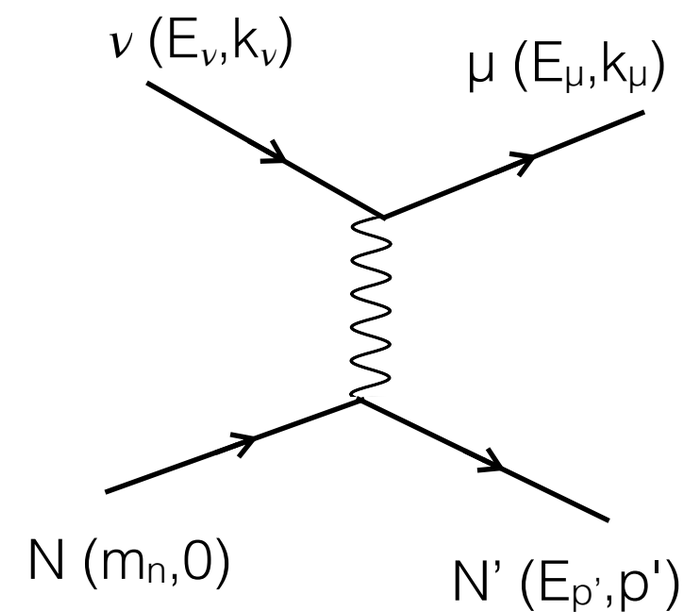
Neutrino energy reconstruction



Cherenkov detector



- Kinematic Reconstruction

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2\left(M - E_l + |k_l|\cos\theta_l\right)}$$

- Main problems: not exact on nuclear targets, lack of knowledge of the hadronic undetected hadrons in the final state.

For example, when a produced pion is absorbed or undetected the reconstructed neutrino energy is underestimated at least by ~ 300 – 350 MeV

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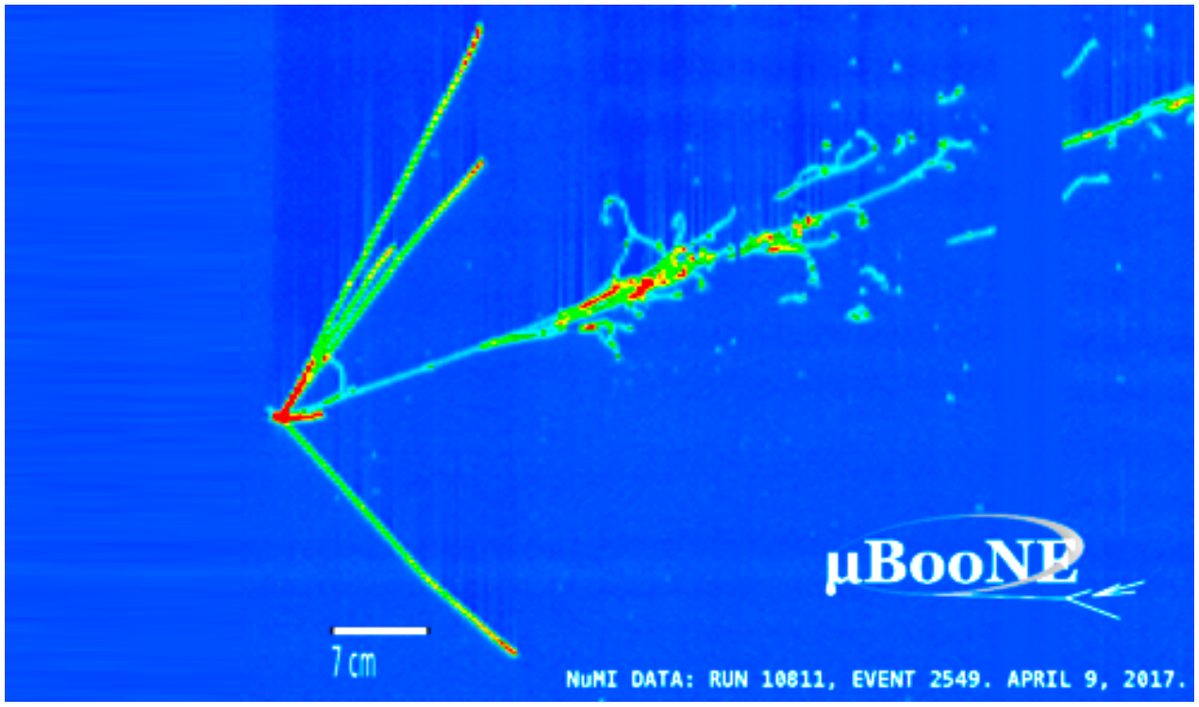
Neutrino energy reconstruction

Tracking detector



- Calorimetric sum: uses all detected (charged) particles

$$E_{\mathrm{cal}} = E_\ell + E_p^{\mathrm{kin}} + \epsilon$$

- The ability to reconstruct the hadronic final state in the most accurate way is a huge experimental challenge and relies on simulations

For example, neutrons typically escape detection and any undetected meson will result as an energy underestimation equal, at least, to the pion mass.

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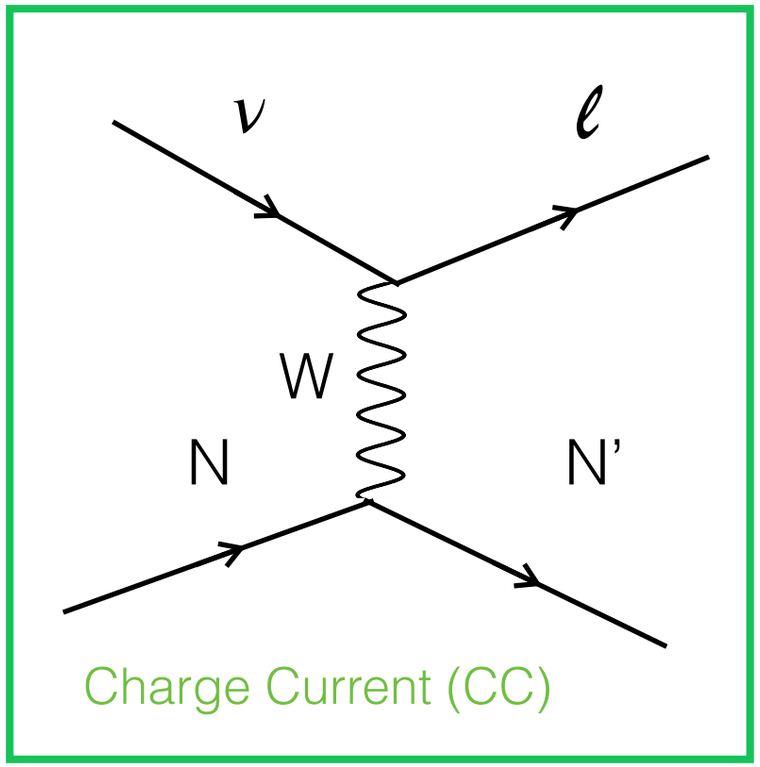
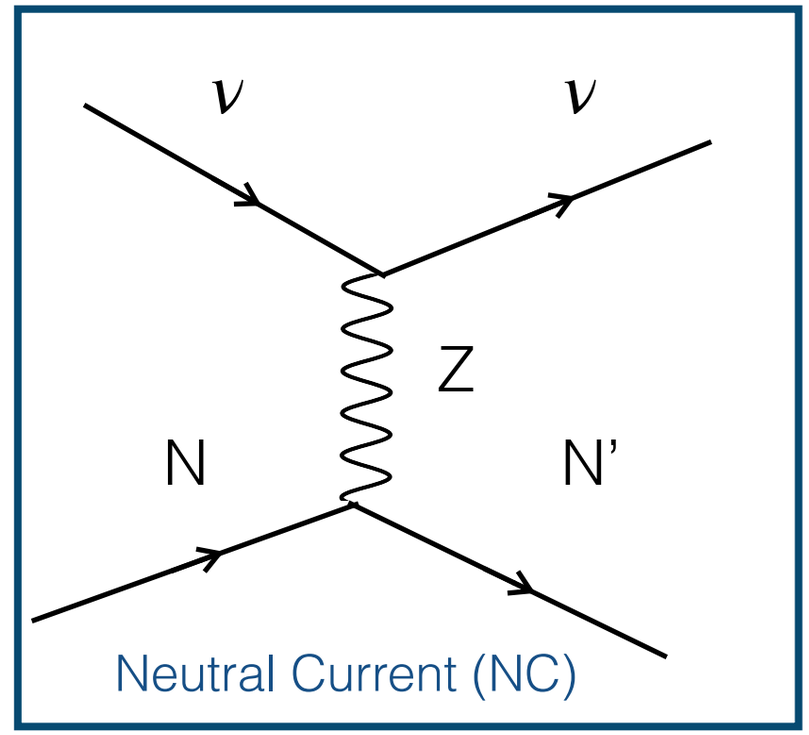
Neutrino-Nucleon scattering





- Exchange of the W boson
- Lepton produced has the same flavor of the neutrino
- Initial and final nucleon have different isospin

- Exchange of the Z boson
- Independent of the neutrino flavor
- Initial and final nucleon have same isospin

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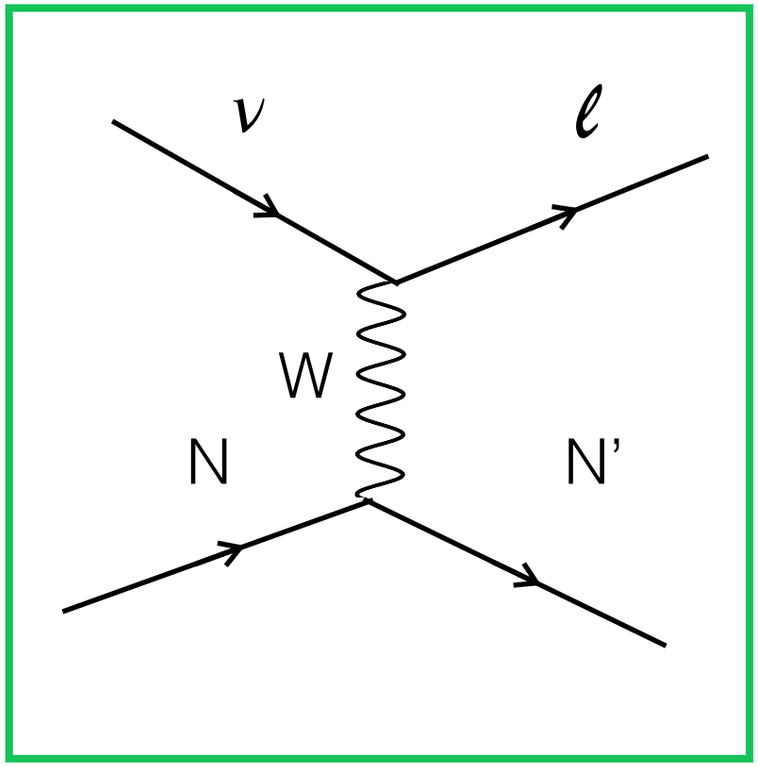
Neutrino-Nucleon scattering

- General expression for the differential cross section

$$d\sigma = \left(\frac{1}{|v_N - v_\ell|} \frac{1}{4E_N^{\text{in}} E_\ell^{\text{in}}} \right) |\mathcal{M}|^2 \prod_f \frac{d^3 p_f}{(2\pi)^3} (2\pi)^4 \delta^4 \left(k_N + k_\ell - \sum_f p_f \right).$$

In the **one boson exchange** approximation:

$$|\mathcal{M}|^2 = L_{\mu\nu} W^{\mu\nu} \frac{1}{P^2}$$



- Leptonic Tensor:

$$L_{\mu\nu} = 8[k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k \cdot k' \pm i\epsilon_{\mu\nu\alpha\beta} k'^\alpha k^\beta]$$

$\nu/\bar{\nu}$

- Hadronic Tensor:

$$W_{\mu\nu} = \sum_{\sigma_i \sigma_f} \frac{1}{2E_p} \int \frac{d^3 p'}{2E_{p'}} \langle N(p)|J^\mu|N'(p')\rangle \langle N'(p')|J^\nu|N(p)\rangle$$
$$\times \delta^{(4)}(p' + k' - p - k)$$

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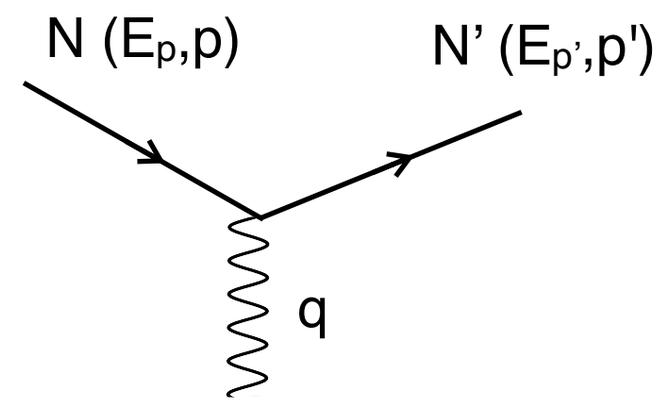
Neutrino-Nucleon scattering

- Electroweak current operator:

$$\langle N'|J^\mu|N\rangle = \bar{u}(p')\Gamma^\mu u(p) = J_V^\mu + J_A^\mu$$

Vector Axial



- The vector contribution is given by:

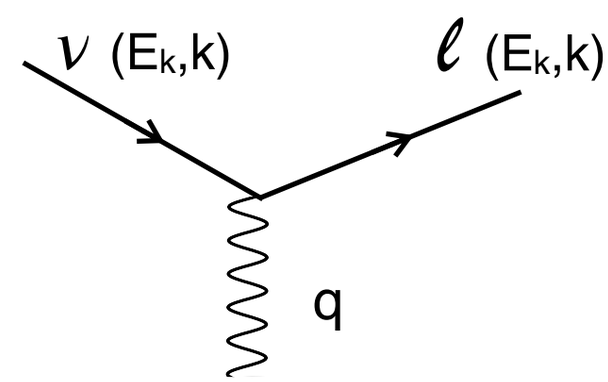
$$J_V^\mu = \mathcal{F}_1\gamma^\mu + i\sigma^{\mu\nu}q_\nu\frac{\mathcal{F}_2}{2M}$$

- The axial contribution is given by:

$$J_A^\mu = -\gamma^\mu\gamma_5\mathcal{F}_A - q^\mu\gamma_5\frac{\mathcal{F}_P}{M}$$

- In the Leptonic vertex:

$$\langle \ell^-|j^\mu|\nu_\ell\rangle = \bar{u}_\ell(k')\gamma^\mu(1-\gamma_5)u_{\nu_\ell}(k)$$



T. Leitner, O. Buss, L. Alvarez-Ruso, and U. Mosel, Electron- and neutrino-nucleus scattering from the quasielastic to the resonance region, Phys. Rev. C 79, 034601 (2009).

Neutrino-Nucleon scattering

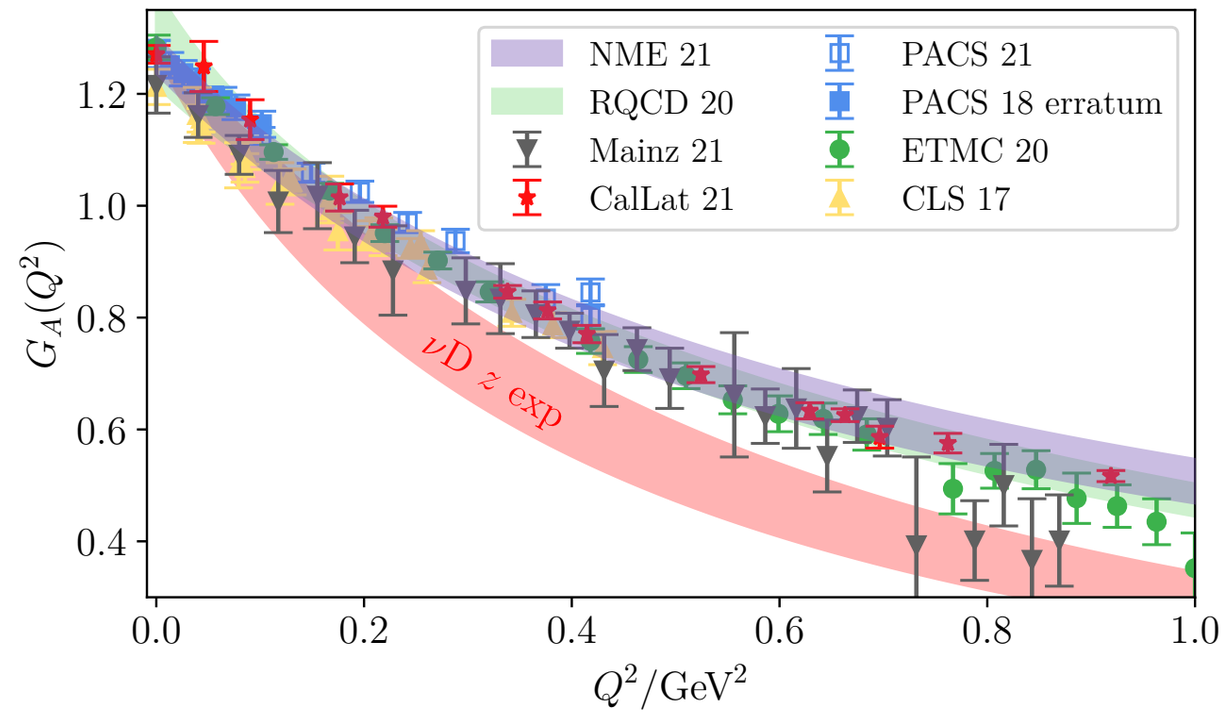
- The axial form-factor has been fit to the dipole form

$$F_A(q^2) = \frac{g_A}{(1 - q^2/m_A^2)^2}$$

- The intercept g_A=-1.2723 is known from neutron β decay

- Different values of m_A from experiments
  - m_A =1.02 GeV q.e. scattering from deuterium
  - m_A =1.08 GeV pion electroproduction
  - m_A =1.20 GeV @ K2K
  - m_A =1.35 GeV @ MiniBooNE
- The last two determinations of m_A assume a nuclear model for the target material

J. Carlson, M. Wagman, et al, 2203.09030
Contribution to 2022 Snowmass Summer Study



- Summary of current LQCD calculations of the nucleon axial form factor compared to z-expansion

- A full and robust prediction accounting of all systematics involved in the lattice-QCD calculations has not been achieved, yet.

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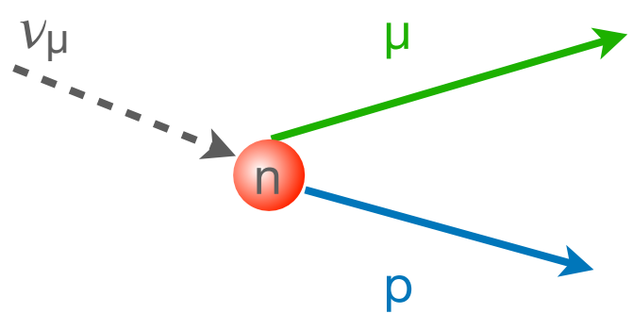
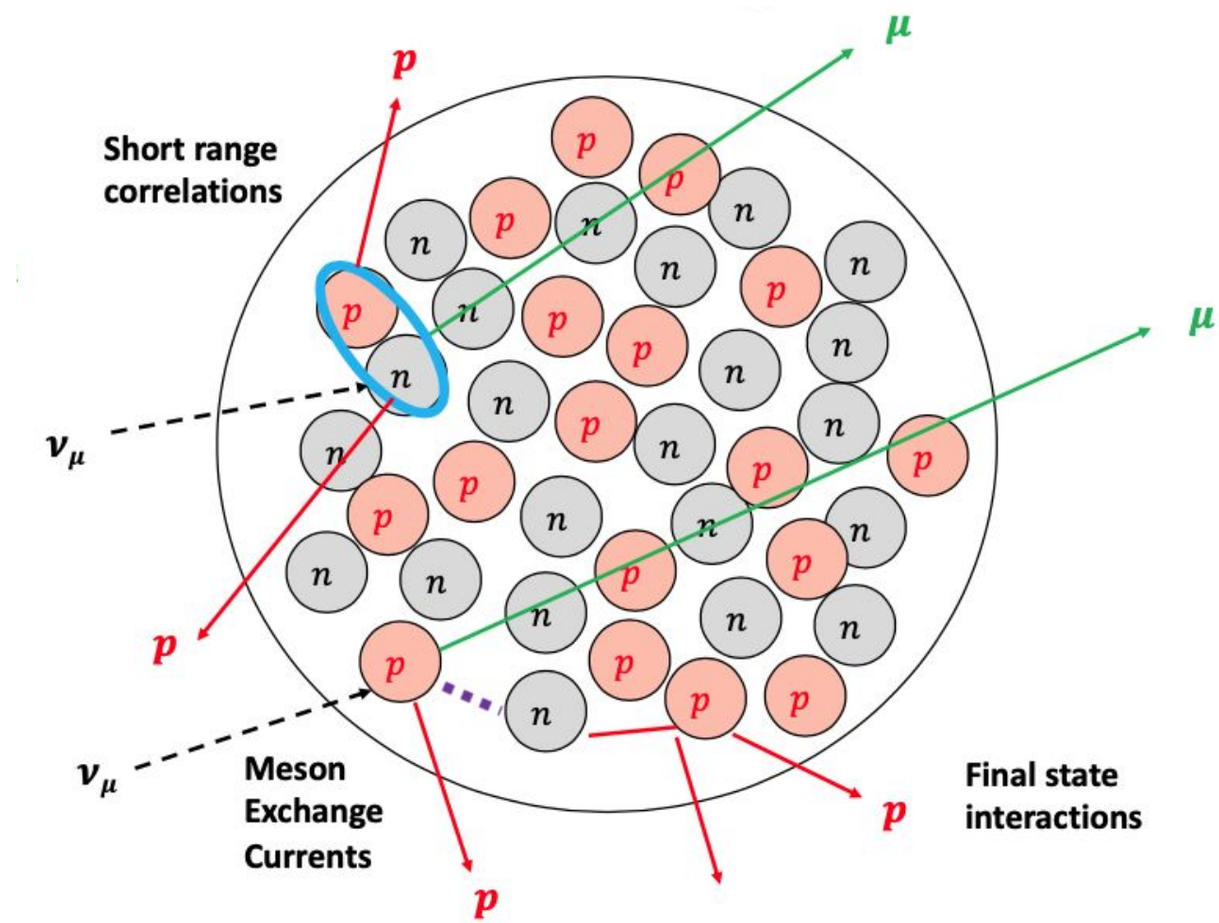
From theory to experiment

Free nucleon scattering case





Nuclear model describing the target nucleus

Different reaction mechanisms depending on the momentum transferred to the the nucleus

Final state interactions: describe how the particles propagate through the nuclear medium

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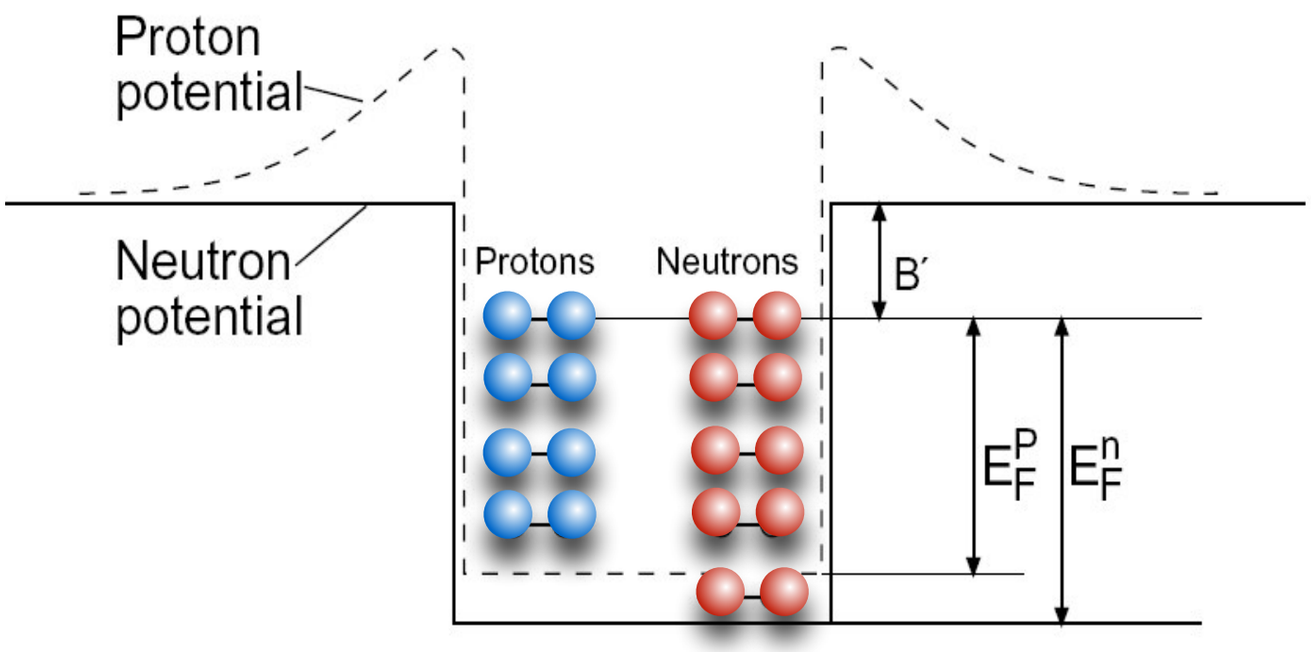
Initial state: global Fermi gas



- Simple picture of the nucleus: only statistical correlations are retained (Pauli exclusion principle)

- Protons and neutrons are considered as moving freely within the nuclear volume

- The nuclear potential wells are rectangular: constant inside the nucleus and goes sharply to zero at its edge

- The energy of the highest occupied state is the Fermi energy: E_F

- The difference B' between the top of the well and the Fermi level is constant for most nuclei and is just the average binding energy per nucleon B'/A ~ 7-8 MeV

C. Bertulani, Nuclear Physics in a Nutshell

Noemi Rocco, nrocco@fnal.gov

Initial state: shell Model

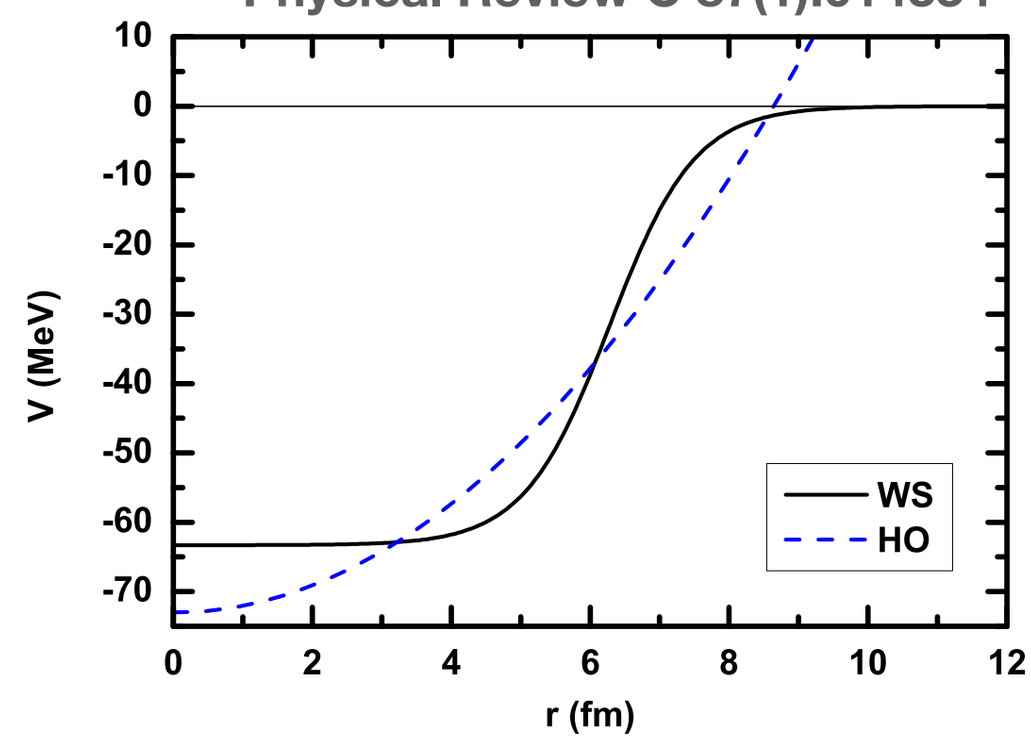
- As in the Fermi Gas model: the nucleons move within the nucleus independently of each other
- Difference: the nucleons are not free: subject to a central potential

Harmonic Oscillator: $$V(r) = \frac{1}{2} m\omega r^2$$

Wood Saxon: $$V(r) = \frac{V_0}{1 + e^{\frac{r-R}{a_0}}}$$

Each nucleon moves in an **average potential** created by the other nucleons, the **parameters** of the potential should be chosen to best reproduce the **experimental results**

Physical Review C 87(1):014334



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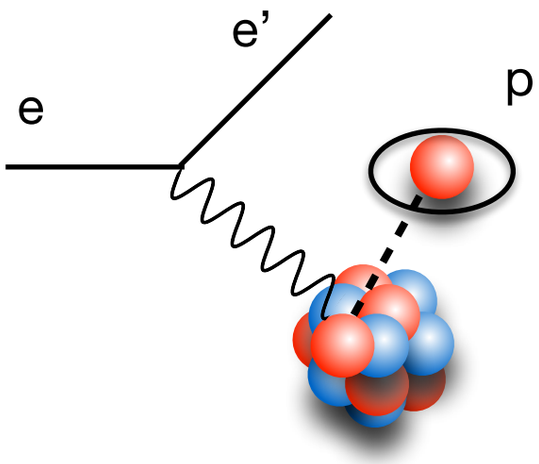
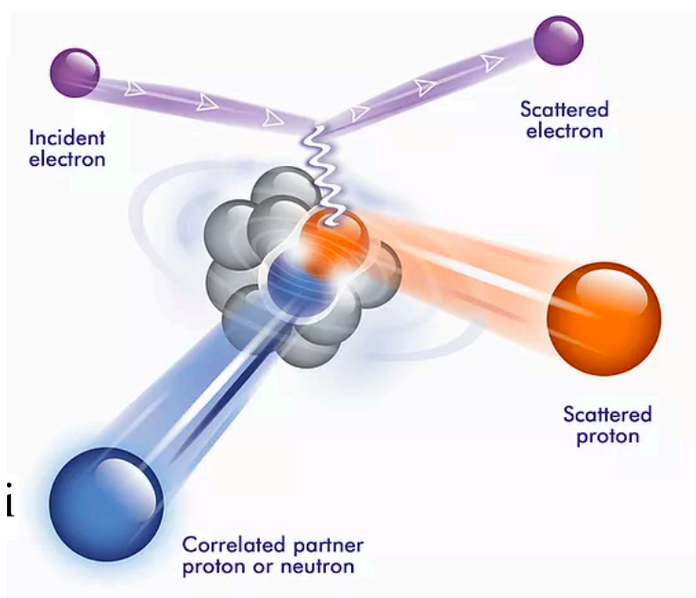
(e,e'p) scattering experiments

- (e,e'p) experiments are extremely important to investigate the internal structure of the nucleus

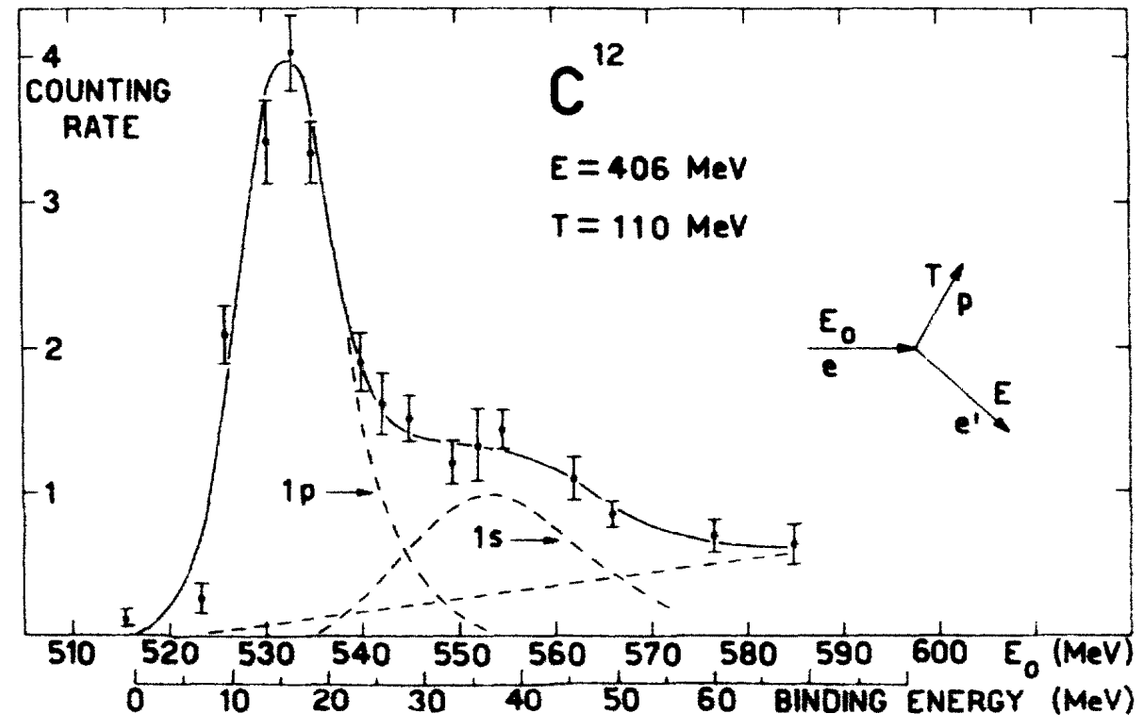


SRC: high relative momentum, back-to-back



O. Hen et al. Science 364 (2014) 614, E. Piasetzky et al. PRL (2006)

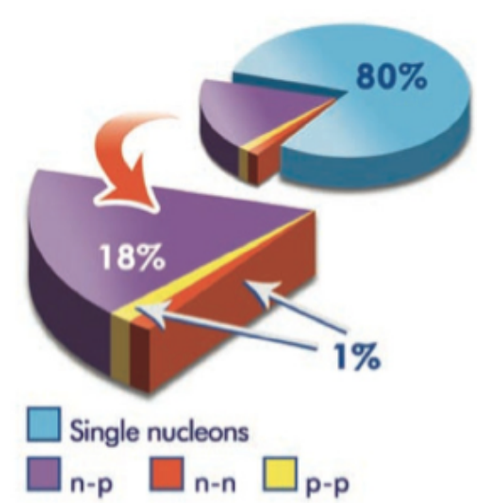
U.Amaldi et al, Phys. Rev. Lett. 13, 10 (1964)



Shell structure of the nucleus visible

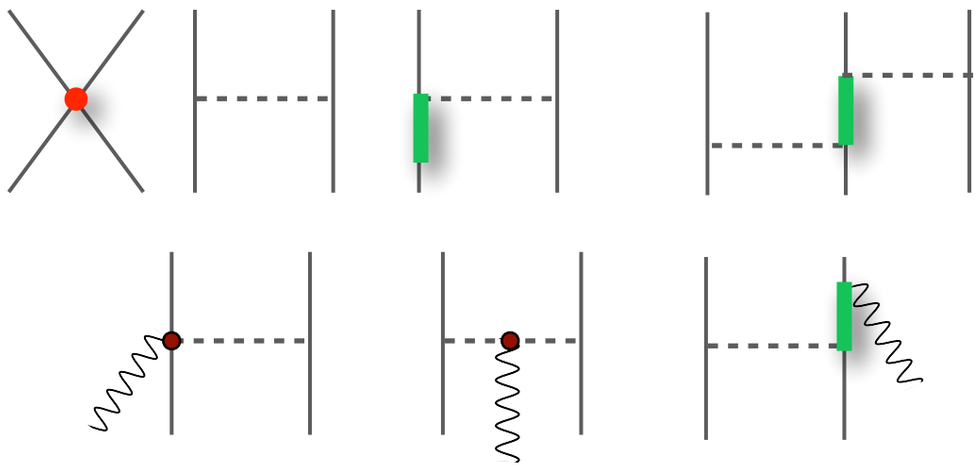
Recent experiments showed that there is more:
Short Range correlated pairs

~ 20% of nucleons in various nuclei have an high momentum, belong to SRC pairs



The basic model of nuclear theory

Effective Hamiltonians and consistent currents

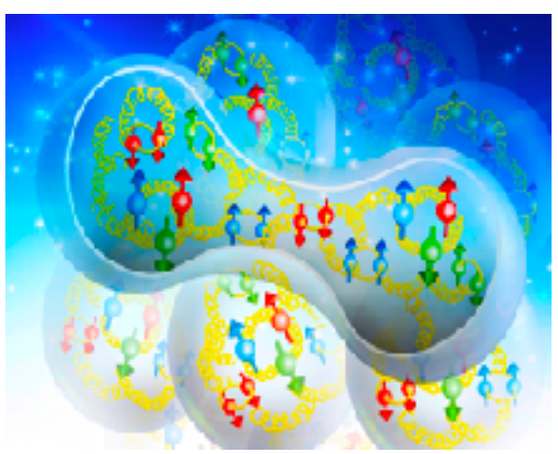


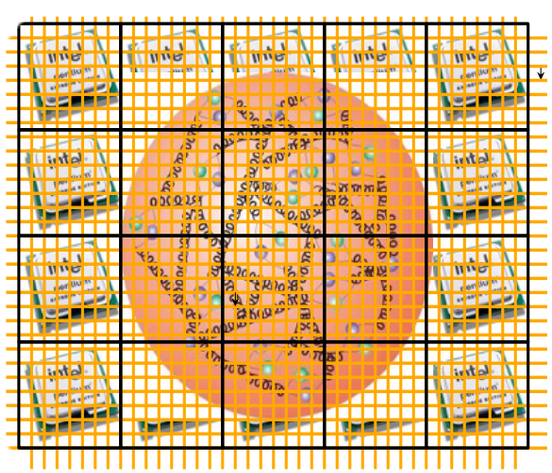
Accurate nuclear many-body methods

$$H|\Psi_n\rangle = E_n|\Psi_n\rangle$$

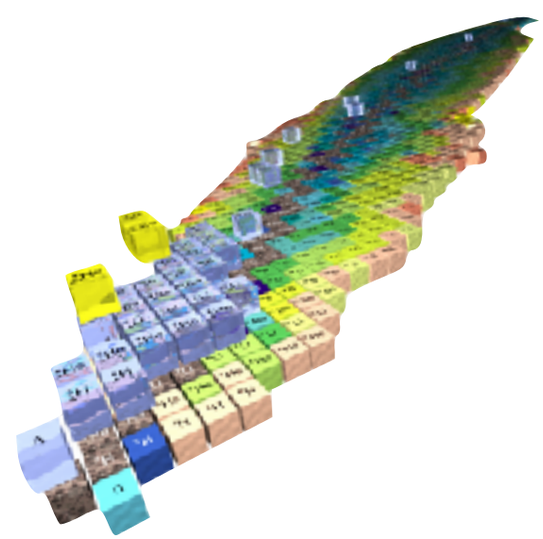
$$J_{mn} = \langle\Psi_m|J|\Psi_n\rangle$$

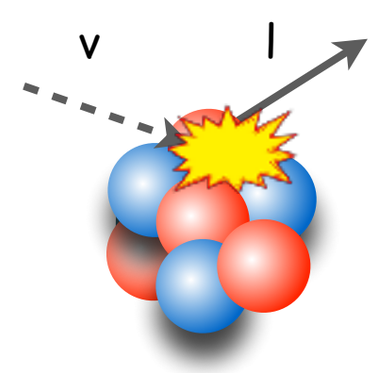
Quantum Chromodynamcs





Nuclei and electroweak interactions





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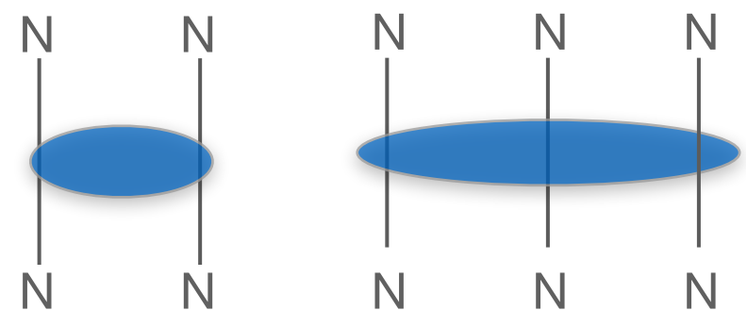
The basic model of nuclear theory

Effective field theories are the link between QCD and nuclear observables. At low energy, the effective degrees of freedom are pions and nucleons:

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

1-body **2-body** **3-body**

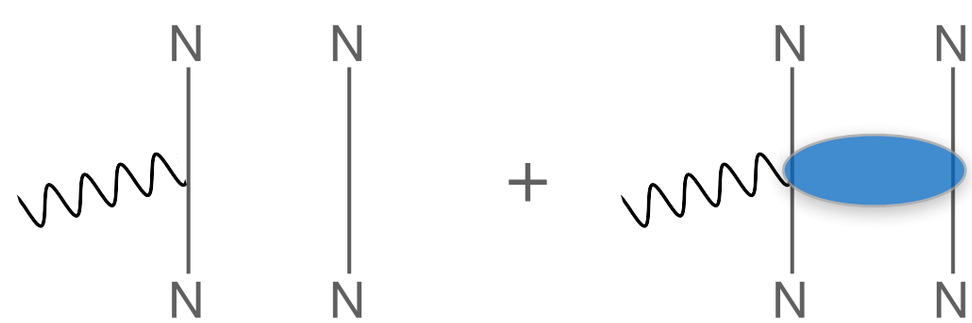


R. Machleidt , D. R. Entem, Phys.Rept.503:1-75,2011

E. Epelbaum, (Lectures), arXiv:1001.3229

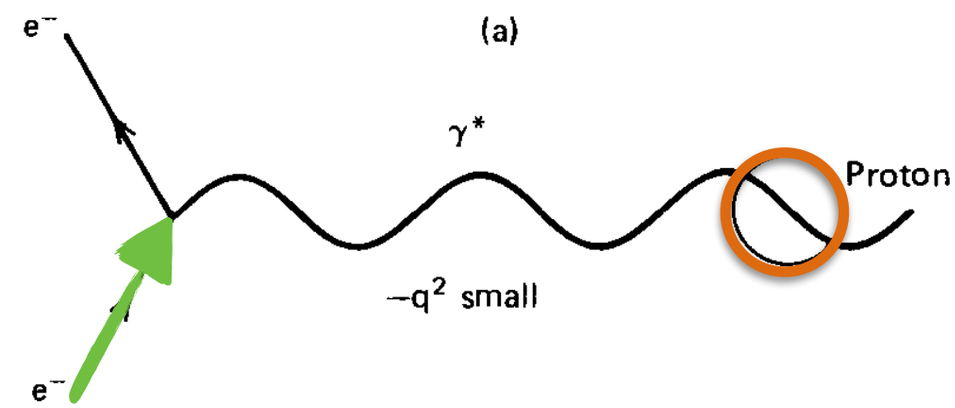
The Hamiltonian structure implies that the current operator includes one and two-body contributions

$$J^\mu(q) = \sum_i j_i^\mu + \sum_{i<j} j_{ij}^\mu + \dots$$

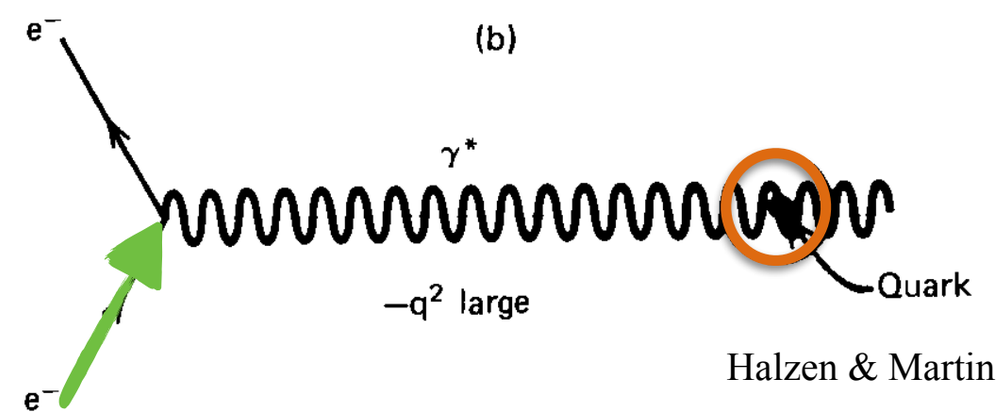


Probing the target structure

The interaction depends on the **mediator** energy (dubbed as energy transfer ω)



Higher energy transfer = smaller de Broglie wavelength = the probe can resolve the structure inside the nucleon



Halzen & Martin

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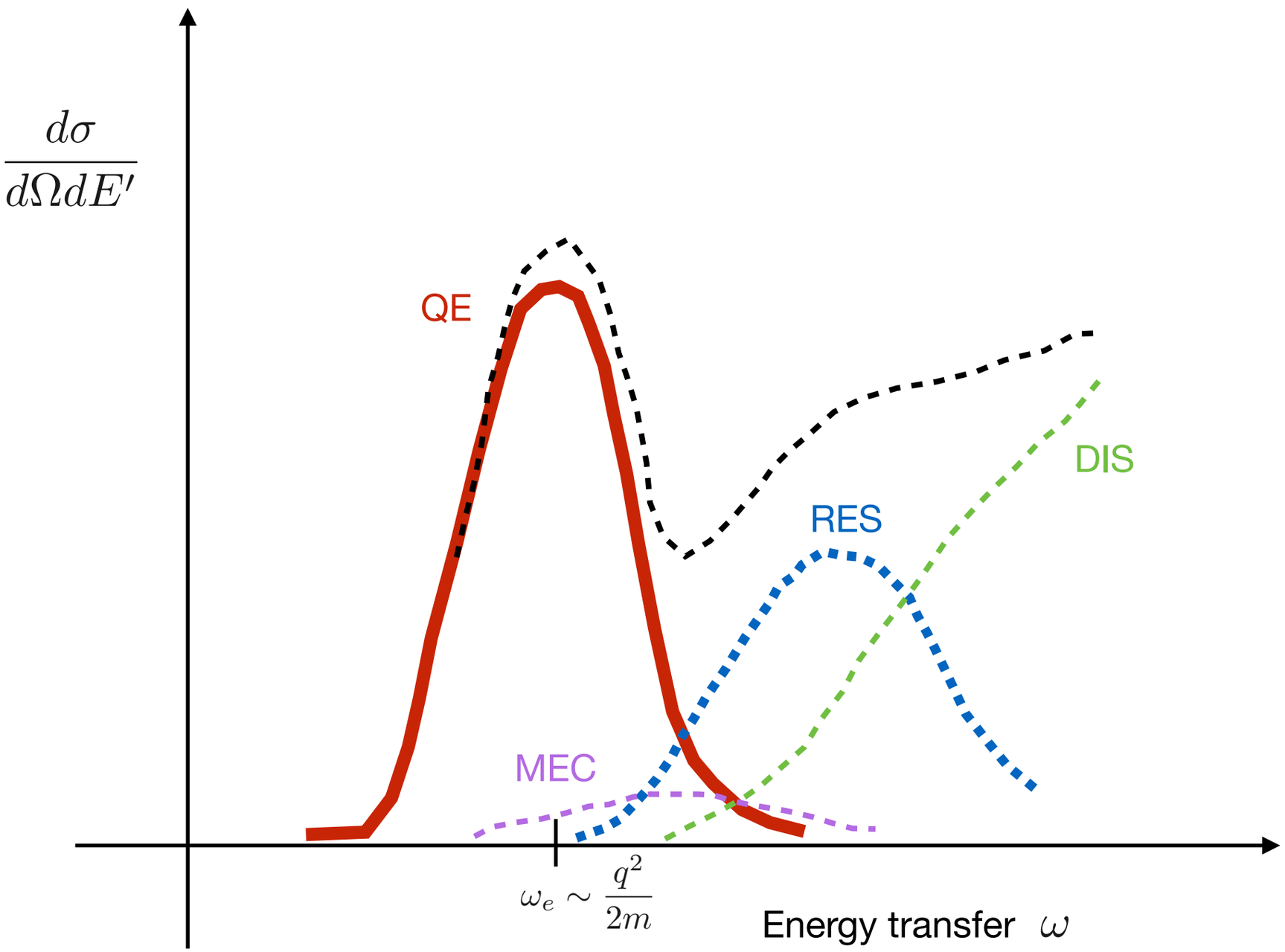
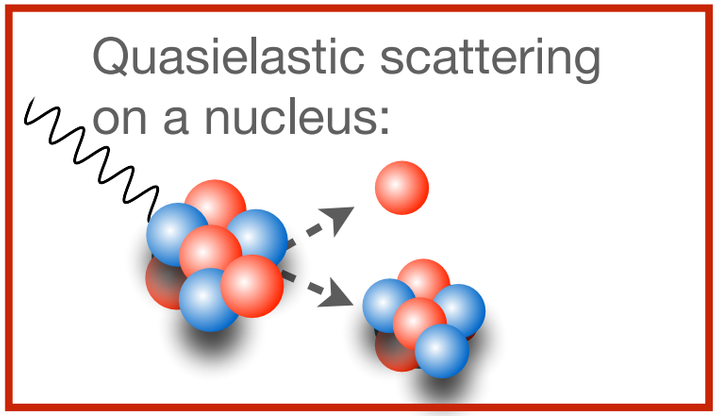
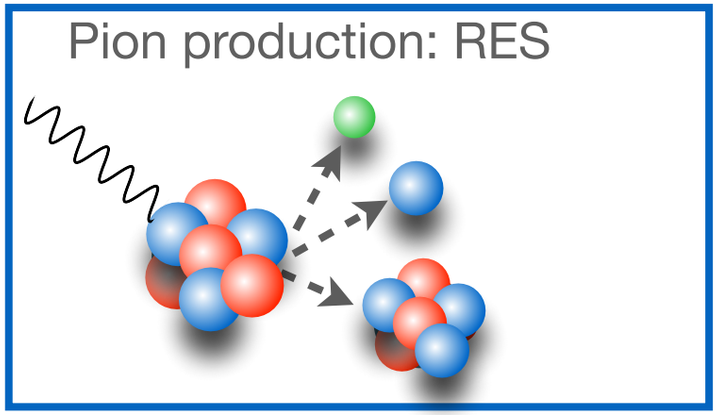
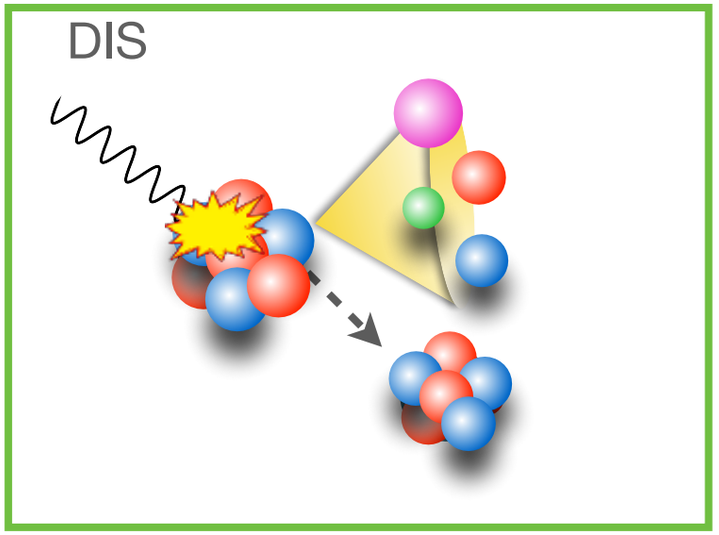
Lepton-nucleus cross section

Different reaction mechanisms contributing to lepton-nucleus cross section
—fixed value of the beam energy (monochromatic)









In neutrino experiments these contributions are not nicely separated

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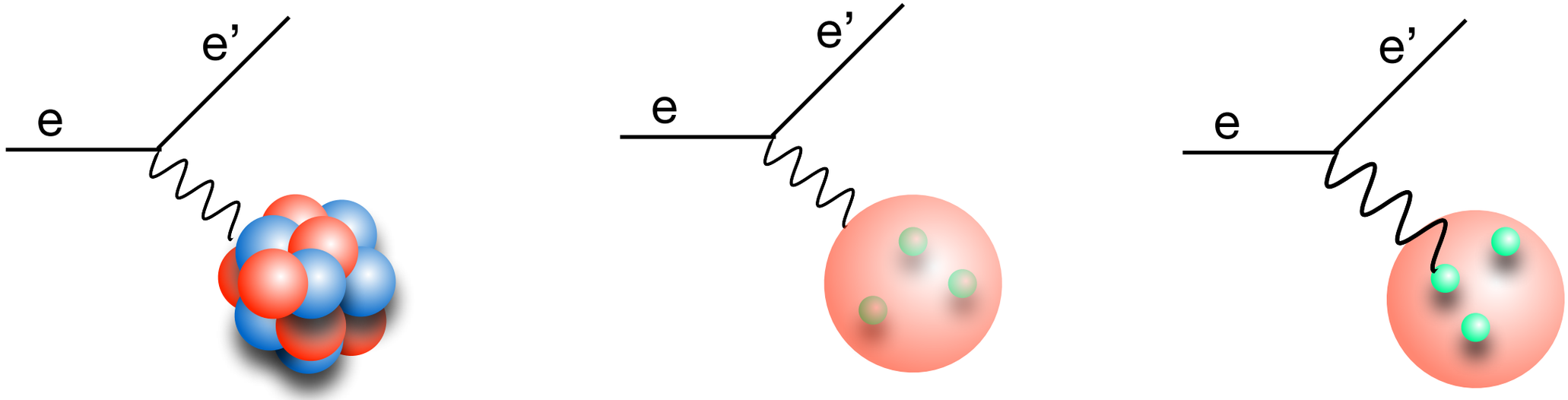
Theory of lepton-nucleus scattering

- The most general expression for the hadron tensor that you may find in many textbooks is:

$$W^{\mu\nu} = -g_{\mu\nu}W_1 + \frac{W_2}{M^2}p_\mu p_\nu - i\epsilon_{\mu\nu\alpha\beta}p^\alpha q^\beta \frac{W_3}{2M^2} + q_\mu q_\nu \frac{W_4}{M^2} + (p_\mu q_\nu + q_\mu p_\nu)\frac{W_5}{M^2}$$

- For one-body current processes, one can derive the explicit expressions of W_i as functions of F_1, F_2, F_A, and F_p



- Nuclear level
- Nucleon level
- Quark level

- Universal structure maintained @ different energy scales

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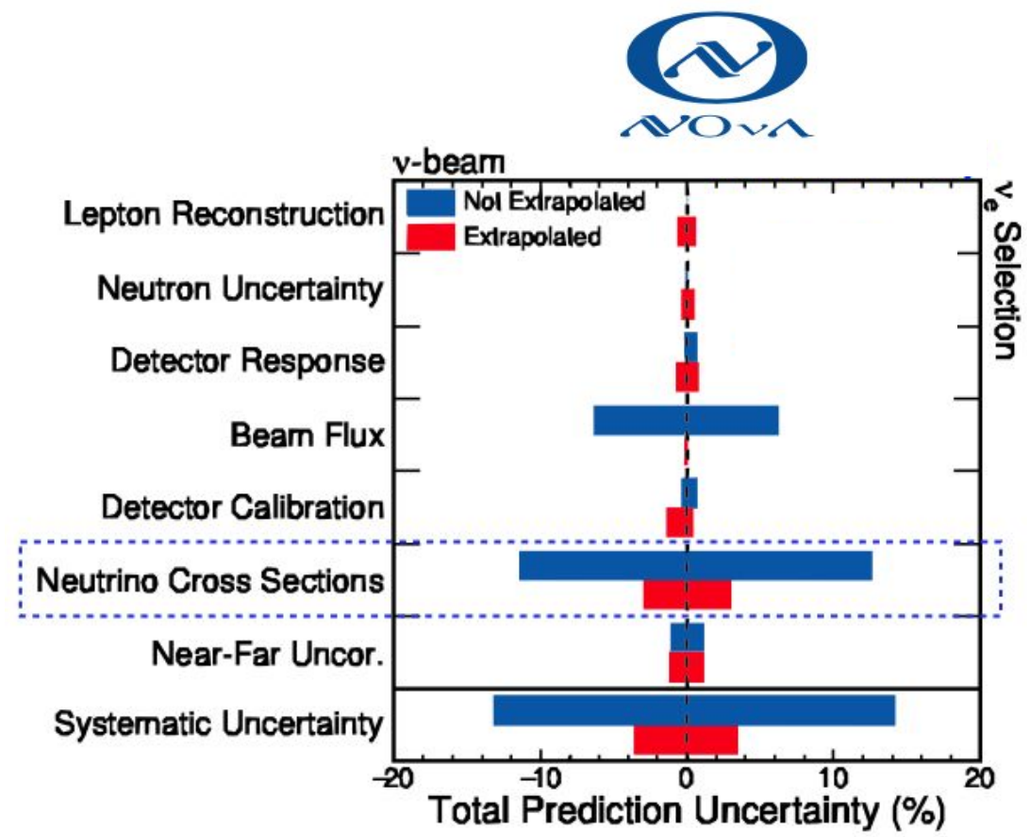
Neutrino interactions play a very important role

Current oscillation experiments report **large systematic uncertainties** associated with the neutrino-nucleus interaction models.

Error source	ν_e FHC	$\bar{\nu}_e$ RHC	$\nu_e / \bar{\nu}_e$ FHC/RHC
Flux and (ND unconstrained)	15.1	12.2	1.2
cross section (ND constrained)	3.2	3.1	2.7
SK detector	2.8	3.8	1.5
SK FSI + SI + PN	3.0	2.3	1.6
Nucleon removal energy	7.1	3.7	3.6
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	2.6	1.5	3.0
NC1γ	1.1	2.6	1.5
NC other	0.2	0.3	0.2
$\sin^2\theta_{23}$ and Δm^2_{21}	0.5	0.3	2.0
$\sin^2\theta_{13}$ PDG2018	2.6	2.4	1.1
All systematics	8.8	7.1	6.0



T2K, Phys. Rev. D 103, 112008 (2021)

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From neutrino-nucleon to neutrino-nucleus

Different **Monte Carlo event generators** on the market

Event generators also used to predict **backgrounds** and **efficiency**

Using a factorization scheme

Many generators also tune theoretical models to data

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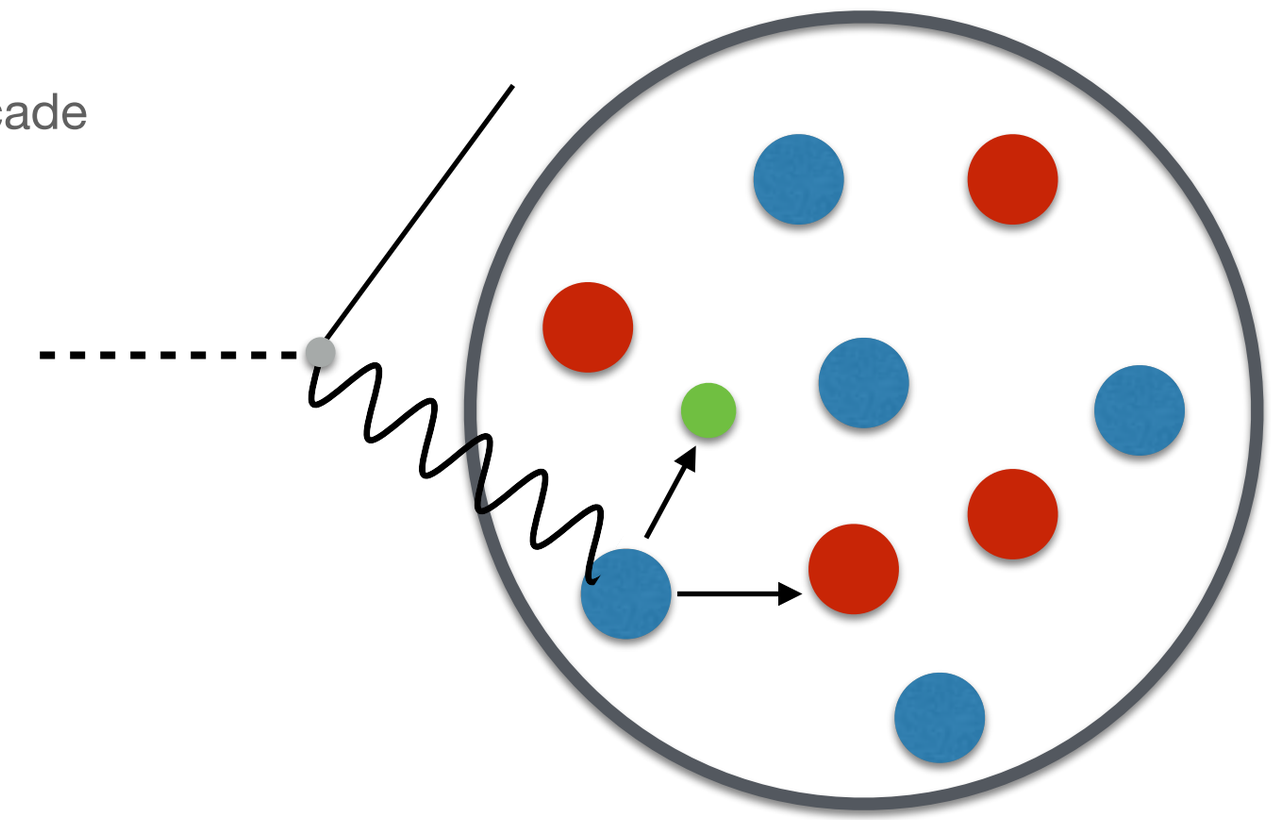
From neutrino-nucleon to neutrino-nucleus

Factorization Scheme:

$$|\mathcal{M}(\{k\} \to \{p\})|^2 \simeq \sum\!\!\!\!\!\!\int_{p'} |\mathcal{V}(\{k\} \to \{p'\})|^2 \times |\mathcal{P}(\{p'\} \to \{p\})|^2$$

- Nuclear Model
- Primary Interaction
- Evolution out of the nucleus (intra-nuclear) cascade



The propagation of **nucleons** through the **<u>nuclear medium</u>** is crucial in the analysis of neutrino oscillation experiments.

- Elastic scattering
- Charge exchange
- Pion Production
- Absorption

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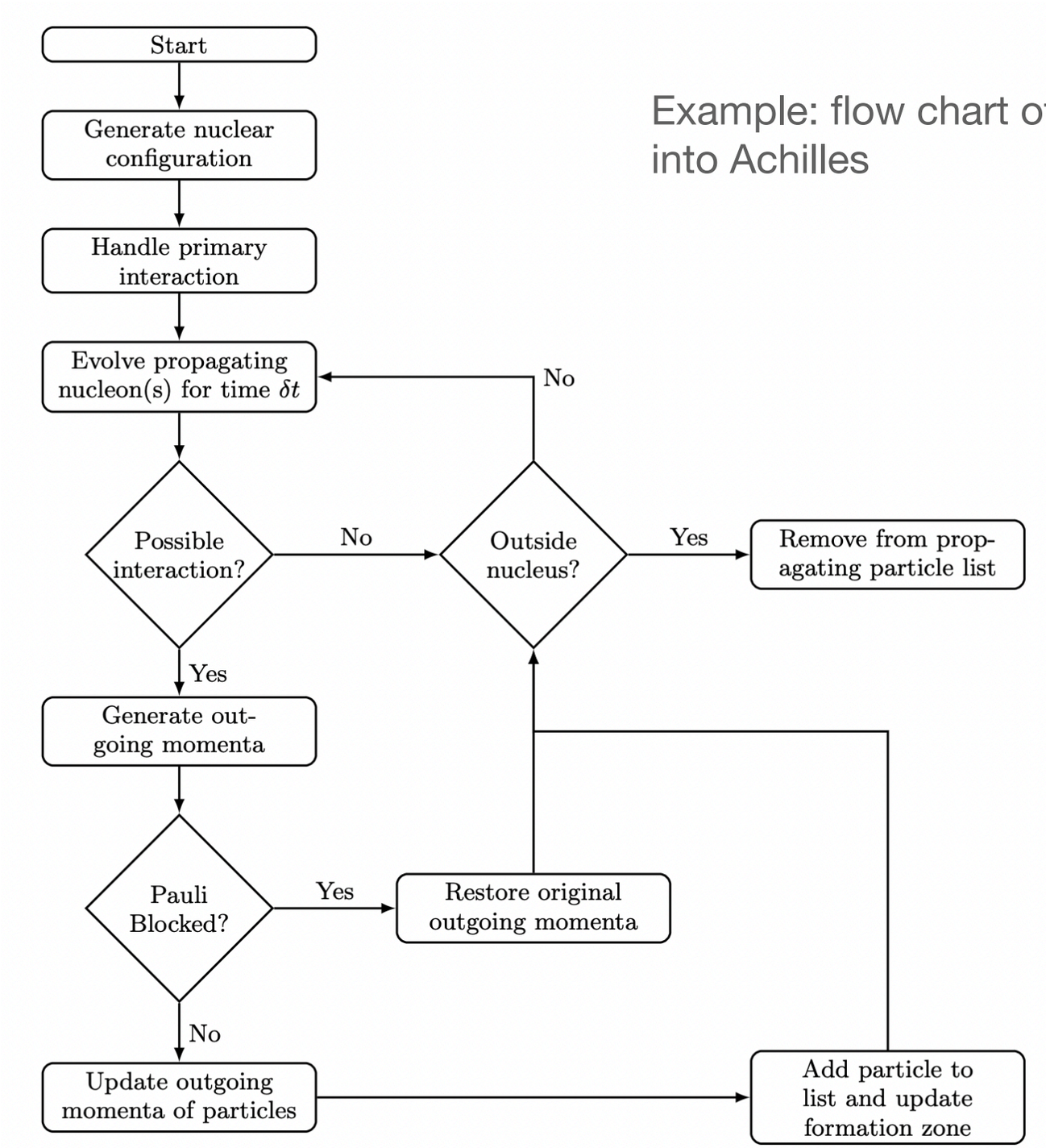
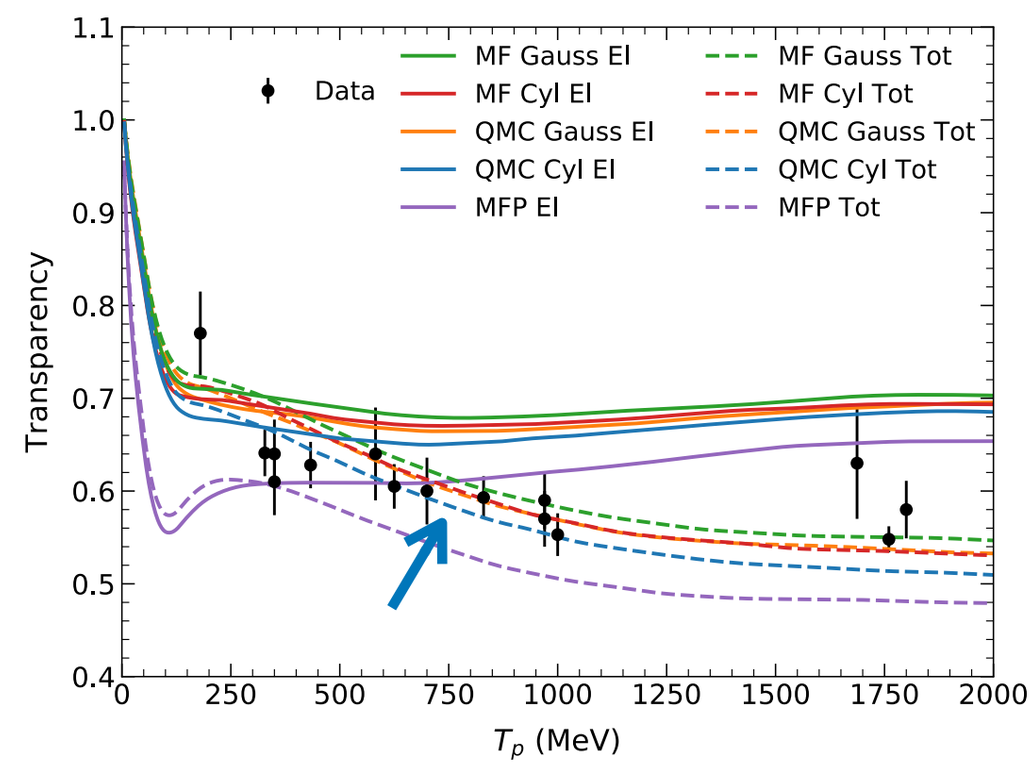
Sampling nucleon configurations



Example: flow chart of the intra-nuclear cascade implemented into Achilles

Transparency data to validate intra-nuclear cascade



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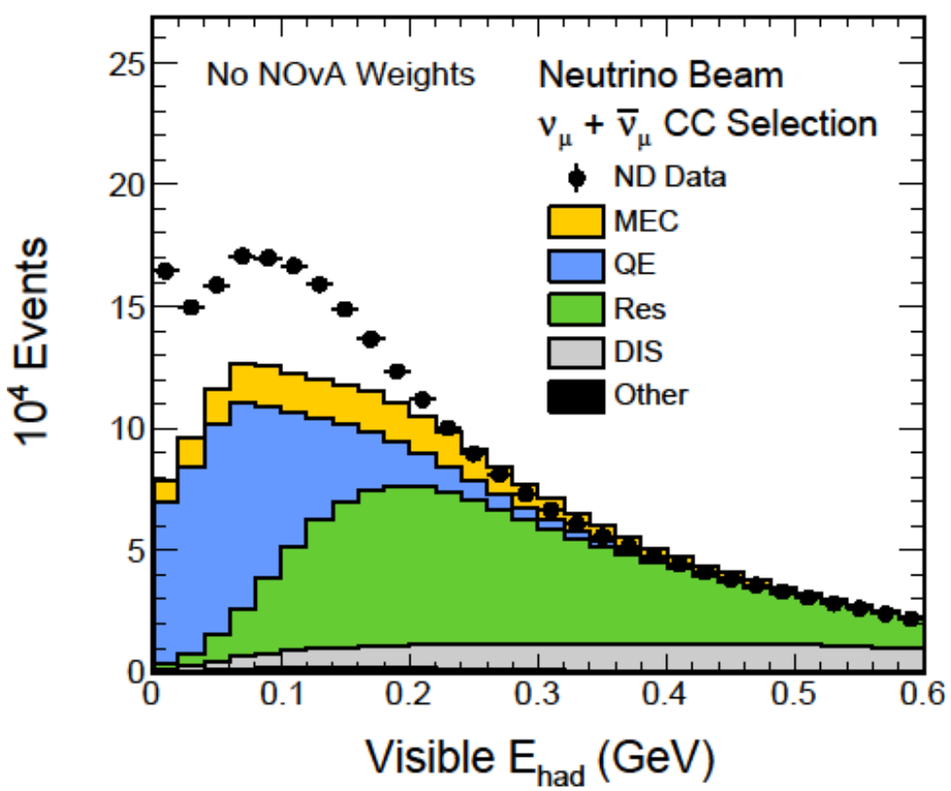
Tuning in Event Generators

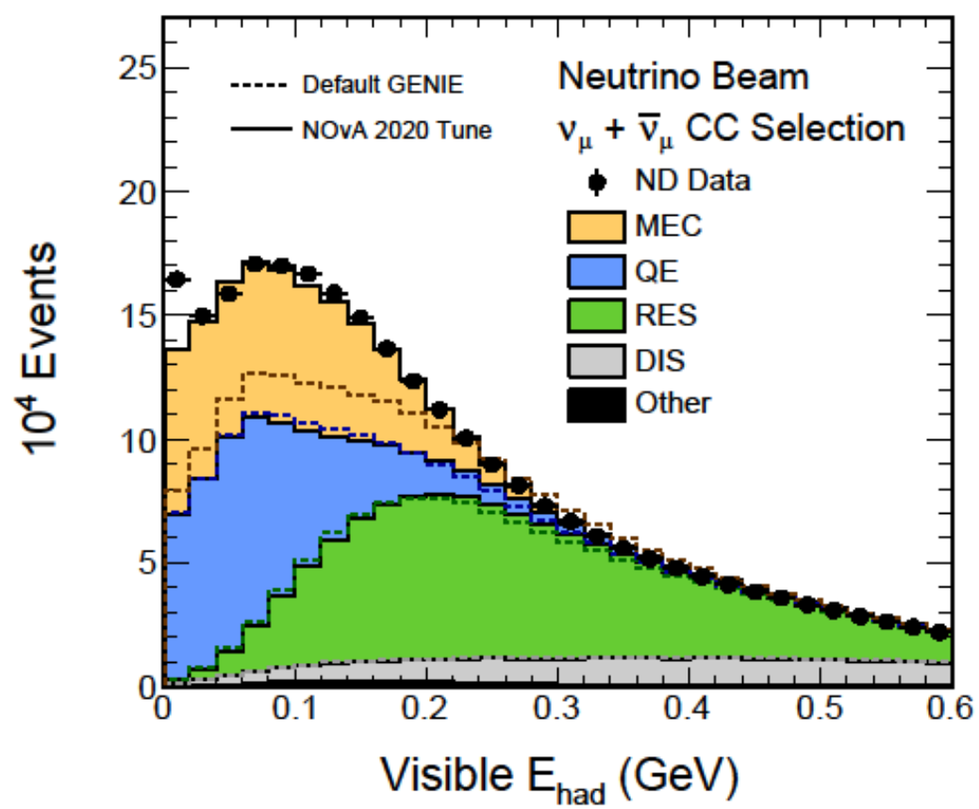
Theory models+simulations are not perfect, experiments correct models using **tuning**

Different experiments rely on different tunings re-weighting different reaction mechanisms

GENIE vs NOvA ND data w no tuning



GENIE vs NOvA ND data w tuning



NOvA collaboration, NuFACT 2022

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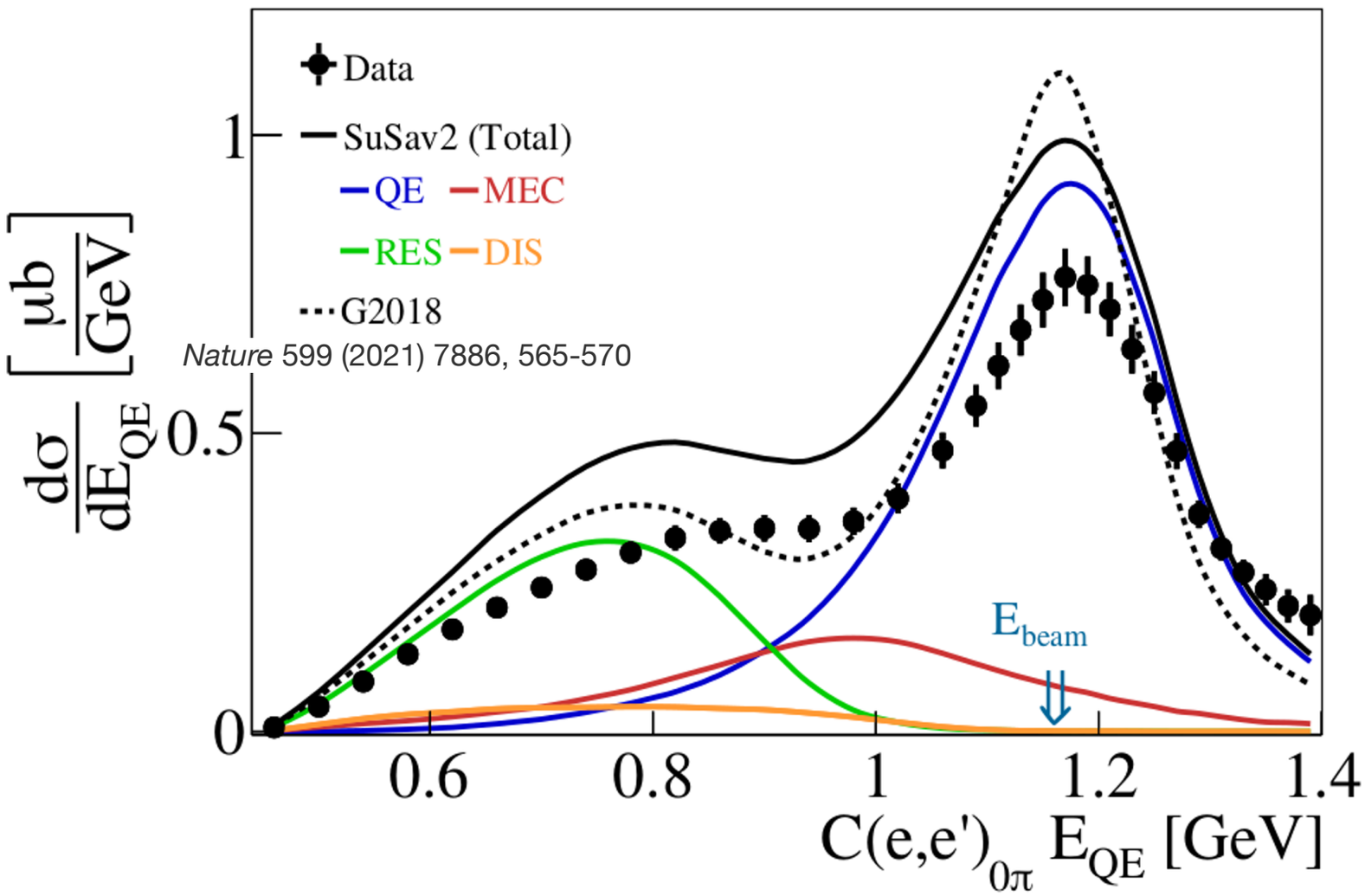
Uncertainty in Neutrino Interactions and Simulations

CLAS and e4v collaboration,
Nature 599 (2021) 7886, 565-570

$$E_{QE} = \frac{2M\epsilon + 2ME_l - m_l^2}{2\left(M - E_l + |k_l|\cos\theta_l\right)}$$

Used semi-exclusive electron scattering data to test the accuracy of interaction models and event generators used in oscillation analyses



The results indicate the **need** for **substantial improvement** in the **accuracy** of the neutrino interactions' models and simulations

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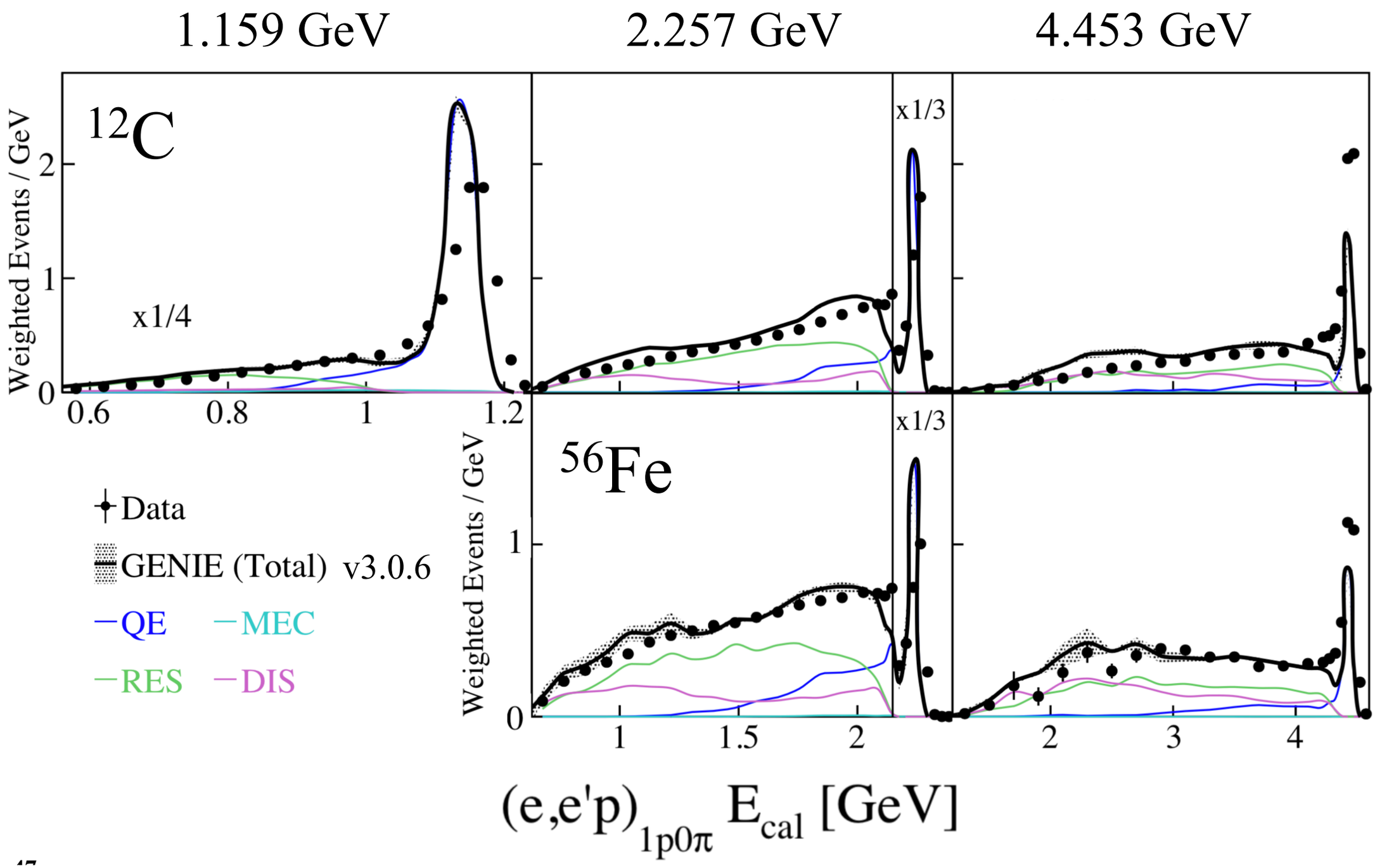
Uncertainty in Neutrino Interactions and Simulations



CLAS and e4v collaboration, Nature 599 (2021) 7886, 565-570

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Conclusions

We still have a lot of open questions in neutrino physics

What's the absolute mass of neutrinos

Are neutrinos Dirac or Majorana particles

What's the neutrino mass ordering

Is CP violated in the neutrino sector

Are there more than three flavors

A diverse range of experiments has been designed to address these questions

Oscillation experiments are entering a precision era: neutrino-nucleus interactions play a key role

Nuclei are used to spot neutrinos to predict their cross section: accurate description of nuclear structure, interaction vertex, event generators.