Neutrino Interactions and Future Experiments

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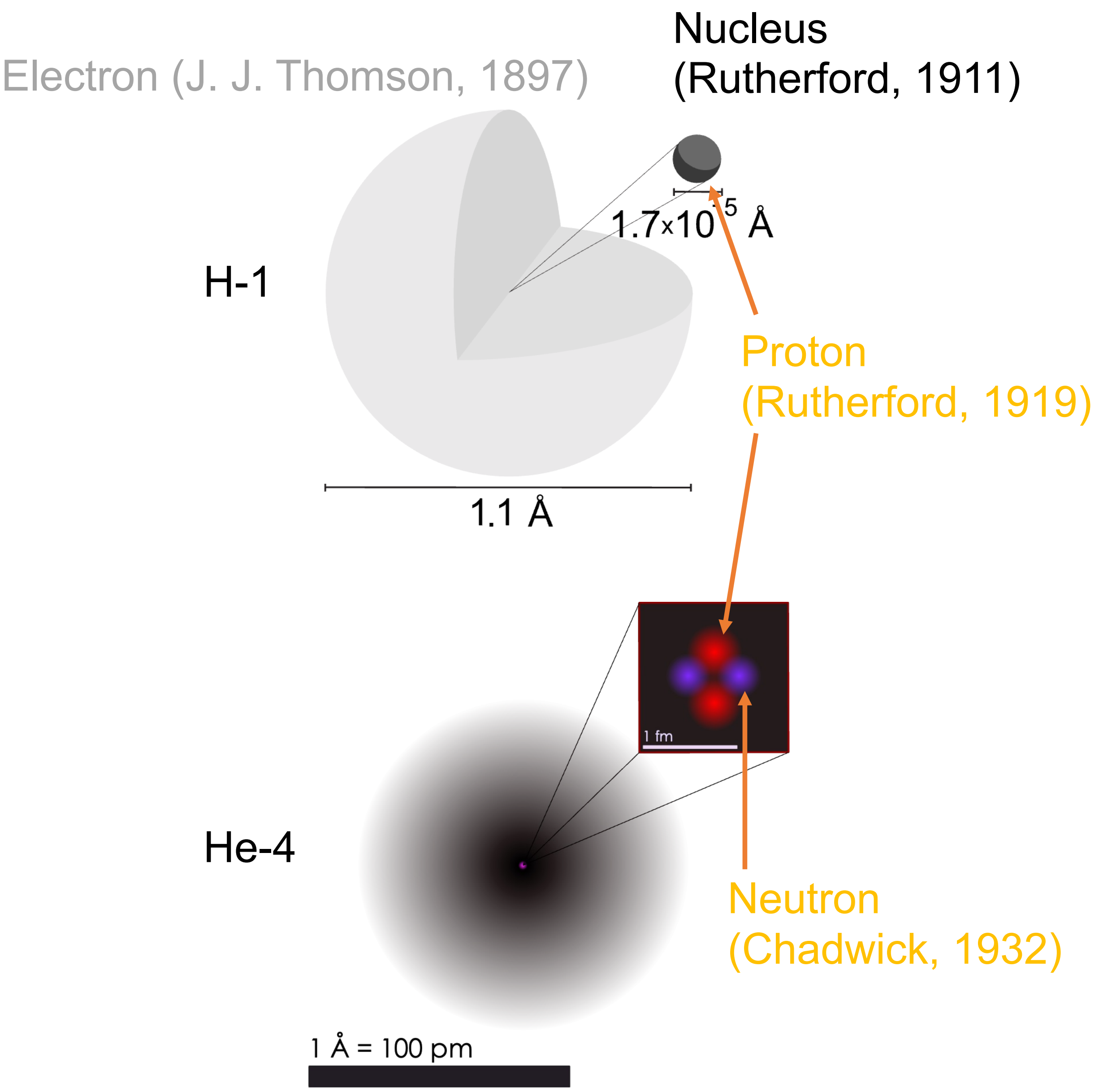
1. Neutrinos in Standard Model

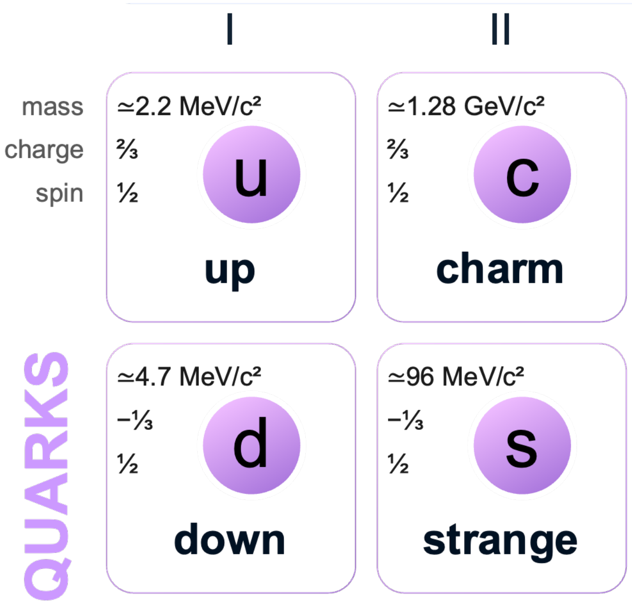
Atom

Elements (Mendeleev, 1869)

Period ↓ / Group →	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		



Fast forward ▶▶



CDF and DØ collaborations (1995)

(Ting/Richter, 1974)

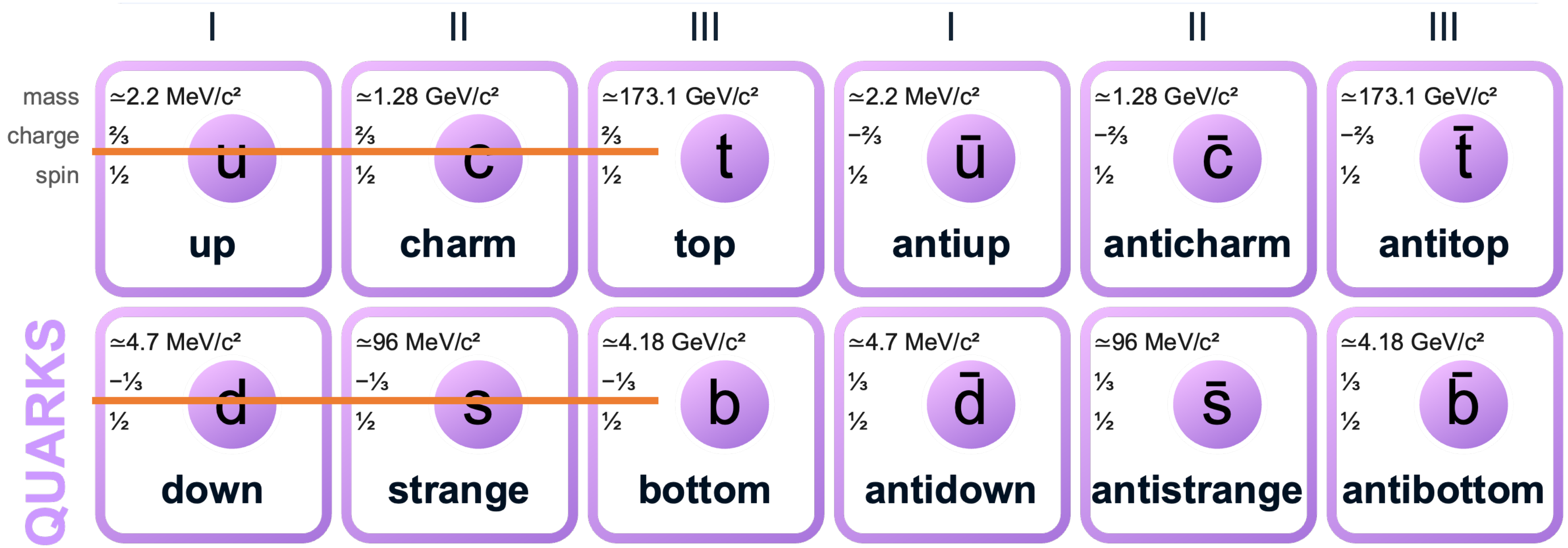
(1950s)

(Lederman, 1977)

Fast forward ▶▶

+ 2/3 *e*

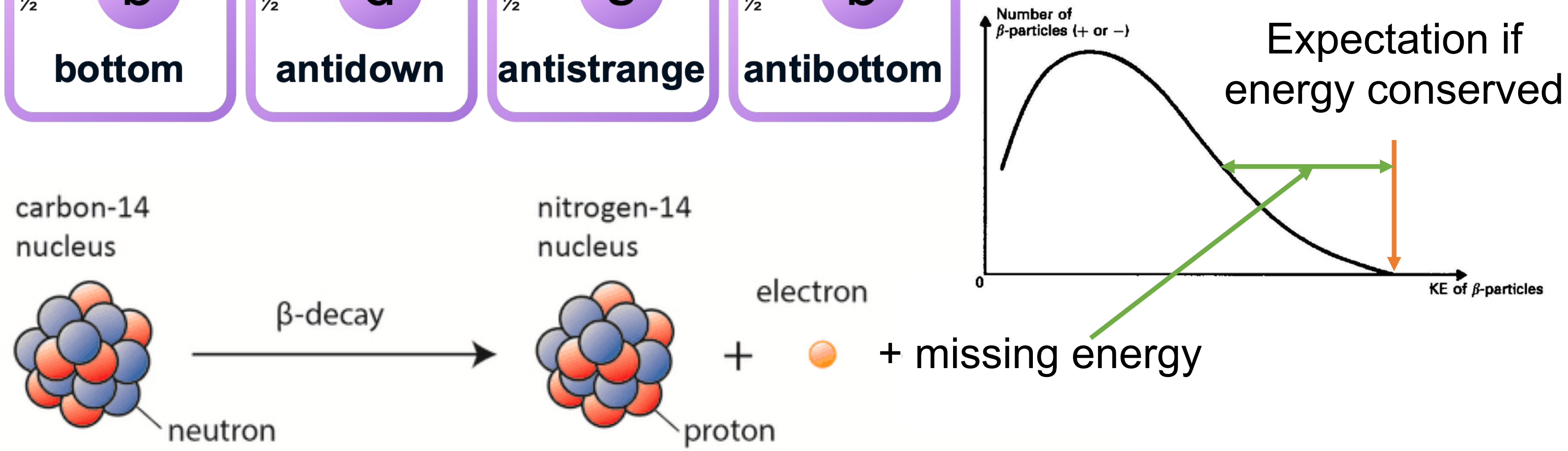
- 1/3 *e*



(Why 3 generations?)

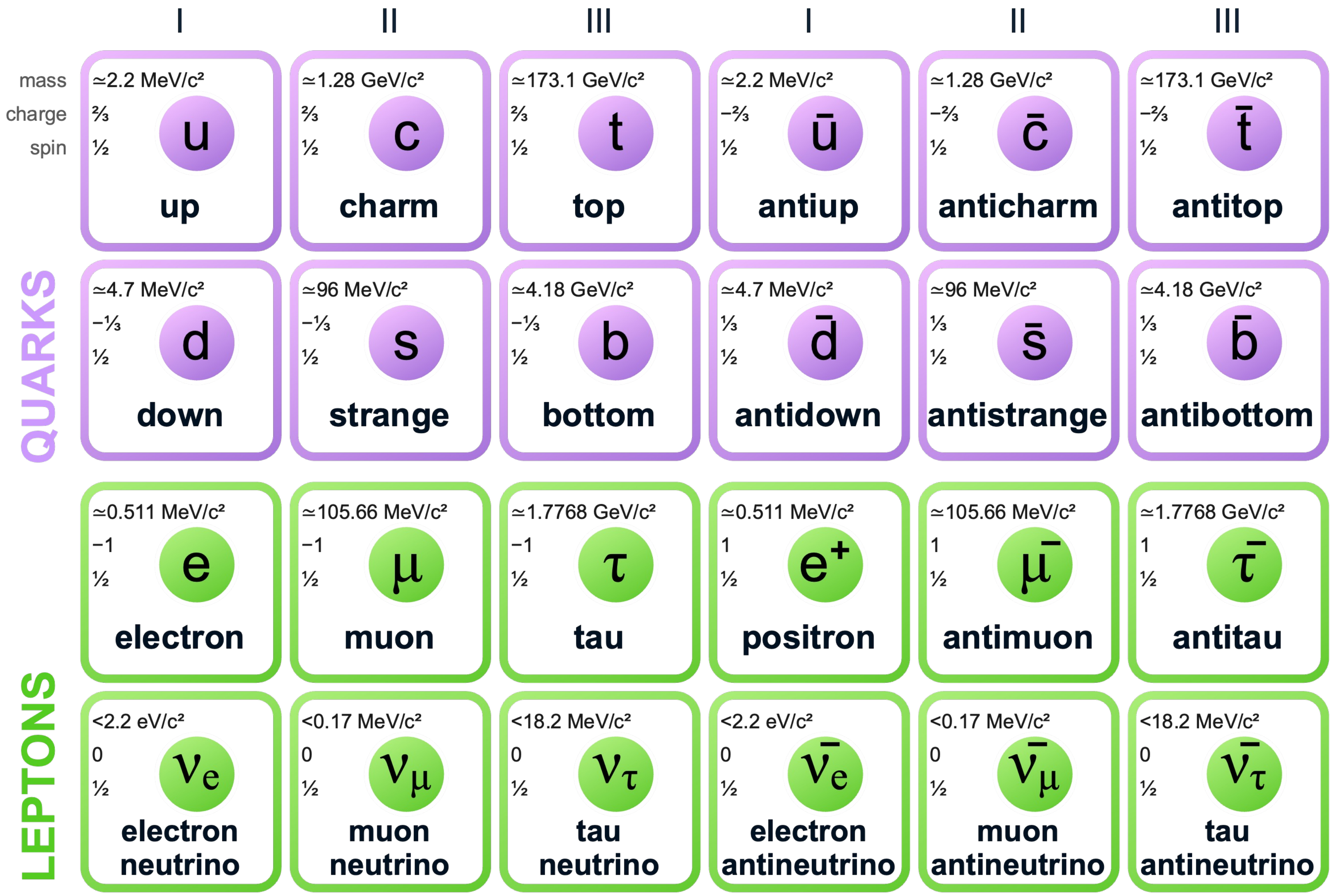
Identical copies except opposite charges

	I	II	III	I	II	III
mass / charge / spin	≃2.2 MeV/c^2, ⅔, ½ **u** **up**	≃1.28 GeV/c^2, ⅔, ½ **c** **charm**	≃173.1 GeV/c^2, ⅔, ½ **t** **top**	≃2.2 MeV/c^2, −⅔, ½ **ū** **antiup**	≃1.28 GeV/c^2, −⅔, ½ **c̄** **anticharm**	≃173.1 GeV/c^2, −⅔, ½ **t̄** **antitop**
QUARKS	≃4.7 MeV/c^2, −⅓, ½ **d** **down**	≃96 MeV/c^2, −⅓, ½ **s** **strange**	≃4.18 GeV/c^2, −⅓, ½ **b** **bottom**	≃4.7 MeV/c^2, ⅓, ½ **d̄** **antidown**	≃96 MeV/c^2, ⅓, ½ **s̄** **antistrange**	≃4.18 GeV/c^2, ⅓, ½ **b̄** **antibottom**
LEPTONS	≃0.511 MeV/c^2, −1, ½ **e** **electron**					



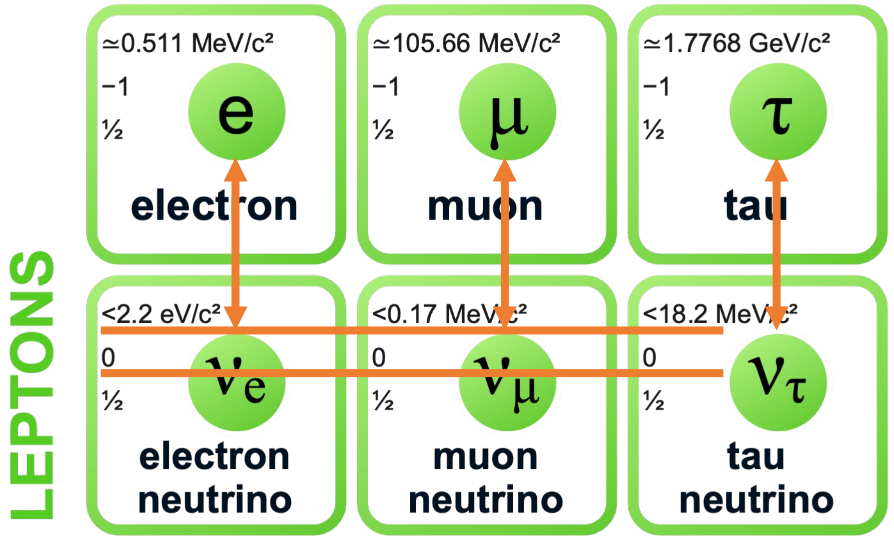
The *first* time to propose a new particle to “cover up” for **fundamental laws**

I have done a terrible thing, I have postulated a particle that cannot be detected. —Pauli, 1930



Fundamental matter in our **current world view: Standard Model**

(Why 3 generations, again?!)



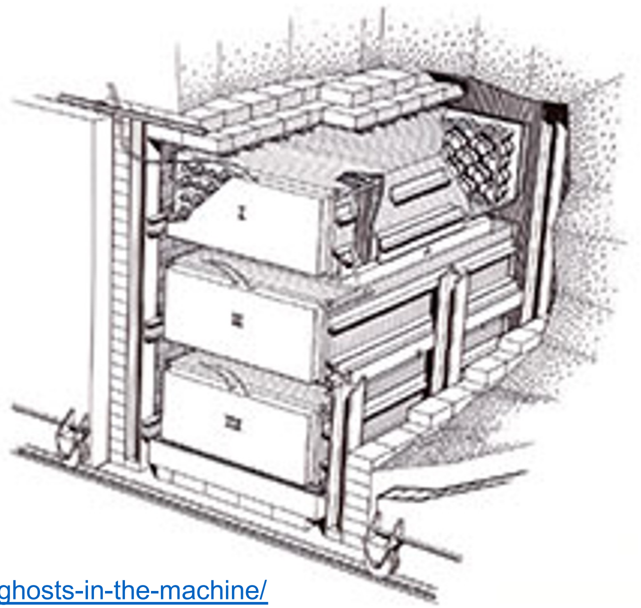
Neutrinos in Standard Model

1. Electric charge = 0
2. Mass = 0 (turns out to be tiny but not zero in Nature!)
3. Have flavours

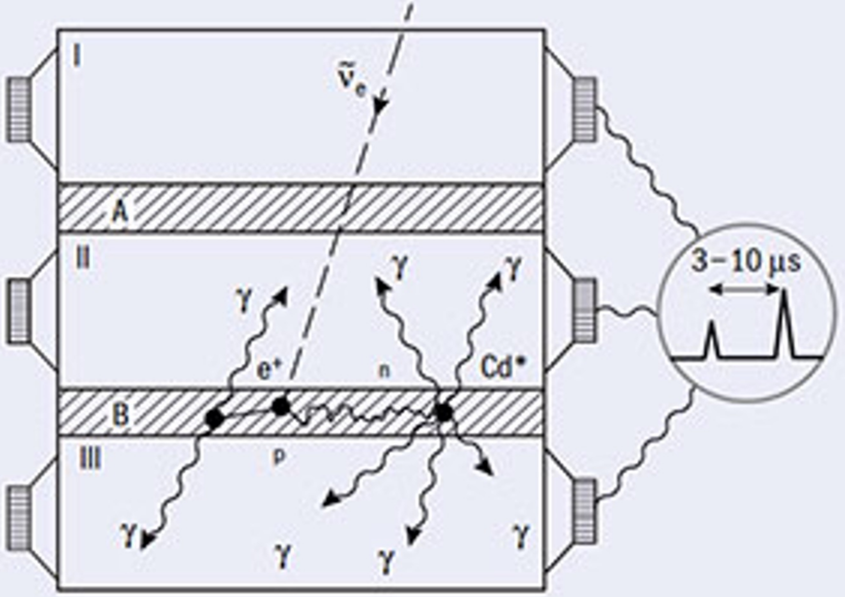
How do we know they exist?

– We wouldn't, really. 60,000,000,000 neutrinos from Sun arriving at Earth every second on every cm^2 surface, and of course we have evolved to ignore them!

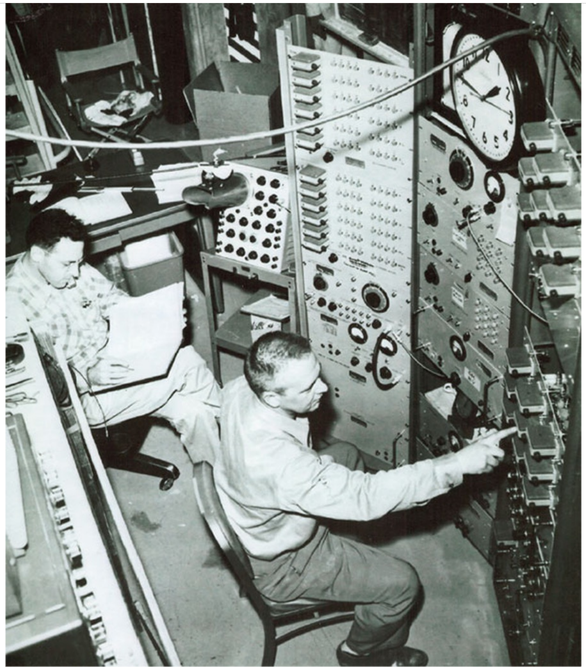
– Discovered by Cowan & Reines, 1956, using nuclear reactors



https://cerncourier.com/a/ghosts-in-the-machine/

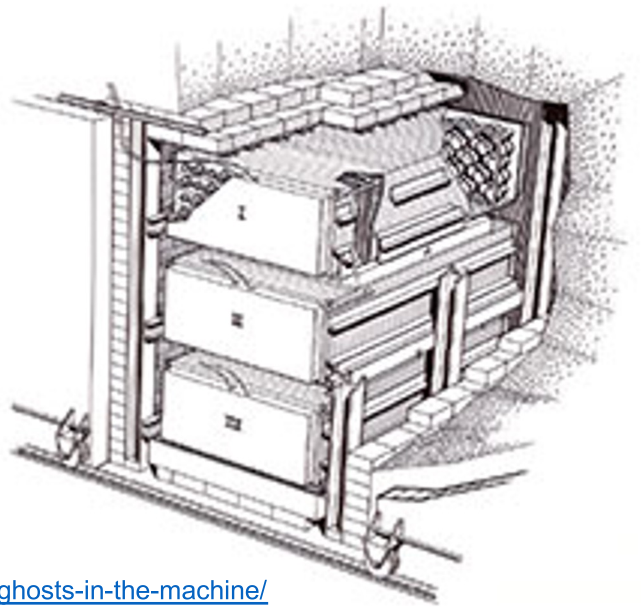


Cowan–Reines Experiment, 1956



The detector used at Savannah River

- Three 1400-litre tanks of liquid scintillator (I, II and III)
- Each viewed by 100 phototubes
- Smaller tanks (A and B) contained 200 litres of water doped with cadmium.



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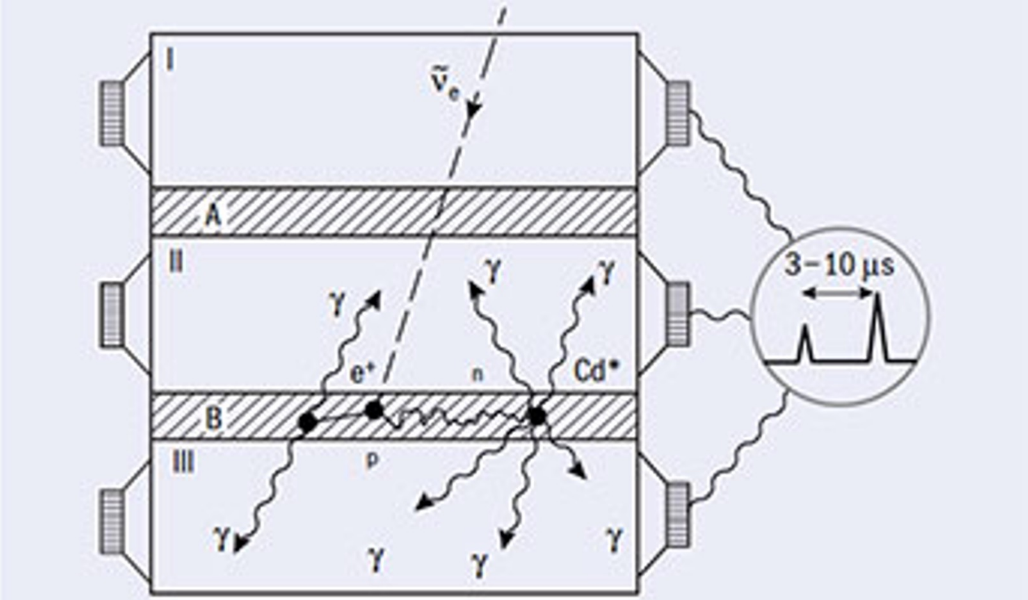
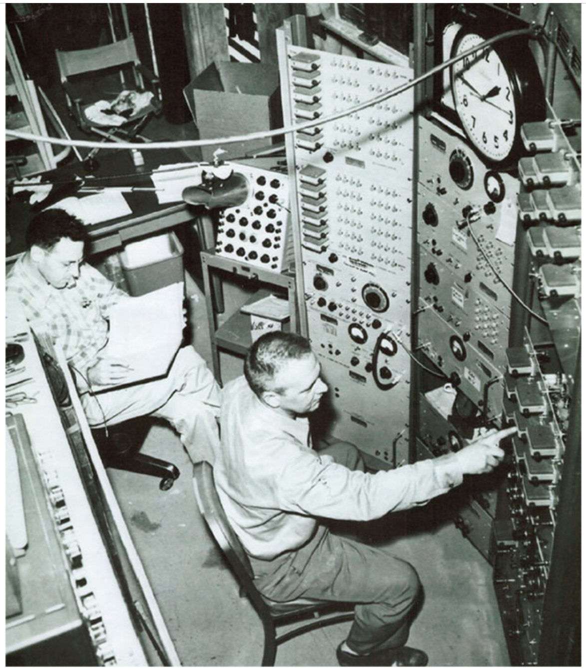


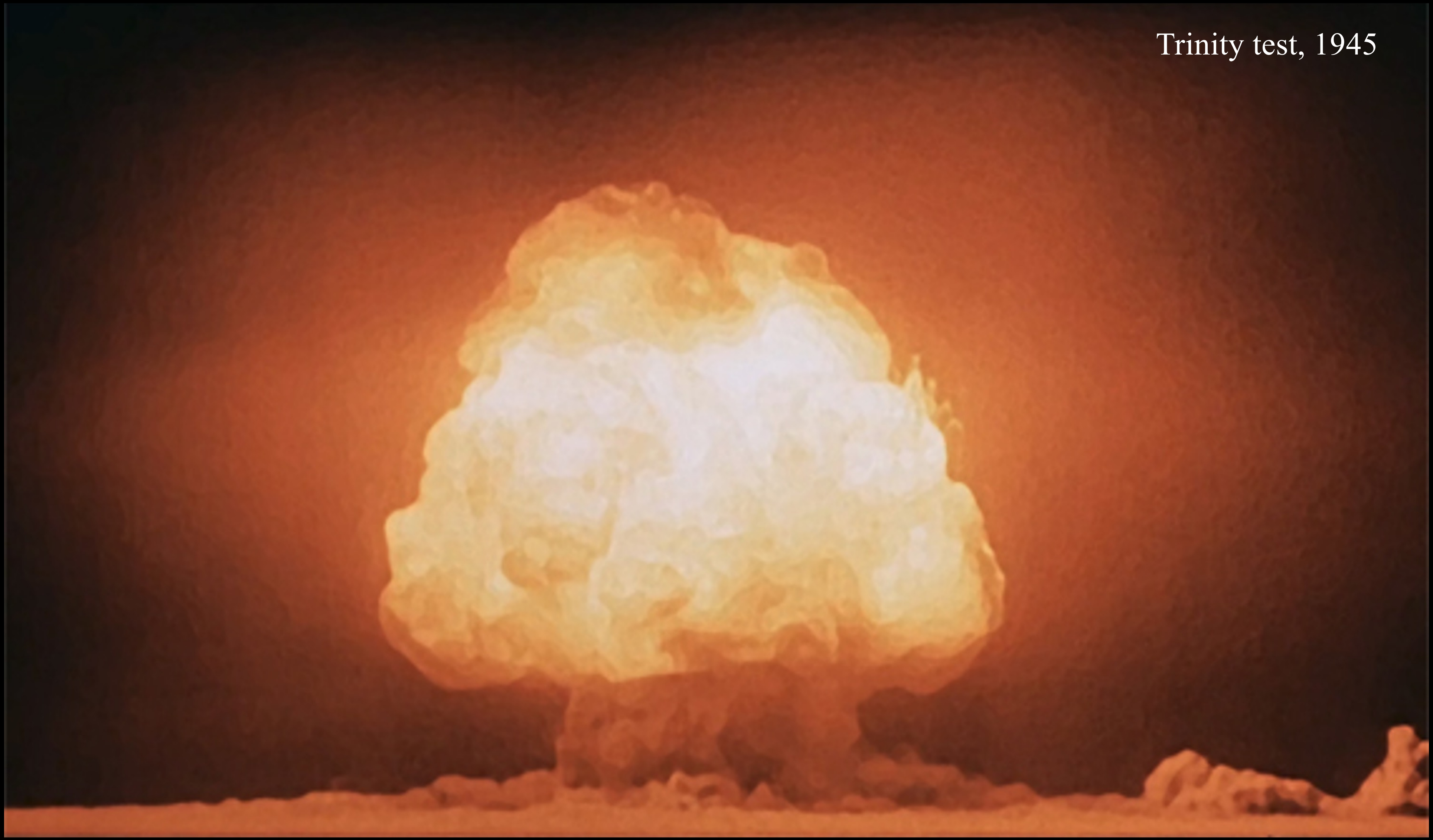
Cowan–Reines Experiment, 1956



Before that, in 1951:

"Some hand-waving and rough calculations led me to conclude that the *bomb* was the best source" (Reines)

"I am become Death, the destroyer of worlds"



2. Massive Neutrinos

Neutrino Mass

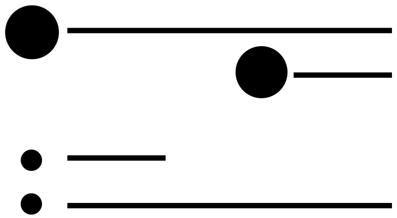
Standard Model | Beyond Standard Model

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \left[\text{PMNS matrix}\right] \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Pontecorvo–Maki–Nakagawa–Sakata

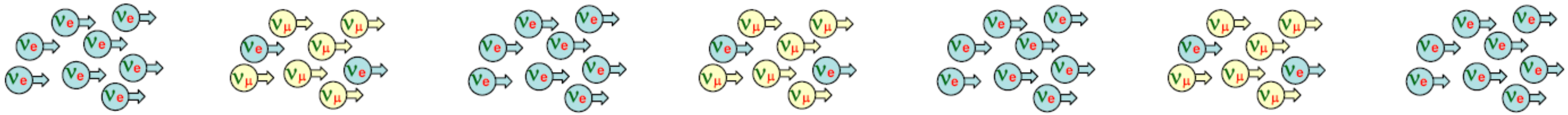
PMNS matrix

Mass Ordering



Normal **Inverted**

Δm^2 leads to neutrino oscillations



[Mark Thomson's Particle Physics lecture notes]

PMNS Matrix

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{13} \neq$ □0 $\rightarrow \delta_{CP}$ can be observed

θ_{12}: mixing between ν_1 and ν_2

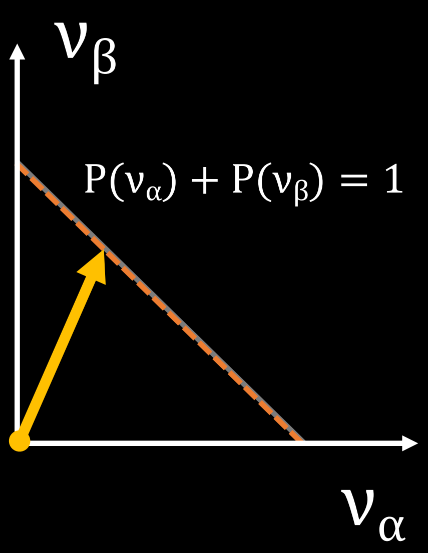
θ□□: mixing between ν□ and ν_τ

θ□□: if 0, effective 2 flavour mixing

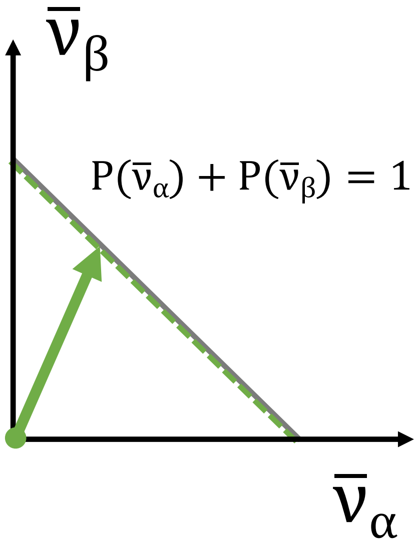
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1' \\ \nu_2' \\ \nu_3 \end{pmatrix}$$

θ_{13} □□0

2-flavor oscillation



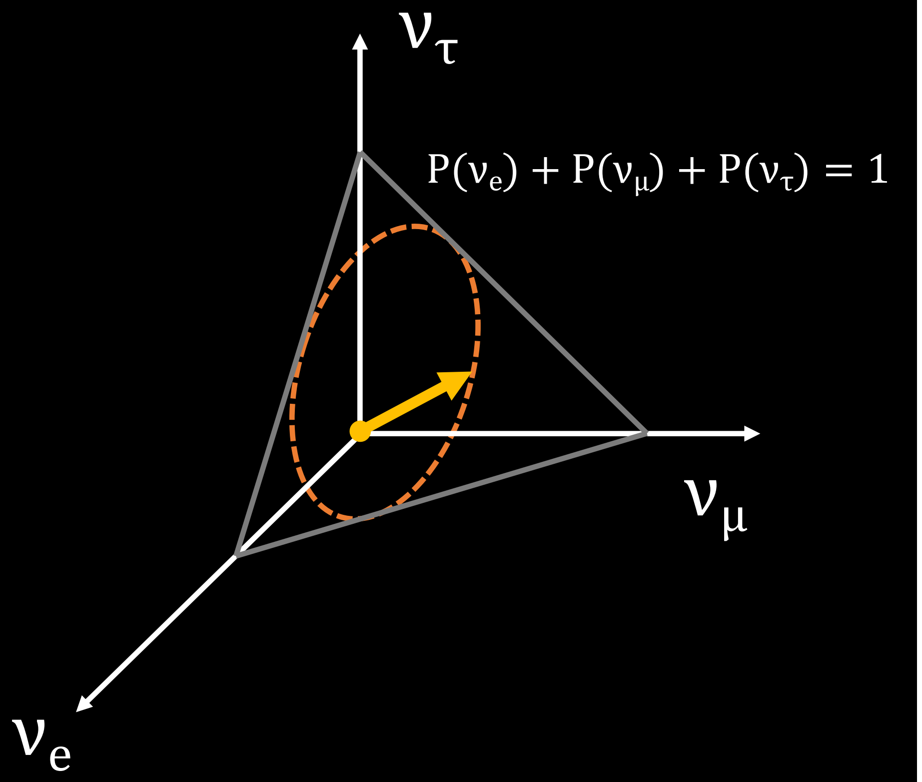
Antineutrinos



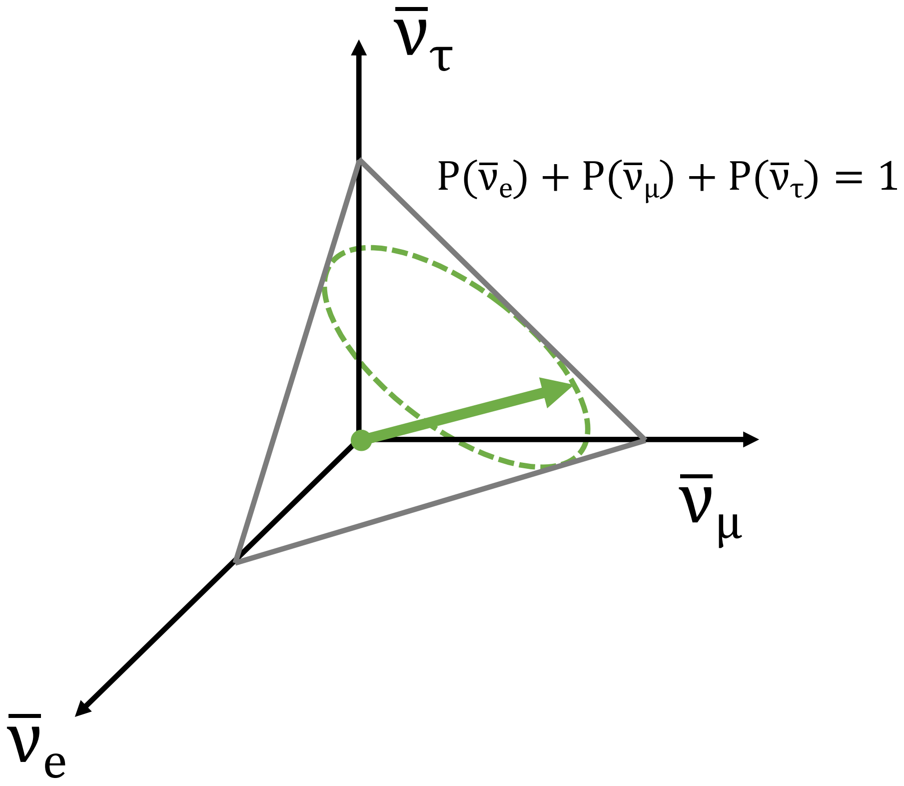
Oscillation as a function of *time*
line-in-**line** → same trivia

$\theta_{13} \neq 0$

3-flavor oscillation



Antineutrinos

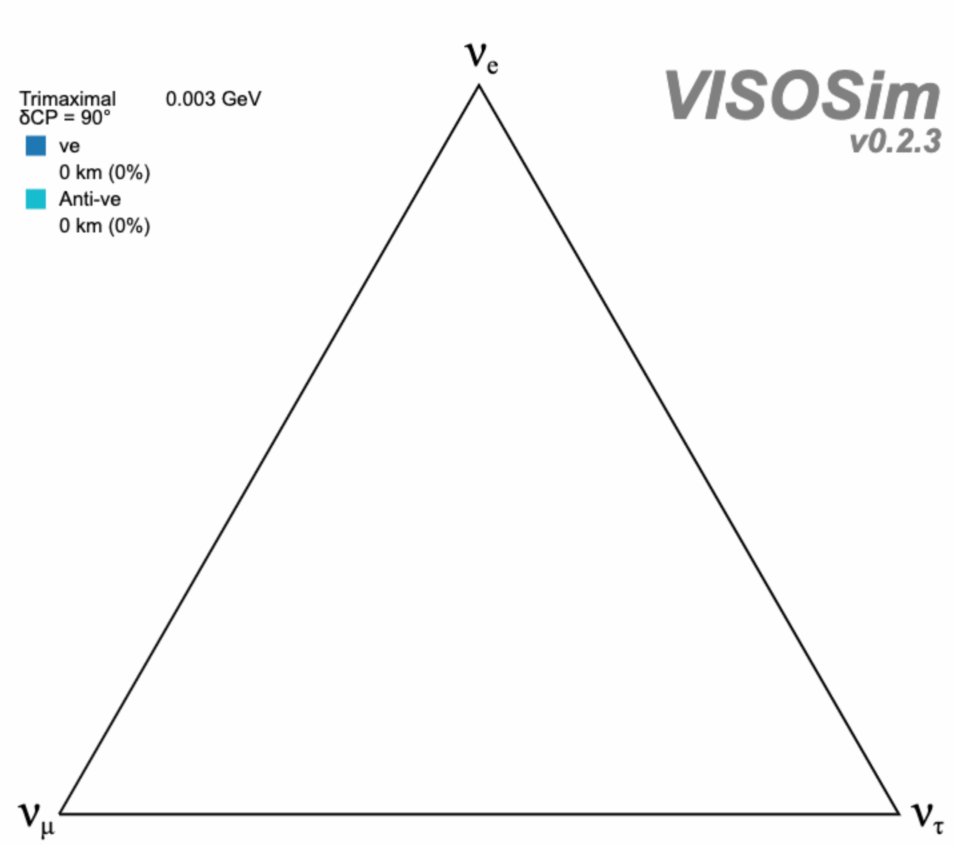


Oscillation as a function of *time*
line-in-**plane** → CP-violation possible

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \text{PMNS} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Trimaximal mixing
— maximally CP-violating

$$(|U_{i\alpha}|^2) = \begin{bmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix}$$



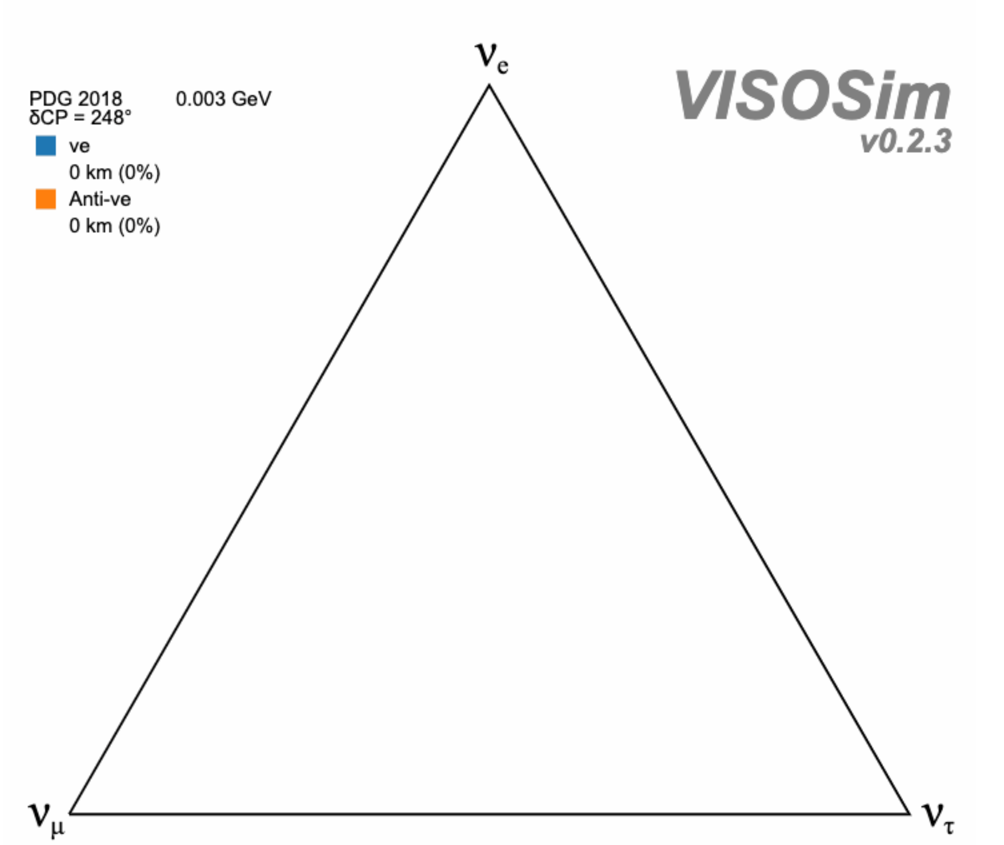
☛ VISOS

Beautiful but *not* how Nature works ¯_(ツ)_/¯

How Nature might work:

$$\begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix}$$

$$= \begin{bmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.233 \ldots 0.507 & 0.461 \ldots 0.694 & 0.631 \ldots 0.778 \\ 0.261 \ldots 0.526 & 0.471 \ldots 0.701 & 0.611 \ldots 0.761 \end{bmatrix}$$

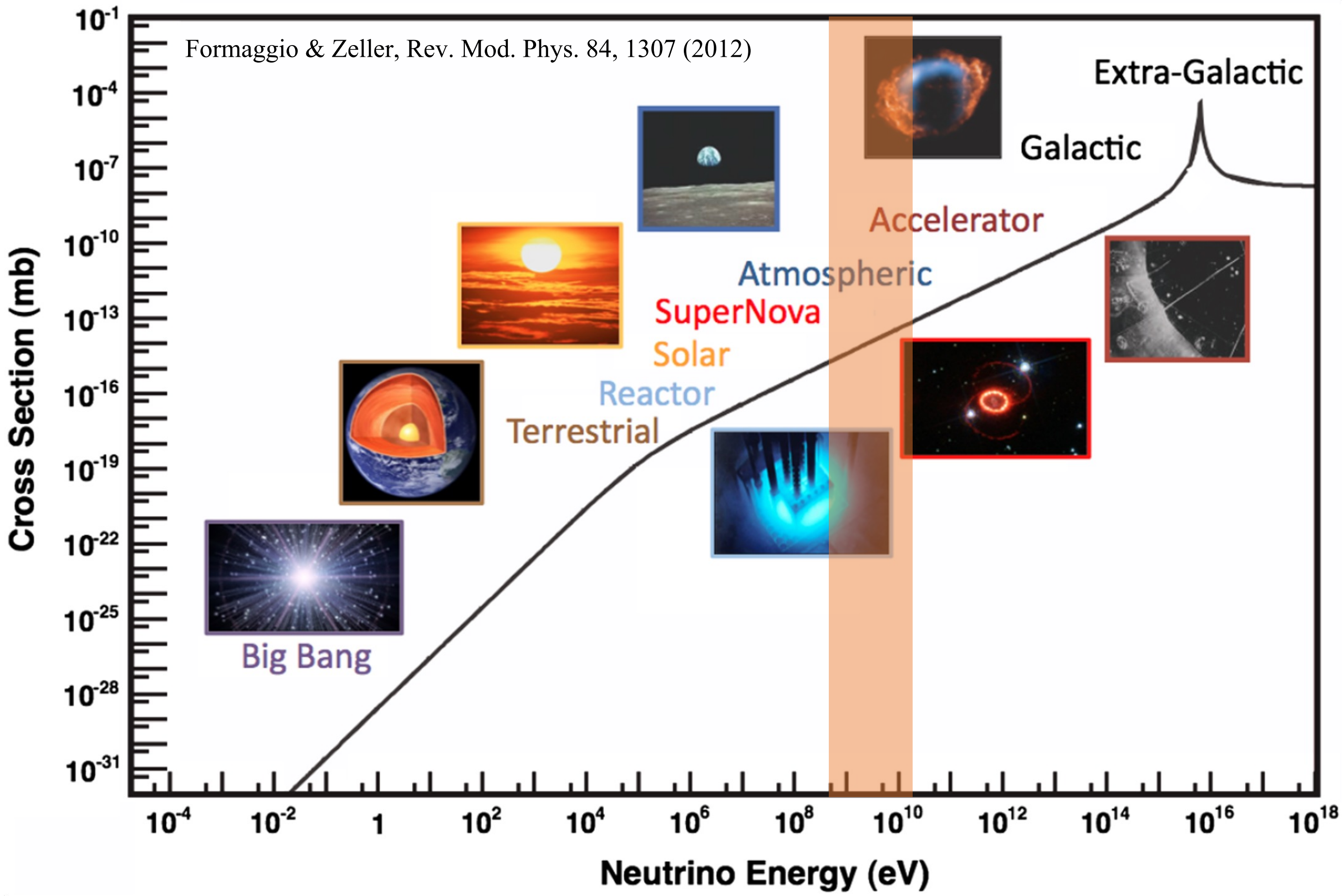


☛ VISOS

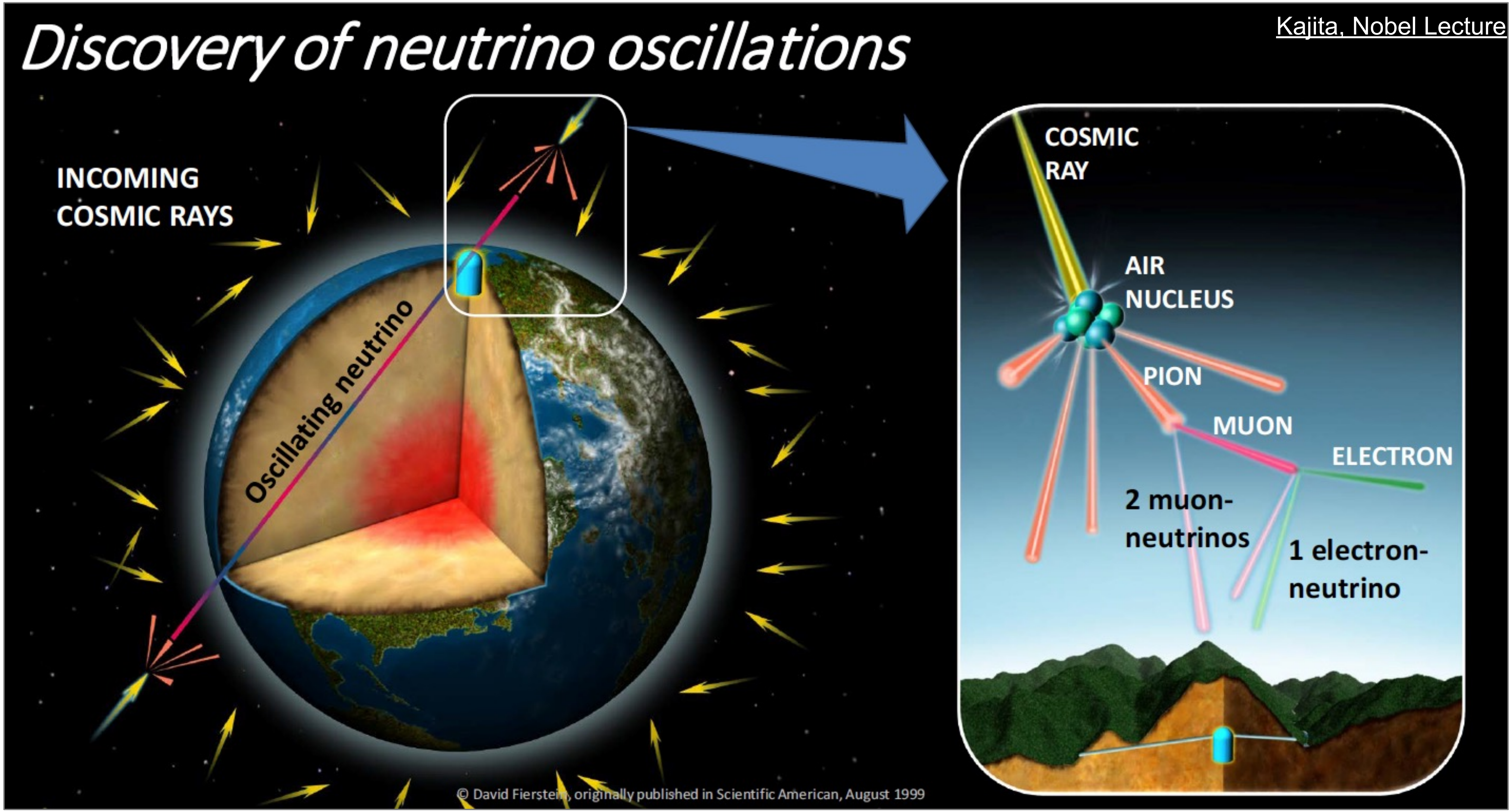
3. Neutrino Experiments

Neutrinos Sources

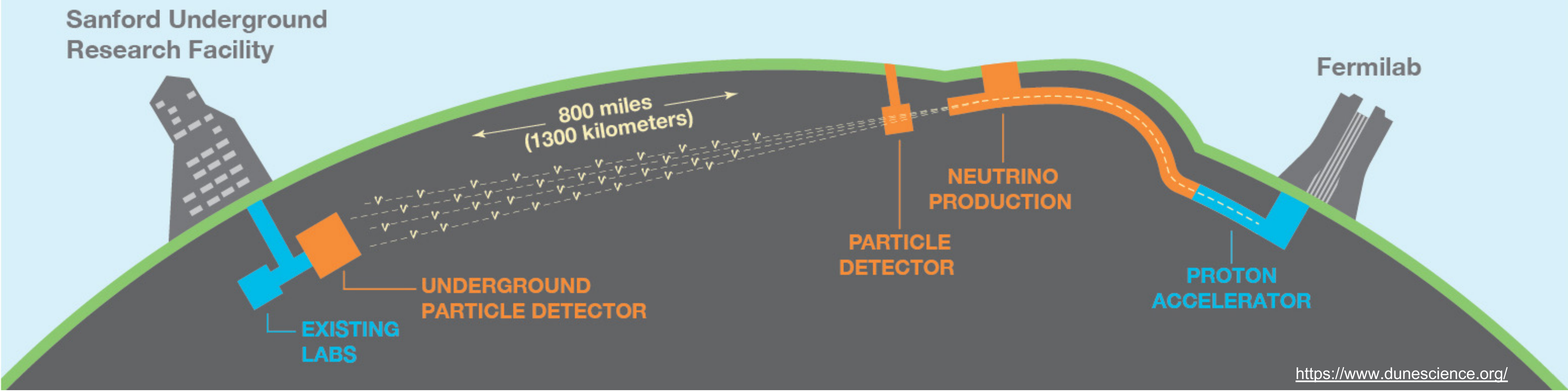
Focus of this talk



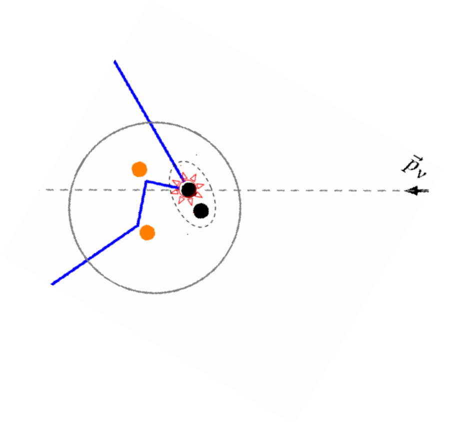
Atmospheric Neutrinos

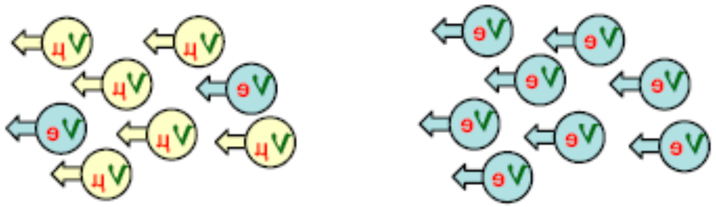


UNDER CONSTRUCTION

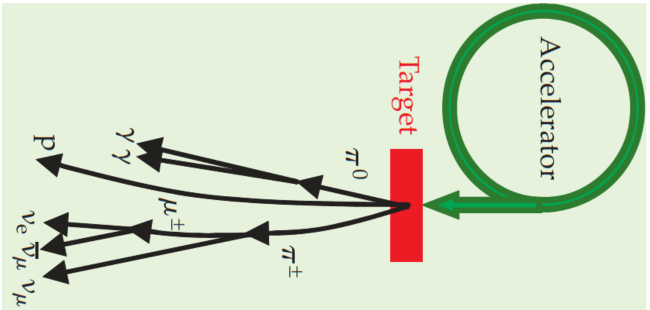


https://www.dunescience.org/





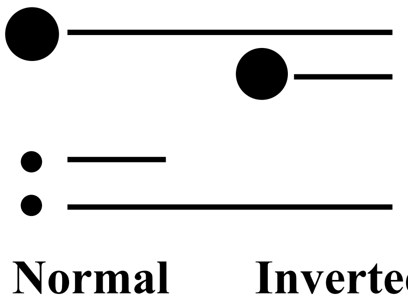
Travel 1/10 of Earth's diameter
(baseline L ~ 1300 km)

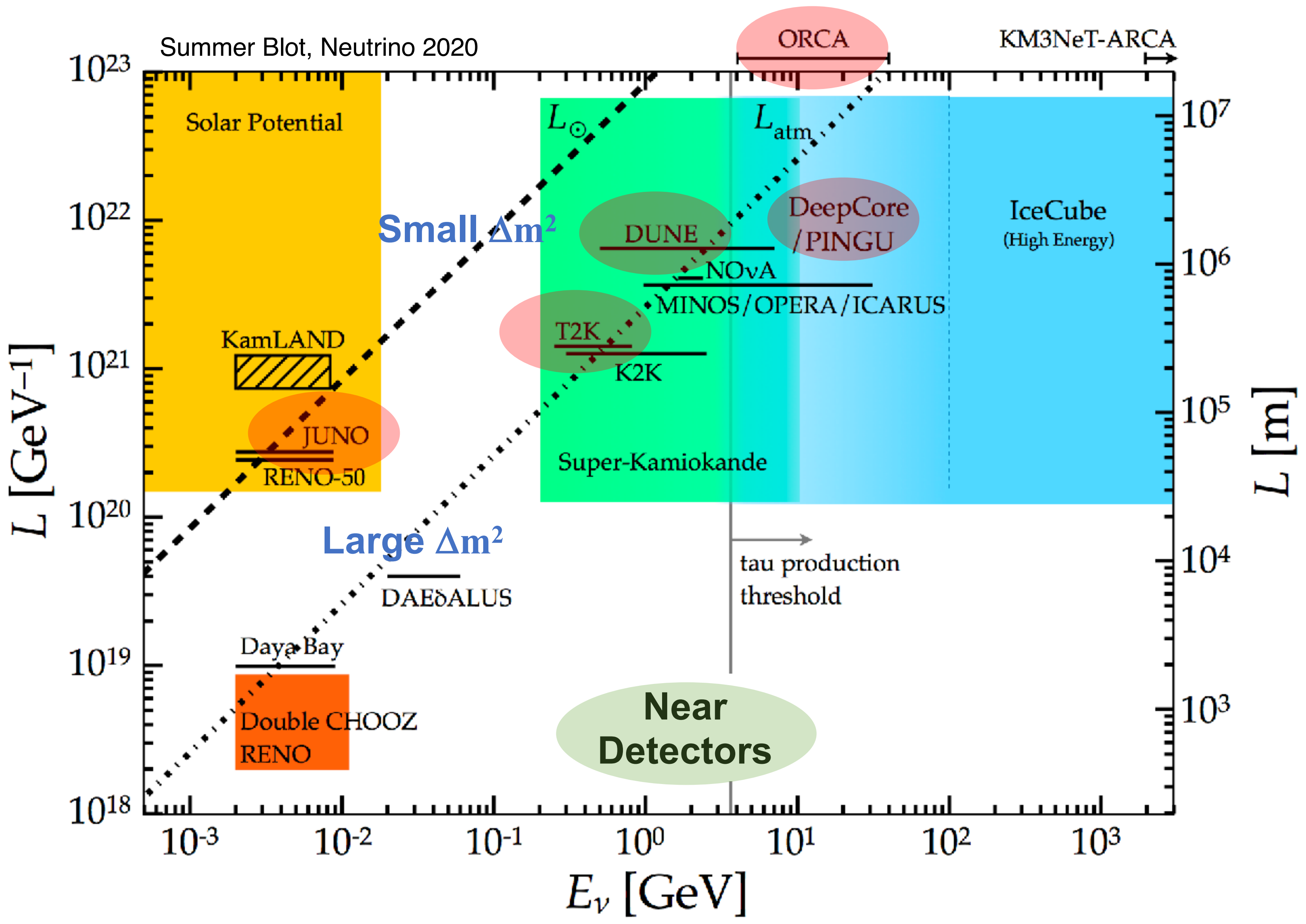


[Physics Today 61, 5, 29 (2008)]

Oscillation phase ~ $\Delta m^2 L/E$

Only two Δm^2

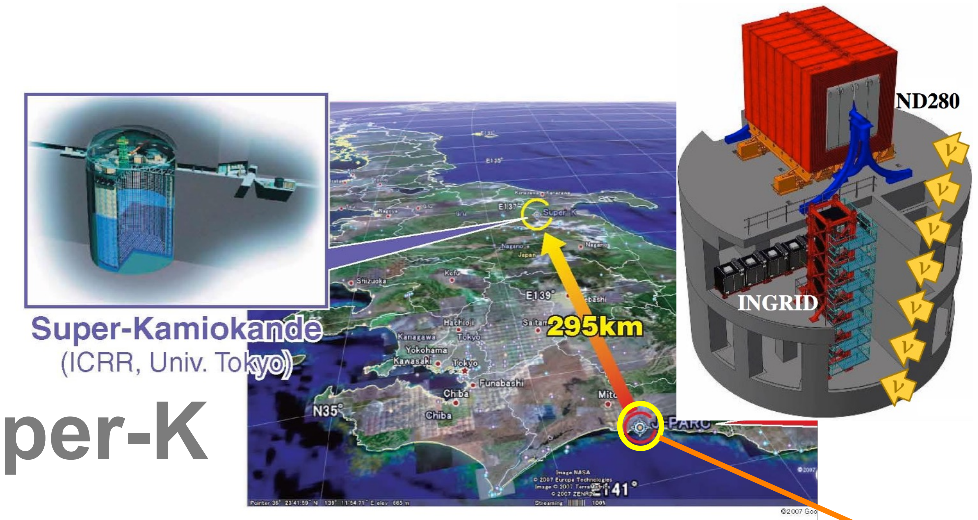




Near Detectors

(more later…)

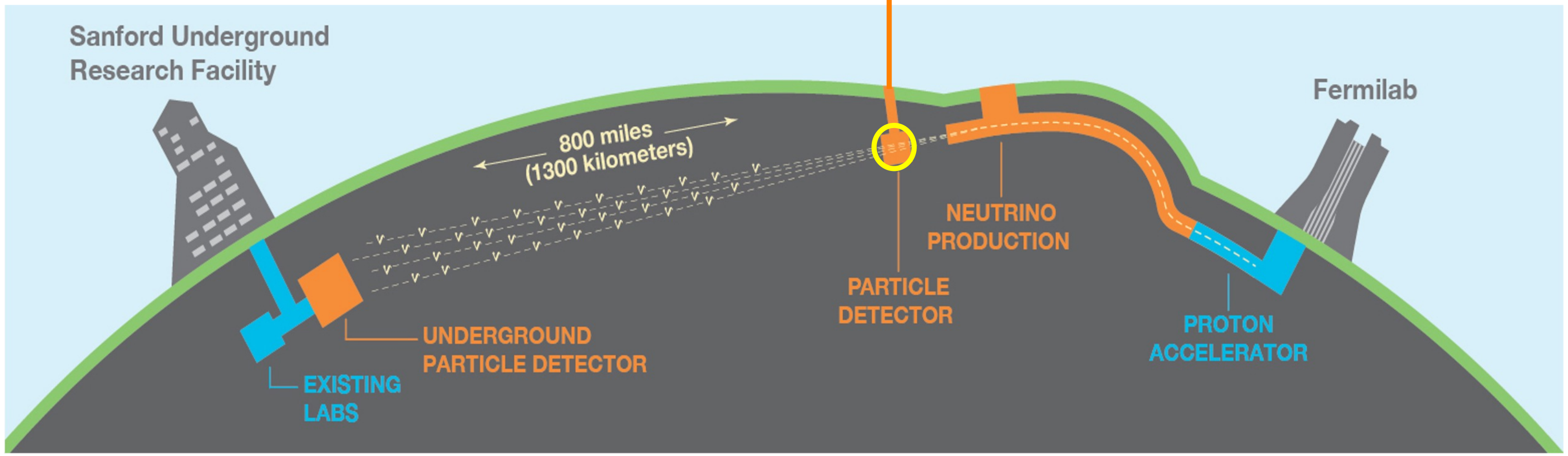
T2K / Hyper-K



NOvA

Near Detectors to measure ν interactions

DUNE



Future oscillation experiments

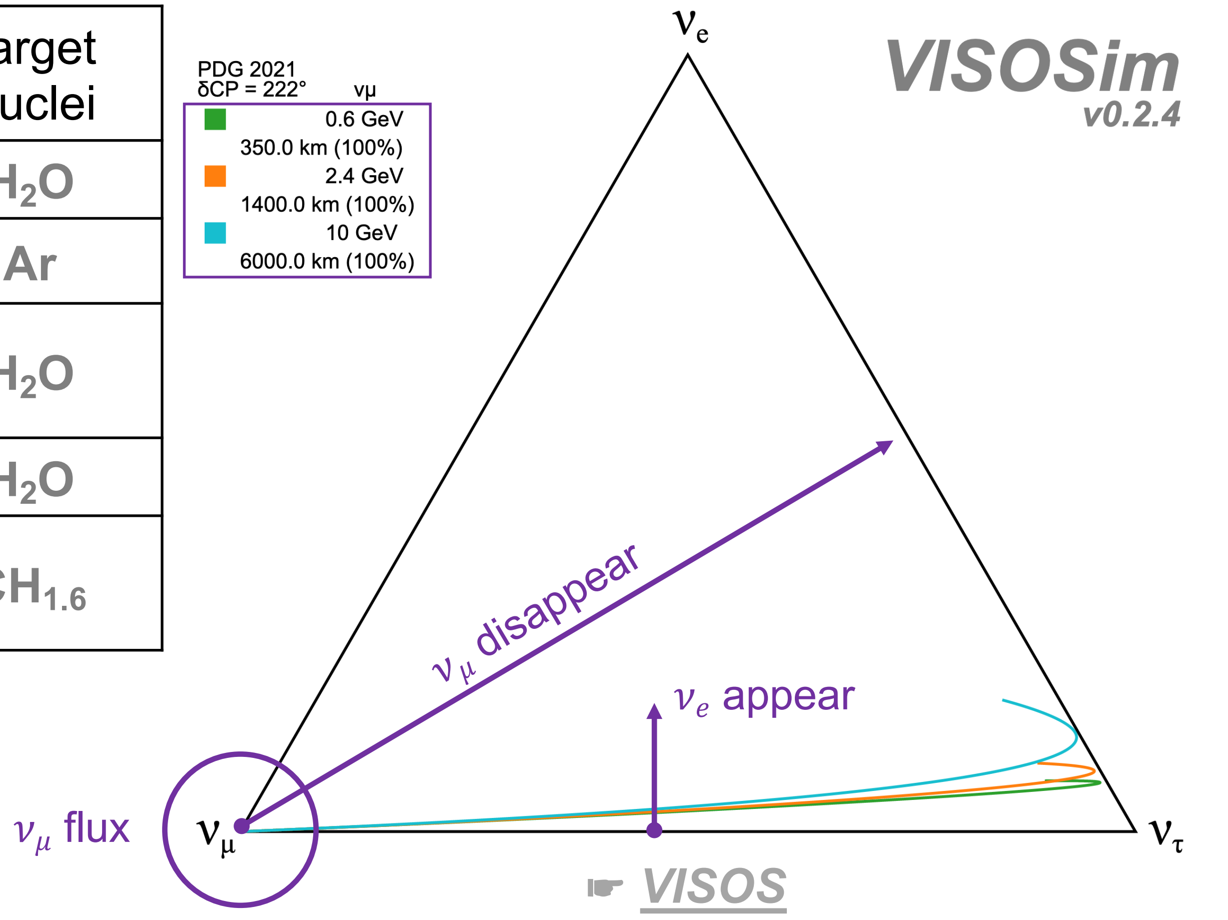
This talk only on

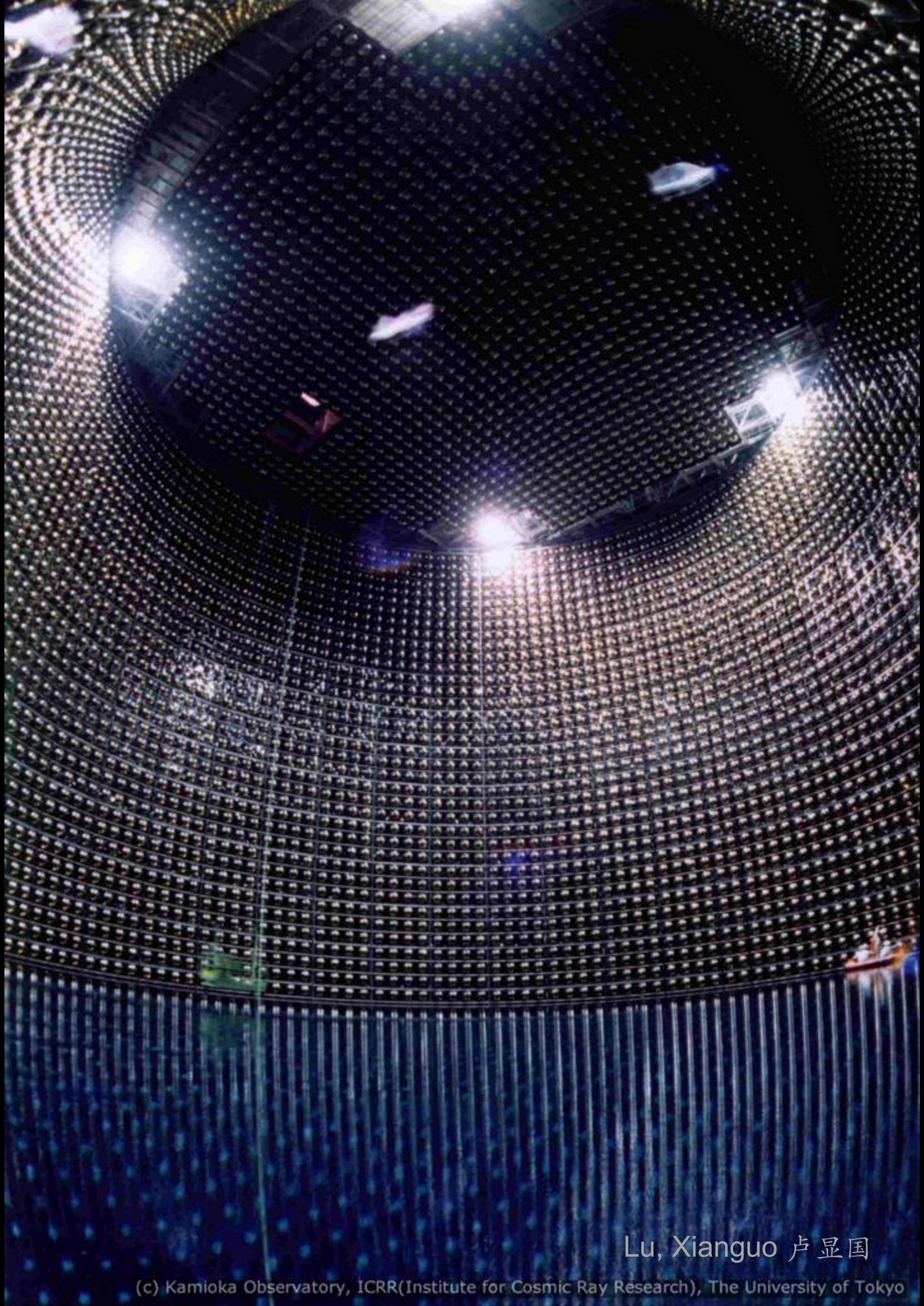
❖ accelerator and atmospheric GeV-ν

❖ ν_μ flux*: ν_μ disappear, ν_e appear

Future Oscillation Experiment	E_ν/GeV @Flux Peak	Detector Technology	Target Nuclei
Hyper-K	**0.6**	**Water Che'**	H_2O
DUNE	**2.4**	**LAr TPC**	**Ar**
IceCube Upgrade	**3-10 (ν Mass Ordering/NMO sensitive region)**	**Cherenkov in ice**	H_2O
KM3NeT/ORCA		**Water Che'**	H_2O
Atmos-ν @ JUNO		**Liquid Scintillator**	$CH_{1.6}$

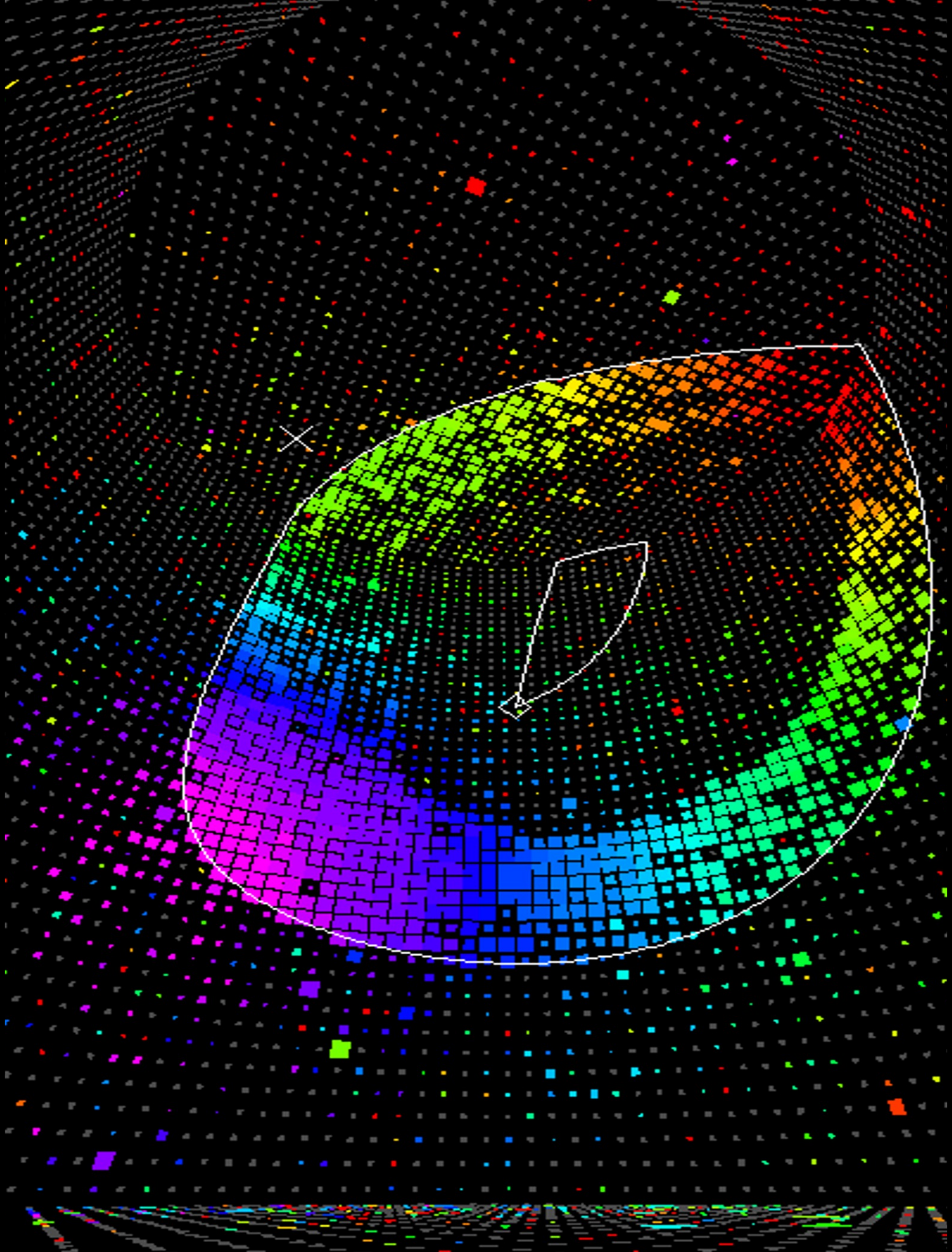
*Referring to neutrinos and/or antineutrinos implicitly depending on the context.



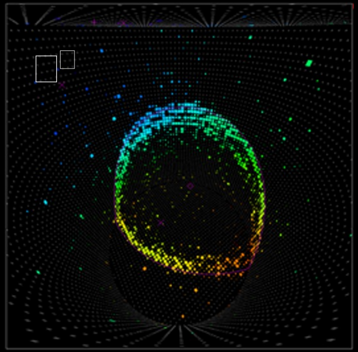


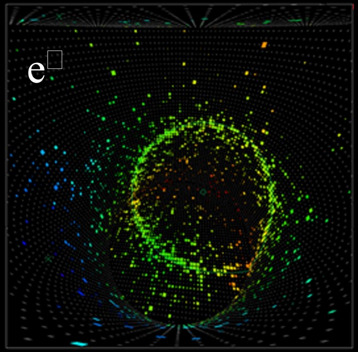
Water Cherenkov detector

Source: http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html



Water Cherenkov detector





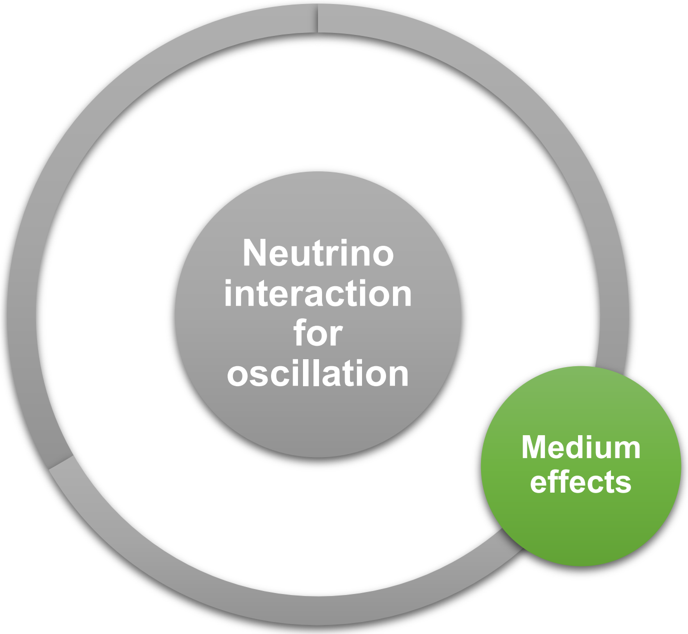
Source: http://www.ps.uci.edu/~tomba/sk/tscan/th

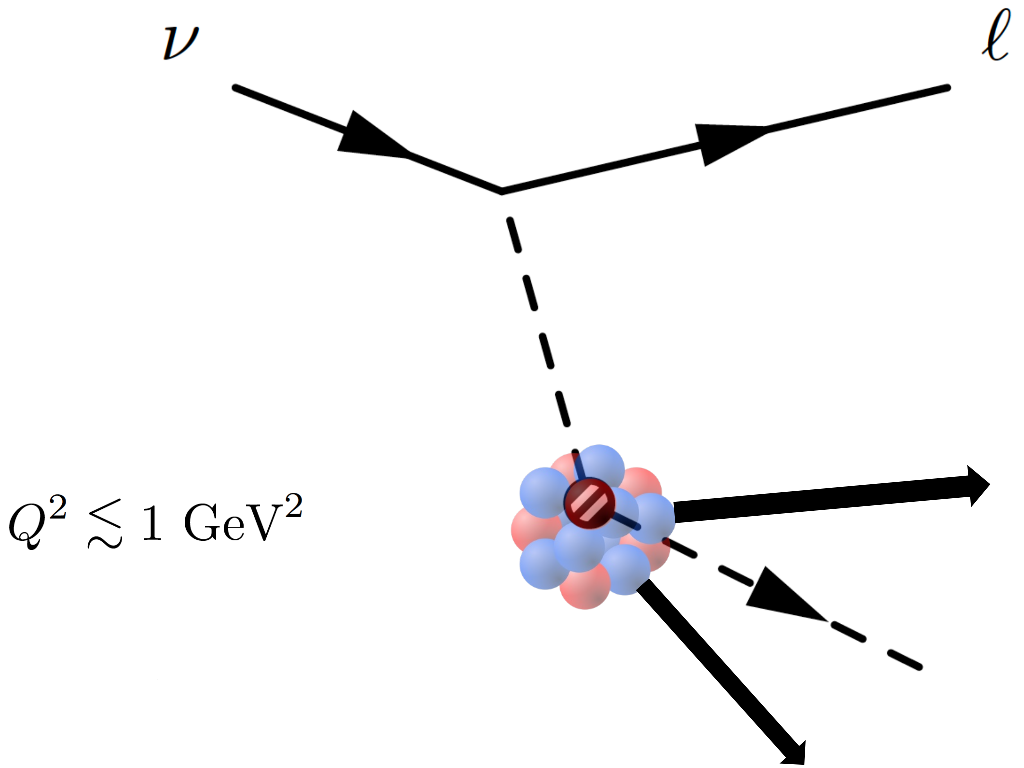
The New Impressive

4. Neutrino Interactions

Interaction inside nuclei

- ❑ $\nu_{\mu/e}$ Charged Current (CC) for ν detection
- ❑ GeV-ν interaction: ν***N*** interaction embedded in ***nuclei (A)***



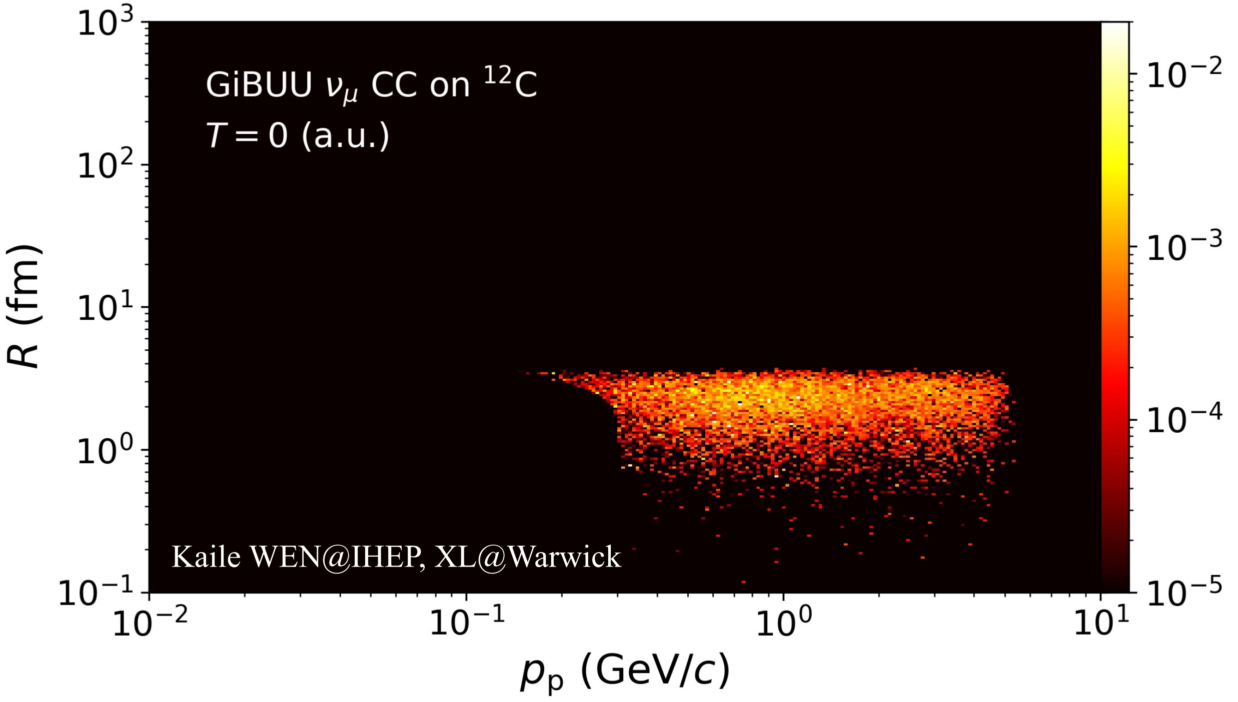


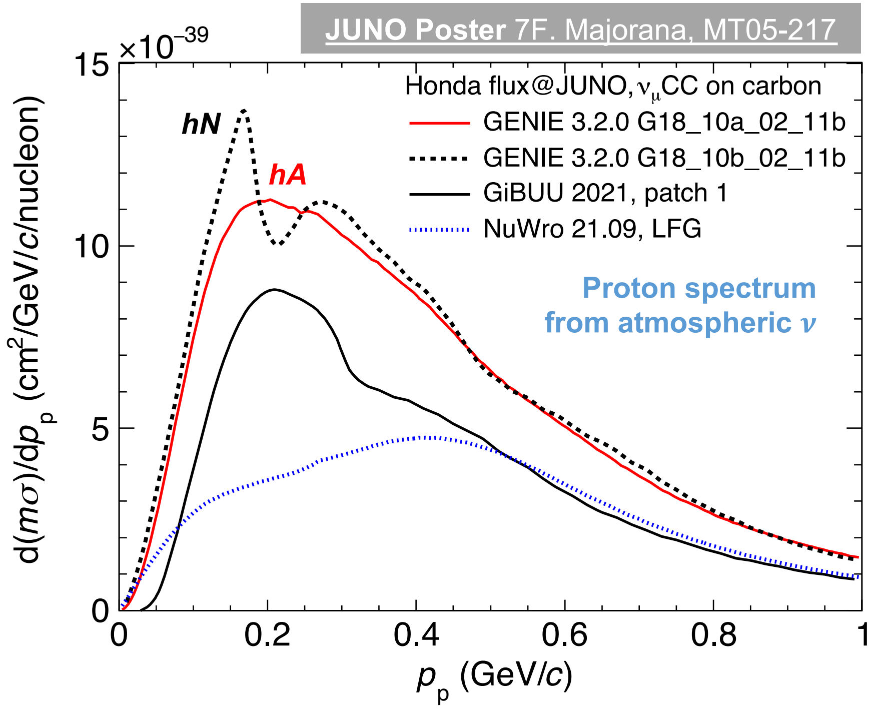
Medium effects—source of systematics

✓ ***ν energy reconstruction, event classification***

❑ Nucleus is a black box

- ❖ Fermi motion & nuclear potential
- ❖ NN correlations
- ❖ Pauli-blocking
- ❖ Multinucleon excitation
- ❖ FSI





† Proton in GiBUU final-state transport
R: radial position, p_p: momentum

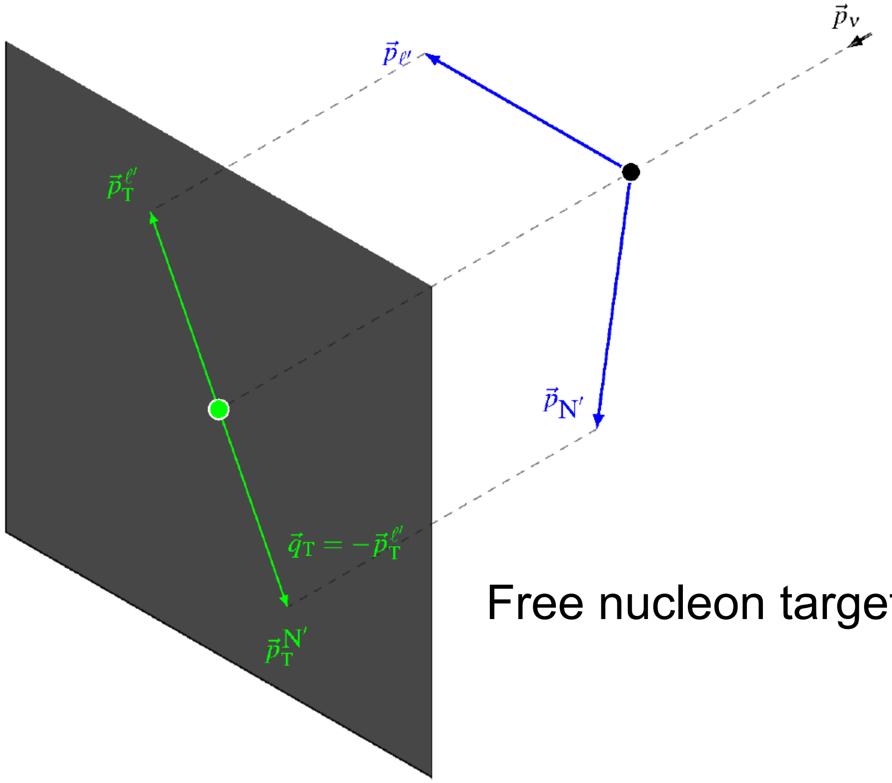
Final-state proton in neutrino interactions: momentum evolves as propagating out of the nucleaus

Medium effects

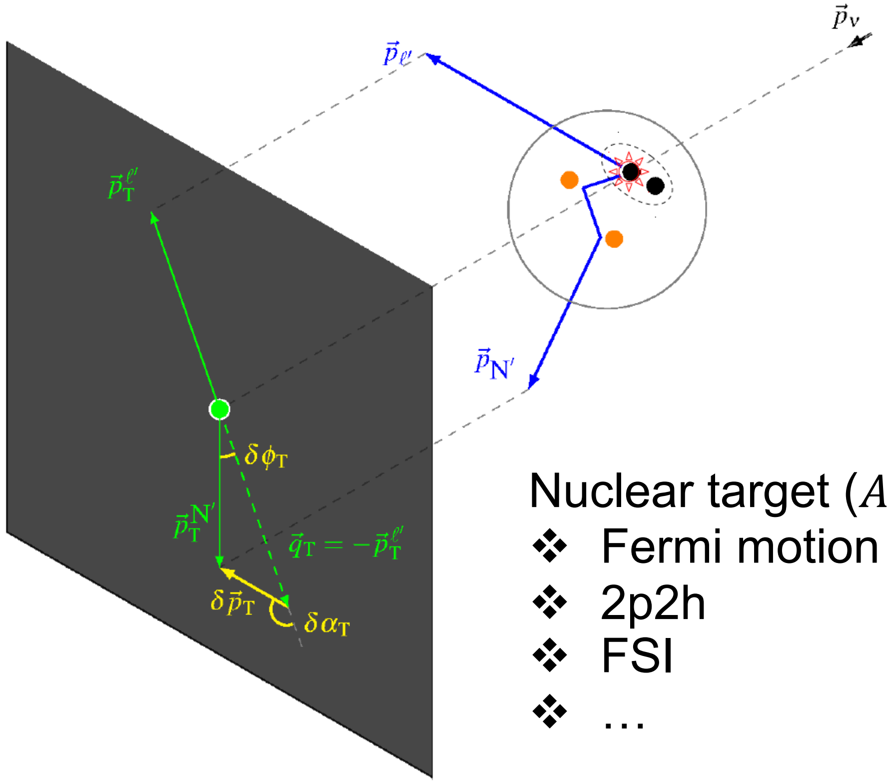
TKI (Transverse Kinematic Imbalance)

- ❑ TK orthogonal to ***unknown*** E_ν
- ❑ Embed in imbalance created by
  - ❖ Nucleus "contacting" medium

✓ ***Signature imbalance probing inside nuclei***



Free nucleon target



Nuclear target ($A > 1$)

- ❖ Fermi motion
- ❖ 2p2h
- ❖ FSI
- ❖ …

What do you see in this sculpture?

Medium effects

TKI

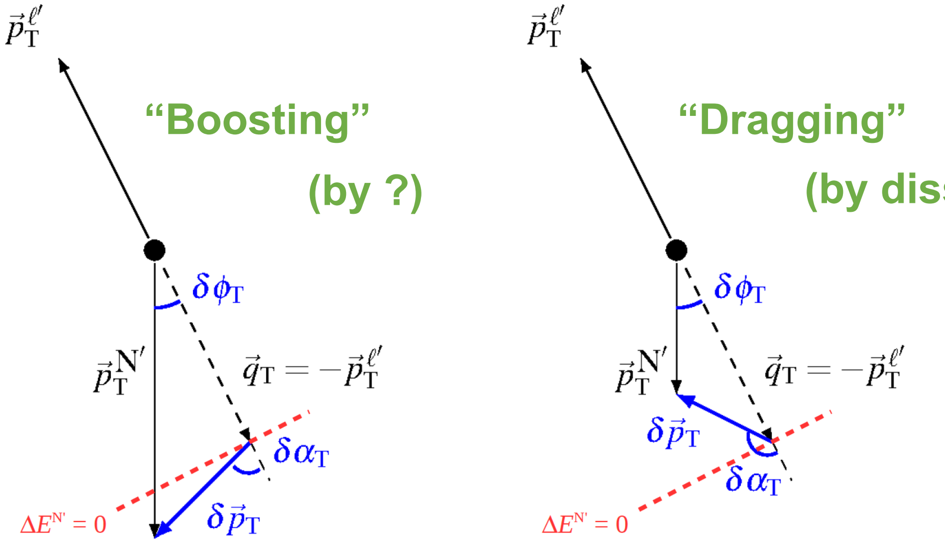
Transverse boosting angle

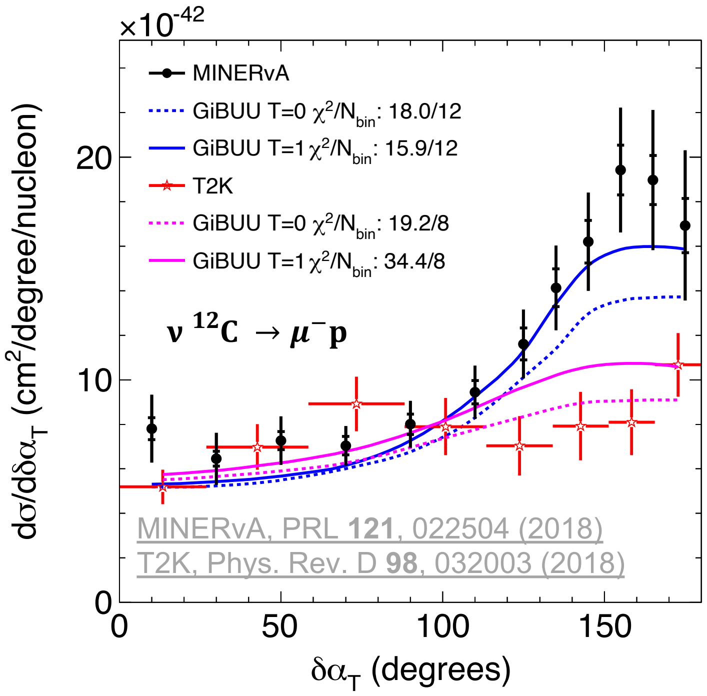
XL *et al.* Phys. Rev. C **94**, 015503 (2016)

Quasielastic-like: $\nu\ ^{12}\mathrm{C} \rightarrow \mu^- \mathrm{p}$

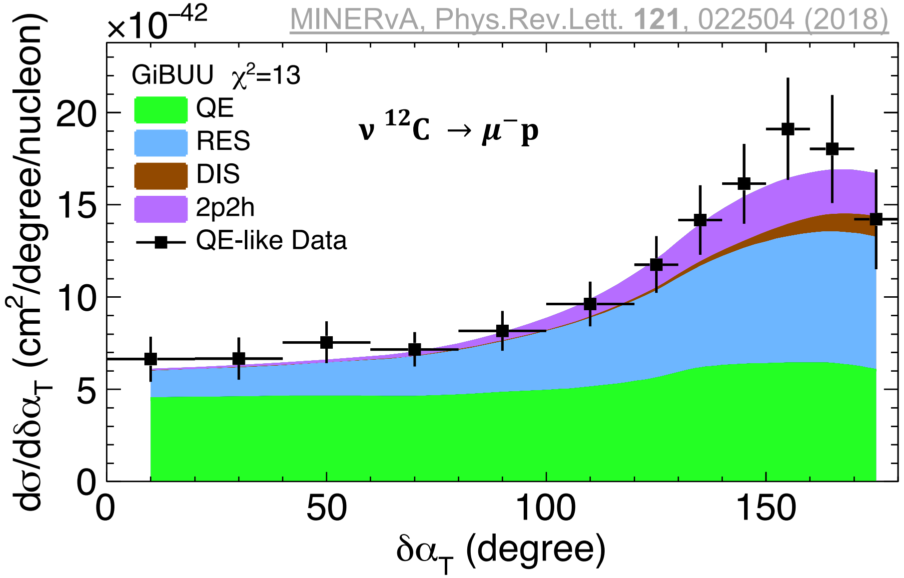
❖ 2p2h, resonance (π production + absorption)

✓ ***Energy dependence*** *(T2K, MINERvA E_ν ~ 0.6, 3 GeV)*

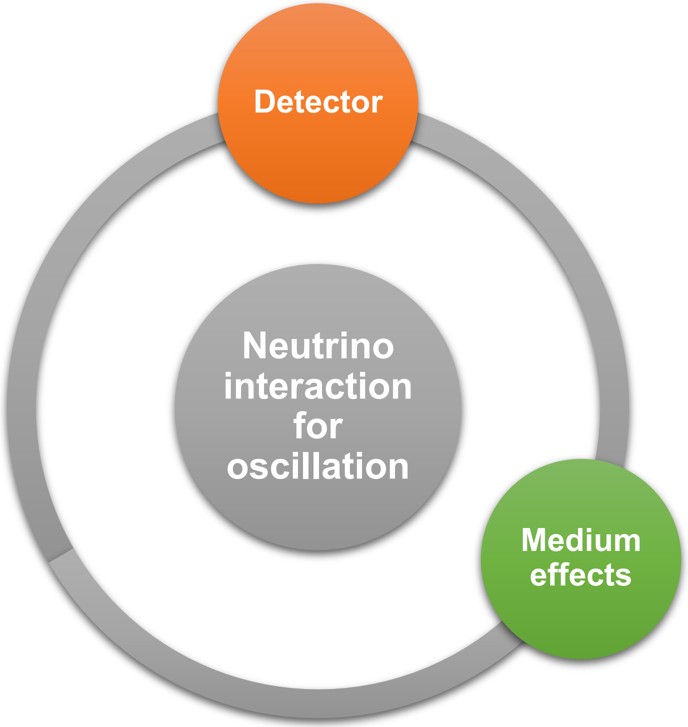




❖ *2p2h*
❖ *RES*
Develop above T2K energy



❖ *2p2h*
❖ *RES*
Dragging = Energy carried away by unobserved particles



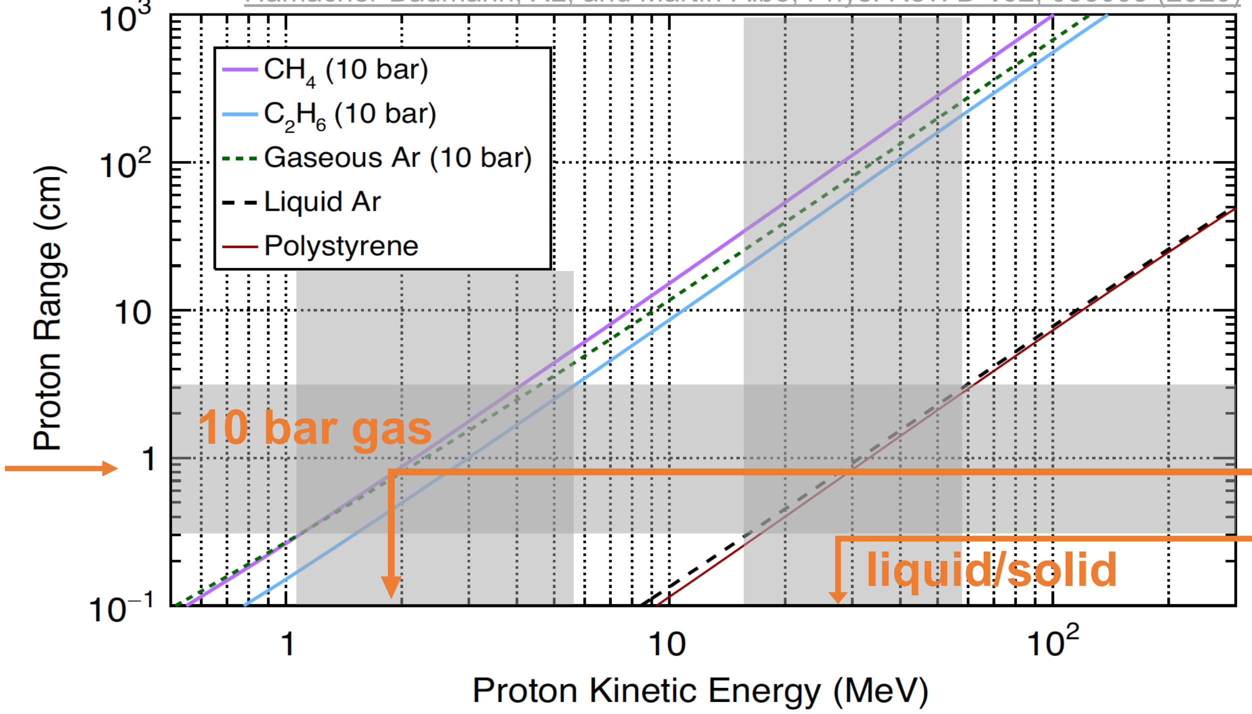
Sensing ν interactions

Embedded in detector, incomplete particle information

- ❖ **Tracking**/Cherenkov **threshold**
- ❖ Angular acceptance
- ❖ PID
- ❖ Neutrals
- ❖ Noise

Proton Range vs Kinetic Energy

Hamacher-Baumann, XL, and Martín-Albo, Phys. Rev. D **102**, 033005 (2020)

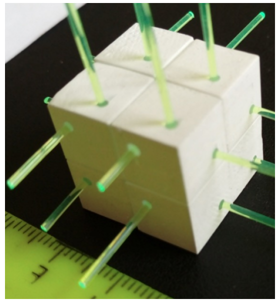


Sensor granularity
~ mm-cm

Tracking threshold
~ few MeV
~ 10s MeV
No momentum measurement below it

Plastic scintillator tracker

- Also ***active target***
  - Tracking + ***calorimetry***

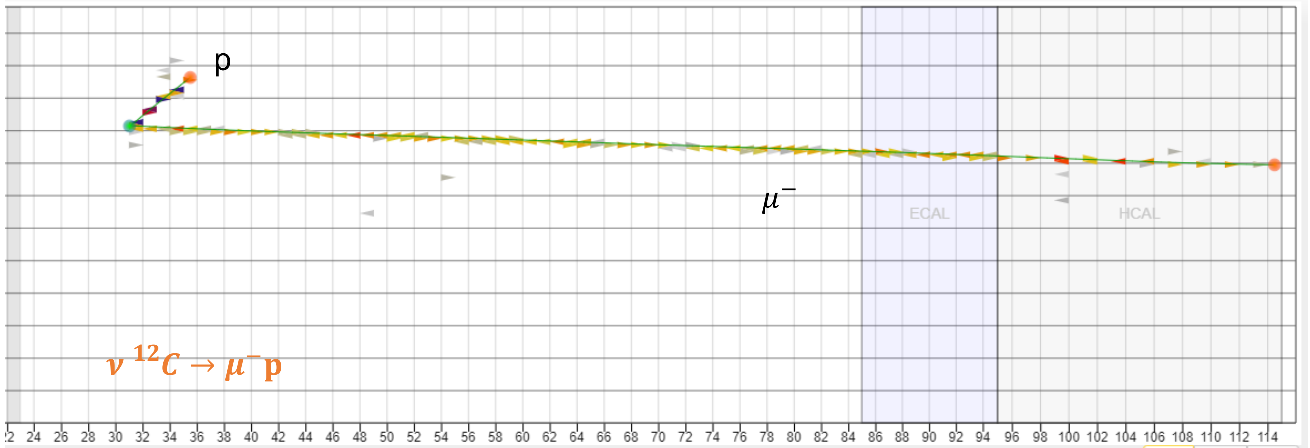


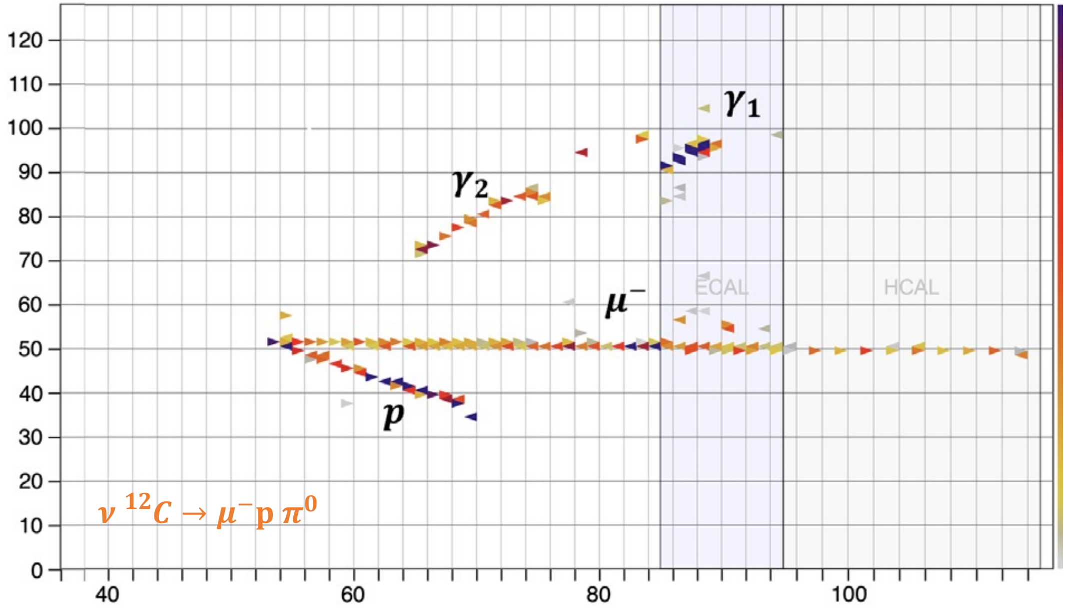
Current role in studying ν interactions

- Largest data set
- Systematic investigation cf. e.g. MINERvA, Eur. Phys. J. ST **230**, 4243 (2021)

MINERvA, Measurement of the axial vector form factor from antineutrino-proton scattering, ***Nature*** 614, 48 (2023)

Typical event display w/ plastic scintillator tracker

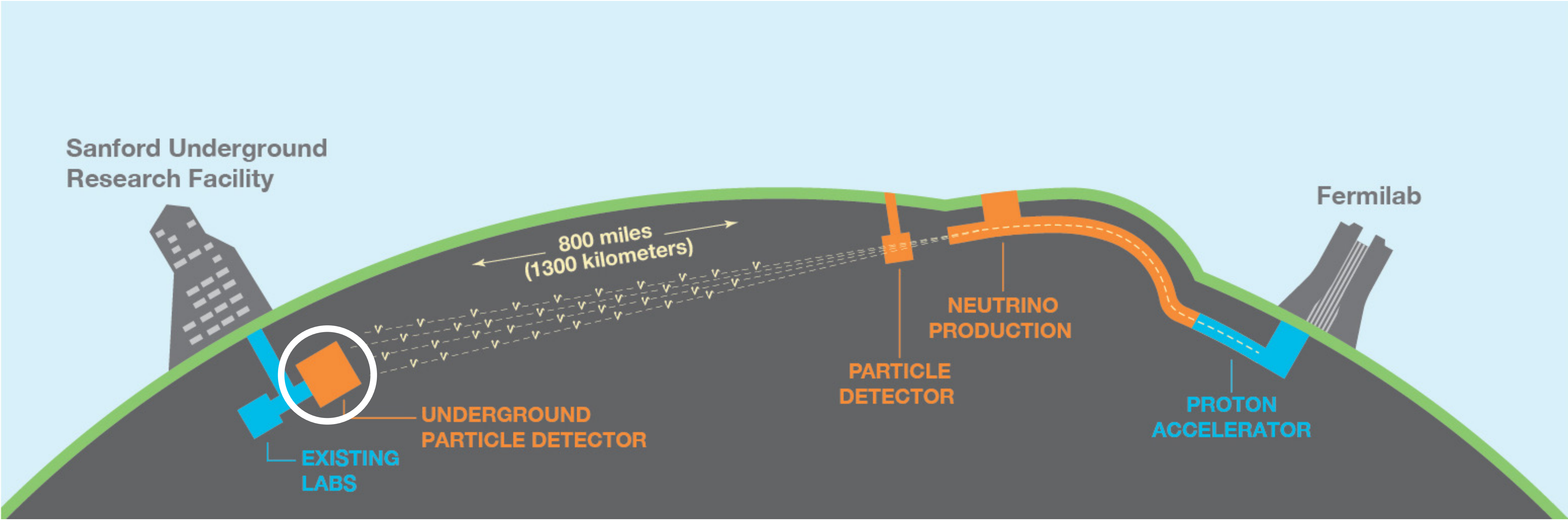




DUNE

Detector

- FD (Far Detector)
  - ❖ LArTPC (Liquid Argon TPC)
  - ✓ ***Mass-scalable for tracking + calo***

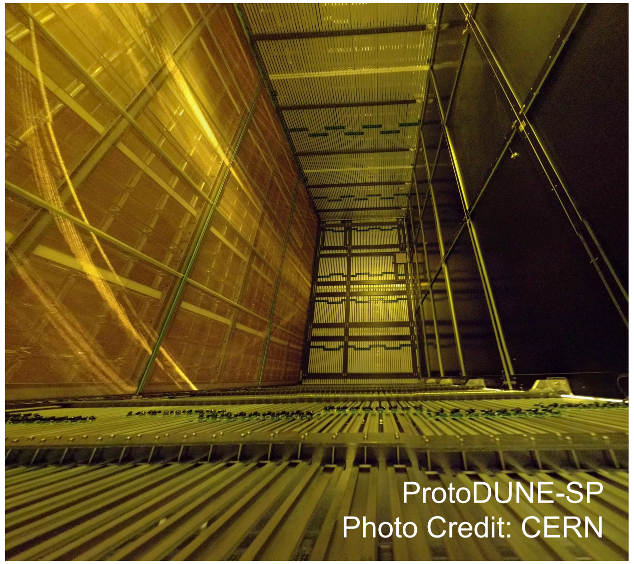


Detector

ProtoDUNE

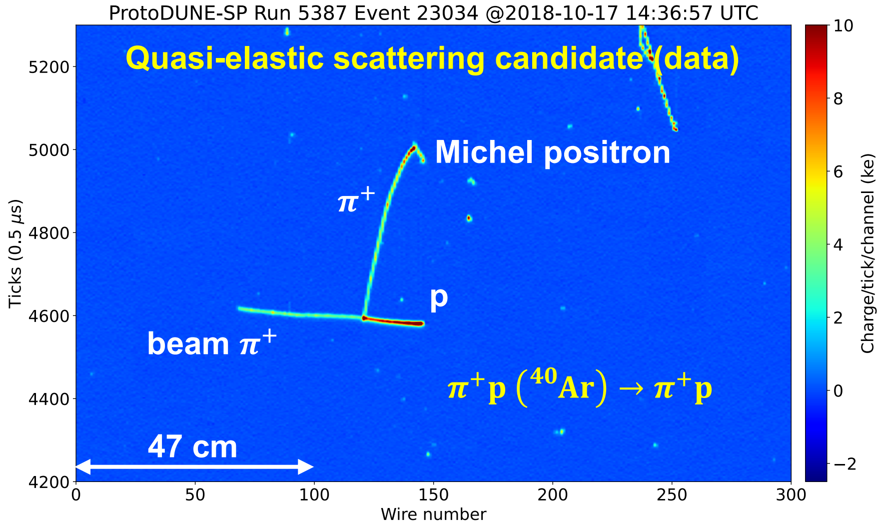
LArTPC Demonstrator at CERN for DUNE FD

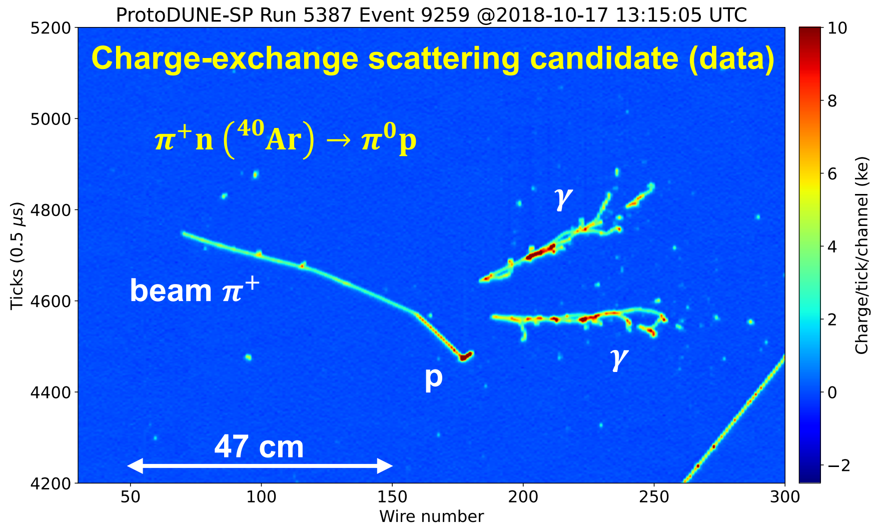
- ❑ Hadron beams of 0.3-7 GeV/*c*
  - ❖ 4.7 mm wire spacing (same as FD)
  - ✓ ***Versatile reconstruction in LAr***



Exclusive event candidates

DUNE, JINST **15**, P12004 (2020)





Kinematic fitting improves π^0 energy resolution from 18% to 12%

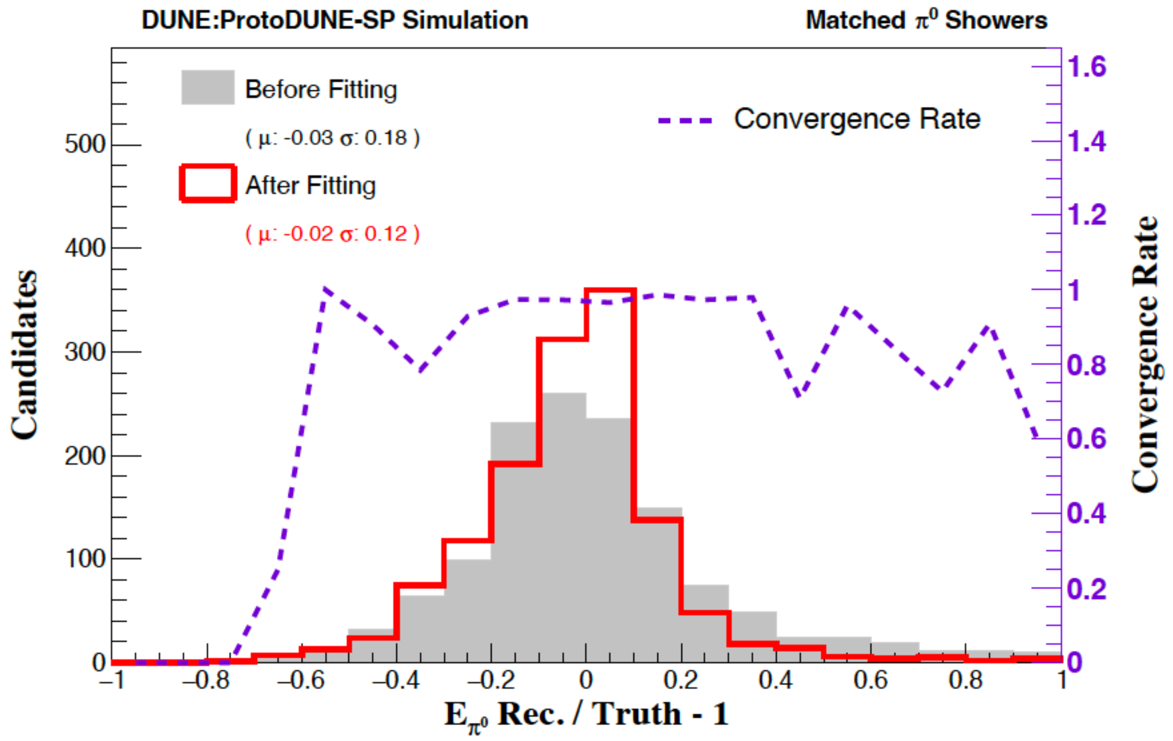


Figure 7.18: The total energy of the π^0 particle before and after the kinematic fitting. The energy resolution is reduced from 18% to 12%. The dashed violet line represents the convergence rate of the fitting in each bin.

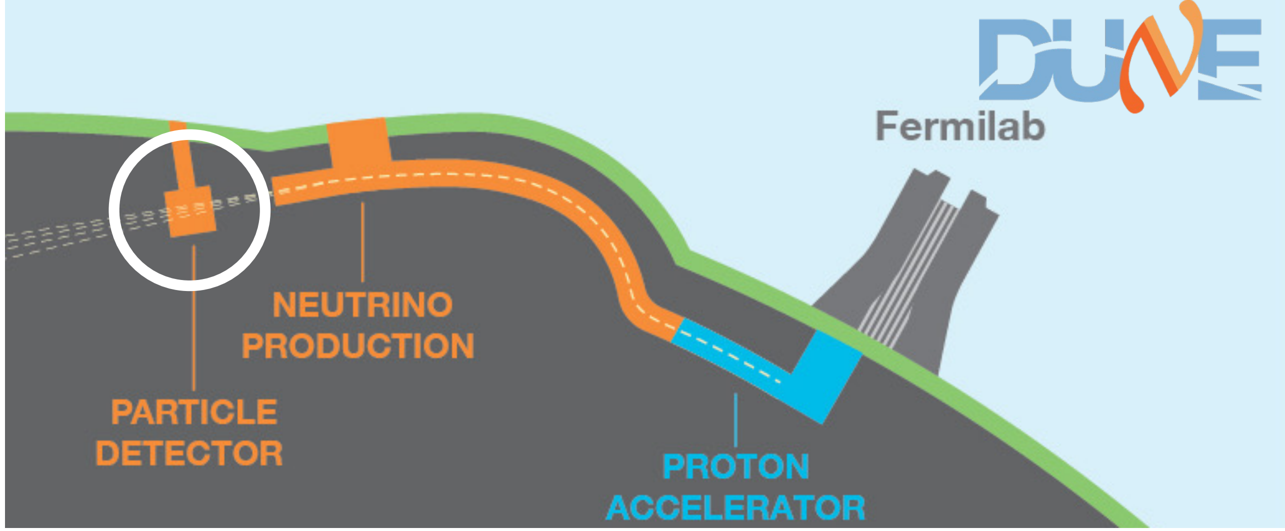
Kang Yang 杨康 (Oxford, PhD thesis, 2023)

Detector

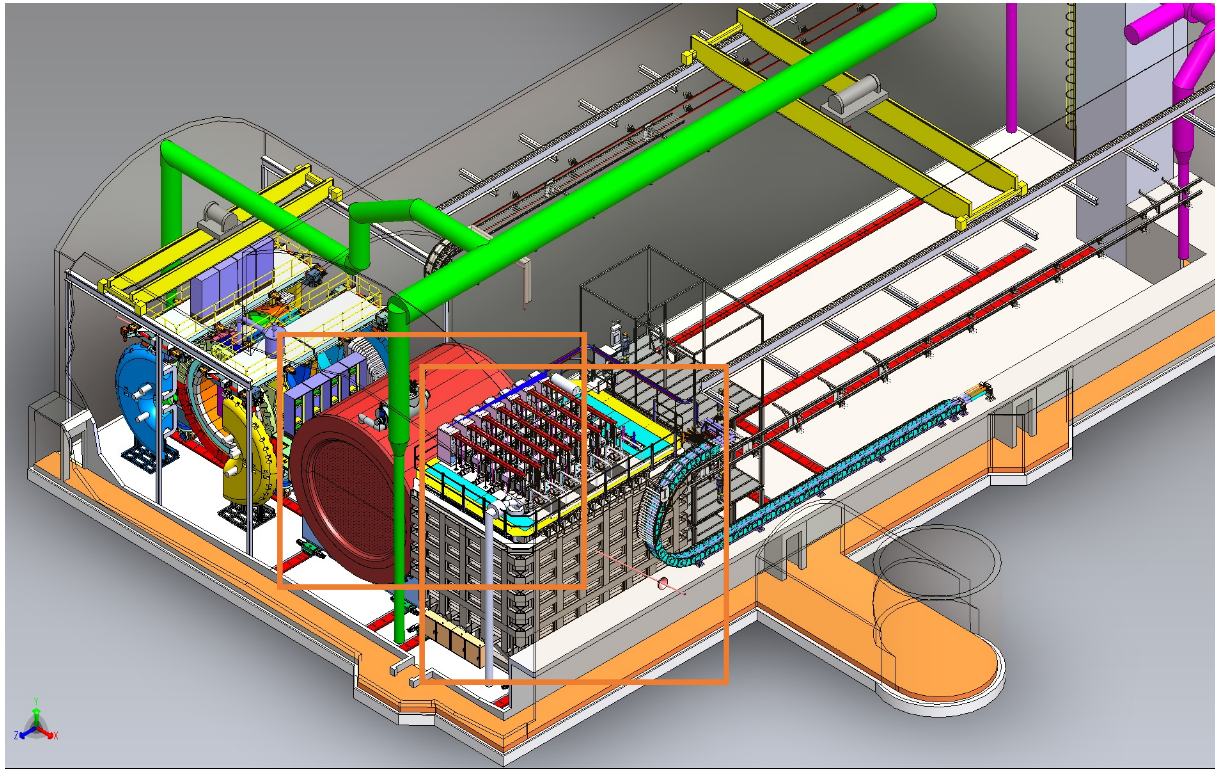
DUNE

- ❑ FD (Far Detector)
  - ❖ LArTPC (Liquid Argon TPC)
  - ✓ *Mass-scalable for tracking + calo*

- ❑ Near Detector ND-LAr
  - ❖ Same technology as FD
- ❑ Near Detector ND-GAr (Gaseous Argon)
  - ❖ 10-bar argon-based gas TPC
  - ❖ ~100 m^3 gas volume surrounded by calorimeter
  - ❖ B-field provides sign selection
  - ✓ ***Large statistics of ν interactions on gas***
  - ✓ ***4π acceptance, very low tracking threshold***
  - ✓ ***Arguably the ultimate detector for ν interactions***

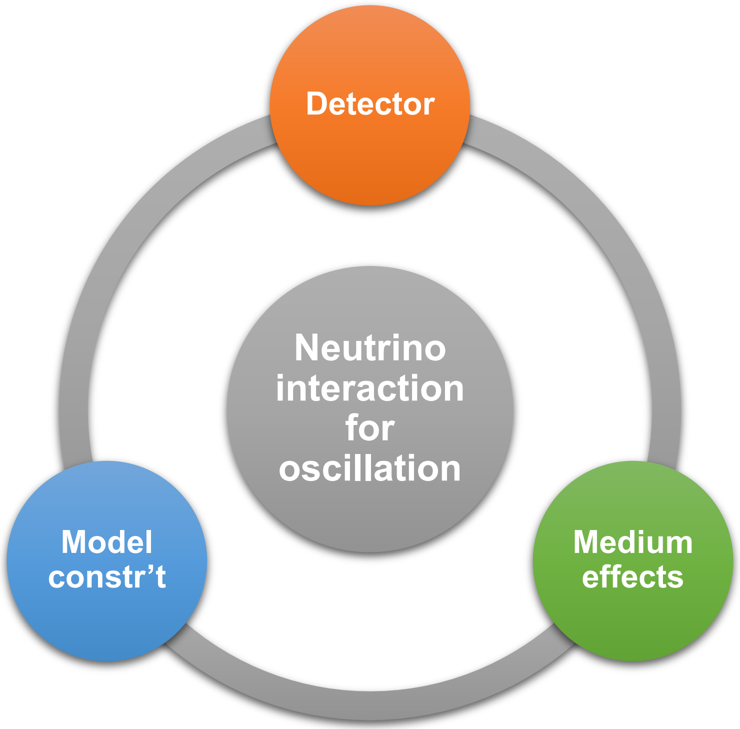


DUNE, instruments **5**, 31 (2021)



Vessel (200 L 10 bar) for high-pressure TPC R&D @ WarTPC lab

Matt Snape (Warwick) and
Philip Hamacher-Baumann (Aachen/Warwick)
August 2022, Warwick



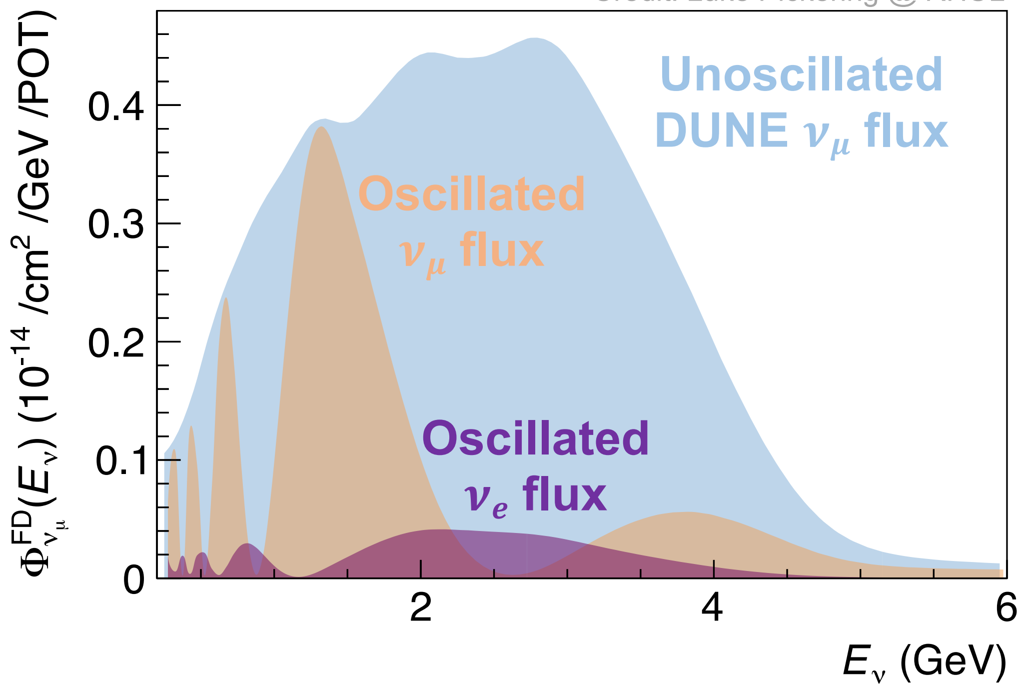
Counting oscillated ν

At ***far detector***, interactions ***cannot*** be measured with ***unknown oscillated flux***

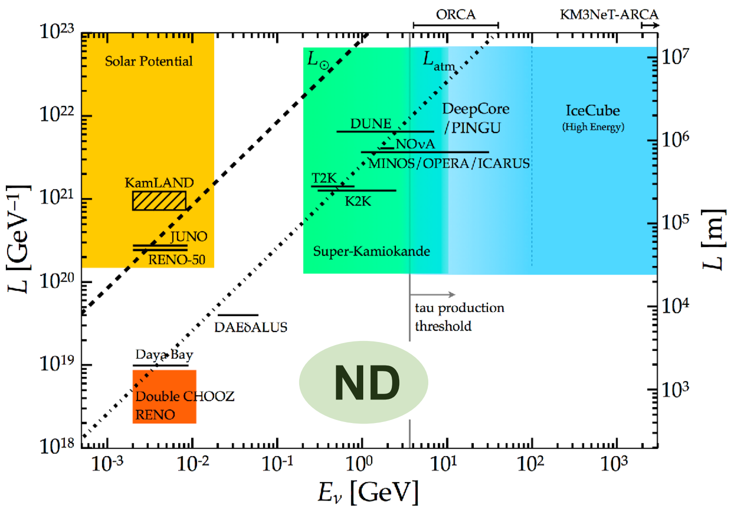
Measurement = (*flux* × *interaction*) ⊕ detector effects

No two unknowns at the same time

Credit: Luke Pickering @ RHUL



❖ **Near detectors for the rescue**

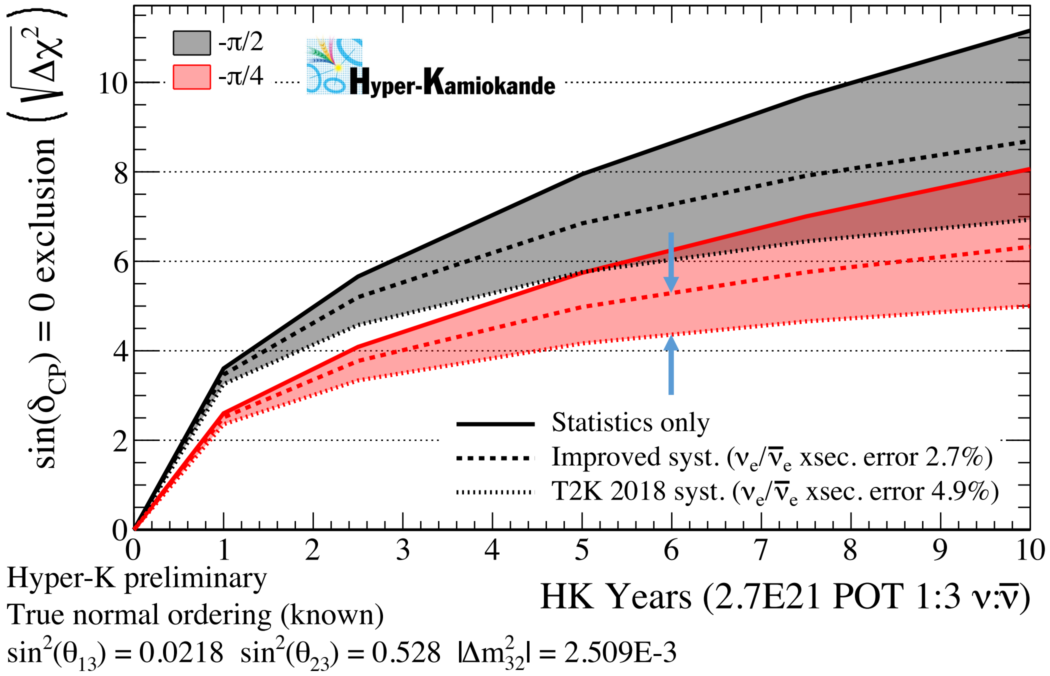


Model constr't

$\nu_e/\bar{\nu}_e$ *interactions*

- ❑ δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- ❑ Need $\nu_e/\bar{\nu}_e$ interaction data
- ❑ ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood fluxes***

Jeanne Wilson's *Hyper-K* in S10 on Thursday



Lepton mass correction ***Hadronic/nuclear response***

$$E_\nu^{\text{tree-level}} = \frac{m_\ell^2 + Q^2}{2\left(E_\ell - p_\ell \cos\theta_\ell\right)}$$

Lepton observables

❖ QED radiative corrections and lepton mass "nudge" Q^2, shifting internal $(q_0, \vec{q}_3)$ phase space

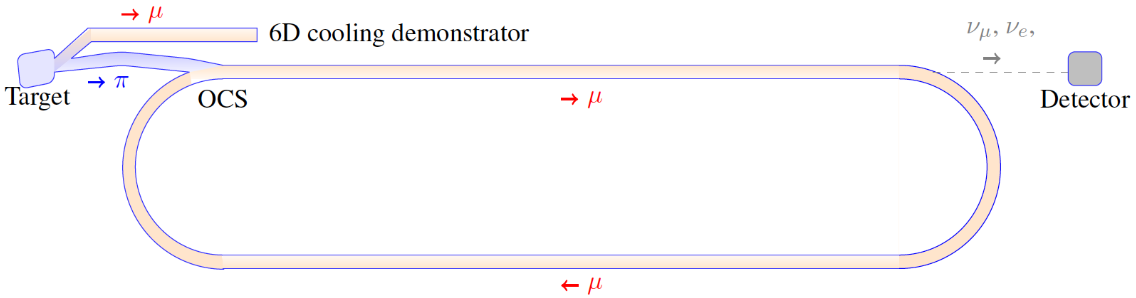
Model constr't

$\nu_e/\bar{\nu}_e$ interactions

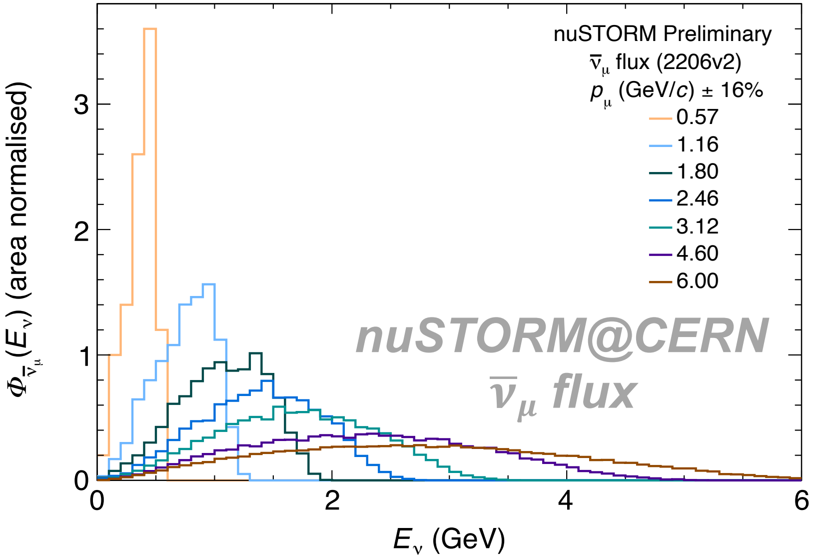
- ❑ δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- ❑ Need $\nu_e/\bar{\nu}_e$ interaction data
- ❑ ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood fluxes***

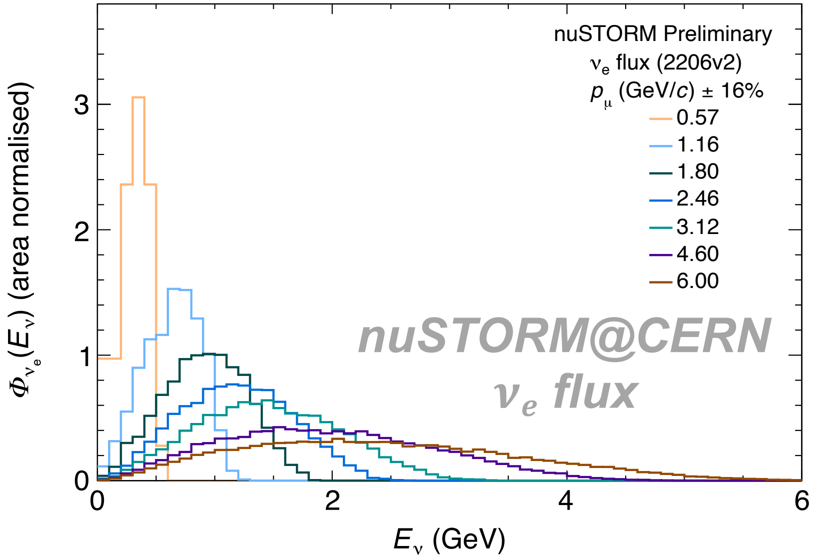
nuSTORM, arXiv:2203.07545

- ❑ ν from STORed Muons (nuSTORM)
  - ❖ $\nu_\mu/\bar{\nu}_e/\bar{\nu}_\mu/\nu_e$ fluxes from $\mu^\pm$ decays
  - ✓ ***1% or better flux precision***



nuSTORM, arXiv:2203.07545





Oscillation-relevant energy regime

Summary

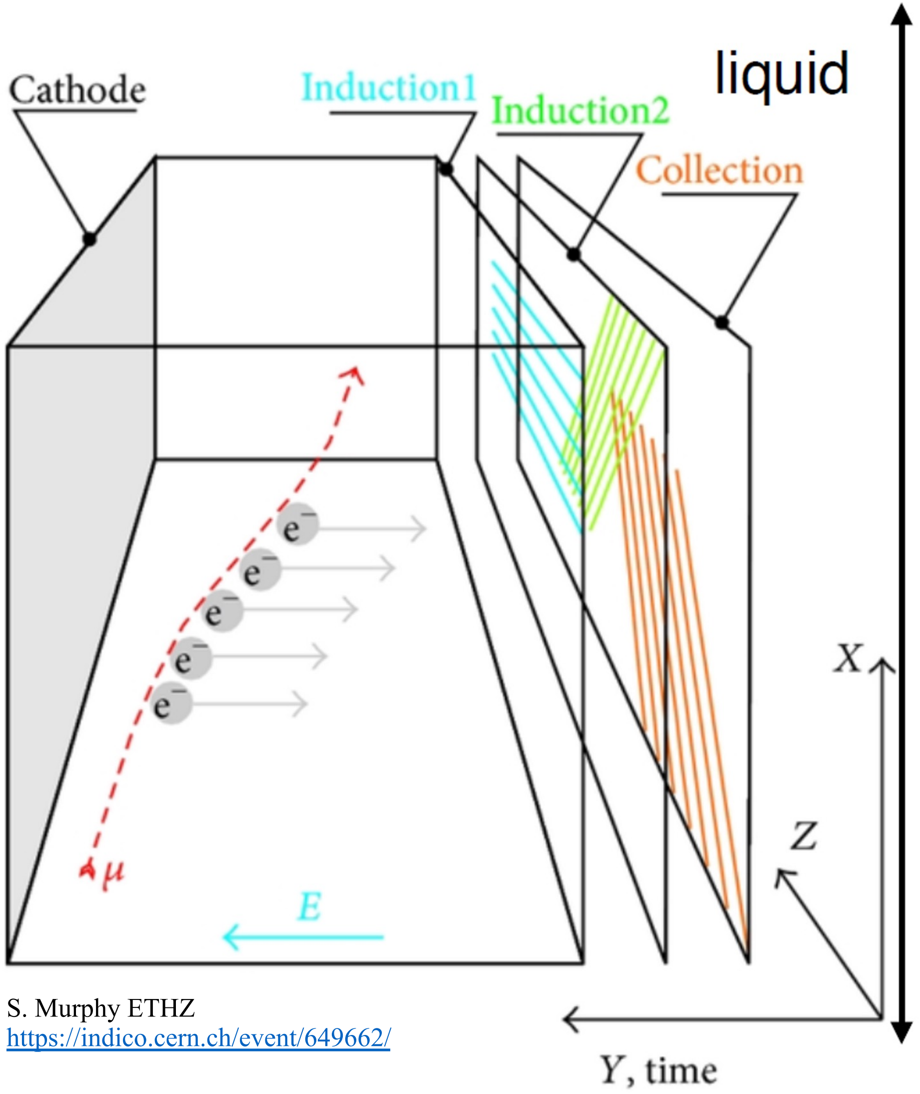
1. Neutrinos in Standard Model
2. Massive Neutrinos
3. Neutrino Experiments
4. Neutrino Interactions
    a. Complicated subject in its own right
    b. Need to measure all final-state particles
    c. How to fully constrain medium effects? – Hot topic in the field!

BACKUP

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{\rm CP} \sin \Delta_{21} \right)$$

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$



S. Murphy ETHZ
https://indico.cern.ch/event/649662/

Liquid argon Time Projection Chamber (LArTPC)

CP Violation

Neutrino oscillations depend on mixing parameters and mass differences.

$c_{ij} = \cos\theta_{ij}$
$s_{ij} = \sin\theta_{ij}$

PMNS matrix

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$\theta_{13} \neq 0 \rightarrow \delta_{CP}$ can be observed

Appearance probability of ν_e in a ν_μ beam

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{CP} \sin \Delta_{21}\right)$$

CP-odd term

* neglecting matter effects

CP Violation

Neutrino oscillations depend on mixing parameters and mass differences.

$c_{ij} = \cos\theta_{ij}$

$s_{ij} = \sin\theta_{ij}$

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{13} \neq$□$0 \rightarrow \delta_{\mathrm{CP}}$ can be observed

Appearance probability of $\bar{\nu}_e$ in a $\bar{\nu}_{\square}$ **beam**

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2 \theta_{23} + \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2 \sin \theta_{13}} \sin \delta_{\mathrm{CP}} \sin \Delta_{21} \right)$$

flip sign

$\delta_{\mathrm{CP}} \rightarrow$ CP violation

CP violation: electron flavor appears from muon-flavor neutrinos and antineutrinos differently.

* neglecting matter effects

Detector

Plastic scintillator tracker

- ❑ Also ***active target***
  - ❖ Tracking + ***calorimetry***
- ❑ T2K Upgrade/***Hyper-K ND*** (more later) sFGD
  - ❖ ***Homogeneous 4π acceptance***
  - ❖ ***Lower tracking threshold***
  - ✓ ***Much improved exclusivity***

Exclusivity: to measure all final states (except nuclear remnant)

T2K Near Detector ND280

FGD (Fine-Grained Detector)

planes of few-cm-thick ***bars***

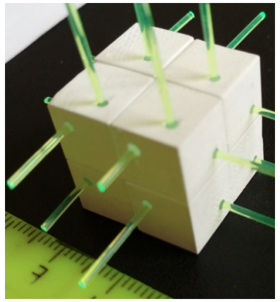
ν interaction in plastic scintillator bars—FGD

ND280 Upgrade

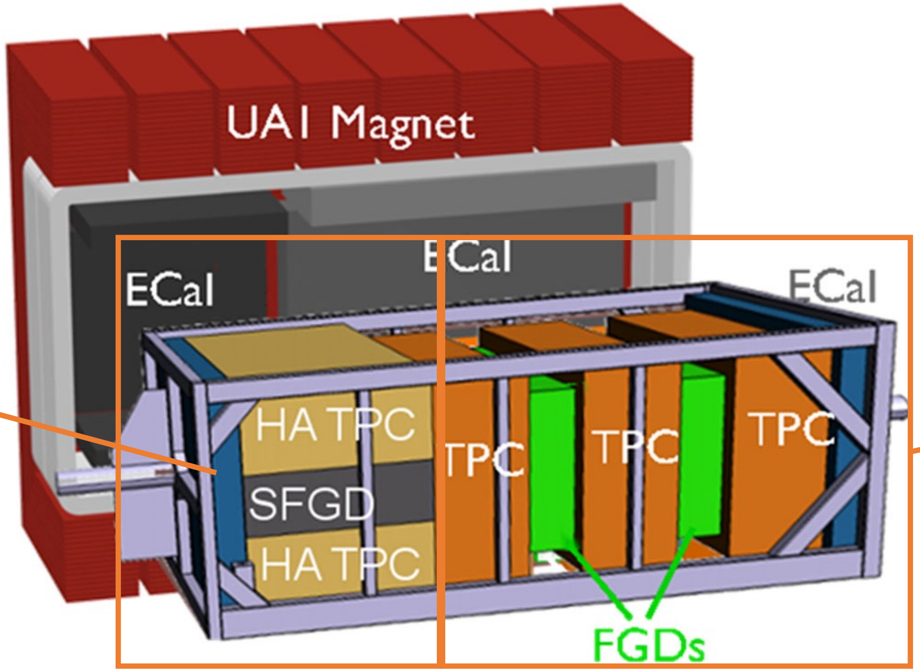
sFGD (SuperFGD)

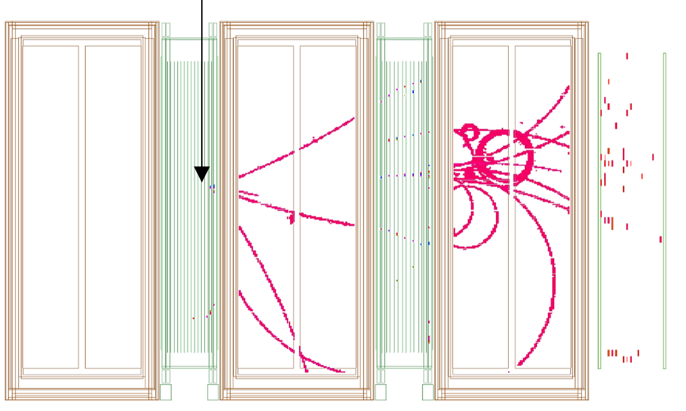
1-cm^3 ***cube***

Blondel *et al*. JINST **13**, P02006 (2018)



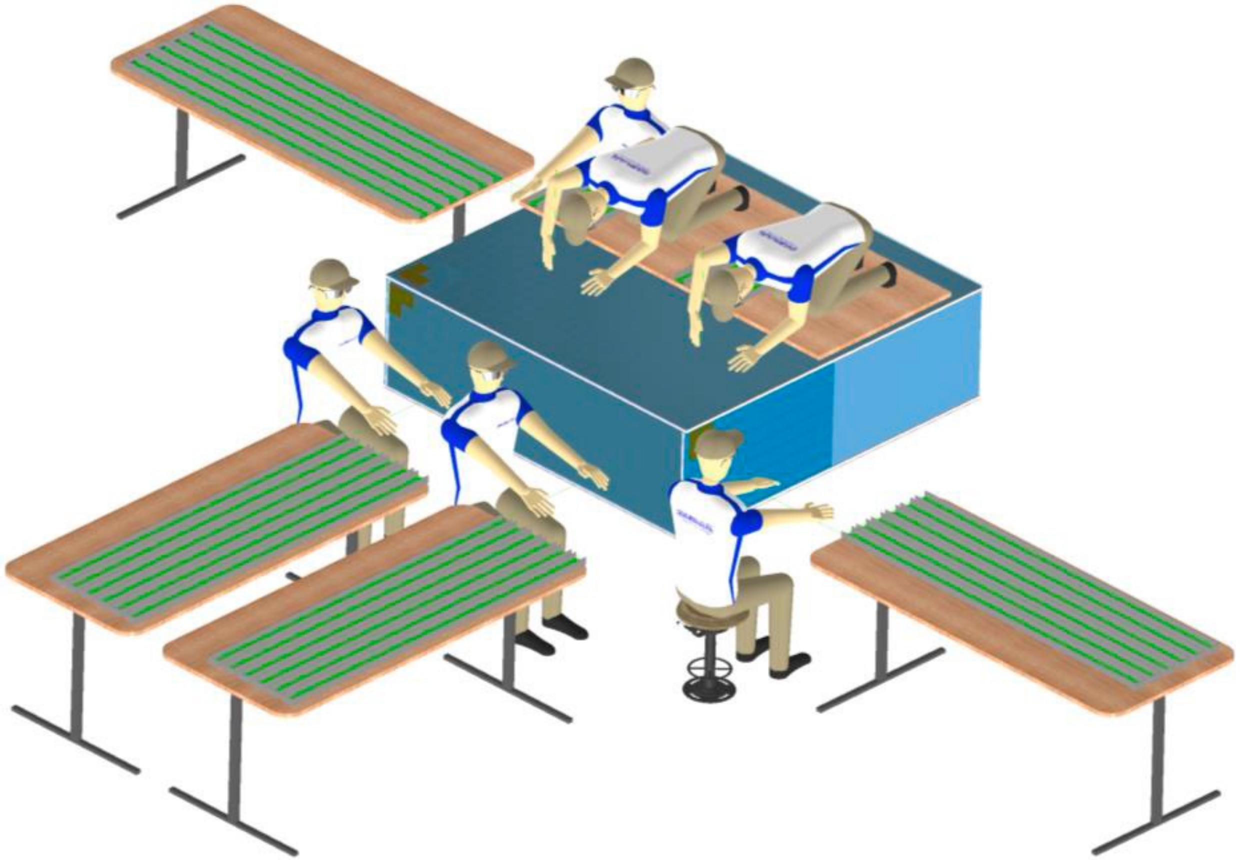
T2K, arXiv:1901.03750





T2K, Nucl. Instrum. Meth. A **659**, 106 (2011)

Cube assembly and fiber insertion …



Weijun Li 利伟君 (Oxford/Warwick)
January 2023, J-PARC

Detector

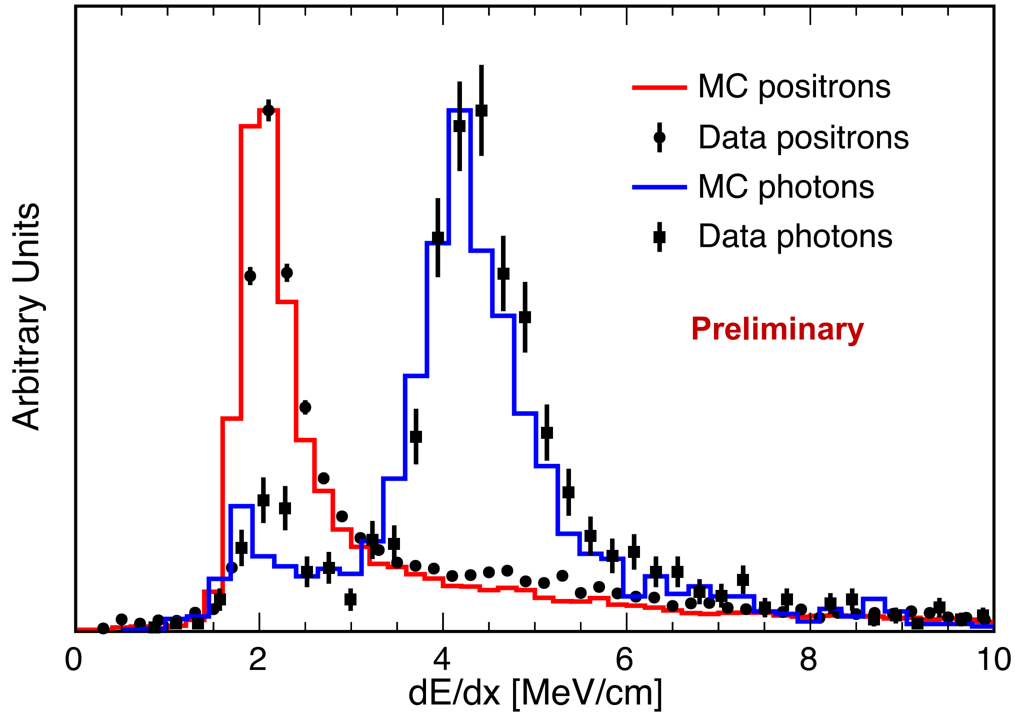
ProtoDUNE

LArTPC Demonstrator at CERN for DUNE FD

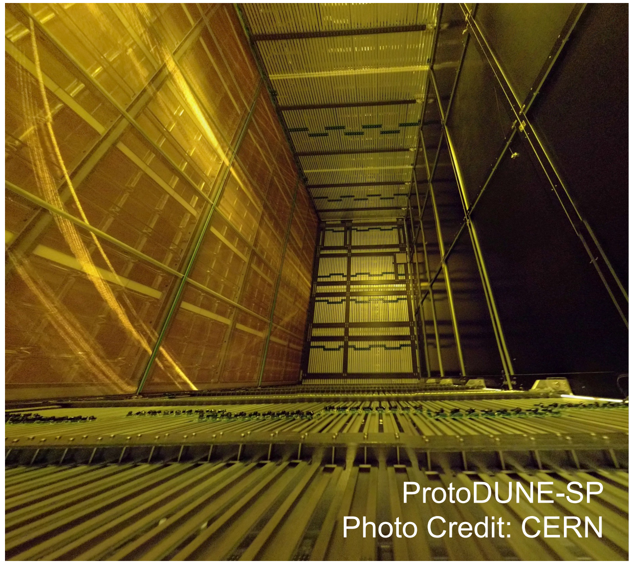
- Hadron beams of 0.3-7 GeV/*c*
  - 4.7 mm wire spacing (same as FD)
  - ✓ ***Versatile reconstruction in LAr***

ProtoDUNE-SP

DUNE, JINST **15**, P12004 (2020)



e/γ separation



Medium effects

TKI

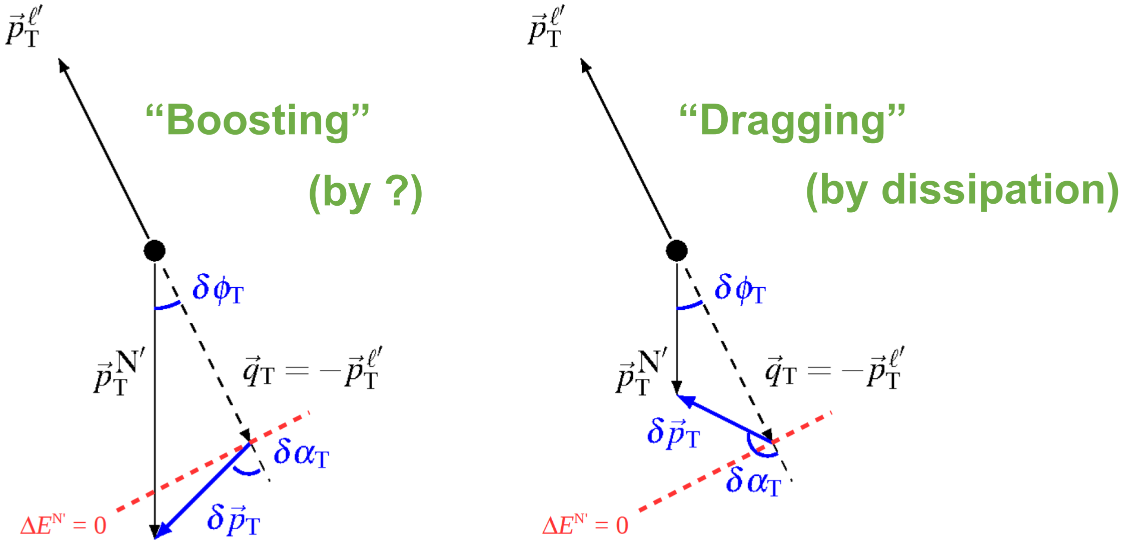
Transverse boosting angle

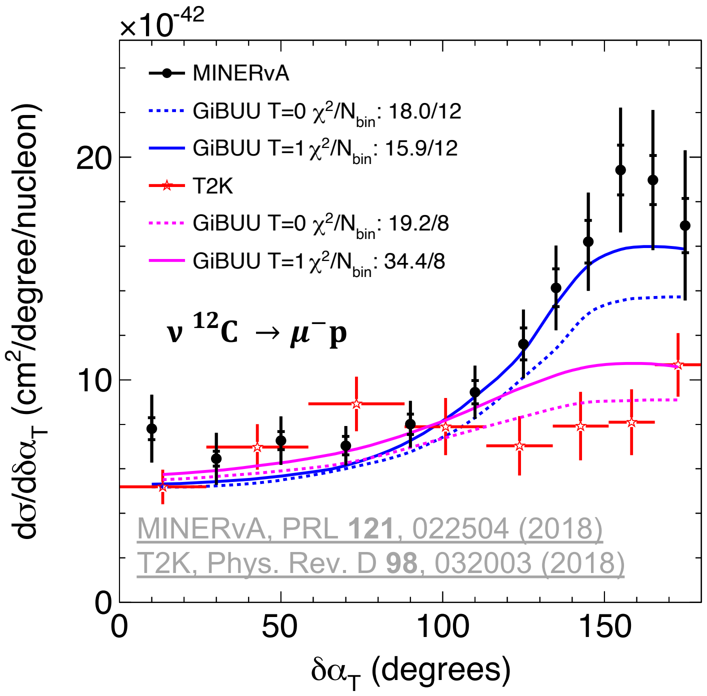
XL *et al.* Phys. Rev. C **94**, 015503 (2016)

Quasielastic-like: $\nu\ {}^{12}C \rightarrow \mu^- p$

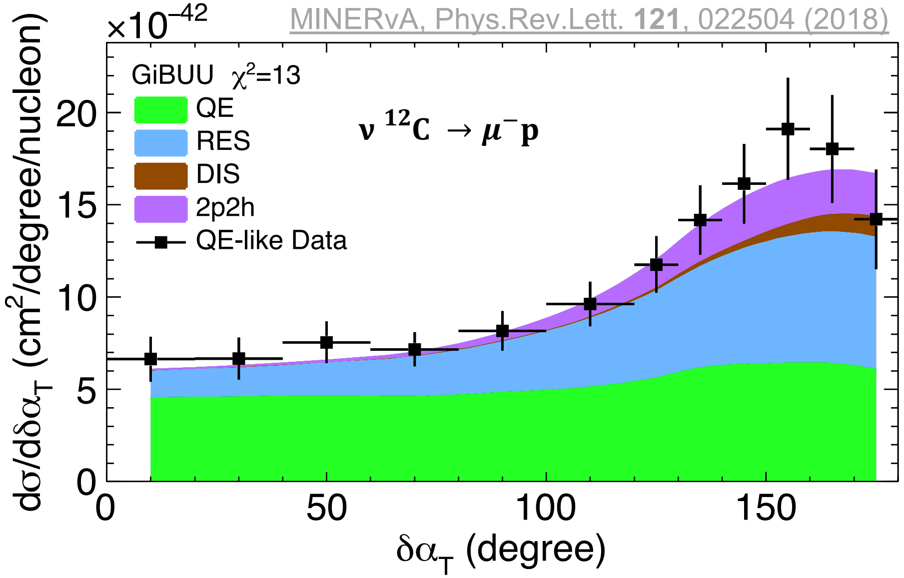
❖ 2p2h, resonance (π production + absorption)

✓ ***Energy dependence*** *(T2K, MINERvA E_ν ~ 0.6, 3 GeV)*





❖ 2p2h
❖ RES
Develop above T2K energy

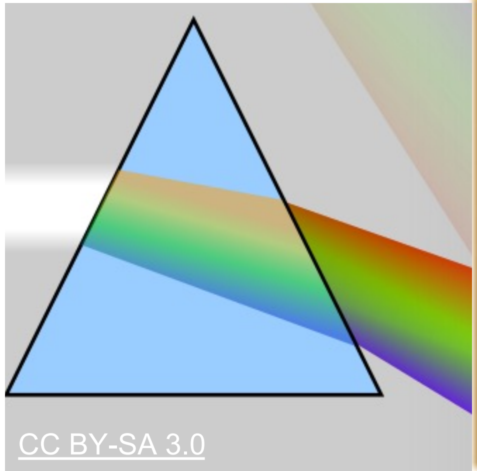


❖ 2p2h
❖ RES
Dragging = Energy carried away by unobserved particles

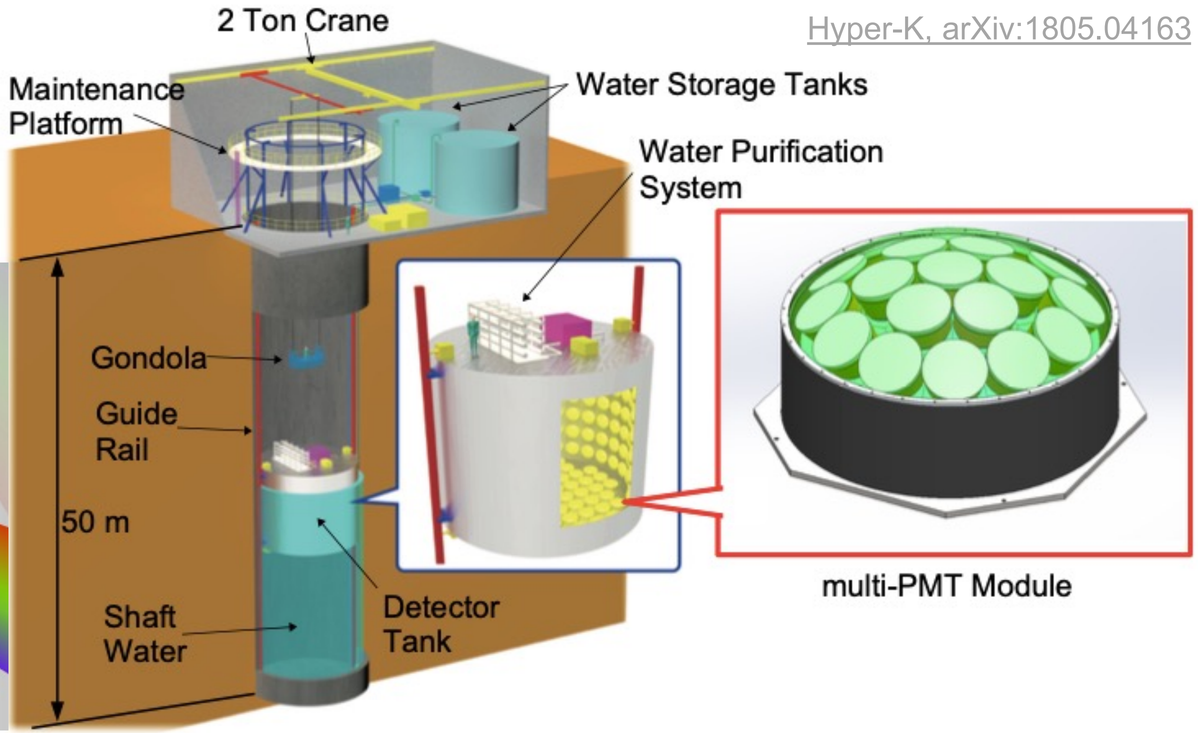
Medium effects

Hyper-Kamiokande

- ❑ FD: water Cherenkov
- ❑ ND: IWCD (Intermediate Water Cherenkov Detector)
  - ❖ Same technology as FD
  - ❖ 50 m vertical shaft @ 750 m from beam source
    - ✓ *1°-4° off-axis (OA) angle ("PRISM Definition Part 1")*



Hyper-K, arXiv:1805.04163



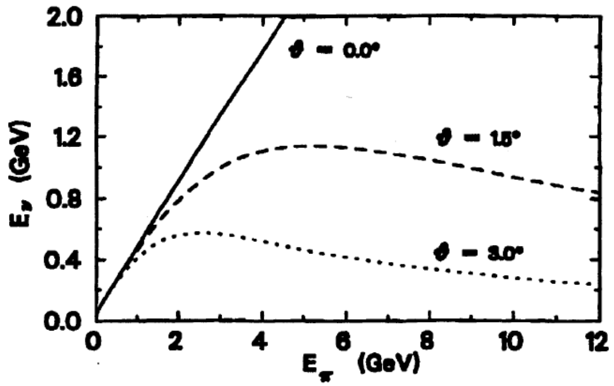
Medium effects

Hyper-Kamiokande

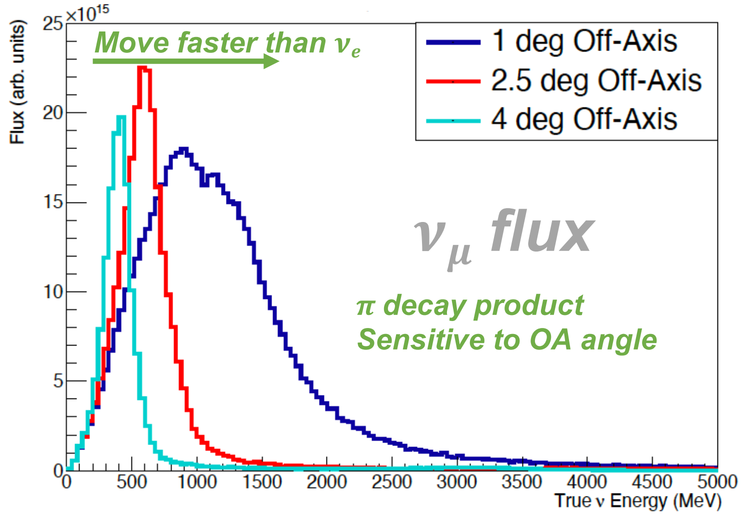
- ❑ FD: water Cherenkov
- ❑ ND: IWCD (Intermediate Water Cherenkov Detector)
  - ❖ Same technology as FD
  - ❖ 50 m vertical shaft @ 750 m from beam source
    - ✓ *1°-4° off-axis (OA) angle ("PRISM Definition Part 1")*
  - ❖ ~ 1% residual $\nu_e/\bar{\nu}_e$ beam components
    - ✓ ***Large fraction at far-OA angle***
    - ✓ ***Constrain $\nu_e/\bar{\nu}_e$ (besides $\nu_\mu/\bar{\nu}_\mu$) cross sections on water (enabled by active γ shielding)***

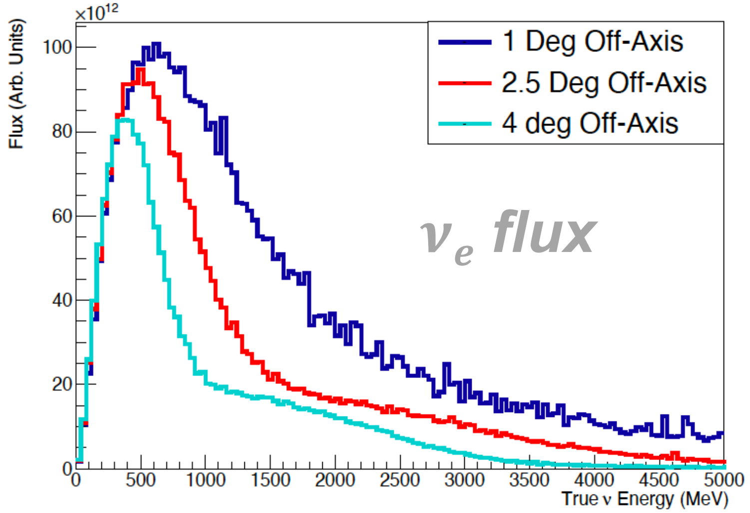
From energy, momentum conservation

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - p_\pi \cos\vartheta)}$$



Hyper-K, J. Phys. Conf. Ser. **2156**, 012121 (2021)





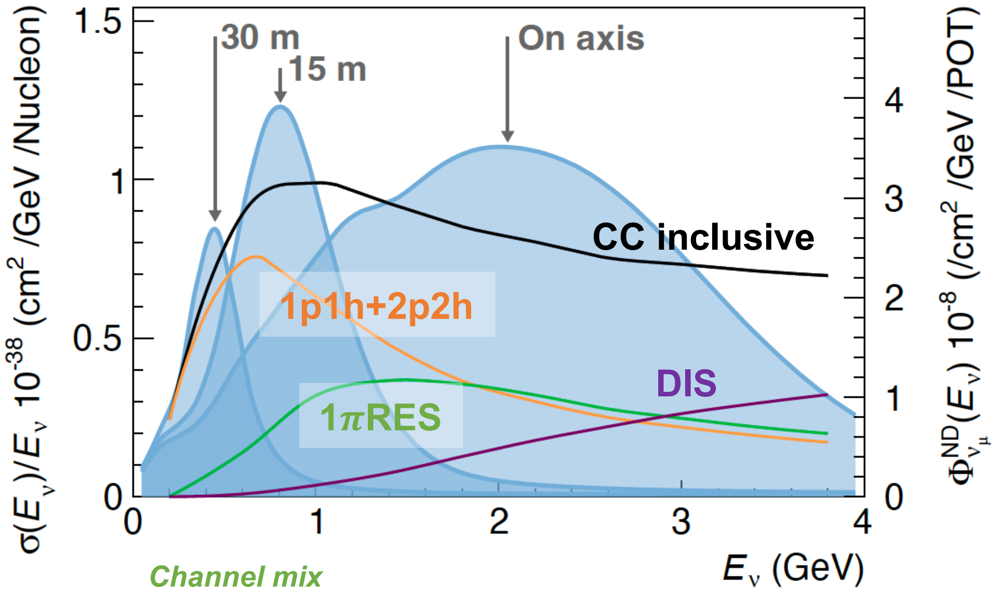
DUNE-PRISM

ND-LAr & ND-GAr

❖ Up to 30 m off axis @ 574 m from beam source

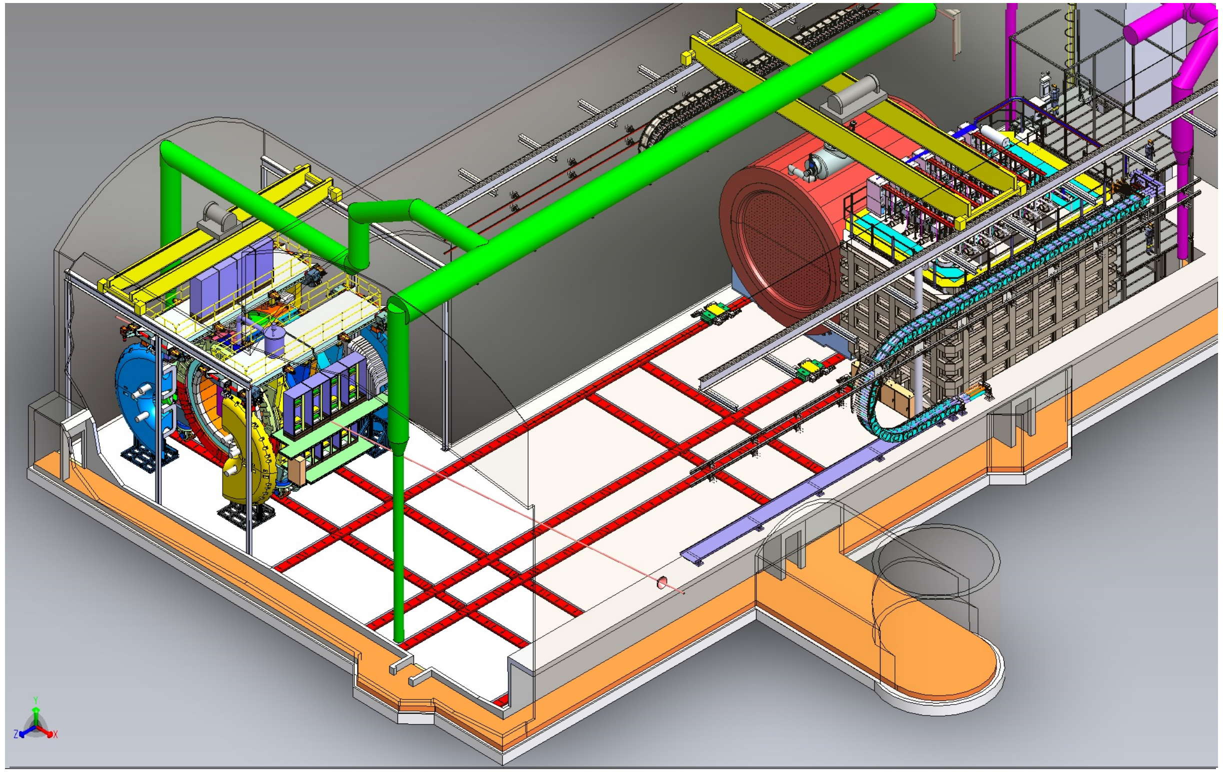
- ✓ *0°-3° off-axis angle*
- ✓ *E_ν up to ~ 3 GeV, covering different interaction dynamics*
- ✓ *Probe energy-dependent medium effects*

DUNE, instruments **5**, 31 (2021)

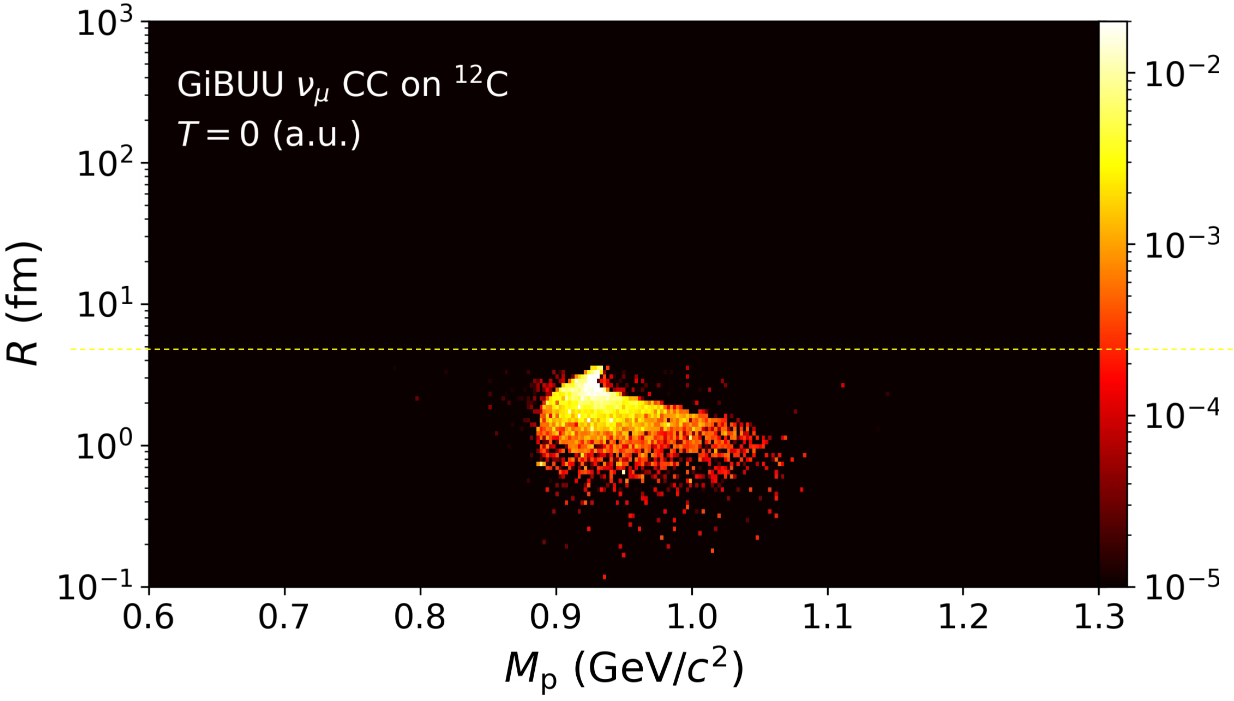


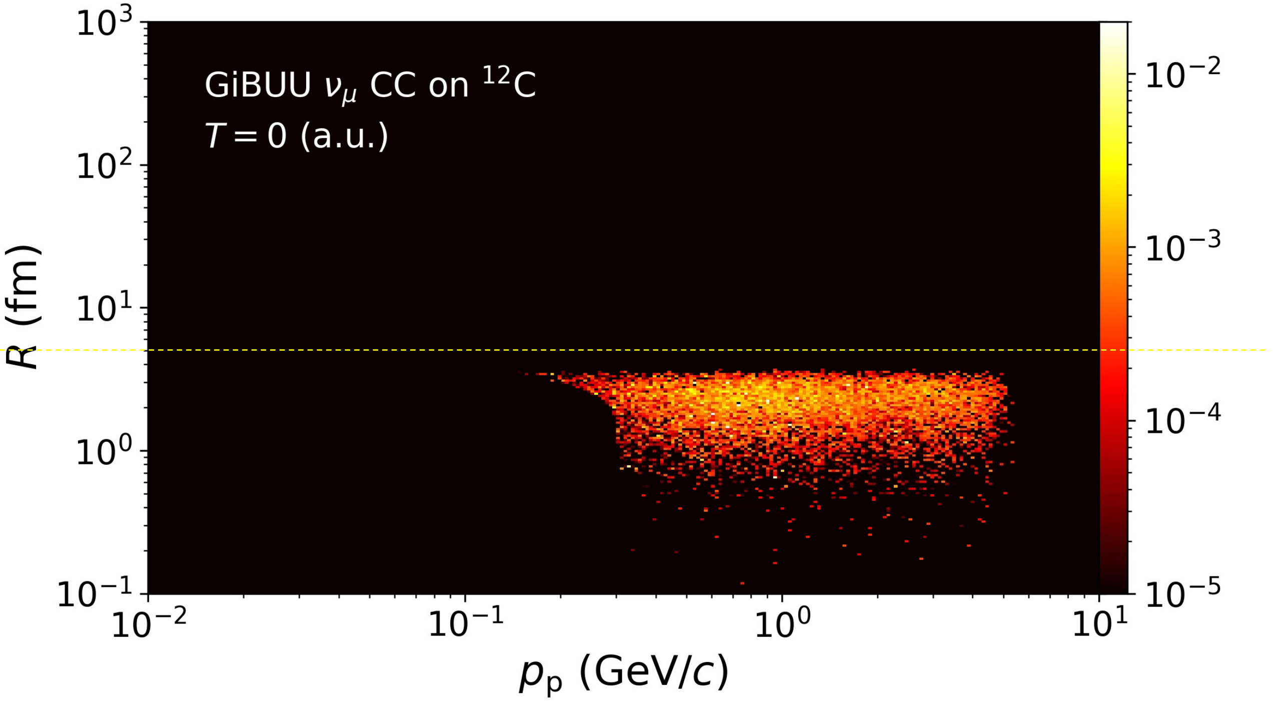
Channel mix evolves with OA location

DUNE, instruments **5**, 31 (2021)



Credit: Kaile WEN@IHEP, Xianguo LU@Warwick





† Proton in GiBUU final-state transport
R: radial position, M_p: mass, p_p: momentum

GiBUU version: Release 2021, patch 1 (Mai 11, 2021)

Input neutrino: ν_μ@5GeV

Target nucleus: ^{12}C

Interaction type： CC

FSI = 0, 1, 2, 3, … , 500

nEnsemble: 4000

X-axis: Mass of final-state proton

M_{proton}= sqrt(p_0^2-p_1^2- p_2^2 -p_3^2)

Y-axis: The distance from nucleus center

R = sqrt(x^2+ y^2 +z^2)

Z-axis: Proportional to Event Rate (with perweight)

GiBUU version: Release 2021, patch 1 (Mai 11, 2021)

Input neutrino: ν_μ@5GeV

Target nucleus: ^{12}C

Interaction type： CC

FSI = 0, 1, 2, 3, … , 500

nEnsemble: 4000

X-axis: Momentum of final-state proton

p_{proton}= sqrt(p_1^2+ p_2^2 +p_3^2)

Y-axis: The distance from nucleus center

R = sqrt(x^2+ y^2 +z^2)

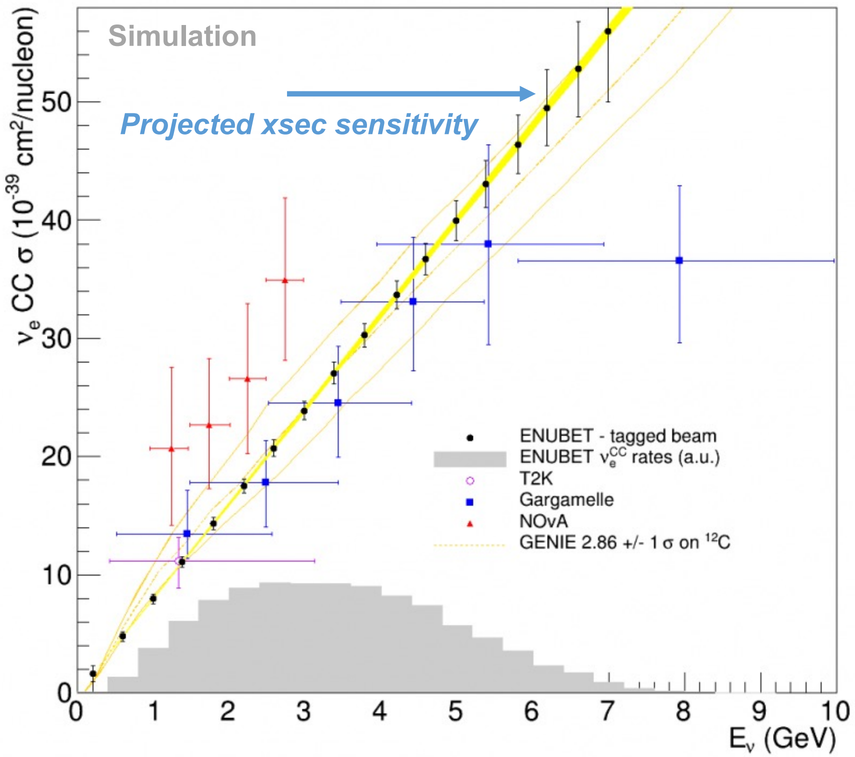
Z-axis: Proportional to Event Rate (with perweight)

$\nu_e/\bar{\nu}_e$ interactions

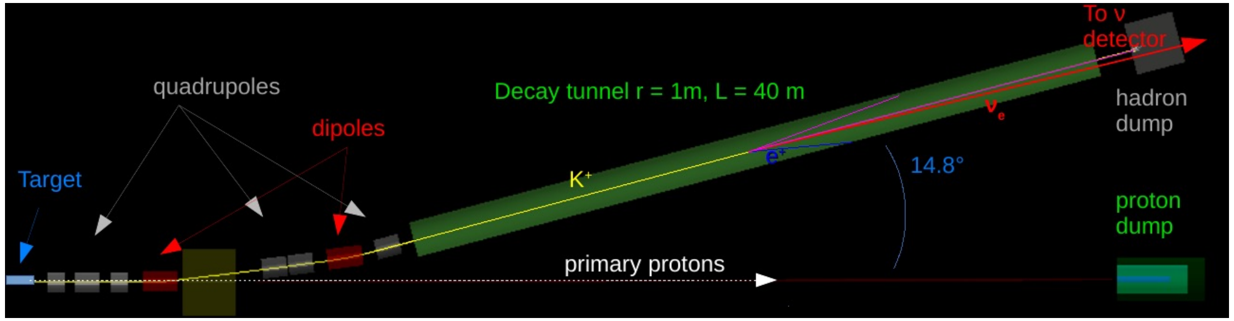
- δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- Need $\nu_e/\bar{\nu}_e$ interaction data
- ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood fluxes***

- Enhanced NeUtrino BEams from kaon Tagging (ENUBET)
  - ν_e from e^+ tagging for $K^+ \to \pi^0 e^+ \nu_e$
  - ν_μ from μ^+ tagging
  - Flux uncertainty ~ 1%

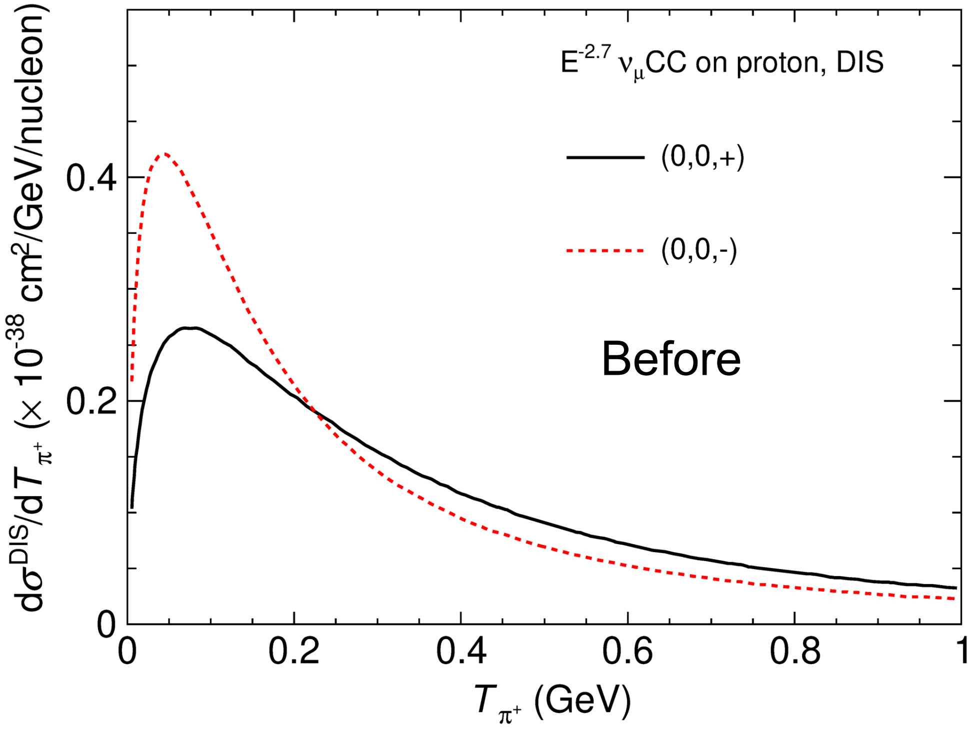
ENUBET, arXiv:2203.08319

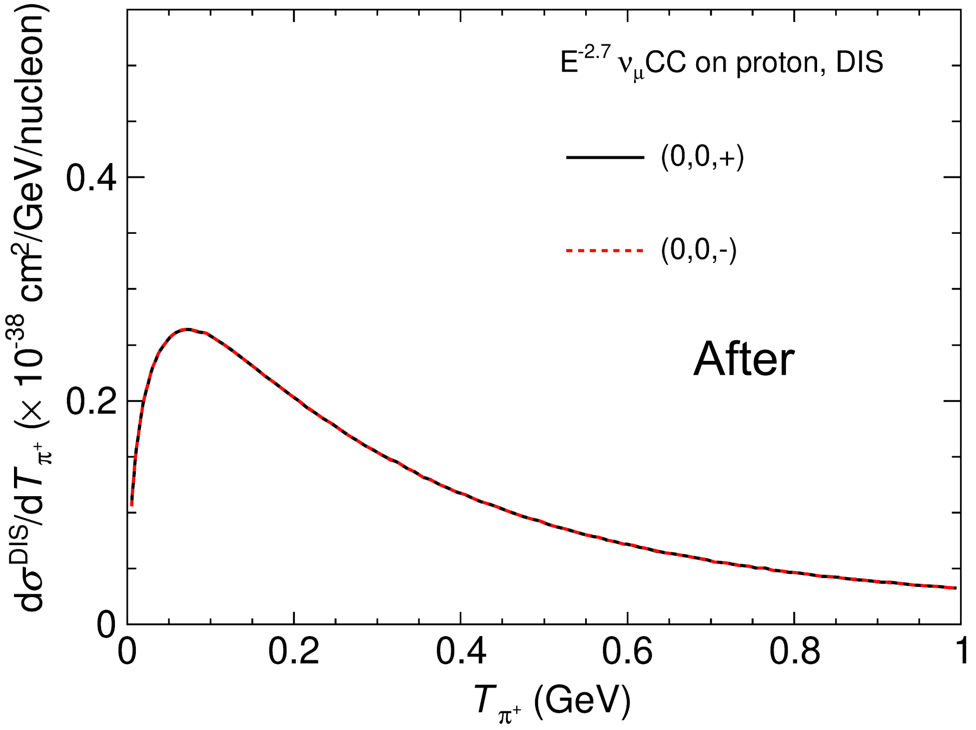


ENUBET, arXiv:2203.08319



Atmospheric neutrino interaction products: big surprise (fixed) in a very popular event generator
(Interesting story: https://github.com/GENIE-MC/Generator/issues/226)





Qiyu Yan 严启宇 (UCAS/Warwick)

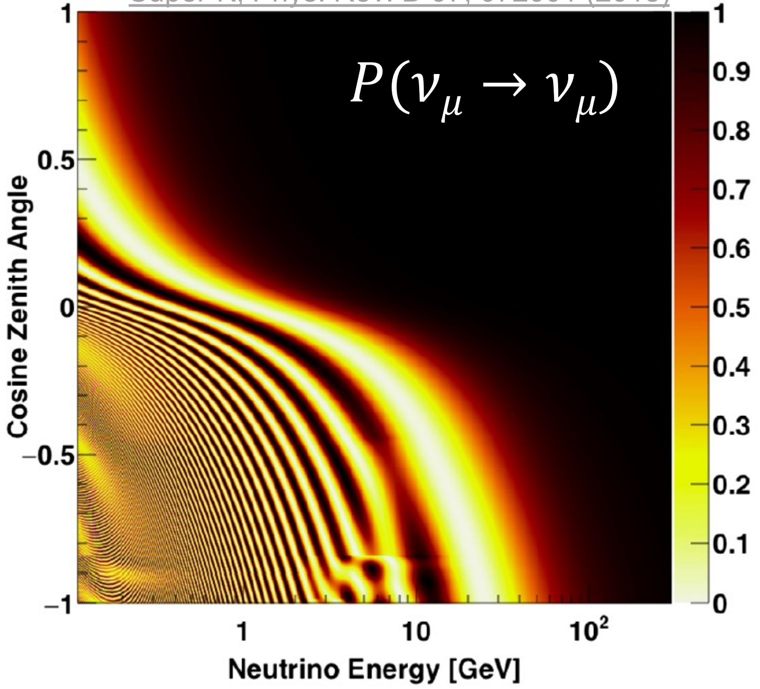
Model constr't

Atmospheric ν

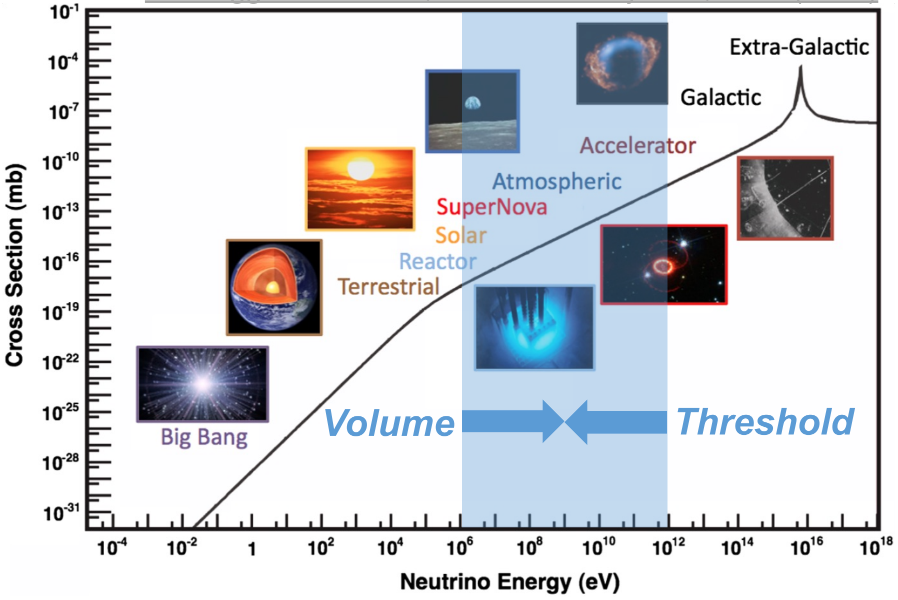
- ❑ ν energy & angle for *L*/*E*-variation

Future Oscillation Experiment	E_ν/GeV	Detector Technology	Target Nuclei
IceCube Upgrade	3-10 (NMO sensitive region)	Cherenkov in ice	H_2O
KM3NeT/ORCA		WC	H_2O
Atmos-ν @JUNO		LS	$CH_{1.6}$

Super-K, Phys. Rev. D 97, 072001 (2018)



Formaggio and Zeller, Rev. Mod. Phys. **84**, 1307 (2012)



GeV-ν interaction more critical and challenging

MeV *TeV*

Model constr't

Atmospheric ν

- ❑ ν energy & angle for *L*/*E*-variation
- ❑ No near detector
  - ❖ ***flux × interaction ambiguity***
- ❑ Sensitive to new unknowns
  - ❖ ***E.g. unconstrained low-momentum proton production (450 MeV/c common tracker threshold)***
  - ❖ ***Impact on very-low-threshold calo***

Future Oscillation Experiment	E_ν/GeV	Detector Technology	Target Nuclei
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- ❑ Dedicated GeV-ν interaction measurements: MINERvA Medium Energy data
  - ✓ ***E_ν peak at 6 GeV, tail up to 20 GeV***
  - ✓ ***CH and nuclear targets***
  - ✓ ***~ 10 M-event data set***

Awaiting the future

Detector

Technology: neutrons

✓ ***ν energy budget and event classification—missing piece for exclusivity***

➢ Tagging and calorimetry exist

➢ 4-momentum determination on the verge (e.g. time of flight)

Medium effects

Analysis methods: ν-hydrogen interaction

✓ ***Complete removal of medium effects***

➢ Established: statistical subtraction between targets

➢ Ideas: ***exclusivity*** + TKI event-by-event selection using mass-scalable H-based compounds

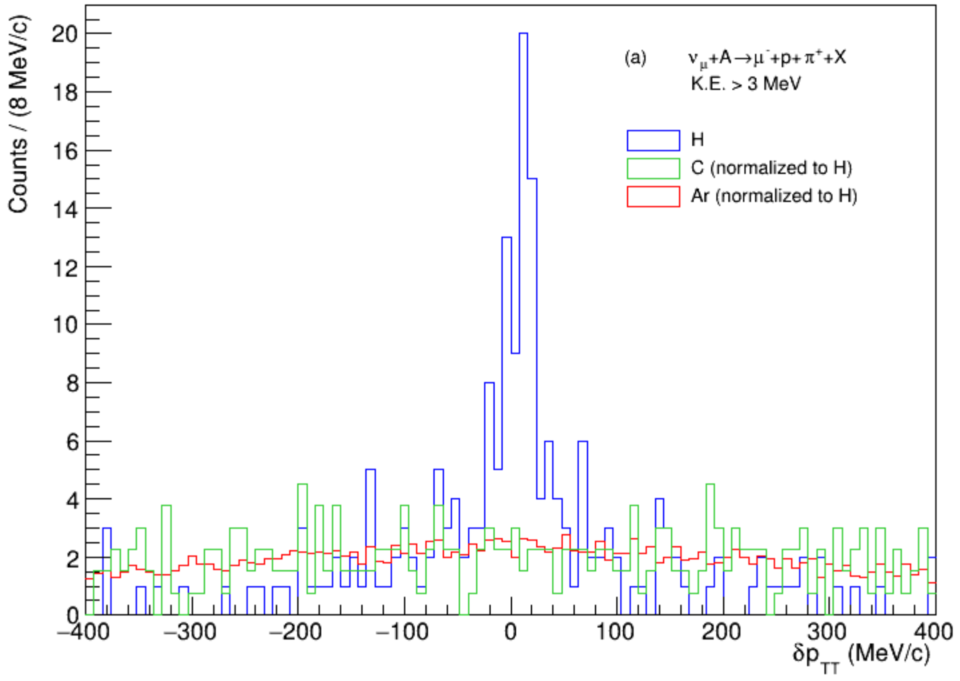
Model constr’t

Ex situ interaction measurements: precise nuclear response

✓ ***Break flux*** $\times$ ***interaction ambiguity***

➢ Electron scattering + ***exclusivity*** for initial-and final-state effects (not vertex)

Selecting hydrogen out of Ar-C-H mixture using TKI



Federico Battisti (Oxford/Warwick)