Neutrino Interactions and Future Experiments with GeV Neutrinos

Lu, Xianguo 卢显国

University of Warwick

PKU HEP Seminar

18 April, 2023

Neutrino Mass

Standard Model | Beyond Standard Model

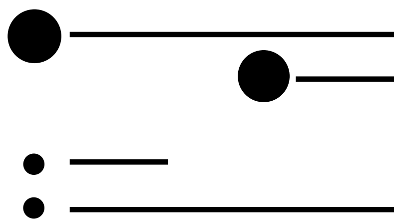
$$\begin{pmatrix}\nu_e \\ \nu_\mu \\ \nu_\tau\end{pmatrix} =$$

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

$$\begin{pmatrix}\nu_1 \\ \nu_2 \\ \nu_3\end{pmatrix}$$

Mass Ordering



Normal **Inverted**

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_{23}: mixing between ν_μ and ν_τ

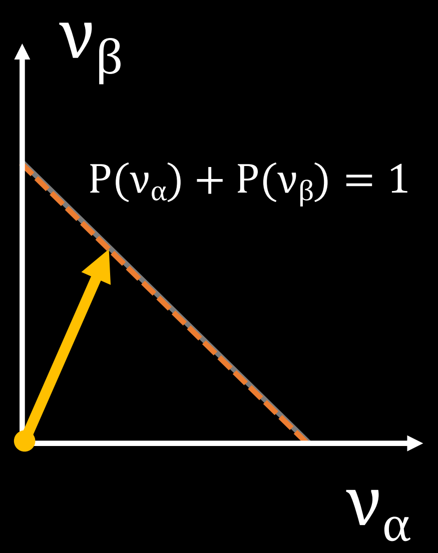
θ_{13}: if 0, effective 2 flavour mixing

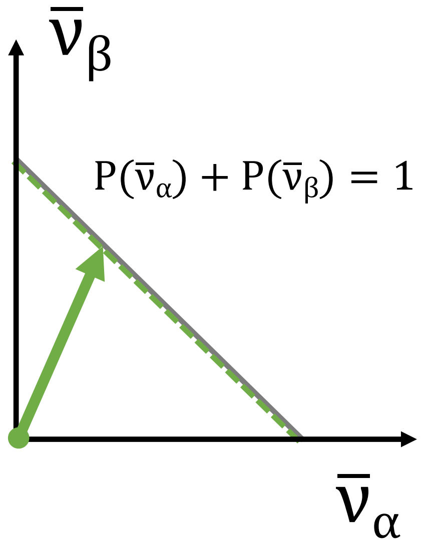
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} \nu_1' \\ \nu_2' \\ \nu_3 \end{pmatrix}$$

$$\nu_\alpha \longleftrightarrow \nu_\beta$$

$$P(\nu_\alpha) + P(\nu_\beta) = 1$$

2-flavor oscillation

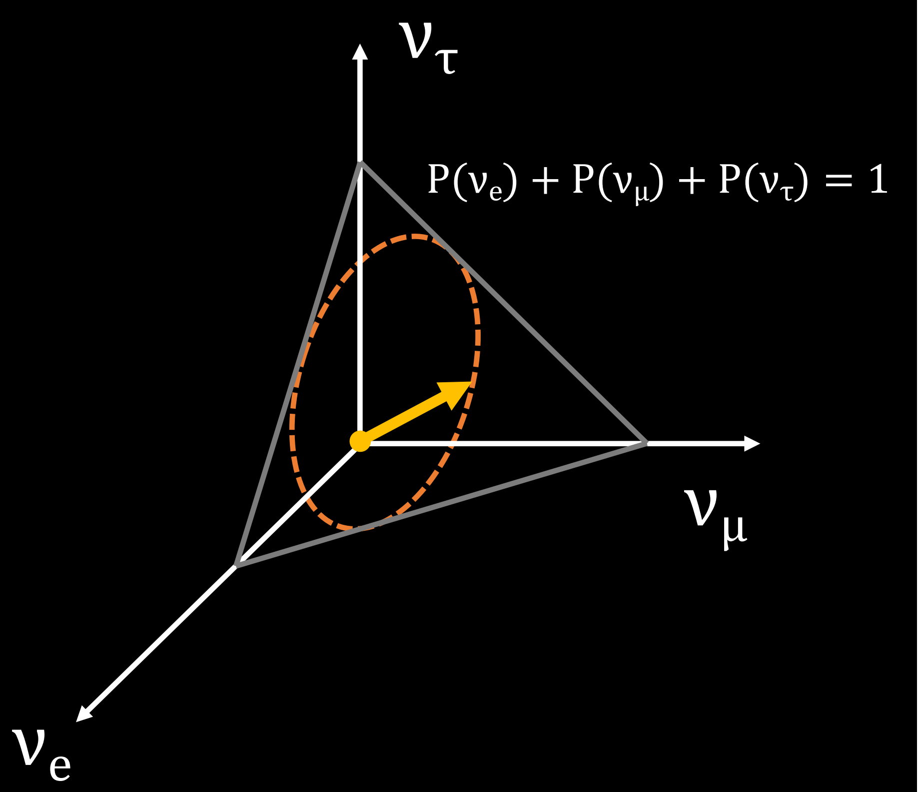


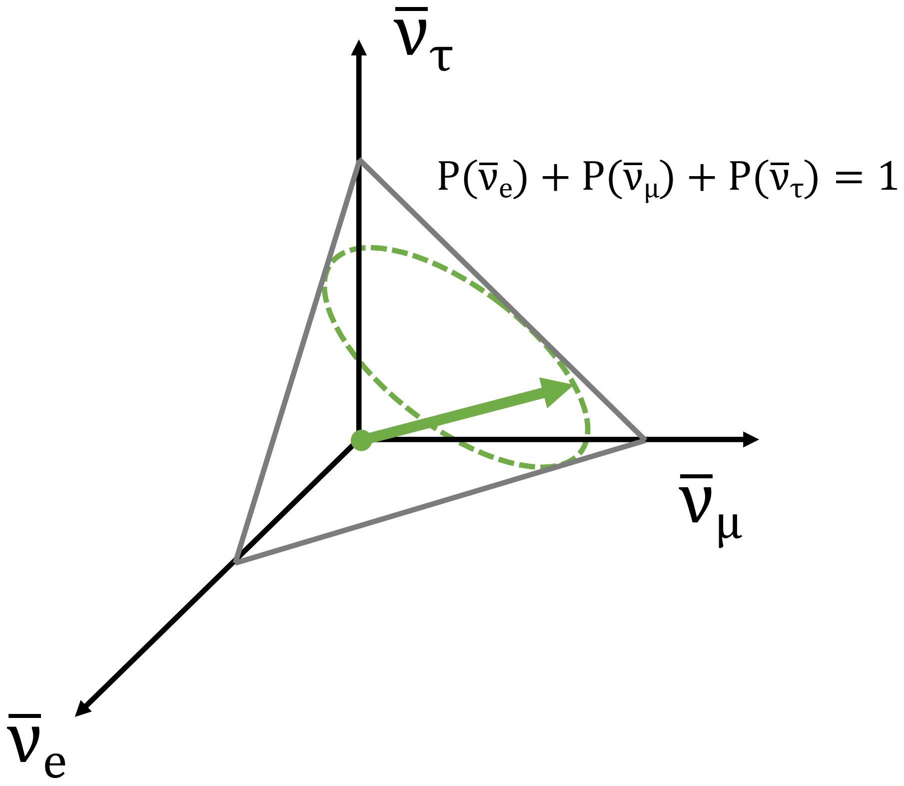


Oscillation as a function of *time*
line-in-**line** → same trivia

Antineutrinos

3-flavor oscillation





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

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**

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

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

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

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

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

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

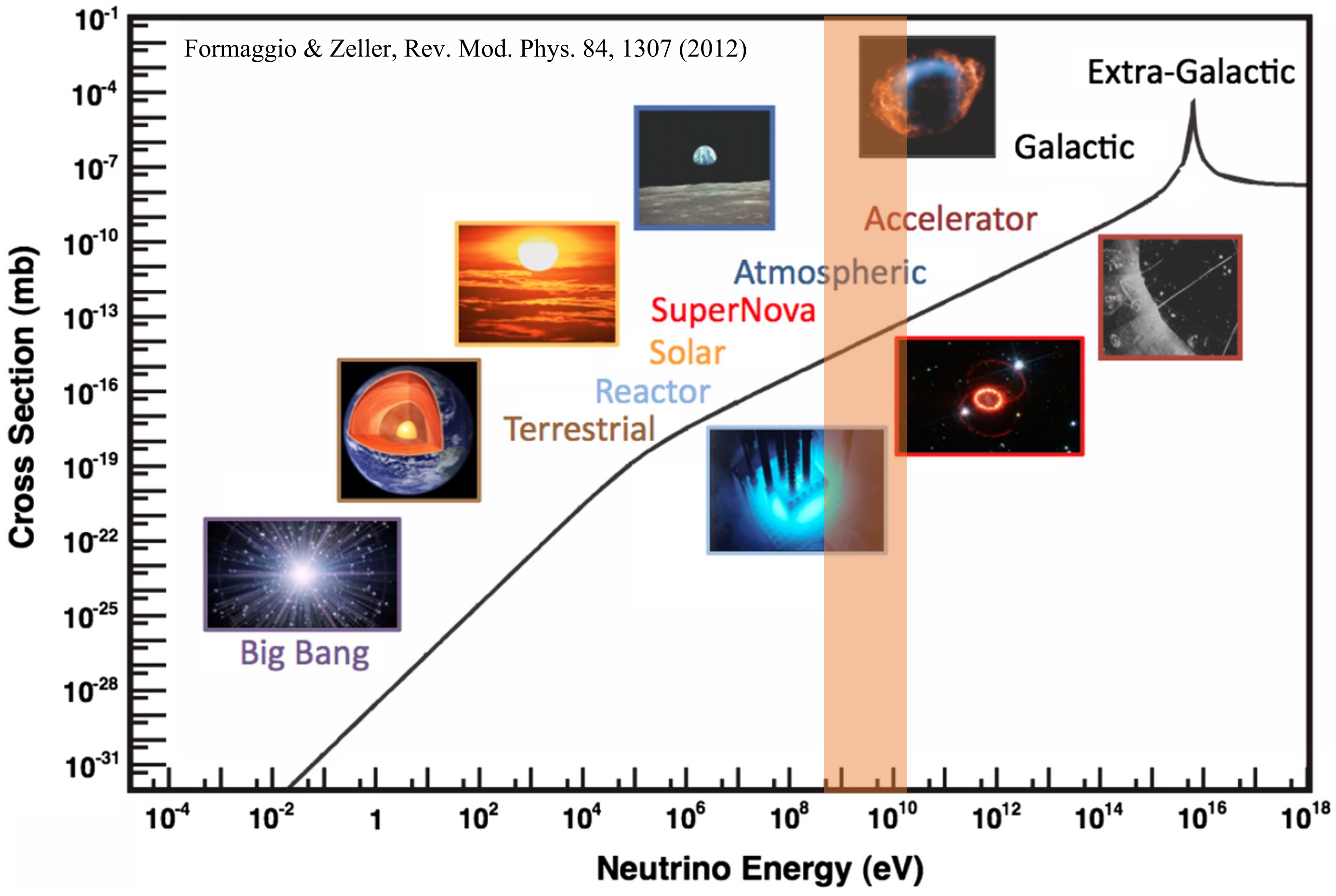
flip sign

$\delta_{CP} \rightarrow$ CP violation

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

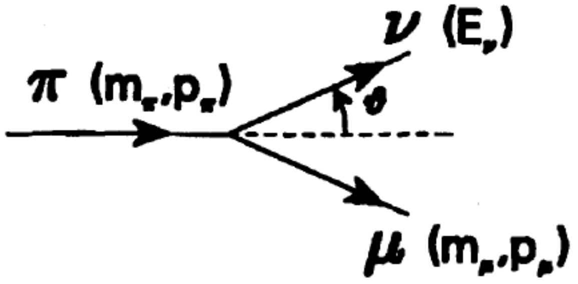
* neglecting matter effects

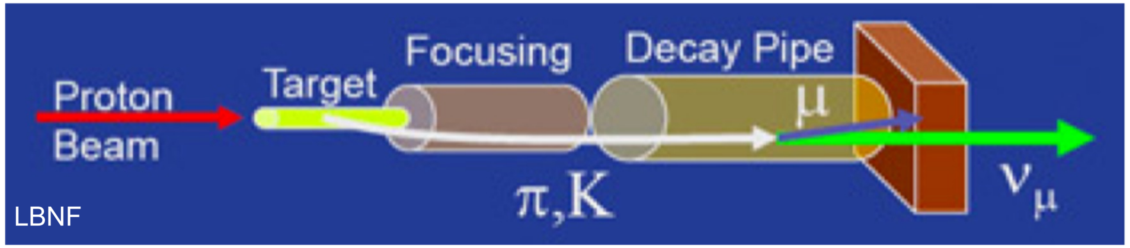
Neutrinos Sources



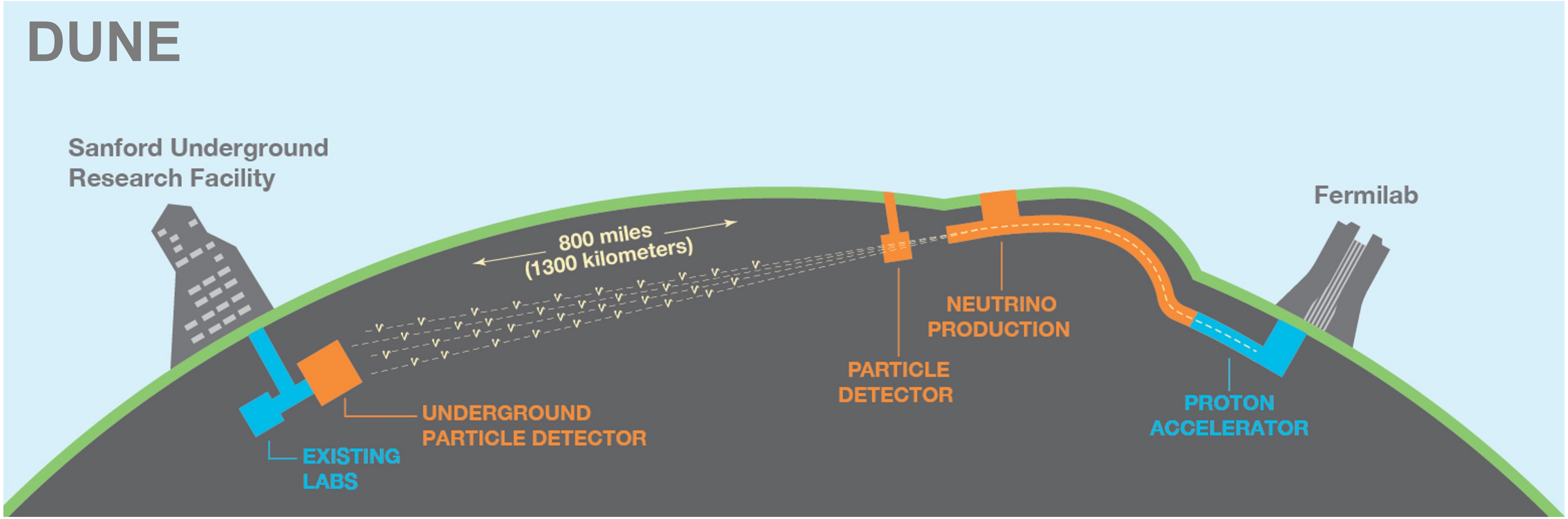
Accelerator Neutrinos

😉 **Ad: K.-J. Plows and XL, Modeling heavy neutral leptons in accelerator beamlines, Phys.Rev.D 107, 055003 (2023).**

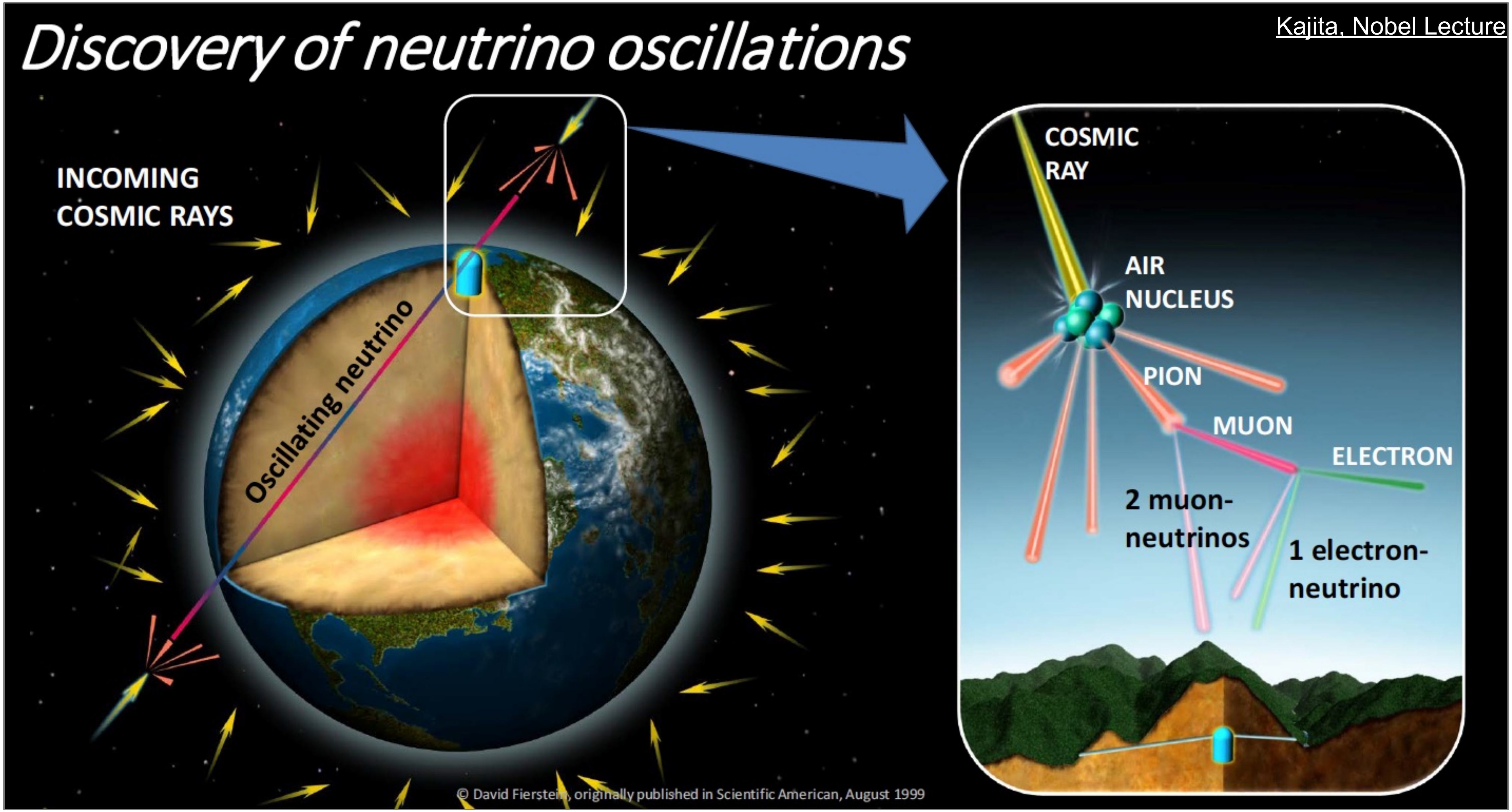




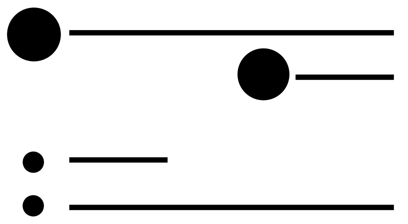
"β decay" of energetic collision products (mostly ν_μ from π)



Atmospheric Neutrinos



Only two Δm^2



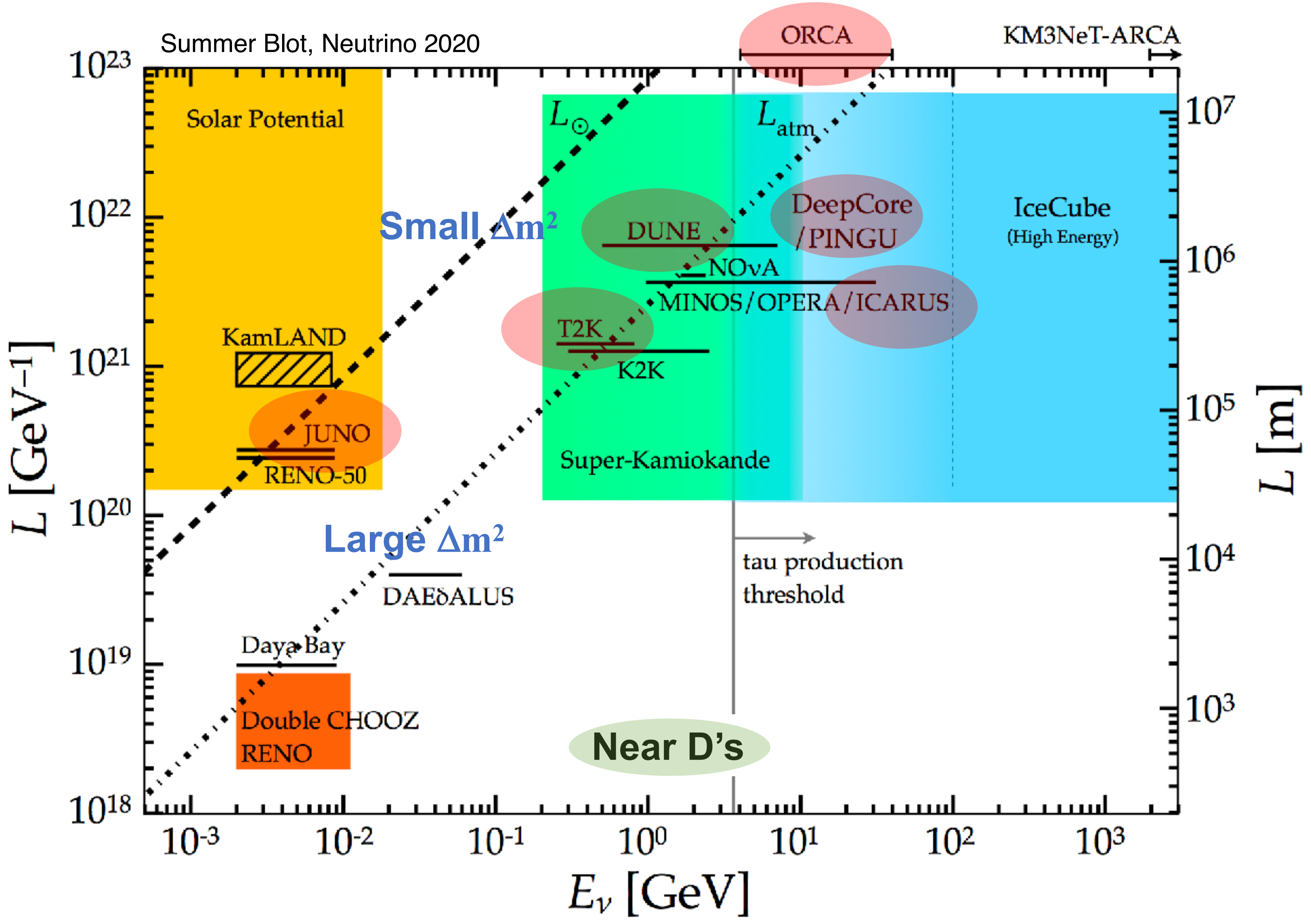
Normal **Inverted**

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

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

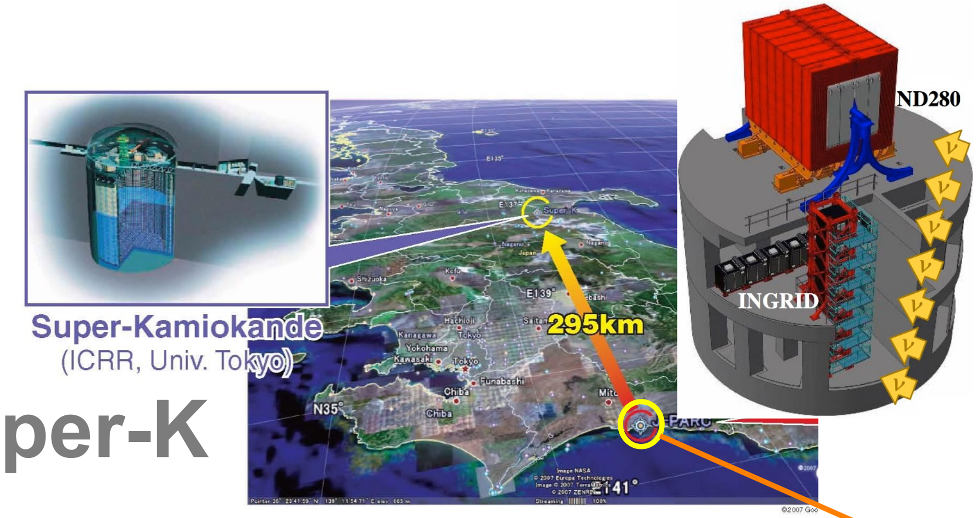
$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

Oscillation phase ~ Δm^2 L/E



Near Detectors

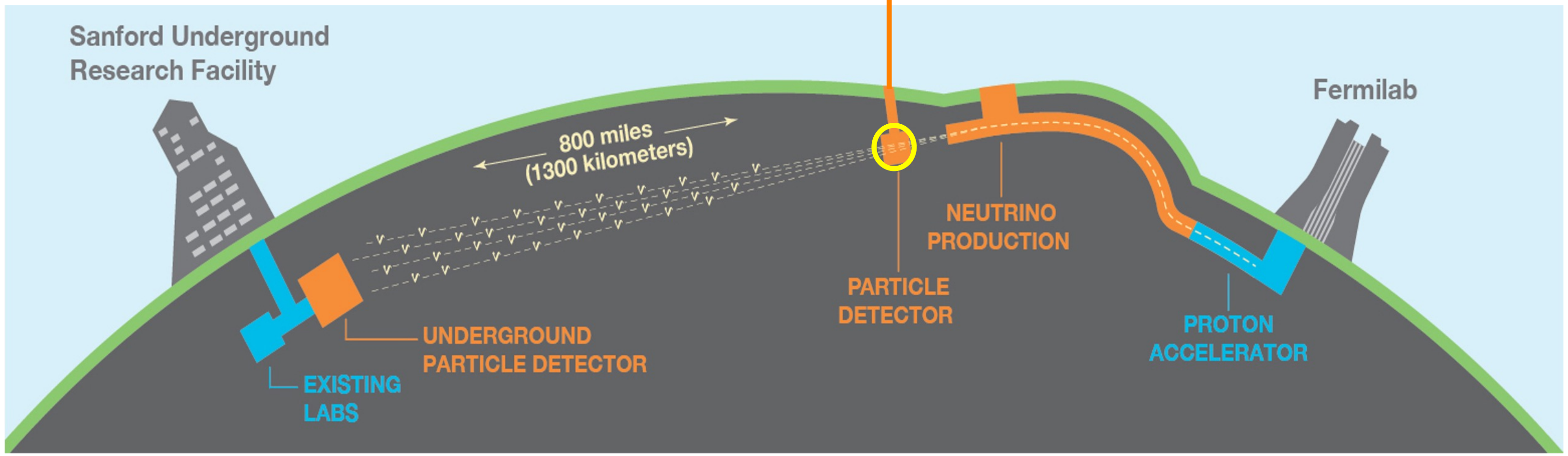
T2K / Hyper-K



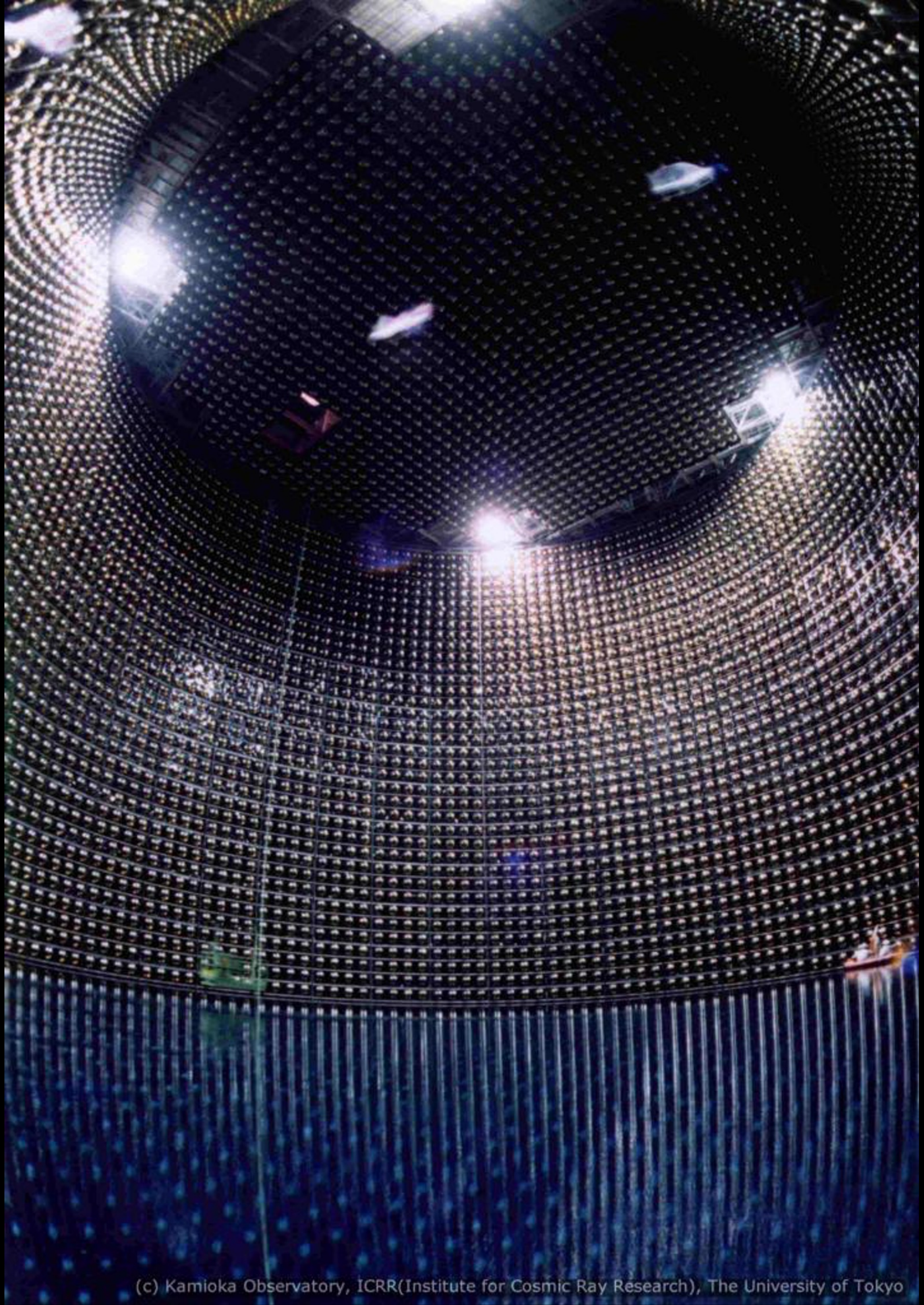
NOvA

Near Detectors to measure ν interactions

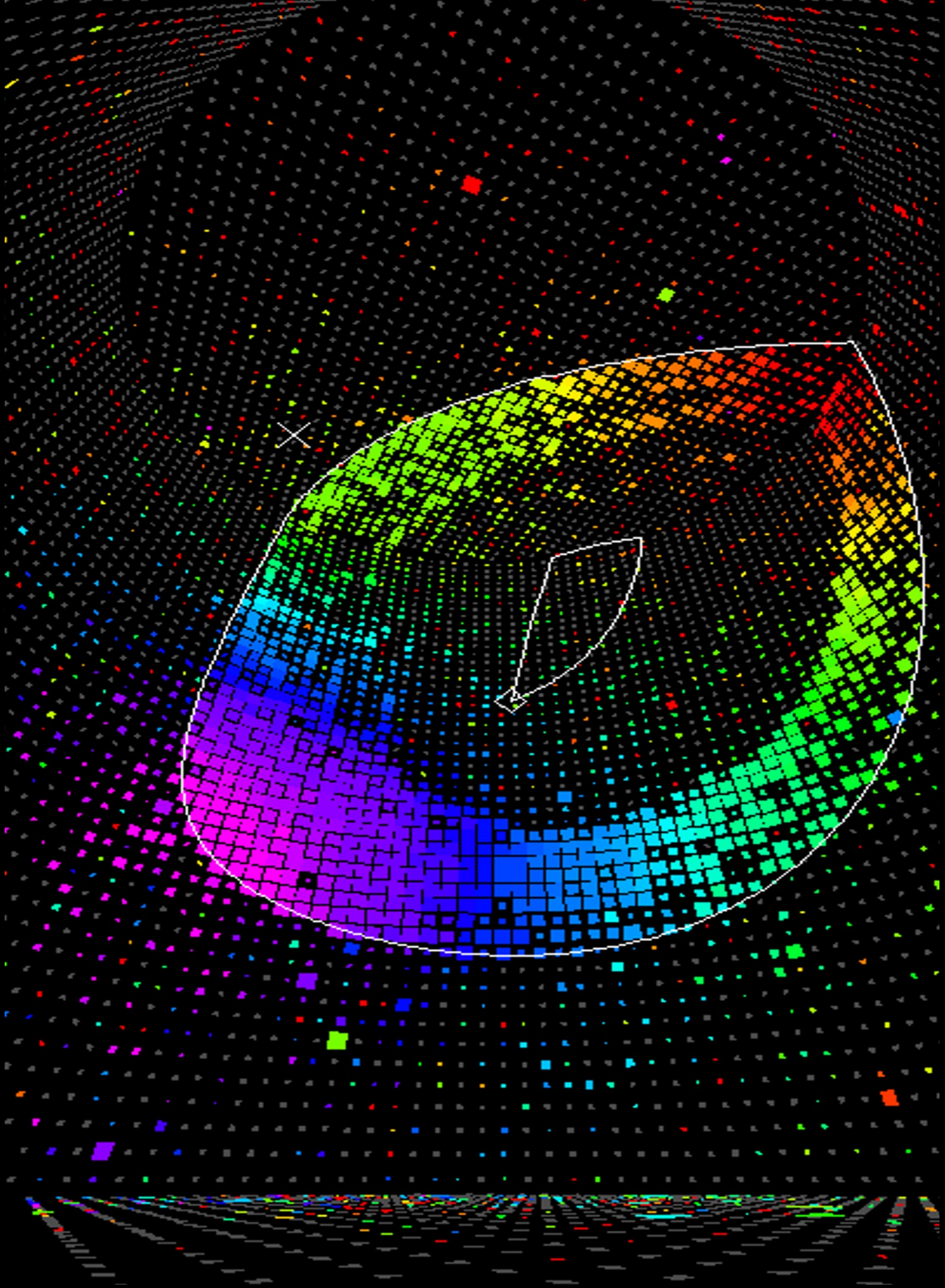
DUNE



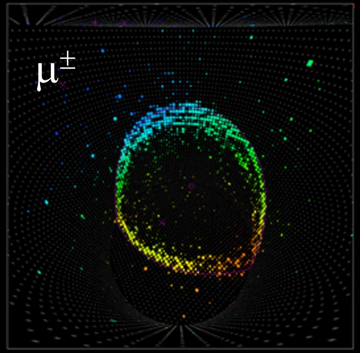
Water Cherenkov detector

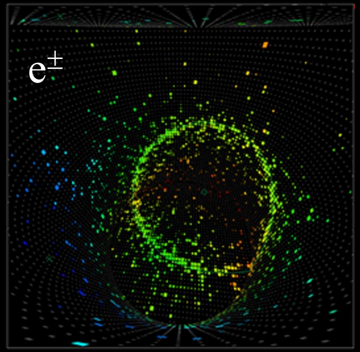


Source: http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html

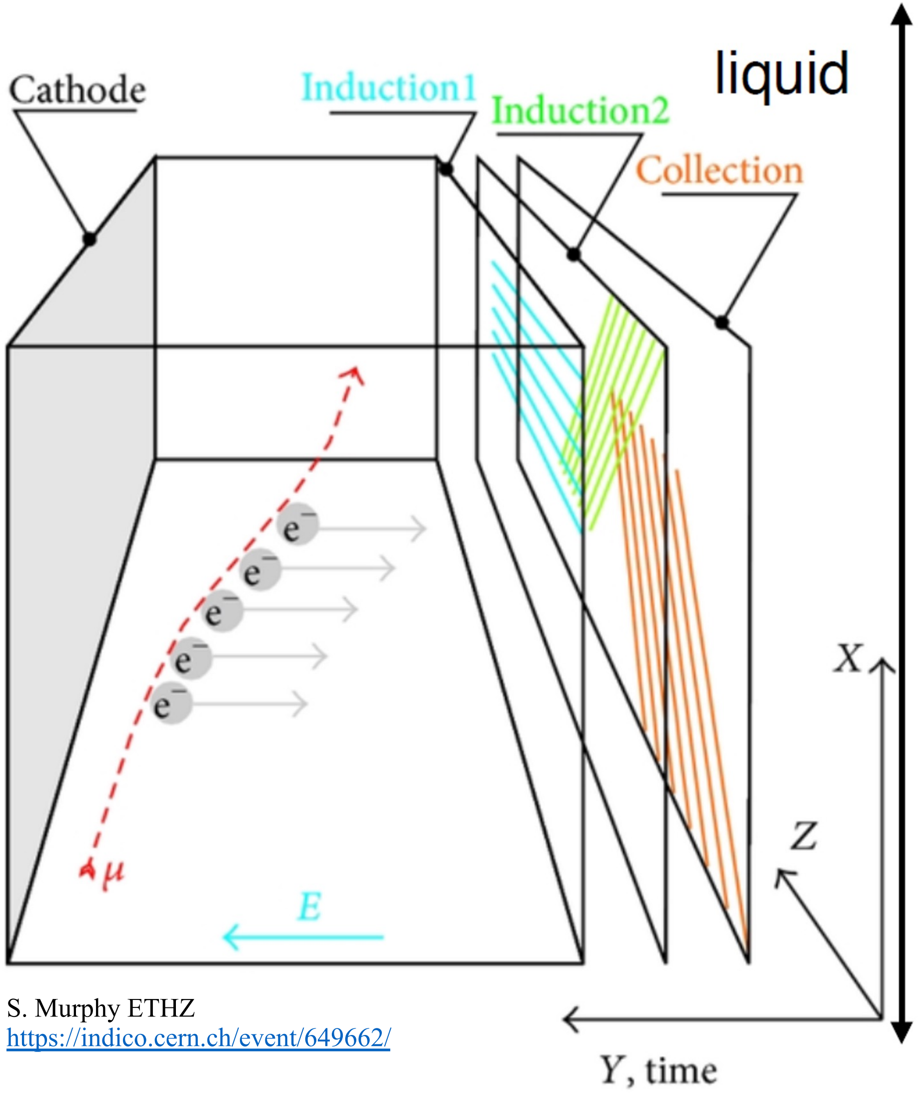


Water Cherenkov detector





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



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

Liquid argon Time Projection Chamber (LArTPC)

The New Impressive

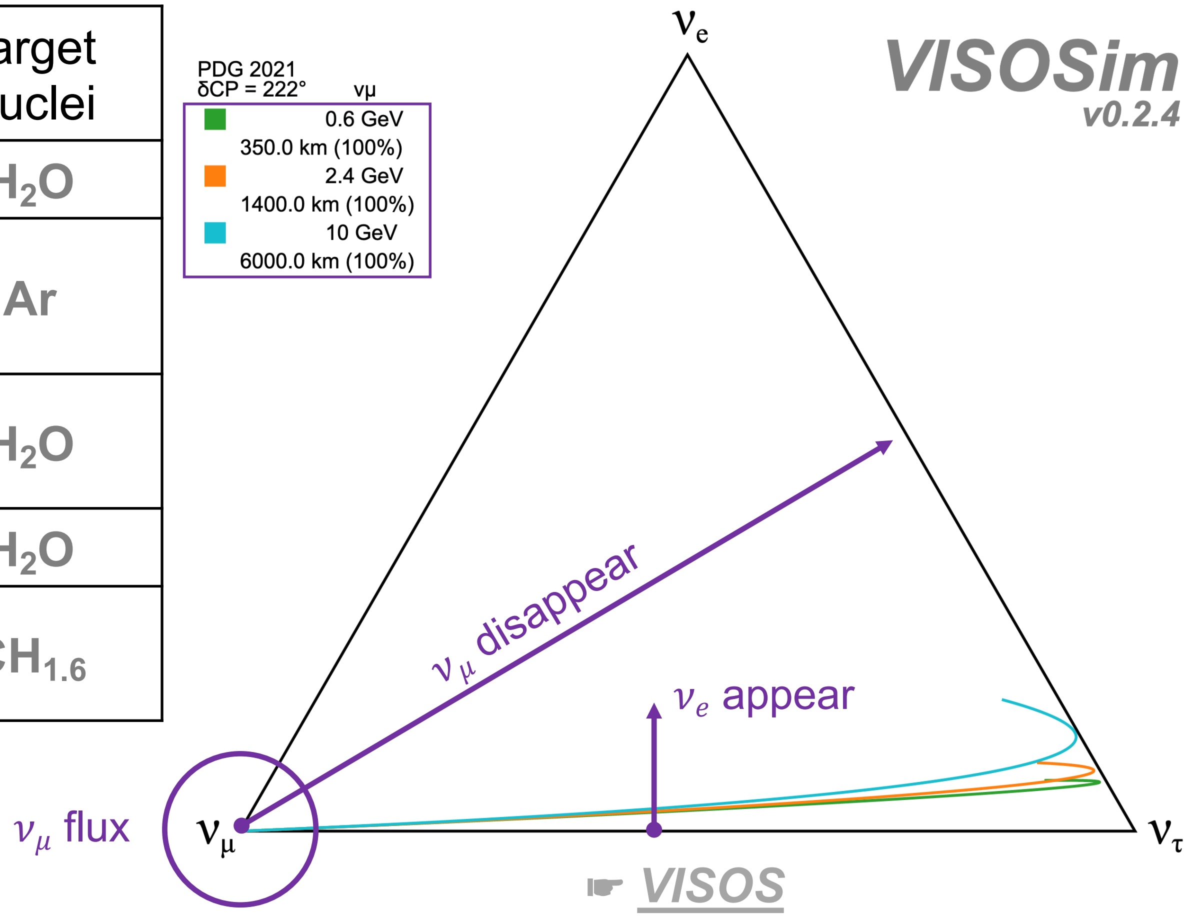
Future oscillation experiments

This talk only on

❖ accelerator and atmospheric GeV-ν

❖ ν_μ flux*: ν_μ disappear, ν_e appear

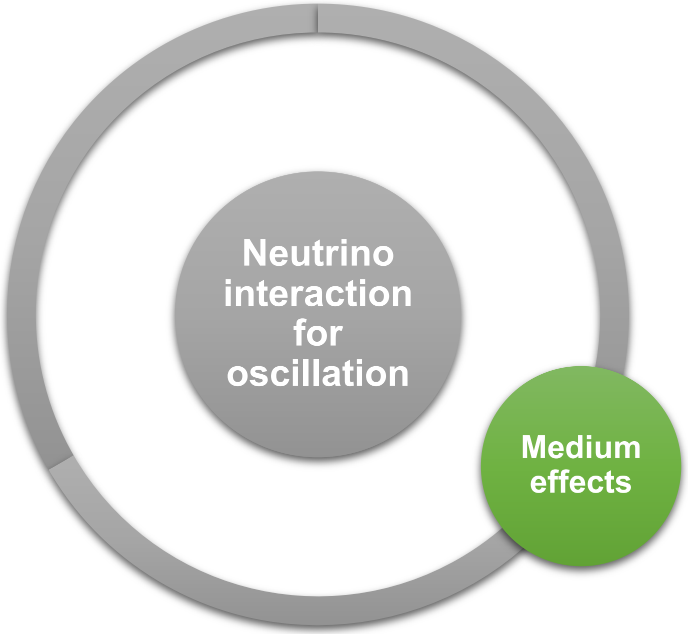
Future Oscillation Experiment	E_ν/GeV @Flux Peak	Detector Technology	Target Nuclei
Hyper-K	**0.6**	**WC**	H_2O
ICARUS + SBND	**0.8**	**LAr TPC**	**Ar**
DUNE	**2.4**		
IceCube Upgrade	**3-10 (ν Mass Ordering/NMO sensitive region)**	**Cherenkov in ice**	H_2O
KM3NeT/ORCA		**WC**	H_2O
Atmos-ν @ JUNO		**LS**	$CH_{1.6}$

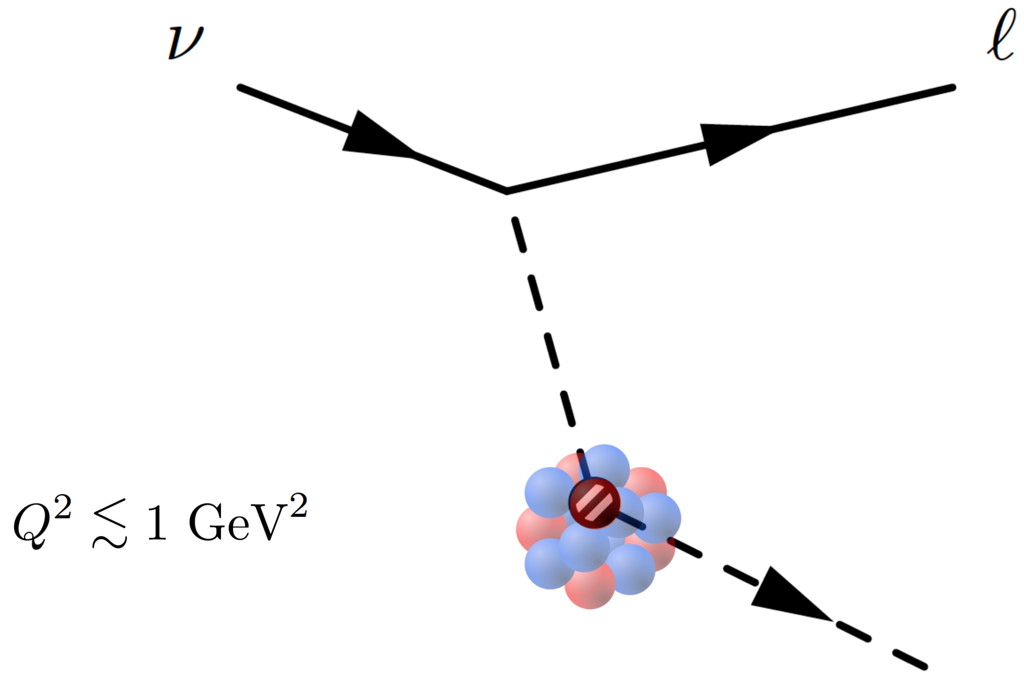


*Referring to neutrinos and/or antineutrinos implicitly depending on the context.

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***

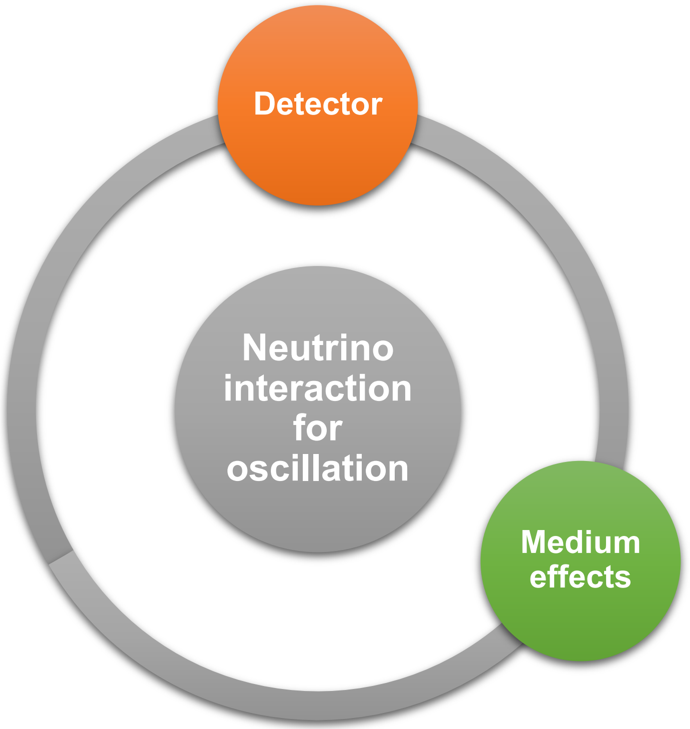
❑ Through initial state, vertex, final state

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

Sensing ν interactions

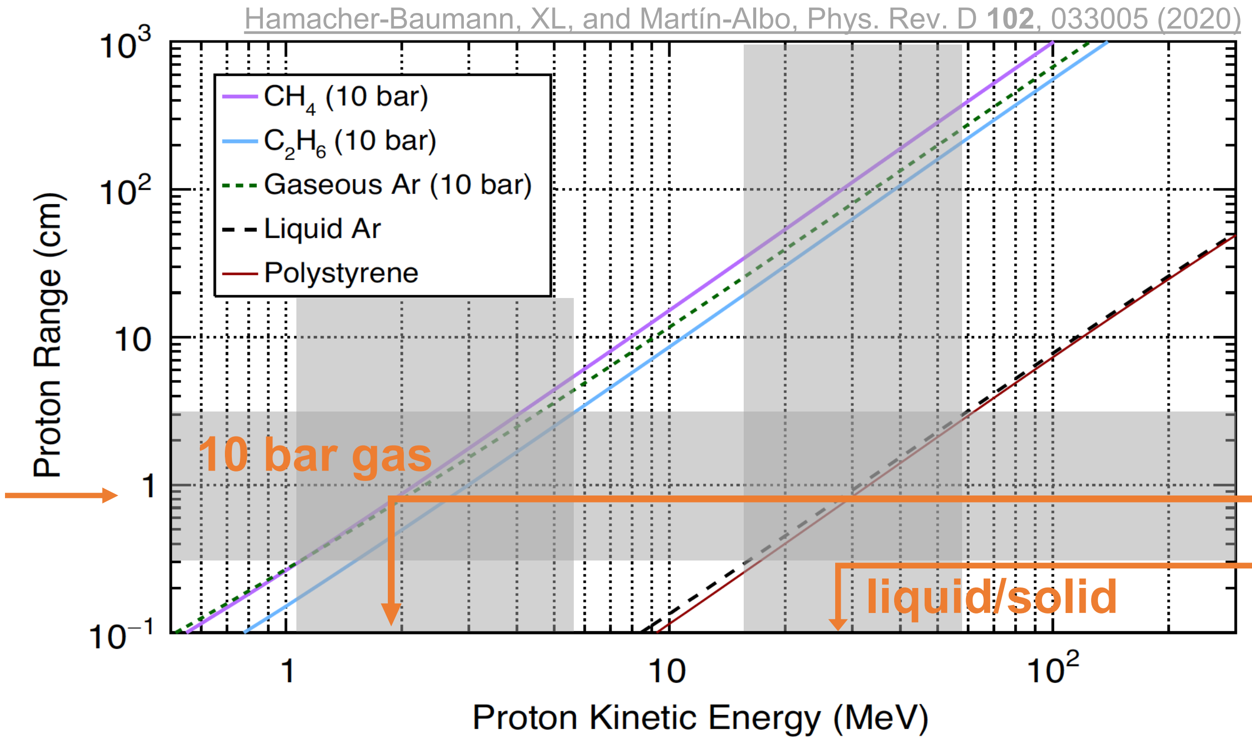
Embedded in detector, incomplete particle information

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



Proton Range vs Kinetic Energy

Sensor granularity
~ mm-cm



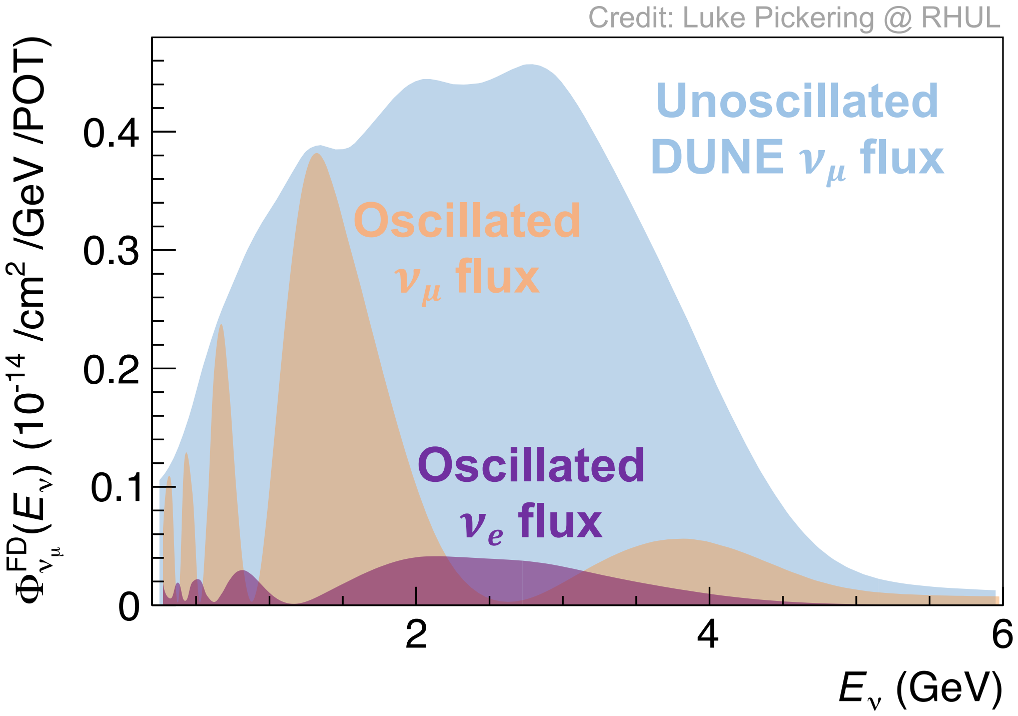
Tracking threshold
~ few MeV
~ 10s MeV
No momentum measurement downwards

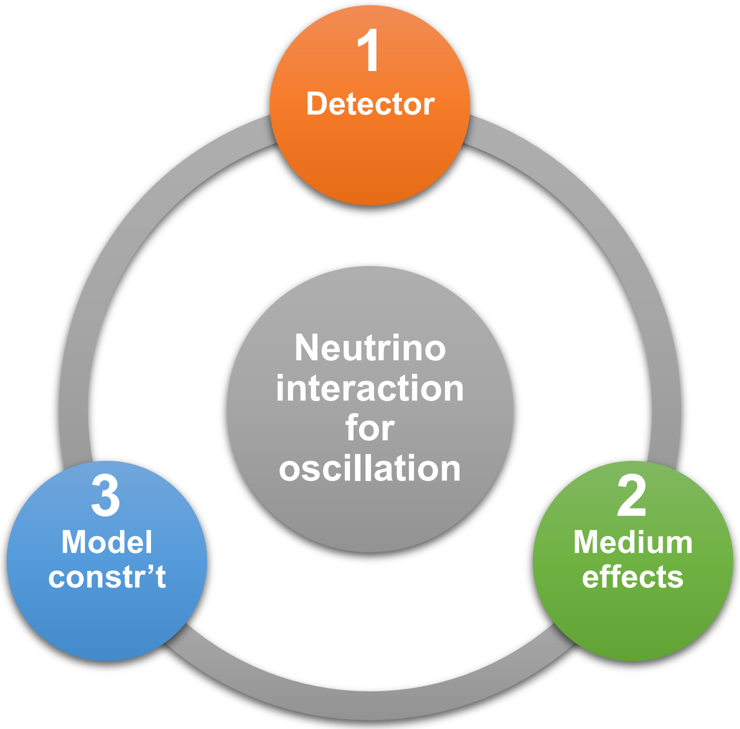
Counting oscillated ν

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

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

No two unknowns at the same time





- **Near detectors** for accelerator-ν experiments
- Non-accel: rely on **externally constrained** models
- **Unconstrained** flavour and/or target nuclei

Plastic scintillator tracker

Detector

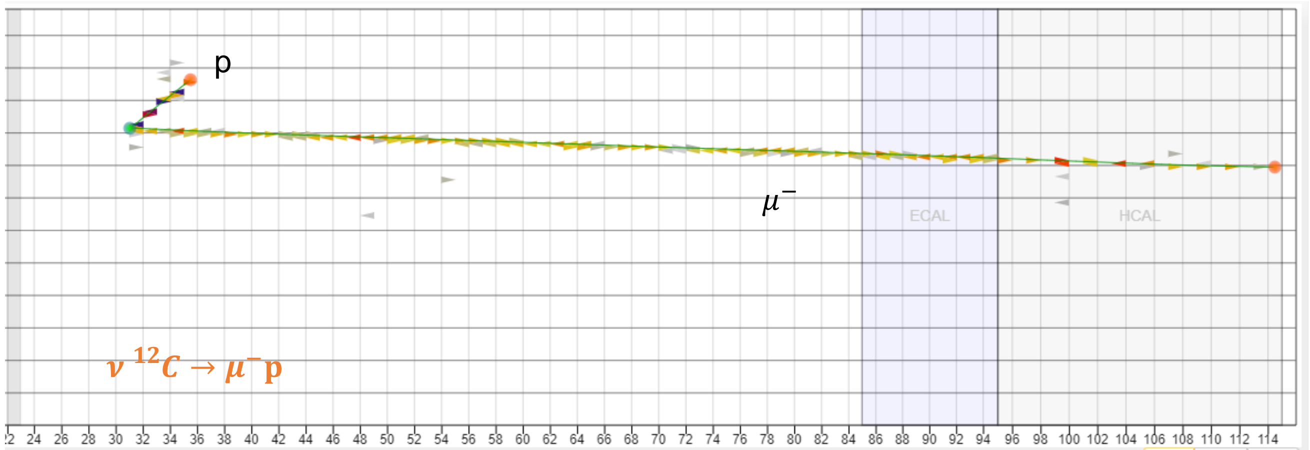
- ❑ Also ***active target***
  - ❖ Tracking + ***calorimetry***

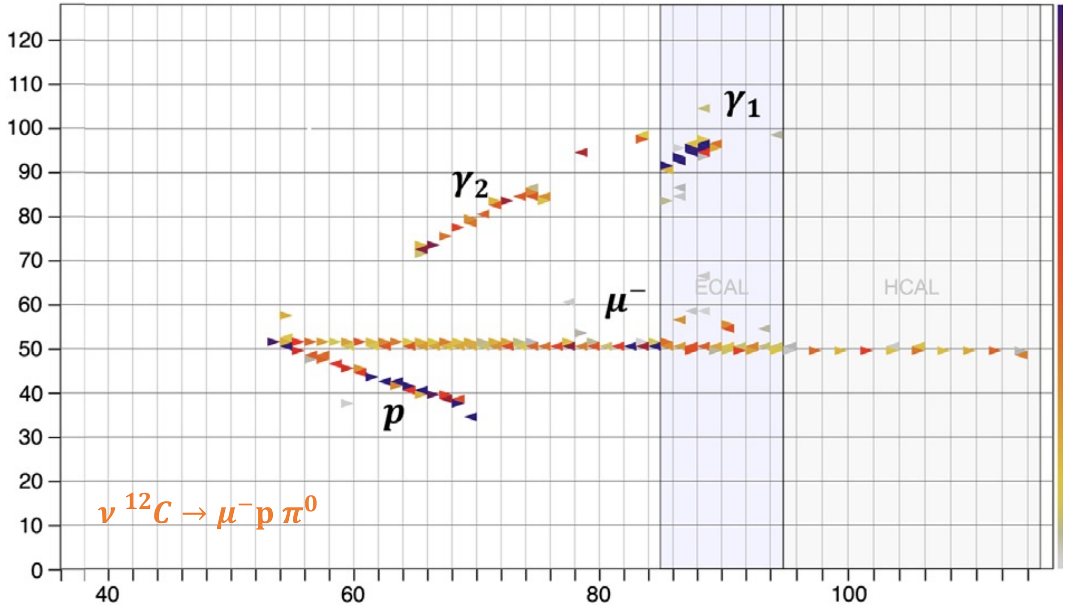
Current role in studying ν interactions

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

Hydrogen target from CH-C subtraction:
T. Cai *et al*. [MINERvA], Measurement of the axial vector form factor from antineutrino-proton scattering, ***Nature*** 614, 48 (2023)

Typical event display w/ plastic scintillator tracker





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***

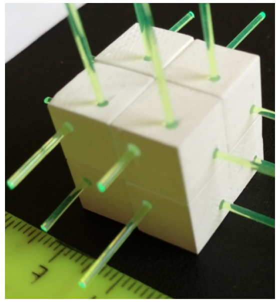
ν interaction in plastic scintillator bars—FGD

ND280 Upgrade

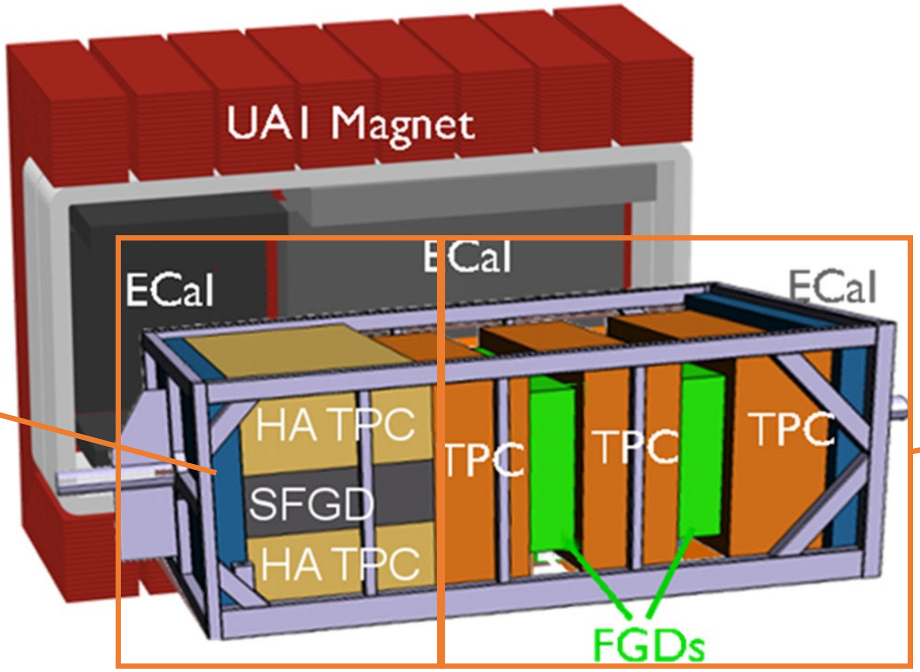
sFGD (SuperFGD)

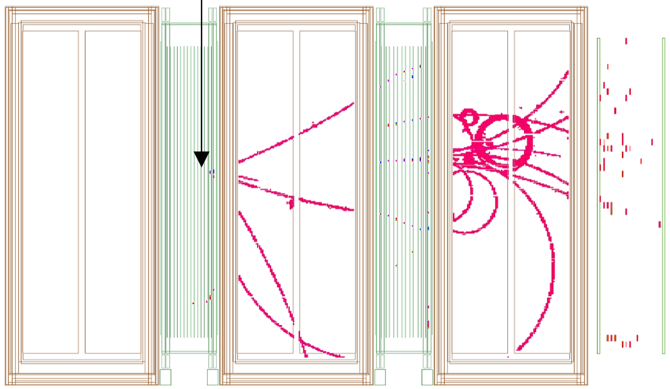
1-cm^3 ***cube***

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



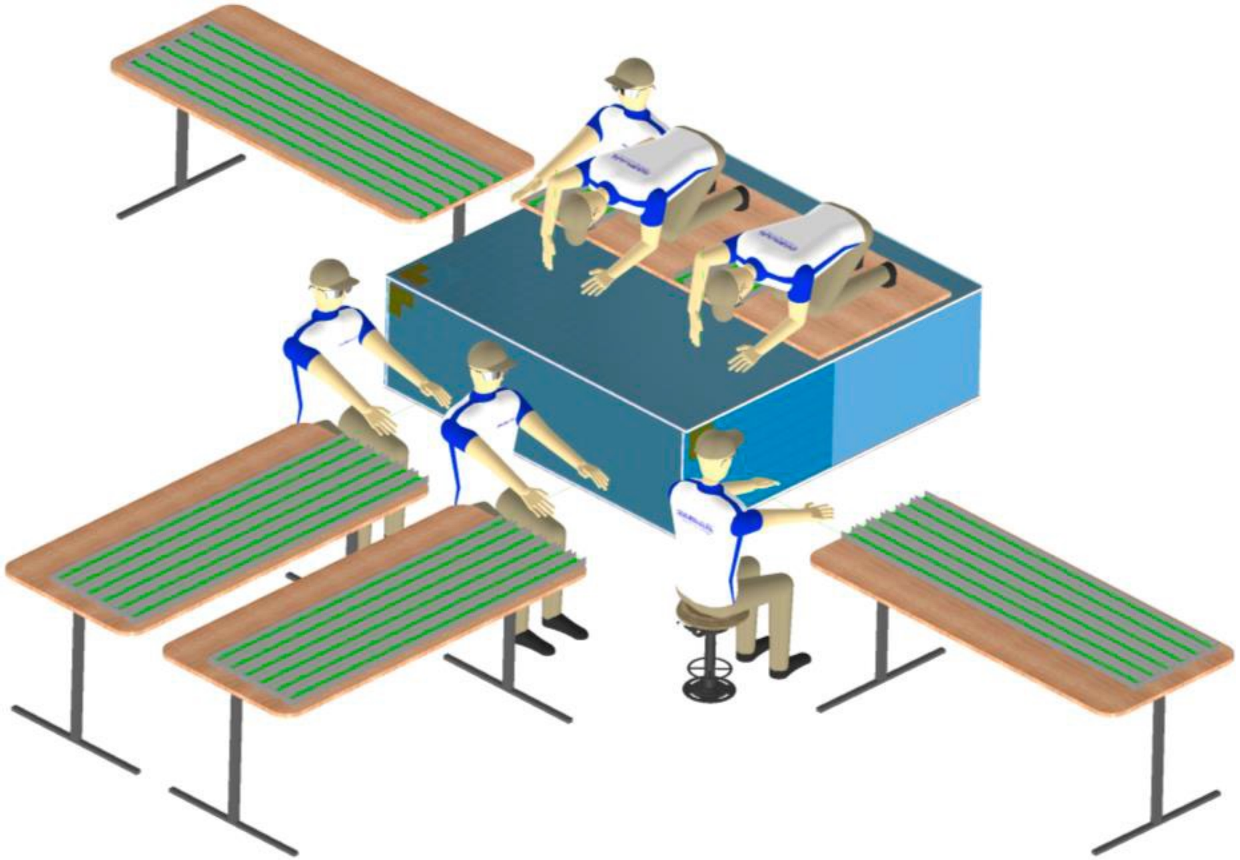
T2K, arXiv:1901.03750





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

Cube assembly and fiber insertion …



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

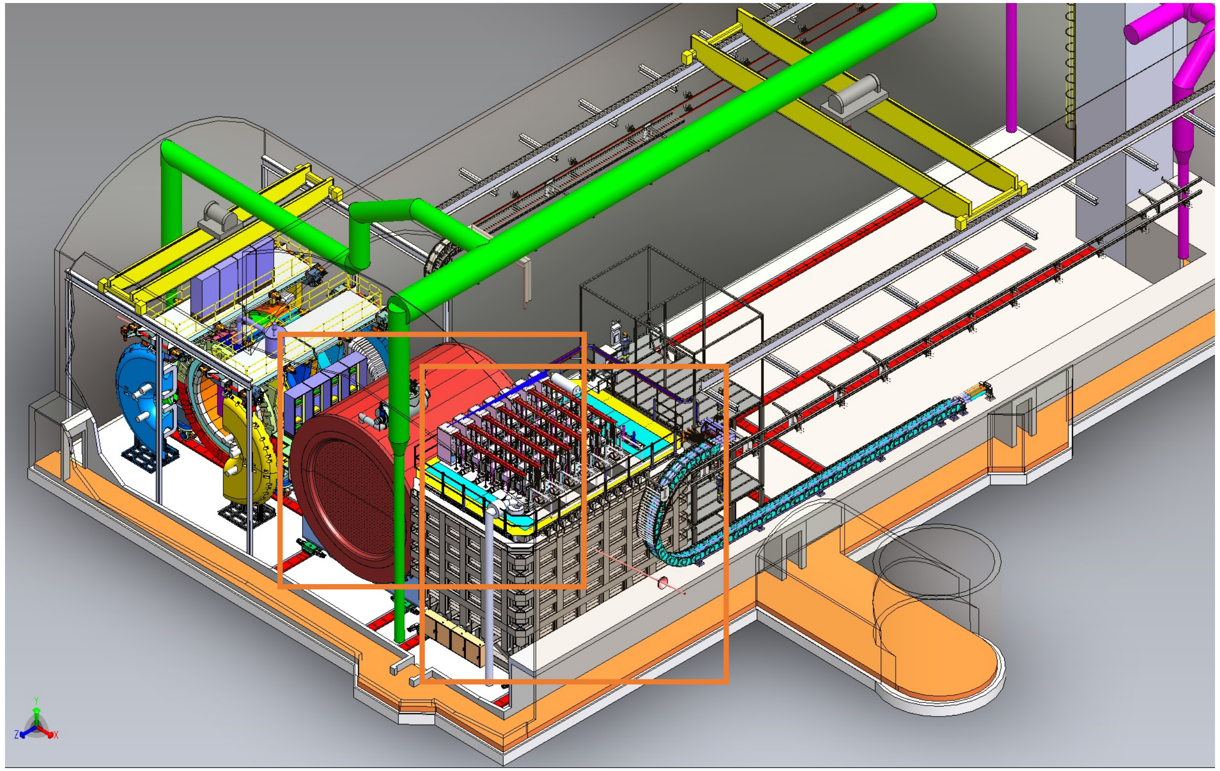
Detector

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)—Reference Design
  - 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 ultimate exclusivity for ν interactions***

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



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

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

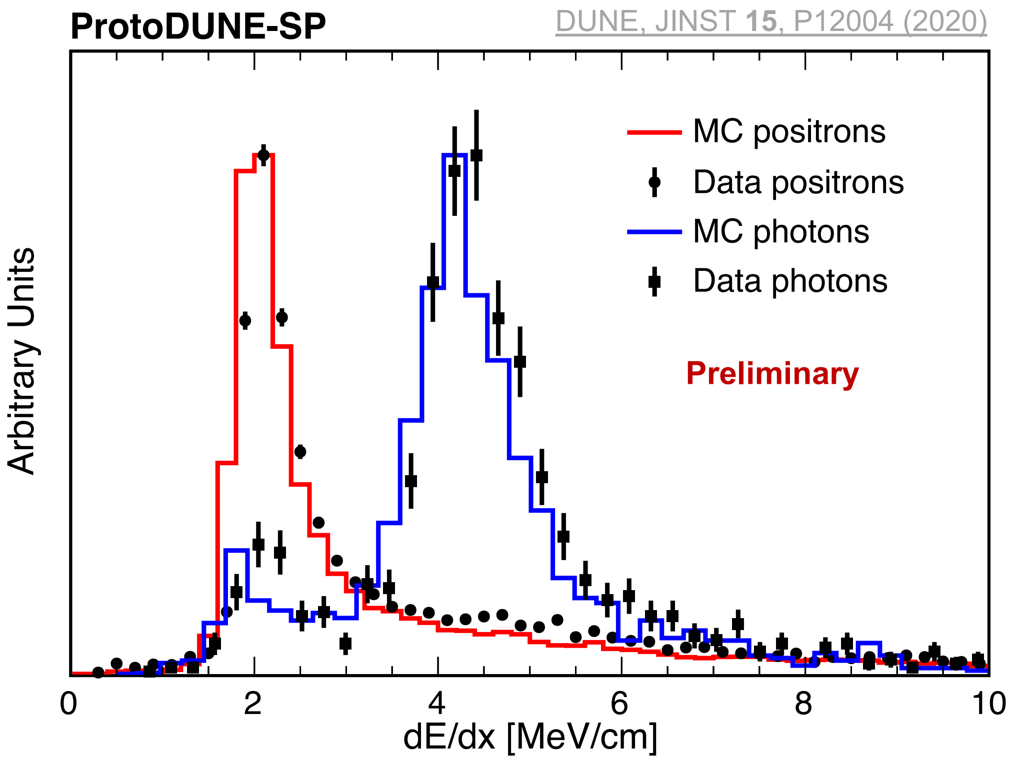
Matt Snape (Warwick) and
Philip Hamacher-Baumann (Aachen/Warwick)
August 2022, Warwick

Detector

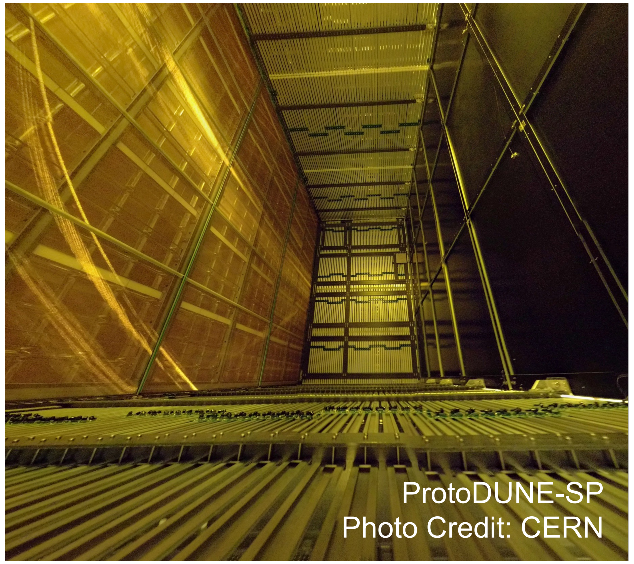
ProtoDUNE

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***



e/γ separation



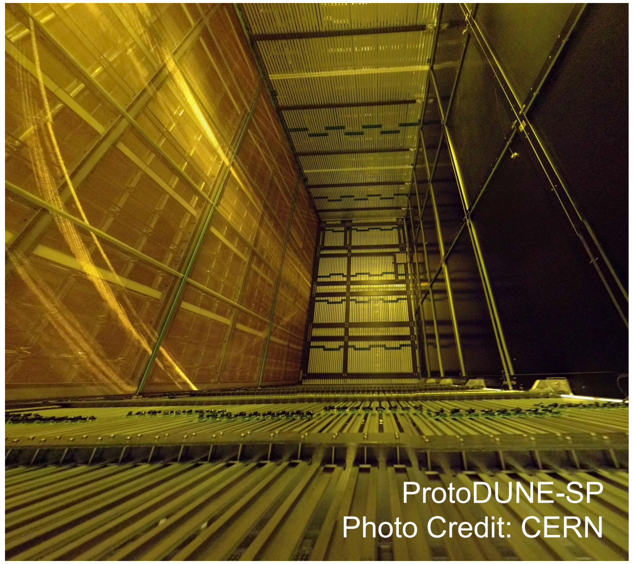
Detector

ProtoDUNE

LArTPC Demonstrator at CERN for DUNE FD

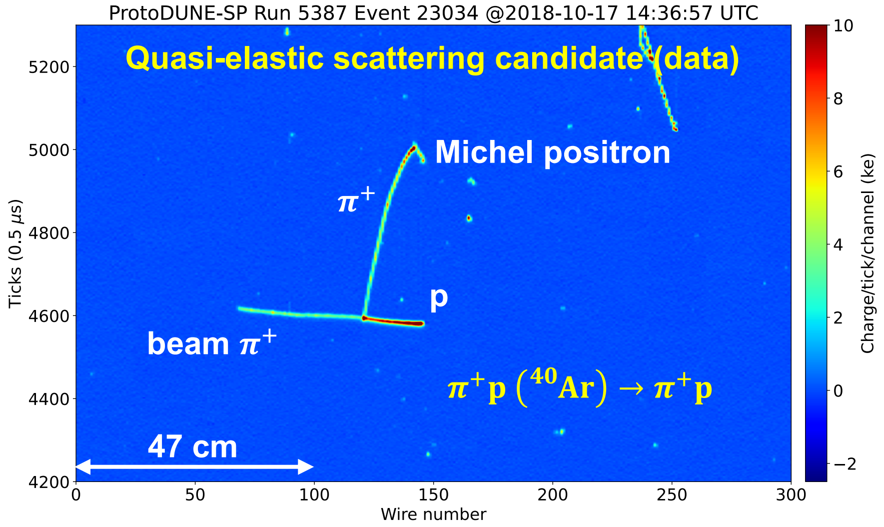
- ❑ Hadron beams of 0.3-7 GeV/*c*
  - ❖ 4.7 mm wire spacing (same as FD)
  - ✓ ***Versatile reconstruction in LAr***
  - ✓ ***hAr interactions to constrain ν-int. FSI***
  - ✓ ***Exclusivity + beam energy, can "see" inside argon nuclei***

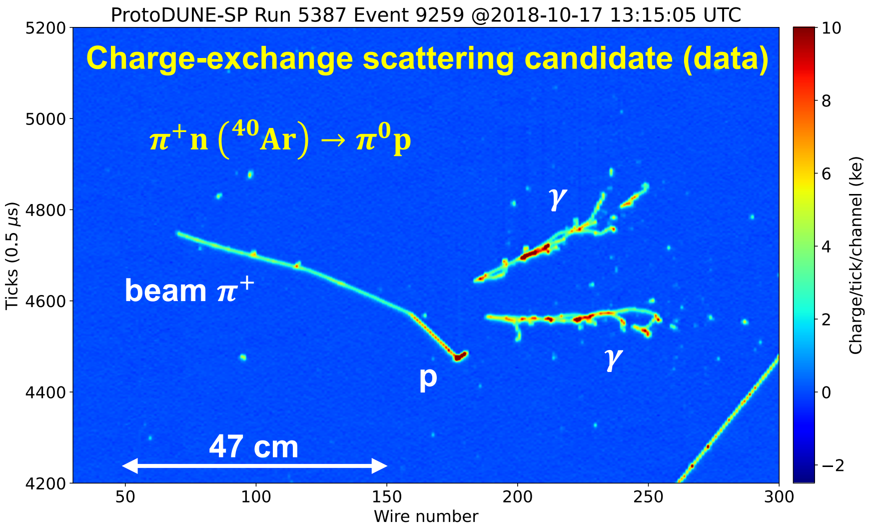
Exclusivity: to measure all final states (except nuclear remnant)



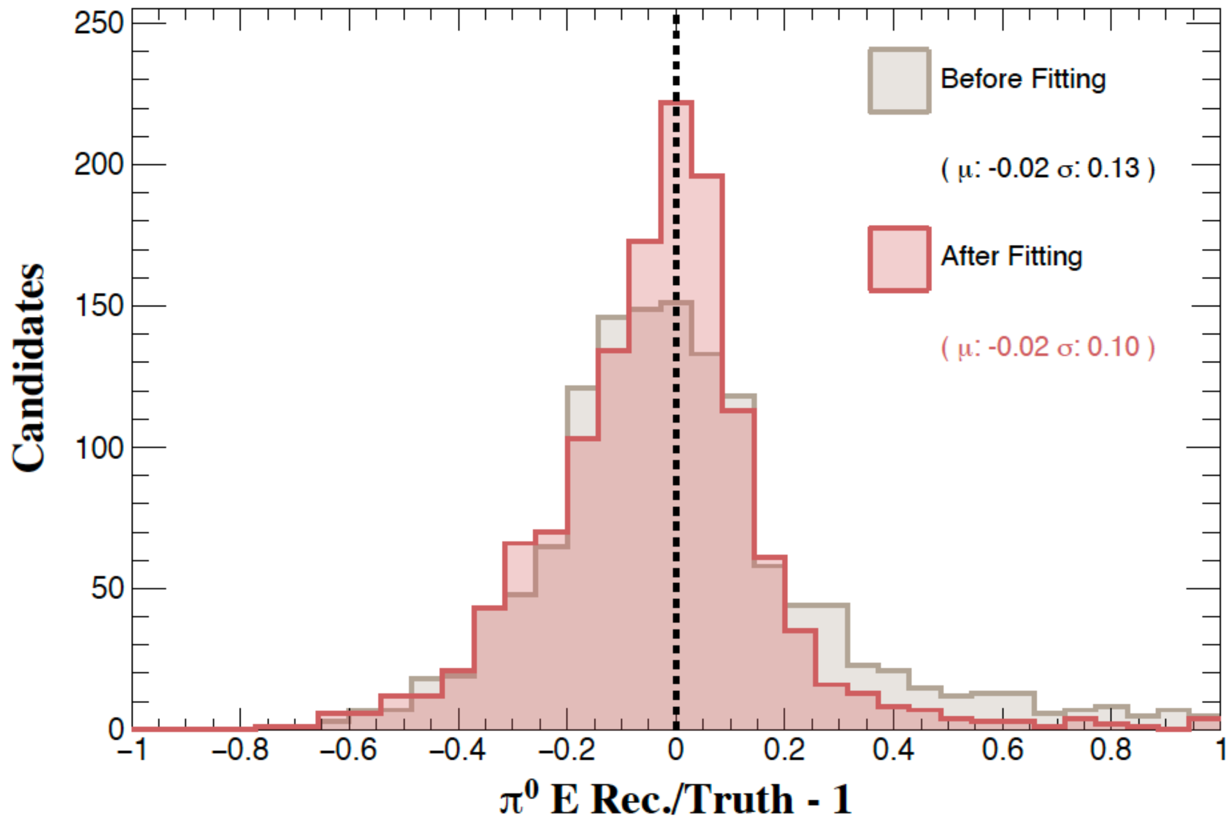
Exclusive event candidates

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

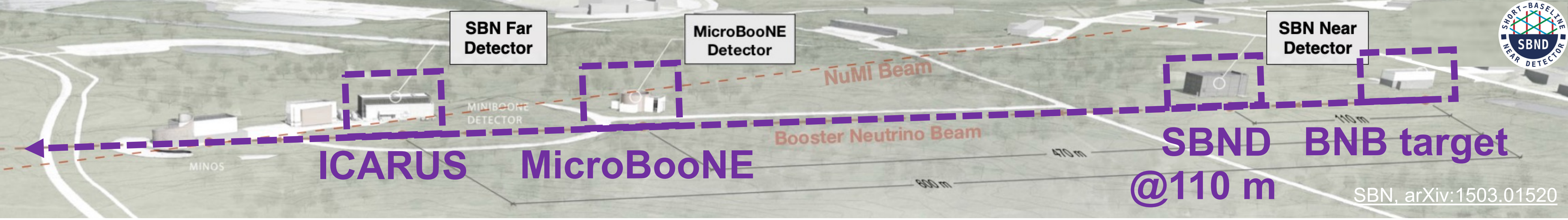




Kinematic fitting improves π^0 energy resolution from 13% to 10%



Kang Yang 杨康 (Oxford/Warwick)

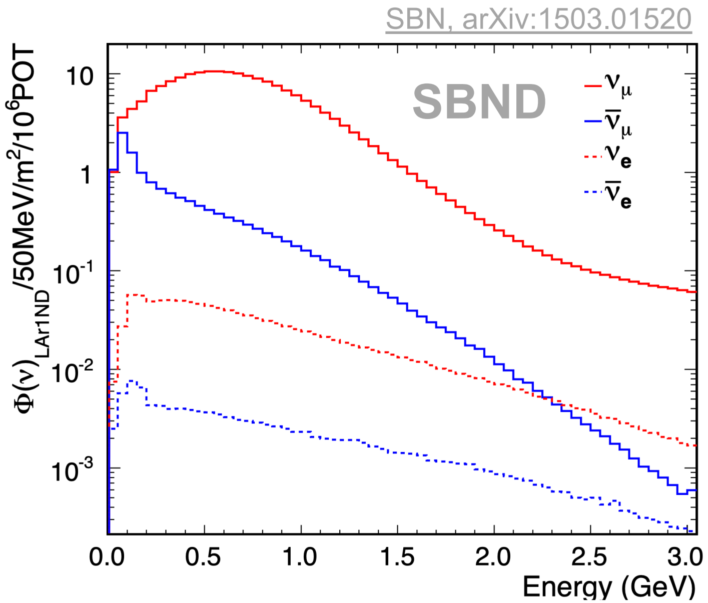


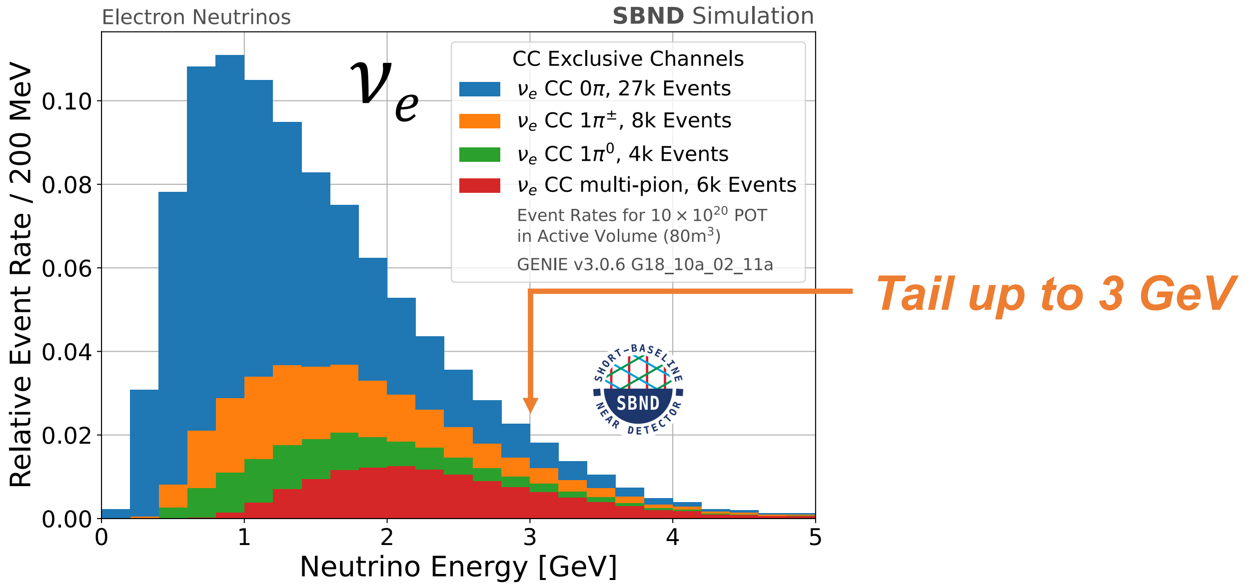
SBND

Detector

20~30 × current world νAr data

- ***Large statistics for ν_μ and ν_e***



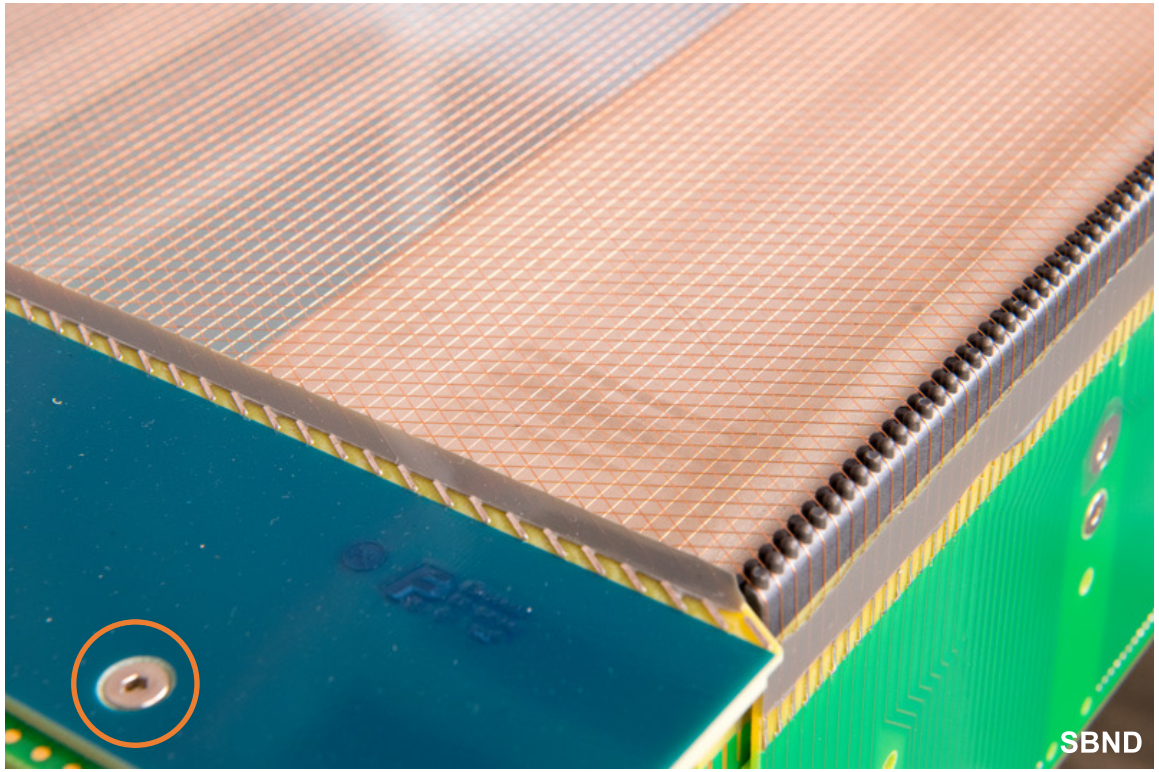


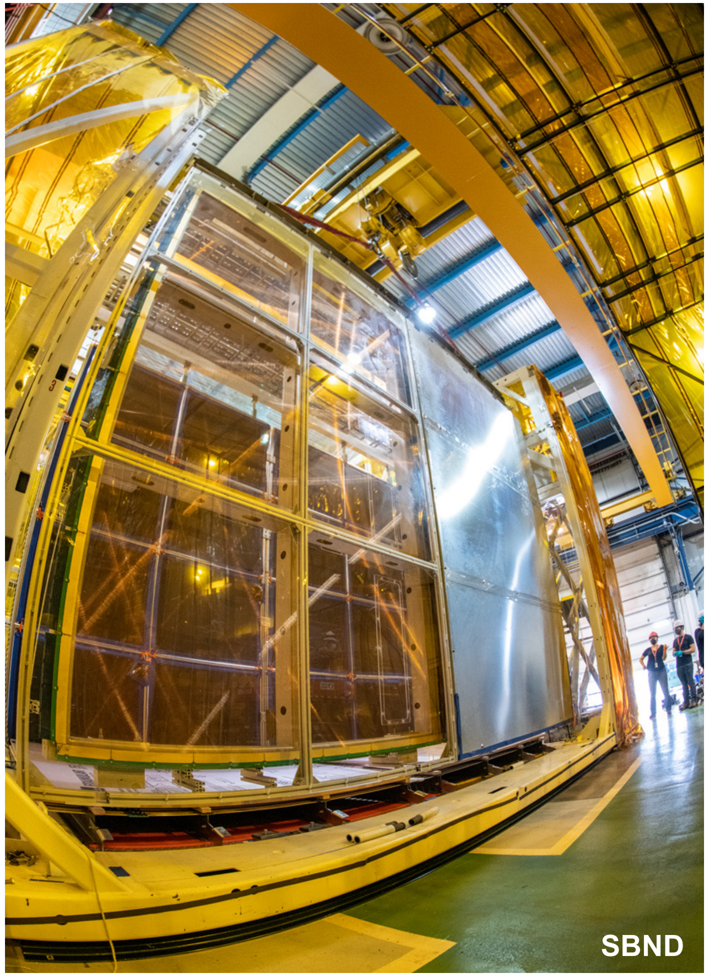
Detector

SBND

20~30 × current world νAr data

- 3 mm wire spacing (same as MicroBooNE and ICARUS)





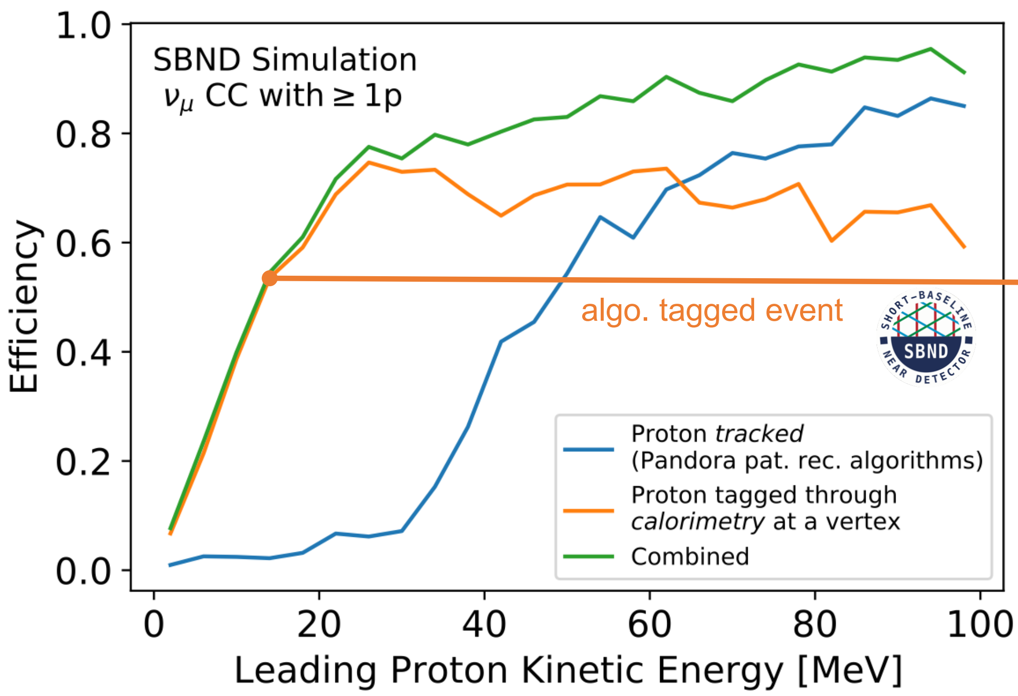
Detector

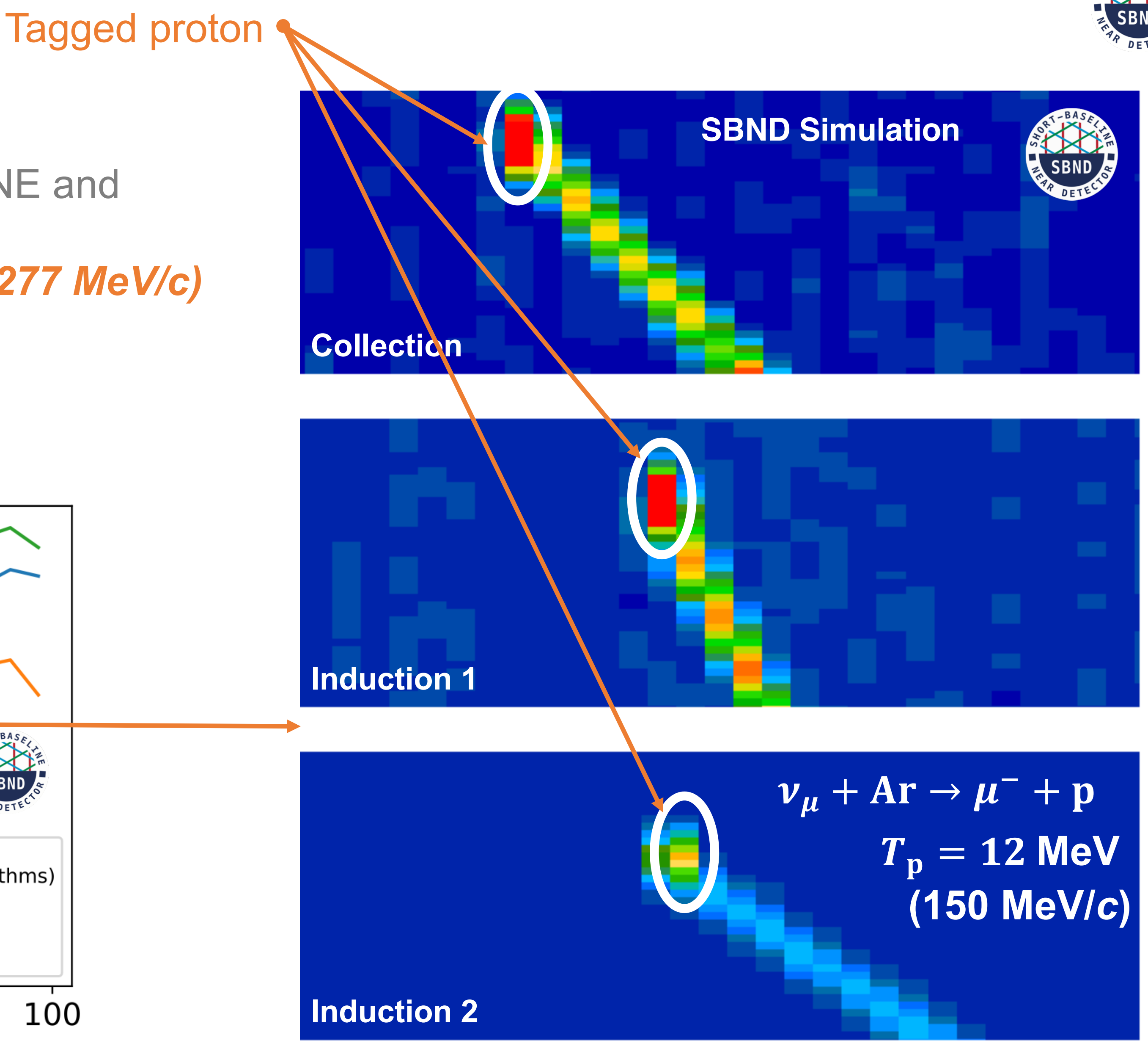
SBND

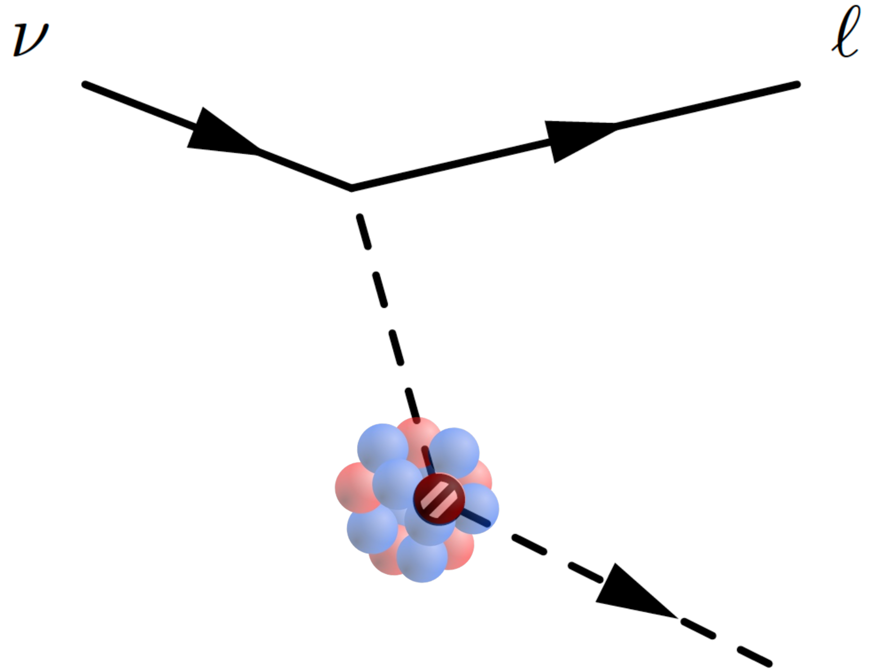
20~30 × current world νAr data

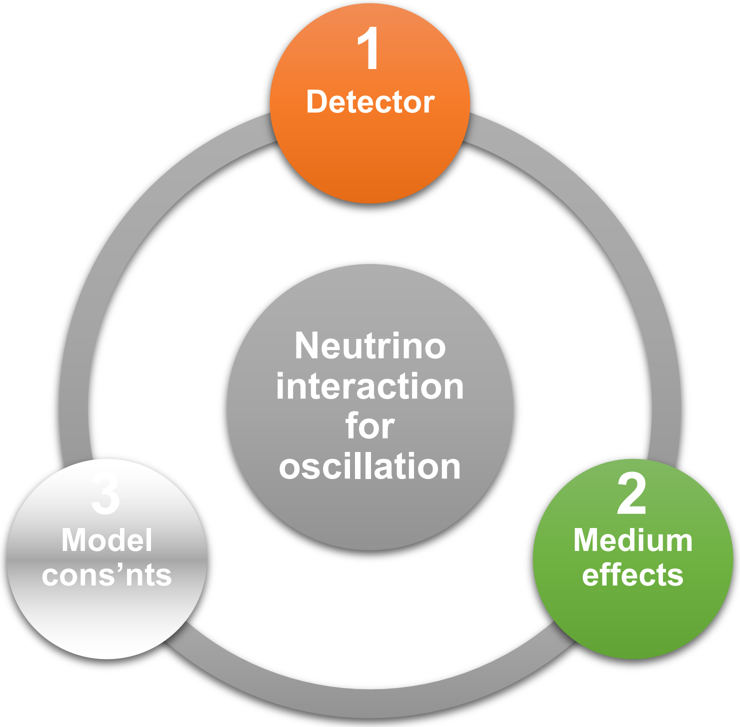
- ❖ 3 mm wire spacing (same as MicroBooNE and ICARUS)
- ✓ ***Proton tracking threshold ~ 40 MeV (277 MeV/c)***
- ✓ ***Proton tagging at vertex***

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

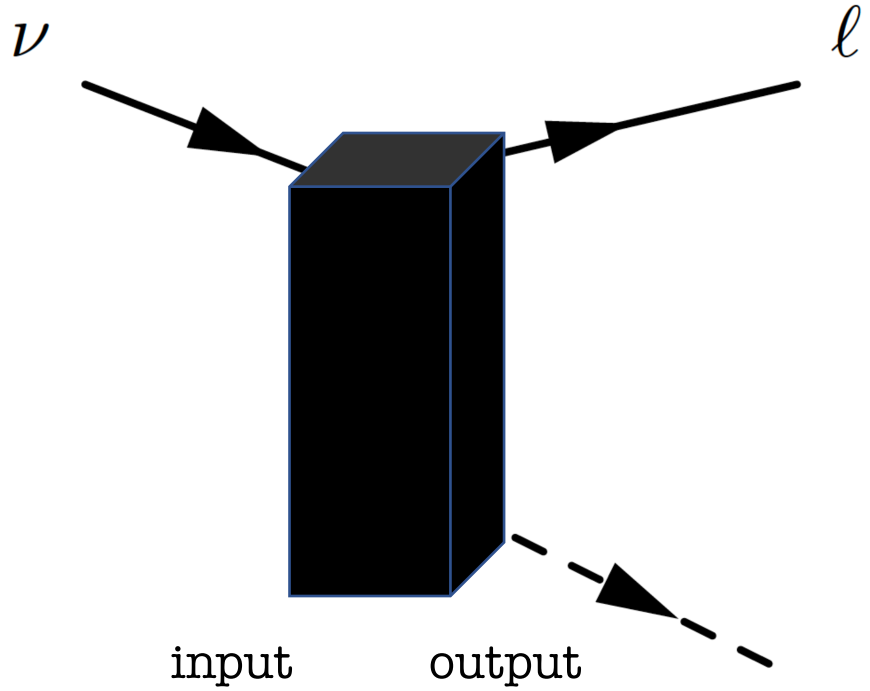


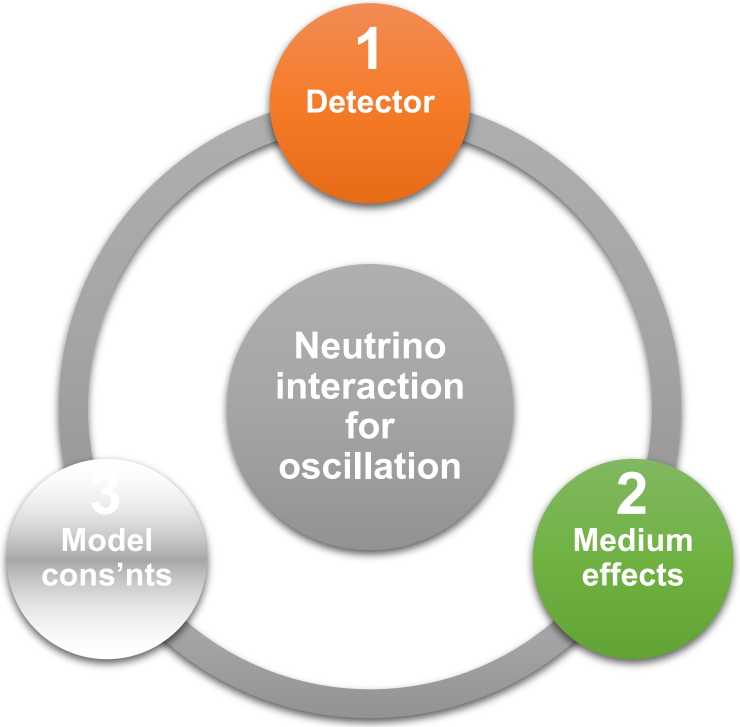






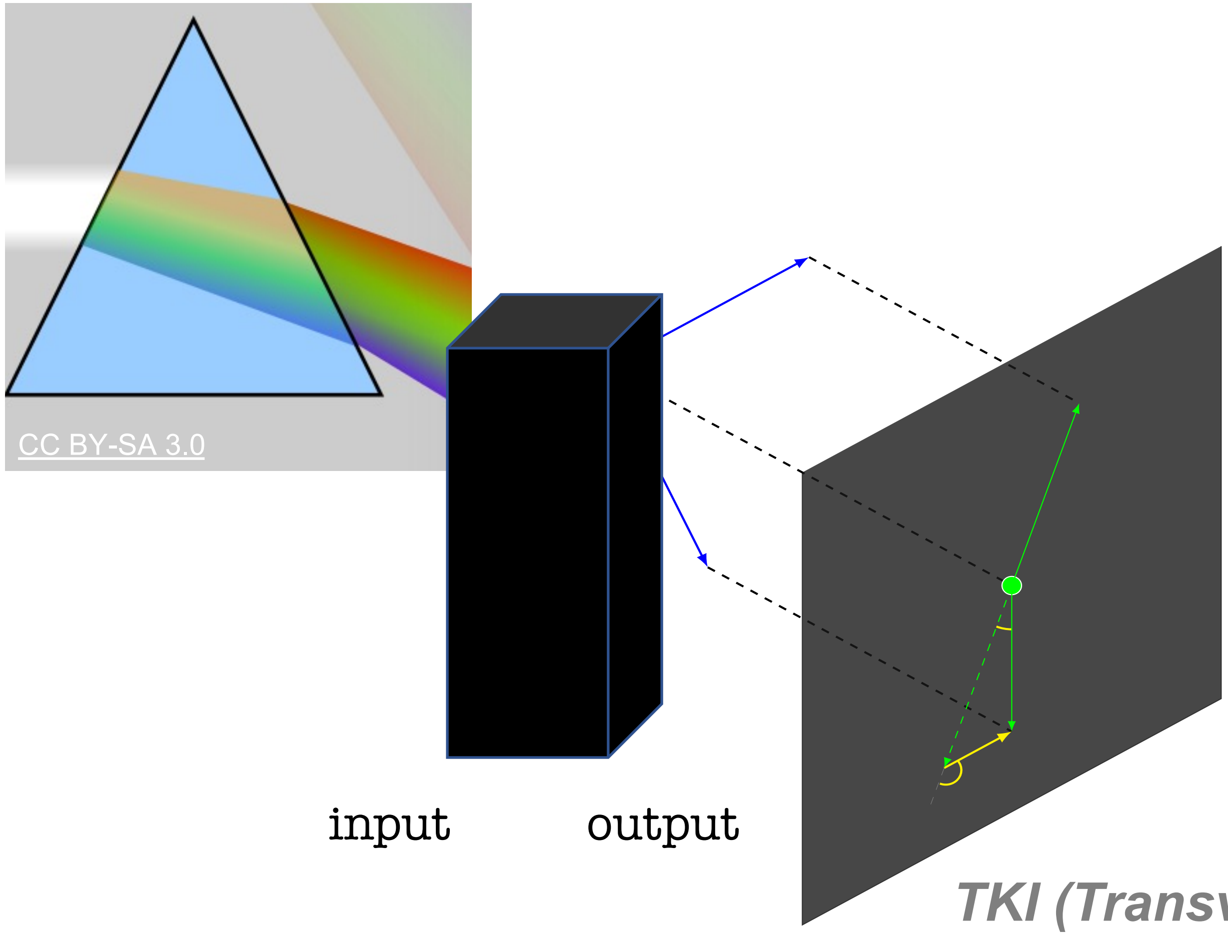
Detector limit can be pushed, but inside of a nucleus is never allowed…



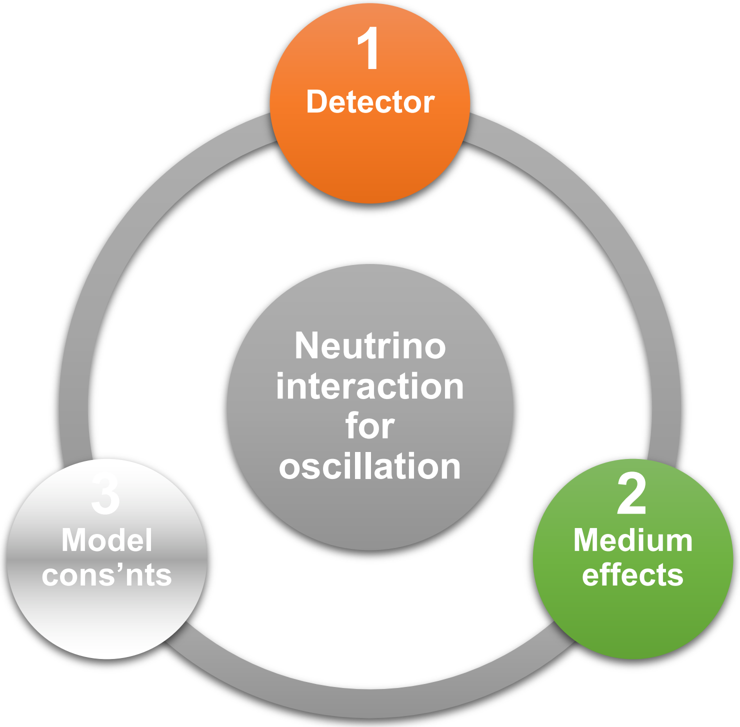


Detector limit can be pushed, but inside of a nucleus is never allowed…

PRISM (Precision Reaction Independent Spectrum Measurement)



TKI (Transverse Kinematic Imbalance)

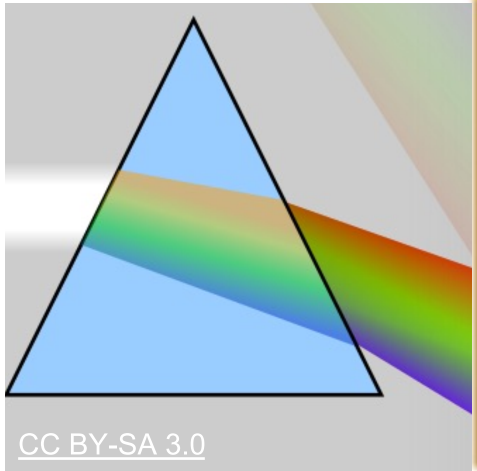


Detector limit can be pushed, but inside of a nucleus is never allowed…

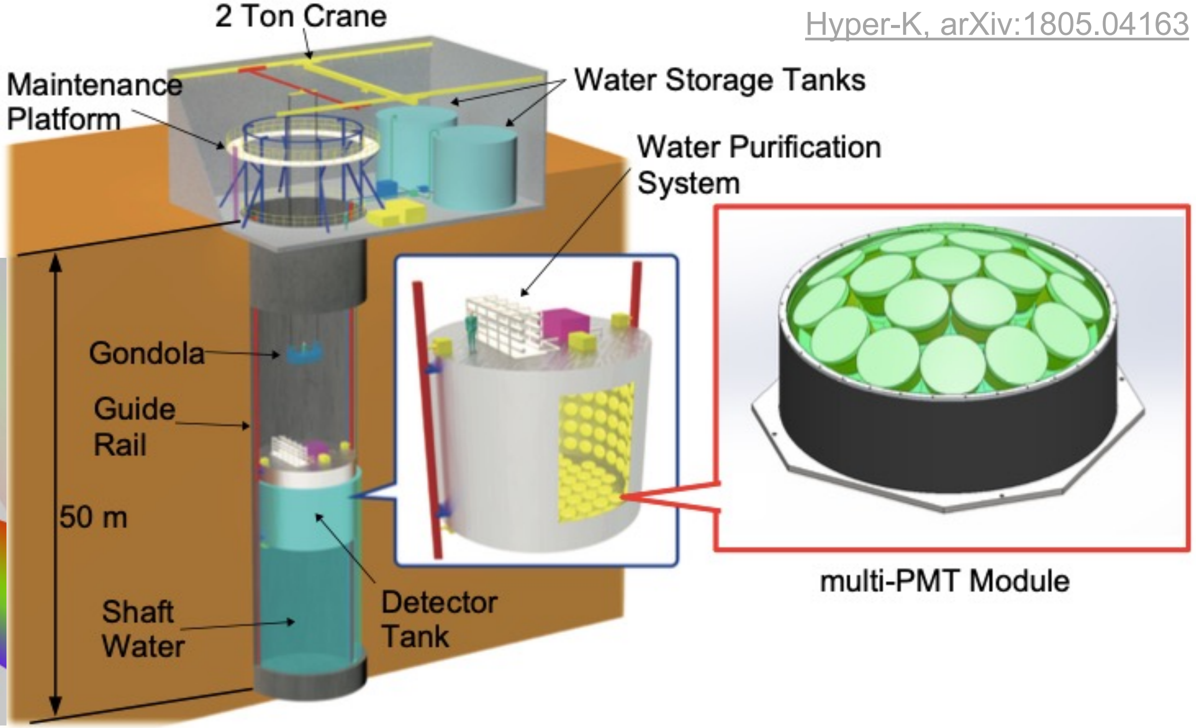
Medium effects

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



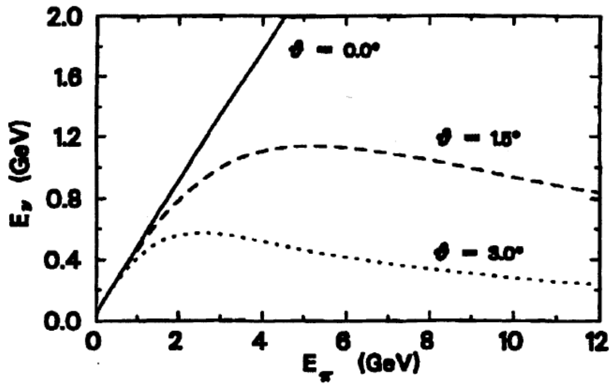
Medium effects

Hyper-Kamiokande

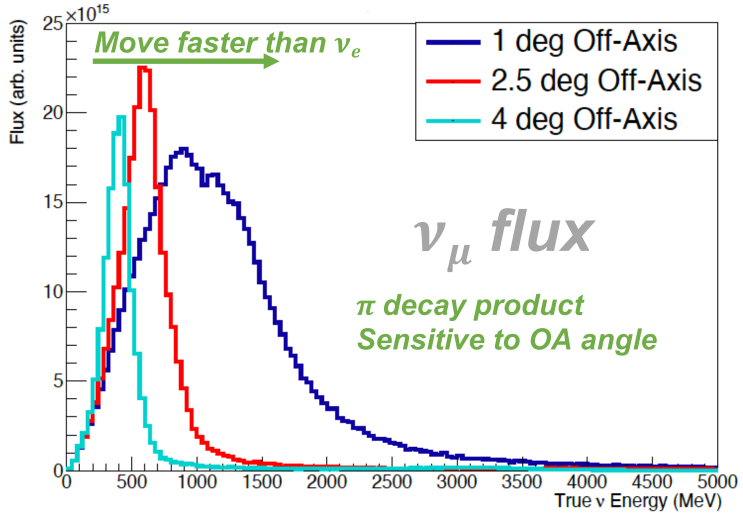
- ❑ FD: water Cherenkov
- ❑ ND: IWCD (Intermediate Water Cherenkov Detector)
  - ❖ Same technology as FD
  - ❖ 50 m vertical shaft @ 750 m from beam source
    - ✓ *1°-4° off-axis (OA) angle ("PRISM Definition Part 1")*
  - ❖ ~ 1% residual $\nu_e/\bar{\nu}_e$ beam components
    - ✓ ***Large fraction 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)***

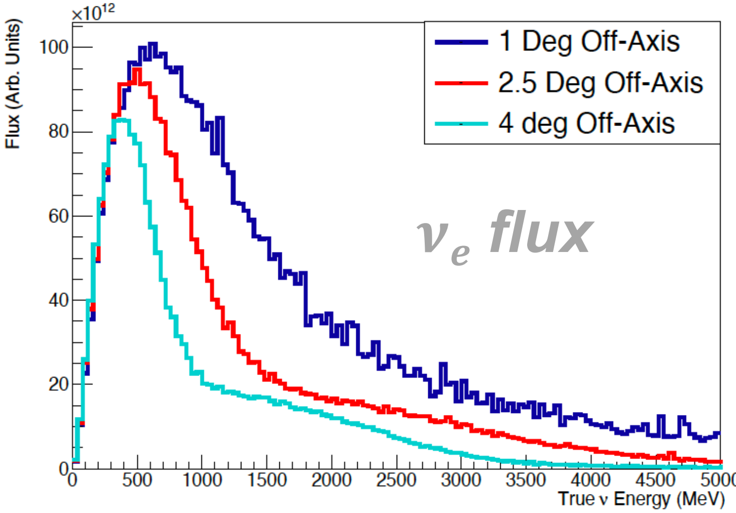
From energy, momentum conservation

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



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





Medium effects

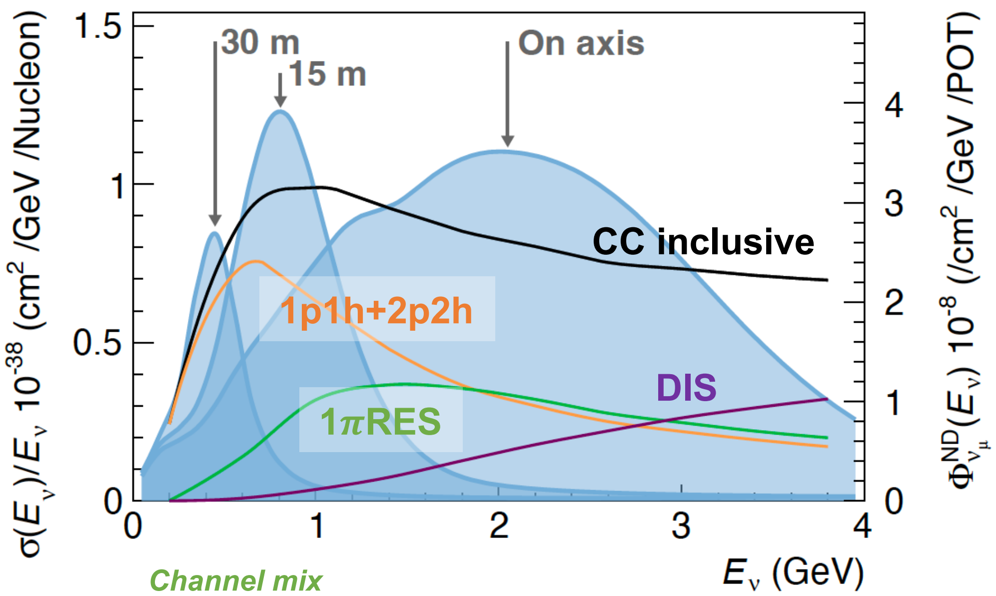
DUNE-PRISM

ND-LAr & ND-GAr

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

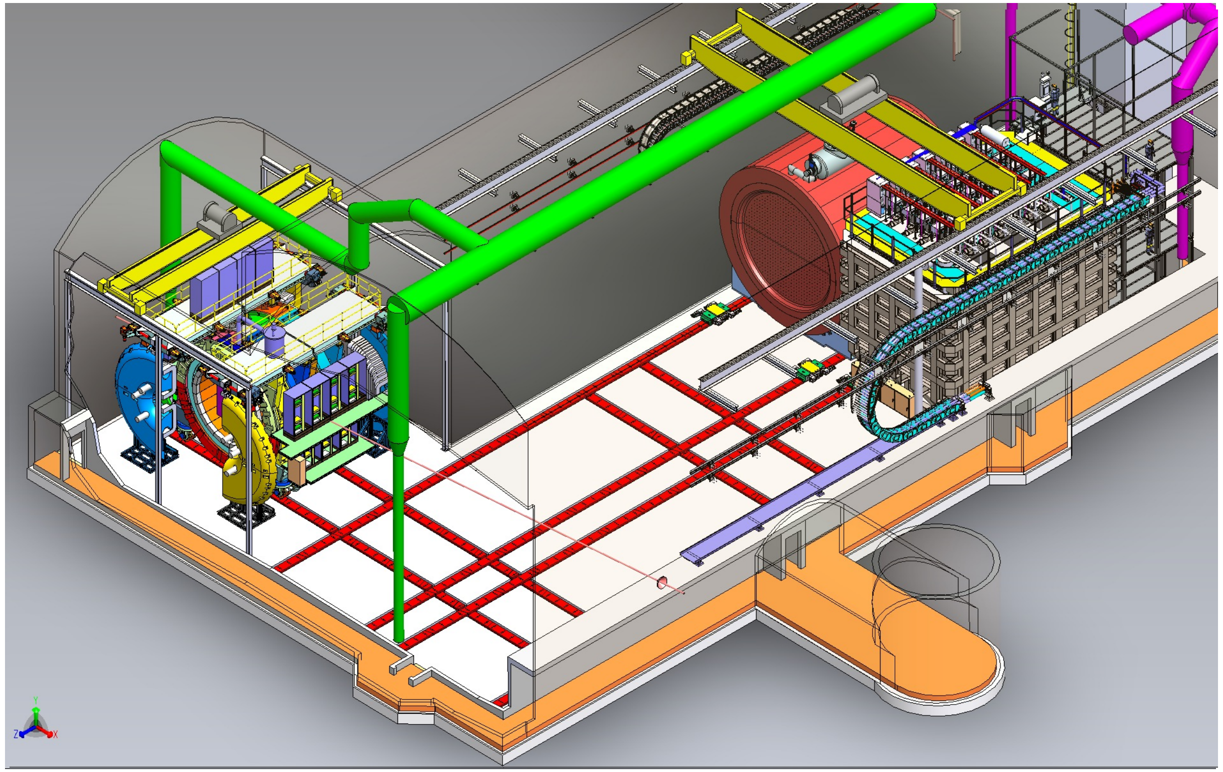
- ✓ *0°-3° off-axis angle*
- ✓ *E_ν up to ~ 3 GeV, covering different interaction dynamics*
- ✓ *Probe energy-dependent medium effects*

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



Channel mix evolves with OA location

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

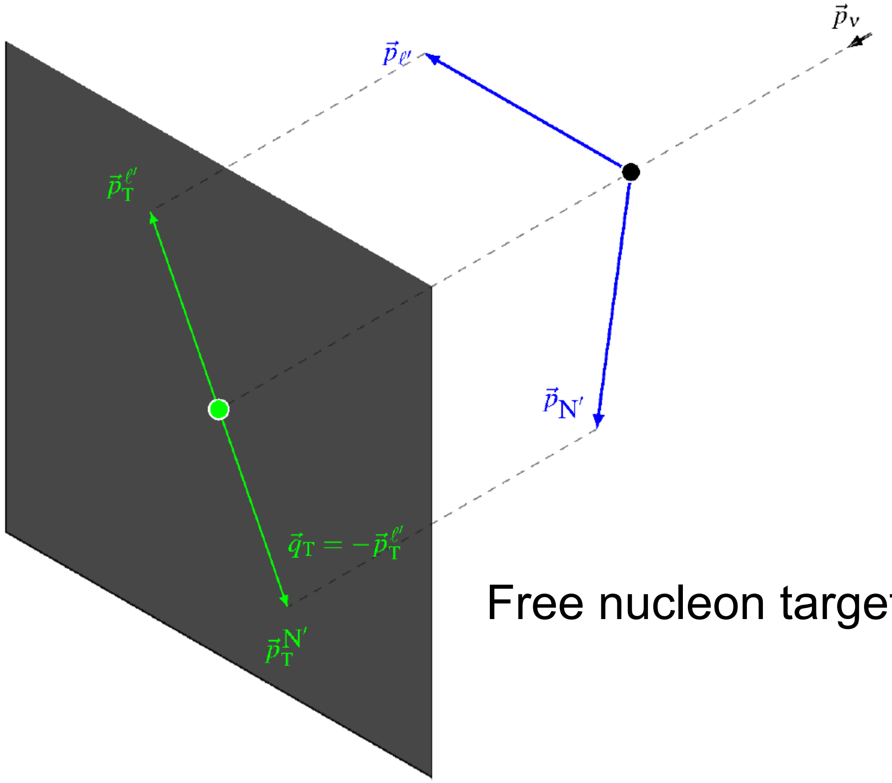


Medium effects

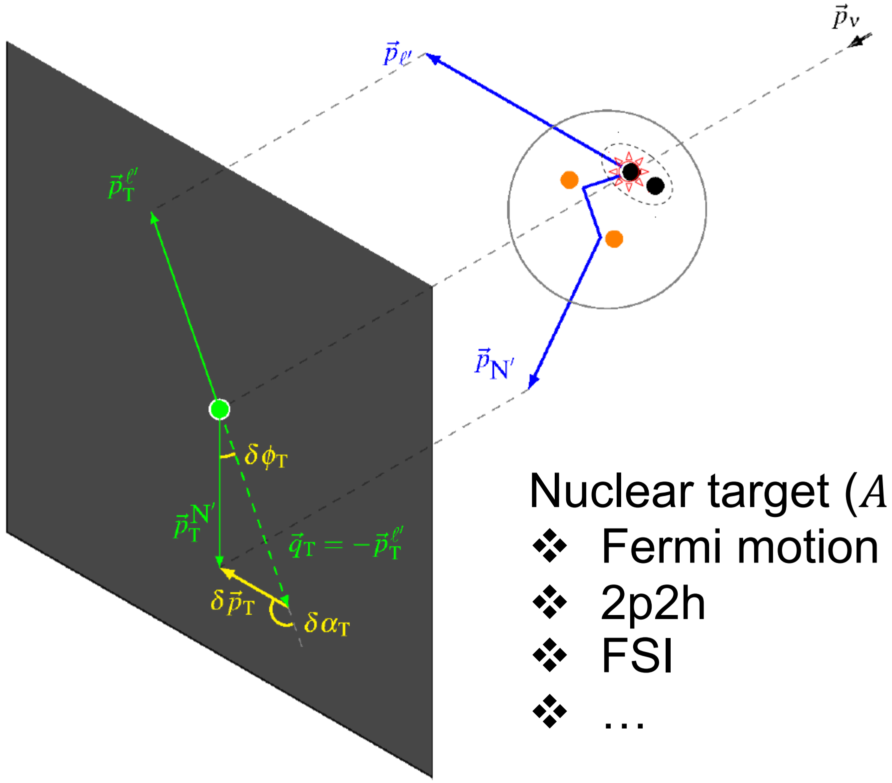
TKI (Transverse Kinematic Imbalance)

- ❑ TK orthogonal to ***unknown*** E_ν
- ❑ Embed in imbalance created by
  - ❖ Nucleus "contacting" medium ✓ ***Signature imbalance probing inside nuclei***
  - ❖ Detector loss & secondary interactions ✗ ***Mock nuclear effects***

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



Free nucleon target



Nuclear target ($A > 1$)
- ❖ Fermi motion
- ❖ 2p2h
- ❖ FSI
- ❖ …

Medium effects

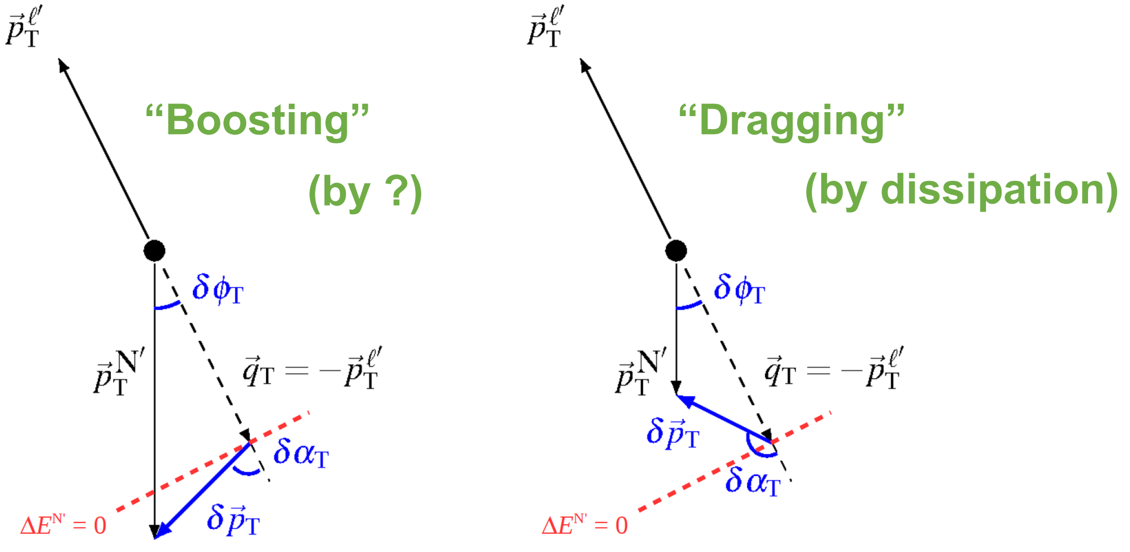
TKI

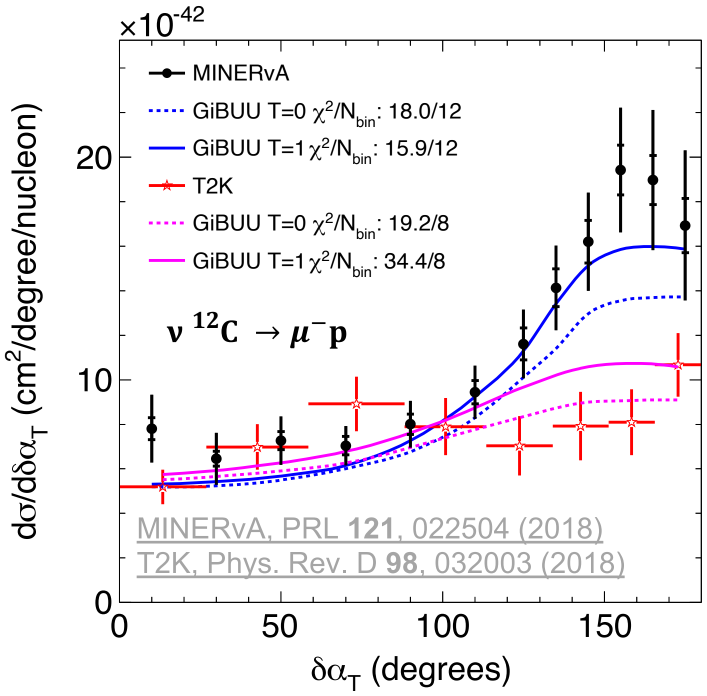
Transverse boosting angle

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

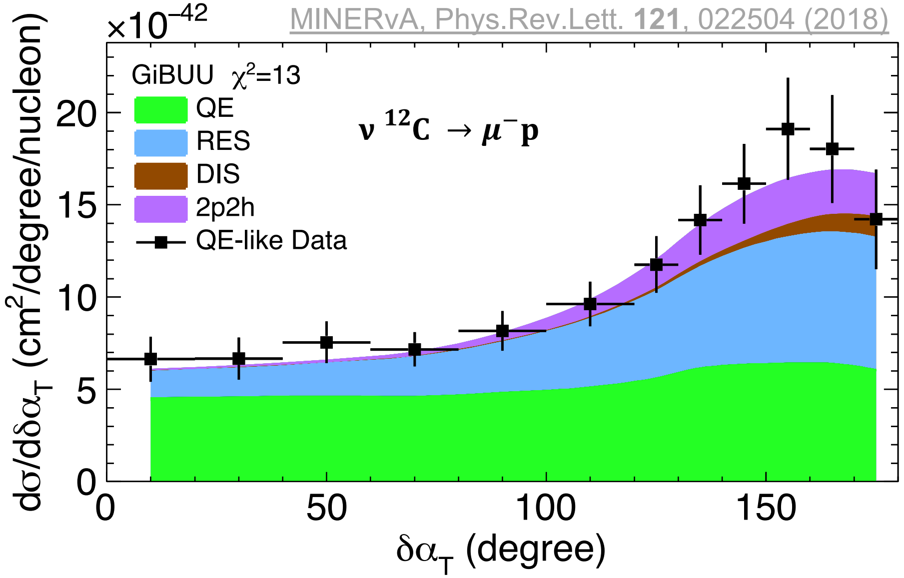
Quasielastic-like: $\nu\ ^{12}\mathrm{C} \rightarrow \mu^- \mathrm{p}$

- ❖ 2p2h, resonance (π production + absorption)
  - ✓ ***Energy dependence*** *(T2K, MINERvA E_ν ~ 0.6, 3 GeV)*





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

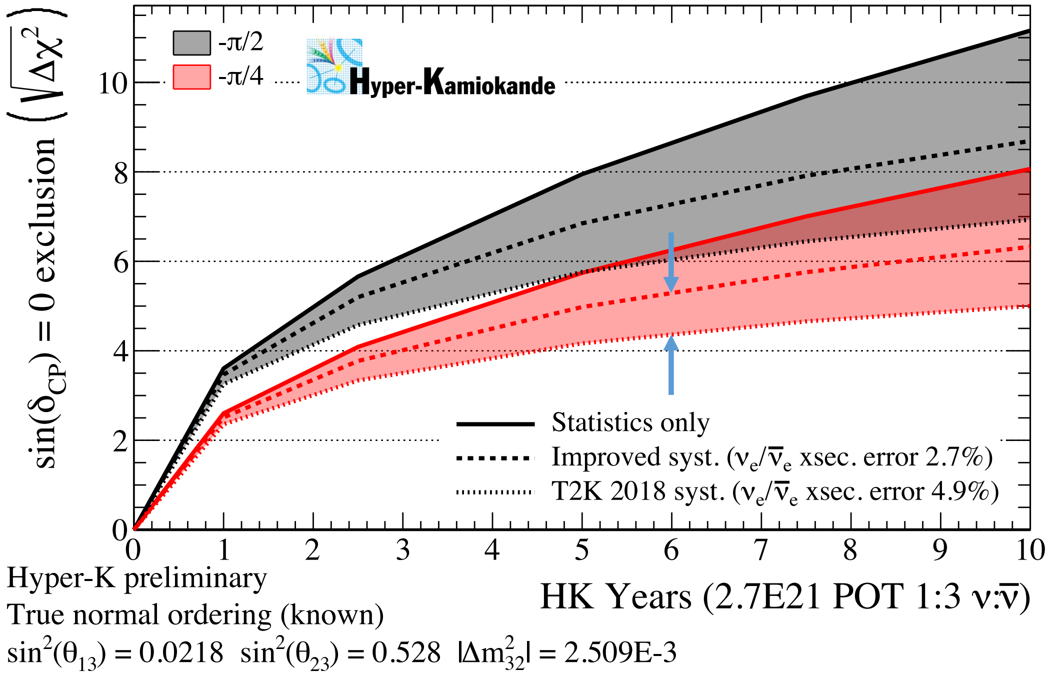


❖ *2p2h*
❖ *RES*
Dragging = Energy carried away by unobserved particles

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

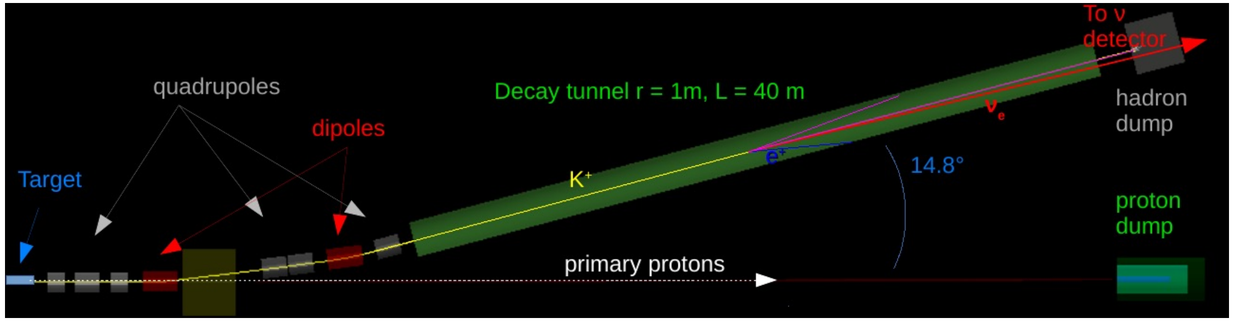
❖ QED radiative corrections and lepton mass "nudge" Q^2, shifting internal $(q_0, \vec{q}_3)$ phase space

Model constr't

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

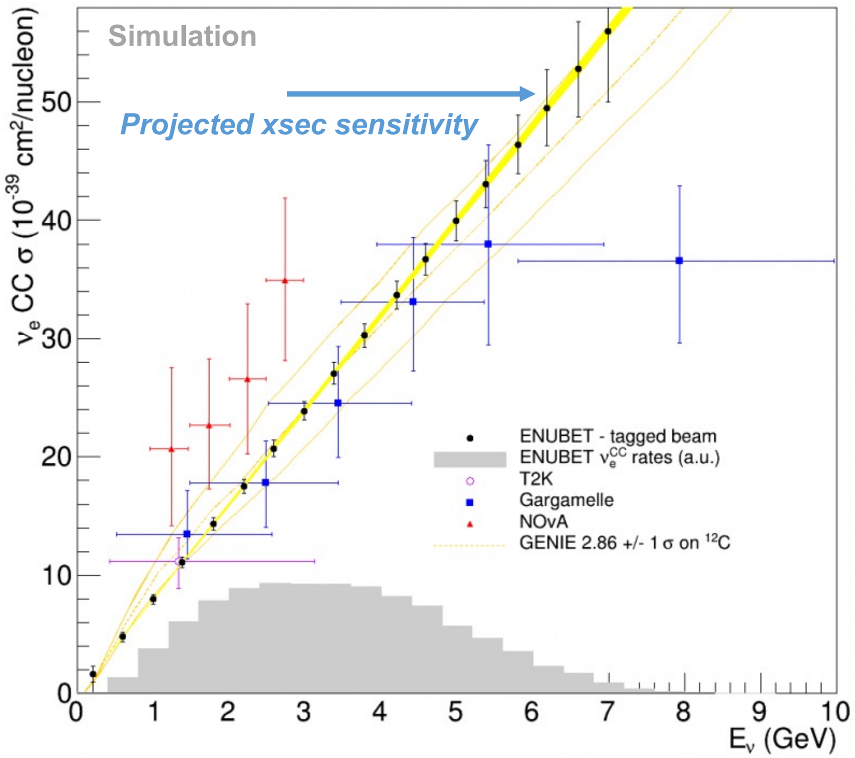
- ❑ $\delta_{\rm CP}$ requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- ❑ Need $\nu_e/\bar{\nu}_e$ interaction data
- ❑ ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics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

ENUBET, arXiv:2203.08319



- ❑ 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

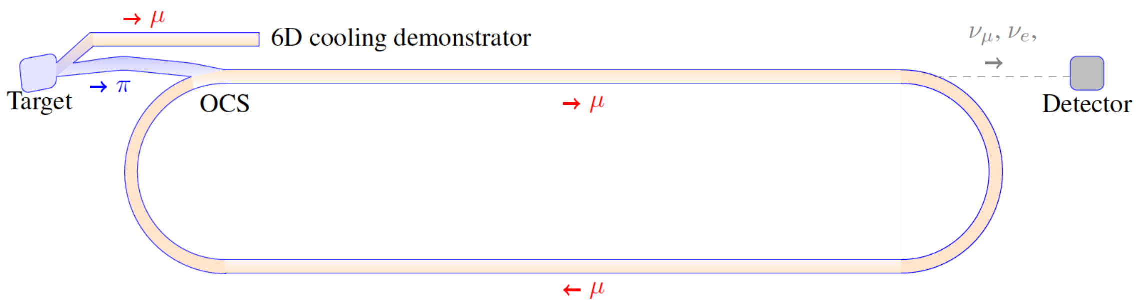


$\nu_e/\bar{\nu}_e$ interactions

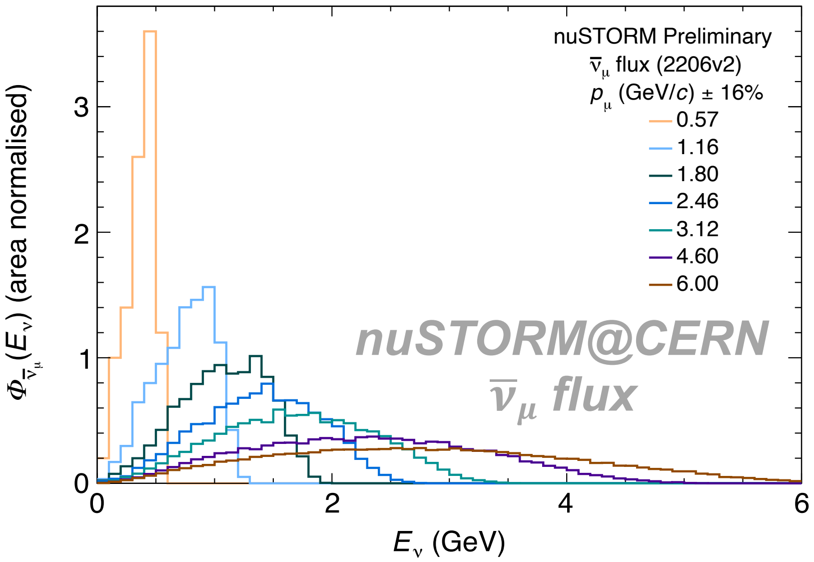
- ❑ δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- ❑ Need $\nu_e/\bar{\nu}_e$ interaction data
- ❑ ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood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

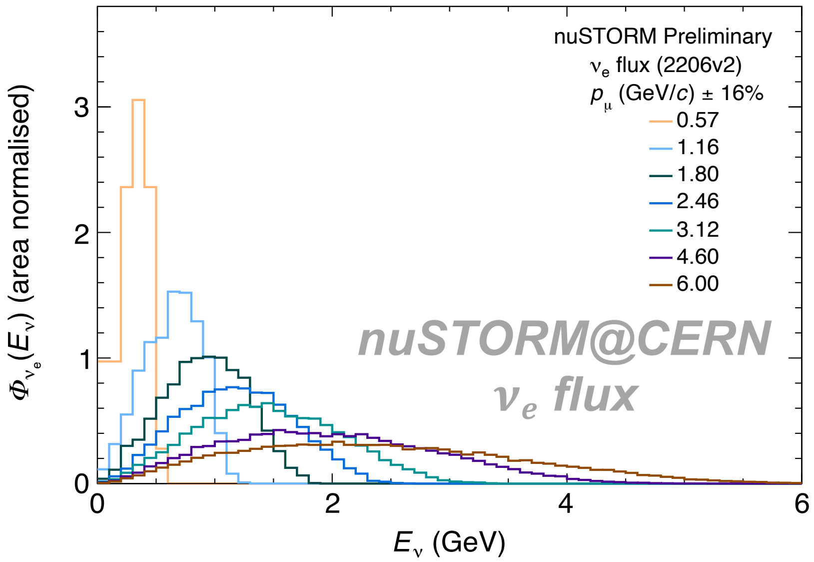
nuSTORM, arXiv:2203.07545

- ❑ 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

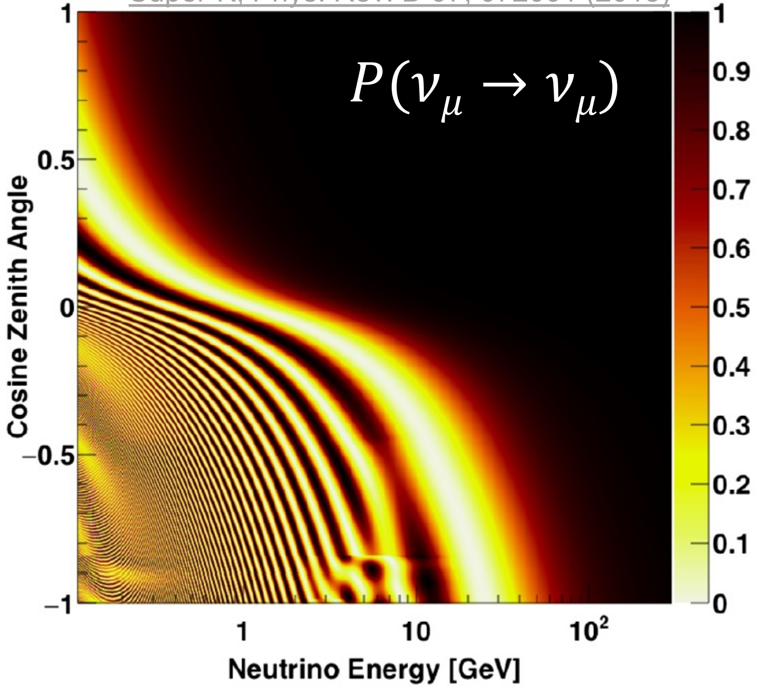
Model constr't

NMO with atmospheric ν

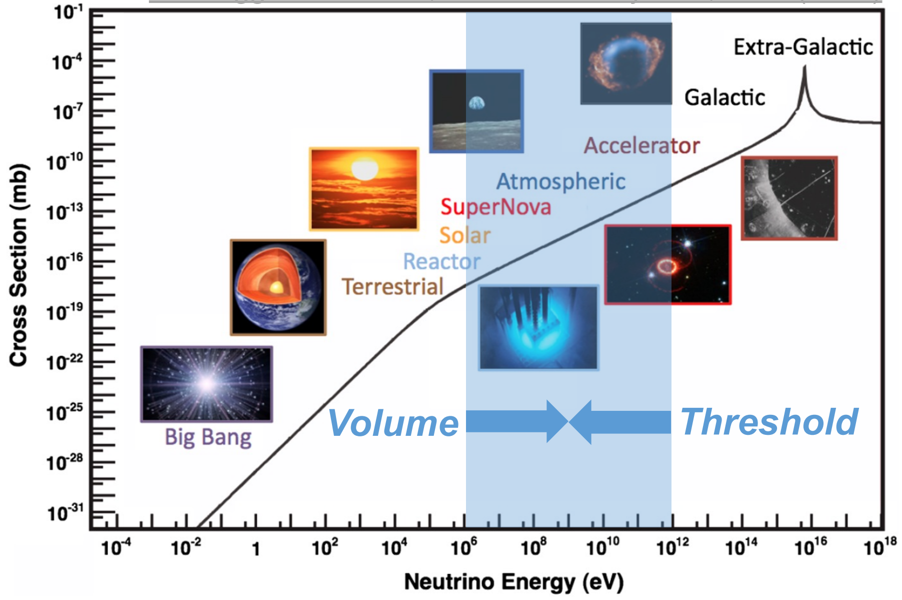
- ν energy & angle for *L*/*E*-variation

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)



MeV *TeV*

GeV-ν interaction more critical and challenging

Model constr't

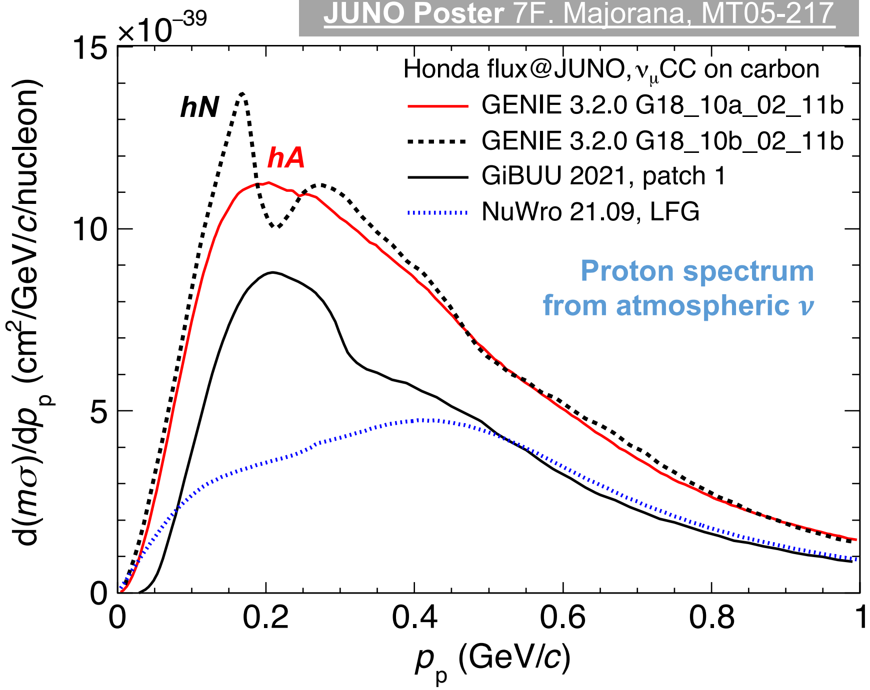
NMO with atmospheric ν

- ❑ 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*

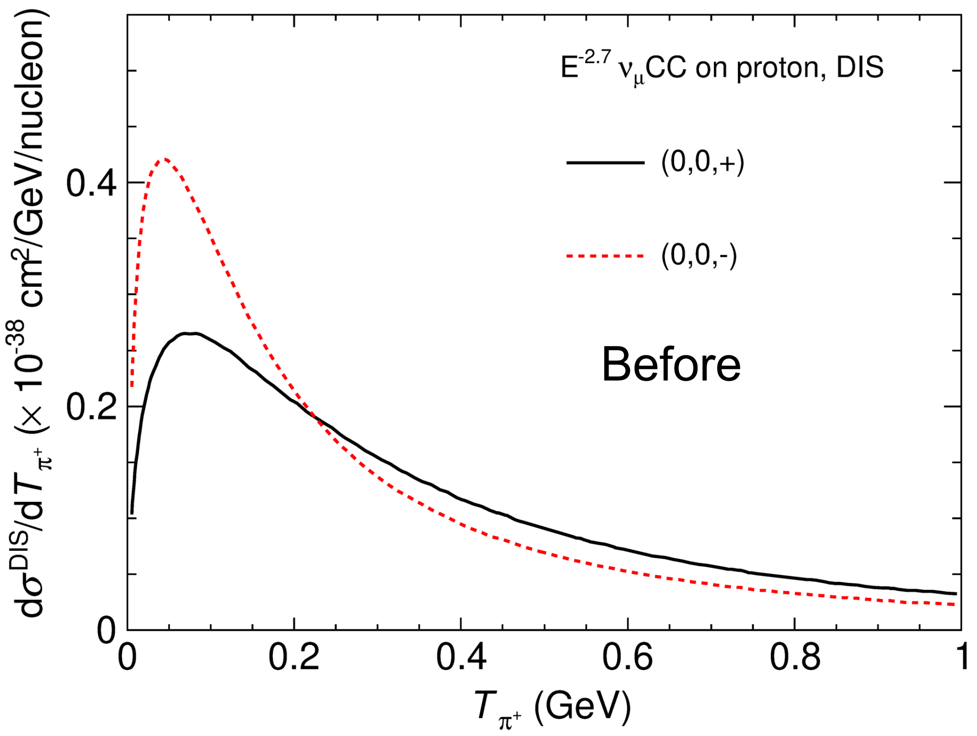
Future Oscillation Experiment	E_ν/GeV	Detector Technology	Target Nuclei
IceCube Upgrade	3-10 (NMO sensitive region)	Cherenkov in ice	H_2O
KM3NeT/ORCA		WC	H_2O
Atmos-ν @JUNO		LS	$CH_{1.6}$

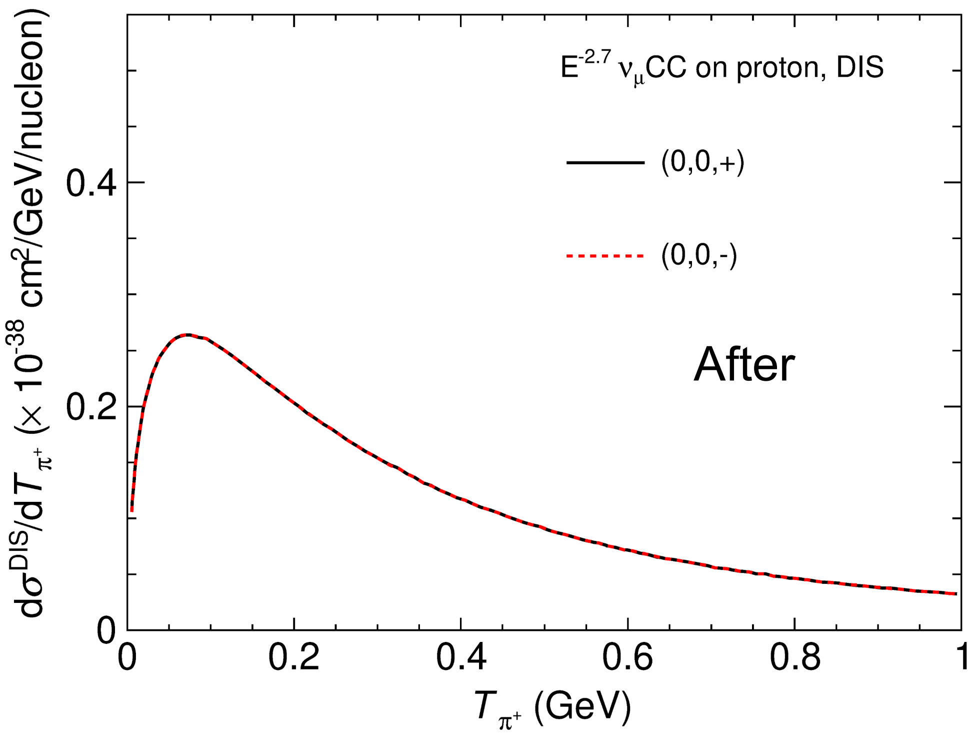
- ❑ Dedicated GeV-ν interaction measurements: MINERvA Medium Energy data
  - ✓ *E_ν peak at 6 GeV, tail up to 20 GeV*
  - ✓ *CH and nuclear targets*
  - ✓ *~ 10 M-event data set*

JUNO Poster 7F. Majorana, MT05-217



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)

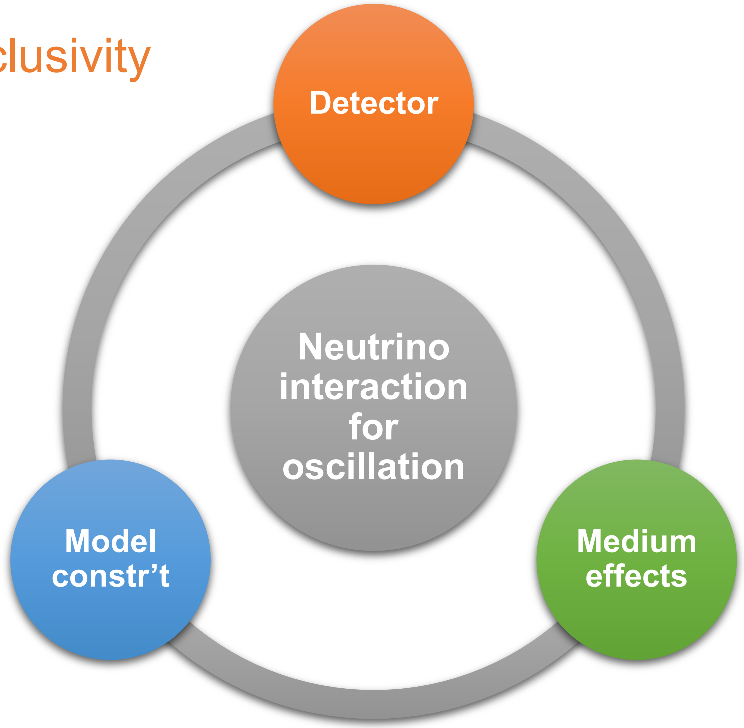
Summary

Future oscillation experiments require *surgical precision* inside a *black box*

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

Technology pushing the limit of exclusivity
- ❑ Plastic scintillator tracker
- ❑ Liquid Argon TPC

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



Dedicated *ex situ* interaction measurements
- ❑ $\nu_e/\bar{\nu}_e$ interactions
- ❑ Atmospheric NMO measurements

Novel analysis methods
- ❑ PRISM flux scan
- ❑ Signature TKI

Awaiting the future

Detector

Technology: neutrons

- ✓ ***ν energy budget and event classification—missing piece for <u>exclusivity</u>***
- ➢ 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: ***<u>exclusivity</u>*** + 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 + ***<u>exclusivity</u>*** for initial-and final-state effects (not vertex)

BACKUP