Neutrino Interactions in the Few-GeV Regime

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YETI School 2024—The 3 *Neutrino* Problem

IPPP, Durham

2024 July 31

Outline

1. Experimental Techniques
    a. Standard Model and massive neutrinos
    b. GeV neutrino experiments
    c. Detectors
    d. MINERvA measurements
2. Neutrino Scattering and Nuclear Structure
    a. Neutrino-nucleon interactions
    b. Nuclear models
    c. Neutrino-nucleus interactions
3. TKI Phenomenology
    a. Definitions
    b. Measurements and interpretations

Questions for ***Quiz*** and ***Homework*** are prepared. Number of * (0-3) indicates the difficulty.

Focus of this lecture

❖ Survey of experimental techniques to inform what we can *do*.
❖ Introduction to theory to explain what we are dealing with.
❖ First experience with one of the current trends in the field via phenomenology.
❖ Overall, to provide a taste of understanding and guessing to ease your Day One in the field.

Great lectures on neutrinos with focus on interactions if you want to dive into the subject

1. Kevin McFarland, University of Rochester, ***Neutrino interactions***, Center for Excellence in Particle Physics (CCEPP) School, 25-26 August 2021
2. Steve Boyd, University of Warwick, ***Neutrino Physics***, ***Warwick Week*** Lecture, 2024

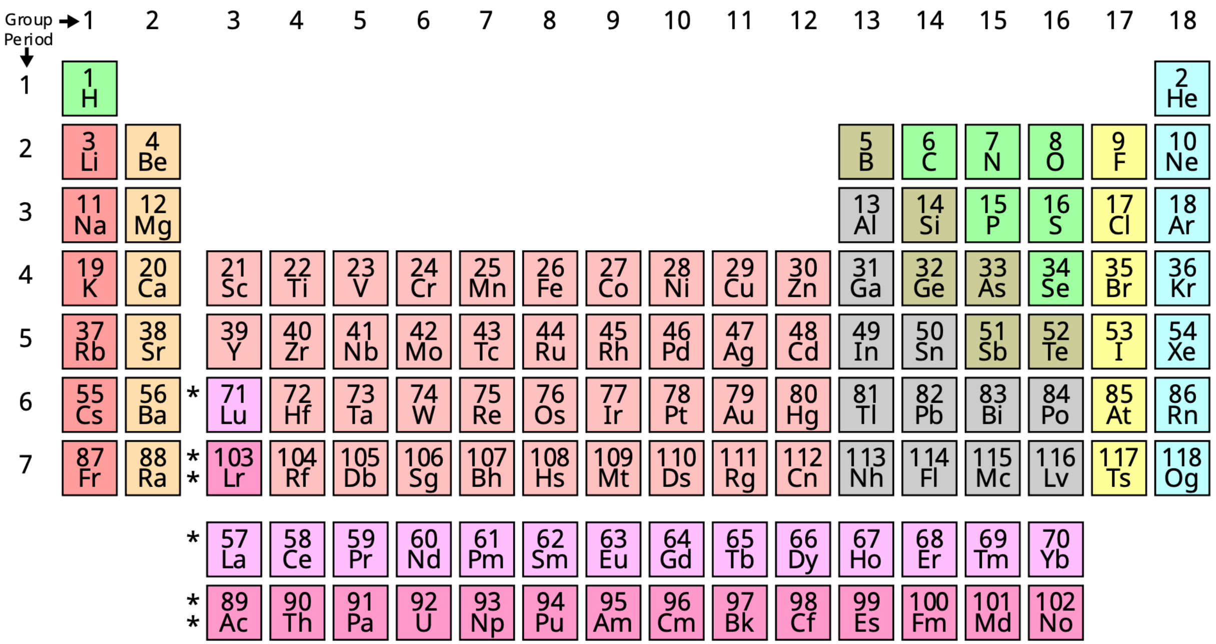
Great text on nuclear, particle, and neutrino physics

1. Giunti, C., Kim, C. W. (2007). ***Fundamentals of Neutrino Physics and Astrophysics***. United Kingdom: OUP Oxford.
2. Povh, B., Rith, K., Scholz, C., Zetsche, F., Rodejohann, W. (2015). ***Particles and Nuclei: An Introduction to the Physical Concepts***. Germany: Springer Berlin Heidelberg. ***7th Ed***.
3. Donnelly, T. W., Formaggio, J. A., Holstein, B. R., Milner, R. G., Surrow, B. (2017). ***Foundations of Nuclear and Particle Physics***. United Kingdom: Cambridge University Press.
4. Zuber, K. (2020). ***Neutrino Physics***. United Kingdom: CRC Press. ***3rd Ed***.
5. Rubbia, A. (2022). ***Phenomenology of Particle Physics***. United Kingdom: Cambridge University Press.

Part 1: Experimental Techniques

Elements

(Mendeleev, 1869)



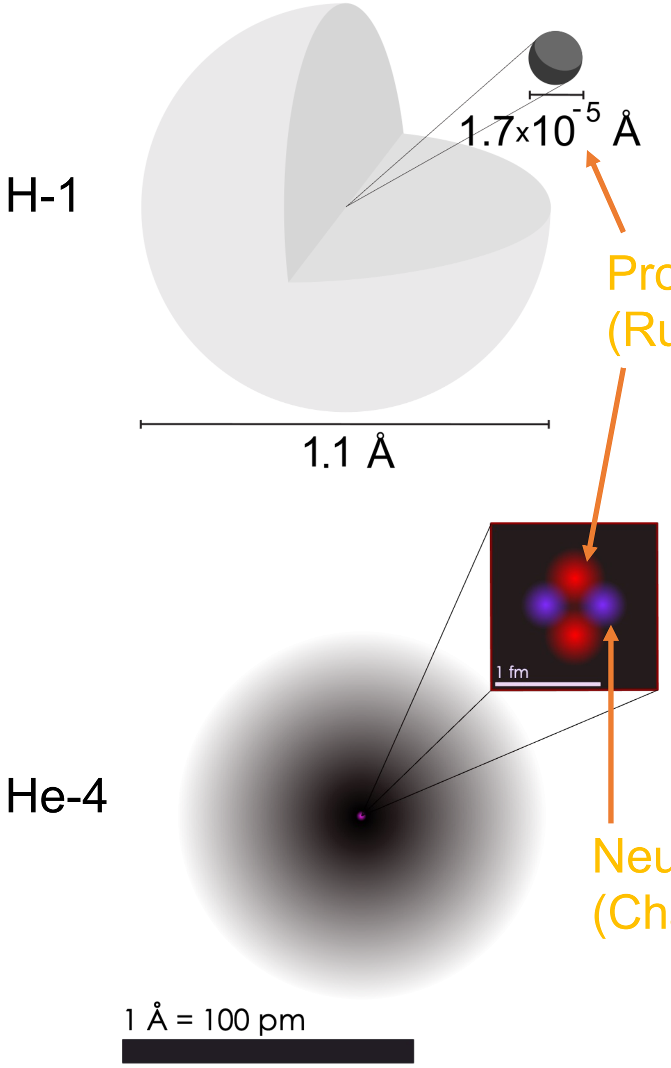
Quiz: How many neutrons does argon have?

Atom

Electron (J. J. Thomson, 1897)

Nucleus

(Rutherford, 1911)



Proton

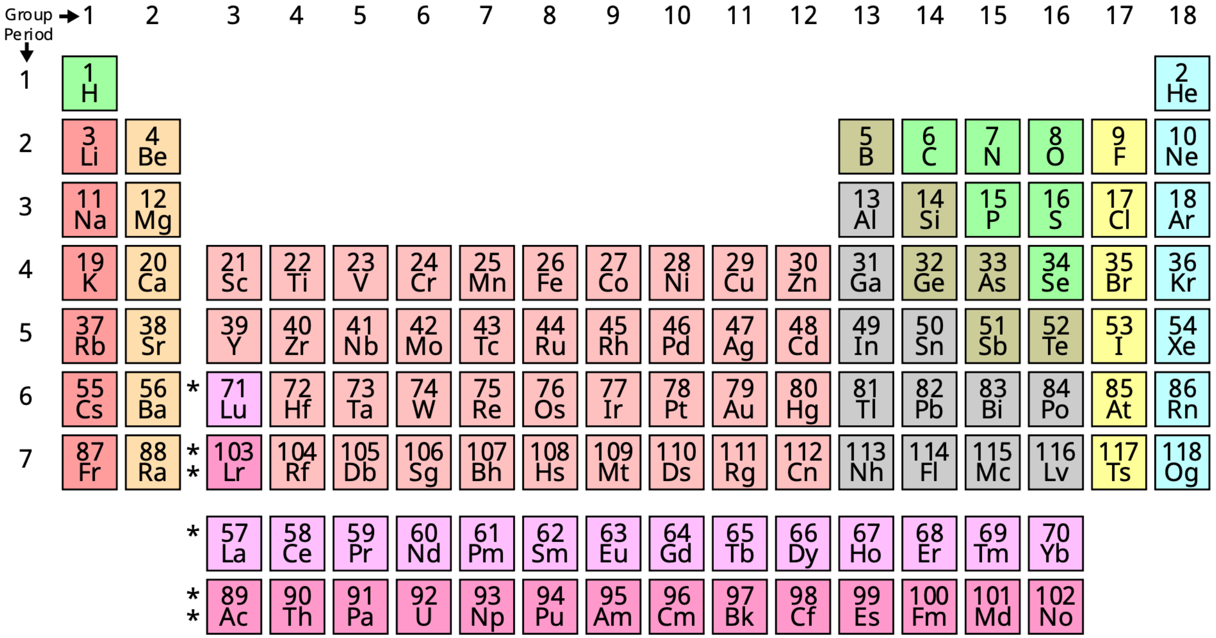
(Rutherford, 1919)

Neutron

(Chadwick, 1932)

Elements

(Mendeleev, 1869)



Quiz: How many neutrons does argon have?

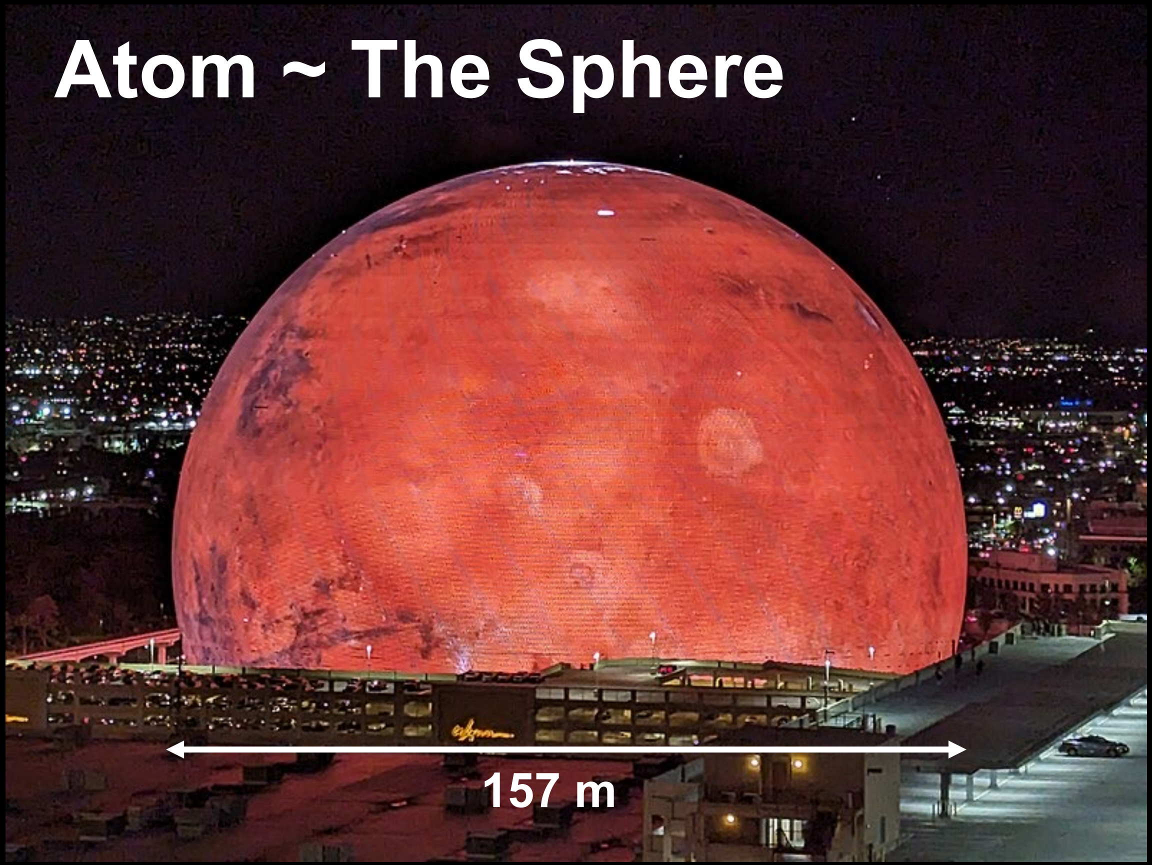
Atom

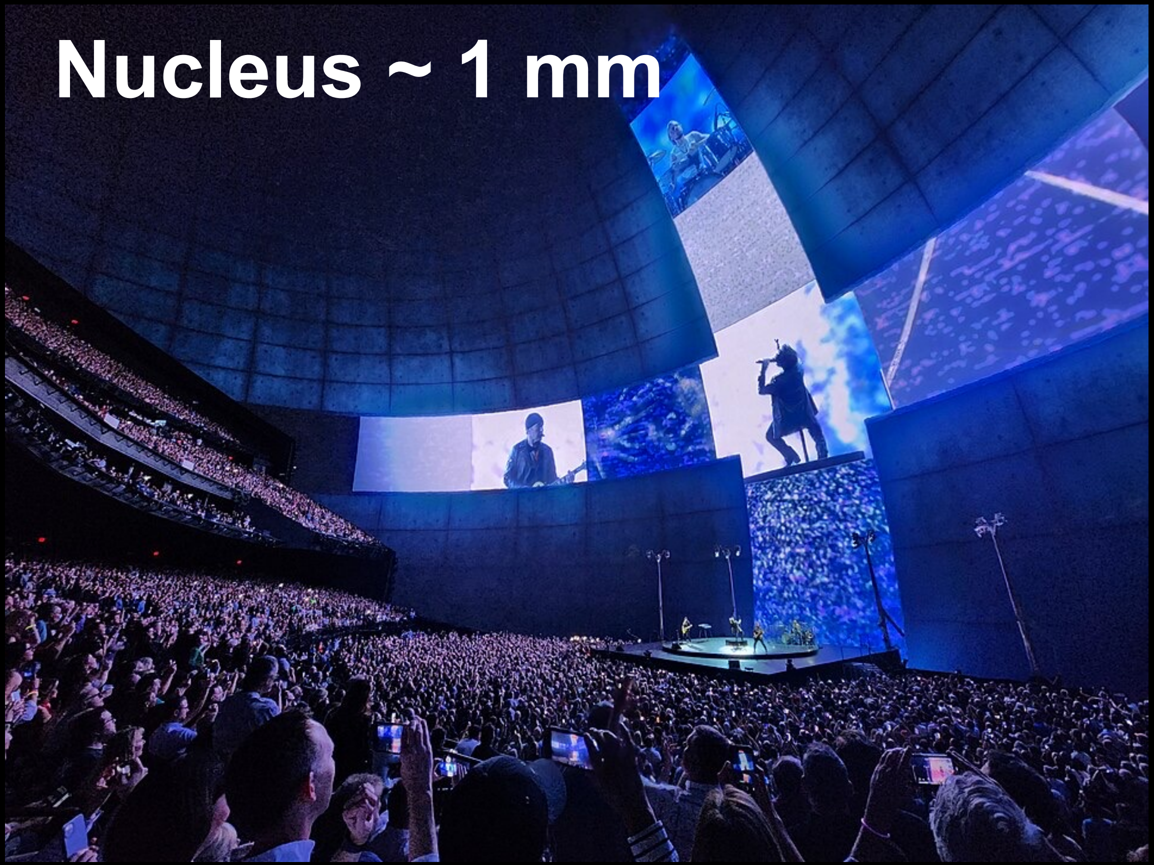
Electror 911)

l, 1919)

1932)

1 Å = 100 pm





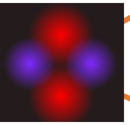
Source: https://en.wikipedia.org/wiki/Sphere_(venue)

Recall what we can do with atoms (how long did it take us?)

- ❑ Can we probe inside the nuclei? If yes, how?
- ❑ Can we manipulate the nucleus and nucleons?

… In the Three-*Body*-Problem (三体) universe, it would mean that we could make Droplets (水滴).

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



		I	II	III	I	II	III
QUARKS	mass / charge / spin	≃2.2 MeV/c² / ⅔ / ½	≃1.28 GeV/c² / ⅔ / ½	≃173.1 GeV/c² / ⅔ / ½	≃2.2 MeV/c² / −⅔ / ½	≃1.28 GeV/c² / −⅔ / ½	≃173.1 GeV/c² / −⅔ / ½
		u **up**	c **charm**	t **top**	$\bar{u}$ **antiup**	$\bar{c}$ **anticharm**	$\bar{t}$ **antitop**
QUARKS	mass / charge / spin	≃4.7 MeV/c² / −⅓ / ½	≃96 MeV/c² / −⅓ / ½	≃4.18 GeV/c² / −⅓ / ½	≃4.7 MeV/c² / ⅓ / ½	≃96 MeV/c² / ⅓ / ½	≃4.18 GeV/c² / ⅓ / ½
		d **down**	s **strange**	b **bottom**	$\bar{d}$ **antidown**	$\bar{s}$ **antistrange**	$\bar{b}$ **antibottom**
LEPTONS	mass / charge / spin	≃0.511 MeV/c² / −1 / ½	≃105.66 MeV/c² / −1 / ½	≃1.7768 GeV/c² / −1 / ½	≃0.511 MeV/c² / 1 / ½	≃105.66 MeV/c² / 1 / ½	≃1.7768 GeV/c² / 1 / ½
		e **electron**	μ **muon**	τ **tau**	e^+ **positron**	$\bar{\mu}$ **antimuon**	$\bar{\tau}$ **antitau**
LEPTONS	mass / charge / spin	<2.2 eV/c² / 0 / ½	<0.17 MeV/c² / 0 / ½	<18.2 MeV/c² / 0 / ½	<2.2 eV/c² / 0 / ½	<0.17 MeV/c² / 0 / ½	<18.2 MeV/c² / 0 / ½
		ν_e **electron neutrino**	ν_μ **muon neutrino**	ν_τ **tau neutrino**	$\bar{\nu}_e$ **electron antineutrino**	$\bar{\nu}_\mu$ **muon antineutrino**	$\bar{\nu}_\tau$ **tau antineutrino**

Neutrinos in SM

1. Electric charge = 0
2. Mass = 0
3. Have flavours

In **nature**, neutrino mass gap leads to oscillations.

In **practice**, neutrino mass can be neglected in neutrino interactions.

Neutrino Mass

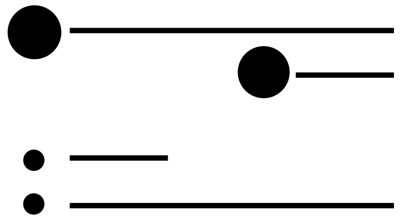
Standard Model | Beyond Standard Model

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

Pontecorvo–Maki–Nakagawa–Sakata

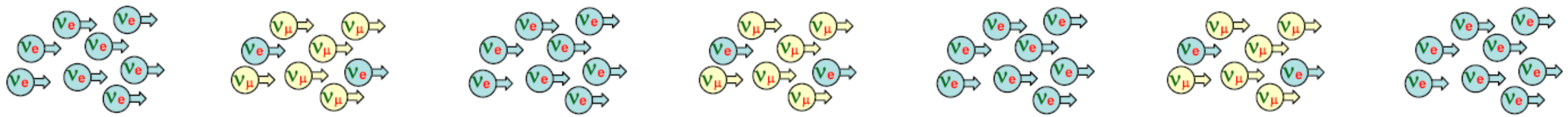
PMNS matrix

Mass Ordering



Normal **Inverted**

Δm^2 leads to neutrino oscillations



Mark Thomson, 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

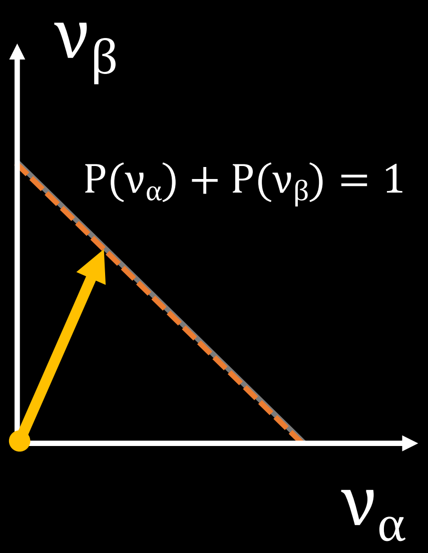
θ_{23}: mixing between ν_μ and ν_τ

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

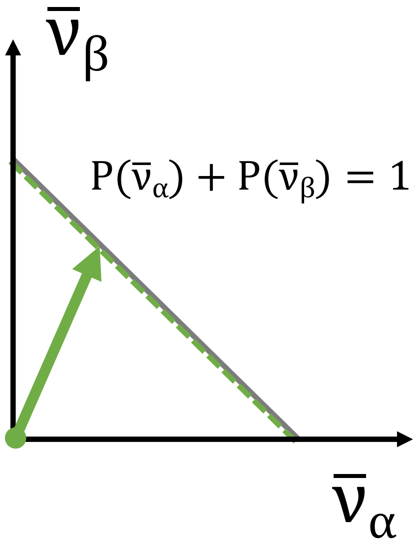
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}\nu_1'\\ \nu_2'\\ \nu_3\end{pmatrix}$$

$\theta_{13} = 0$

2-flavor oscillation



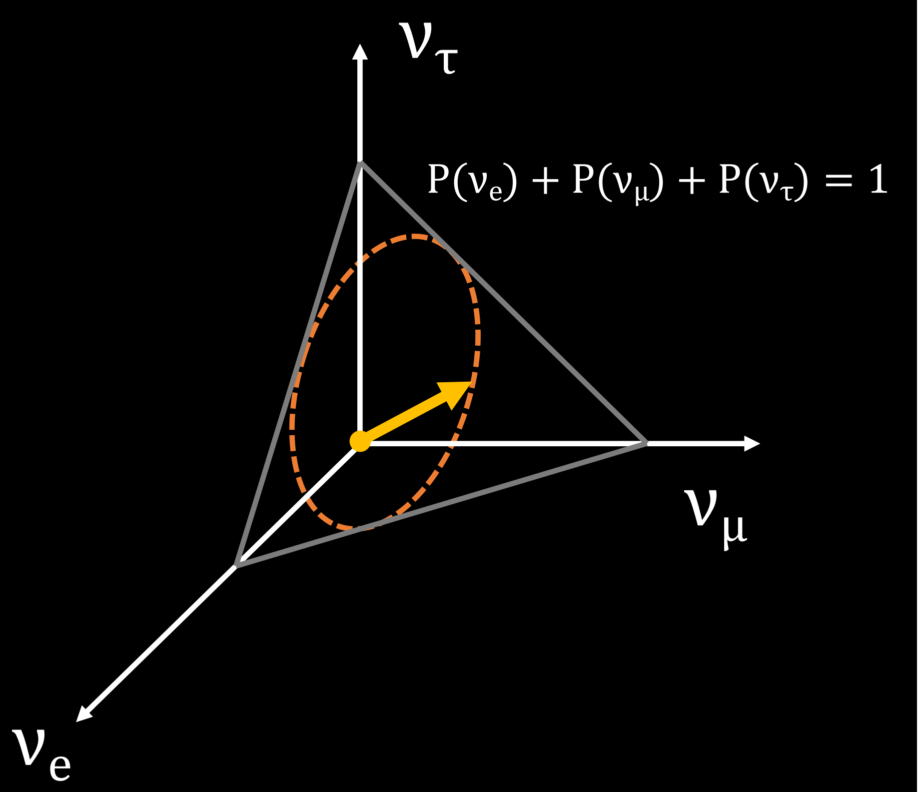
Antineutrinos



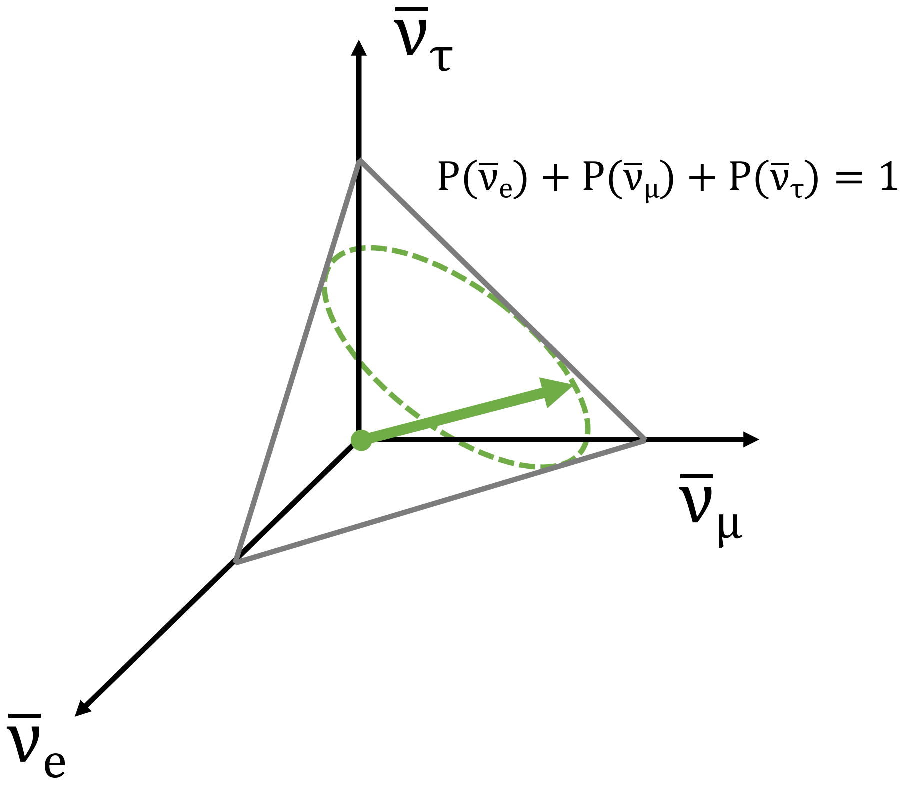
Oscillation as a function of *time*
line-in-**line** → same trivia

$\theta_{13} \neq 0$

3-flavor oscillation



Antineutrinos



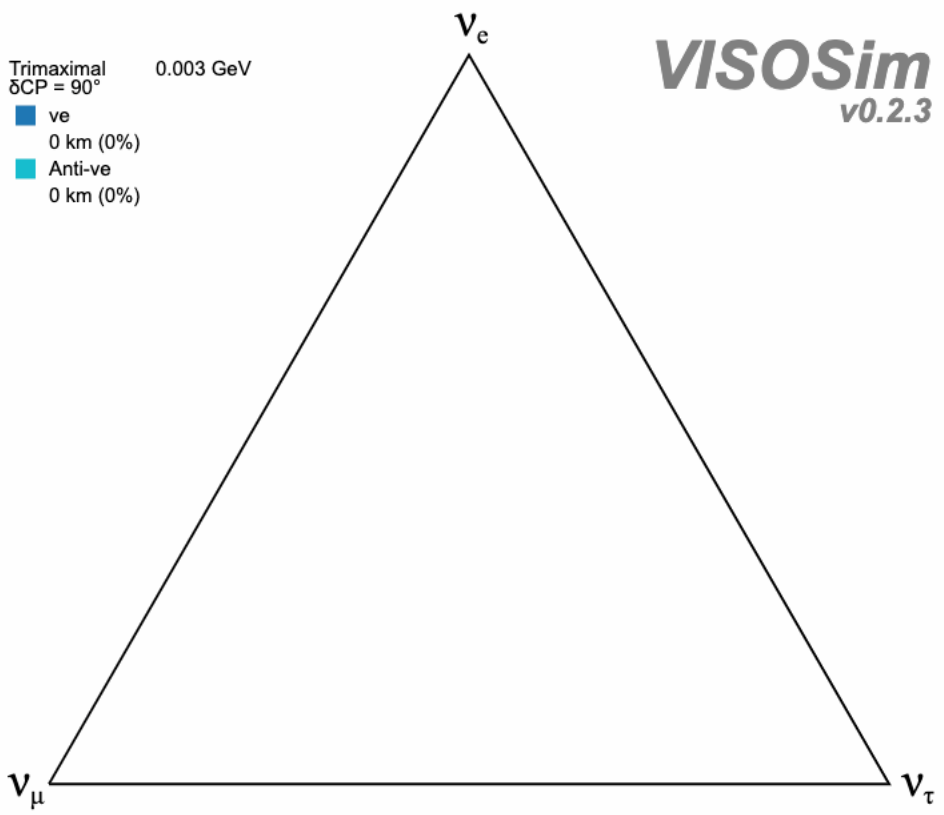
Oscillation as a function of *time*
line-in-**plane** → CP-violation possible

PMNS

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

Trimaximal mixing
— maximally CP-violating

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



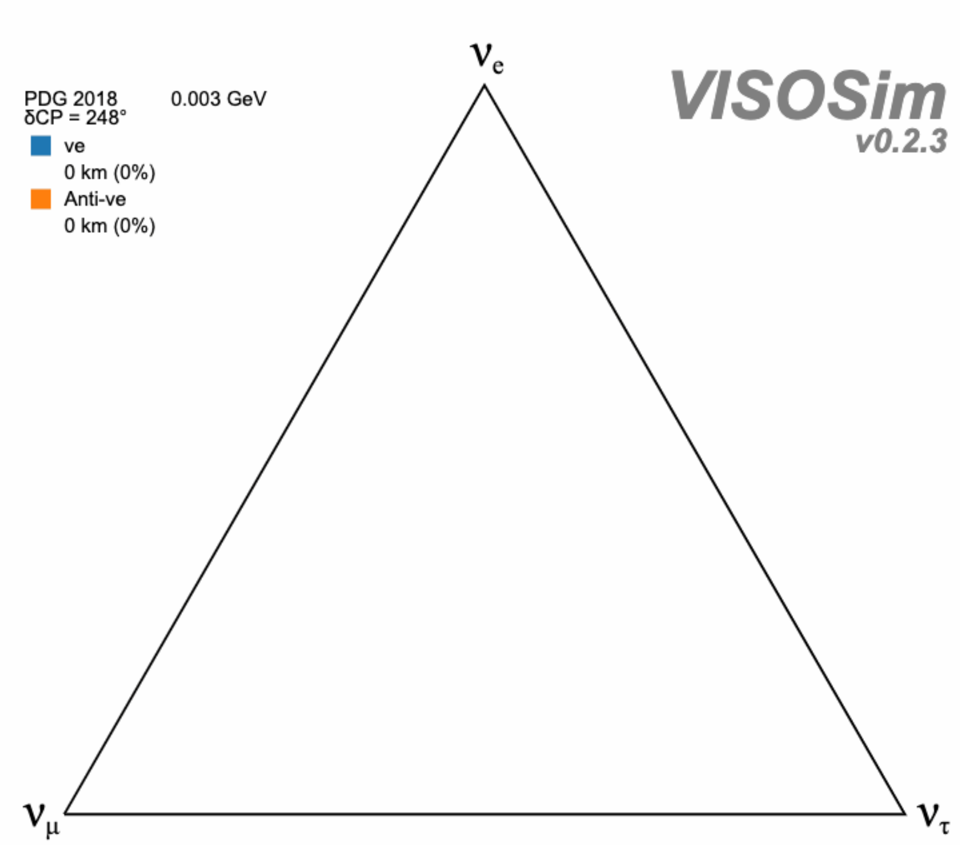
☛ VISOS

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

How Nature might work:

$$\begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu 1}| & |U_{\mu 2}| & |U_{\mu 3}| \\ |U_{\tau 1}| & |U_{\tau 2}| & |U_{\tau 3}| \end{bmatrix}$$

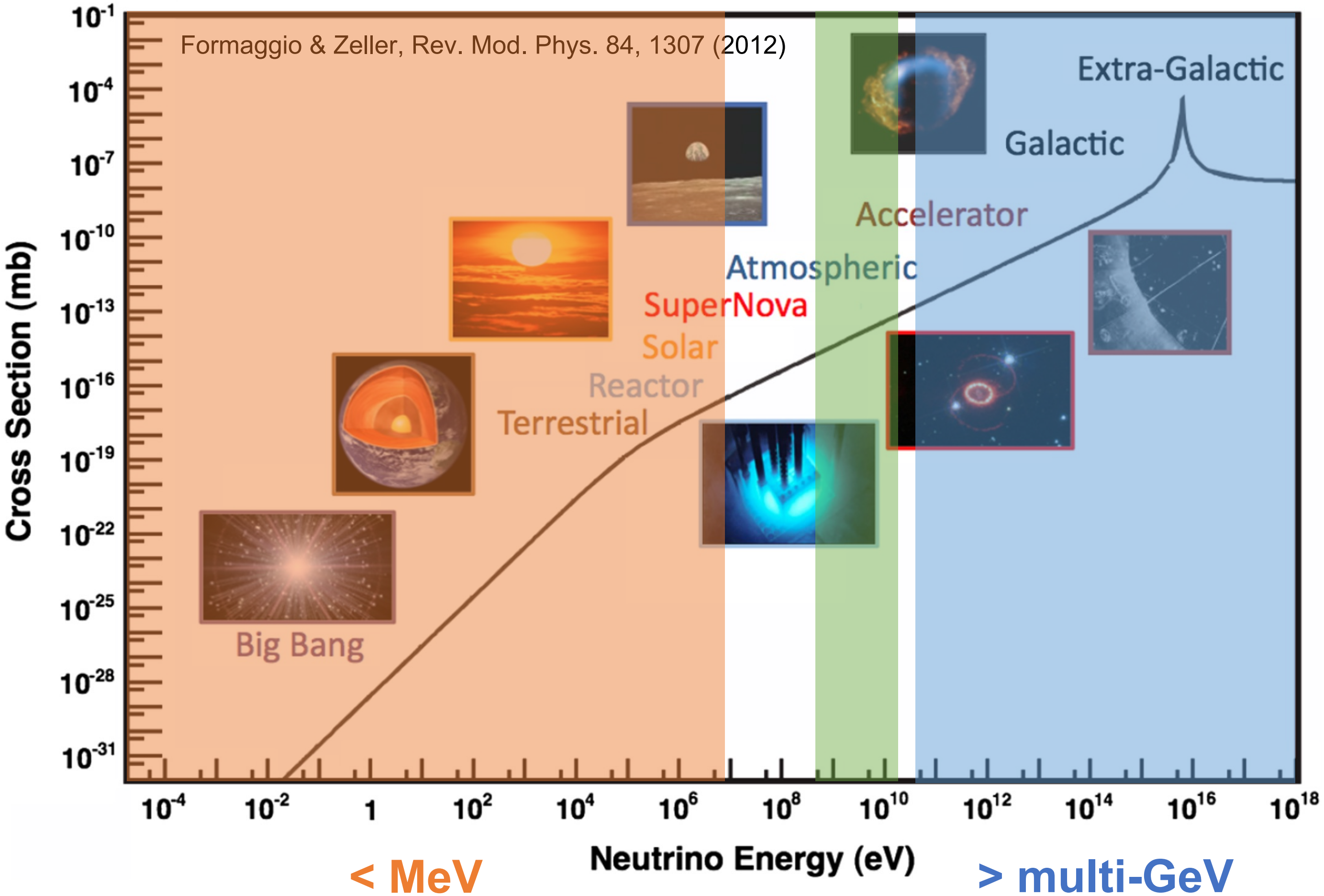
$$= \begin{bmatrix} 0.801 \ldots 0.845 & 0.513 \ldots 0.579 & 0.143 \ldots 0.156 \\ 0.233 \ldots 0.507 & 0.461 \ldots 0.694 & 0.631 \ldots 0.778 \\ 0.261 \ldots 0.526 & 0.471 \ldots 0.701 & 0.611 \ldots 0.761 \end{bmatrix}$$



☛ VISOS

Why Study GeV (= atmospheric + accelerator)?

GeV
See single/pair/cluster nucleons
Models (+guess/intuition)



< MeV
See the whole nucleus
Nuclear database

> multi-GeV
See individual quarks
pQCD, EW

Physical reasons

Neutrino for *CP*-violation

- ❑ Need to detect *accelerator* neutrinos at *O*(1) GeV

GeV-neutrinos also relevant for

- ❑ Mass hierarchy measurement via atmospheric neutrino oscillations
- ❑ Background to rare event searches

Technical reasons

Difficult to *control*

✓ *Control*: we know how good/bad things are.

Quiz: Here is a model

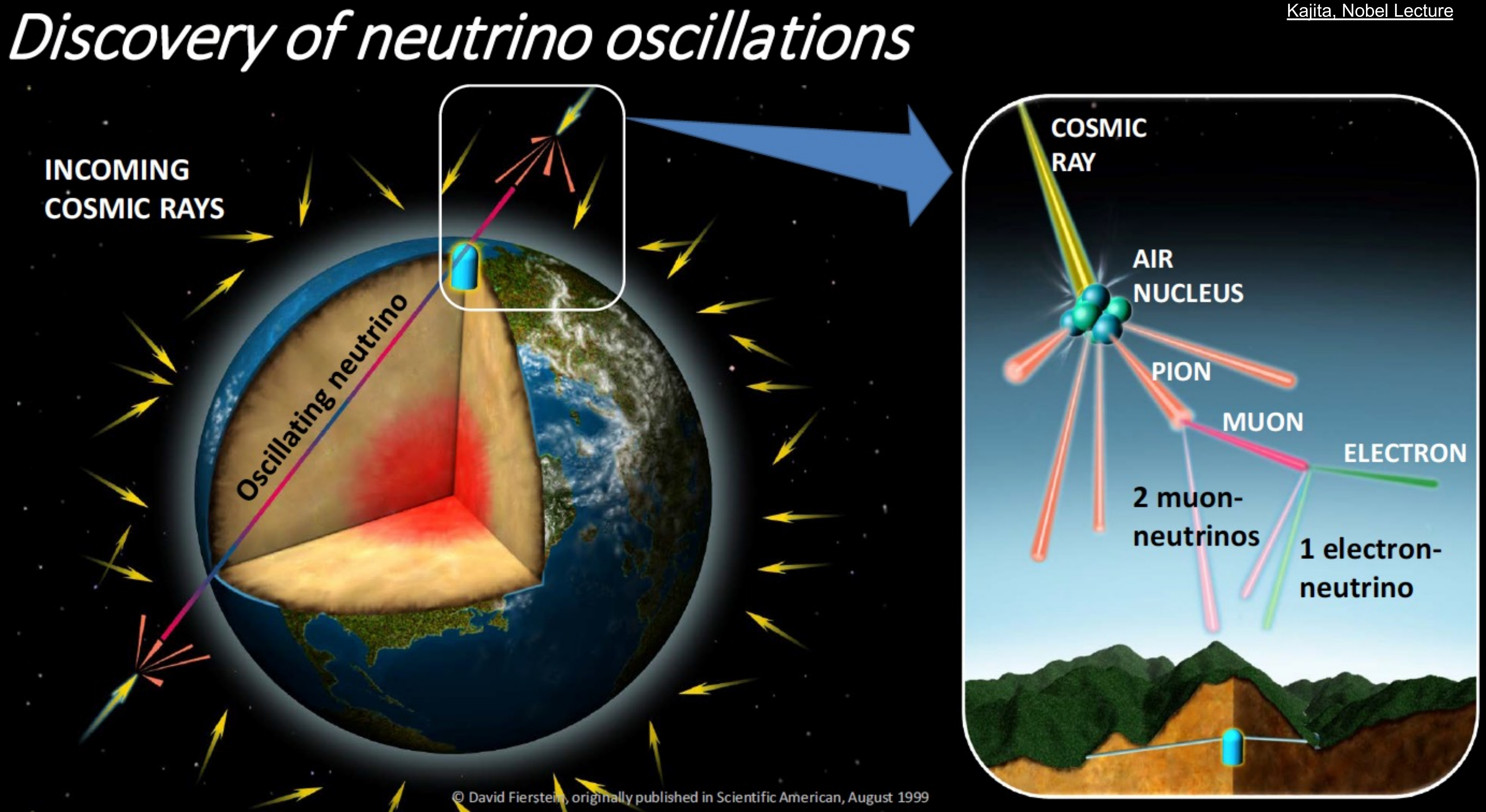
$$1\ year = \pi \times 10^{\#days\ of\ a\ week}\ seconds$$

It is wrong by a few __%.

A: 10 *B: 1* *C: 0.1*

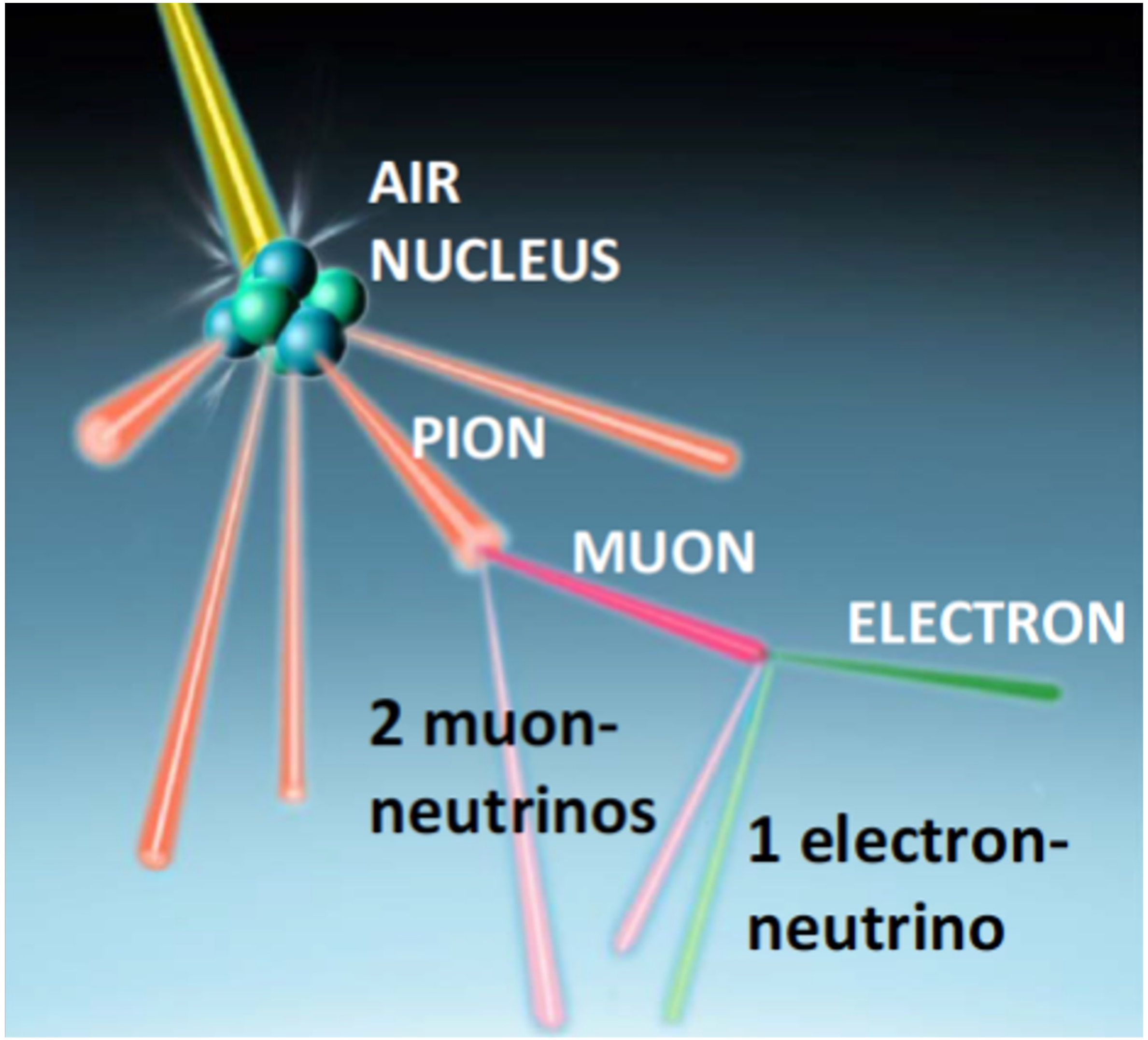
Atmospheric Neutrinos

Kajita, Nobel Lecture



Accelerator Neutrinos

How to obtain a controlled sample of neutrinos?



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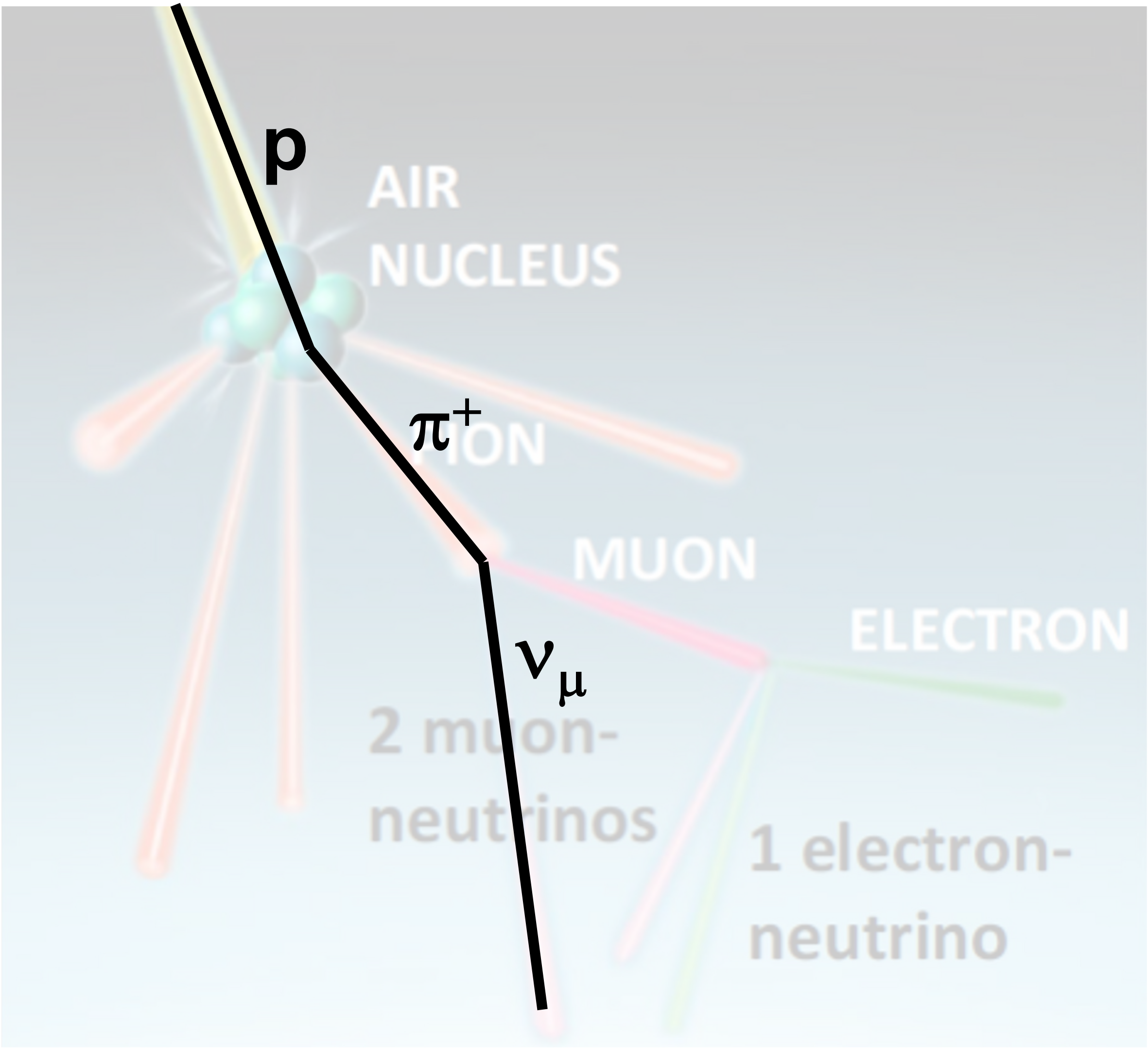
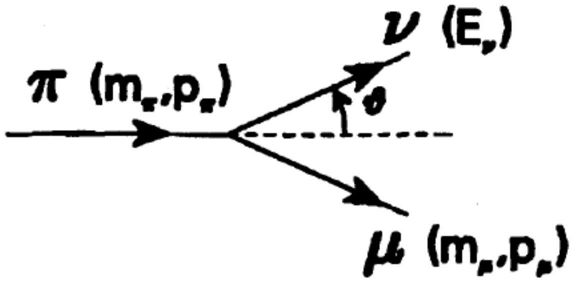


Let's start from π decays



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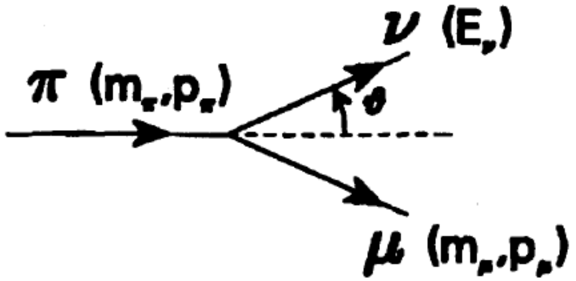

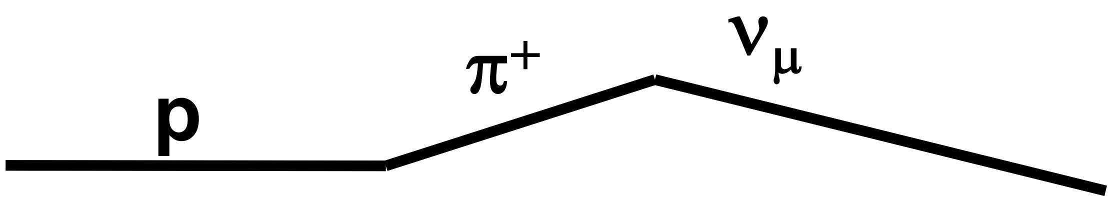

Accelerator Neutrinos

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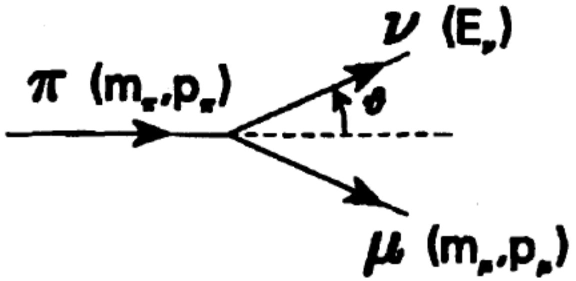
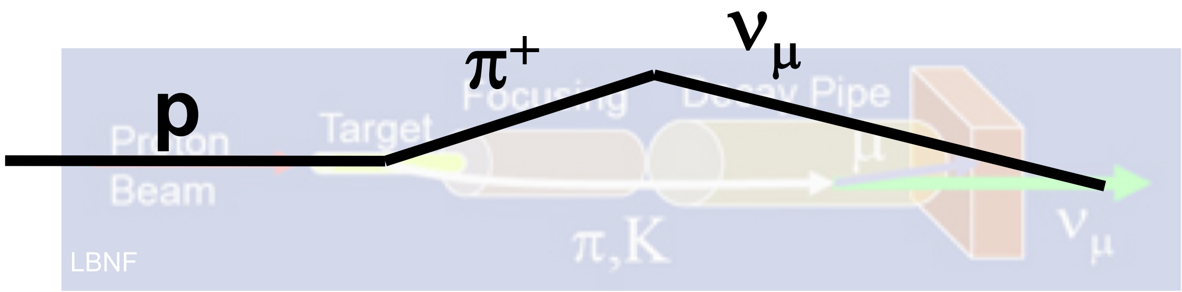




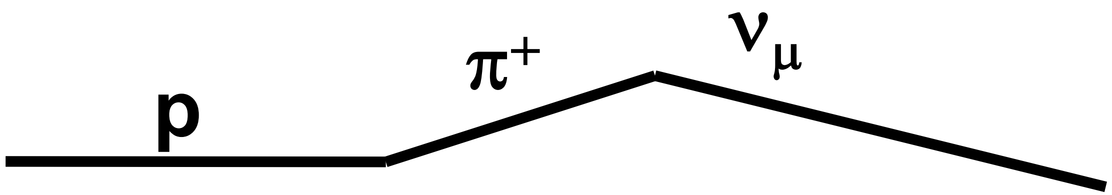
"β decay" of energetic collision products (mostly ν_μ from π)

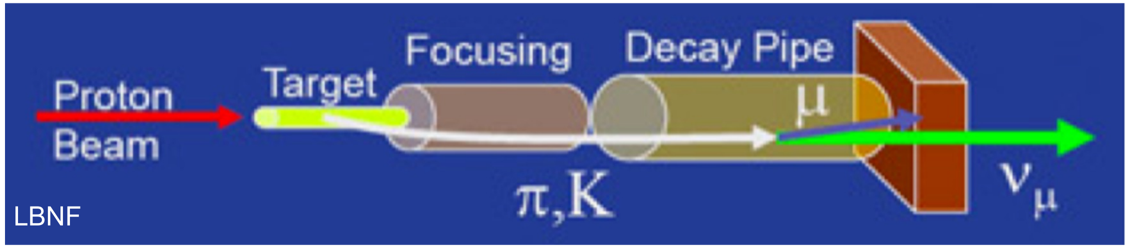
Neutrino beams from accelerators → Directional

Charge selection on π → High purity ν or $\bar{\nu}$ beams

Accelerator Neutrinos

How to obtain a controlled sample of neutrinos?





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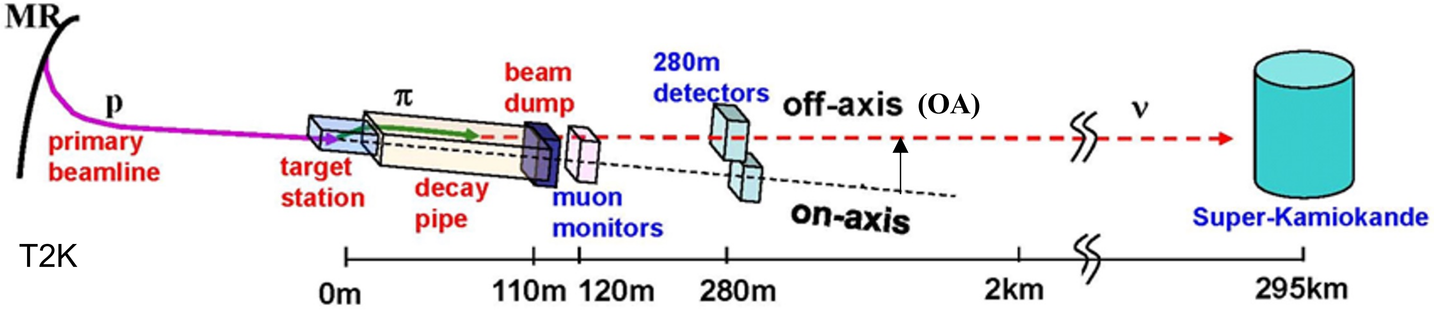
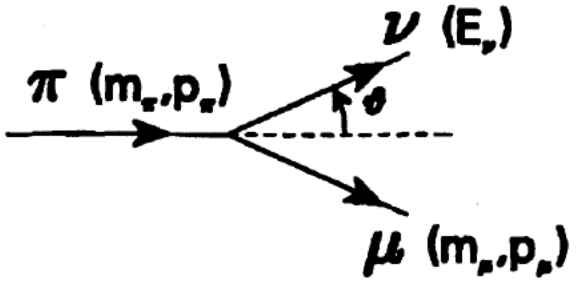
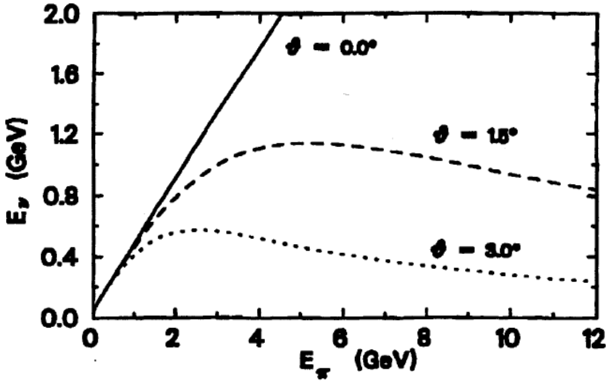


Let's start from π decays



From energy, momentum conservation

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

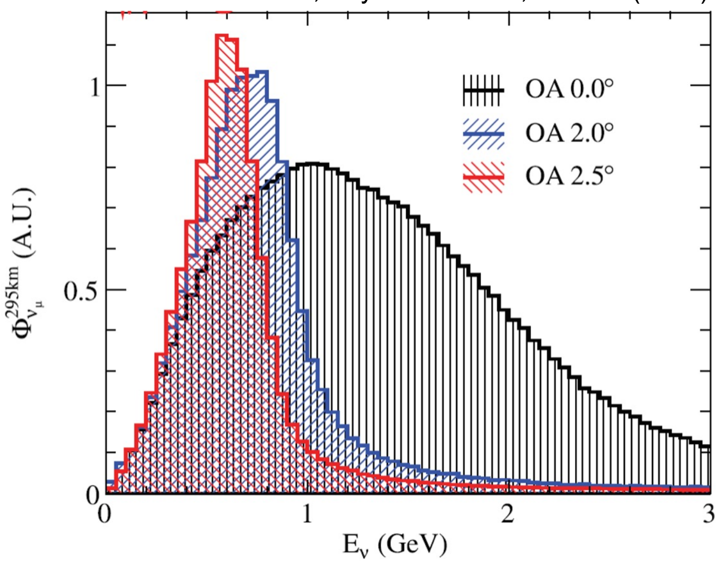


Off-axis (OA) technique → Narrow-band beams

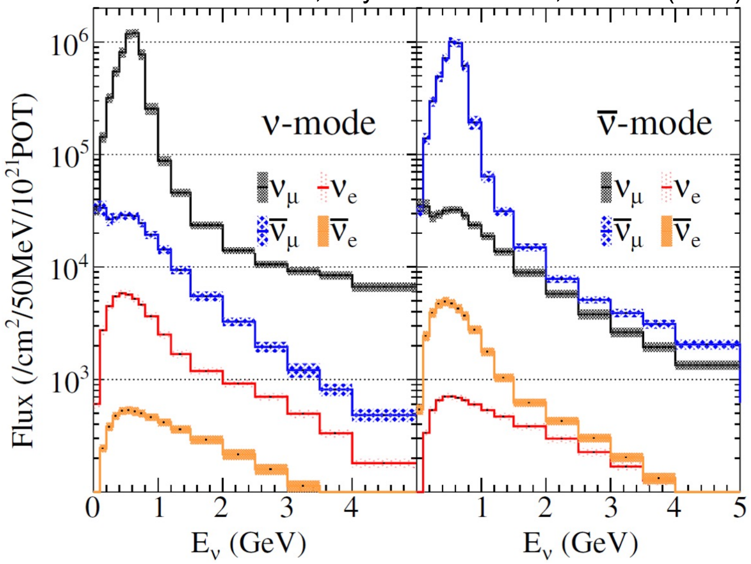
D. Beavis, et al., P889: long baseline neutrino oscillation experiment at the AGS, Report No. BNL-52459, April, 1995

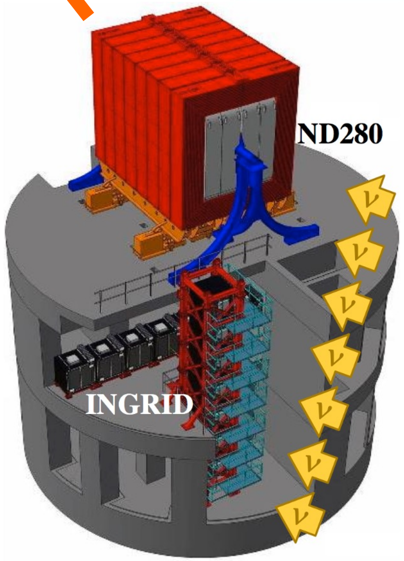
Accelerator Neutrino Experiments

T2K, Phys. Rev. D 87, 012001 (2013)



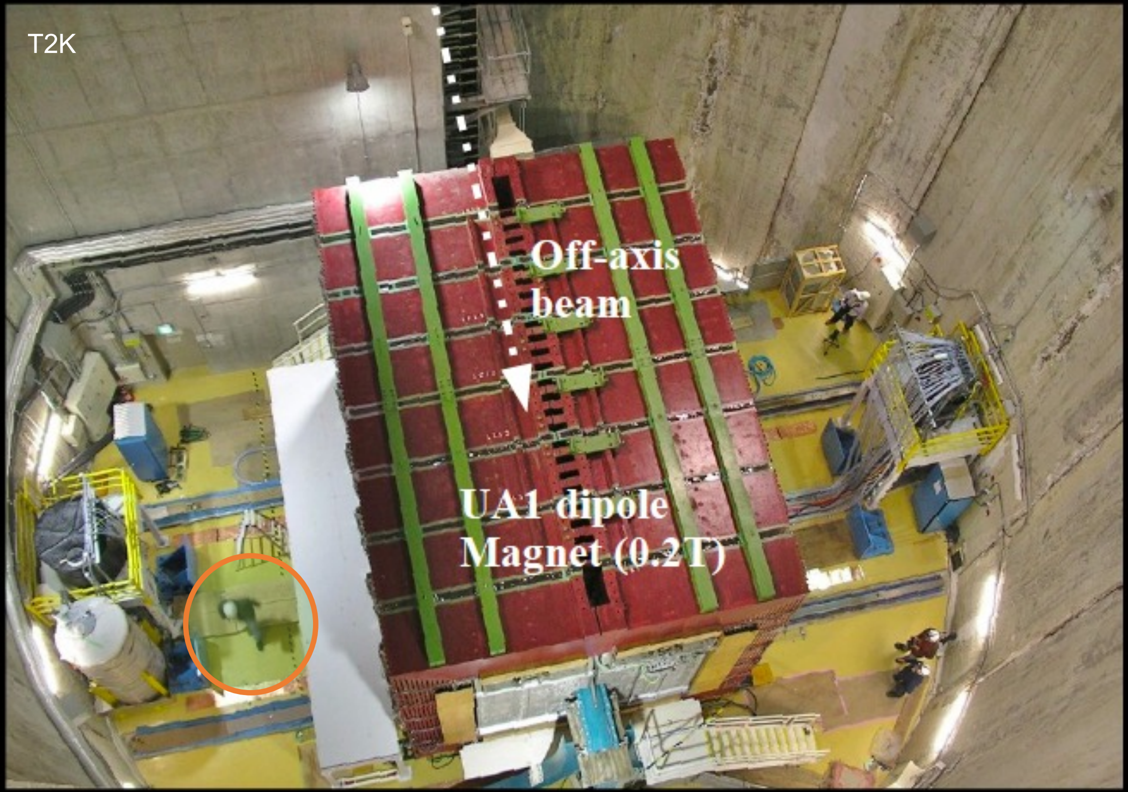
T2K, Phys.Rev.Lett. 116, 181801 (2016)



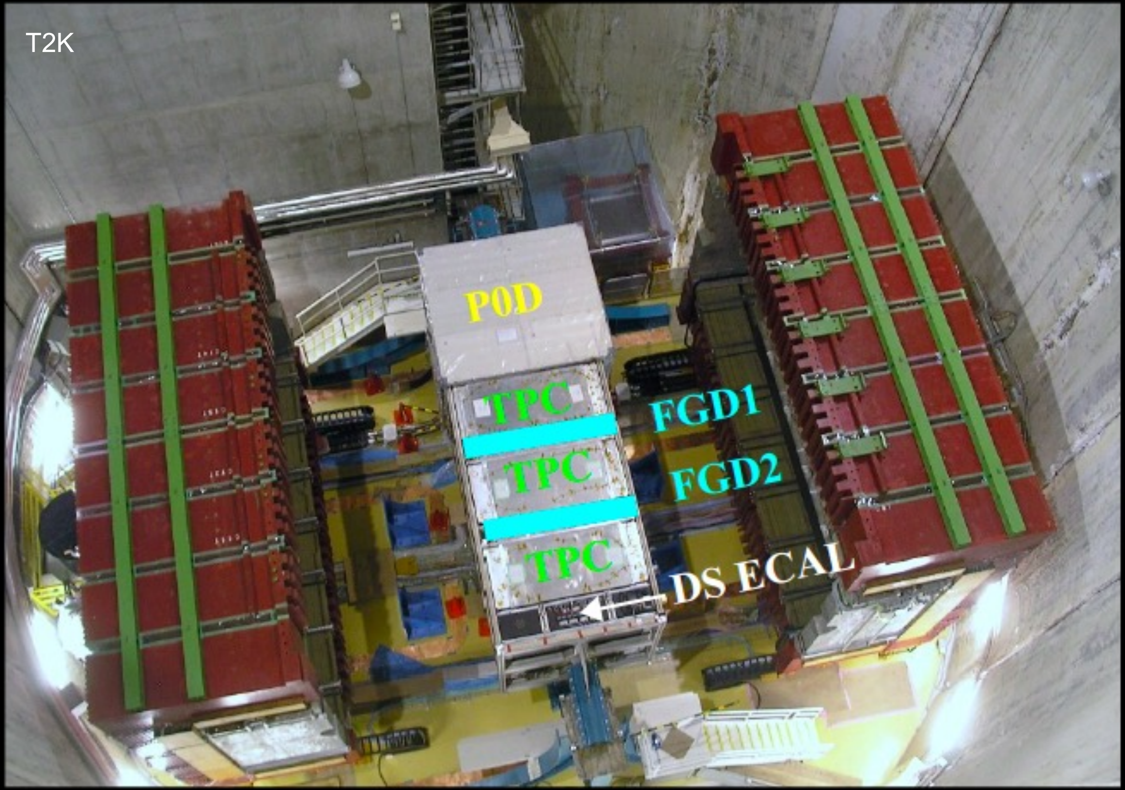


Near Detector

T2K off-axis near detector (ND280)



T2K off-axis near detector (ND280)



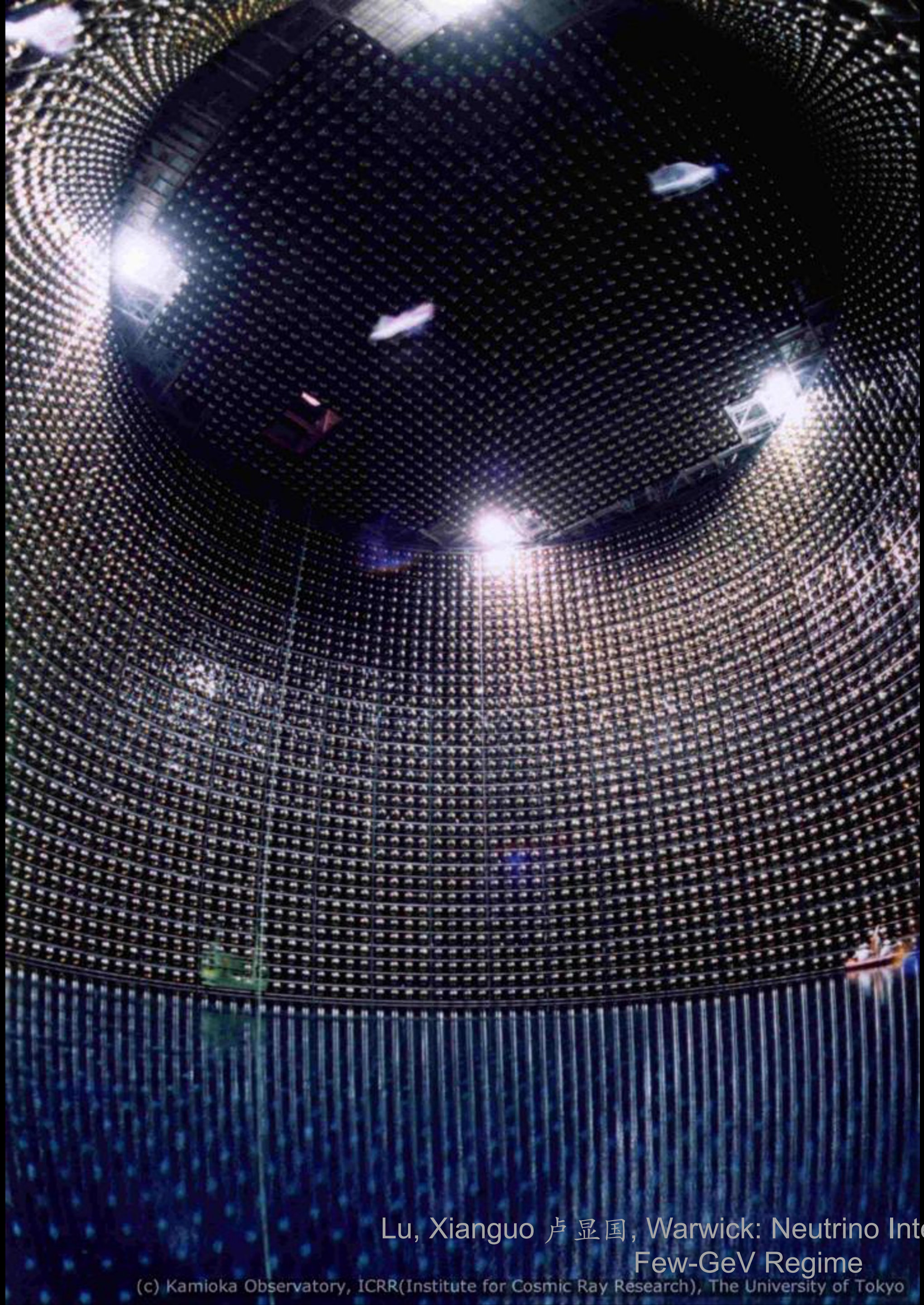
P0D: Pi0 Detector
contains H_2O targets

Tracker:
- FGD: Fine-Grained Detector
  1. plastic scintillator C_8H_8 target
  2. $C_8H_8 + H_2O$ target
- TPC

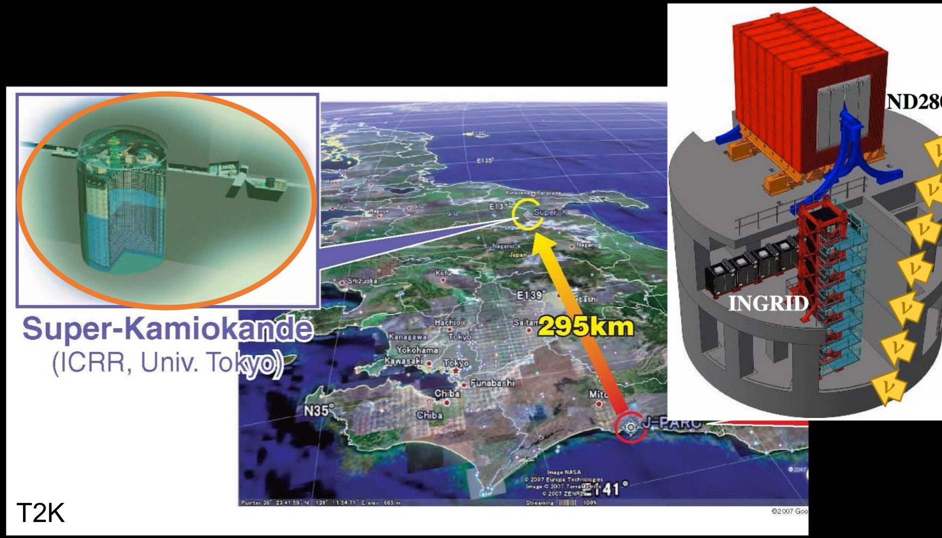
ECAL:
surrounding P0D and tracker

Side Muon Range Detector:
in magnet yokes

→
- constrain beam flux and cross section for oscillation analysis
- stand-alone neutrino interaction measurements



Water Cherenkov detector

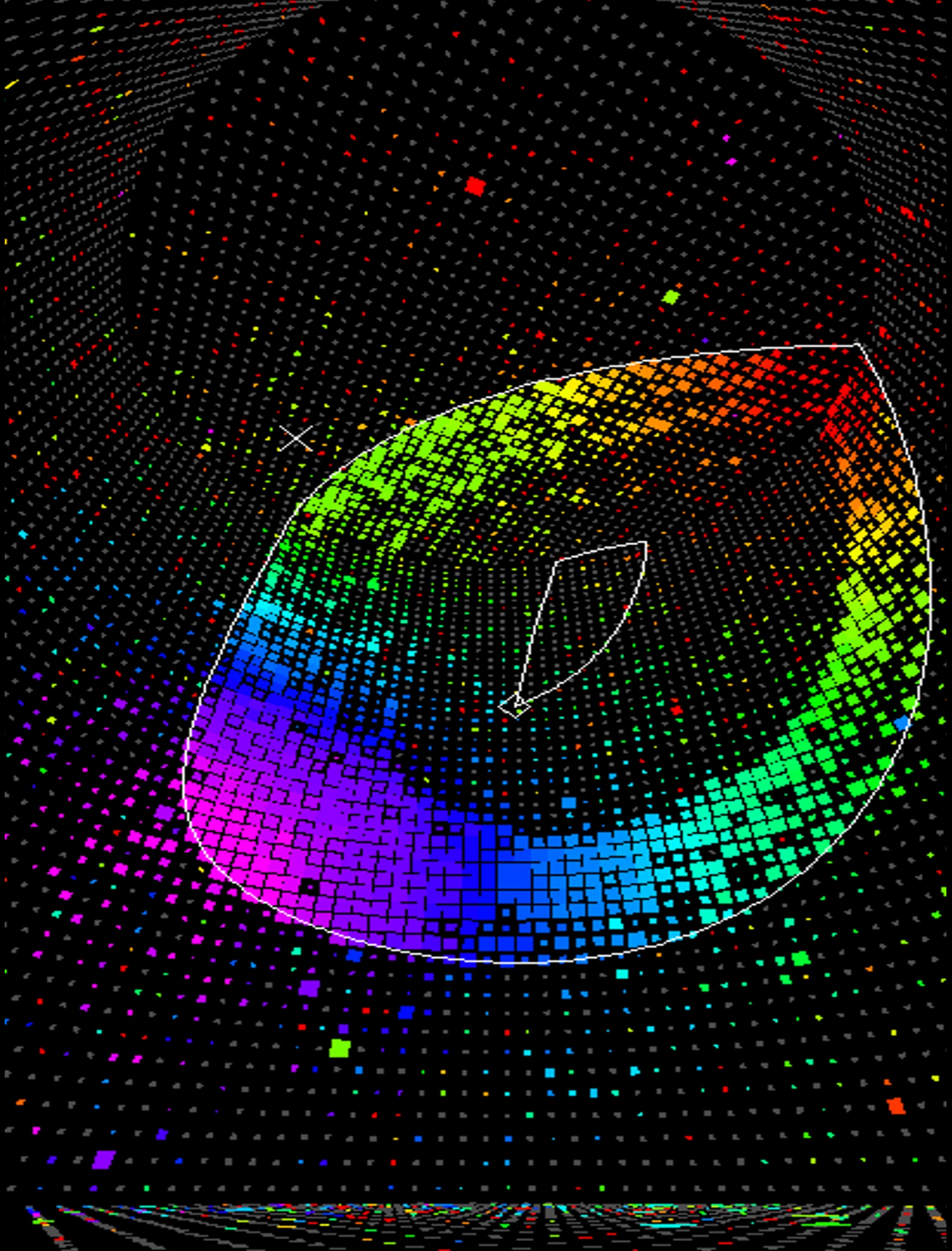


50 kt water Cherenkov

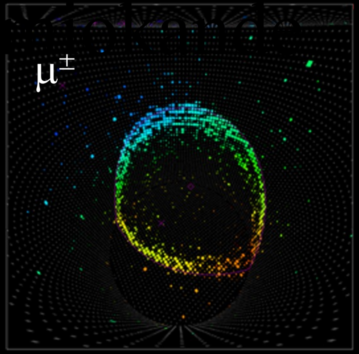
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector
  - time and amplitude of Cherenkov light

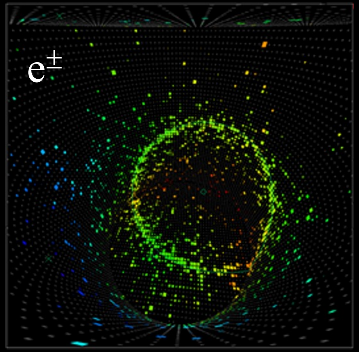
Quiz:
Assuming height=diameter, what is the diameter of the 50kt-water tank in meters?

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



Water Cherenkov detector





SuperK

Homework: Calculate the Cherenkov light threshold (in total energy, kinetic energy, and momentum) for e, μ, π^+, K^+, p, τ.

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

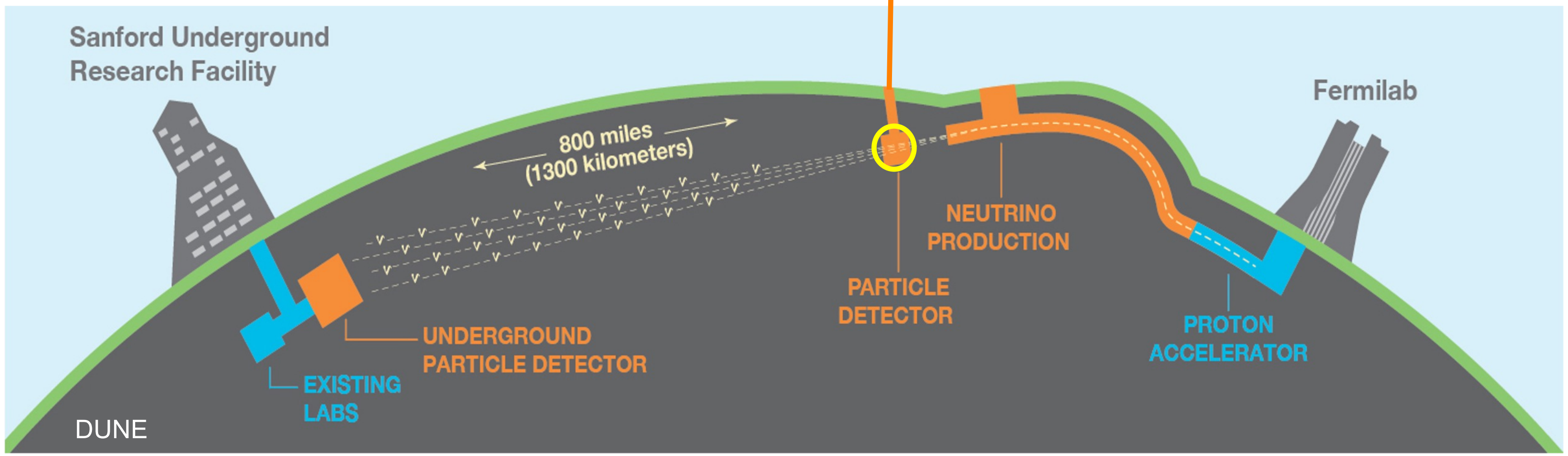
Accelerator Neutrino Experiments

T2K / Hyper-K

NOvA

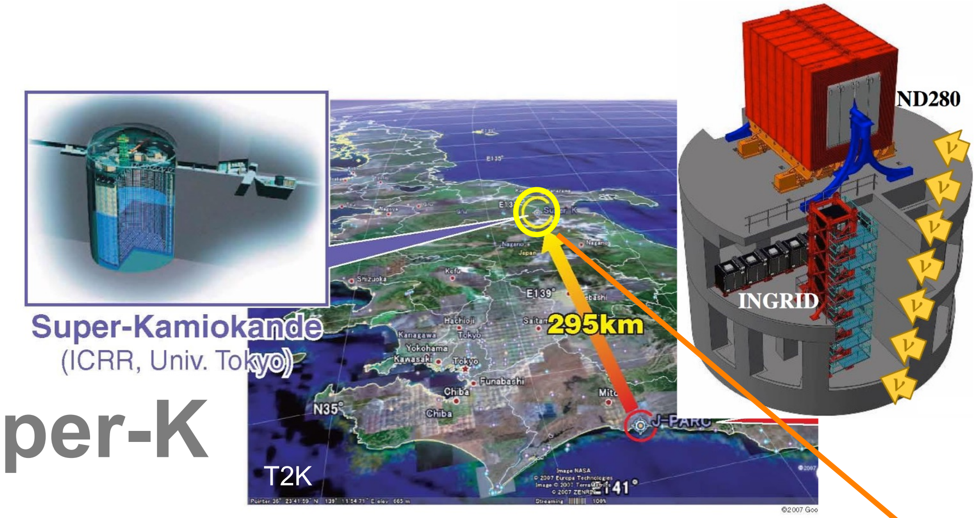
Near Detectors to measure ν interaction

DUNE



Accelerator Neutrino Experiments

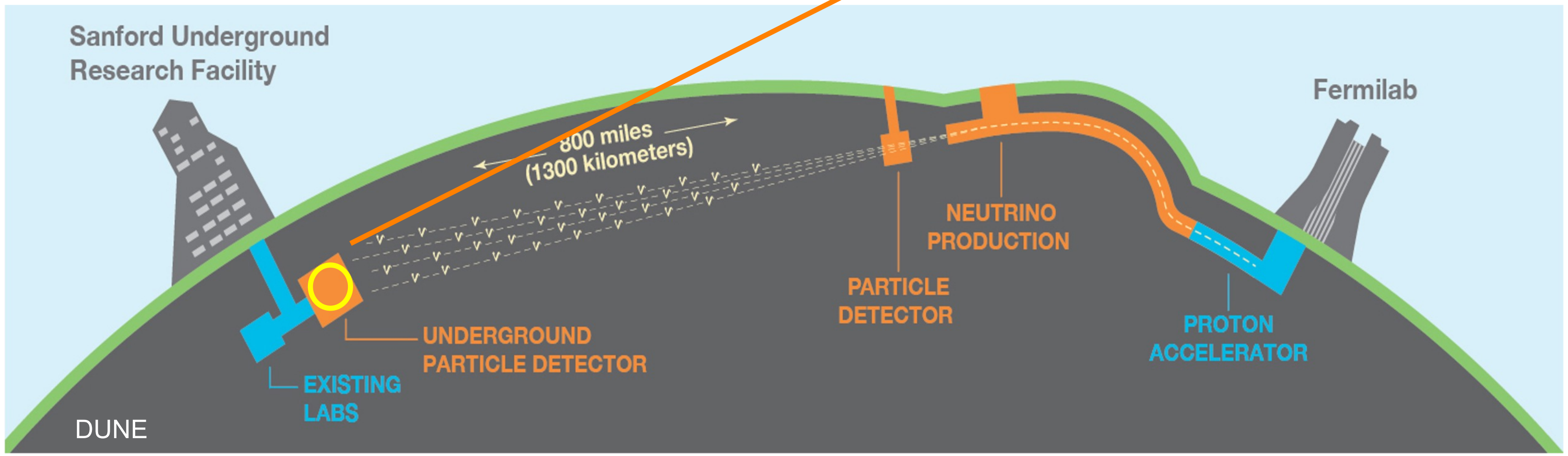
T2K / Hyper-K



Far Detectors to measure ν oscillation

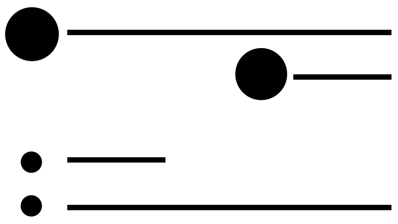
NOvA

DUNE

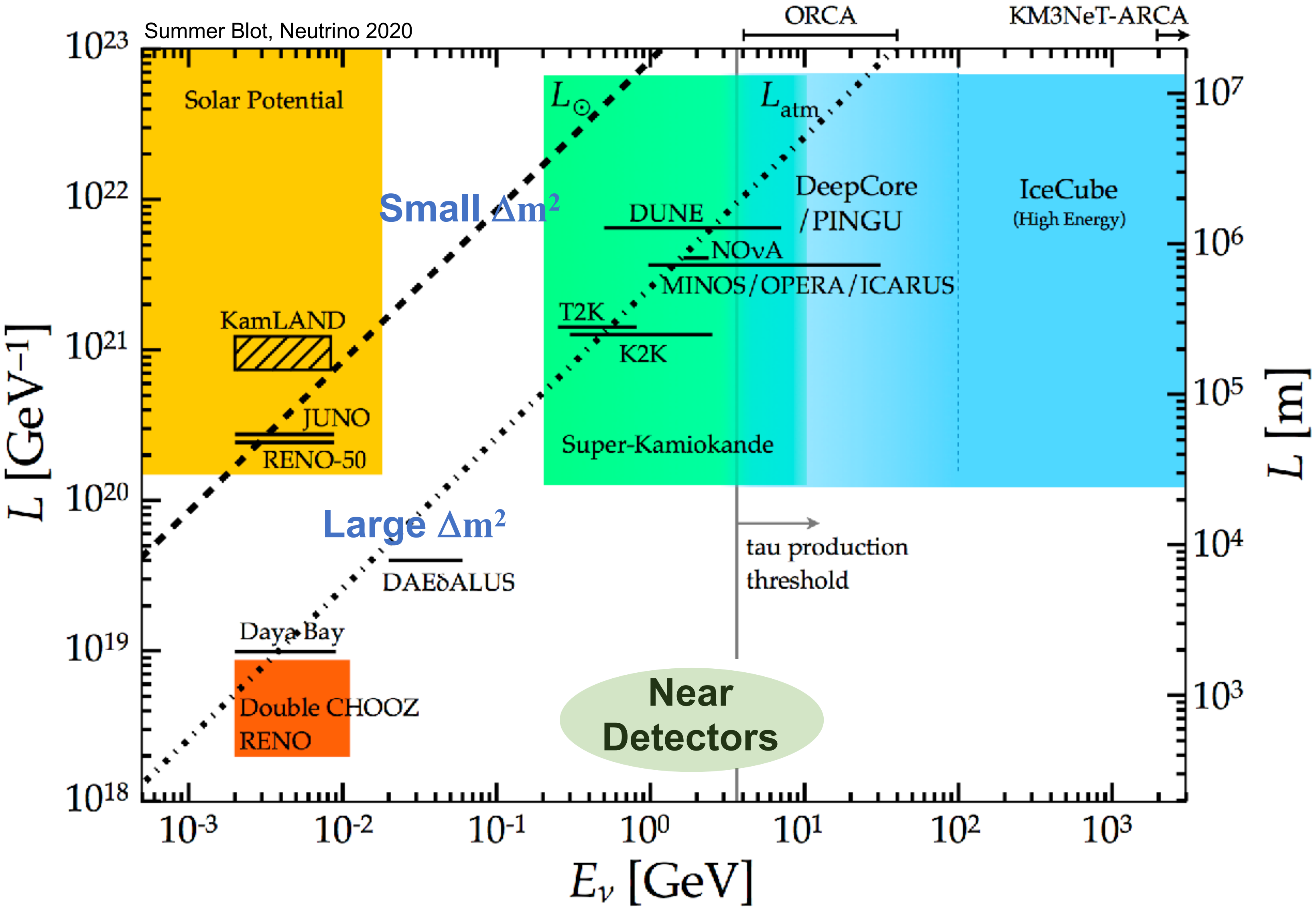


Oscillation phase ~ $\Delta m^2 L/E$

Only two Δm^2



Normal **Inverted**



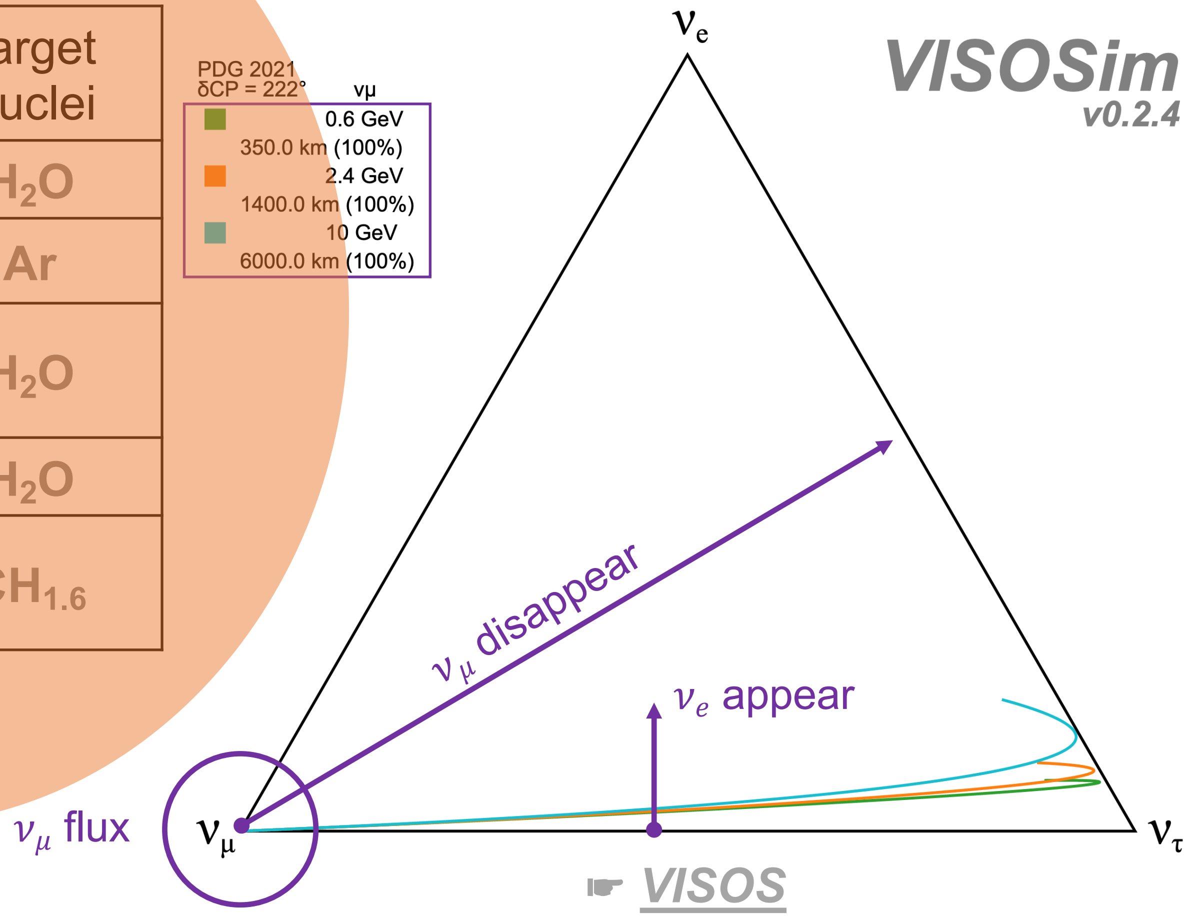
Detector considerations

❖ Accelerator and atmospheric GeV-ν experiments

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.

❖ ν_μ flux*: ν_μ disappear, ν_e appear



Detector

Sensing ν interactions

Homework: Calculate proton momentum for 10 MeV and 100 MeV kinetic energy.

Embedded in detector, incomplete particle information

- **Tracking**/Cherenkov **threshold**
- Angular acceptance
- Particle Identification (PID)
- Neutrals
- Noise

Proton Range $\sim (\text{kinetic energy})^2 / (\text{material density})$

(Range: how far a particle can travel in a medium)

vs

Kinetic Energy

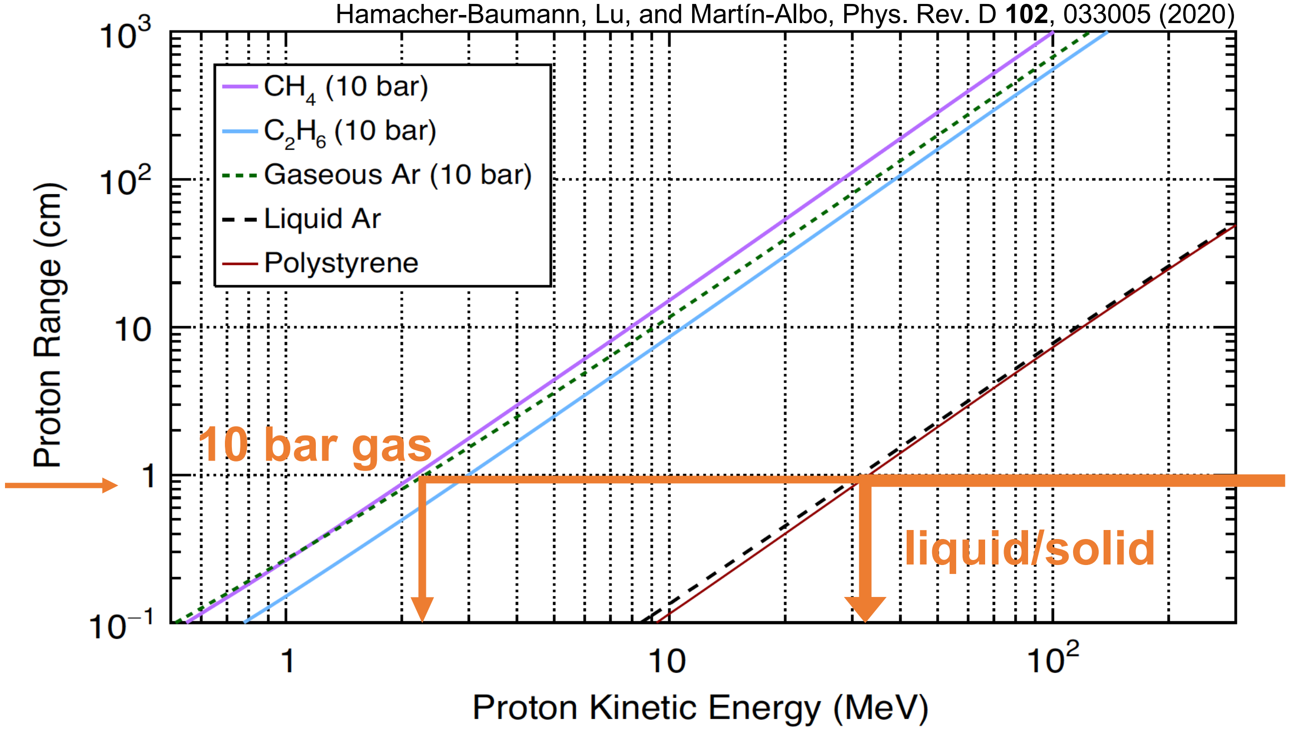
Quiz: Air density at STP in kg/m³? What about water (in its usual liquid condition)?

A: 10^3 B: 1 C: 10^{-3}

Quiz: Density ratio between liquid air and water (at their own conditions)? What about polystyrene (a kind of plastics) vs. water?

A: 10 B: 1 C: 0.1

Sensor granularity ~ mm-cm



Tracking threshold

(no momentum measurement possible below it)

~ few MeV for 10 bar gas

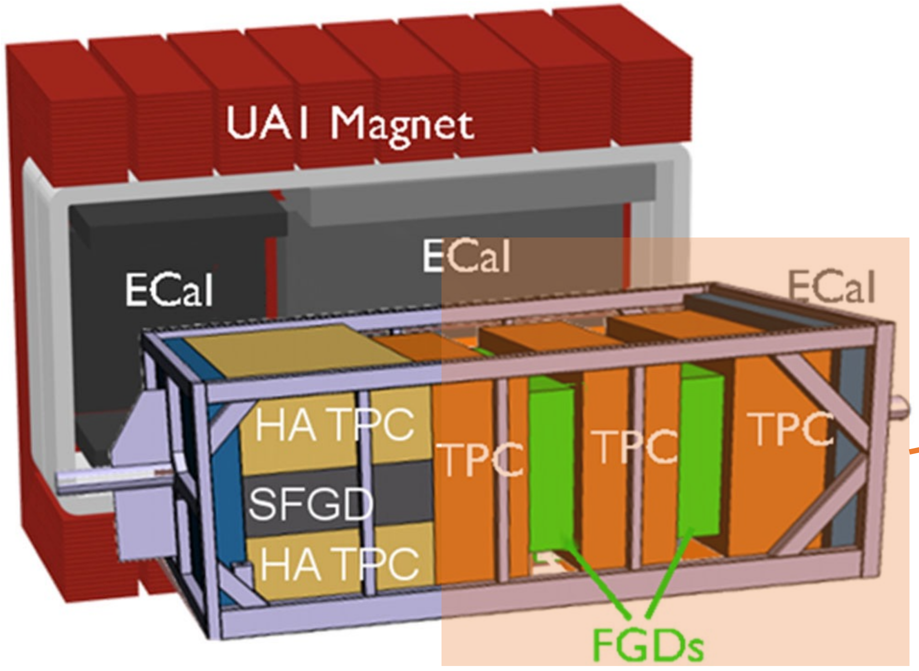
~ 10s MeV for liquid/solid

T2K Near Detector ND280

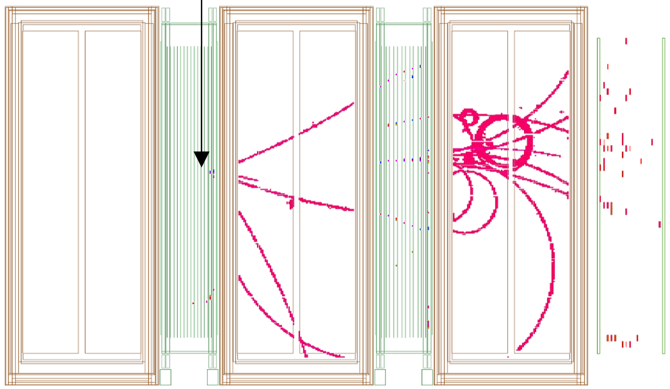
FGD (Fine-Grained Detector)

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

T2K, arXiv:1901.03750



ν interaction in plastic scintillator bars—FGD



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

Detector

Plastic scintillator tracker

- ❑ Also ***active target***
  - ❖ Tracking + ***calorimetry***
- ❑ T2K Upgrade 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***

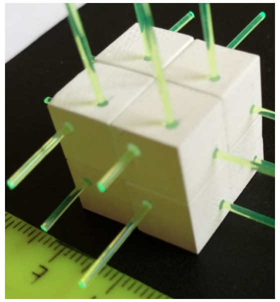
ν interaction in plastic scintillator bars—FGD

ND280 Upgrade

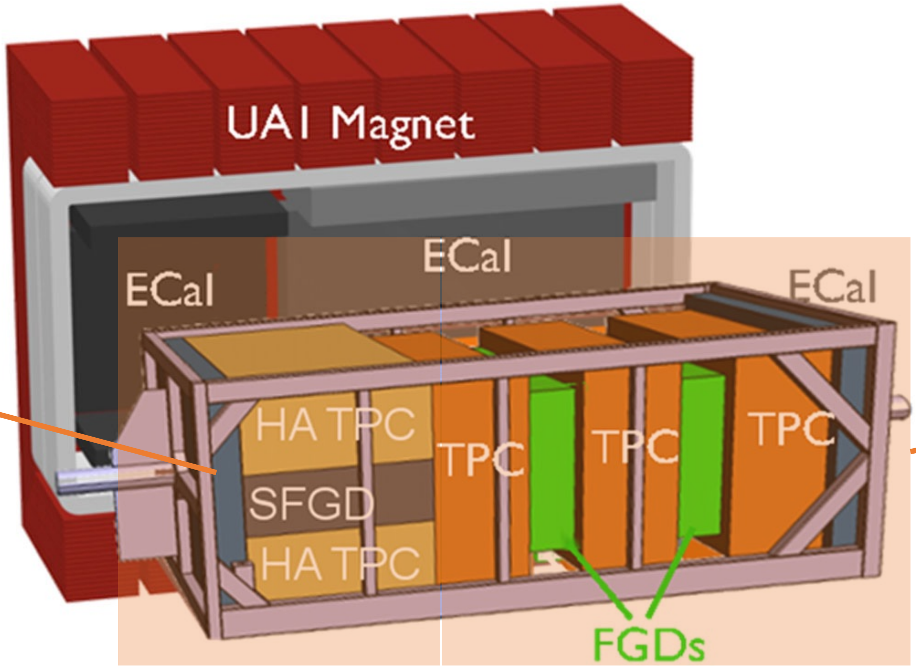
sFGD (SuperFGD)

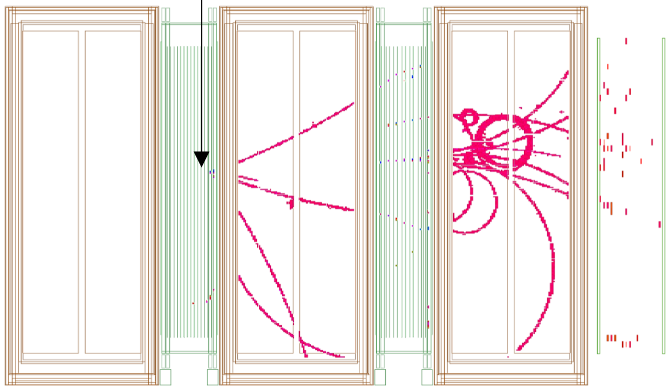
1-cm^3 ***cube***

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



T2K, arXiv:1901.03750





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

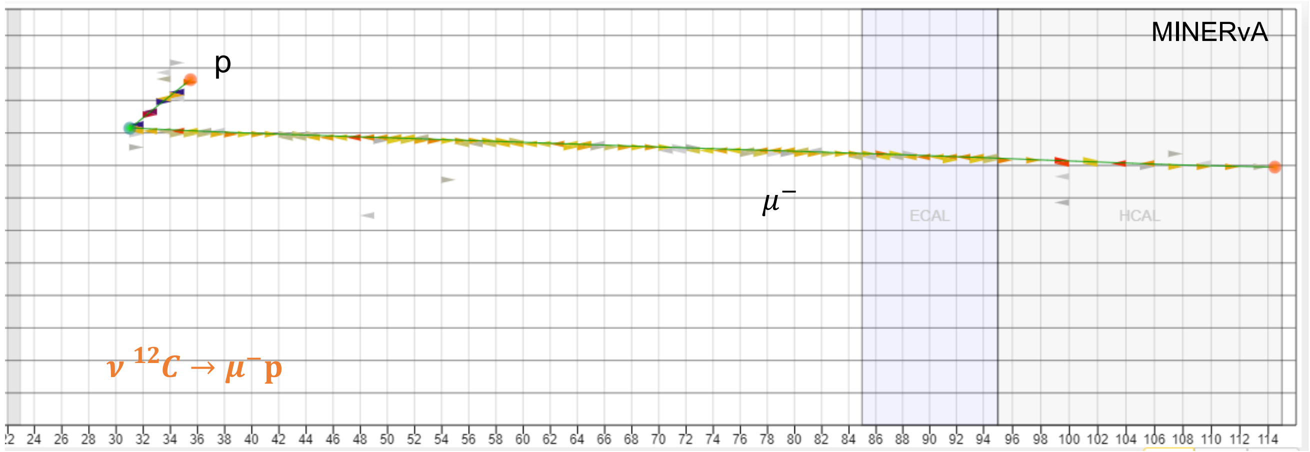
Detector

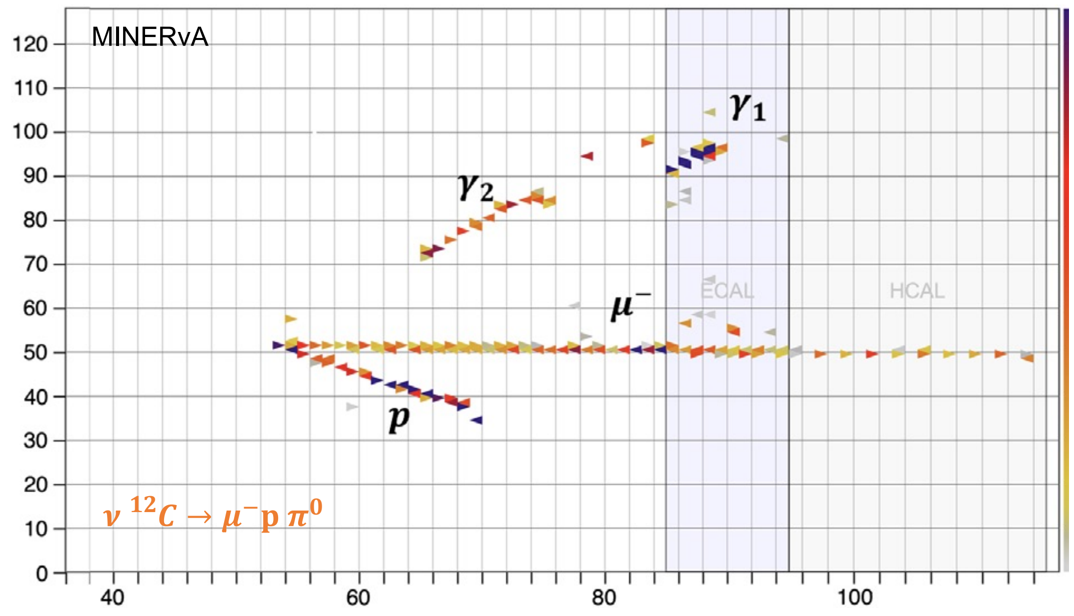
Plastic scintillator tracker

- 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)

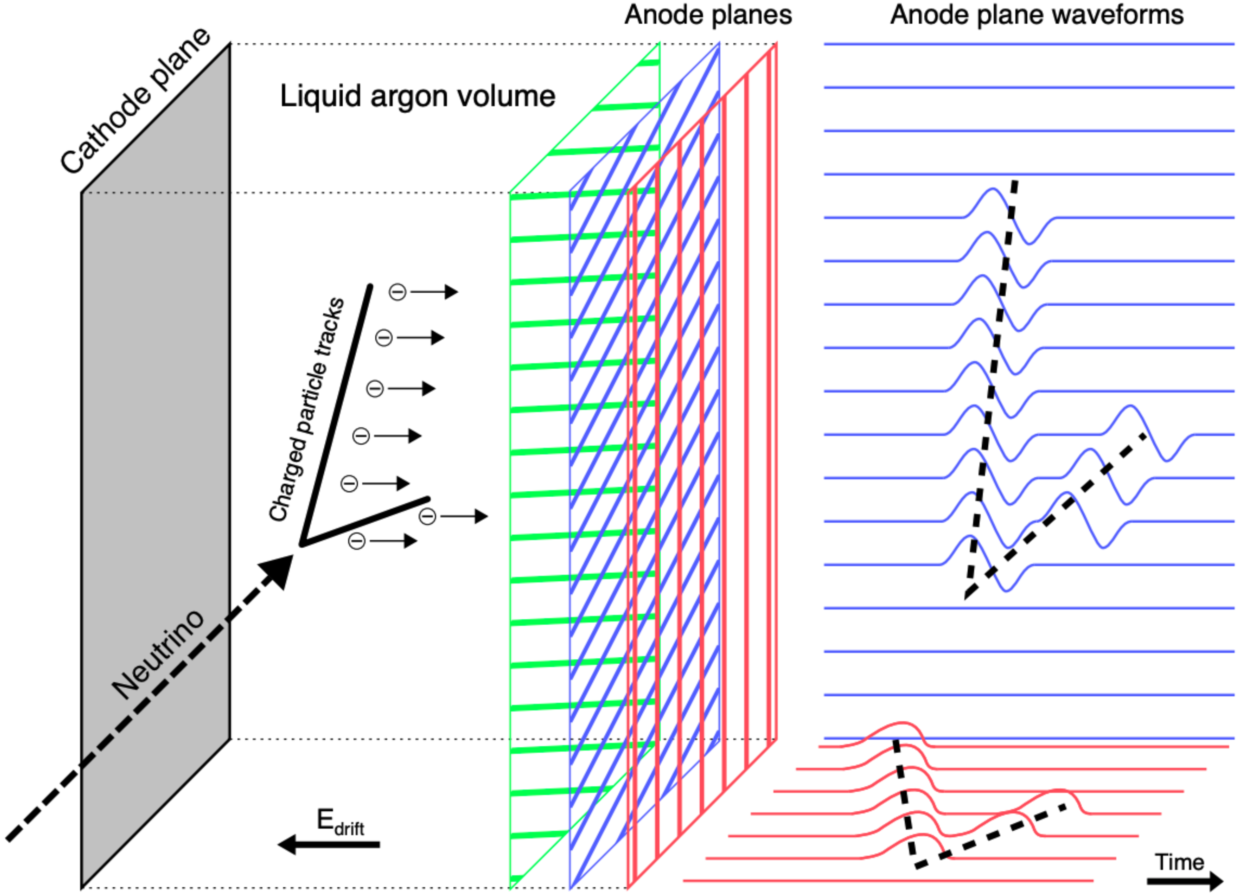
Typical event display w/ plastic scintillator tracker





Time Projection Chamber (TPC)

Detector



Vermeulen, FERMILAB-THESIS-2021-05

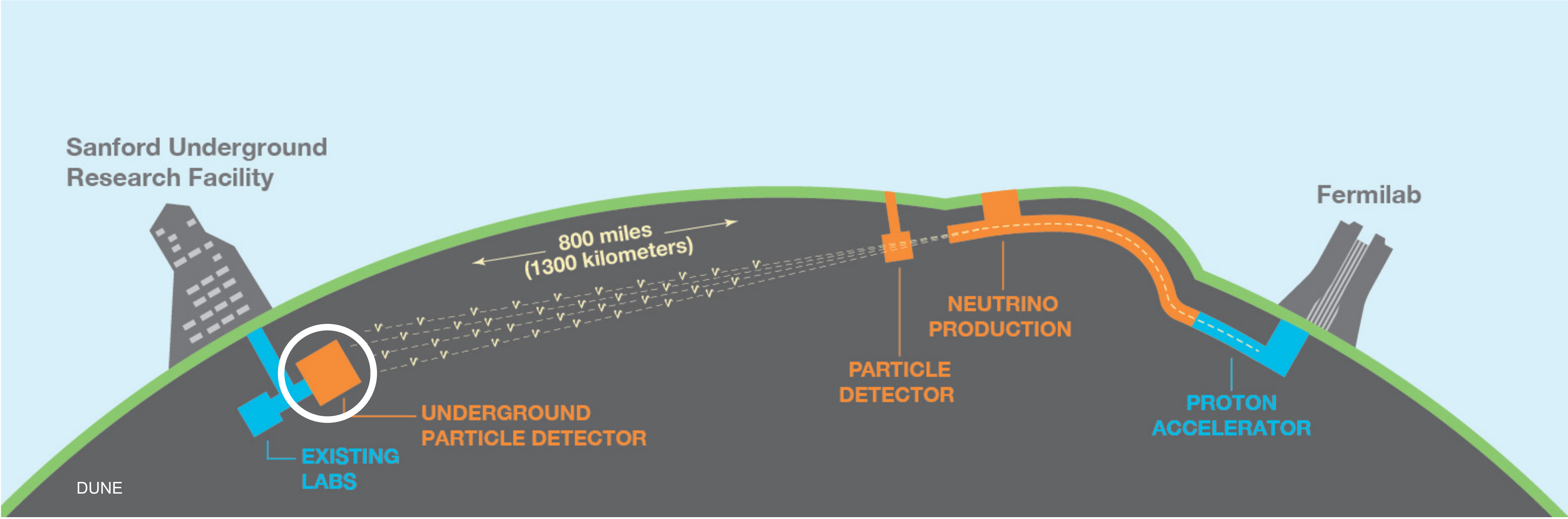
Detector

DUNE

- FD (Far Detector)
  - LArTPC (Liquid Argon TPC)
  - ✓ ***Mass-scalable (~10kt) for tracking + calo***

Quiz: What is Earth's diameter in unit of DUNE's baseline?

A: 100 B: 50 C: 10

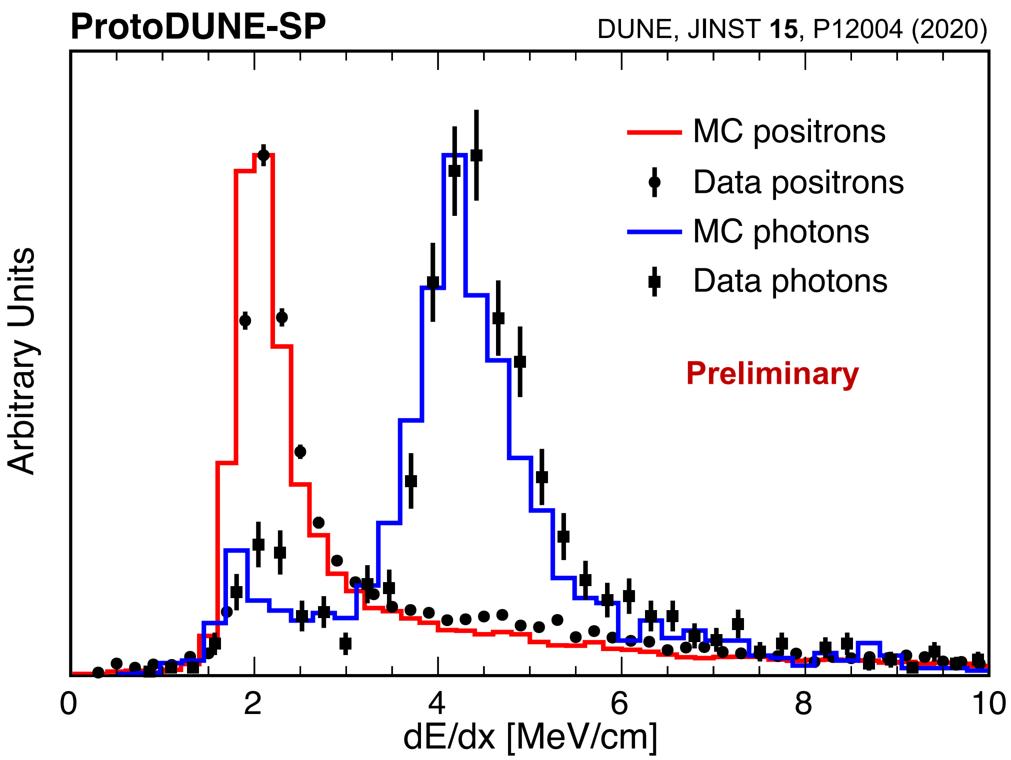


Detector

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

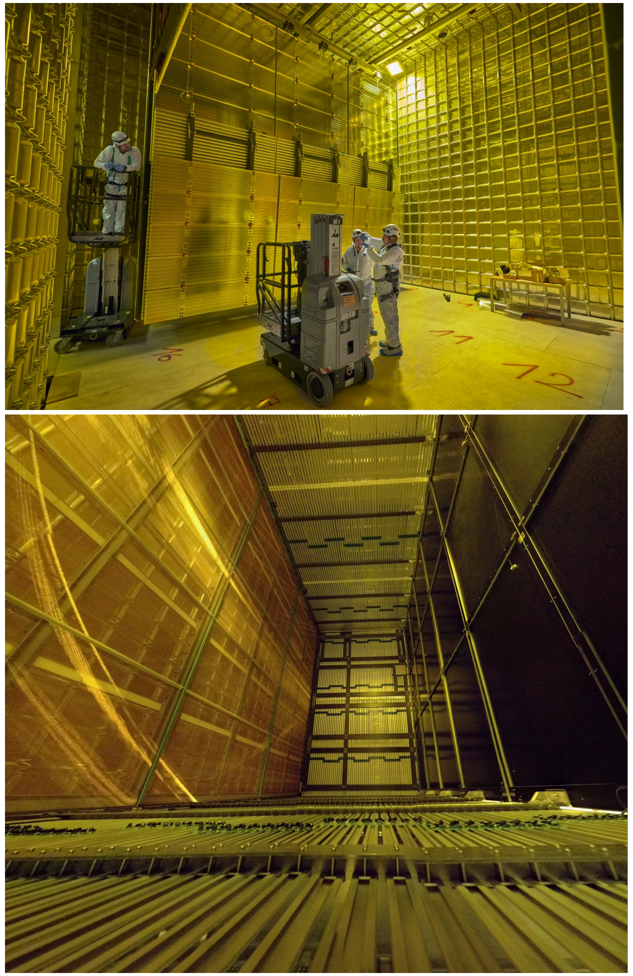


Photo Credit: CERN

ProtoDUNE

LArTPC Demonstrator at CERN for DUNE FD

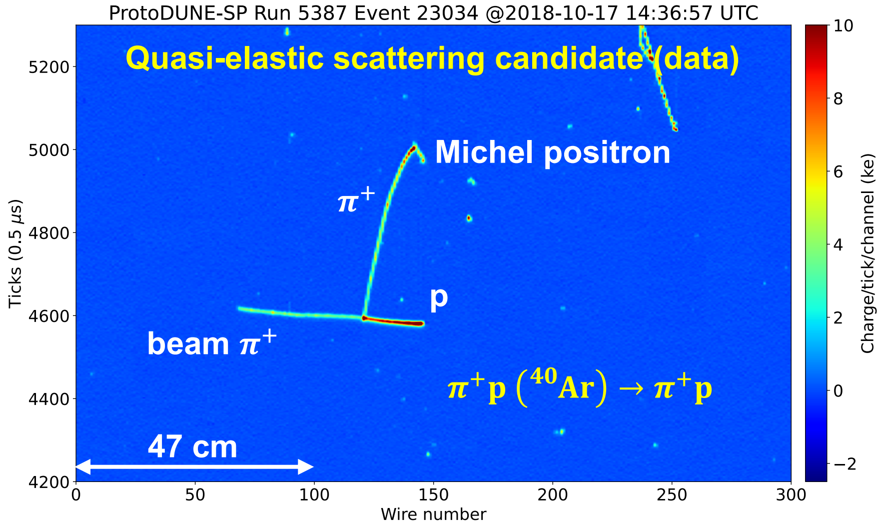
- ❑ Hadron beams of 0.3-7 GeV/c
  - ❖ 4.7 mm wire spacing (same as FD)
  - ✓ ***Versatile reconstruction in LAr***
  - ✓ ***<u>Exclusivity</u> + beam energy, can "see" inside argon nuclei***

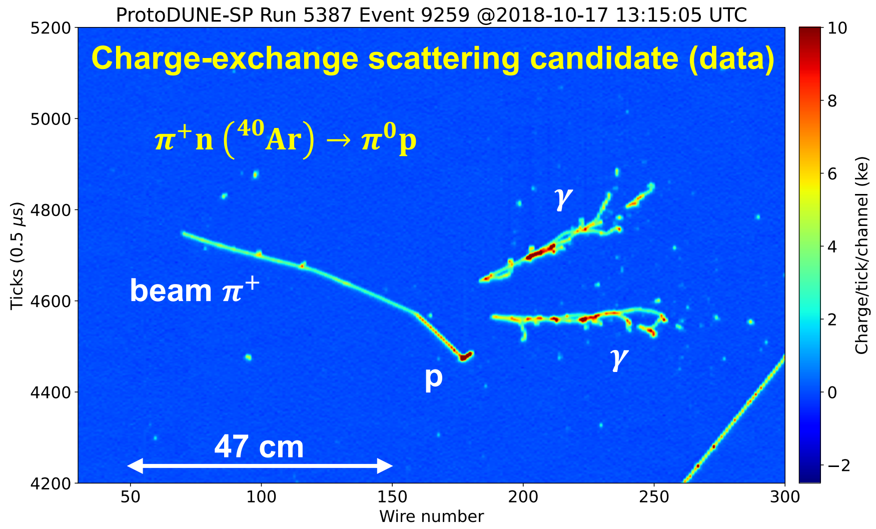
Homework: If we need to have signals from at least 6 wires in LArTPC to reconstruct a proton track, what is the tracking threshold?

<u>Exclusivity</u>: to measure all final states (except nuclear remnant)

Exclusive event candidates

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

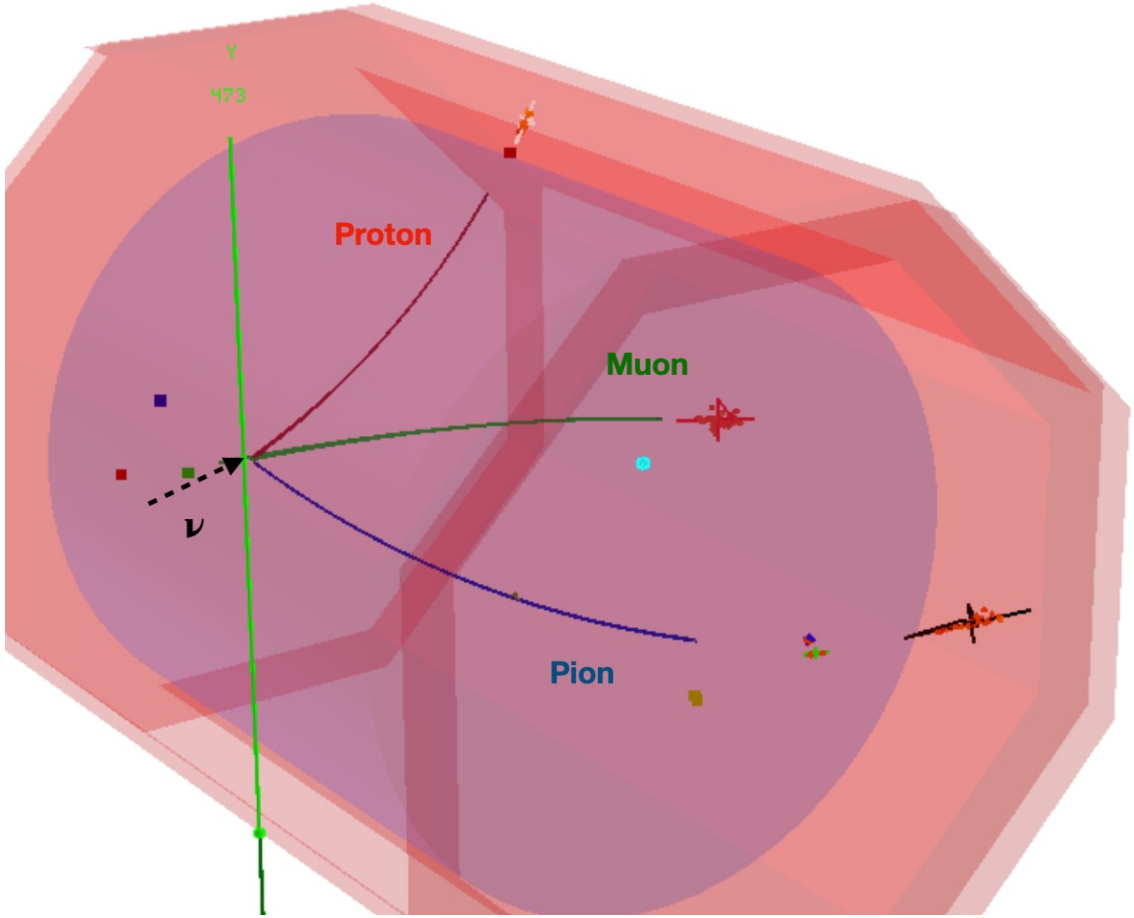




Detector

Hydrogen-rich high-pressure TPC

- ❑ Why gas TPC? Why high pressure?
  - ❖ Acceptance, tracking threshold
  - ❖ Target mass



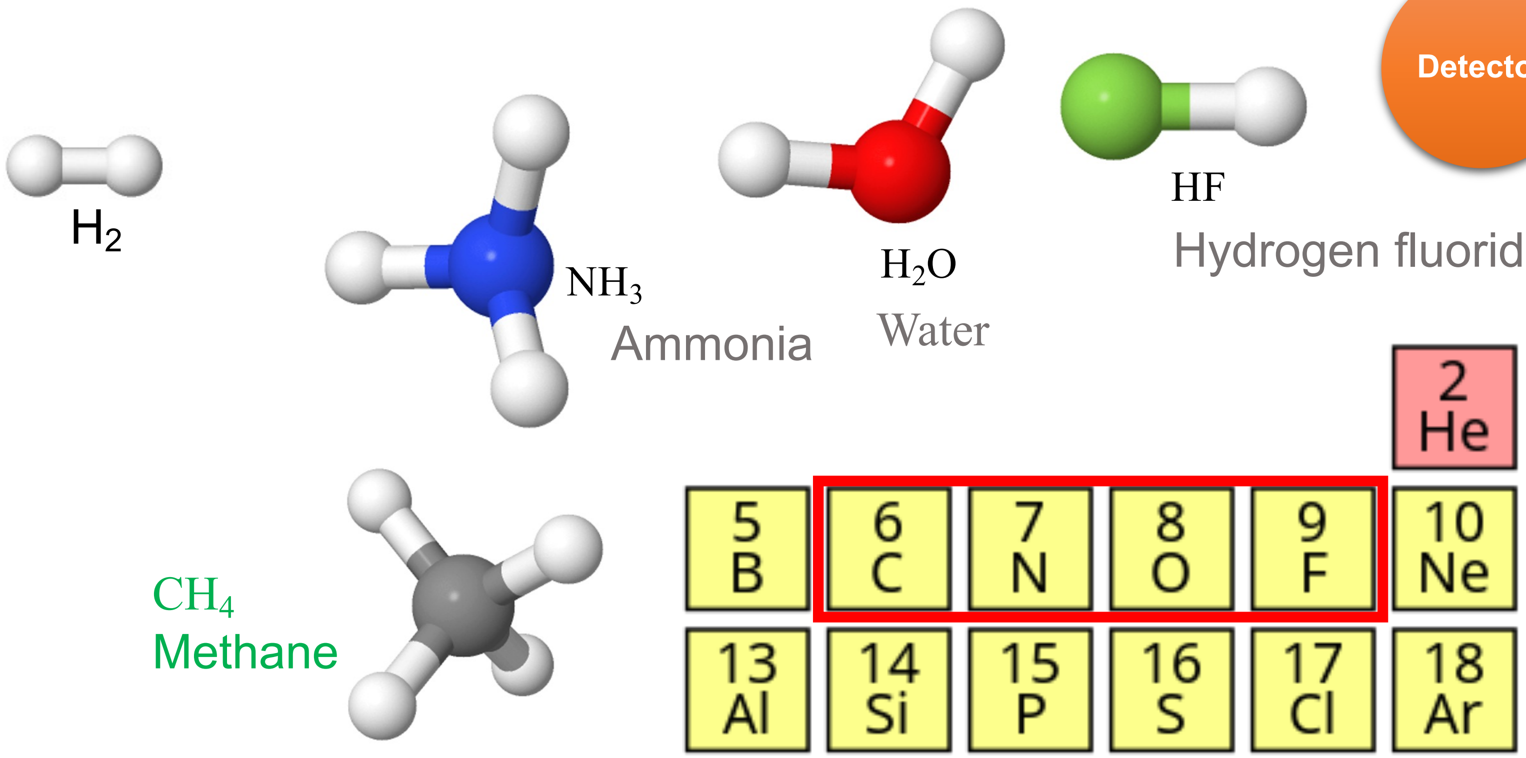
Raaf, TPC Mini Workshop

Hamacher-Baumann, Lu, Martín-Albo, Phys.Rev.D 102, 033005 (2020)

Detector

Hydrogen-rich high-pressure TPC

- ❑ Why gas TPC? Why high pressure?
  - ❖ Acceptance, tracking threshold
  - ❖ Target mass
- ❑ Why not pure hydrogen TPC
  - ❖ Bubble chamber: worse tracking
  - ❖ H_2 gas: not hydrogen-rich enough
- ❑ How rich is rich enough?
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y



http://www.jmol.org/

Hamacher-Baumann, Lu, Martín-Albo, Phys.Rev.D 102, 033005 (2020)

Detector

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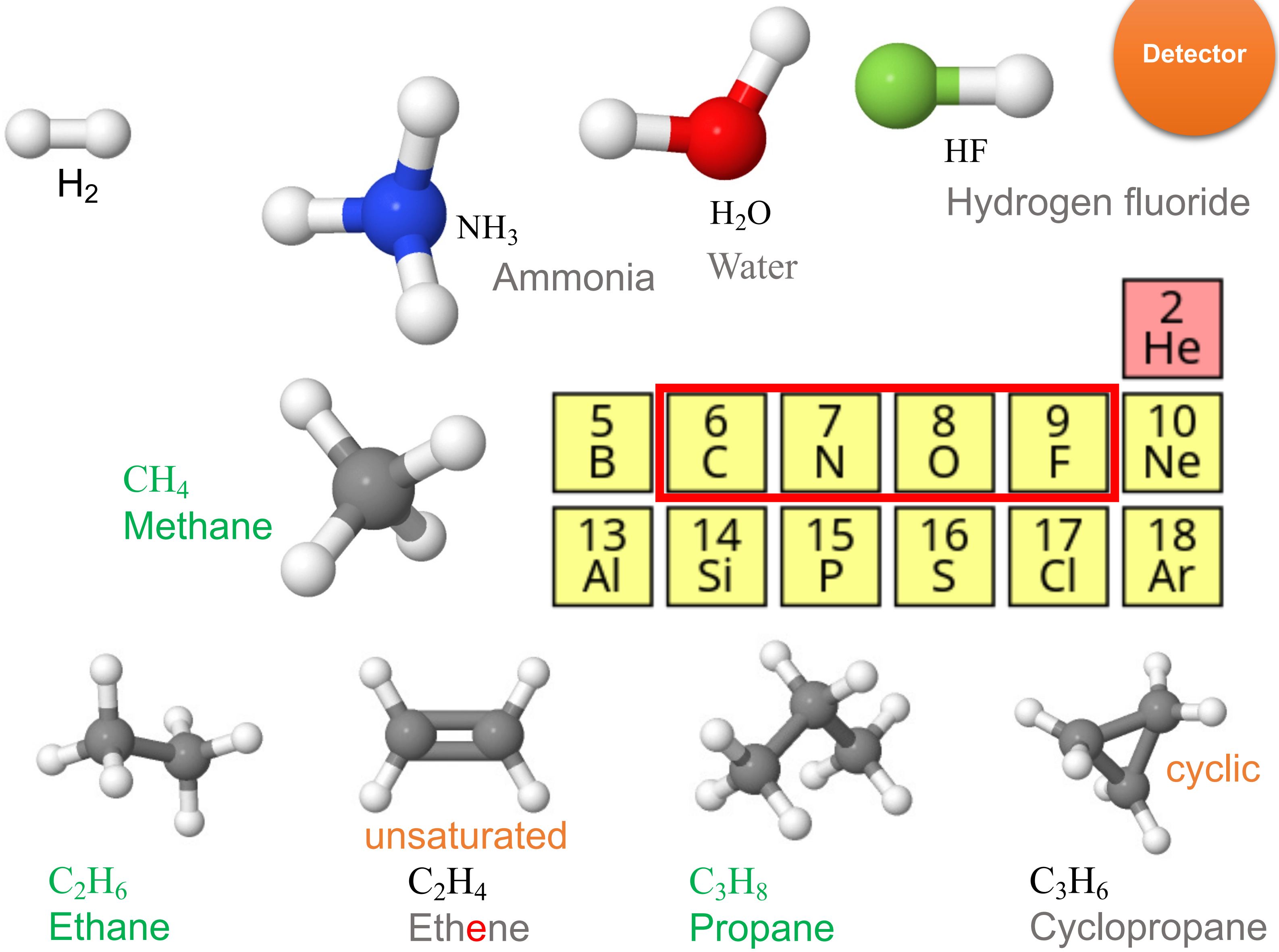
- ❑ How rich is rich enough?
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y
    - ➢ Saturated, acyclic: Alkane C_nH_{2n+2}
      - ✓ CH_4 most efficient H-carrier, but not the largest one



http://www.jmol.org/

Hamacher-Baumann, Lu, Martín-Albo, Phys.Rev.D 102, 033005 (2020)

Detector

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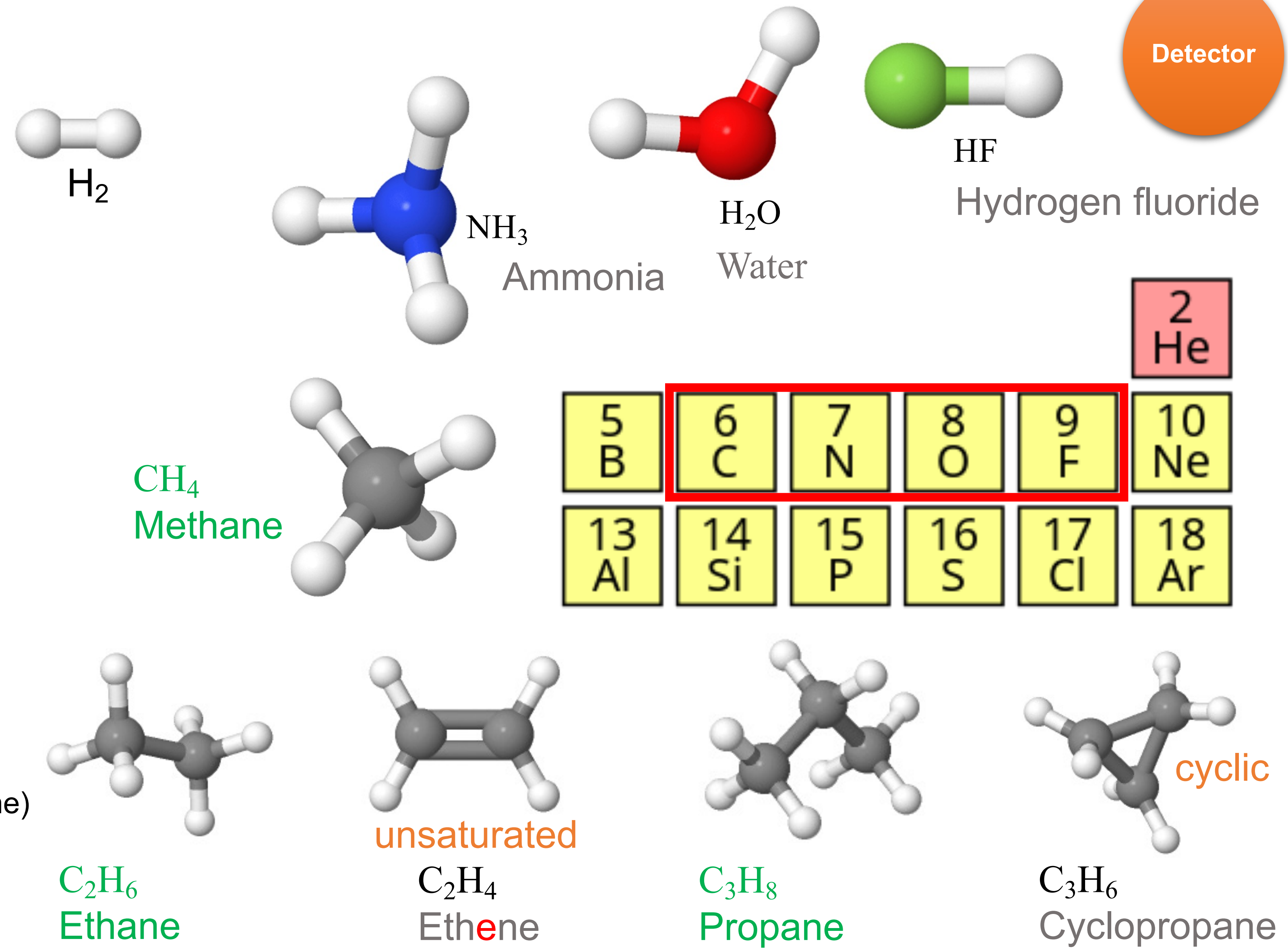
- ❑ How rich is rich enough?
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y
    - ➢ Saturated, acyclic: Alkane C_nH_{2n+2}
      - ✓ CH_4 most efficient H-carrier, but not the largest one
  - ❖ Maximal partial pressure limited by vapor pressure
    - ➢ Theoretically hydrogen-richest mix at 10 bar: $C_{3.93}H_{9.86}$

= 17% $C(CH_3)_4$ (neopentane) + 35% iC_4H_{10} (isobutane) + 24% C_4H_{10} (butane) + 24% C_3H_8 (propane)

Homework: Write down all (anti)neutrino-hydrogen interactions whose final-state particles are all electrically charged.

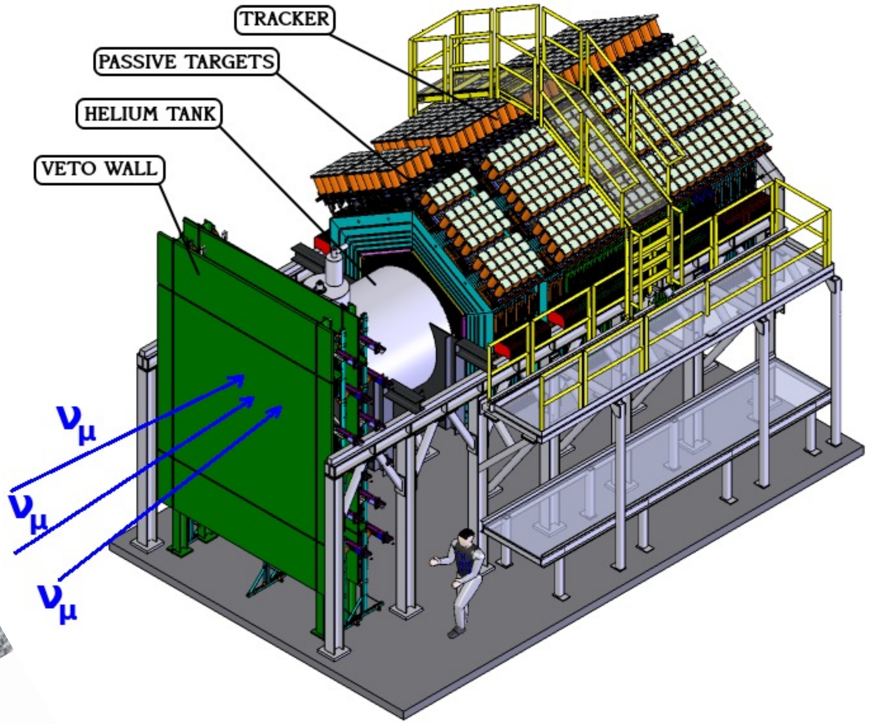


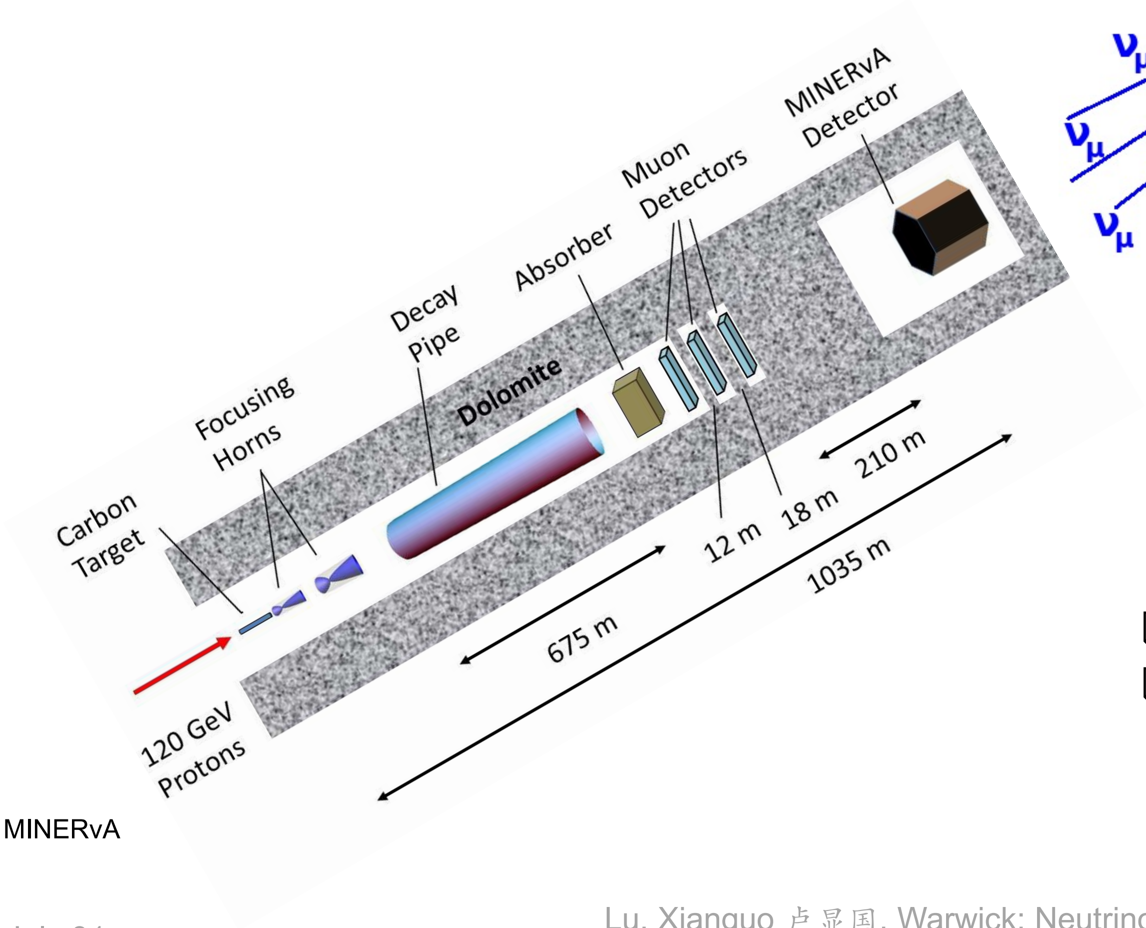
http://www.jmol.org/

Hamacher-Baumann, Lu, Martín-Albo, Phys.Rev.D 102, 033005 (2020)

MINERvA@FNAL

A dedicated ν-interaction experiment





MINERvA

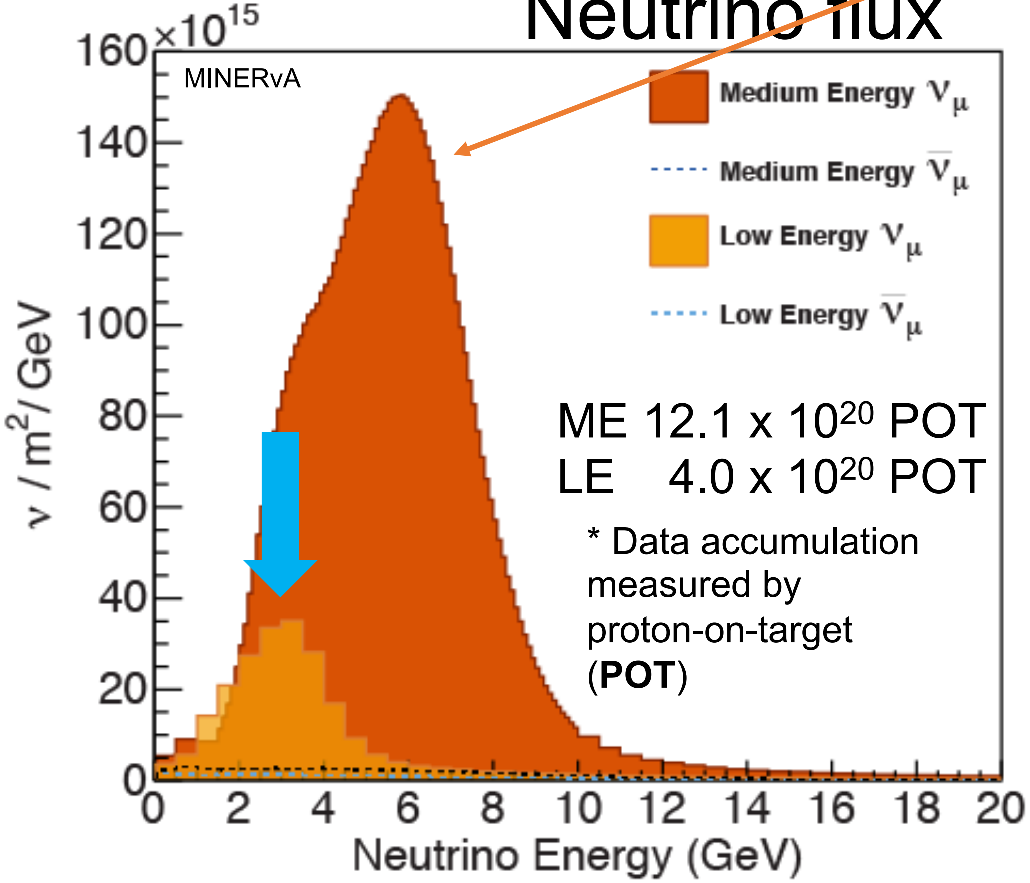
- ❑ 5.4 ton active scintillator fiducial volume
- ❑ 10-μs beam spill, ~ 1 event in tracker per spill

ME: gigantic data sets!

(all MINERvA results here are w/ LE)

LE: Low Energy, peak at 3 GeV
ME: Medium Energy, peak at 6 GeV

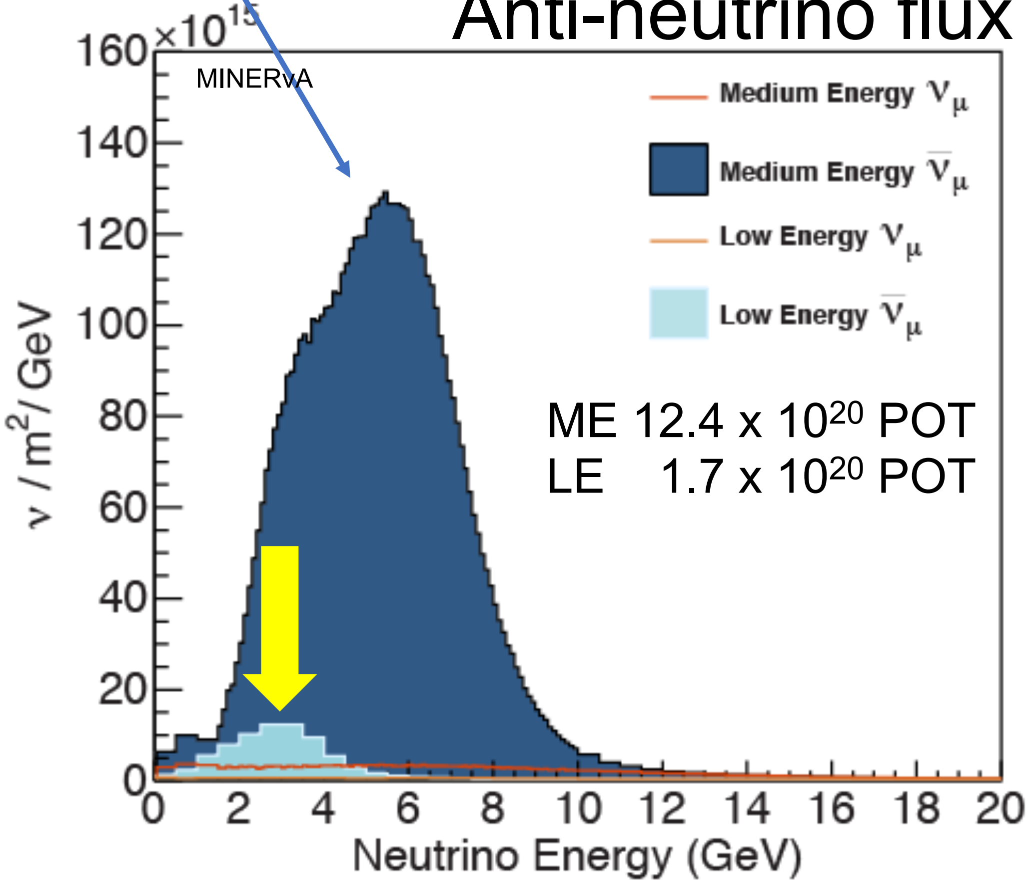
Neutrino flux



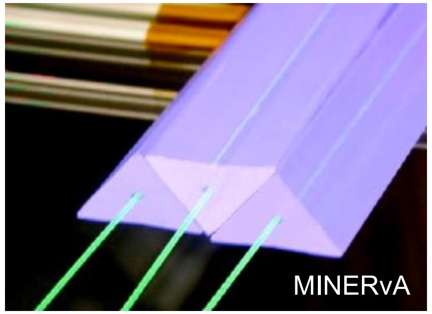
ME 12.1 x 10^{20} POT
LE 4.0 x 10^{20} POT

* Data accumulation measured by proton-on-target (**POT**)

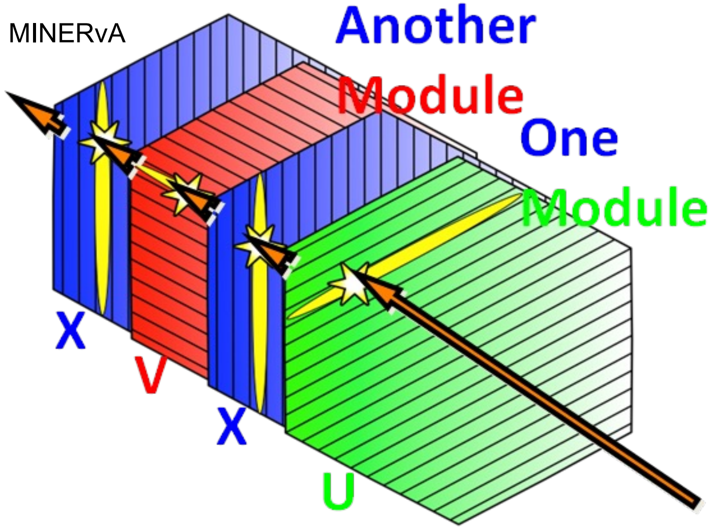
Anti-neutrino flux



ME 12.4 x 10^{20} POT
LE 1.7 x 10^{20} POT

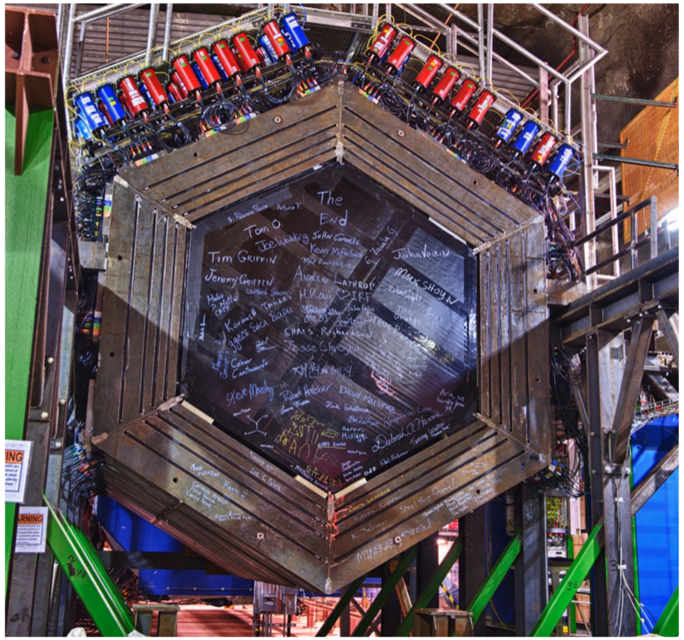


- ❑ Scintillator bar (CH)
- ❑ 3.3 cm base, 1.7 cm height
- ❑ 3 ns timing resolution

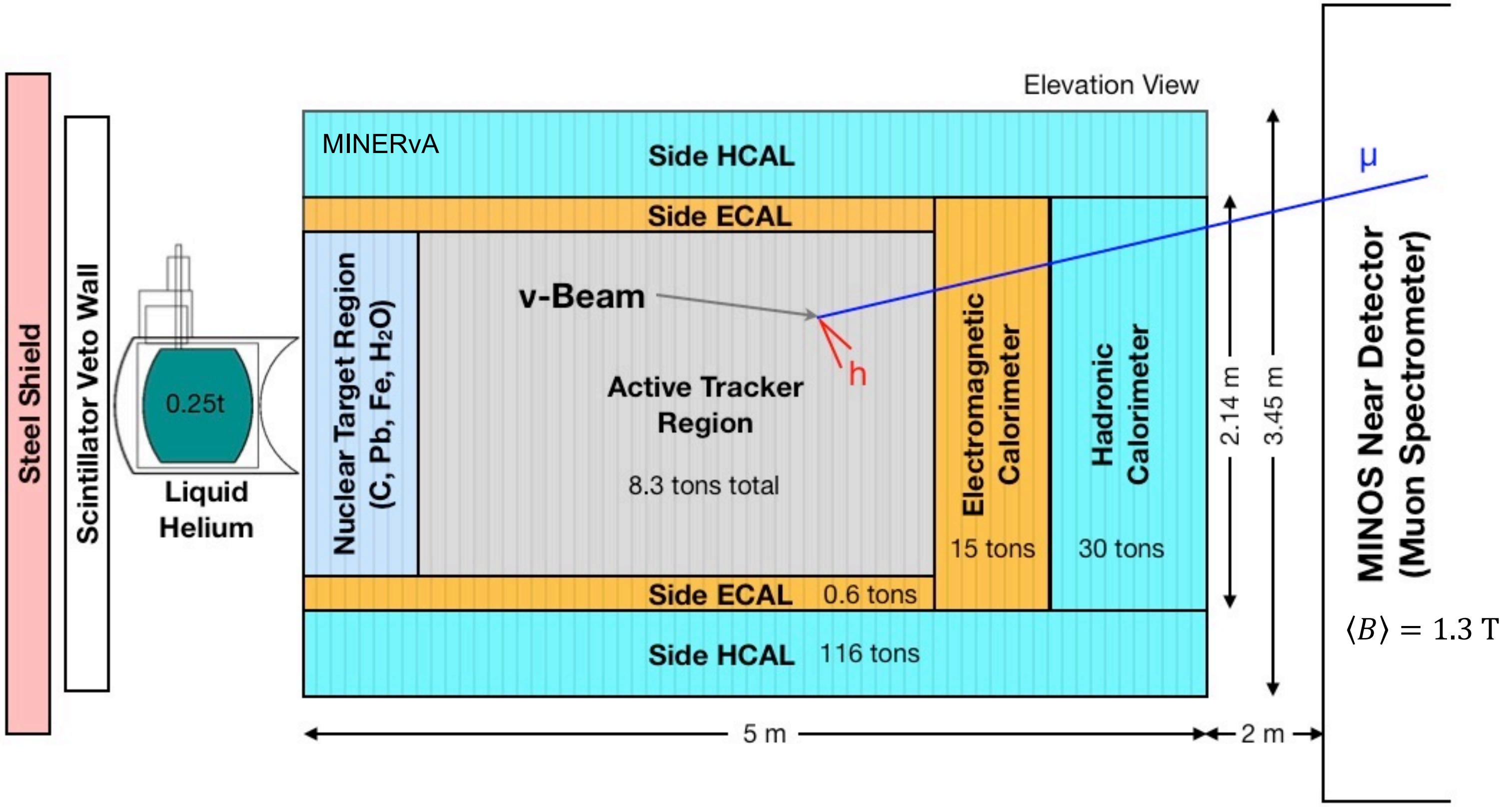


- ❑ 3 views
- ❑ 2.7 mm position resolution per plane

Photo Credit: R. Hahn



- ❑ Non-magnetized

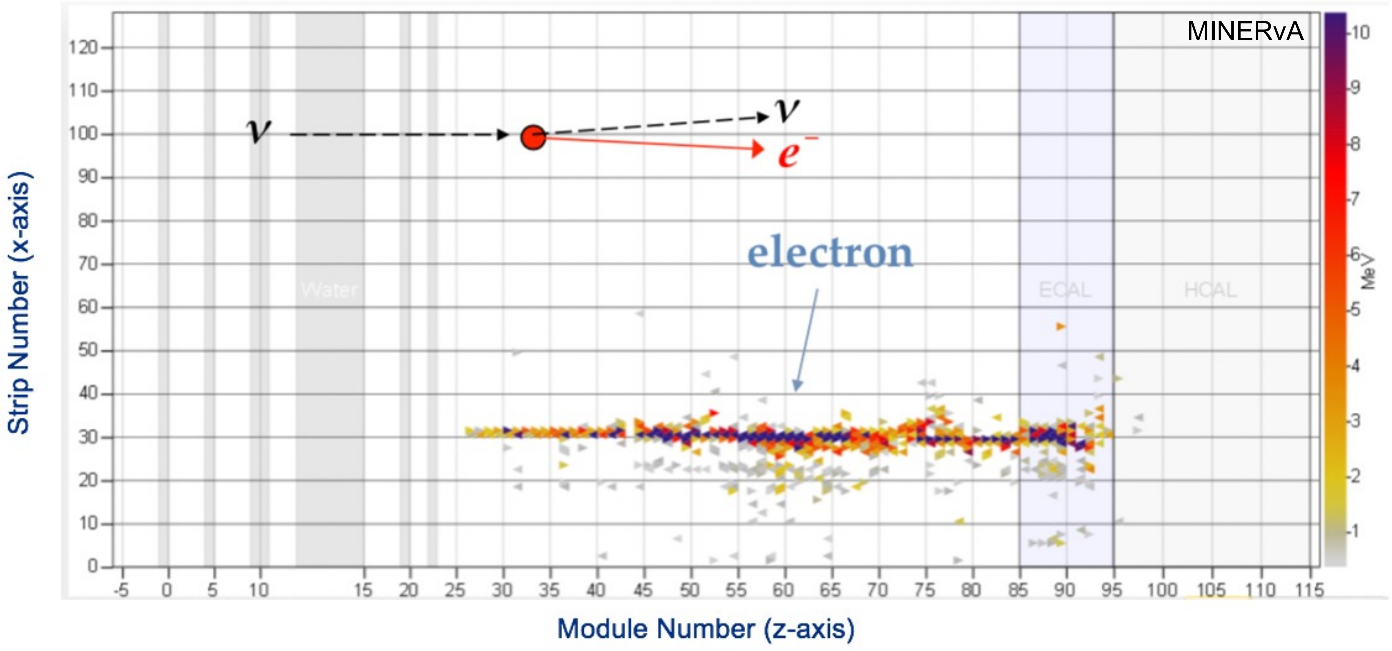


- ❑ Muon momentum resolution (range + curvature) 8% @ 6 GeV/c
- ❑ Proton threshold 100 MeV K.E., momentum (by range) resolution 2% @ 1 GeV/c
- ❑ π^0 momentum resolution ~20%
- ❑ High-energy charged π energy resolution by calorimetry $18\% + 8\% / \sqrt{E_\pi/\mathrm{GeV}}$
- ❑ Can also detect neutrons

Neutrino-Electron Elastic Scattering

Well-understood SM process

$$\nu e \longrightarrow \nu e$$



Homework: Write down the Feynman diagram(s) for ν-e elastic scattering.

- ❑ Beam flux prediction:
  GEANT4+hadron production data
- ❑ *in situ* flux constrained by νe scattering [MINERvA, Phys.Rev. D93, 112007 (2016), Phys. Rev. D 100, 092001 (2019)]
  - ❖ reduced by ~ 10%
  - ❖ uncertainty near the peak reduced from 8% to 4%

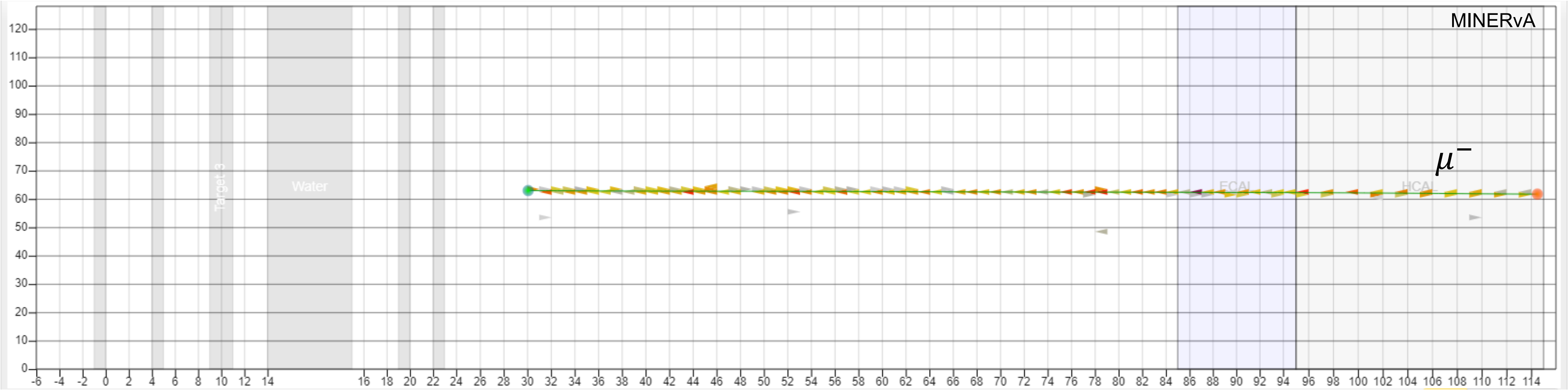
Inverse Muon Decay

(Muon decay $\mu^- \to \nu_\mu + e^- + \bar{\nu}_e$)

Another well-understood SM process

$$\nu_\mu + e^- \to \mu^- + \nu_e$$

Inverse muon decay

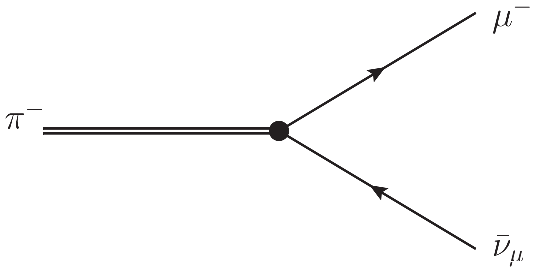


New flux constraint method [MINERvA, Phys.Rev.D 104, 092010 (2021)]

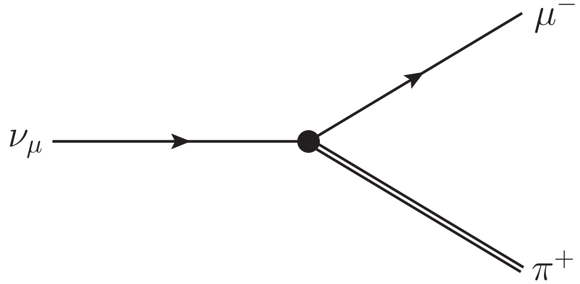
Homework:

1. ***Write down the Feynman diagram(s).***
2. ***What is the minimum neutrino energy for this process to happen (that is, the neutrino energy threshold)?***
3. ***Can this technique constrain $\bar{\nu}_\mu$ flux?***

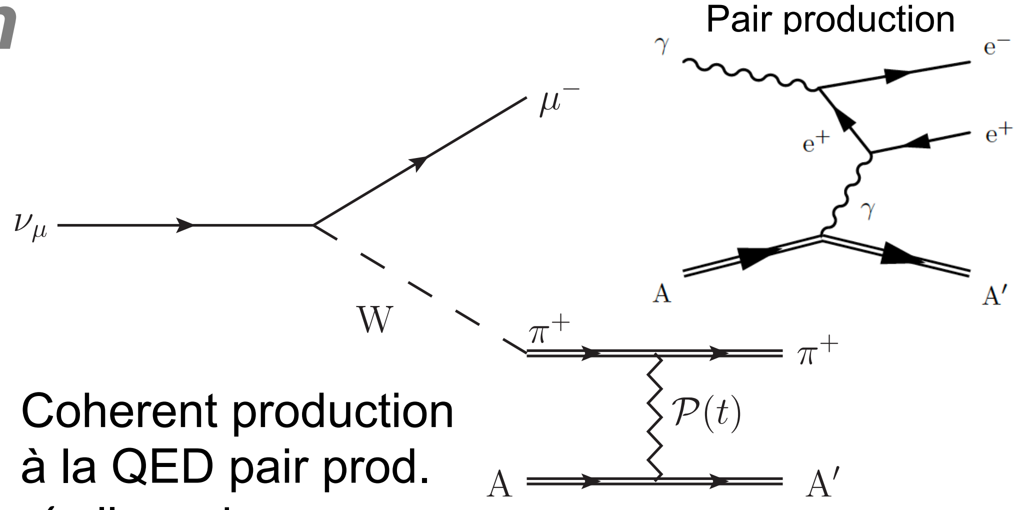
Charged-Current Coherent π Production



Pion decay



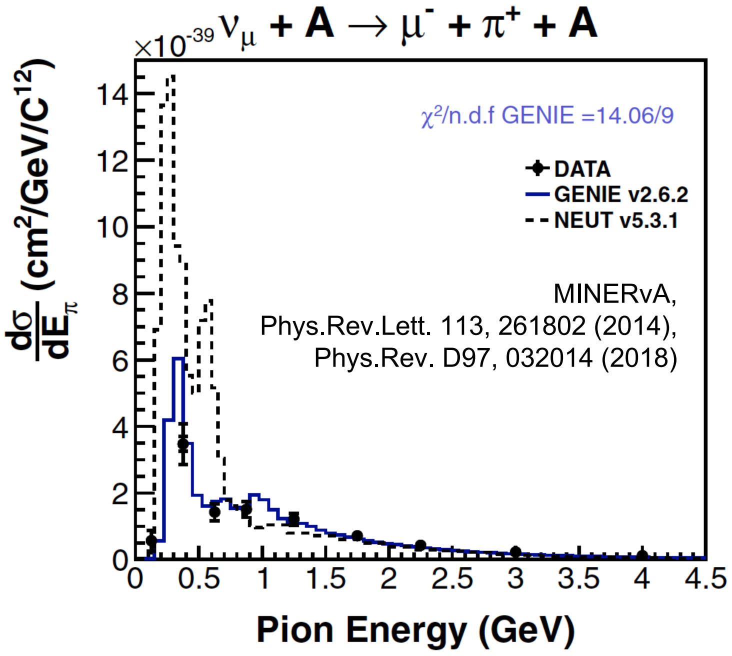
"Inverse pion decay"
✗ forbidden
✓ IF ν_μ is replaced by a heavy neutrino (heavy neutral lepton)

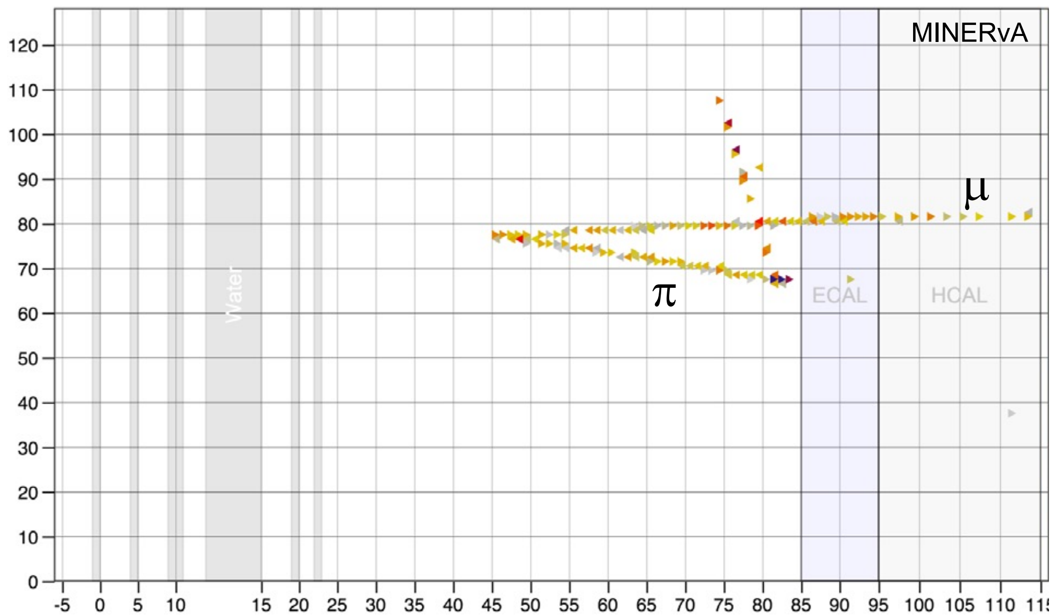


Coherent production
à la QED pair prod.
✓ allowed

❑ Intrinsic background to HNL search

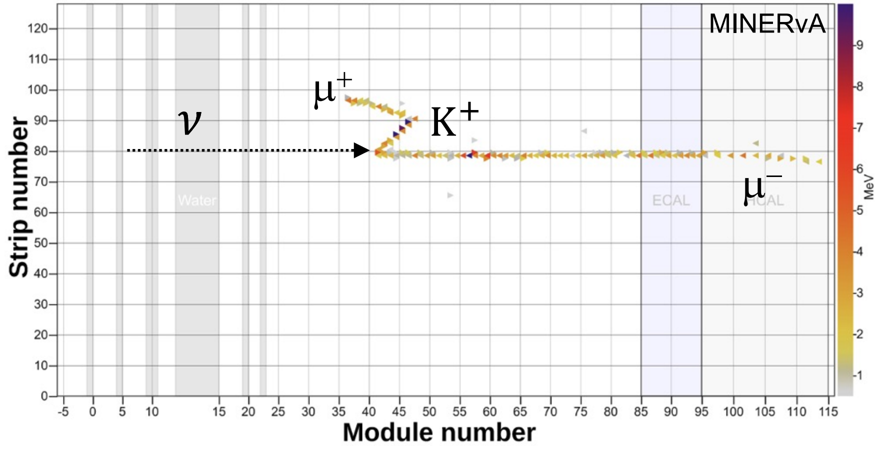
[T2K, Phys.Rev. D100, 052006 (2019)]

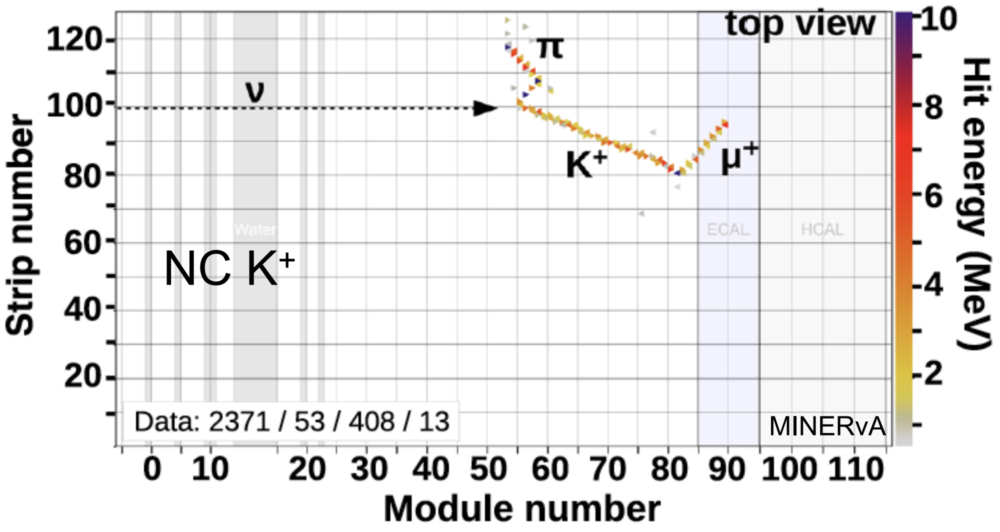




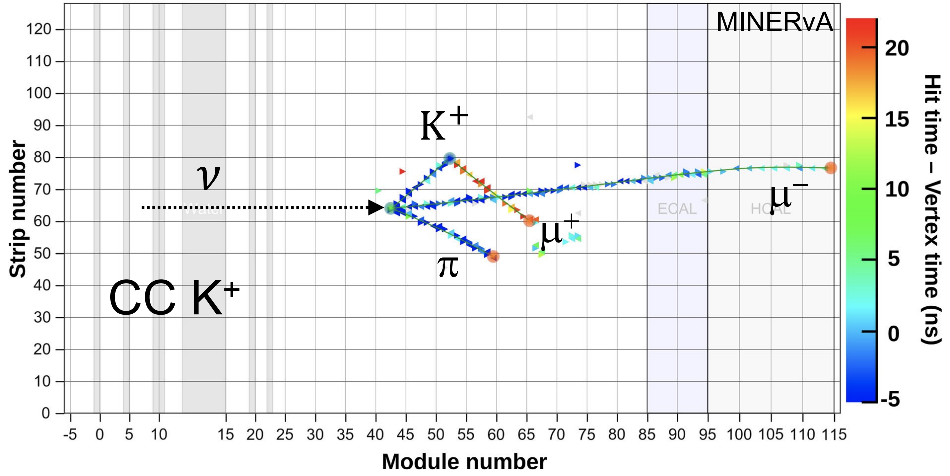
Kaon Production

"Inverse kaon decay"
— Coherent K⁺

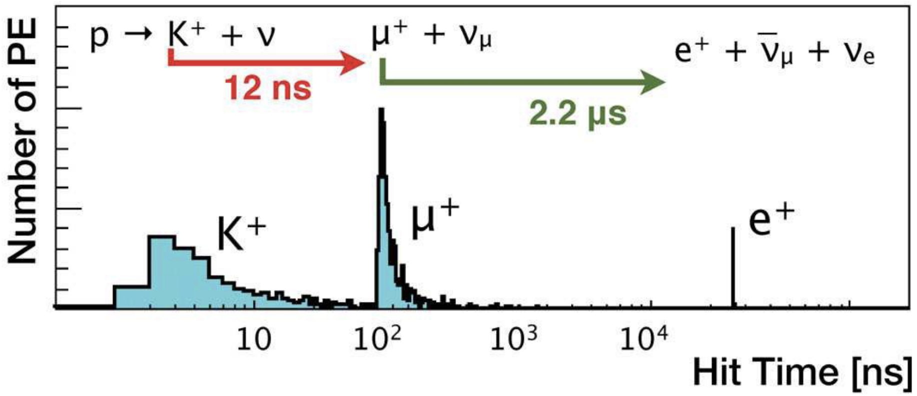




- ❑ K⁺ decay-at-rest signature
  12.4 ns lifetime, kink, energy deposit



JUNO, J.Phys.G 43, 030401 (2016)



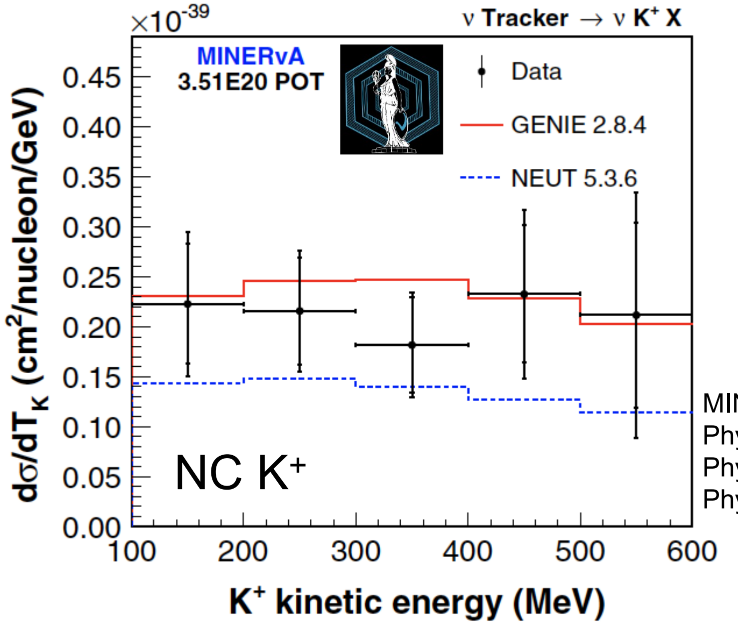
- ❑ Proton *decay at rest* → K^+ 105 MeV K.E.
- ✓ Nice kinematic signature with decay chain coincidence
  Or not?

Protons inside a nucleus

- ❑ Bound nucleons are moving—Fermi motion
- ❑ Interactions while exiting, very often breaking up the nucleus—final state interactions (FSI)

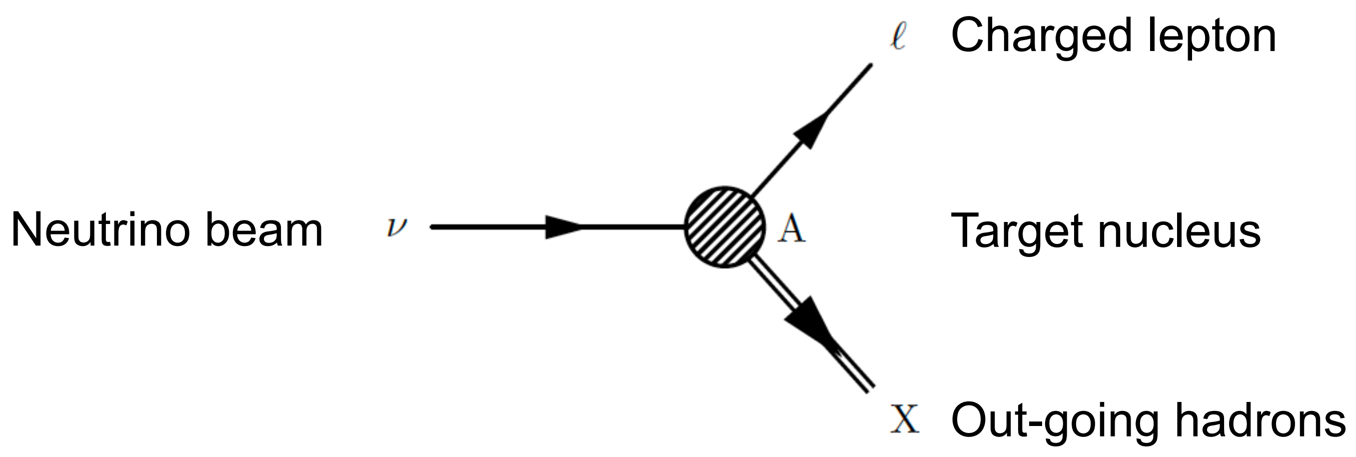
Bound-proton decay

- ❑ K^+ 20-200 MeV K.E. (not considering FSI)
- ✗ background from K^+ production by atmospheric neutrinos



MINERvA,
Phys.Rev. D94, 012002 (2016),
Phys.Rev.Lett. 117, 061802 (2016),
Phys.Rev.Lett. 119, 011802 (2017)

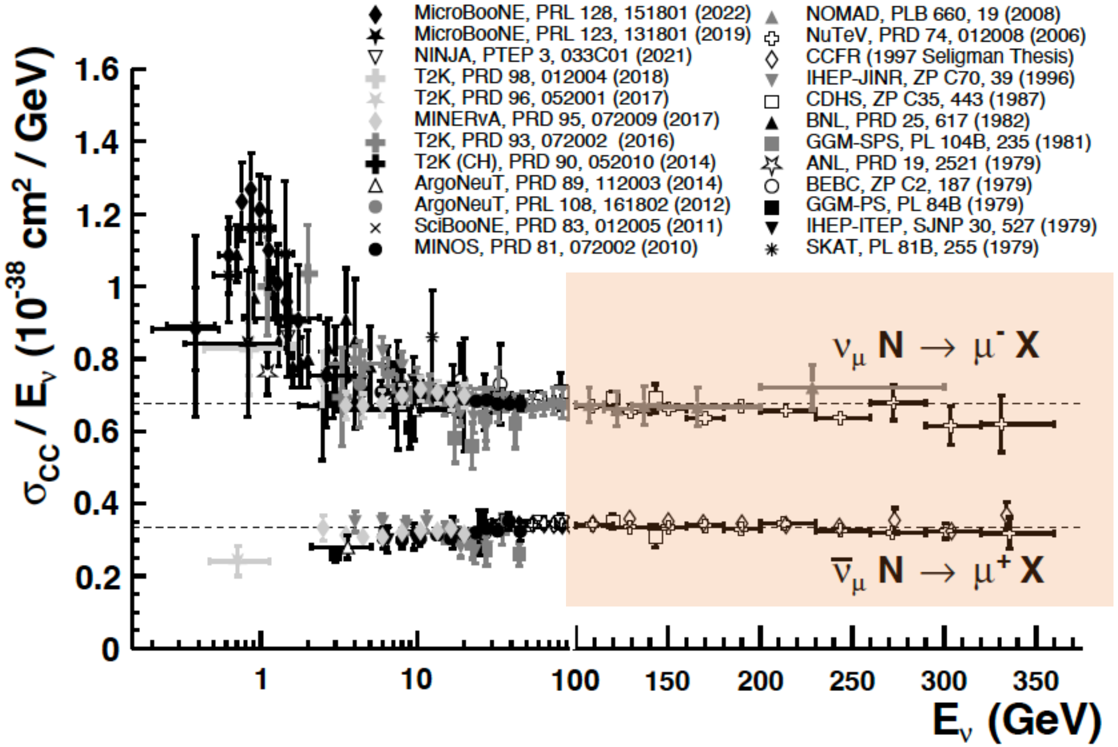
Part 2: Neutrino Scattering and Nuclear Structure



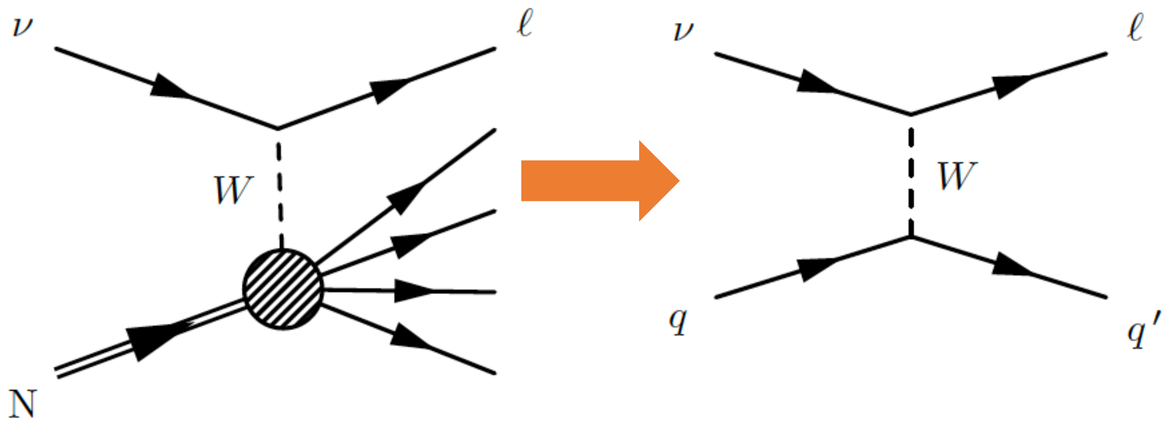
Settings

1. Neutrino beam on at-rest nuclear target
   - ❖ Nucleus A, nucleon N
2. Only consider charged current (W-exchange)
3. Residual nucleus not detectable

PDG, PTEP 2022, 083C01 (2022)



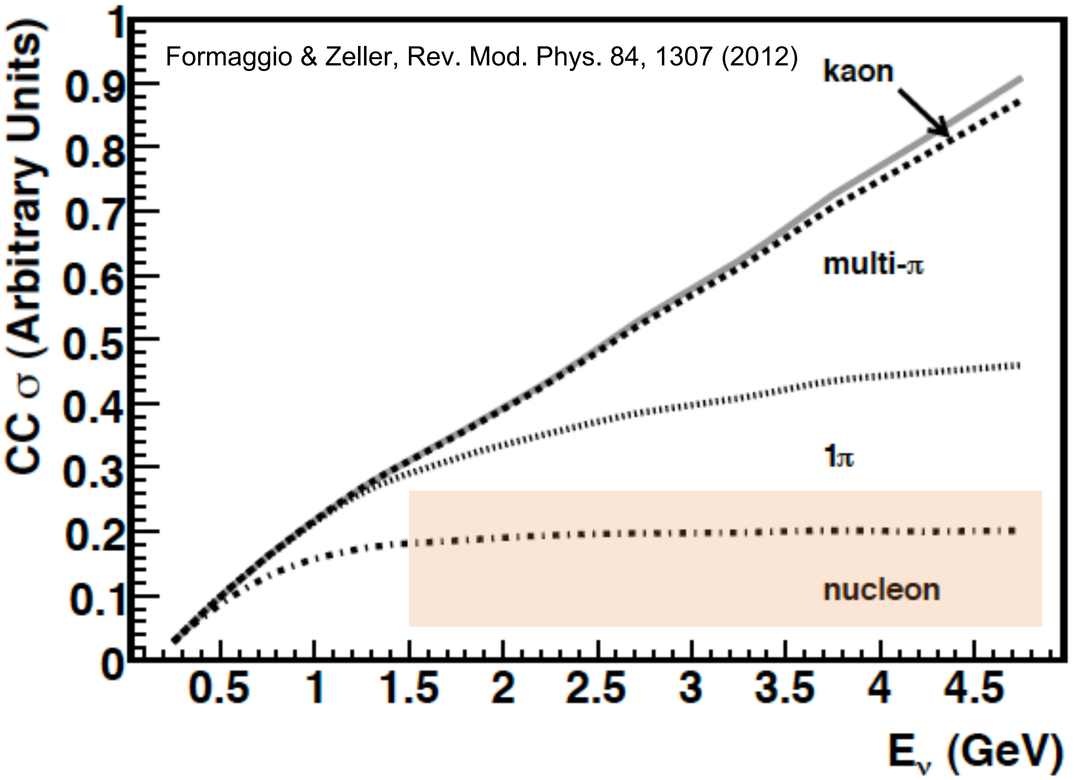
Deep Inelastic Scattering (DIS)



Homework**: Explain $\sigma_{CC}^{\nu N}/\sigma_{CC}^{\bar{\nu} N} \simeq 2$ ***at high energy.***

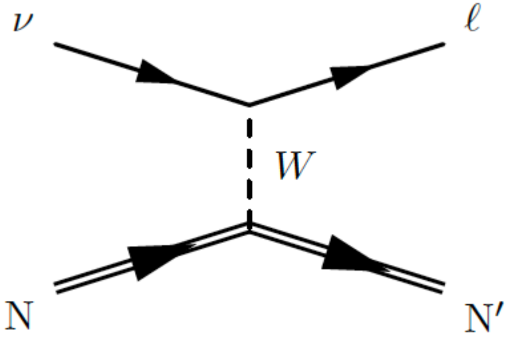
- ❑ At high energy, ν interacting with quarks, $\sigma \sim E_\nu$

Homework: Calculate the energy threshold of ν_e and ν_μ CCQE scattering on nucleons.

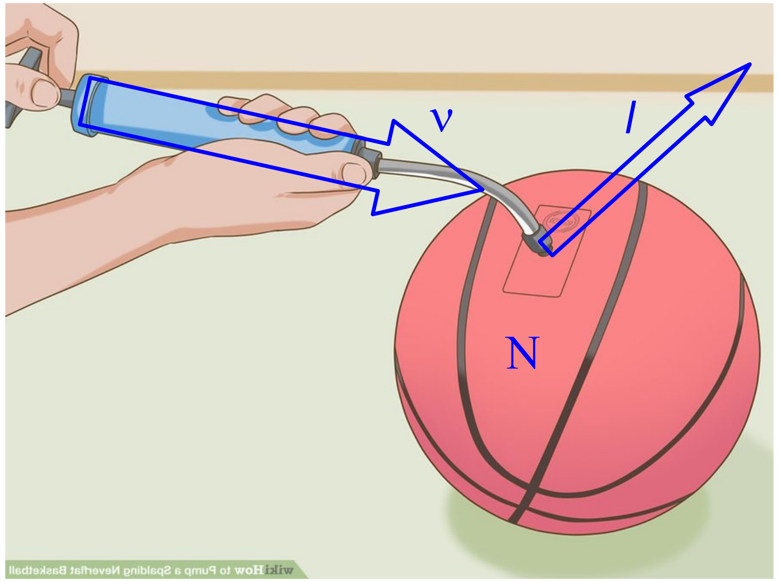


σ_{QE} starts to saturate at 1 GeV

Quasielastic (QE)

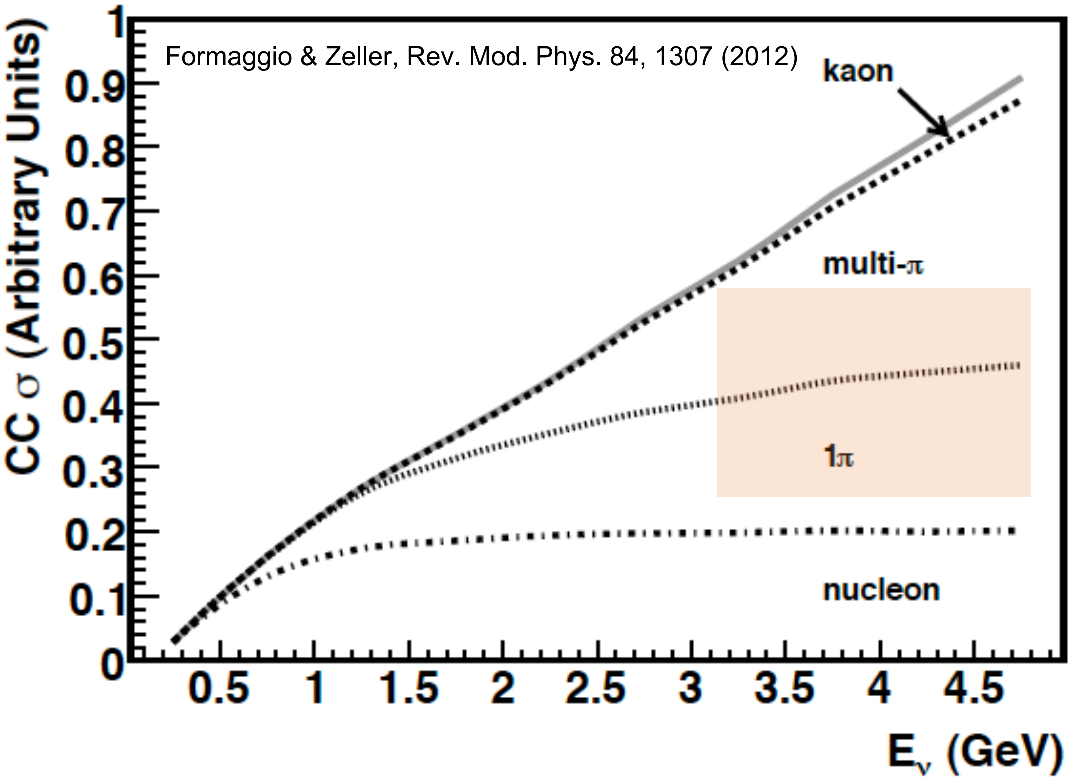


Final-state lepton takes away energy excess



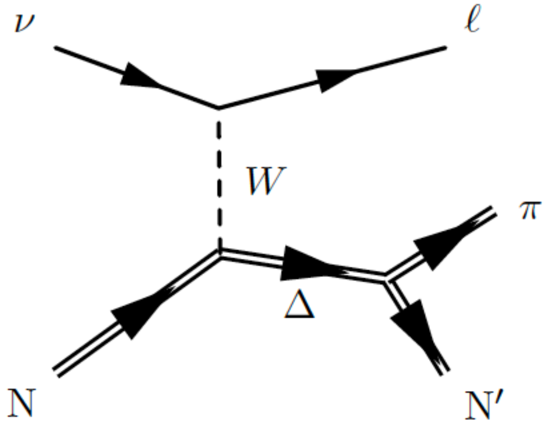
Source: http://www.wikihow.com/Pump-a-Spalding-Neverflat-Basketball

Homework*: Using isospin arguments (CG coefficients), show that the cross-section ratio between $\nu_\mu p \to \mu^- p\pi^+$, $\nu_\mu n \to \mu^- p\pi^0$, and $\nu_\mu n \to \mu^- n\pi^+$ ***is 9:2:1 (assuming Δ dominance).***



Homework: Check the quantum numbers and quark contents of Δ and N* on PDG (Google "pdg delta resonance"; navigate https://pdg.lbl.gov/).

Resonant production (RES)



$\nu p \to \ell^- \Delta^{++} \to \ell^- p\pi^+$

$\nu n \to \ell^- \Delta^{+} \to \ell^- p\pi^0$

$\nu n \to \ell^- \Delta^{+} \to \ell^- n\pi^+$

$\bar{\nu} n \to \ell^+ \Delta^{-} \to \ell^+ n\pi^-$

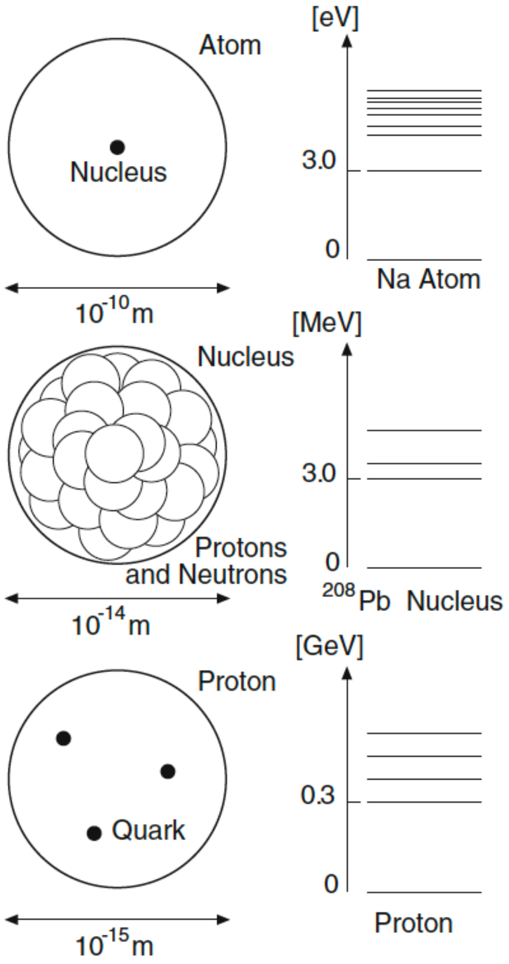
$\bar{\nu} p \to \ell^+ \Delta^{0} \to \ell^+ n\pi^0$

$\bar{\nu} p \to \ell^+ \Delta^{0} \to \ell^+ p\pi^-$

- ❖ Besides Δ, there are also many other resonances, e.g. N resonances (N*)
- ❖ Non-resonant background: diagrams with the same initial and final states but without the intermediate resonance

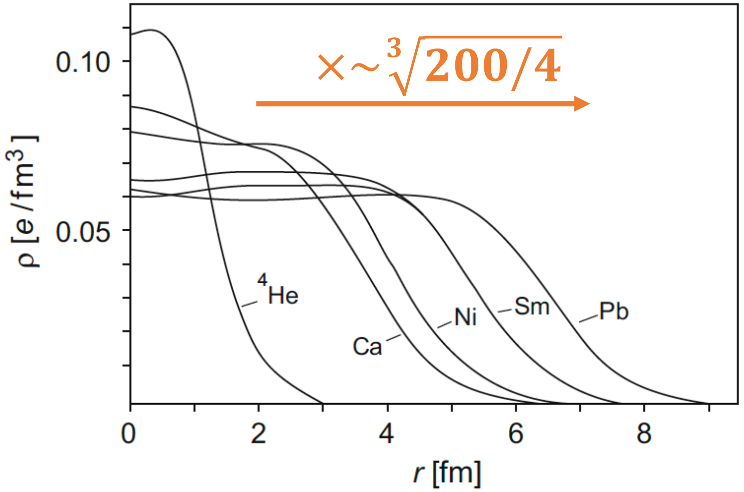
Excitation energy

Quiz: What is the momentum scale for 1 fm according to the uncertainty principle?



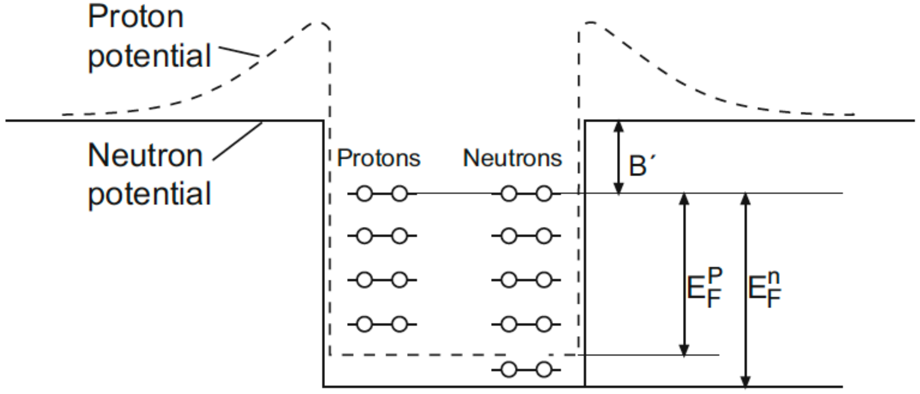
Homework**: What charge is seen by neutrino CC scattering?

Electric charge density seen by *electron* scattering



Fermi gas

Nucleons need to “ladder up” the momentum space due to overlap of wavefunction in configuration space



$$p_F \propto (\text{nucleon density})^{\frac{1}{3}} \propto \frac{1}{R}$$

(local) density varies with *r*

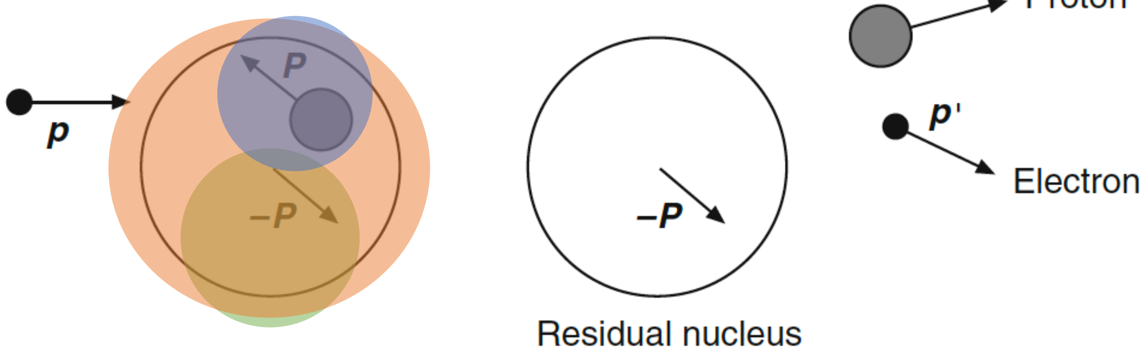
Nucleus radius (global)

All figures from Povh, et al. Particles and Nuclei

Shell model (no longer non-interacting gas)

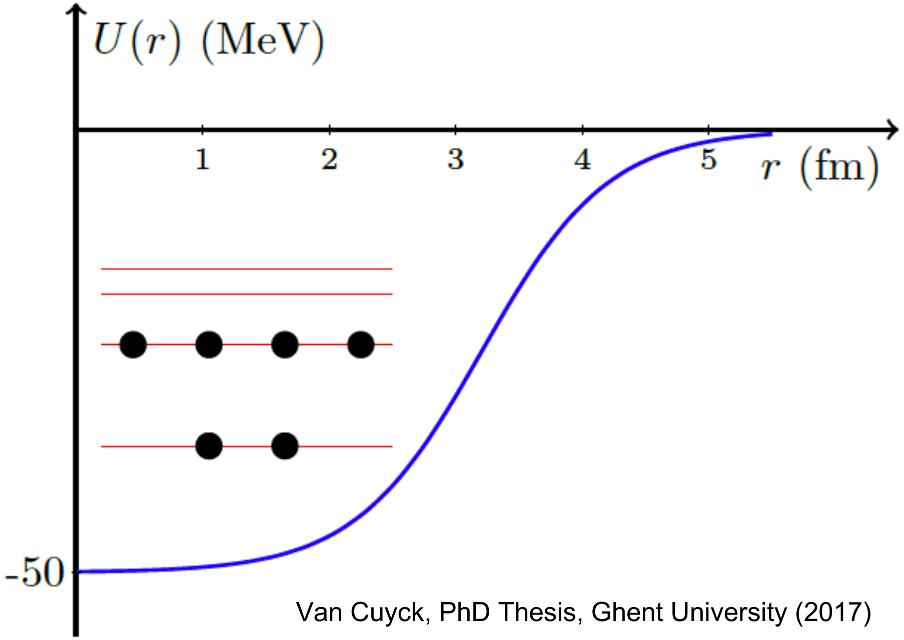
- Mean field: each nucleon moving freely in a potential approximated for the sum of interactions with all other nucleons.
- Confining (radial-dependent) mean-field potential leads to energy levels

Nucleus at rest
Sum of all nucleons' Fermi motion = 0
Fermi motion



Sum of all other nucleons' Fermi motion

Povh, et al. Particles and Nuclei



Van Cuyck, PhD Thesis, Ghent University (2017)

Table 6.1 Fermi momentum P_F and effective average potential S for various nuclei. These values were obtained from an analysis of quasi-elastic electron scattering at beam energies between 320 and 500 MeV and at a fixed scattering angle of 60° [12, 18]. The errors are approximately 5 MeV/c (P_F) and 3 MeV (S)

Nucleus	^{6}Li	^{12}C	^{24}Mg	^{40}Ca	^{59}Ni	^{89}Y	^{119}Sn	^{181}Ta	^{208}Pb
P_F (MeV/c)	169	221	235	249	260	254	260	265	265
S (MeV)	17	25	32	33	36	39	42	42	44

Povh, et al. Particles and Nuclei

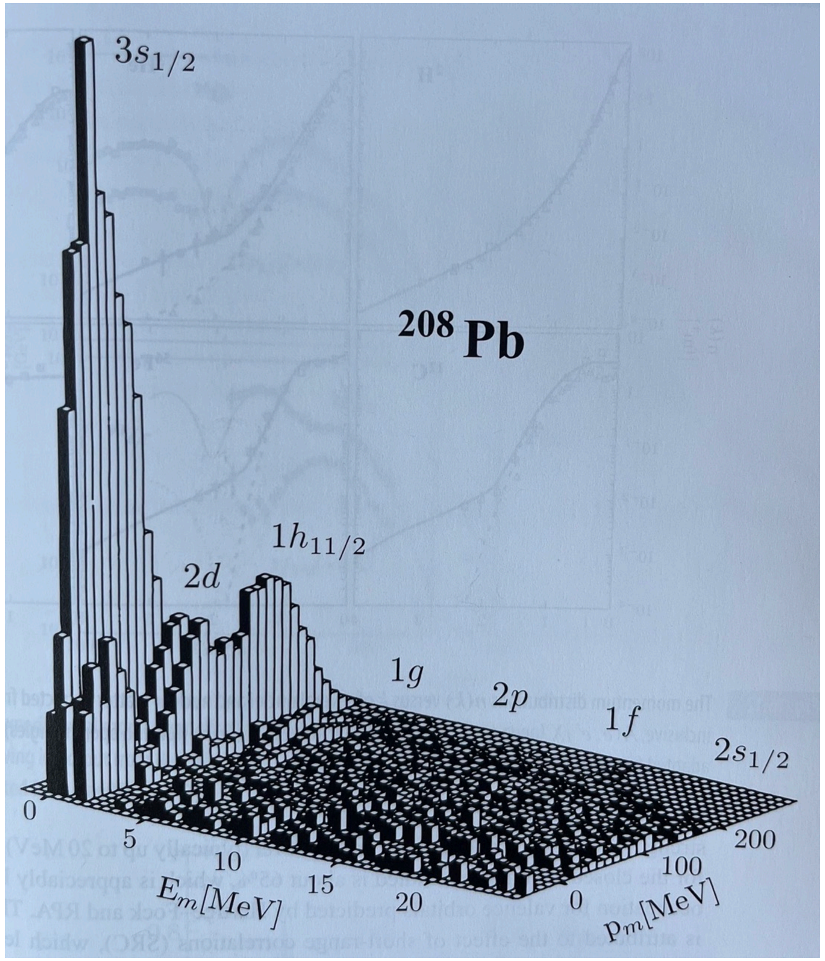
Free-moving ≠ free, the potential makes the nucleon off-shell

$$E_N = \sqrt{M_N^2 + \vec{p}^2} + \epsilon$$

Spectral function

Probability density as a function of nucleon energy and momentum (or their equivalent)

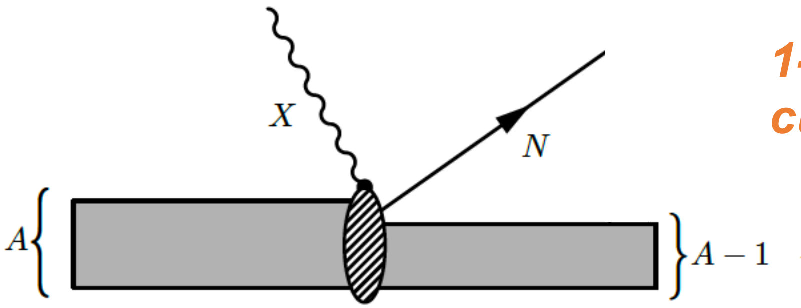
Homework*: What would the spectral function look like if the proton is on-shell (as in Fermi gas).



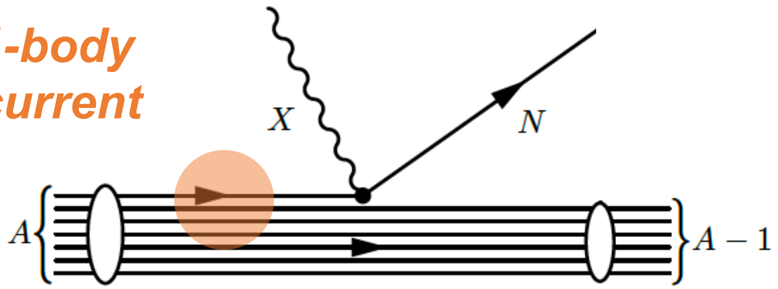
^{208}Pb spectral function represented by missing energy and missing momentum, using cross section data for the ^{208}Pb(e, e′p)^{207}Tl* reaction.

Quint, PhD thesis, University of Amsterdam, 1988

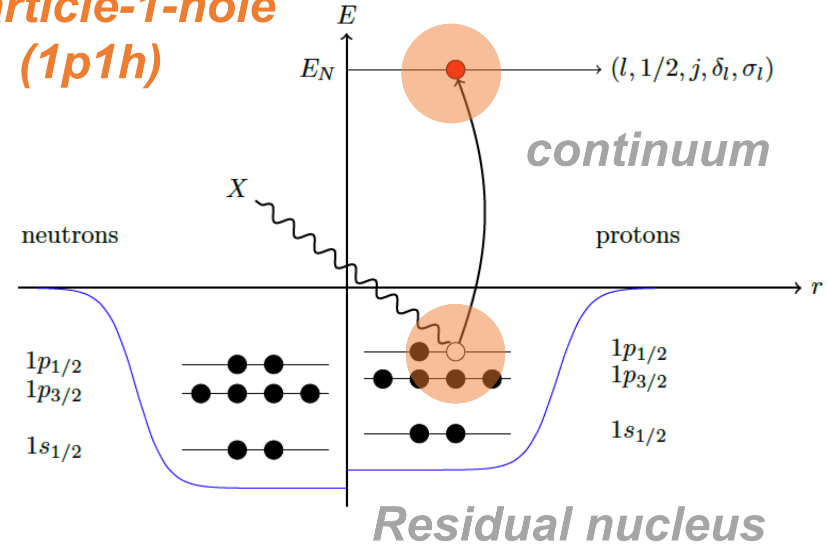
Impulse approximation (IA)

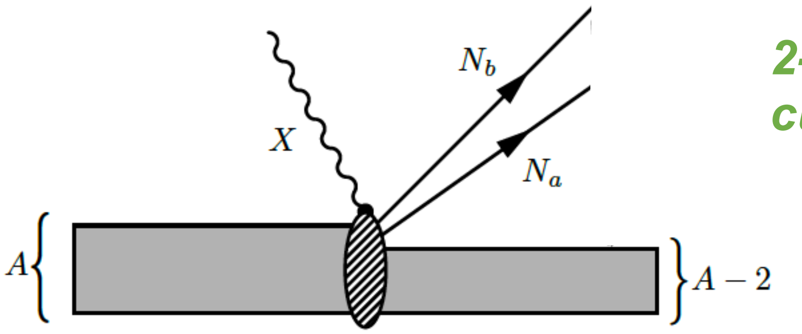


1-body current

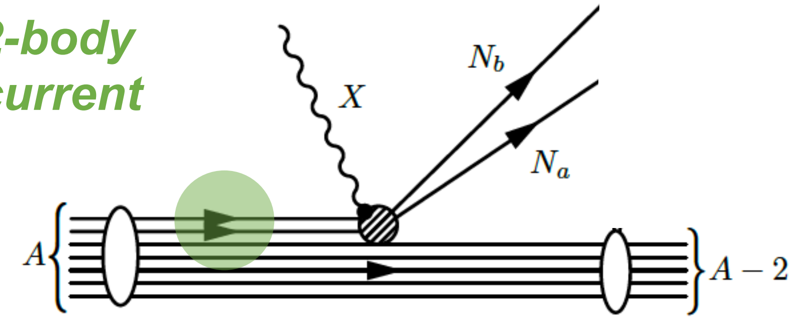


1-particle-1-hole (1p1h)

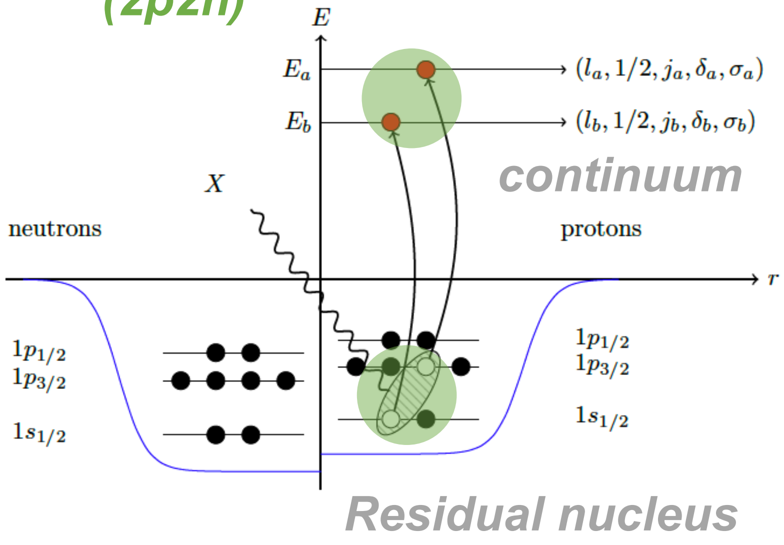




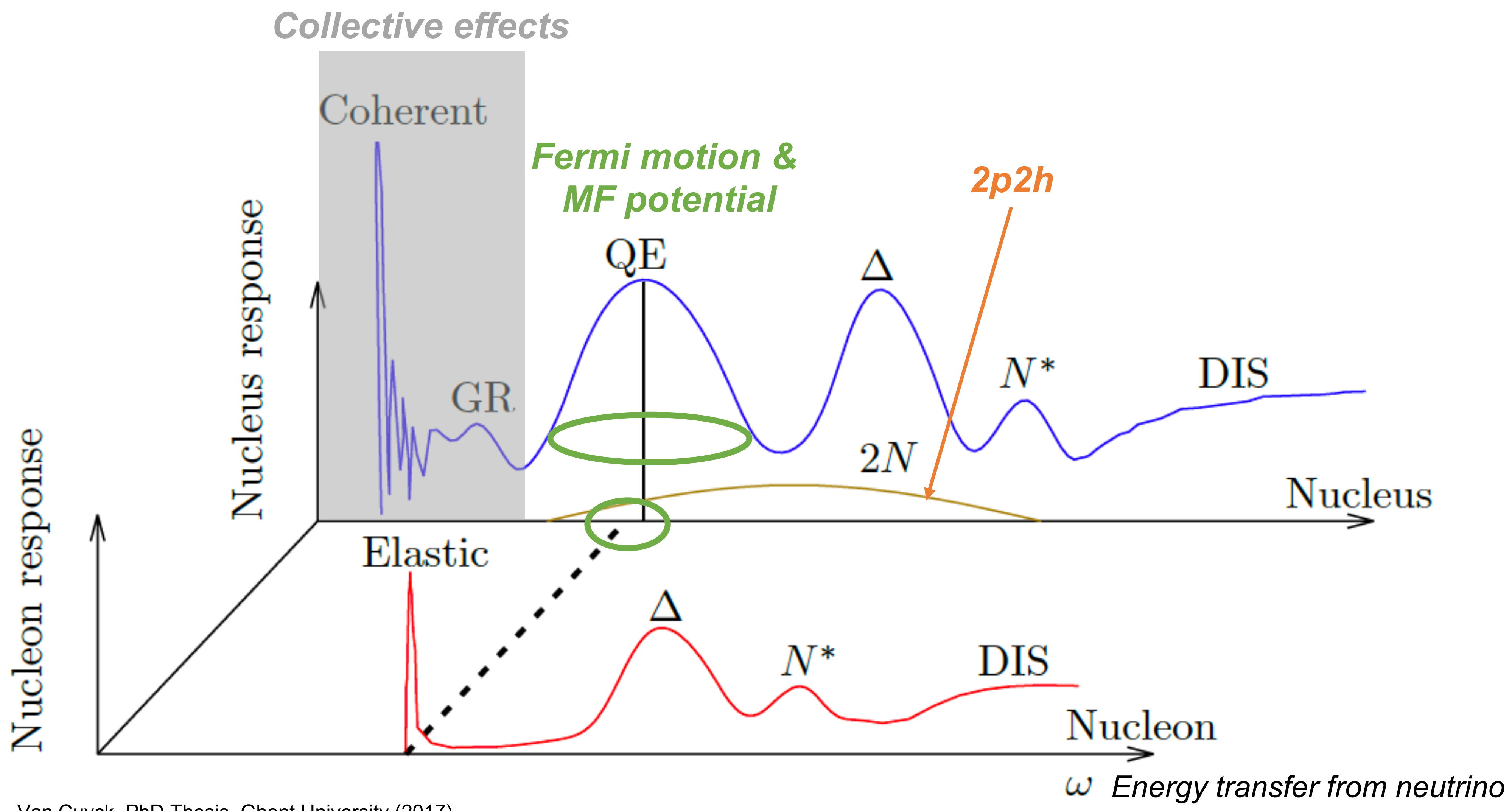
2-body current



2-particle-2-hole (2p2h)

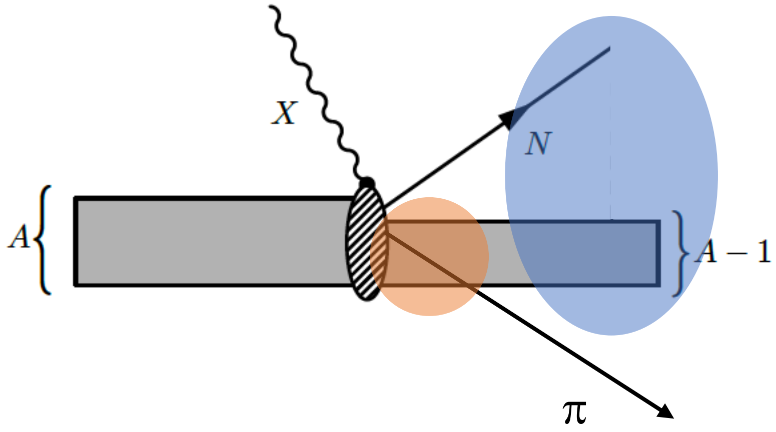


All figures from Van Cuyck, PhD Thesis, Ghent University (2017)

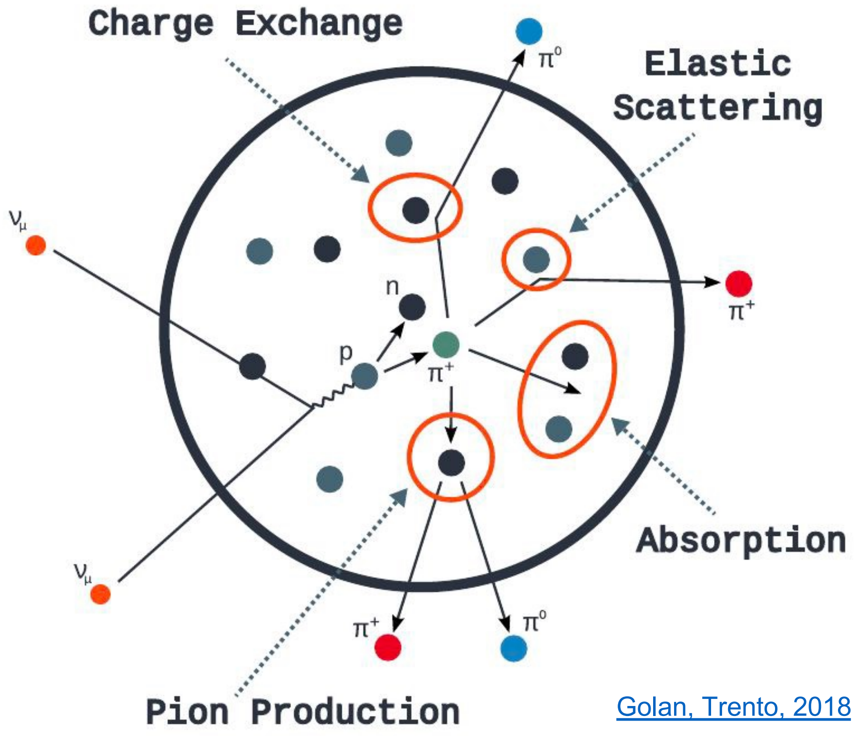


Van Cuyck, PhD Thesis, Ghent University (2017)

Final-state interaction (FSI)



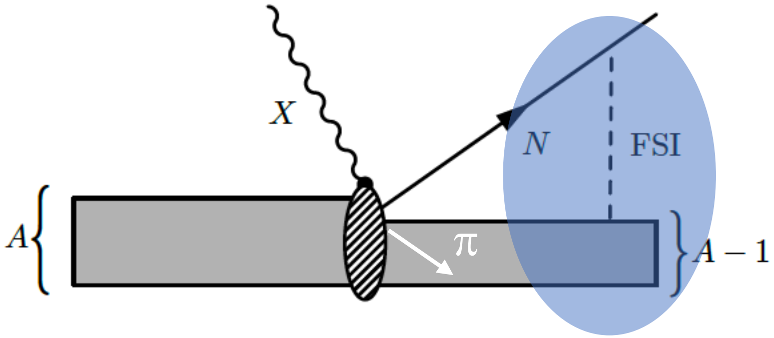
Van Cuyck, PhD Thesis, Ghent University (2017)



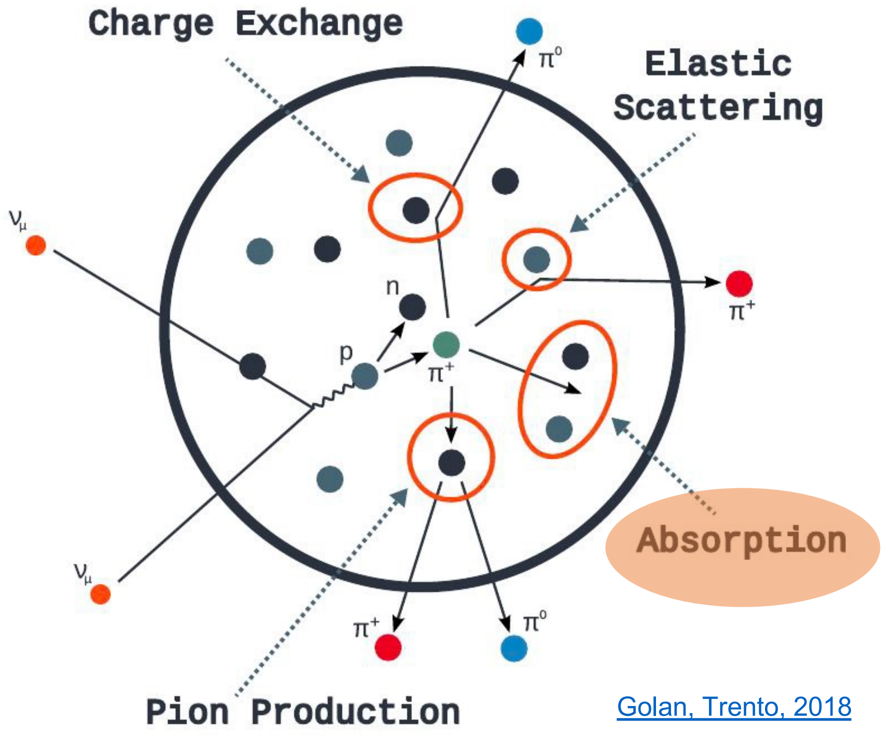
Golan, Trento, 2018

Final-state interaction (FSI)

Can not identify RES experimentally

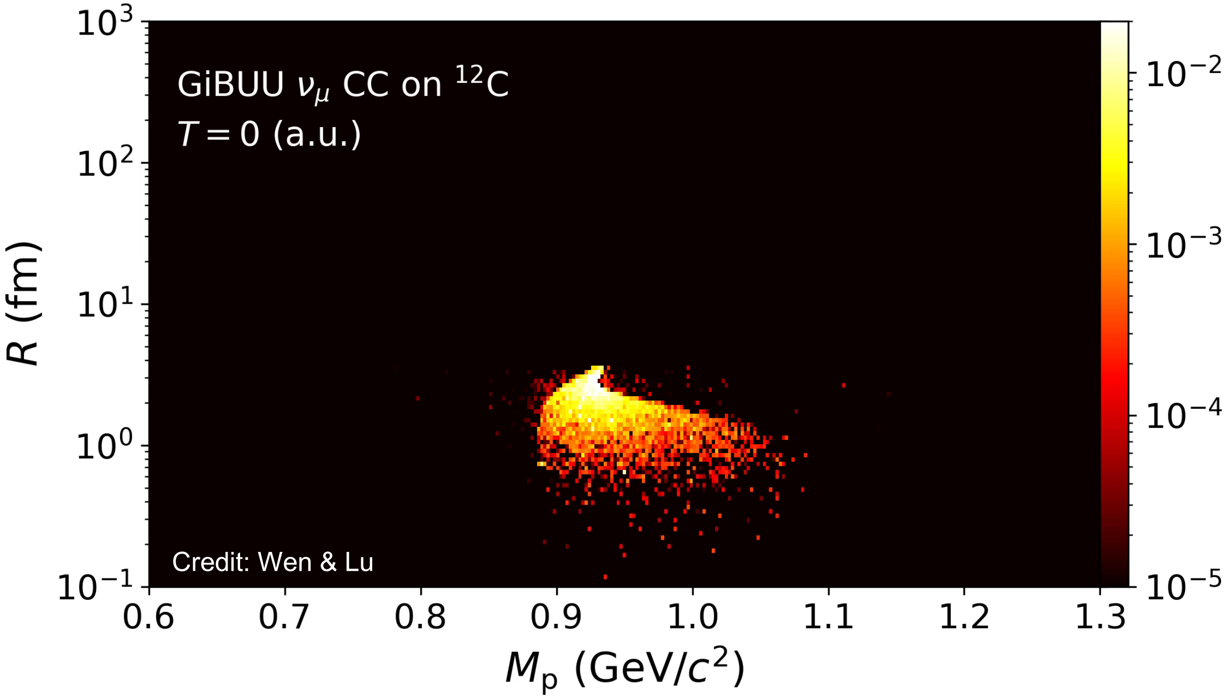


Van Cuyck, PhD Thesis, Ghent University (2017)



[Golan, Trento, 2018]

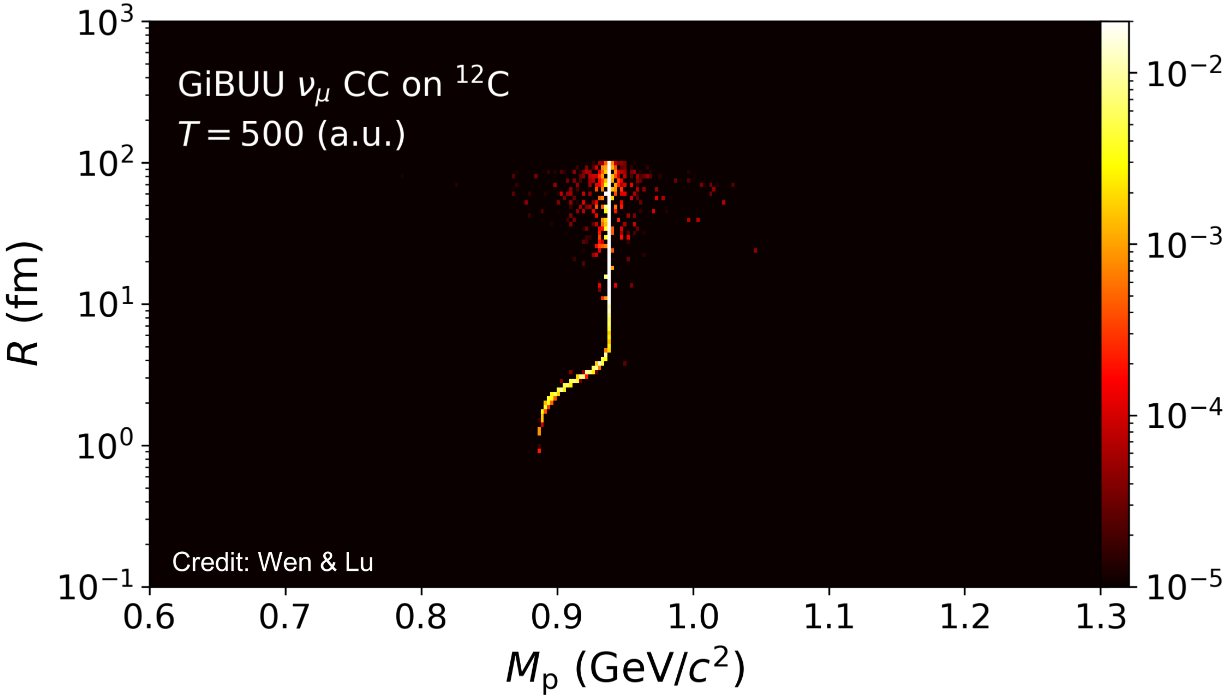
Final-state interaction (FSI)



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

Final-state proton inside nucleus: ***mass*** evolves as it propagates out of the nucleus.

Final-state interaction (FSI)



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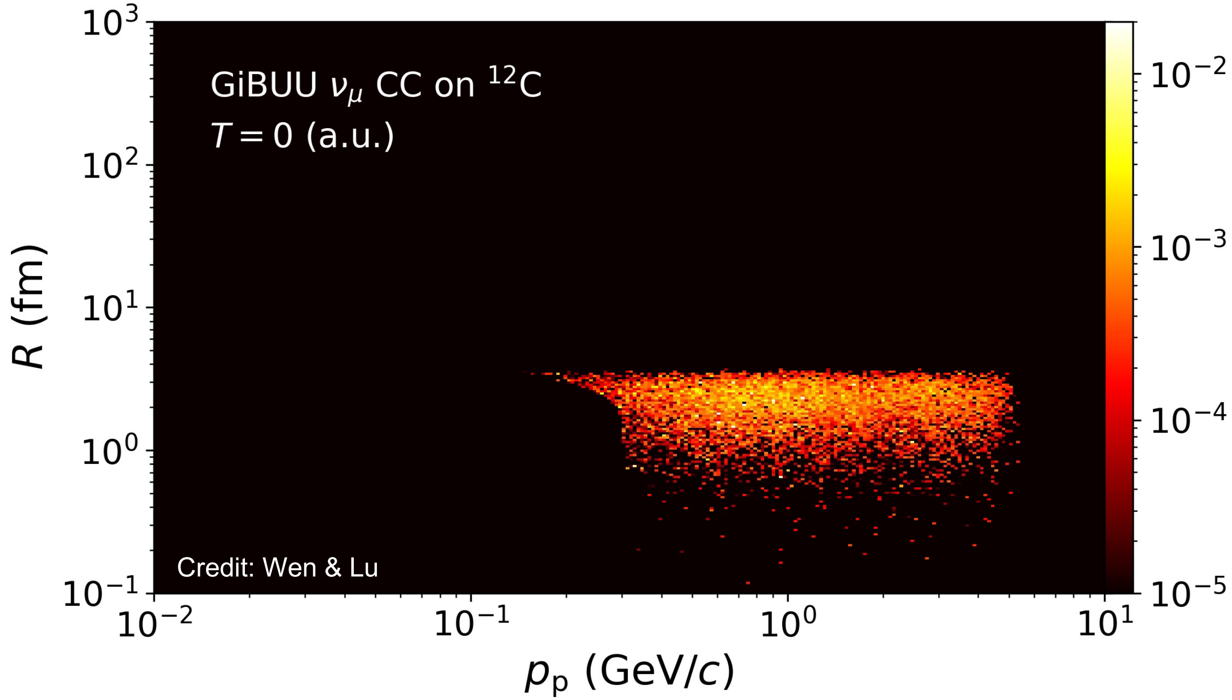
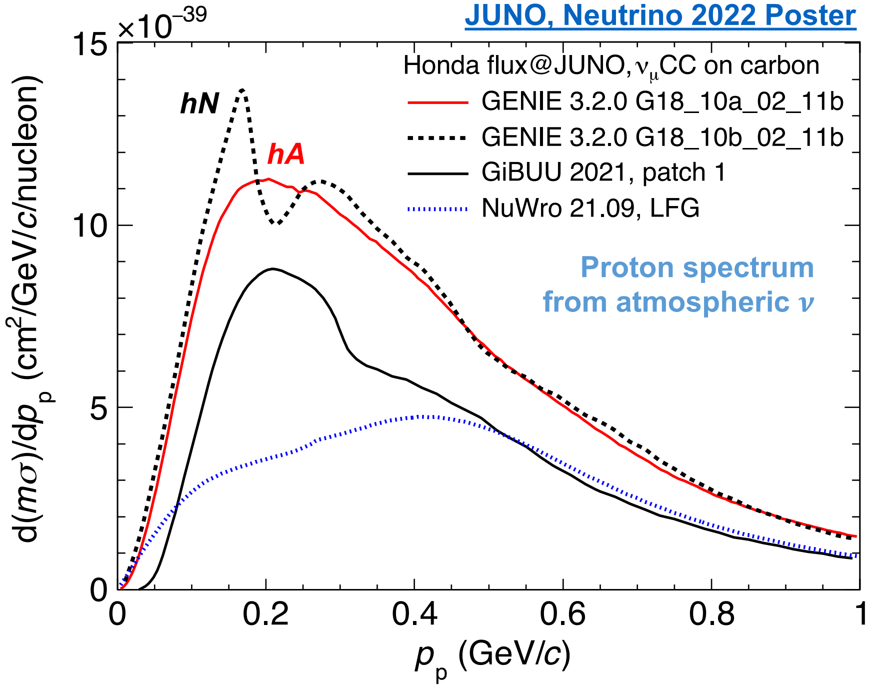
Final-state interaction (FSI)

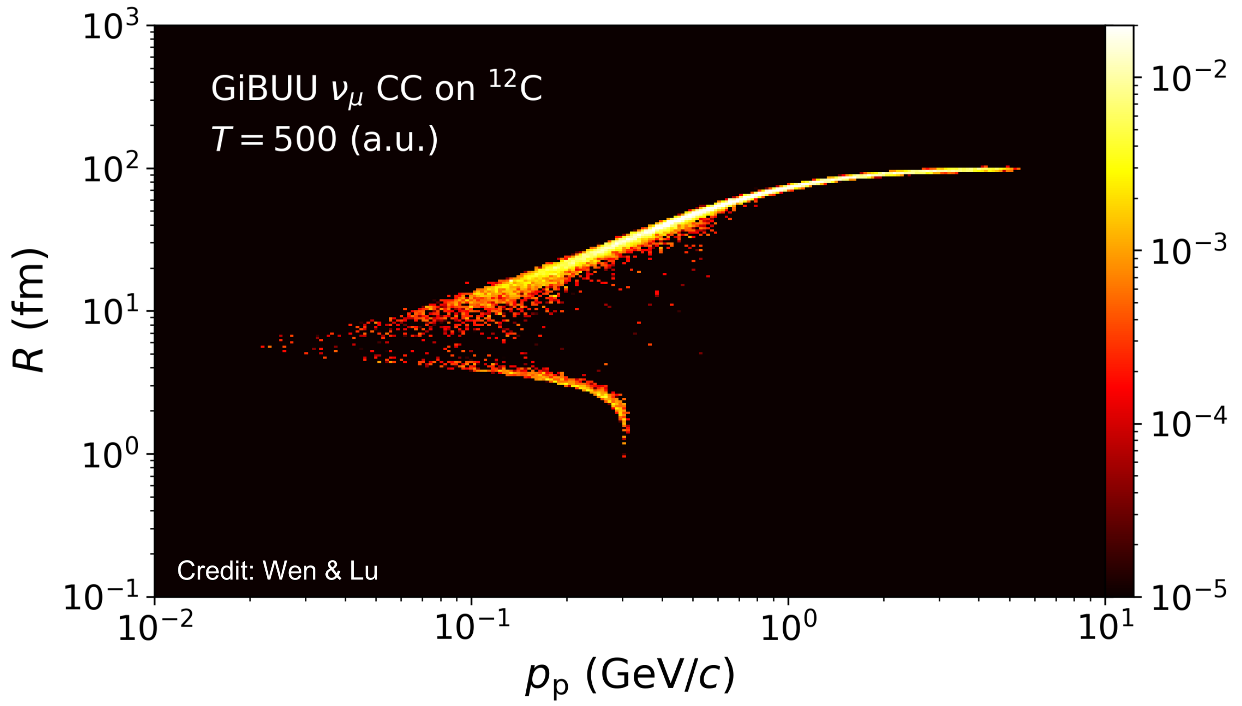




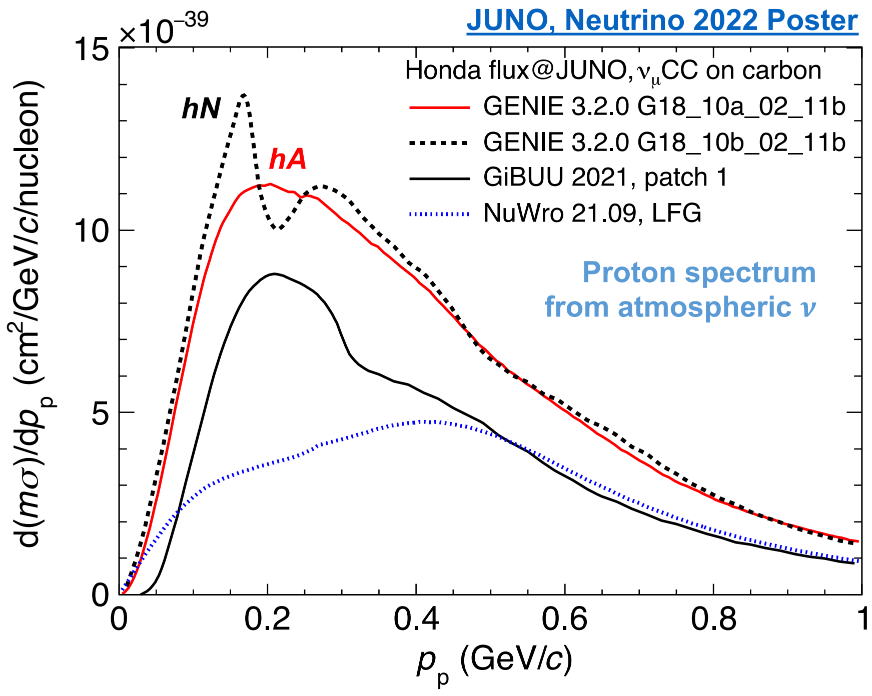
† Proton in GiBUU final-state transport
R: radial position, p_p: momentum

Final-state proton in neutrino interactions: ***momentum*** evolves as it propagates out of the nucleus.

Final-state interaction (FSI)



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

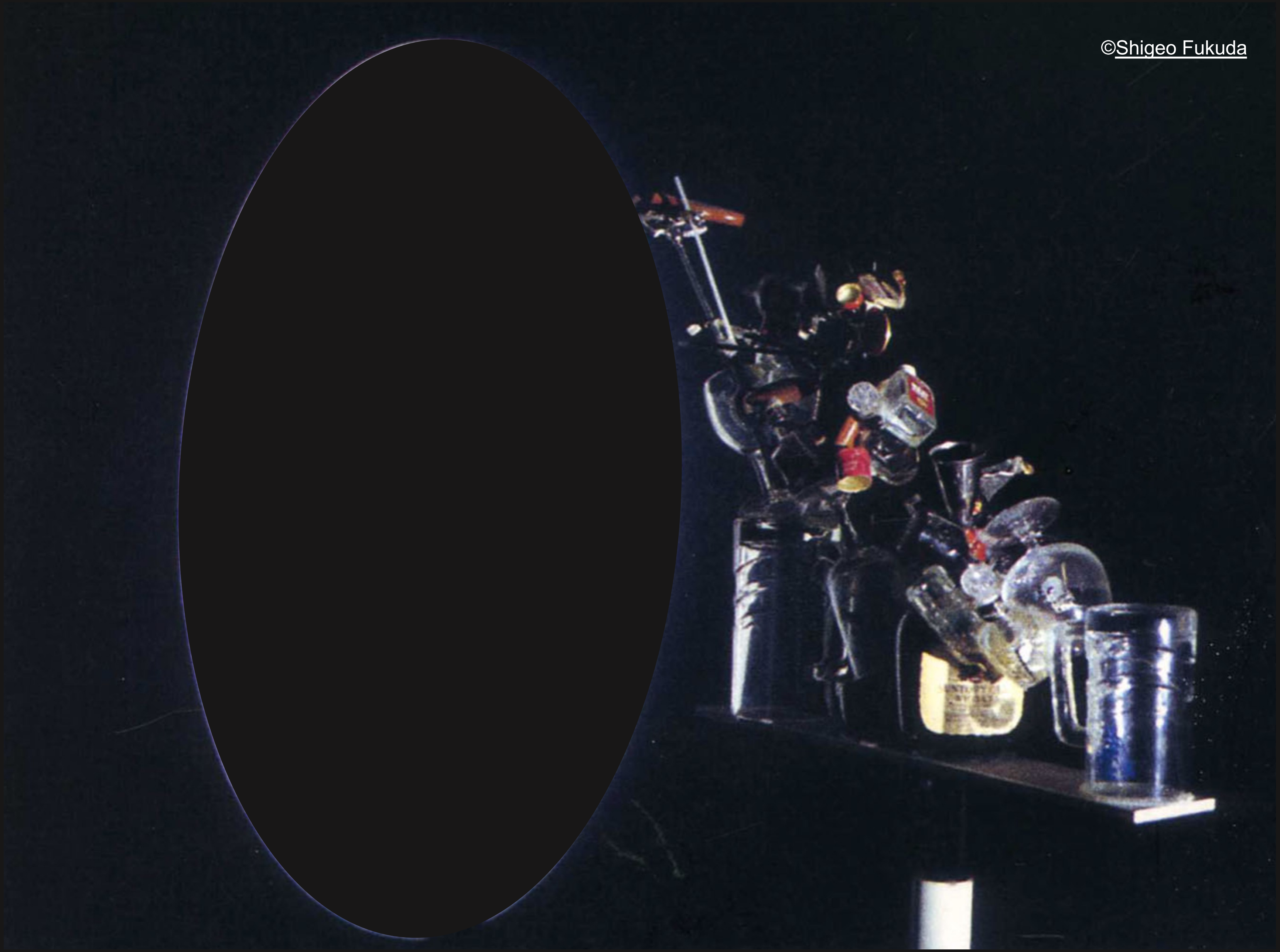


Final-state proton in neutrino interactions: ***momentum*** evolves as it propagates out of the nucleus.

Homework: In the GiBUU FSI movie:

1. ****** Calculate the physical time unit, i.e. how long is T=1 a.u.?***
2. ******** Locate the forbidden region. Explain its mechanism. What determines its boundary?***

Part 3: TKI Phenomenology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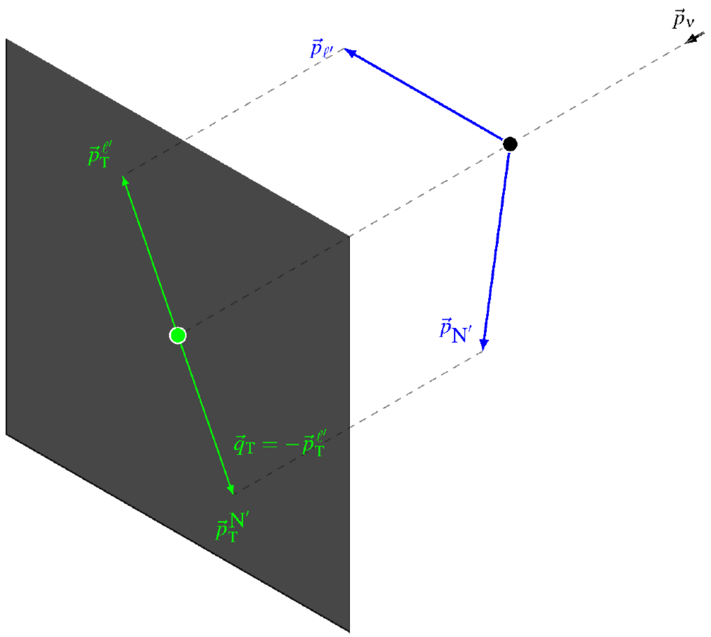
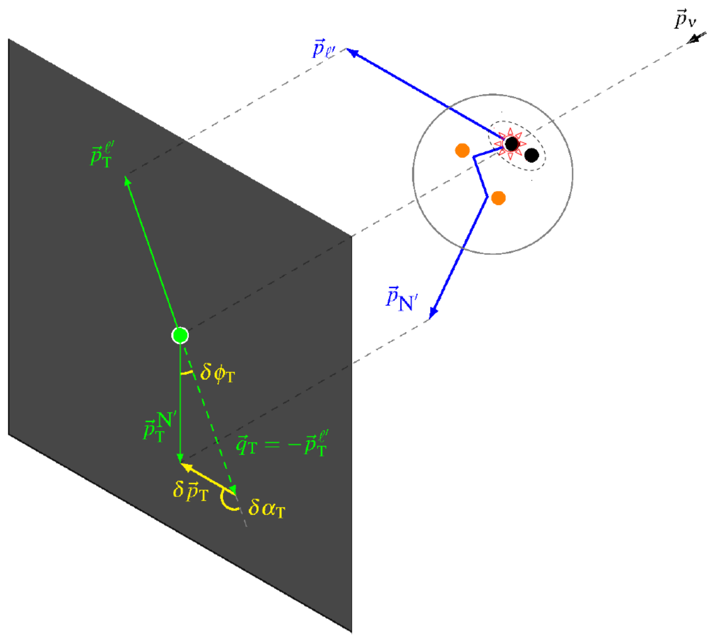
Transverse Kinematic Imbalance (TKI)



Stationary free nucleon target



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

Missing energy

From Wikipedia, the free encyclopedia

[…]

neutrinos.[1] In general, missing energy is used to infer the presence of non-detectable particles and is expected to be a signature of many theories of physics beyond the Standard Model.[2][3][4]

[…]

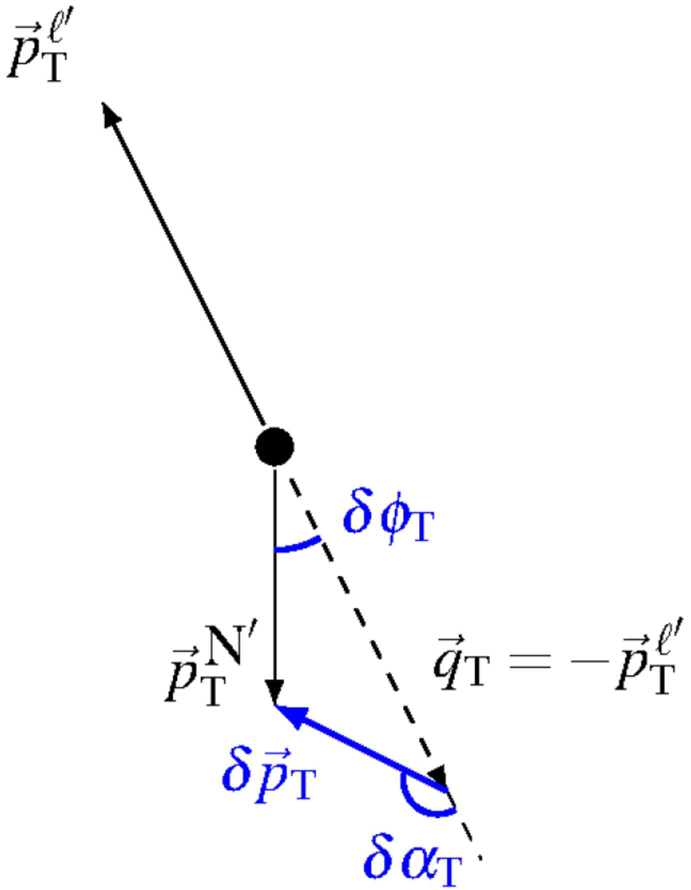
hadron colliders.[5] The initial momentum of the colliding partons along the beam axis is not known —

TKI

Multi-dimensional observation
- ❑ Momentum (magnitude)
- ❑ Angle
- ❑ Asymmetry

Lu, *et al.*, Phys.Rev.D 92, 051302 (2015)
Lu, *et al.*, Phys.Rev.C 94, 015503 (2016)

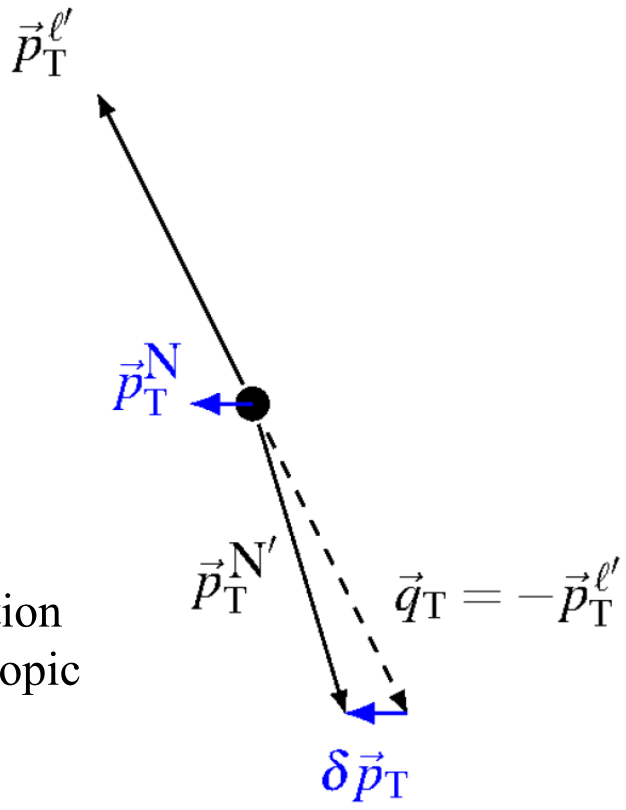
Transverse Boosting Angle $\delta\alpha_T$



if Fermi motion only

$\delta\vec{p}_T = \vec{p}_T^{\,N}$

$\delta\alpha_T$ is Fermi motion direction → isotropic



$\delta\vec{p}_T$

—total transverse momentum

—transverse momentum imbalance

—missing pT

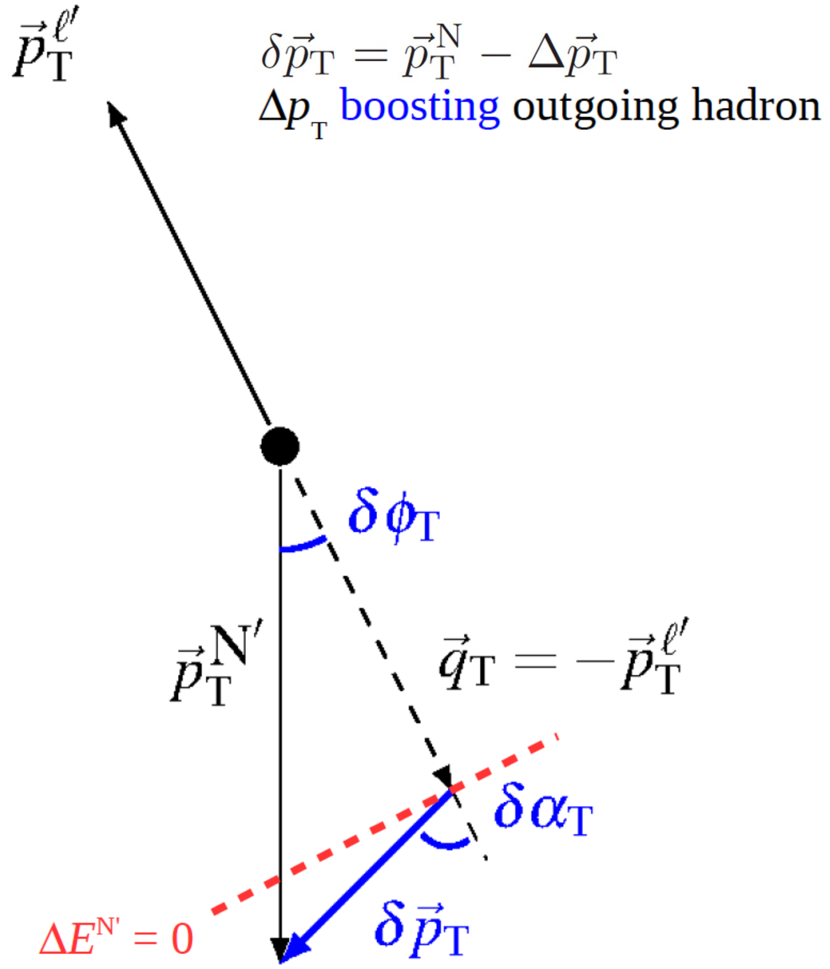
—...

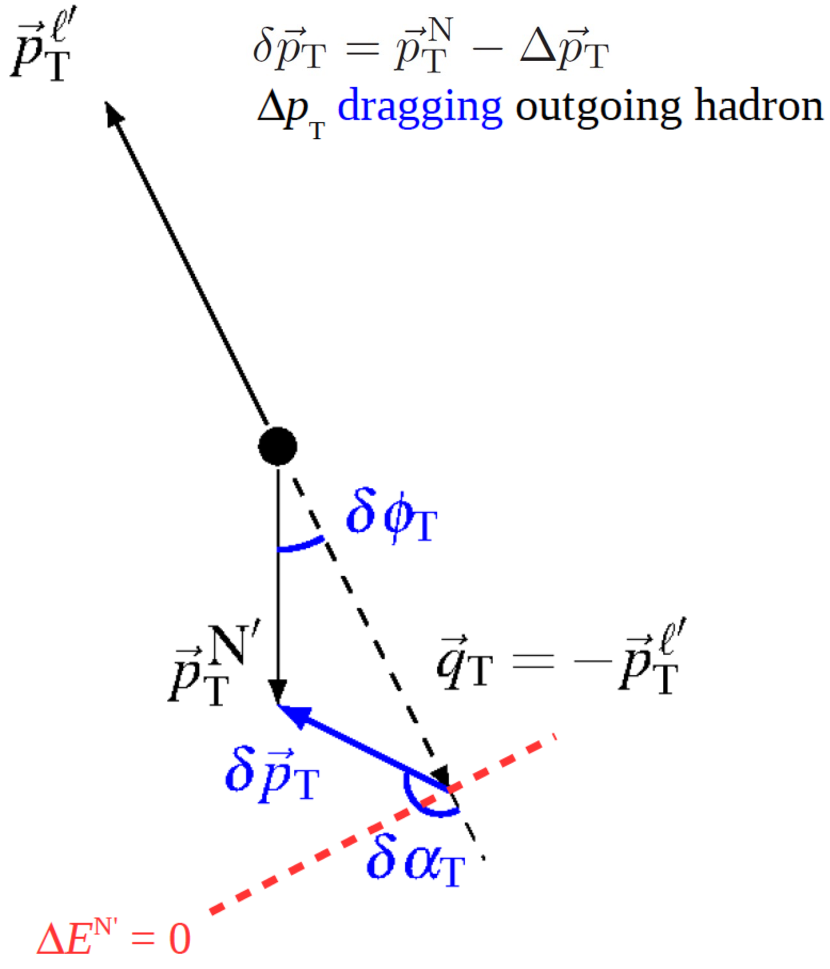
In full

$$\delta\vec{p}_T = \vec{p}_T^{\,N} - \Delta\vec{p}_T$$

FSI and missing particles

Transverse Boosting Angle $\delta\alpha_T$





FSI and momentum sharing with extra particles
- ❑ pion absorption
- ❑ 2p2h

Emulated Nucleon Momentum p_N

[Furmanski & Sobczyk, Phys.Rev.C 95, 065501 (2017)]

A more general analysis of kinematic imbalance

Transverse: $0 = \vec{p}_T^{\ell'} + \vec{p}_T^{N'} - \delta\vec{p}_T$

Longitudinal: $E_\nu = p_L^{\ell'} + p_L^{N'} - \delta p_L$

New variable: $p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$

Neutrino energy is unknown (in the first place), equations are not closed.

Assuming exclusive μ-p-A' final states
Use energy conservation to close the equations

$$E_\nu + m_A = E_{\ell'} + E_{N'} + E_{A'}$$

$$E_{A'} = \sqrt{m_{A'}^2 + p_n^2}$$

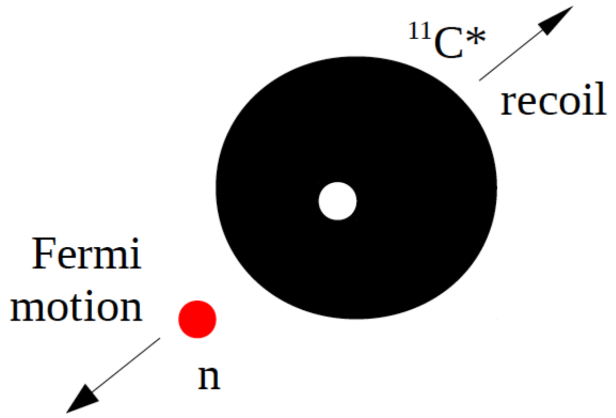
p_n : recoil momentum of the nuclear remnant

final-state

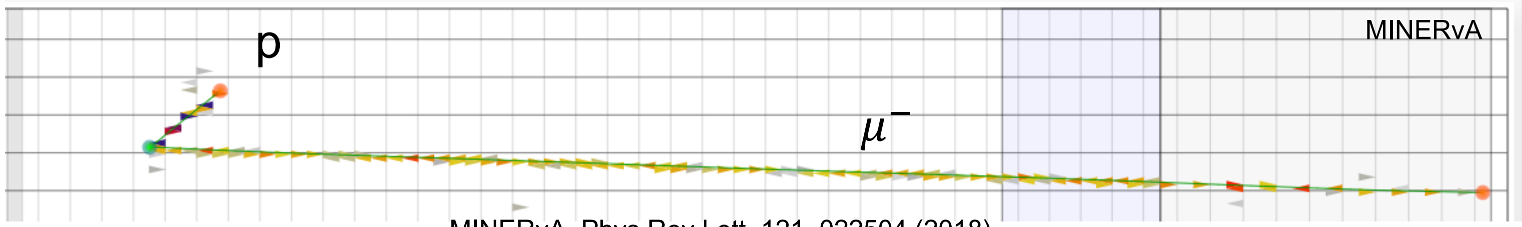
Dual Interpretation

For CCQE, A' = $^{11}C^*$
No more unknowns
p_n : neutron Fermi motion

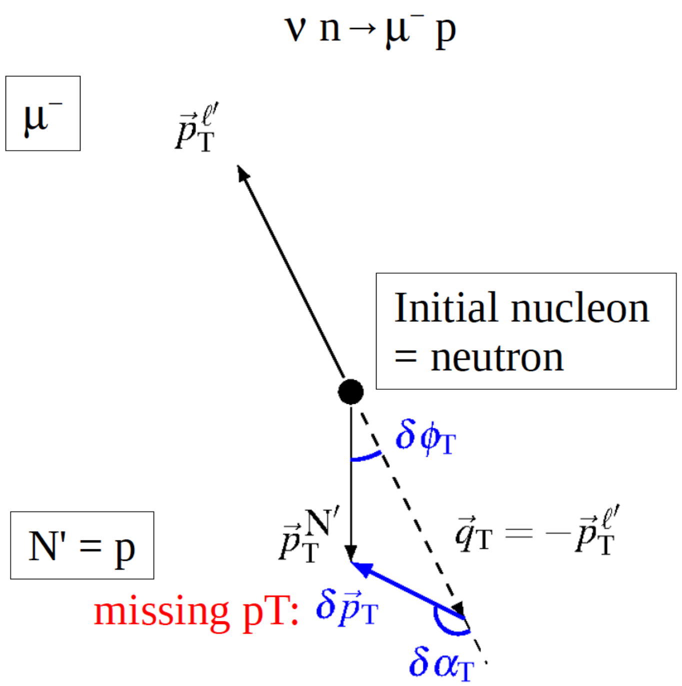
initial-state

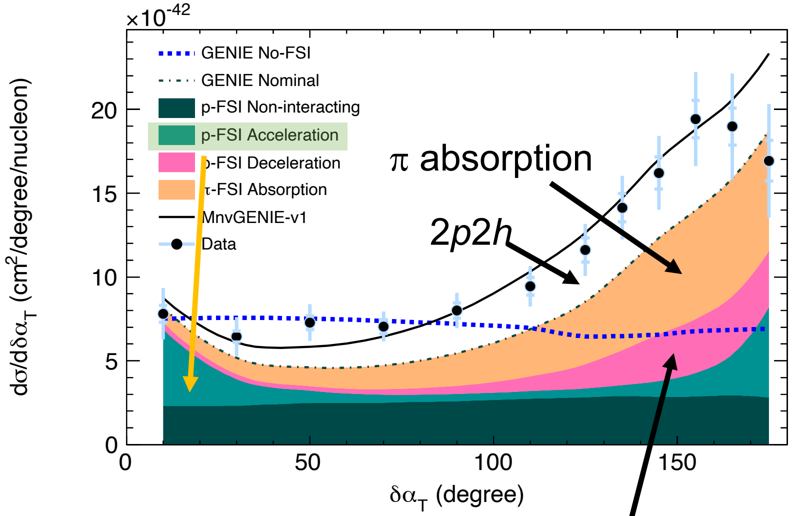


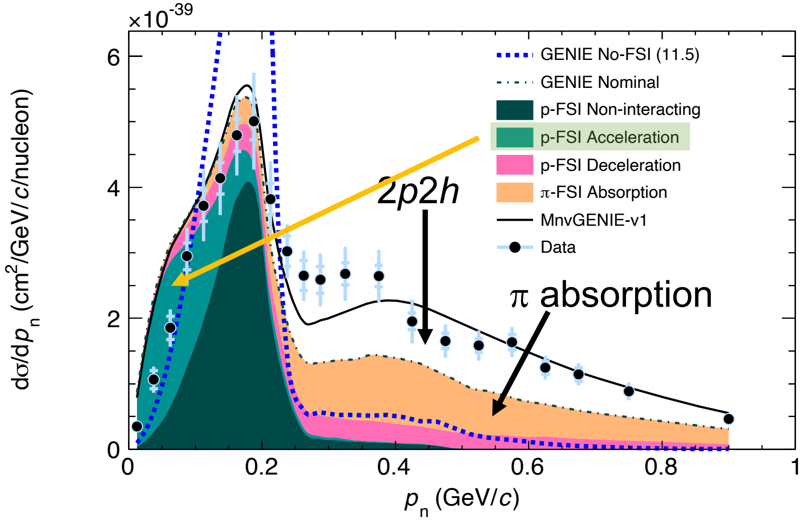
TKI: CC0π



MINERvA, Phys.Rev.Lett. 121, 022504 (2018)



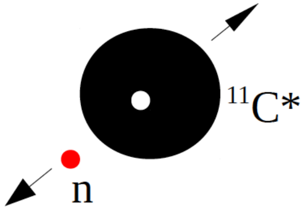


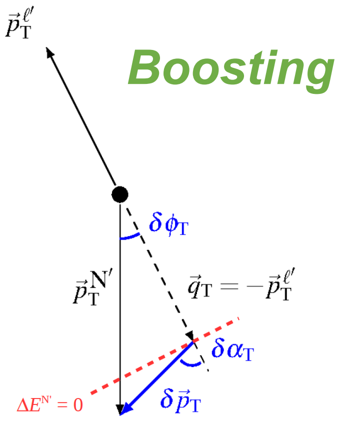


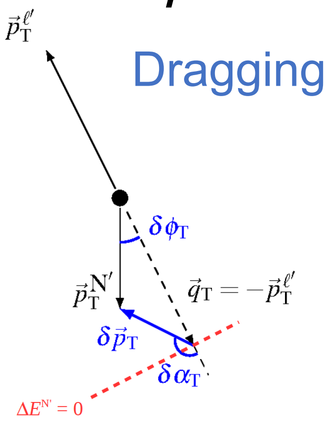
Assuming target remnant $^{11}C^*$

$$p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$$

$\sim [1 + O(10\%)] \times \delta p_T$





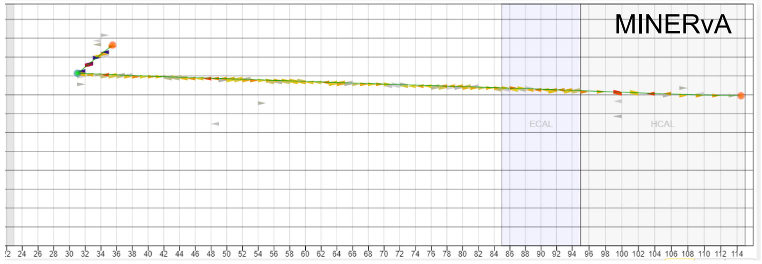


Abnormal acceleration?!

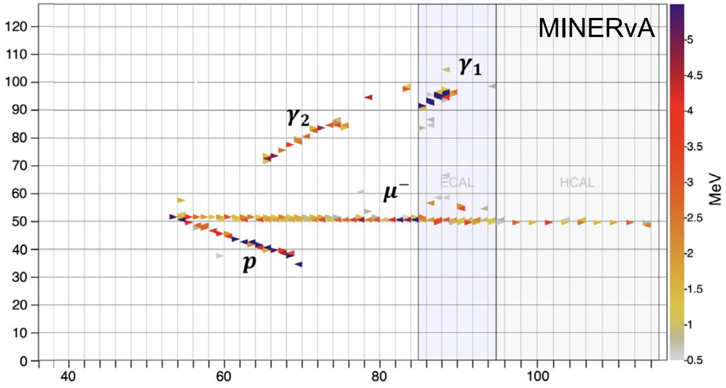
- ❑ GENIE FSI (v2.8 hA)
- ✓ ***Not dark energy***
- ✓ ***Identified by $\delta\alpha_T$ prior to measurement***
- ✓ Fixed after measurement

TKI: CCπ^0

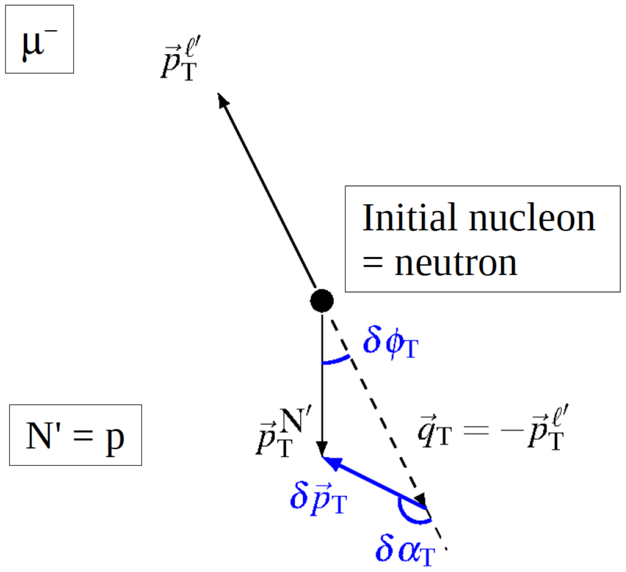
Surprising consistency!



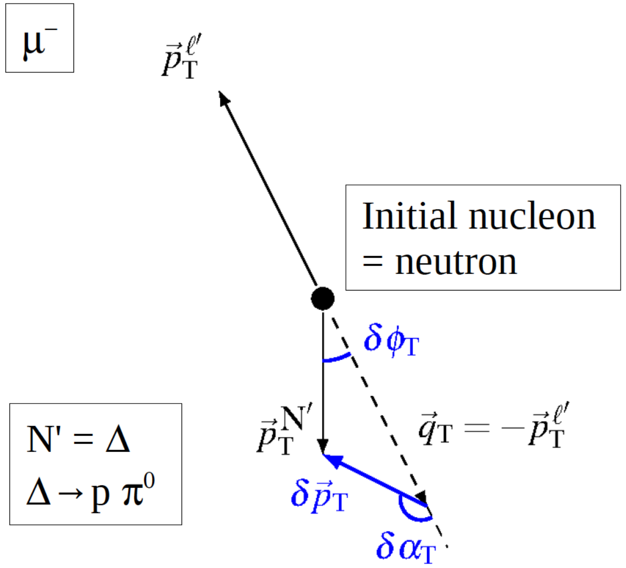
$\nu\, n \to \mu^- \, p$



$\nu\, n \to \mu^- \, p\, \pi^0$

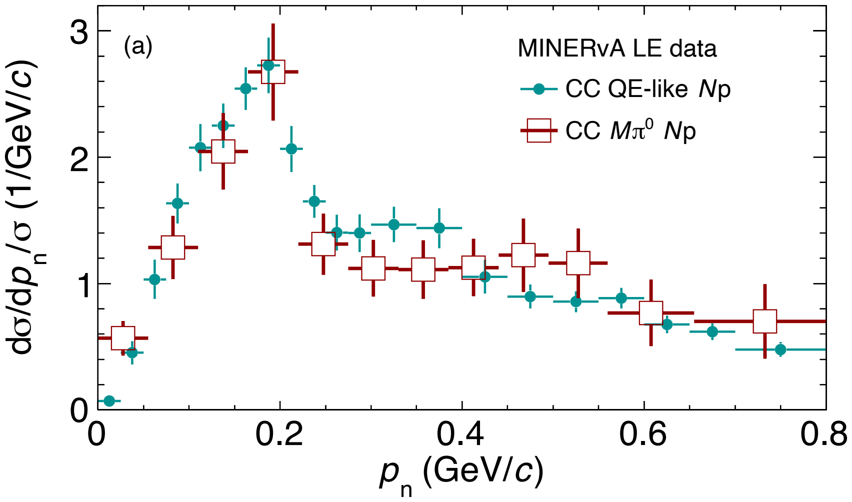


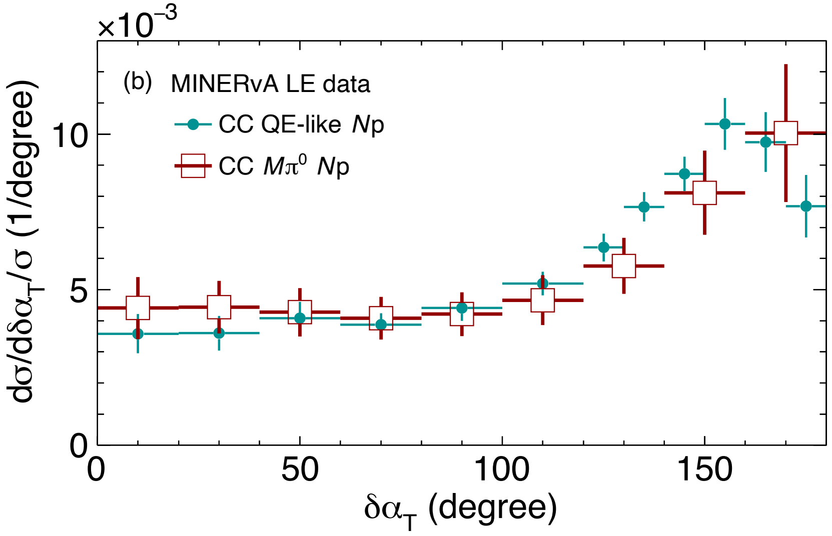
via CC0π measurement



via inclusive π^0 production

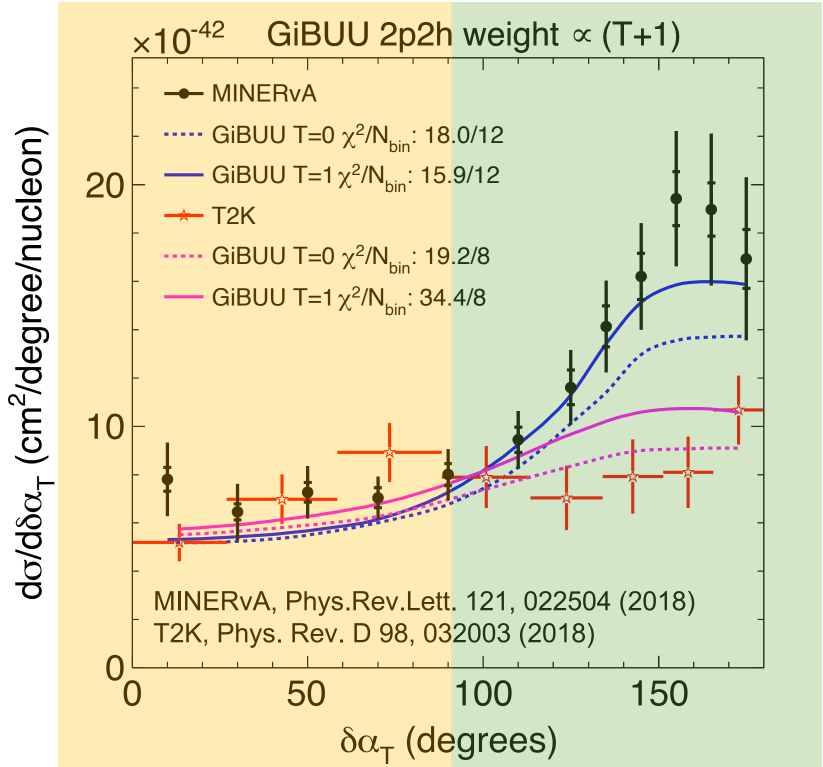
[Lu & Sobczyk, Phys.Rev.C 99, 055504 (2019)]

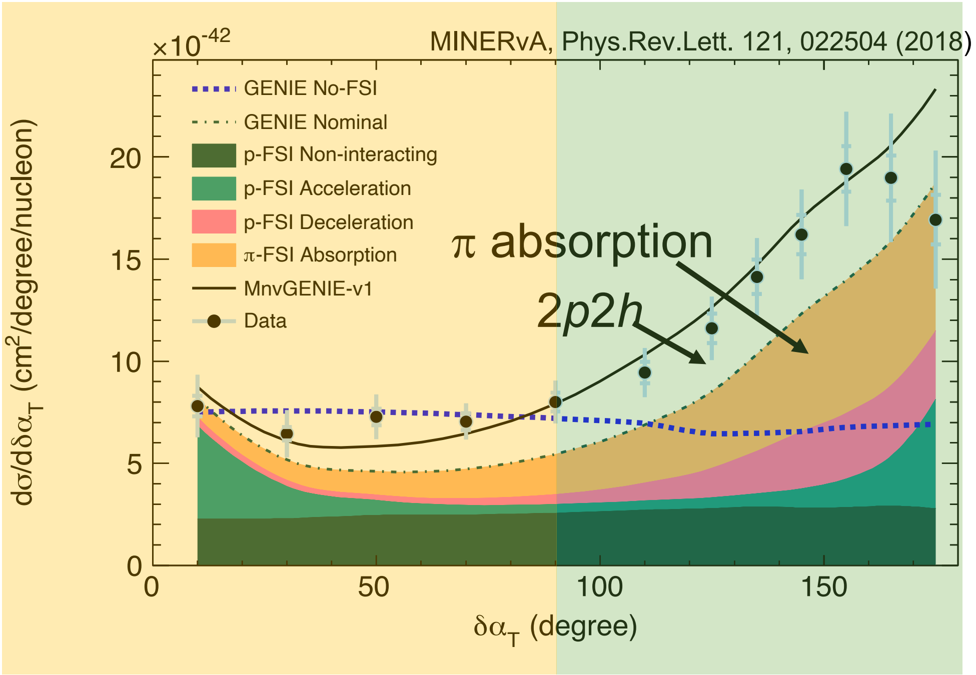




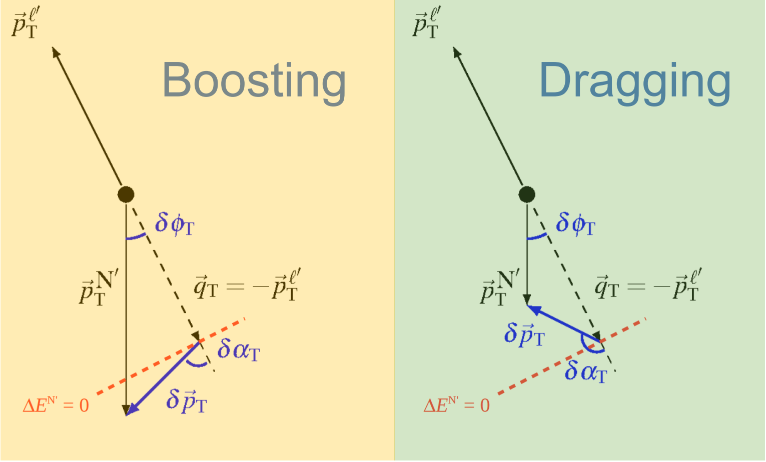
MINERvA, Phys. Rev. D 102, 072007 (2020)

TKI: FSI and 2p2h

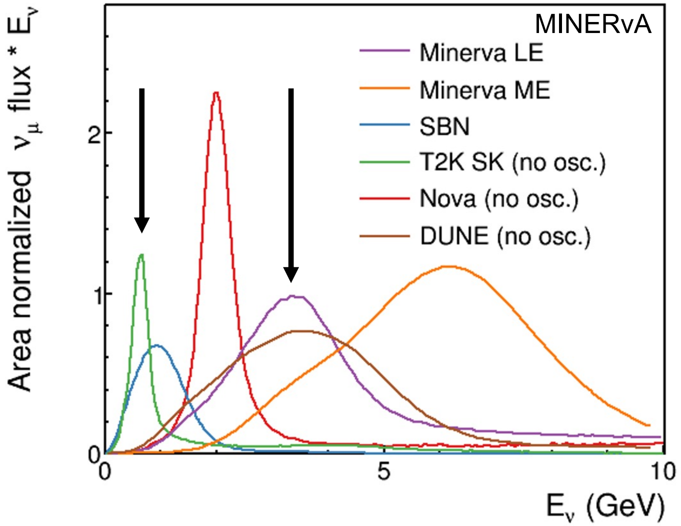




- ➢ Consistent QE xsec



- ➢ At T2K energy: smaller pion production and absorption
- ➢ Also sensitive to 2p2h



Neutrino Interactions in the Few-GeV Regime

1. Experimental Techniques
   a. Standard Model and massive neutrinos: **from elements to quark and leptons**
   b. GeV neutrino experiments
      i. **Neutrino production**
      ii. **Neutrino detection**
   c. Detectors
      i. **Plastic scintillator tracker**
      ii. **Liquid argon TPC**
      iii. **High-pressure gas TPC**
   d. MINERvA measurements
      i. **Flux and detector**
      ii. **Neutrino-electron elastic scattering, inverse muon decay, CC coherent production, and kaon production**
2. Neutrino Scattering and Nuclear Structure
   a. Neutrino-nucleon interactions: **DIS, QE, and RES**
   b. Nuclear models: **Fermi gas, shell model, and spectral function**
   c. Neutrino-nucleus interactions: **nuclear currents and FSI**
3. TKI Phenomenology
   a. Definitions**: transverse boosting angle and emulated nucleon momentum**
   b. Measurements and interpretations: **CC0π vs. CCπ^0 and MINERvA vs. T2K**

Quiz

1. ***How many neutrons does argon have?***
2. ***Here is a model:*** $1\ year = \pi \times 10^{\#days\ of\ a\ week}\ seconds$***. It is wrong by a few __%. (A: 10, B: 1, C: 0.1)***
3. ***Assuming height=diameter, what is the diameter of the 50kt-water tank in meters?***
4. ***Air density at STP in kg/m³? What about water (in its usual liquid condition)? (A:*** 10^3***, B: 1, C:*** 10^{-3}***)***
5. ***Density ratio between liquid air and water (at their own conditions)? What about polystyrene (a kind of plastics) vs. water? (A: 10, B: 1, C: 0.1)***
6. ***What is Earth's diameter in unit of DUNE's baseline? (A: 100, B: 50, C: 10)***
7. ***What is the momentum scale for 1 fm according to the uncertainty principle?***

Homework

1. Calculate the Cherenkov light threshold (in total energy, kinetic energy, and momentum) for e, μ, π^+, K^+, p, τ.
2. Calculate proton momentum for 10 MeV and 100 MeV kinetic energy.
3. If we need to have signals from at least 6 wires in LArTPC to reconstruct a proton track, what is the tracking threshold?
4. Write down all (anti)neutrino-hydrogen interactions whose final-state particles are all electrically charged.
5. Write down the Feynman diagram(s) for ν-e elastic scattering.
6. Inverse muon decay
   1) Write down the Feynman diagram(s).
   2) What is the minimum neutrino energy for this process to happen (that is, the neutrino energy threshold)?
   3) Can this technique constrain $\bar{\nu}_\mu$ flux?
7. ** Explain $\sigma_{\mathrm{CC}}^{\nu\mathrm{N}}/\sigma_{\mathrm{CC}}^{\bar{\nu}\mathrm{N}} \simeq 2$ at high energy.
8. Calculate the energy threshold of ν_e and ν_μ CCQE scattering on nucleons.
9. Check the quantum numbers and quark contents of Δ and N* on PDG (Google "pdg delta resonance"; navigate https://pdg.lbl.gov/).
10. * Using isospin arguments (CG coefficients), show that the cross-section ratio between $\nu_\mu \mathrm{p} \rightarrow \mu^- \mathrm{p}\pi^+$, $\nu_\mu \mathrm{n} \rightarrow \mu^- \mathrm{p}\pi^0$, and $\nu_\mu \mathrm{n} \rightarrow \mu^- \mathrm{n}\pi^+$ is 9:2:1 (assuming Δ dominance).
11. ** What charge is seen by neutrino CC scattering?
12. * What would the spectral function look like if the proton is on-shell (as in Fermi gas).
13. In the GiBUU FSI movie:
    1) * Calculate the physical time unit, i.e. how long is T=1 a.u.?
    2) *** Locate the forbidden region. Explain its mechanism. What determines its boundary?

BACKUP

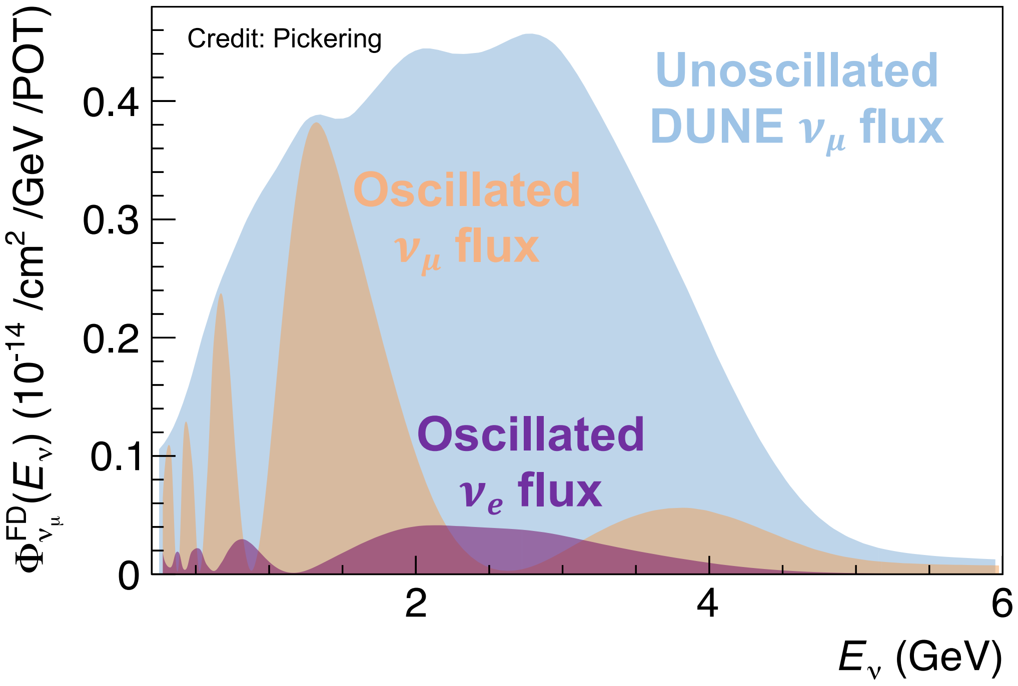
The New Impressive

Counting oscillated ν

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

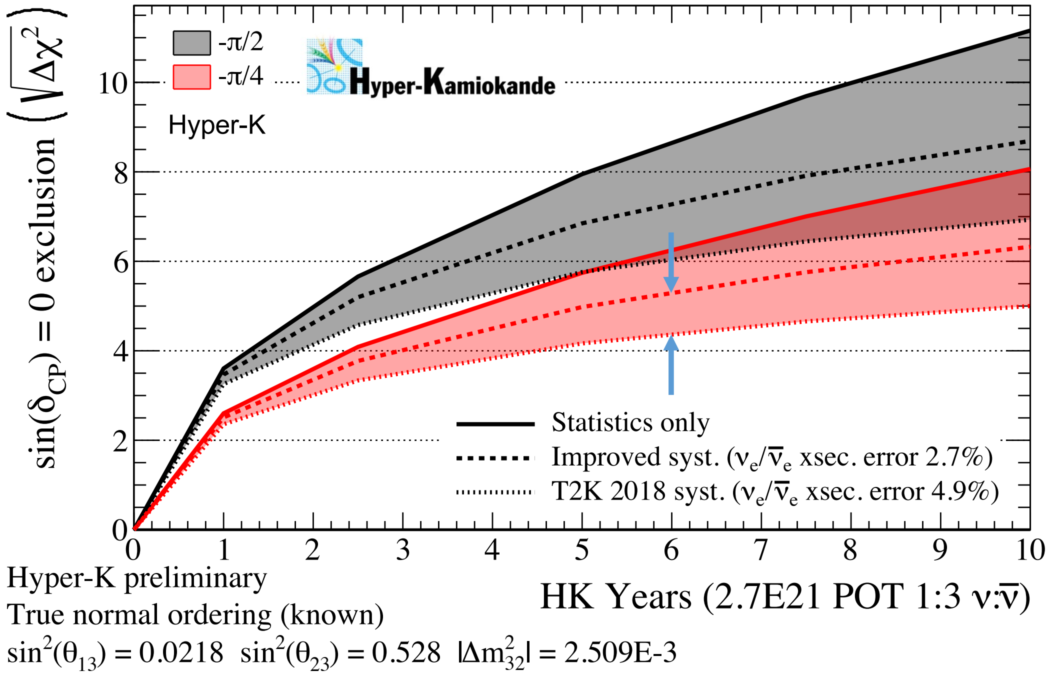
Measurement = (*flux* × *interaction*) ⊕ detector effects

No two unknowns at the same time



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



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

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

- ❑ δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
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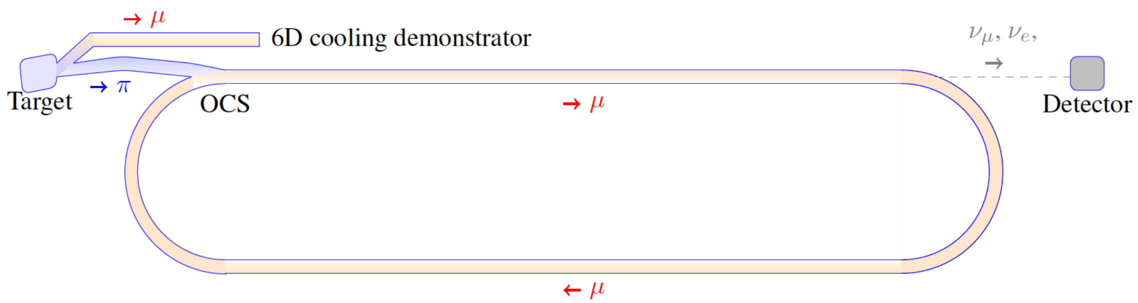
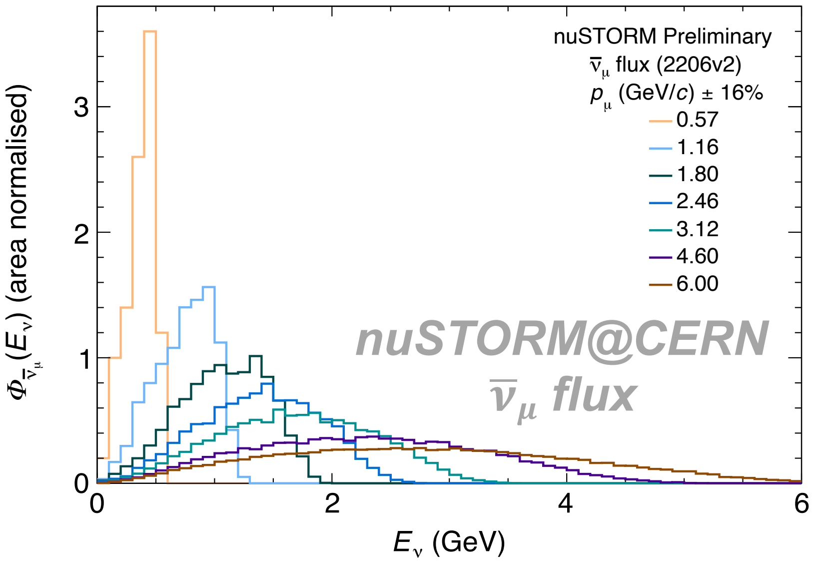
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood fluxes***

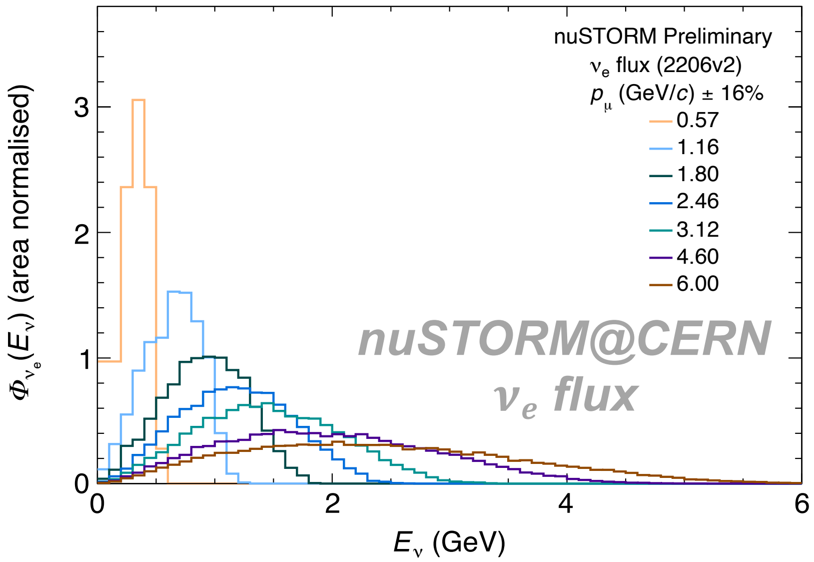
- ❑ ν from STORed Muons (nuSTORM)
  - ❖ $\nu_\mu/\bar{\nu}_e/\bar{\nu}_\mu/\nu_e$ fluxes from $\mu^\pm$ decays
  - ✓ ***1% or better flux precision***



nuSTORM, arXiv:2203.07545

nuSTORM, arXiv:2203.07545





Oscillation-relevant energy regime