Neutrino Interactions

LU Xianguo 卢显国
University of Warwick

2^{nd} JUNO Neutrino Summer School
2025 August 23, Hangzhou

国科大杭州高等研究院
Hangzhou Institute for Advanced Study, UCAS

Accelerator and Atmospheric Neutrinos
Part 2: The More Interesting Part

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Outline

1. Experimental Techniques
   a. Standard-Model ν interactions
   b. Detectors
   c. MINERvA highlights
2. Nuclear Effects
   a. Structure
   b. Dynamics
3. TKI Phenomenology
   a. Key variables
   b. Current results

Quizzes and ***Homework*** are again prepared. Number of * (0-3) indicates the difficulty.

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

- Steve Boyd, University of Warwick, *Neutrino Physics Lectures*, Warwick Week, 2025

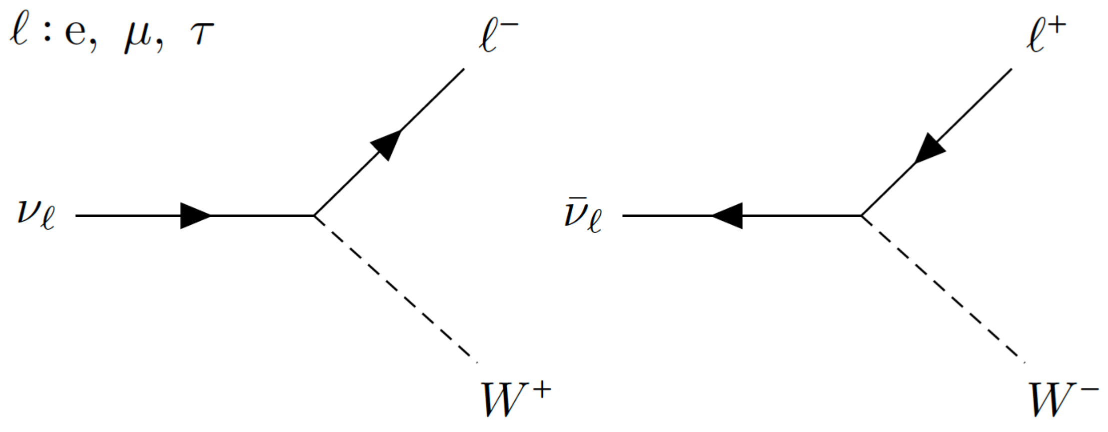
Great text on nuclear, particle, and neutrino physics

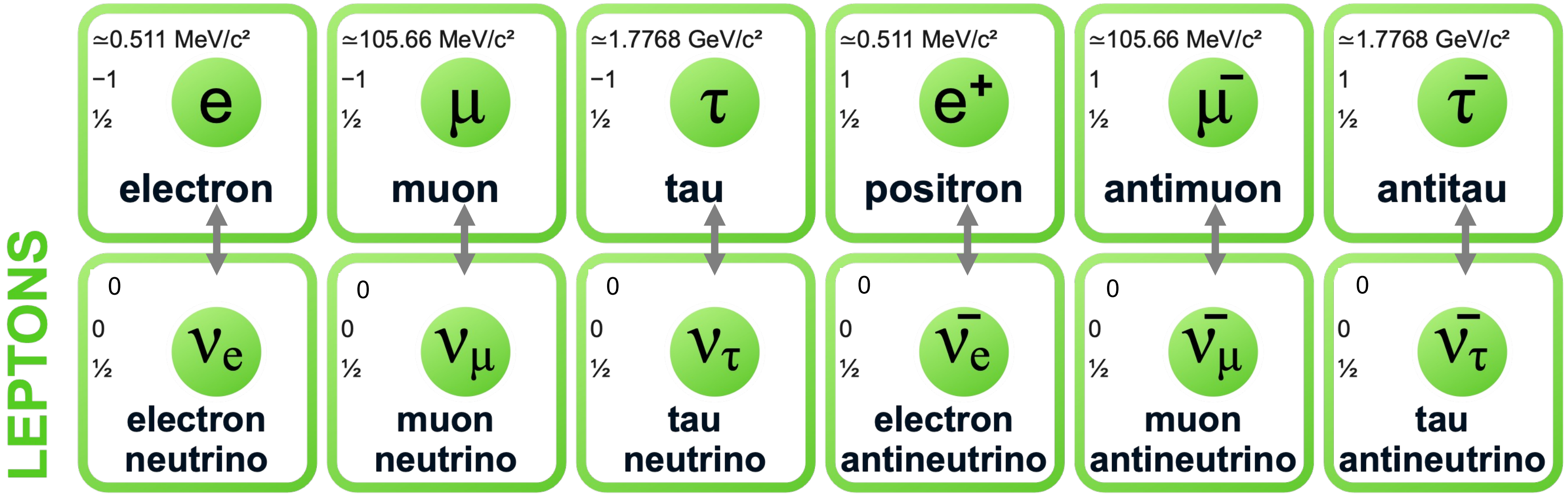
1. Mohapatra, R. N., Pal, P. B. (2004). *Massive Neutrinos in Physics and Astrophysics*. India: World Scientific.
2. Giunti, C., Kim, C. W. (2007). *Fundamentals of Neutrino Physics and Astrophysics*. United Kingdom: OUP Oxford.
3. Povh, B., Rith, K., Scholz, C., Zetsche, F., Rodejohann, W. (2015). *Particles and Nuclei: An Introduction to the Physical Concepts*. Germany: Springer Berlin Heidelberg. *7th Ed*.
4. 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.
5. Zuber, K. (2020). *Neutrino Physics*. United Kingdom: CRC Press. *3rd Ed*.
6. Rubbia, A. (2022). *Phenomenology of Particle Physics*. United Kingdom: Cambridge University Press.

Part 1: Experimental Techniques

Starting point for neutrino interaction …
… done with BSM yesterday

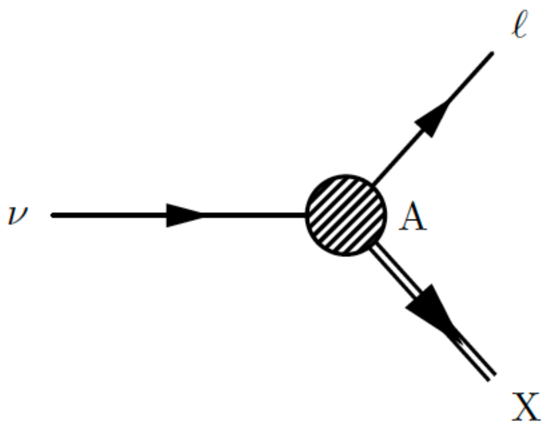
Neutrinos and antineutrinos in Standard Model
1. Charge neutral
2. Massless
❖ How can we tell all 6 of them apart?
3. Flavour, defined by charged-current interactions





Charged lepton
— easy detection
— flavour oscillation tagging

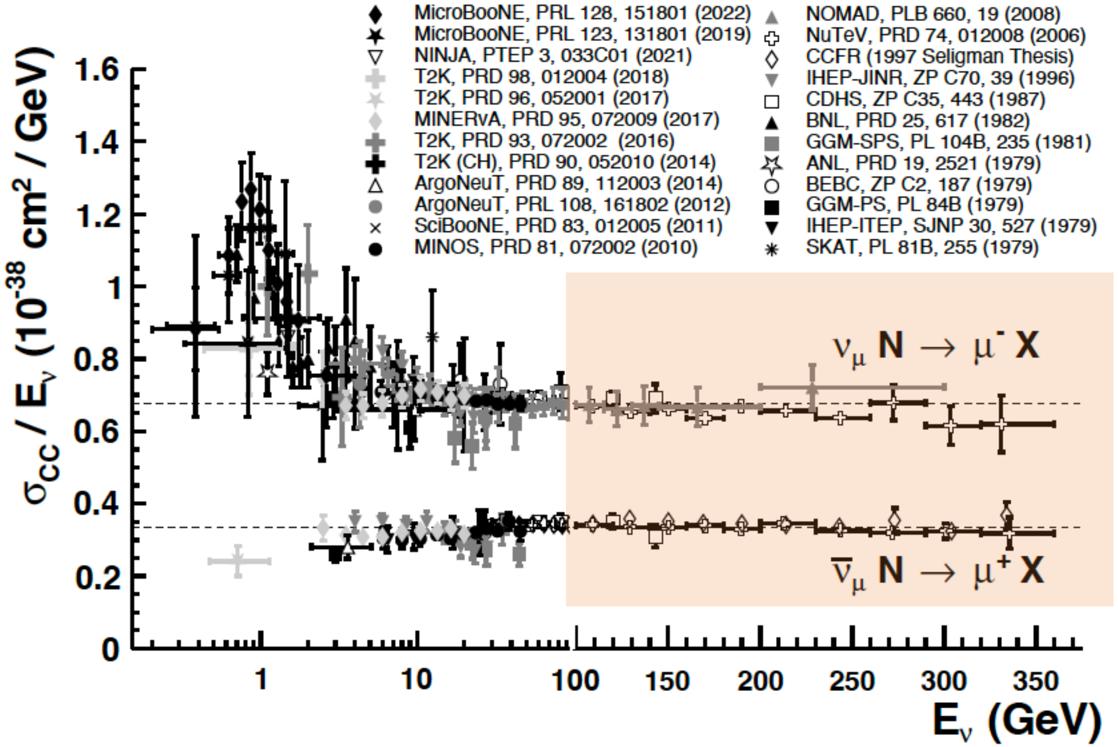
Incoming neutrinos and antineutrinos



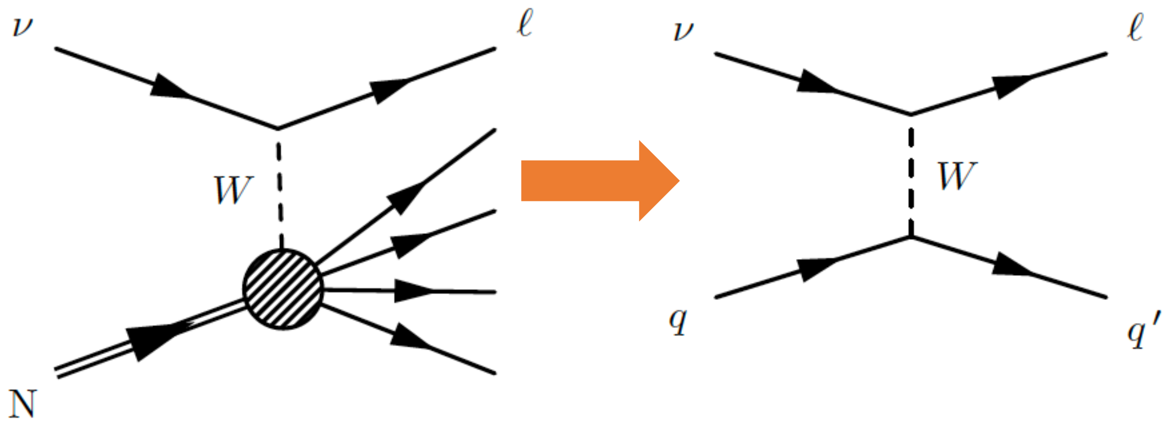
Target nucleus

Out-going hadrons

PDG, PTEP 2022, 083C01 (2022)



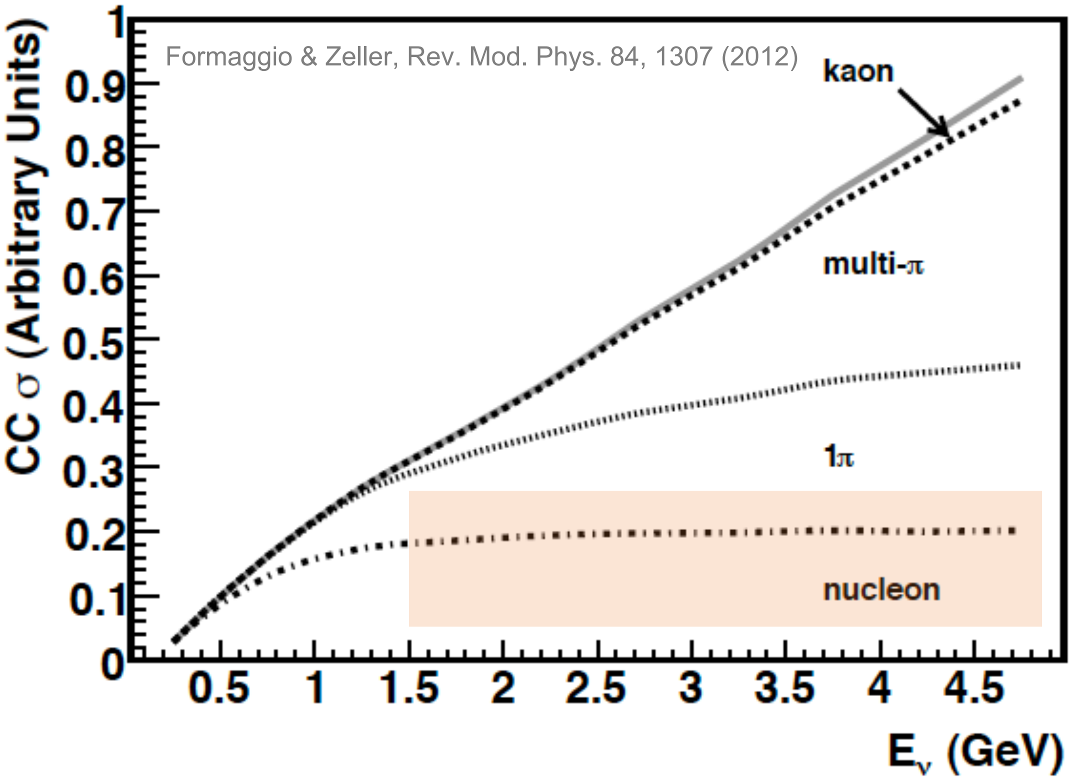
Deep Inelastic Scattering (DIS)



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

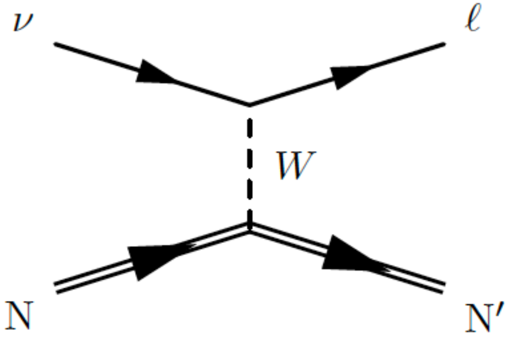
- ❑ At high energy, ν interacting with quarks, $\sigma \sim E_\nu$

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

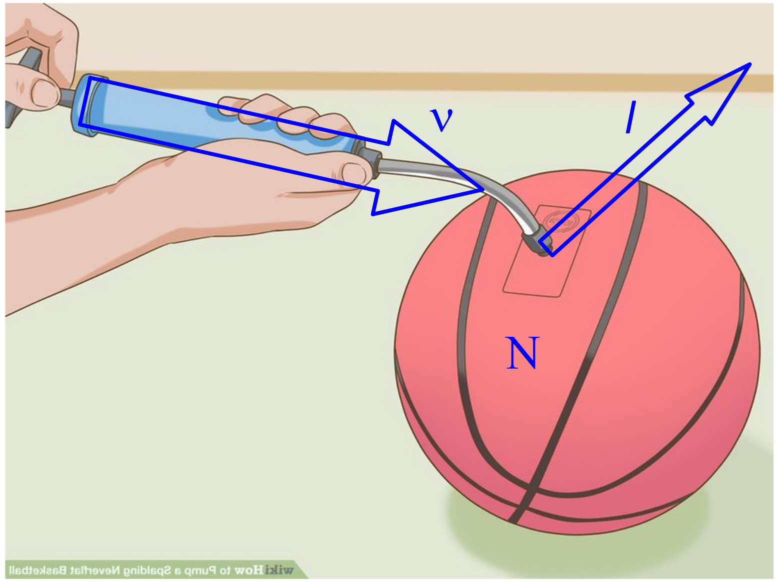


σ_{QE} starts to saturate at 1 GeV

Quasielastic (QE)

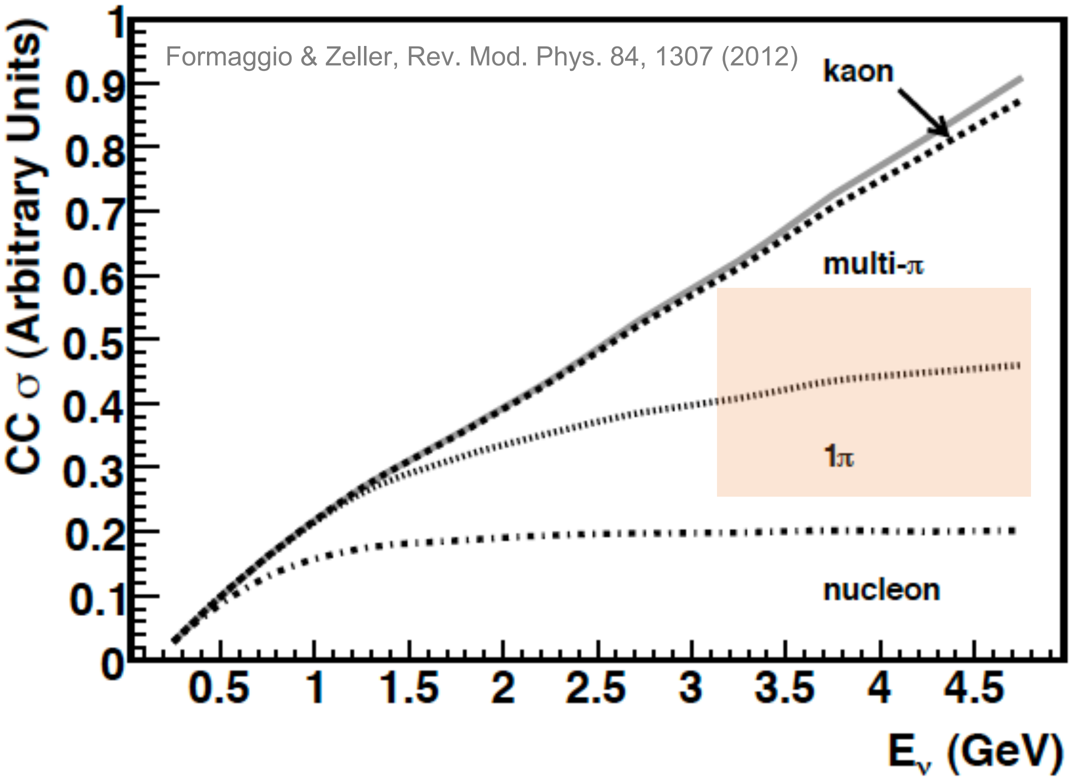


Final-state lepton takes away energy excess



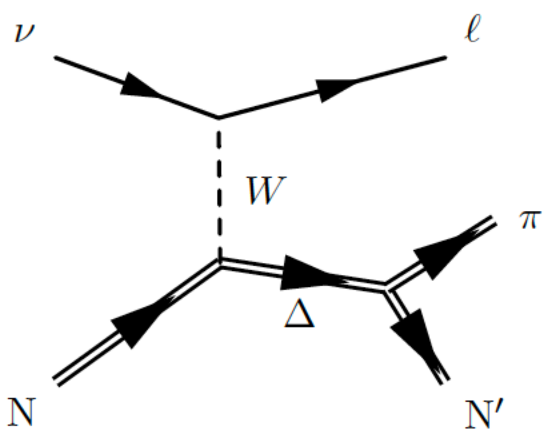
Source: http://www.wikihow.com/Pump-a-Spalding-Neverflat-Basketball

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)



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

- ❖ Other resonances, e.g. N*
- ❖ Non-resonant diagrams

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

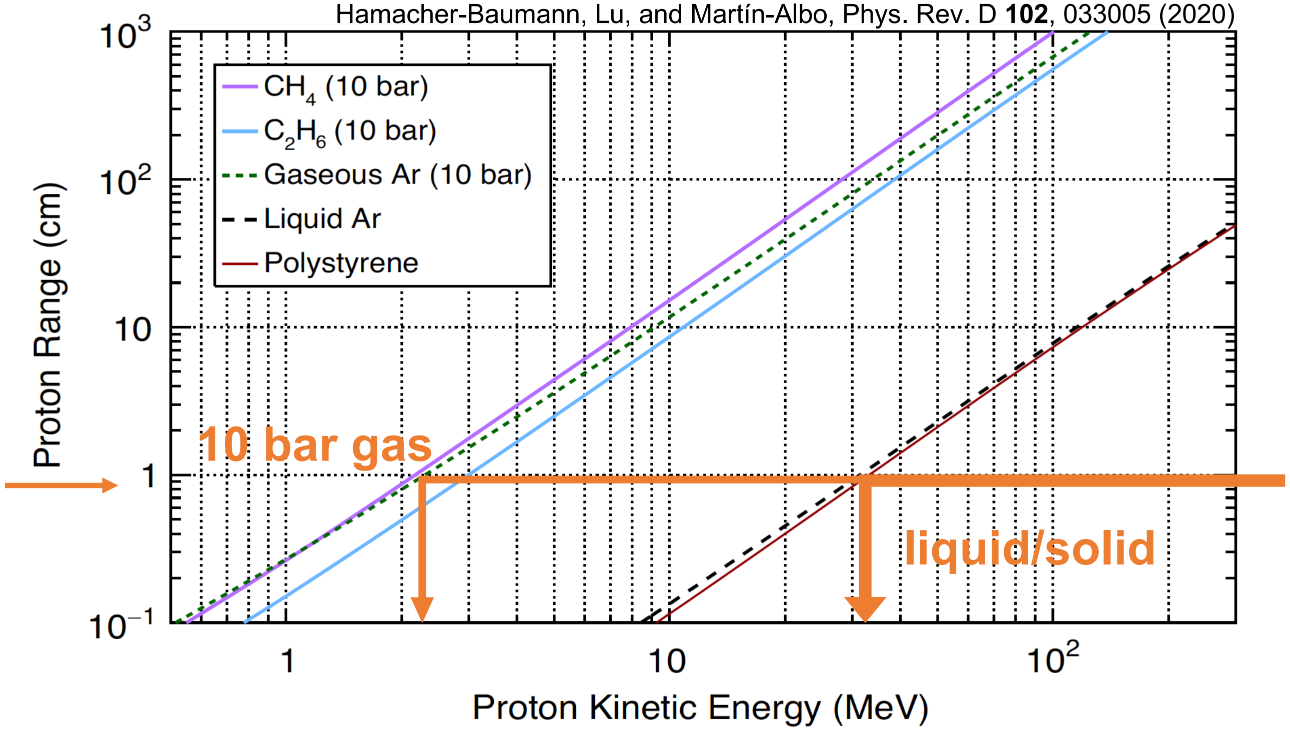
Proton Range ~ $(\text{kinetic energy})^2/(\text{material density})$

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

vs

Kinetic Energy

Sensor granularity ~ mm-cm



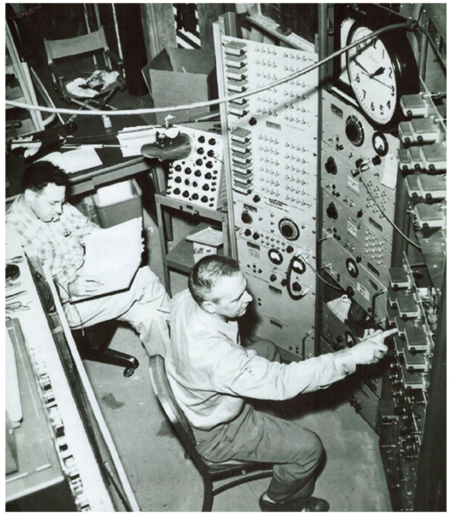
Tracking threshold
(no momentum measurement possible below it)
~ few MeV for 10 bar gas
~ 10s MeV for liquid/solid

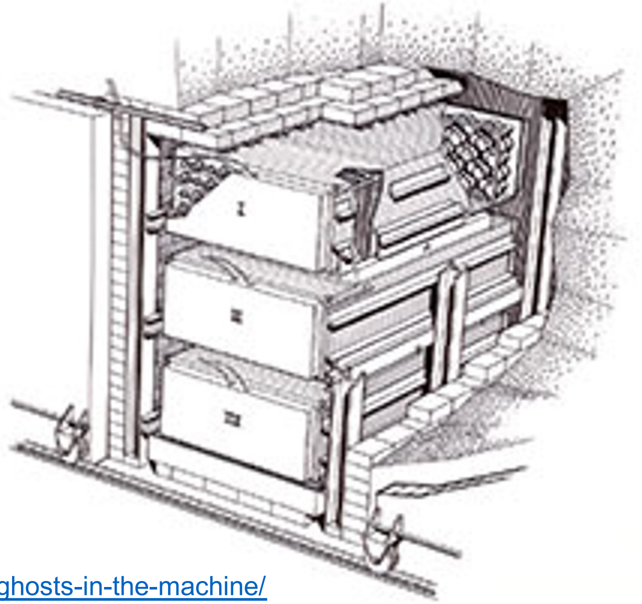
Quiz: Air density at STP in kg/m^3? What about water (in its usual liquid condition)?

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

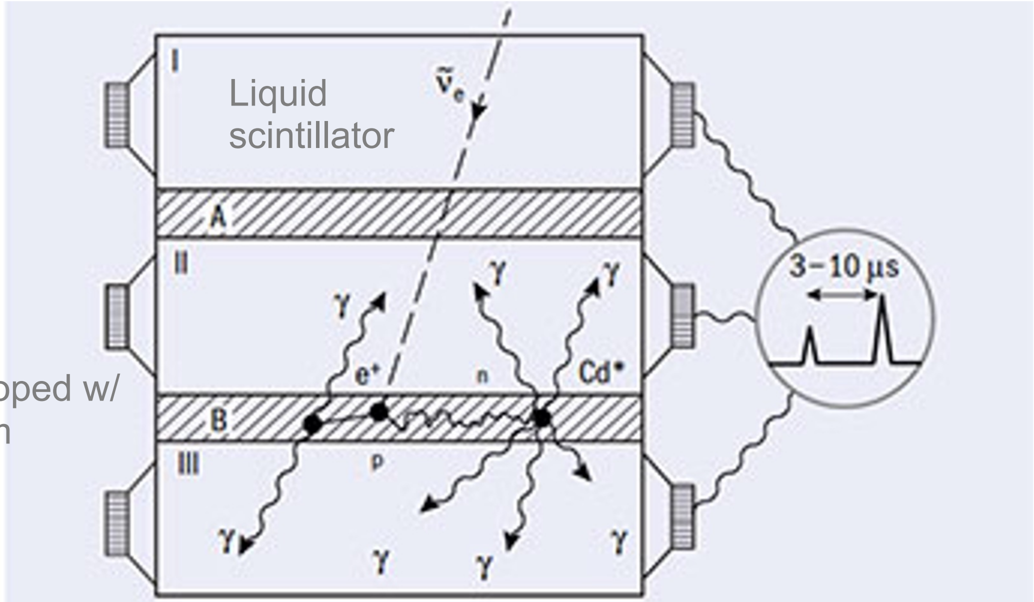




https://cerncourier.com/a/ghosts-in-the-machine/

Nuclear reactor
MeV antineutrinos

Water doped w/
cadmium



Cowan–Reines Experiment, 1956

The first observation of neutrino interactions

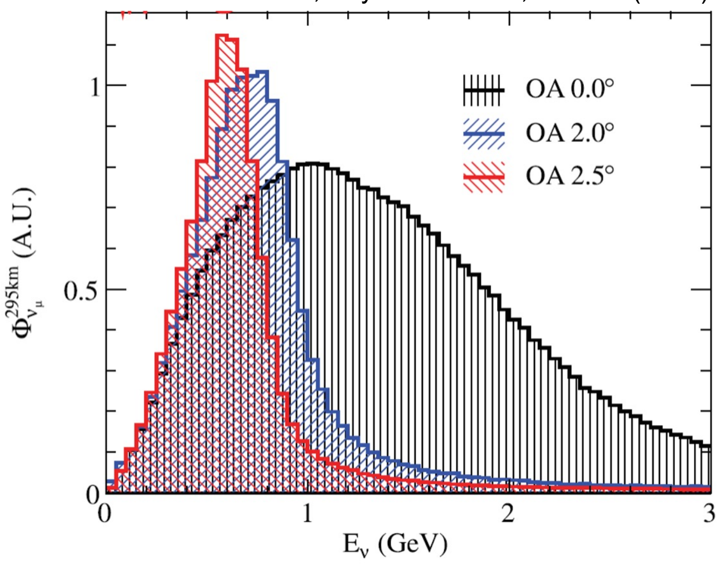
Before that:

Some hand-waving and rough calculations led me to conclude that the ***bomb*** was the best source. –Reines, 1951

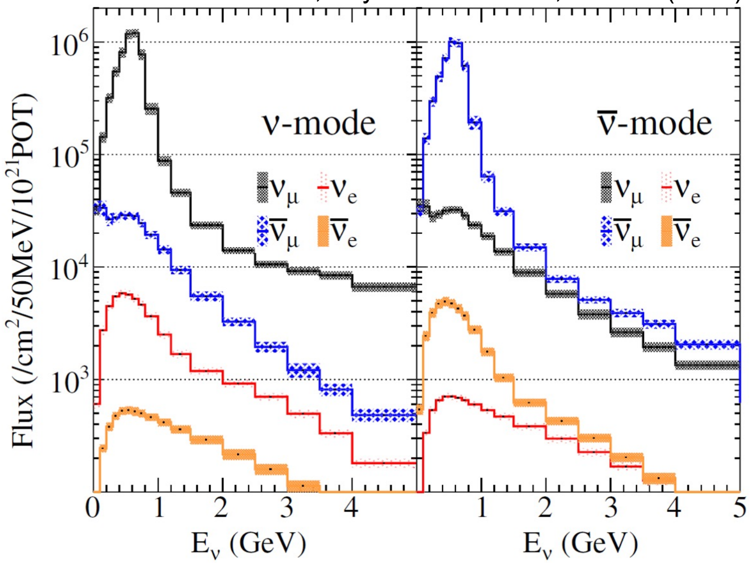
Neutrino Experiments Nowadays

T2K

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

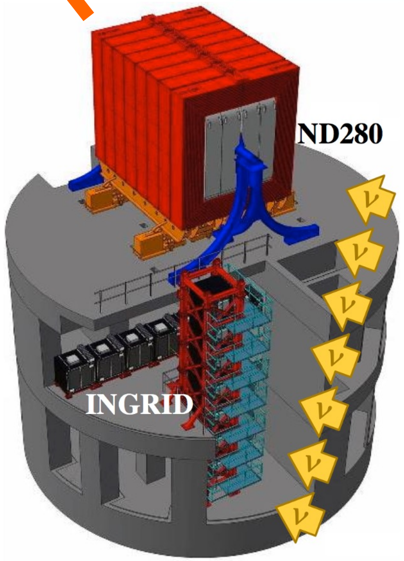


T2K, Phys.Rev.Lett. 116, 181801 (2016)



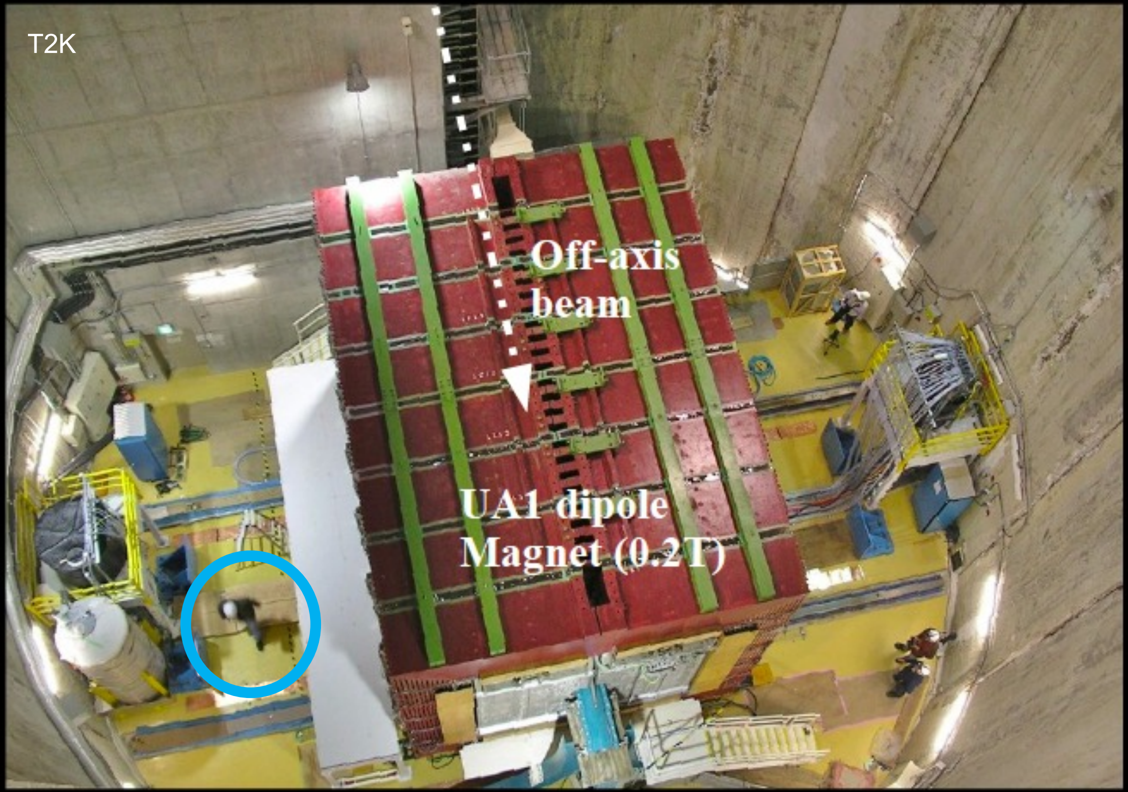
… we are done with the flux and oscillation measurements

Let's look at the detectors today…

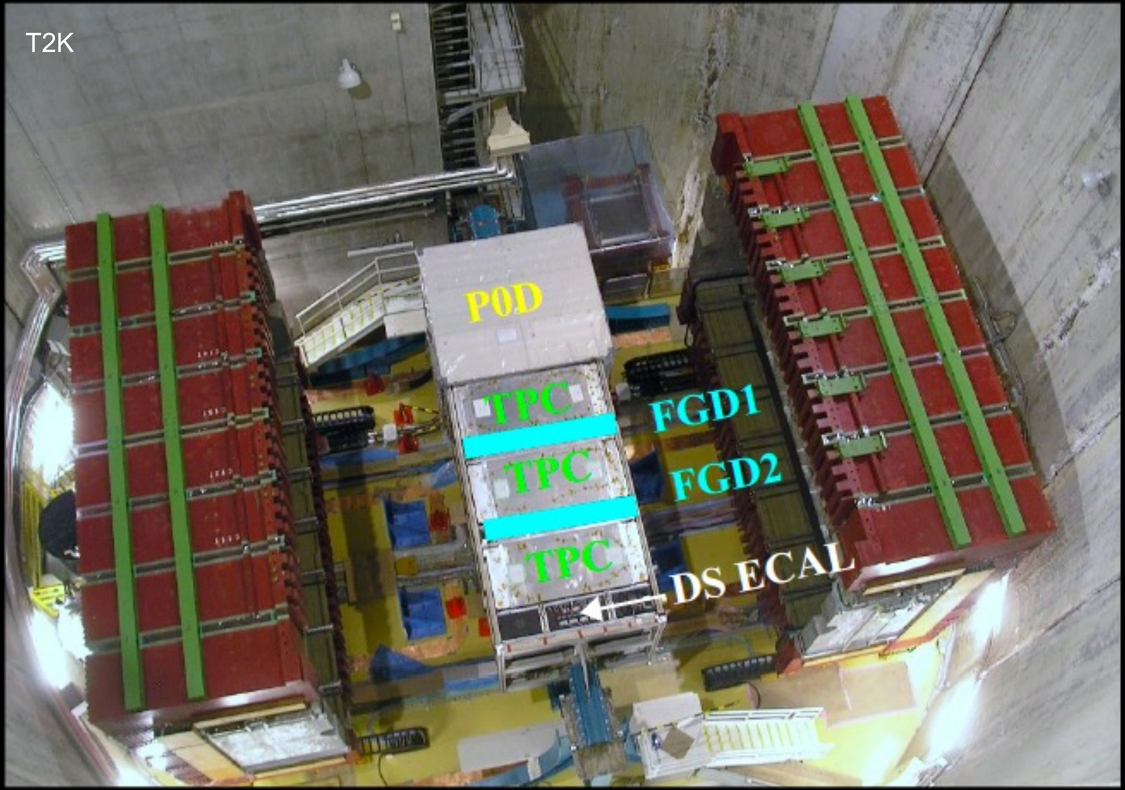


Near Detector

T2K off-axis near detector (ND280)



T2K off-axis near detector (ND280)



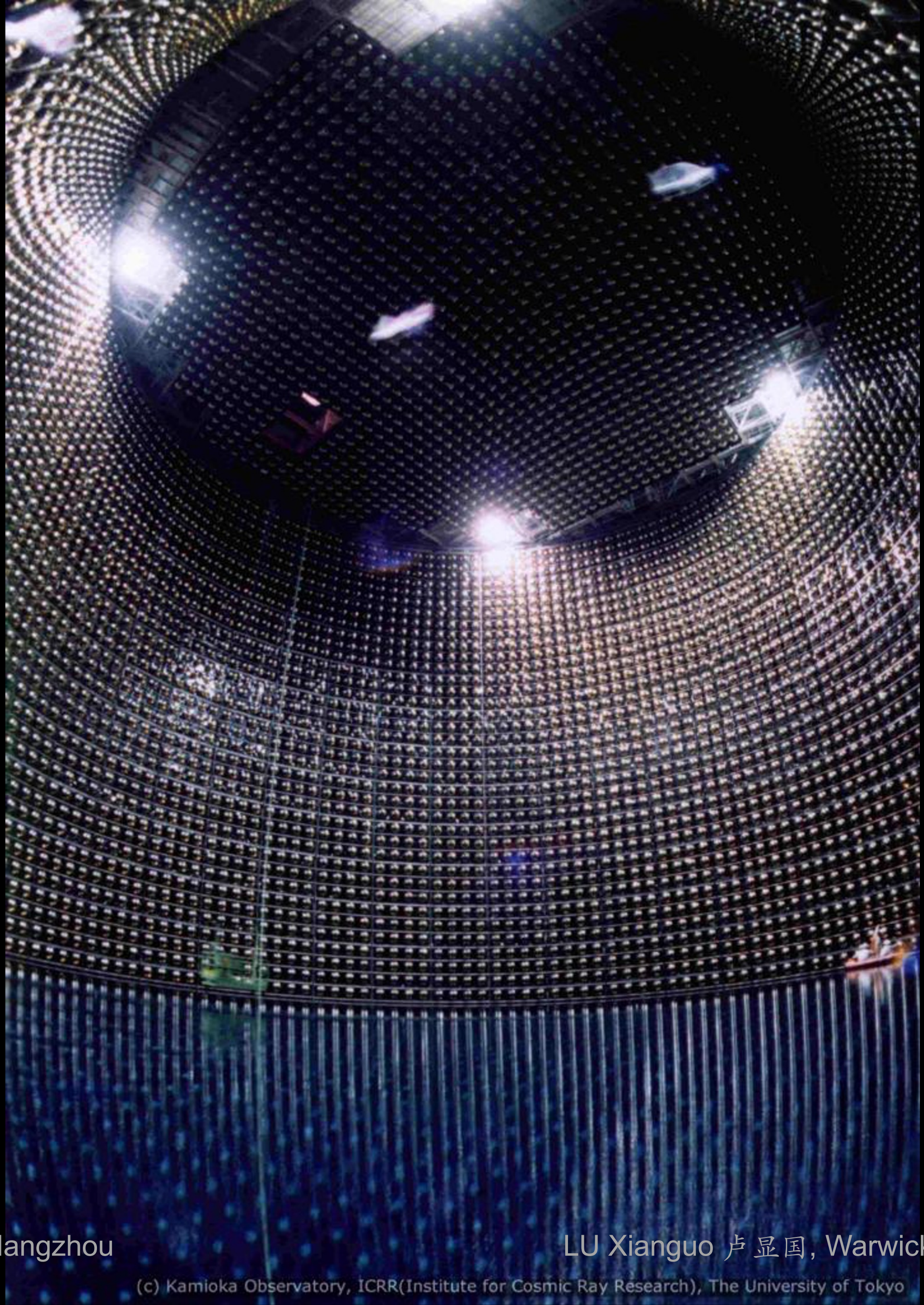
P0D: Pi0 Detector
contains H_2O targets

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

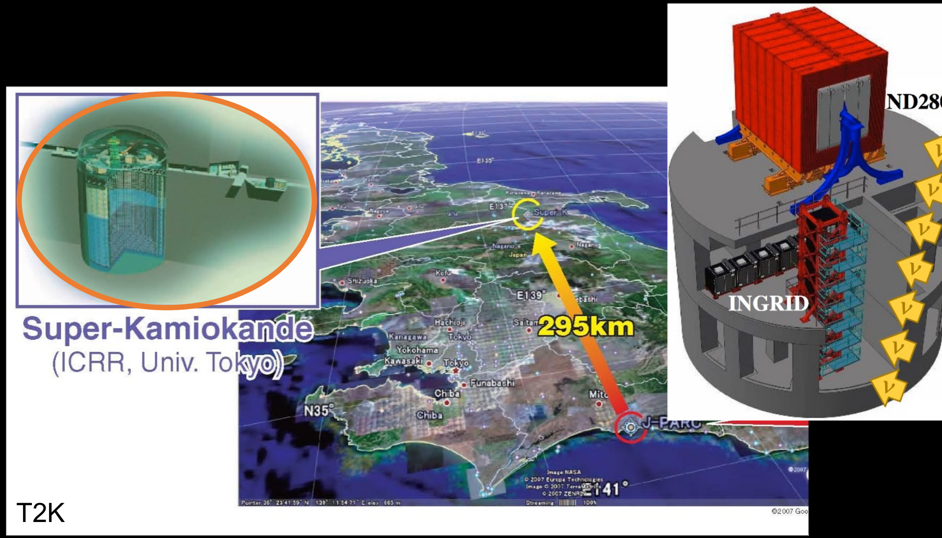
ECAL:
surrounding P0D and tracker

Side Muon Range Detector:
in magnet yokes

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



Water Cherenkov detector



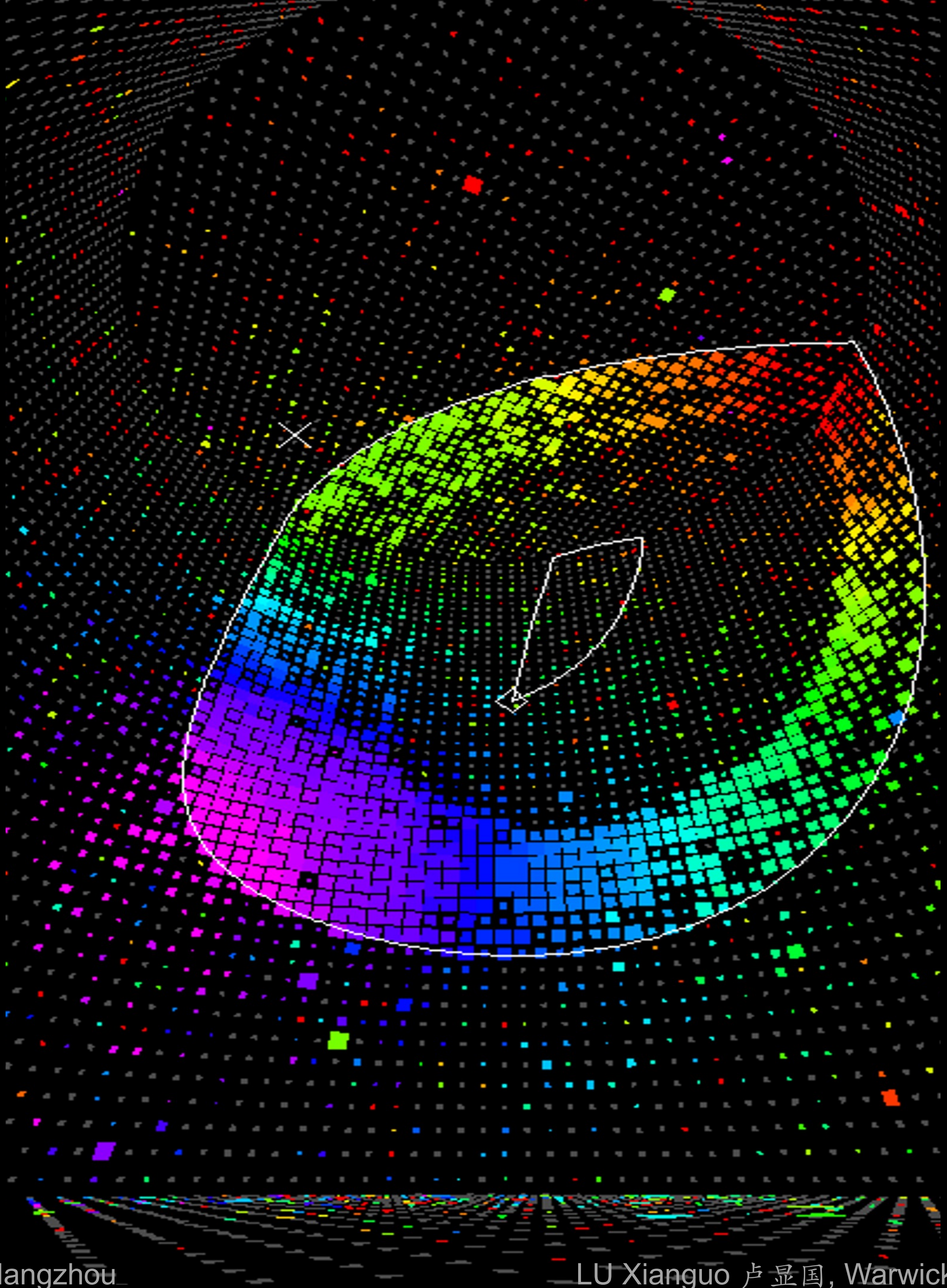
50 kt water Cherenkov

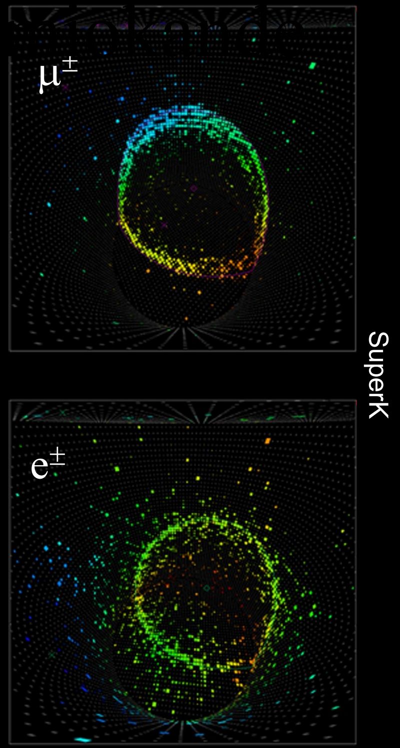
- ❑ 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector
  - ➢ time and amplitude of Cherenkov light

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





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

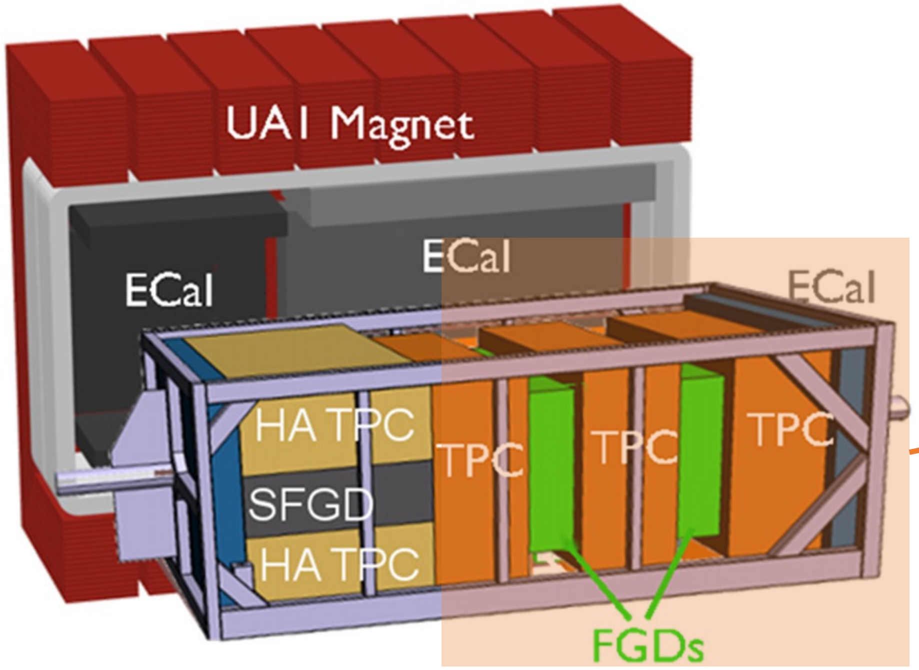
Detector

T2K Near Detector ND280

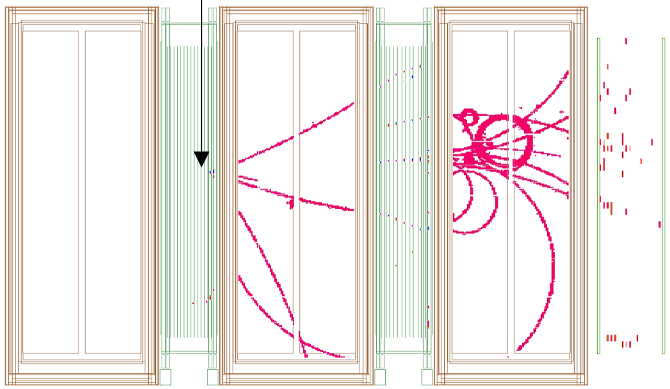
FGD (Fine-Grained Detector)

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***

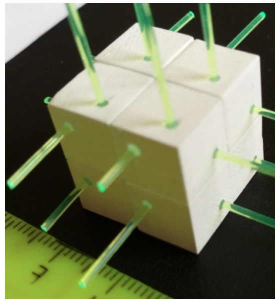
Exclusivity: to measure all final states (except nuclear remnant)

T2K Near Detector ND280
FGD (Fine-Grained Detector)
planes of few-cm-thick ***bars***

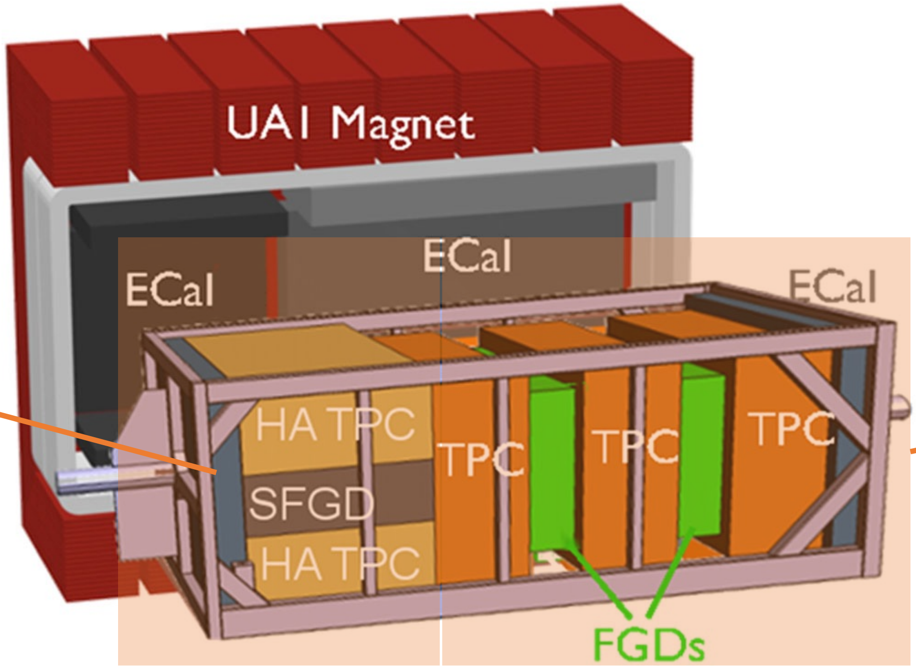
ν interaction in plastic scintillator bars—FGD

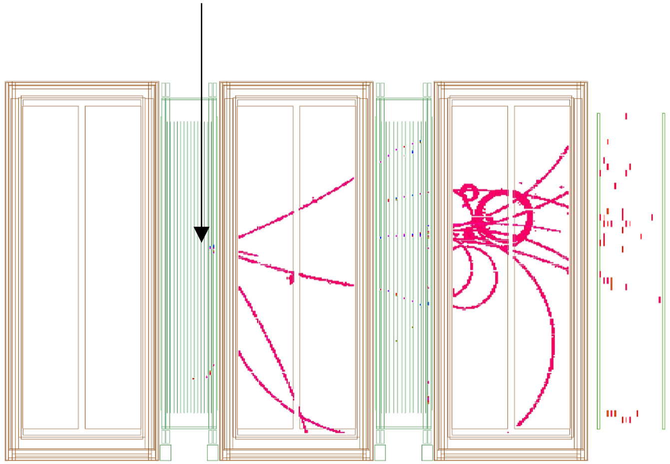
ND280 Upgrade
sFGD (SuperFGD)
1-cm^3 ***cube***

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



T2K, arXiv:1901.03750





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

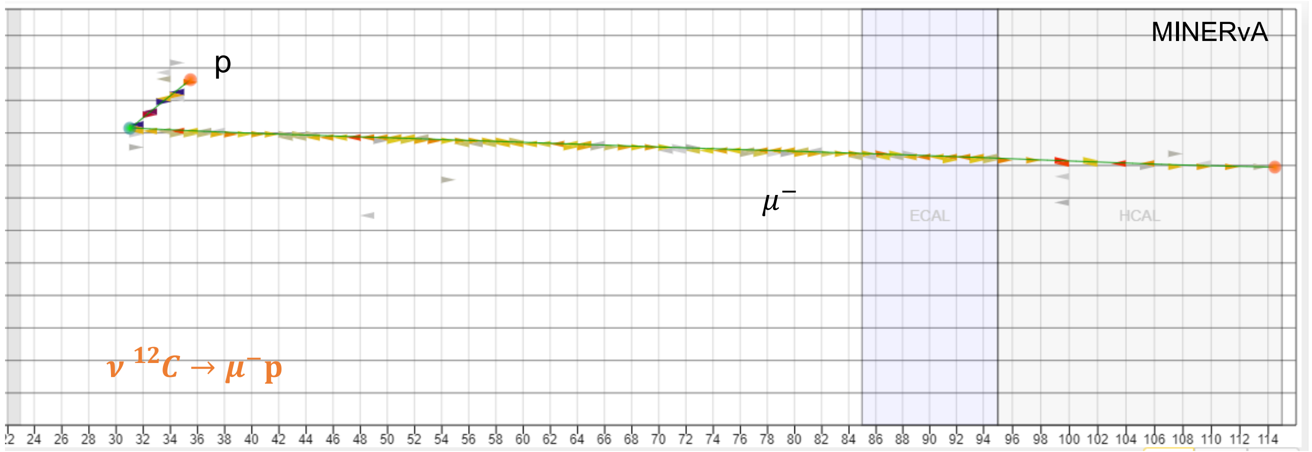
Plastic scintillator tracker

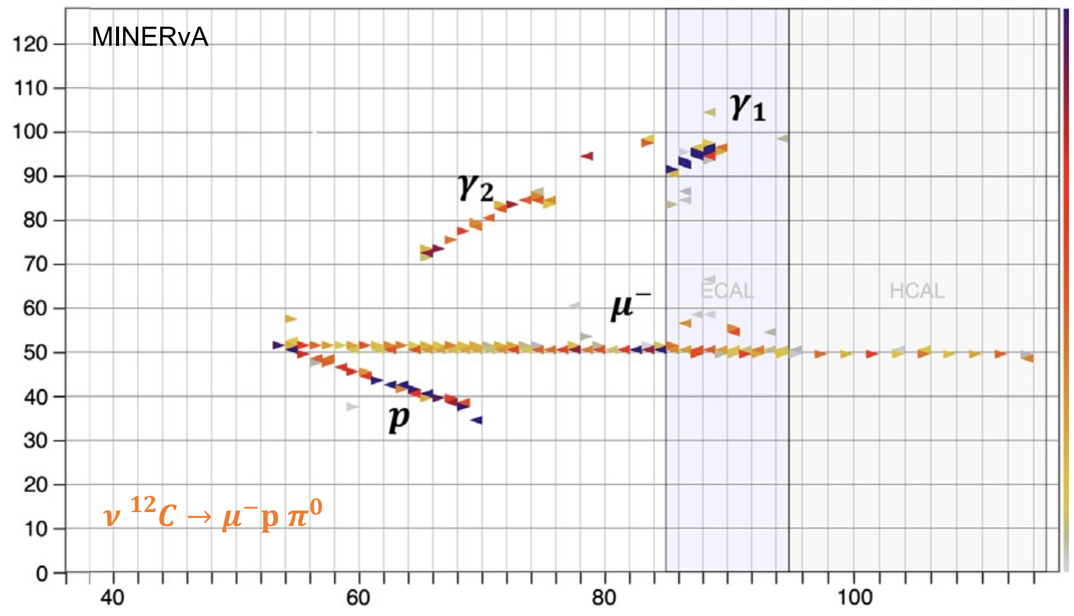
- ❑ Also ***active target***
  - ❖ Tracking + ***calorimetry***

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





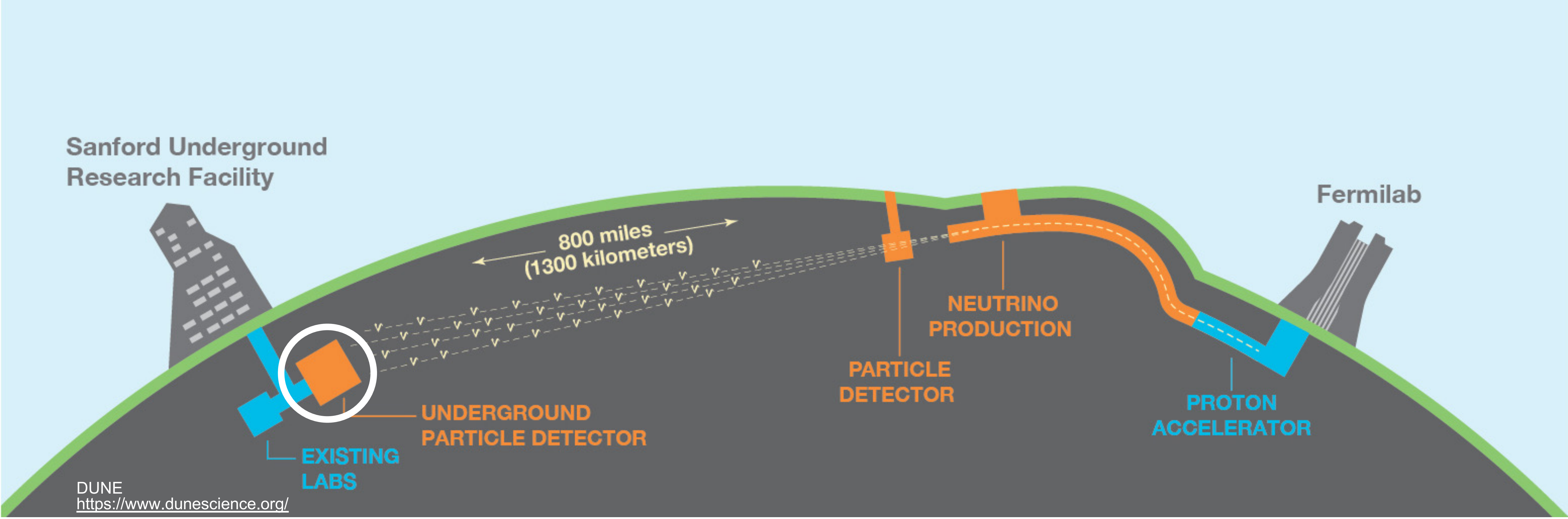
Detector

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?

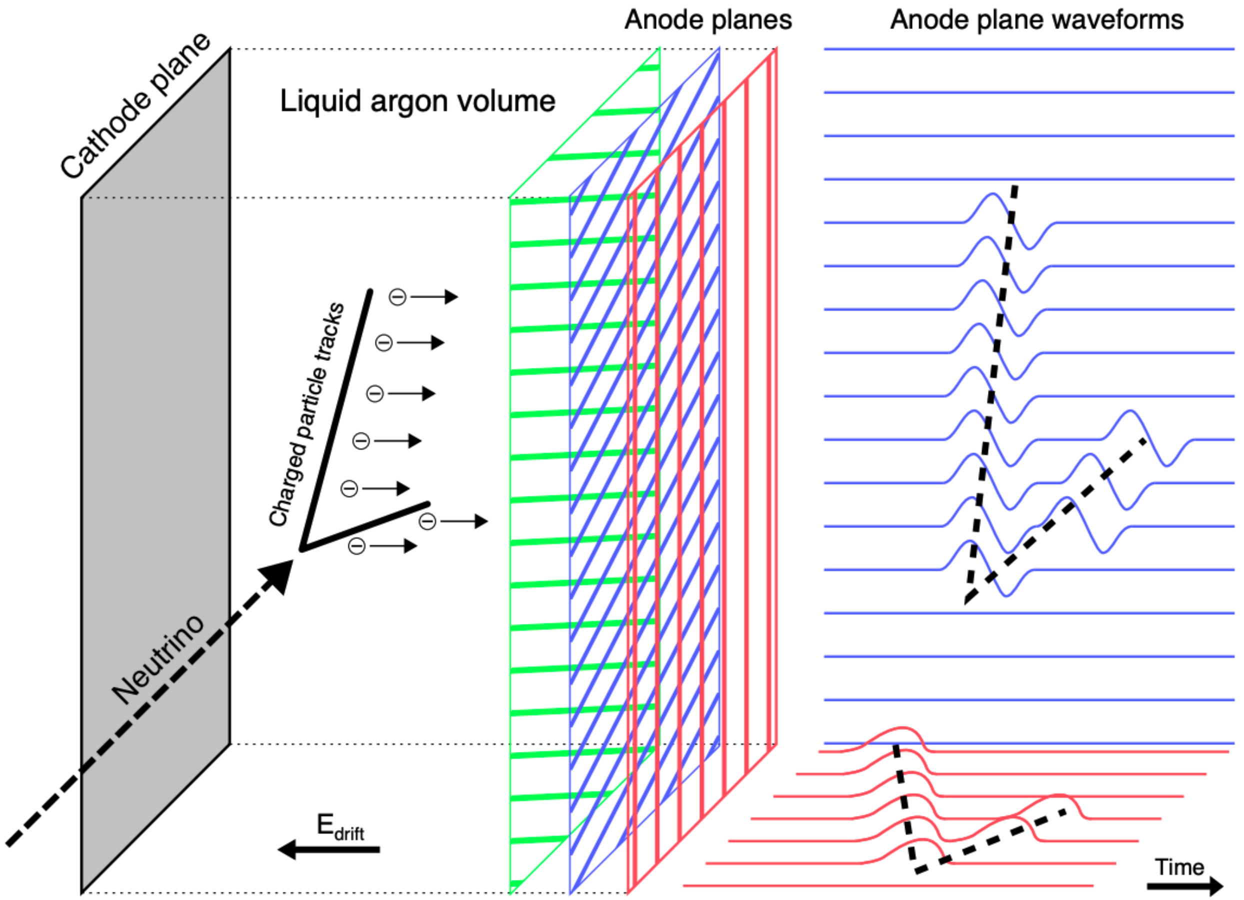
A: 100 B: 50 C: 10



DUNE
https://www.dunescience.org/

Time Projection Chamber (TPC)

Detector



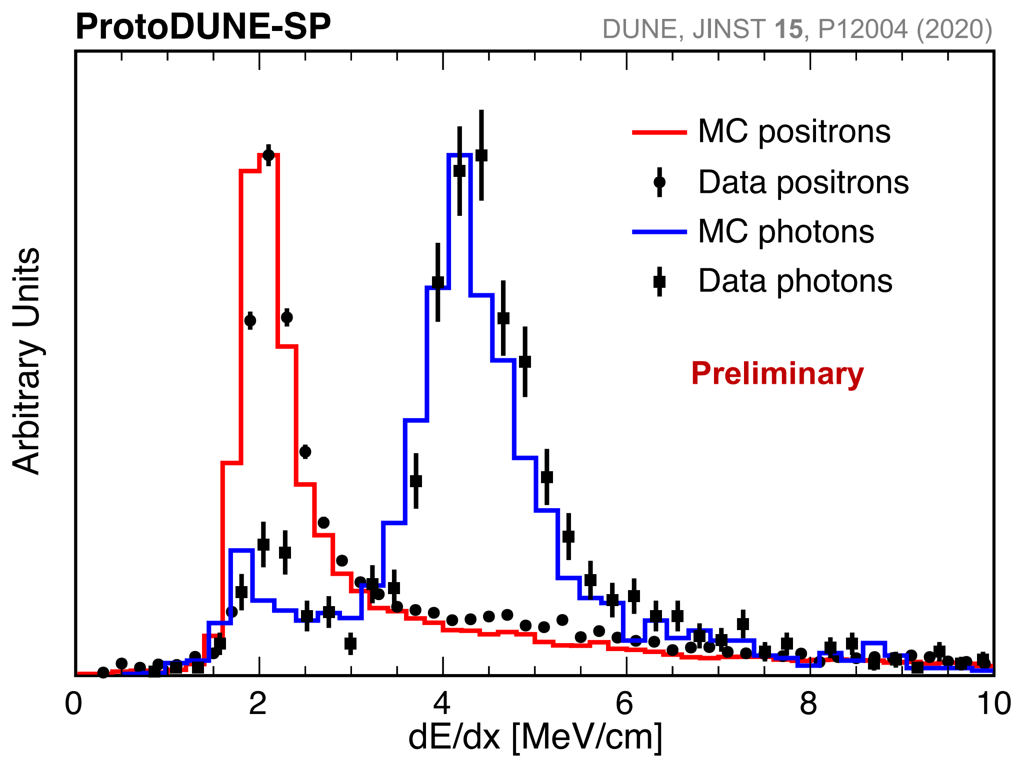
Vermeulen, FERMILAB-THESIS-2021-05

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

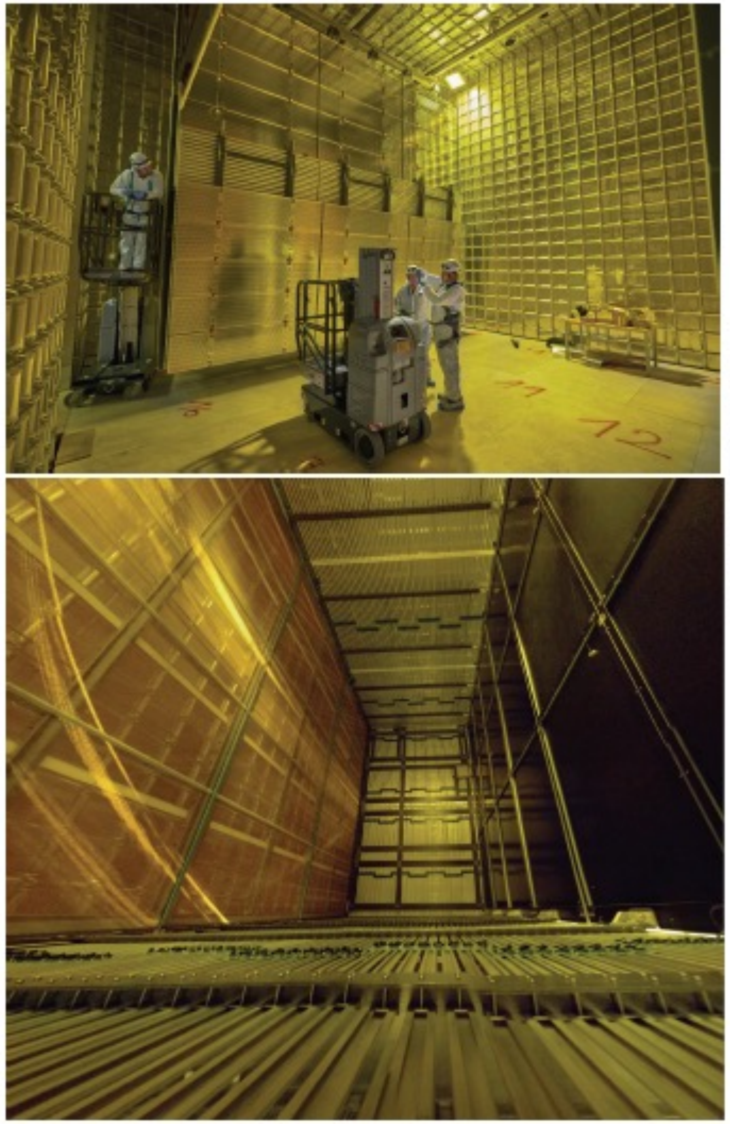


Photo Credit: CERN

Detector

ProtoDUNE

LArTPC Demonstrator at CERN for DUNE FD

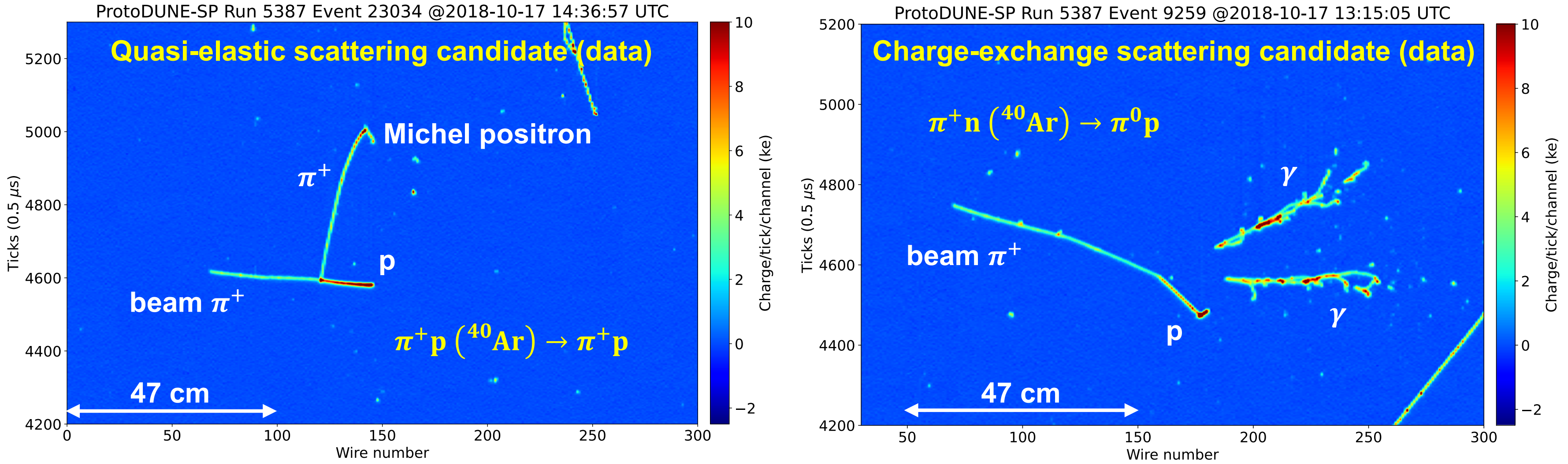
- Hadron beams of 0.3-7 GeV/c
  - 4.7 mm wire spacing (same as FD)
  - ✓ *Versatile reconstruction in LAr*
  - ✓ ***Exclusivity* + beam energy, can "see" inside argon nuclei**

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

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

Exclusive event candidates

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

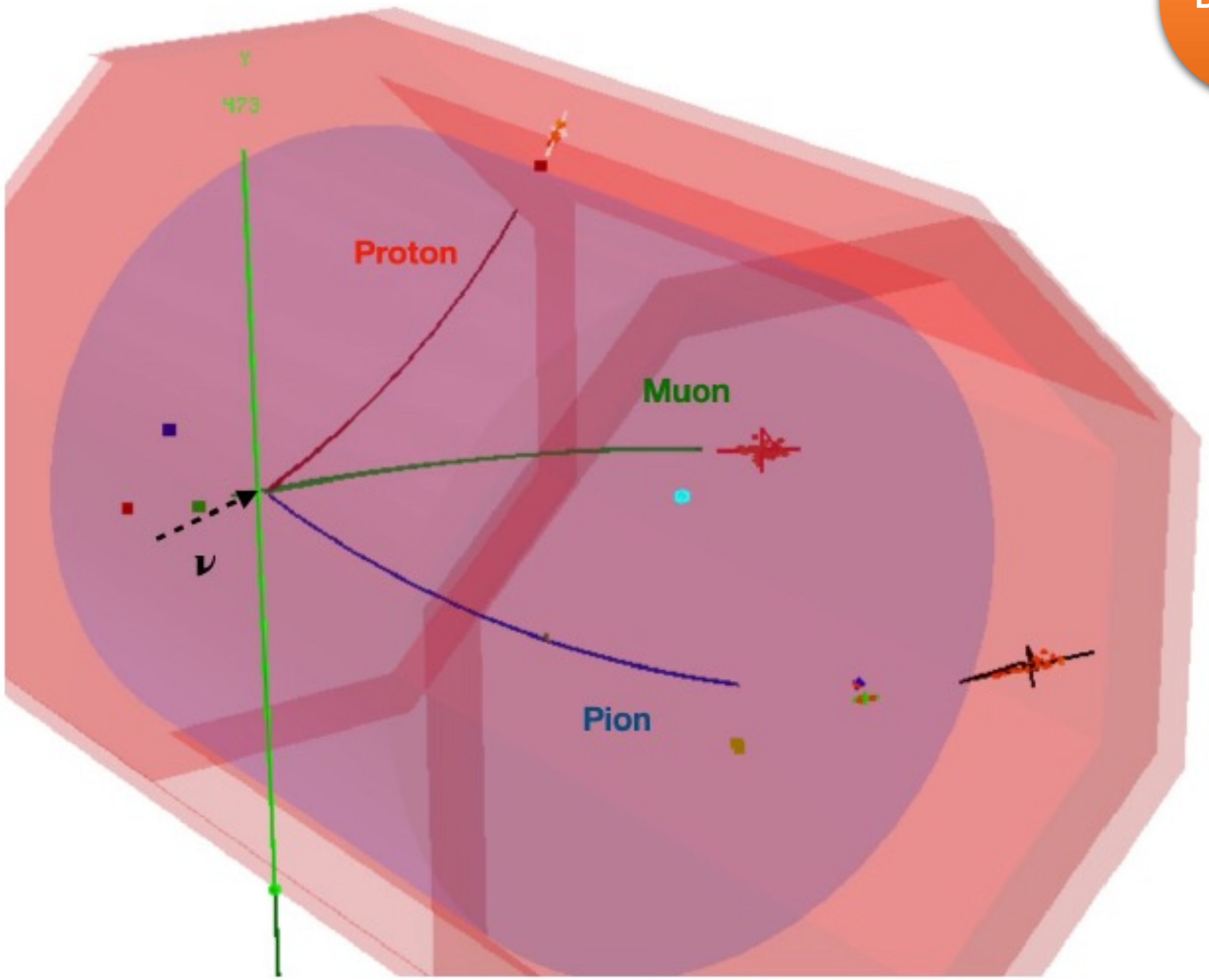


Detector

Hydrogen-rich high-pressure TPC

- ❑ Why hydrogen? Why gas TPC? Why high pressure?
  - ❖ *Spoiler alert!* No nuclear effects
  - ❖ Acceptance, tracking threshold
  - ❖ Target mass

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



Raaf, TPC Mini Workshop

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

Hydrogen-rich high-pressure TPC

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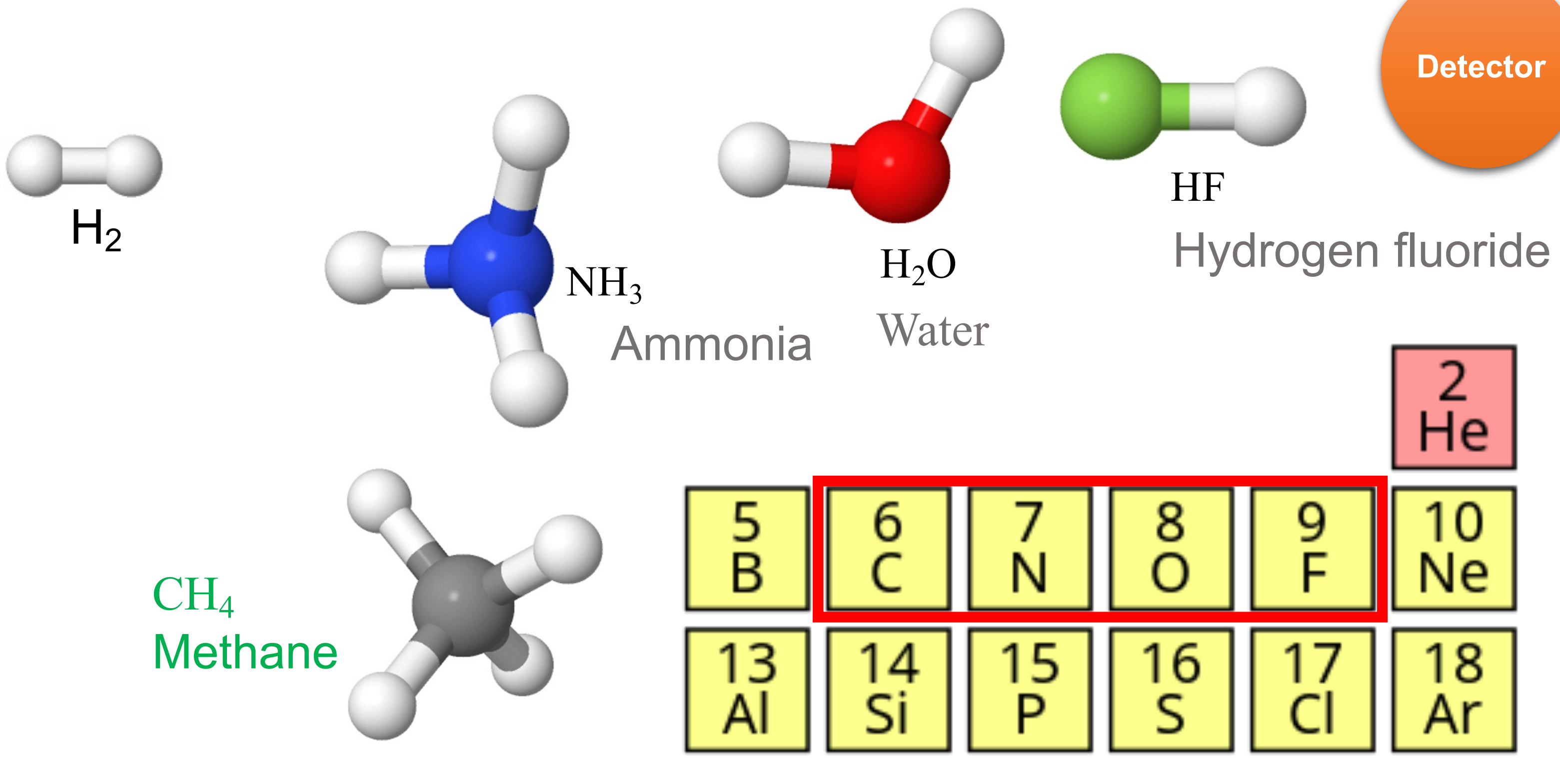
- ❑ Why not pure hydrogen TPC
  - ❖ Bubble chamber: worse tracking
  - ❖ H_2 gas: not hydrogen-rich enough
- ❑ How rich is rich enough?
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y

Detector



http://www.jmol.org/

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

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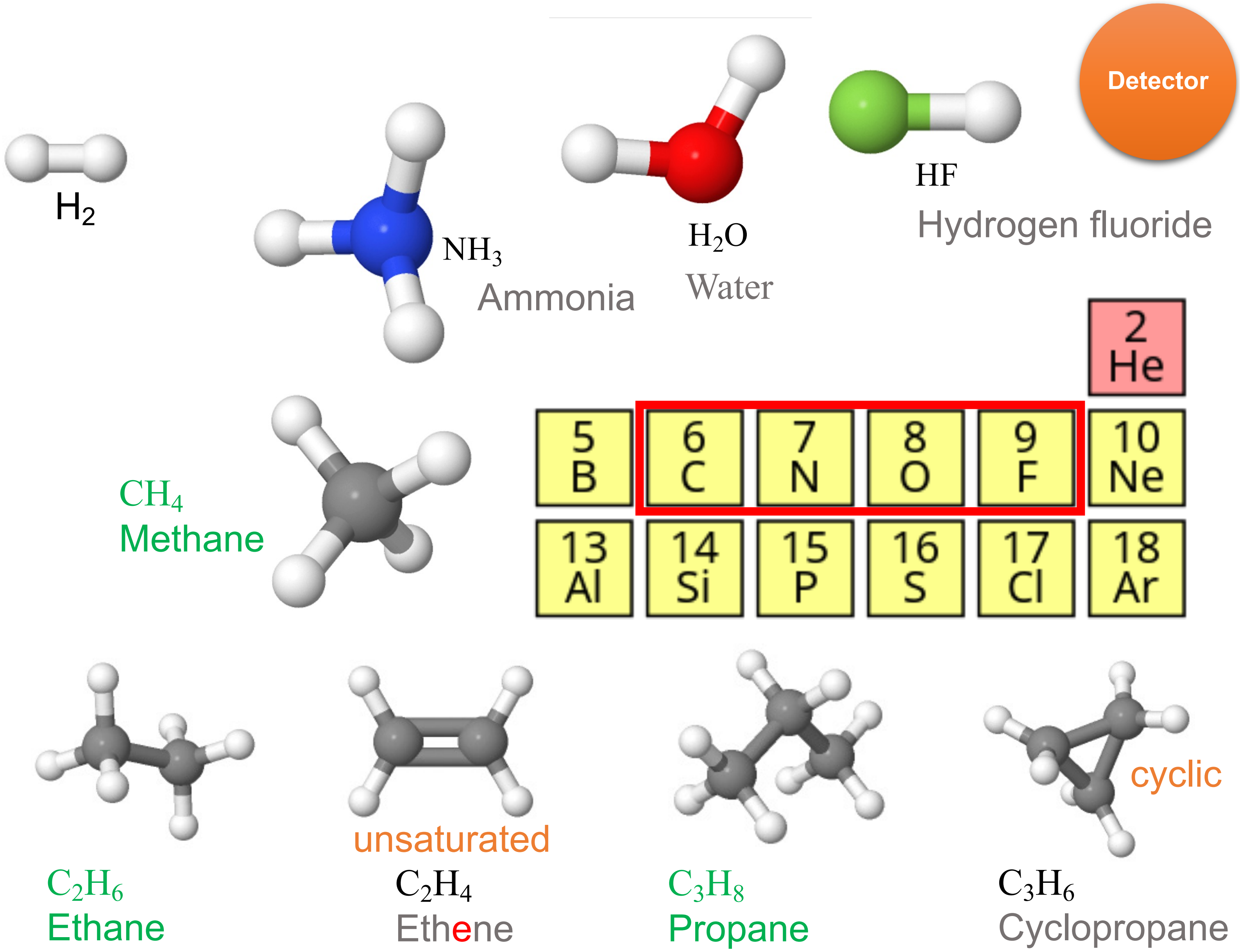
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y
    - ➢ Saturated, acyclic: Alkane C_nH_{2n+2}
      - ✓ CH_4 most efficient H-carrier, but not the largest one



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

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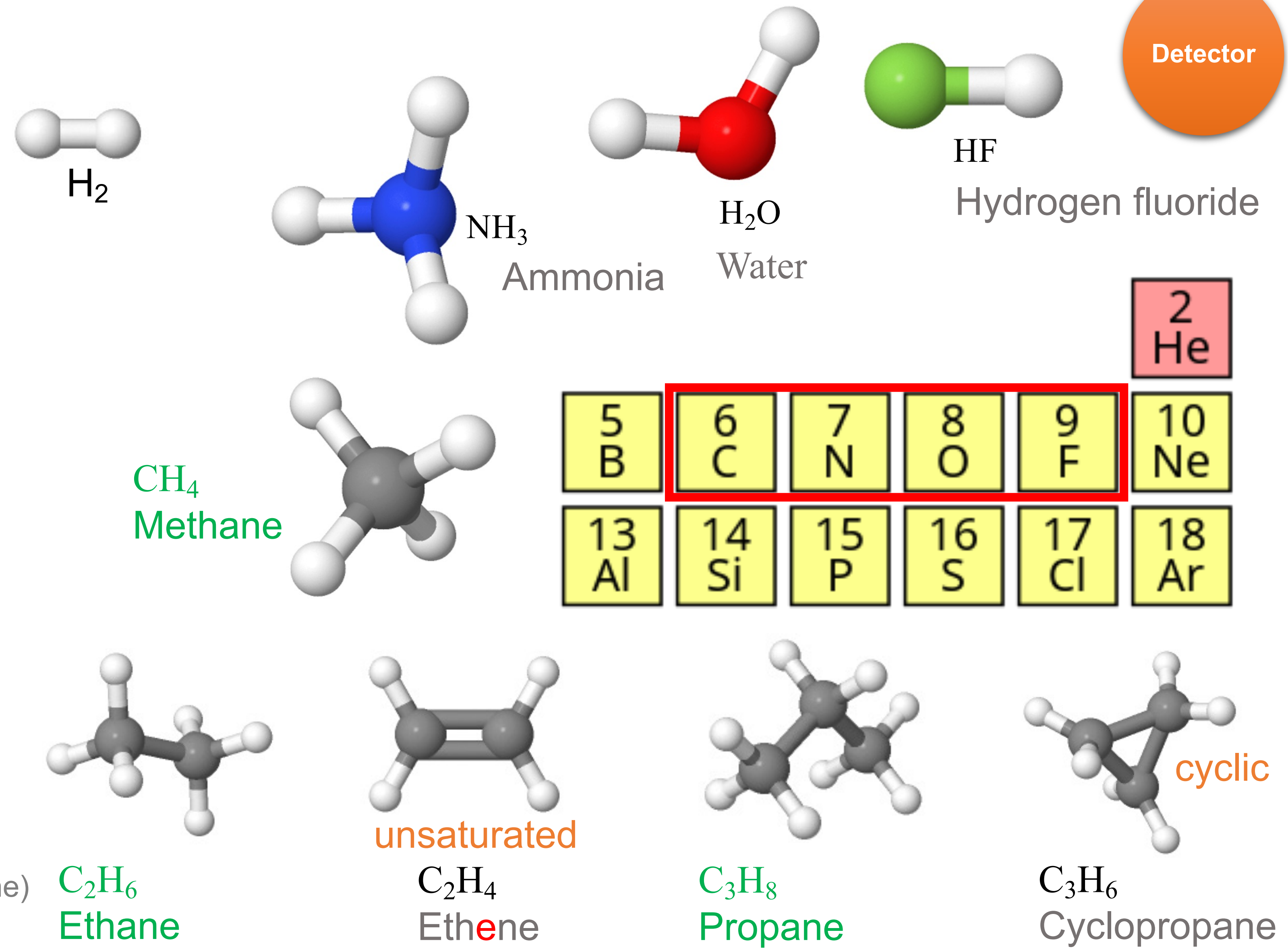
    - ➢ Saturated, acyclic: Alkane C_nH_{2n+2}
      - ✓ CH_4 most efficient H-carrier, but not the largest one
  - ❖ Maximal partial pressure limited by vapor pressure
    - ➢ Theoretically hydrogen-richest mix at 10 bar: $C_{3.93}H_{9.86}$

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

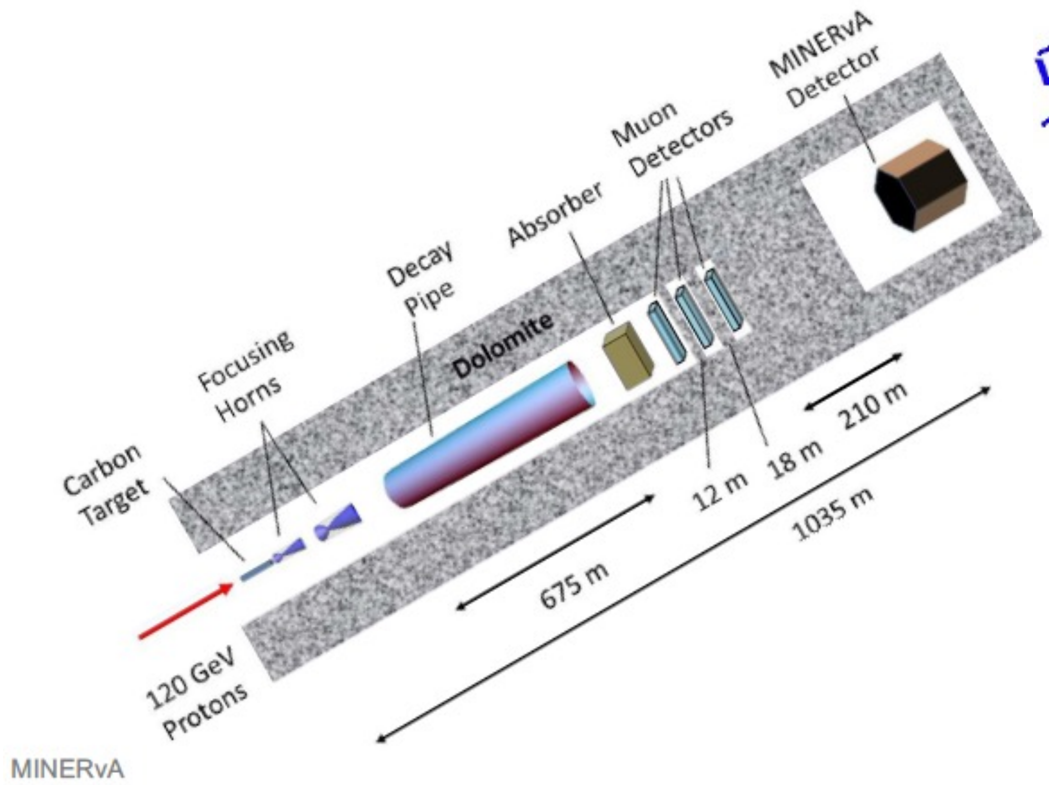


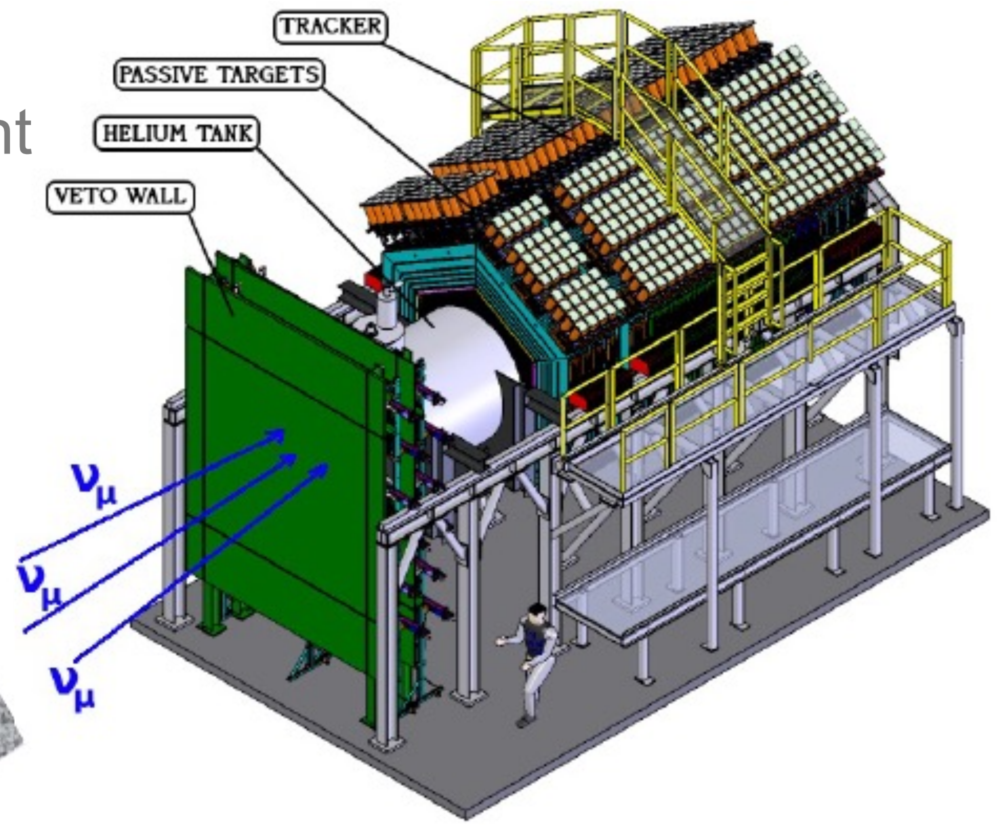
http://www.jmol.org/

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

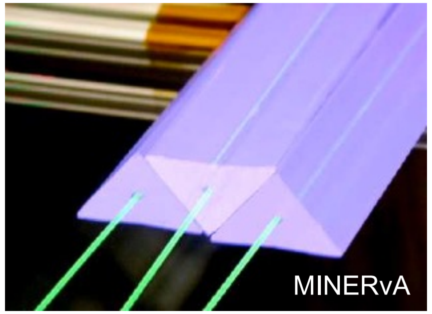
MINERvA@FNAL

A dedicated ν-interaction experiment

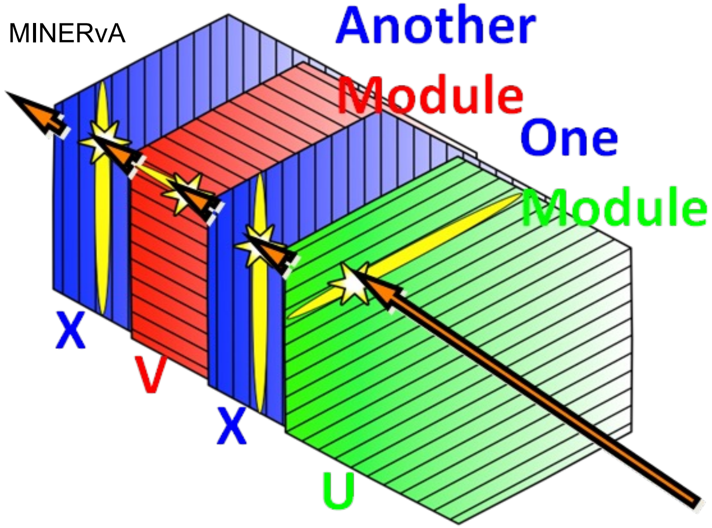




- ❑ 5.4 ton active scintillator fiducial volume
- ❑ 10-μs beam spill, ~ 1 event in tracker per spill

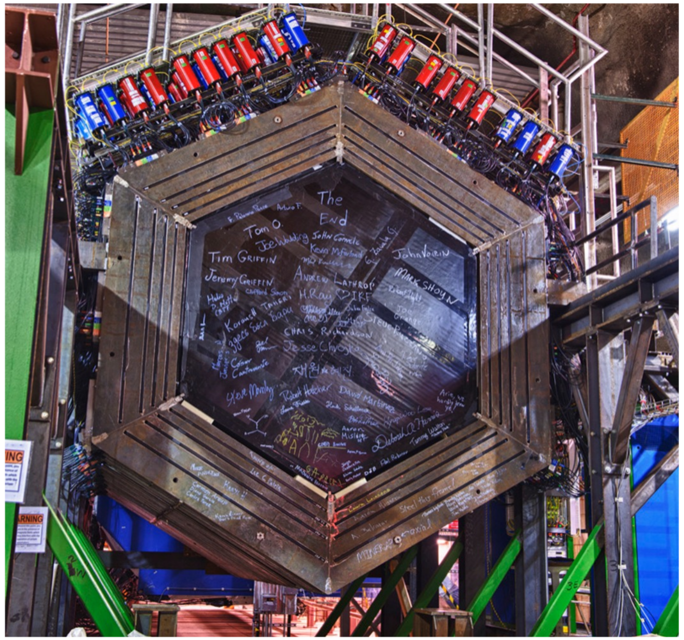


- ❑ Scintillator bar (CH)
- ❑ 3.3 cm base, 1.7 cm height
- ❑ 3 ns timing resolution

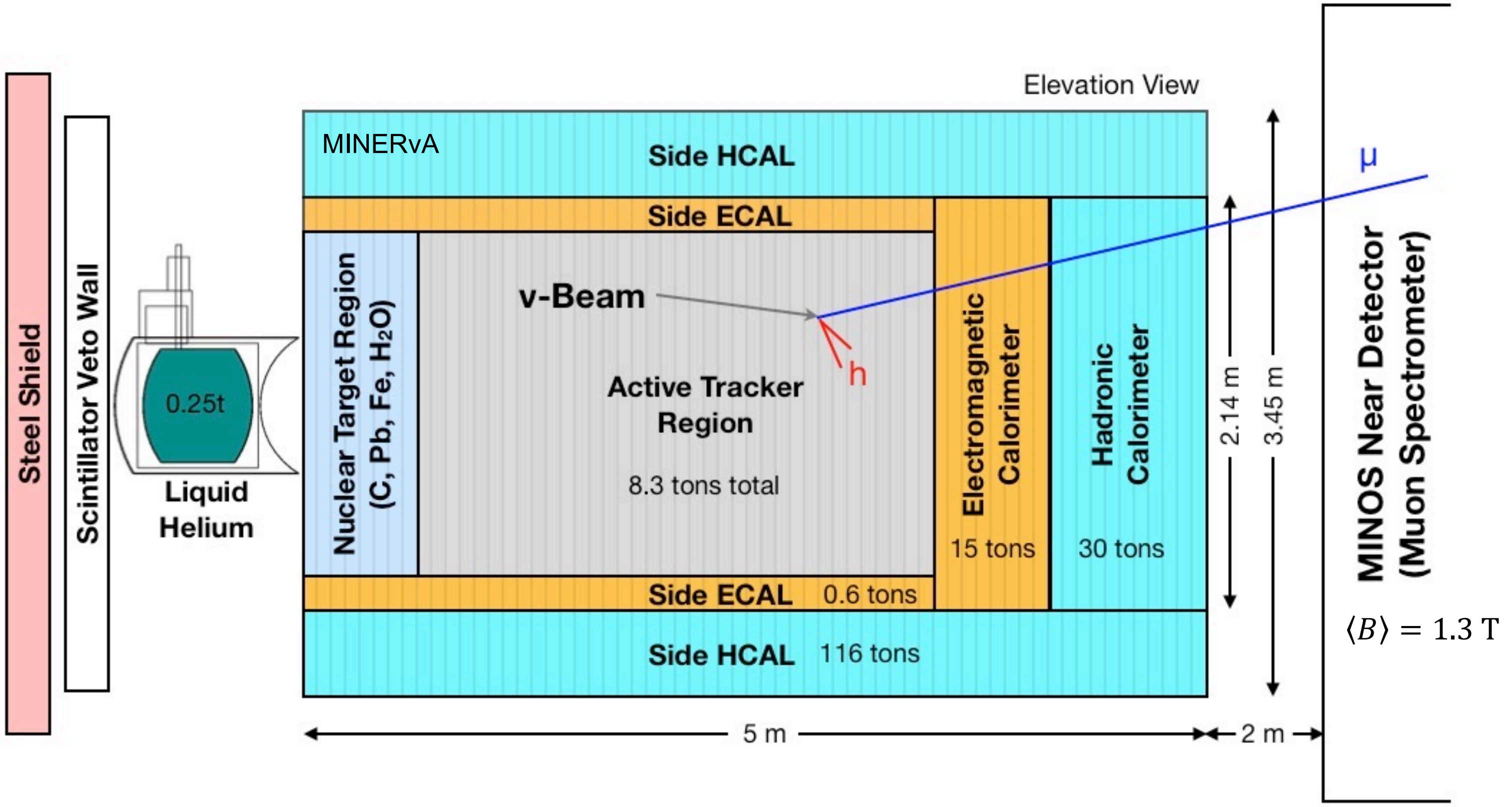


- ❑ 3 views
- ❑ 2.7 mm position resolution per plane

Photo Credit: R. Hahn



- ❑ Non-magnetized

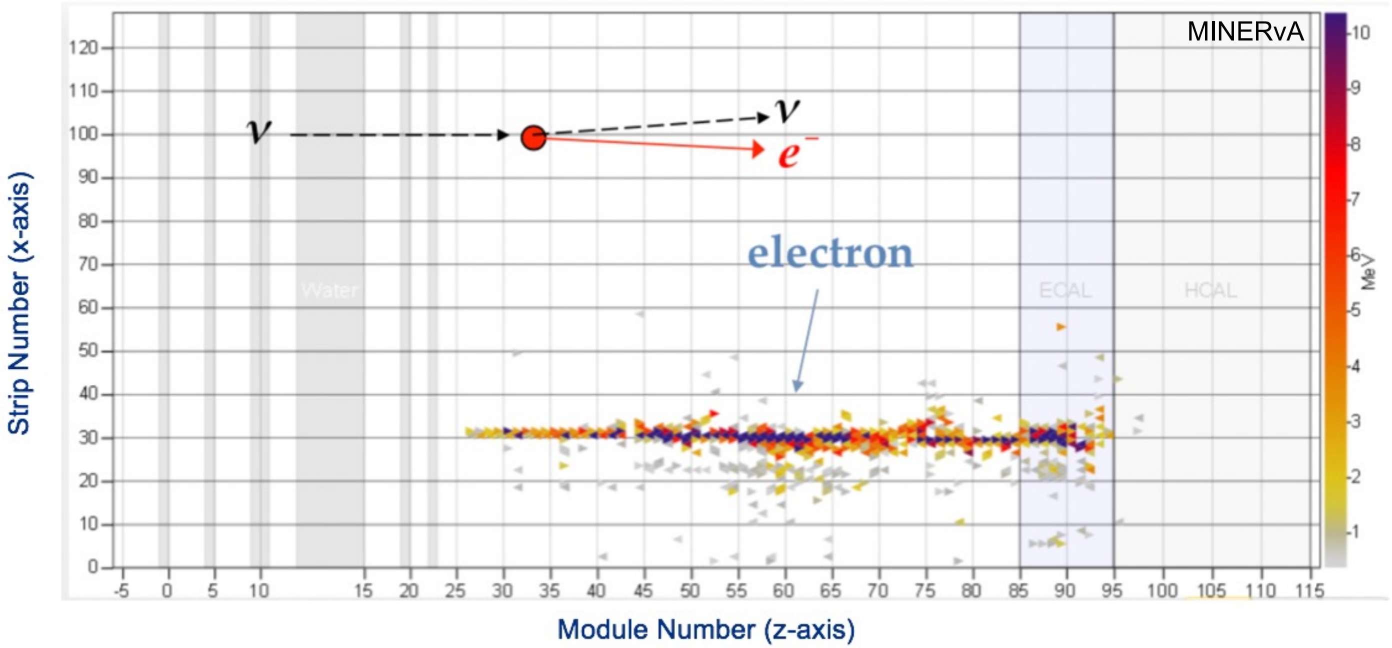


- ❑ Muon momentum resolution (range + curvature) 8% @ 6 GeV/c
- ❑ Proton threshold 100 MeV K.E., momentum (by range) resolution 2% @ 1 GeV/c
- ❑ π^0 momentum resolution ~20%
- ❑ High-energy charged π energy resolution by calorimetry $18\% + 8\% / \sqrt{E_\pi/\mathrm{GeV}}$
- ❑ Can also detect neutrons

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%

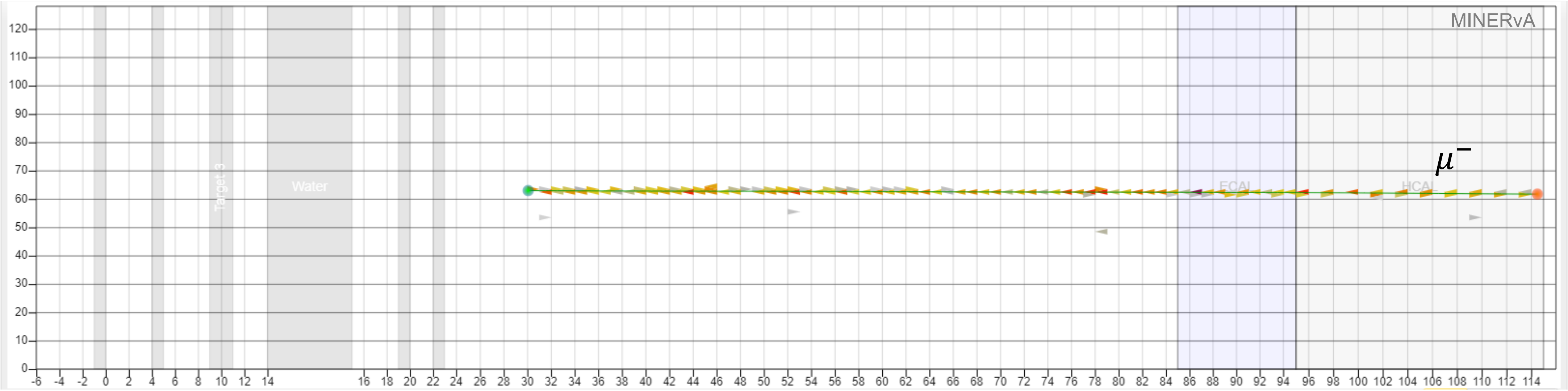
Inverse Muon Decay

(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

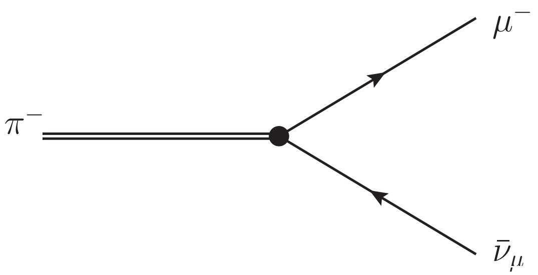


New flux constraint method [MINERvA, Phys.Rev.D 104, 092010 (2021)]

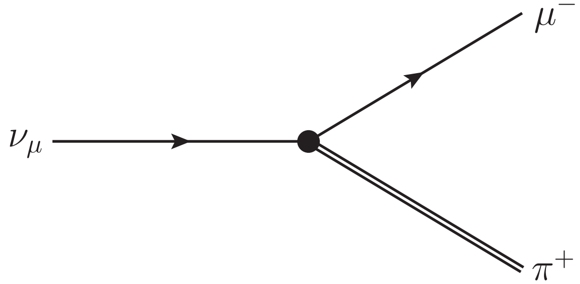
Homework:

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?***

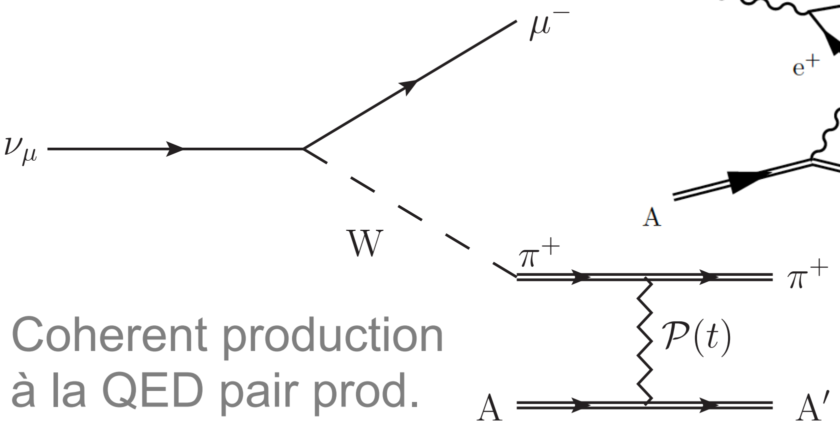
Charged-Current Coherent π Production



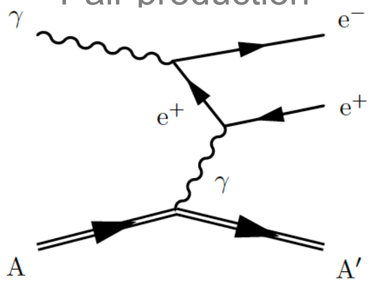
Pion decay



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



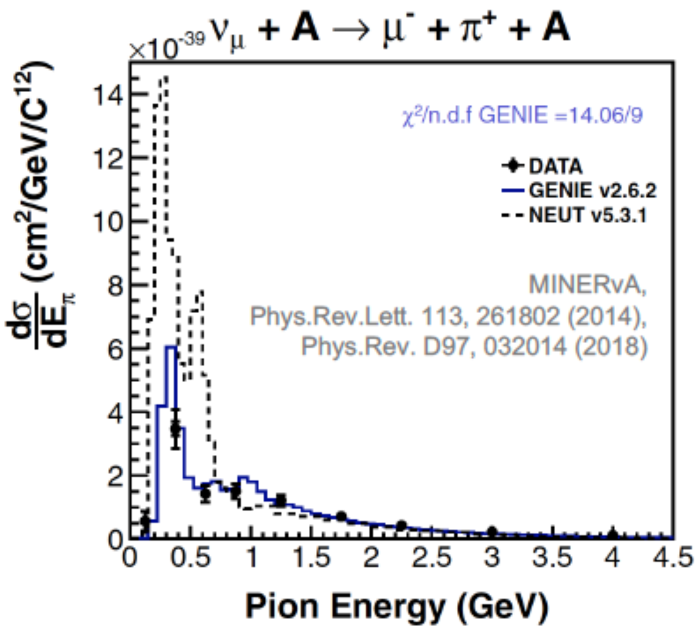
Pair production

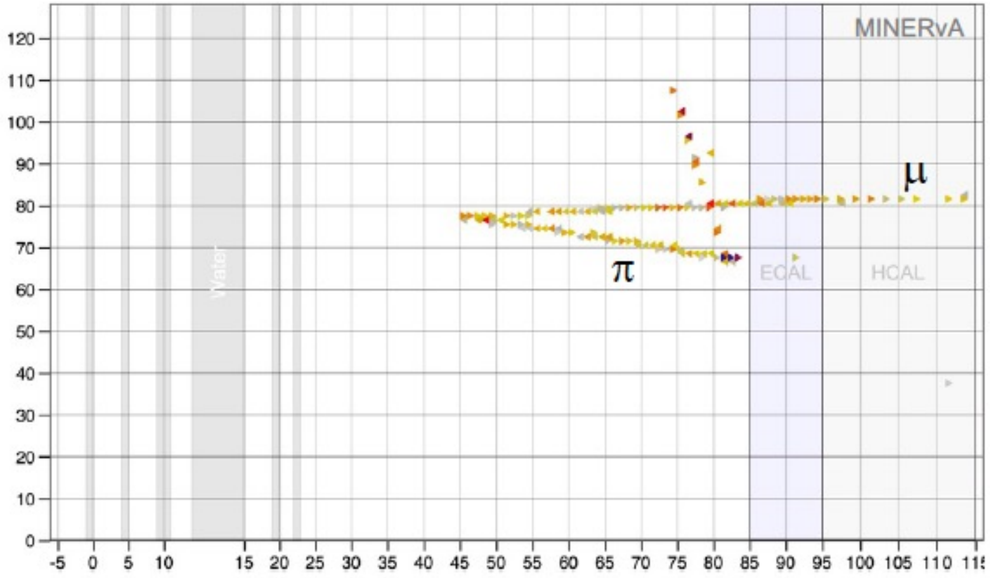


Coherent production
à la QED pair prod.
✓ allowed

❑ Intrinsic background to HNL search

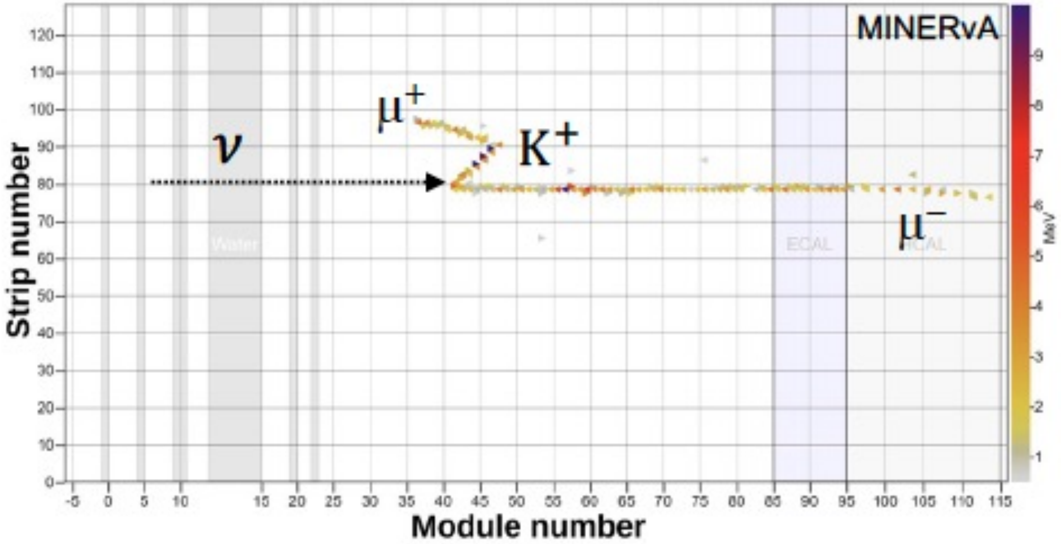
[T2K, Phys.Rev. D100, 052006 (2019)]

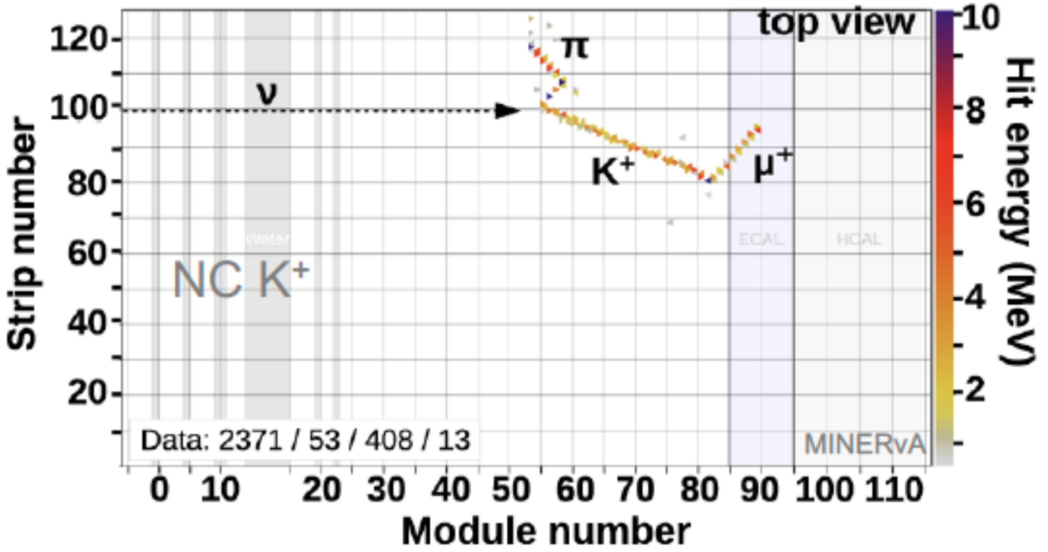


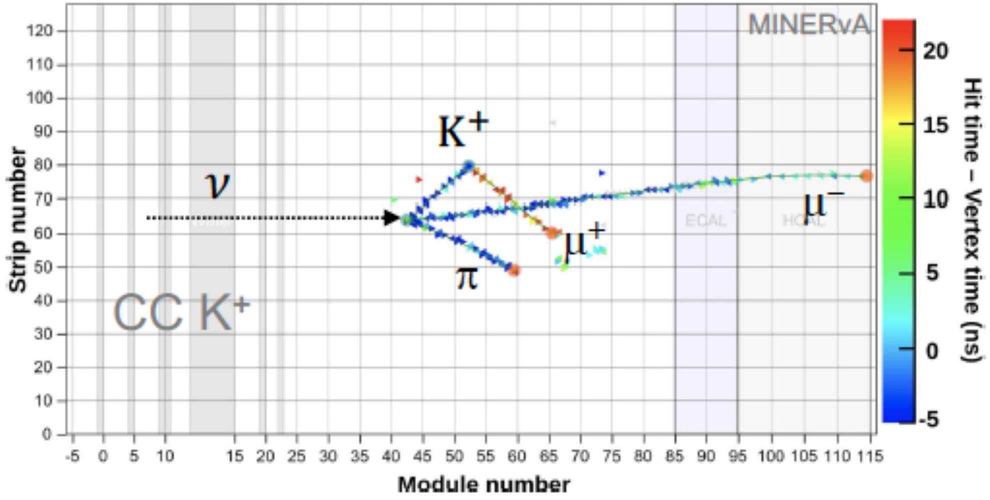


Kaon Production

"Inverse kaon decay"
— Coherent K^+

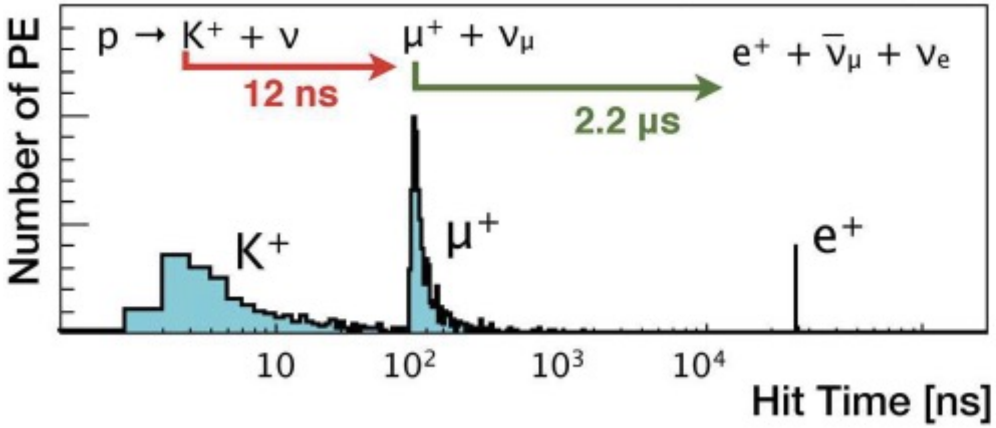






- ❑ K^+ decay-at-rest signature
  12.4 ns lifetime, kink, energy deposit

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



- ❑ Proton *decay at rest* → K^+ 105 MeV K.E.
- ✓ Nice kinematic signature with decay chain coincidence

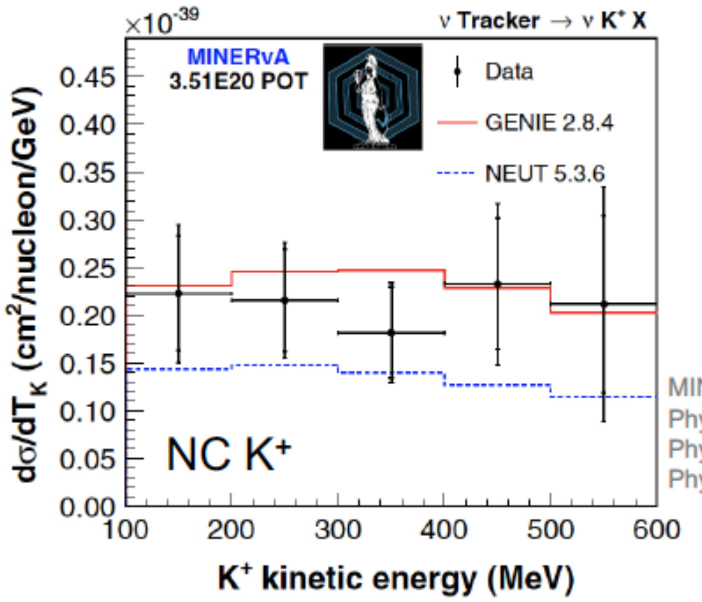
  Or not?

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: Nuclear Effects

—it's all about systematics

Quiz: Here is a model

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

It is wrong by a few __%.

A: 10 B: 1 C: 0.1

Elements

(Mendeleev, 1869)

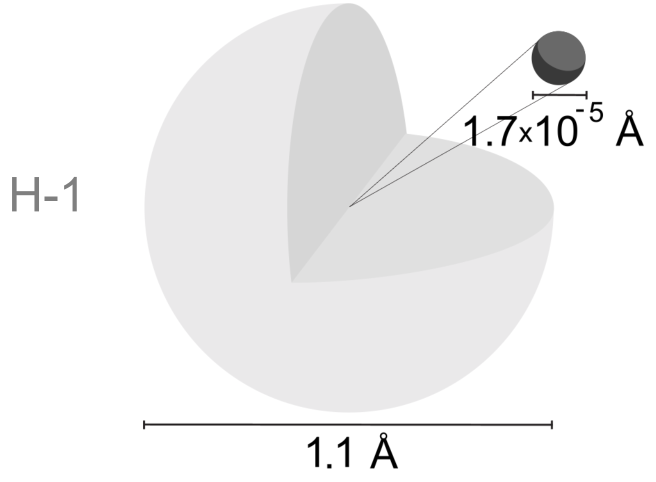
Group → / Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 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		

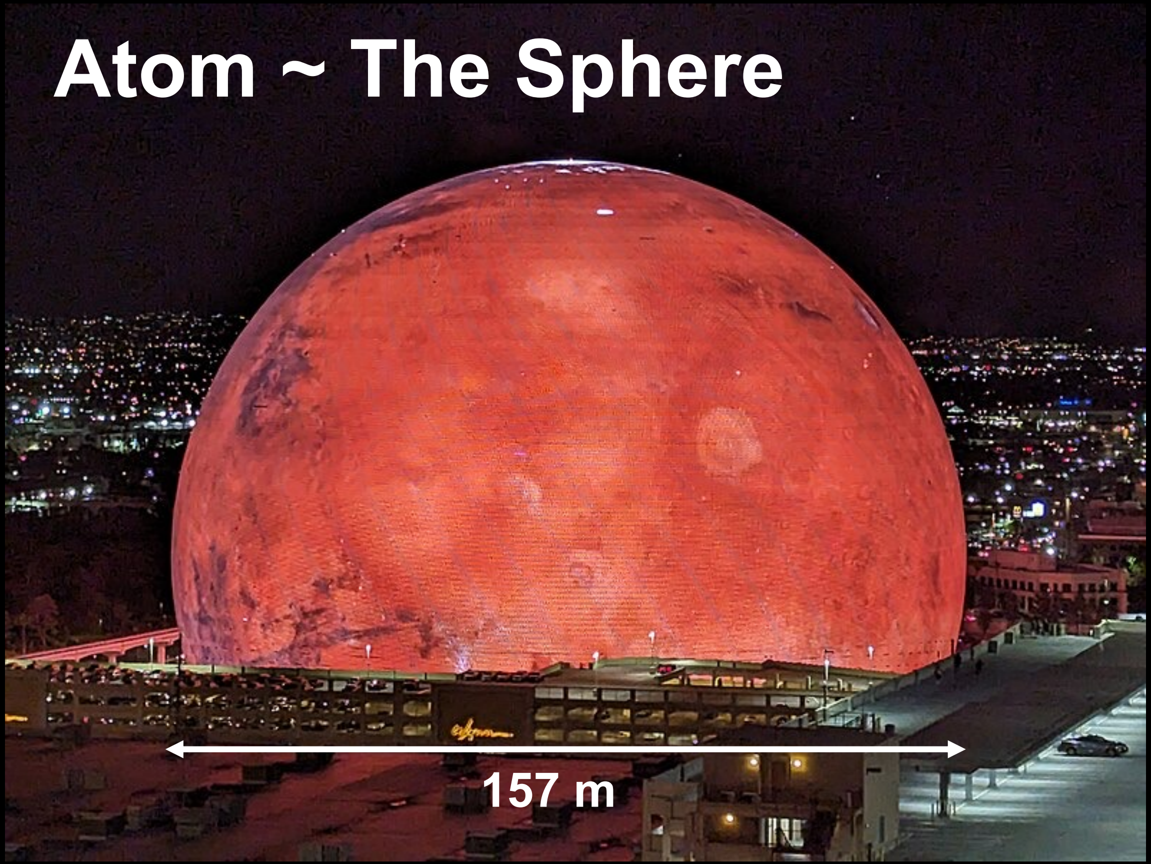
Quiz: How many neutrons does argon have?

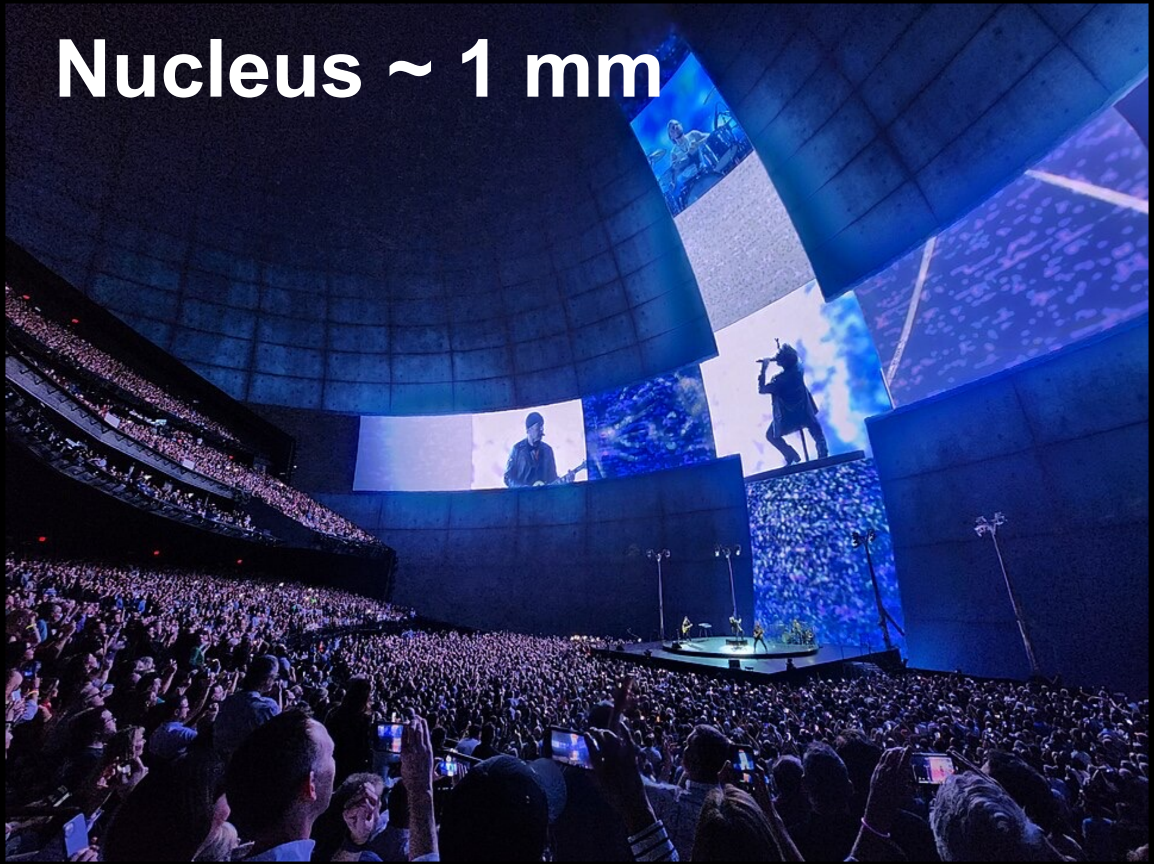
Atom

Electron (J. J. Thomson, 1897)

Nucleus
(Rutherford, 1911)



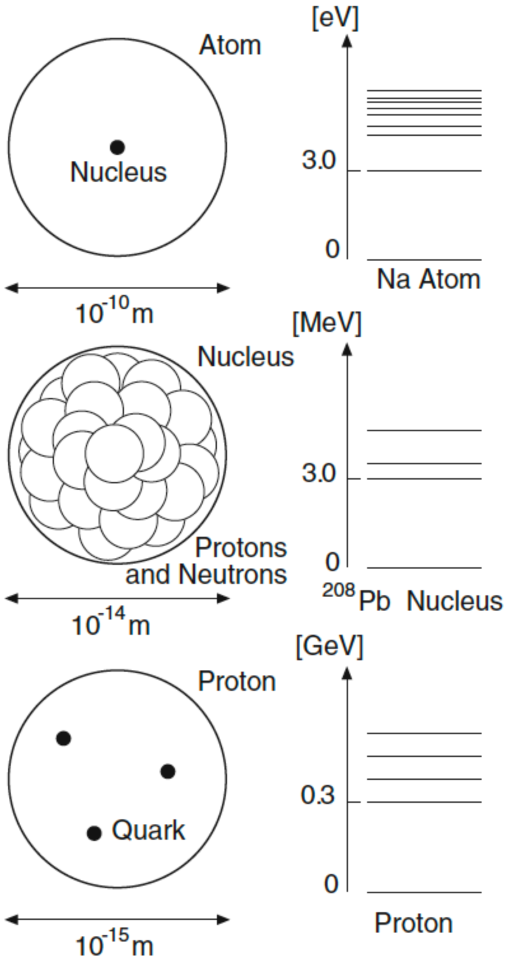




Source: https://en.wikipedia.org/wiki/Sphere_(venue)

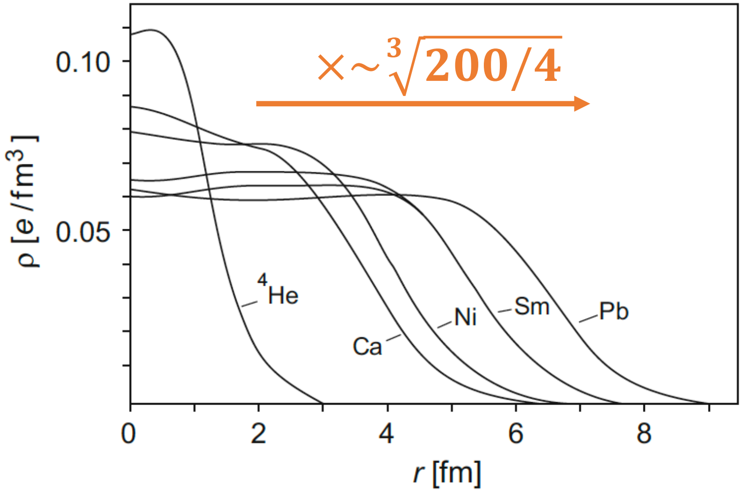
Excitation energy

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



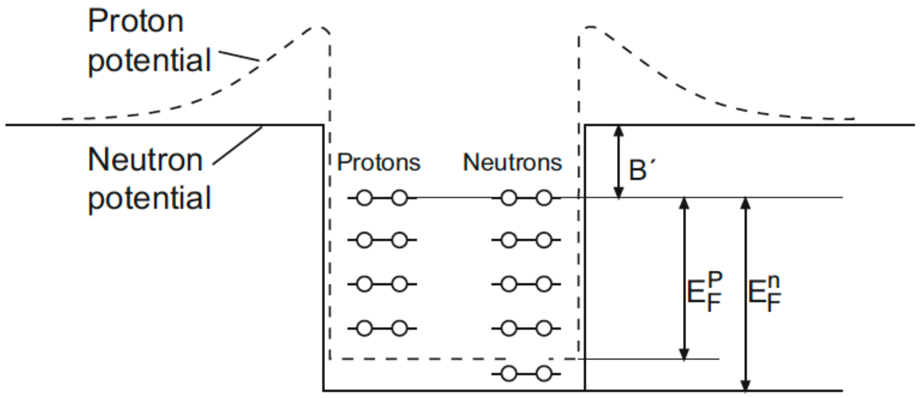
Homework**: What charge is seen by neutrino CC scattering?

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



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

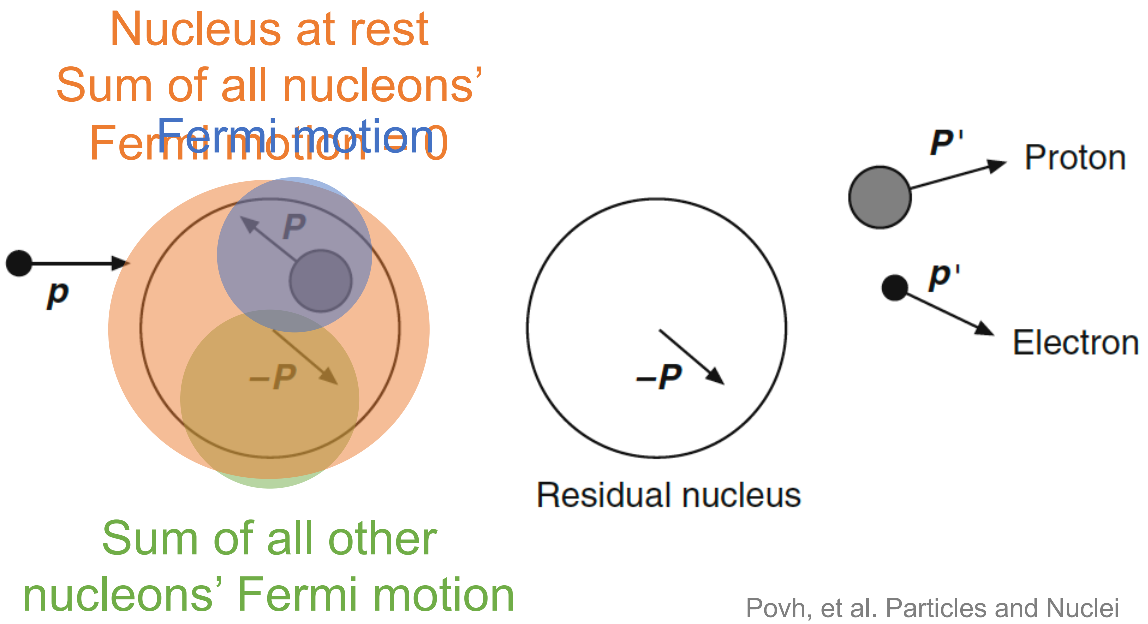
(local) density varies with *r*

Nucleus radius (global)

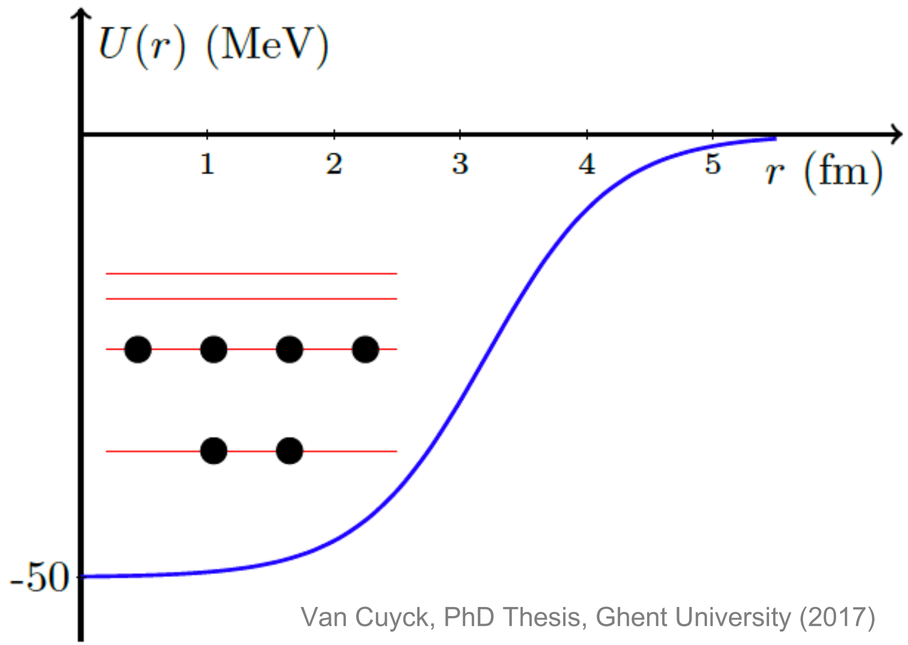
All figures from Povh, et al. Particles and Nuclei

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



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

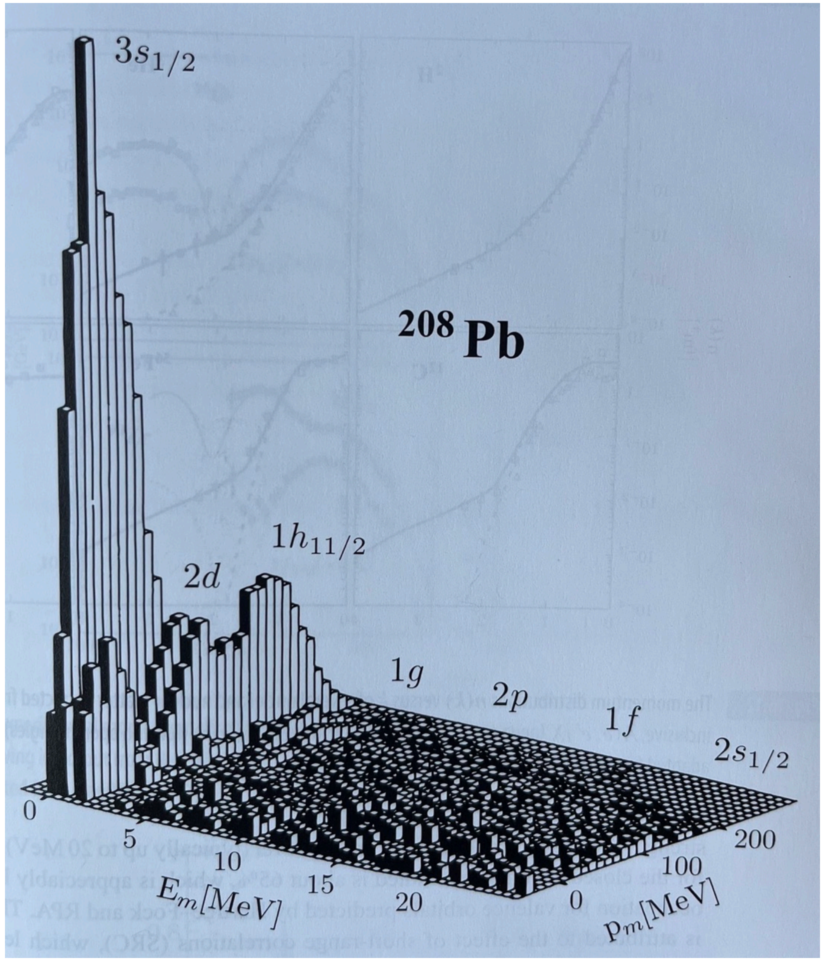
Free-moving ≠ free, the potential makes the nucleon off-shell

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

Spectral function

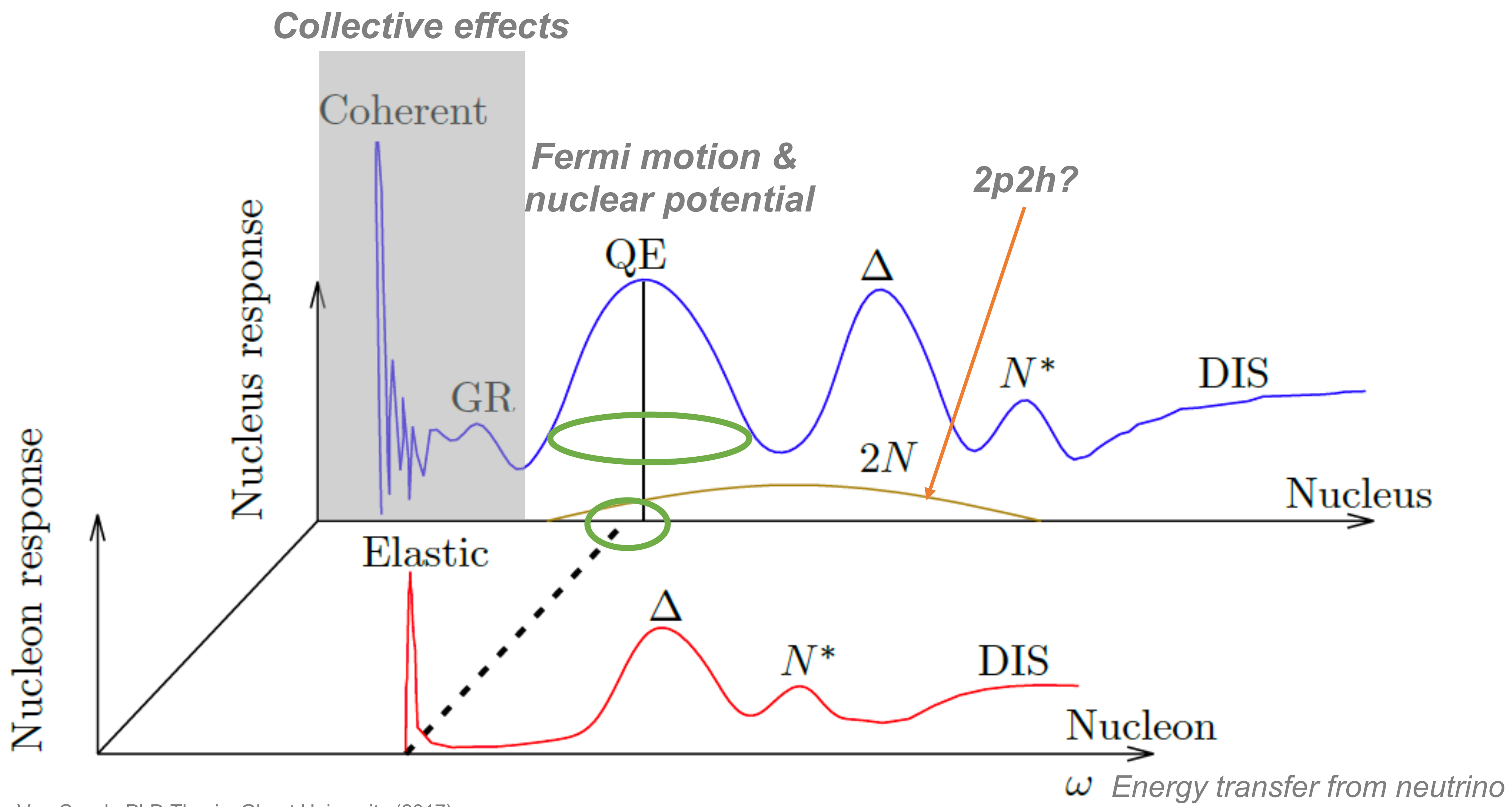
Probability density as a function of nucleon energy and momentum (or their equivalent)

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



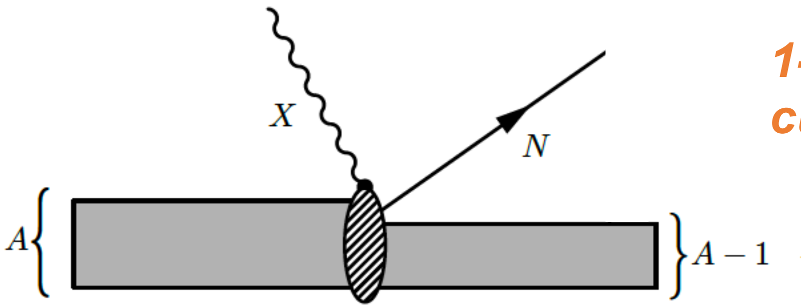
^{208}Pb spectral function represented by missing energy and missing momentum, using cross section data for the ^{208}Pb(e, e′p)^{207}Tl* reaction.

Quint, PhD thesis, University of Amsterdam, 1988

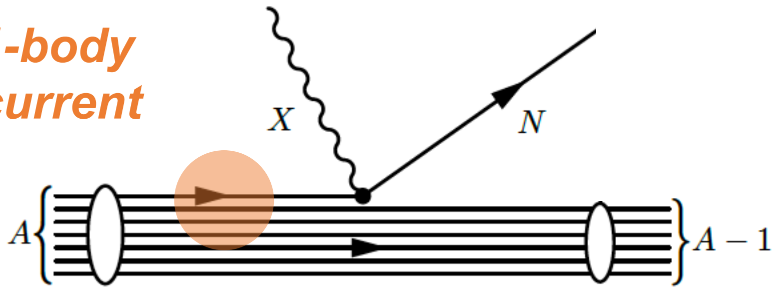


Van Cuyck, PhD Thesis, Ghent University (2017)

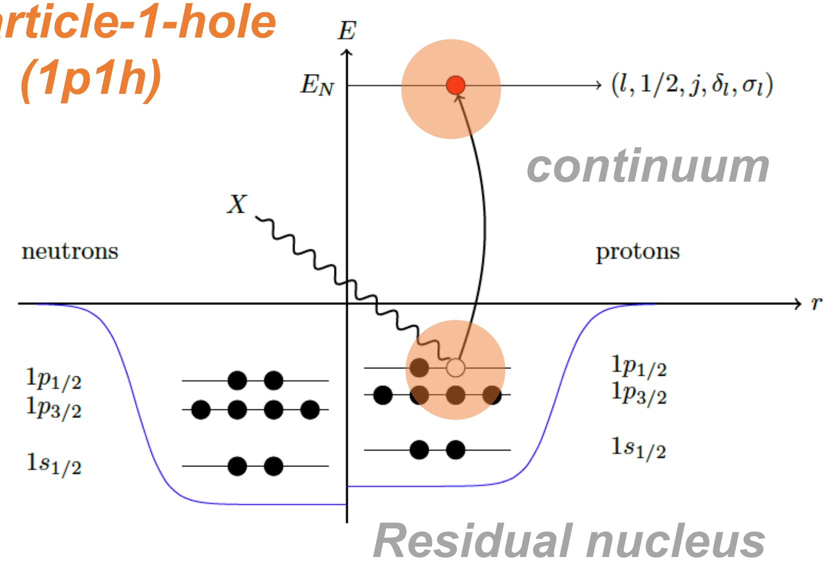
Impulse approximation (IA)

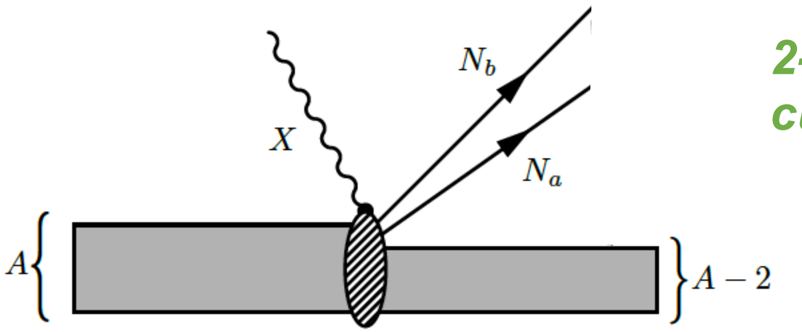


1-body current

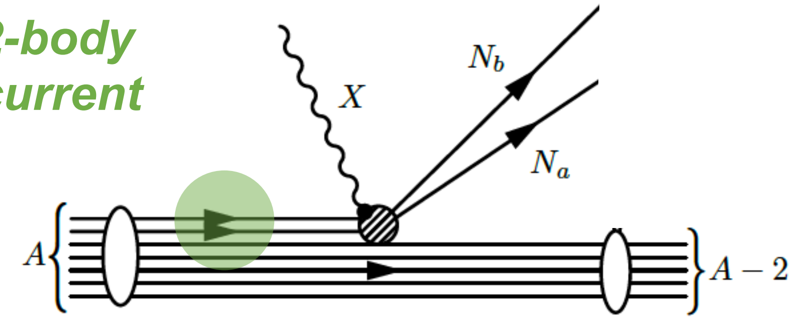


1-particle-1-hole (1p1h)

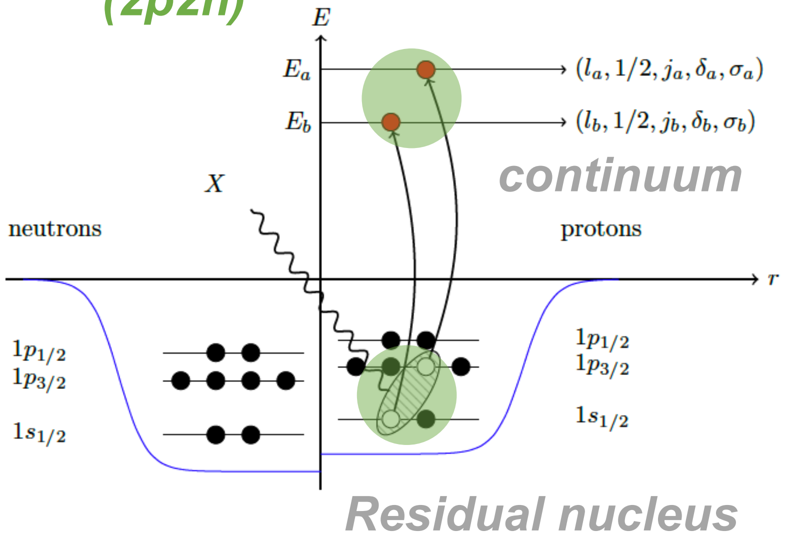




2-body current

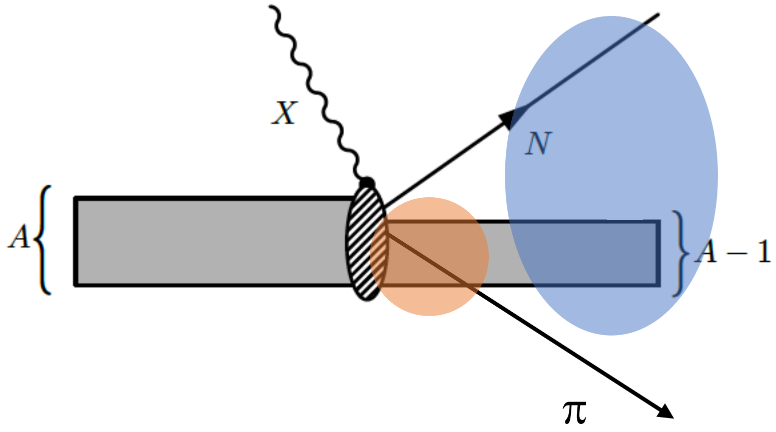


2-particle-2-hole (2p2h)

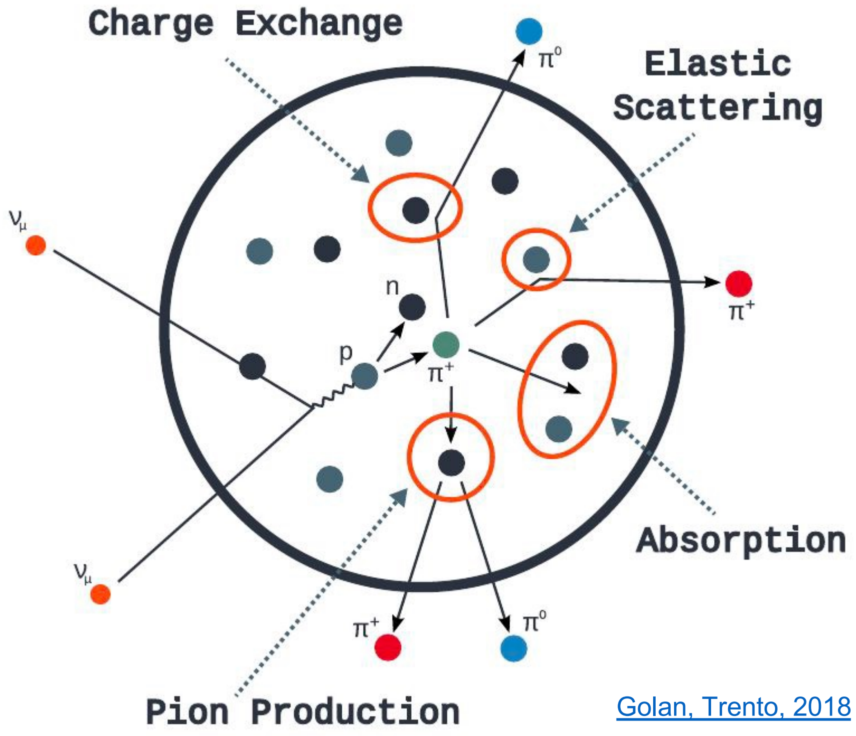


All figures from Van Cuyck, PhD Thesis, Ghent University (2017)

Final-state interaction (FSI)



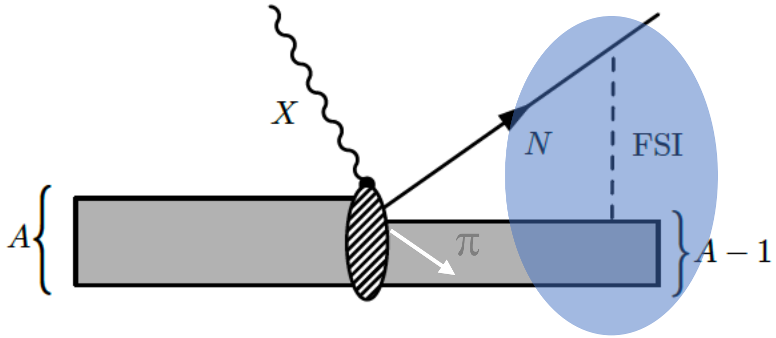
Van Cuyck, PhD Thesis, Ghent University (2017)



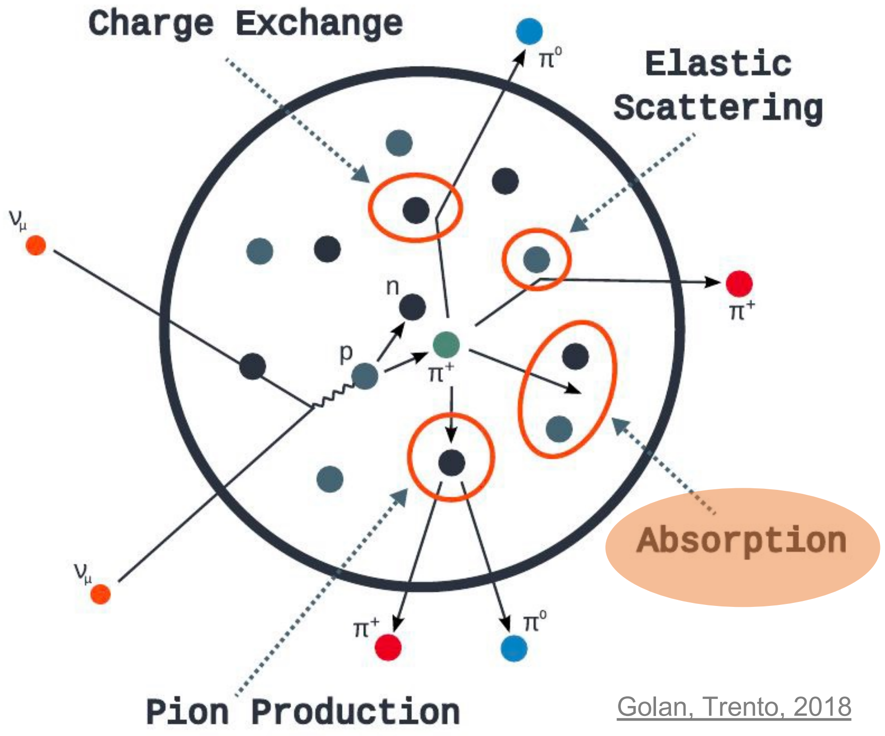
Golan, Trento, 2018

Final-state interaction (FSI)

Can not identify RES experimentally

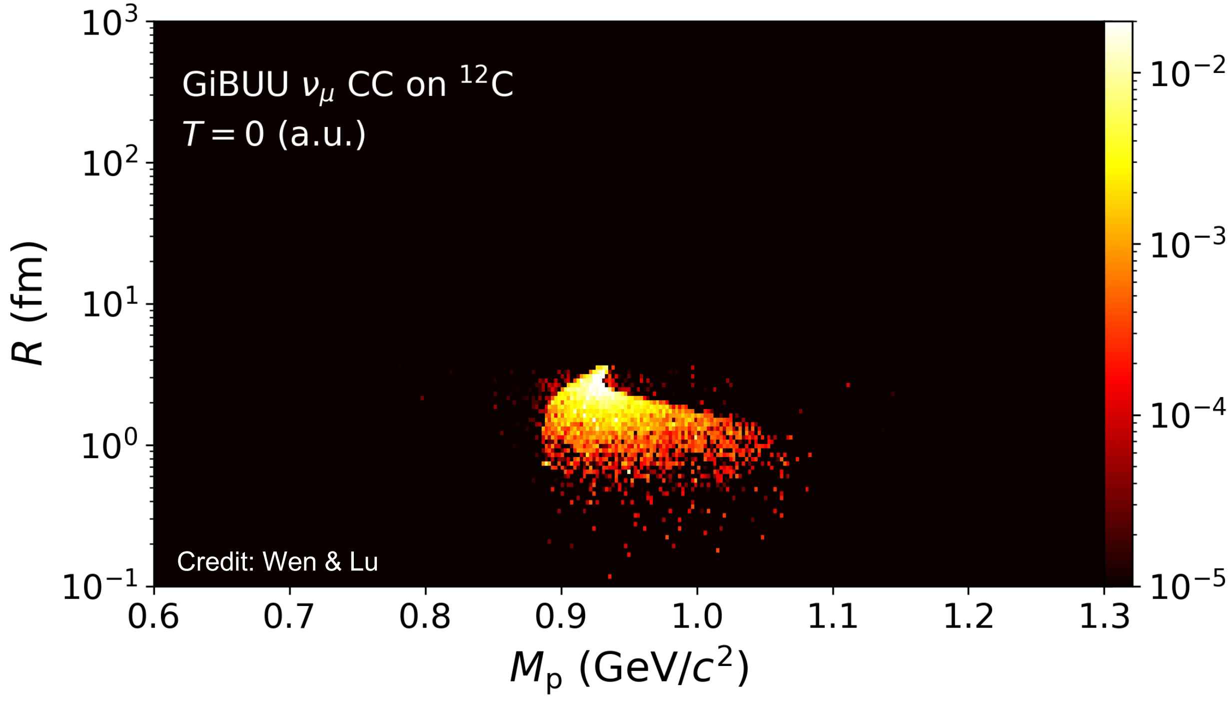


Van Cuyck, PhD Thesis, Ghent University (2017)



Golan, Trento, 2018

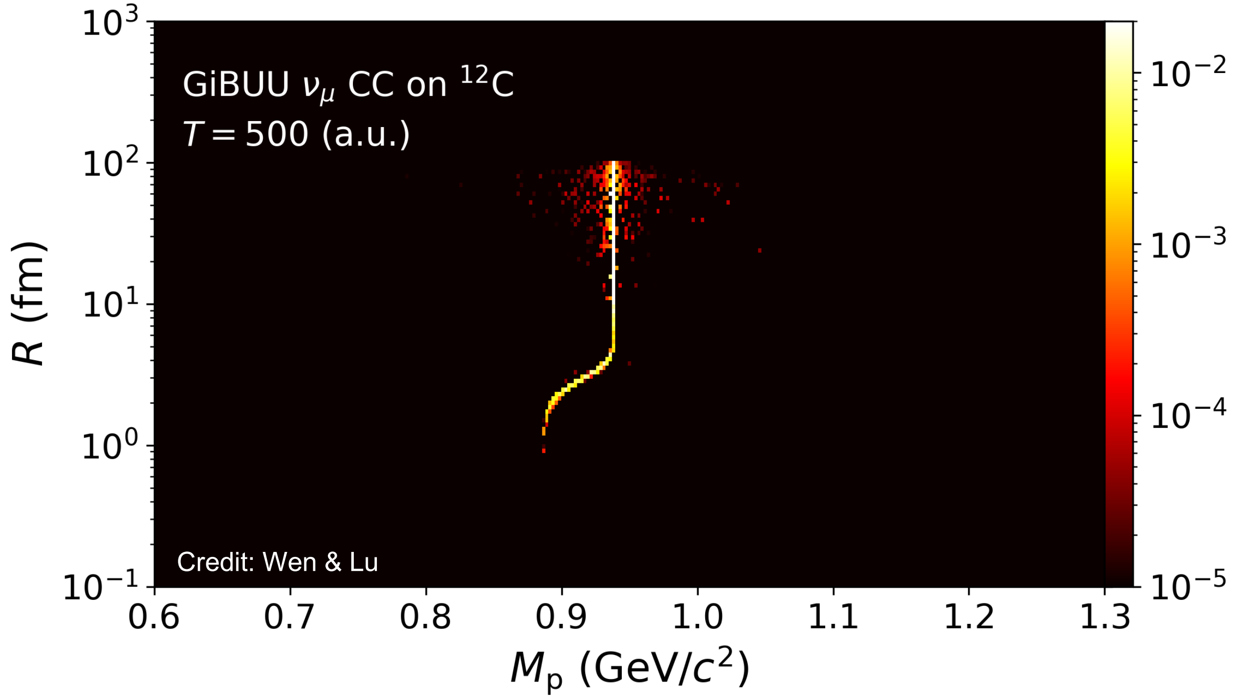
Final-state interaction (FSI)



† 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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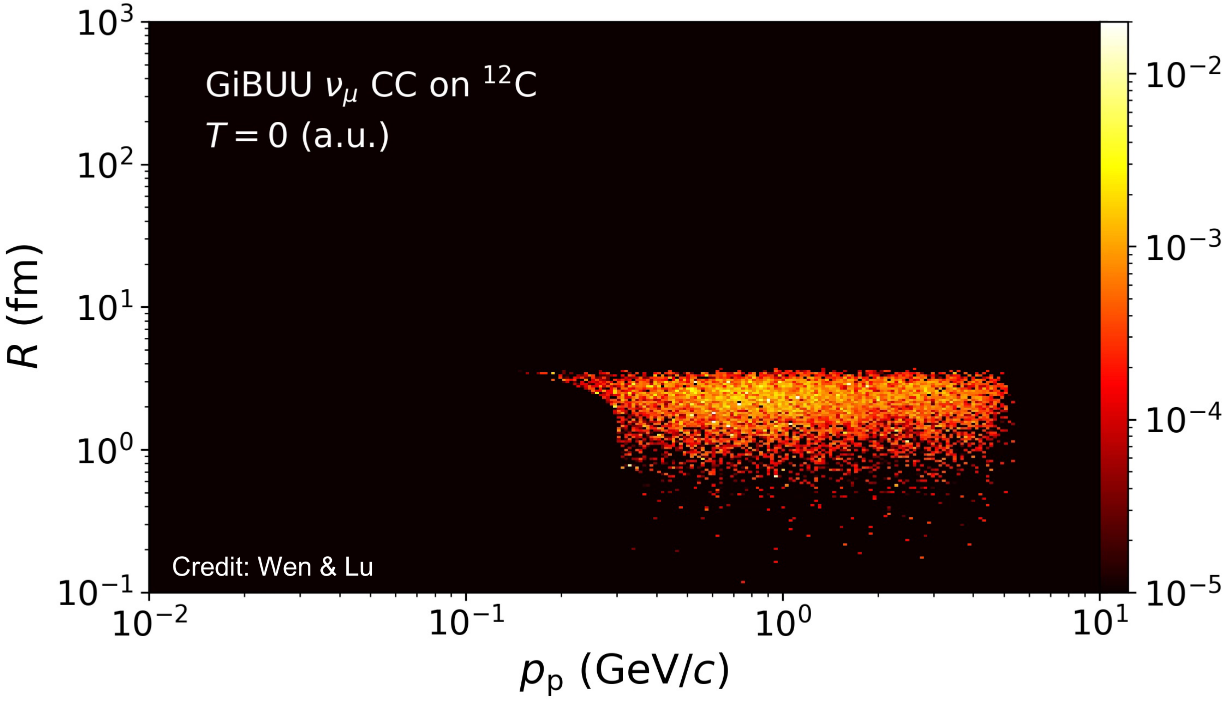
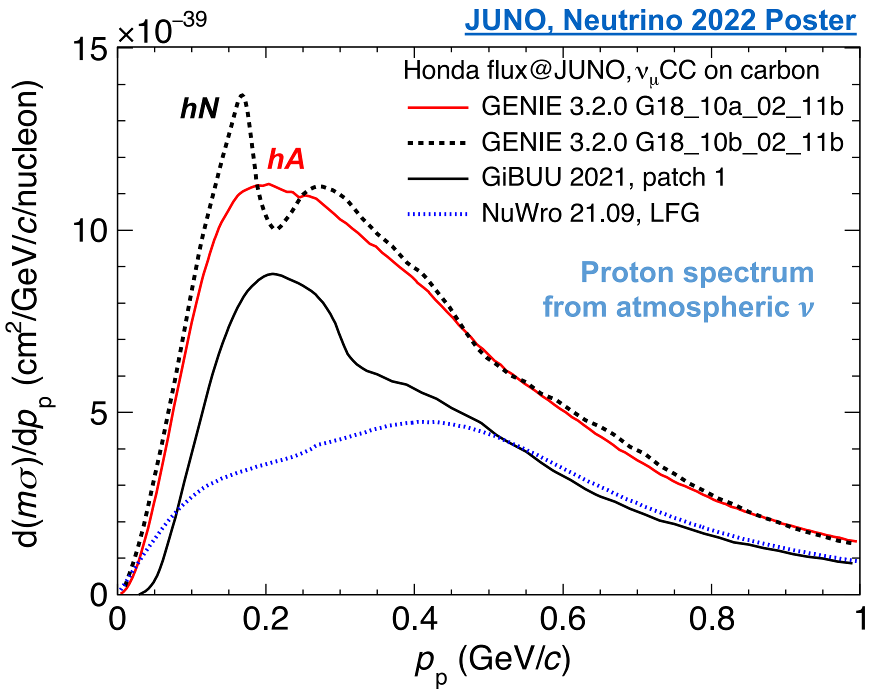
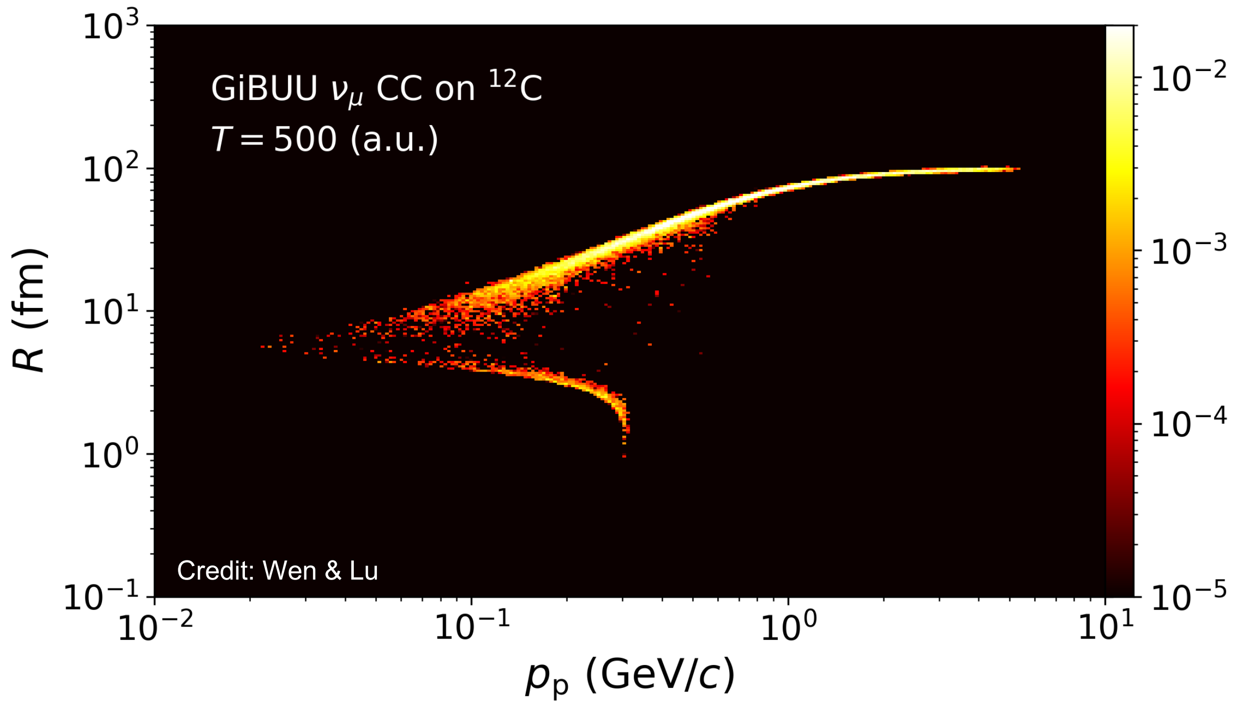


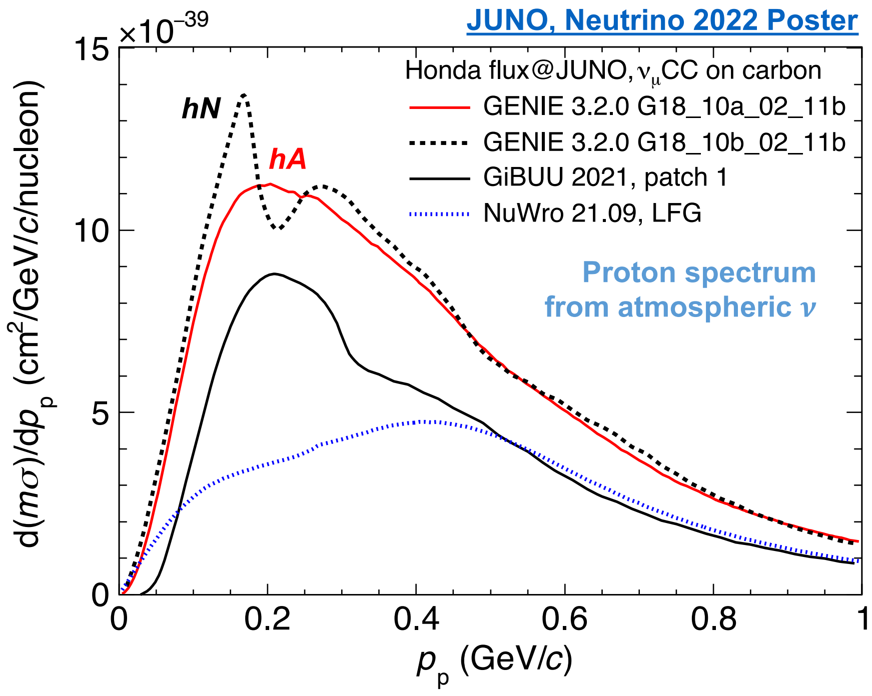


† Proton in GiBUU final-state transport
R: radial position, p_p: momentum

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.

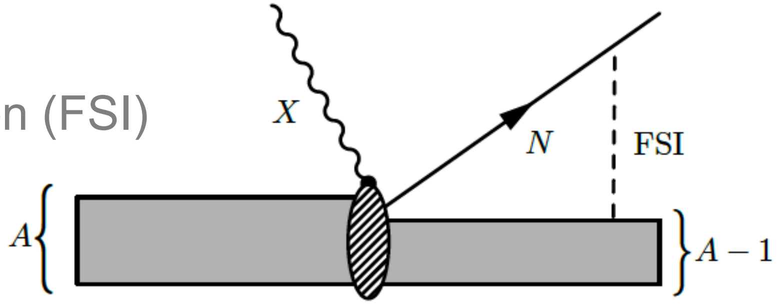
Homework: In the GiBUU FSI movie:

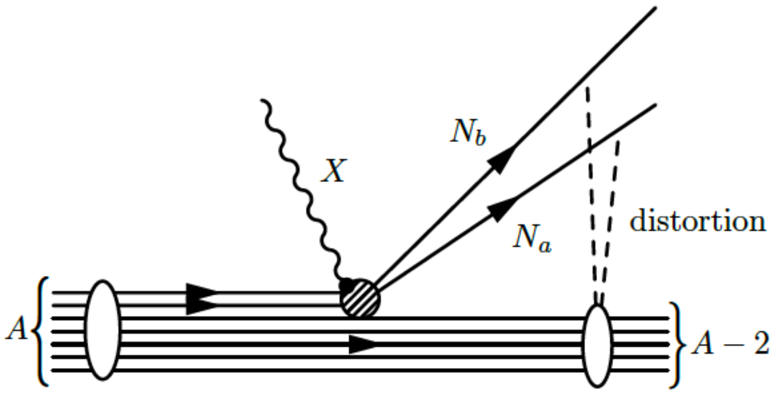
1. **** Calculate the physical time unit, i.e. how long is T=1 a.u.?***
2. ****** Locate the forbidden region. Explain its mechanism. What determines its boundary?***

Why Neutrino Interactions?

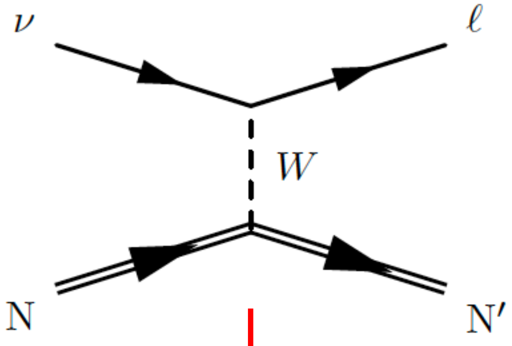
How well can we measure neutrino energy?
(reminder: oscillation very sensitive to baseline and energy, *L*/*E*)

Fermi motion,
Final State Interaction (FSI)
❑ spread

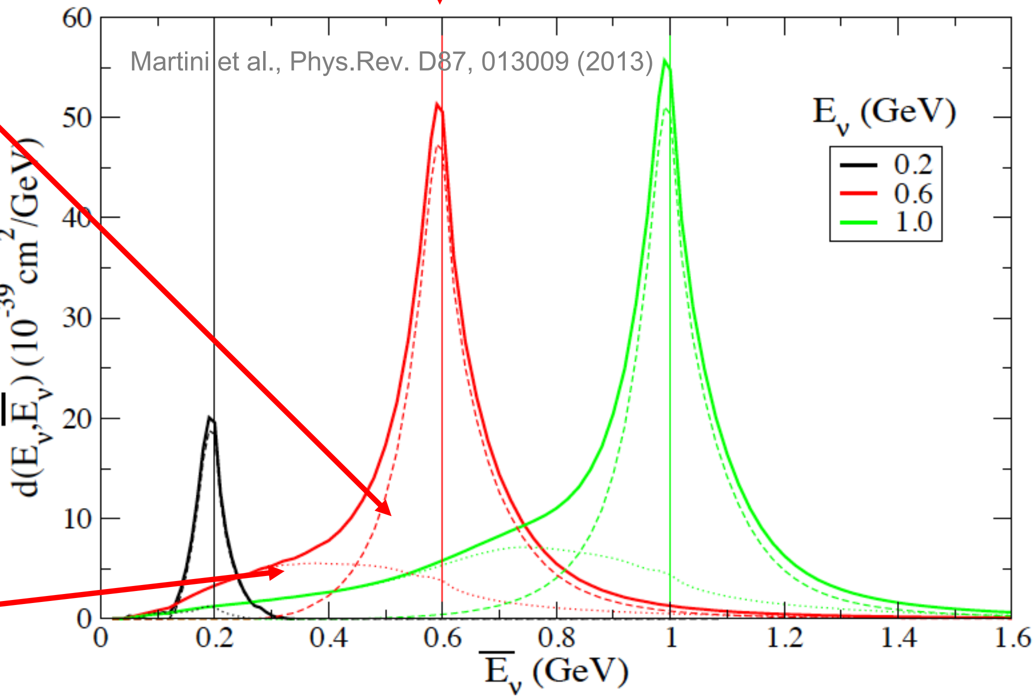




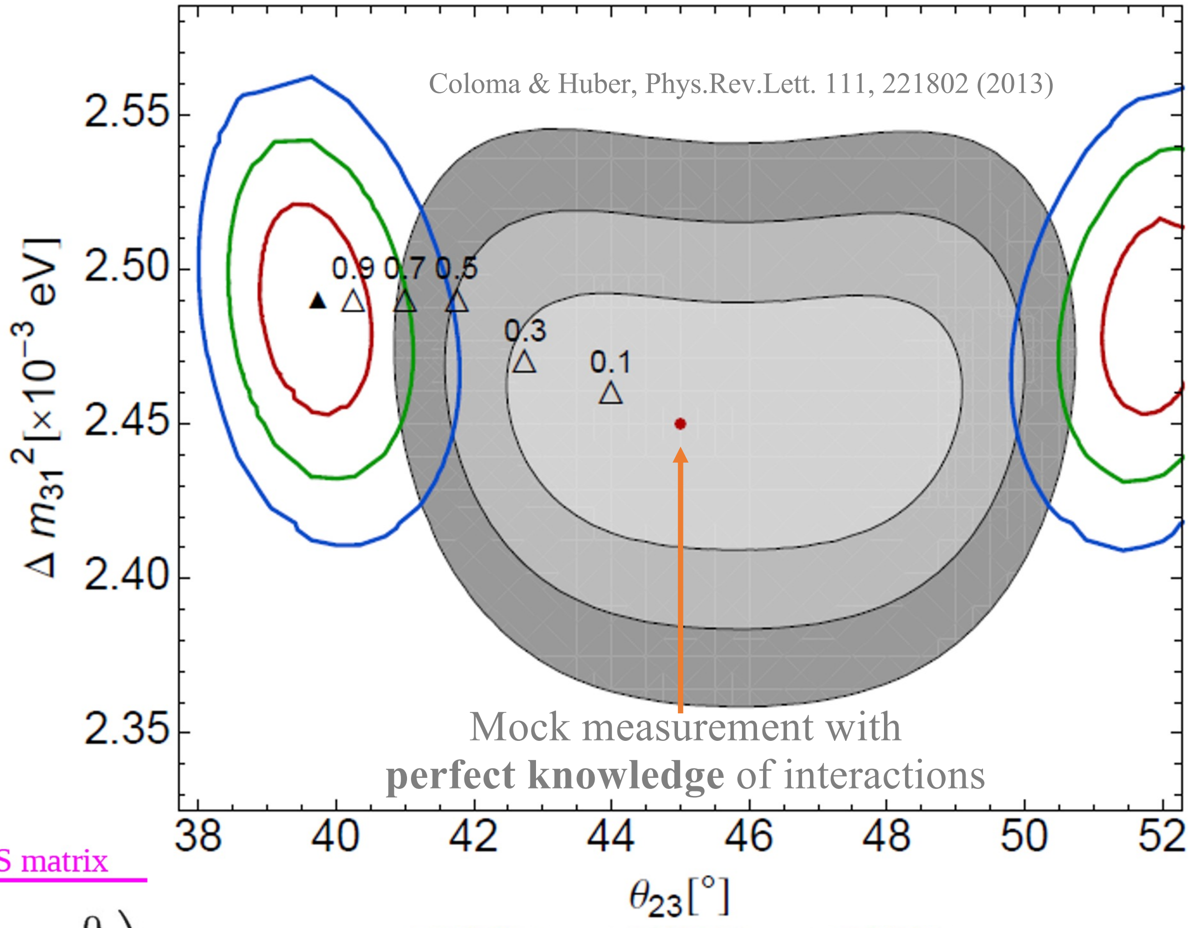
2-particle-2-hole (2*p*2*h*),
pion absorption (missing particles)
❑ Large fraction of large bias and spread



2-body reaction
❑ precise



Intranuclear Dynamics and Neutrino Oscillation Measurements



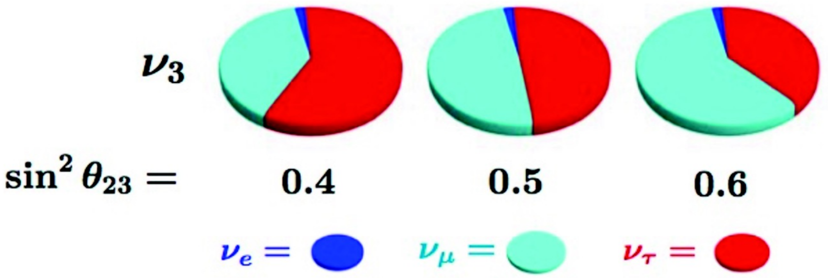
Mixing between
μ and τ flavors

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

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

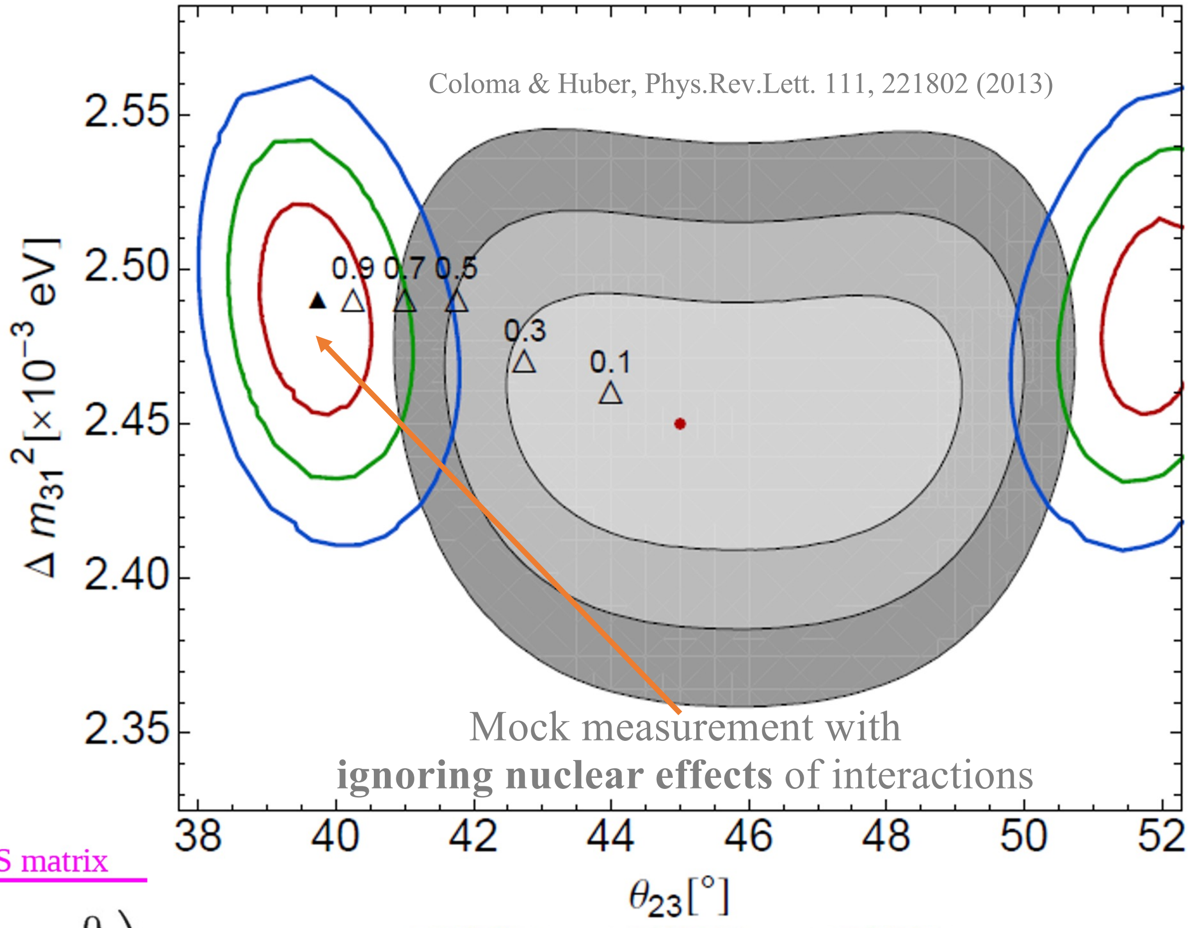
PMNS matrix

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



Parke, 1801.09643

Intranuclear Dynamics and Neutrino Oscillation Measurements



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

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

PMNS matrix

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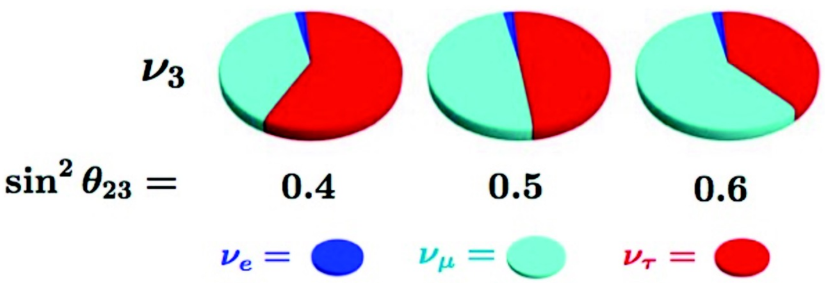
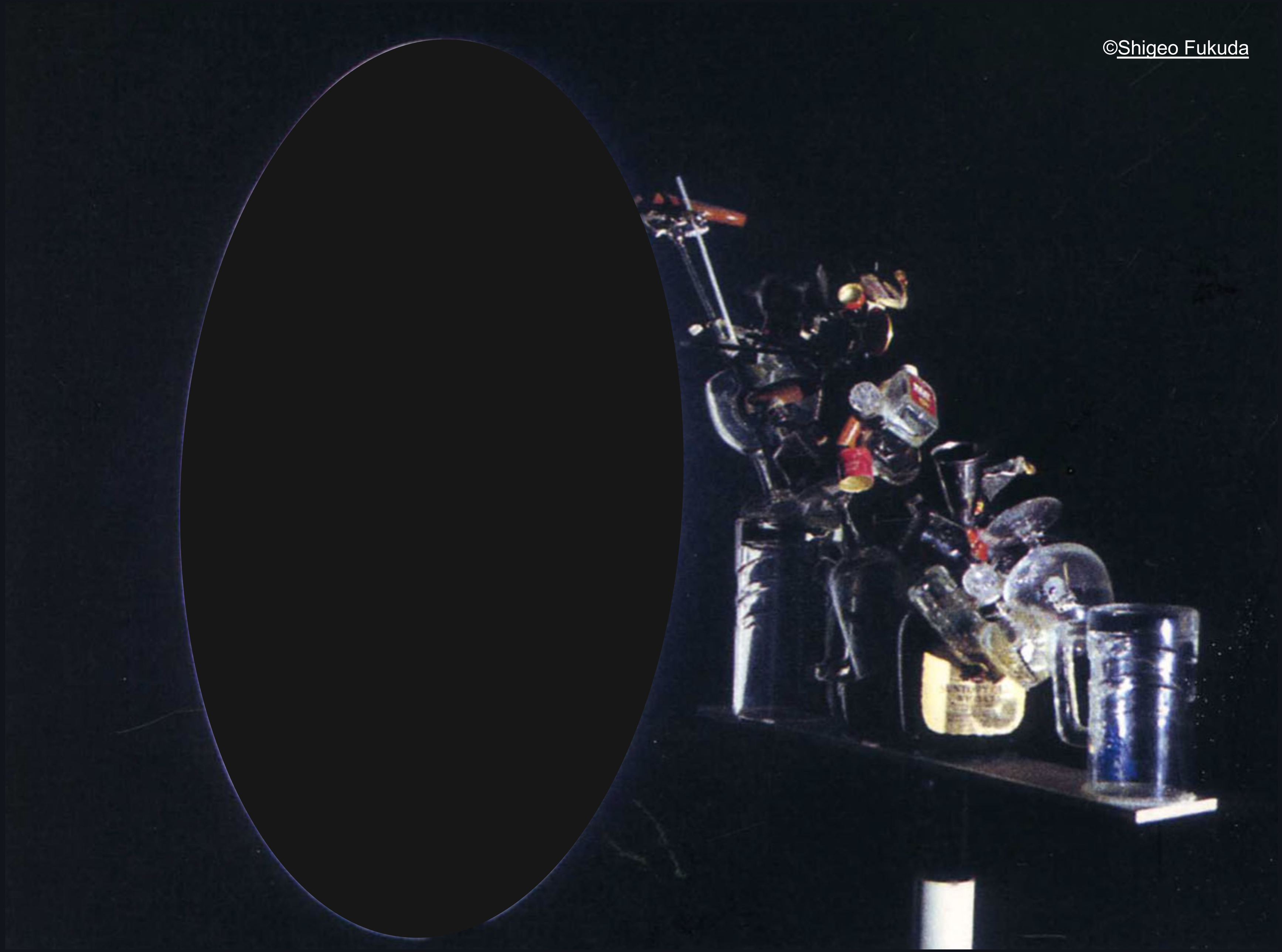


Parke, 1801.09643

Part 3: TKI Phenomenology

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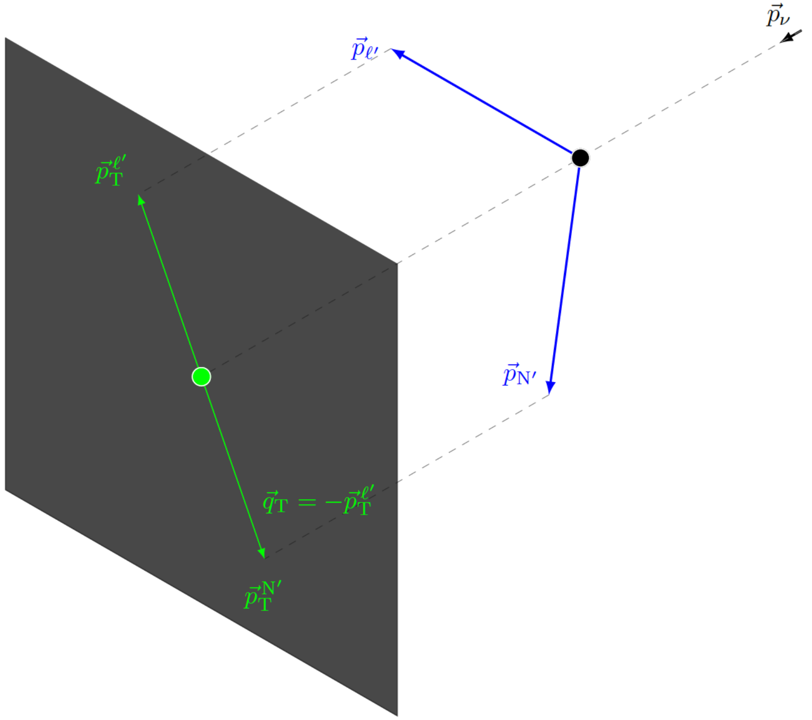
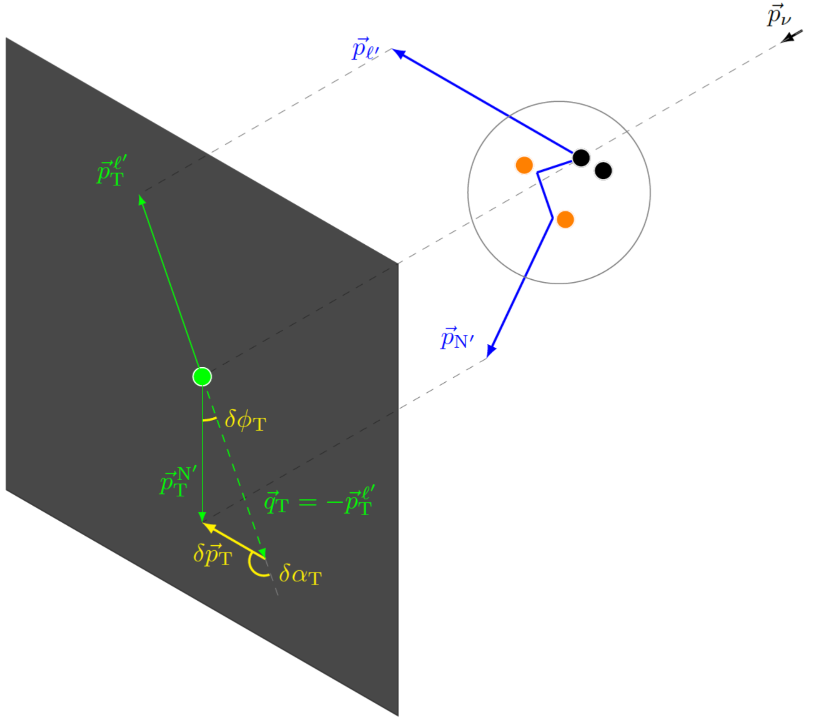
Transverse Kinematic Imbalance (TKI)



Stationary free nucleon target



Nuclear target ($A > 1$)
- ❑ Fermi motion
- ❑ Final-state interactions (FSI)
- ❑ 2-particle-2-hole (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]

[…]

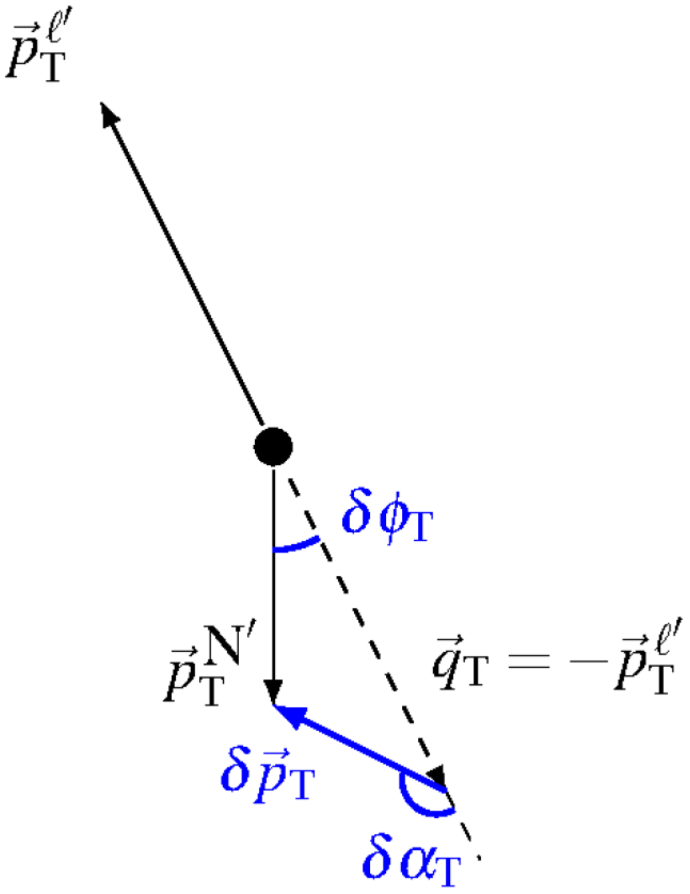
hadron colliders.[5] The initial momentum of the colliding partons along the beam axis is not known —

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)
Lu & Sobczyk, Phys.Rev.C 99, 055504 (2019)
Cai, Lu, Ruterbories, Phys.Rev.D 100, 073010 (2019)

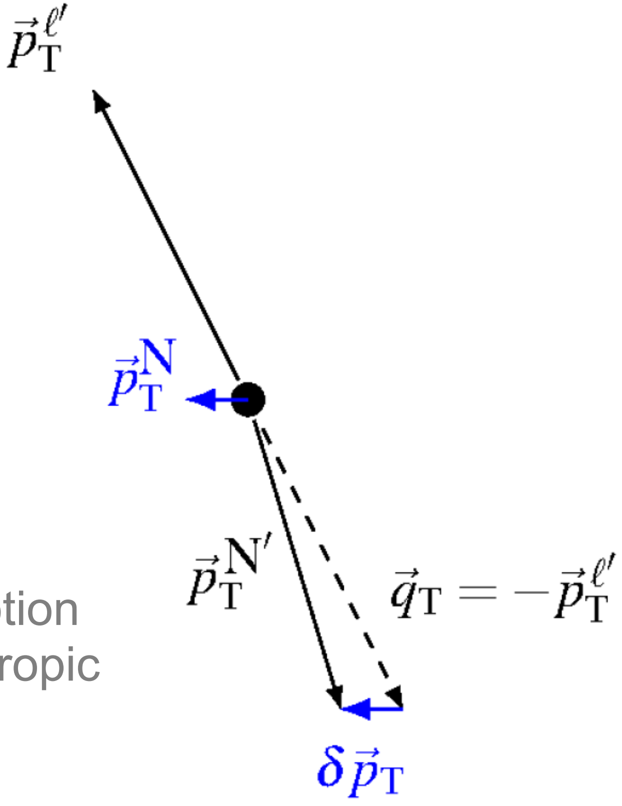
Transverse Boosting Angle $\delta\alpha_T$



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

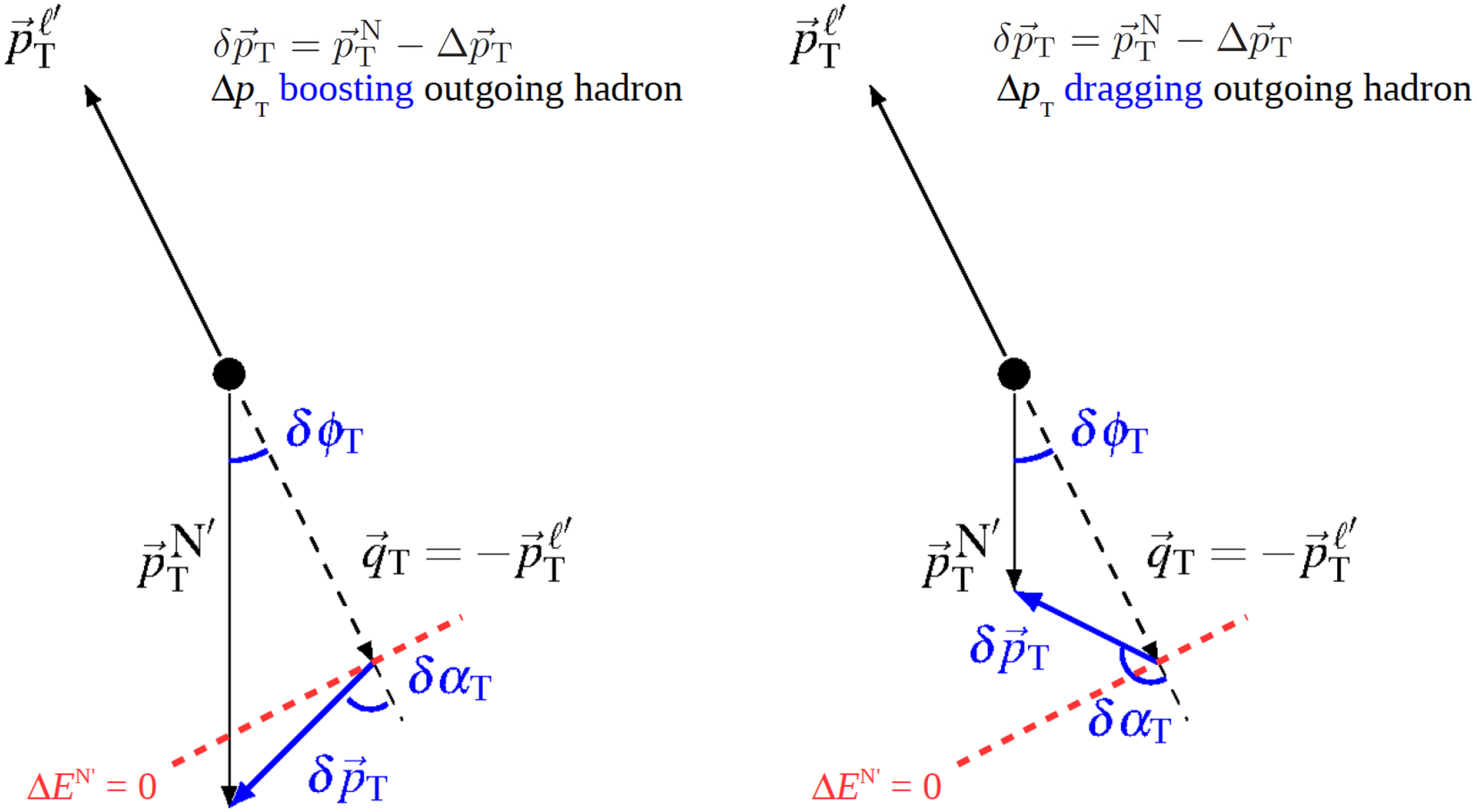
—...

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

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

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

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

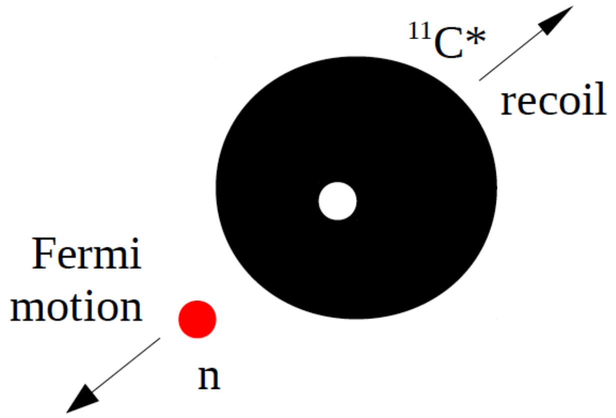
p_n : recoil momentum of the nuclear remnant

final-state

Dual Interpretation

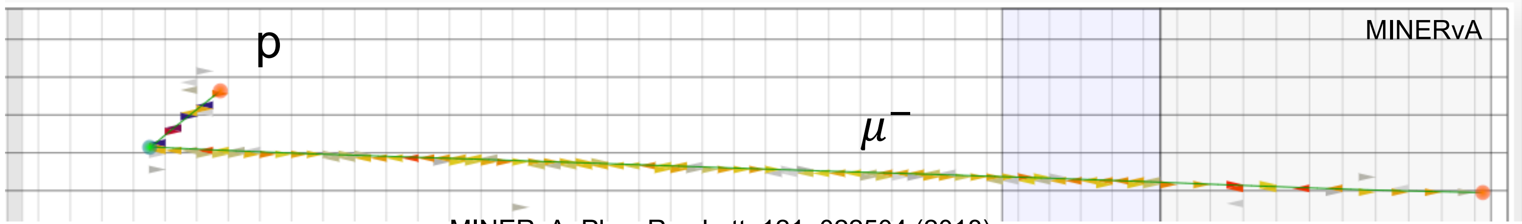
For CCQE, A' = $^{11}C^*$
No more unknowns
p_n : neutron Fermi motion

initial-state

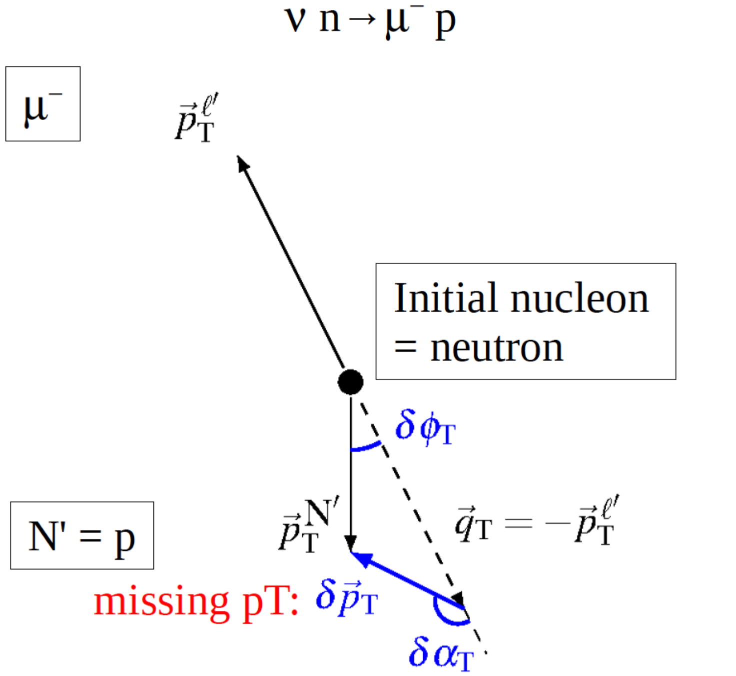


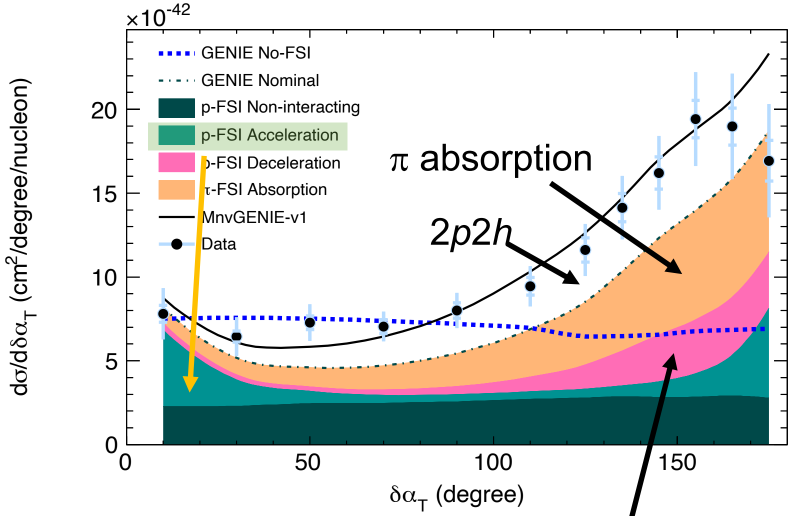
- Furmanski & Sobczyk, Phys.Rev.C 95, 065501 (2017): calculation of p_N.
- Lu & Sobczyk, Phys.Rev.C 99, 055504 (2019): p_N was proposed for the study of nuclear effects as a generalisation of δp_T

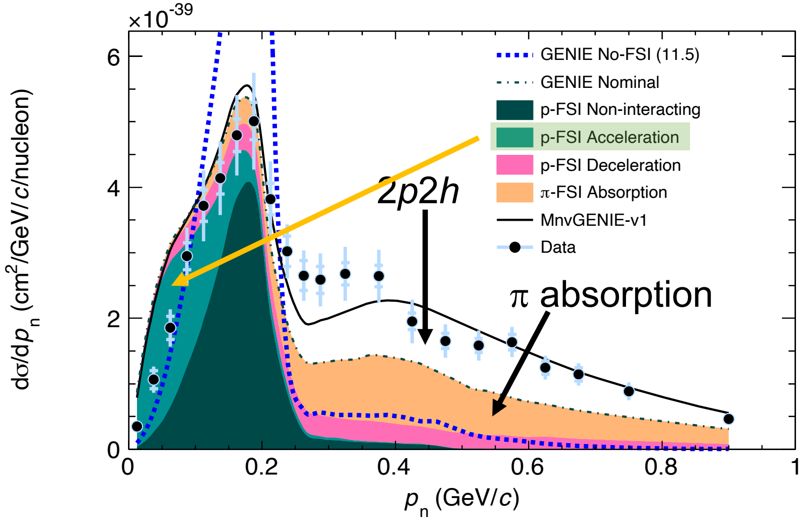
TKI: CC0π



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



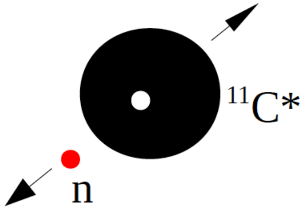


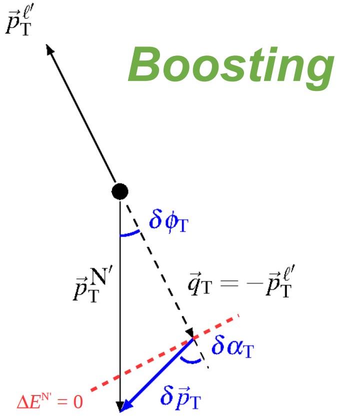


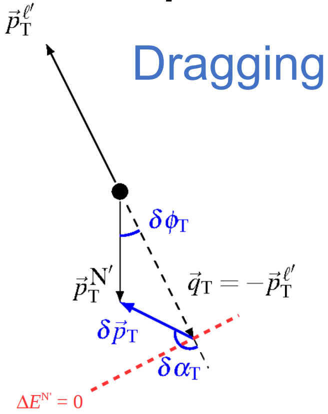
Assuming target remnant ^{11}C*

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

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







Abnormal acceleration?!

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

Generalisation #1
p_N: 3D, but mainly transverse

Btw, why "TKI (transverse kinematic imbalance)"?

PHYSICAL REVIEW C **99**, 055504 (2019)

Final-state correlations → Kinematic Imbalance

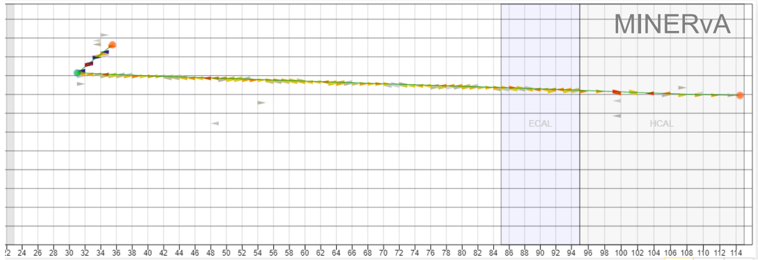
Generalized: not capturing the core of the method; can have various generalizations (see next slide)

- ✓ ***Transverse*** was chosen to represent the method, hence TKI

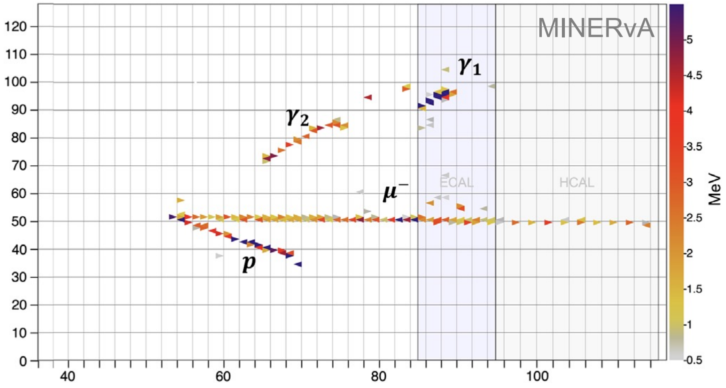
Identification of nuclear effects in neutrino and antineutrino interactions on nuclei using generalized final-state correlations

TKI: CCπ^0

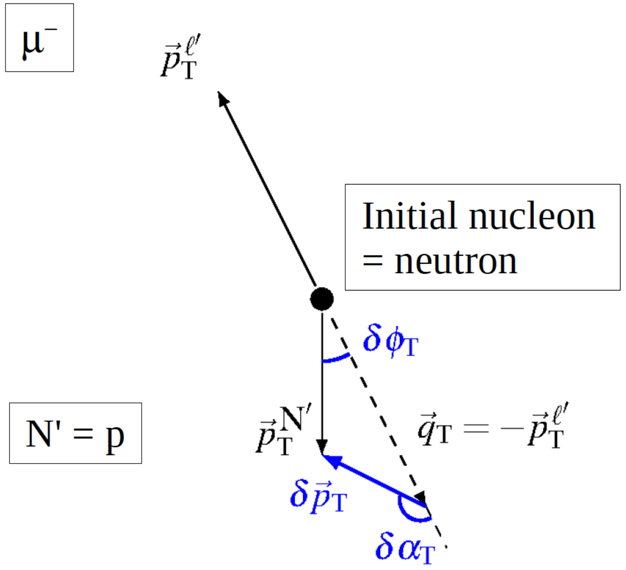
Surprising consistency!



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

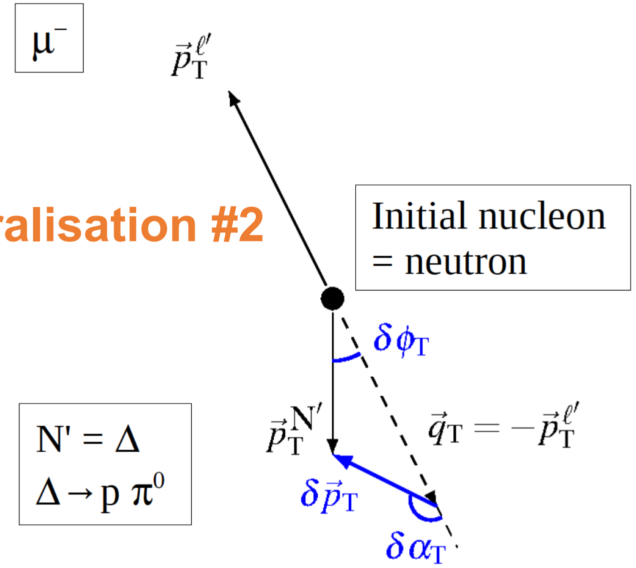


$\nu\, n \rightarrow \mu^- p\, \pi^0$



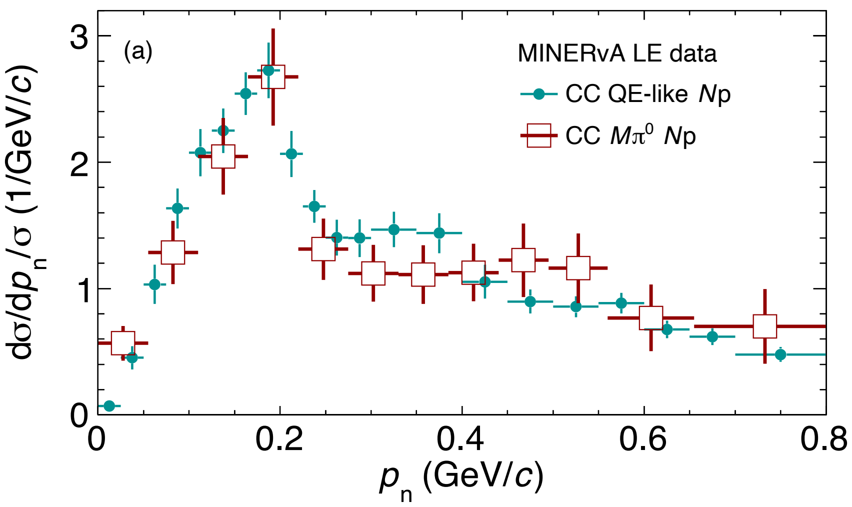
via CC0π measurement

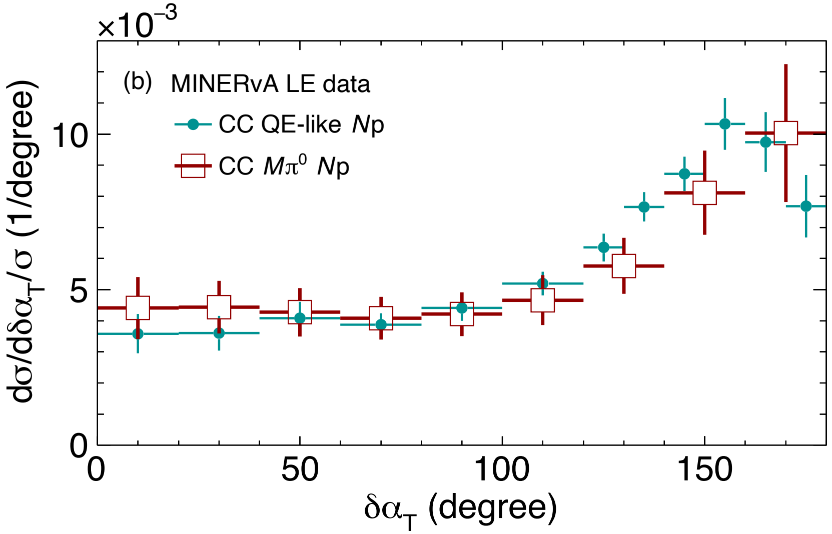
Generalisation #2



via inclusive π^0 production

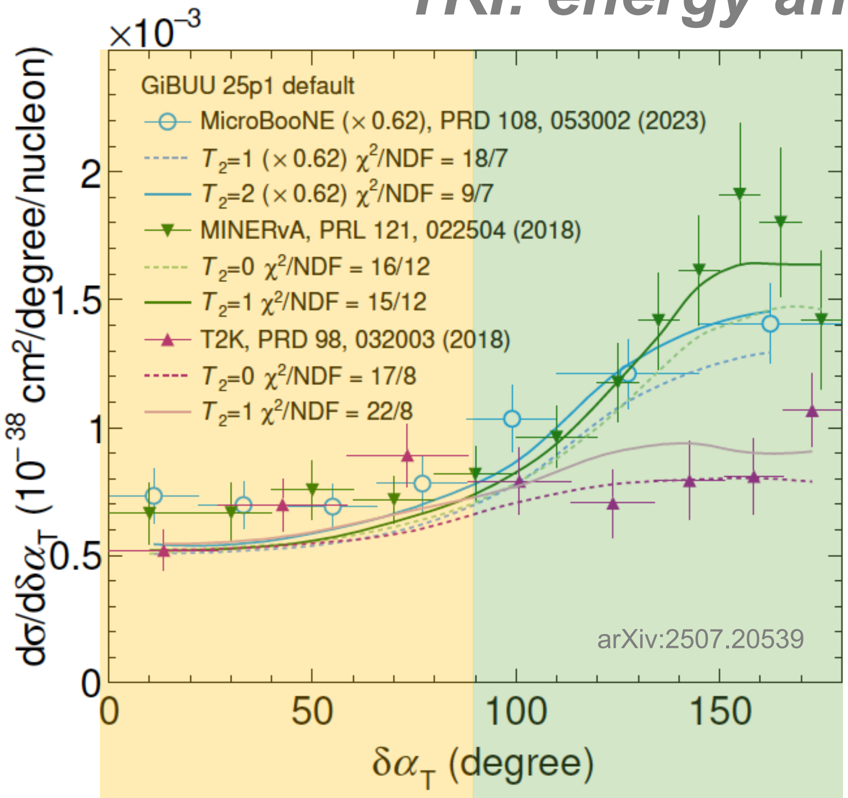
[Lu & Sobczyk, Phys.Rev.C 99, 055504 (2019)]

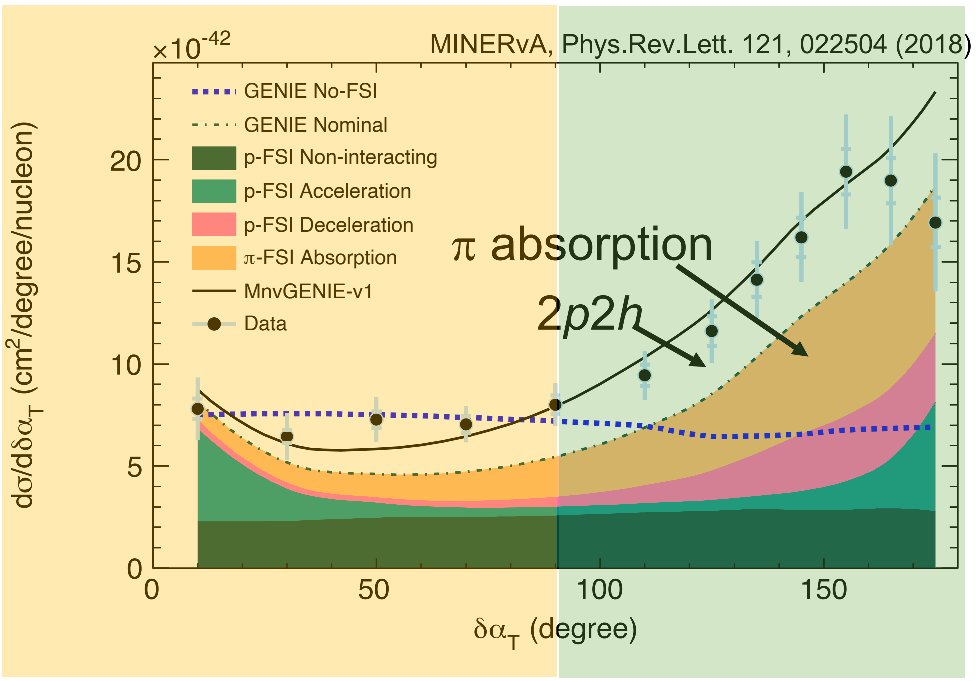


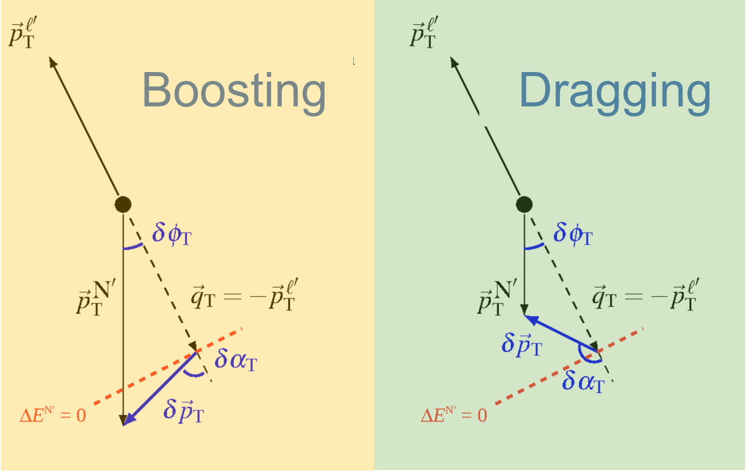


MINERvA, Phys. Rev. D 102, 072007 (2020)

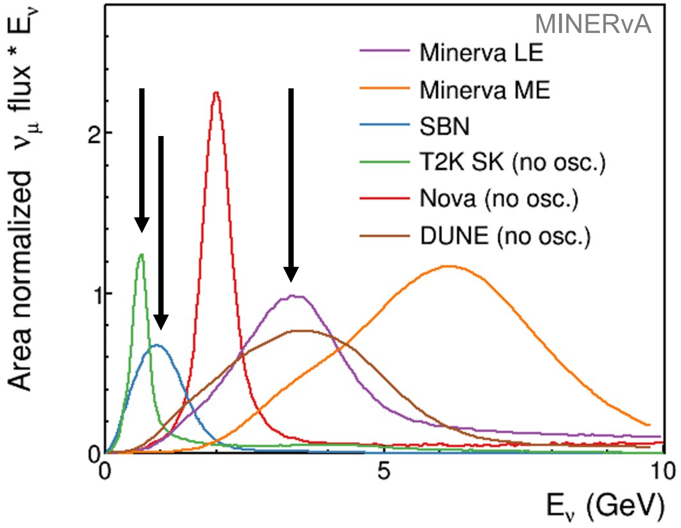
TKI: energy and target dependence







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



Neutrino Interactions

1. Experimental Techniques
    a. Standard-Model ν interactions: **complex degrees of freedom**
    b. Detectors: **plastic scintillator, TPC**
    c. MINERvA highlights: **"easy" channels—ν-e elastic scattering, inverse μ decay, CC coherent production, kaon production**
2. Nuclear Effects
    a. Structure: **Fermi gas, shell model, spectral function**
    b. Dynamics: **currents & FSI**
3. TKI Phenomenology
    a. Key variables: **transverse boosting angle ($\delta\alpha_T$), emulated nucleon momentum (p_N), generalised in correlations and topology**
    b. Current results: **MINERvA, T2K, MicroBooNE**

Quiz

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

Homework

1. ** Explain $\sigma_{\mathrm{CC}}^{\nu\mathrm{N}}/\sigma_{\mathrm{CC}}^{\bar{\nu}\mathrm{N}} \simeq 2$ at high energy.
2. Calculate the energy threshold of ν_e and ν_μ CCQE scattering on nucleons.
3. Check the quantum numbers and quark contents of Δ and N* on PDG (Google "pdg delta resonance"; navigate https://pdg.lbl.gov/).
4. * Using isospin arguments (CG coefficients), show that the cross-section ratio between $\nu_\mu \mathrm{p} \to \mu^- \mathrm{p}\pi^+$, $\nu_\mu \mathrm{n} \to \mu^- \mathrm{p}\pi^0$, and $\nu_\mu \mathrm{n} \to \mu^- \mathrm{n}\pi^+$ is 9:2:1 (assuming Δ dominance).
5. Calculate proton momentum for 10 MeV and 100 MeV kinetic energy.
6. Calculate the Cherenkov light threshold (in total energy, kinetic energy, and momentum) for e, μ, π^+, K^+, p, τ.
7. If we need to have signals from at least 6 wires in LArTPC to reconstruct a proton track, what is the tracking threshold?
8. Write down all (anti)neutrino-hydrogen interactions whose final-state particles are all electrically charged.
9. Write down the Feynman diagram(s) for ν-e elastic scattering.
10. 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?
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

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