Science and Technology Facilities Council

NEUTRINO 2022

XXX International Conference on Neutrino Physics and Astrophysics

WARWICK
THE UNIVERSITY OF WARWICK

Neutrino Interactions and Future Oscillation Experiments

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Neutrino 2022, Virtual Seoul

3 June 2022

Future oscillation experiments

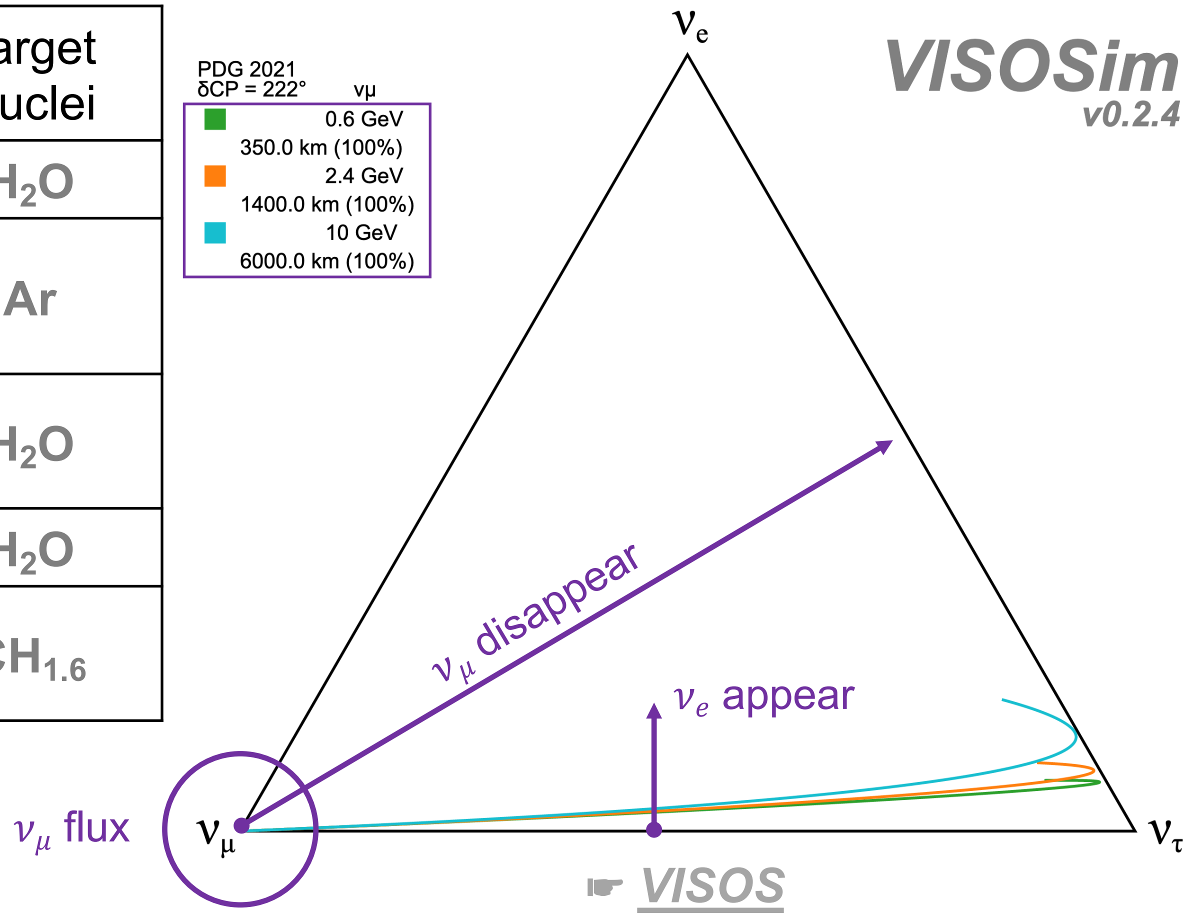
This talk only on

- ❖ accelerator and atmospheric GeV-ν

- ❖ ν_μ flux*: ν_μ disappear, ν_e appear

ν_τ appearance cf. Tom Stuttard's *IceCube* in S12 on Thursday

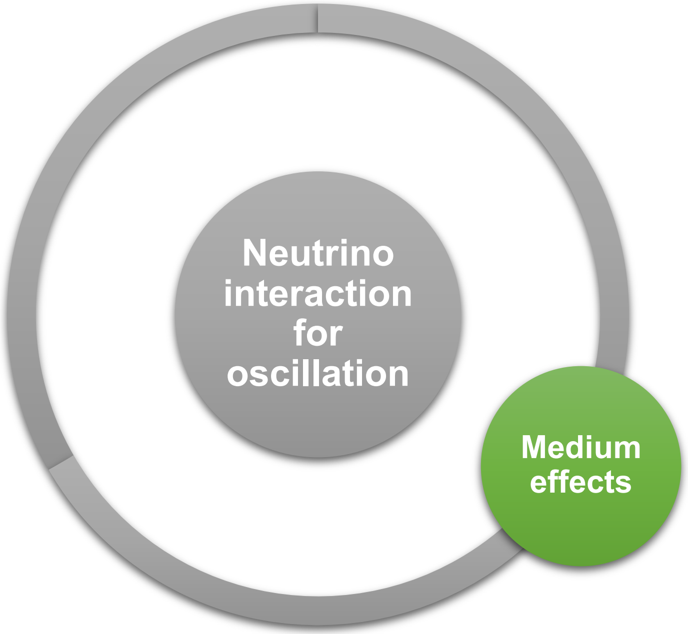
Future Oscillation Experiment	E_ν/GeV @Flux Peak	Detector Technology	Target Nuclei
Hyper-K	**0.6**	**WC**	**H_2O**
ICARUS + SBND	**0.8**	**LAr TPC**	**Ar**
DUNE	**2.4**		
IceCube Upgrade	**3-10 (ν Mass Ordering/NMO sensitive region)**	**Cherenkov in ice**	**H_2O**
KM3NeT/ORCA		**WC**	**H_2O**
Atmos-ν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

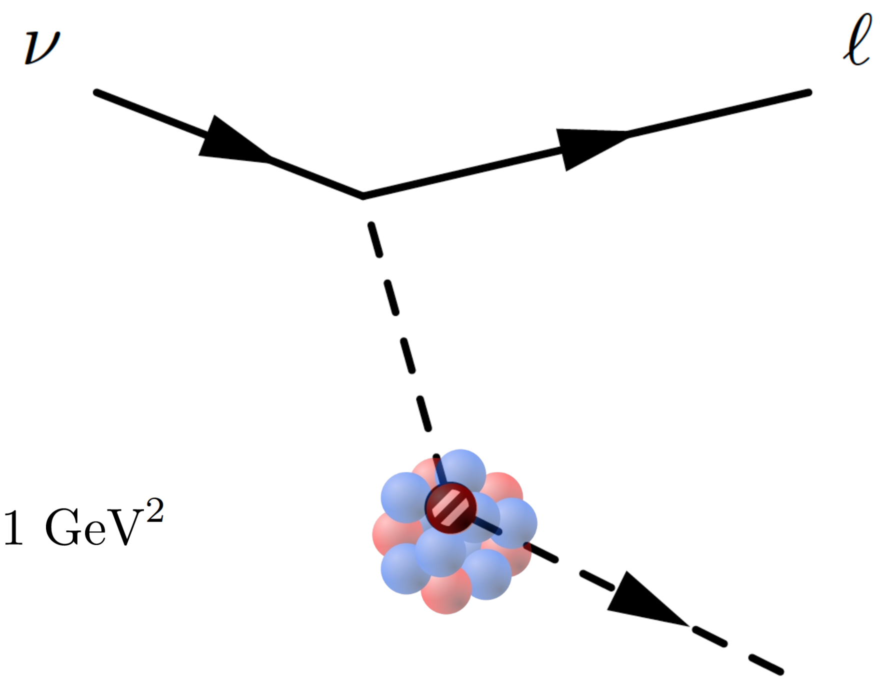


*Referring to neutrinos and/or antineutrinos implicitly depending on the context.

Interaction inside nuclei

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





Medium effects—source of systematics

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

❑ Through initial state, vertex, final state

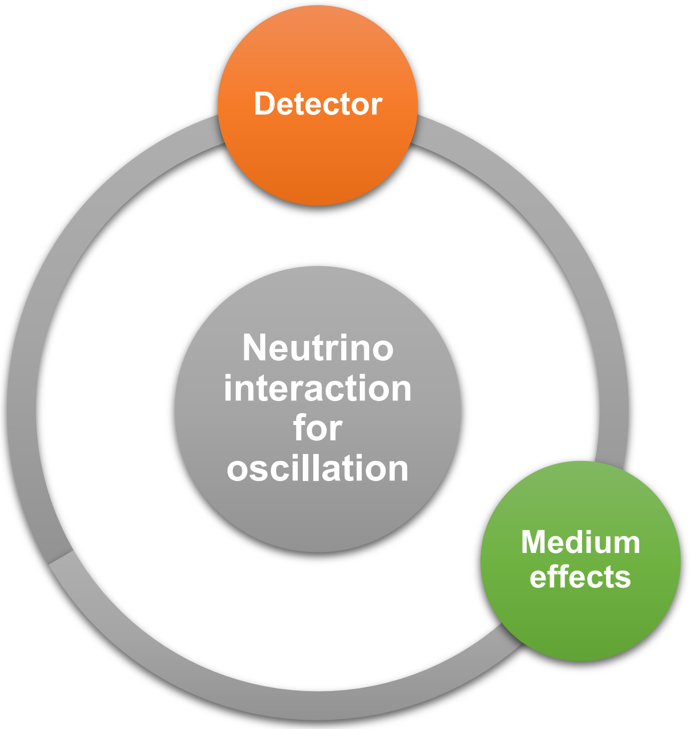
- ❖ Fermi motion & nuclear potential
- ❖ NN correlations
- ❖ Multinucleon excitation
- ❖ Pauli-blocking
- ❖ FSI

For details and impact on oscillation measurements, cf. preceding talks:
Natalie Jachowicz's *Theory of neutrino interactions*
Laura Fields's *Overview of recent neutrino cross section measurements*

Sensing ν interactions

Embedded in detector, incomplete particle information

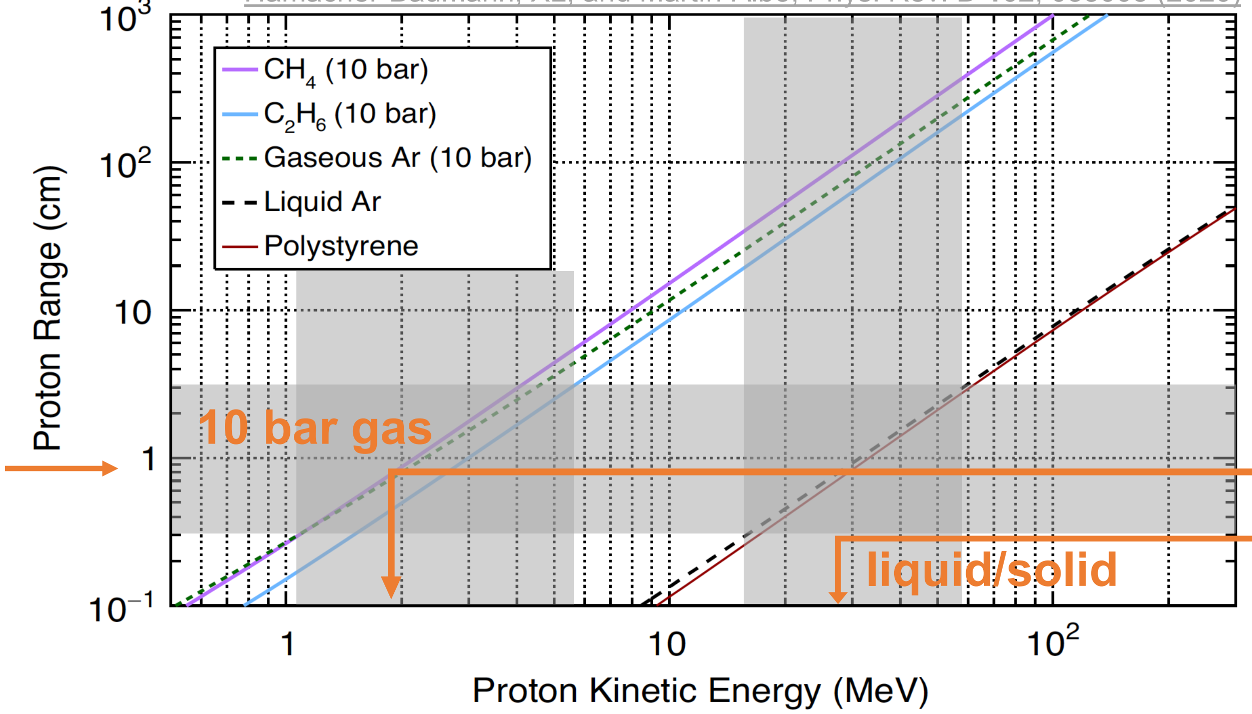
- ❖ **Tracking**/Cherenkov **threshold**
- ❖ Angular acceptance
- ❖ PID
- ❖ Neutrals
- ❖ Noise



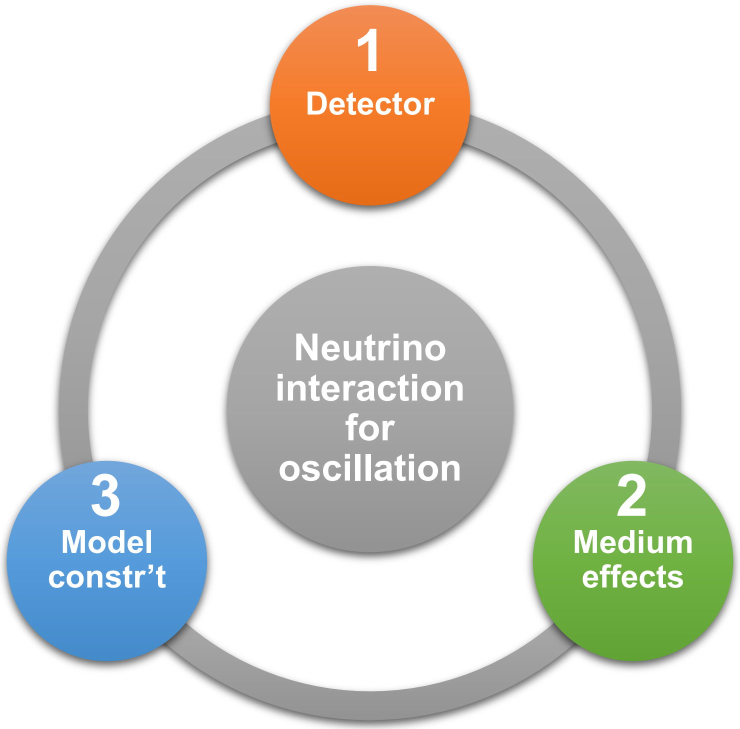
Proton Range vs Kinetic Energy

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

Sensor granularity
~ mm-cm



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



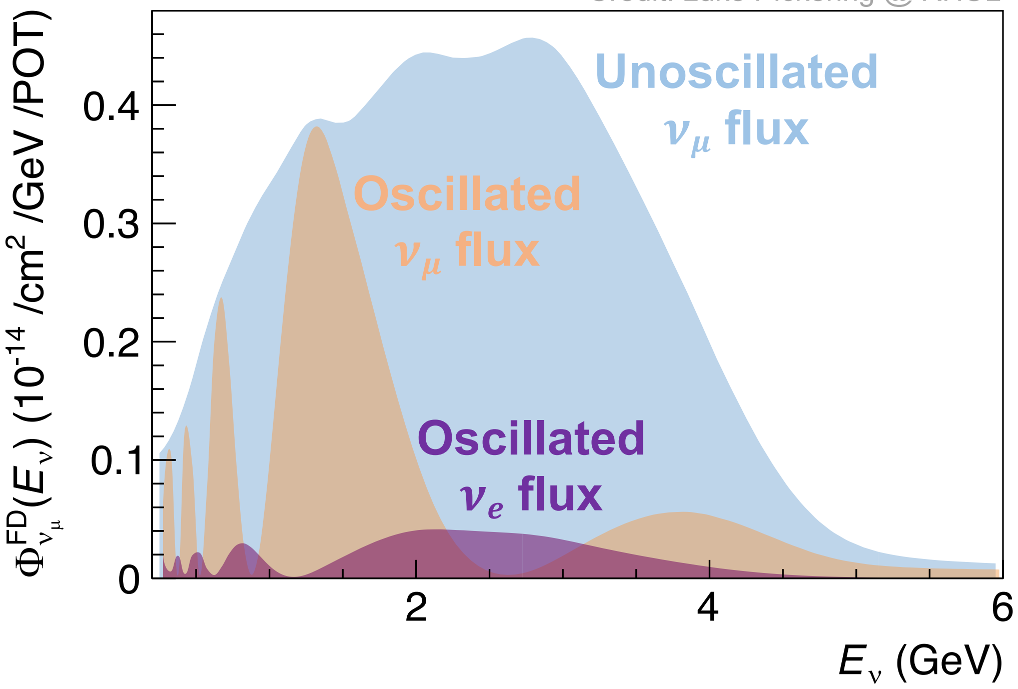
Counting oscillated ν

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

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

No two unknowns at the same time

Credit: Luke Pickering @ RHUL



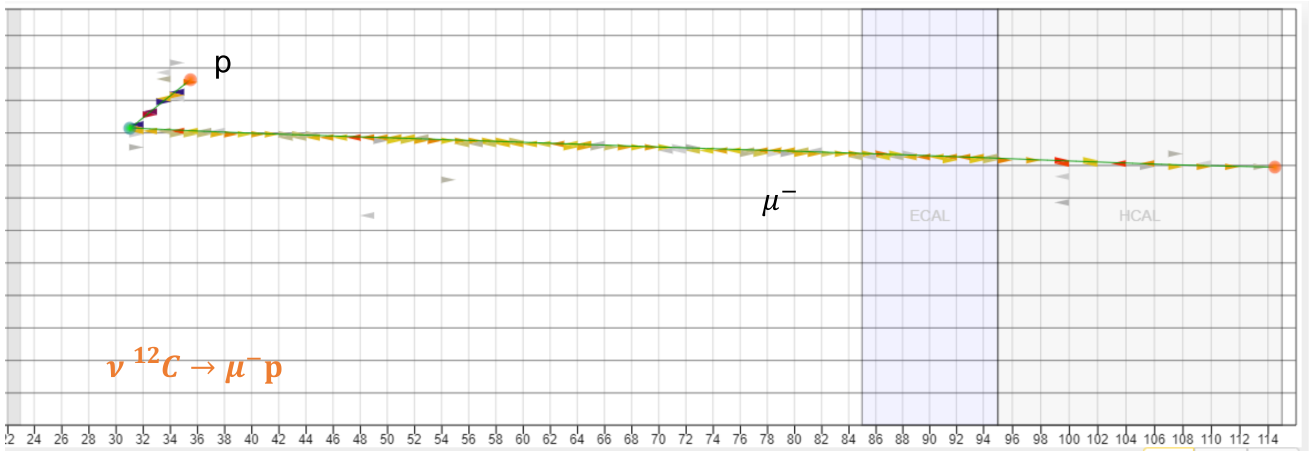
- **Near detectors** for accelerator-ν experiments
- Non-accel: rely on **externally constrained** models
- **Unconstrained** flavour and/or target nuclei

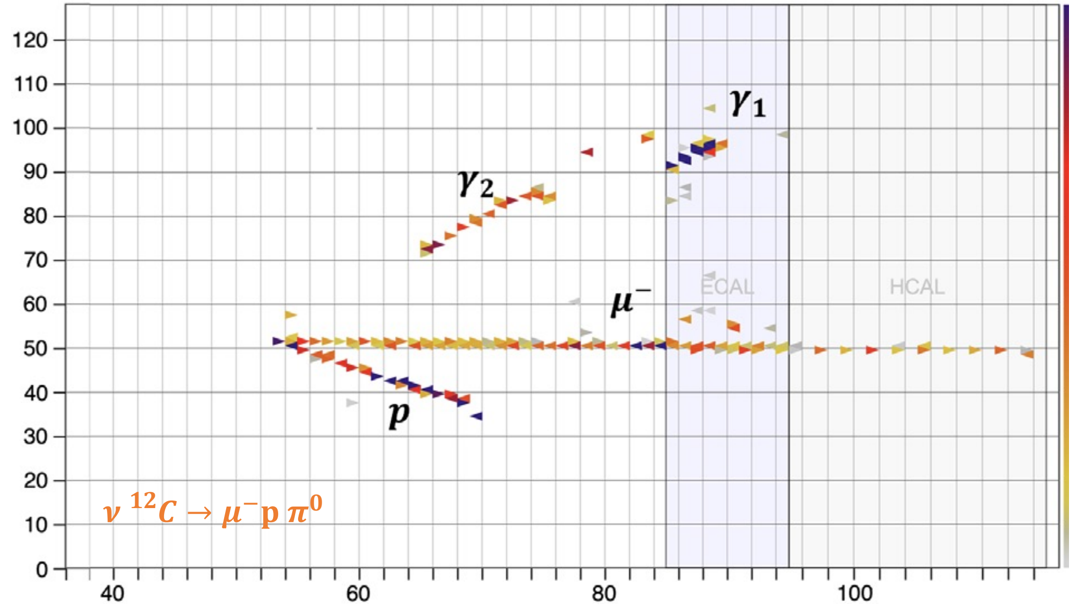
Plastic scintillator tracker

- ❑ 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

Plastic scintillator tracker

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

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

T2K Near Detector ND280

FGD (Fine-Grained Detector)

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

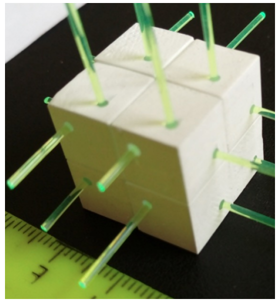
ν interaction in plastic scintillator bars—FGD

ND280 Upgrade

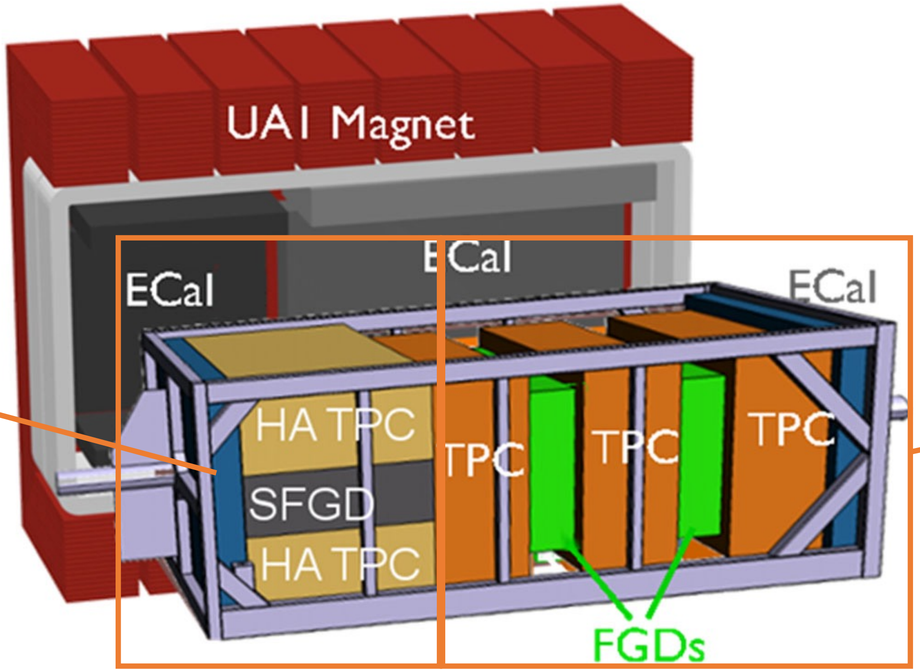
sFGD (SuperFGD)

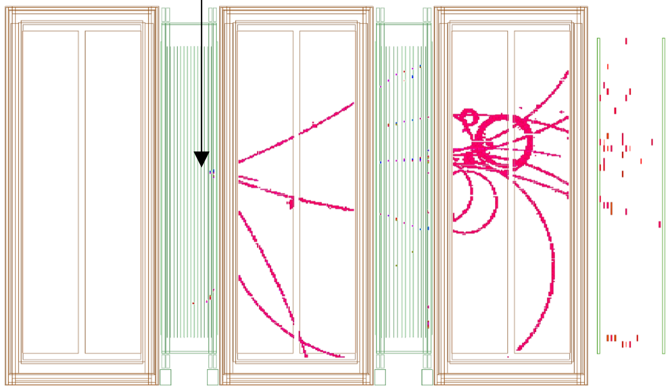
1-cm^3 ***cube***

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



T2K, arXiv:1901.03750





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

Detector

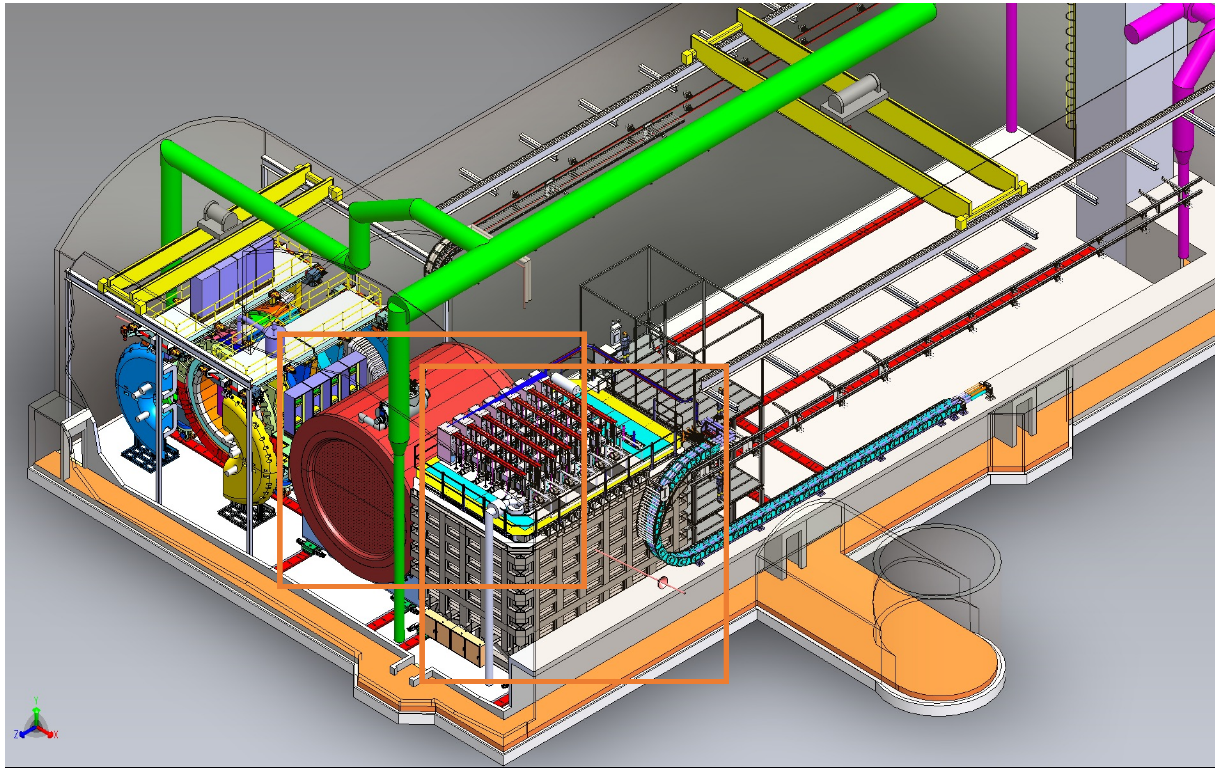
DUNE

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

For LArTPC technical details, cf. Angela Fava's *LAr TPC R&D* in S19 on Saturday

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

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



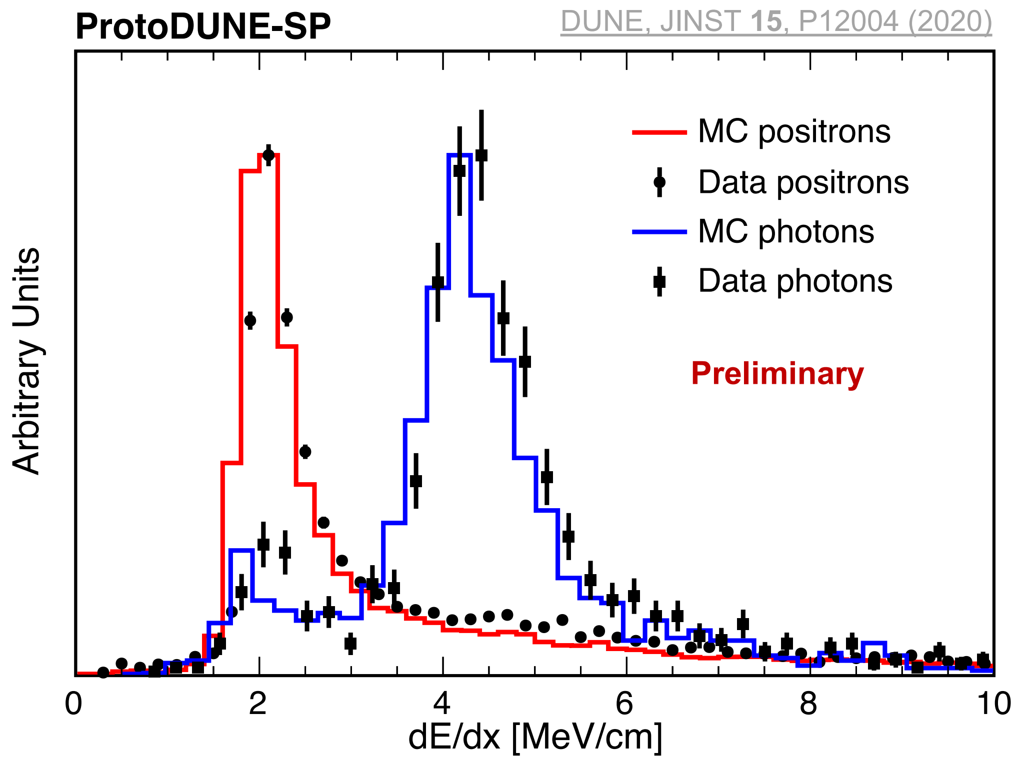
Exclusivity: to measure all final states (except nuclear remnant)

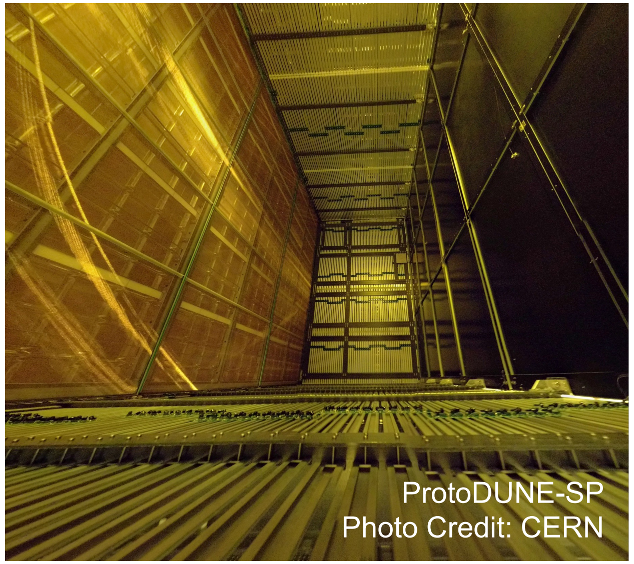
Detector

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

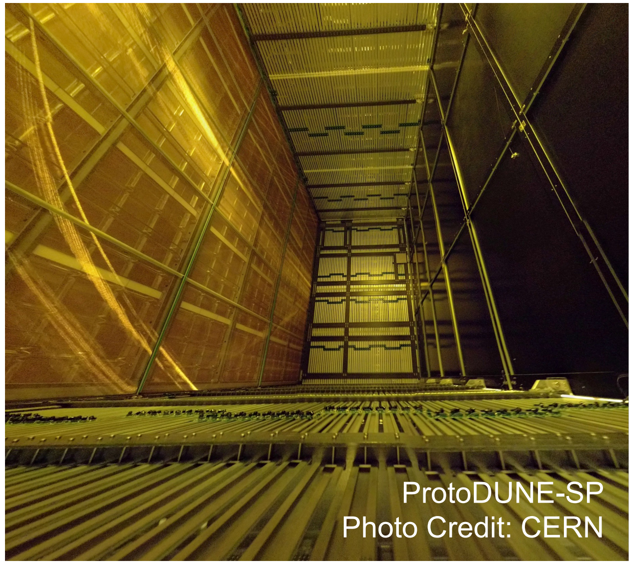
ProtoDUNE

Detector

LArTPC Demonstrator at CERN for DUNE FD

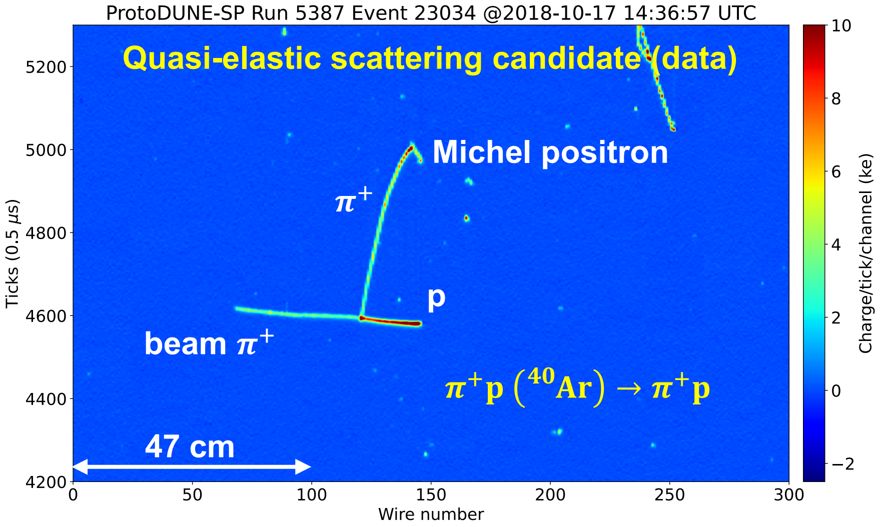
- Hadron beams of 0.3-7 GeV/c
  - 4.7 mm wire spacing (same as FD)
  - ✓ ***Versatile reconstruction in LAr***
  - ✓ ***hAr interactions to constrain ν-int. FSI***
  - ✓ ***Exclusivity + beam energy, can "see" inside argon nuclei***

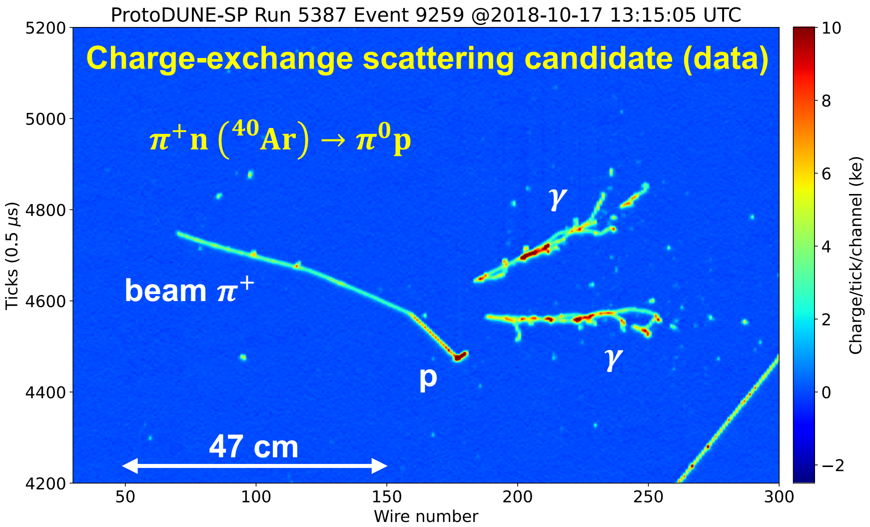
Exclusivity: to measure all final states (except nuclear remnant)

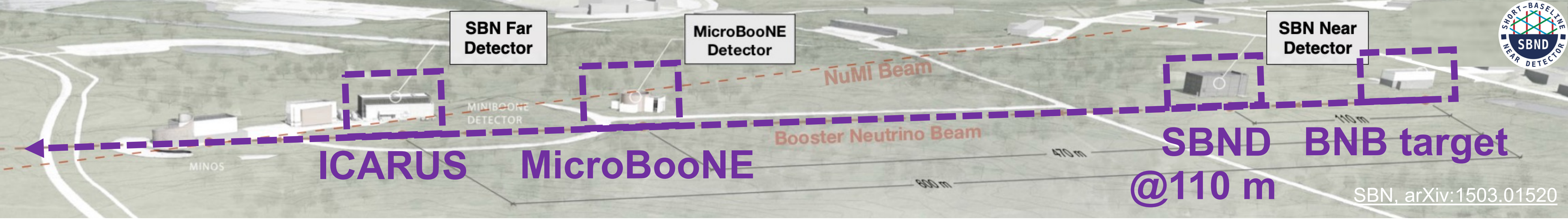


Exclusive event candidates

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







Detector

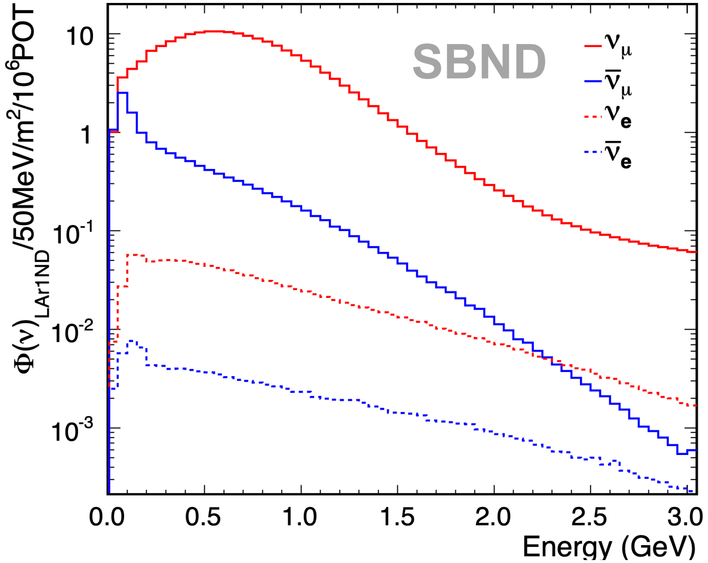
SBND

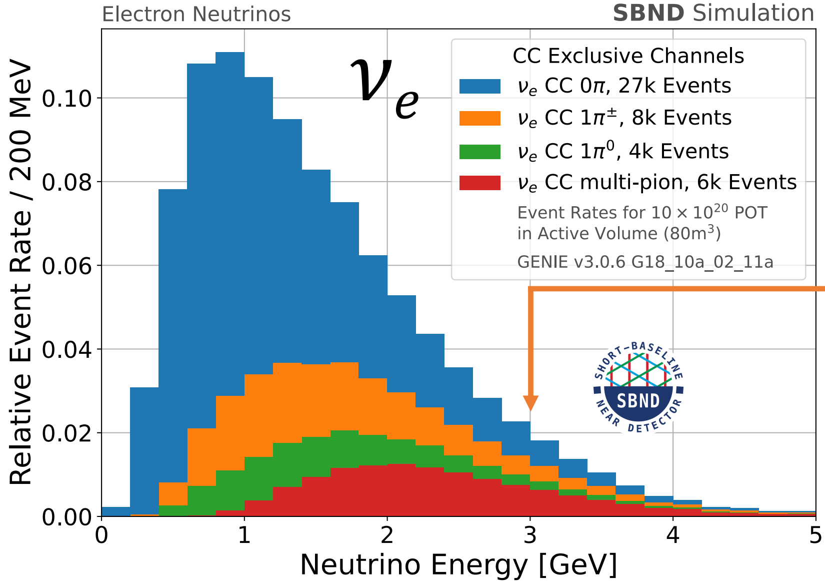
20~30 × current world νAr data

❖ ***Large statistics for ν_μ and ν_e***

SBND Poster 7F. Majorana, MT05-383

SBN, arXiv:1503.01520





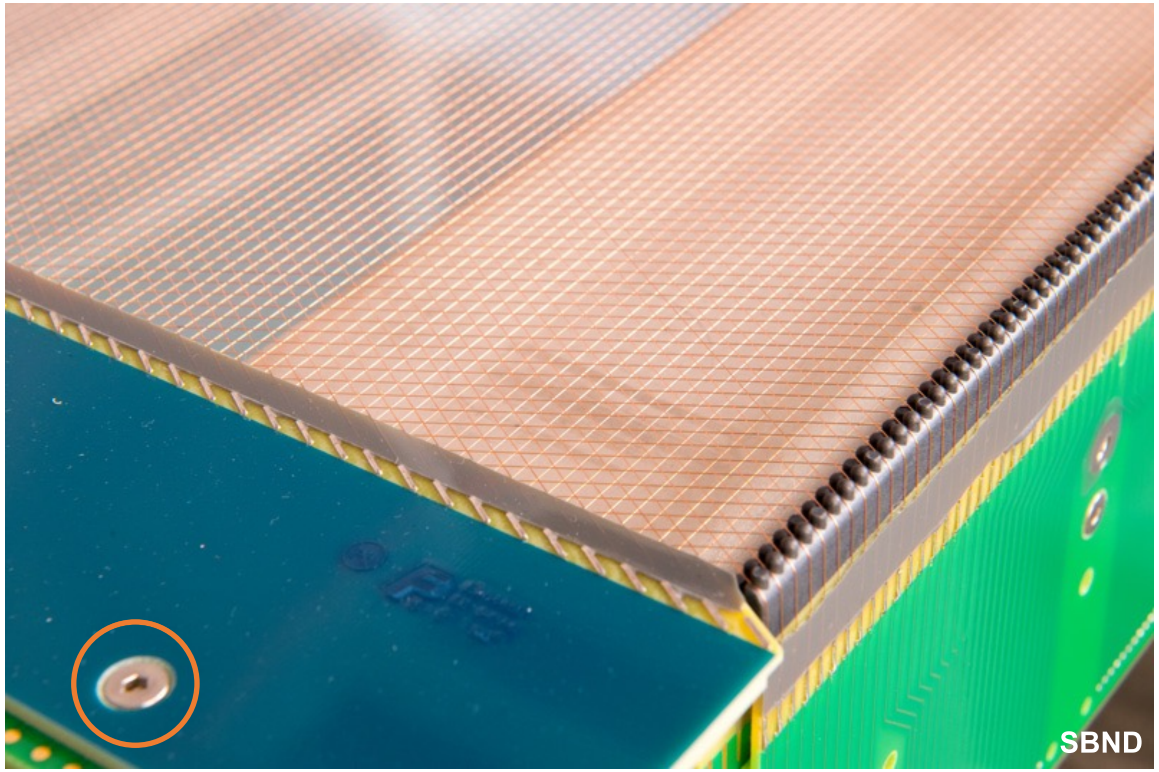
Tail up to 3 GeV

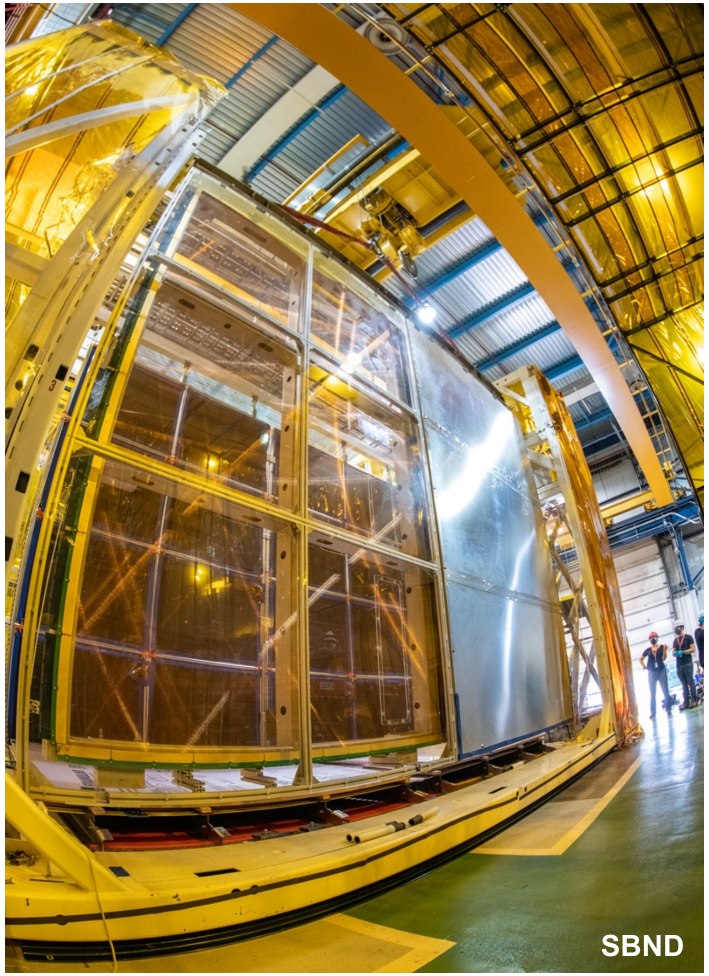
Detector

SBND

20~30 × current world νAr data

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





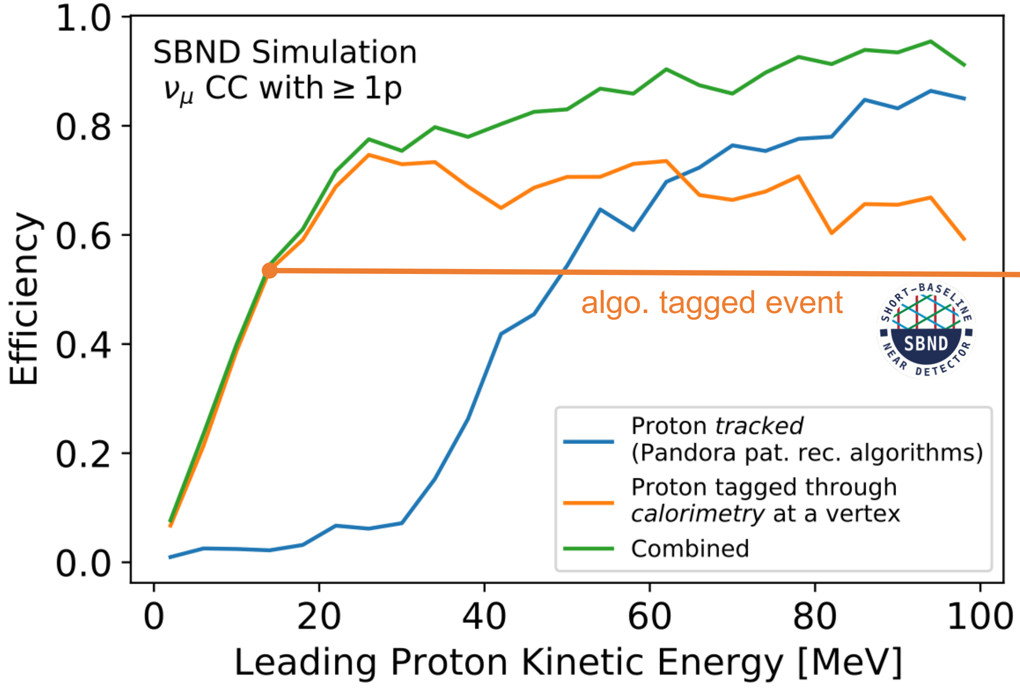
Detector

SBND

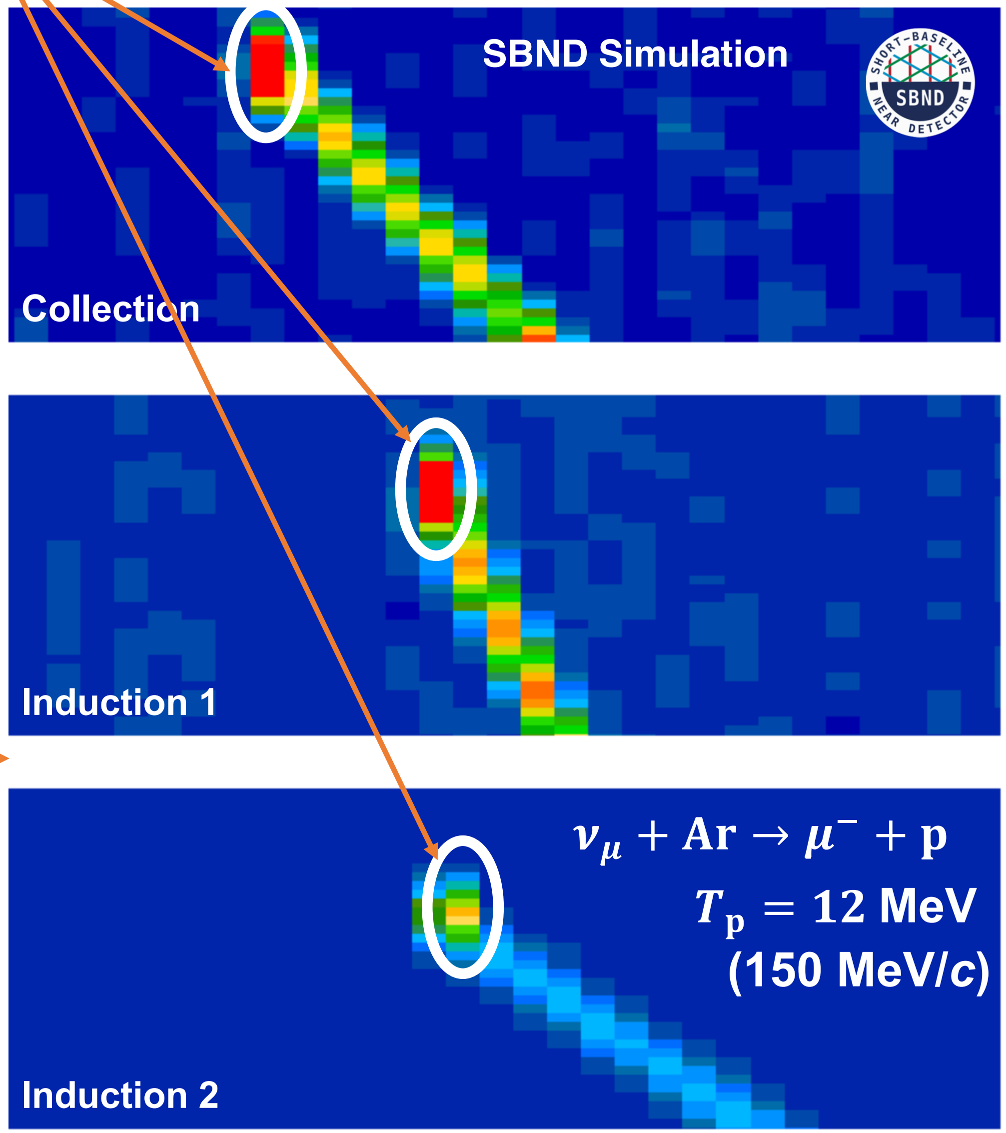
20~30 × current world νAr data

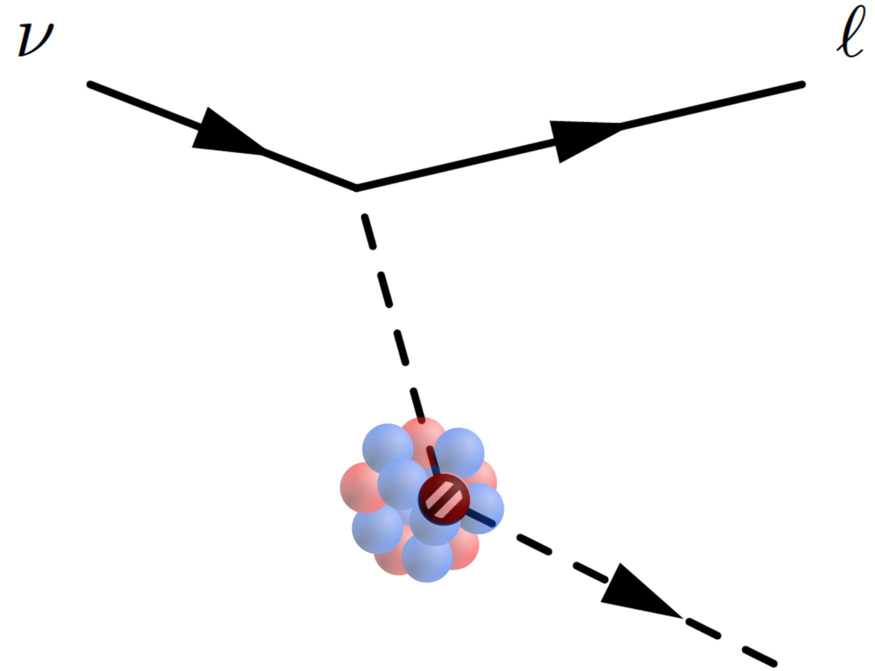
- ❖ 3 mm wire spacing (same as MicroBooNE and ICARUS)
- ✓ ***Proton tracking threshold ~ 40 MeV (277 MeV/c)***
- ✓ ***Proton tagging at vertex***

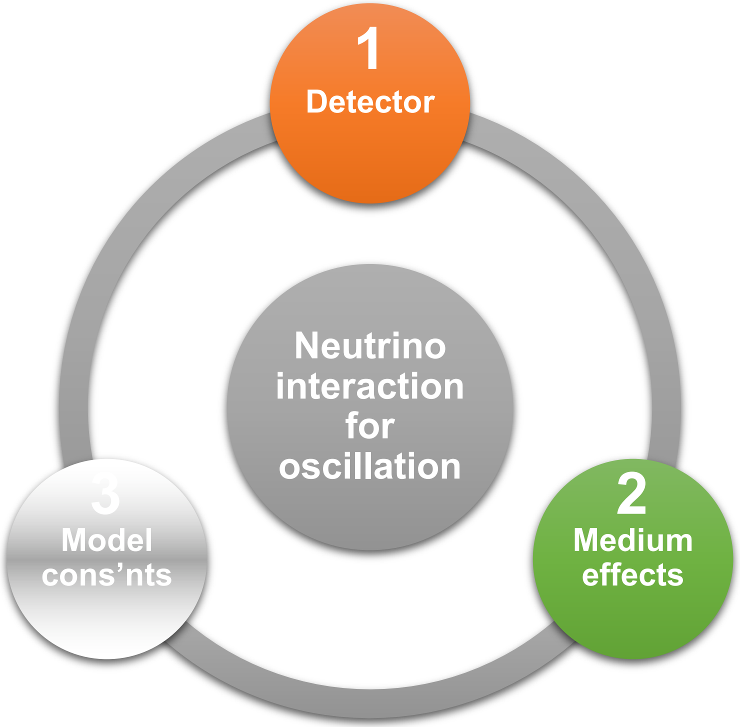
***Exclusivity**: to measure all final states (except nuclear remnant)*



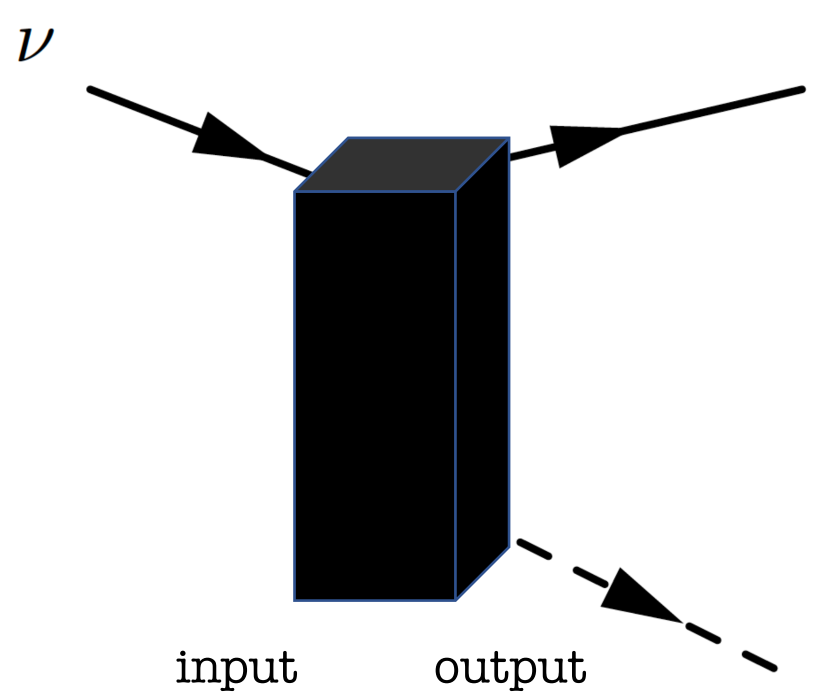
Tagged proton

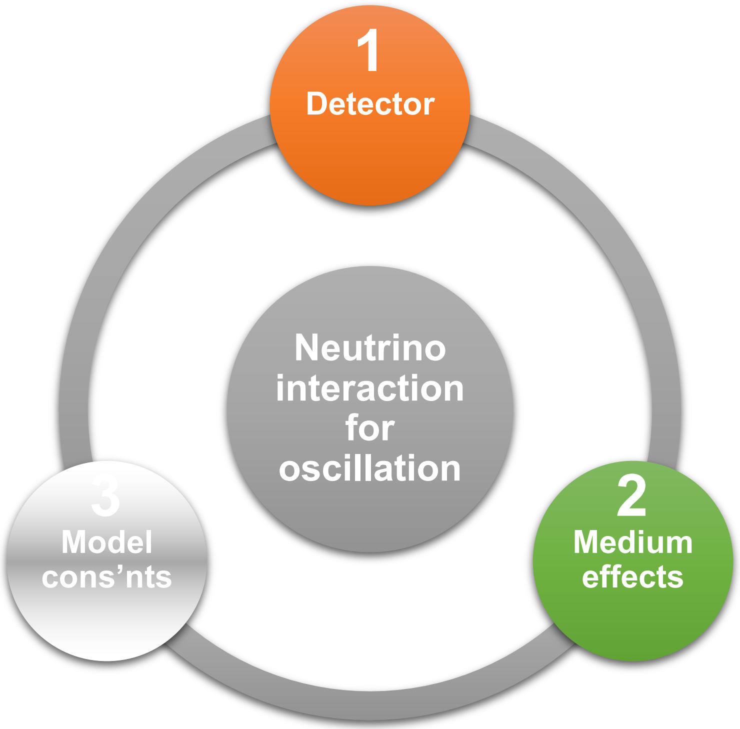






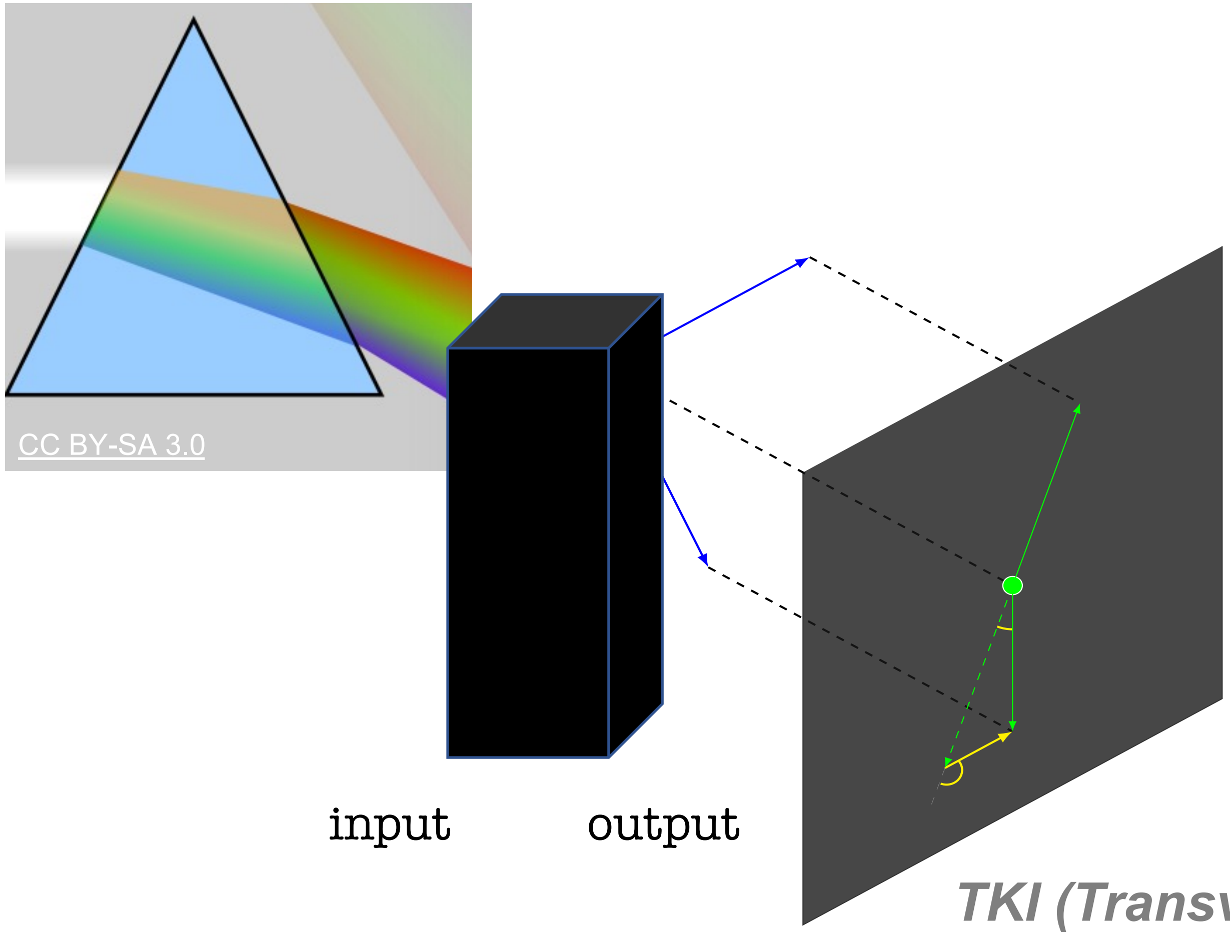
Detector limit can be pushed, but inside of a nucleus is never allowed…



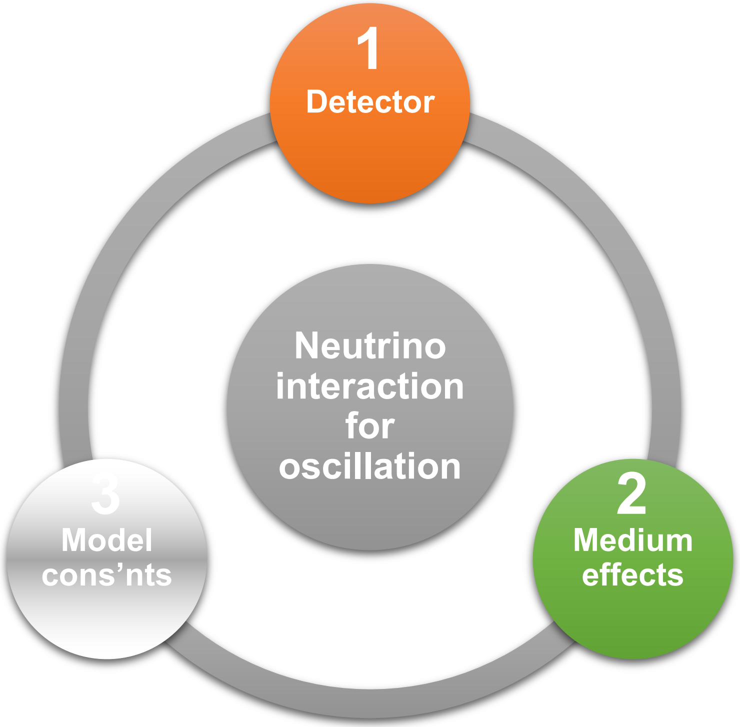


Detector limit can be pushed, but inside of a nucleus is never allowed…

PRISM (Precision Reaction Independent Spectrum Measurement)



TKI (Transverse Kinematic Imbalance)



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

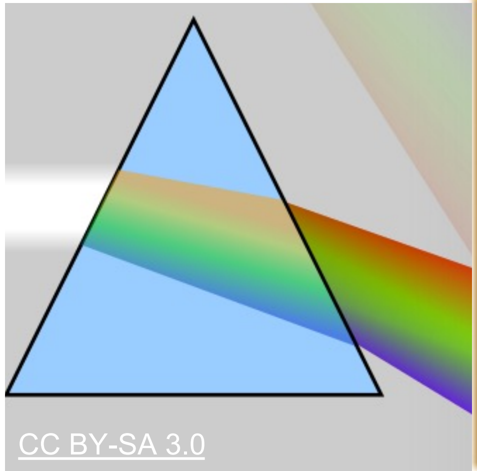
Medium effects

Hyper-Kamiokande

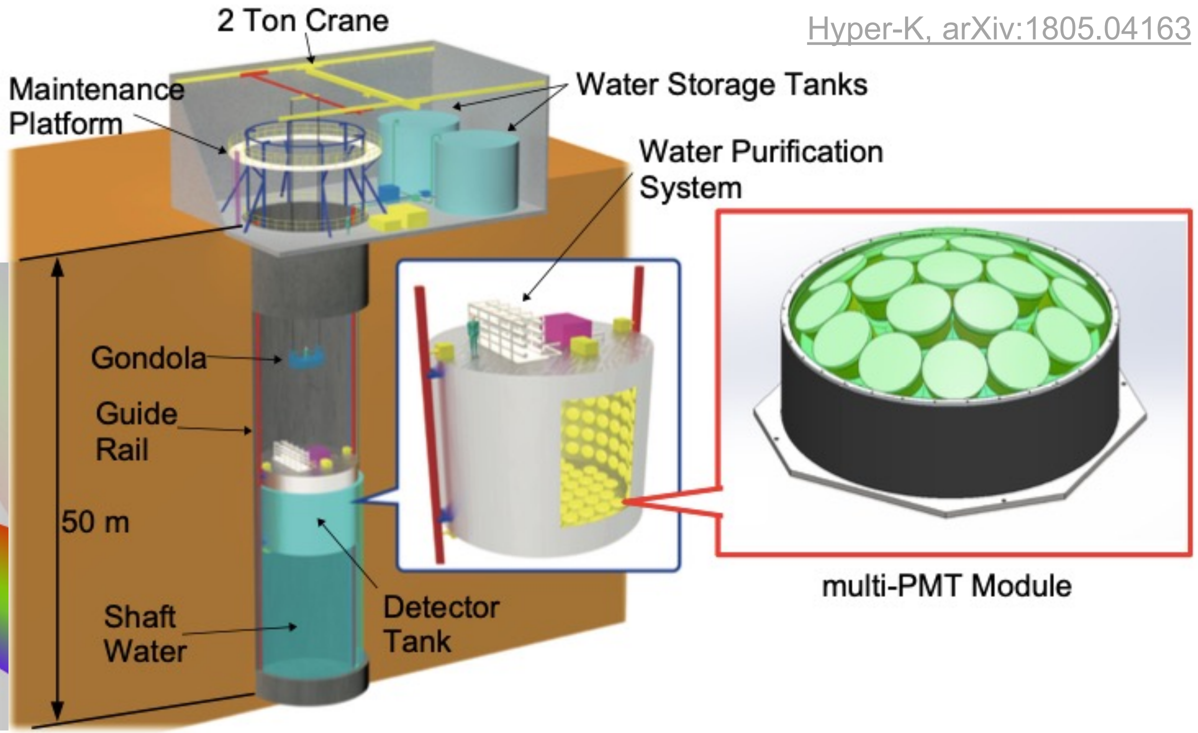
Hyper-Kamiokande

Hyper-K Poster 7F. Majorana, MT05-404

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



Hyper-K, arXiv:1805.04163



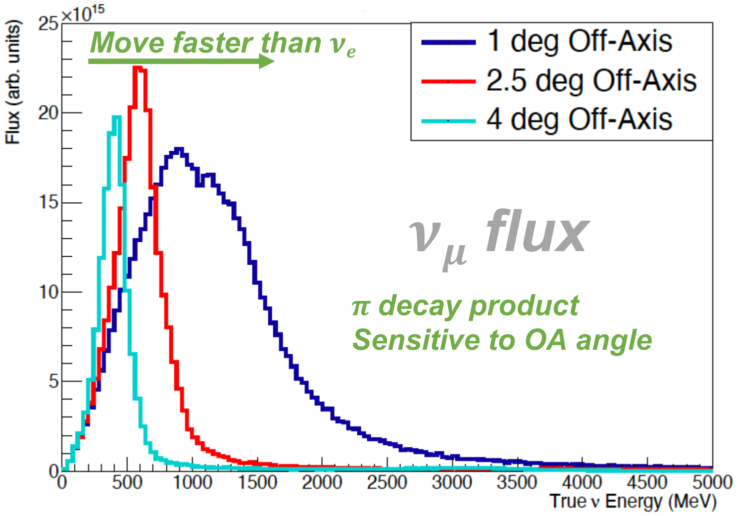
Medium effects

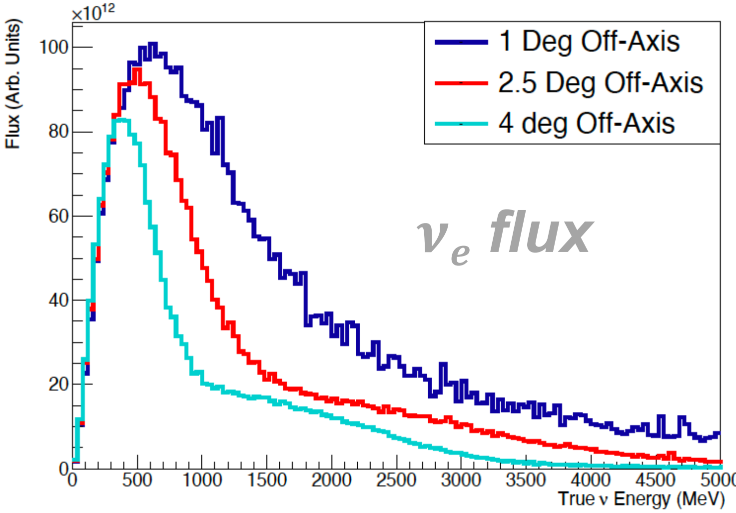
Hyper-Kamiokande

Hyper-K Poster 7F. Majorana, MT05-404

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

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





Medium effects

DUNE-PRISM

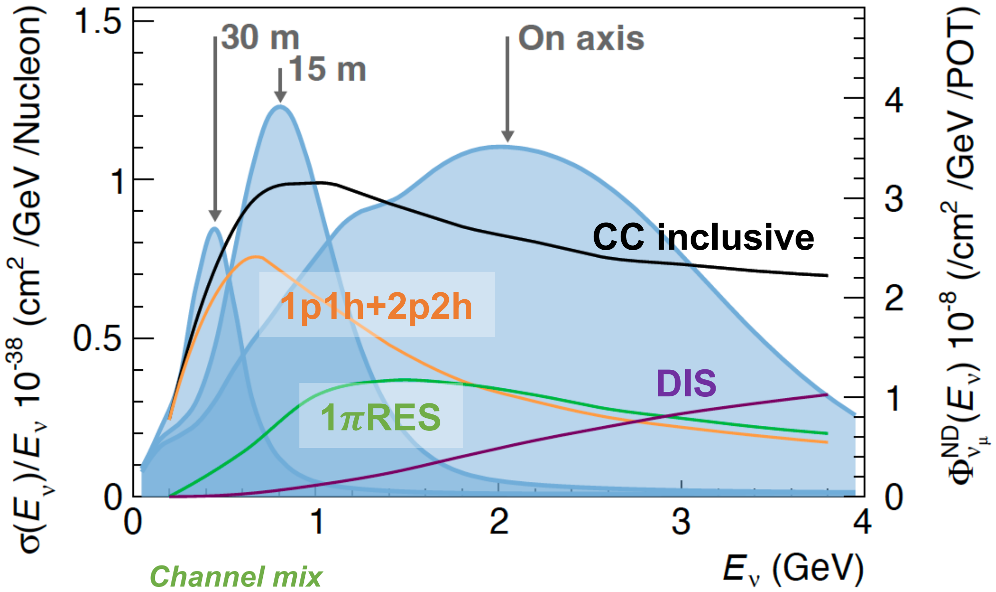
ND-LAr & ND-GAr

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

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

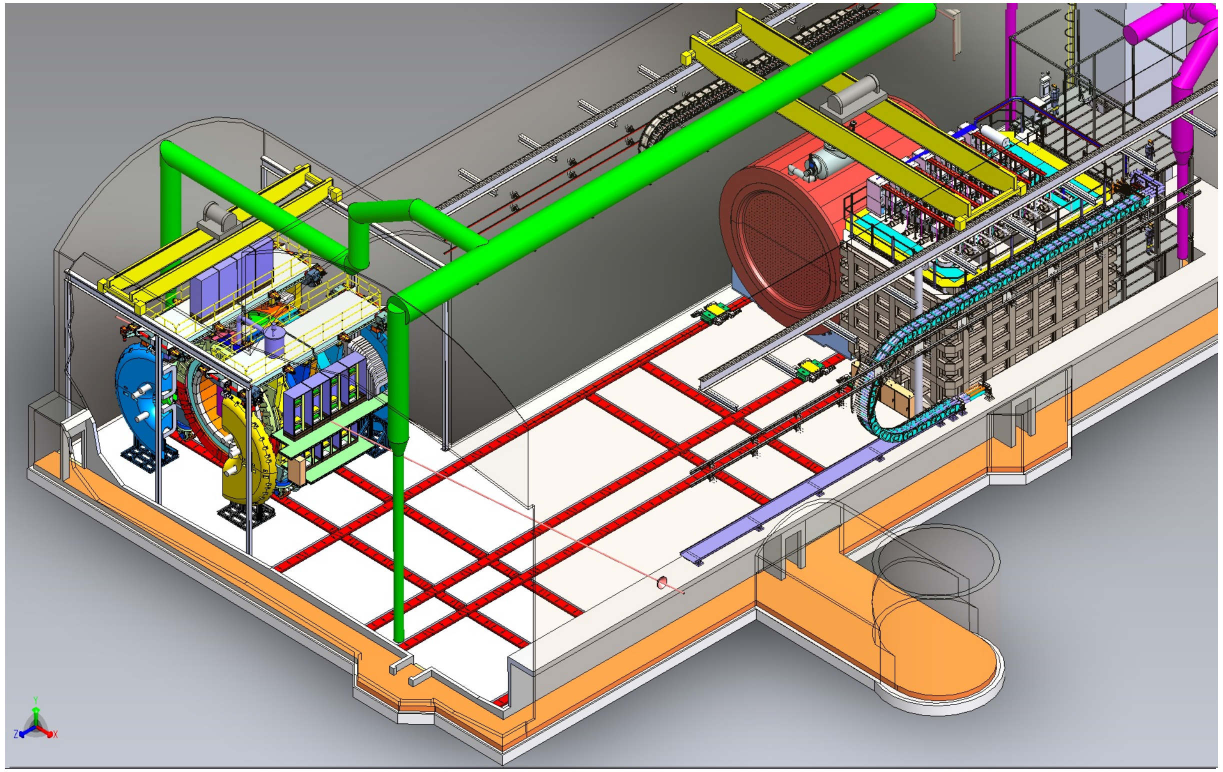
➢ SBND-PRISM see Anne Schukraft's *ICARUS* + *SBND* in S2 on Tuesday

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



Channel mix evolves with OA location

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



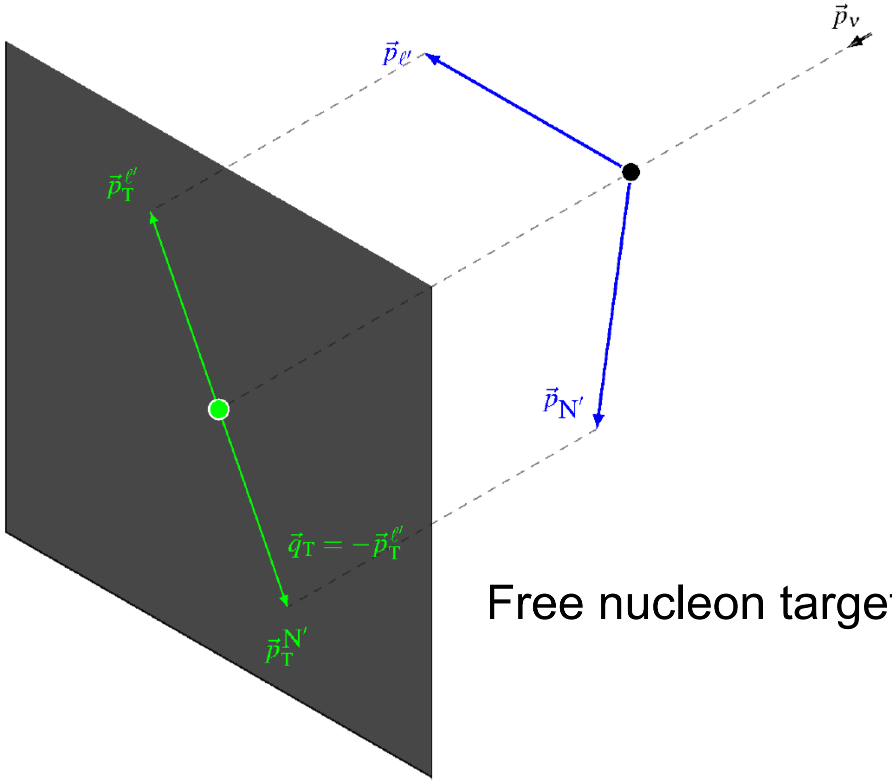
Medium effects

TKI (Transverse Kinematic Imbalance)

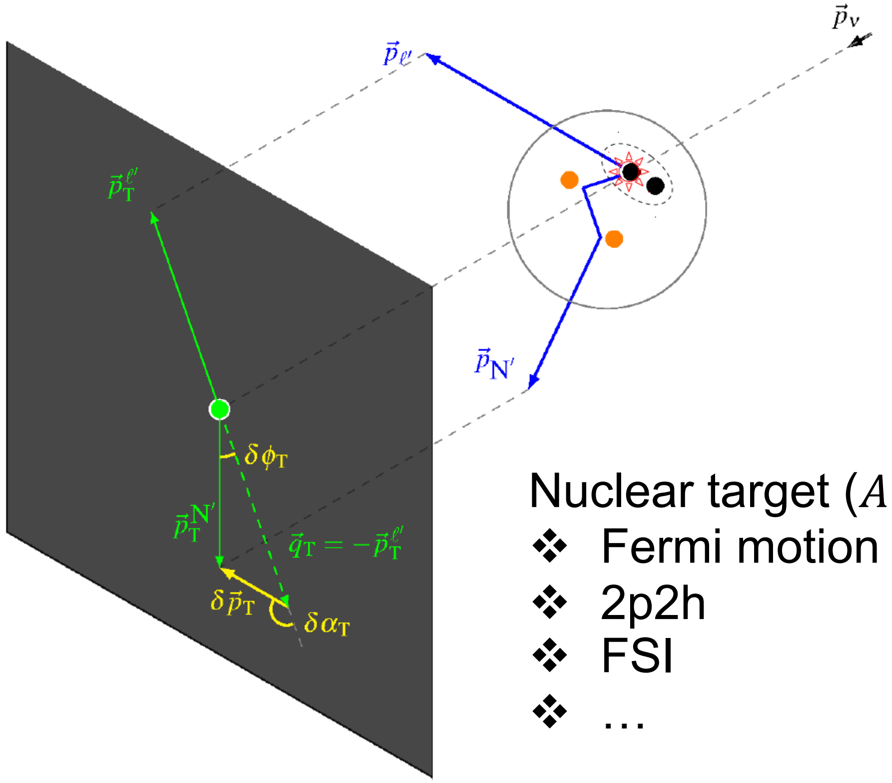
- ❑ TK orthogonal to ***unknown*** E_ν
- ❑ Embed in imbalance created by
  - ❖ Nucleus "contacting" medium ✓ ***Signature imbalance probing inside nuclei***
  - ❖ Detector loss & secondary interactions ✗ ***Mock nuclear effects***

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

- ➢ Previous mention:
  O. Hen, S11 Thursday
  N. Jachowicz, L. Fields, S17 preceding
- ➢ Upcoming:
  S. Gardiner, S18 Saturday



Free nucleon target



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

Medium effects

TKI

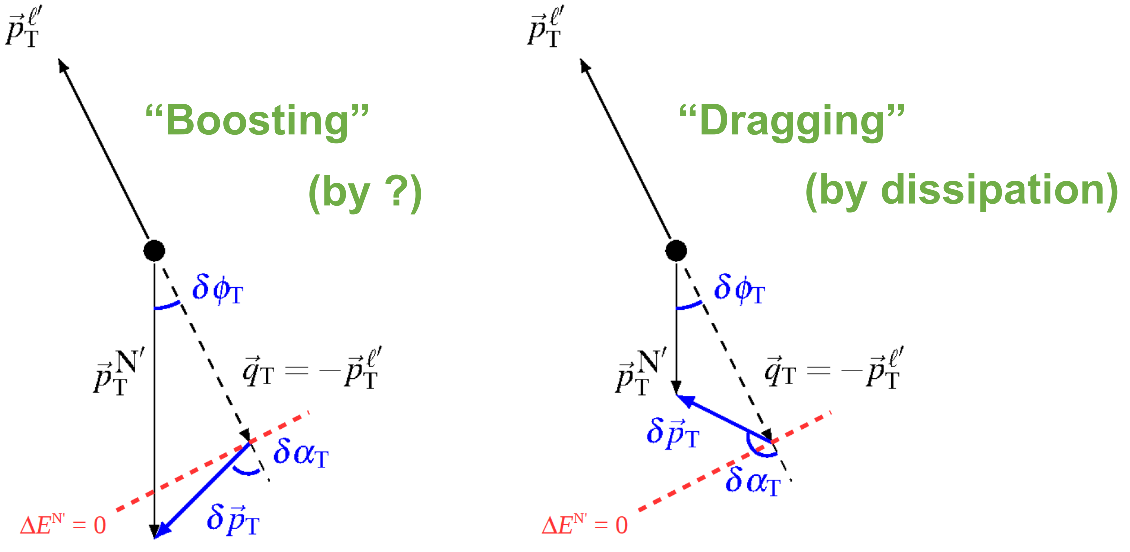
Transverse boosting angle

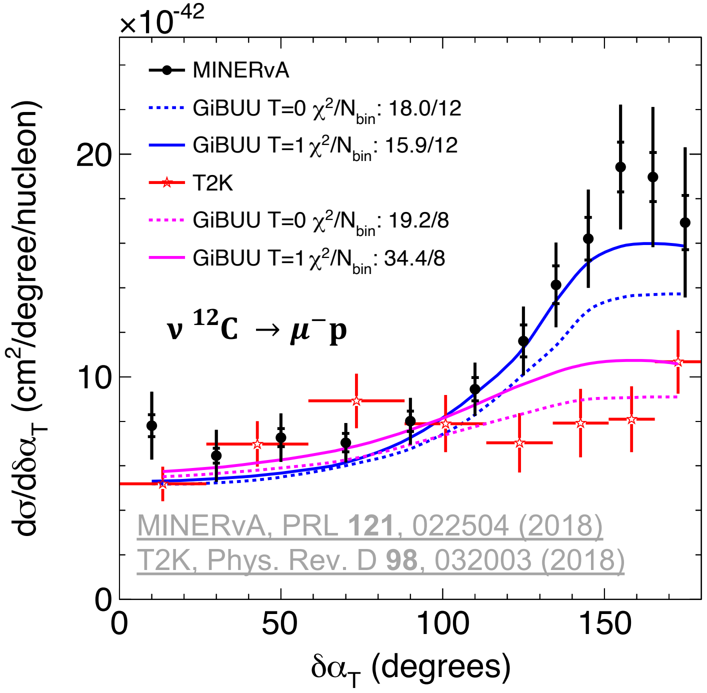
XL *et al.* Phys. Rev. C **94**, 015503 (2016)

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

❖ 2p2h, RES (π production + absorption)

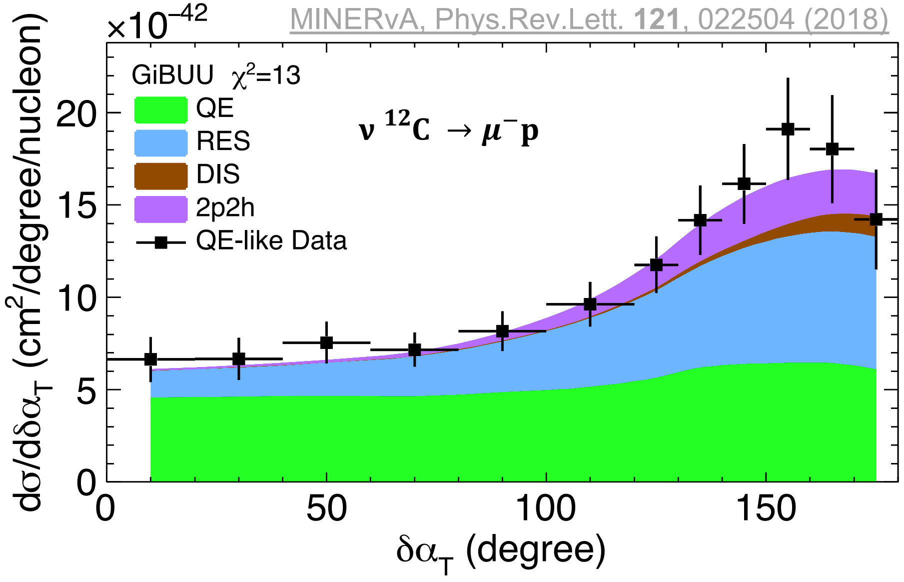
✓ ***Energy dependence*** *(T2K, MINERvA E_ν ~ 0.6, 3 GeV)*





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

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



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

TKI

Medium effects

Transverse boosting angle

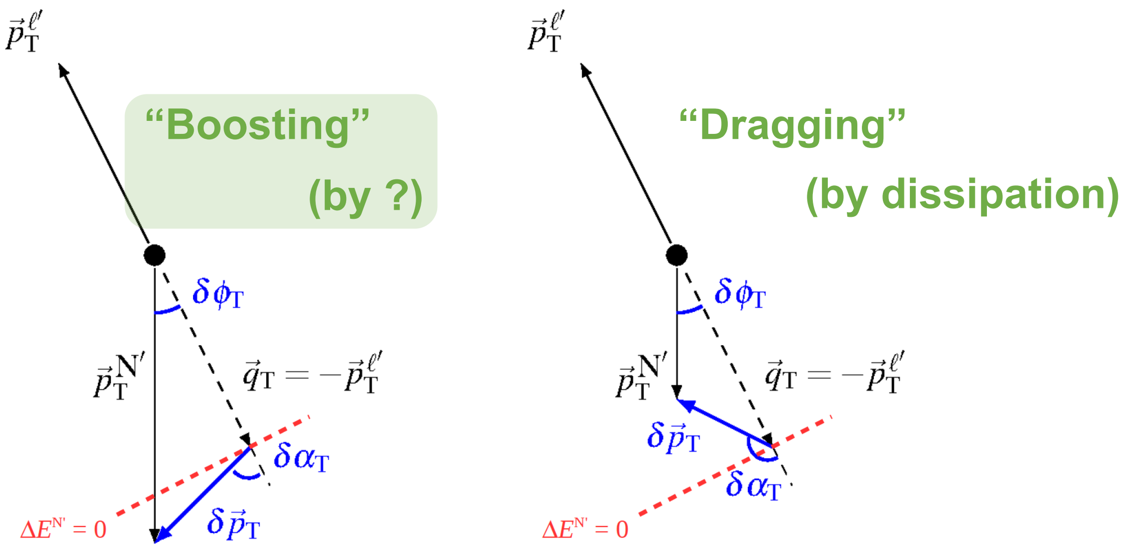
XL *et al.* Phys. Rev. C **94**, 015503 (2016)

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

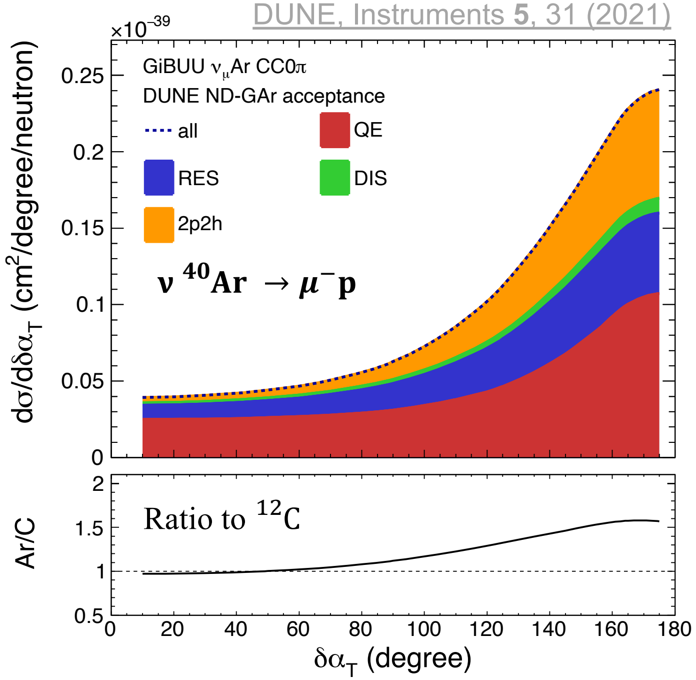
- 2p2h, RES (π production + absorption)
  - ✓ ***Energy dependence*** ***(T2K, MINERvA E_ν ~ 0.6, 3 GeV)***
  - ✓ ***Target dependence***

\+ Further transverse decomposition

  - ✓ ***Removal energy*** cf. MINERvA, PRD **101**, 092001 (2020)



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

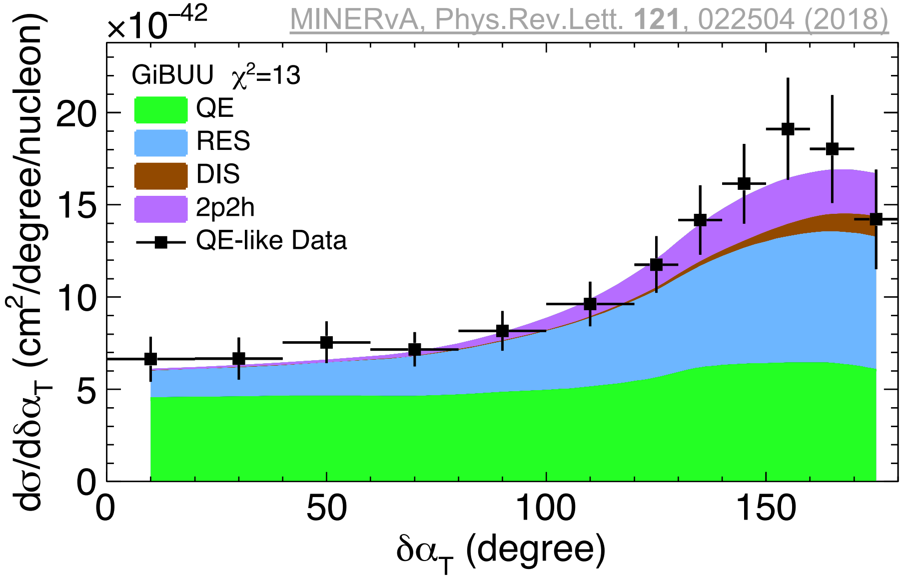


Predicted target scaling: Powerful benchmark to relate different nuclei w/ minimum model dependence?
Need experimental validation first!

- ***QE***
- ***RES (soft pion)***

No boosting, just Fermi motion

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



Medium effects

TKI

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

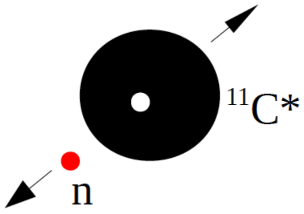
Emulated nucleon momentum

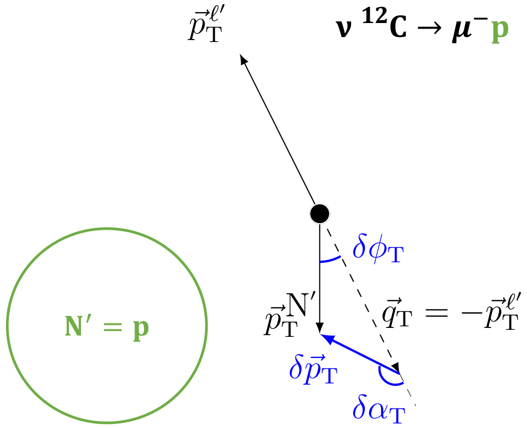
+ Assumed ***exclusivity*** w/ remnant

✓ ***Fermi motion "=" Remnant recoil***

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

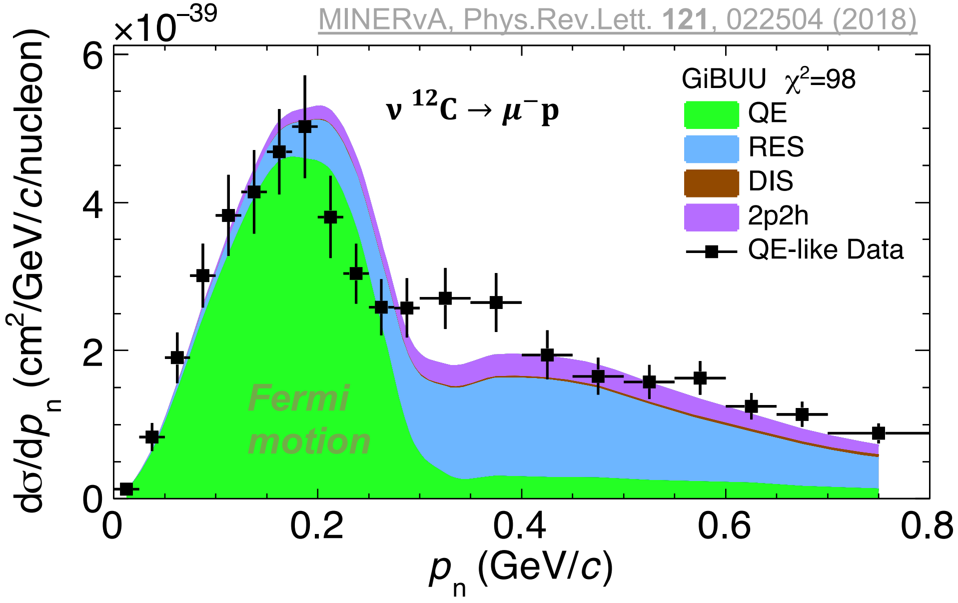
$$p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$$





Furmanski and Sobczyk, Phys. Rev. C **95**, 065501 (2017)
XL and Sobczyk, Phys.Rev.C **99**, 055504 (2019)

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



Medium effects

TKI

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

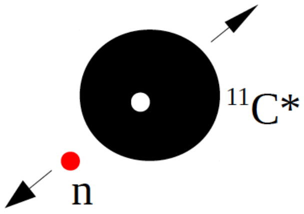
Emulated nucleon momentum

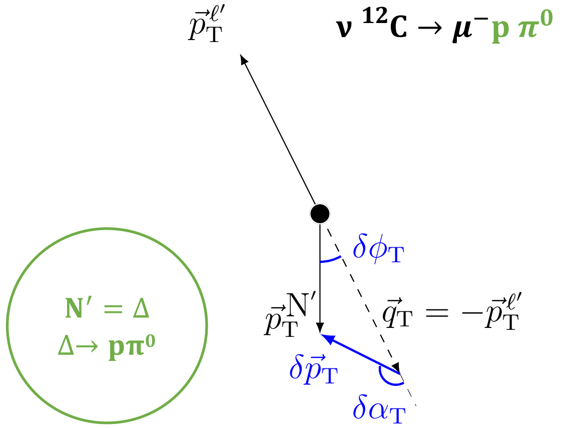
+ Assumed ***exclusivity*** w/ remnant

  ✓ ***Fermi motion "=" Remnant recoil***

Assuming target remnant ^{11}C*

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

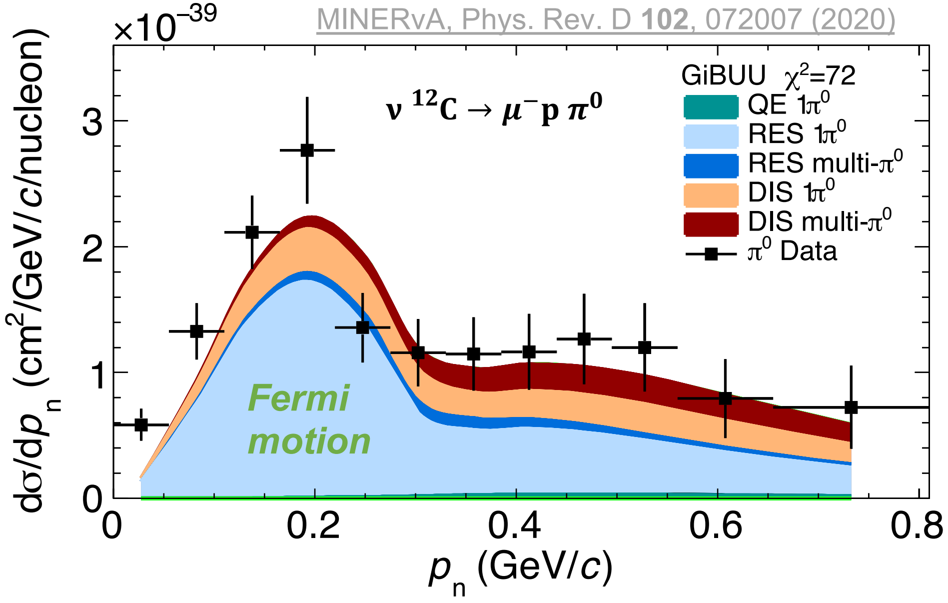




Furmanski and Sobczyk, Phys. Rev. C **95**, 065501 (2017)
XL and Sobczyk, Phys.Rev.C **99**, 055504 (2019)

+ Combining all hadrons
  - ✓ ***Probe beyond QE***
  - ❖ $\nu\ n \to \mu^- p\ \pi^0$ →
  - ❖ $\nu\ p \to \mu^- p\ \pi^+$ cf. T2K, Phys. Rev. D **103**, 112009 (2021)

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

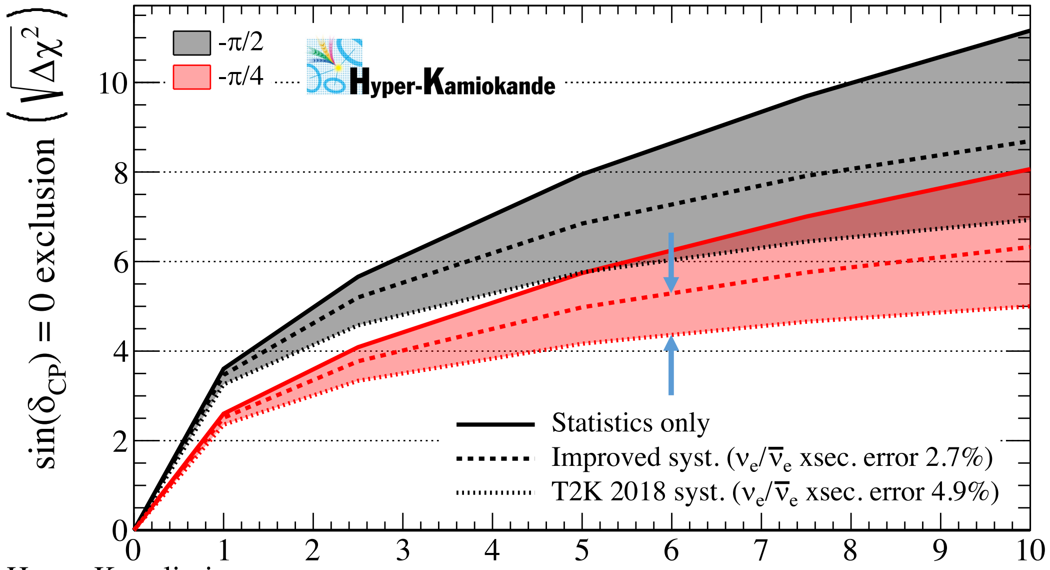


Model constr't

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

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

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



Hyper-K preliminary
True normal ordering (known)
$\sin^2(\theta_{13}) = 0.0218$ $\sin^2(\theta_{23}) = 0.528$ $|\Delta m^2_{32}| = 2.509\text{E-}3$

Lepton mass correction · *Hadronic/nuclear response*

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

Lepton observables

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

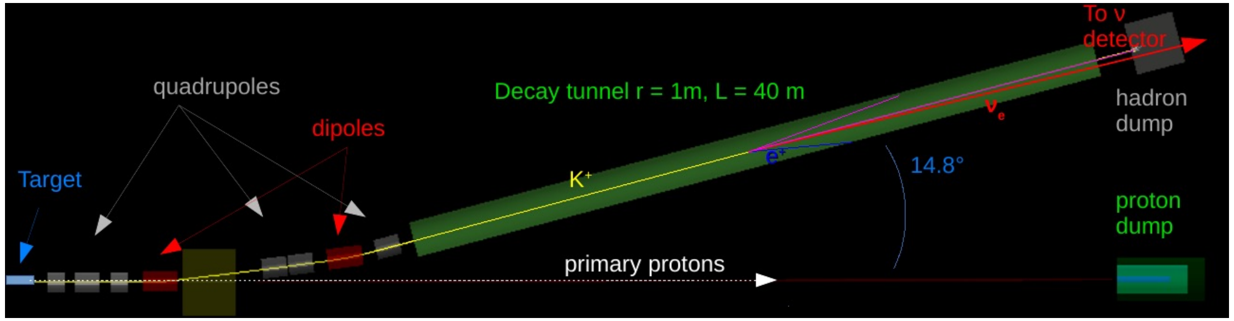
Model constr't

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

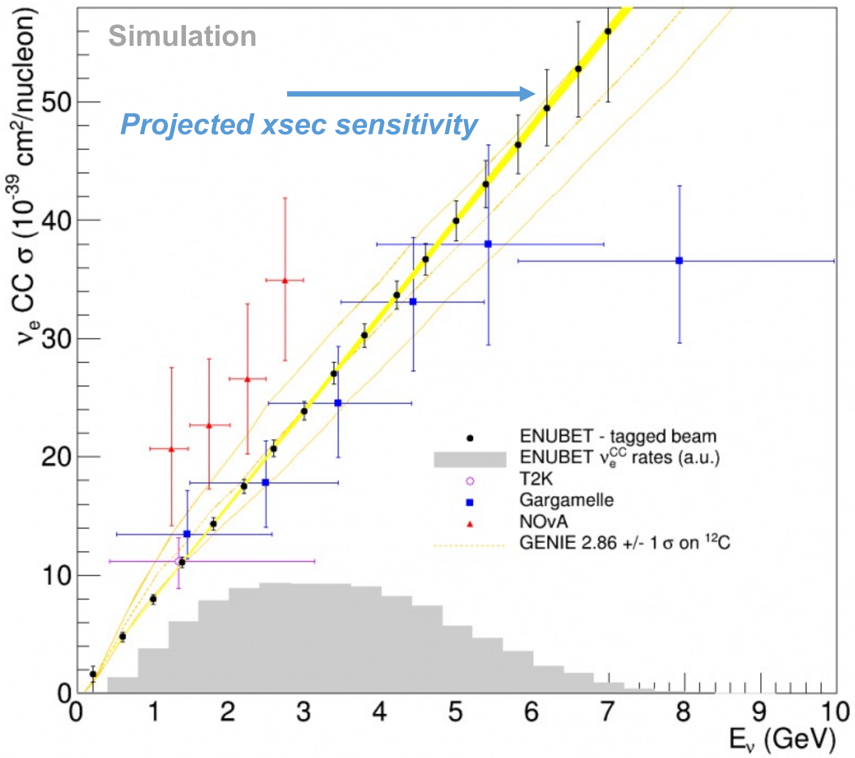
- ❑ δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- ❑ Need $\nu_e/\bar{\nu}_e$ interaction data
- ❑ ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood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

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

ENUBET, arXiv:2203.08319



ENUBET, arXiv:2203.08319



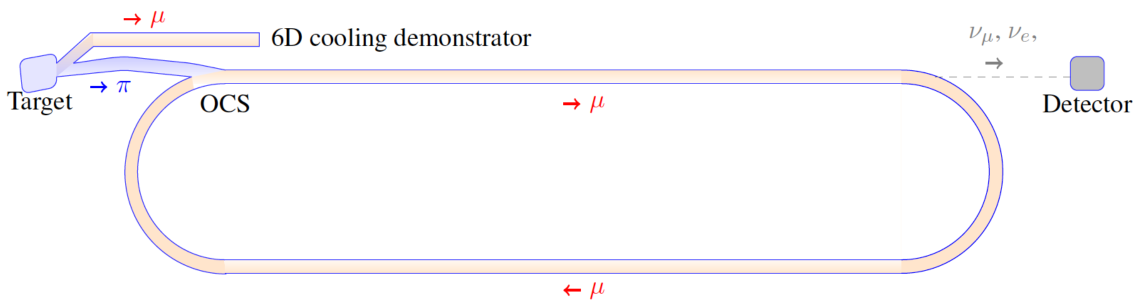
Model constr't

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

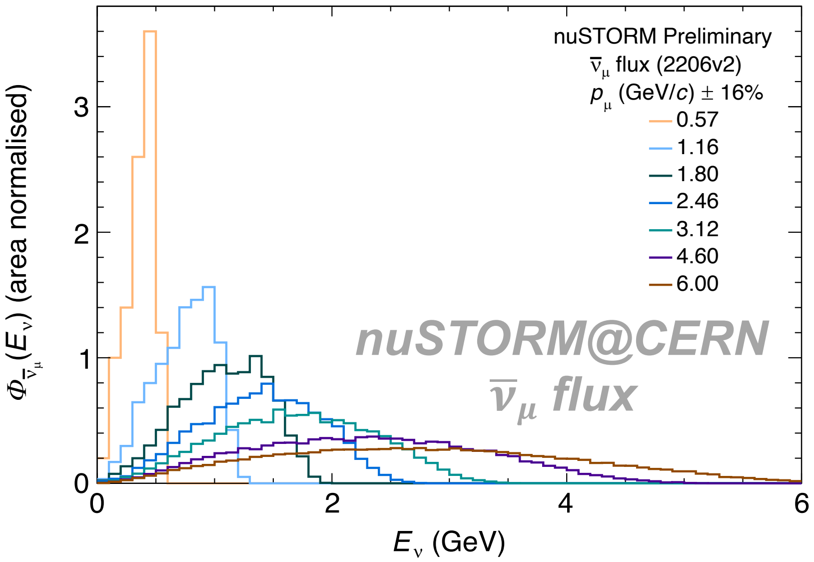
- ❑ δ_{CP} requires ν_e and $\bar{\nu}_e$ appearance
  - ✓ Suppress ν_e and $\bar{\nu}_e$ bkg in beams
- ❑ Need $\nu_e/\bar{\nu}_e$ interaction data
- ❑ ν_μ-A + lepton universality constrains ν_e-A to 1st order precision
- ❑ Oscillation requires 2nd order precision
  - ✓ ***Higher statistics and better-understood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

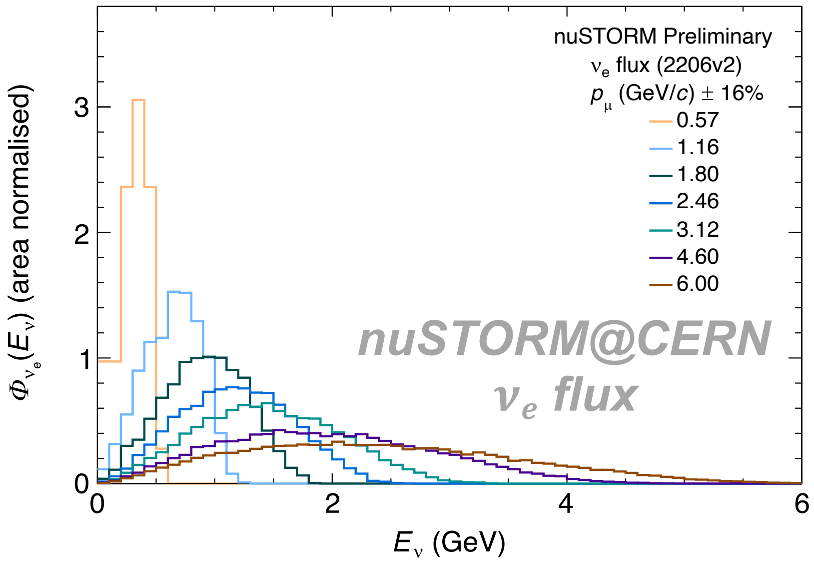
nuSTORM, arXiv:2203.07545

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



nuSTORM, arXiv:2203.07545





Oscillation-relevant energy regime

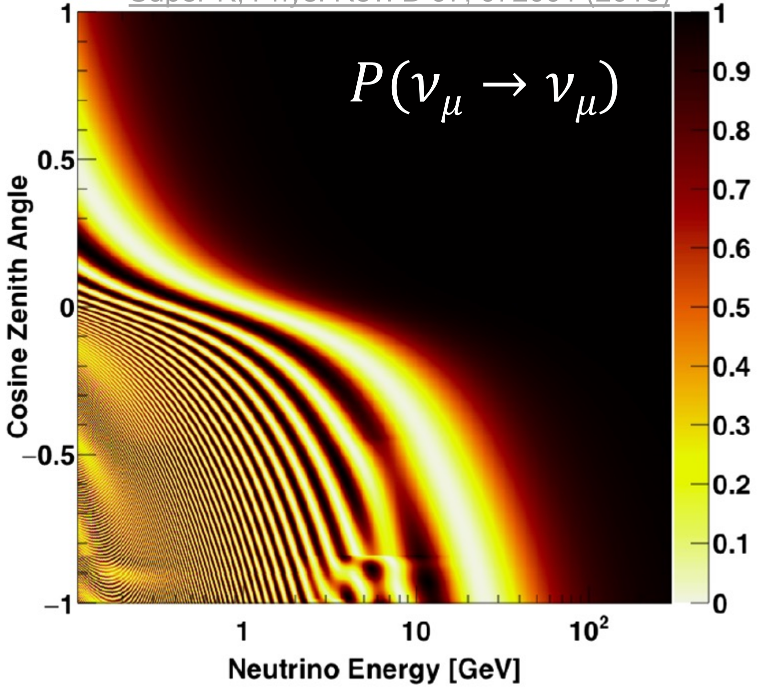
Model constr't

NMO with atmospheric ν

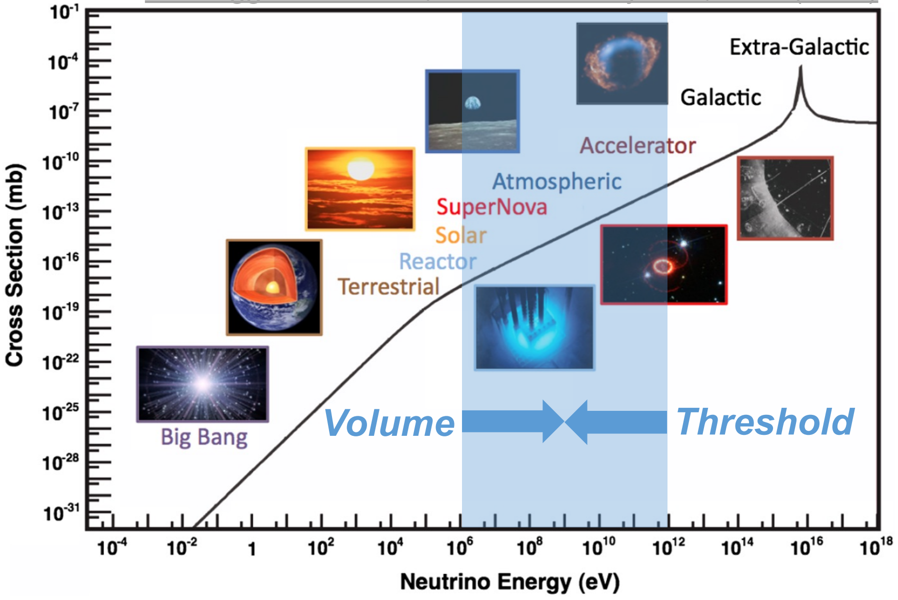
- ❑ ν energy & angle for L/E-variation

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

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



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



MeV TeV

GeV-ν interaction more critical and challenging

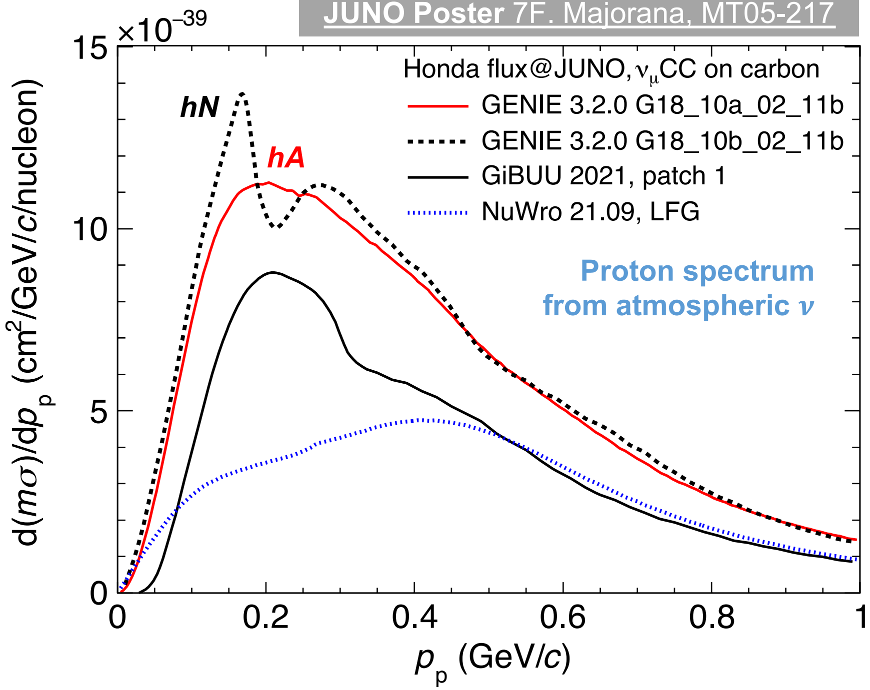
Model constr't

NMO with atmospheric ν

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

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

JUNO Poster 7F. Majorana, MT05-217



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

Summary

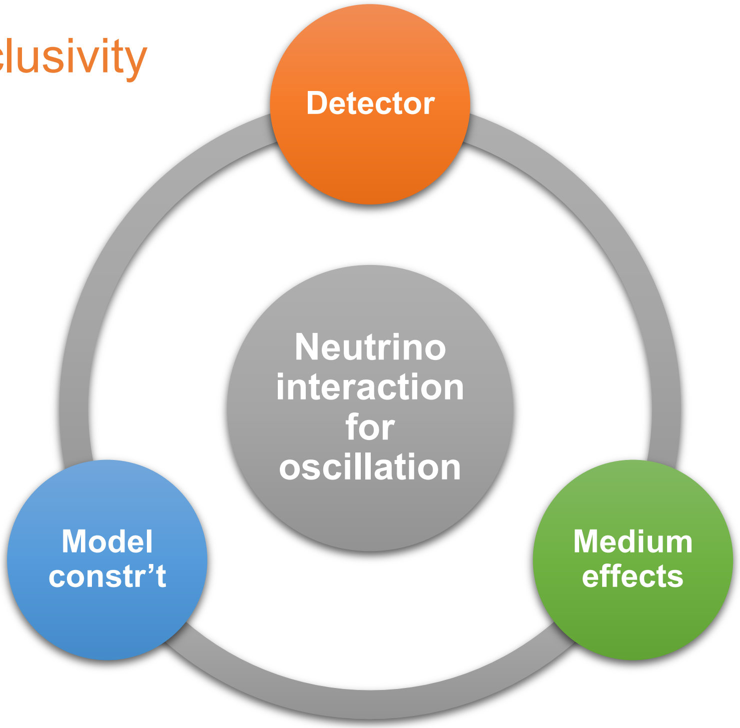
Future oscillation experiments require *surgical precision* inside a *black box*

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

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

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

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



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

Awaiting the future

Detector

Technology: neutrons

✓ ***ν energy budget and event classification—missing piece for exclusivity***
- Tagging and calorimetry exist
- 4-momentum determination on the verge (e.g. time of flight)

Medium effects

Analysis methods: ν-hydrogen interaction

✓ ***Complete removal of medium effects***
- Established: statistical subtraction between targets
- Ideas: ***exclusivity*** + TKI event-by-event selection using mass-scalable H-based compounds

Model constr't

Ex situ interaction measurements: precise nuclear response

✓ ***Break flux $\times$ interaction ambiguity***
- Electron scattering + ***exclusivity*** for initial-and final-state effects (not vertex)

Acknowledgement

Special thanks to

L. Fields, S. Manly, W. A. Mann, F. Sánchez,

and the following collaborations for their discussions

DUNE (A. Bross, T. Miao, R. Petti, L. Pickering, J. Raaf, L. Whitehead, C. Wret, T. Yang),

ENUBET (A. Longhin),

Hyper-K (F. Sánchez, J. Wilson),

IceCube (T. Stuttard, T. Yuan),

JUNO (Q. Yan, J. Zhao),

KM3NeT/ORCA (A. Heijboer),

nuSTORM (L. Alvarez-Ruso, K. Long, M. Pfaff), and

SBND (O. Palamara, D. Schmitz, A. Schukraft).

BACKUP

Snowmass NF06: Neutrino Interactions Report

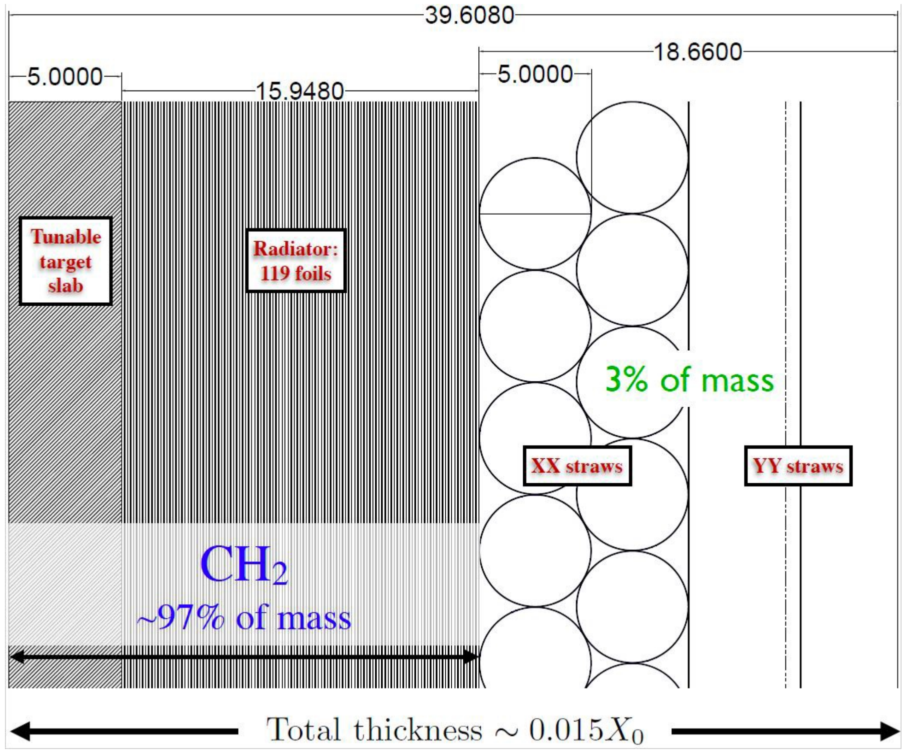
Collaborations	Kinematics	Targets	Scattering
E12-14-012 (JLab) (Data collected: 2017)	E_e = 2.222 GeV θ_e = 15.5, 17.5, 20.0, 21.5 θ_p = -39.0, -44.0, -44.5, -47.0 -50.0	Ar, Ti Al, C	(e, e') $(e, e'p)$
e4nu/CLAS (JLab) (Data collected: 1999, 2022)	E_e = 1, 2, 4, 6 GeV $\theta_e > 5$	H, D, He, C, Ar, ^{40}Ca, ^{48}Ca, Fe, Sn	(e, e') e, p, n, π, γ in the final state
LDMX (SLAC) (Planned)	E_e = 4.0 GeV $\theta_e < 40$		(e, e') e, p, n, π in the final state
A1 (MAMI) (Data collected: 2020) (More data planned)	E_e = 1.6 GeV	H, D, He C, O, Al Ca, Ar, Xe	(e, e') 2 additional charged particles
eALBA (Planned)	E_e = 500 MeV - few GeV	C, CH Be, Ca	(e, e')

Table 1: Current and planned electron scattering experiments [46]

Electron-scattering experiments:
- Known beam energy as constraint
- Usually less often demanding full acceptance (angle and momentum) for exclusivity
- Could be improved in dedicated e-scattering detectors for neutrinos.

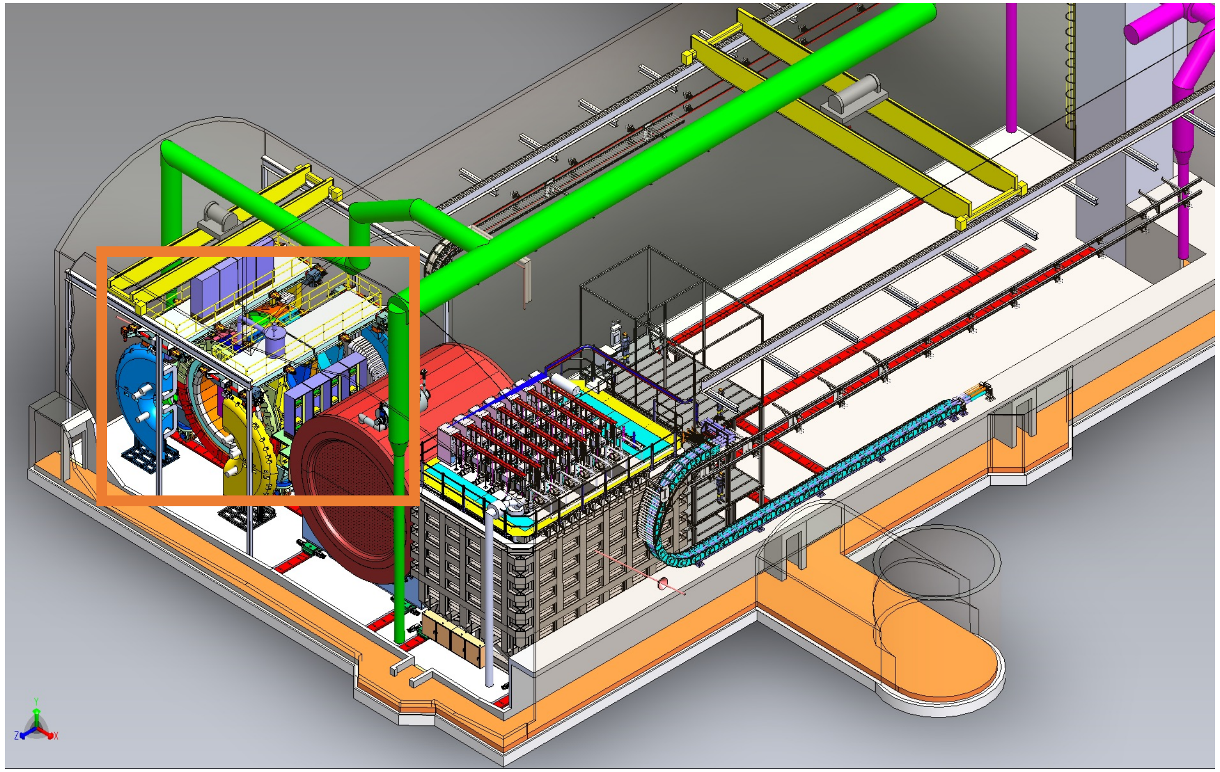
Contact: Federico Sanchez federico.sancheznieto@unige.ch

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



* Dimensions in mm

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

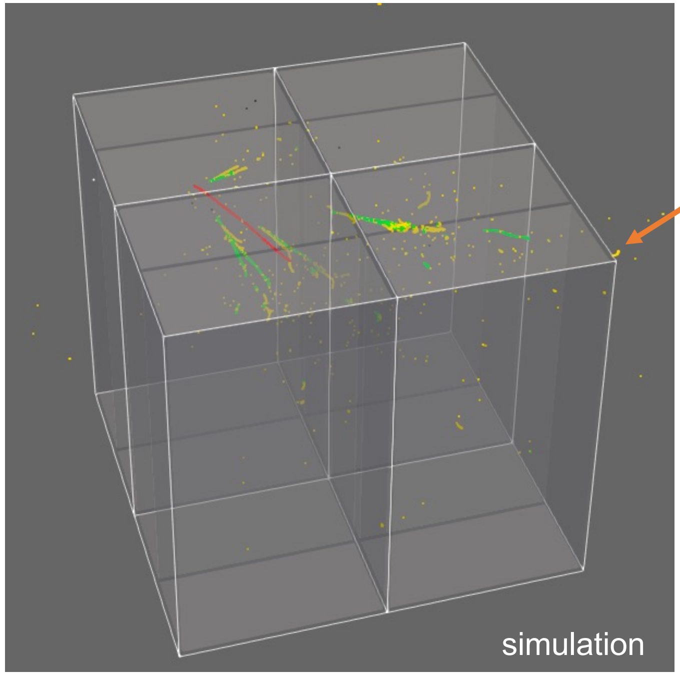


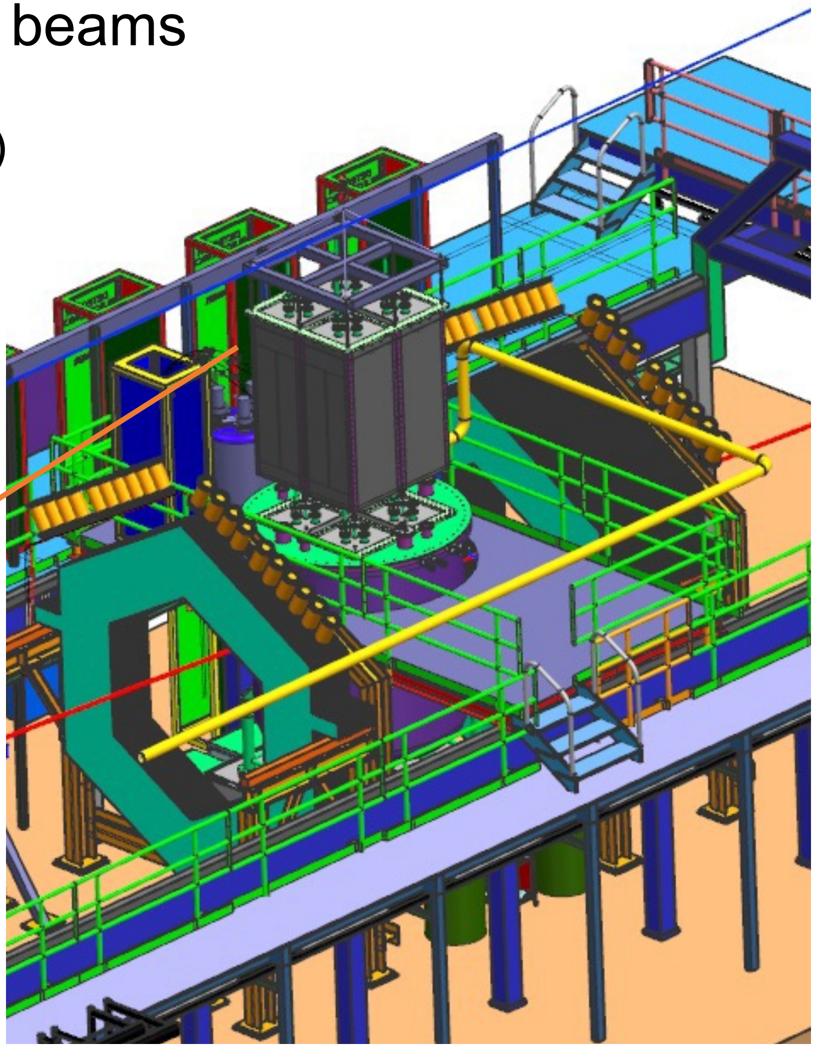
DUNE Near Detector: SAND

- STT (Straw Tube Tracker)
  - Polypropylene/CH_2 tuneable (passive) target
  - Interleaved w/ Ø5 mm ***tube*** tracking ***layer***
  - ✓ ***Rich program of ν interactions on hydrogen***

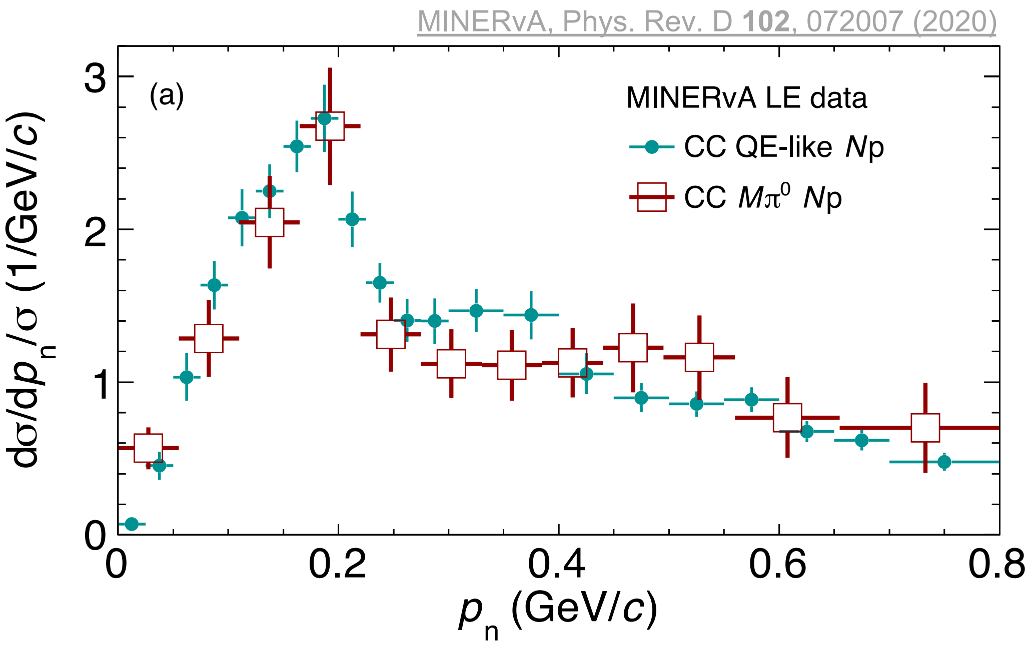
- ProtoDUNE-Horizontal Drift: closer to FD final design
- ProtoDUNE-Near Detector: ArgonCube 2×2 at NuMI beams
  - Demonstrator for DUNE ND-LAr
  - Optically separated modules, pixelated readout (4 mm pitch)
  - ✓ ***Cope with pile-up expected at ND-LAr***
  - ν_μ and $\bar{\nu}_\mu$ beams peaked at 6 GeV

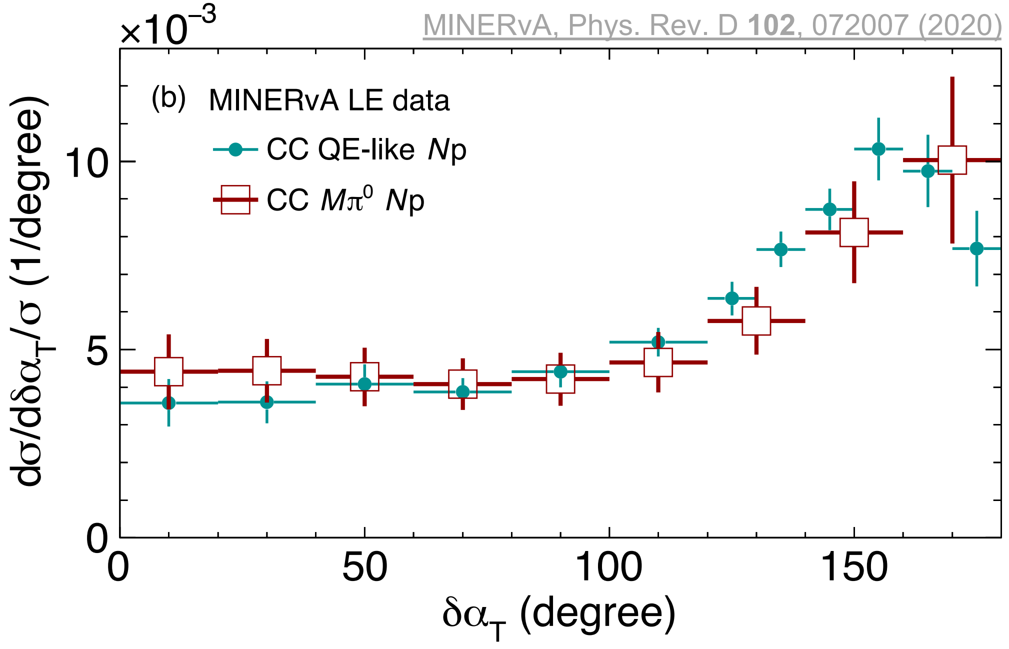
DUNE, instruments **5**, 31 (2021)



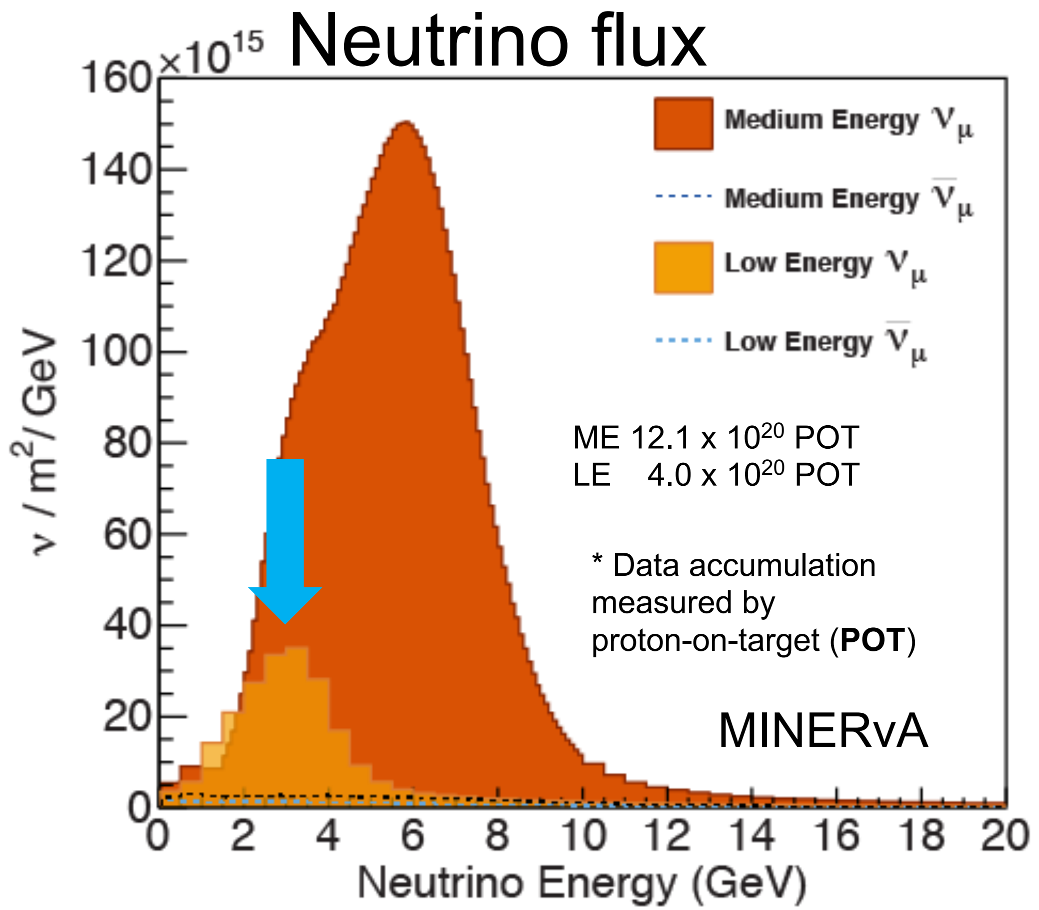


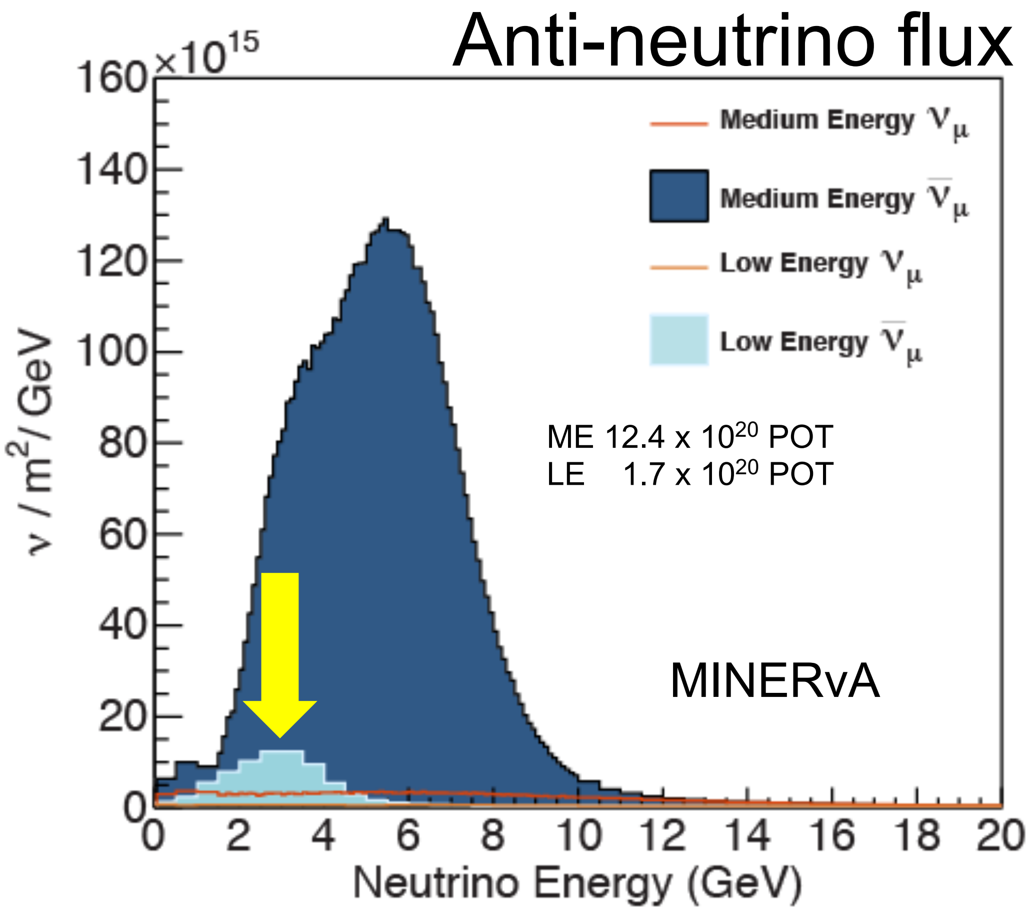
Sandwiched by repurposed MINERvA detector components

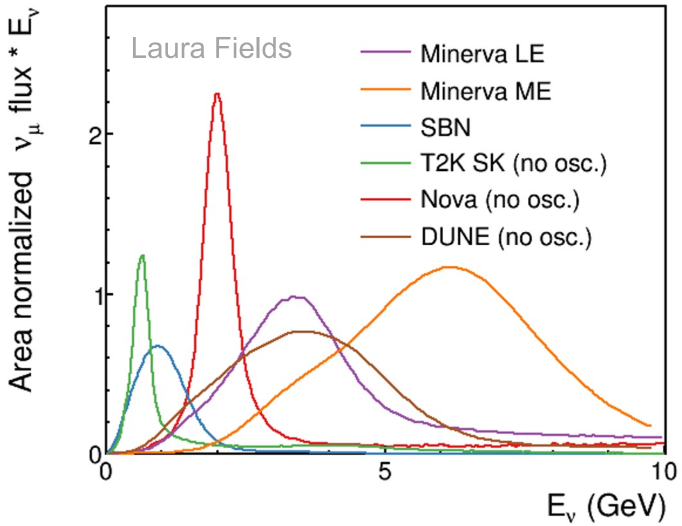

MINERvA, Phys. Rev. D 102, 072007 (2020)
(a)
MINERvA LE data
CC QE-like Np
CC Mπ0 Np
dσ/dp_n/σ (1/GeV/c)
p_n (GeV/c)
0
1
2
3
0
0.2
0.4
0.6
0.8

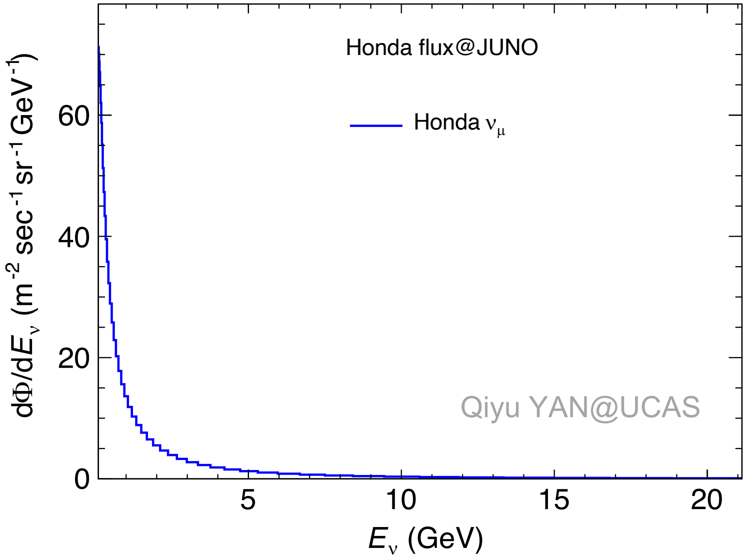

MINERvA, Phys. Rev. D 102, 072007 (2020)
×10−3
(b)
MINERvA LE data
CC QE-like Np
CC Mπ0 Np
dσ/dδα_T/σ (1/degree)
δα_T (degree)
0
5
10
0
50
100
150

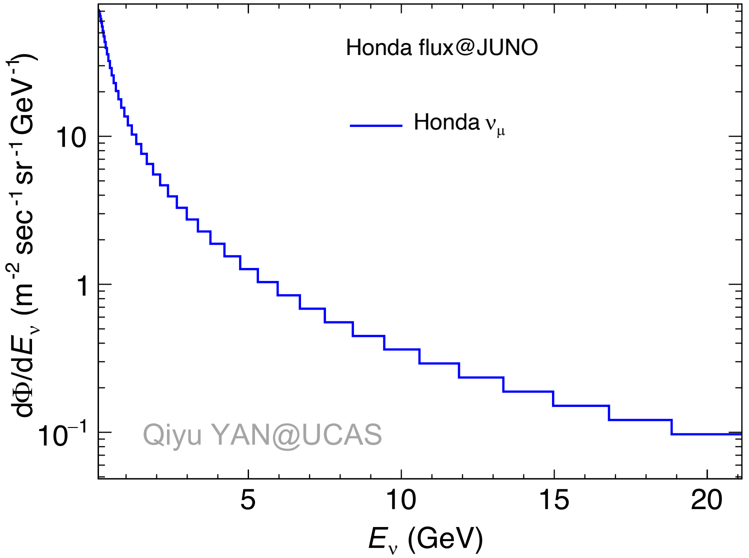
LE: Low Energy, peak at 3 GeV
ME: Medium Energy, peak at 6 GeV






Laura Fields
Minerva LE
Minerva ME
SBN
T2K SK (no osc.)
Nova (no osc.)
DUNE (no osc.)
Area normalized ν_μ flux * E_ν
E_ν (GeV)


Honda flux@JUNO
Honda ν_μ
Qiyu YAN@UCAS
$d\Phi/dE_\nu$ (m^{-2} sec^{-1} sr^{-1} GeV^{-1})
E_ν (GeV)


Honda flux@JUNO
Honda ν_μ
Qiyu YAN@UCAS
$d\Phi/dE_\nu$ (m^{-2} sec^{-1} sr^{-1} GeV^{-1})
E_ν (GeV)