Neutrino Interactions with Transverse Kinematic Imbalance

— An *incomplete* Review of MINERvA Results and TKI-Community Efforts

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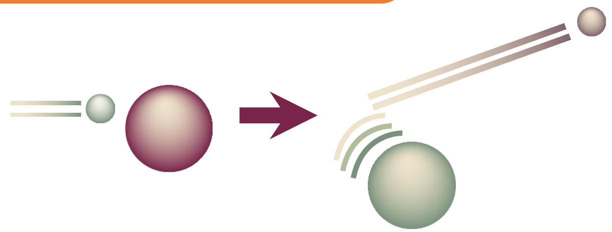
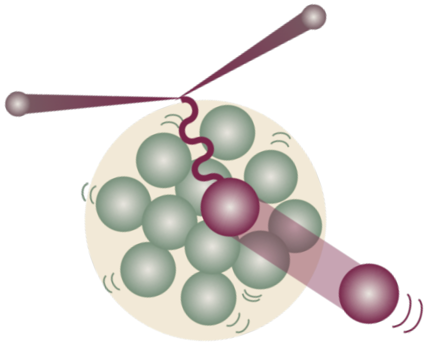
University of Oxford

IHEP EPD Seminar
7 April 2021

These artwork by Cheryl Patrick

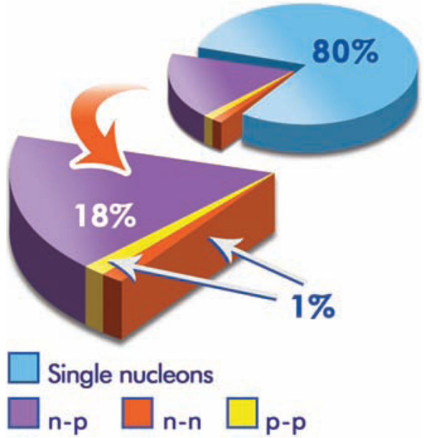


Interaction on a proton or neutron



e-A scattering

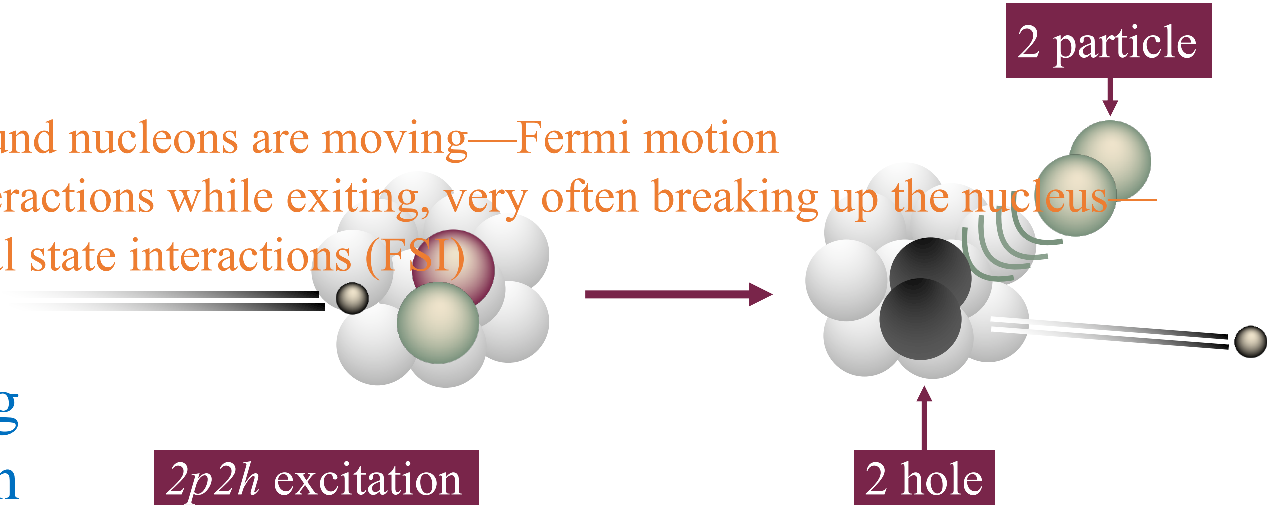
Subedi *et al.*, Science 320, 1476 (2008)



From electron-nucleus scattering

- ❑ Fermi motion
- ❑ FSI breaking up nucleus
- ❑ 2*p*2*h* excitation

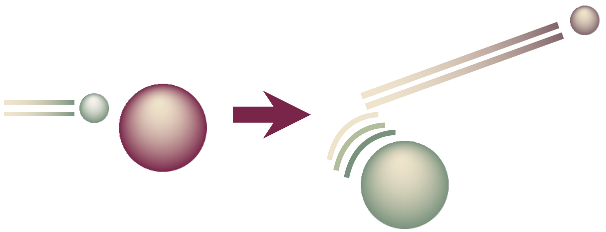
- ❑ Bound nucleons are moving—Fermi motion
- ❑ Interactions while exiting, very often breaking up the nucleus—final state interactions (FSI)



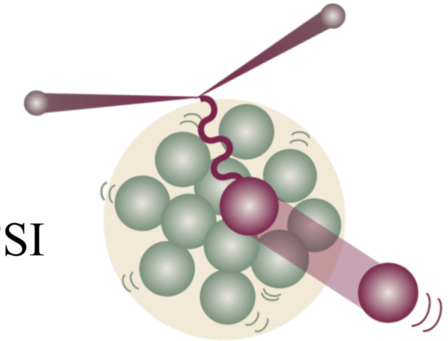
All exist in neutrino-nucleus scattering

But we don't know enough

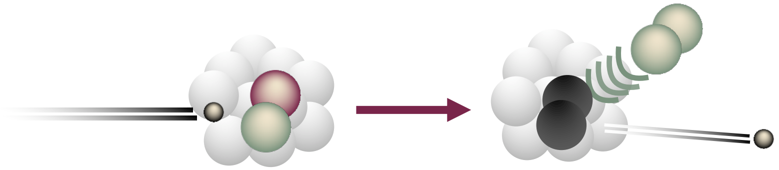
How well can we measure neutrino energy?
(reminder: oscillation very sensitive to baseline and energy, L/E)



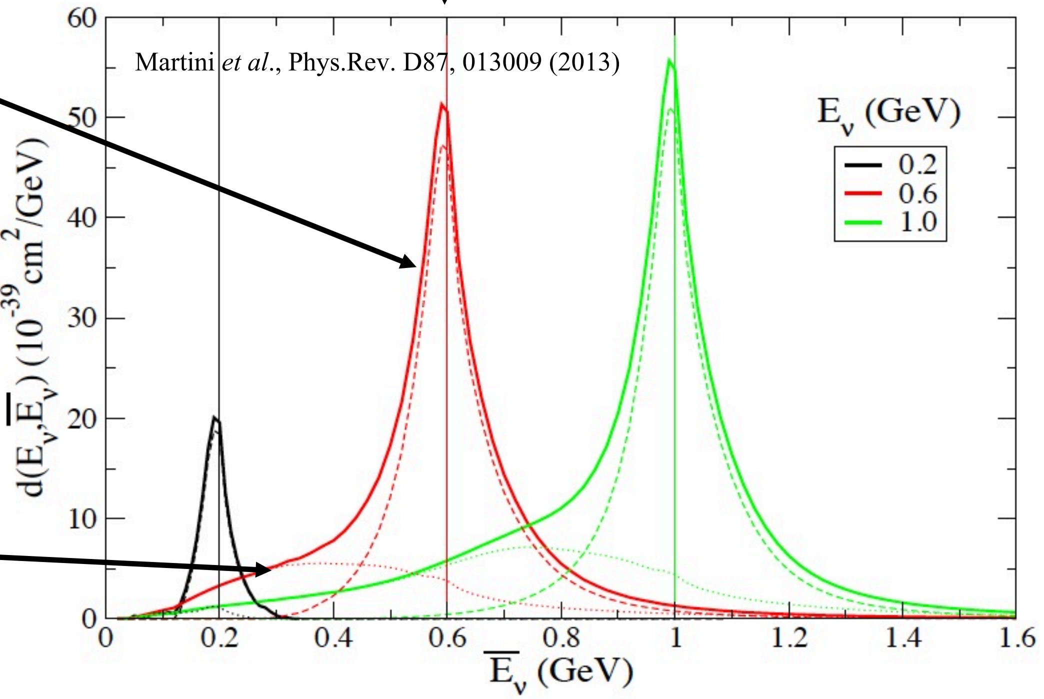
2-body reaction
—precise



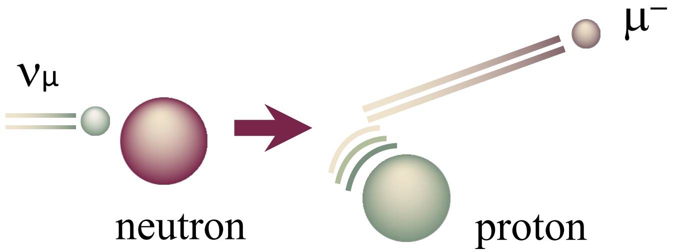
Fermi motion, FSI
—spread

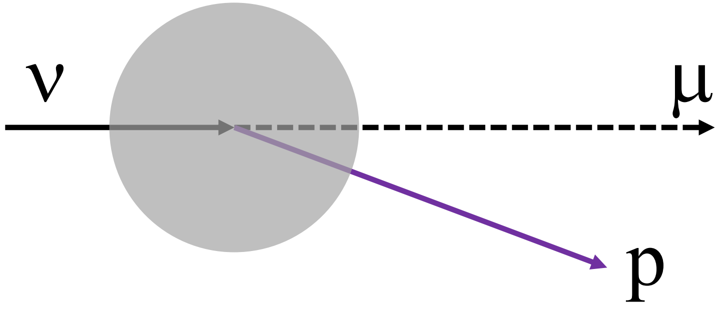


2p2h
—large (not well known) fraction of large bias and spread



Charged-current (CC) quasielastic (QE)





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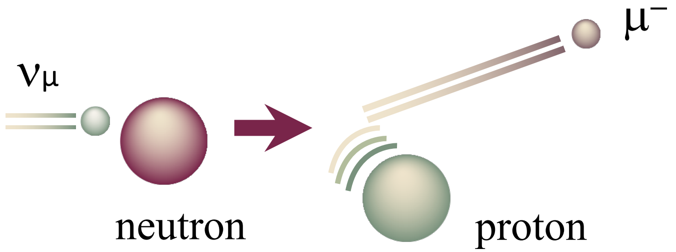
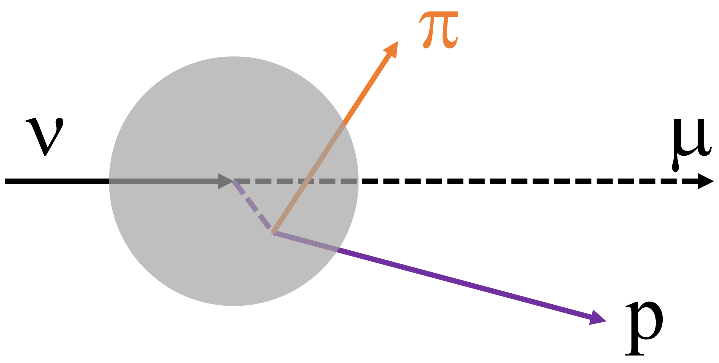


FSI can *also* modify final-state topology

vertex | detector

QE — FSI produces π → 1π

Resonance (RES)



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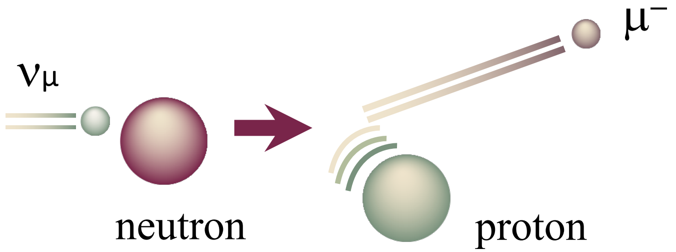

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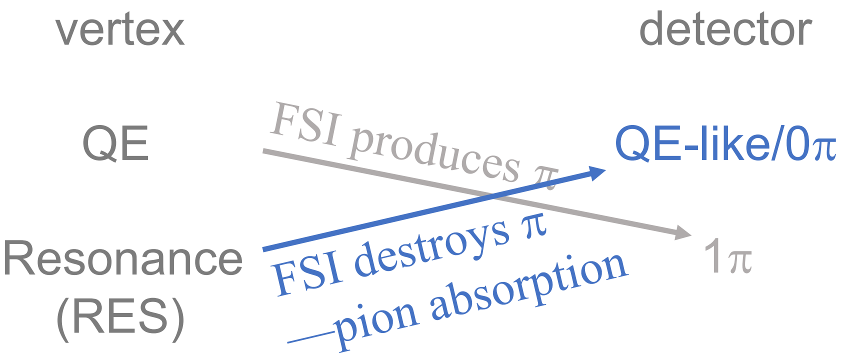
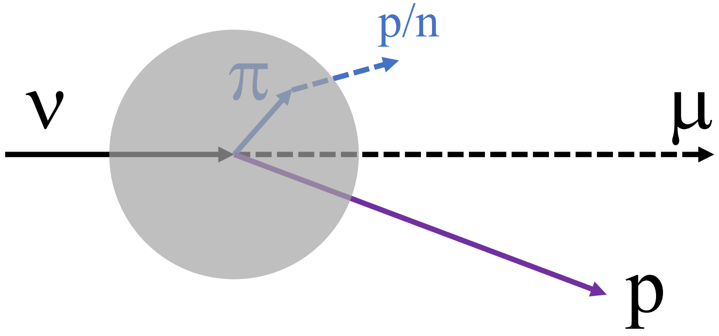
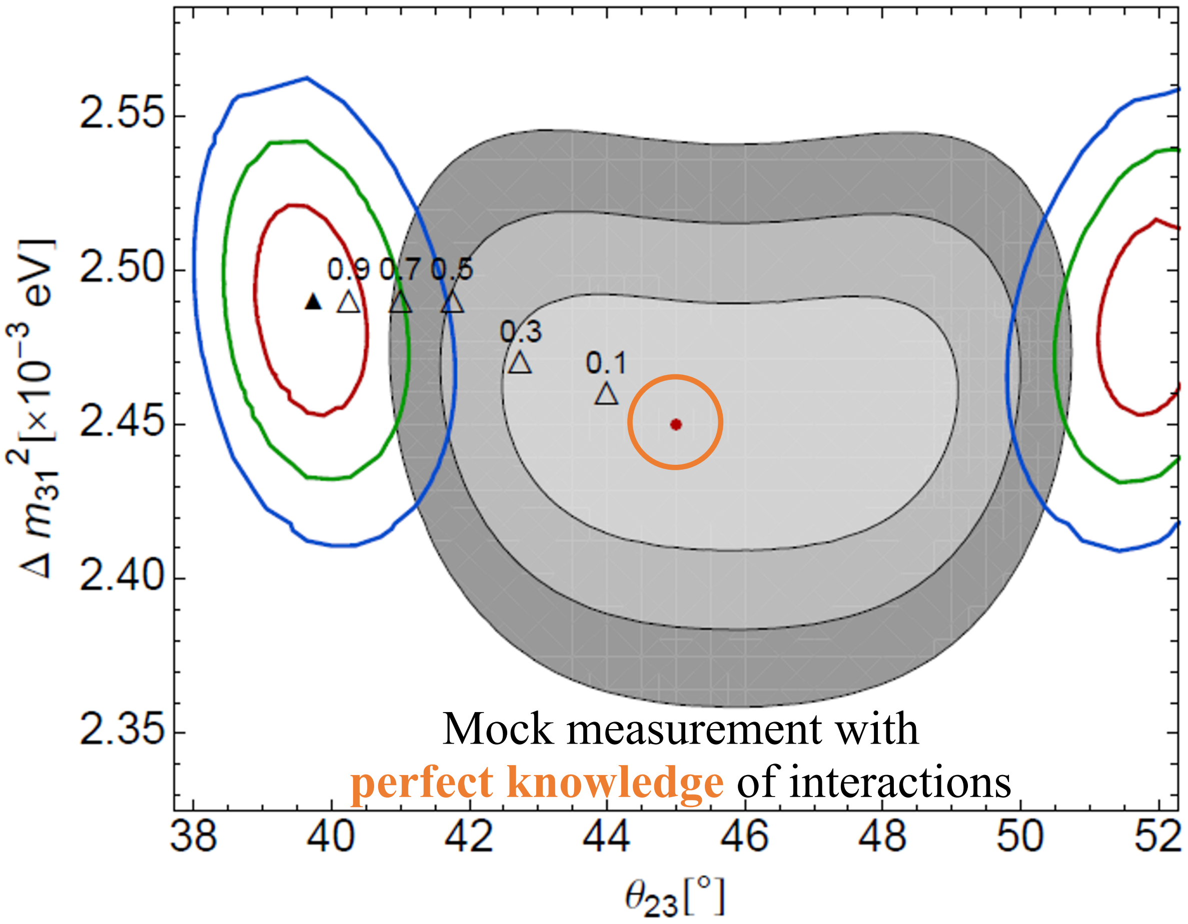


Difficulty in cross section measurements already at *definition* level!



Coloma & Huber, Phys.Rev.Lett. 111, 221802 (2013)



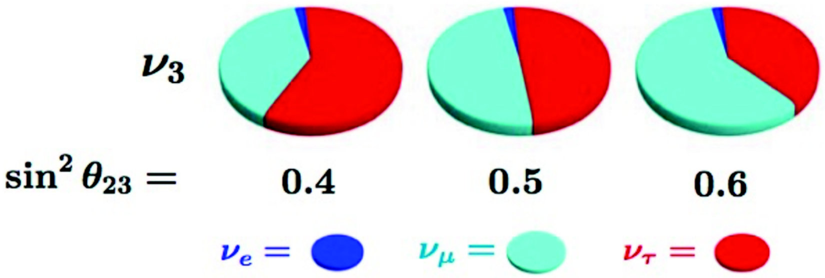
Mixing between
μ and τ flavors

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

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

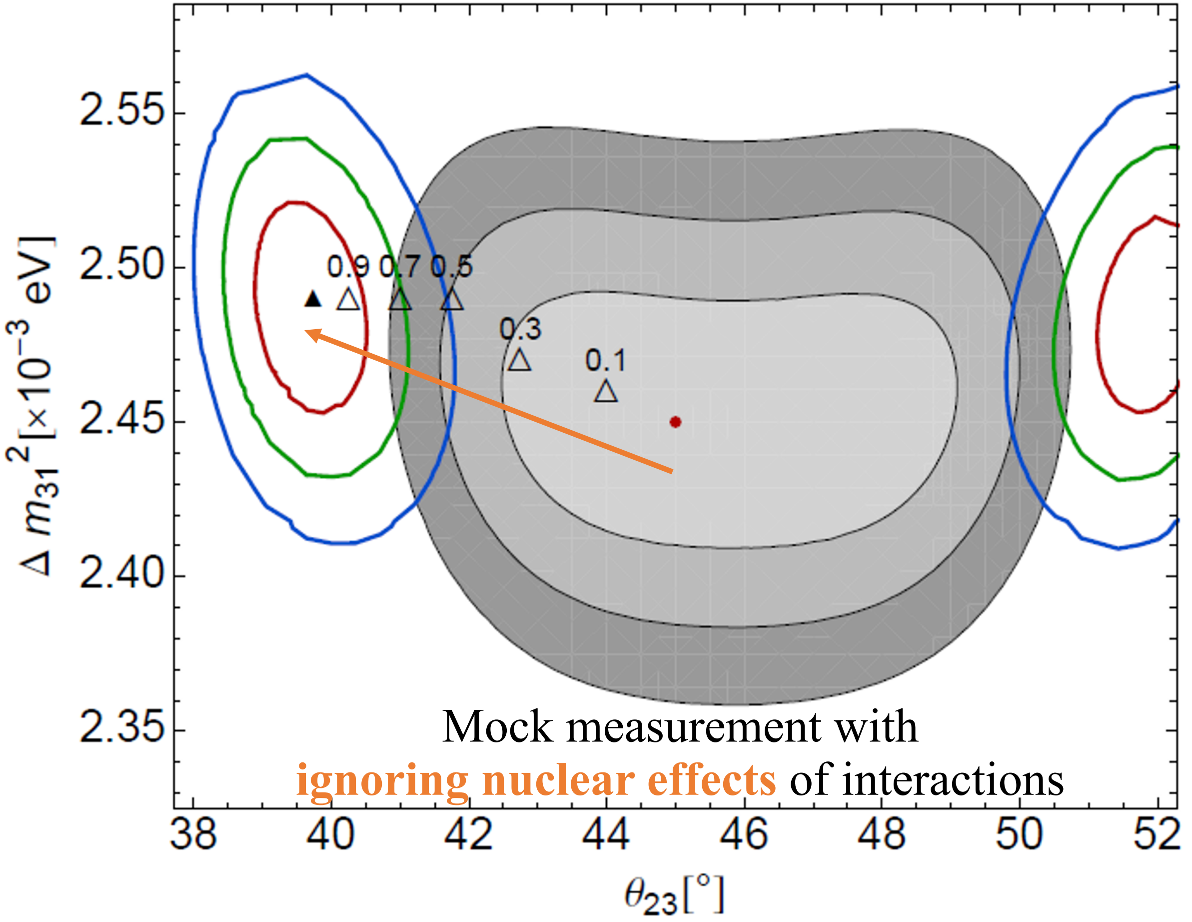
PMNS matrix

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



Cartoon from Parke, 1801.09643

Coloma & Huber, Phys.Rev.Lett. 111, 221802 (2013)



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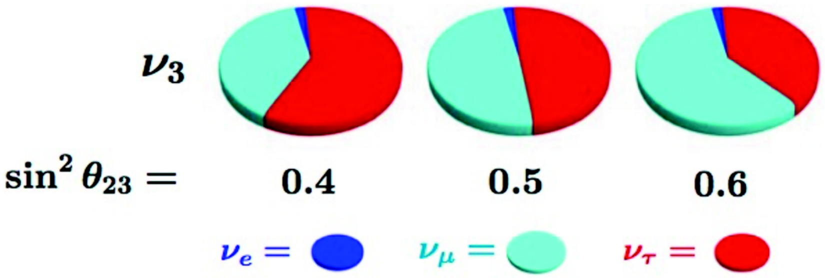

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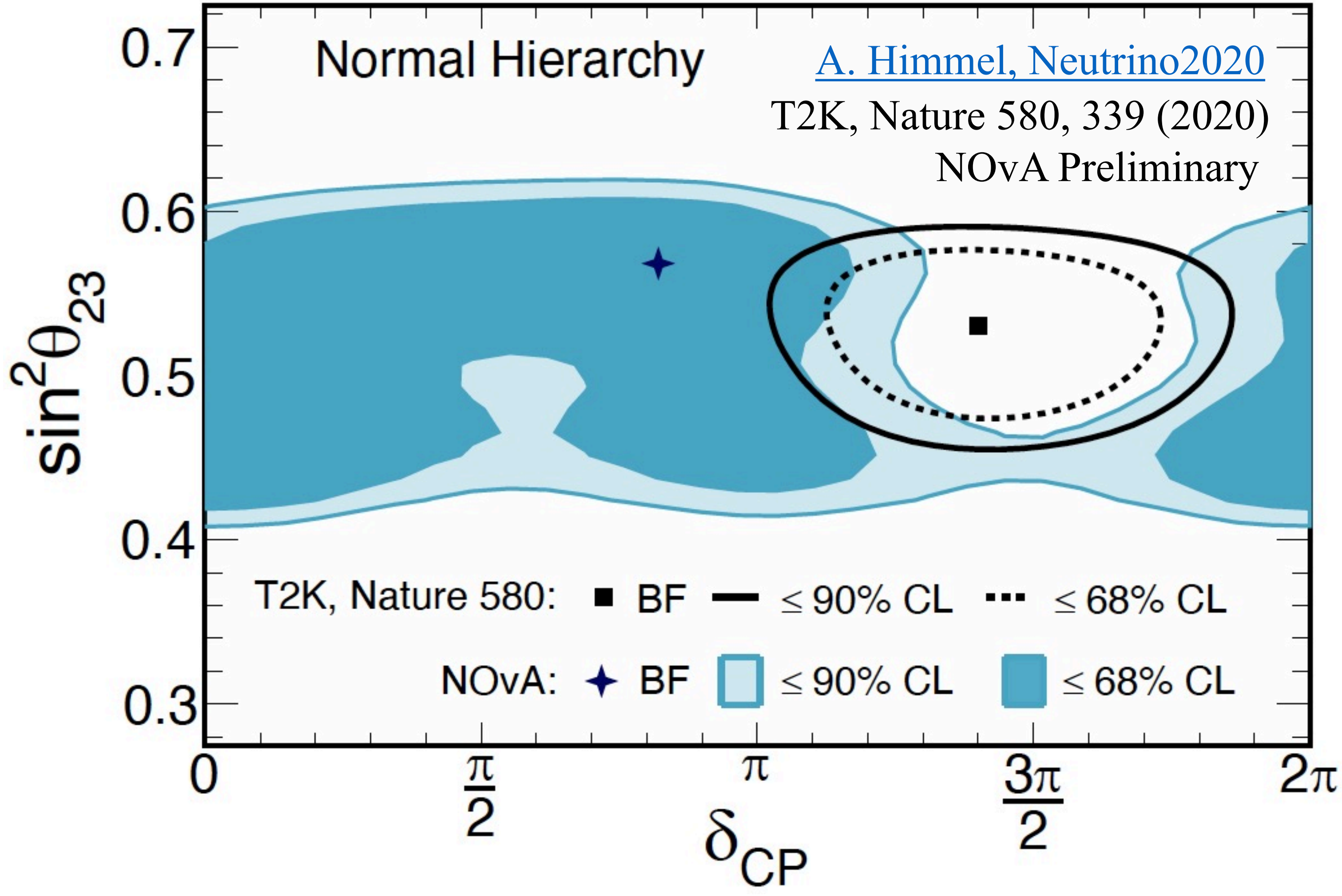


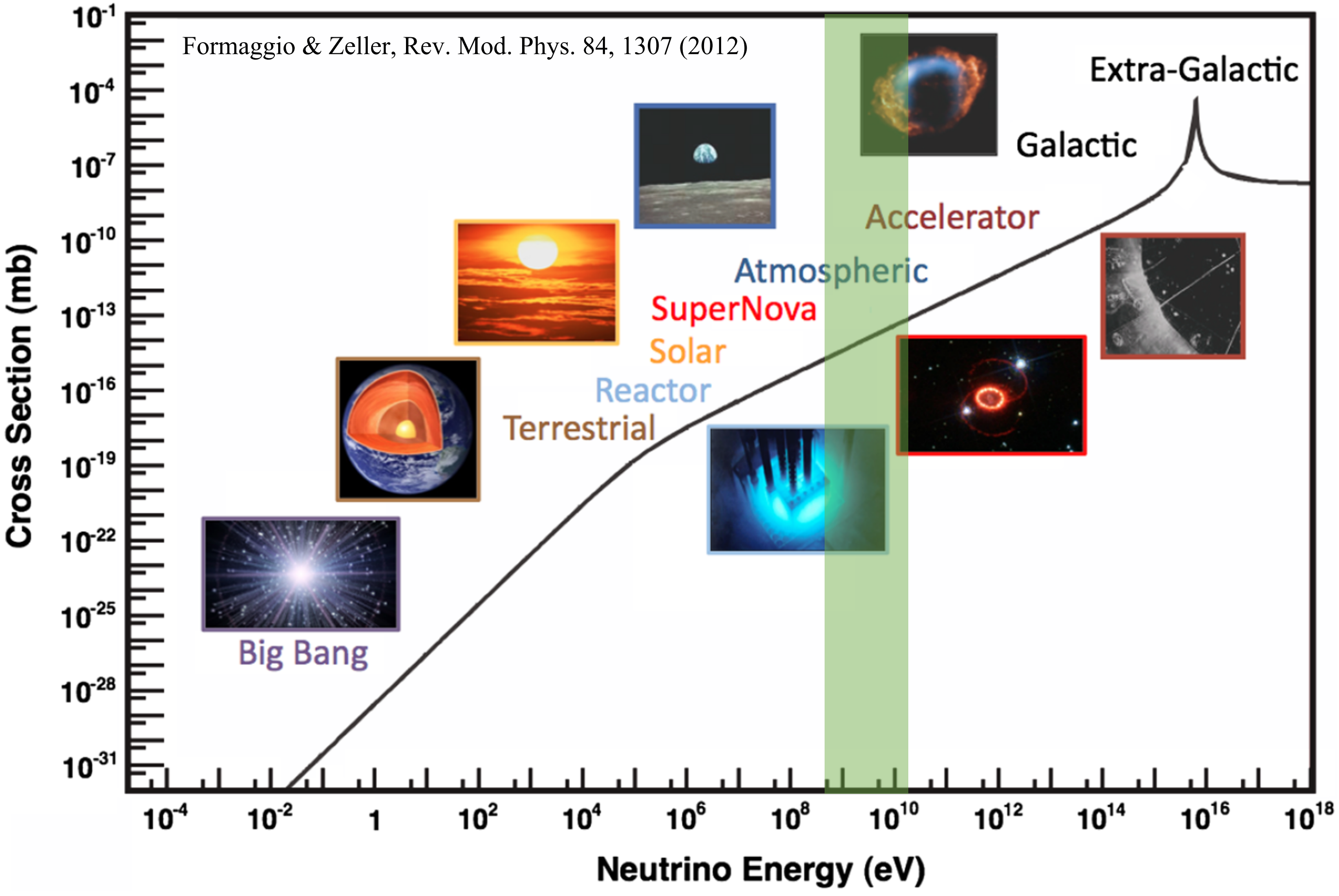
- ❑ T2K published the first closed 3σ (99.73%) confidence interval of δ_{CP} [T2K, Nature 580, 339 (2020)]
  - ❖ Both CP-conserving points excluded at 2σ (95.45%) [T2K, 2101.03779].
- ❑ In contradiction to NOvA 2020 preliminary results.

Type of Uncertainty	$\nu_e/\bar{\nu}_e$ Candidate Relative Uncertainty (%)
Super-K Detector Model	1.5
Pion Final State Interaction and Rescattering Model	1.6
Neutrino Production and Interaction Model Constrained by ND280 Data	2.7
Electron Neutrino and Antineutrino Interaction Model	3.0
Nucleon Removal Energy in Interaction Model	3.7
Modeling of Neutral Current Interactions with Single γ Production	1.5
Modeling of Other Neutral Current Interactions	0.2
Total Systematic Uncertainty	6.0

[T2K, Nature 580, 339 (2020)]

T2K measurement systematic uncertainties

- ❑ (Flux normalisation 9%)
- ❑ Signal relative rate uncertainty dominated by neutrino interactions
    - ❖ Single largest: nucleon removal energy



Neutrino for CP-violation

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

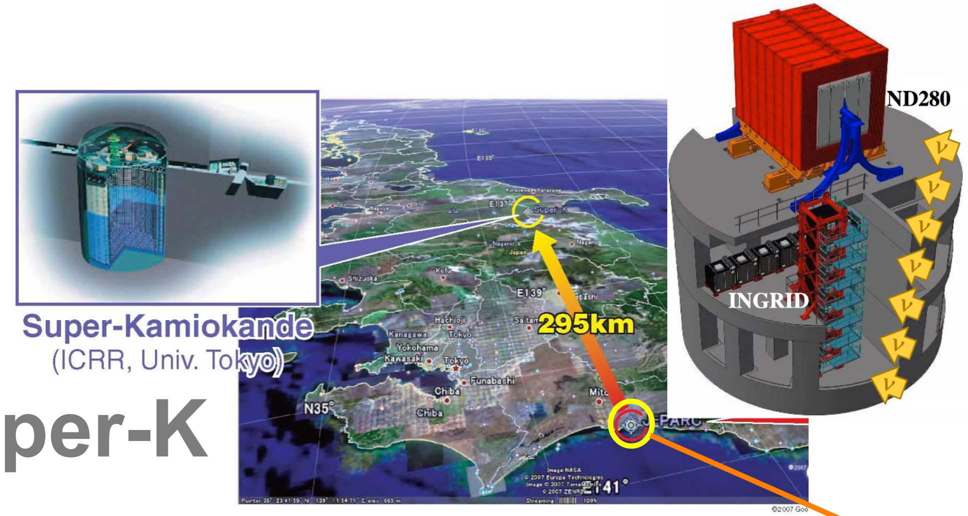
GeV-neutrinos also relevant for

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

Outline

- ❑ Neutrino interactions with MINERvA
- ❑ Transverse Kinematic Imbalance (TKI)
  - ❖ Ideas and measurements
  - ❖ Further ideas, including
    - ➢ Hydrogen-rich high-pressure TPC

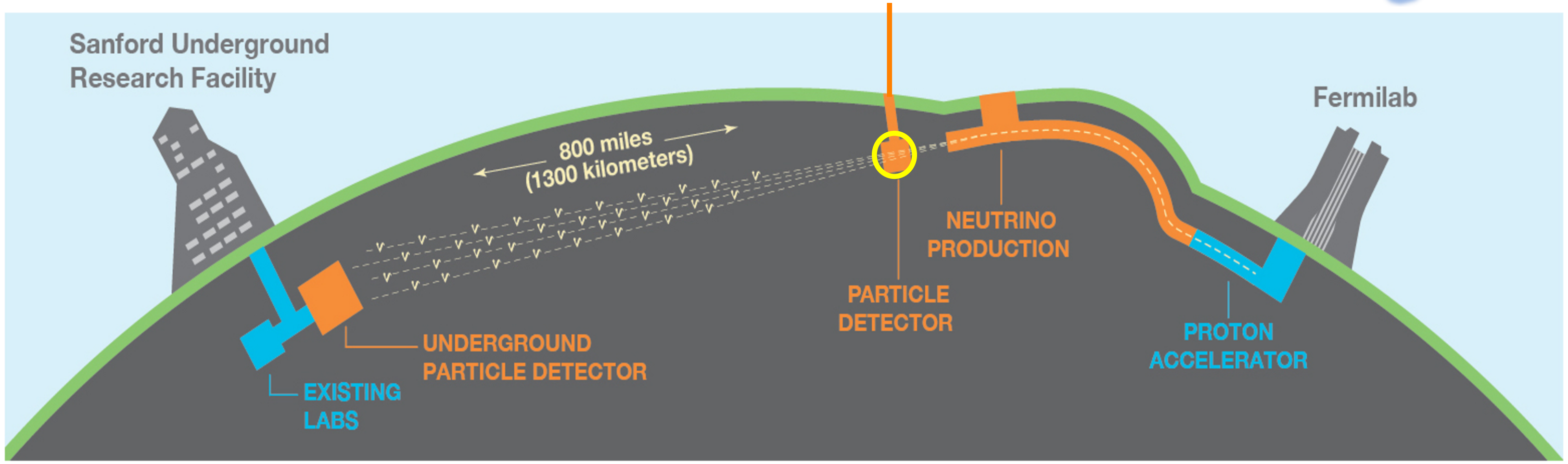
T2K / Hyper-K



NOvA

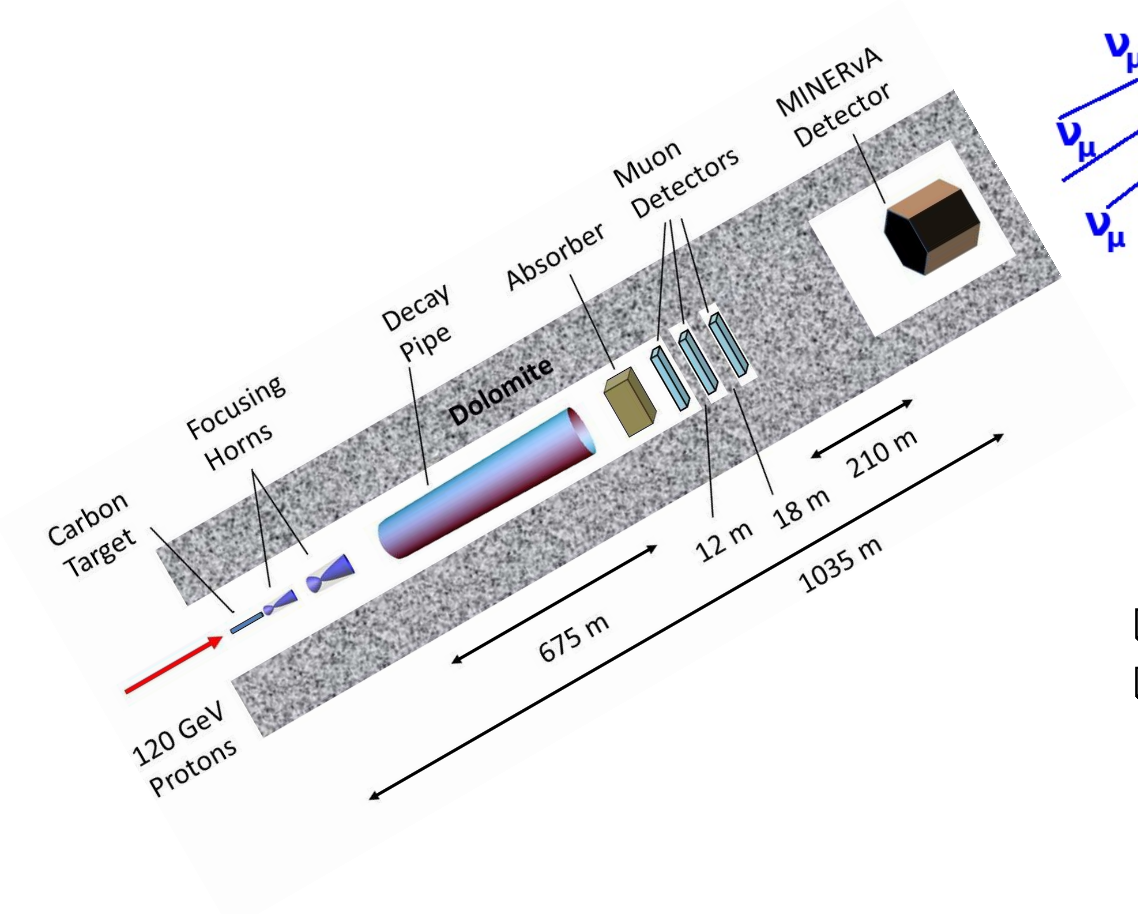
Near Detectors to measure ν interactions

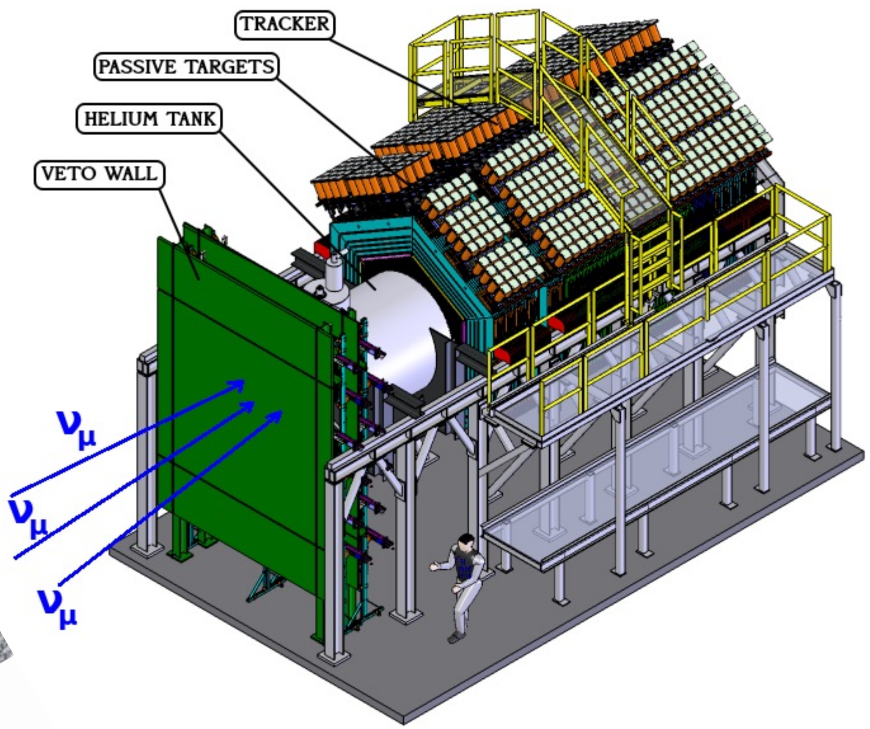
DUNE



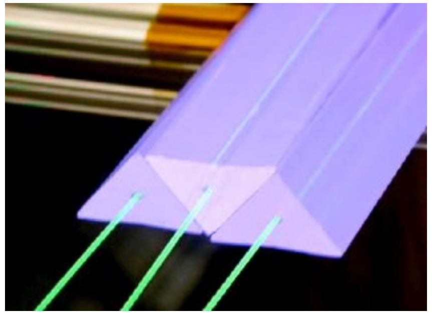
MINERvA@FNAL

A dedicated *ν-interaction* experiment

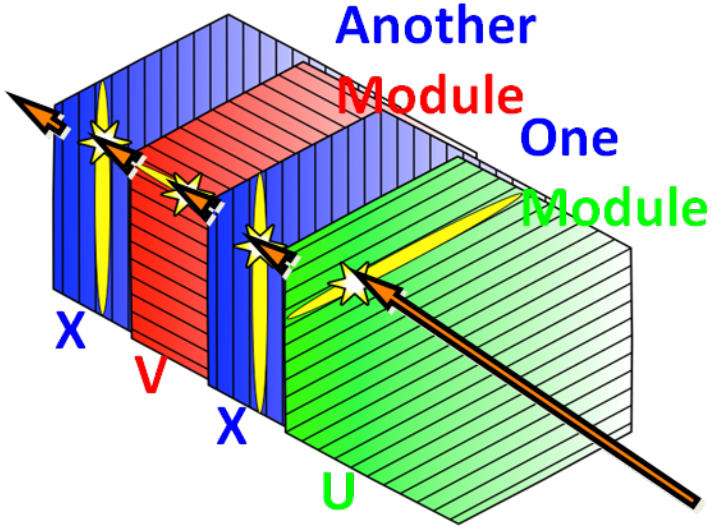




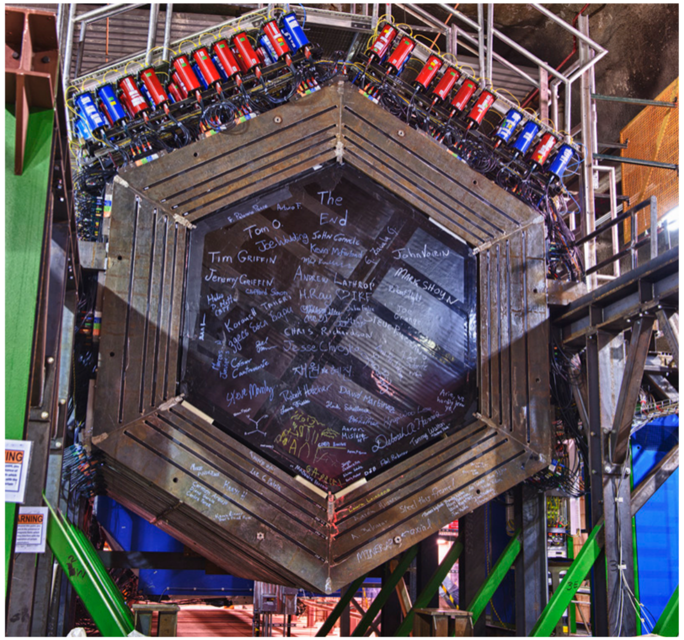
- ❑ 5.4 ton active scintillator fiducial volume
- ❑ 10-μs beam spill, ~ 1 event in tracker per spill



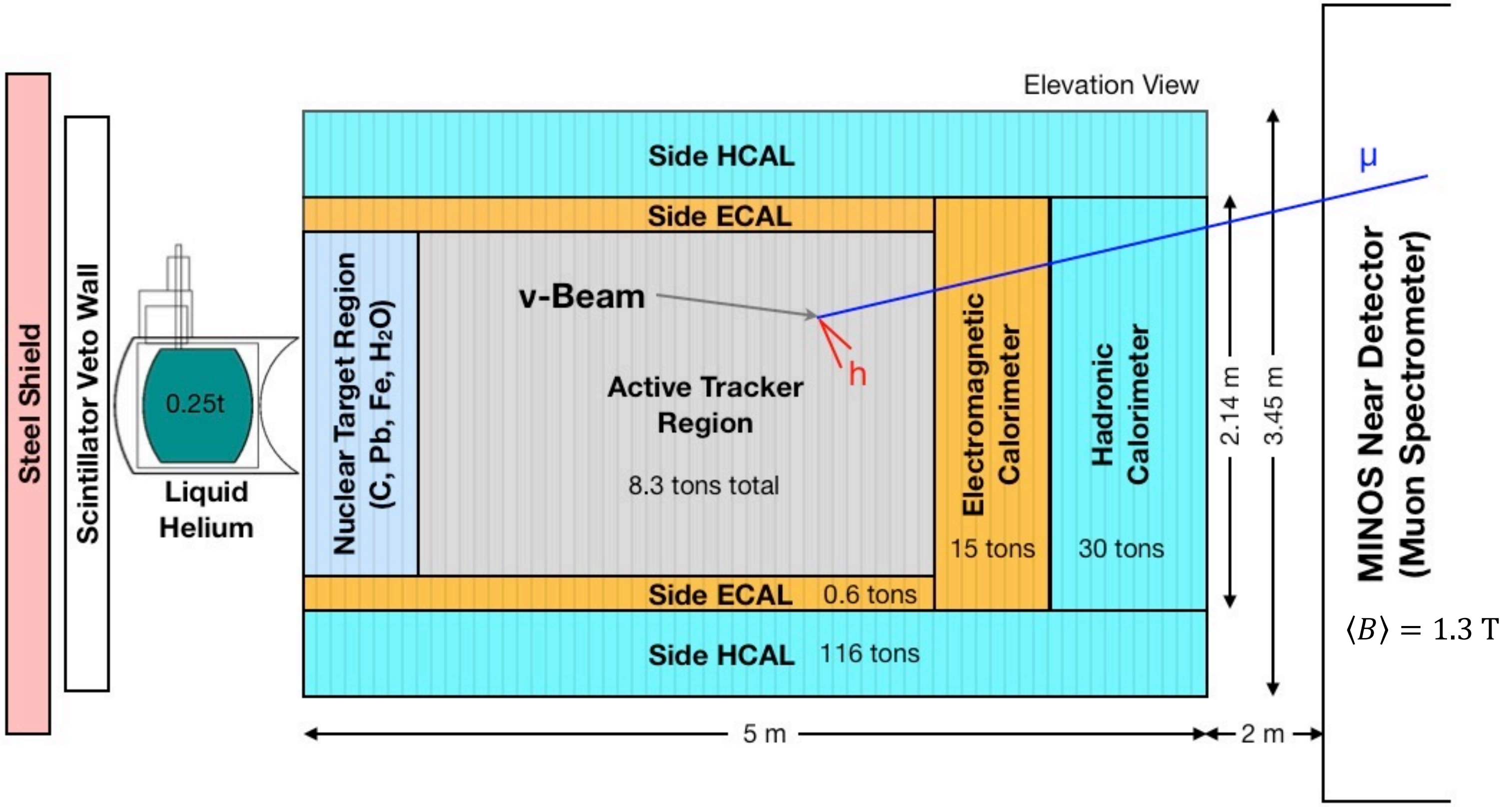
- ❑ Scintillator bar (CH)
- ❑ 3.3 cm base, 1.7 cm height
- ❑ 3 ns timing resolution



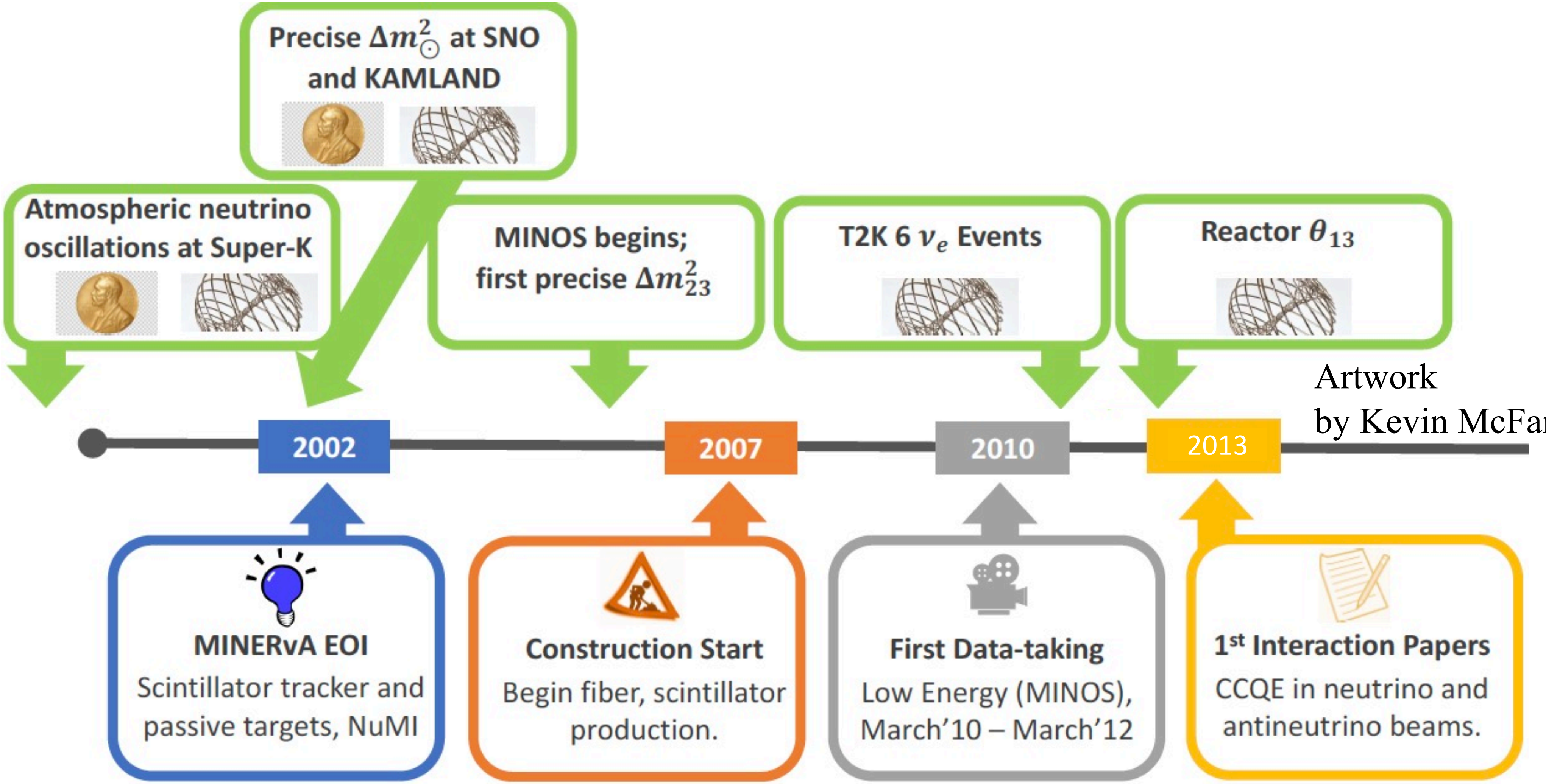
- ❑ 3 views
- ❑ 2.7 mm position resolution per plane



- ❑ 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 $18\% + 8\% / \sqrt{E_\pi/\mathrm{GeV}}$
- ❑ We can also detect neutrons (BACKUP)



Artwork
by Kevin McFarland

2013-2019: Medium Energy (NOvA-era) data-taking

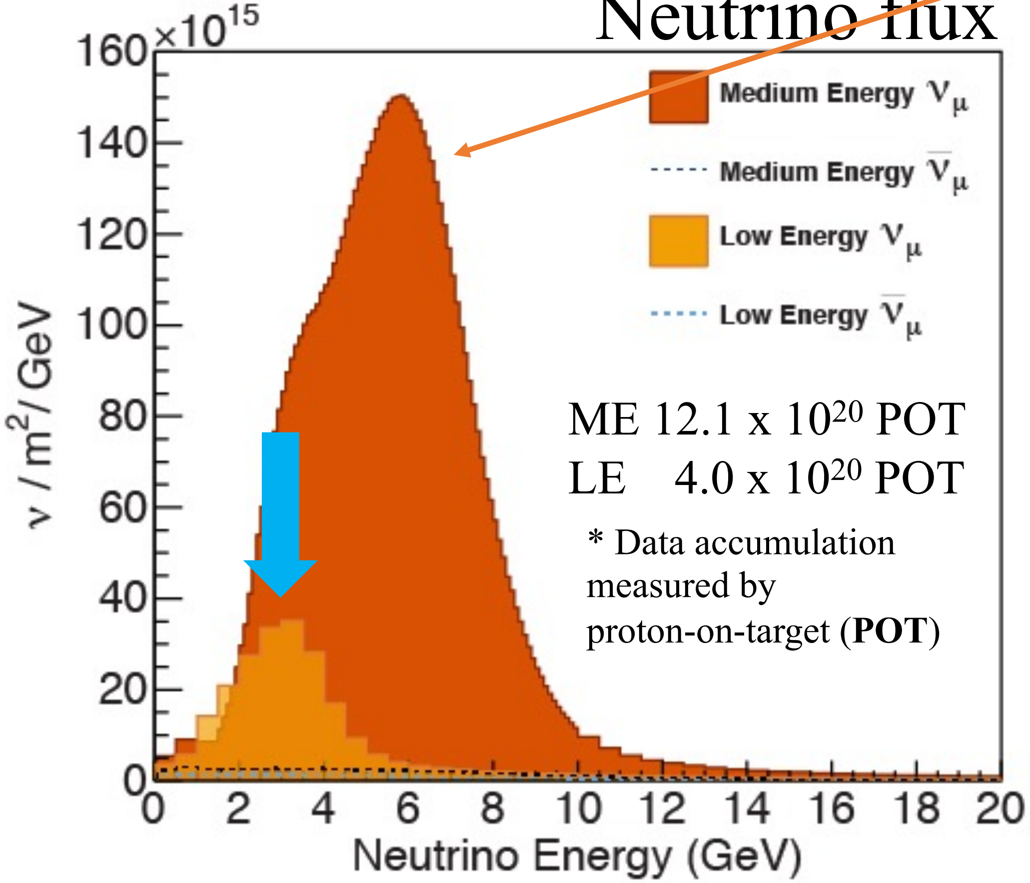
- *Constraint of the MINERνA medium energy neutrino flux using neutrino-electron elastic scattering*, **Phys.Rev. D100, 092001 (2019)**
- *High-Statistics Measurement of Neutrino Quasielasticlike Scattering at 6 GeV on a Hydrocarbon Target*, **Phys.Rev.Lett. 124, 121801 (2020)**

ME: gigantic data sets!

Beyond 50 GeV!
(BACKUP)

LE: Low Energy, peak at 3 GeV (12 PRL, 19 PRD, 1 PLB)
ME: Medium Energy, peak at 6 GeV

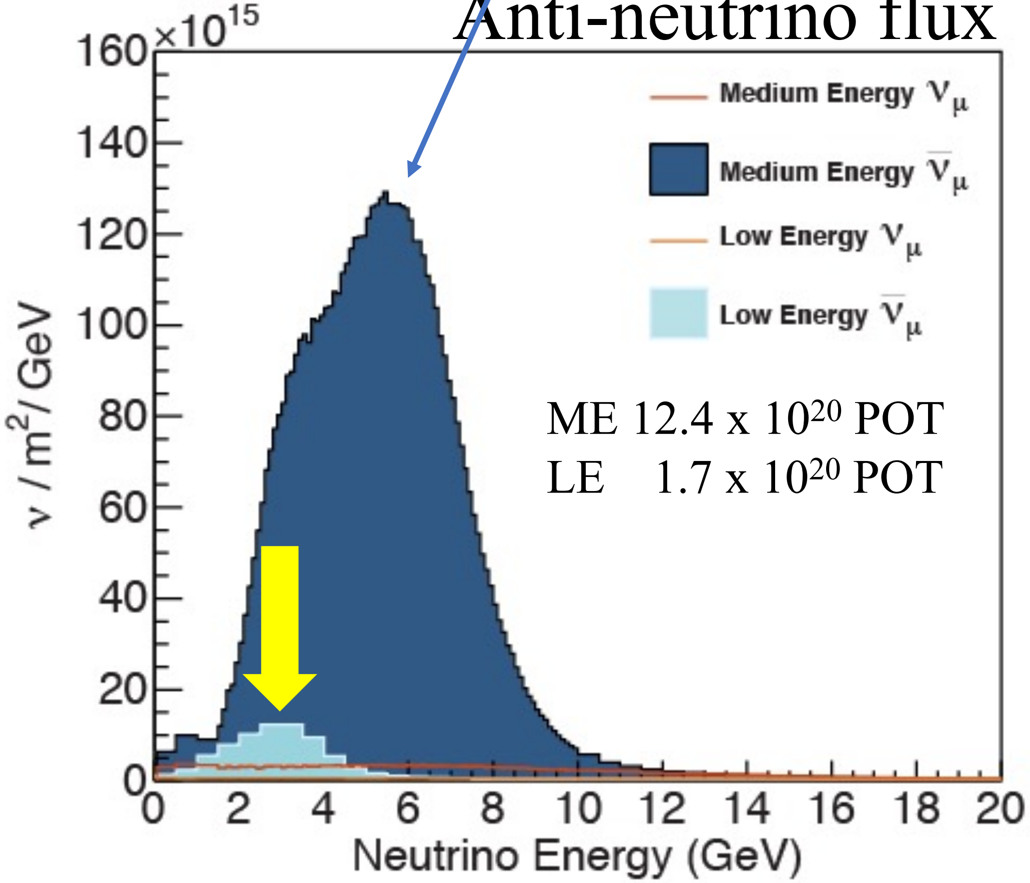
Neutrino flux



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

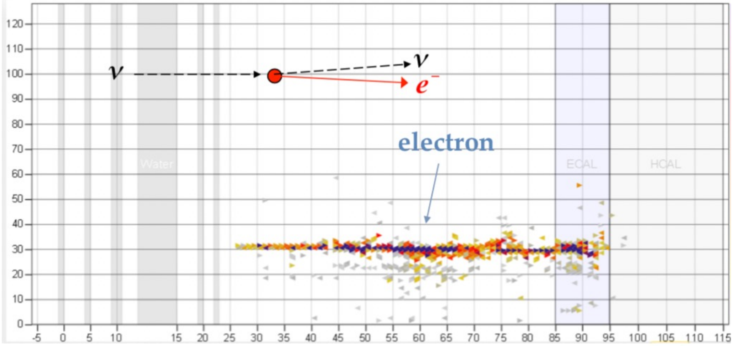
* Data accumulation measured by proton-on-target (**POT**)

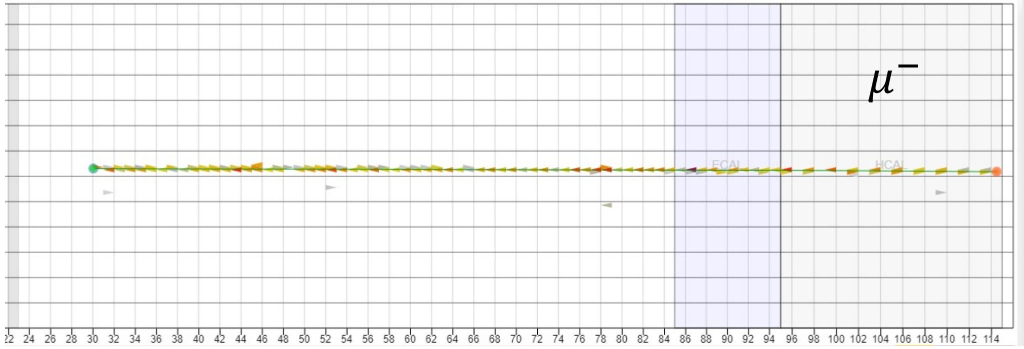
Anti-neutrino flux

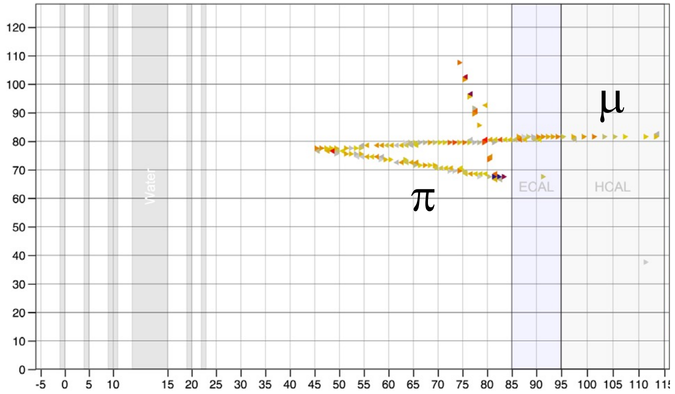


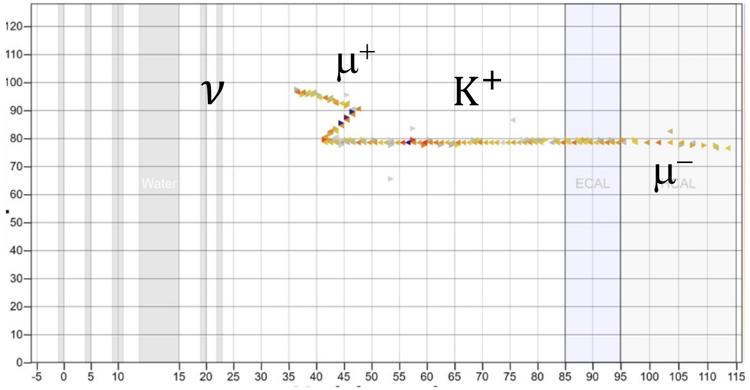
ME 12.4 x 10^{20} POT
LE 1.7 x 10^{20} POT

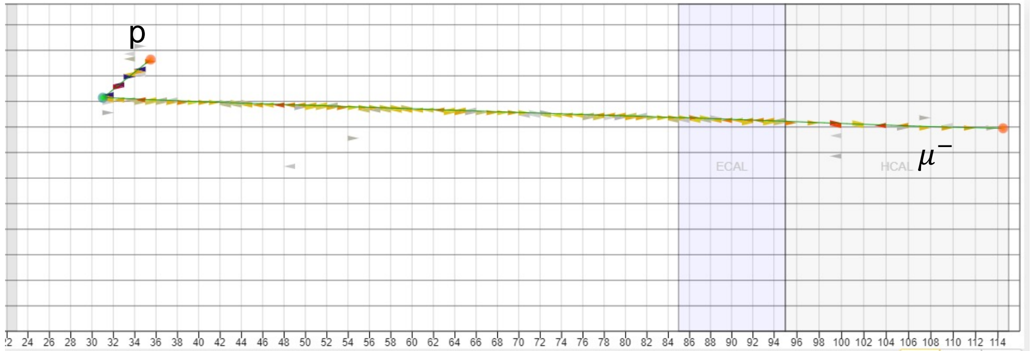
Neutrino Interactions

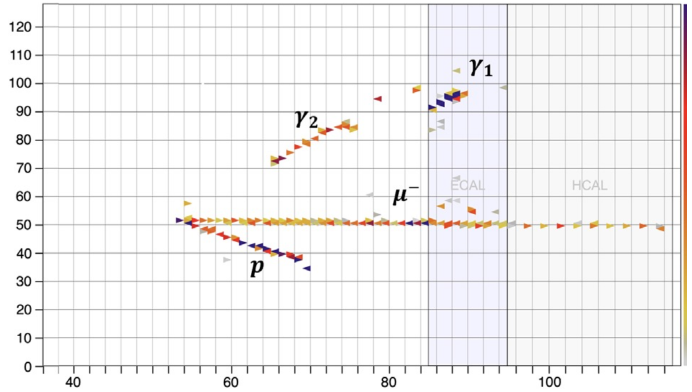










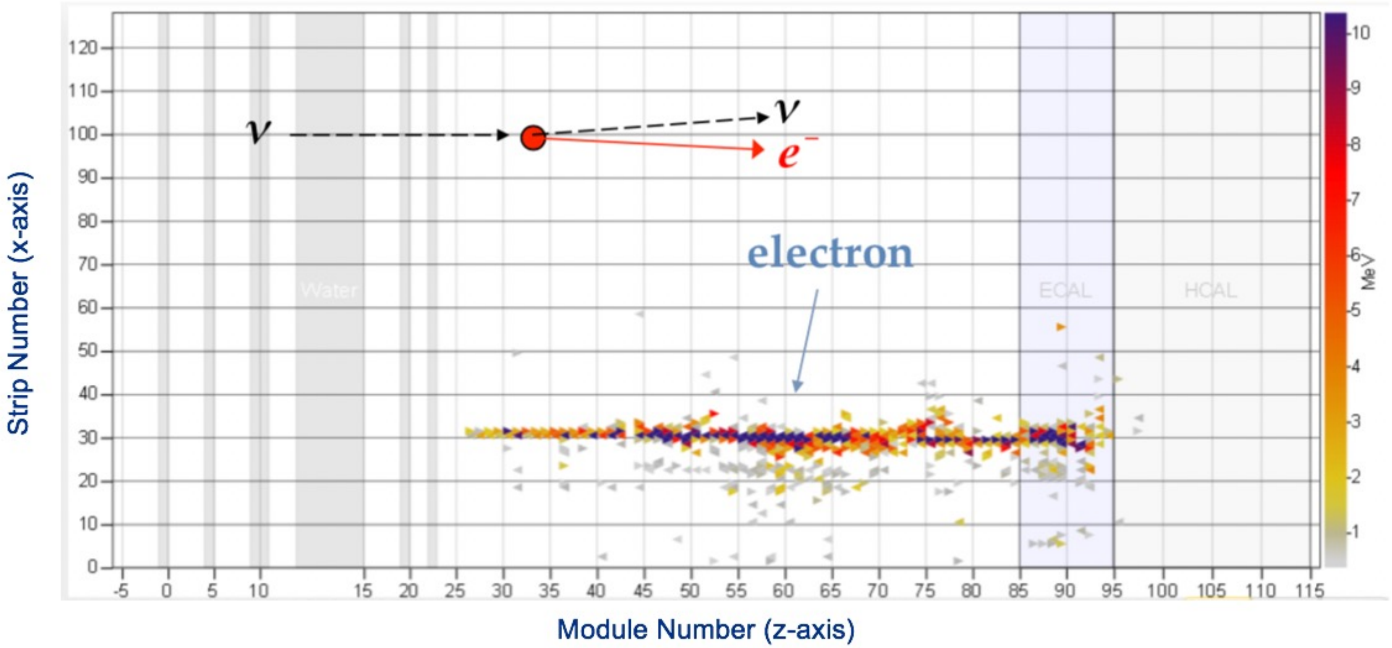


Neutrino-Electron Elastic Scattering

LE: Phys.Rev. D93, 112007 (2016)
ME: Phys. Rev. D 100, 092001 (2019)

Well-understood SM process

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



LE: 135 events
ME: 810 events

- ❑ Beam flux prediction:
  GEANT4+hadron production data
- ❑ *in situ* flux constrained by νe scattering
  - ❖ reduced by ~ 10%
  - ❖ uncertainty near the peak reduced from 8% to 4%

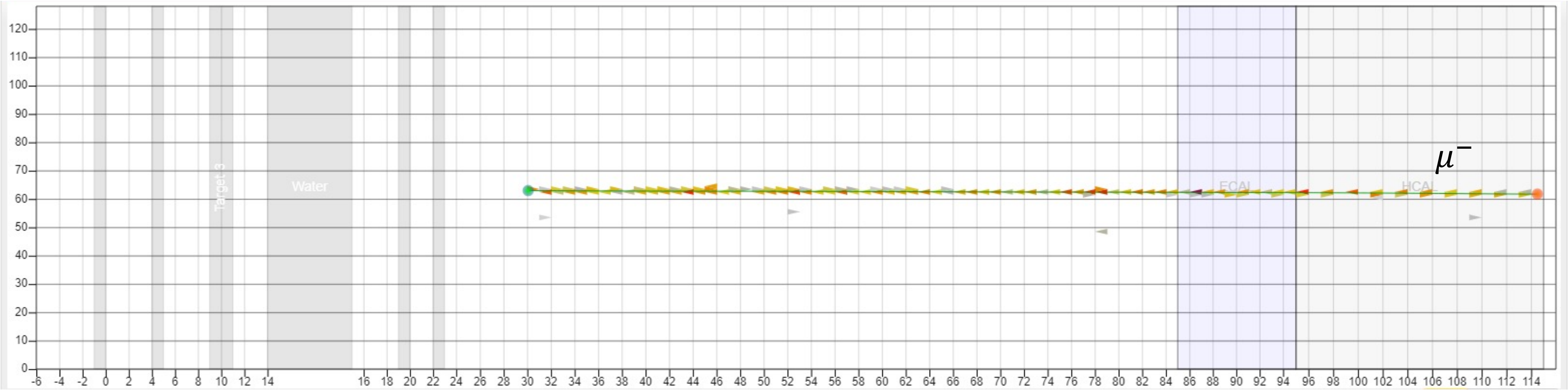
Inverse Muon Decay

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

Another well-understood SM process

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

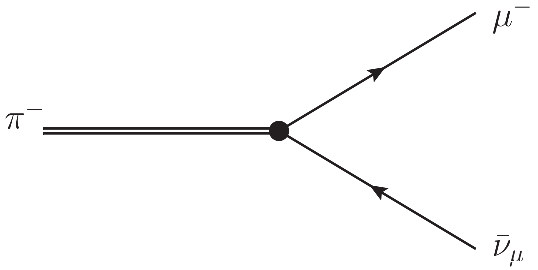
Inverse muon decay



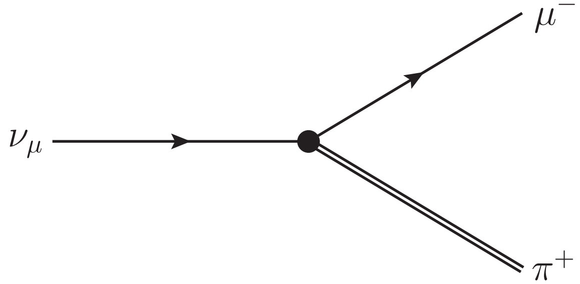
New flux constraint method—stay tuned!

Charged-Current Coherent π Production

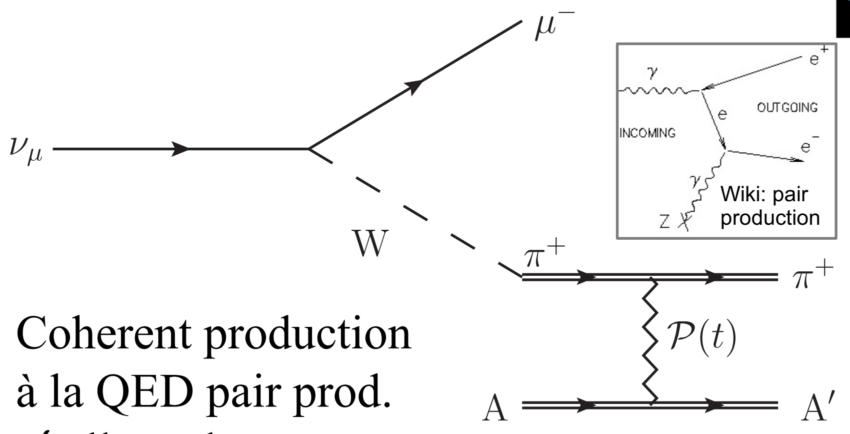
LE: Phys.Rev.Lett. 113, 261802 (2014)
Phys.Rev. D97, 032014 (2018)



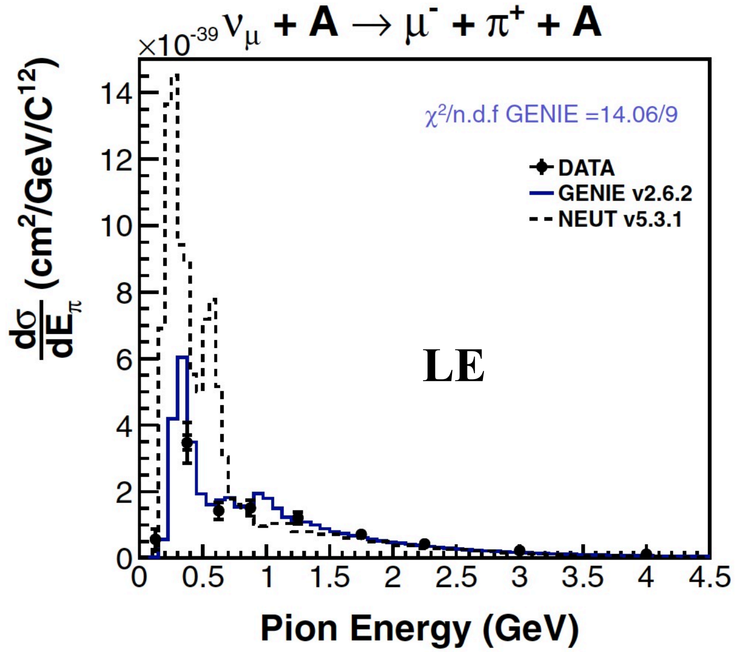
Pion decay

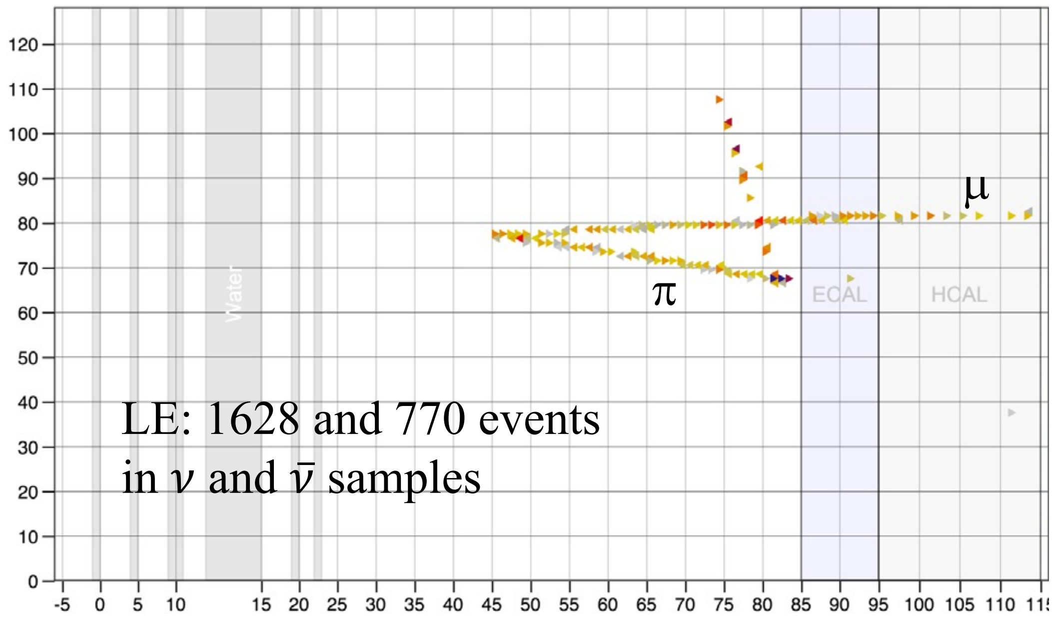


"Inverse pion decay"
✗ forbidden
✓ IF ν_μ is replaced by a heavy neutrino (heavy neutral lepton)



Coherent production
à la QED pair prod.
✓ allowed
❑ Intrinsic background to HNL search
[T2K, Phys.Rev. D100, 052006 (2019)]



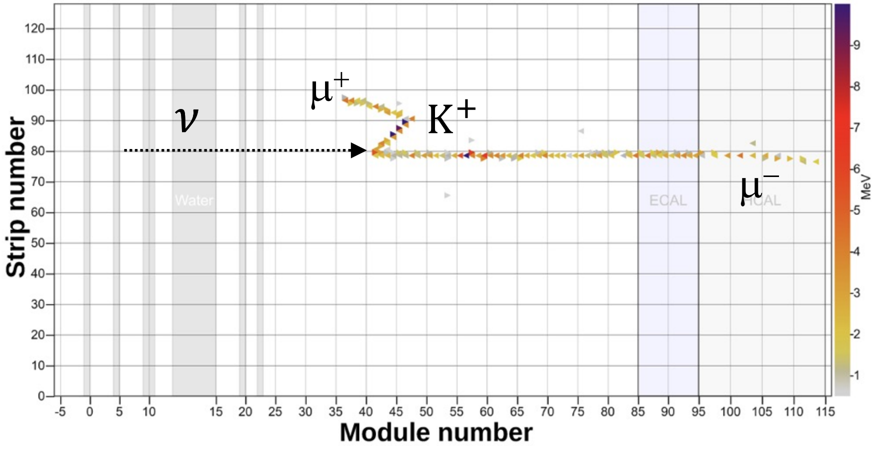


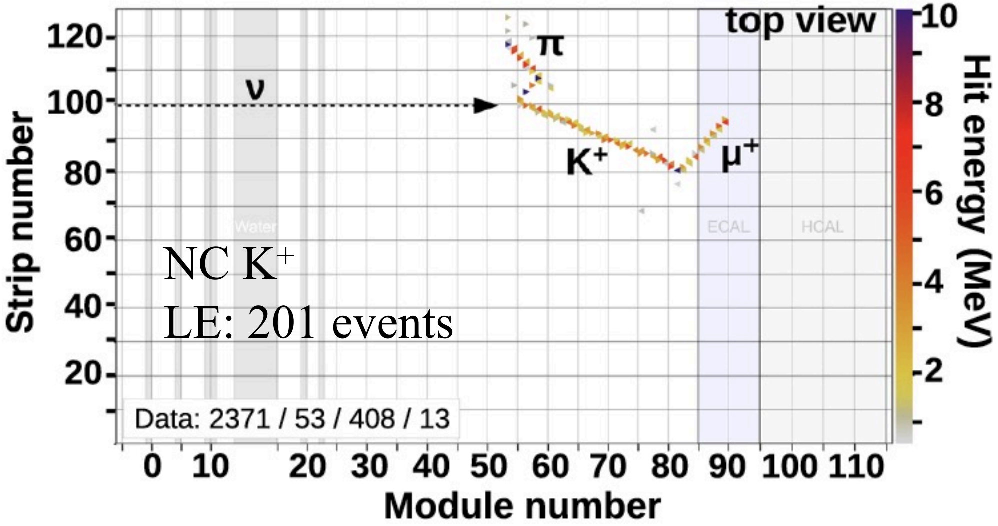
LE: 1628 and 770 events
in ν and $\bar{\nu}$ samples

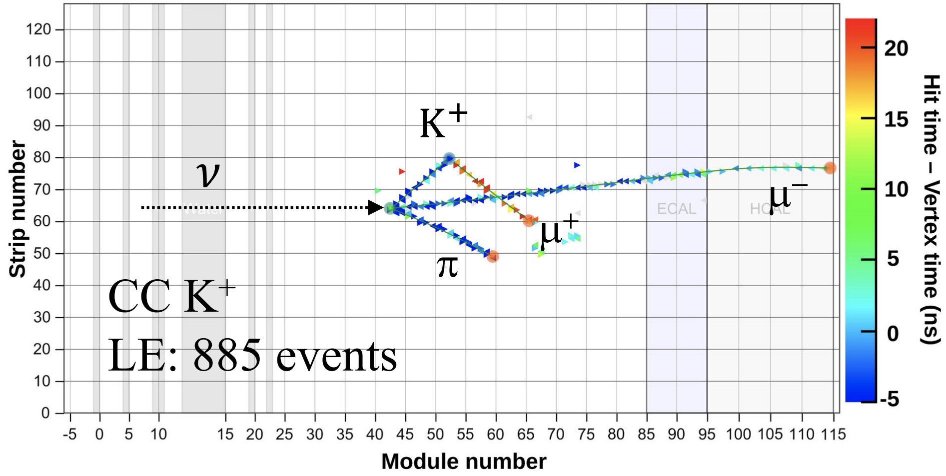
Kaon Production

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

"Inverse kaon decay"
— Coherent K^+

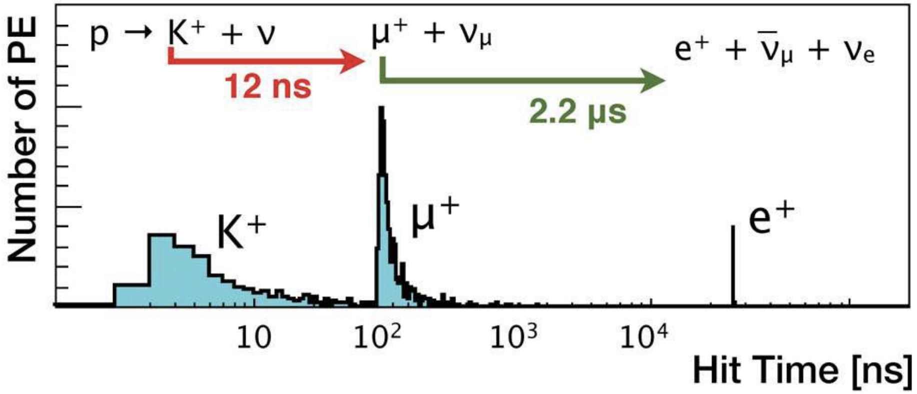






- K^+ decay-at-rest signature
  12.4 ns lifetime, kink, energy deposit
- LE: 6 events, predicted BG 1.77, 3.0σ

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



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

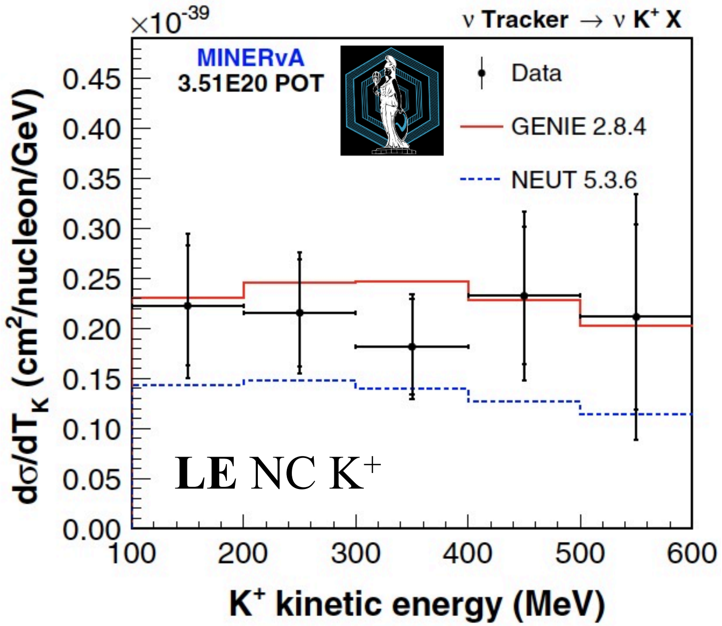
  Or not?

Protons inside a nucleus

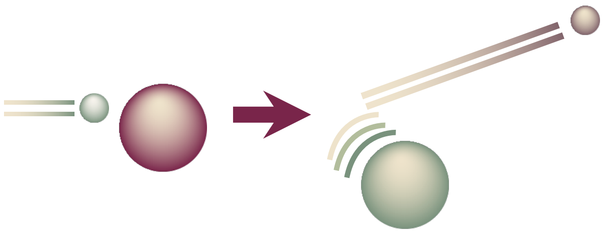
- ❑ Bound nucleons are moving—Fermi motion
- ❑ Interactions while exiting, very often breaking up the nucleus—final state interactions (FSI)

Bound-proton decay

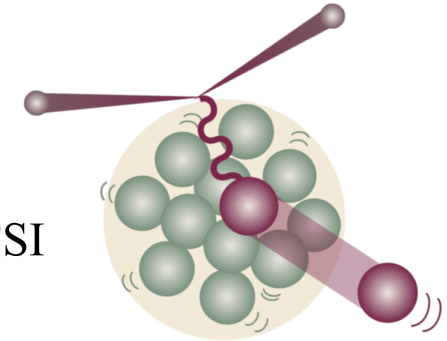
- ❑ K^+ 20-200 MeV K.E. (not considering FSI) [JUNO, J.Phys.G 43, 030401 (2016)]
- ✗ background from K^+ production by atmospheric neutrinos
- → MINERvA can constrain it!



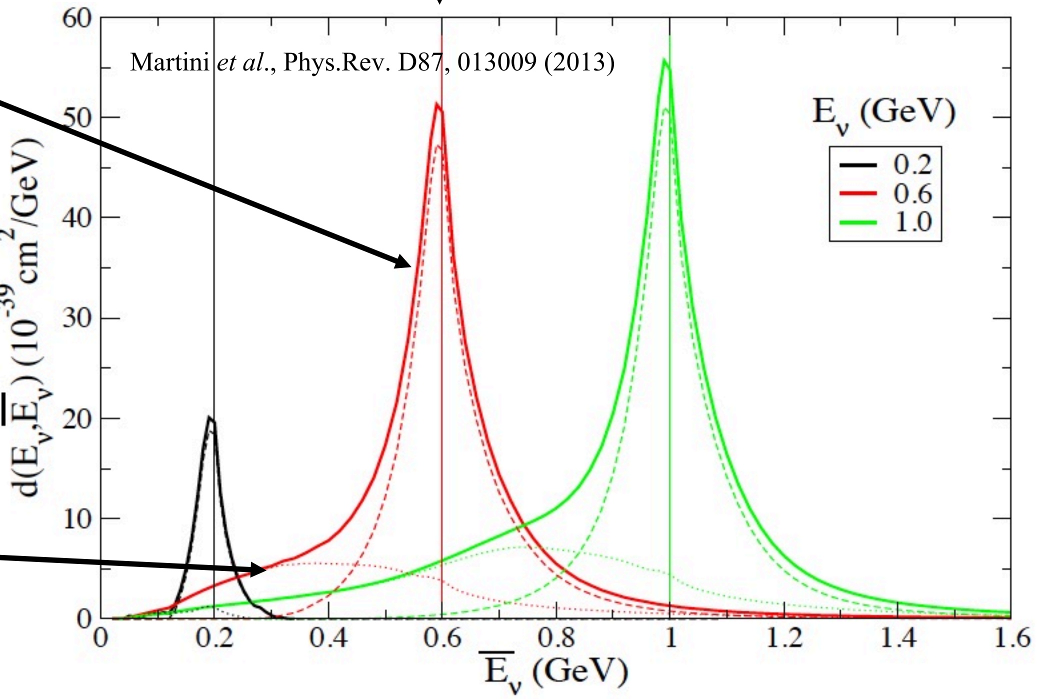
How well can we measure neutrino energy?
(reminder: oscillation very sensitive to baseline and energy, L/E)

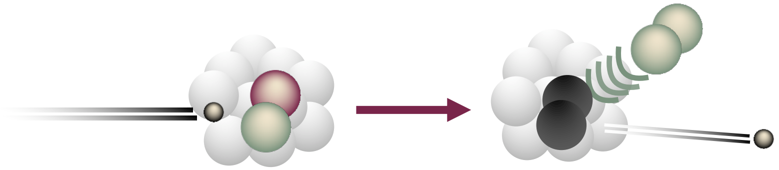


2-body reaction
—precise



Fermi motion, FSI
—spread





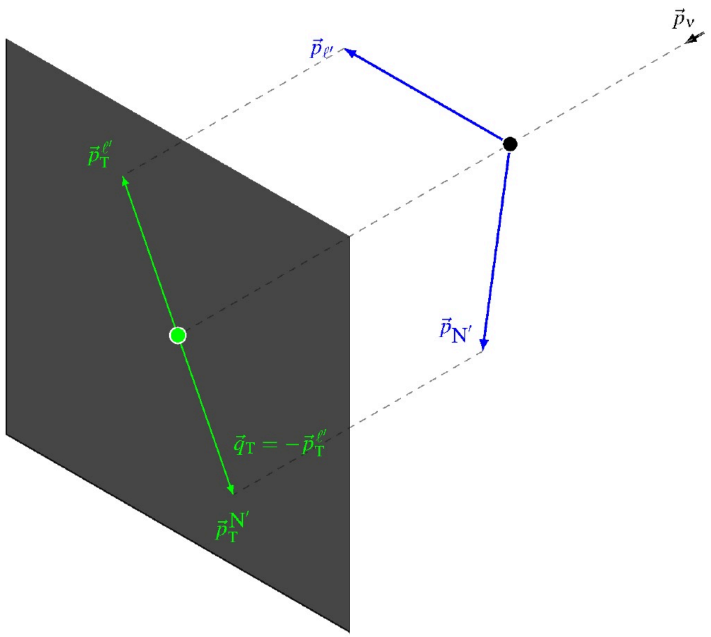
2p2h
—large (not well known) fraction of large bias and spread

Let’s think about something simpler…

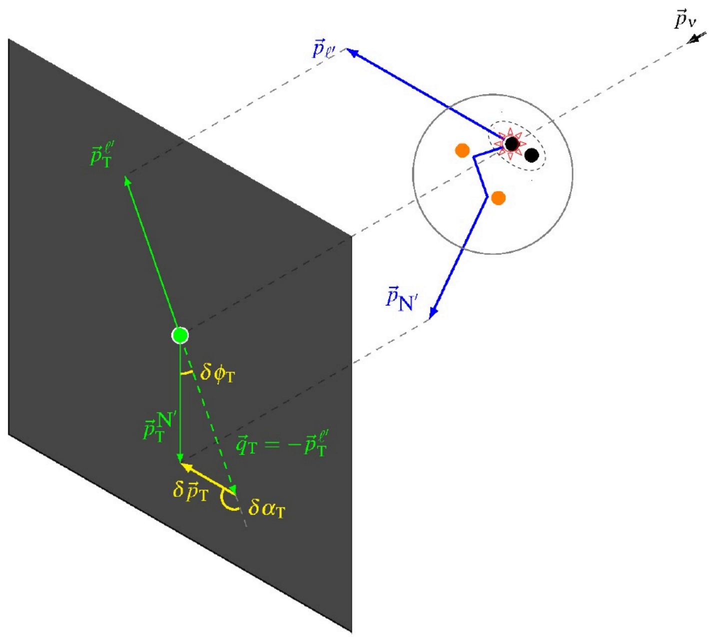
What do you see in this sculpture?

Transverse Kinematic Imbalance (TKI) 横向运动失衡法

– Precisely identify intranuclear dynamics, or the absence thereof, in interactions between nuclei and GeV-neutrinos from accelerators



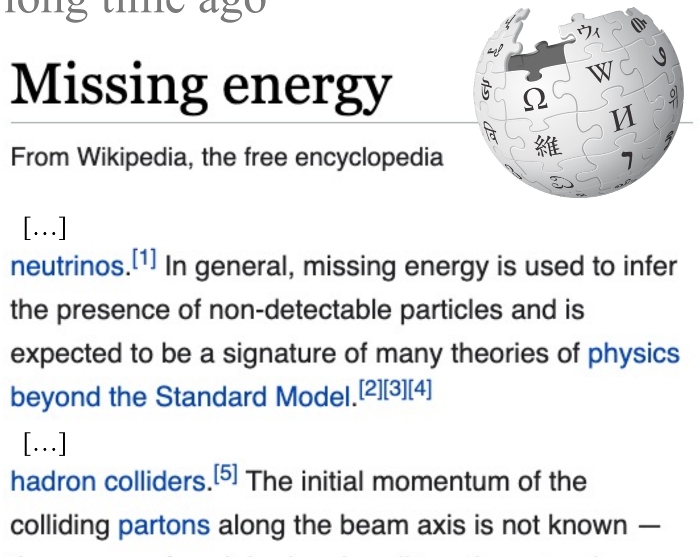
Stationary free nucleon target



Nuclear target ($A > 1$)

- ❑ Fermi motion
- ❑ Removal energy
- ❑ FSI
- ❑ 2p2h

Our collider neighbors have been using something similar since a long time ago



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

Transverse Kinematic Imbalance (TKI) 横向运动失衡法

— Community Effort So Far

Idea papers

XL *et al.*, Phys.Rev.D 92, 051302 (2015)
XL *et al.*, Phys.Rev.C 94, 015503 (2016)
Furmanski & Sobczyk, Phys.Rev.C 95, 065501 (2017)
Duyang *et al.*, 1809.08752
XL & Sobczyk, Phys.Rev.C 99, 055504 (2019)
Duyang *et al.*, Phys.Lett.B 795, 424 (2019)
Cai, XL, Ruterbories, Phys.Rev.D 100, 073010 (2019)
Cai *et al.* [MINERvA] Phys.Rev.D 101, 092001 (2020) [cf. Bodek & Cai, Eur.Phys.J.C 79, 293 (2019)]
Munteanu *et al.*, Phys.Rev.D 101, 092003 (2020)
Hamacher-Baumann, XL, Martín-Albo, Phys.Rev.D 102, 033005 (2020)

Measurements

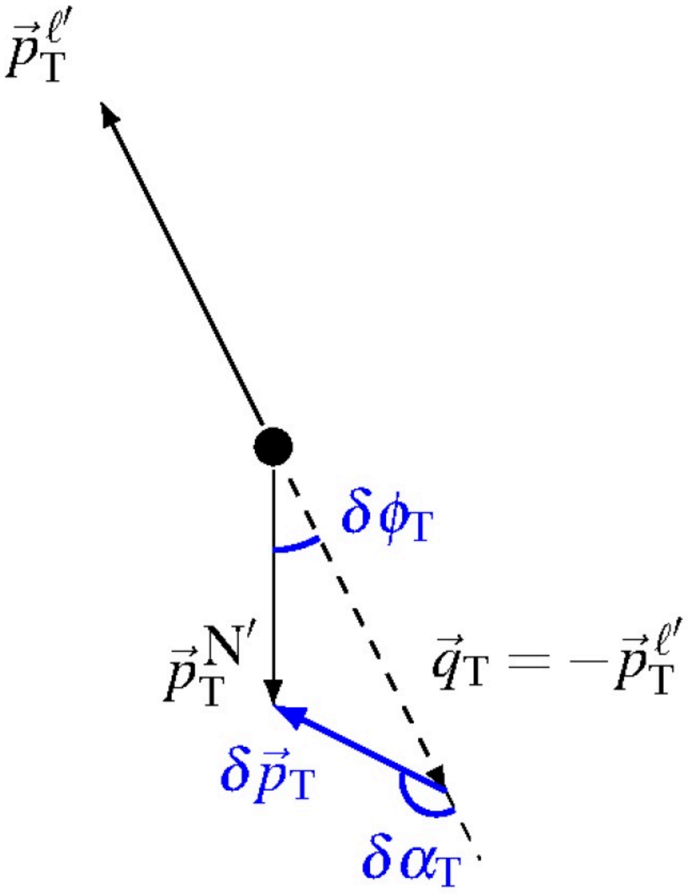
T2K Phys.Rev.D 98, 032003 (2018)
MINERvA Phys.Rev.Lett. 121, 022504 (2018)
MINERvA Phys.Rev.D 101, 092001 (2020)
MINERvA Phys.Rev.D 102, 072007 (2020)
T2K 2102.03346

Phenomenology

Dolan *et al.*, Phys.Rev.C 98, 045502 (2018)
Dolan, 1810.06043
Harewood & Gran, 1906.10576
Bourguille, Nieves, Sanchez, 2012.12653

Applications can also be found in
T2K ND Upgrade TDR, 1901.03750
DUNE ND CDR, 2103.13910

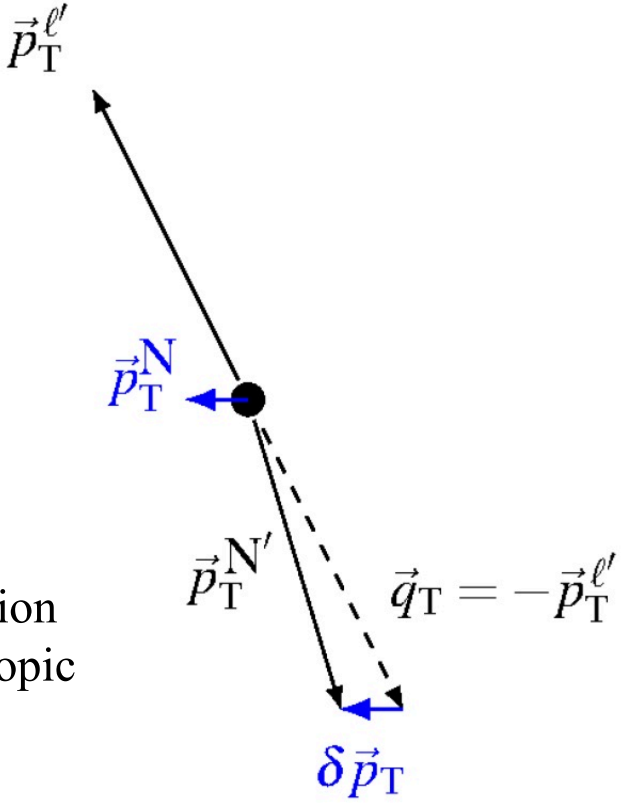
Transverse Boosting Angle $\delta\alpha_T$ [XL *et al.*, Phys.Rev.C 94, 015503 (2016)]



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

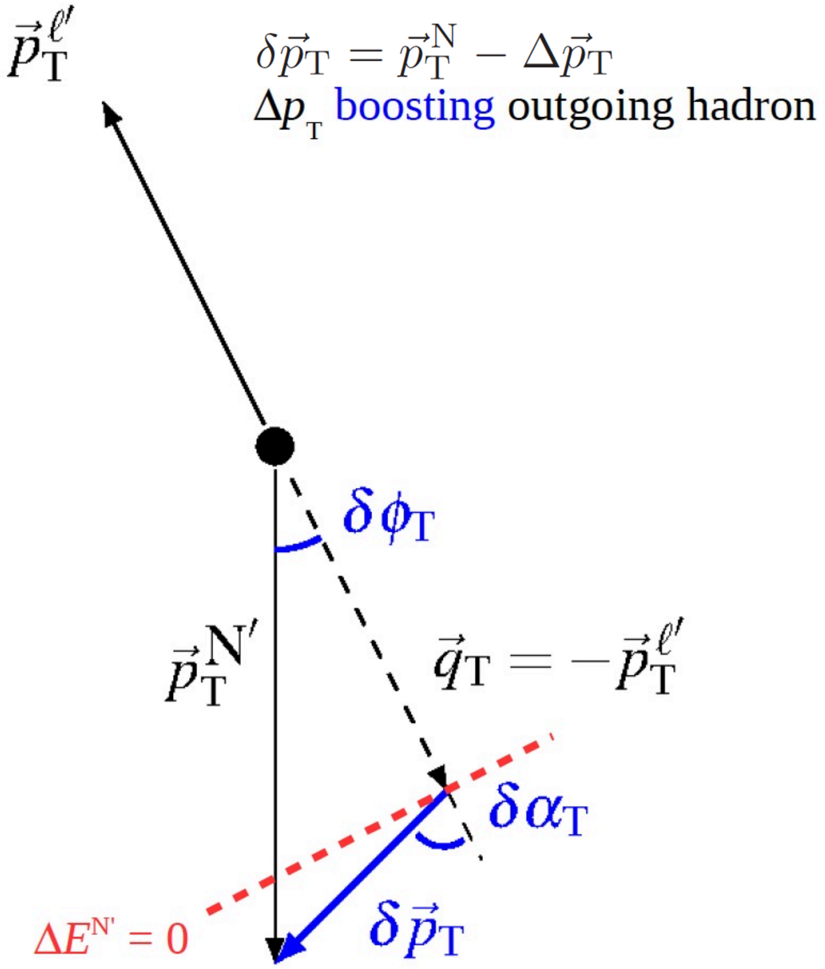
—...

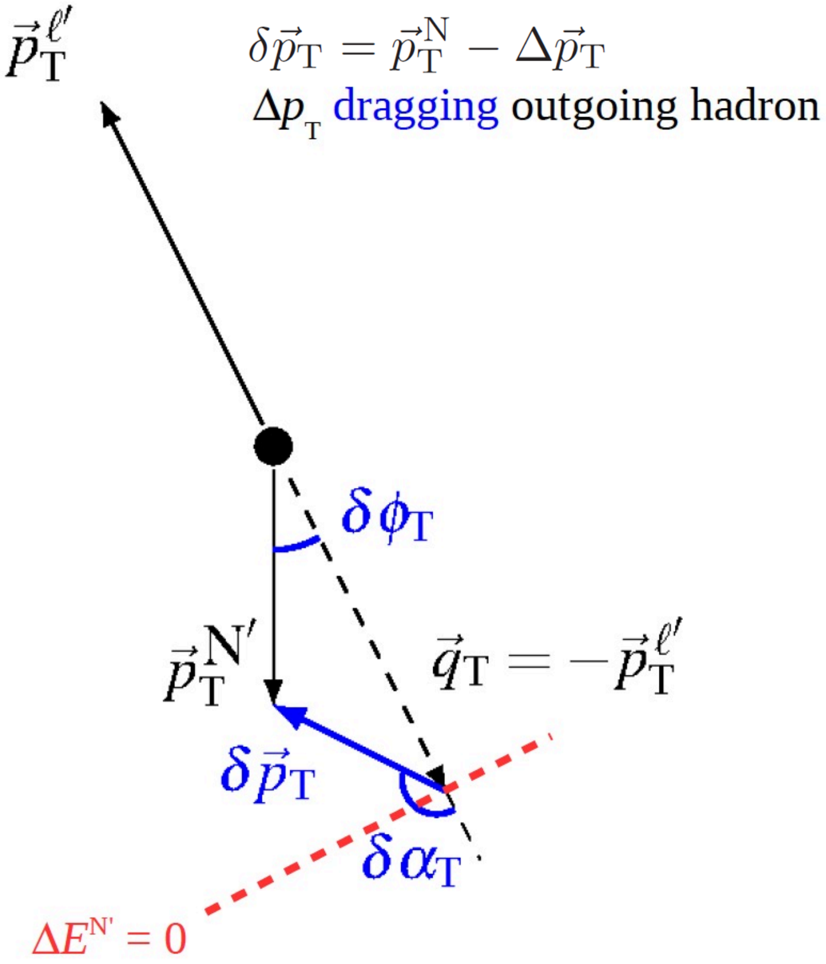
In full

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

FSI and missing particles

Transverse Boosting Angle $\delta\alpha_T$ [XL *et al.*, Phys.Rev.C 94, 015503 (2016)]





FSI and momentum sharing with extra particles

- ❑ Nucleus break-up
- ❑ 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

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

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

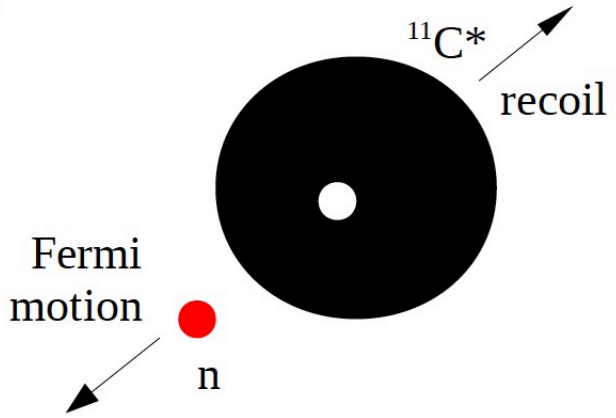
p_n: recoil momentum of the nuclear remnant

final-state

Dual Interpretation

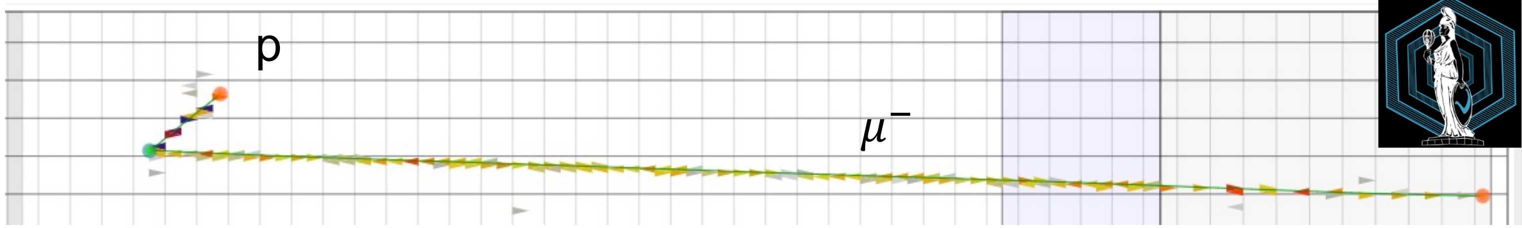
For CCQE, A' = $^{11}C^*$
No more unknowns
p_n: neutron Fermi motion

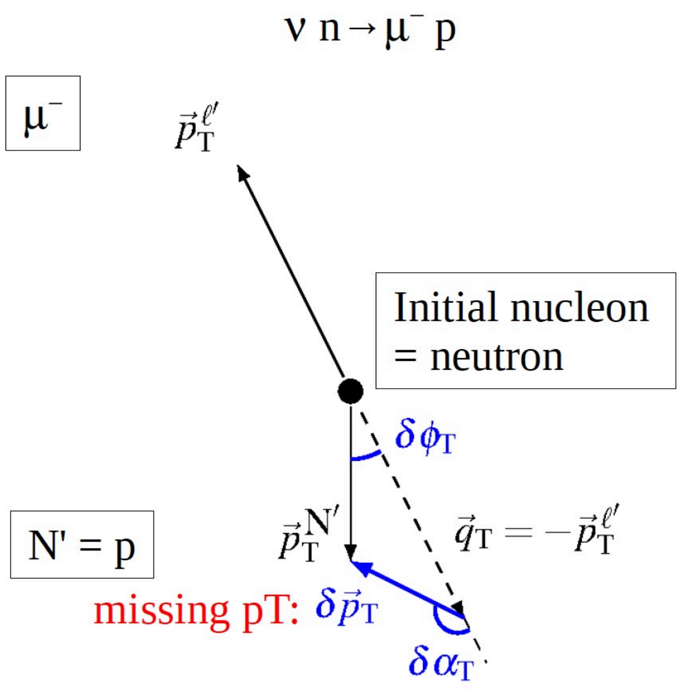
initial-state



TKI CCQE-like

LE: Phys.Rev.Lett. 121, 022504 (2018)

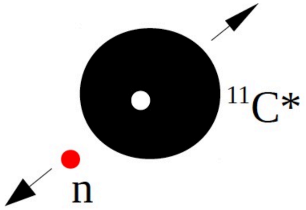


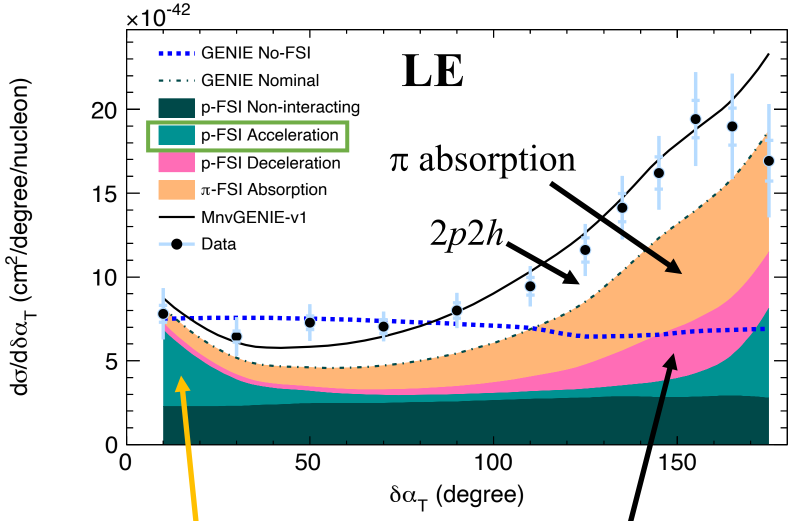


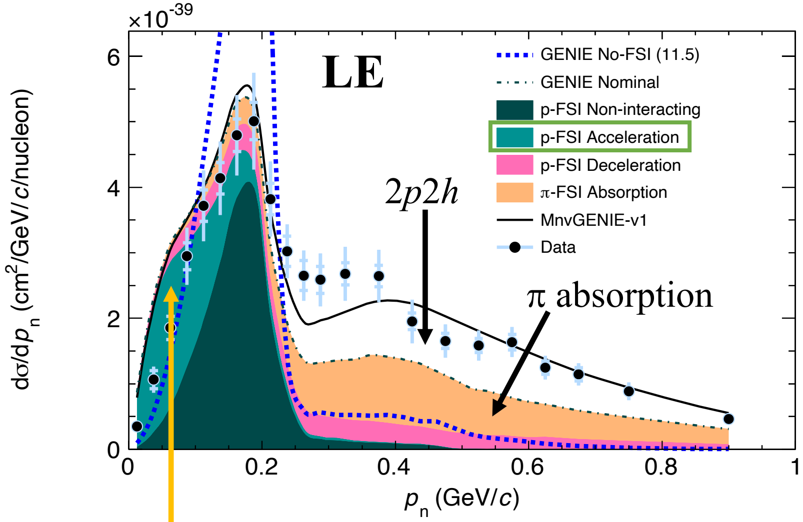
Assuming target remnant $^{11}C^*$

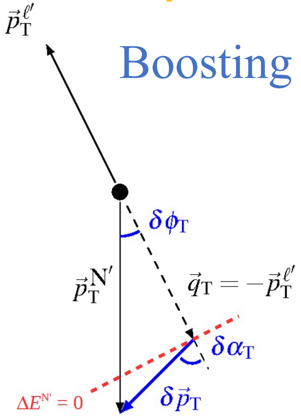
$$p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$$

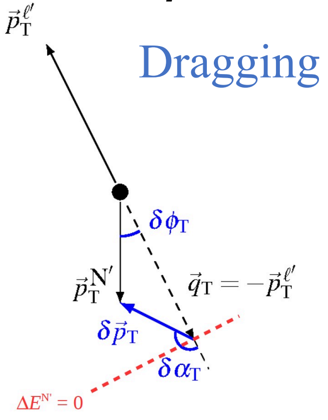
$\sim [1 + O(10\%)] \times \delta p_T$











Abnormal acceleration

- ❑ GENIE FSI (v2.8 hA)

  —not dark energy

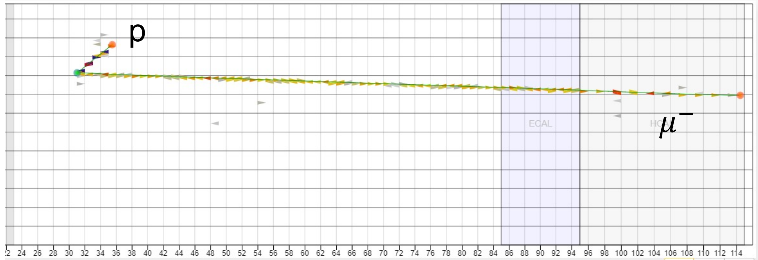
- ❑ Removed in later versions

TKI CCπ^0

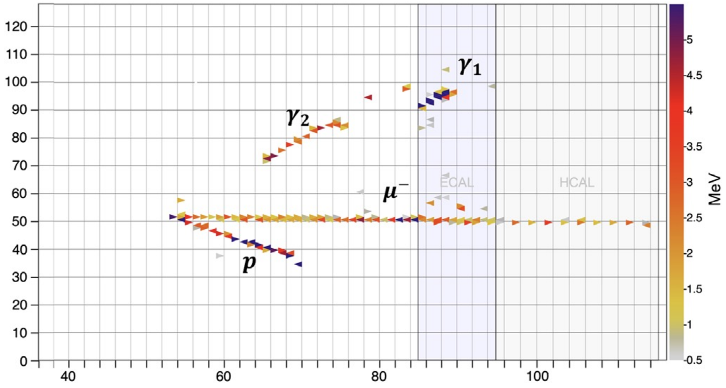
LE: Phys. Rev. D 102, 072007 (2020)

Partly expected, partly very surprising consistency!

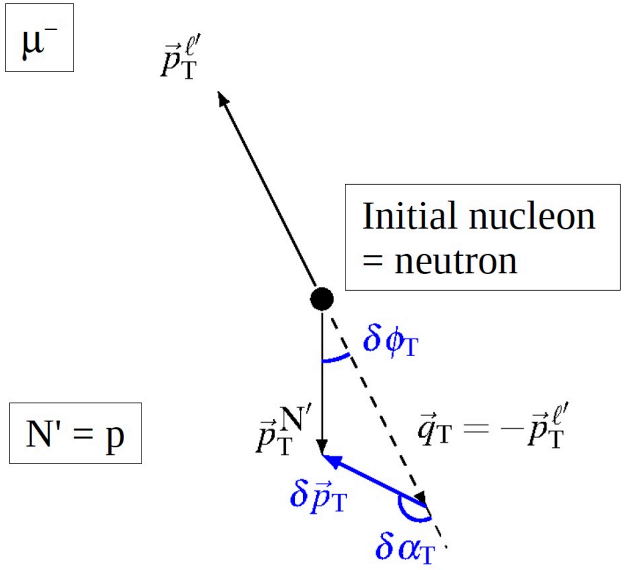
Now compare data to models separately



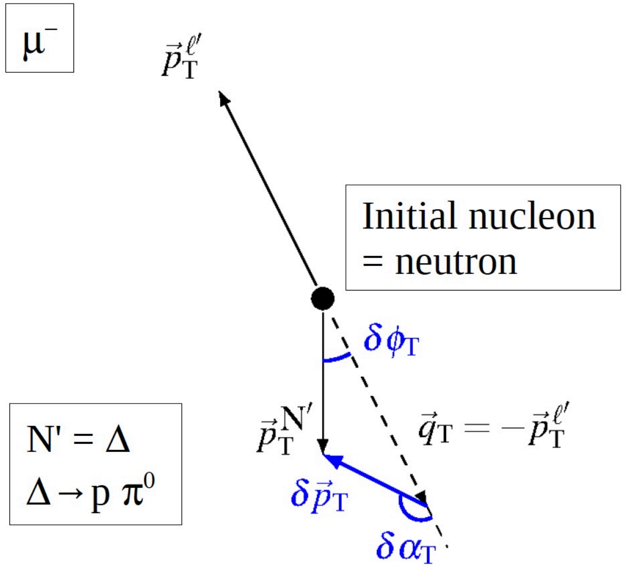
$\nu\, n \rightarrow \mu^- p$



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

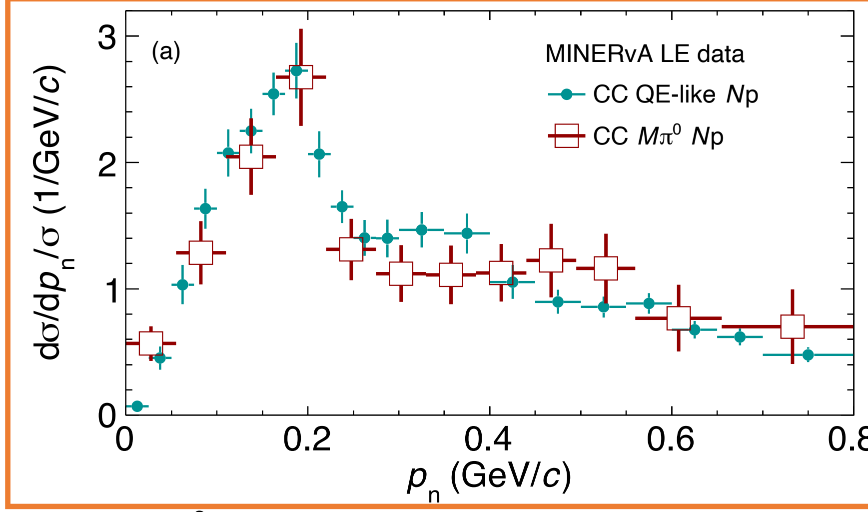


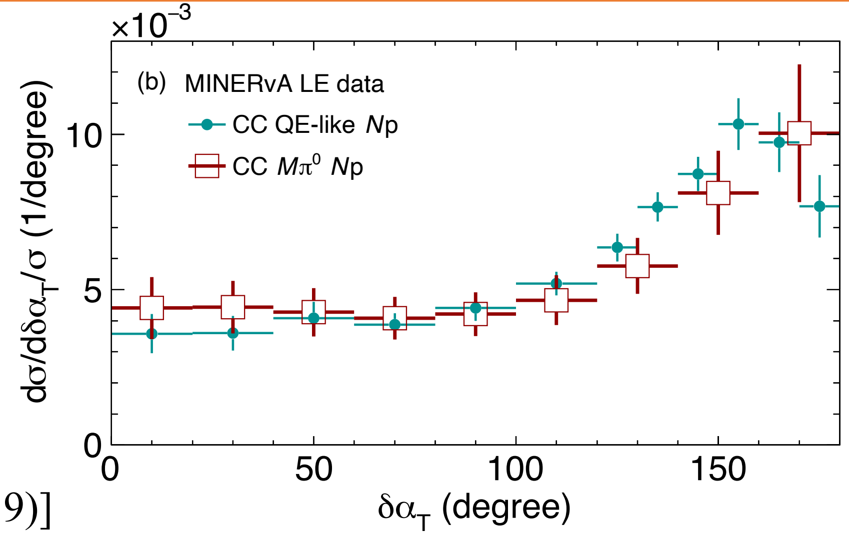
via QE-like measurement



via inclusive π^0 production

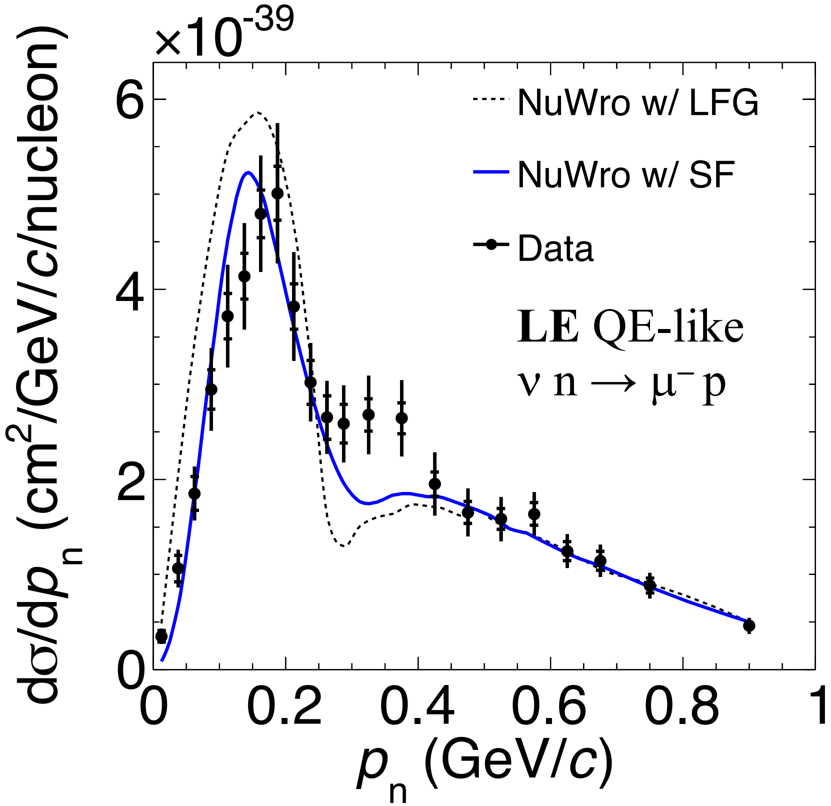
[XL & Sobczyk, Phys.Rev.C 99, 055504 (2019)]

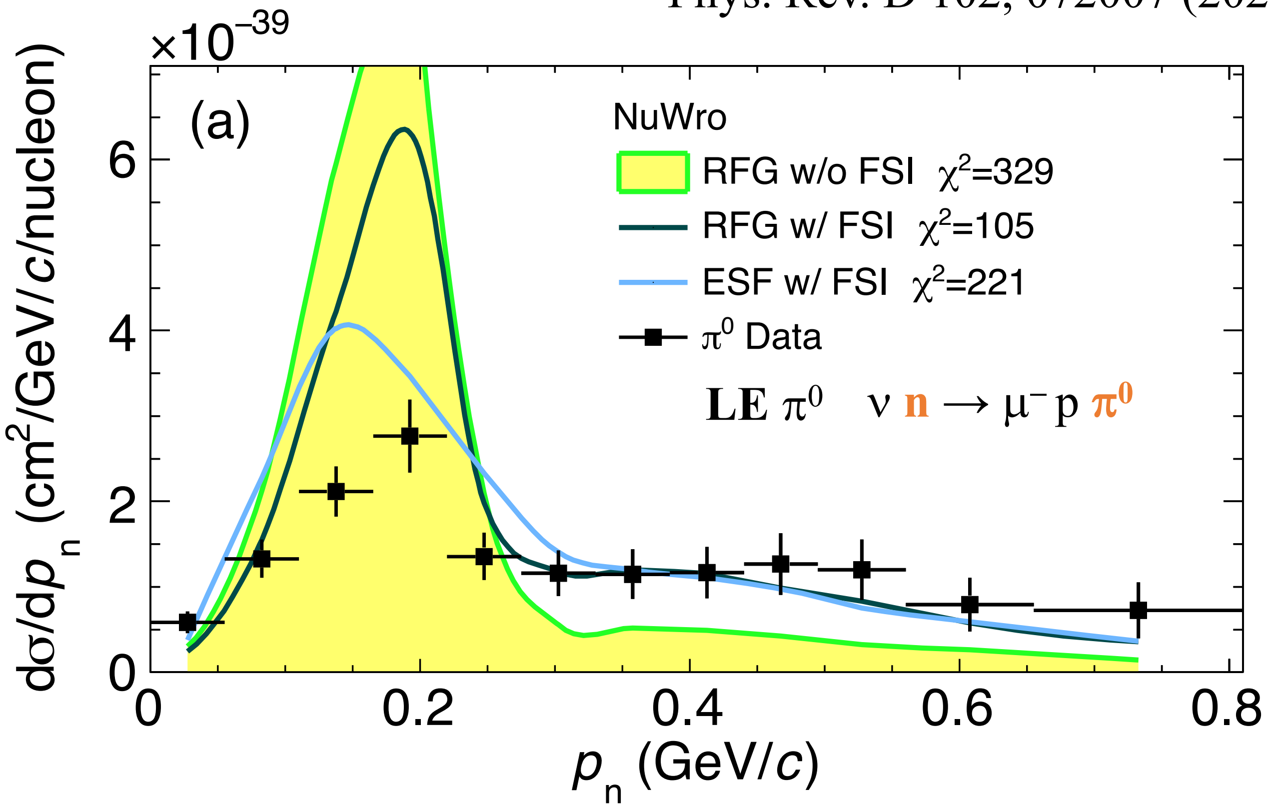




TKI—Initial-state effects

LE: Phys.Rev.Lett. 121, 022504 (2018)
Phys. Rev. D 102, 072007 (2020)



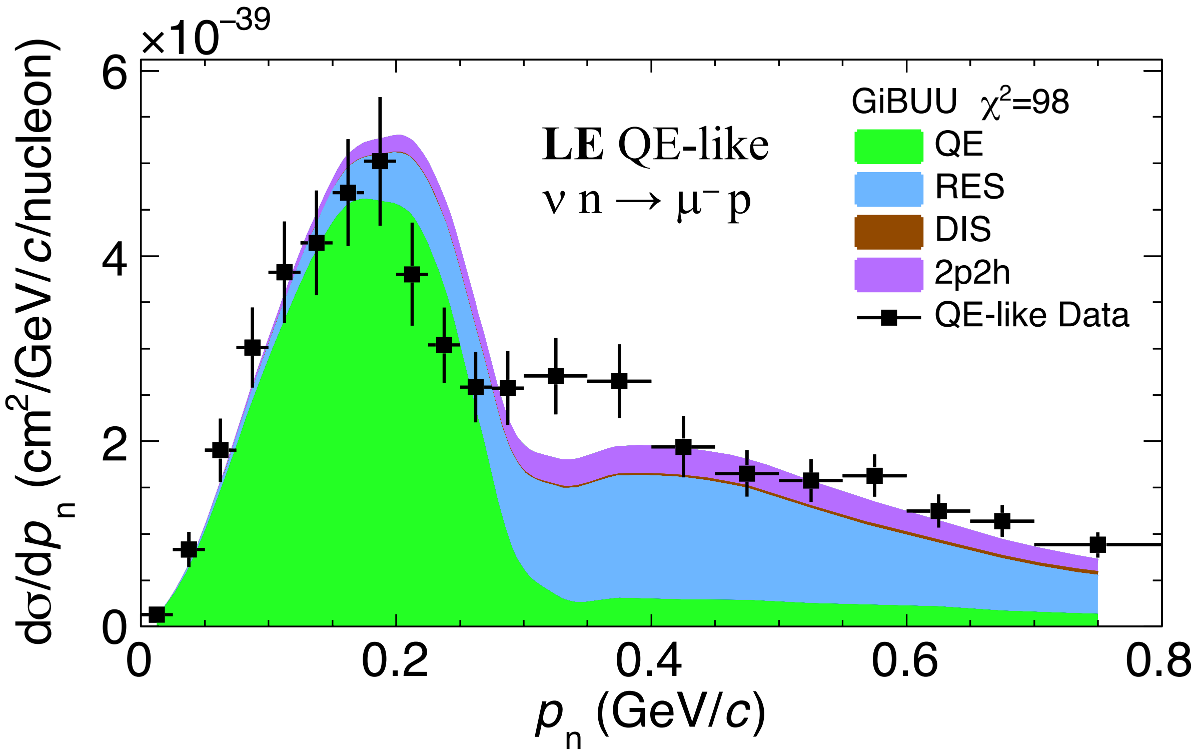


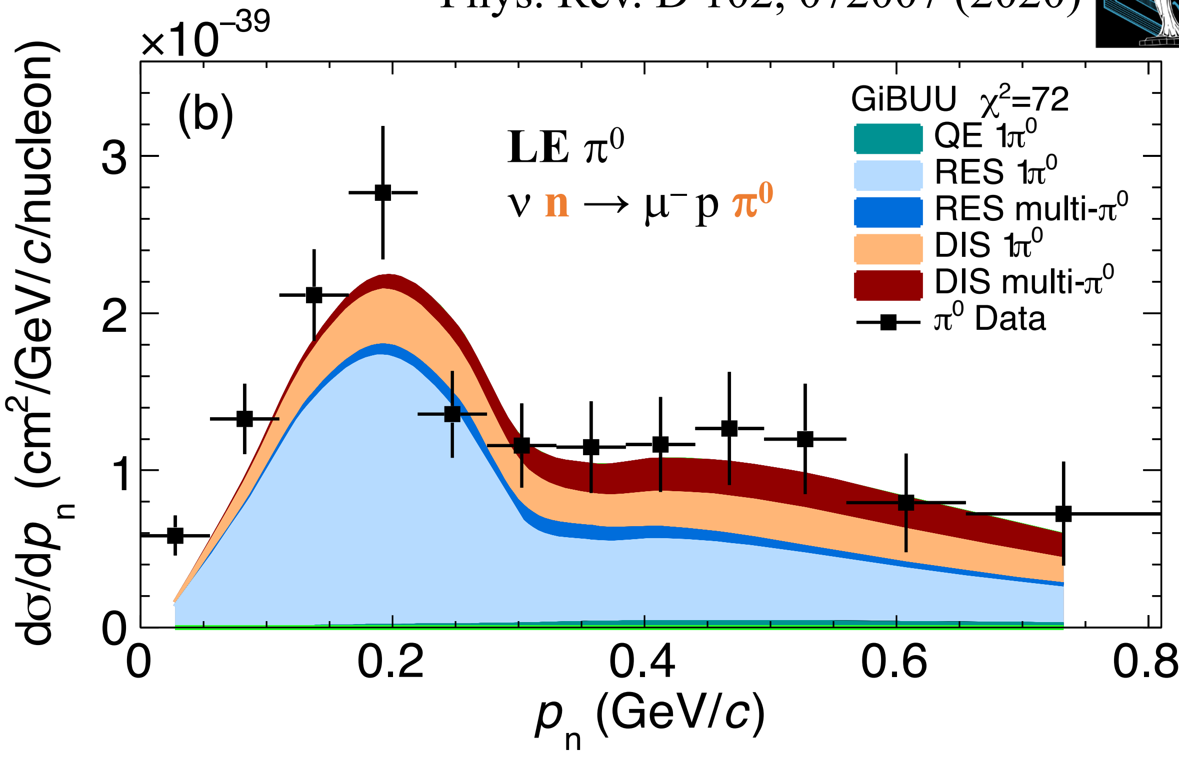
Initial-state models:

- ❑ **Relativistic Fermi gas (RFG)**—simple Fermi gas model
- ❑ **Local Fermi gas (LFG)**—Fermi motion sampling depends on nucleon location (local density)
- ❑ **Spectral function (SF)** and **effective spectral function (ESF)**—Fermi motion and removal energy sampling, short range correlation (SRC) leading to momentum exceeding Fermi surface
  - ❖ Decent agreement for $\nu n \rightarrow \mu p$, but *not* for $\nu n \rightarrow \mu p \pi$

TKI—Initial-state effects

LE: Phys.Rev.Lett. 121, 022504 (2018)
Phys. Rev. D 102, 072007 (2020)





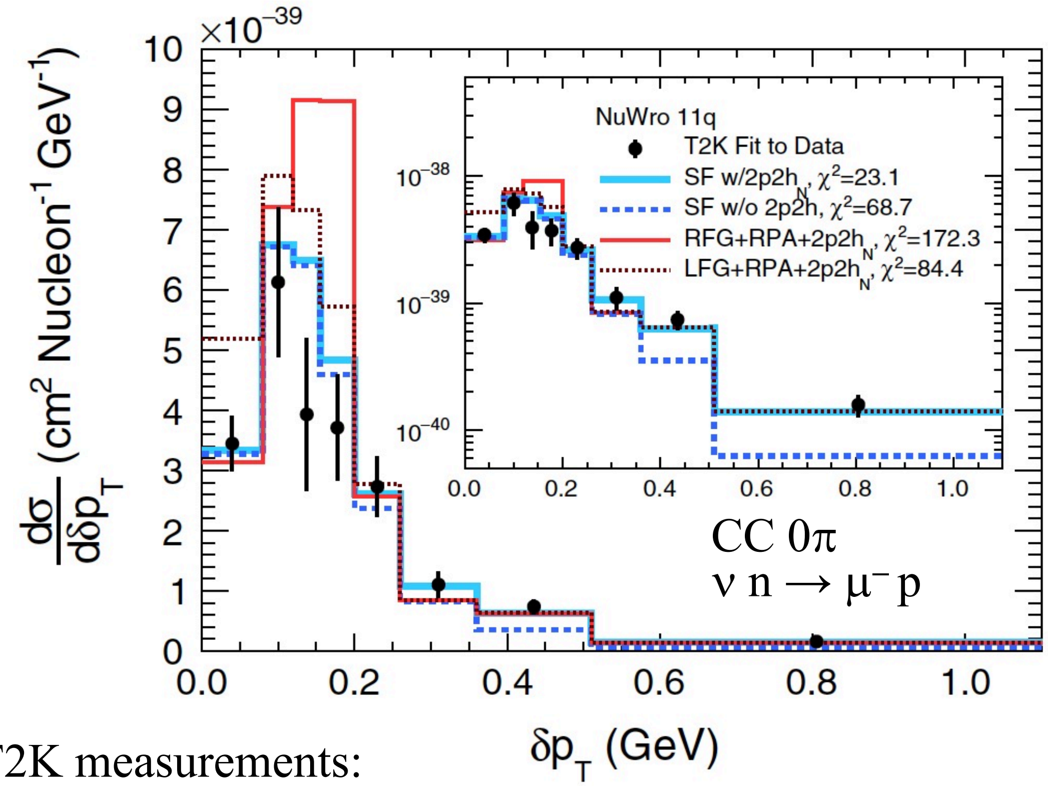
GiBUU offers very different predictions

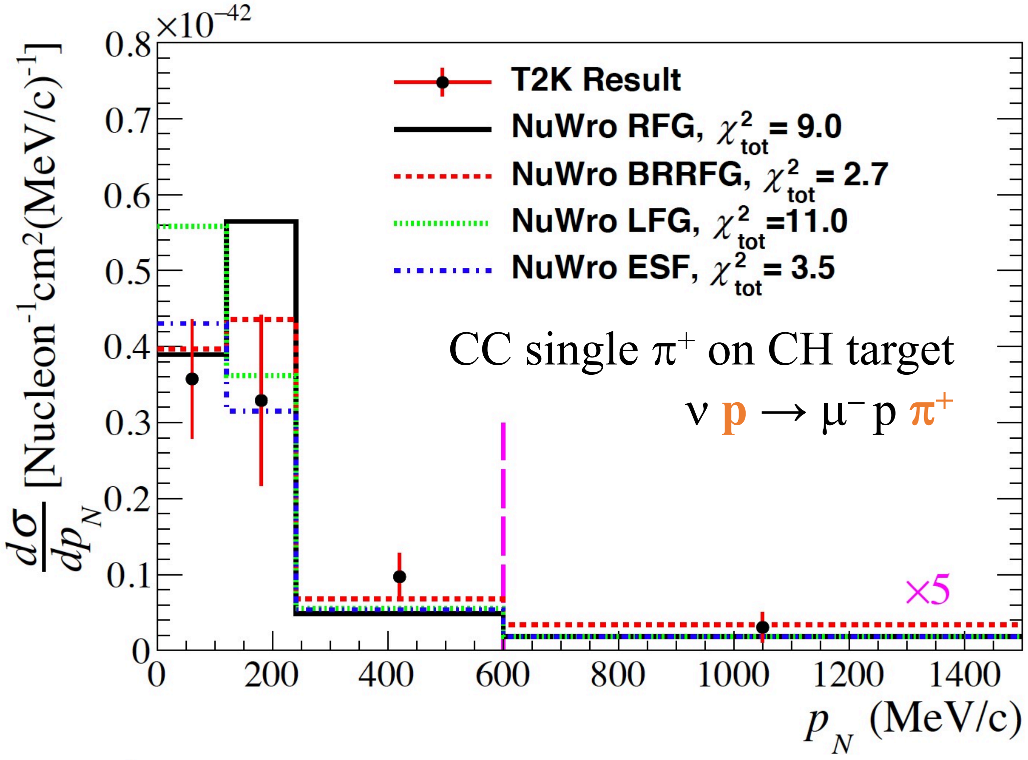
- ❑ Local Fermi gas embedded in nuclear potential
  - ❖ "More same" implementation of models in different channels
  - ❖ Fermi motion peak location better agree with π^0 data
    - ➢ But height *below* data

NB: 2p2h only in QE-like production, not overt pion production
FSI and 2p2h start to decouple

TKI—Initial-state effects

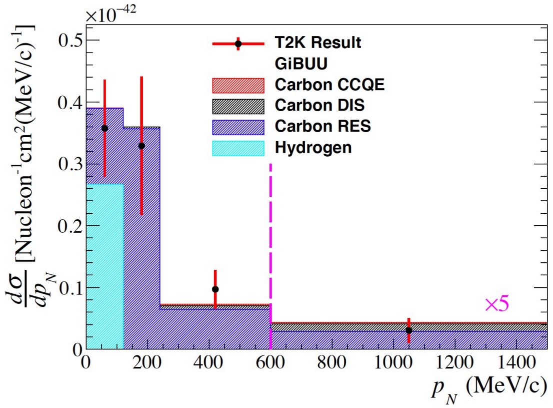
T2K: Phys.Rev.D 98, 032003 (2018)
2102.03346

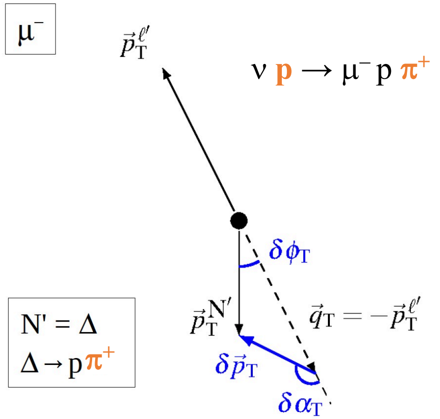




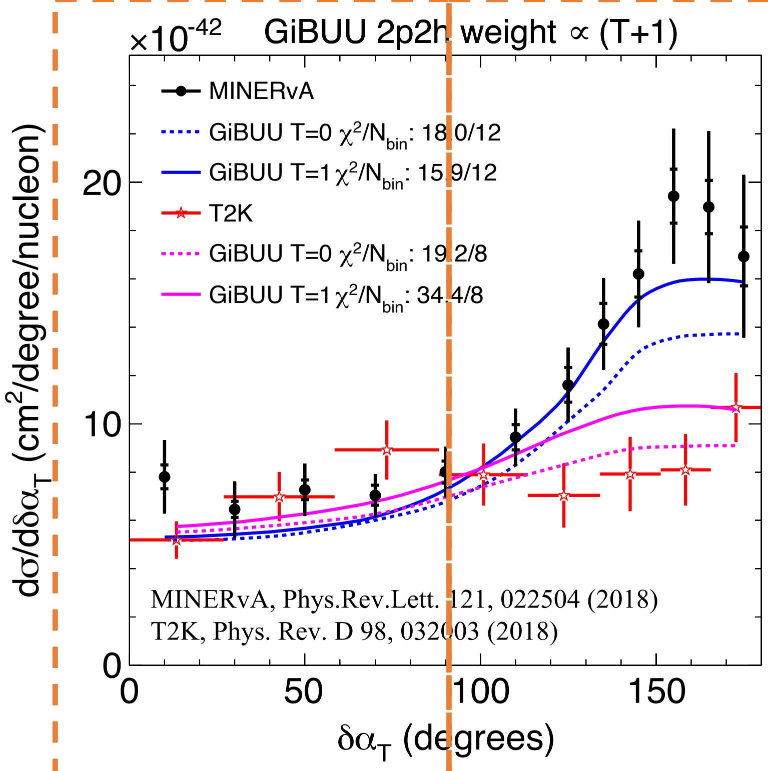
T2K measurements:

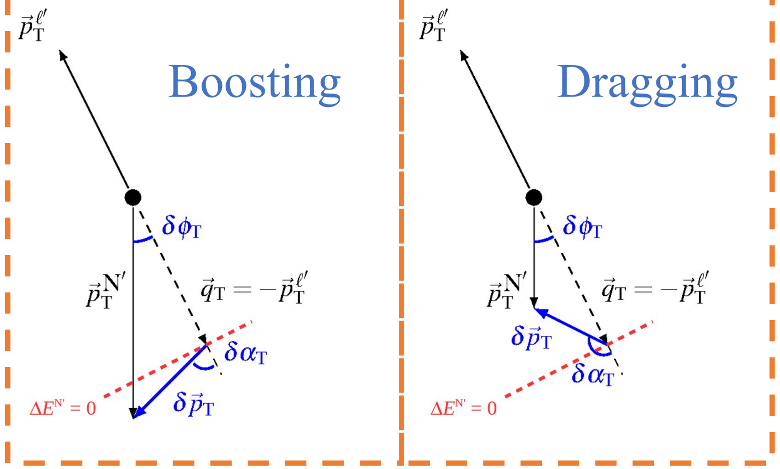
- CC 0π
  - Same-ish signal definition as MINERvA
  - Same observation: prefer SF over LFG
- CC single π⁺:
  - Complementary channel: have additional hydrogen contribution
  - ESF seems OK

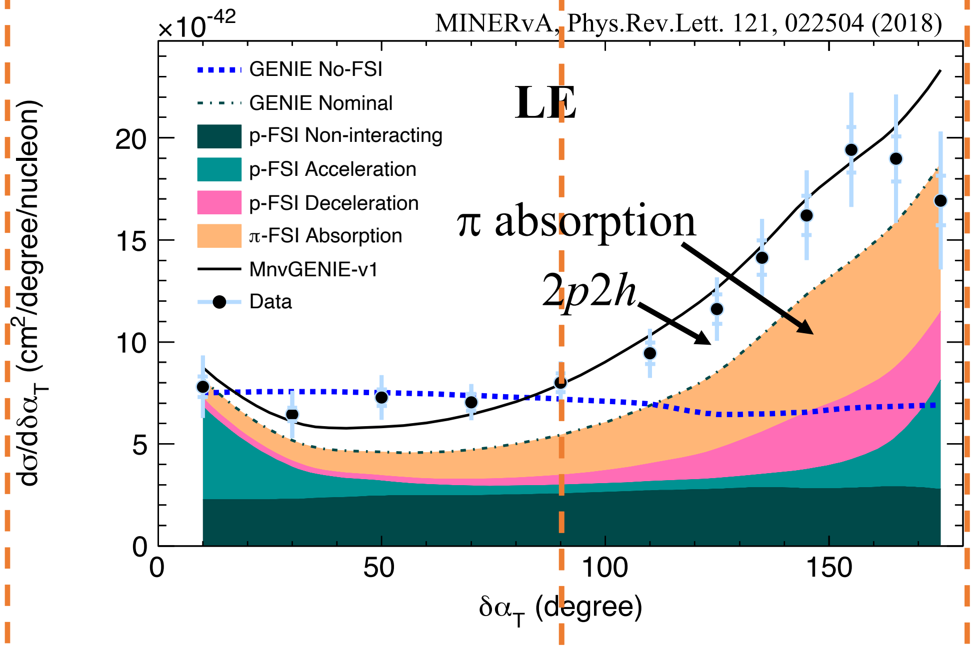




TKI—Final-state effects and 2p2h

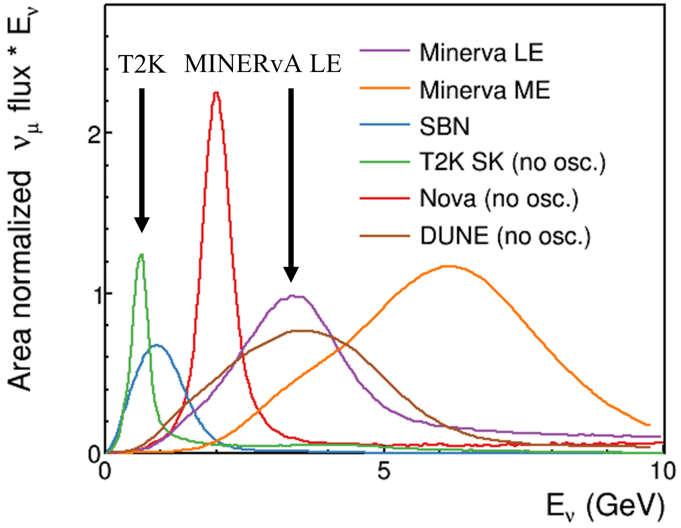






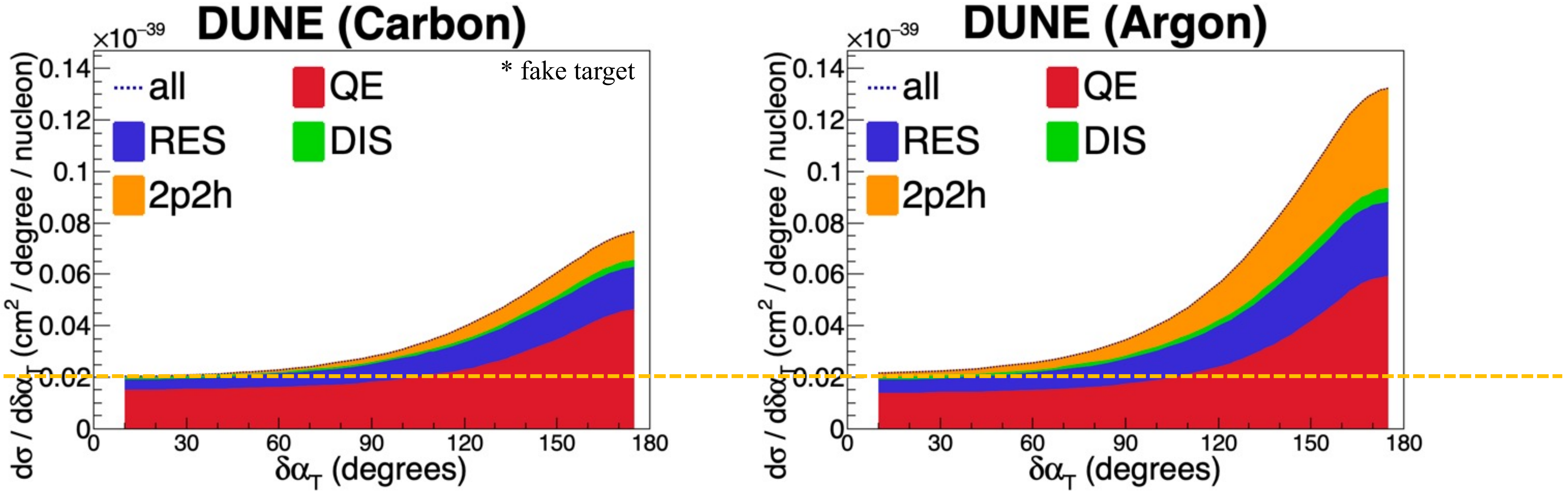
Consistent pure QE cross section (no boosting FSI in Nature)

- Smaller pion production and absorption at T2K energy
- Sensitive to 2p2h



TKI—Final-state effects and 2p2h

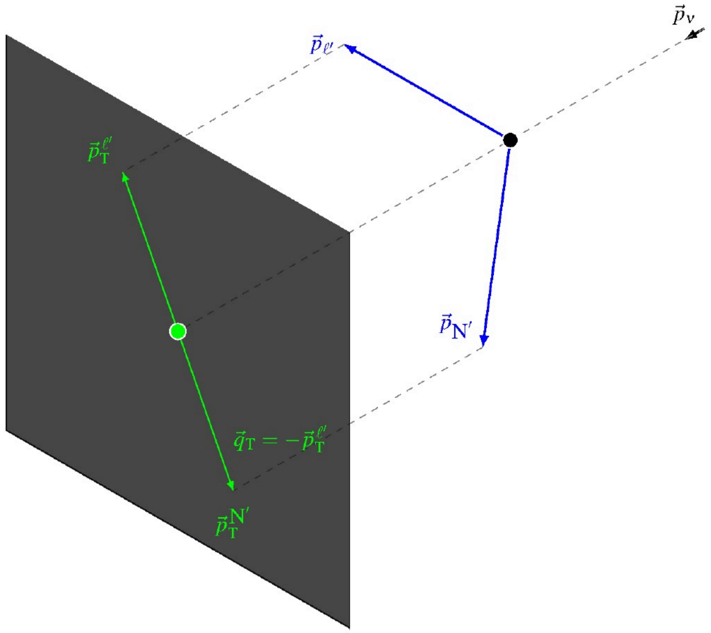
DUNE: 2103.13910



DUNE Ar gas TPC near detector, based on GiBUU QE-like predictions

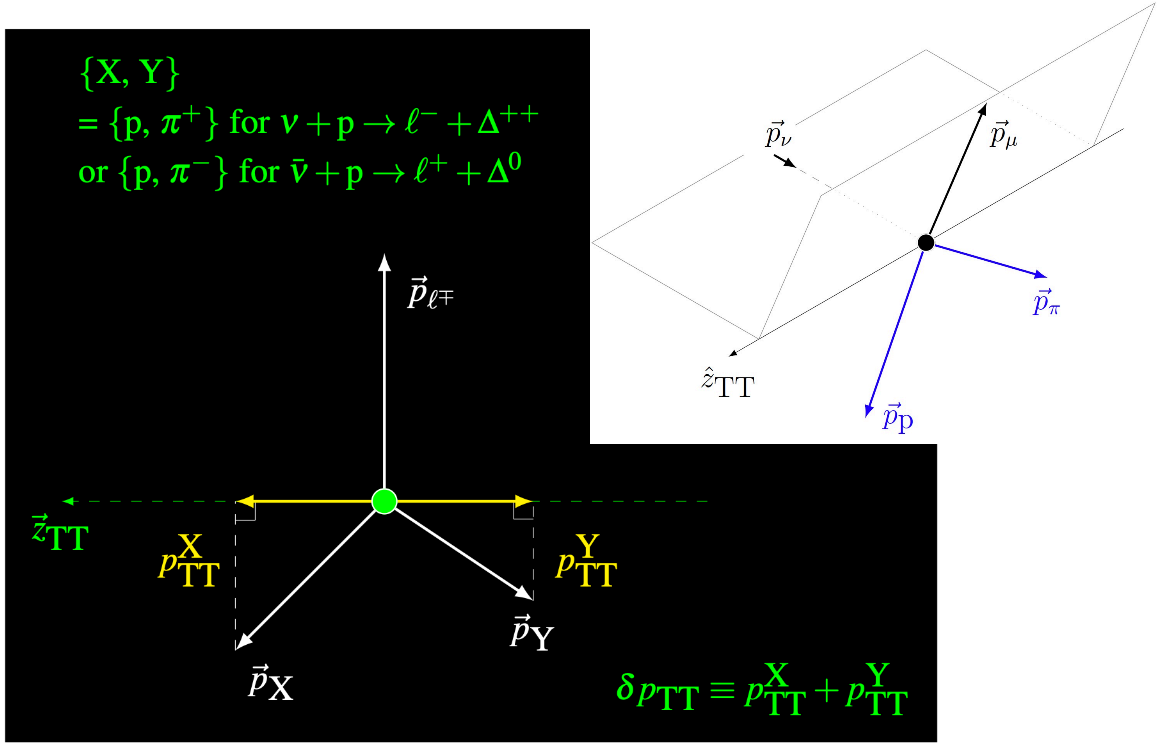
- ❑ Small $\delta\alpha_T$: very similar between C (fake target) and Ar
  - ✓ Predictable baseline constrained by C data from other experiments
  - ✓ Powerful calibration for new target material—*there is no ideal ν-Ar data for DUNE*
- ❑ Large $\delta\alpha_T$: target-dependent FSI (including pion absorption) and 2p2h

Further Ideas

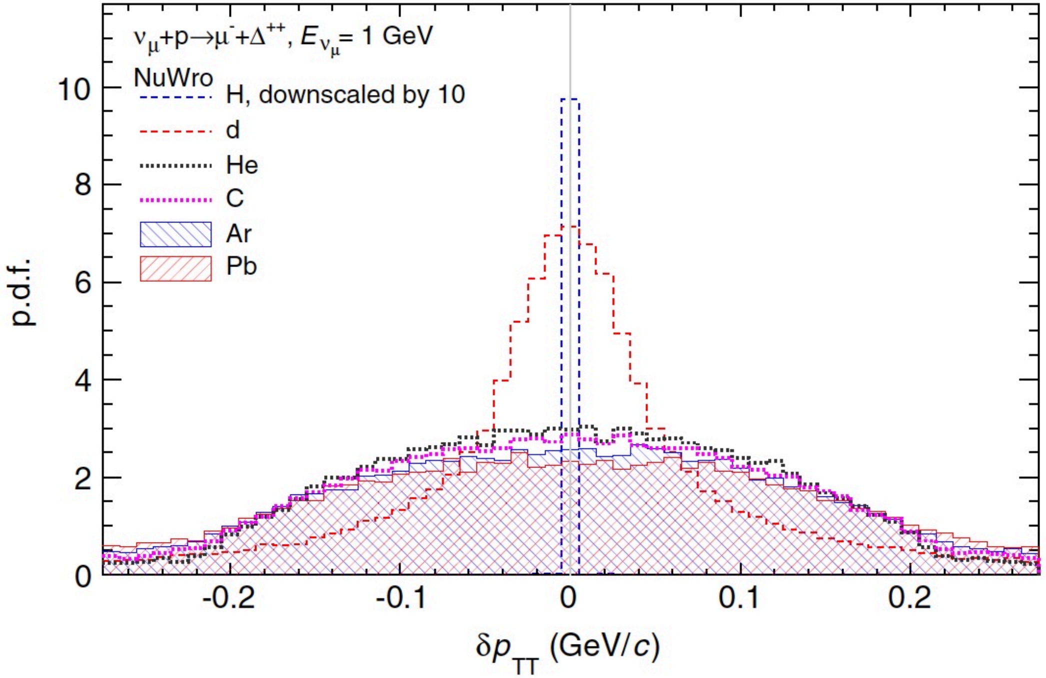


Consider only charged particle productions from ν-and $\bar{\nu}$-H interactions

- Leading channel has 3 final-state particles: μ, π, p



[XL *et al.*, Phys.Rev.D 92, 051302 (2015)]



Double-transverse momentum imbalance δp_{TT}

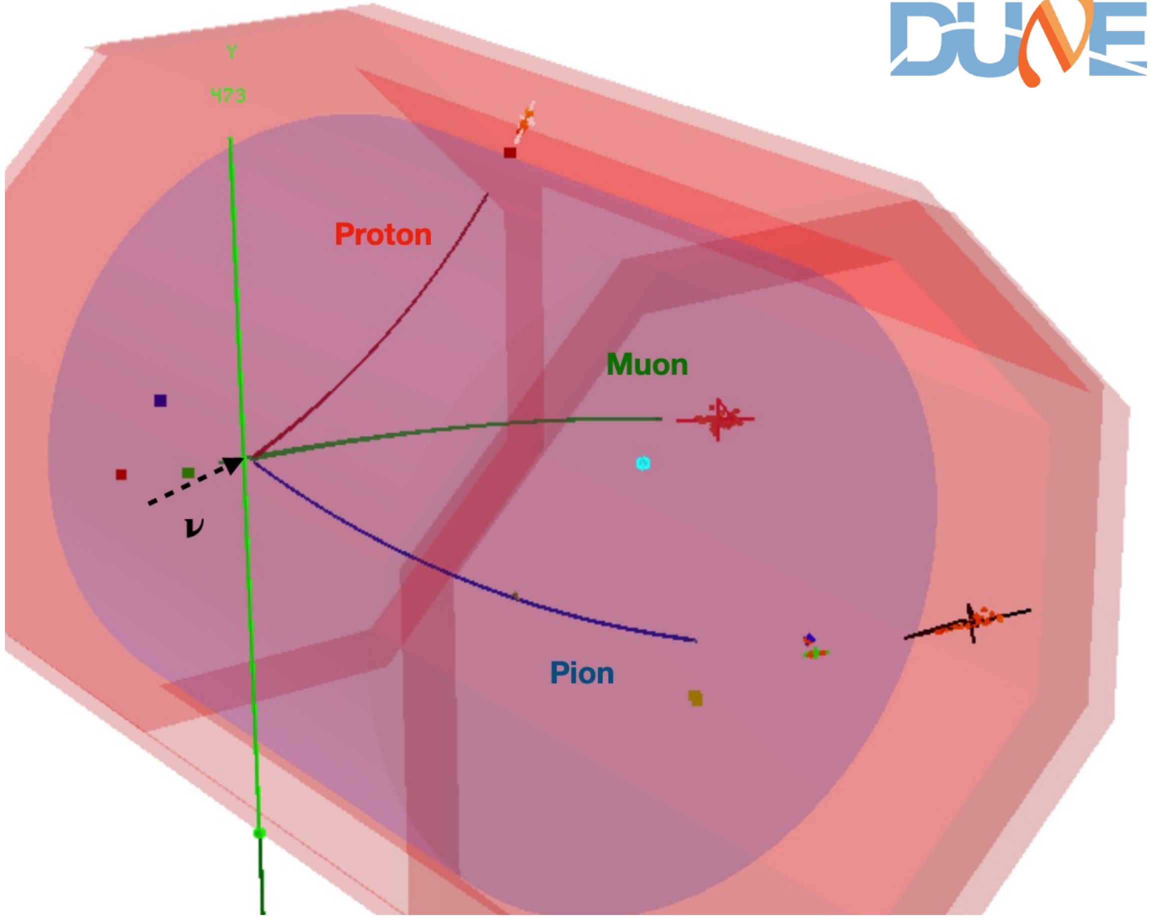
- H: 0
- A: *irreducible* broadening O(200 MeV) by Fermi motion etc.
- AH compound:

  ν-and $\bar{\nu}$-H can be extracted
- Given good enough tracking, can work for any targets

  Examples: plastic scintillator (CH or CH_2)

Hydrogen-rich high-pressure TPC

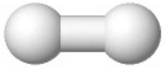
- Why gas TPC? Why high pressure?
  - Acceptance, tracking threshold
  - Target mass



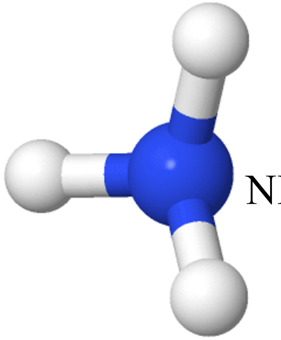
Raaf, TPC Mini Workshop
https://indico.cern.ch/event/827540/contributions/3487180/

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

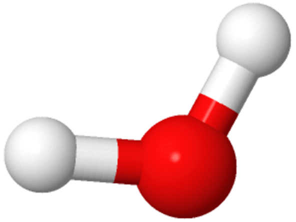


H_2



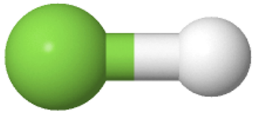
NH_3

Ammonia



H_2O

Water

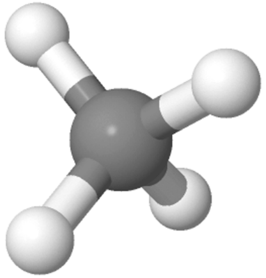


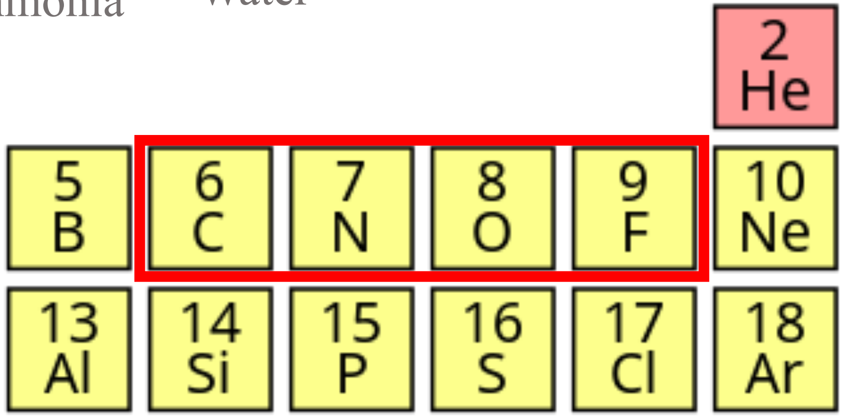
HF

Hydrogen fluoride

CH_4

Methane





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

Jmol: an open-source Java viewer for chemical structures in 3D.
http://www.jmol.org/

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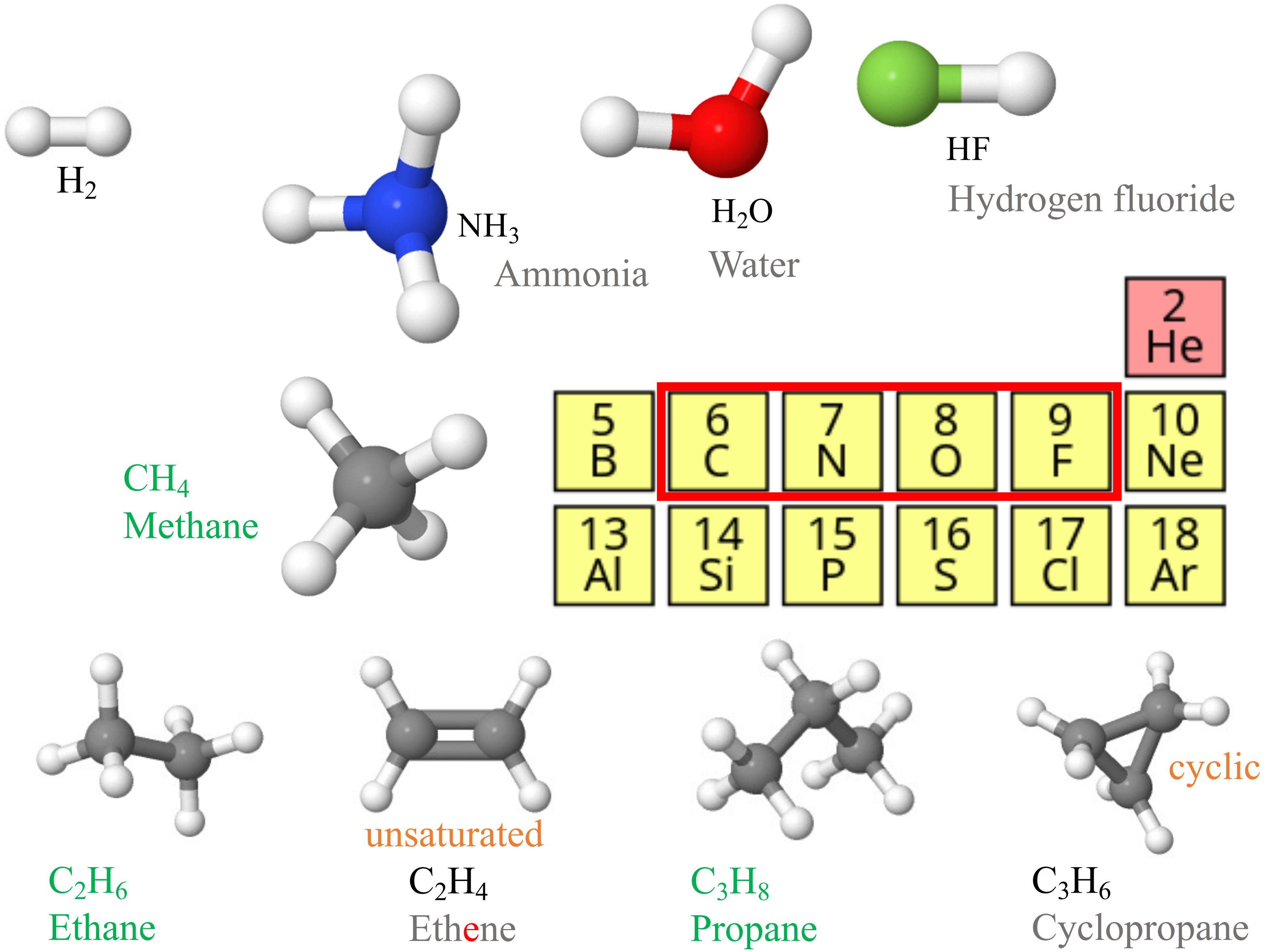
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y
    - ➢ Saturated, acyclic: Alkane C_nH_{2n+2}
      - ✓ CH_4 most efficient H-carrier, but not the largest one



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

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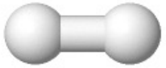
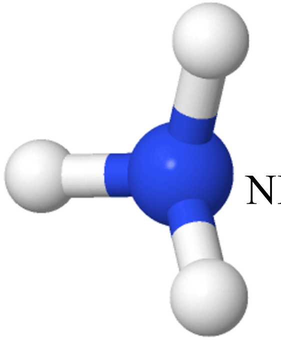
  - ❖ Element carrying as much hydrogen as possible: Carbon base C_xH_y
    - ➢ Saturated, acyclic: Alkane C_nH_{2n+2}
      - ✓ CH_4 most efficient H-carrier, but not the largest one
  - ❖ Maximal partial pressure limited by vapor pressure
    - ➢ Theoretically hydrogen-richest mix at 10 bar: $C_{3.93}H_{9.86}$

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

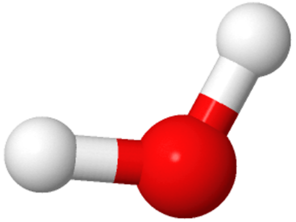
[Hamacher-Baumann, XL, Martín-Albo, Phys.Rev.D 102, 033005 (2020)]



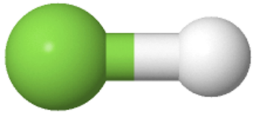
H_2



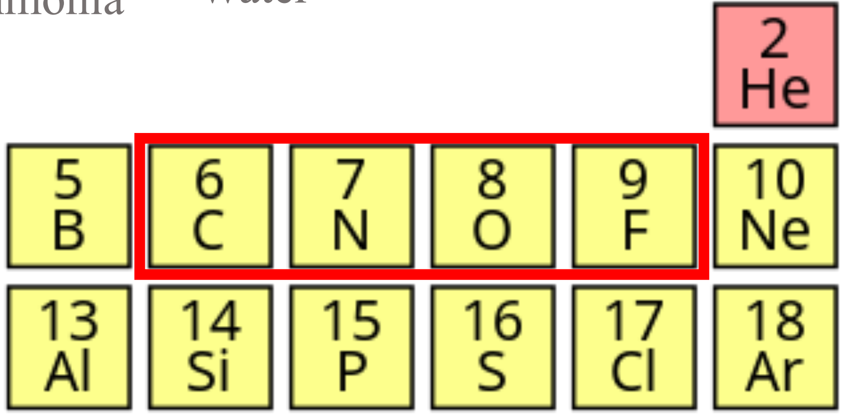
NH_3 Ammonia

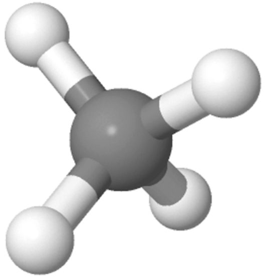


H_2O Water

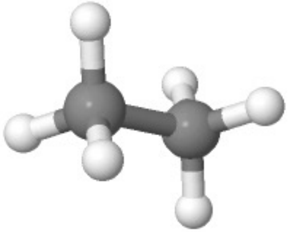


HF Hydrogen fluoride

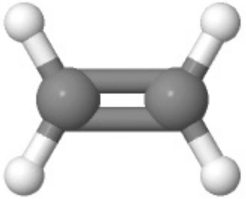




CH_4 Methane

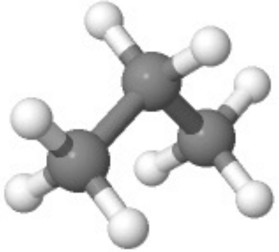


C_2H_6 Ethane

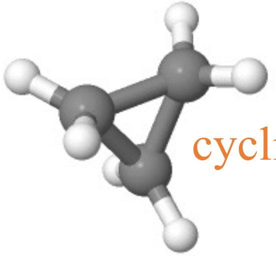


unsaturated

C_2H_4 Ethene



C_3H_8 Propane

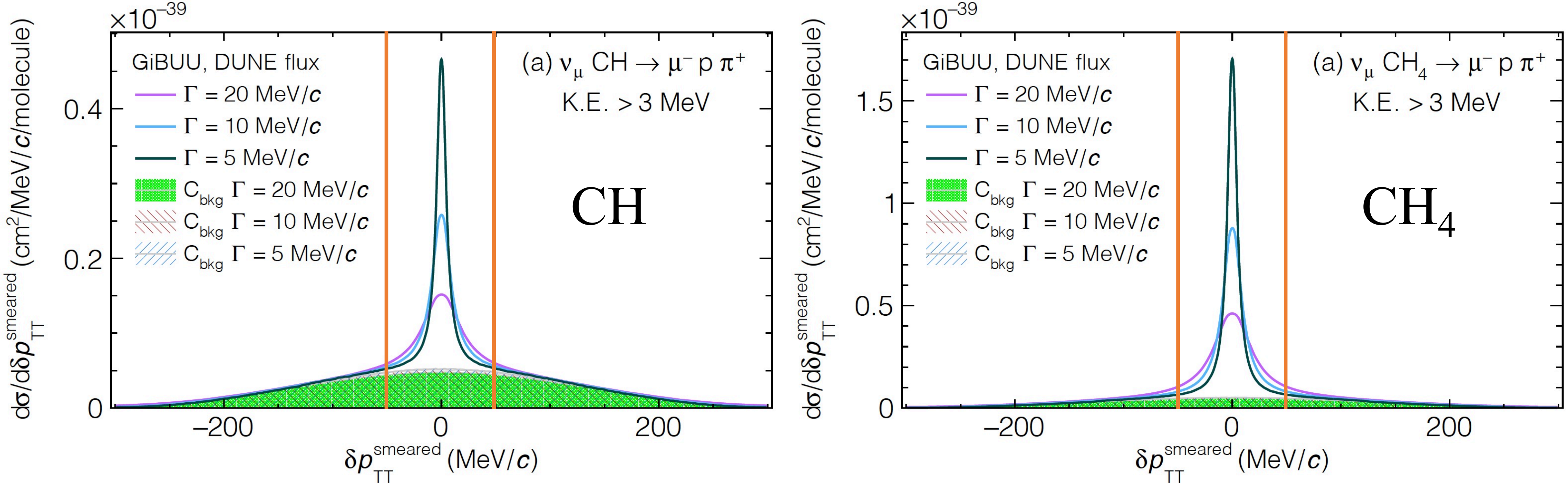


cyclic

C_3H_6 Cyclopropane

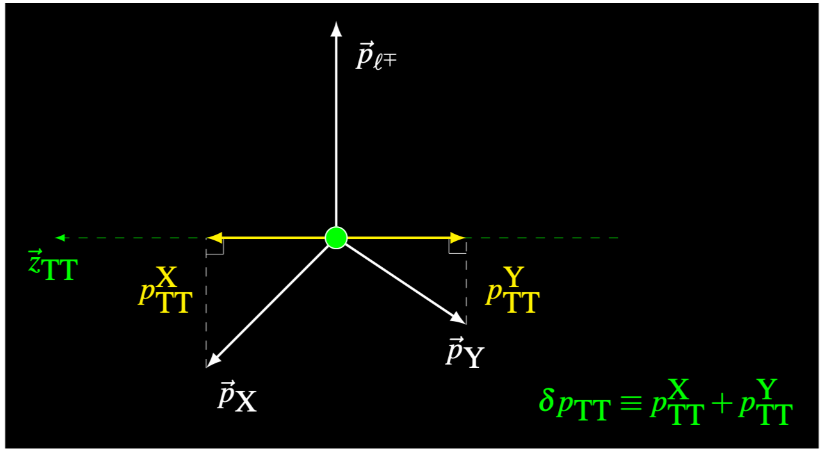
Jmol: an open-source Java viewer for chemical structures in 3D.
http://www.jmol.org/

Hydrogen-rich high-pressure TPC + TKI



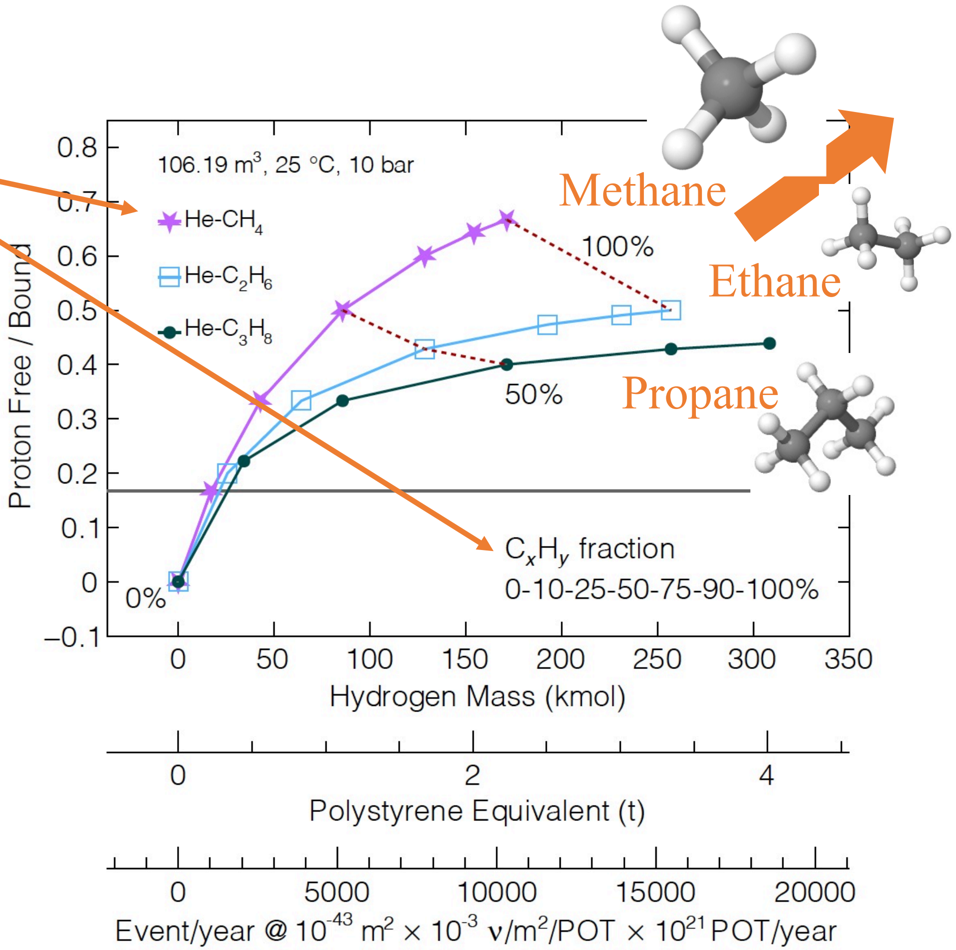
Simulation: "event rates" as a function of "reconstructed" δp_{TT}

- ❑ Hydrogen signal sharpens with better tracking resolution Γ
- ❑ Background shape *locked* by intrinsic nuclear effects
- ❑ More hydrogen purer selection
  - ❖ CH_4 4 times better than CH in signal/background



[Hamacher-Baumann, XL, Martín-Albo, Phys.Rev.D 102, 033005 (2020)] helium + alkane

- ❑ Hydrogen is free proton
- ❑ Bound protons in nuclei are background



Typical pion production cross section

DUNE proposed flux

Hydrogen-rich high-pressure TPC

Pure and more hydrogen events

- ✓ Can be purer than CH
- ❑ With large volume and powerful beam flux
  - ✓ Can go up to 4t CH-equivalent
    - ❖ H_2: 1t
  - ✓ 20k events/year
- ✓ Not covered in this talk:
  - ❖ Demonstrated by simulation mixture is workable
- ✓ Further design work on-going—stay tuned!

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

Summary

- MINERvA
  - 5.4 t scintillator tracker + nuclear targets + calorimeter + magnetized muon spectrometer
  - LE program was completed, ME analyses in pipeline with more than 10 times statistics, reaching neutrino energy beyond 50 GeV
  - A full scientific program of ν *interactions*
- TKI
  - New emerging activities in analysis and detector design
  - Measurements from MINERvA and T2K, and actually more on-going

Sunday, April 18, 2021
3:57PM - 4:09PM
Live

L14.00002: Using Transverse Kinematic Imbalance to Probe Intranuclear Dynamics in Pion Scattering on Argon in ProtoDUNE
Kang Yang

  - ν *interactions*
    - ✓ Initial state probed by p_N is a challenge
      - ➢ Strong constraint for model consistency in different channels
    - ✓ Pure QE baseline at small $\delta\alpha_T$ powerful calibration tool
      - ➢ Safe extrapolation between different targets
    - ✓ FSI and 2p2h start to decouple when combining QE-like + pion production
    - Next step: direct input to δ_{CP} measurements in T2K
      - ➢ We have absolutely no idea by how much the systematics will improve, but we will certainly make those uncertainties *correct*.
    - ν-and $\bar{\nu}$-H scattering can be revived since 1980s? (*Hydrogen-rich high-pressure TPC*)

Thank you!

Cueva de las Manos, Perito Moreno, Argentina. The art in the cave is dated between 13,000–9,000 BP, stenciled, mostly left hands are shown.

BACKUP

Standard Model | Beyond Standard Model

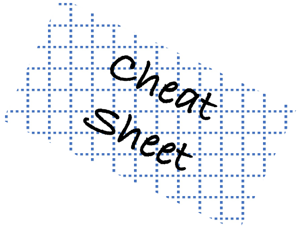
$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \text{PMNS matrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

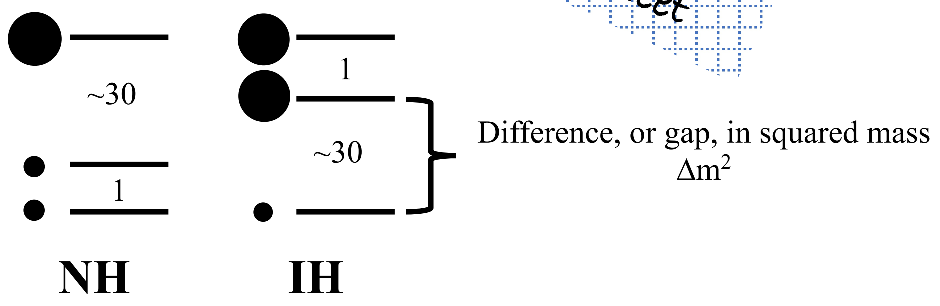
Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

- ❑ Neutrinos have mass

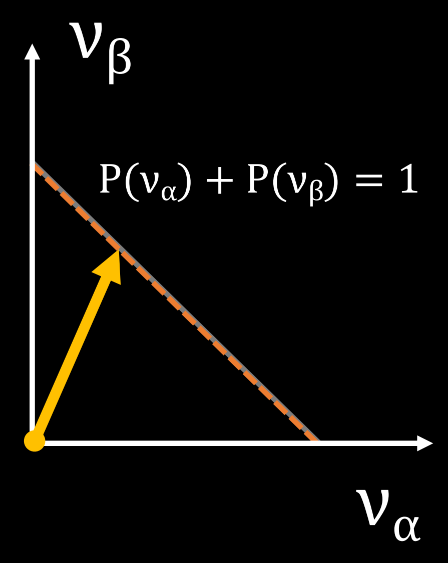
Normal or Inverted Hierarchy

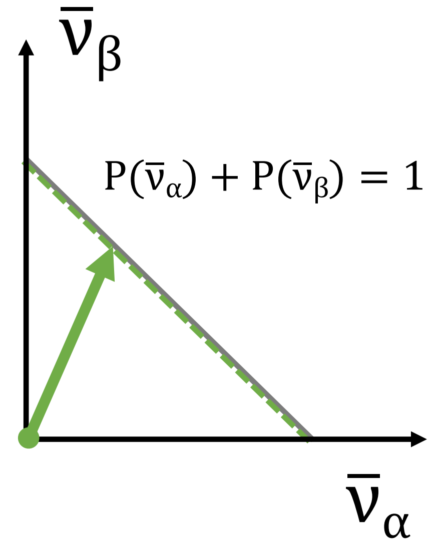




Δm^2 leads to neutrino oscillations

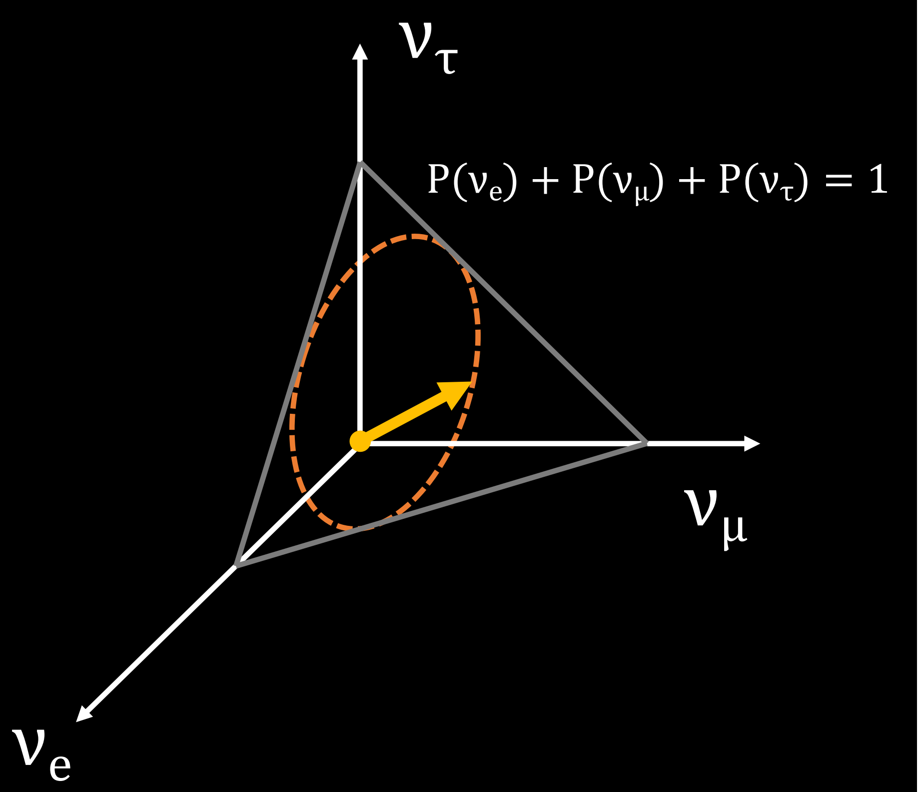
2-flavor oscillation

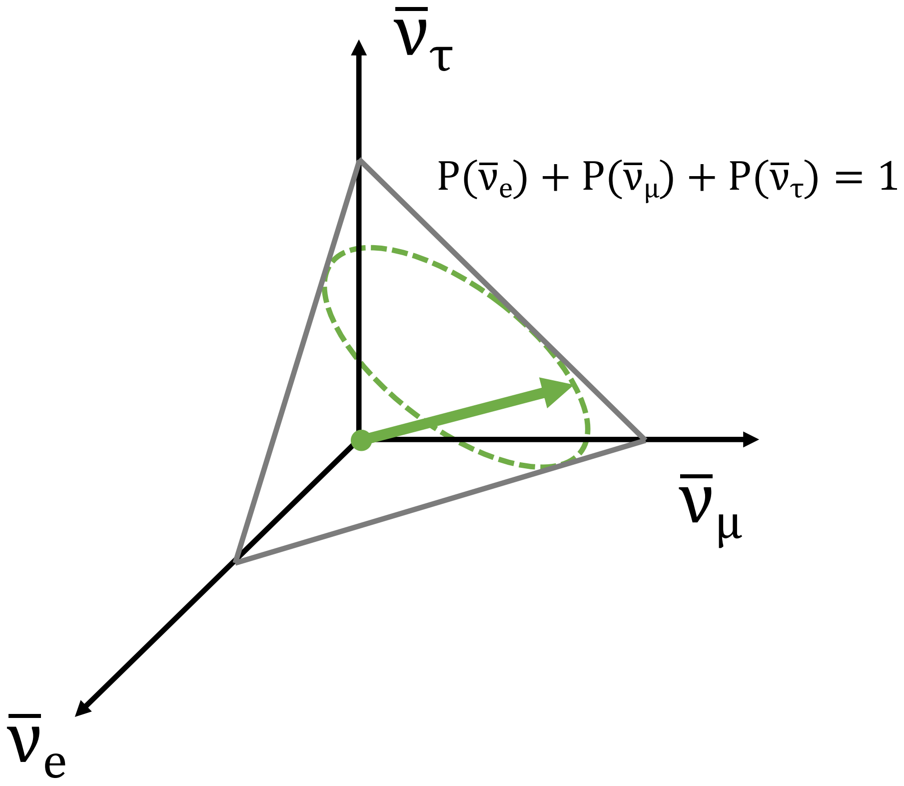




Oscillation as a function of *time*
line-in-**line** → same trivia

3-flavor oscillation





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

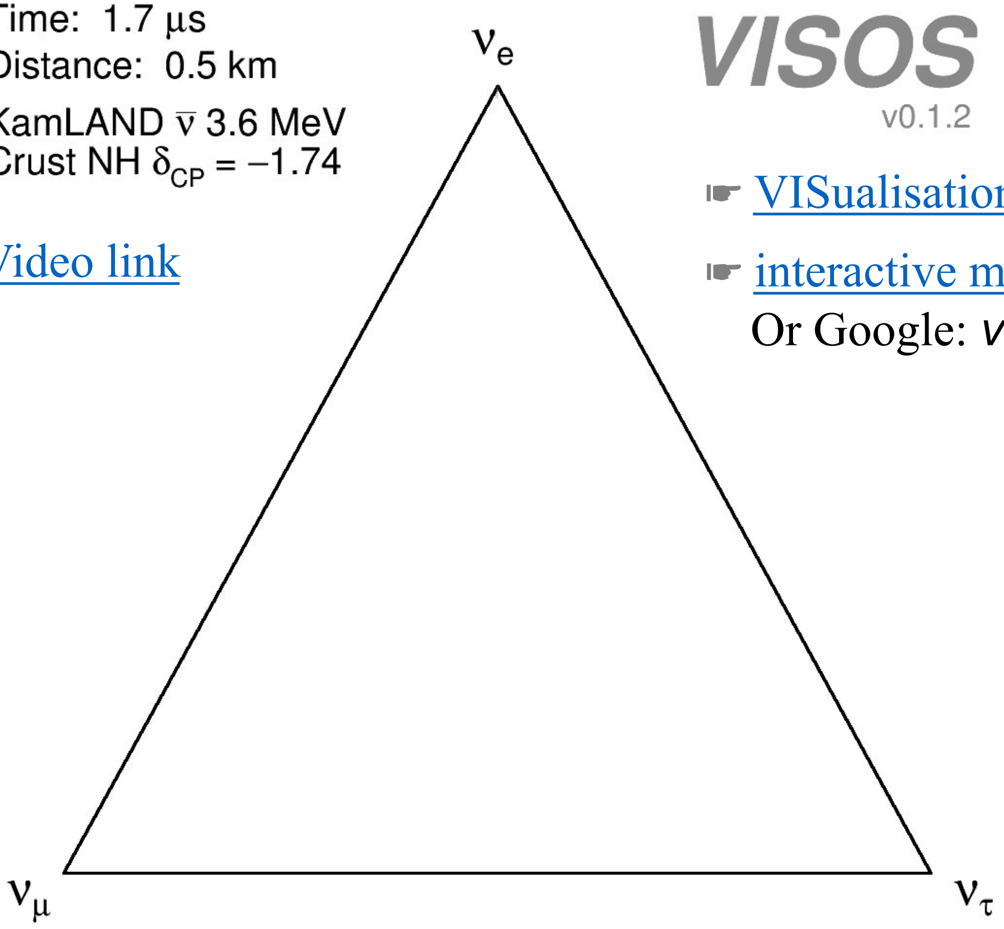
Neutrino Oscillation

Three flavors, two Δm^2 → **two oscillations: fast and slow**$_{\times 30}$

Time: 1.7 μs
Distance: 0.5 km

KamLAND $\bar{\nu}$ 3.6 MeV
Crust NH $\delta_{CP} = -1.74$

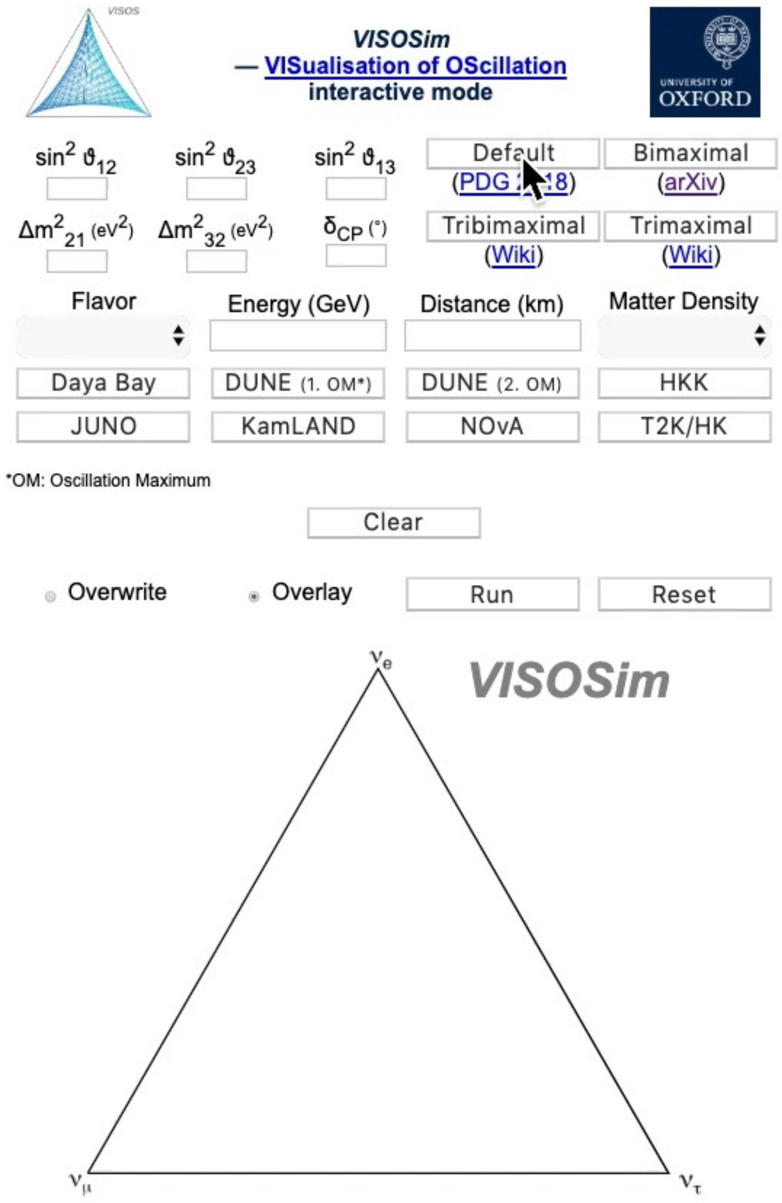
Video link



VISOS
v0.1.2

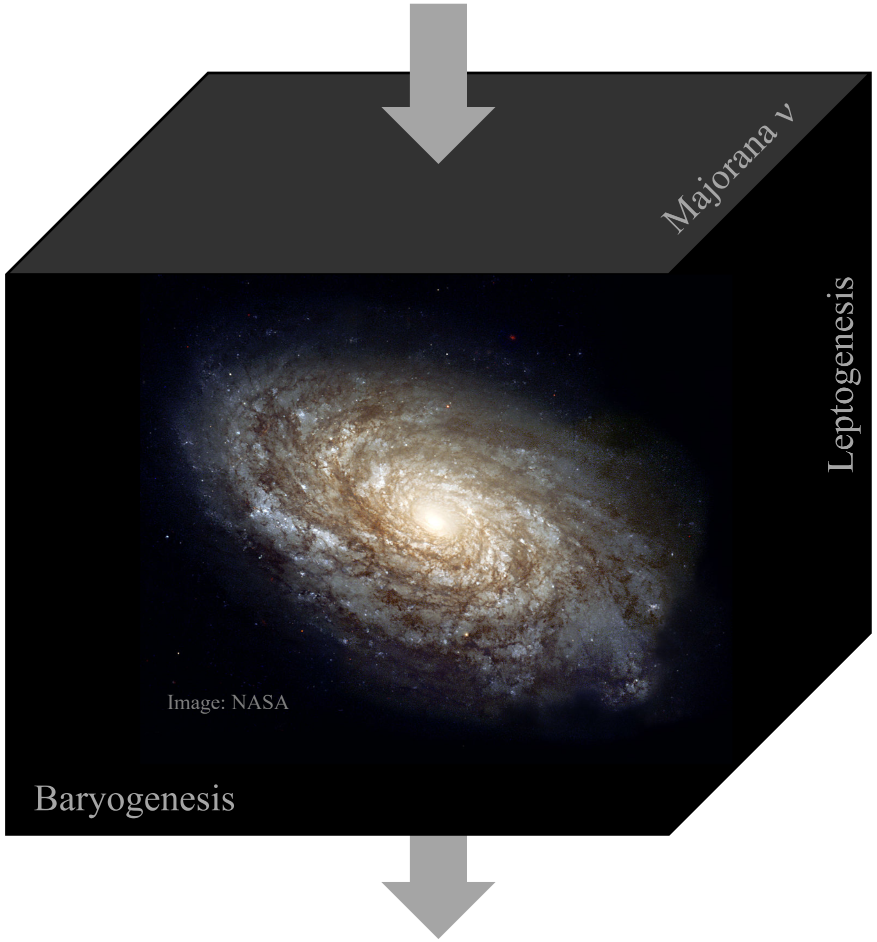
☛ VISualisation of OScillation

☛ interactive mode
Or Google: *visosim*



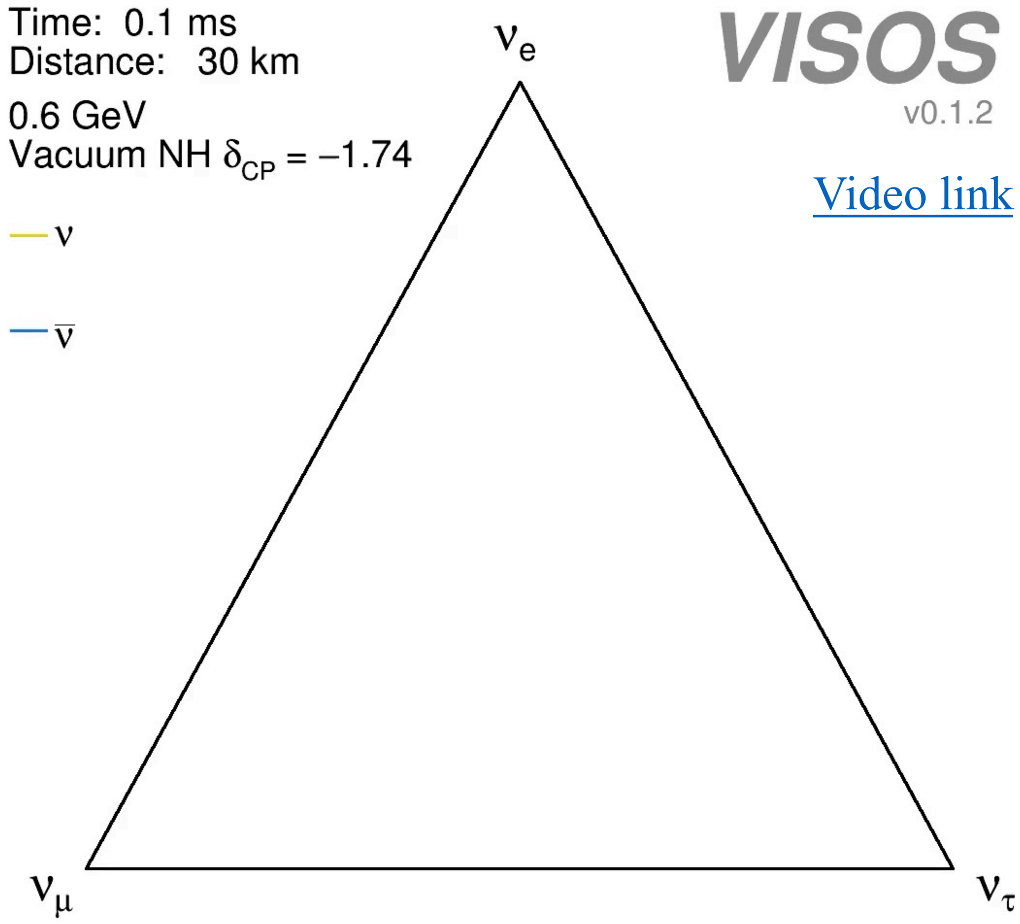
Rasched Haidari, XL, University of Oxford (with support from Oxford Particle Physics Summer Internship Programme 2019)

Neutrino and antineutrino oscillate differently?



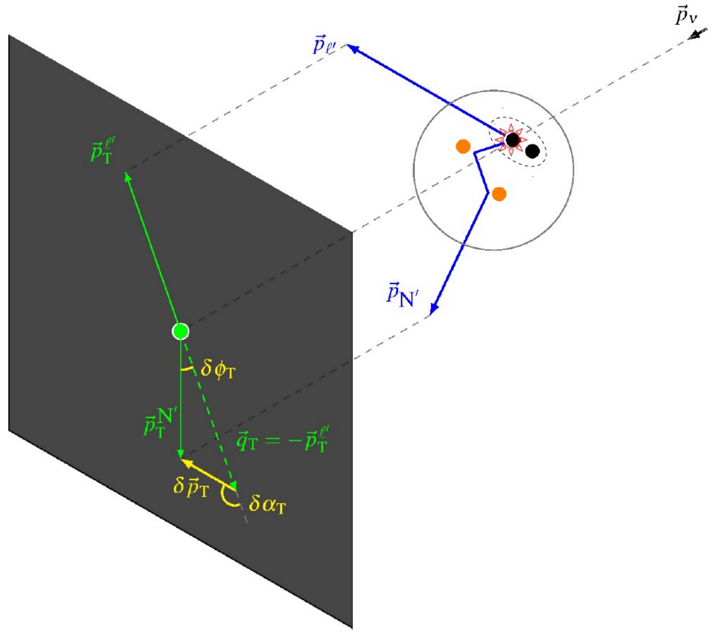
Why the Universe is dominated by matter

Check CPV with 0.6 GeV ν_μ and $\bar{\nu}_\mu$

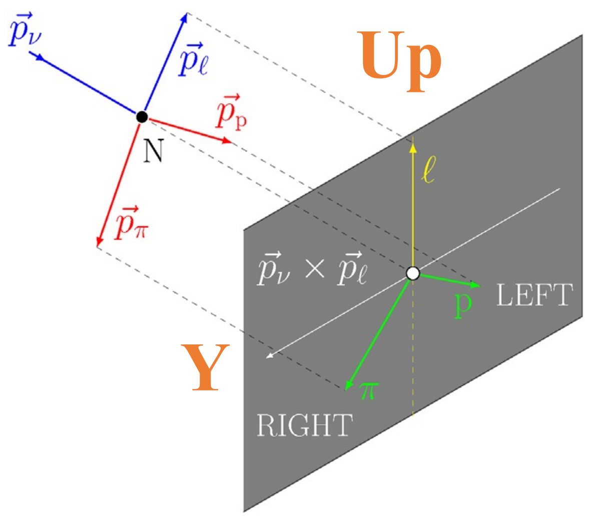


Video link

Further Ideas



$\nu N \to \mu N'\pi$



Pion prefers one side: L-R asymmetry

- ❑ Resonant and nonresonant interference
- ❑ Predicted by Adler and more recent models
- ❑ Difficult measurement* by ANL, MINERvA, T2K, consistent with 0 within error

[Adler, Ann. Phys. (N.Y.) 50, 189 (1968), Sobczyk *et al*., Phys. Rev. D 98, 073001 (2018), Kabirnezhad, Phys. Rev. D 97, 013002 (2018), Niewczas *et al*., Phys. Rev. D 103, 053003 (2021)]

*Caveats!

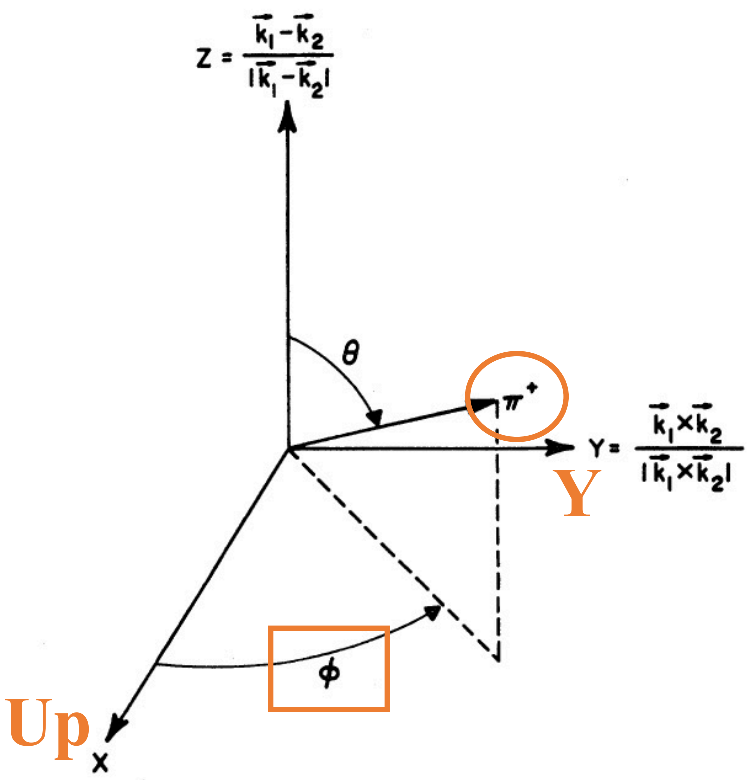


FIG. 14. Definition of the azimuthal ϕ and polar θ angles in the Adler system. $\vec{k}_1$ and $\vec{k}_2$ are vectors along the ν and μ^- directions, respectively, in the $N\pi$ rest system.

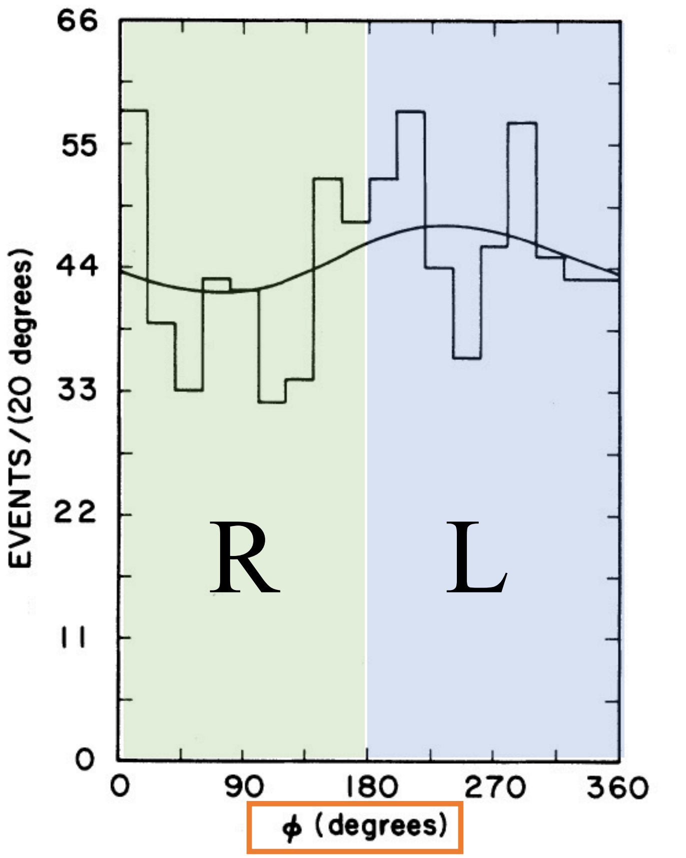
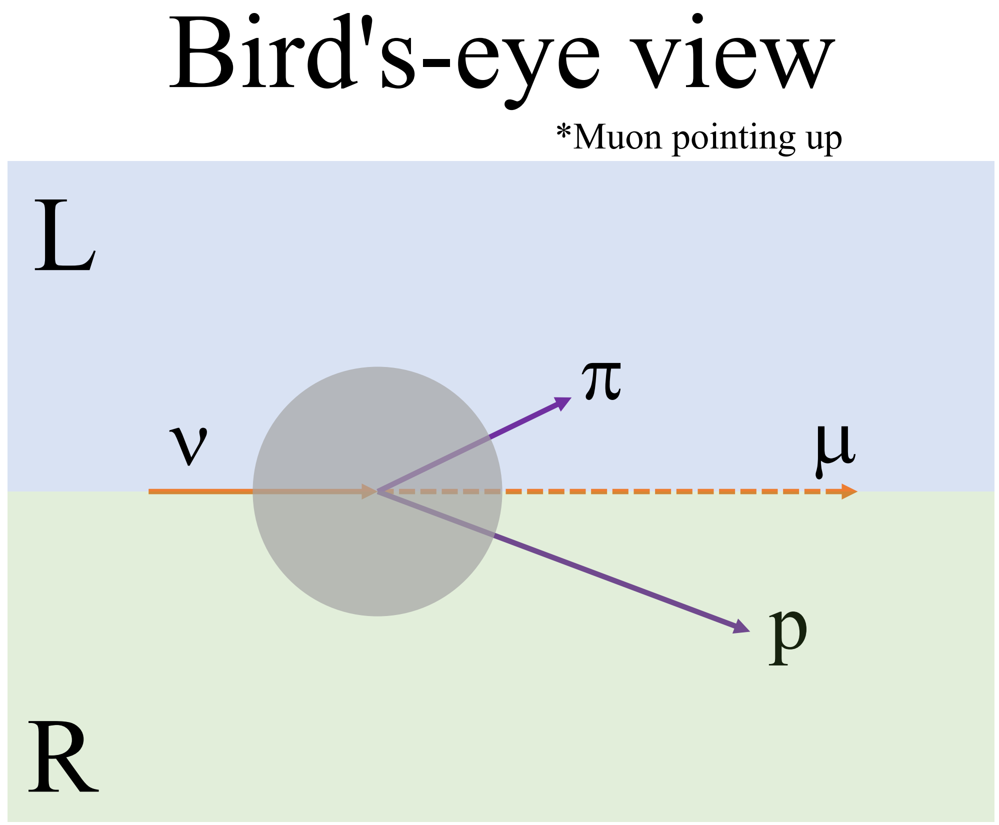
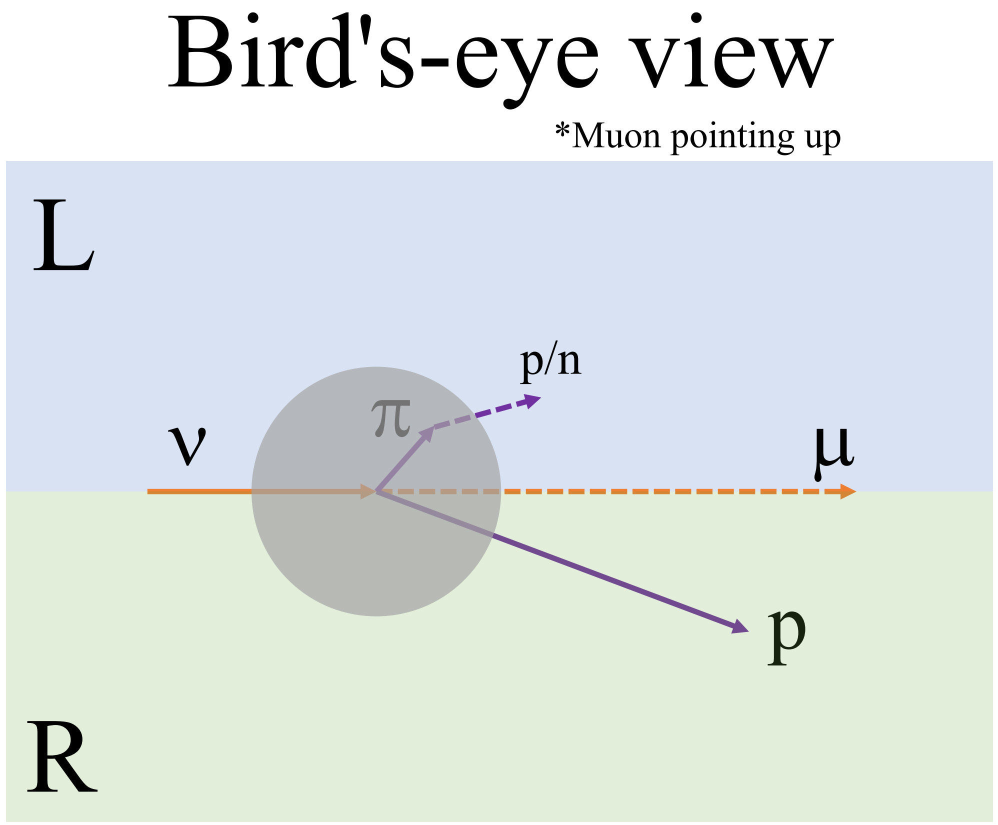


FIG. 16. Distribution of events in the pion azimuthal angle ϕ for the final state $\mu^- p \pi^+$, with $M(p\pi^+) < 1.4$ GeV. The curve is the area-normalized prediction of the Adler model.

ANL data and Adler model [Radecky *et al*., Phys. Rev. D 25, 1161 (1982)]



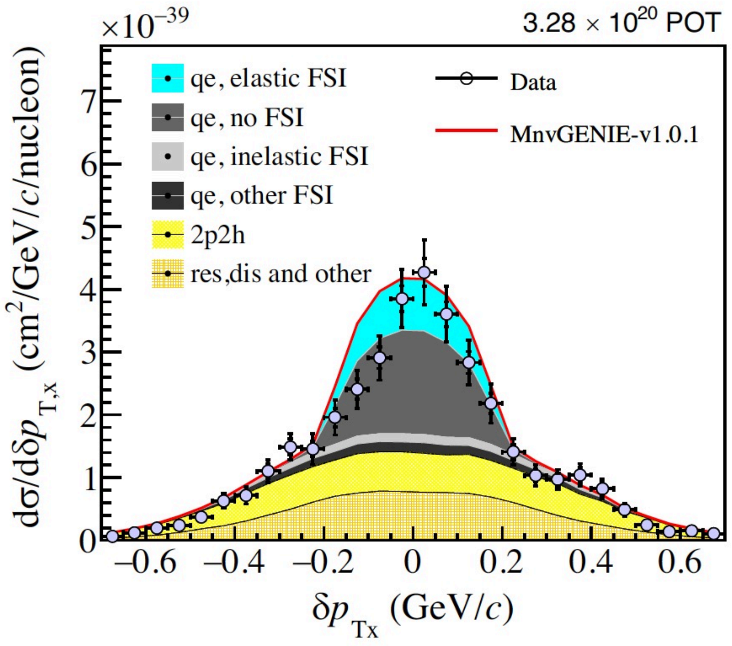
$$\nu A \rightarrow \mu p \pi A'$$



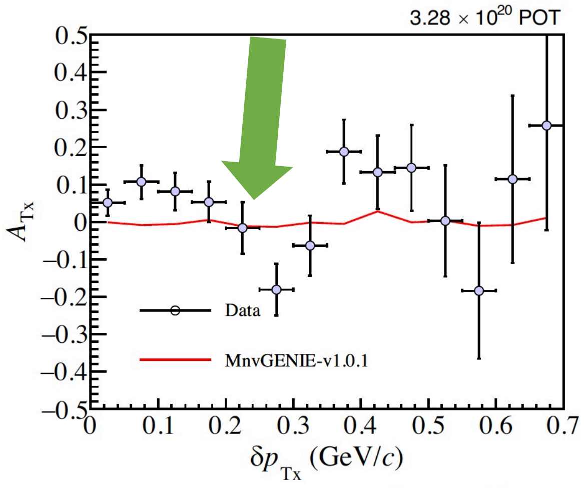
$$\nu A \rightarrow \mu p A'$$

LR asymmetry of (leading) proton in QE-like/0π

[Cai, XL, Ruterbories, Phys.Rev.D 100, 073010 (2019)]

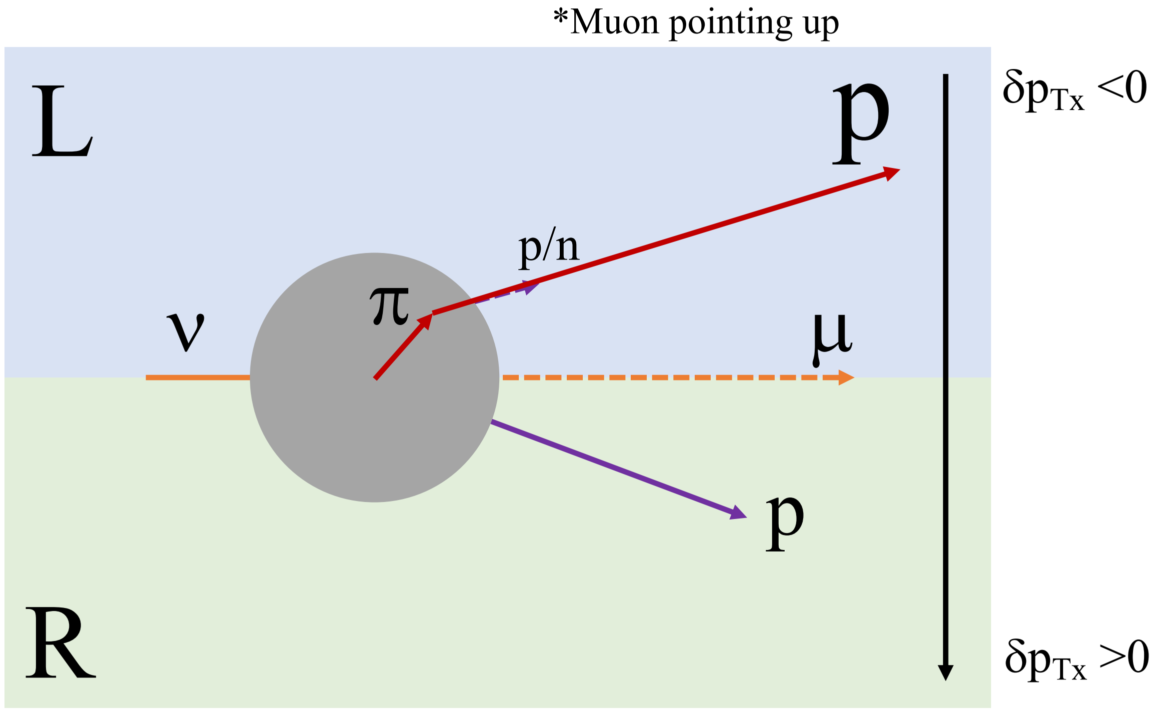


LE: Phys.Rev.D 101, 092001 (2020)



$$A_{\mathrm{Tx}}(|\delta p_{\mathrm{Tx}}|) = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Bird's-eye view



$$\nu A \rightarrow \mu p A'$$

LR asymmetry of (leading) proton in QE-like/0π ?!

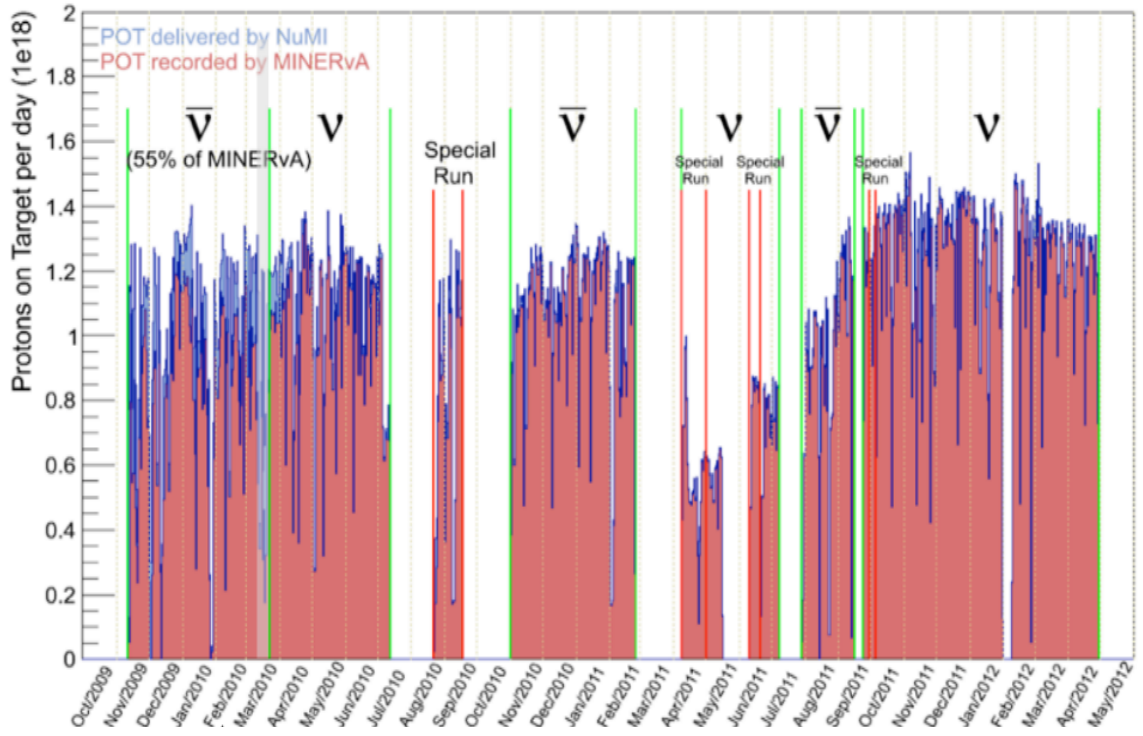
Have searched in MINERvA:

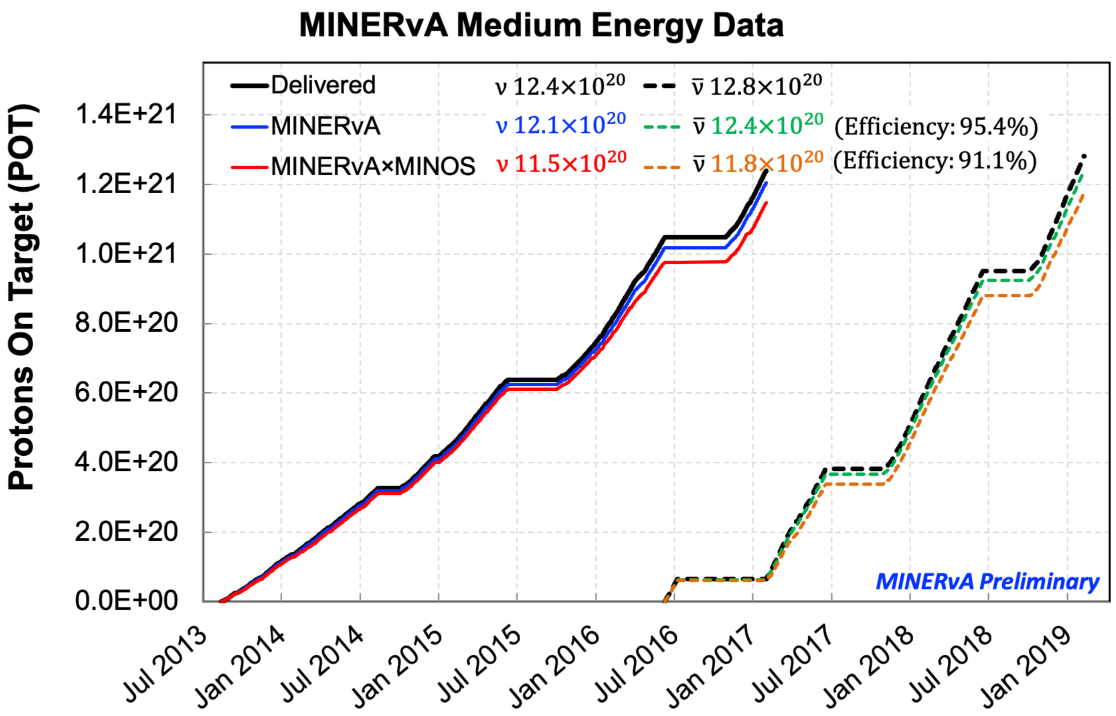
- ❖ Asymmetry is dynamic
- ❖ Asymmetry-flip expected as pion kicking out energetic proton

Assuming LR-asymmetry comes from RES

- ❑ Overall will be smeared or diluted, but it will tell us
- ✓ pion is indeed absorbed
  - —Or, how do we actually know pions are absorbed in ν interactions?
- ✓ how much 2p2h there is
- ❑ Can be measured more precisely in new detectors?

[Cai, XL, Ruterbories, Phys.Rev.D 100, 073010 (2019)]

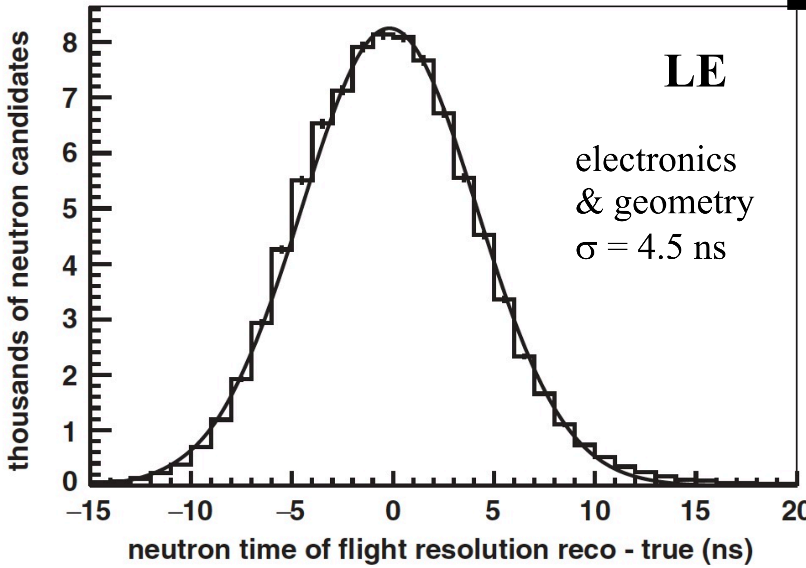

POT delivered by NuMI
POT recorded by MINERvA
Protons on Target per day (1e18)
(55% of MINERvA)
Special Run
Special Run
Special Run
Special Run

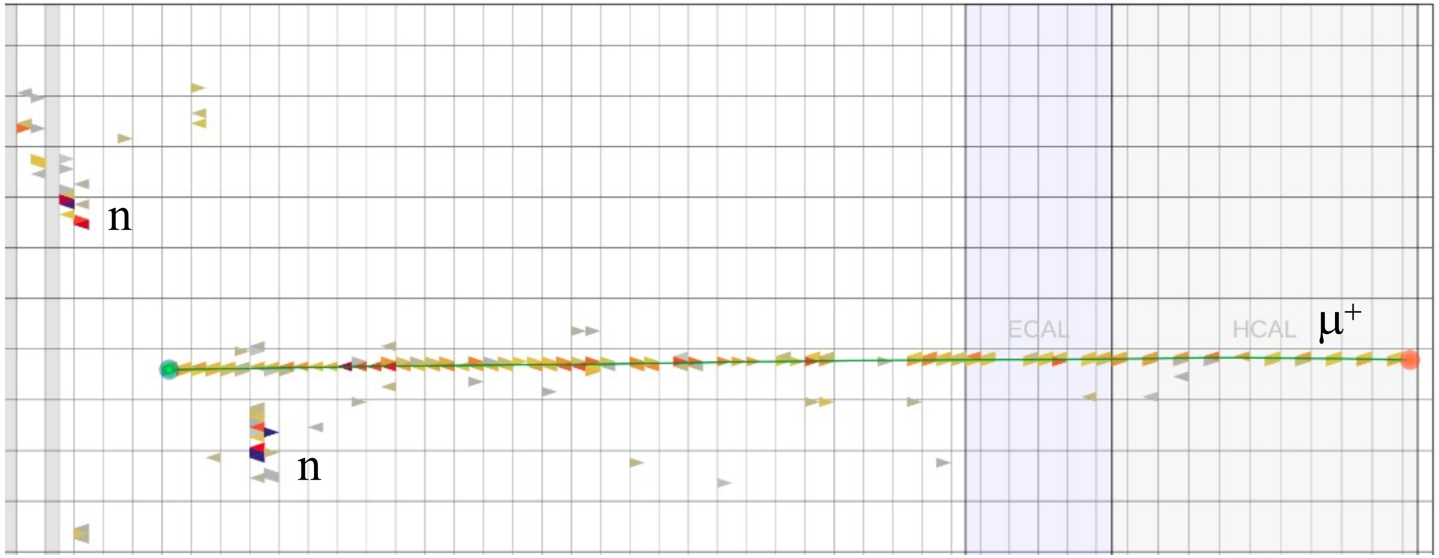

MINERvA Medium Energy Data
Delivered
MINERvA
MINERvA×MINOS
ν 12.4×10^20
ν 12.1×10^20
ν 11.5×10^20
ν̄ 12.8×10^20
ν̄ 12.4×10^20 (Efficiency: 95.4%)
ν̄ 11.8×10^20 (Efficiency: 91.1%)
Protons On Target (POT)
MINERvA Preliminary

Neutron detection

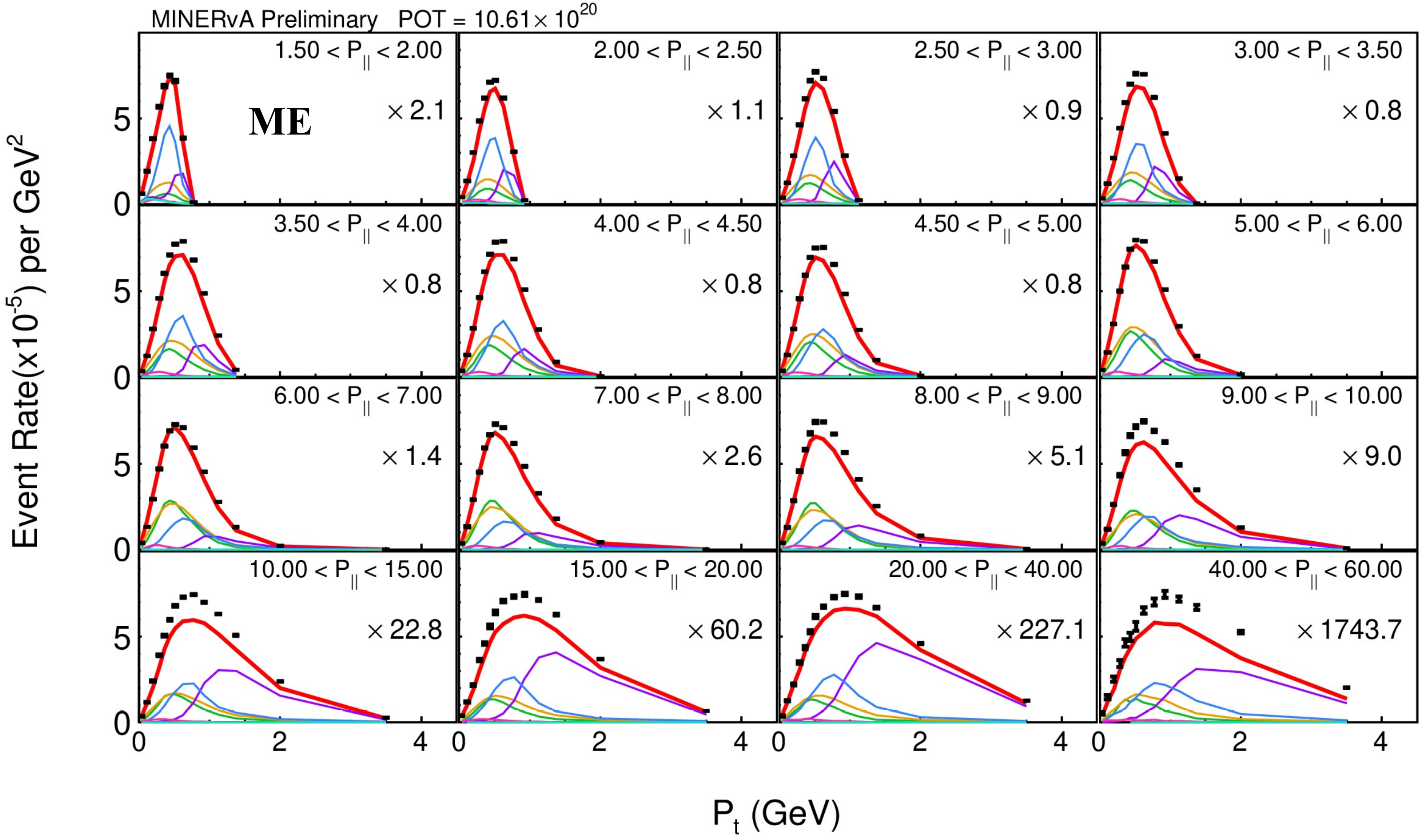
LE: Phys.Rev. D100, 052002 (2019)

- Energy deposit provided by protons from n-H and n-C interactions
  - ✓ Low detection threshold 1.5 MeV (after restricting to low momentum transfer at event level using calorimetry)
- Neutron time-of-flight provided by hit time
  - ✓ Large active fiducial volume compared to neutron's 10 cm interaction length at 20 MeV KE
  - ✓ 4.5 ns neutron timing resolution





- ❑ ν_μ Charged-Current inclusive events with forward muon ($\theta_\mu < 20^o$)
  - ✓ Muon $p_t \sim Q^2$
  - ✓ Muon $p_{||} \sim$ neutrino energy



ME: neutrino energy goes beyond 50 GeV!

Neutrino-Electron Elastic Scattering [**LE**: Phys.Rev. D93, 112007 (2016); **ME**: Phys. Rev. D 100, 092001 (2019)]

Well-understood SM process

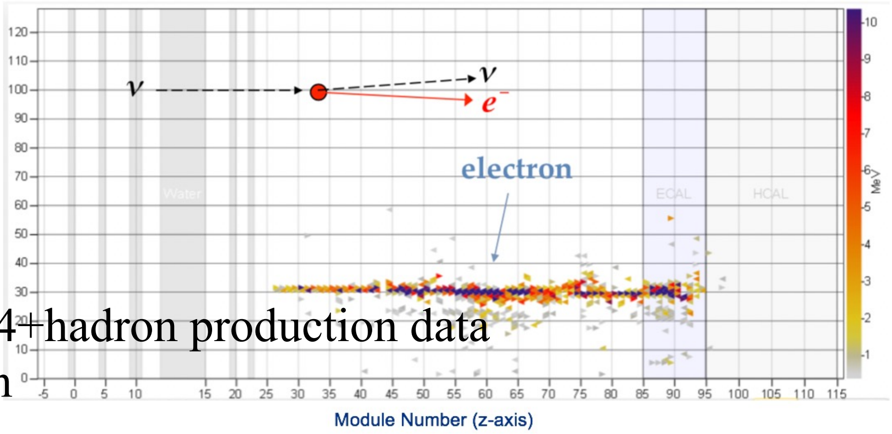
$$\nu e \longrightarrow \nu e$$

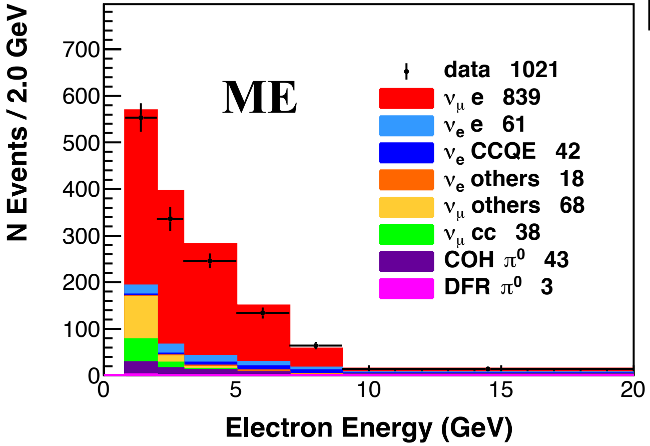
LE: 135 events

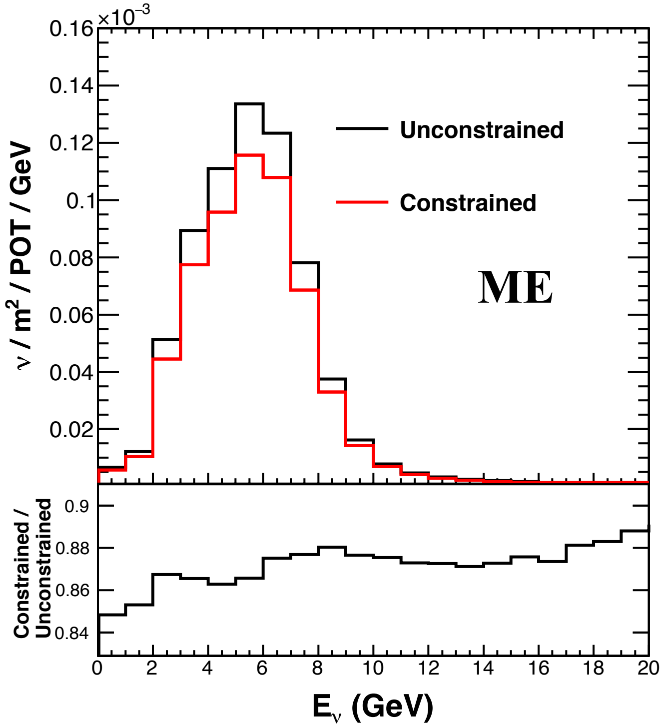
ME: 810 events

Beam flux prediction from GEANT4+hadron production data

in situ flux = event rate/cross section



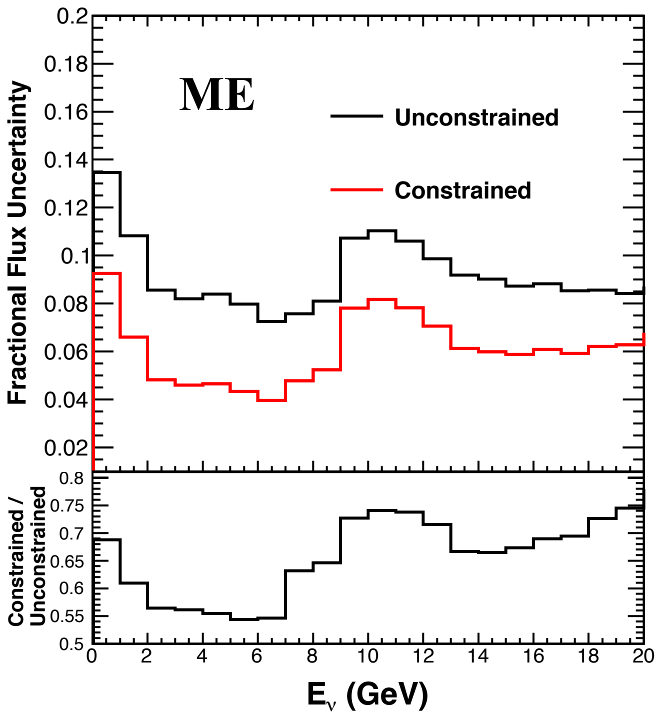




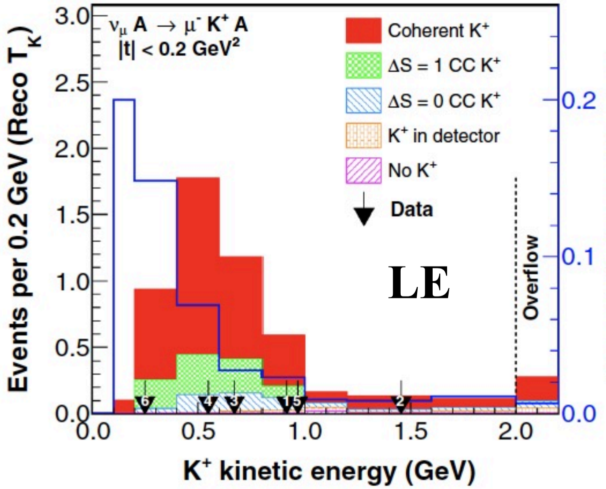
ME ν_μ flux Unconstrained: prediction from GEANT4+hadron production data

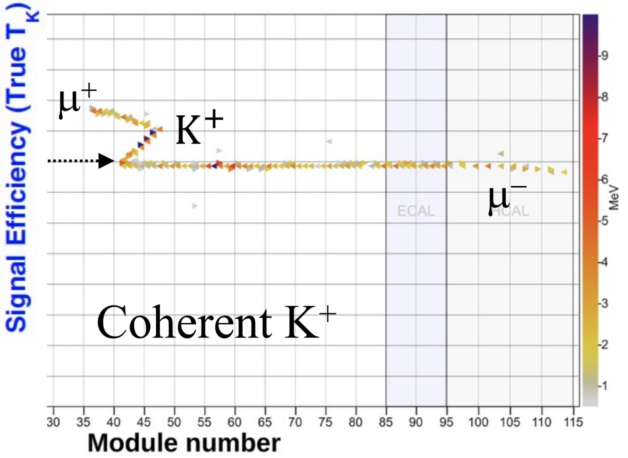
in situ flux = event rate/cross section

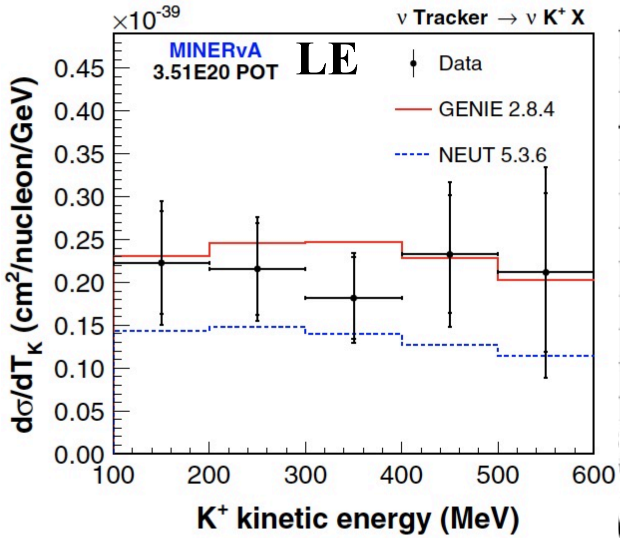
- ❑ reduced by ~ 10% after constraint
- ❑ uncertainty near the peak is reduced from 8% to 4%

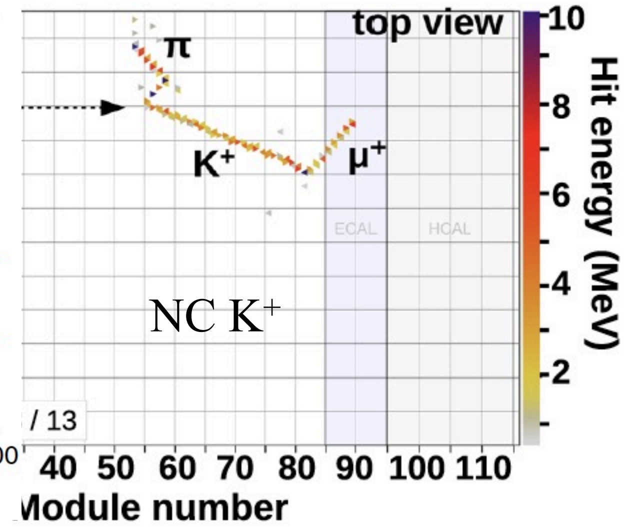


Kaon Production [LE: Phys.Rev. D94, 012002 (2016), Phys.Rev.Lett. 117, 061802 (2016), Phys.Rev.Lett. 119, 011802 (2017)]

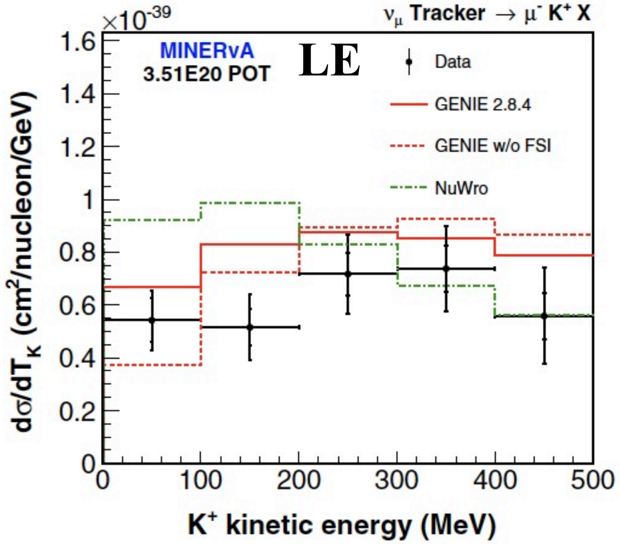


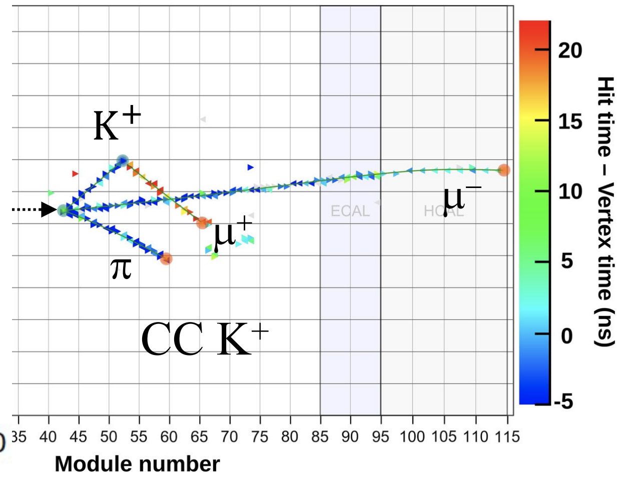






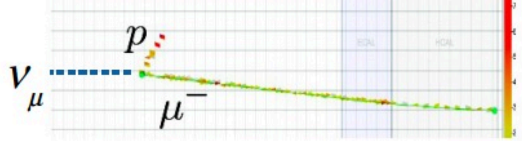
- K$^+$ decay-at-rest signature: 12.4 ns lifetime, kink, energy deposit
- Coherent K$^+$: 6 events, predicted BG 1.77, 3.0σ
- Neutral-current (NC) K$^+$: 201 events
  - 100 MeV tracking threshold
  - Momentum by range up to 600 MeV
  - Background K$^+$ can be produced in detector by π^+ reaction and K^0 charge exchange.
- Charged-current (CC) K$^+$: 885 events
  - + If below tracking threshold: decay μ^+ 11 ns later than μ^-, near vertex. Momentum by range via visual scans.



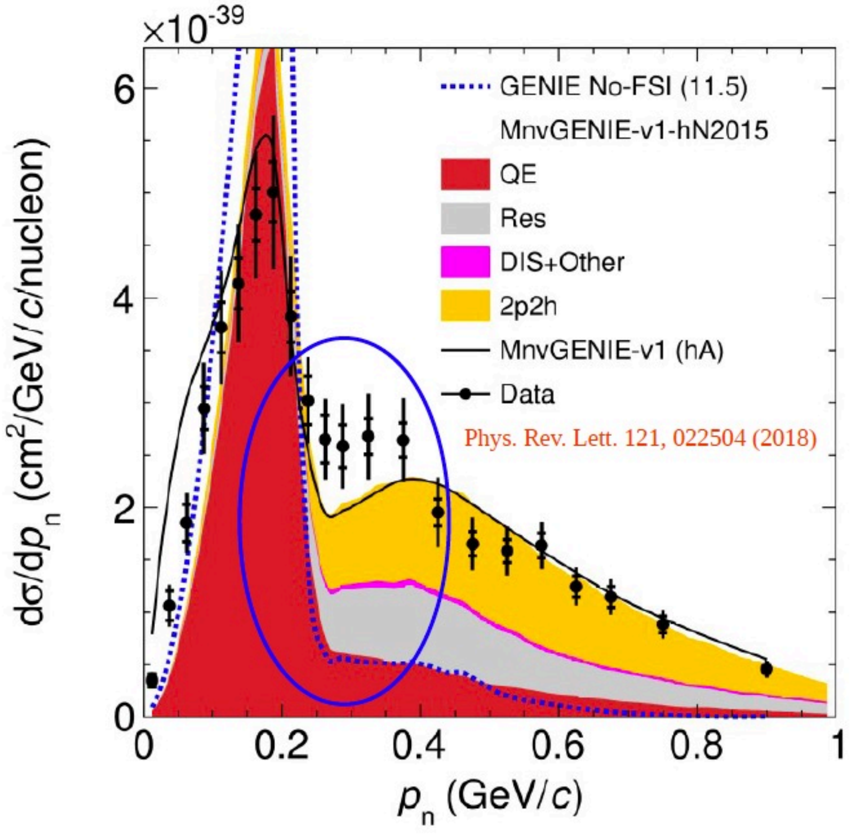


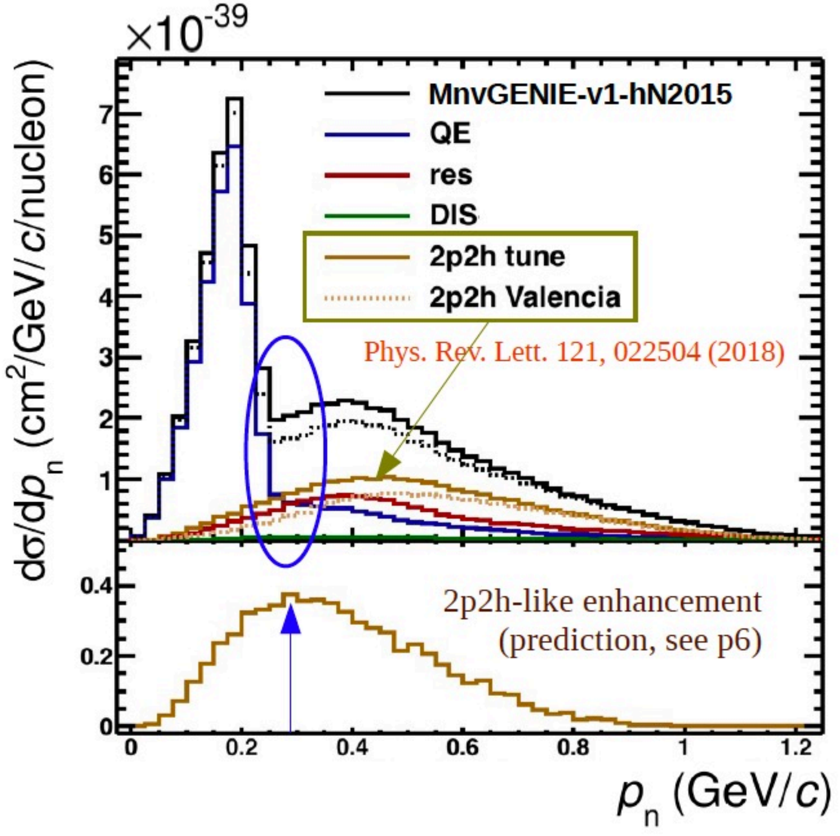
TKI measurements @ MINERvA

– QE-like measurement on C probing ν n→μ p



2p2h-like enhancement needs to be even stronger to fill the dip





Xianguo Lu, Oxford

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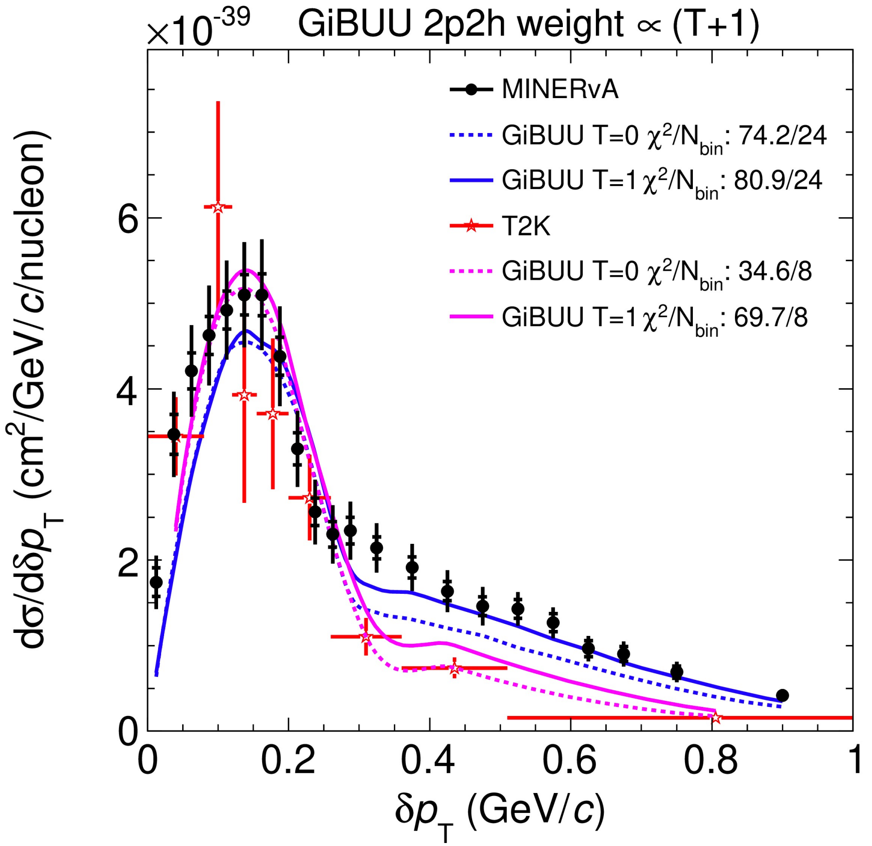
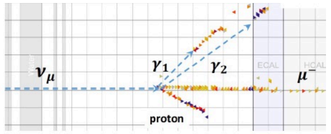


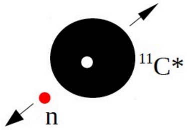
$\times10^{-39}$ GiBUU 2p2h weight ∝ (T+1)
MINERvA
GiBUU T=0 χ^2/N_{bin}: 74.2/24
GiBUU T=1 χ^2/N_{bin}: 80.9/24
T2K
GiBUU T=0 χ^2/N_{bin}: 34.6/8
GiBUU T=1 χ^2/N_{bin}: 69.7/8
$d\sigma/d\delta p_T$ (cm^2/GeV/c/nucleon)
δp_T (GeV/c)
0
2
4
6
0.2
0.4
0.6
0.8
1

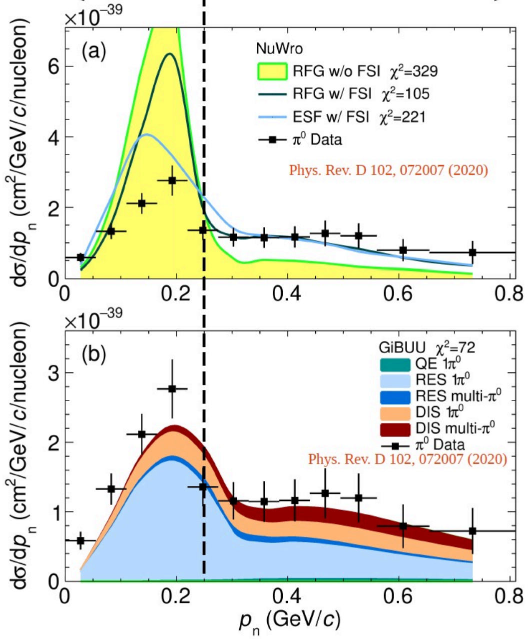
TKI measurements @ MINERvA

– Inclusive π^0 production on C probing $\nu\, n \to \mu\, p\, \pi^0$



Fermi motion (RES) | Large missing pT (FSI-RES/DIS)





- ✗ Fermi motion peak in pion production worse modeled than in QE
- ✓ Large missing pT region reasonably modeled

Xianguo Lu, Oxford

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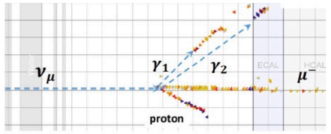
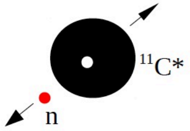
TKI measurements @ MINERvA

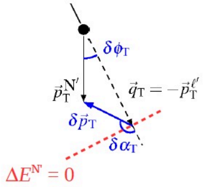
– Inclusive π^0 production on C probing $\nu\, n \to \mu\, p\, \pi^0$



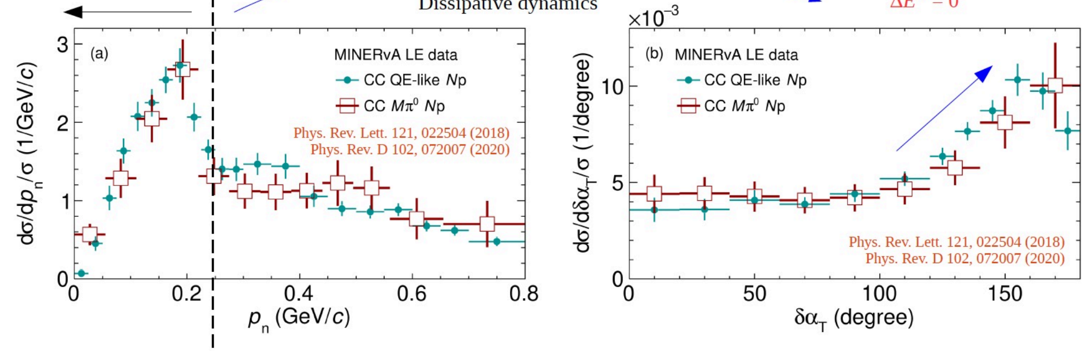
Shape comparison between QE-like and pion production

- Probing same neutron Fermi motion in carbon
- Suggests similar dynamics at large missing pT





Large missing pT (δp_T)
Dissipative dynamics



Large missing pT: pion absorption
Open π (pion production)

↕

absorbed π (QE-like)

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- Nominal: version 2.8.4
  - global Fermi Gas (RFG) model with Bodek-Ritchie (BR) tail [Bodek & Ritchie, Phys. Rev. D 23, 1070 (1981)]
  - hA FSI [Dytman & Meyer, AIP Conf.Proc. 1405, 213 (2011)]
- MnvGENIE-v1: GENIE MINERvA Tune (v1)
  - Added Random Phase Approximation (RPA) [Nieves *et al*., Phys.Rev. C70, 055503 (2004)]
  - Non-resonance pion production scaled down by 75% [Wilkinson *et al*., Phys.Rev. D90, 112017 (2014)]
  - Valencia 2p2h [Nieves *et al*., Phys.Lett. B707, 72 (2012); Sobczyk, Phys. Rev. C 86, 015504 (2012); Gran *et al*., Phys.Rev. D88, 113007 (2013); Schwehr *et al*., arXiv:1601.02038]
    - Tuned to MINERvA inclusive data → significant enhancement in small 4-momentum transfer region [MINERvA, Phys.Rev.Lett. 116, 071802 (2016)]

END