FB23
THE 23rd INTERNATIONAL CONFERENCE ON FEW-BODY PROBLEMS IN PHYSICS (FB23)
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Neutrino Interactions in the Few-GeV Regime

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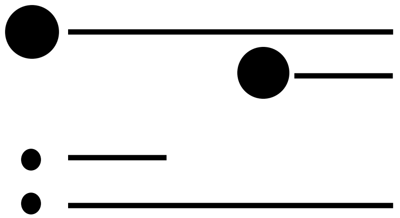
FewBody23, Beijing
2024 September 26

Neutrino Mass

Standard Model | Beyond Standard Model

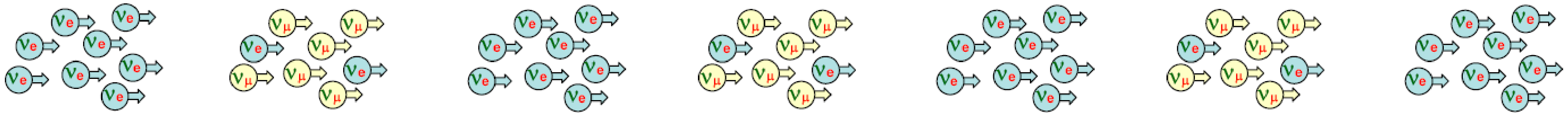
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \text{Pontecorvo–Maki–Nakagawa–Sakata PMNS matrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Mass Ordering



Normal **Inverted**

Δm^2 leads to neutrino oscillations



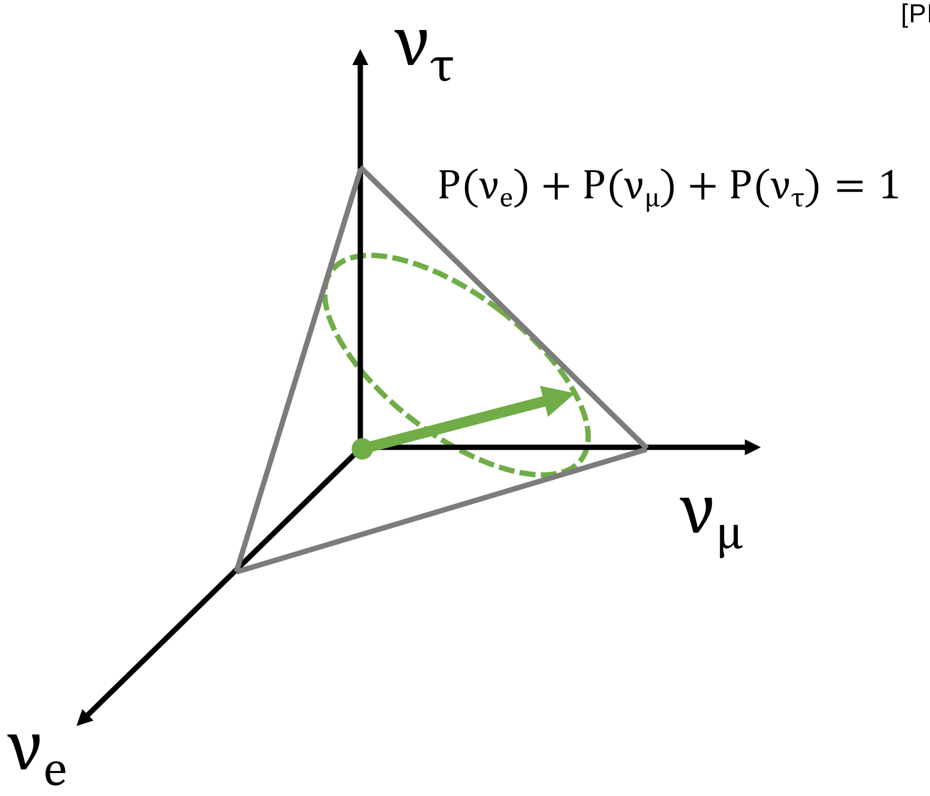
[Mark Thomson, Particle Physics lecture notes]

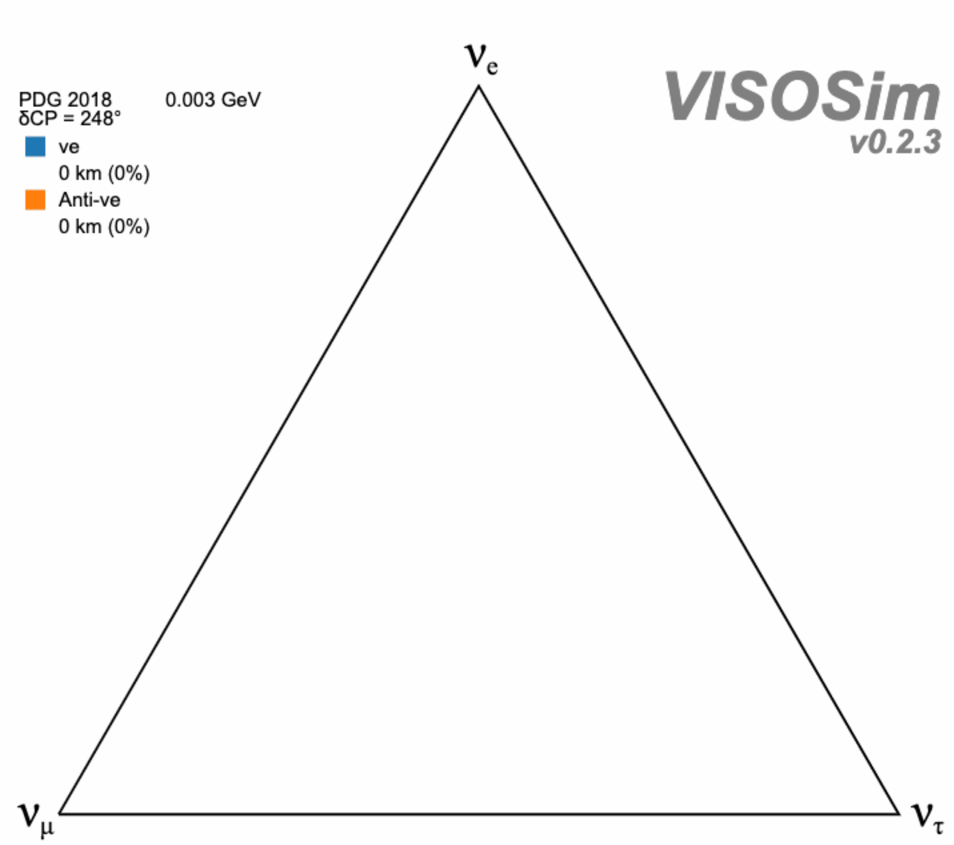
PMNS matrix

$$\begin{bmatrix} |U_{e1}| & |U_{e2}| & |U_{e3}| \\ |U_{\mu1}| & |U_{\mu2}| & |U_{\mu3}| \\ |U_{\tau1}| & |U_{\tau2}| & |U_{\tau3}| \end{bmatrix}$$

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

[PDG]

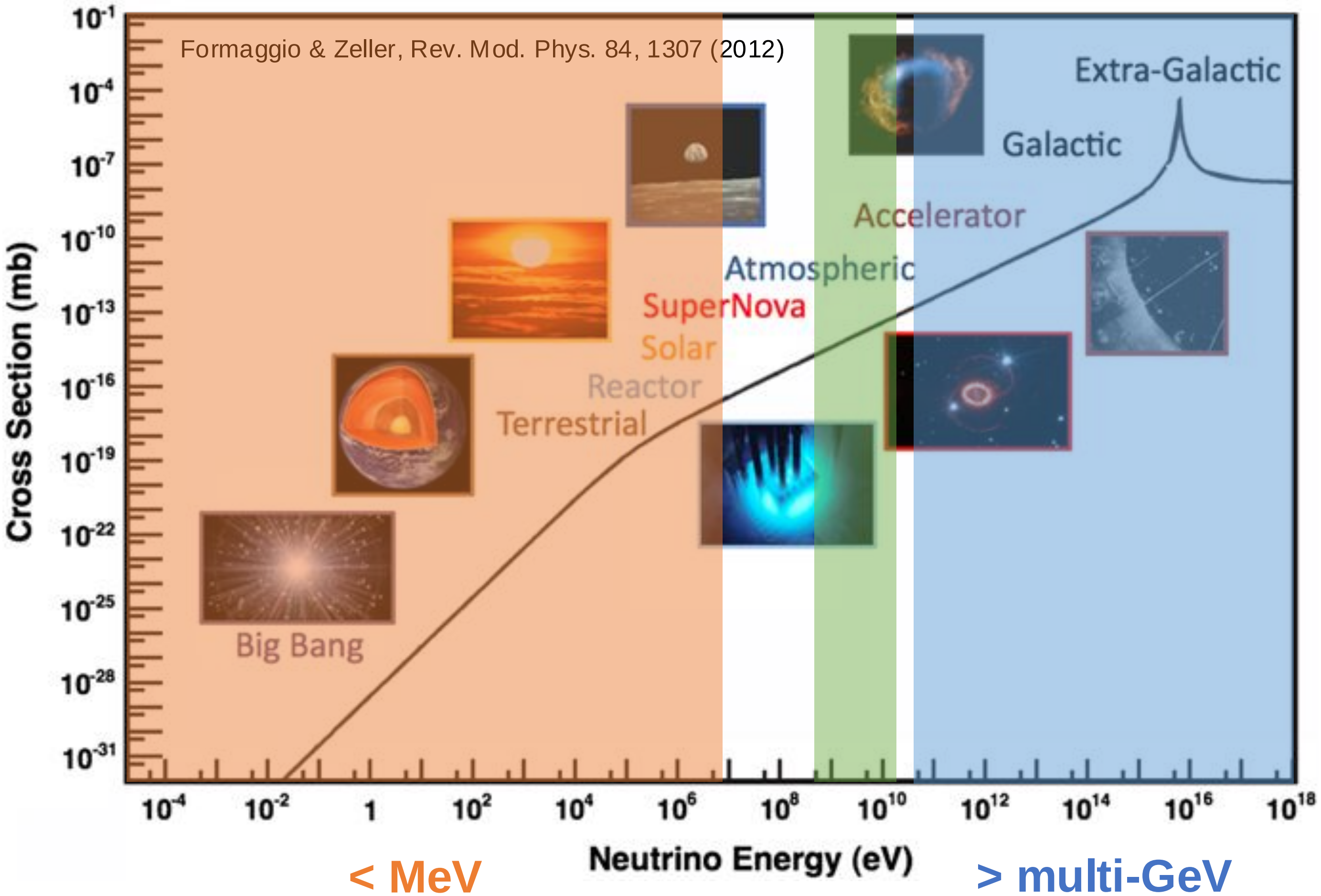




☛ VISOS

Why Study GeV (= atmospheric + accelerator)?

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



< MeV
See the whole nucleus
Nuclear database

> multi-GeV
See individual quarks
pQCD, EW

Physical reasons

Neutrino for *CP*-violation

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

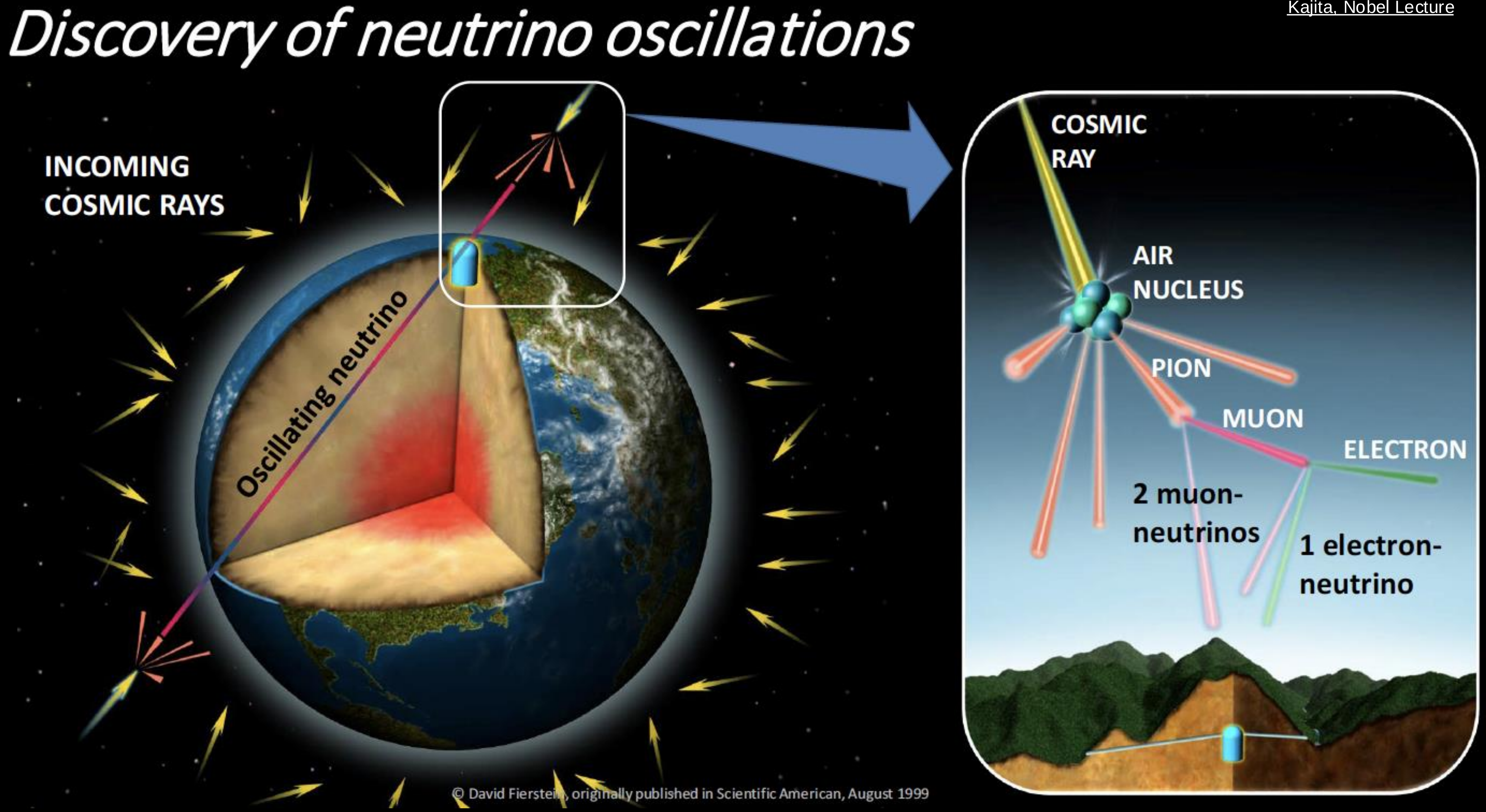
GeV-neutrinos also relevant for

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

Technical reasons:
Difficult to *control*

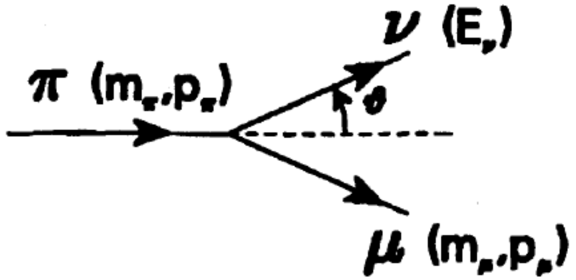
Atmospheric Neutrinos

Kajita, Nobel Lecture



Accelerator Neutrinos

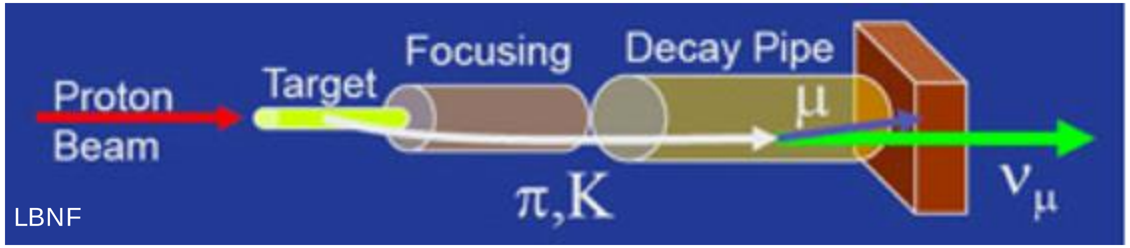
Let's start from π decays

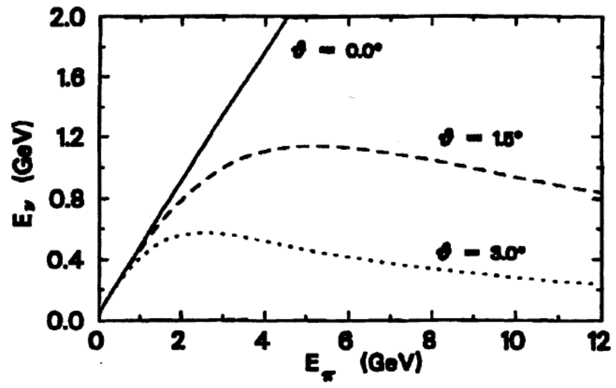


How to obtain a controlled sample of neutrinos?

From energy, momentum conservation

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

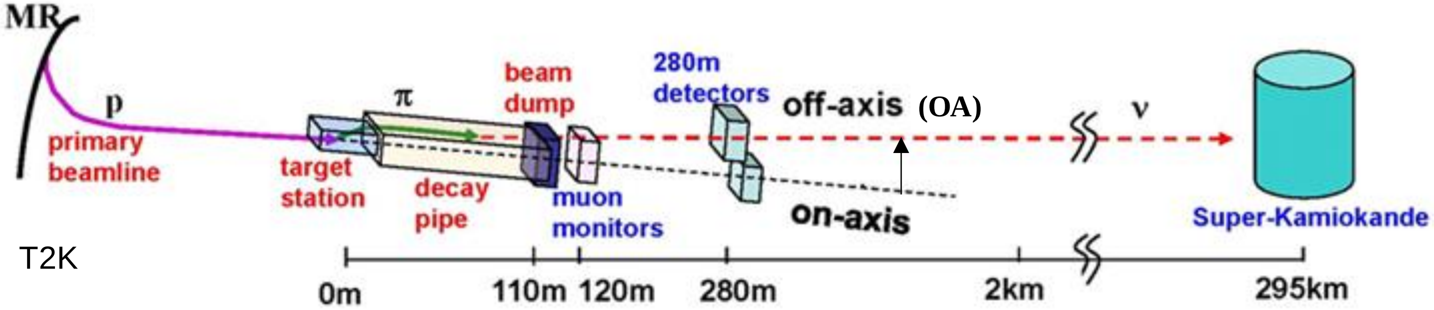




"β decay" of energetic collision products (mostly ν_μ from π)

Neutrino beams from accelerators → Directional

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



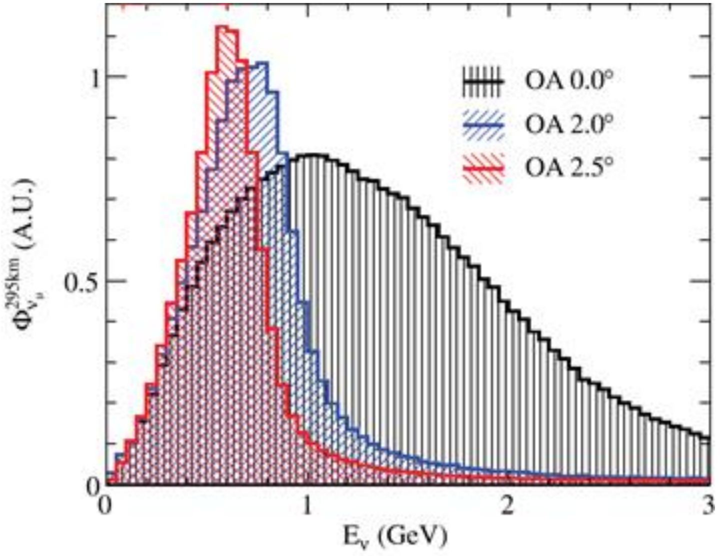
T2K

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

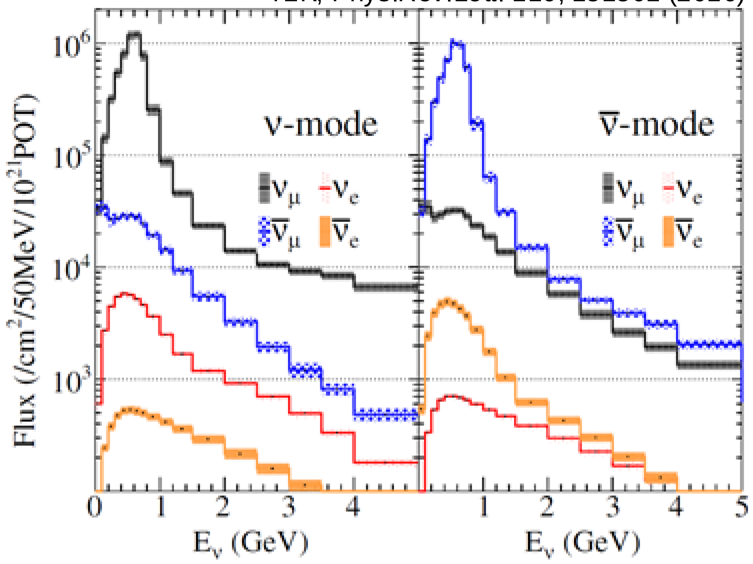
D. Beavis, et al., P889: long baseline neutrino oscillation experiment at the AGS, Report No. BNL-52459, April, 1995

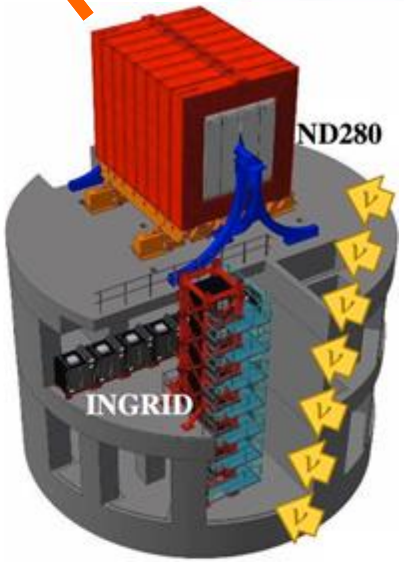
Accelerator Neutrino Experiments

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



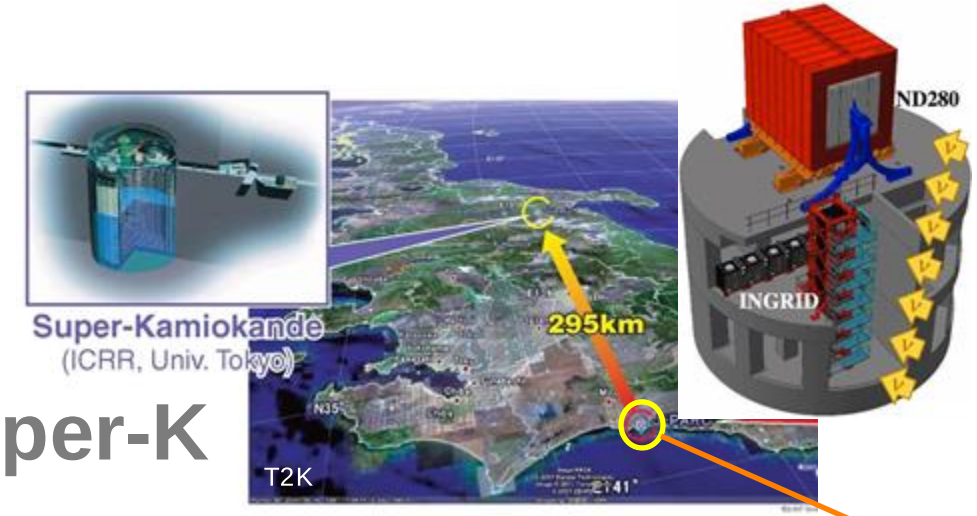
T2K, Phys.Rev.Lett. 116, 181801 (2016)





Near Detector

Accelerator Neutrino Experiments

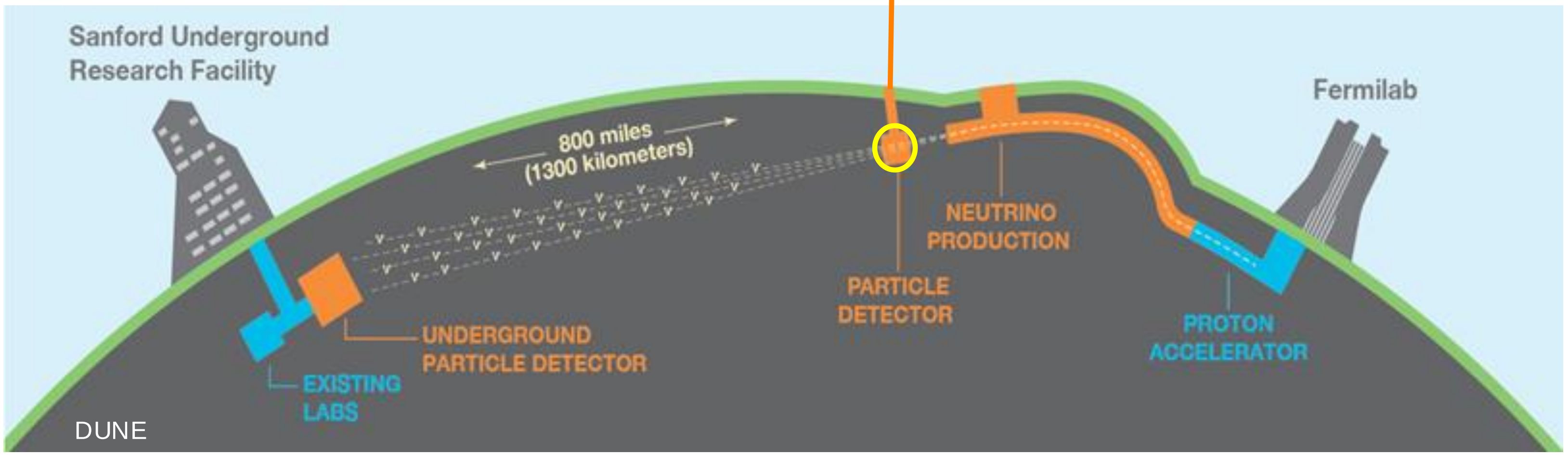


T2K / Hyper-K

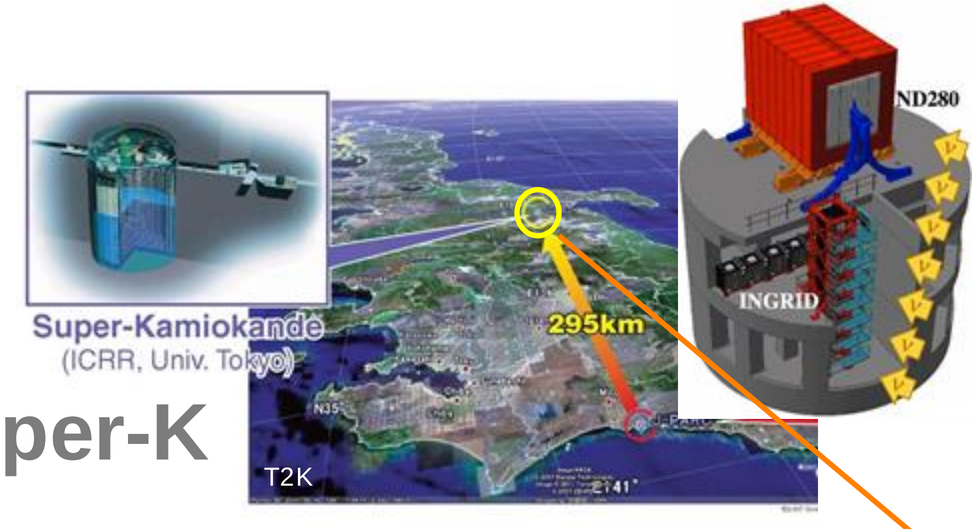
NOvA

Near Detectors to measure ν interaction

DUNE



Accelerator Neutrino Experiments

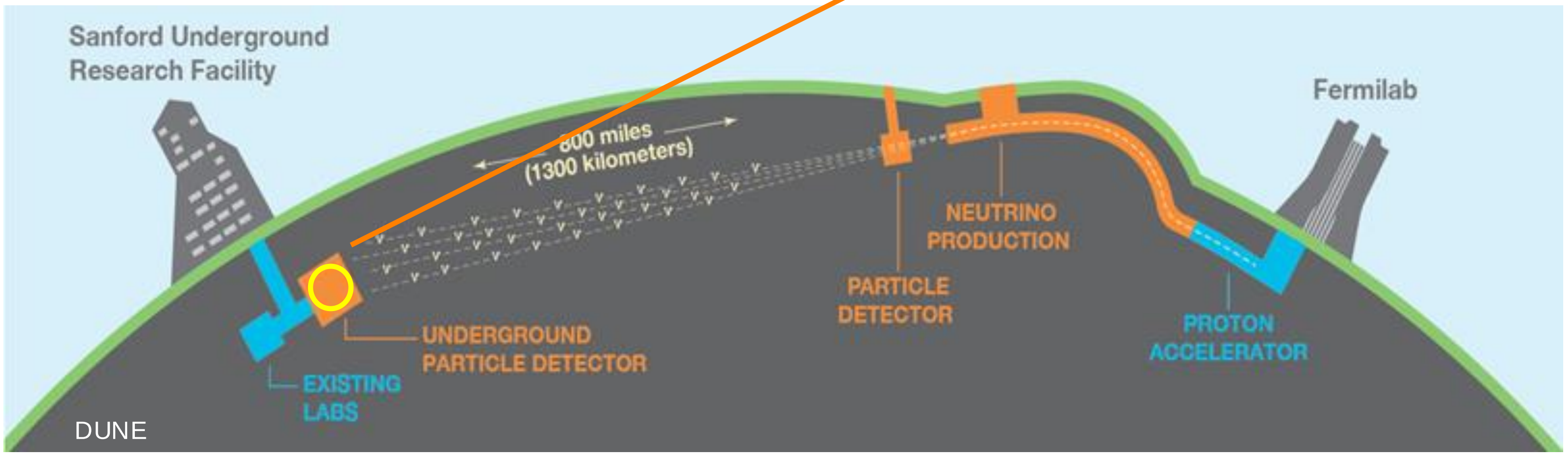


T2K / Hyper-K

NOvA

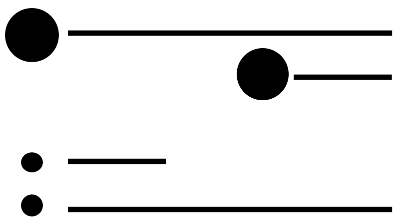
Far Detectors to measure ν oscillation

DUNE



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

Only two Δm^2



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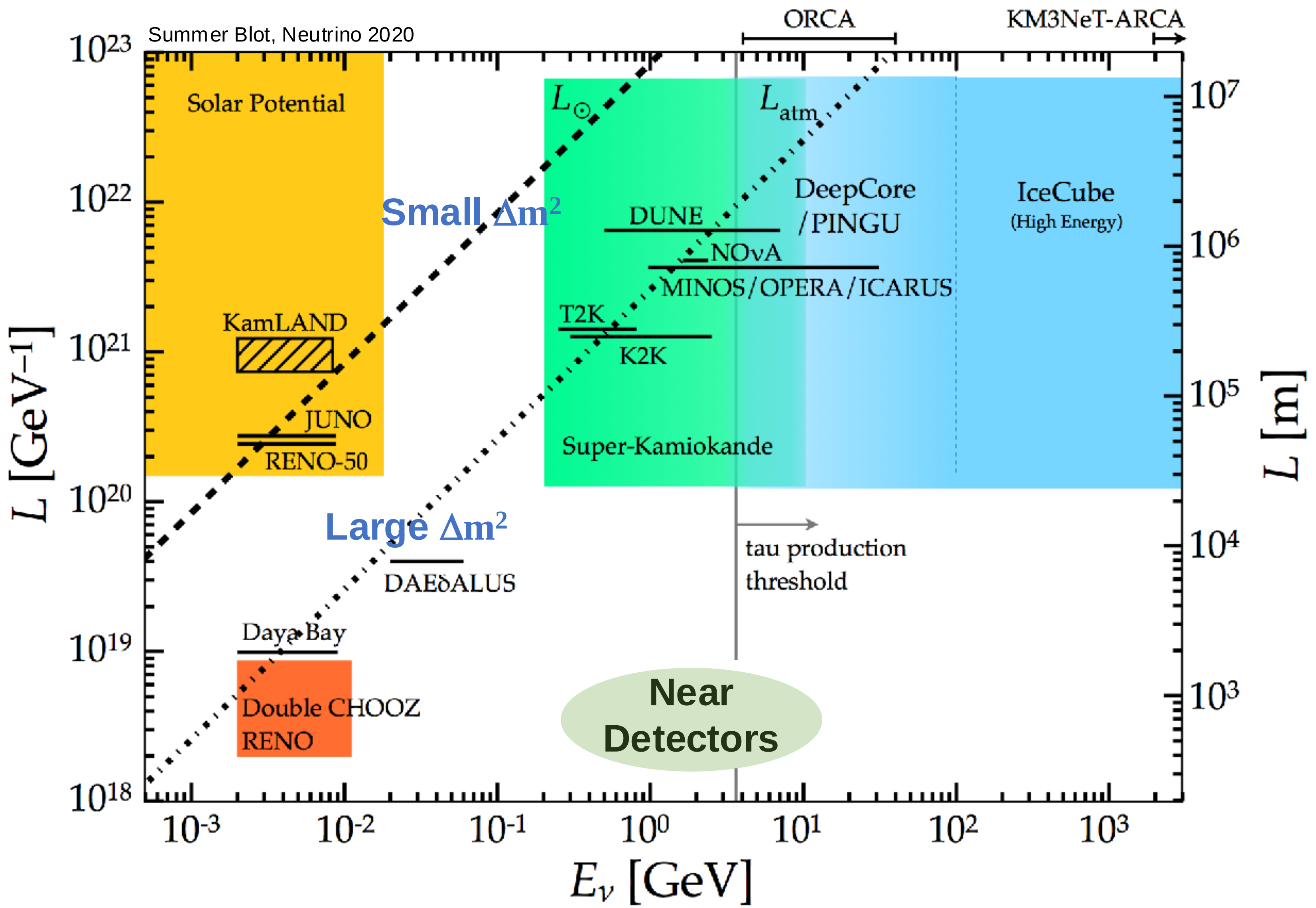


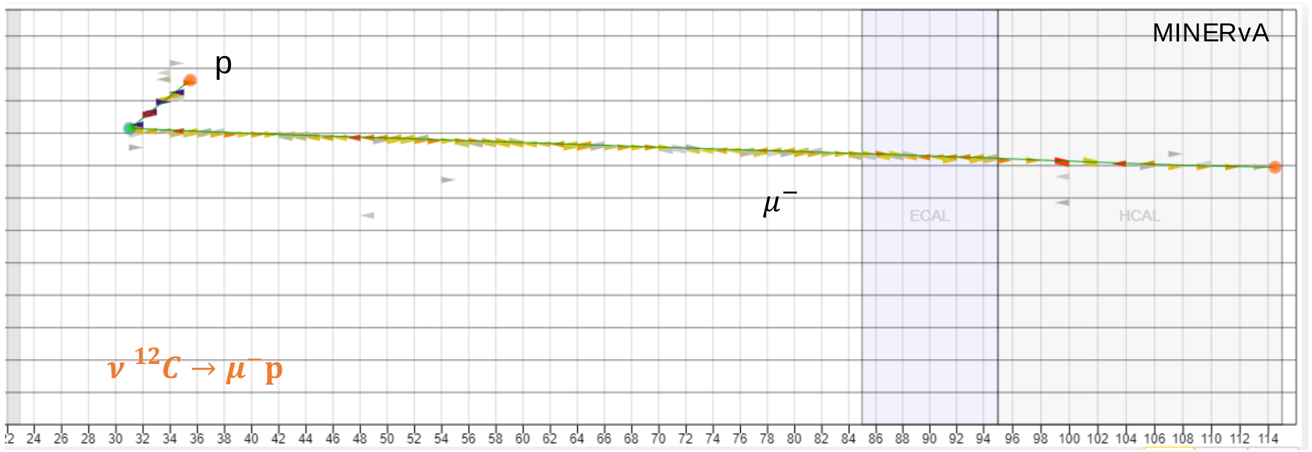
ν @ detector: e.g. plastic scintillator tracker

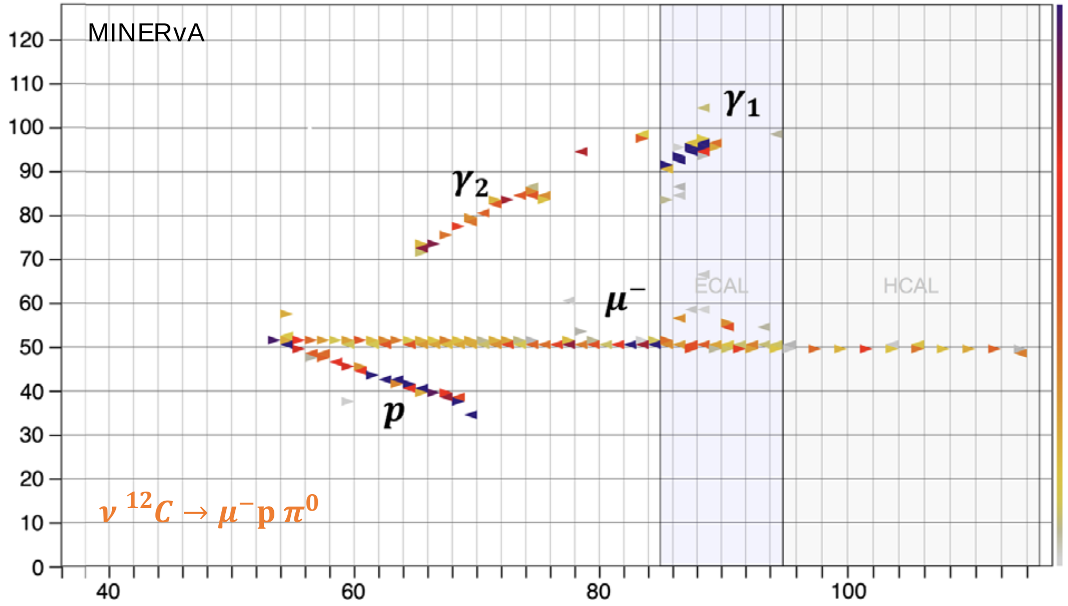
- ❑ Tracker, also ***active target***
  - ❖ Tracking + ***calorimetry***

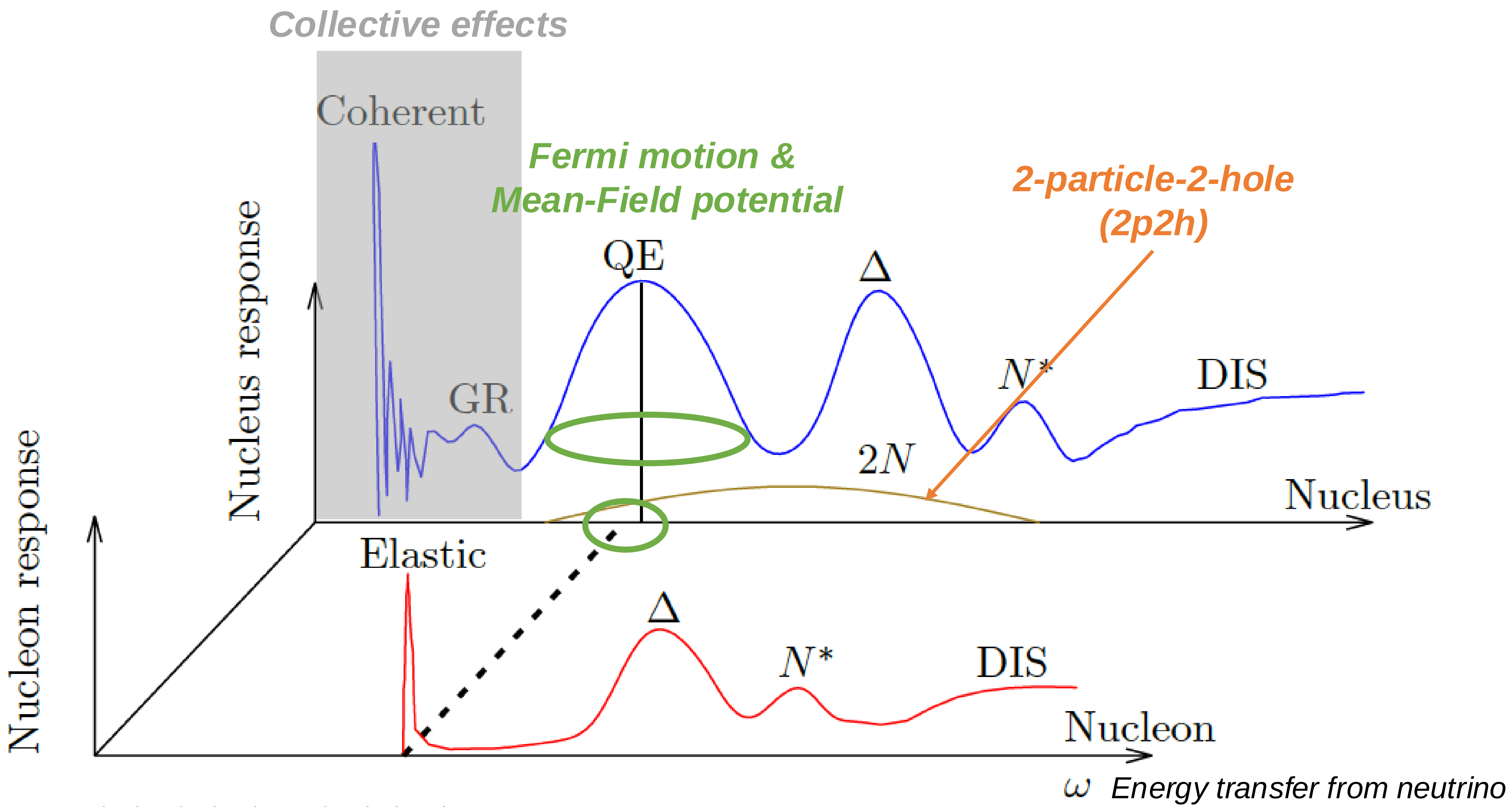
Current role in studying ν interactions

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

Typical event display w/ plastic scintillator tracker

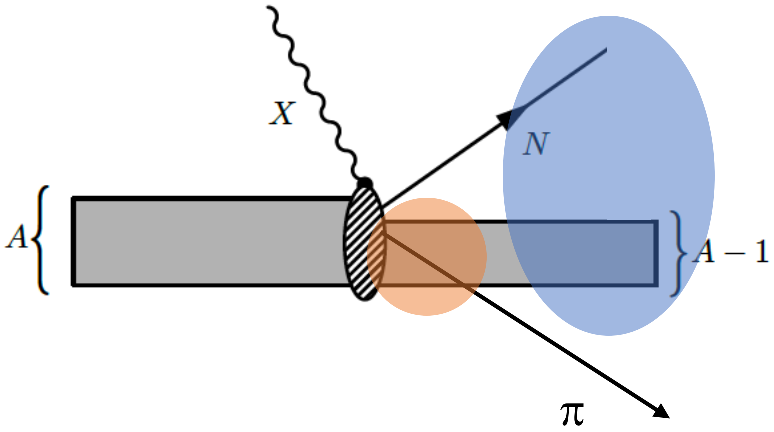






Van Cuyck, PhD Thesis, Ghent University (2017)

Final-state interaction (FSI)



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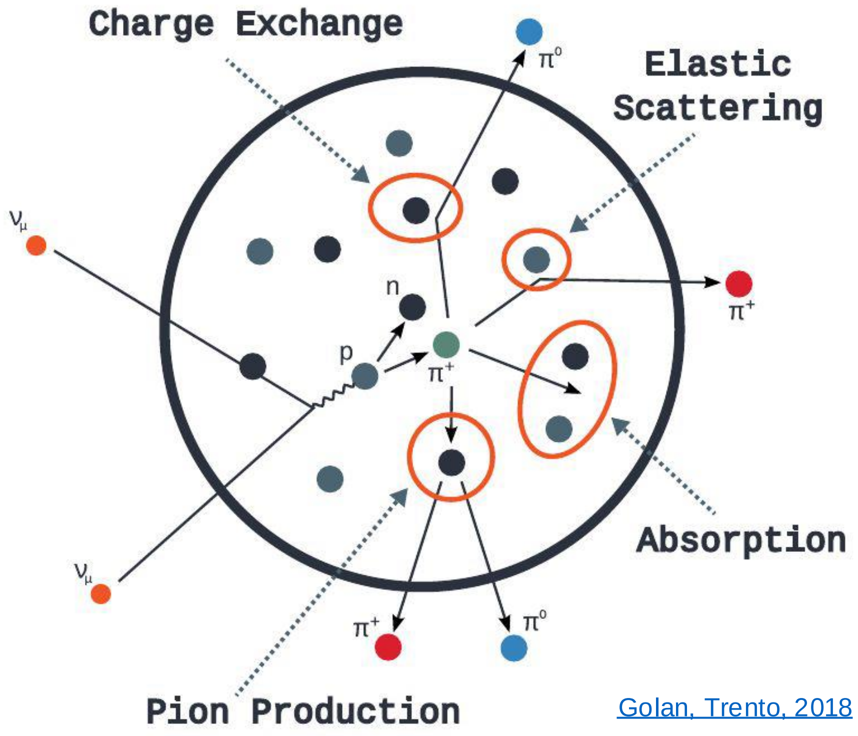
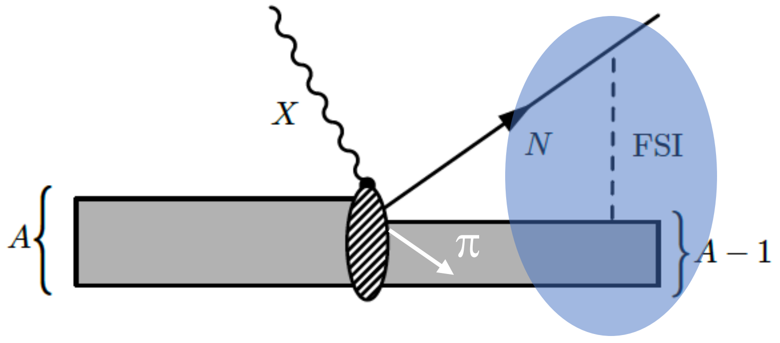


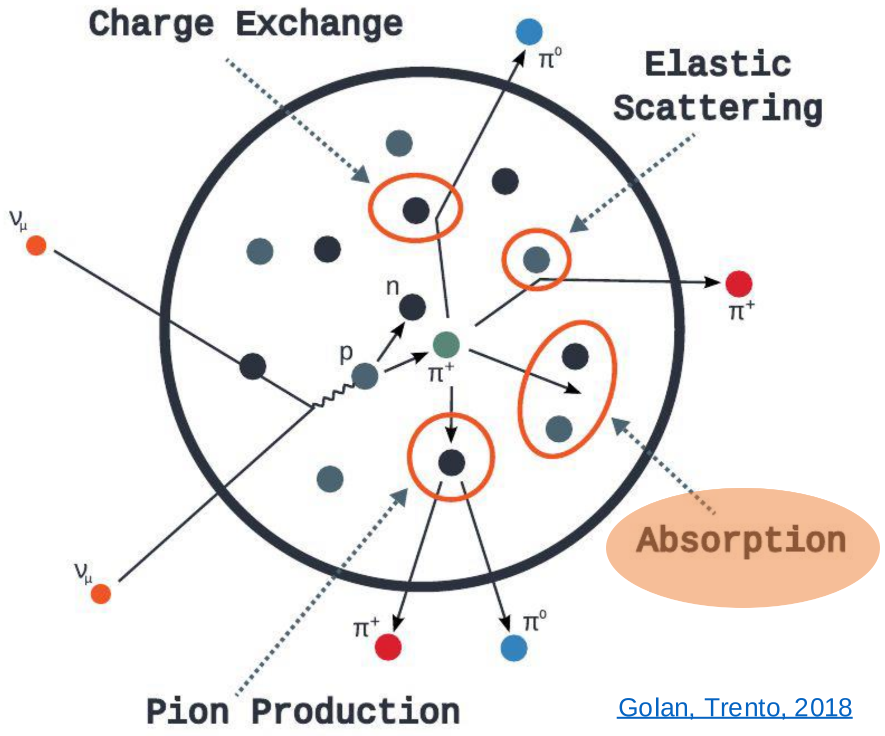
Golan, Trento, 2018

Final-state interaction (FSI)

Can not identify *resonant production* (RES) experimentally



Van Cuyck, PhD Thesis, Ghent University (2017)



Golan, Trento, 2018

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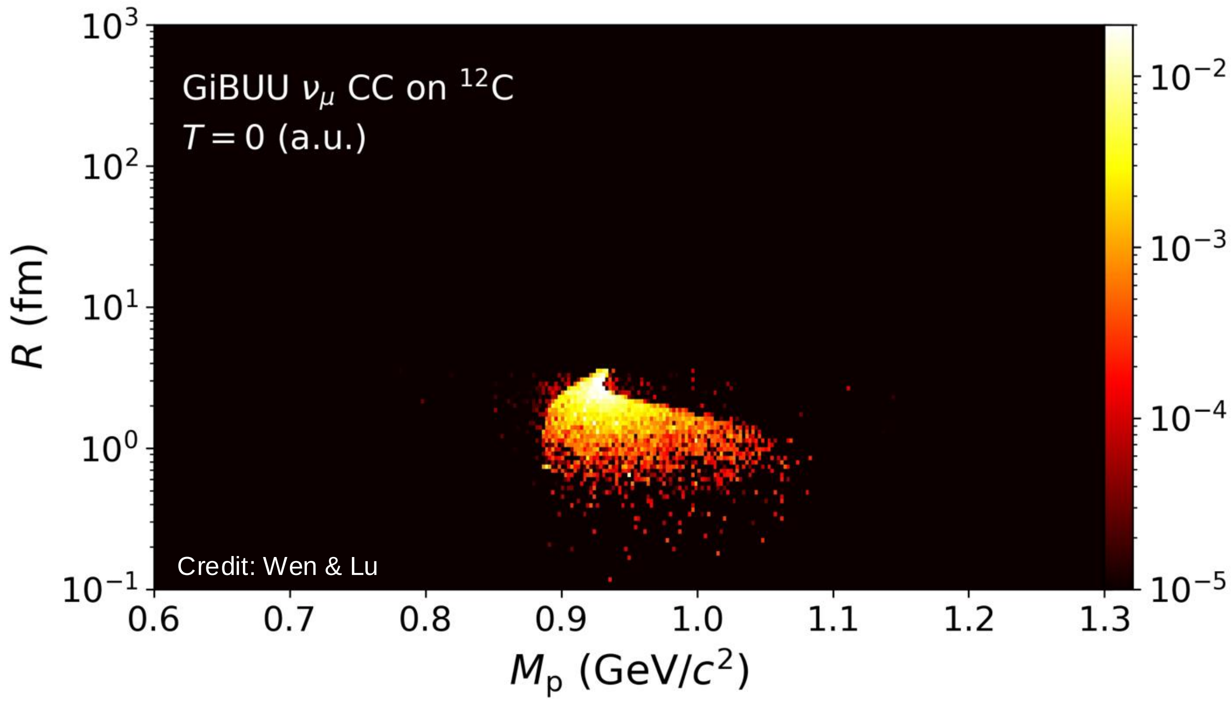
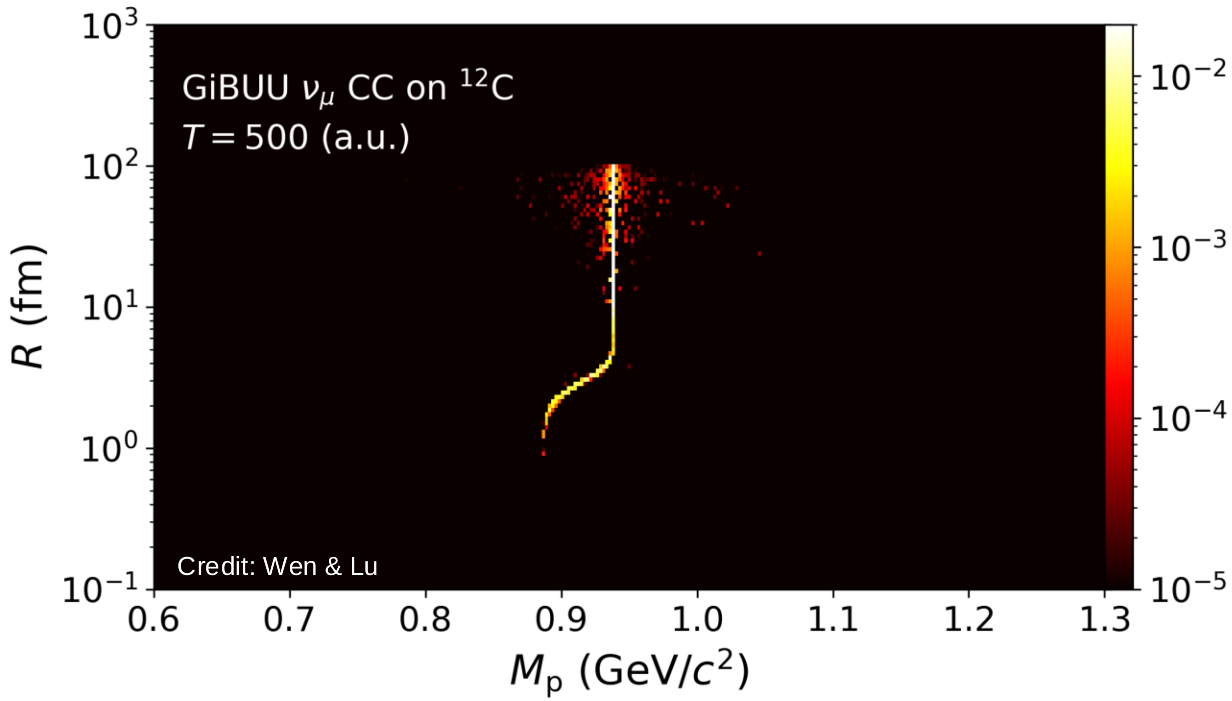


† Proton in GiBUU final-state transport
R: radial position, M_p: mass

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

Final-state interaction (FSI)



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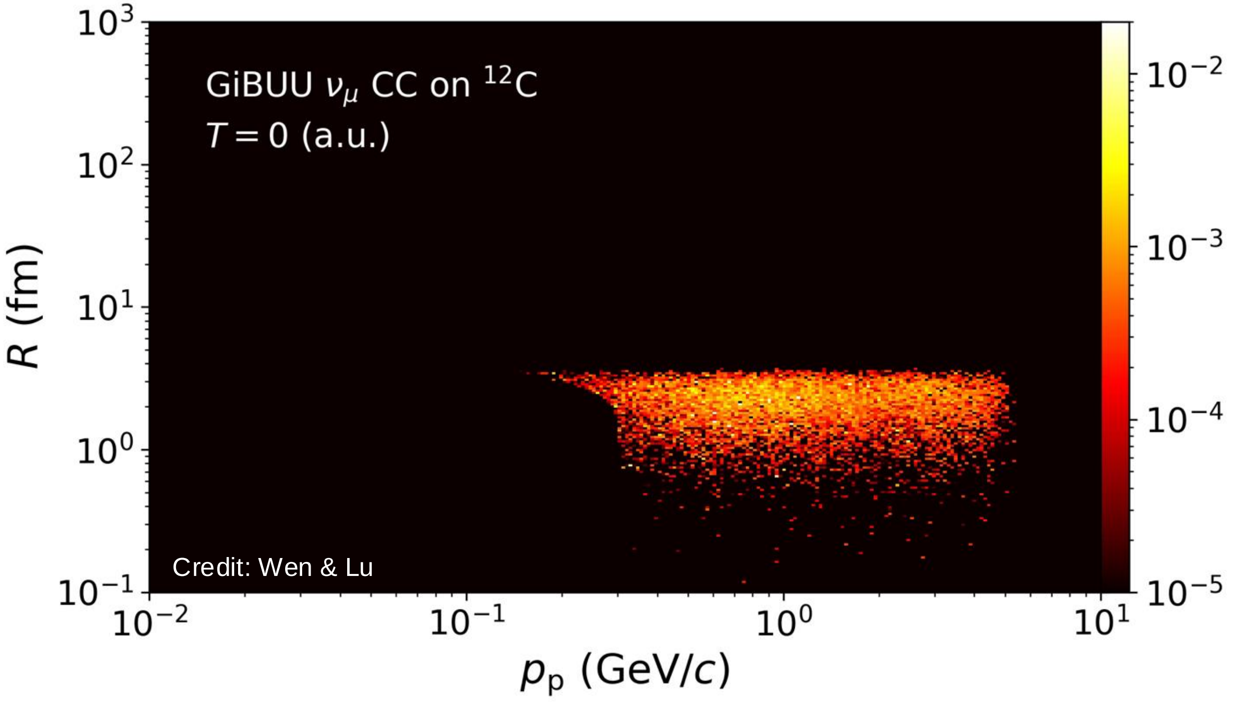

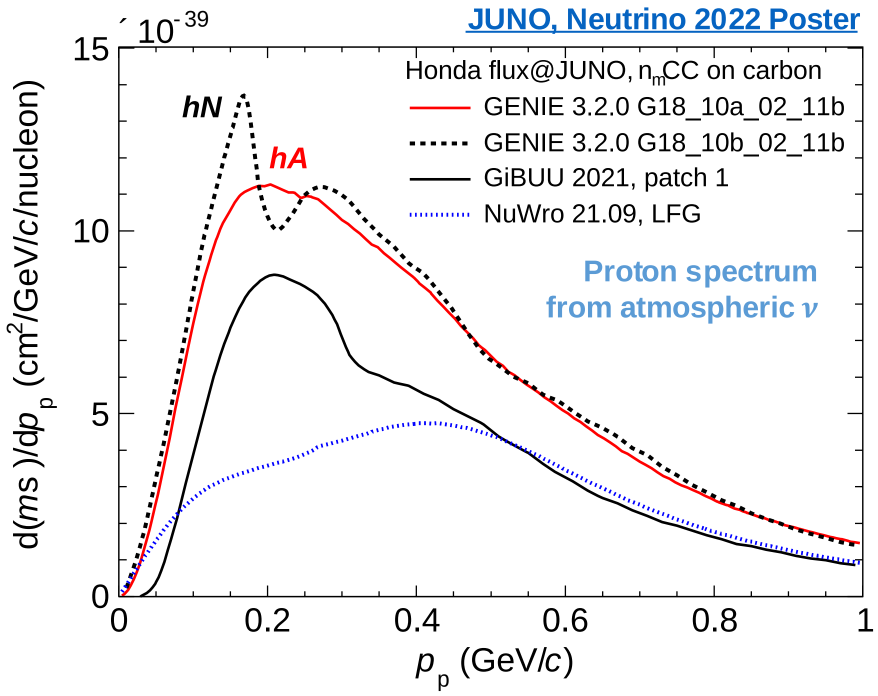

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Final-state proton in neutrino interactions: ***momentum*** evolves as it propagates out of the nucleus.

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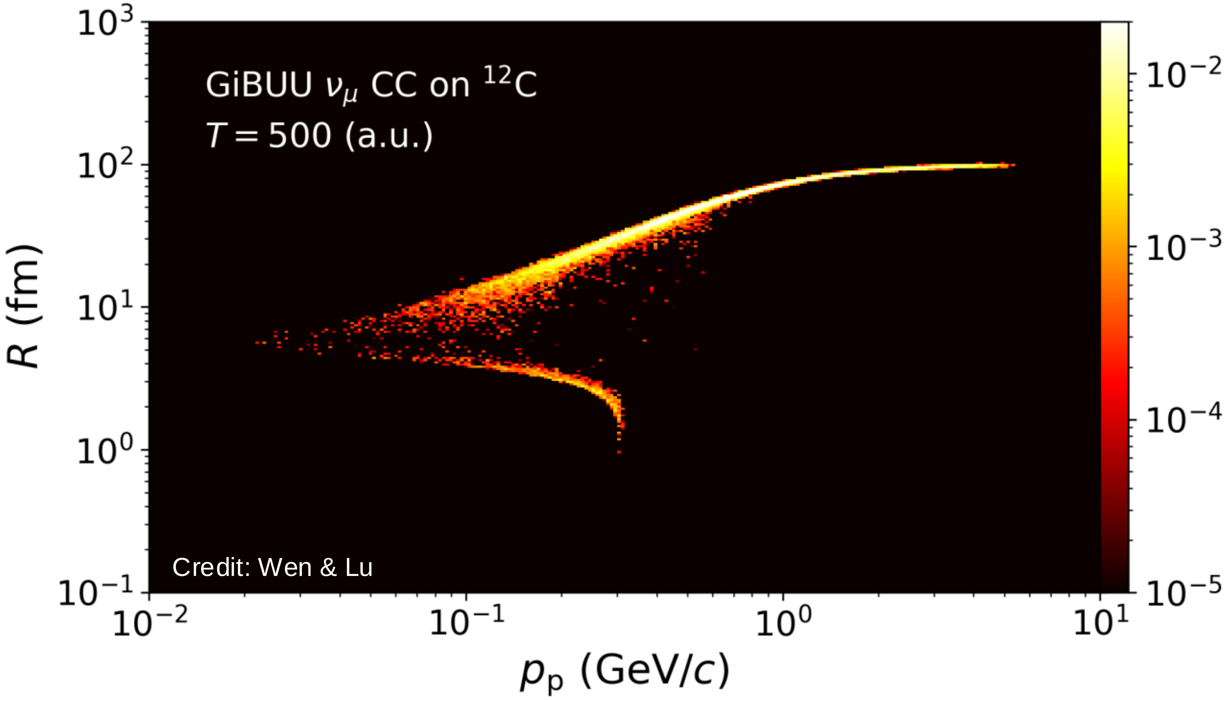

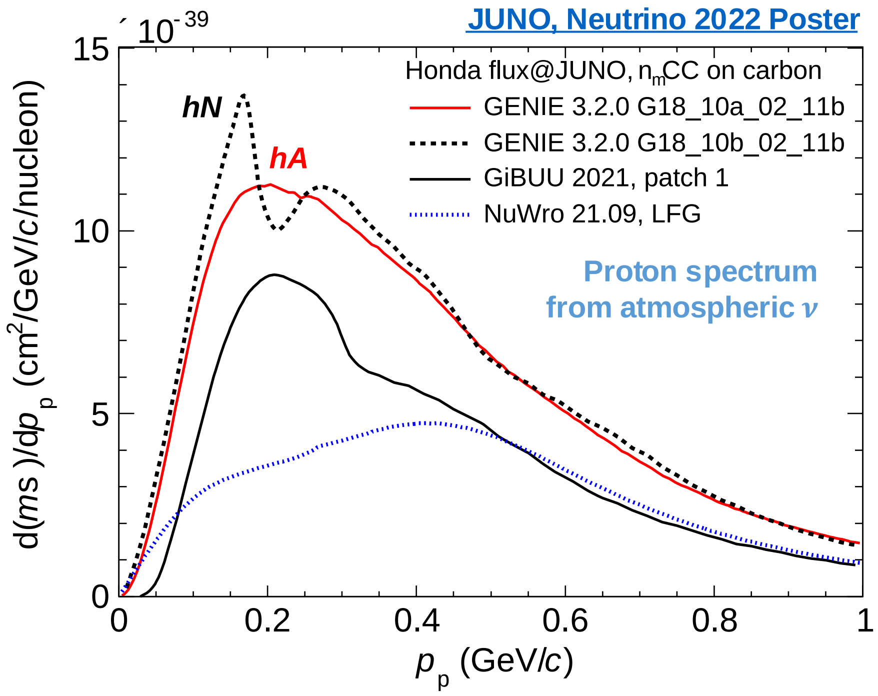

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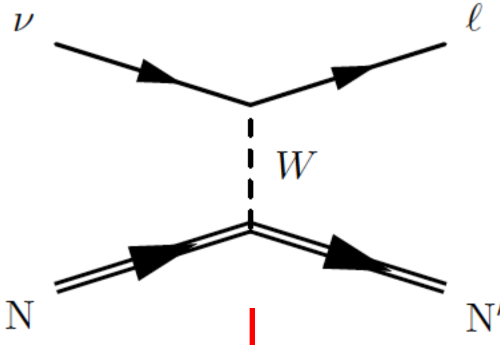
Final-state proton in neutrino interactions: ***momentum*** evolves as it propagates out of the nucleus.

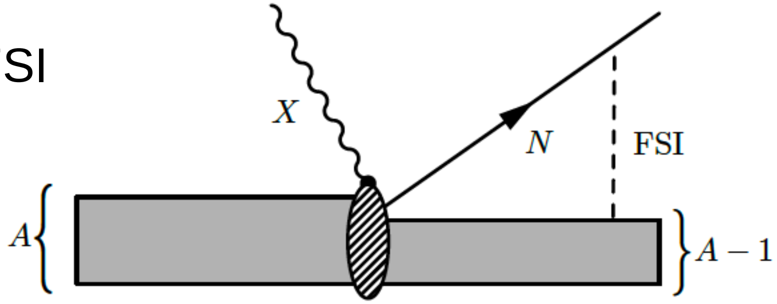
Intranuclear Dynamics and Neutrino Oscillation Measurements

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

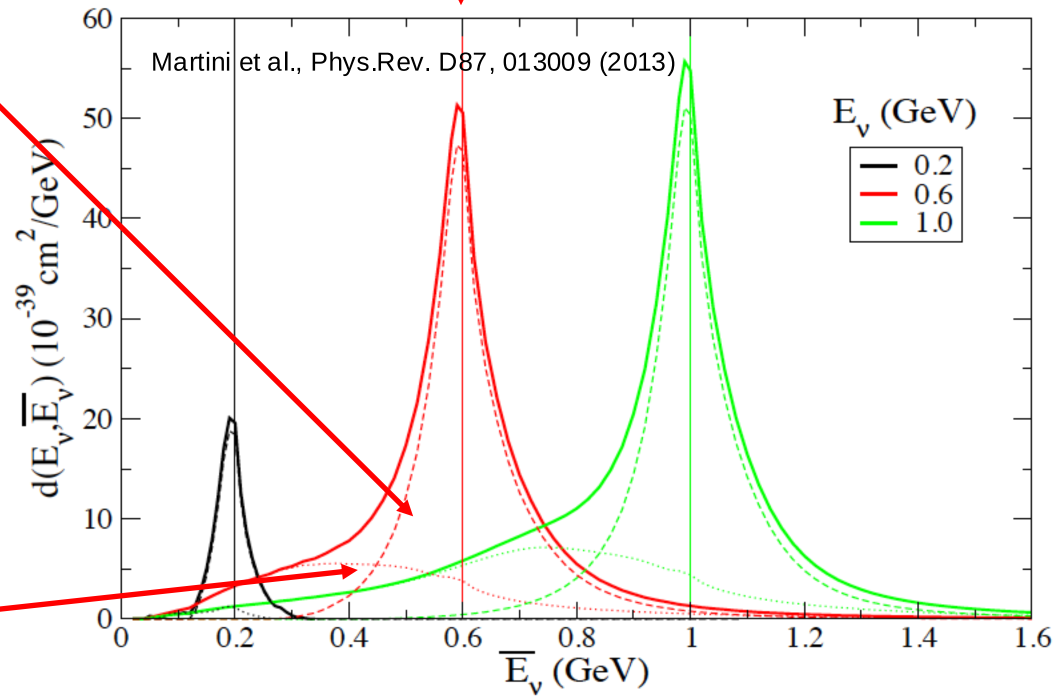


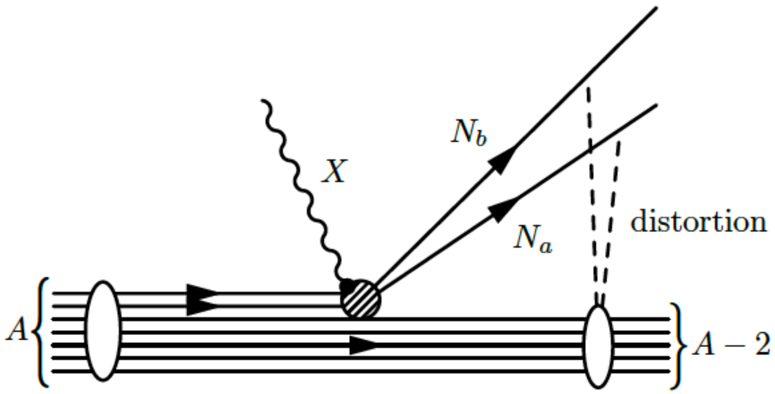
2-body reaction
❑ precise

Fermi motion, FSI
❑ spread



V. Cuyck

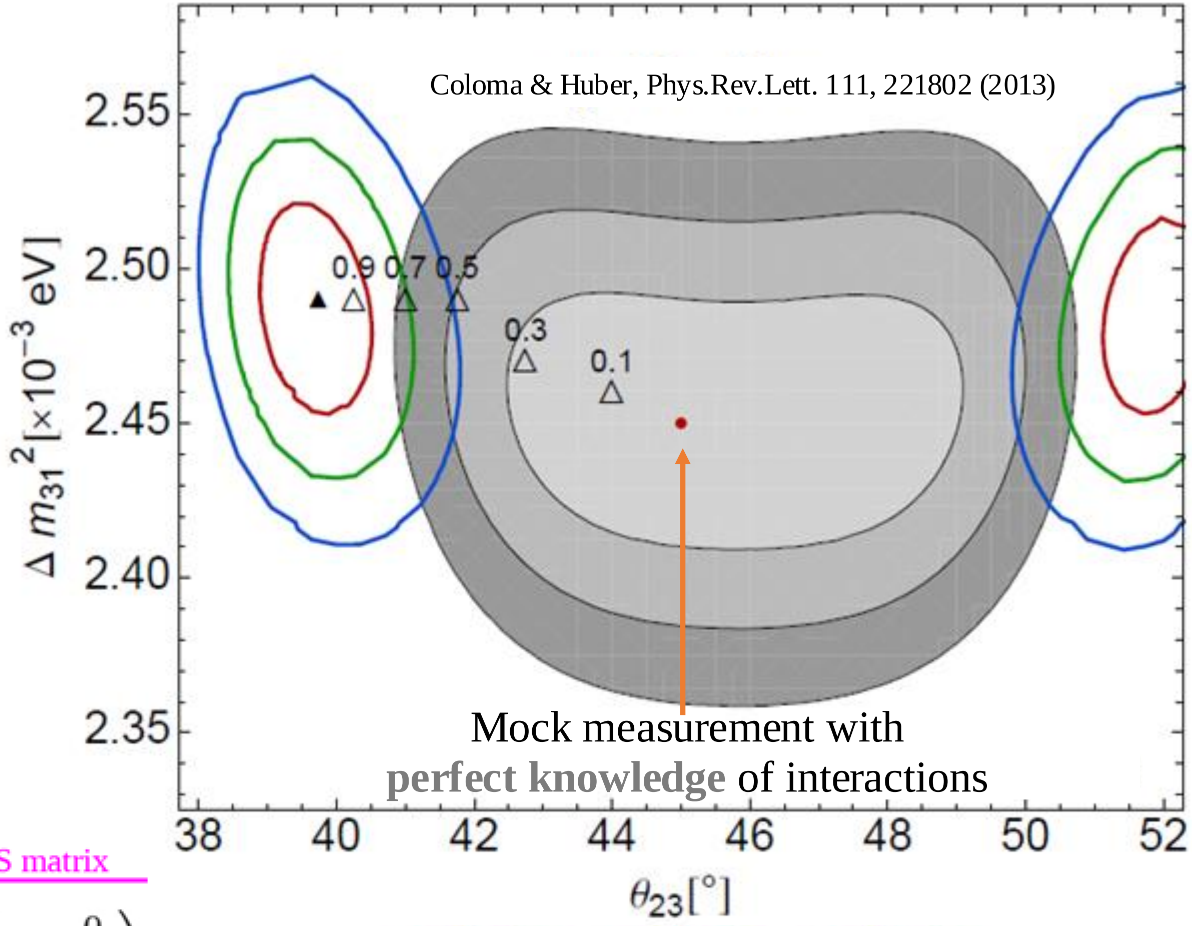




V. Cuyck

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

Intranuclear Dynamics and Neutrino Oscillation Measurements



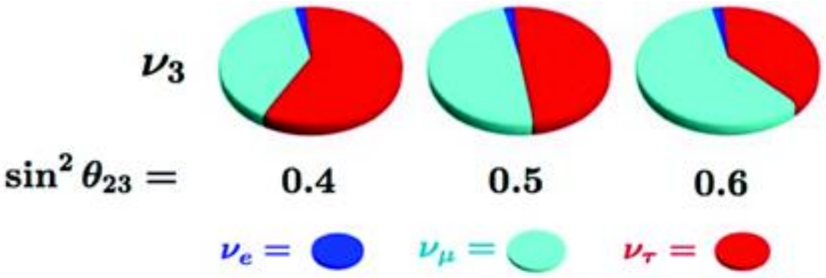
Mixing between
μ and τ flavors

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

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

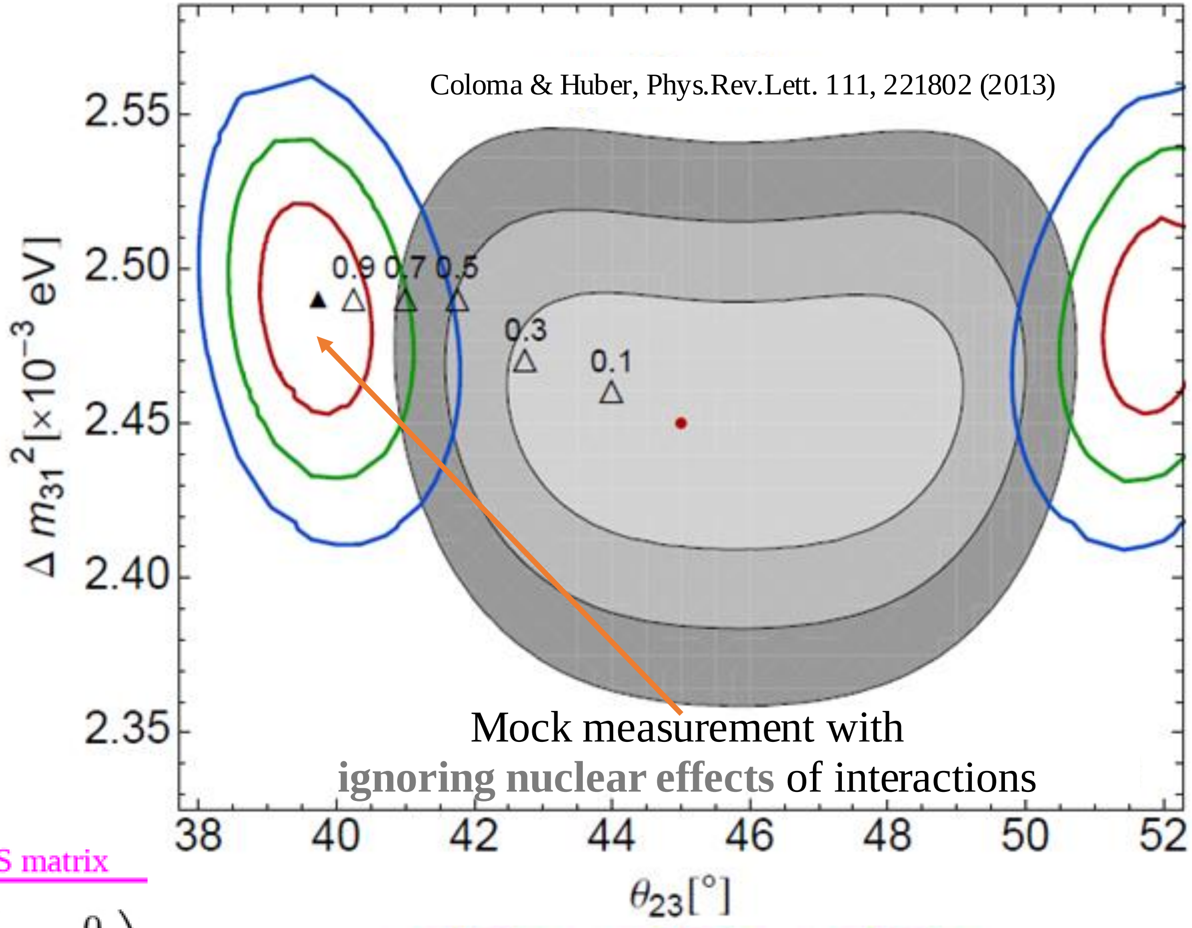
PMNS matrix

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



Parke, 1801.09643

Intranuclear Dynamics and Neutrino Oscillation Measurements



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

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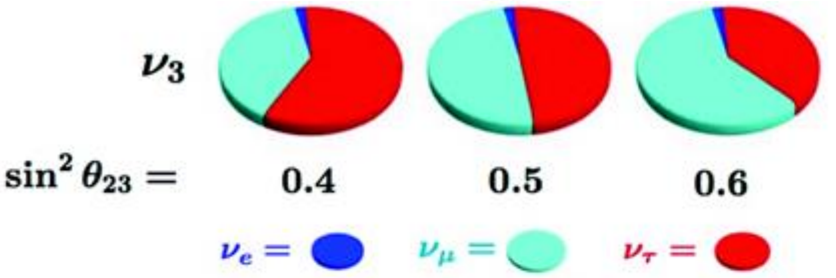
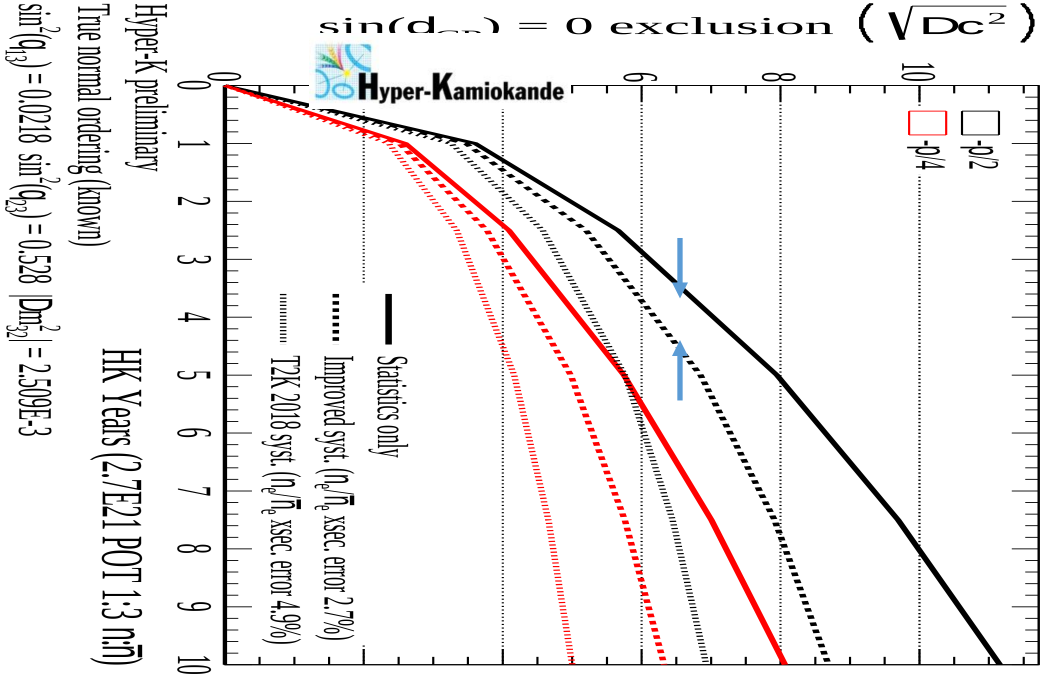


Parke, 1801.09643

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

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

Jeanne Wilson, Neutrino2022



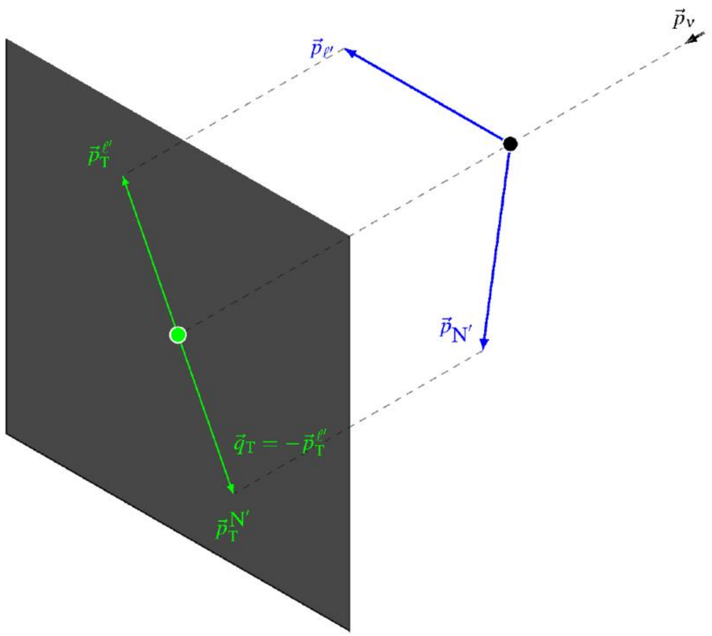
Lepton mass correction ***Hadronic/nuclear response***

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

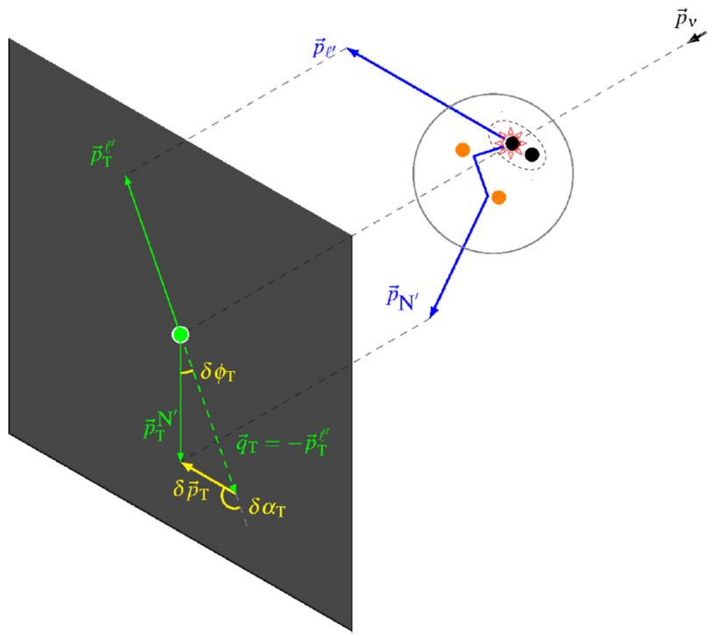
Lepton observables

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

Transverse Kinematic Imbalance (TKI) to measure intranuclear dynamics

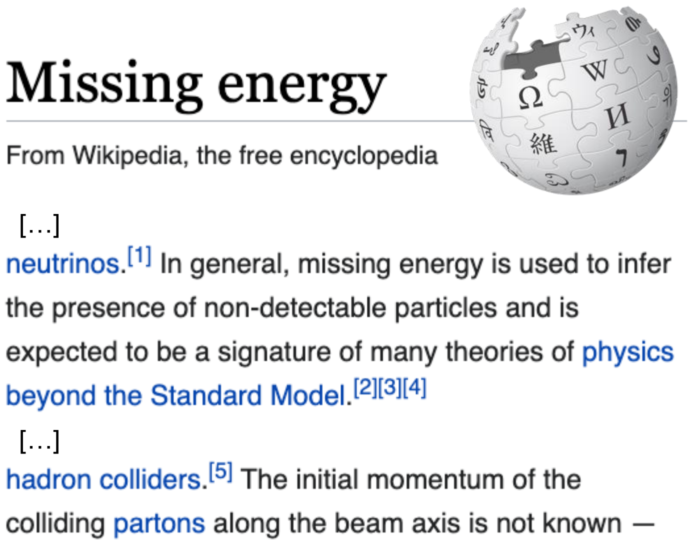


Stationary free nucleon target



Nuclear target ($A > 1$)

- ❑ Fermi motion
- ❑ FSI
- ❑ 2p2h



Missing energy

From Wikipedia, the free encyclopedia

[…]

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

[…]

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

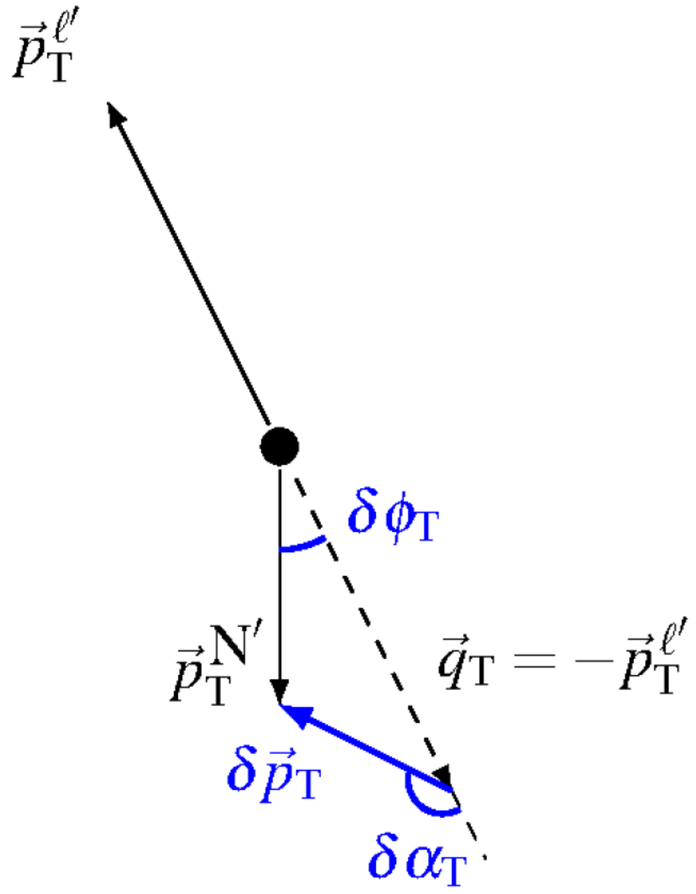
TKI

Multi-dimensional observation

- ❑ Momentum (magnitude)
- ❑ Angle
- ❑ Asymmetry

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

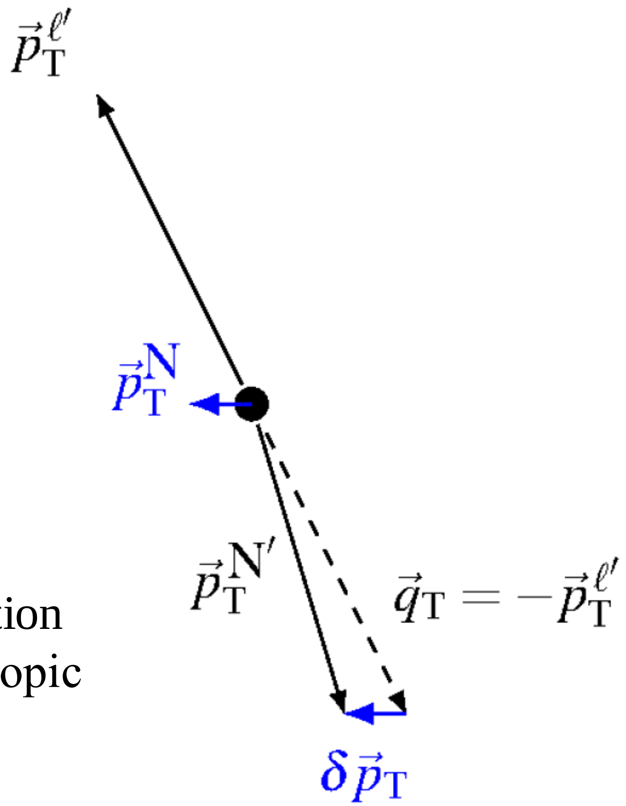
Transverse Boosting Angle $\delta\alpha_T$



if Fermi motion only

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

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



$\delta\vec{p}_T$

—total transverse momentum

—transverse momentum imbalance

—missing pT

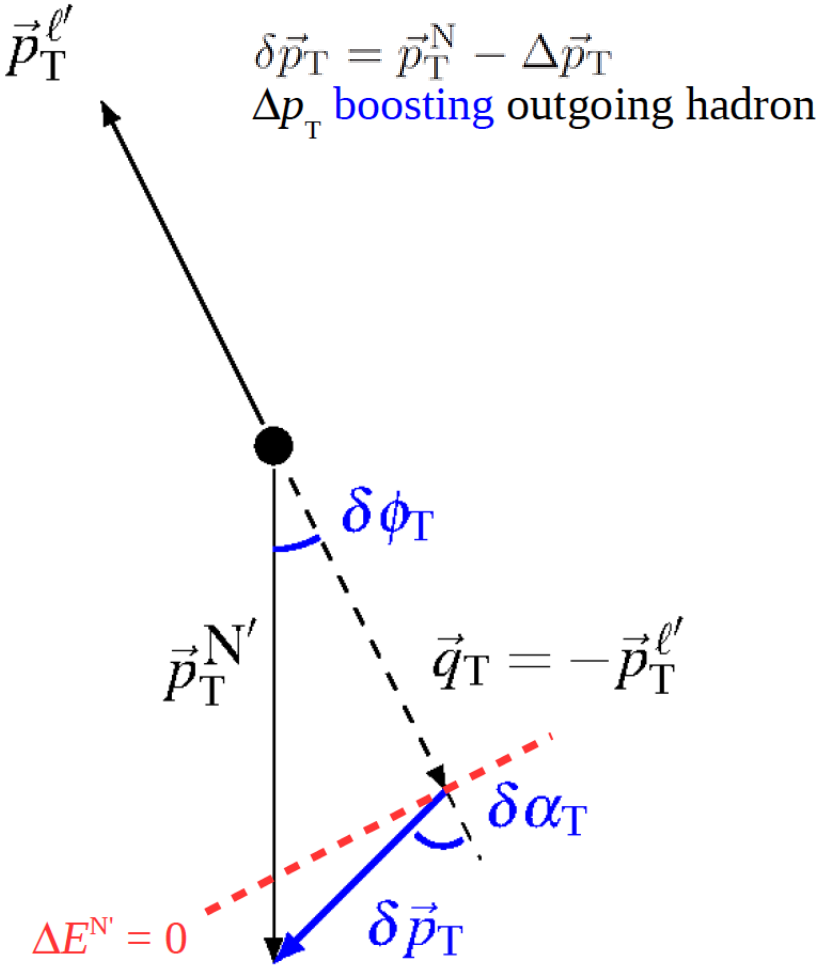
—...

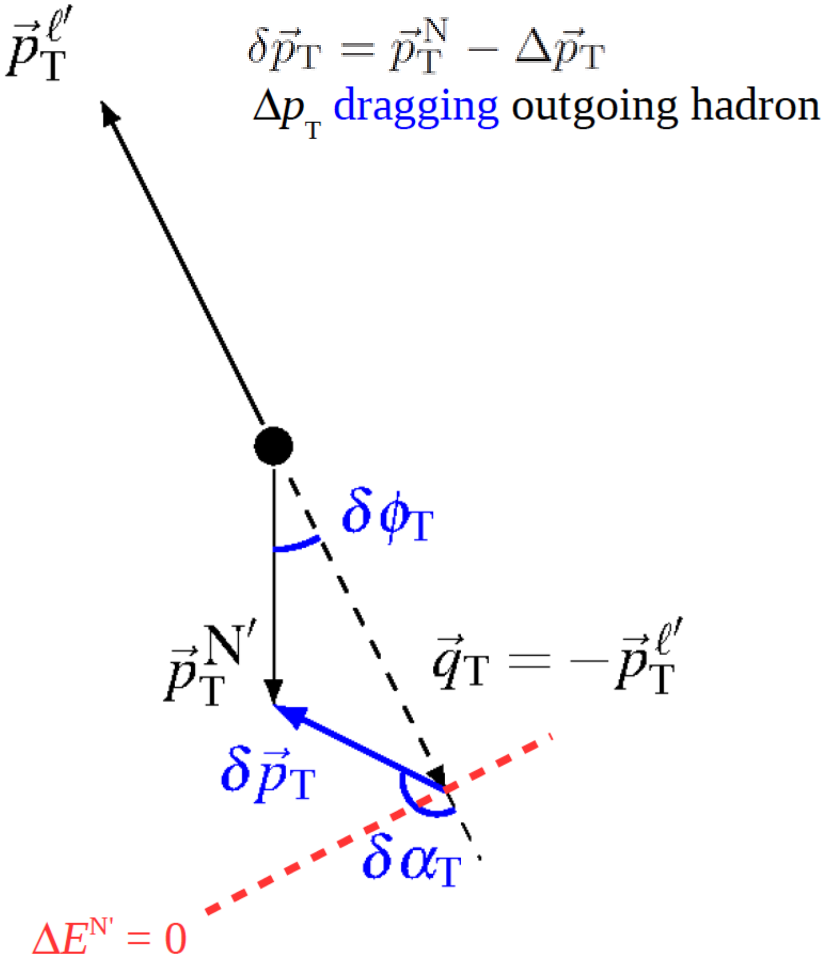
In full

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

FSI and missing particles

Transverse Boosting Angle $\delta\alpha_T$





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

Emulated Nucleon Momentum p_N

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

A more general analysis of kinematic imbalance

Transverse: $$0 = \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'} - \delta\vec{p}_{\mathrm{T}}$$

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

New variable: $$p_{\mathrm{n}} \equiv \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$$

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

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

$$E_{\mathrm{A}'} = \sqrt{m_{\mathrm{A}'}^2 + p_{\mathrm{n}}^2}$$

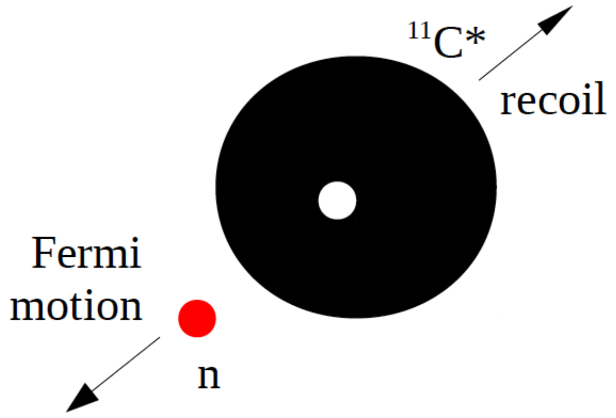
p_n: recoil momentum of the nuclear remnant

final-state

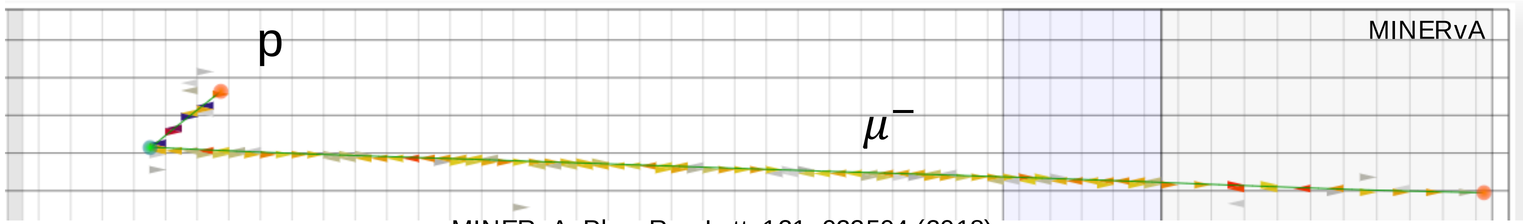
Dual Interpretation

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

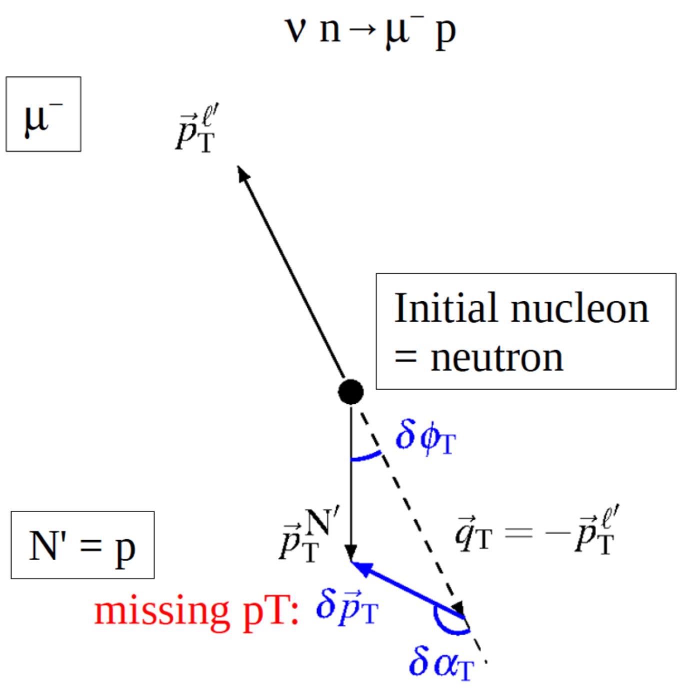
initial-state



TKI: CC0π



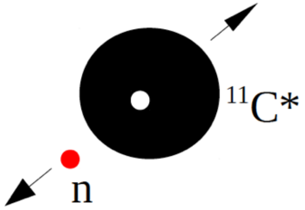
MINERvA, Phys.Rev.Lett. 121, 022504 (2018)

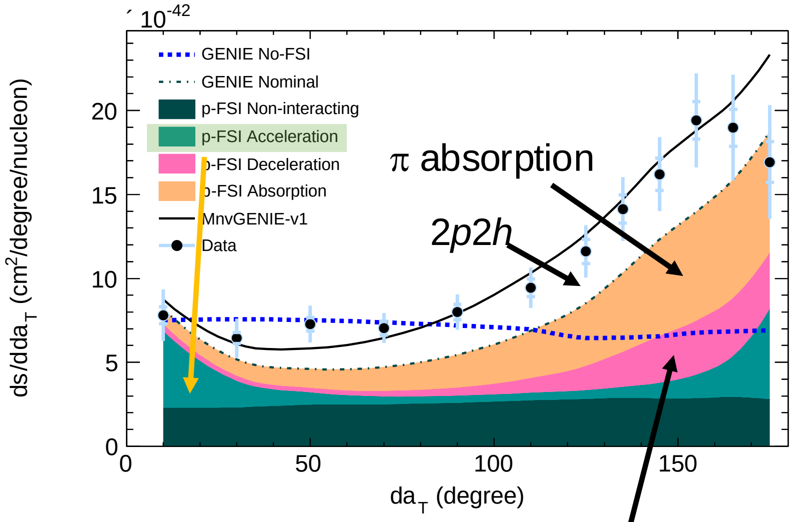


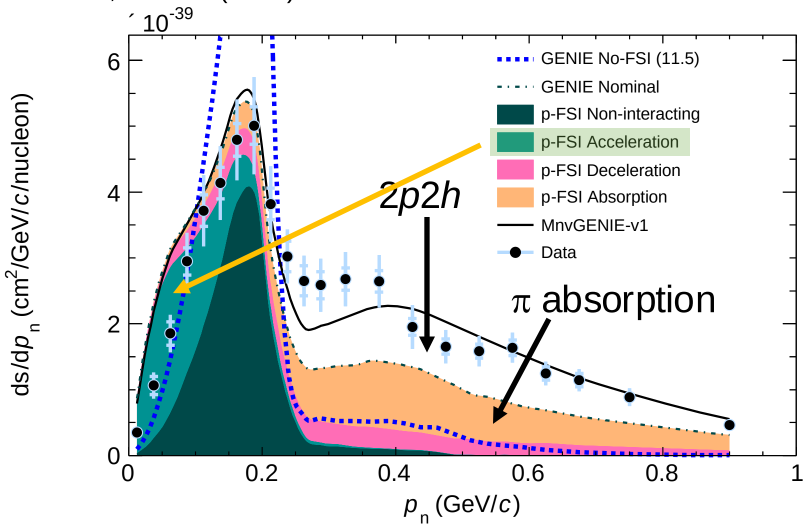
Assuming target remnant $^{11}C^*$

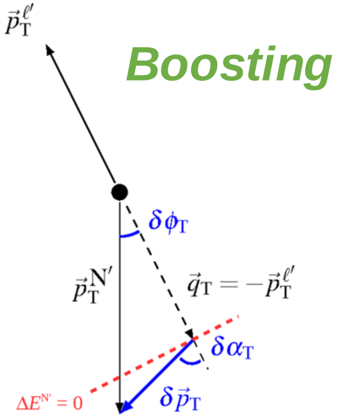
$$p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$$

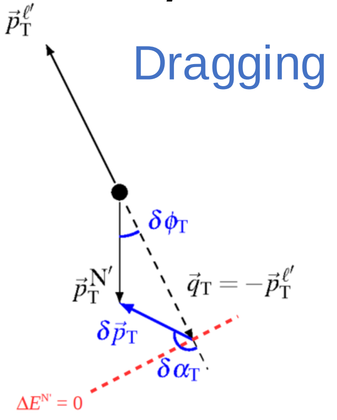
$\sim [1 + O(10\%)] \times \delta p_T$







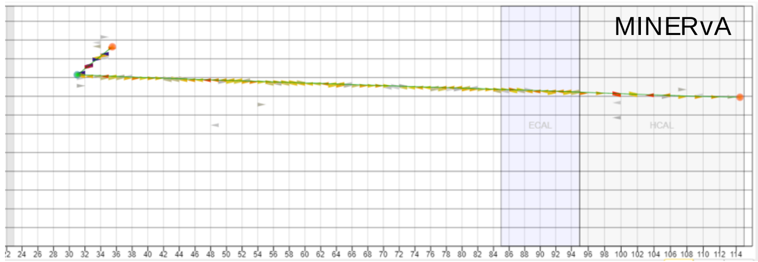




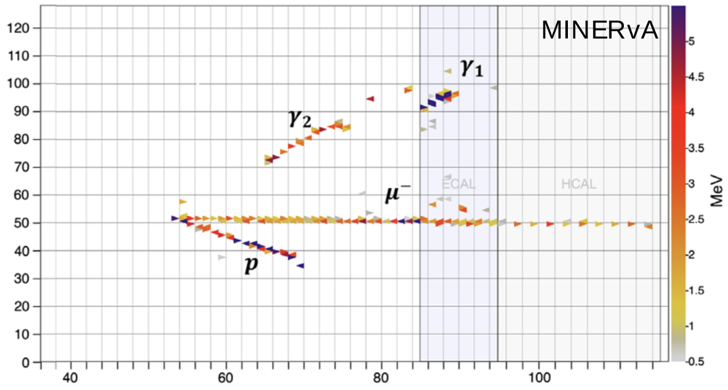
Abnormal acceleration?!

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

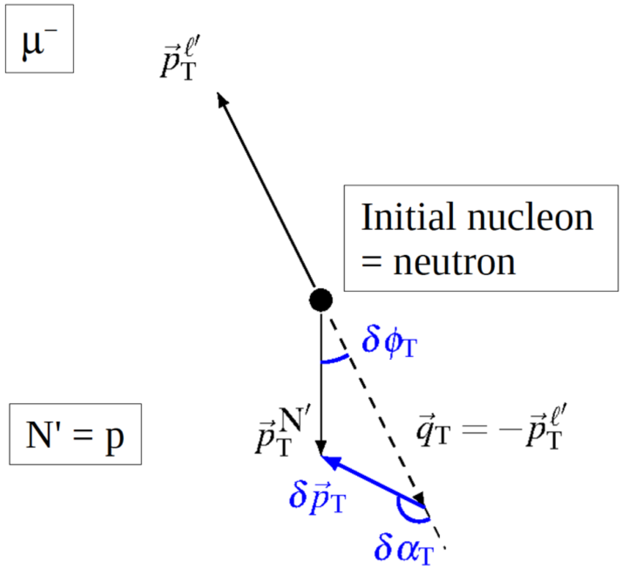
TKI: CCπ^0



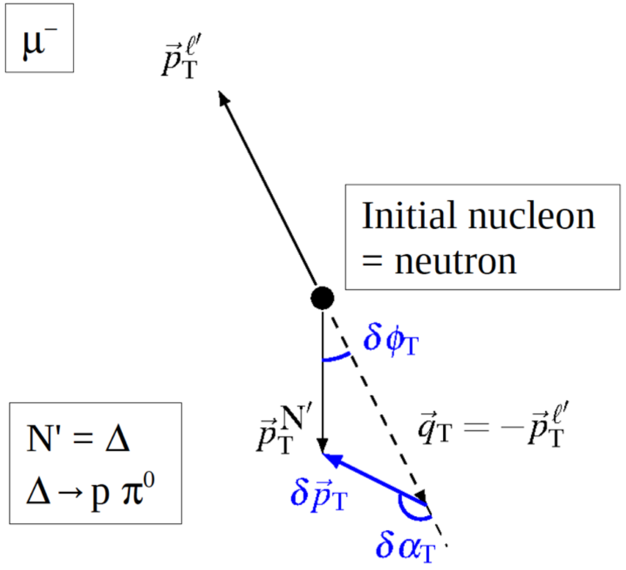
$\nu\, n \rightarrow \mu^- p$



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



via CC0π measurement

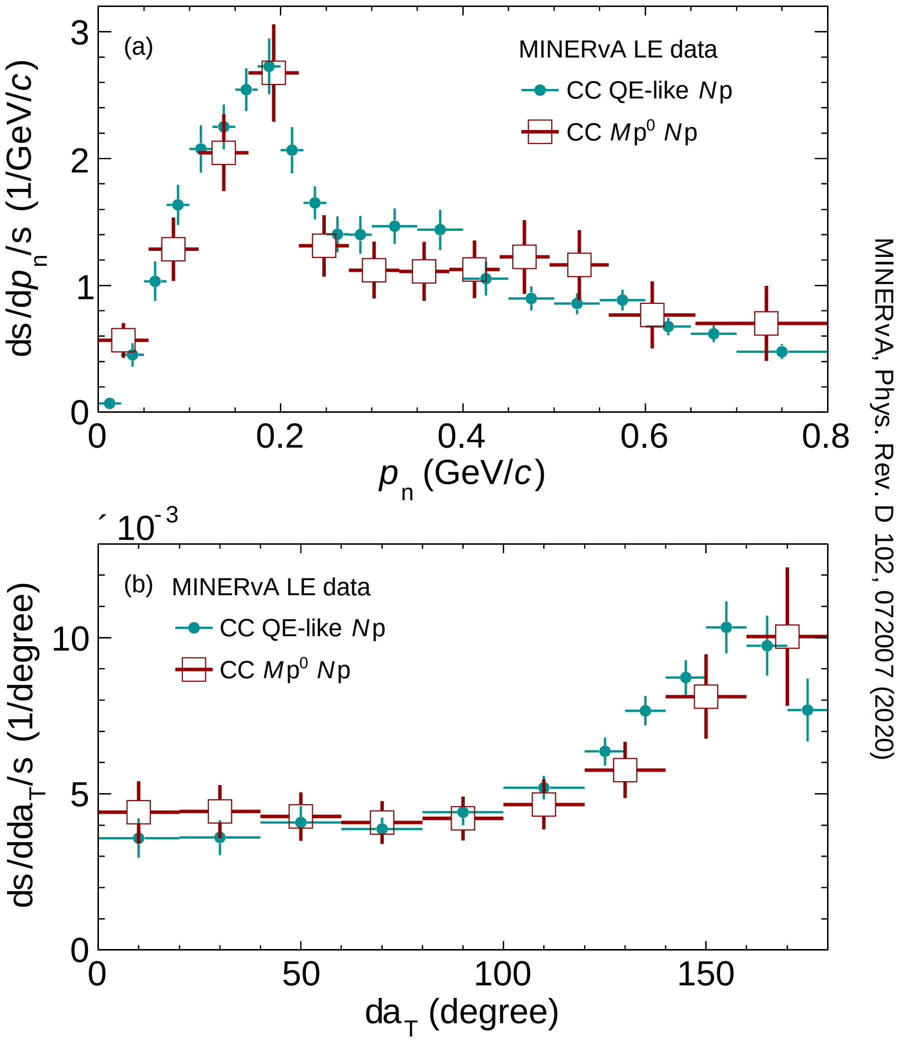


via inclusive π^0 production

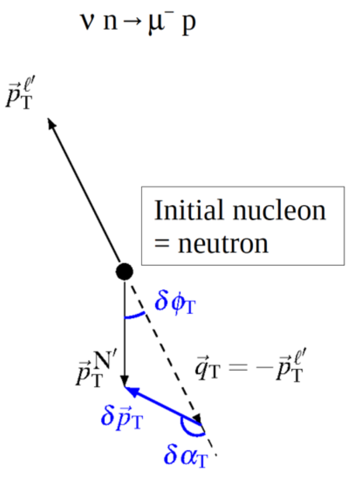
[Lu & Sobczyk, Phys.Rev.C 99, 055504 (2019)]

Surprising consistency!

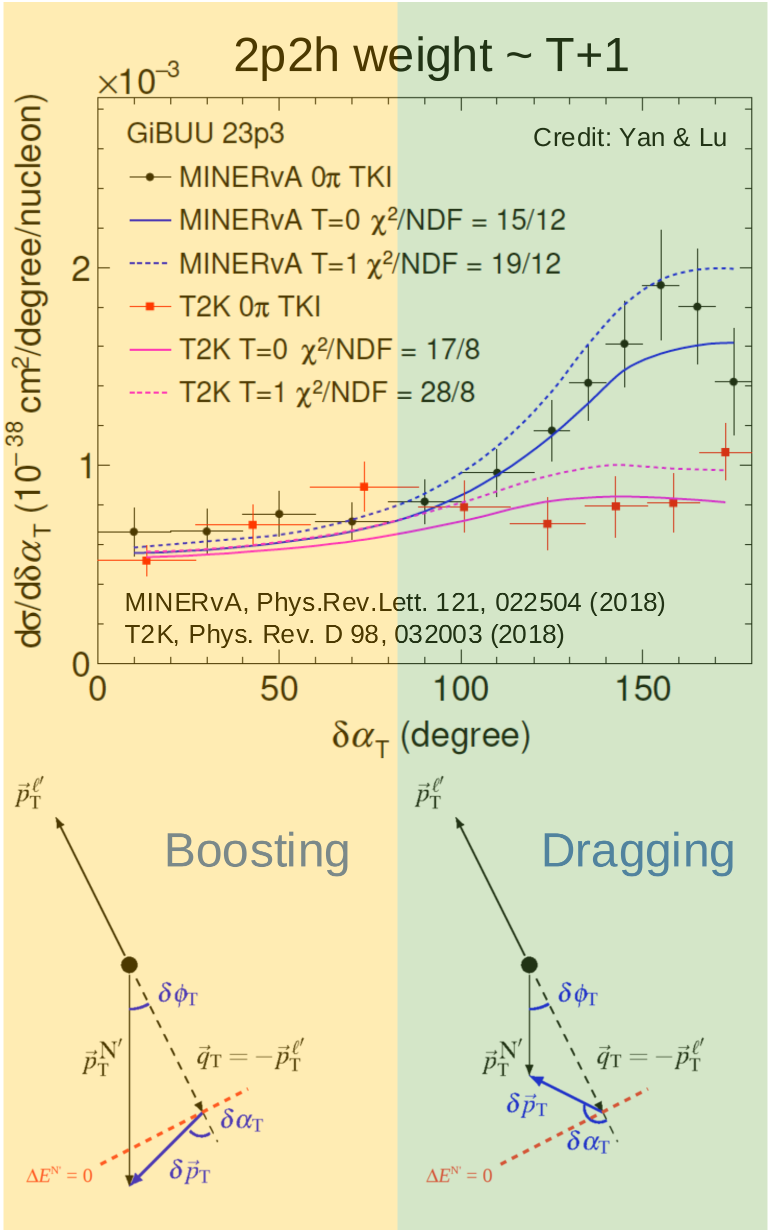
[More detailed discussions see
Q. Yan (严启宇)'s talk in the afternoon session]

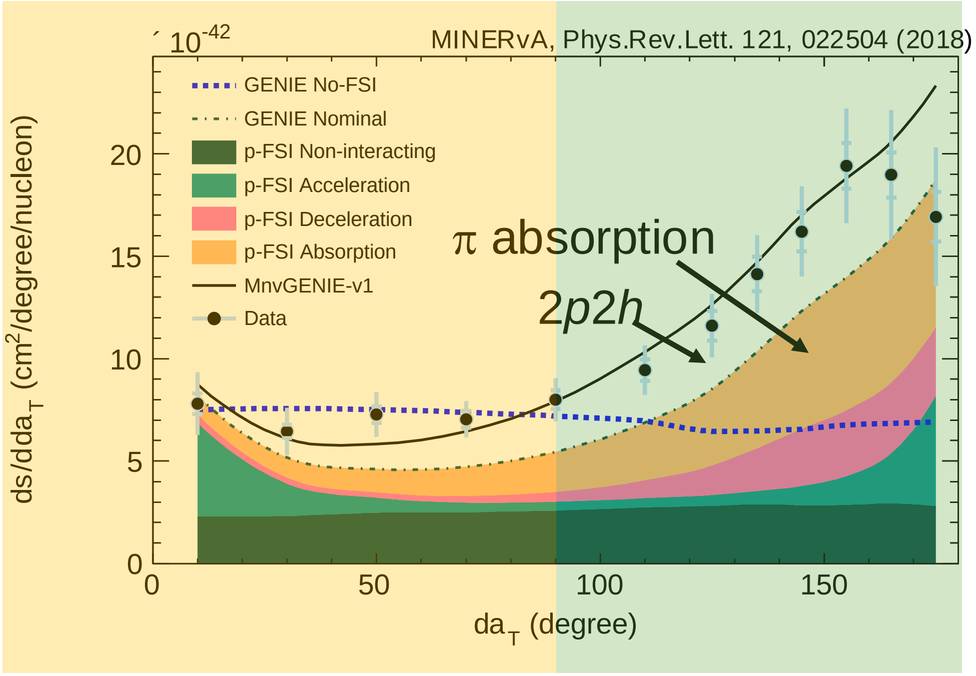


TKI: FSI and 2p2h

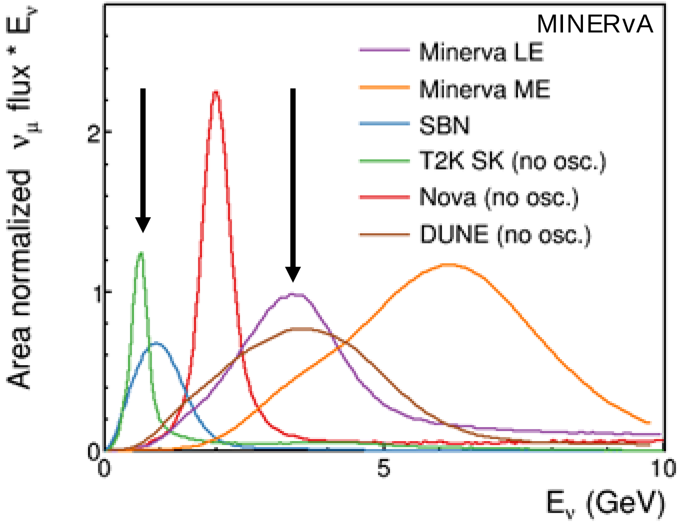


- Consistent QE xsec





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



Summary and Conclusion

1. Neutrino interactions: critical for precise oscillation measurements
   - Affect energy reconstruction through Fermi motion, FSI, and 2p2h
   - Ambiguous event category: require practical topology (CC0π, CC1π, etc.) rather than physical interactions (quasi-elastic, resonant, DIS, etc.)
   - δ_{CP} measurement: sensitive to ν_e interactions deviation from ν_μ

2. Neutrino interactions: essential for studying nuclear dynamics.
   - Nuclear medium response to electroweak probe
   - Rich phenomenology + a growing field beyond neutrino = *no conclusion yet*

3. Transverse Kinematic Imbalance (TKI): a new tool for probing individual intranuclear medium effects.
   - Enlarging body of individual and joint analyses with data from T2K, MINERvA and others

BACKUP

PMNS Matrix

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

PMNS matrix

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

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

θ_{12}: mixing between ν_1 and ν_2

θ_{23}: mixing between ν_μ and ν_τ

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

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

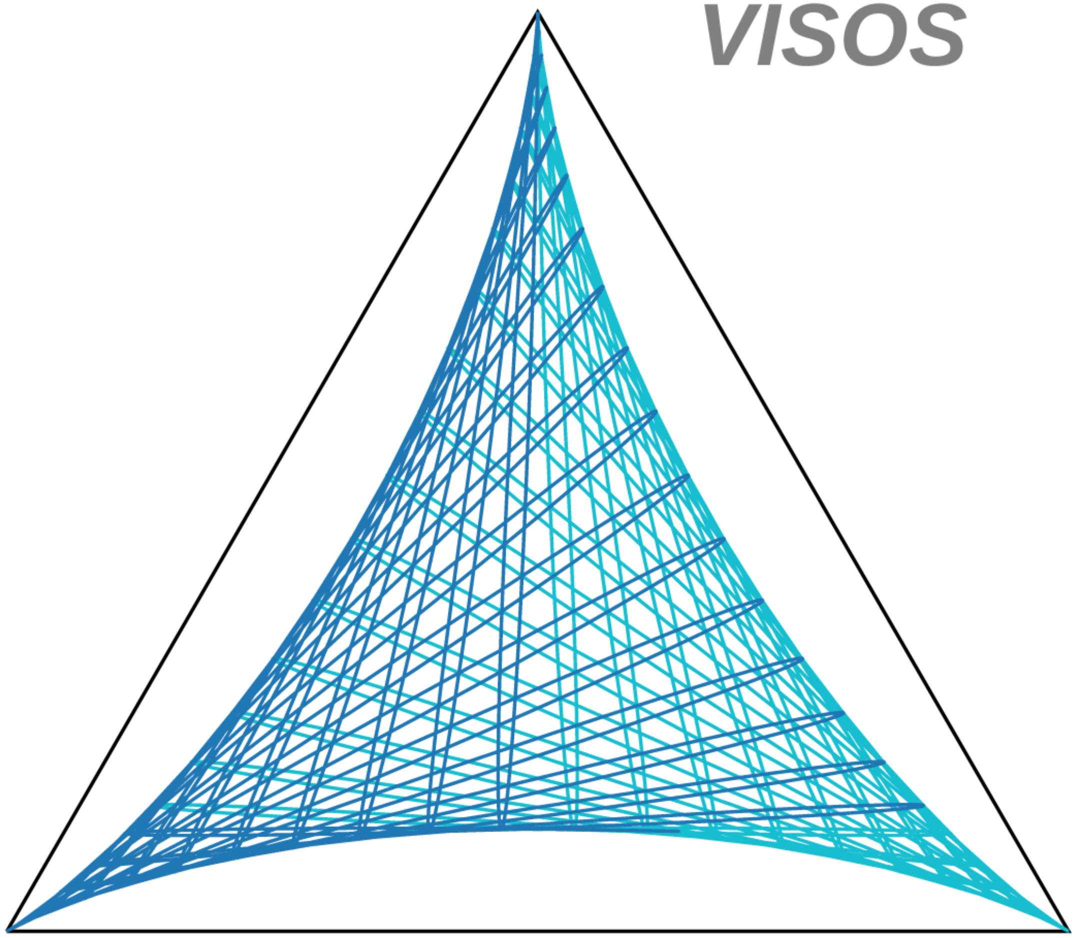
PMNS

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

Trimaximal mixing
— maximally CP-violating

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

VISOS



☛ VISOS

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

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