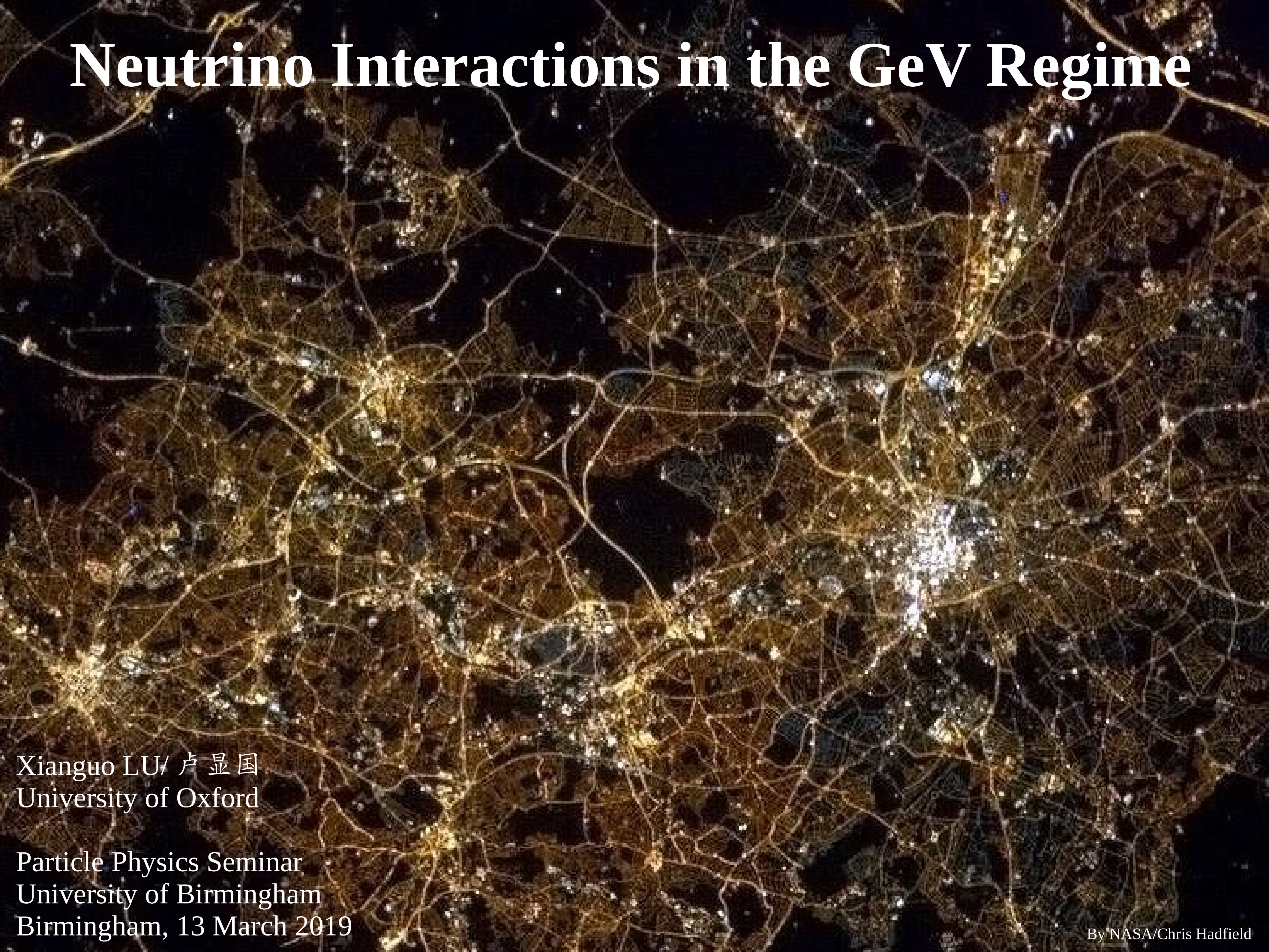
Neutrino Interactions in the GeV Regime



By NASA/Chris Hadfield

Xianguo LU/ 卢显国
University of Oxford

Particle Physics Seminar
University of Birmingham
Birmingham, 13 March 2019

Neutrino Interactions in the GeV Regime

Outline

- Neutrino Oscillations

– An identity-changing game – Underlying math – Seeing is believing

- Oscillation Measurements

– Accelerator-based neutrino experiments – #measured ν / #produced ν

– Beam flux, ν and $\bar{\nu}$ interactions

– ν and $\bar{\nu}$ interactions – Impact of ν and $\bar{\nu}$ interactions

- Interaction Measurements

– MINERvA

– Inclusive 'low-recoil' analysis – Inclusive to exclusive

- Exclusive Measurements

– Why particle spectra won't work

- Transverse Kinematic Imbalance (TKI)

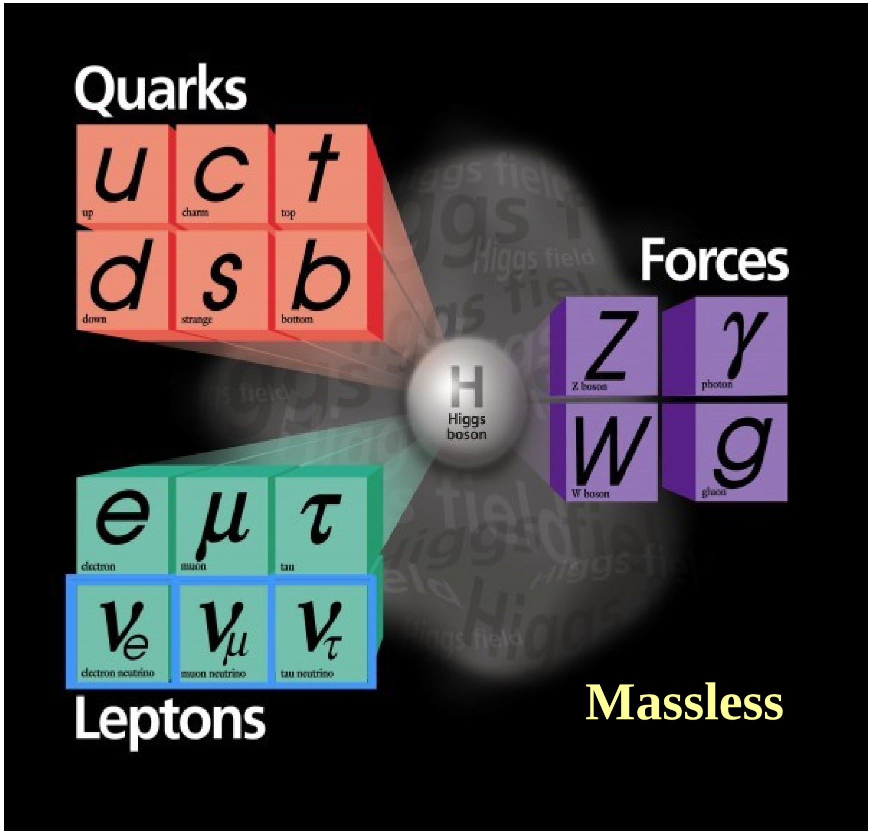
– Principle – Analysis – Future experiments – The very idea

– Initial-state kinematics – Neutron initial-state kinematics – Proton initial-state kinematics

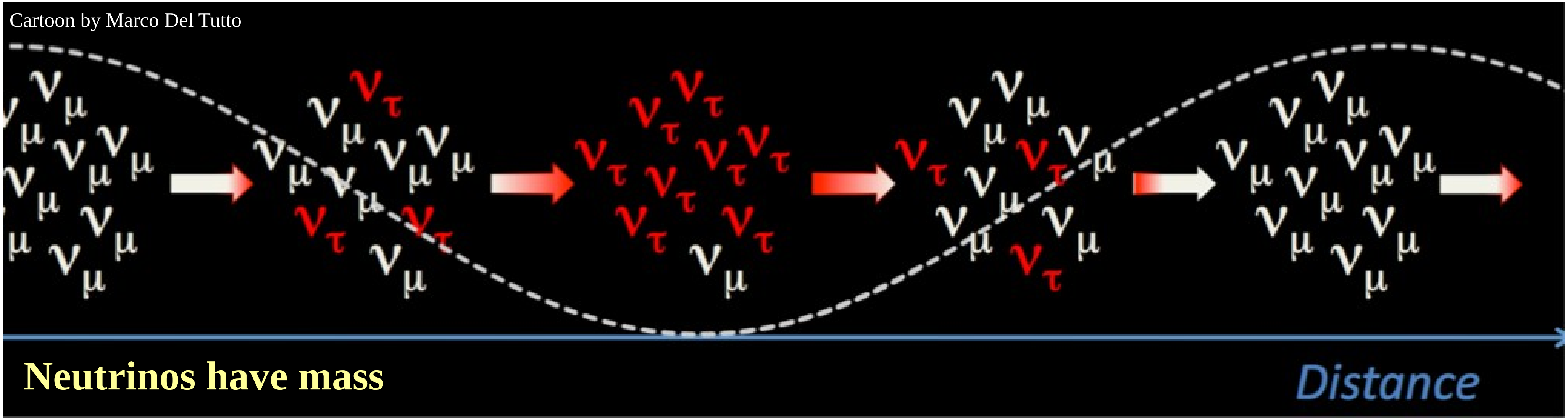
- Neutrino-Hydrogen Interactions

– Review – The very idea – Perspective

Physics Beyond Standard Model
via
Neutrino Oscillations

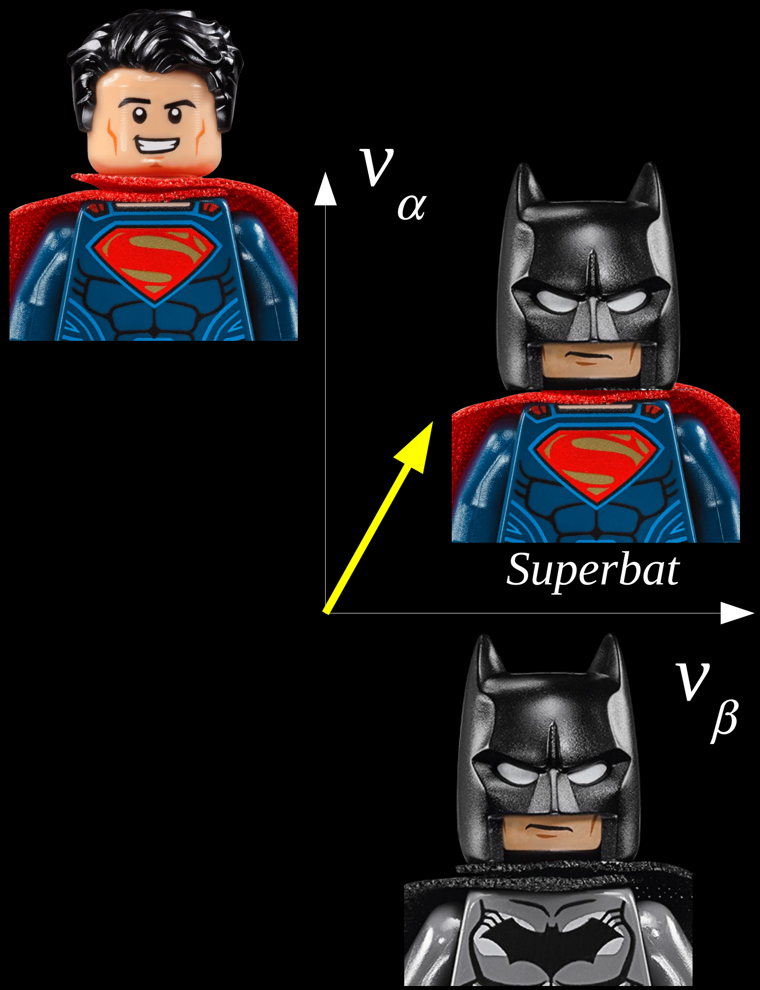


Cartoon by Marco Del Tutto



Neutrino Oscillations

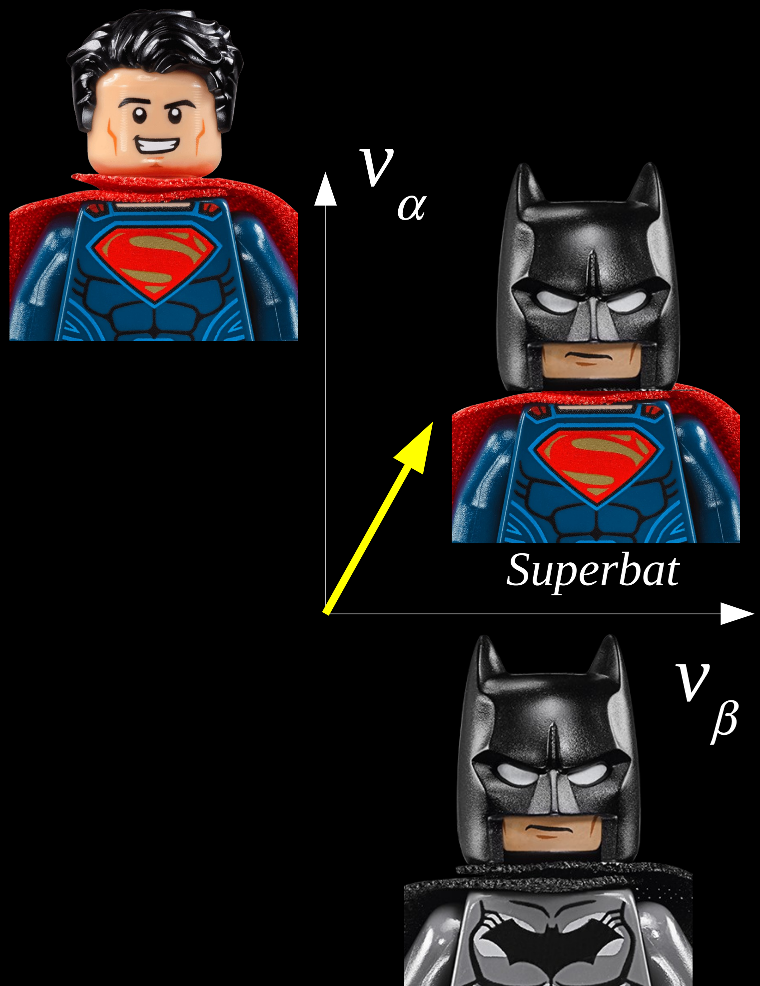
– An identity-changing game



https://www.lego.com

Neutrino Oscillations

– An identity-changing game



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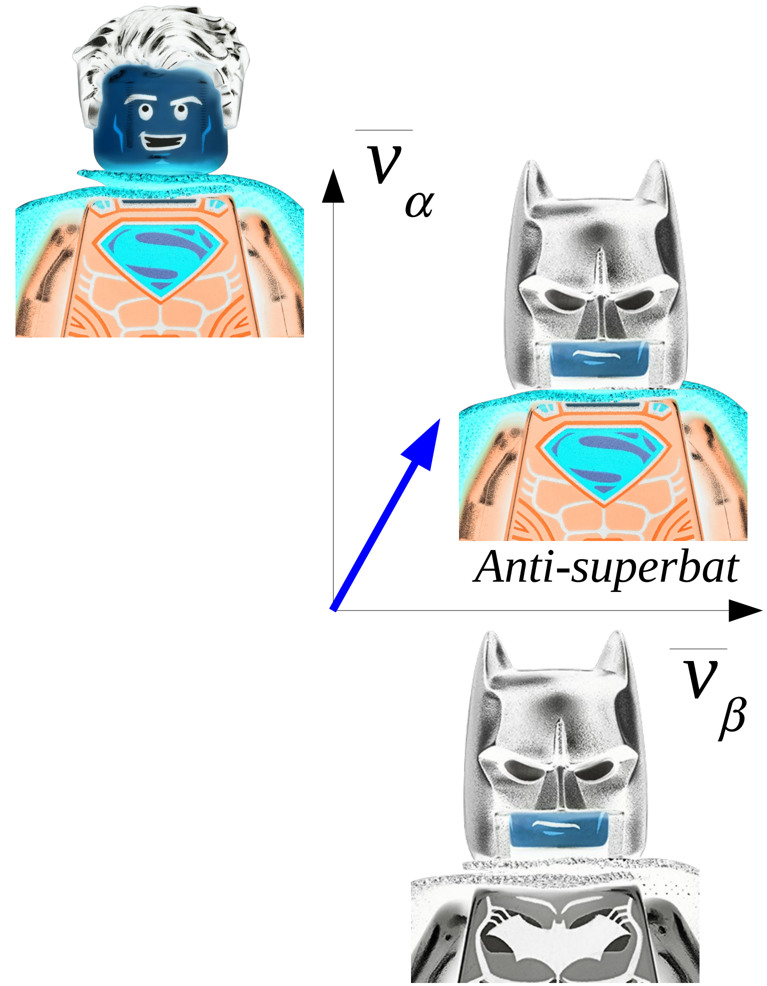
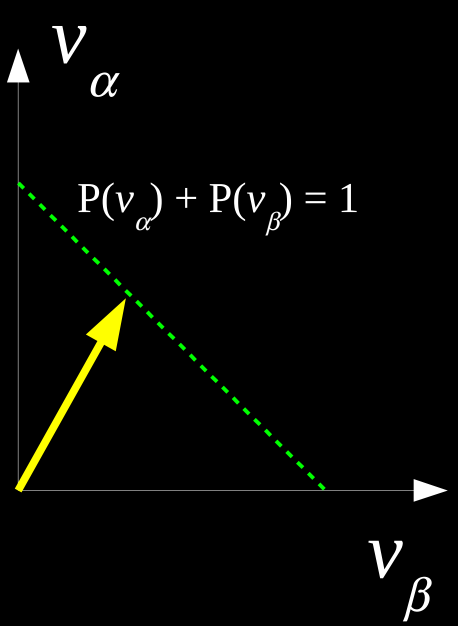
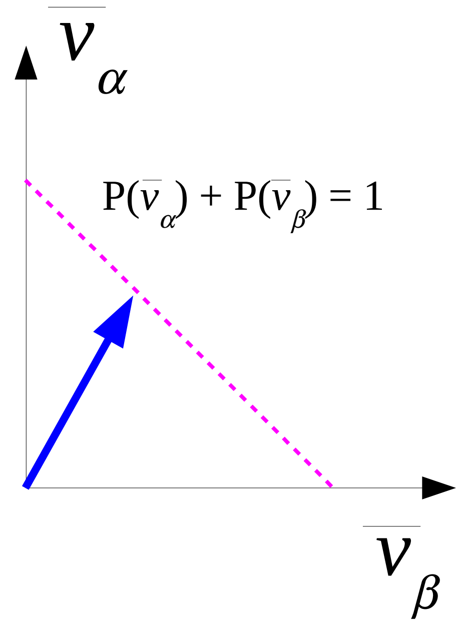


Neutrino Oscillations

– An identity-changing game



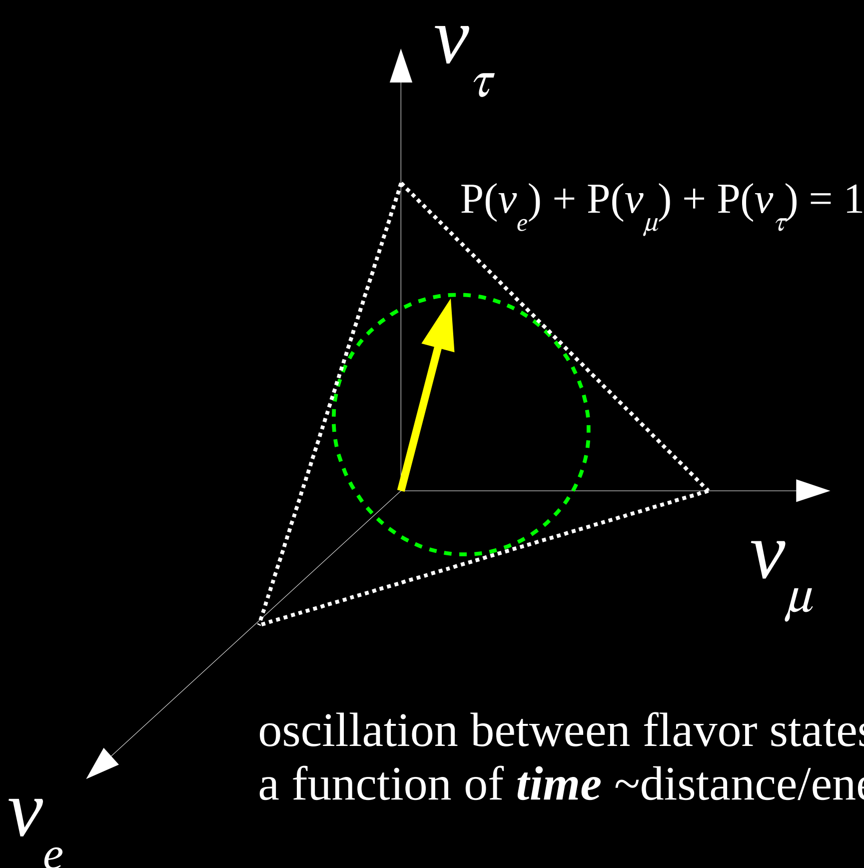


oscillation between flavor states as a function of ***time*** ~distance/energy

Only 2 flavors, same oscillation behavior

Neutrino Oscillations
– An identity-changing game

*3-flavor paradigm



oscillation between flavor states as
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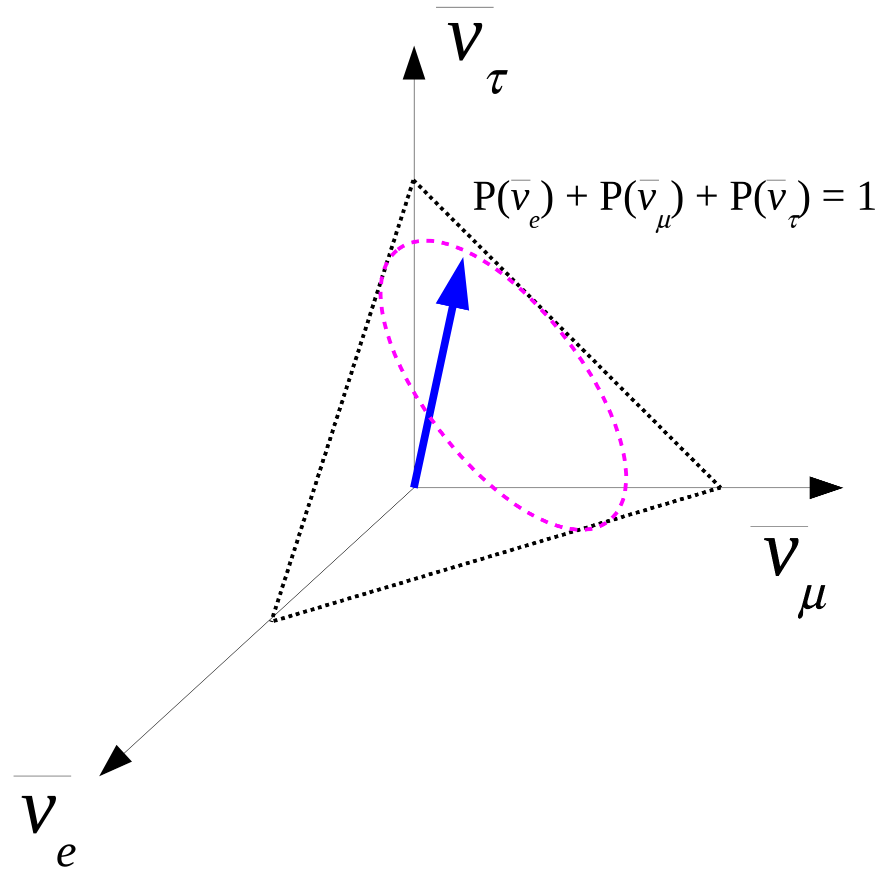
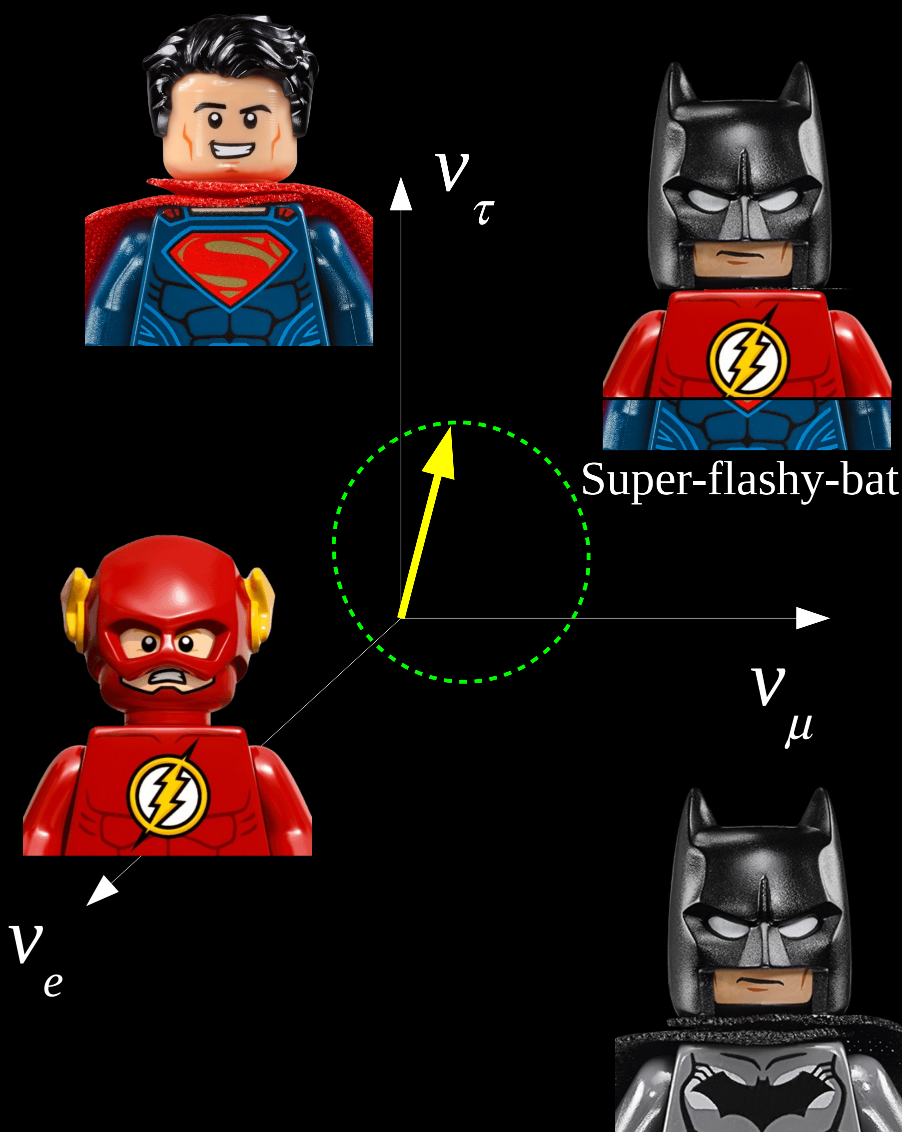
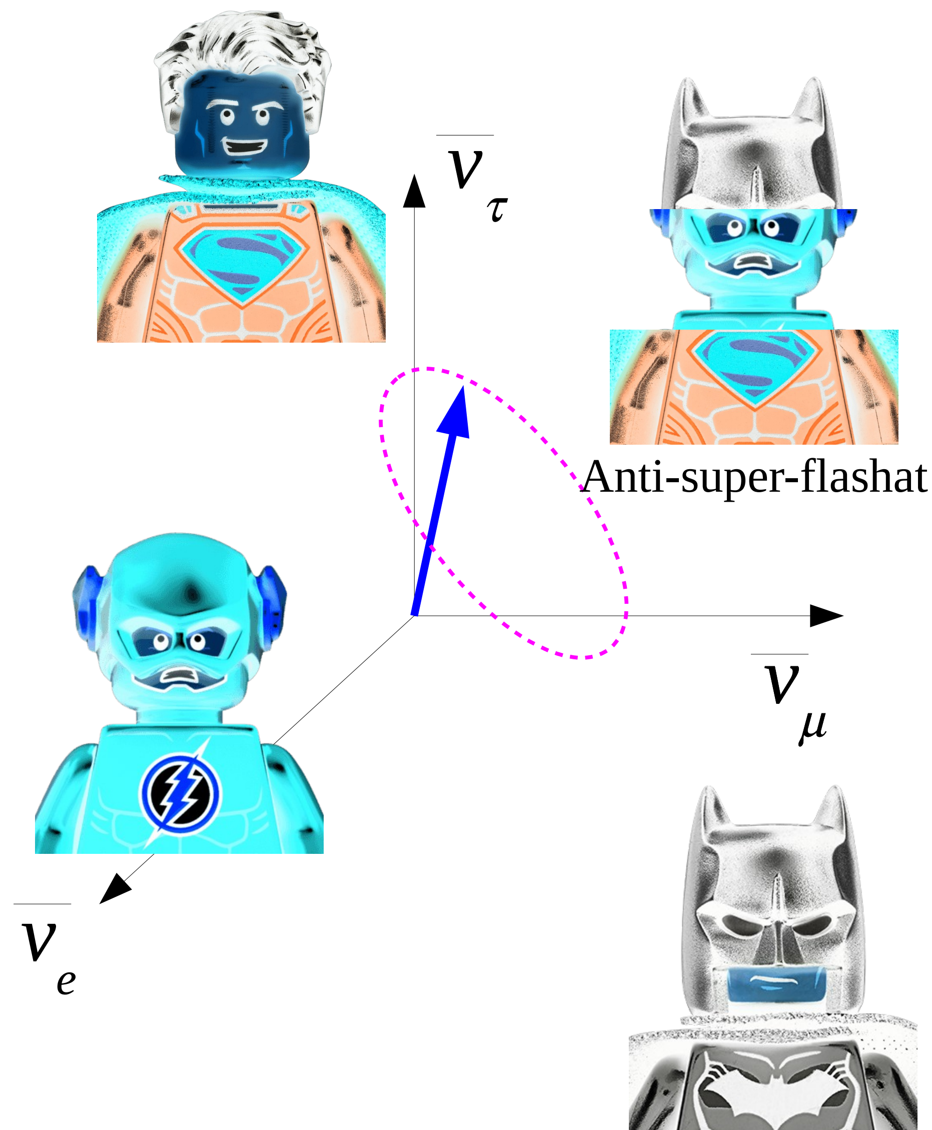


Neutrino Oscillations
– An identity-changing game





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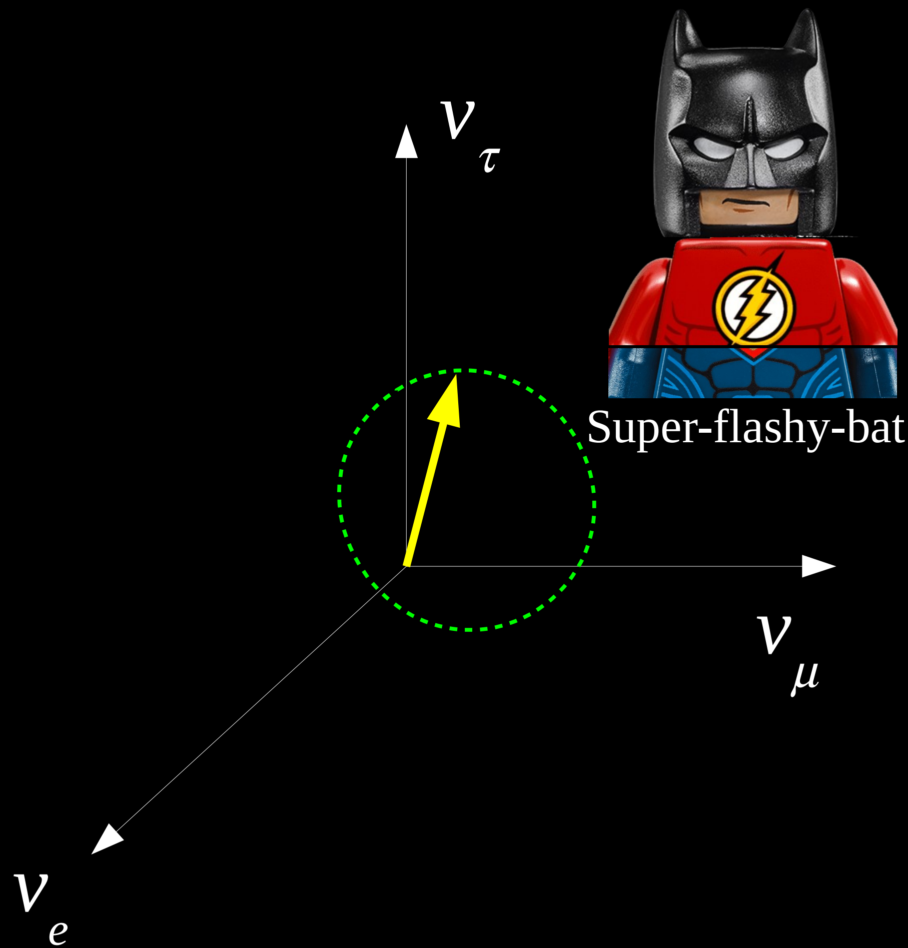
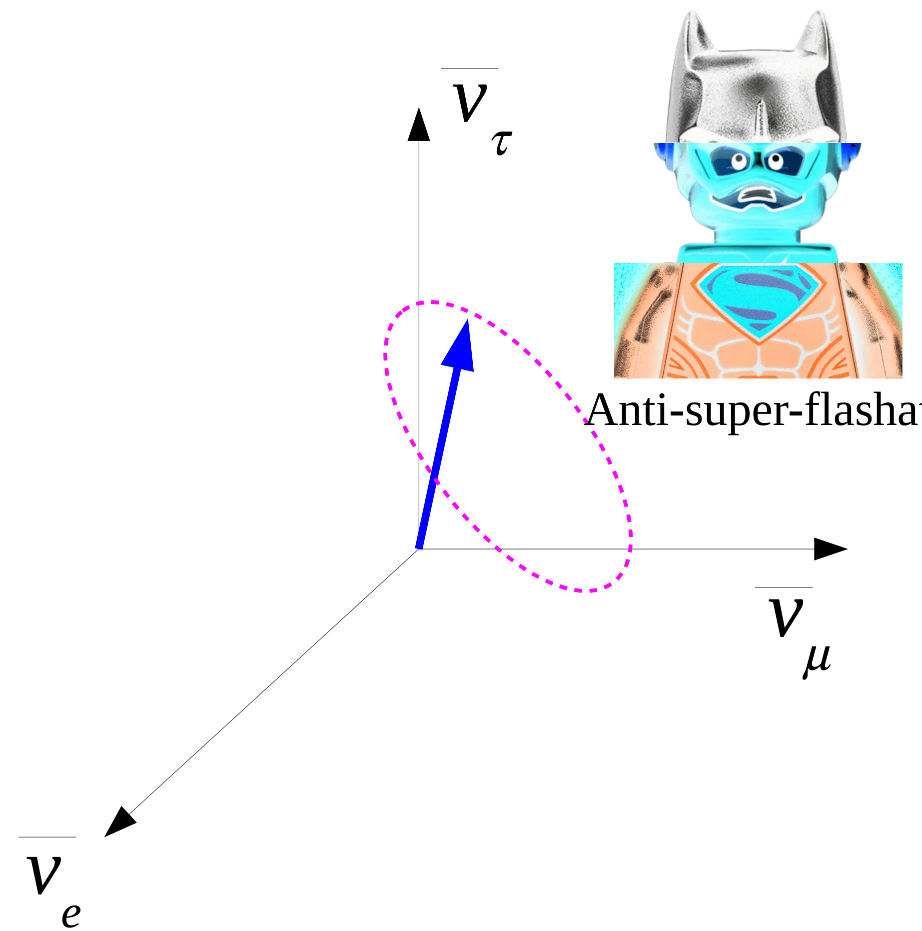
Neutrino Oscillations
– An identity-changing game





Oscillation property difference
→ *CP-Symmetry violation (CP violation)*

Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

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

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

- What is the absolute neutrino mass?
- Why is this mass so small?
- How is the different mass ordered?
- Are there more than 3 types of neutrino?

Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

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

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

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

Neutrino Oscillations
– Underlying math

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

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

$$\Delta m^2_{ij} \equiv m_i^2 - m_j^2$$

With a ν_μ beam

$$P(\nu_\mu \to \nu_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2\theta_{23} - \frac{\sin 2\theta_{12} \sin 2\theta_{23}}{2\sin\theta_{13}} \sin\delta_{CP} \sin\Delta_{21}\right)$$

CP-odd term

* neglecting matter effects

Neutrino Oscillations
– Underlying math

Neutrino oscillations depend on mixing parameters and mass differences.

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

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

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

$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$

With a $\bar{\nu}_\mu$ beam

flip sign

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 2\theta_{13} \sin^2 \Delta_{32} \left(\sin^2\theta_{23} + \frac{\sin 2\theta_{12}\sin 2\theta_{23}}{2\sin\theta_{13}} \sin\delta_{CP} \sin\Delta_{21}\right)$$

$\delta_{CP} \rightarrow$ CP violation

* neglecting matter effects

Neutrino Oscillations
– Seeing is believing

Charge–Parity symmetry Violation (CPV)?

Matter | *Antimatter*

Neutrino Oscillations
– Seeing is believing

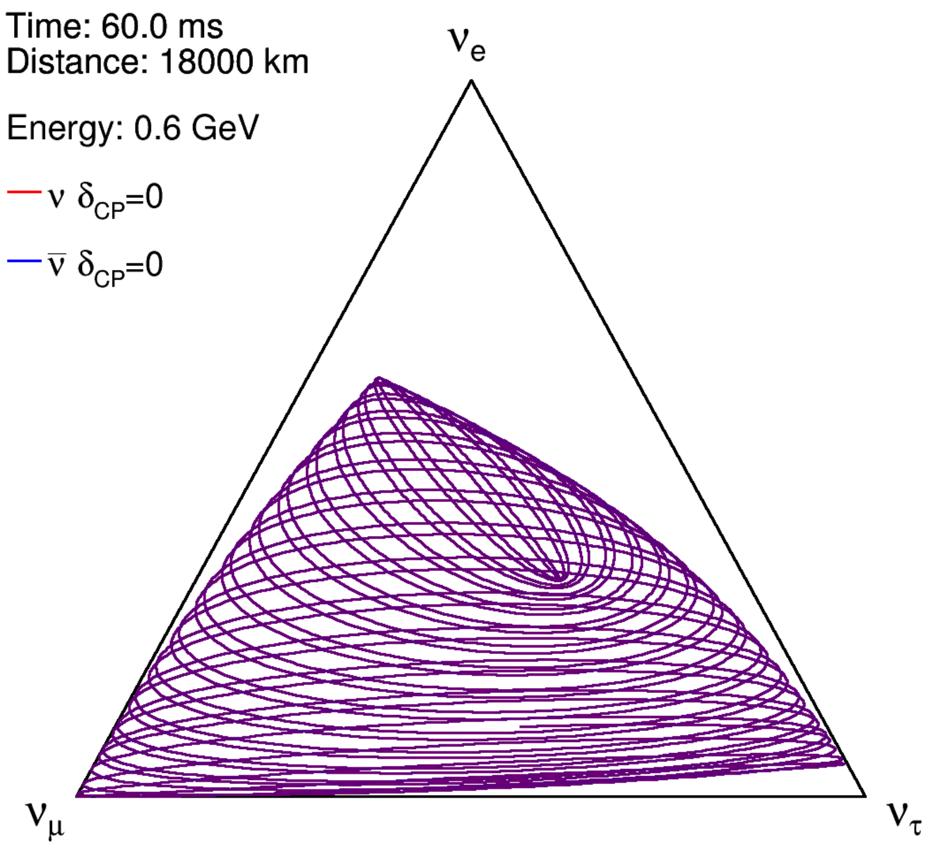
Charge–Parity symmetry Violation (CPV)?

$$\nu_\mu \rightarrow \nu_e \quad \underset{\text{CPV}}{\neq} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Neutrino Oscillations
– Seeing is believing

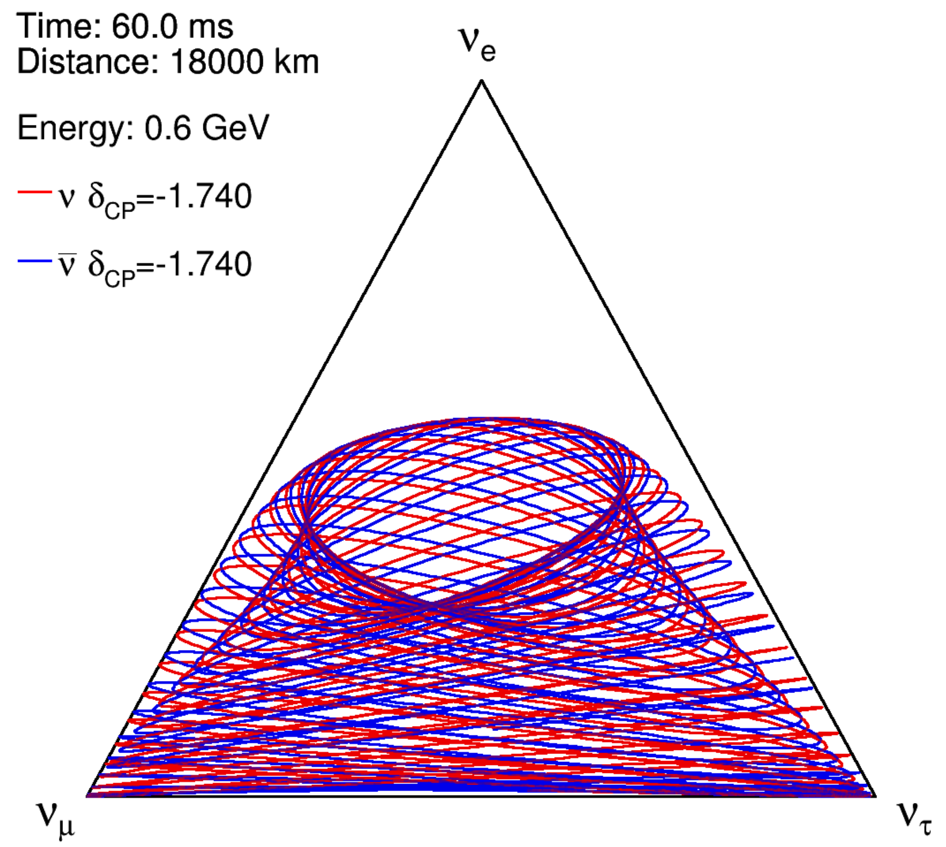
Time trajectory in probability space

No CPV



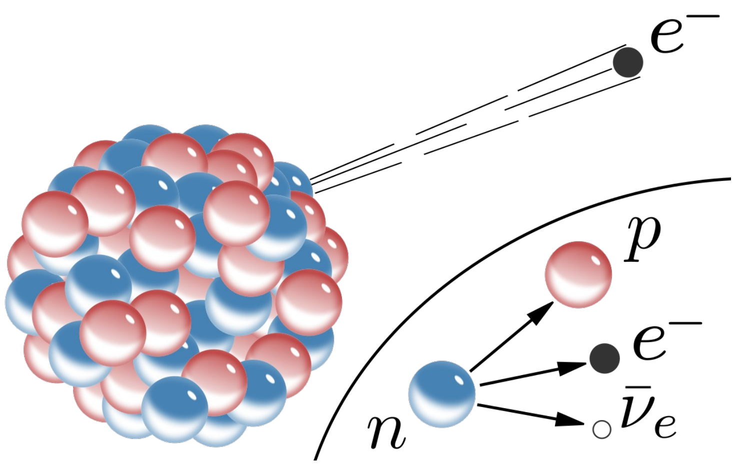
http://www-pnp.physics.ox.ac.uk/~luxi/transport/visual/visos/vacuumnumuantinumu_cpoff.mov

CPV

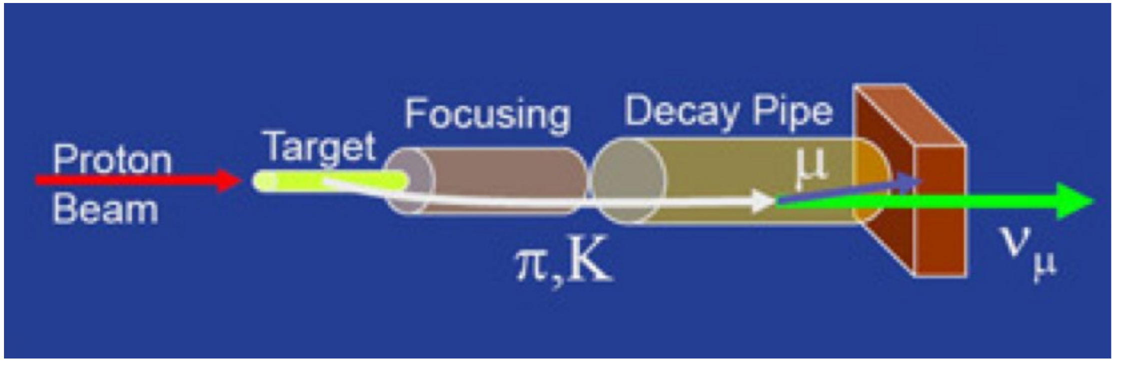


http://www-pnp.physics.ox.ac.uk/~luxi/transport/visual/visos/vacuumnumuantinumu_cpon.mov

Oscillation Measurements
– Accelerator-based neutrino experiments



By Inductiveload



https://lbnf.fnal.gov/beam.html

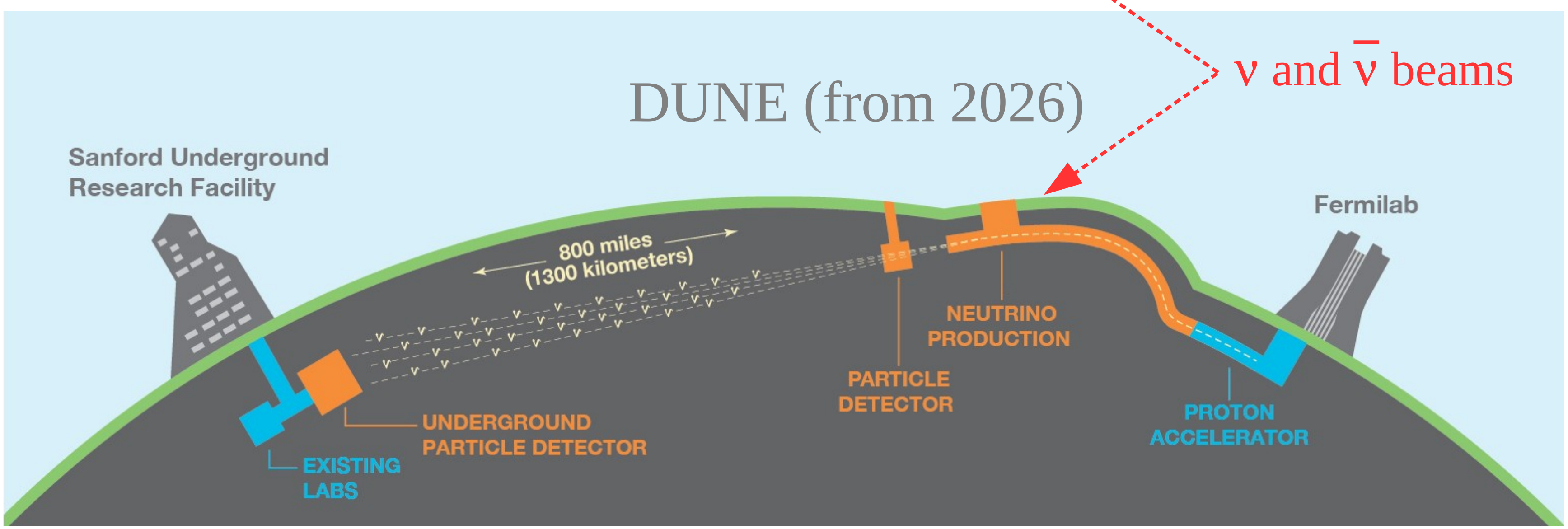
Nuclear β decay
MeV regime

ν beam: “β decay” of highly boosted collision products
GeV regime

* also the cross section is larger at GeV

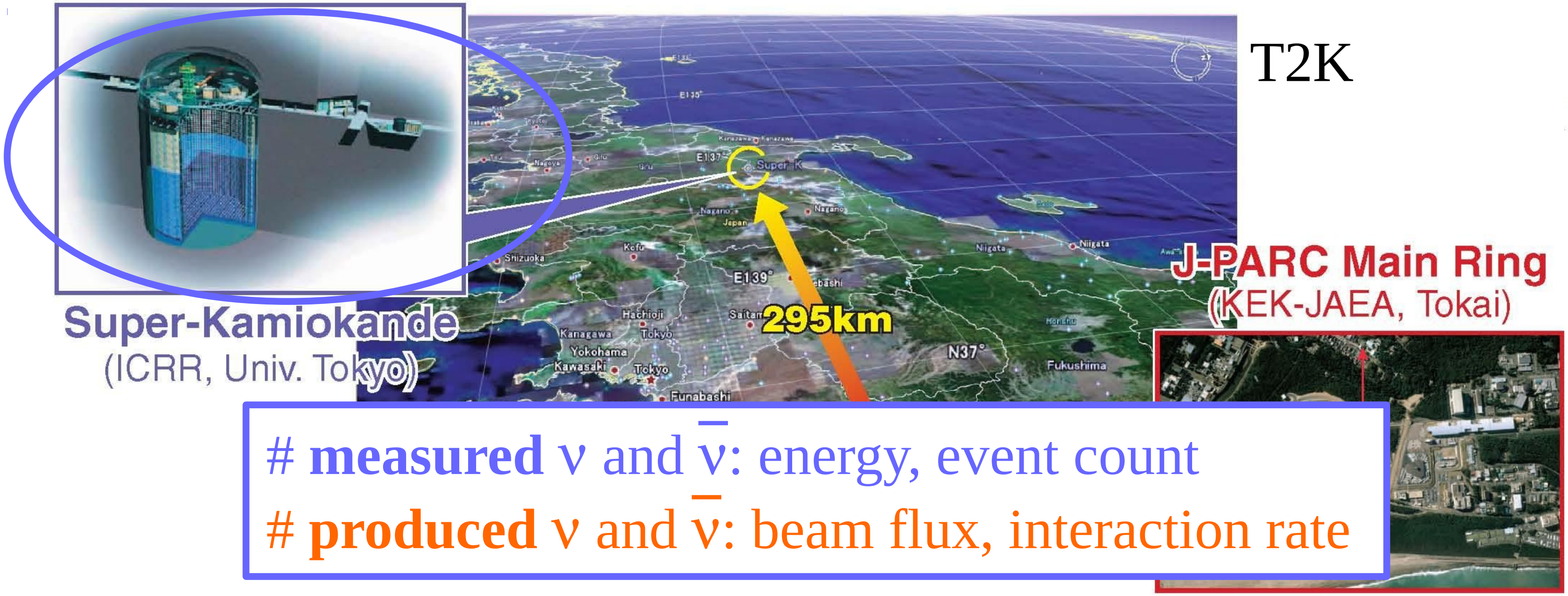
Oscillation Measurements
– Accelerator-based neutrino experiments

T2K



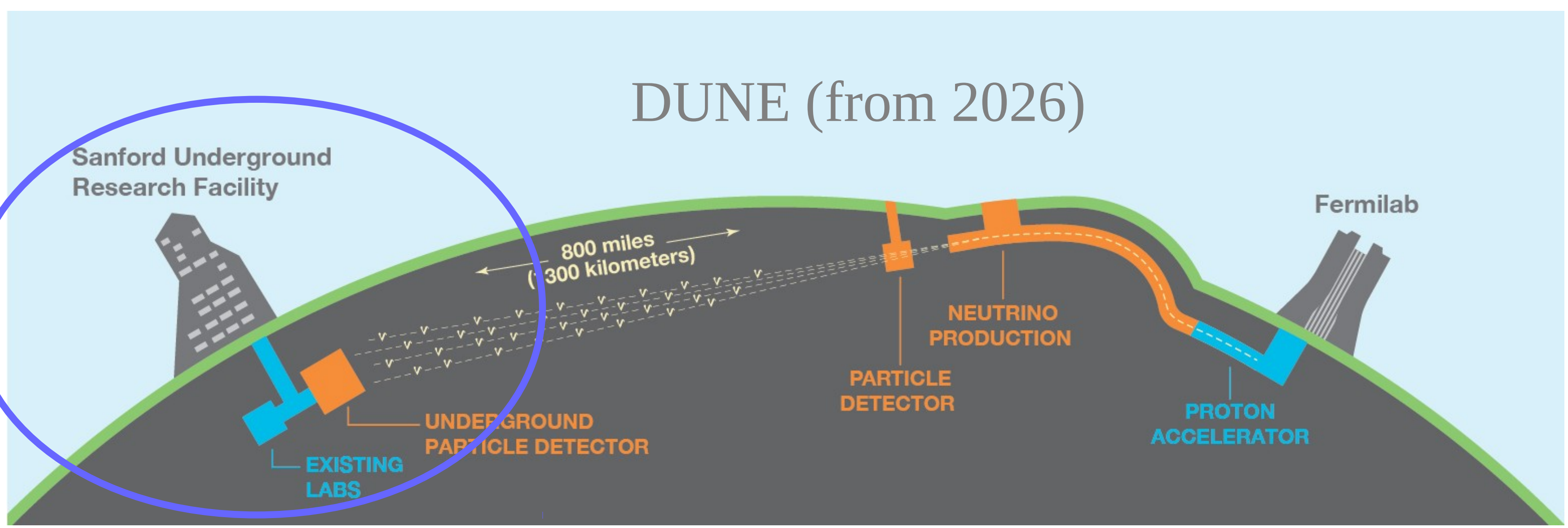
Oscillation Measurements

– *#measured ν / #produced ν*



measured ν and $\bar{\nu}$: energy, event count

produced ν and $\bar{\nu}$: beam flux, interaction rate

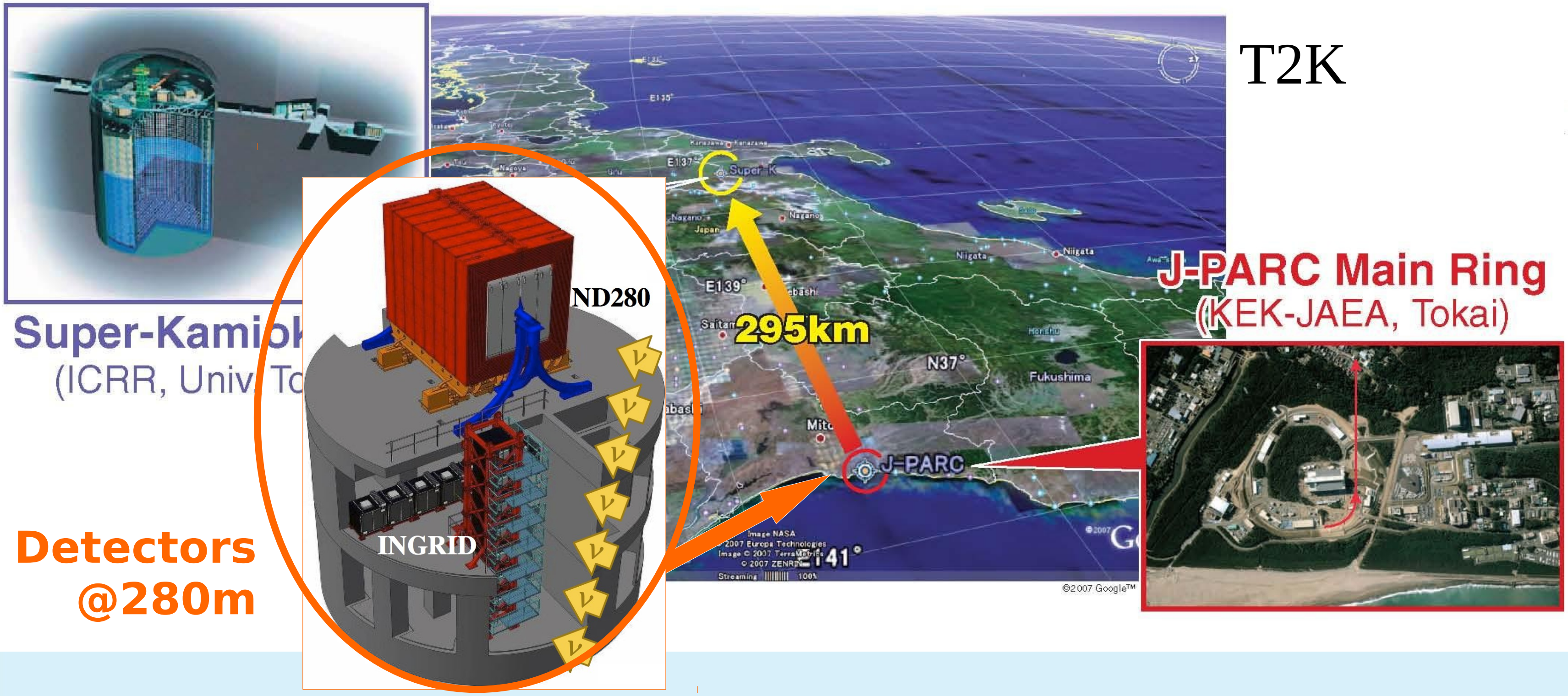


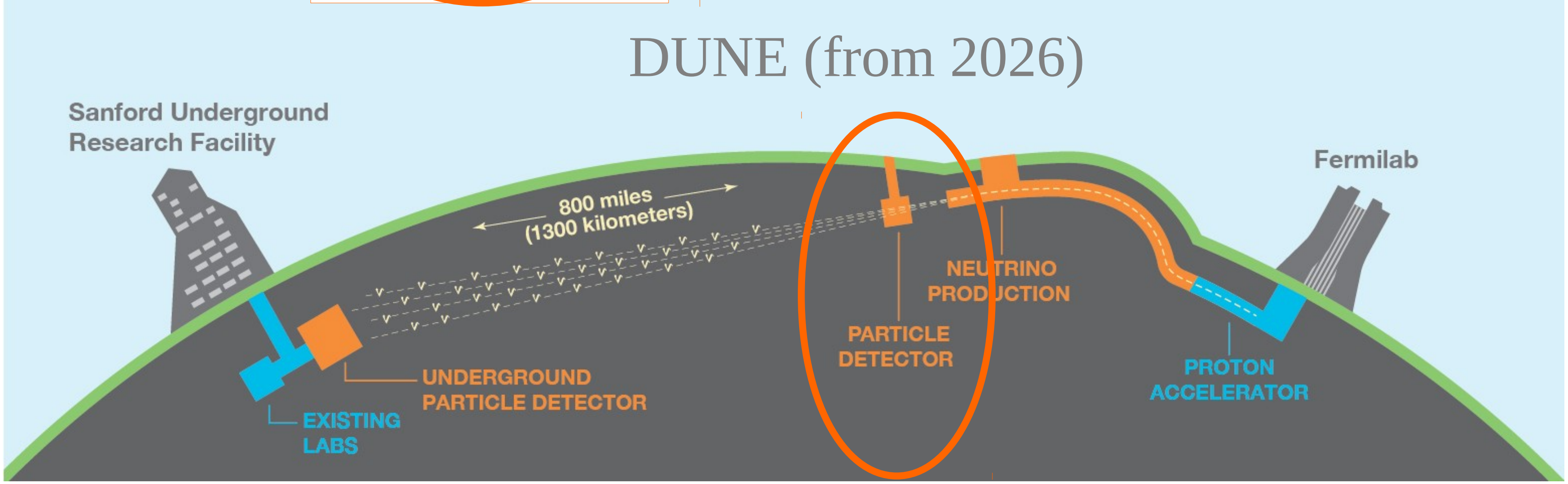
Oscillation Measurements

– Beam flux, ν and $\bar{\nu}$ interactions

T2K

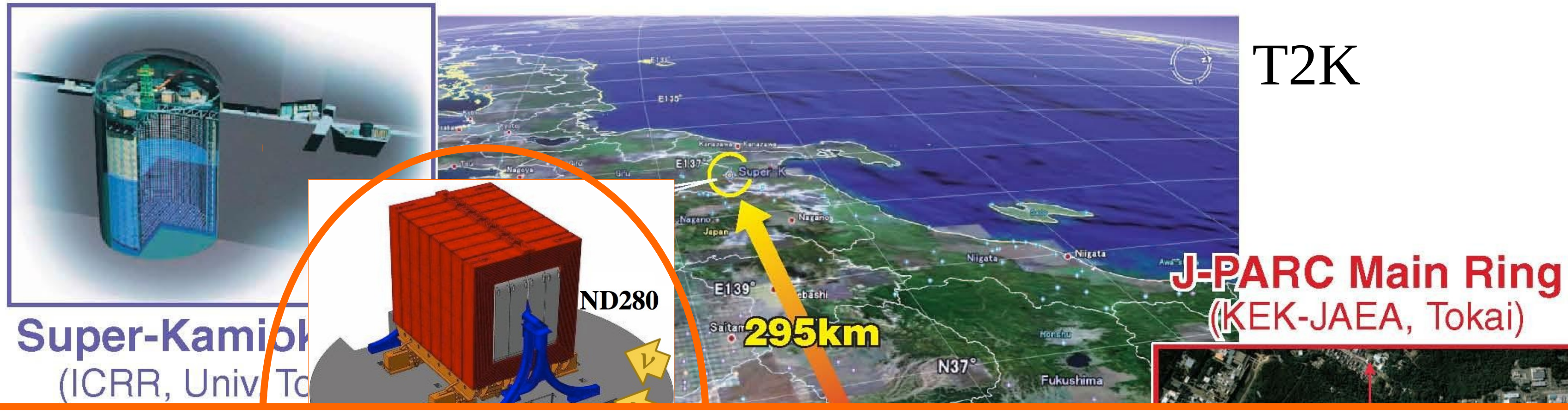
Near Detectors @280m



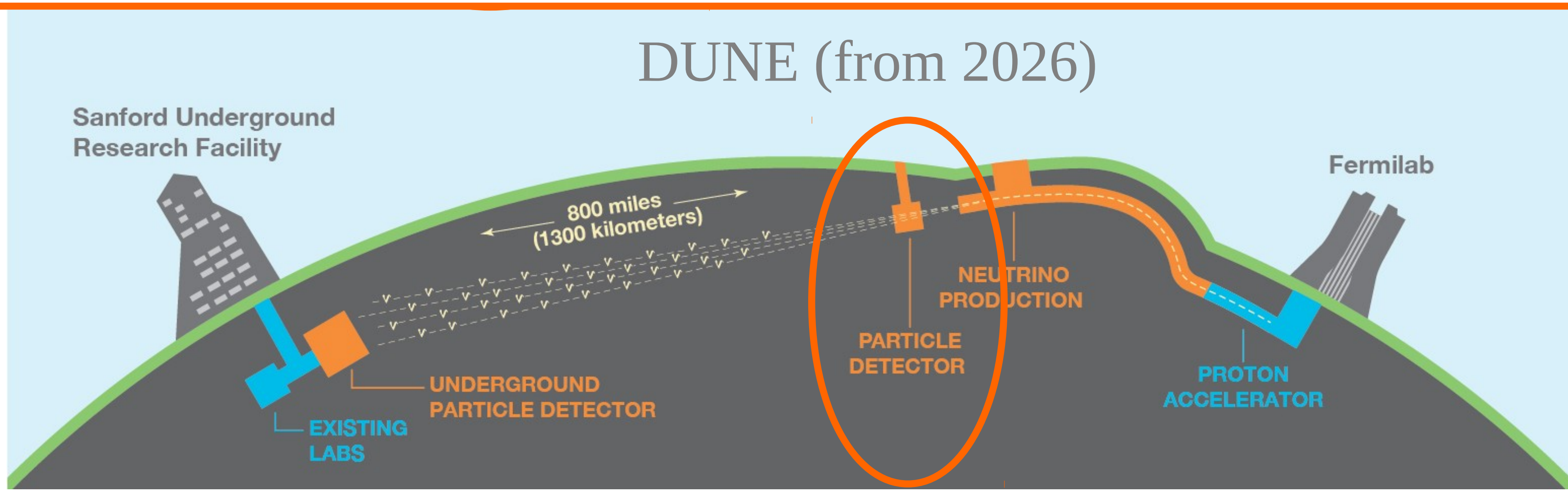


Oscillation Measurements

– Beam flux, ν and ν̄ interactions



- Now@**T2K**:
  [flux (9%) + interaction (15%)] → 8% after Near Detector constraint
- Target CP violation sensitivity requires total sys. uncertainty < 1-2%
- Neutrino interactions, if not understood, would be fatal

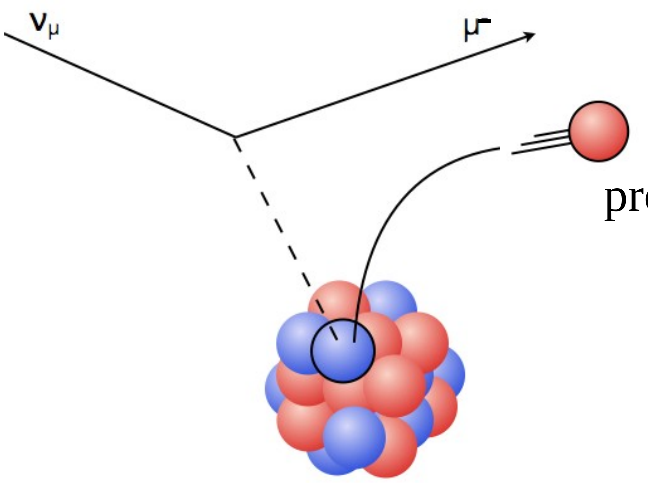


Xianguo Lu, Oxford

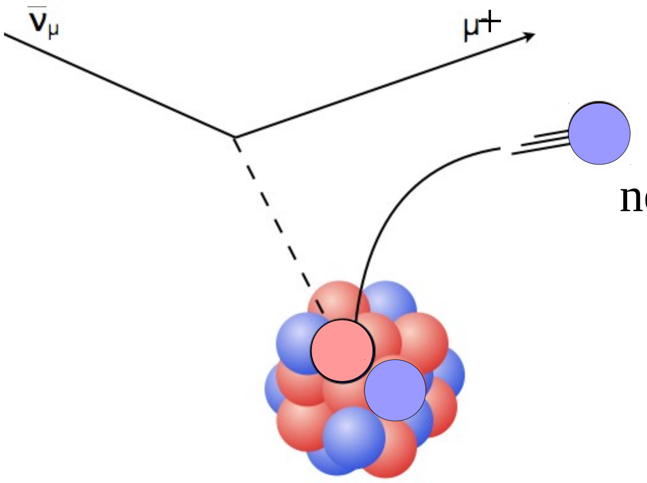
Oscillation Measurements

– ν and $\bar{\nu}$ interactions

Cartoon by Marco Del Tutto



neutrino

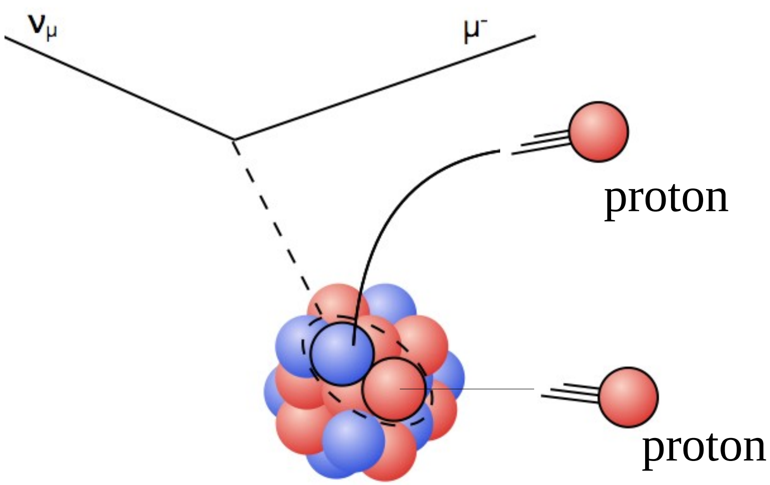


antineutrino

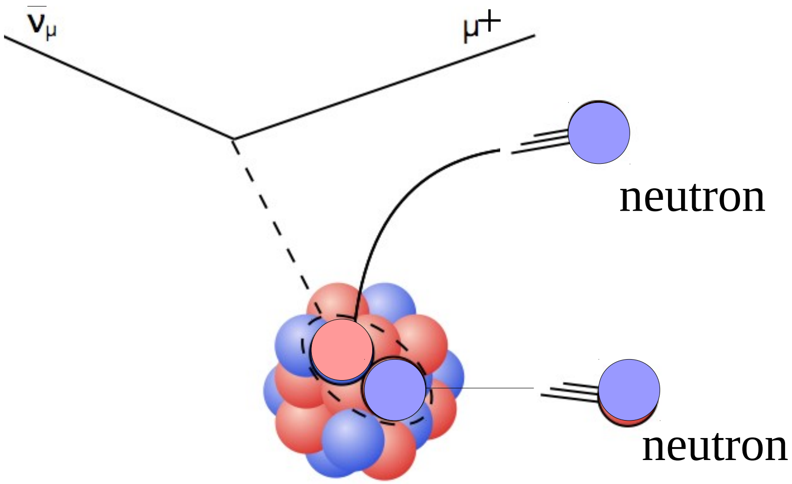
Intrinsic difference in ν and $\bar{\nu}$ event rates without CPV

Oscillation Measurements
– ν and $\bar{\nu}$ interactions

Cartoon by Marco Del Tutto



neutrino



antineutrino

Nuclear effects like “2p2h” make it worse

Nuclear effects: all effects due to target A>1

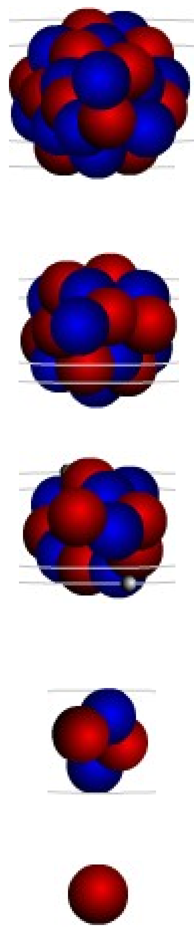
Proton and neutron have VERY different experimental signatures

Oscillation Measurements

– ν and $\bar{\nu}$ interactions

higher event rates

more complicated interactions



Ar — DUNE

O — T2K Far Detector (H_2O)

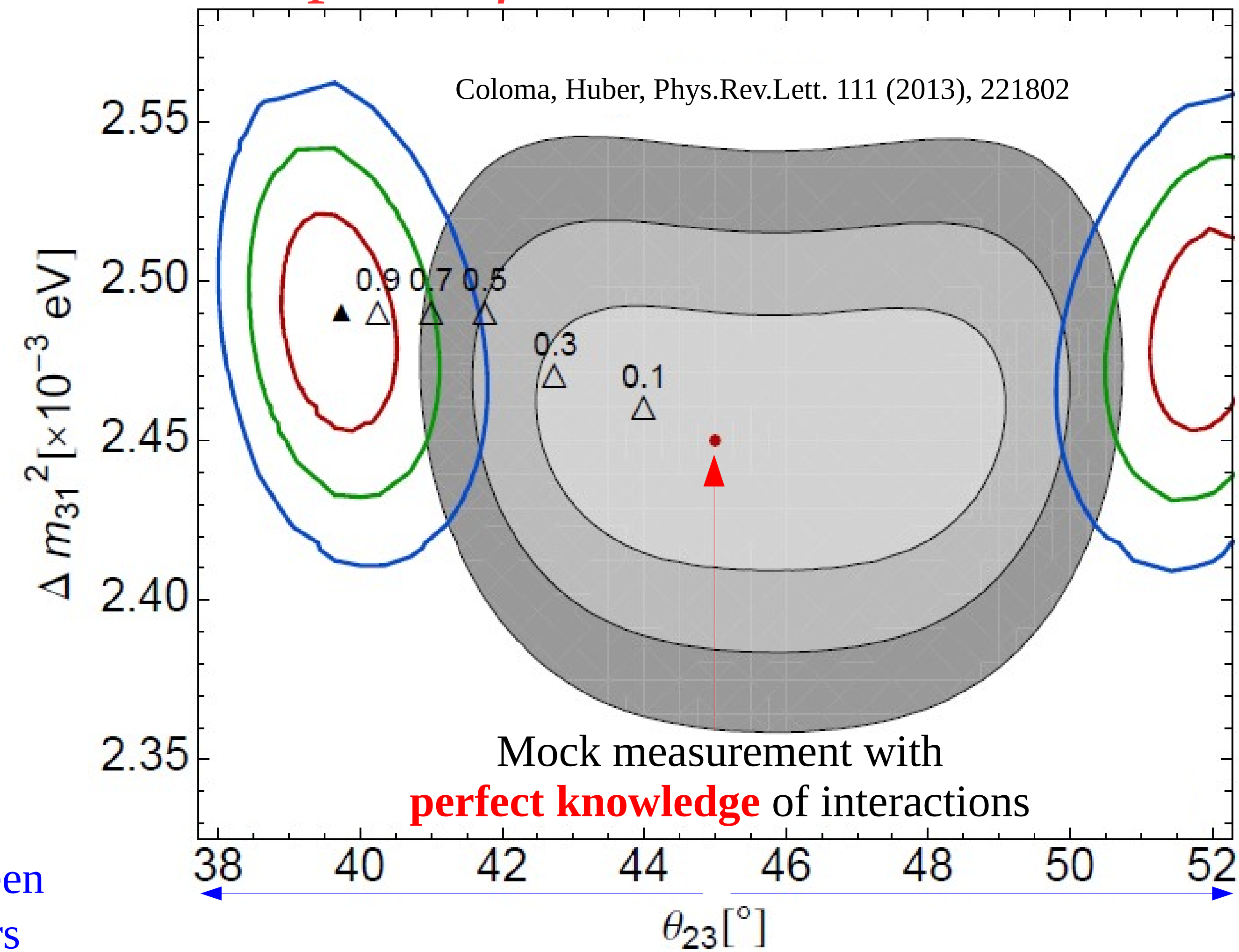
C — T2K Near Detector (CH)

He

H — Simplest interaction

Oscillation Measurements

– Impact of ν and $\bar{\nu}$ interactions



Difference in mass states

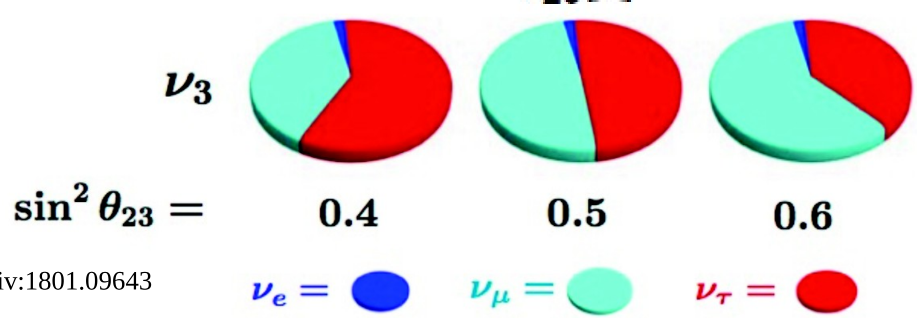
Mixing between μ and τ flavors

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

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

PMNS matrix

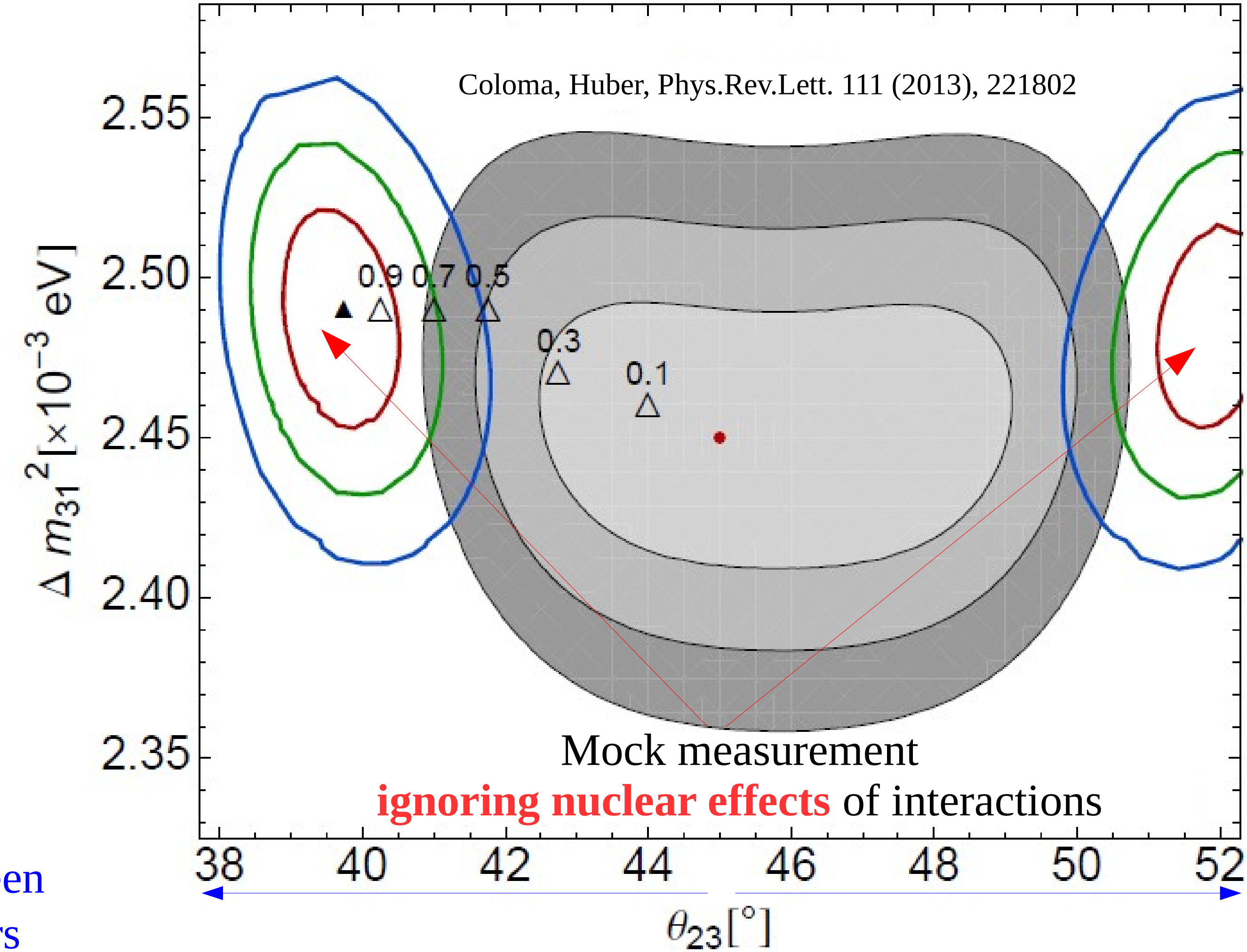
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$



arXiv:1801.09643

Oscillation Measurements

– Impact of ν and $\bar{\nu}$ interactions



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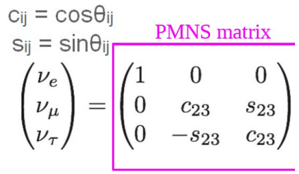
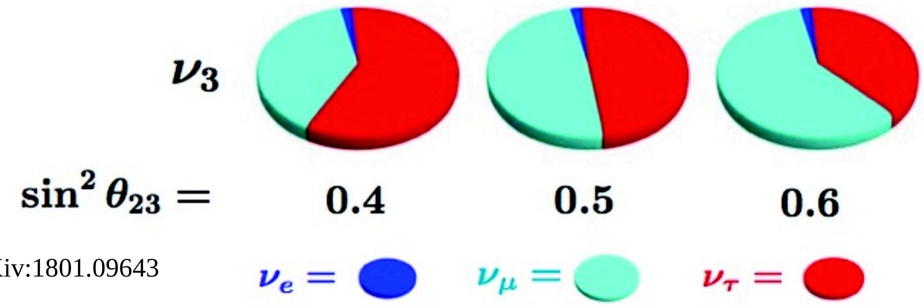
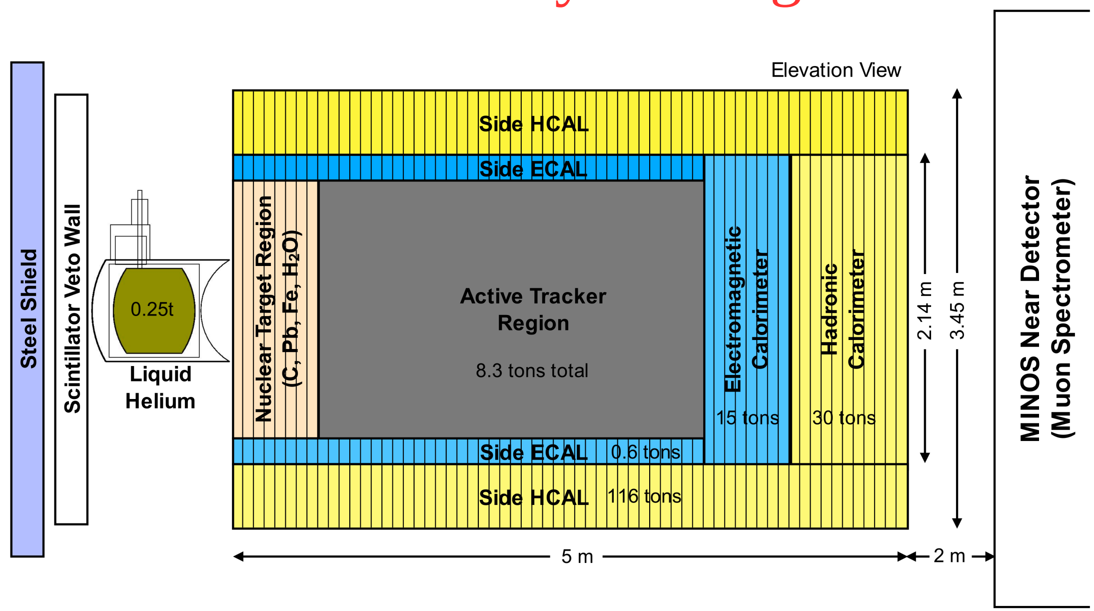




arXiv:1801.09643

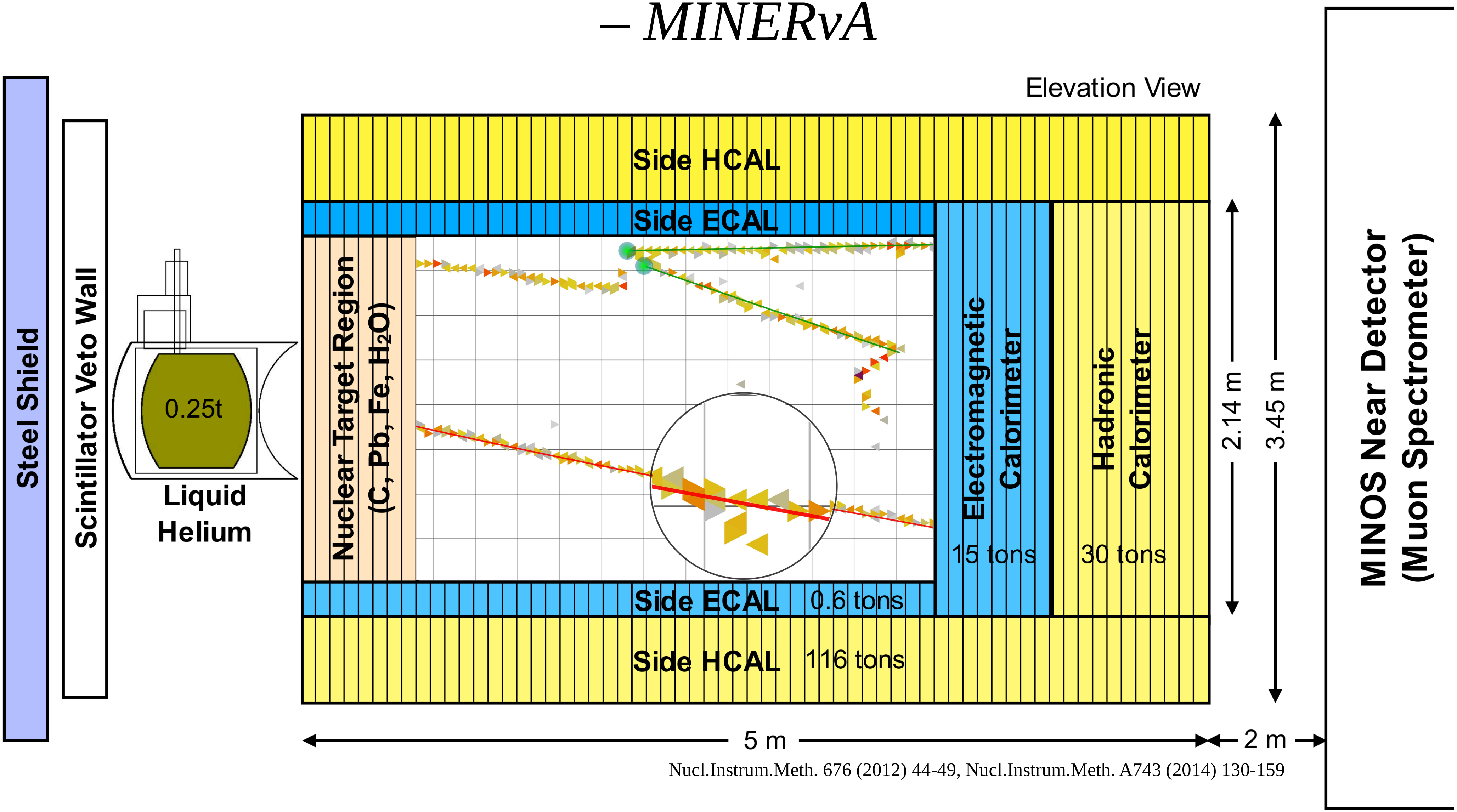
Interaction Measurements
– MINERvA

Only dedicated experiment for ν and $\bar{\nu}$ interactions currently running



Various targets: He, CH, O, Fe, Pb

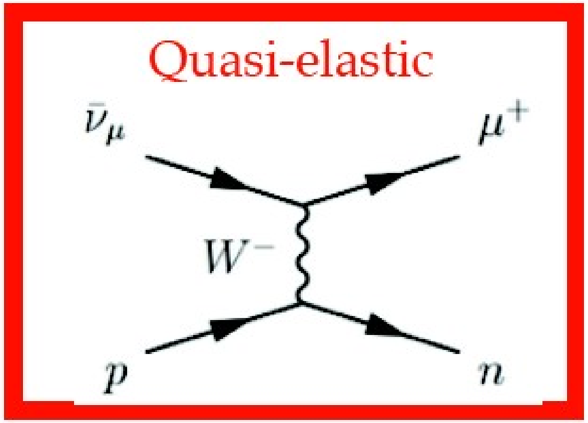
Interaction Measurements
– MINERvA



Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

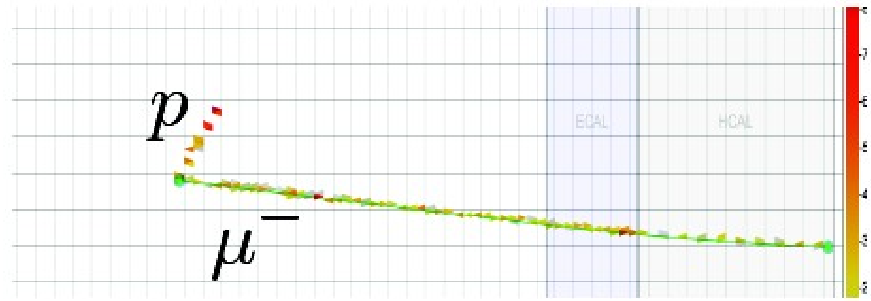
Scintillator tracker:
Hydrocarbon (CH) target
Homogeneous non-magnetized active tracker

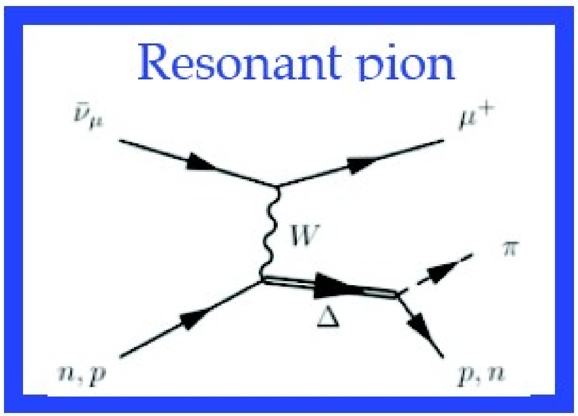
Interaction Measurements
– MINERvA



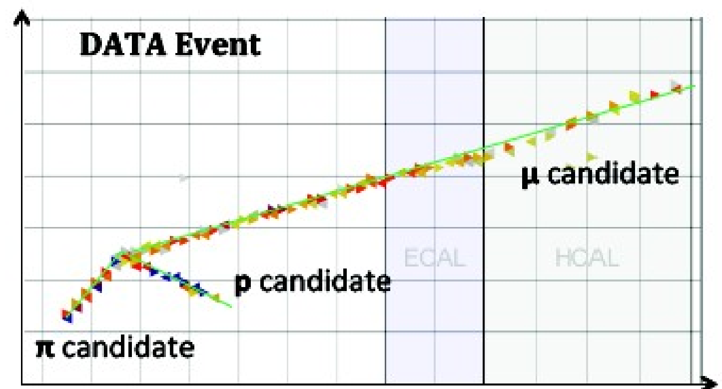
QE

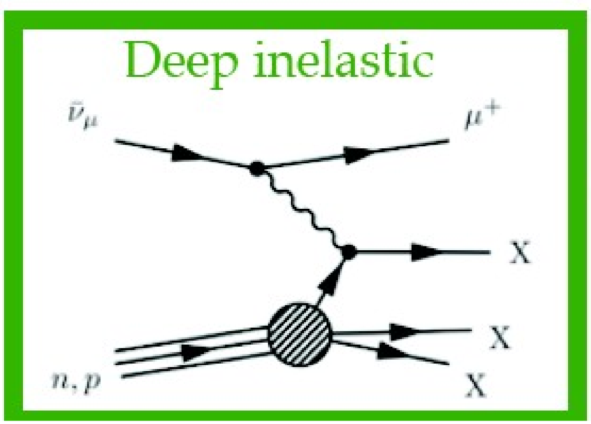
Energy



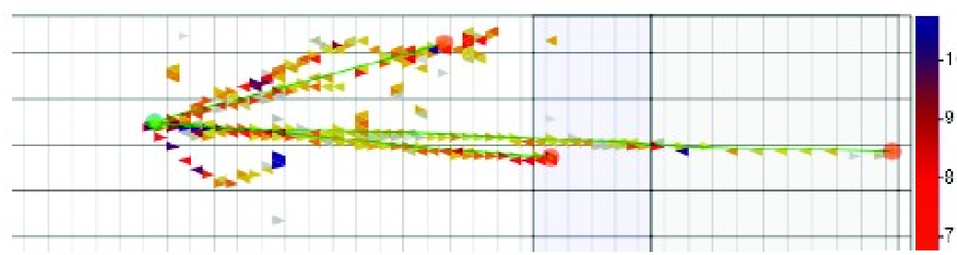


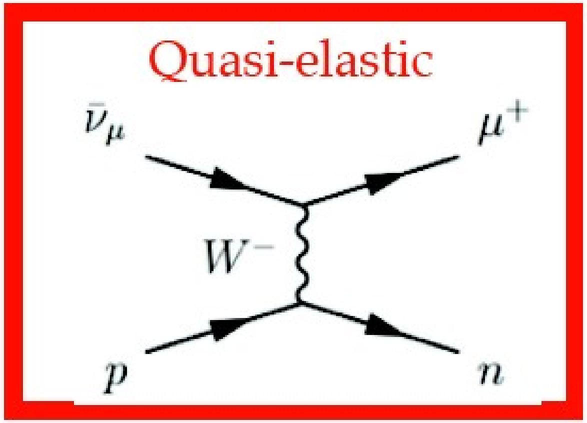
RES



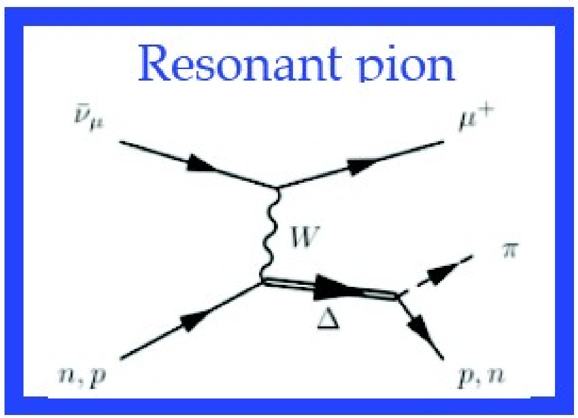


DIS

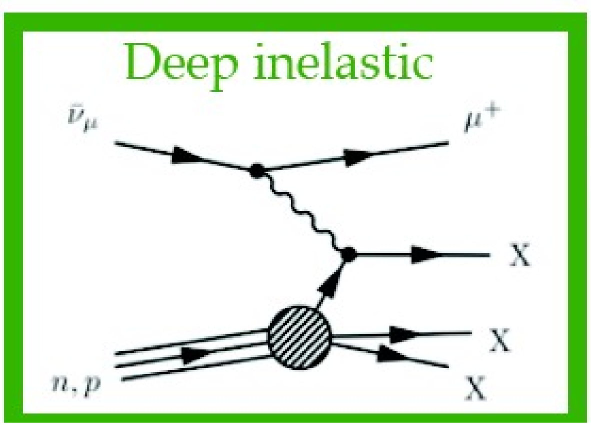




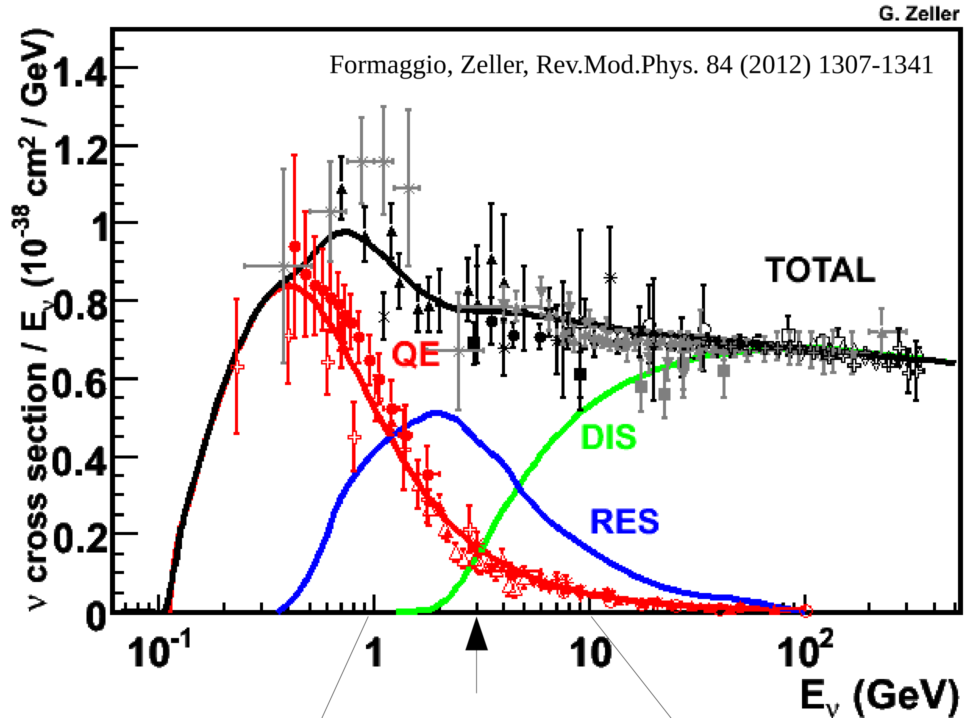
QE



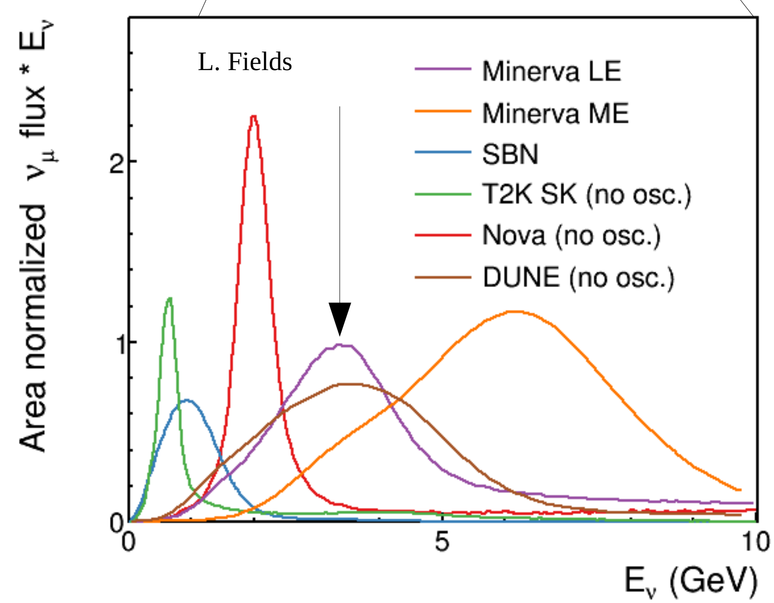
RES

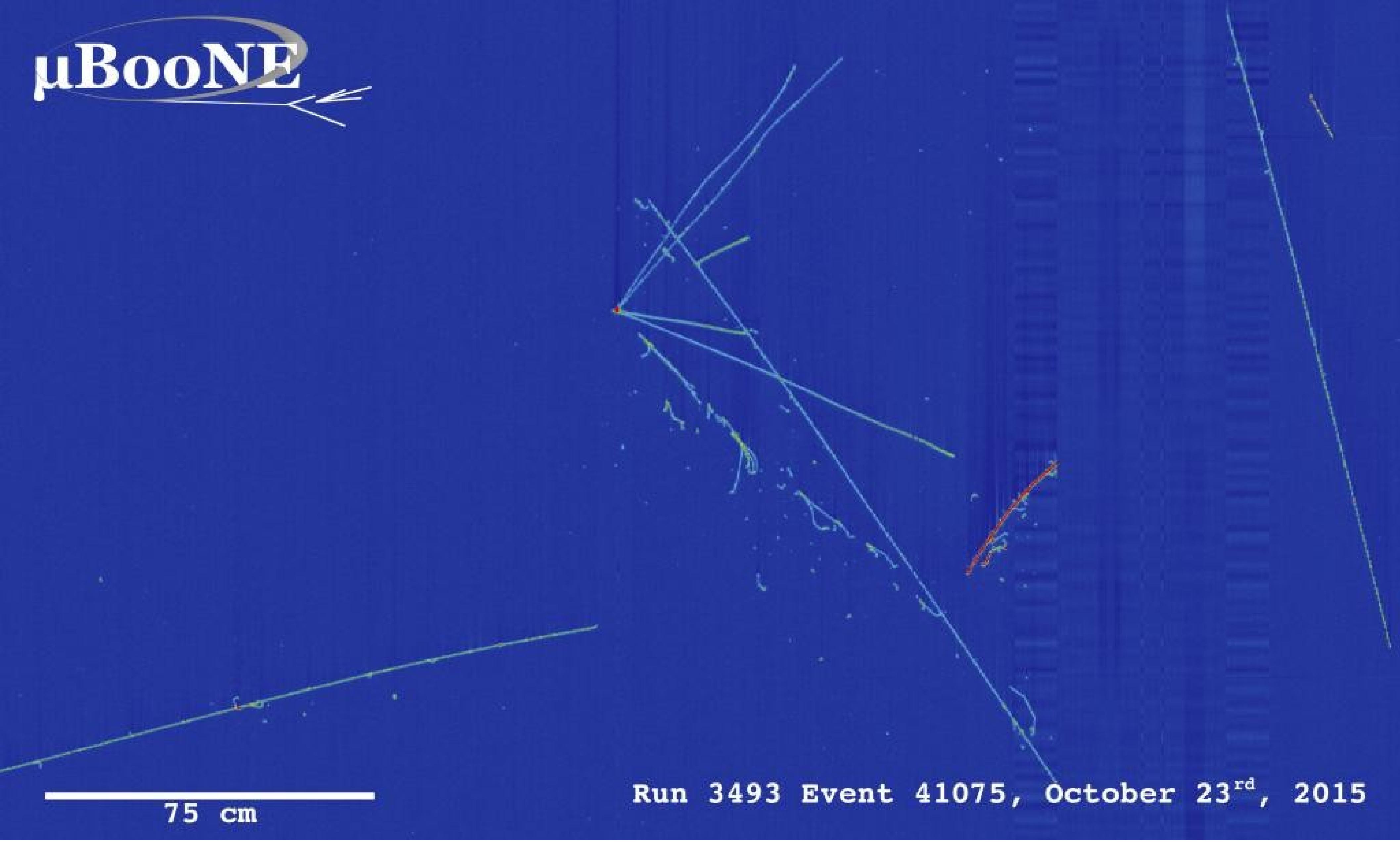


DIS



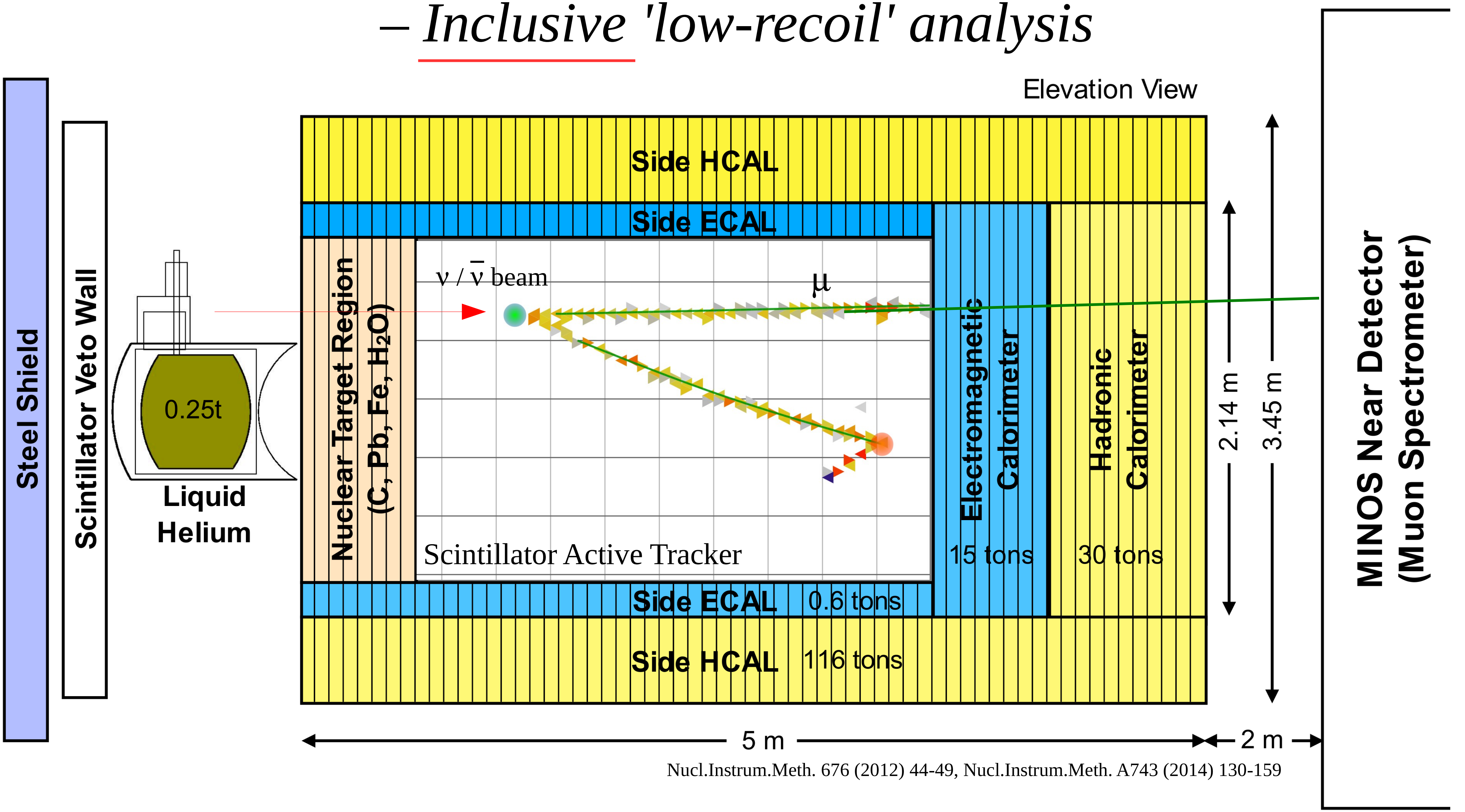
NuMI low energy beam $<E_\nu> \sim 3$ GeV





Homogeneous non-magnetized active tracker
→ same as LAr detector
<u>What do we do with such great detail in final states?</u>

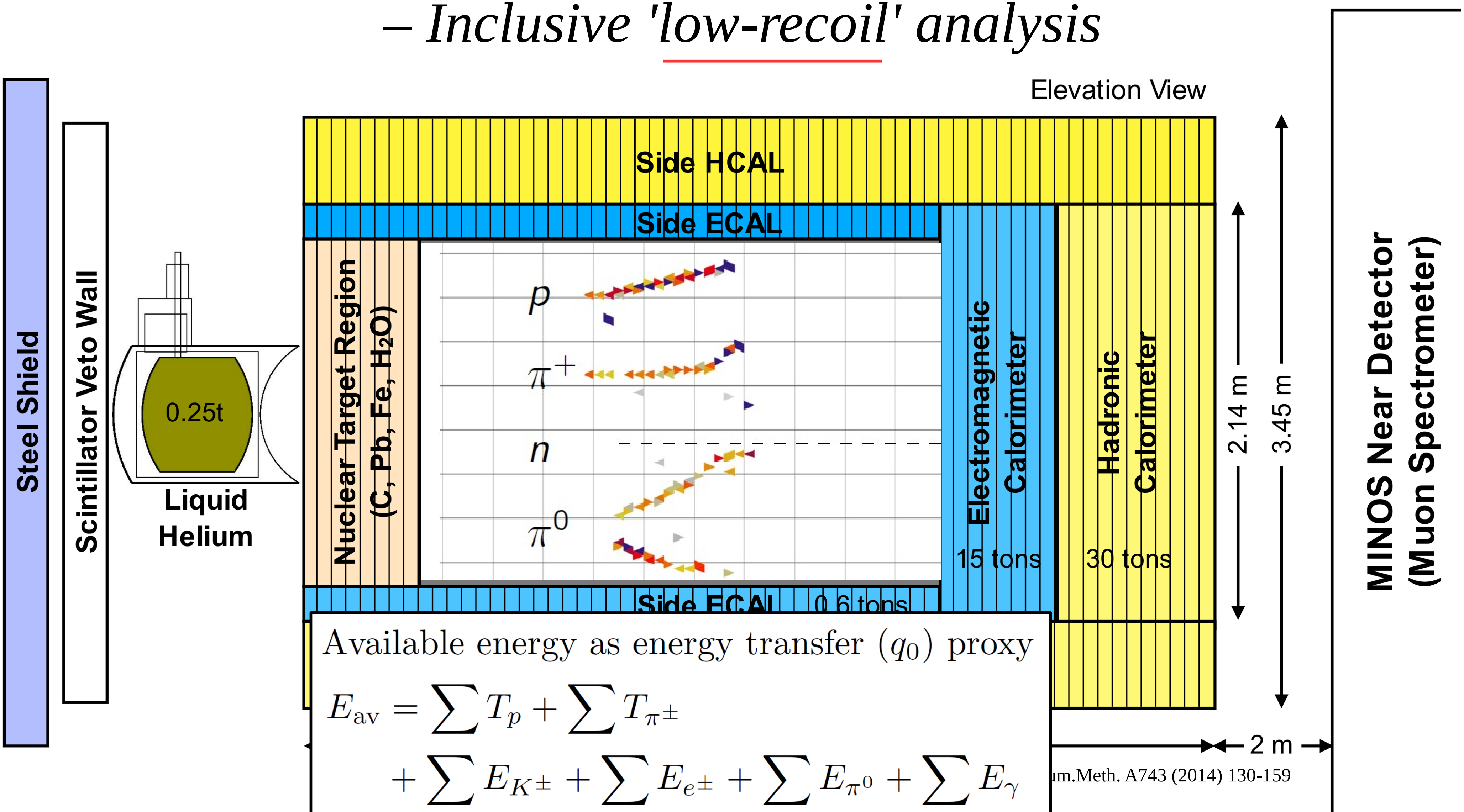
Interaction Measurements
– Inclusive 'low-recoil' analysis



Nucl.Instrum.Meth. 676 (2012) 44-49, Nucl.Instrum.Meth. A743 (2014) 130-159

Interaction Measurements

– Inclusive 'low-recoil' analysis



Available energy as energy transfer (q_0) proxy

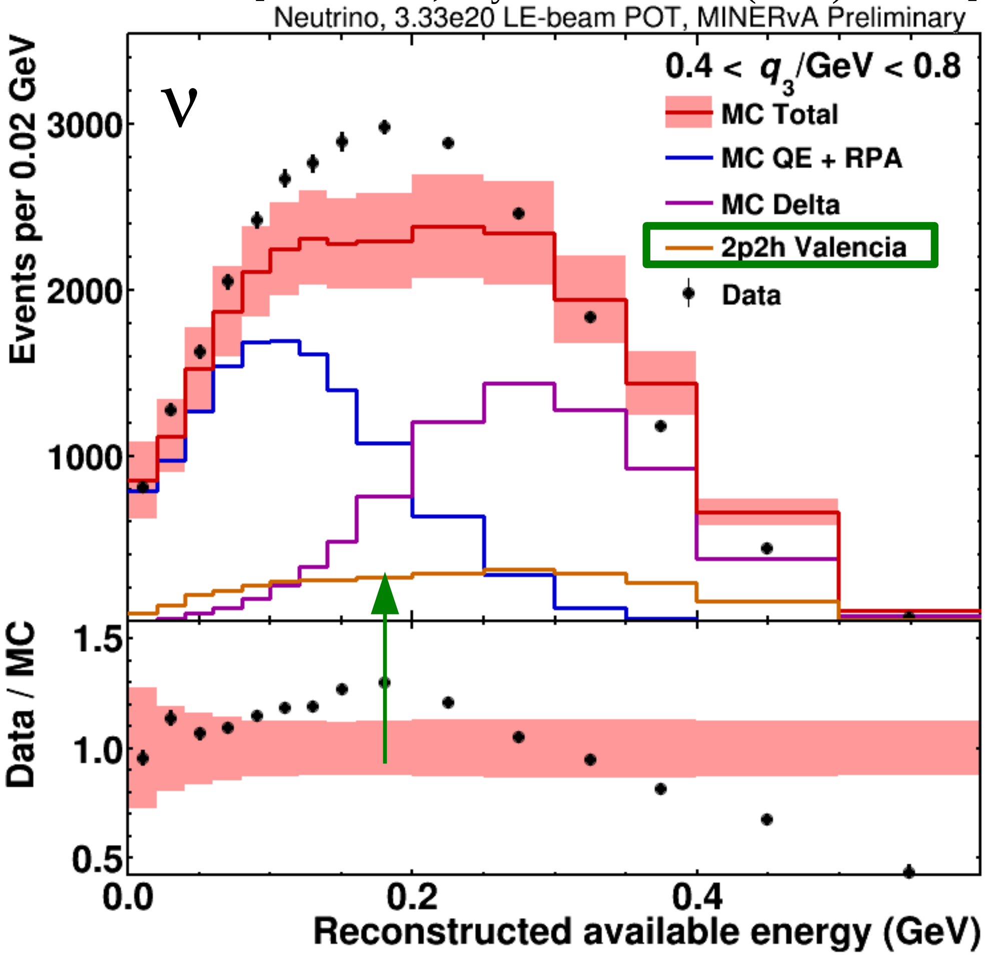
$$E_{\mathrm{av}} = \sum T_p + \sum T_{\pi^\pm} + \sum E_{K^\pm} + \sum E_{e^\pm} + \sum E_{\pi^0} + \sum E_\gamma$$

~ single proton kinetic energy spectrum in QE

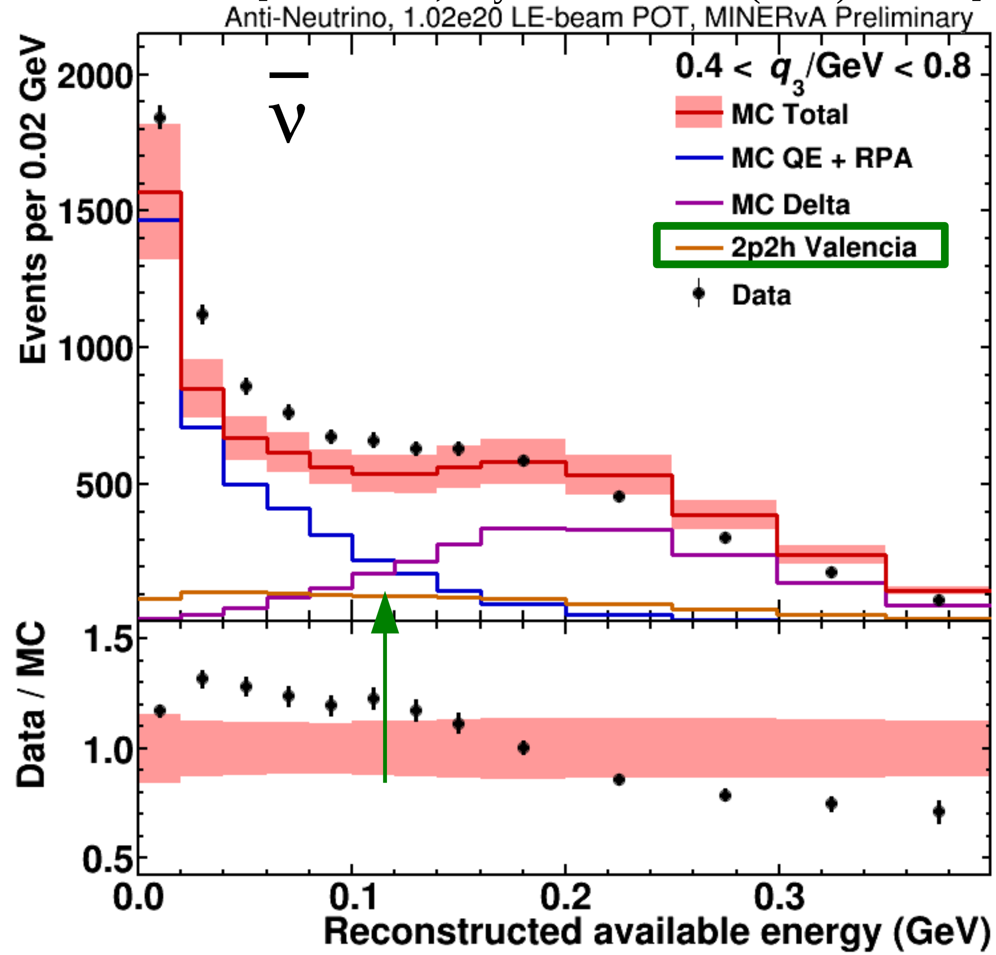
~ π(+p) kinetic energy spectrum in RES

Base Model (GENIE + pion reweight + RPA + 2p2h)

[MINERvA, Phys.Rev.Lett. 116 (2016) 071802]

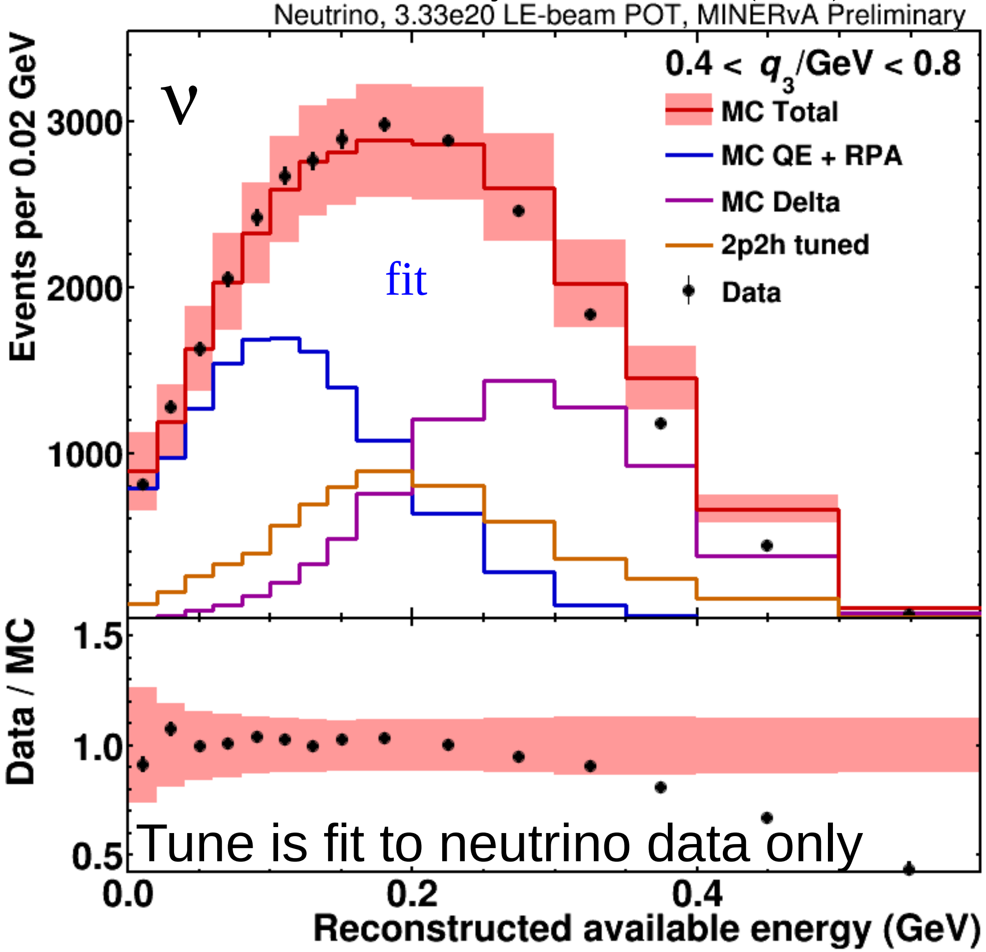


[MINERvA, Phys.Rev.Lett. 120 (2018) 221805]



Base Model + Neutrino Tune = MnvGENIE-v1

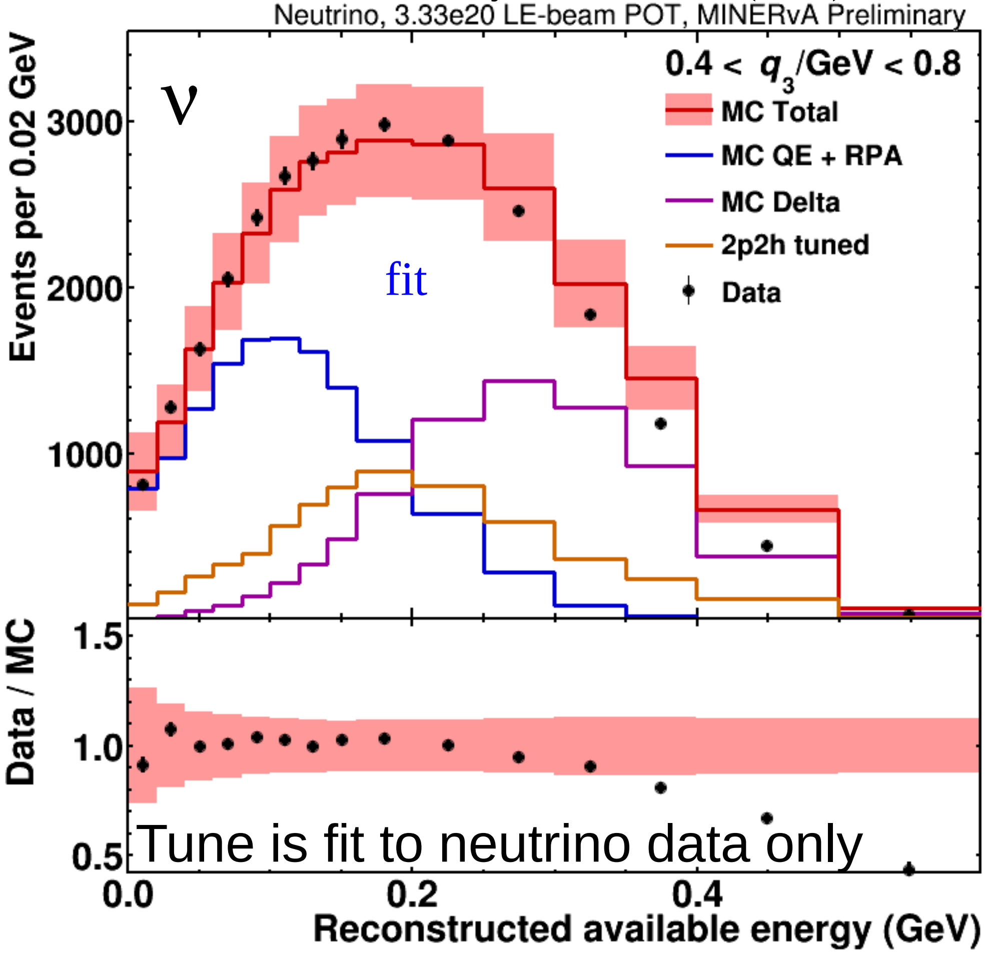
[MINERvA, Phys.Rev.Lett. 116 (2016) 071802]



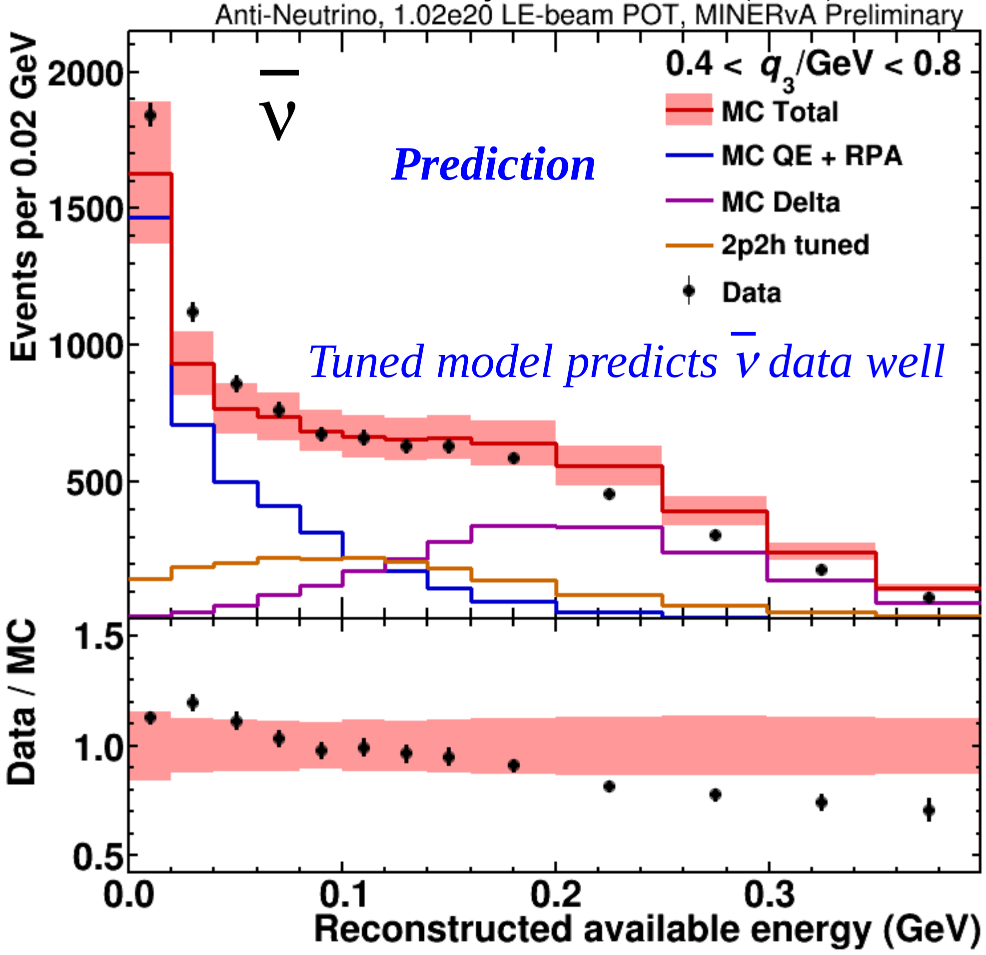
- Neutrino tune
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  G: 2D Gaussian(q0, q3) determined in fit to neutrino data
- *Empirical* modification to 2p2h

Base Model + Neutrino Tune = MnvGENIE-v1

[MINERvA, Phys.Rev.Lett. 116 (2016) 071802]



[MINERvA, Phys.Rev.Lett. 120 (2018) 221805]



- Apply neutrino tune directly to anti-neutrino
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  G: 2D Gaussian(q0, q3) determined in fit to neutrino data
- *Empirical* modification to 2p2h

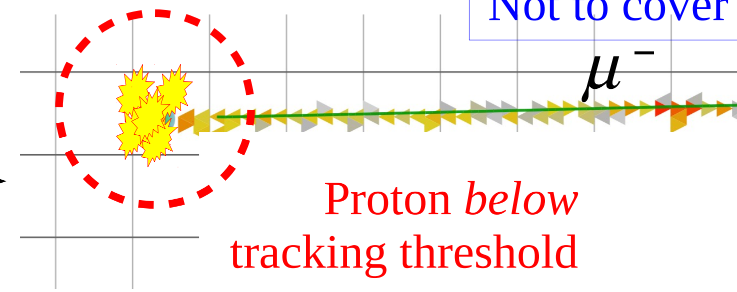
Interaction Measurements

– Inclusive to exclusive

$\bar{\nu}$ inclusive measurements

ν quasi-elastic-like interactions

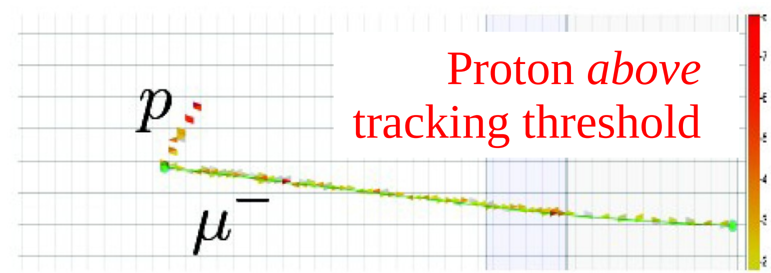
Not to cover in this talk



[MINERvA, Phys.Rev. D99, 012004 (2019)]

ν inclusive measurements
→ 2p2h tune

ν quasi-elastic-like interactions



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

Exclusive Measurements
– Why particle spectra won't work

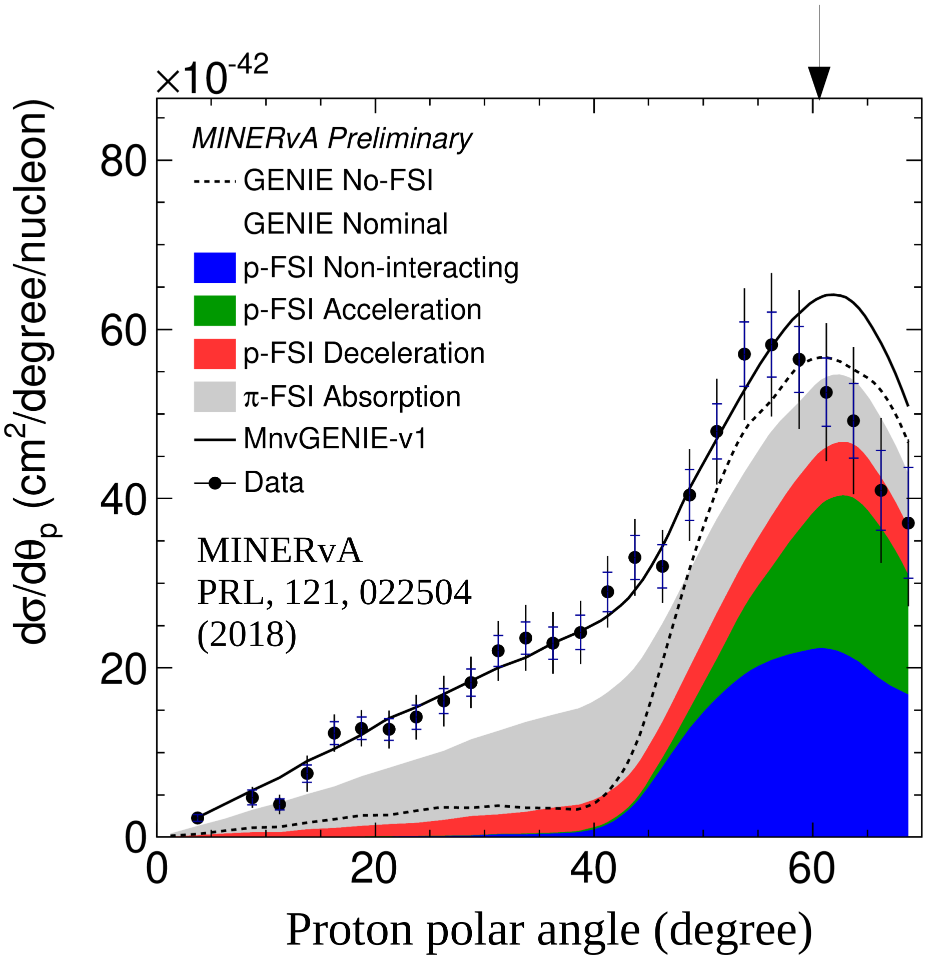
Problematic "lasagna" region:

2p2h

Resonance production with pion absorbed in nucleus

Proton gain & lose energy in nucleus

True quasi-elastic



Why can't we tell what is wrong?

- Without nuclear effects, spectra still depend on
  - flux
  - *nucleon*-level physics

Exclusive Measurements
– Why particle spectra won't work

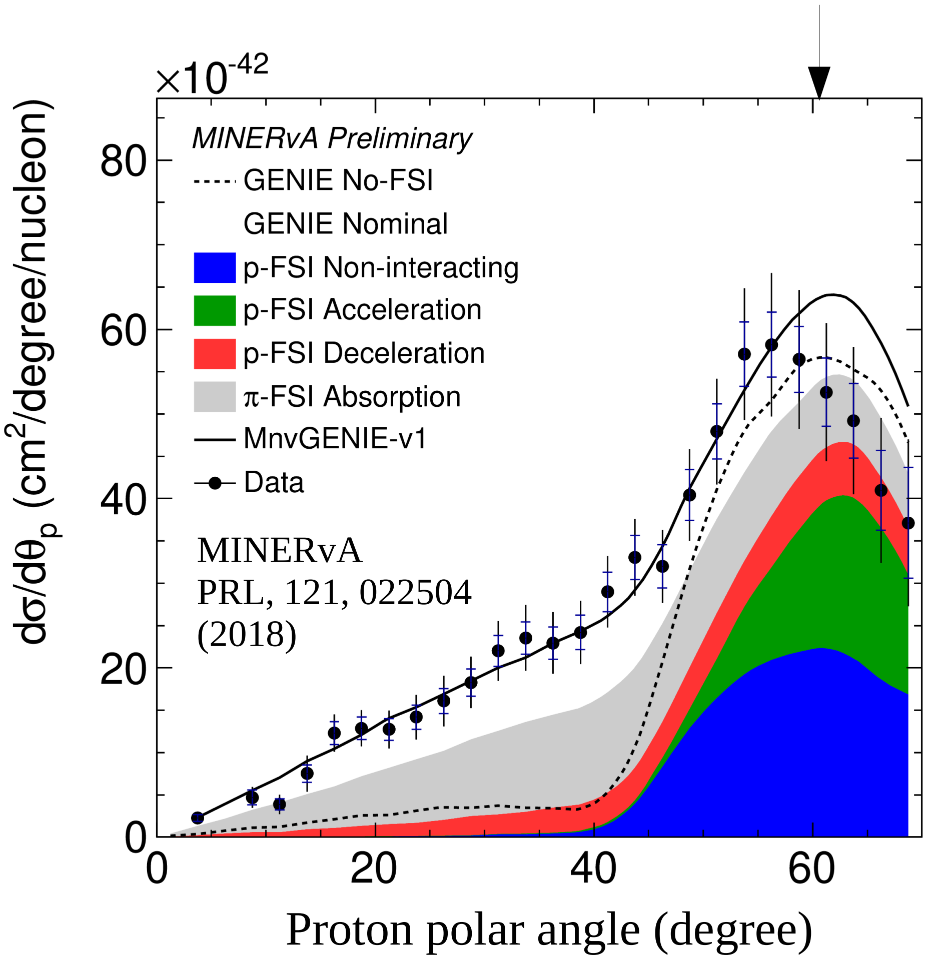
Problematic “lasagna” region:

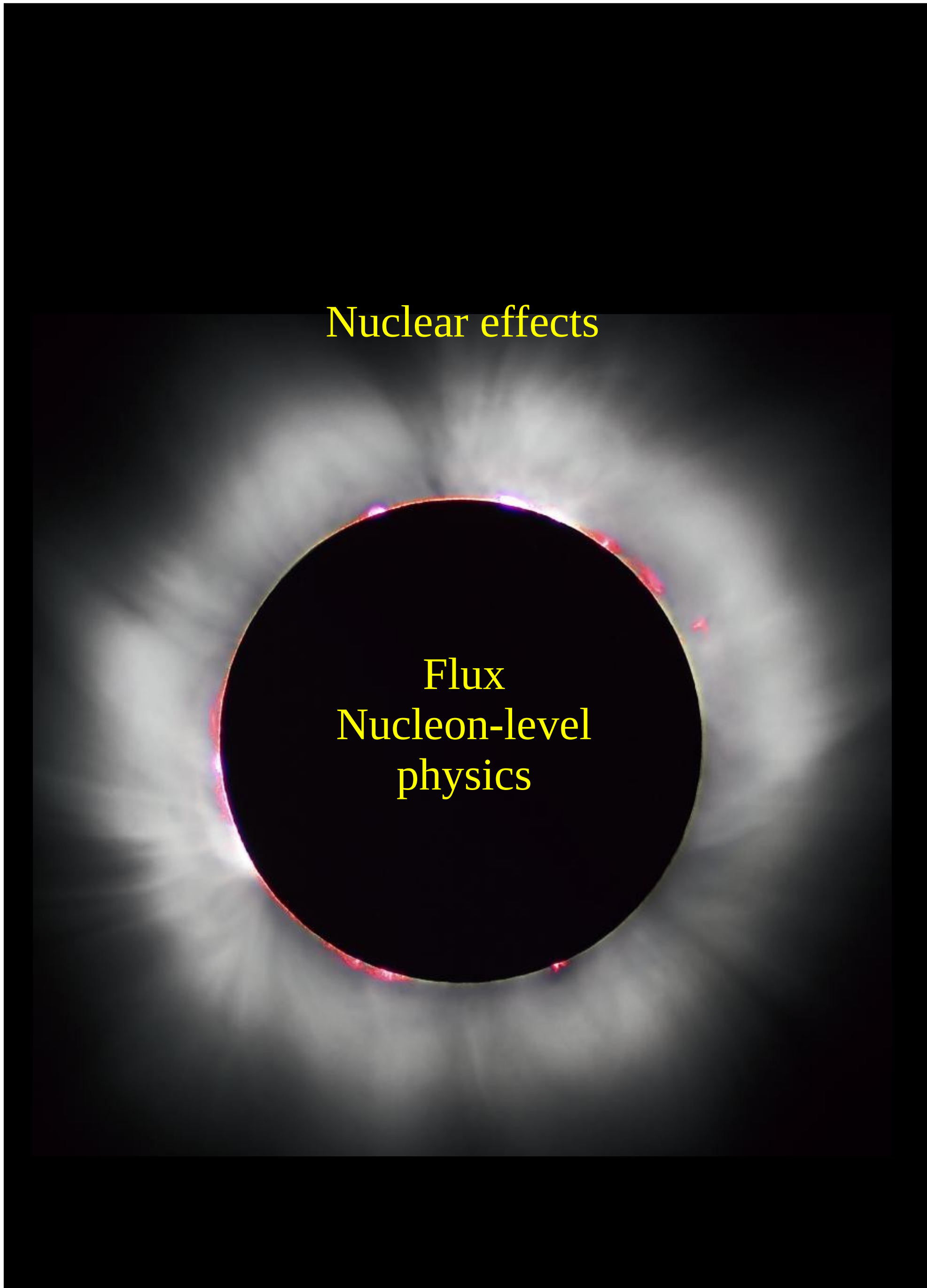
2p2h

Resonance production with pion absorbed in nucleus

Proton gain & lose energy in nucleus

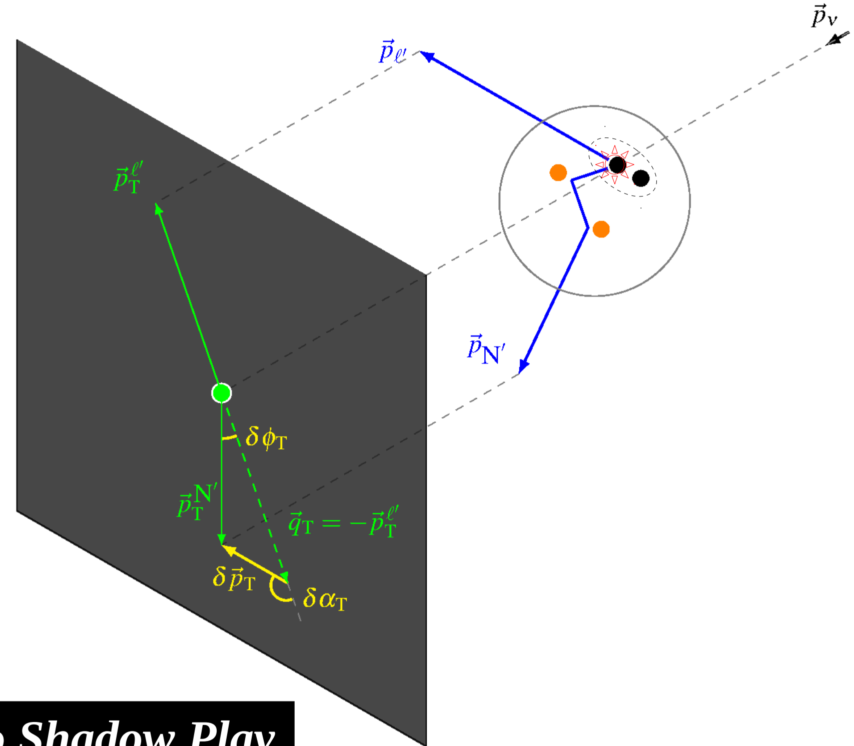
True quasi-elastic



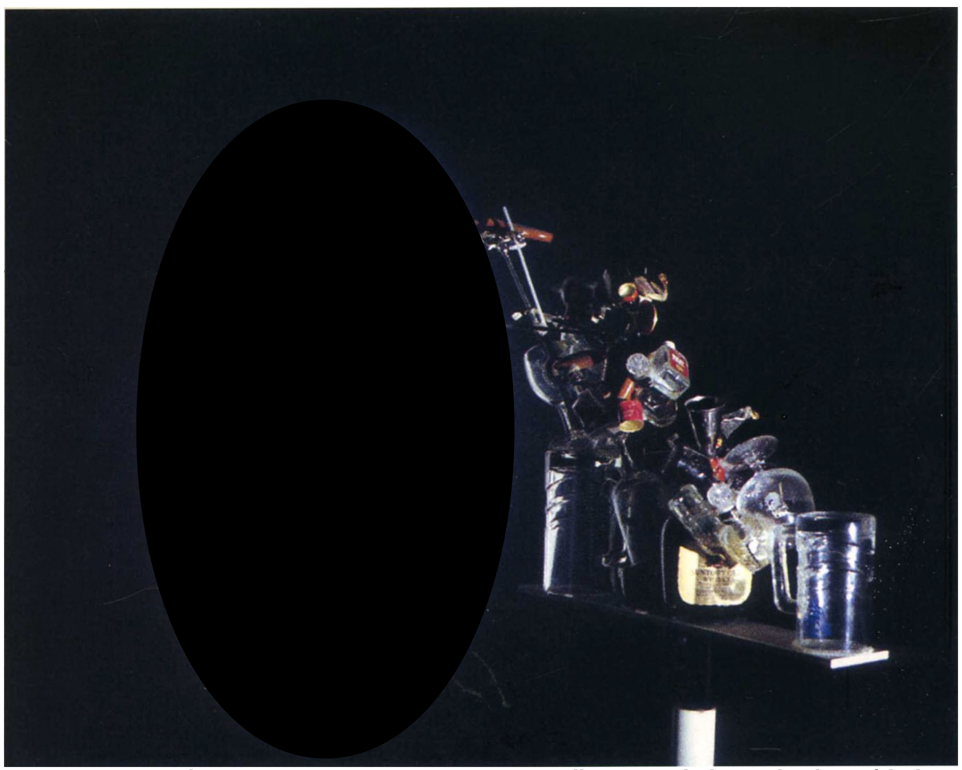


Xianguo Lu, Oxford

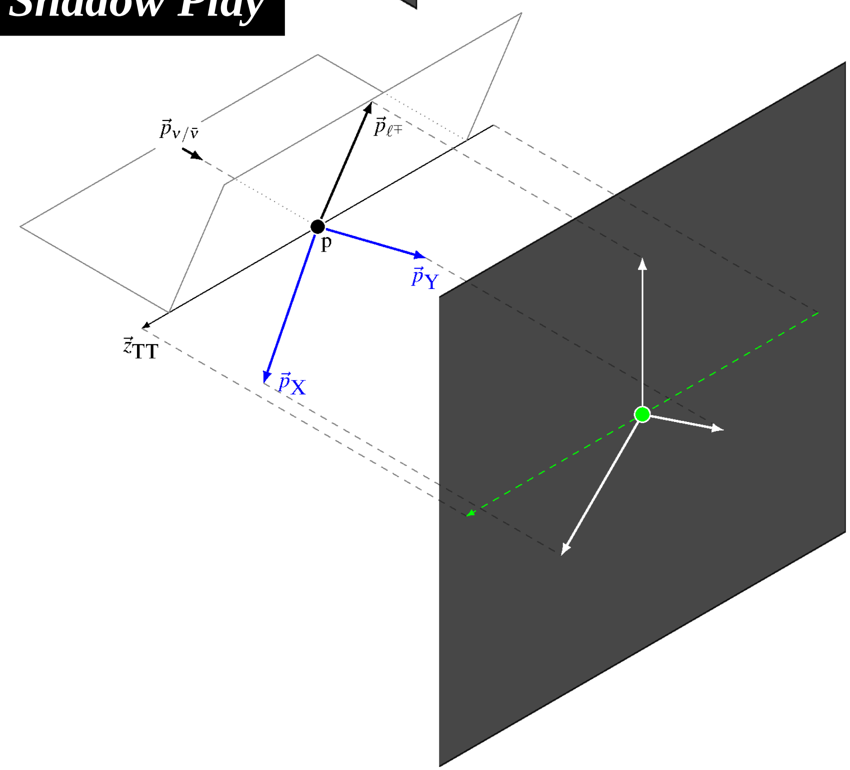
Transverse Kinematic Imbalance (TKI)
– Principle



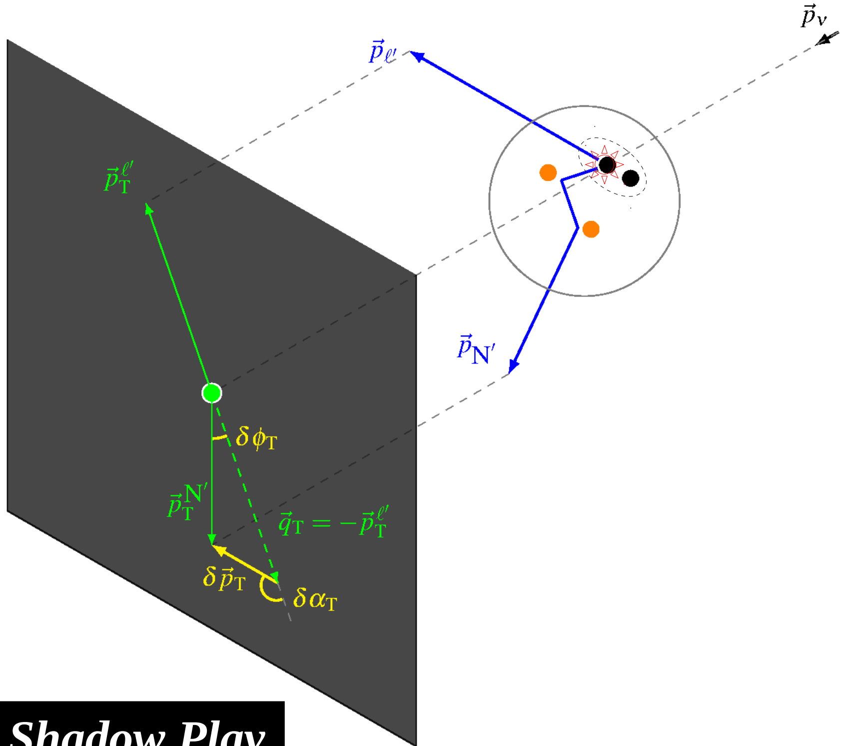
Neutrino Shadow Play



http://www.spoon-tamago.com/2015/08/03/illusionistic-shadow-art-by-shigeo-fukuda/



Transverse Kinematic Imbalance (TKI)
– Principle



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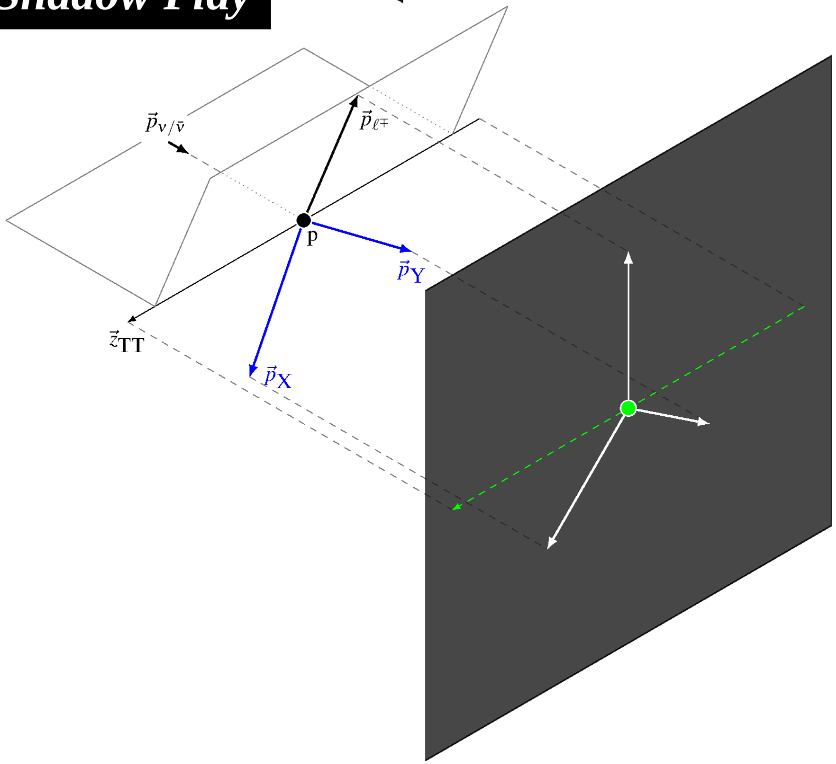
Neutrino Shadow Play

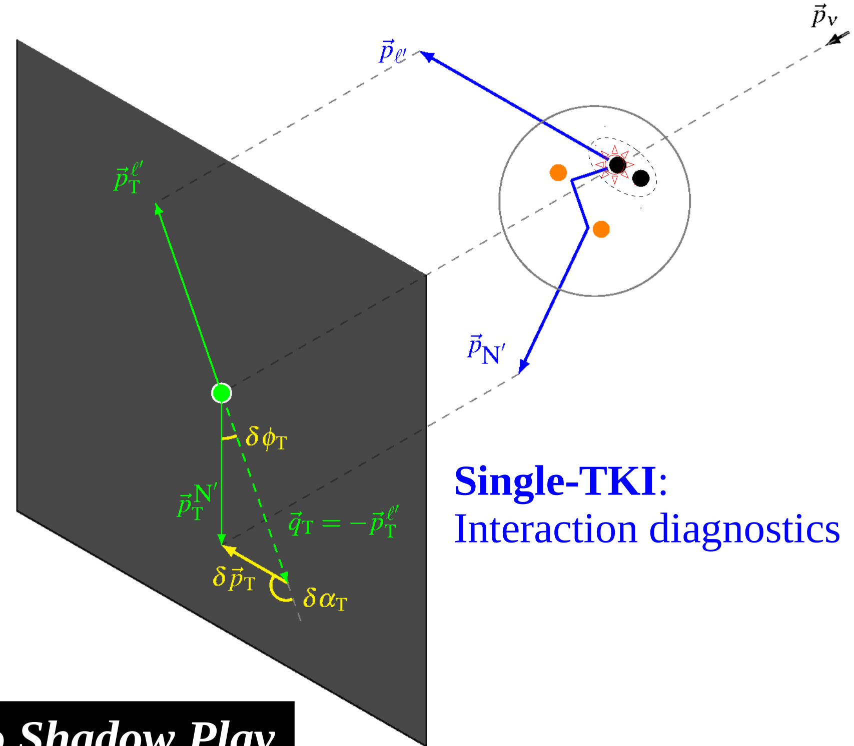


Xianguo Lu, Oxford

Transverse Kinematic Imbalance (TKI)
– Principle

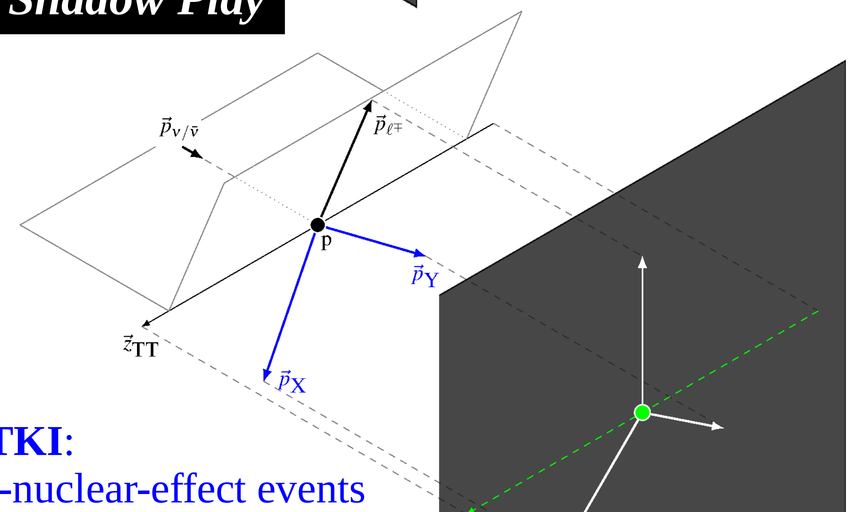
Details can be found in:

- **XL** *et al.* Phys.Rev. D92, 051302 (2015)
- **XL** *et al.* Phys. Rev. C94 015503 (2016)
- **XL**, J. T. Sobczyk, arXiv:1901.06411

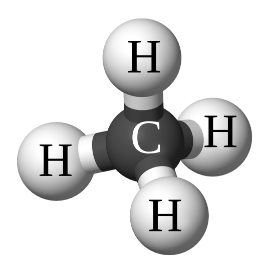


Single-TKI: Interaction diagnostics

Neutrino Shadow Play



Double-TKI: Select no-nuclear-effect events ν-H out of ν-C

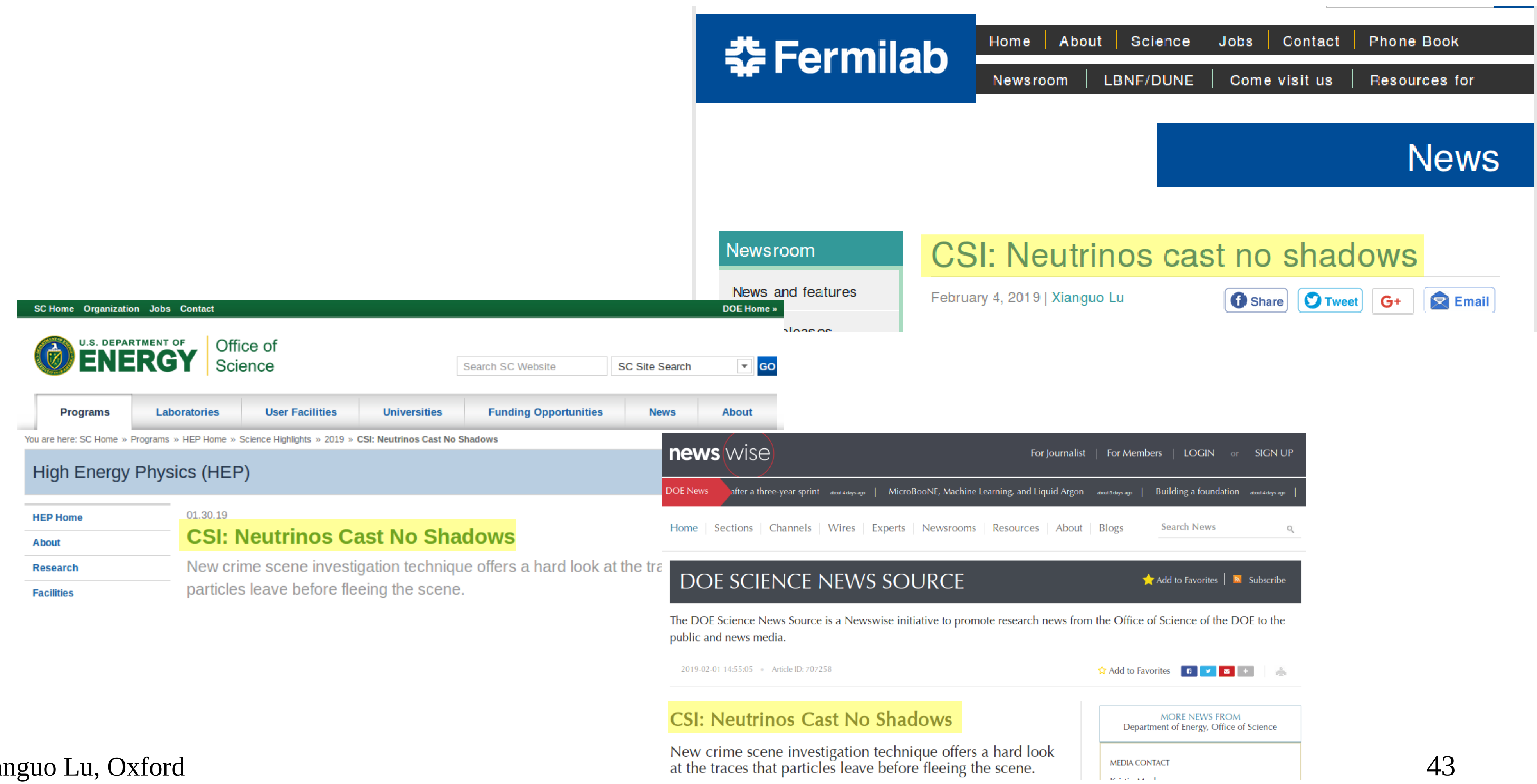


http://www.spoon-tamago.com/2015/08/03/illusionistic-shadow-art-by-shigeo-fukuda/

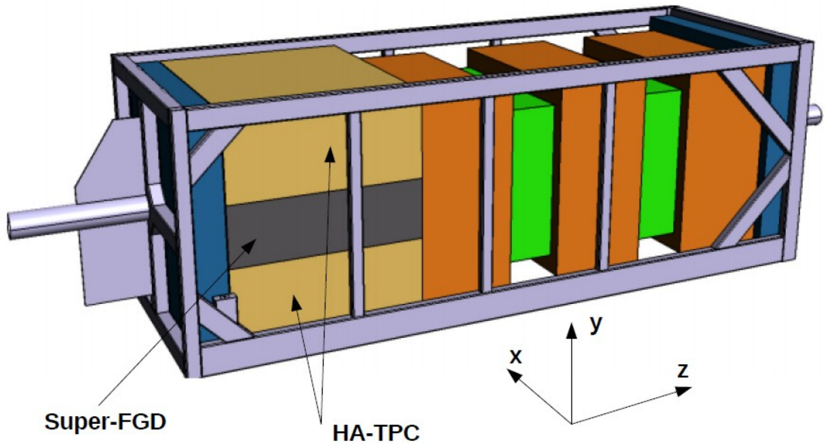
Transverse Kinematic Imbalance (TKI) – Analysis

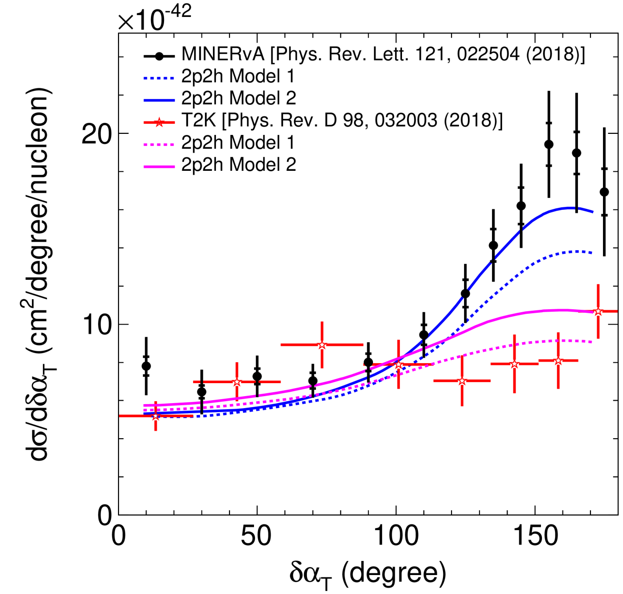
Experimental measurements on single-TKI:

- **T2K**: K. Abe *et al*. Phys.Rev. D98, 032003 (2018)
- **MINERvA**: **XL** *et al*. Phys.Rev.Lett. 121, 022504 (2018)



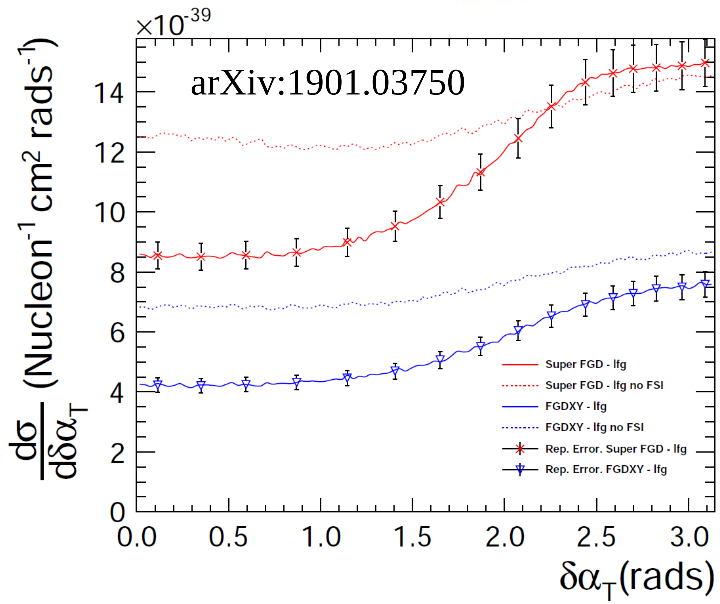
Transverse Kinematic Imbalance (TKI)
– Future experiments

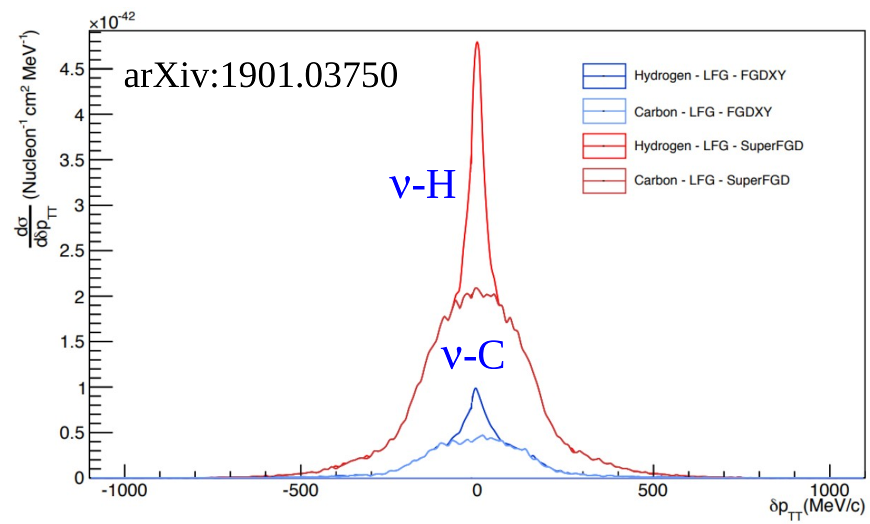




Current T2K & MINERvA

T2K Upgrade Technical Design Report

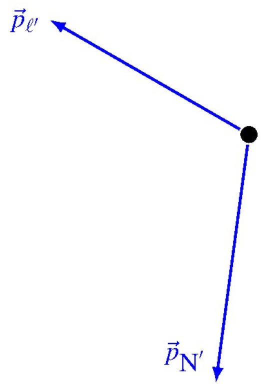




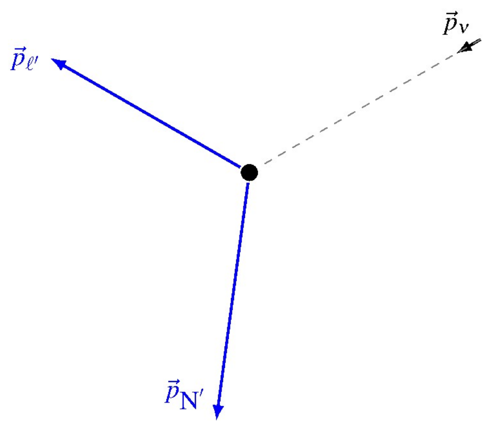
Single-TKI: Interaction diagnostics

Double-TKI: Select ν-H events

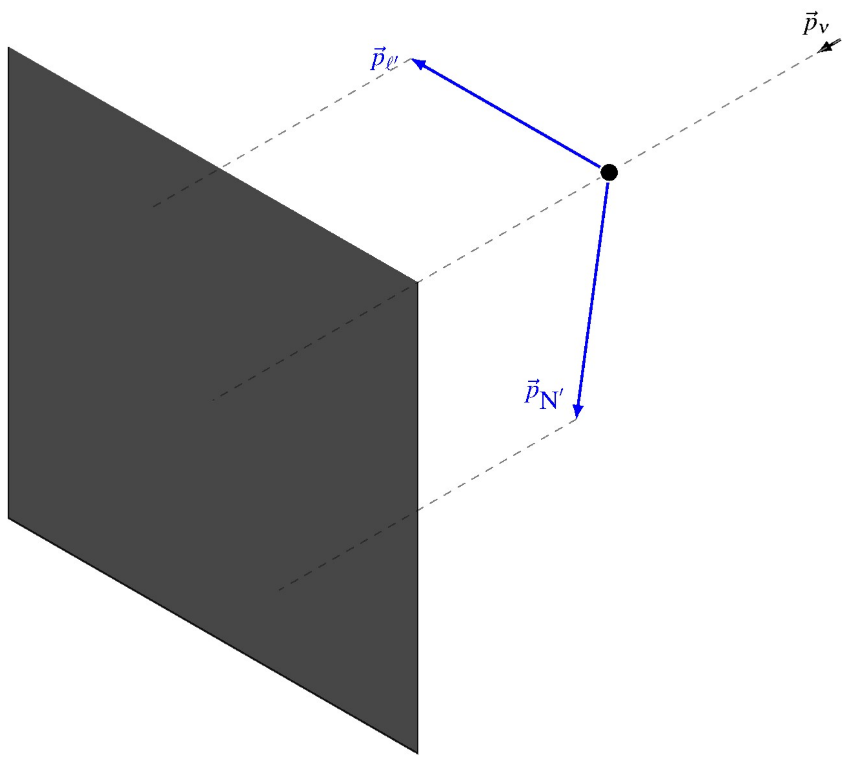
Transverse Kinematic Imbalance (TKI)
– The very idea



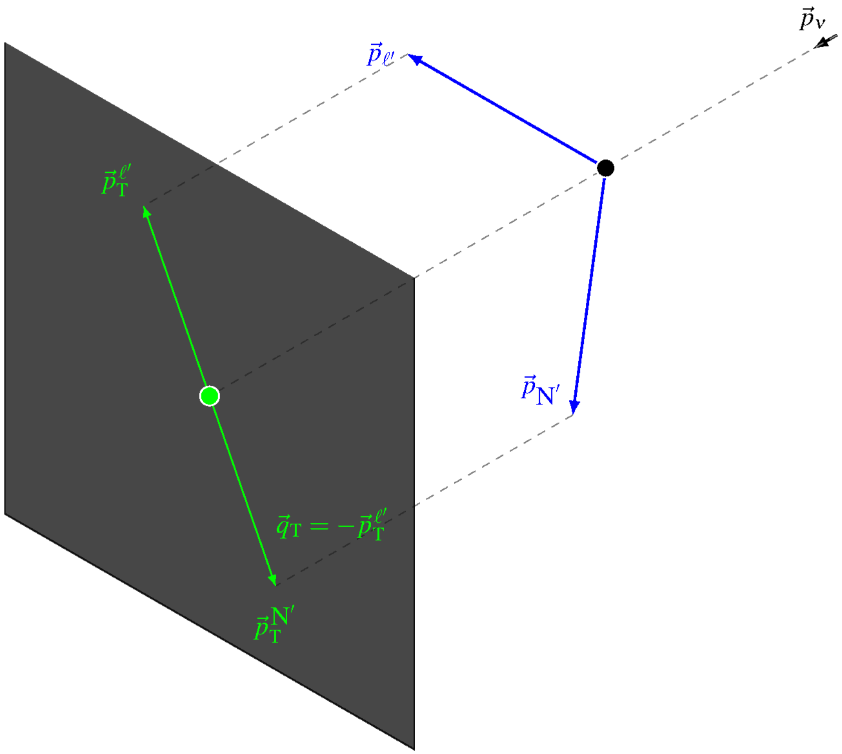
Transverse Kinematic Imbalance (TKI)
– The very idea



Transverse Kinematic Imbalance (TKI)
– The very idea

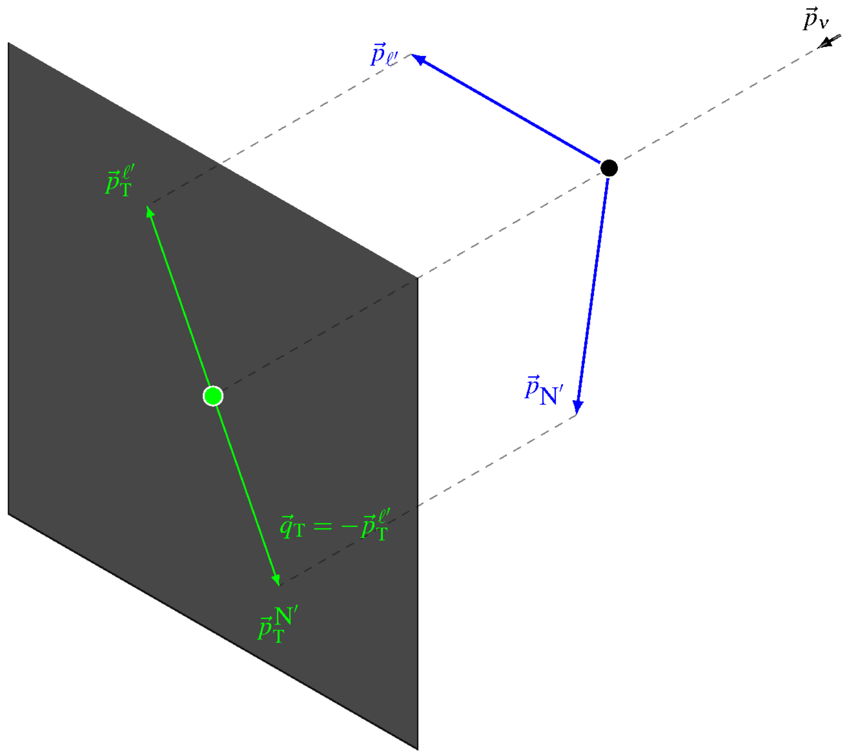


Transverse Kinematic Imbalance (TKI)
– The very idea



Stationary nucleon target

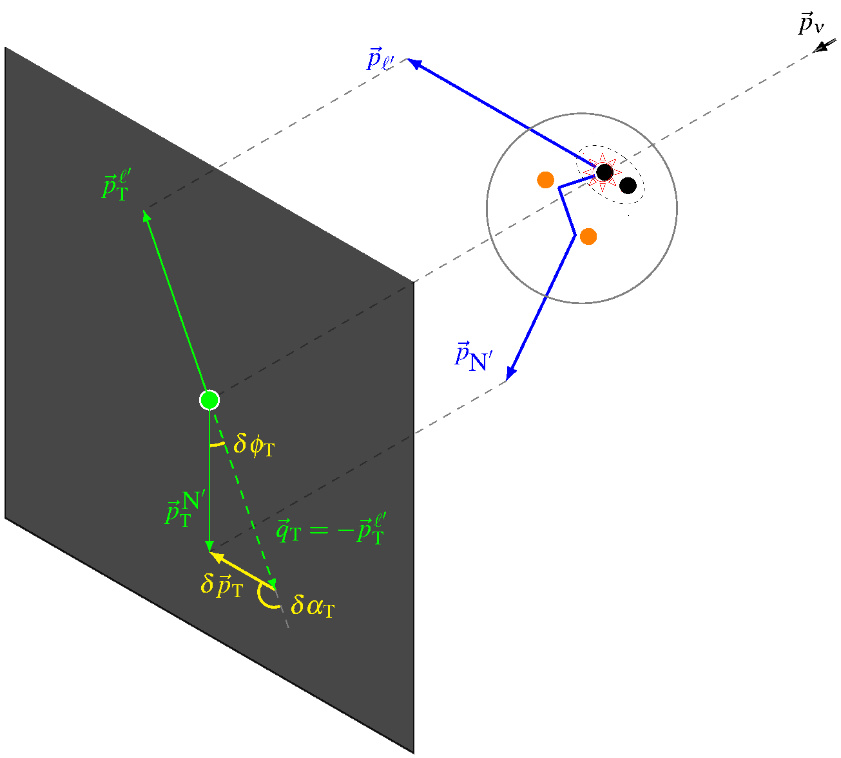
Transverse Kinematic Imbalance (TKI)
– The very idea



Stationary nucleon target

Still back-to-back after changing:
- Flux
- Nucleon structure (form factors)
- Feynman diagram

Transverse Kinematic Imbalance (TKI)
– The very idea



Nuclear target
(A>1)

Imbalances NOT due to

- Flux
- Nucleon structure (form factors)
- Feynman diagram

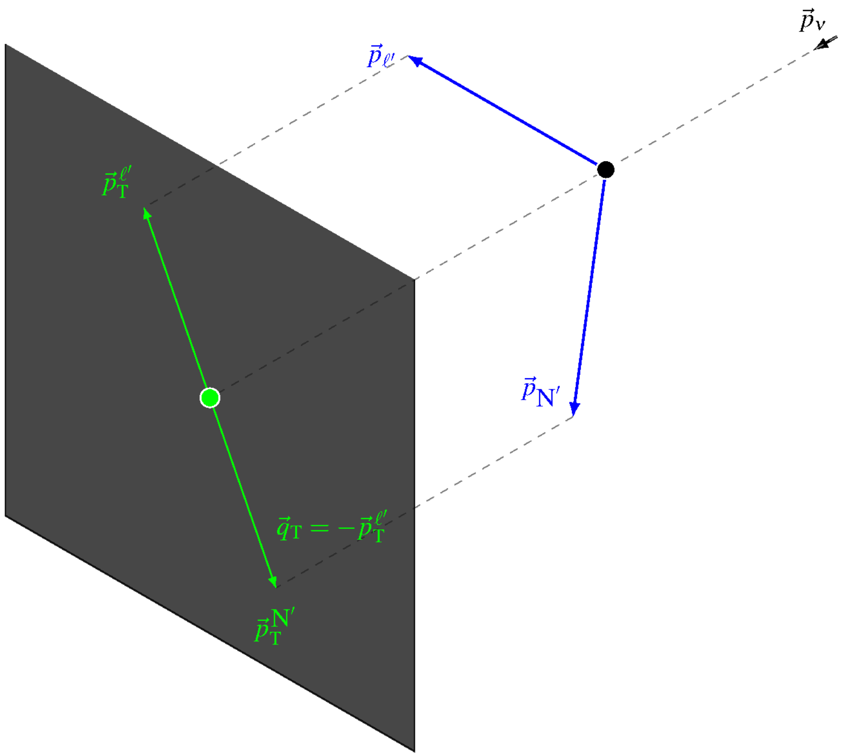
But

- Fermi motion
- Final-state interaction (FSI)
- 2p2h

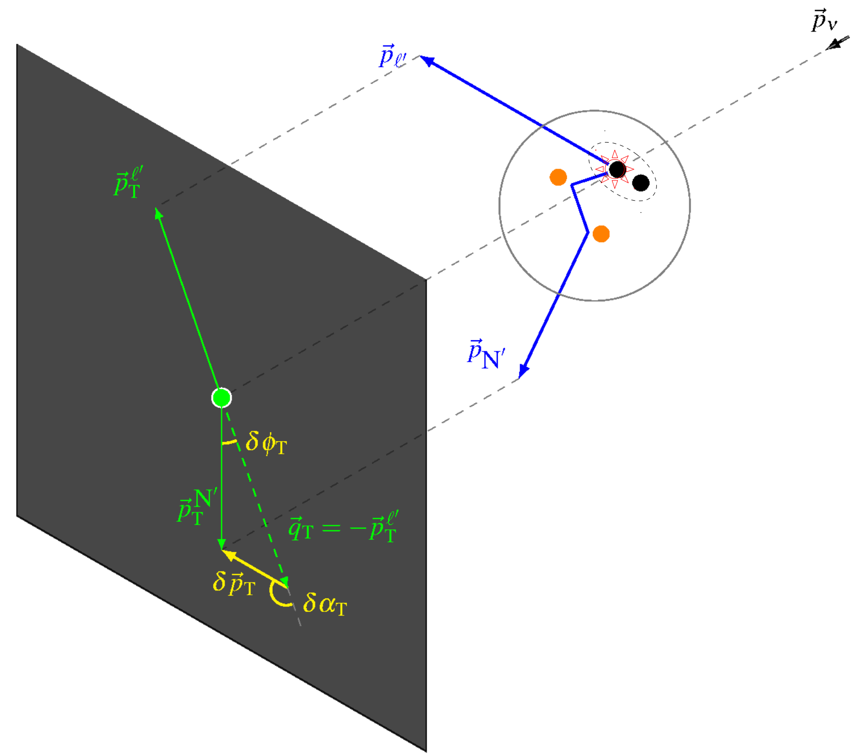
Transverse Kinematic Imbalance (TKI)
– The very idea

$$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\mathrm{N}} - \Delta\vec{p}_{\mathrm{T}}$$

- Fermi motion
- final-state interaction (FSI)
- 2p2h



Stationary nucleon target



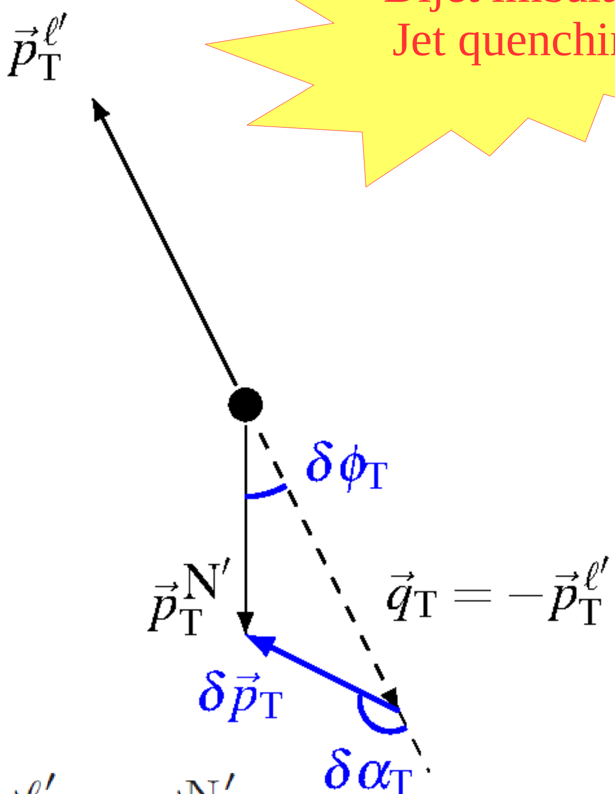
Nuclear target
(A>1)

Transverse Kinematic Imbalance (TKI)
– The very idea

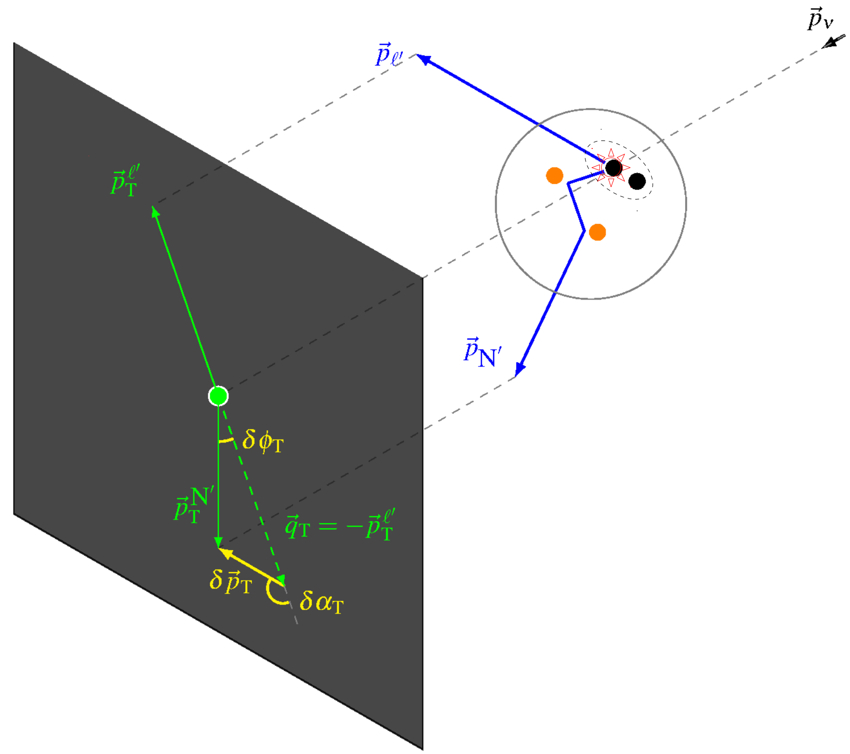
Dijet imbalance /
Jet quenching

$$\delta\vec{p}_{\rm T} = \vec{p}_{\rm T}^{\rm N} - \Delta\vec{p}_{\rm T}$$

- Fermi motion
- final-state interaction (FSI)
- 2p2h



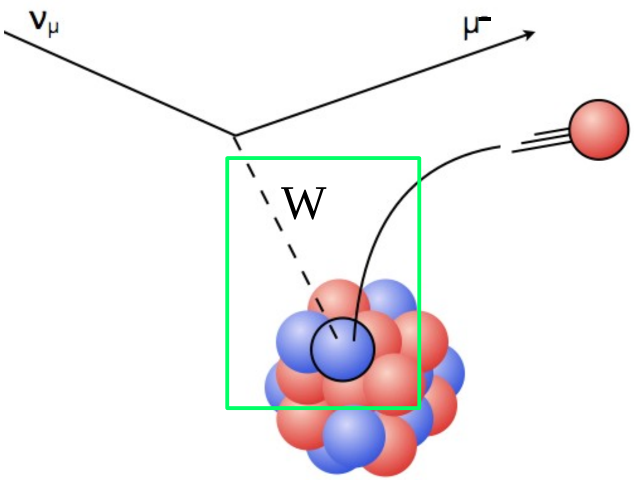
$$\delta\vec{p}_{\rm T} \equiv \vec{p}_{\rm T}^{\ell'} + \vec{p}_{\rm T}^{\rm N'}$$



Nuclear target
(A>1)

Transverse Kinematic Imbalance (TKI)
– Initial-state kinematics

Cartoon by Marco Del Tutto



In the center-of-mass frame

W-boson flux → ← Fermi motion

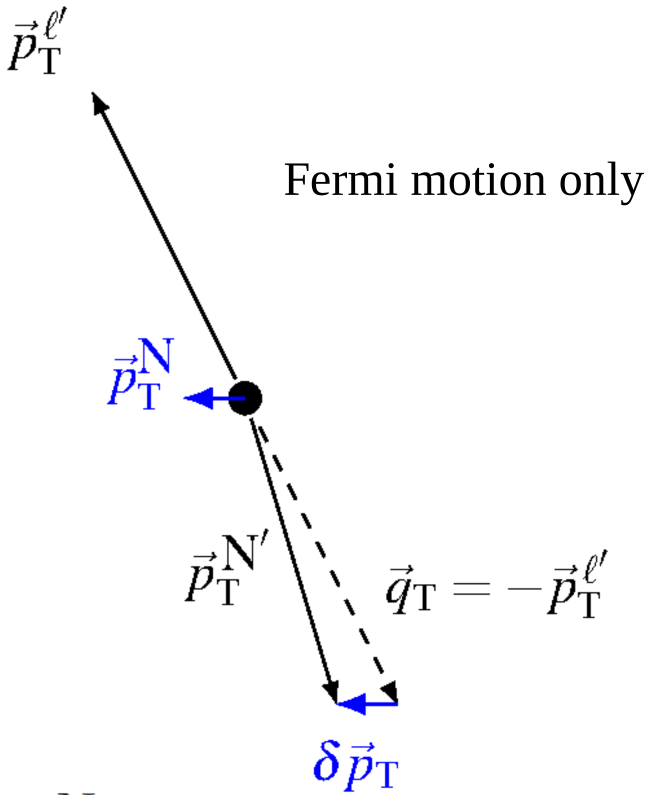
$W^{+/-}$ neutron/proton

The initial-state kinematics of the interaction depend on:
1. Fermi motion of struck nucleon (*static*)
2. Coupling of W+/- to neutron/proton – Fermi-motion dependent weighting (***dynamic***)

1. → could be determined by electron scattering (target specific)
2. → needs neutrinos

→ **How to measure initial state *in situ* in neutrino scattering?**

Transverse Kinematic Imbalance (TKI)
– Initial-state kinematics

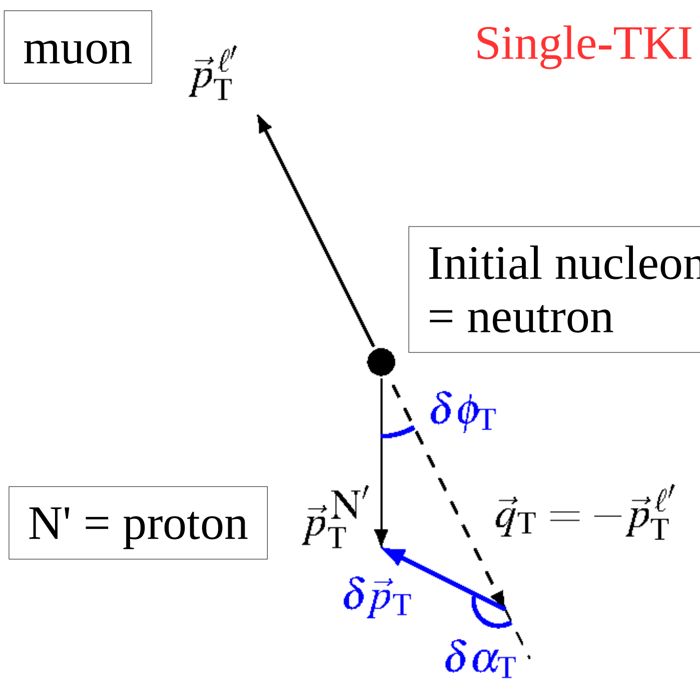


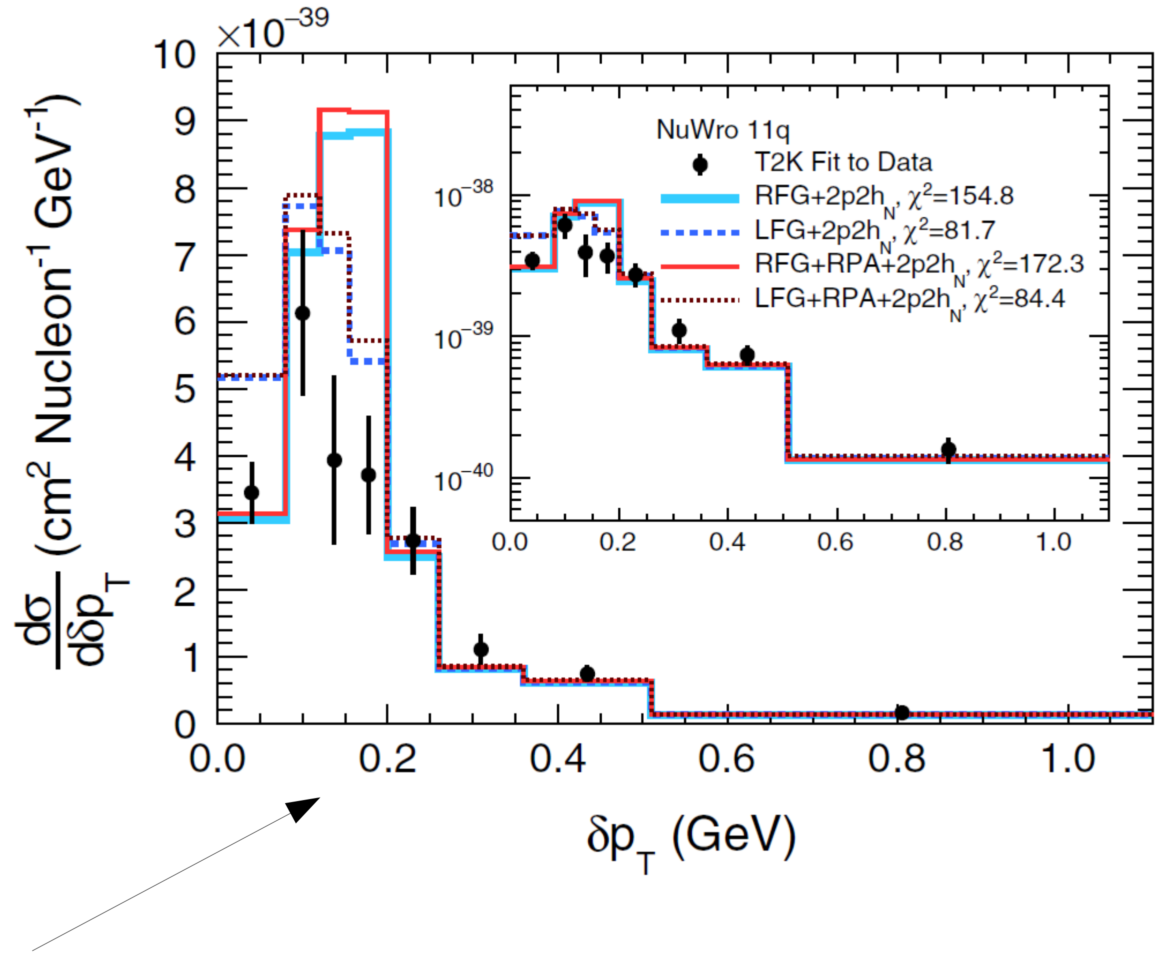
$$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\mathrm{N}}$$

δp_{T} is Fermi motion transverse projection

Transverse Kinematic Imbalance (TKI)
– Initial-state kinematics

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

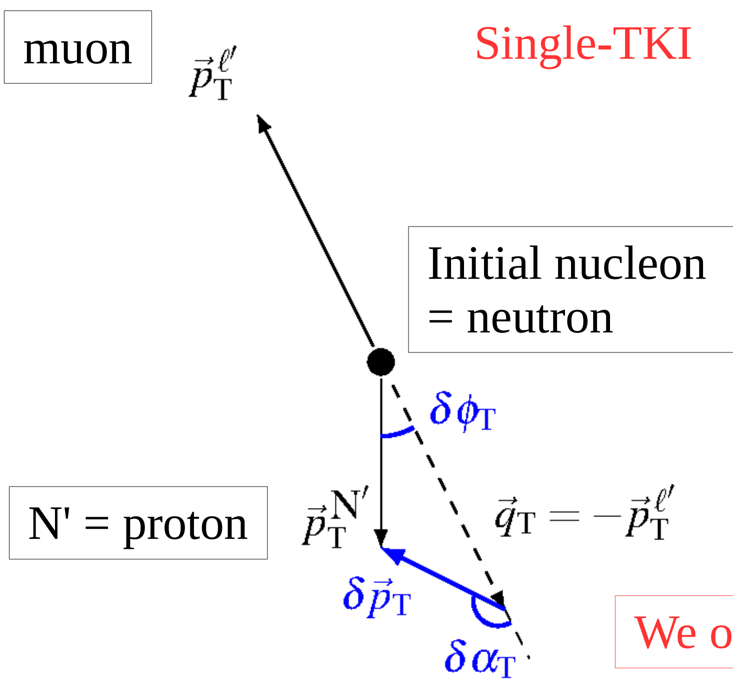


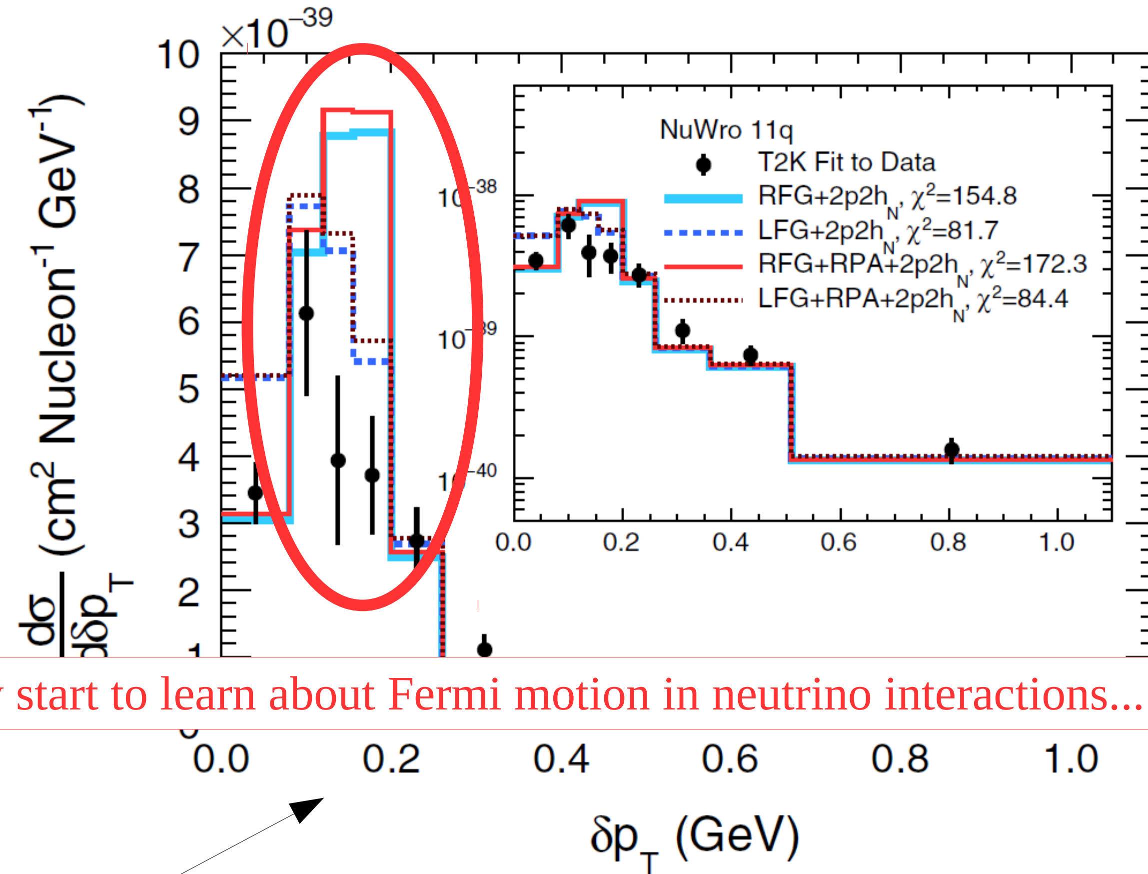


Transverse projection of Fermi motion

Transverse Kinematic Imbalance (TKI)
– Initial-state kinematics

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

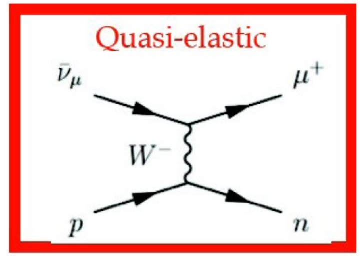




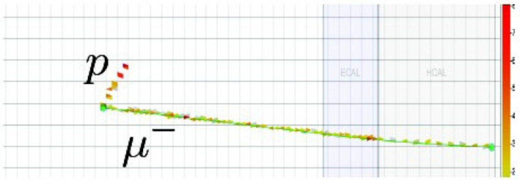
We only start to learn about Fermi motion in neutrino interactions...

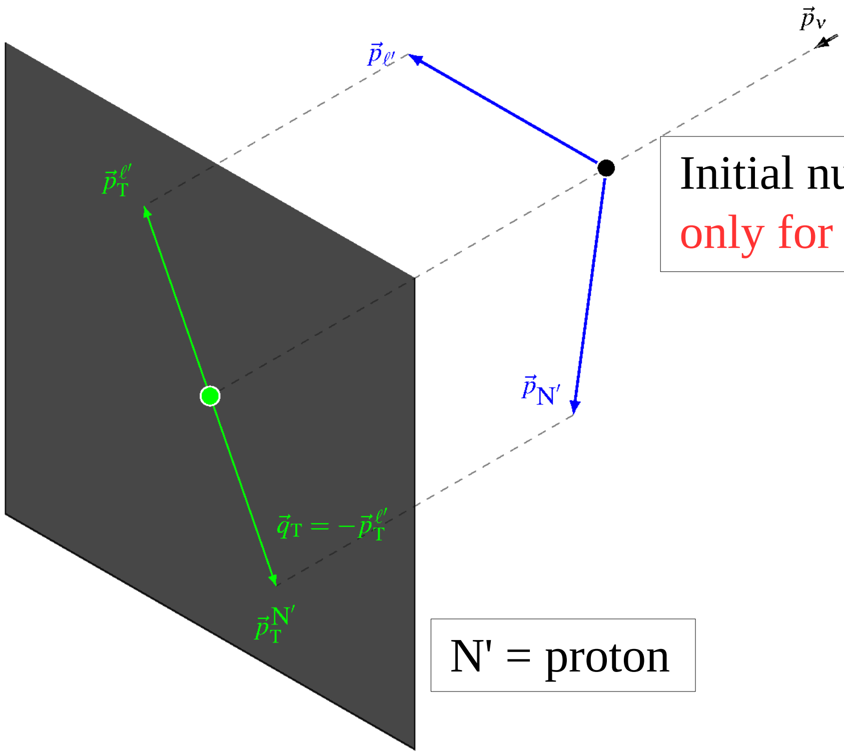
Transverse projection of Fermi motion

Transverse Kinematic Imbalance (TKI)
– Neutron initial-state kinematics



QE





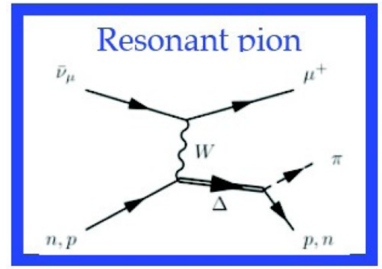
Initial nucleon = neutron only for ν scattering

N' = proton

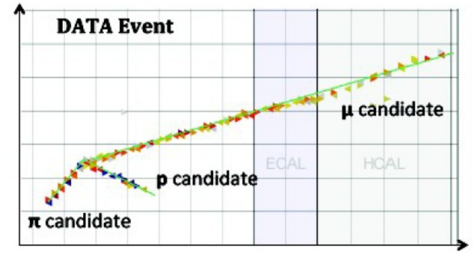
Stationary nucleon target

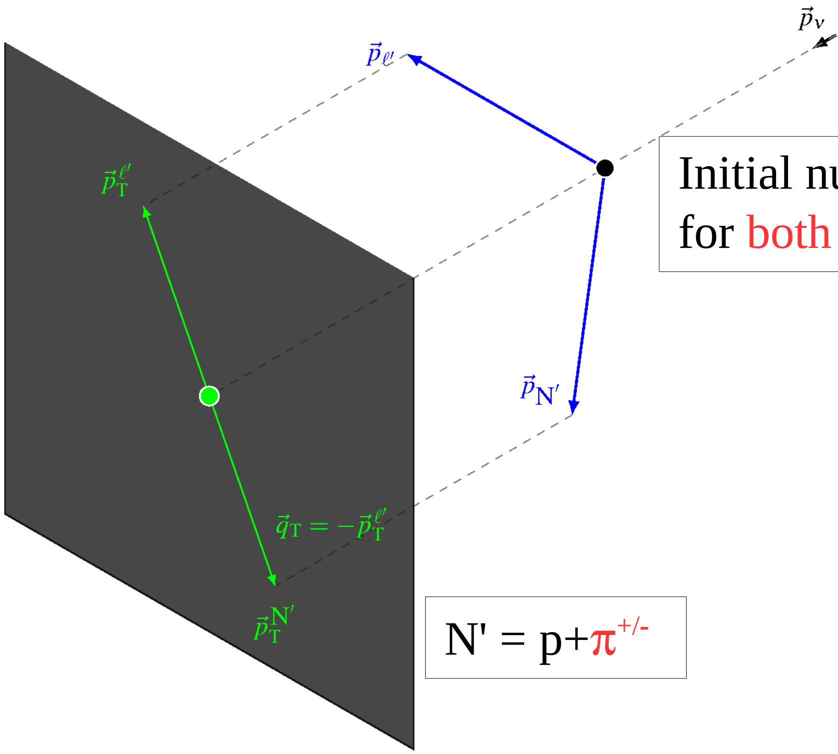
Still back-to-back after changing:
- Flux
- Nucleon structure (form factors)
- Feynman diagram

Transverse Kinematic Imbalance (TKI)
– Proton initial-state kinematics



RES



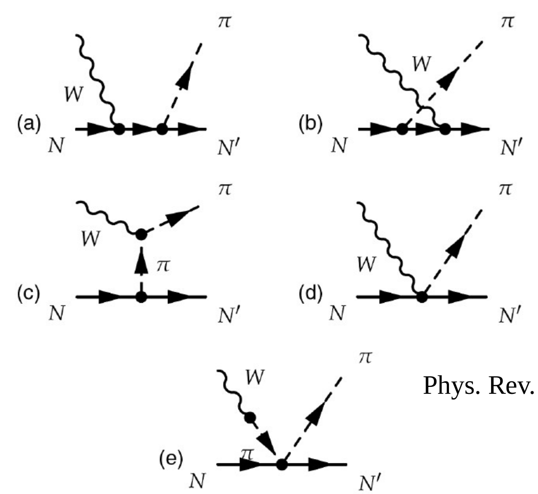


Initial nucleon = proton
for both ν and $\bar{\nu}$ scattering

N' = p+$\pi^{+/-}$

Stationary nucleon target

Still back-to-back after changing:
- Flux
- Nucleon structure (form factors)
- **Feynman diagram: Large uncertainty**



Phys. Rev. D 97, 013002 (2018)

Transverse Kinematic Imbalance (TKI)
– Proton initial-state kinematics

$$\nu 0\pi N\mathrm{p}:\ \nu\mathrm{A}\rightarrow\ell^{-}\mathrm{pX}$$

$$\nu\,\mathrm{n}\rightarrow\ell^{-}\ \mathrm{p}$$

Quasi-elastic

not applicable.

Quasi-elastic

$$\nu 1\pi N\mathrm{p}:\ \nu\mathrm{A}\rightarrow\ell^{-}\mathrm{p}\pi^{+}\mathrm{X}$$

$$\nu\,\mathrm{p}\rightarrow\ell^{-}\ \Delta^{++}\rightarrow\ell^{-}\ \mathrm{p}\ \pi^{+}$$

Resonant production

$$\bar{\nu} 1\pi N\mathrm{p}:\ \bar{\nu}\mathrm{A}\rightarrow\ell^{+}\mathrm{p}\pi^{-}\mathrm{X}$$

$$\bar{\nu}\,\mathrm{p}\rightarrow\ell^{+}\ \Delta^{0}\rightarrow\ell^{+}\ \mathrm{p}\ \pi^{-}$$

Resonant production

neutrino

antineutrino

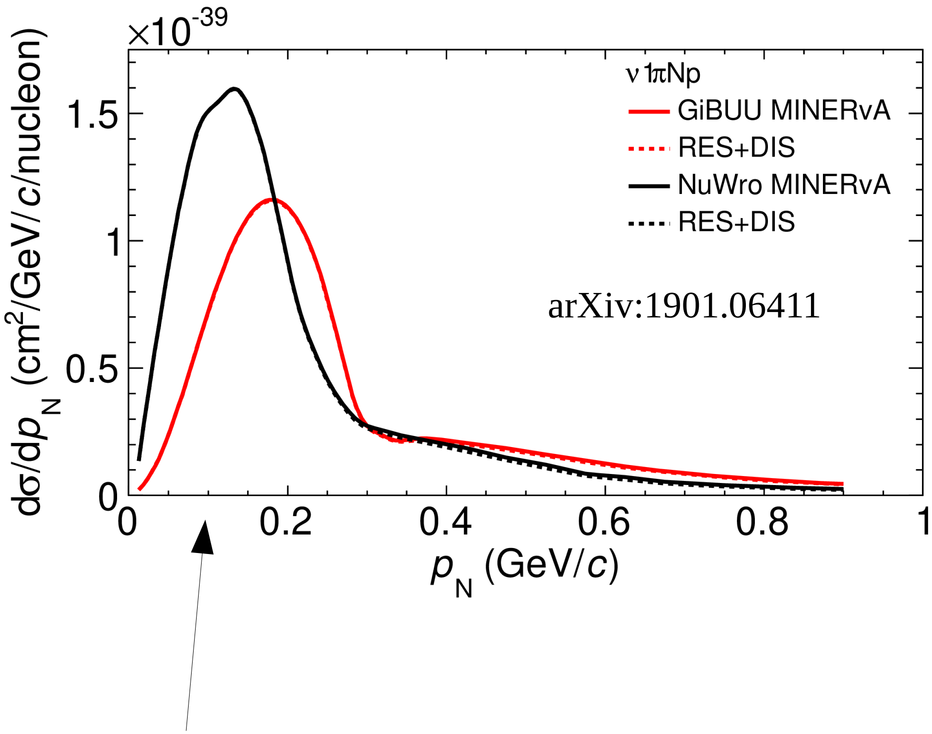
- Neutron Fermi motion can be probed by QE, but only in neutrino scattering
- Proton Fermi motion in RES with both neutrino and antineutrino → *direct comparison of dynamic aspect of initial state, to remove possible confusion with CPV!*

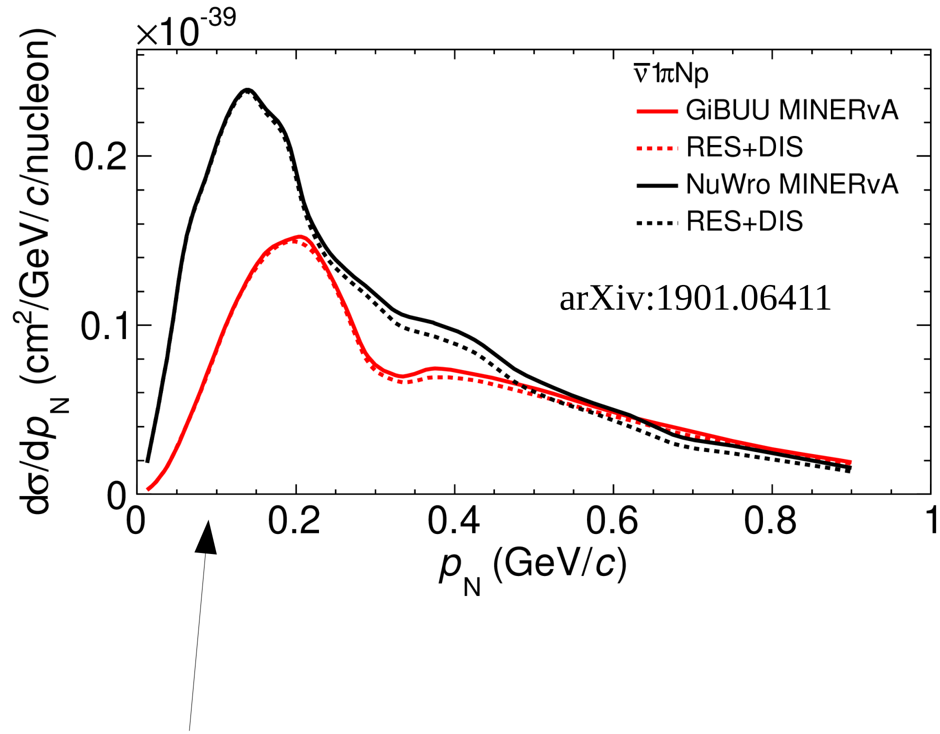
State-of-the-art neutrino interaction event generators: GiBUU and NuWro

p_N: 3D generalization of δp_T [Furmanski, Sobczyk, Phys.Rev. C95 (2017) 065501]

$$\nu 1\pi N\mathrm{p}: \ \nu \mathrm{A} \to \ell^- \mathrm{p} \pi^+ \mathrm{X}$$
$$\nu\ \mathrm{p} \to \ell^-\ \Delta^{++} \to \ell^-\ \mathrm{p}\ \pi^+$$

$$\bar{\nu} 1\pi N\mathrm{p}: \ \bar{\nu} \mathrm{A} \to \ell^+ \mathrm{p} \pi^- \mathrm{X}$$
$$\bar{\nu}\ \mathrm{p} \to \ell^+\ \Delta^{0} \to \ell^+\ \mathrm{p}\ \pi^-$$





Proton Fermi motion seen by ν

Proton Fermi motion seen by $\bar{\nu}$

GiBUU and NuWro have very different predictions for MINERvA

Also very different Fermi motion peaks in ν and $\bar{\nu}$

Measurements on-going...Stay tuned!

Neutrino Interactions in the GeV Regime

Outline

- Neutrino Oscillations

– An identity-changing game – Underlying math – Seeing is believing

- Oscillation Measurements

– Accelerator-based neutrino experiments – #measured ν / #produced ν

– Beam flux, ν and $\bar{\nu}$ interactions

– ν and $\bar{\nu}$ interactions – Impact of ν and $\bar{\nu}$ interactions

- Interaction Measurements

– MINERvA

– Inclusive 'low-recoil' analysis – Inclusi... exclusiv...

- Exclusive Measurements

– Why particle spectra won't work

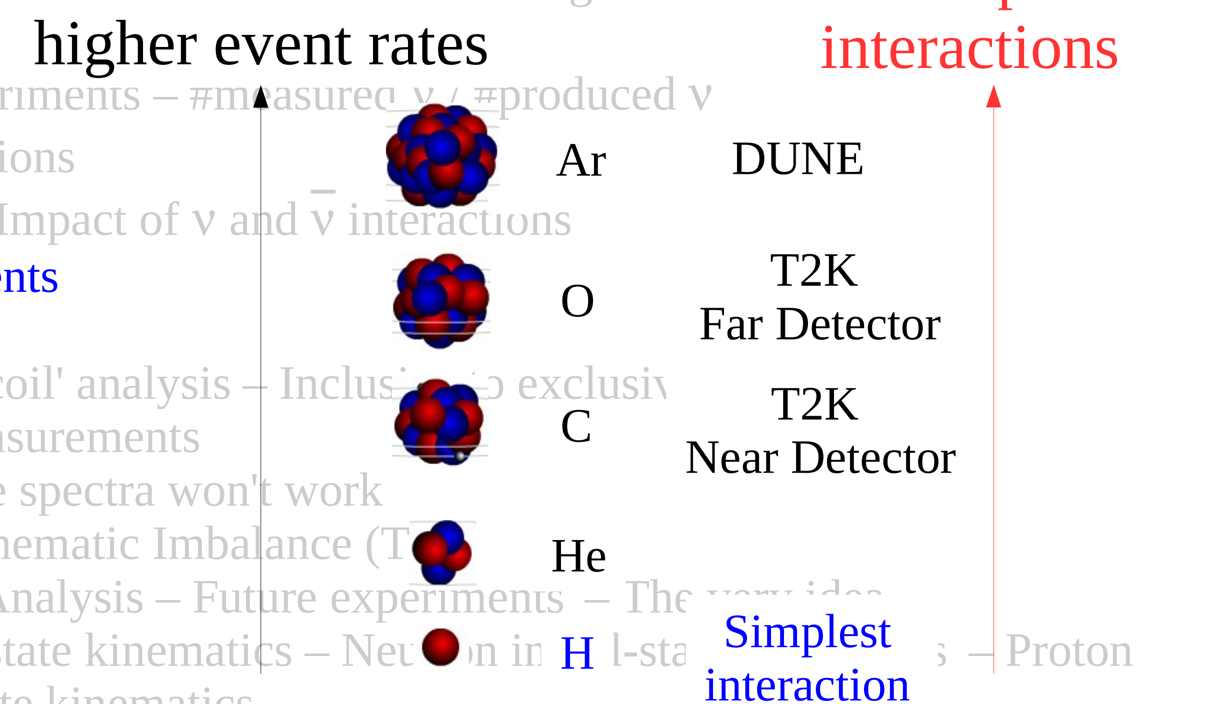
- Transverse Kinematic Imbalance (T...

– Principle – Analysis – Future experiments – The ...

– Initial-state kinematics – Ne... in ...l-sta... – Proton initial-state kinematics

- Neutrino-Hydrogen Interactions

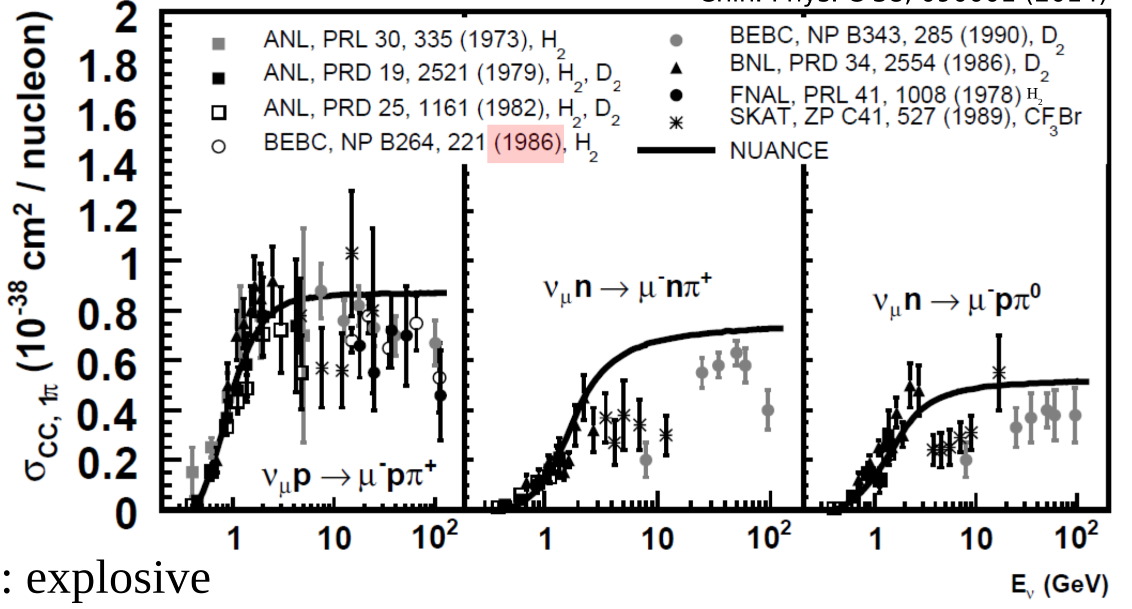
– Review – The very idea – Perspective



Neutrino-Hydrogen Interactions – Review

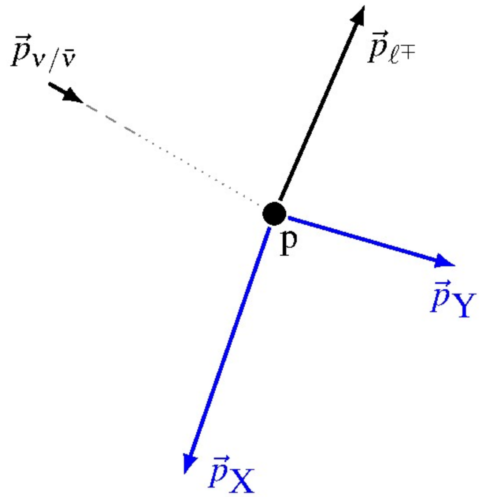
- Pure hydrogen
  - Technical requirement: bubble chamber (historical: 73, 79, 78, 82, 86)

Chin. Phys. C 38, 090001 (2014)



  - Safety issue: explosive
    - Due to buoyancy, more dangerous for underground experiments
- Neutrino interactions on hydrogen:
  - In the last ~30 years there has been no new measurement
  - No nuclear effects → much desired for flux constraint and nucleon cross section input for oscillation analysis
  - Nucleon structure → new frontier of hadron physics

Neutrino-Hydrogen Interactions
– The very idea

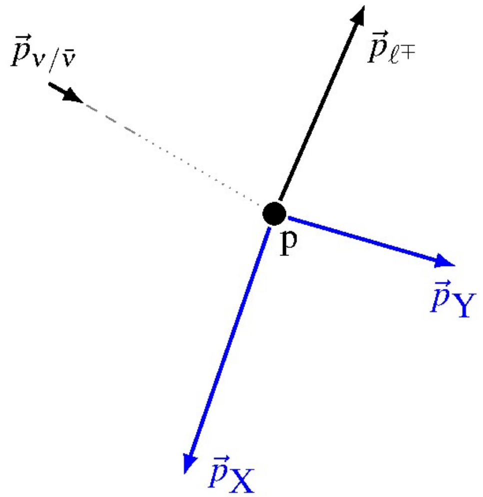


l p interaction → 3 charged particles:
l p → *l'* X Y

[XL, et al. Phys. Rev. D 92, 051302 (2015),
XL, JPS Conf. Proc. 12, 010034 (2016)]

Neutrino-Hydrogen Interactions
– The very idea

$\{X, Y\}$
$= \{p, \pi^+\}$ for $\nu + p \to \ell^- + \Delta^{++}$
or $\{p, \pi^-\}$ for $\bar{\nu} + p \to \ell^+ + \Delta^0$



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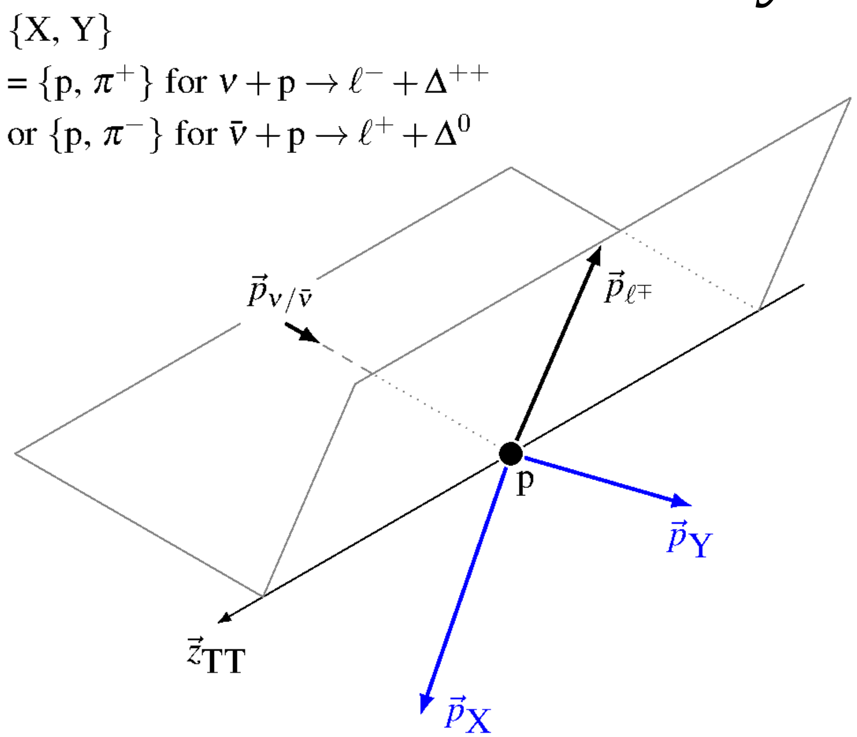

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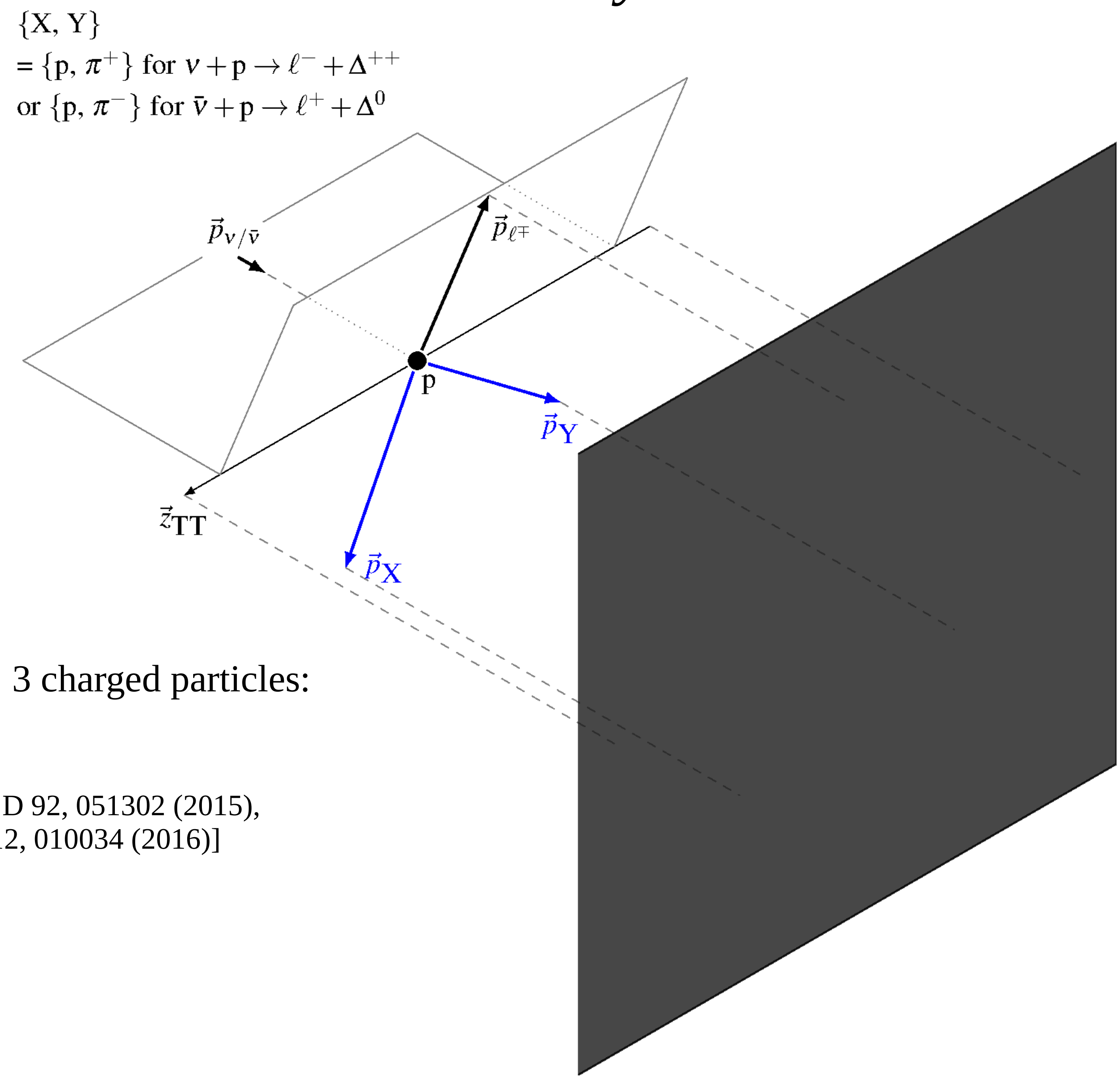

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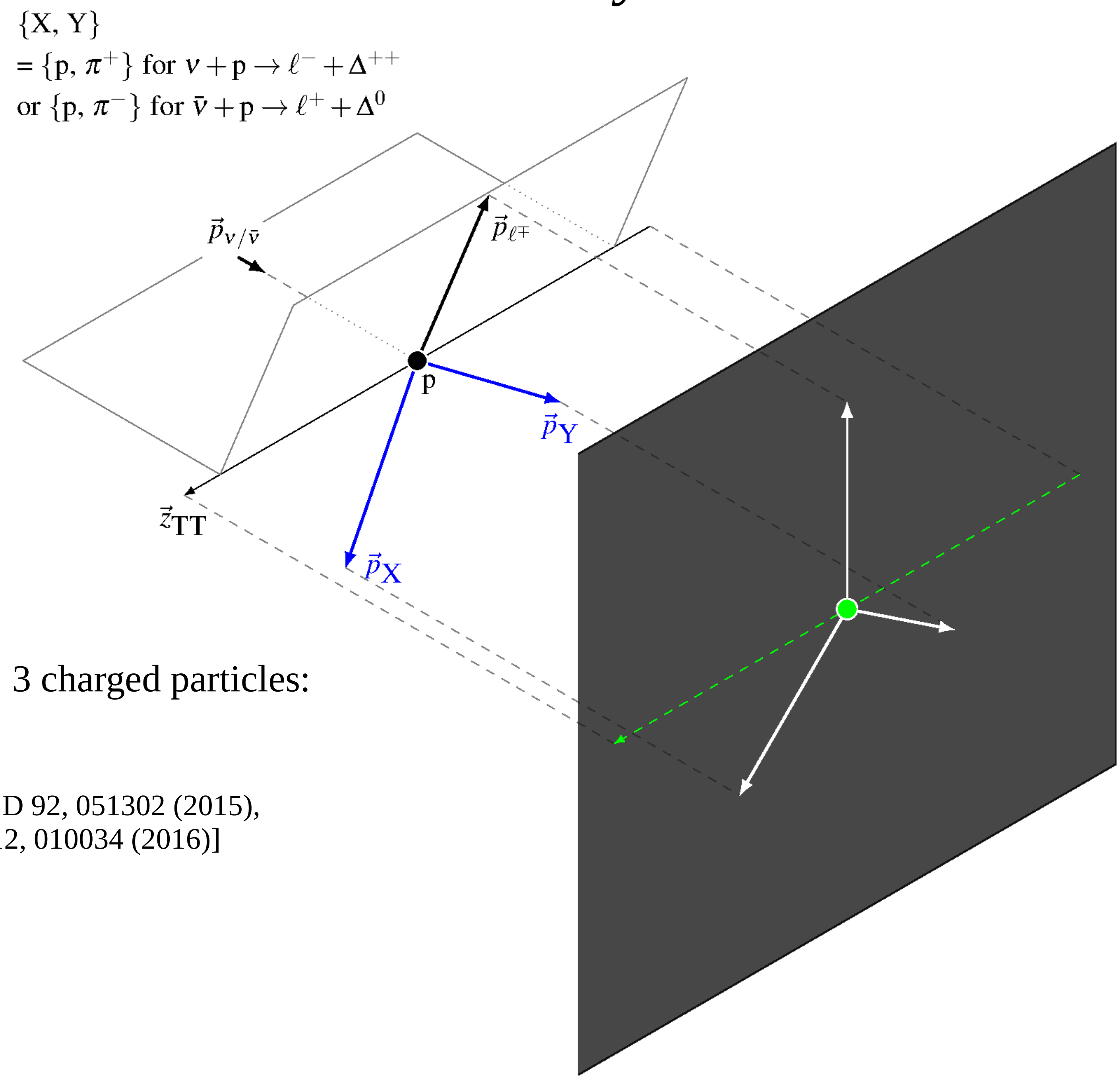

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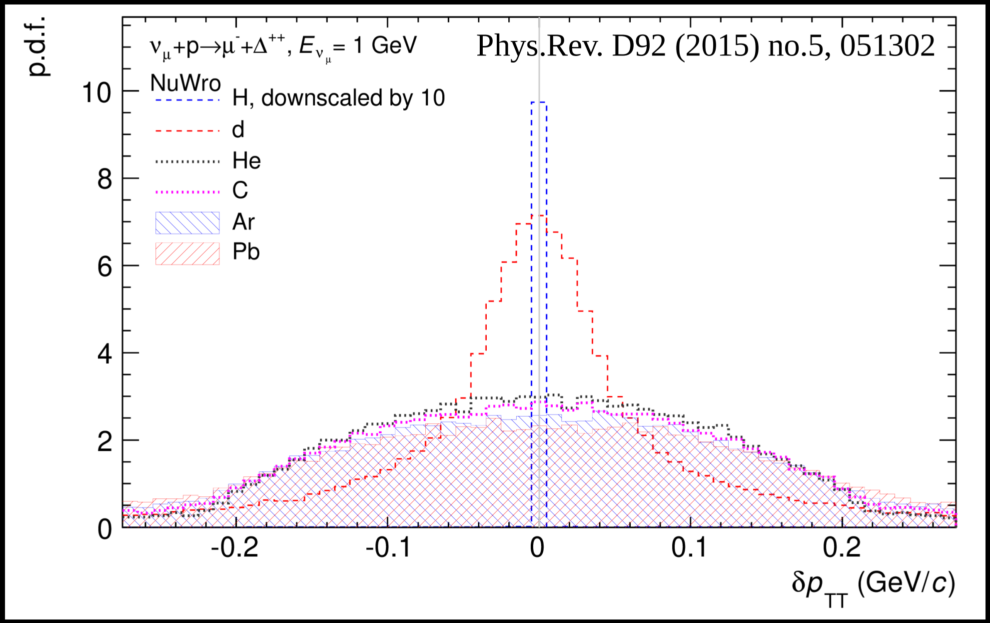

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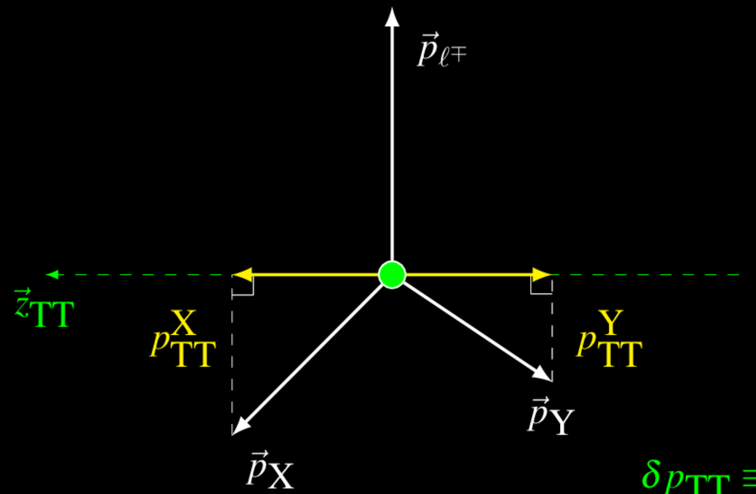
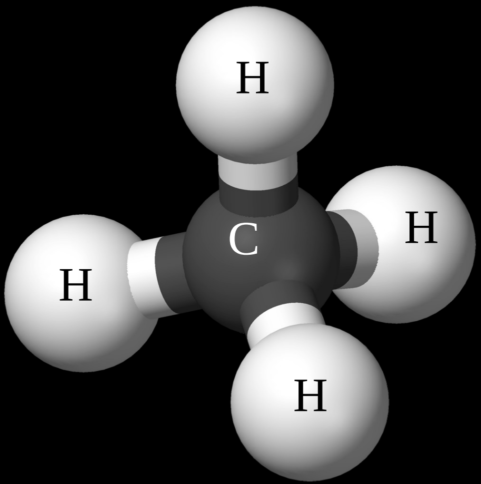


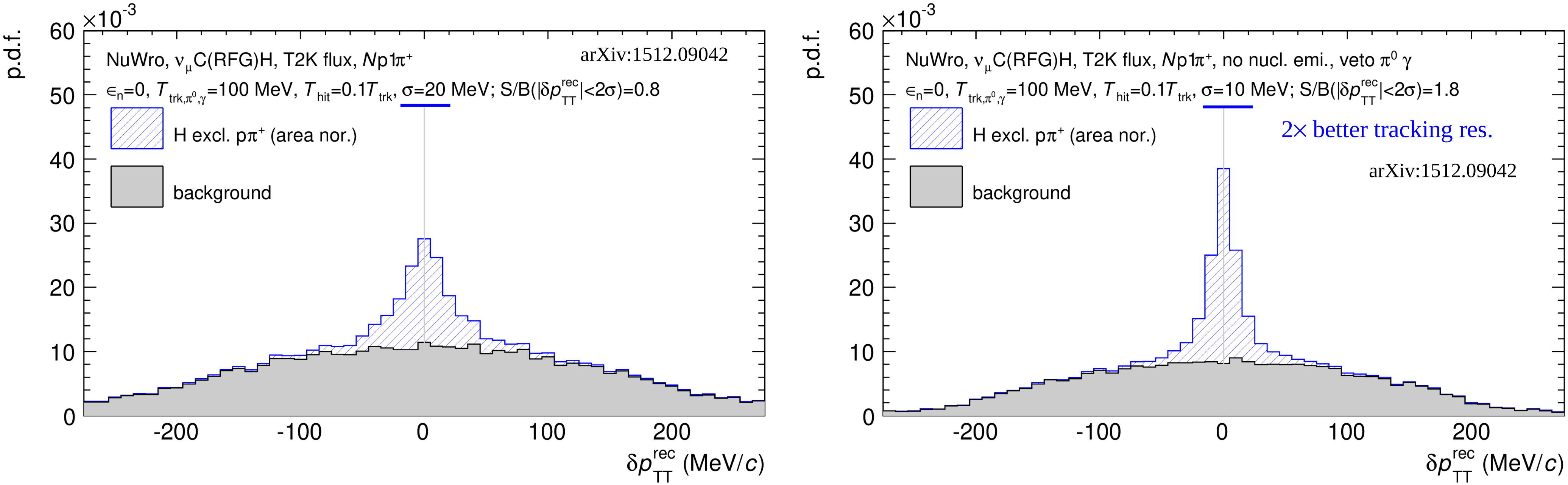
$\delta p_{TT} \equiv p^X_{TT} + p^Y_{TT}$

Double-transverse momentum imbalance δp_{TT}

- H: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion O(200 MeV) and FSI
- CH_n: νH interaction can be extracted
  - νH δp_{TT}~O(<10MeV) after detector smearing
  - νC δp_{TT}~ 200 MeV



Neutrino-Hydrogen Interactions
– Perspective



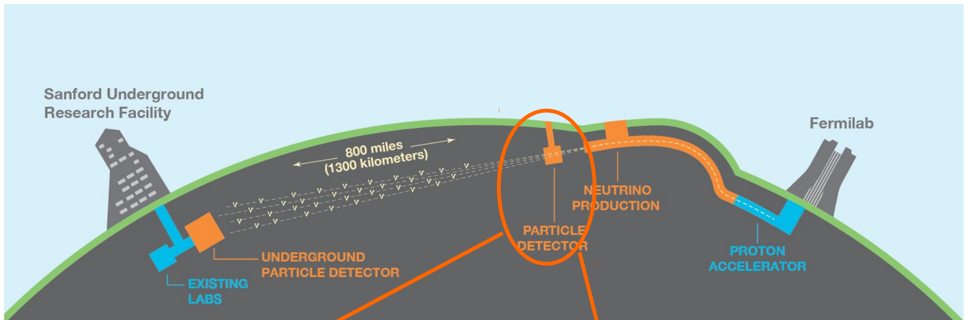
Toy simulation of T2K performance (T2K neutrino flux on CH target)

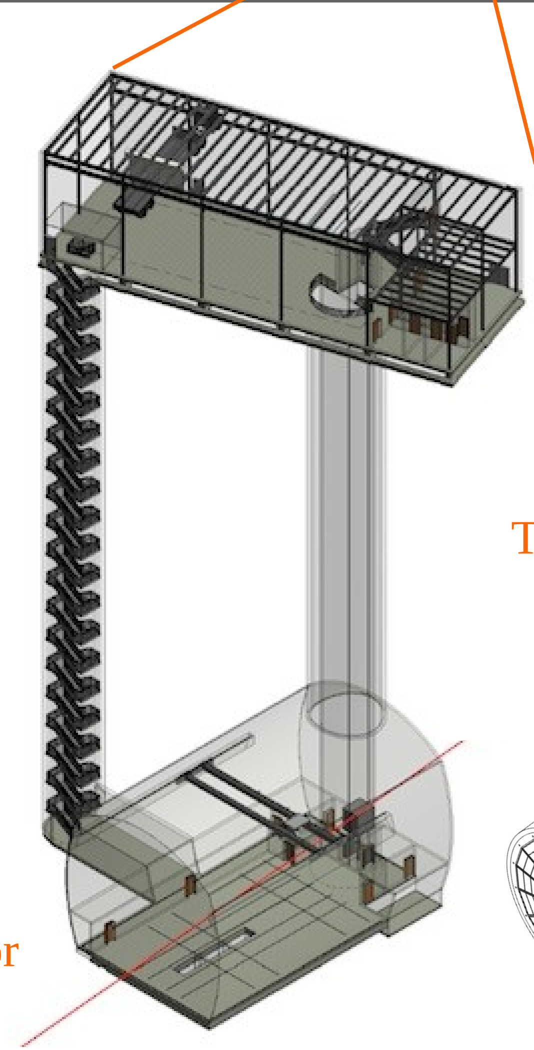
- Realistic detector resolution as T2K gas TPC (~10% at 1 GeV/c)

- When tracking resolution improves, only signal distribution gets narrower, background still wide due to Fermi motion and FSI! → Signal/background improves

Measurements on-going...Stay tuned!

Neutrino-Hydrogen Interactions – Perspective



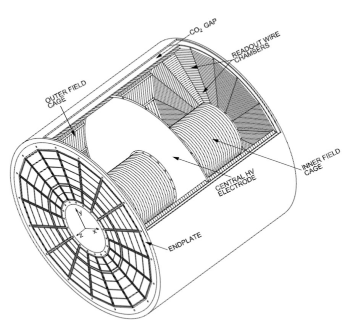


- State-of-the-art tracking resolution in gas TPC
  ALICE TPC (~1% at 1 GeV/c)

- DUNE Near Detector
  High Pressure gas TPC
  can achieve 95% νH purity with

  50% He + 50% CH_4
  or
  50% He + 50% C_2H_6

High-Pressure gas
Time Projection Chamber
(HPgTPC)
Model: ALICE TPC



DUNE
Near
Detector

Summary

1) Neutrino interaction allows measurements of oscillations
   - profound questions of the existence of cosmos
   - Nuclear effects, if not well understood, will forbid such measurements.

2) Neutrino interaction measurements: inclusive 'low-recoil' analysis and Transverse Kinematic Imbalances (TKI)
   - ν-fit 2p2h-like enhancement directly applicable to $\bar{\nu}$
   - TKI cancel nucleon-level baseline physics, remove beam energy dependence, reveal various nature of nuclear effects

3) Neutrino interaction on hydrogen needed for flux constraint and nucleon cross section input for oscillation analysis.
   - TKI (δp_{TT}) provides safe access to νH interaction.
   - DUNE Near Detector HPgTPC with δp_{TT} can achieve 95% purity with careful choice of gas mixture.

Summary

Thank you!

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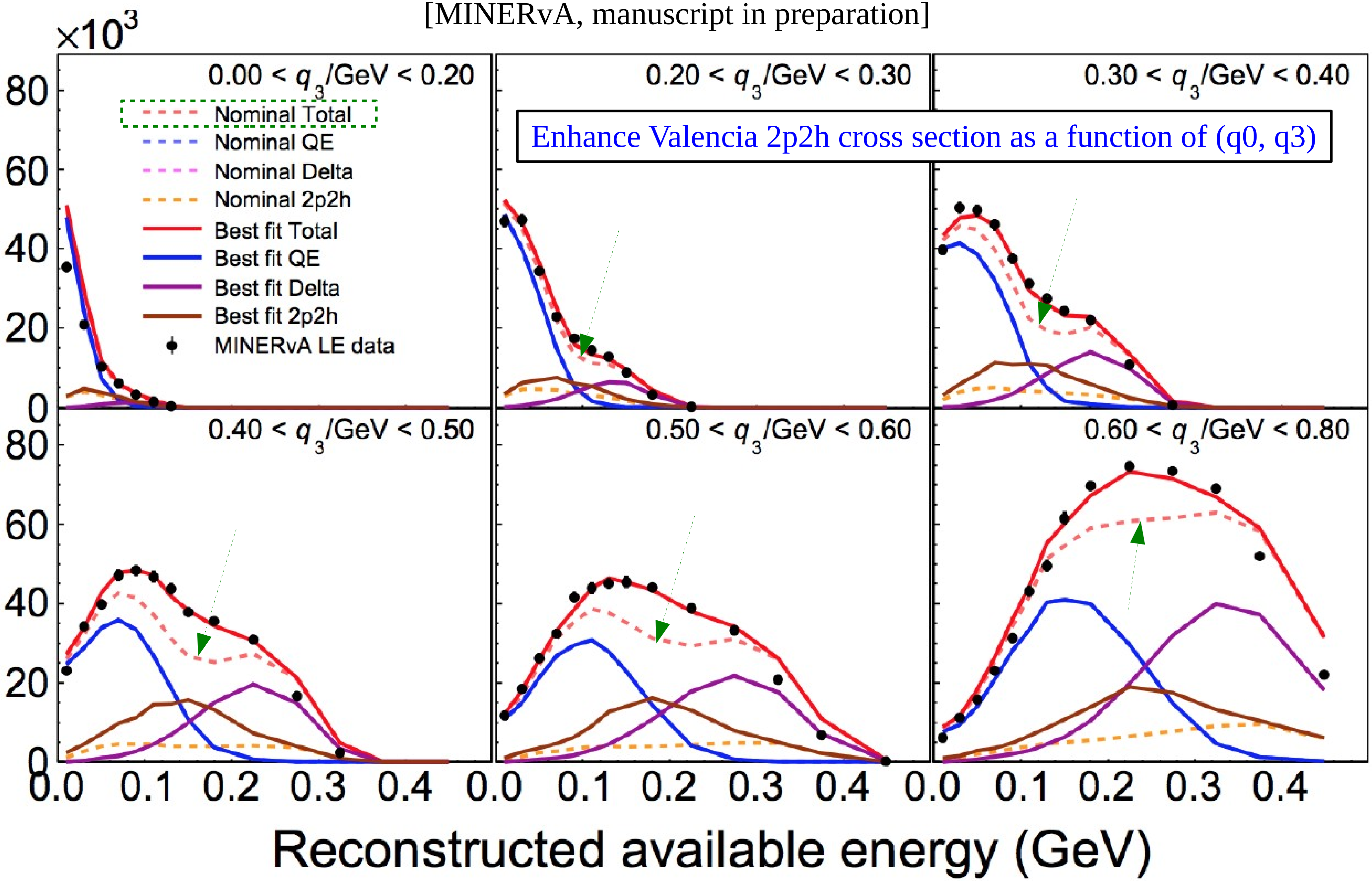
BACKUP

Low-Recoil Tune / *2p2h-like enhancement*

[MINERvA, manuscript in preparation]



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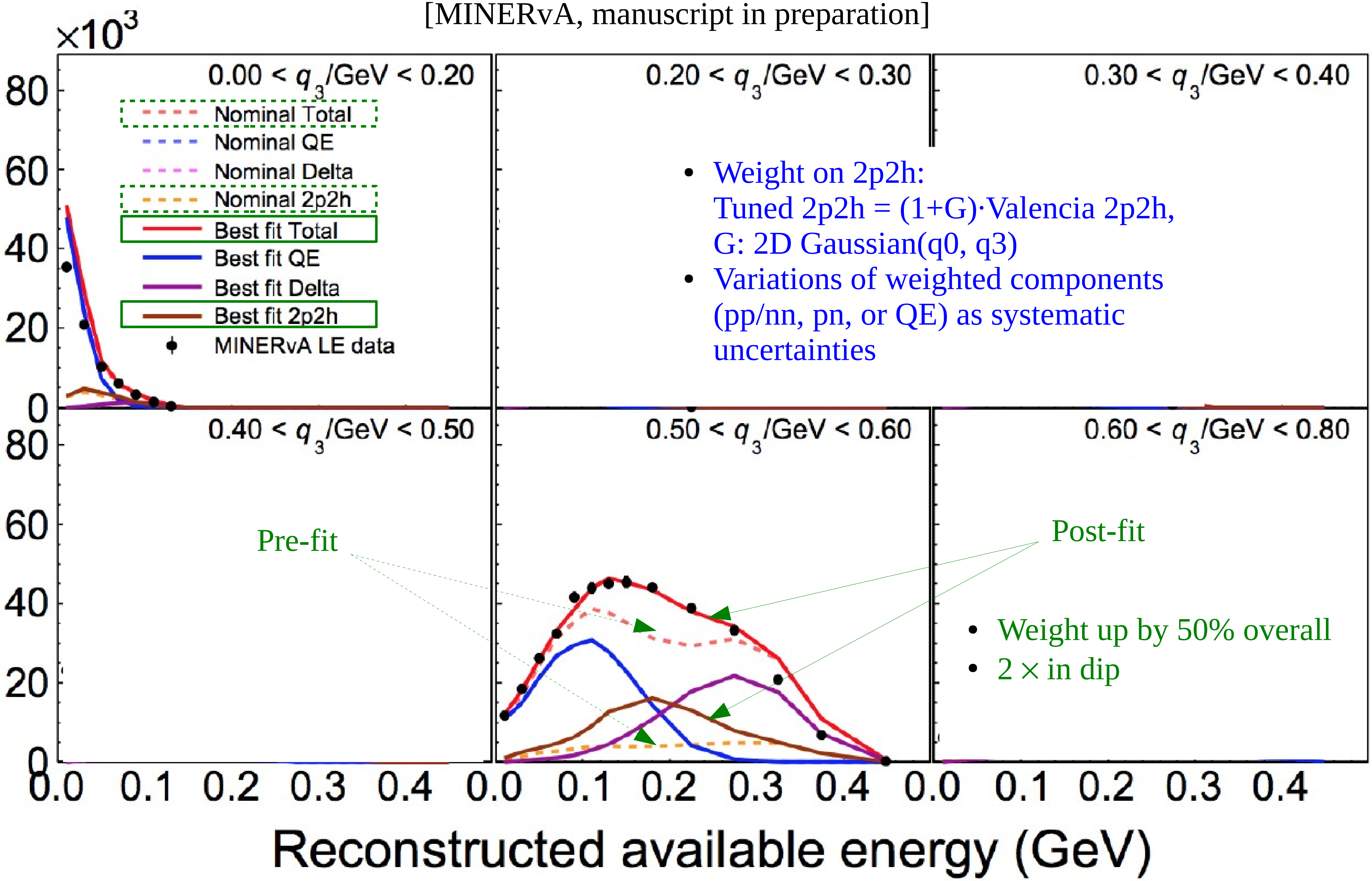
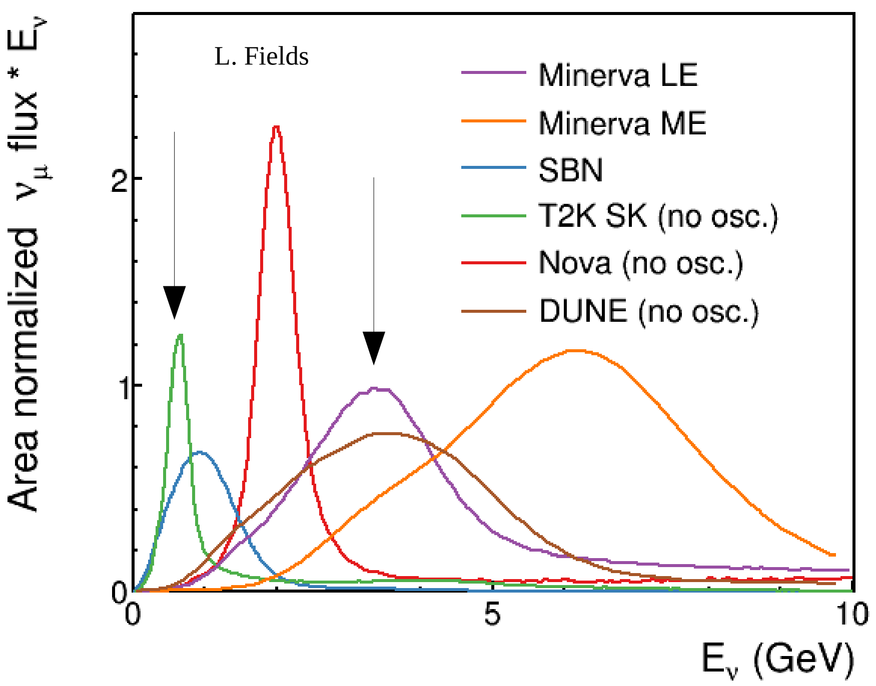


- Weight on 2p2h:
  Tuned 2p2h = (1+G)·Valencia 2p2h,
  G: 2D Gaussian(q0, q3)
- Variations of weighted components (pp/nn, pn, or QE) as systematic uncertainties

- Weight up by 50% overall
- 2 × in dip

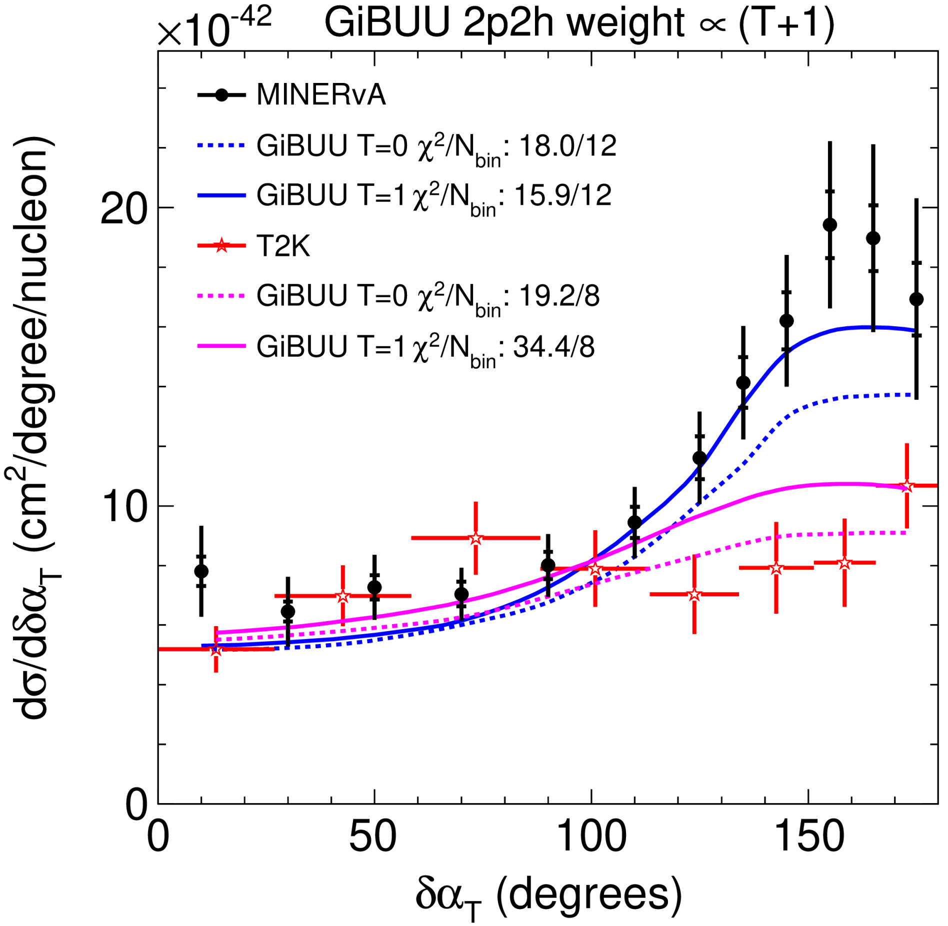


T2K neutrino beam peak at 0.6 GeV

[T2K, Phys. Rev. D 98, 032003 (2018)]

MINERvA at 3 GeV

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



- GiBUU models 2p2h events with weight (T+1), where T is nuclear isospin parameter.
- 2p2h in two model settings (T=0 and 1) at two different energies (0.6 and 3 GeV) all start at $\delta\alpha_T \rightarrow 0$ and then evolve towards $\delta\alpha_T \rightarrow 180^o$ with strong energy dependence.
- Gross feature of energy dependence confirmed by data; contradiction between preference on T at different energies indicates sub-leading order mis-modeling.

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

[Furmanski, Sobczyk, Phys.Rev. C95 (2017) 065501]

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

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

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

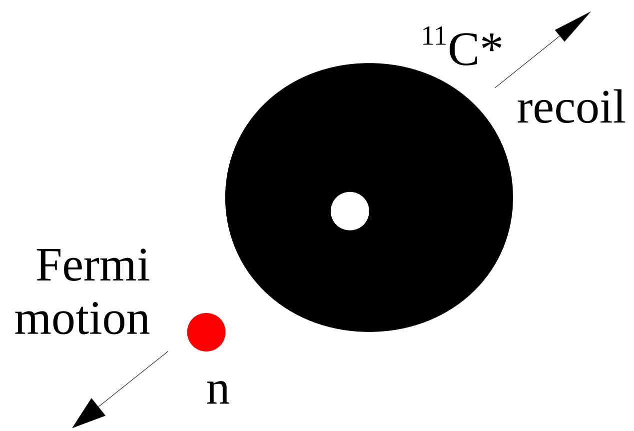
p_{n}: recoil momentum of the nuclear remnant

final-state

Dual Interpretation

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

initial-state

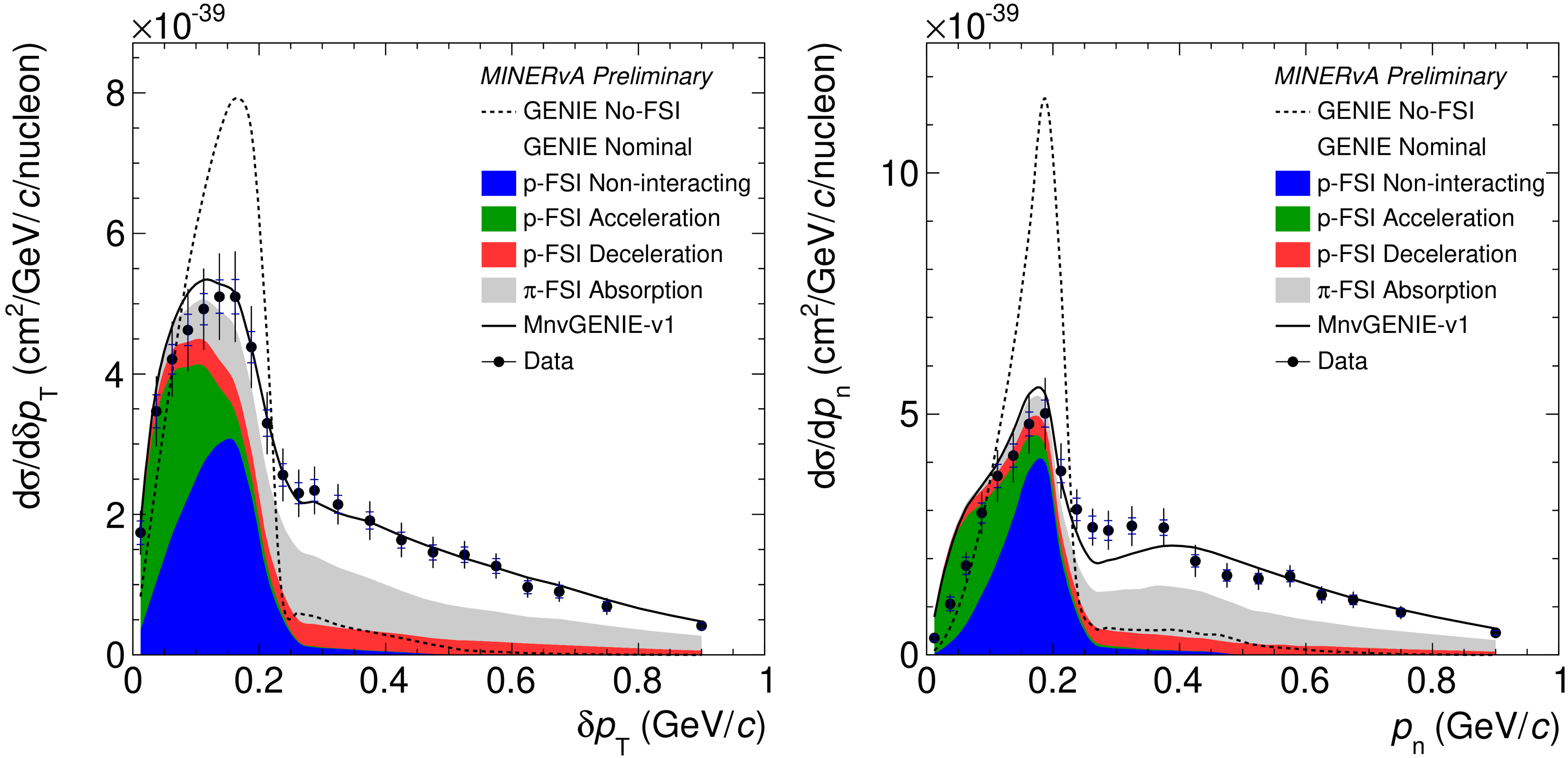


Using energy imbalance to solve longitudinal momentum imbalance [Phys. Rev. C 95, 065501 (2017)]

$\delta p_T \rightarrow p_N$

Single-TKI + p_N = **Final-State Correlations**

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



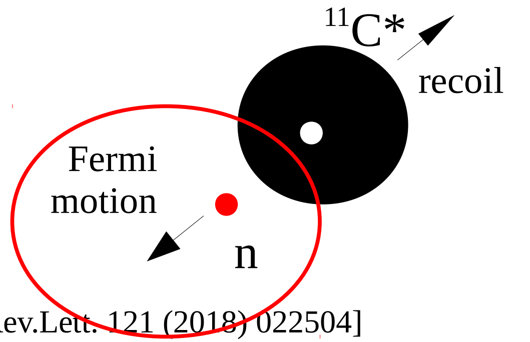
$$\delta\vec{p}_{\mathrm{T}} = \vec{p}_{\mathrm{T}}^{\,\mathrm{N}} - \Delta\vec{p}_{\mathrm{T}}$$

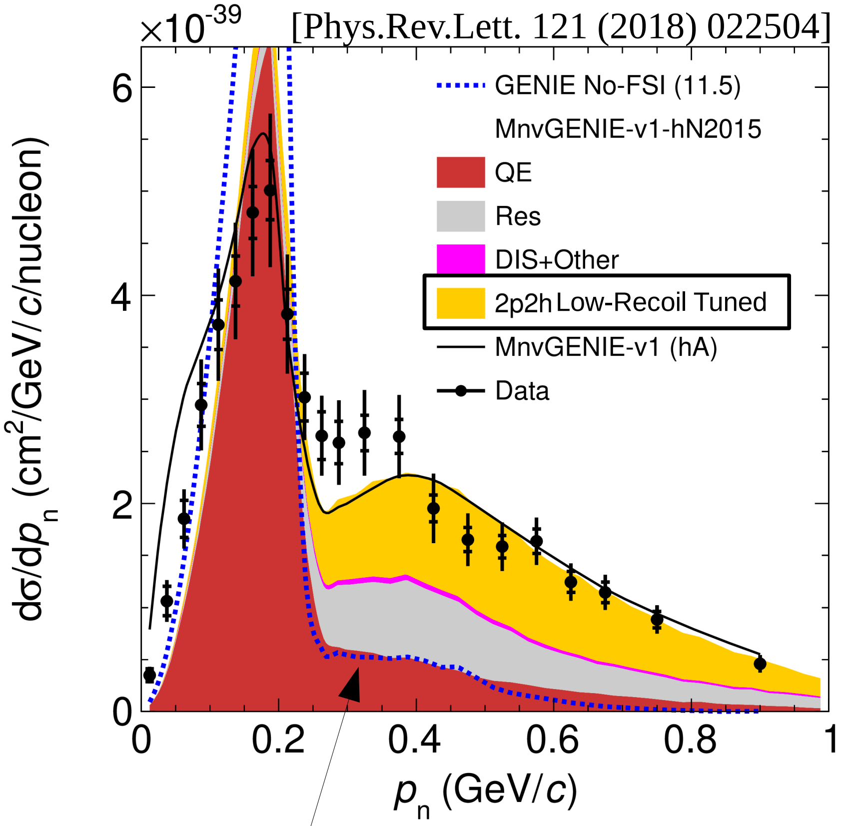
$$p_{\mathrm{n}} \equiv \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$$

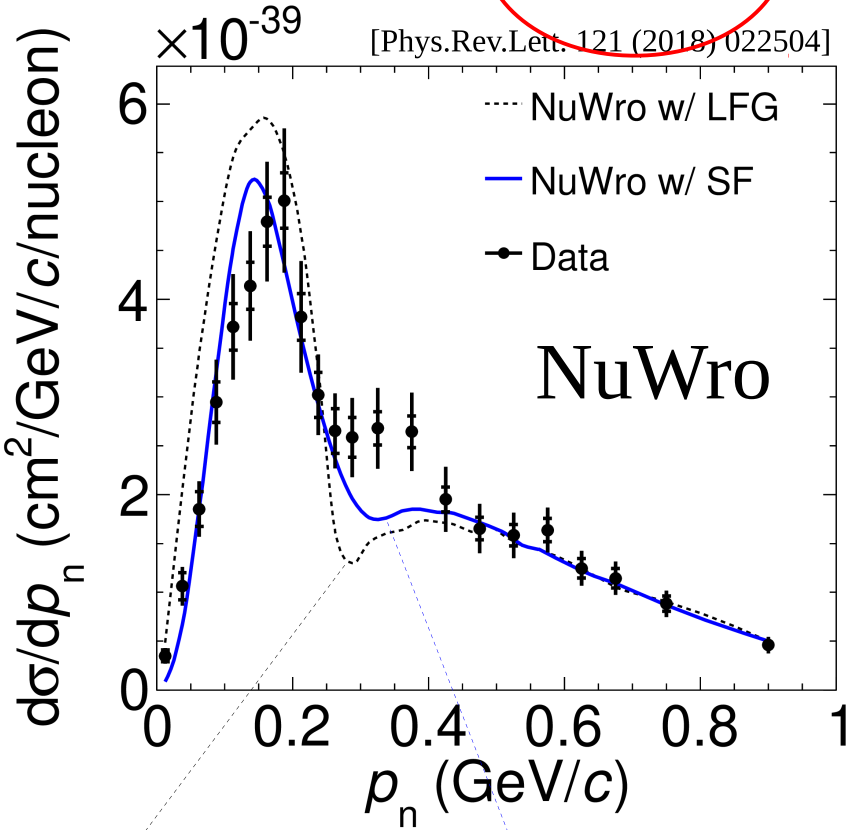
Only differ by longitudinal momentum imbalance

p_n has better physics sensitivity: 3D Fermi momentum

2p2h-like enhancement has Base-Model-dependence







Global Fermi Gas with Bodek-Ritchie tail

Local Fermi Gas

Spectral Function

- Base Model depends on 1p1h and Short Range Correlation (SRC) modeling
- Critical to separate QE and RES to reduce Base-Model-dependence

END