皮影 Shadow play

Source: http://www.cnhubei.com/ztmjys-pyts

Neutrino Shadow Play

Xianguo LU/ 卢显国   University of Oxford

Particle Physics Seminar, University of Liverpool

Liverpool 22 Mar 2017

Outline

1. Understanding matter-antimatter asymmetry with neutrinos
2. Nuclear effects in neutrino-nucleus interactions
3. Measuring neutrino interactions
4. A neutrino shadow play

    Act One: Neutrino energy independent measurement of nuclear effects

    Act Two: Nuclear effect independent measurement of neutrino energy spectra

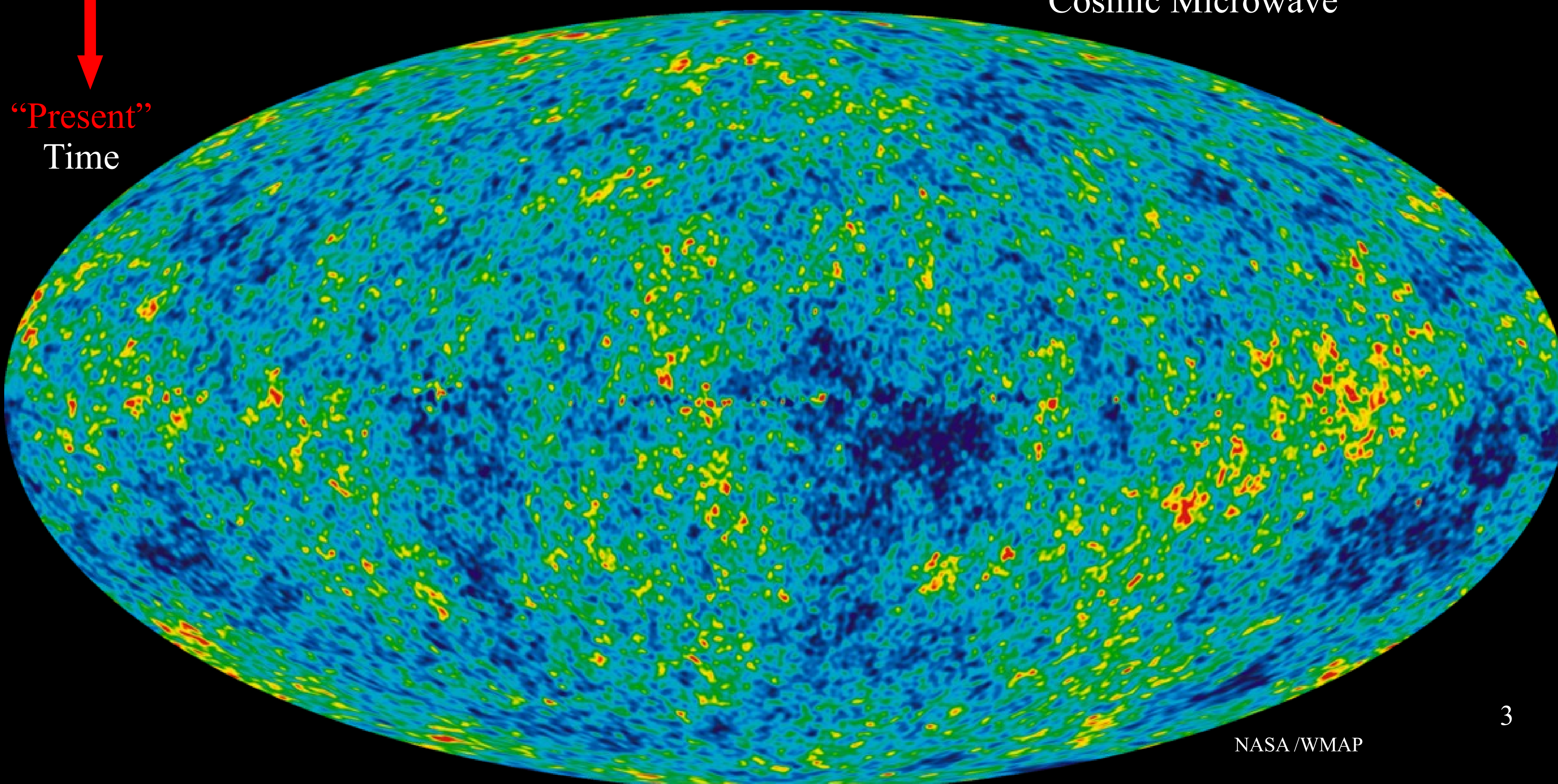
5. Summary

Early Universe

“Present”
Time

Matter-antimatter symmetric

Cosmic Microwave



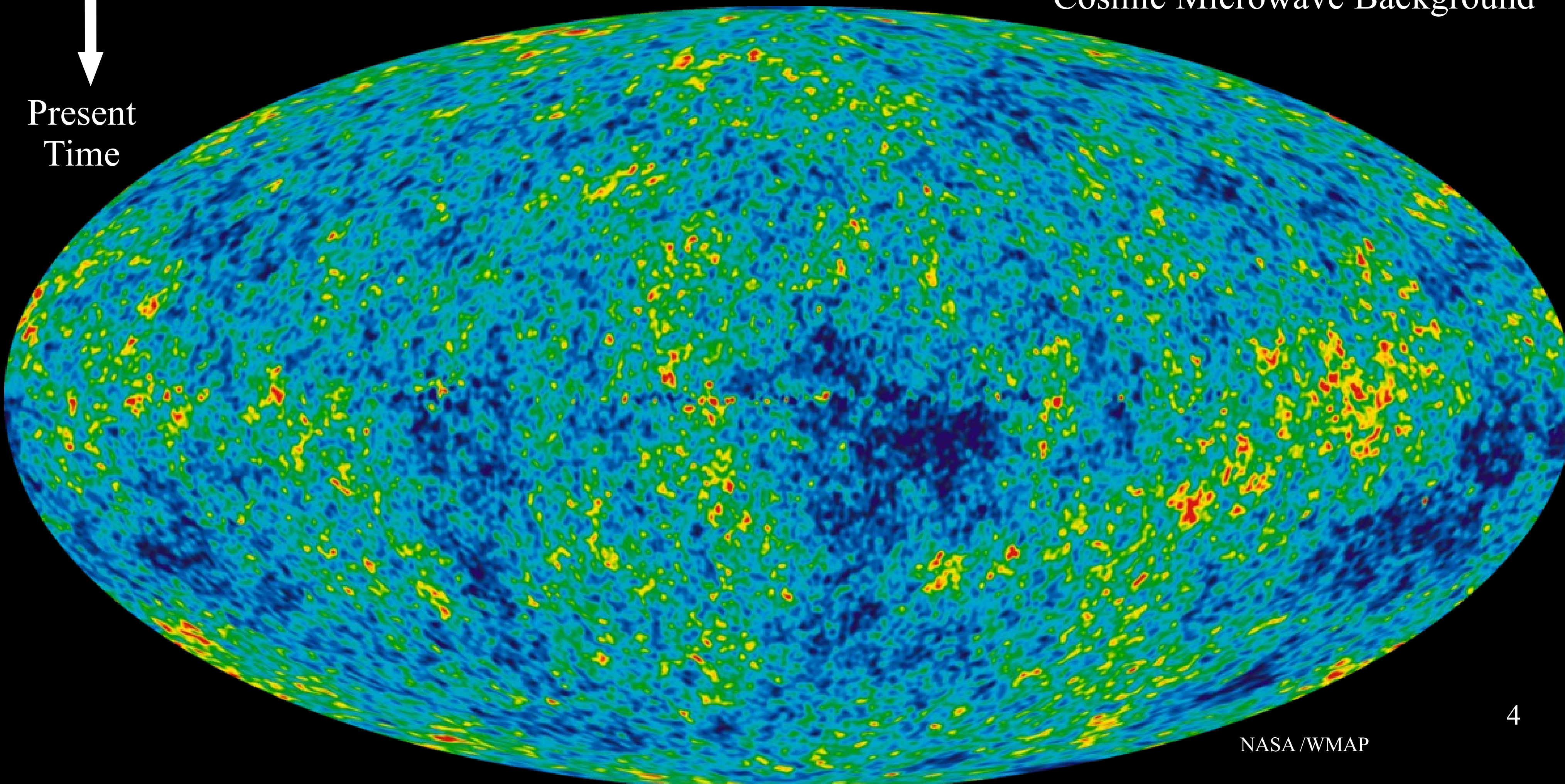
NASA /WMAP

Early Universe

Present Time

Matter-antimatter asymmetric

Cosmic Microwave Background



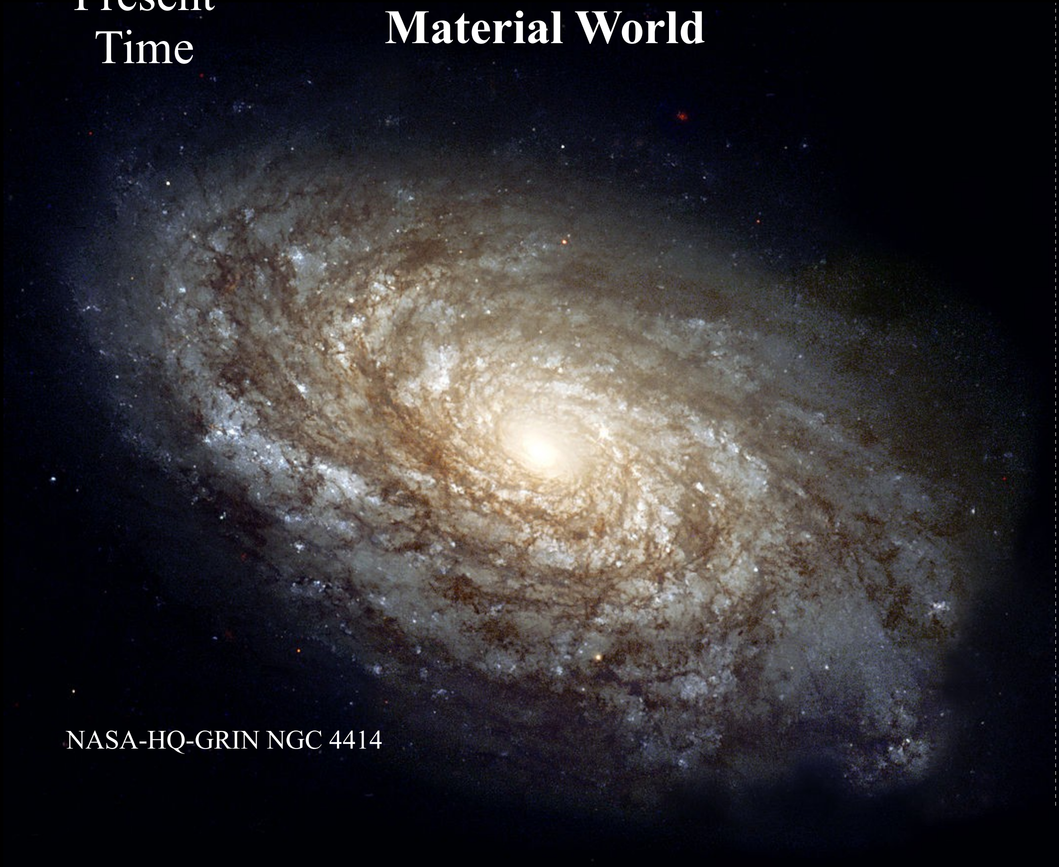
NASA /WMAP

Early Universe

Matter-antimatter asymmetric

Present
Time

Material World



Antimaterial World

Early Universe

Present Time


planetxnews.com

Matter-antimatter asymmetric

Sakharov Conditions:

Baryon number violation

C- and CP-symmetry Violation (CPV)

Interactions out of thermal equilibrium

Material World

Antimaterial World


NASA-HQ-GRIN NGC 4414

Early Universe

Present Time

Matter-antimatter asymmetric

Sakharov Conditions:

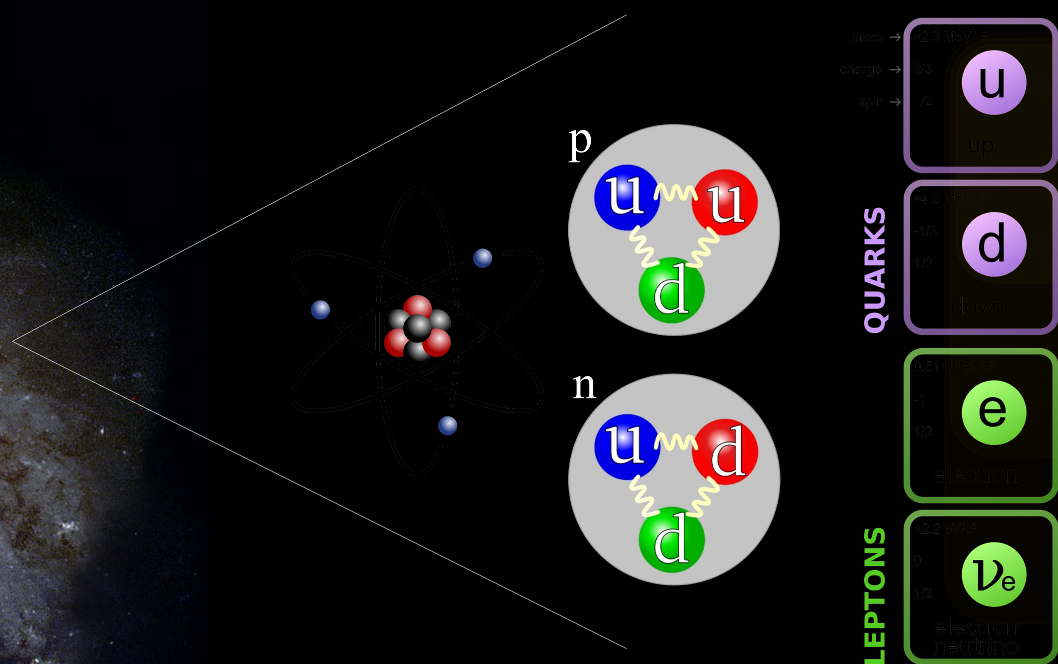
Baryon number violation

C- and CP-symmetry Violation (CPV)

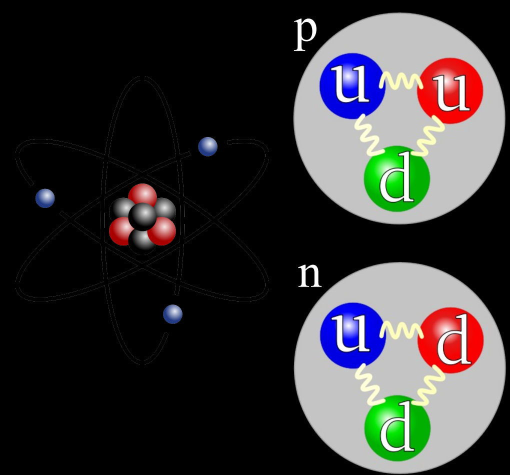
Interactions out of thermal equilibrium

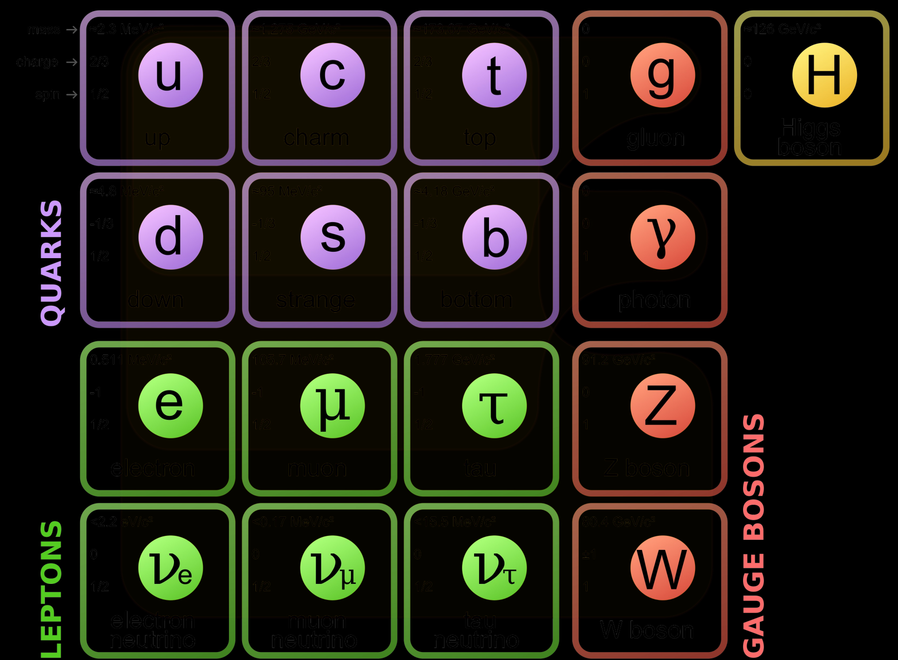
Material World

NASA-HQ-GRIN NGC 4414



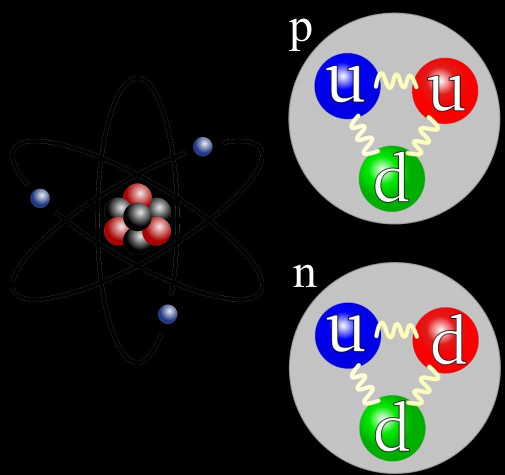
By Rainer Klute/Arpad Horvath/MissMJ FNAL

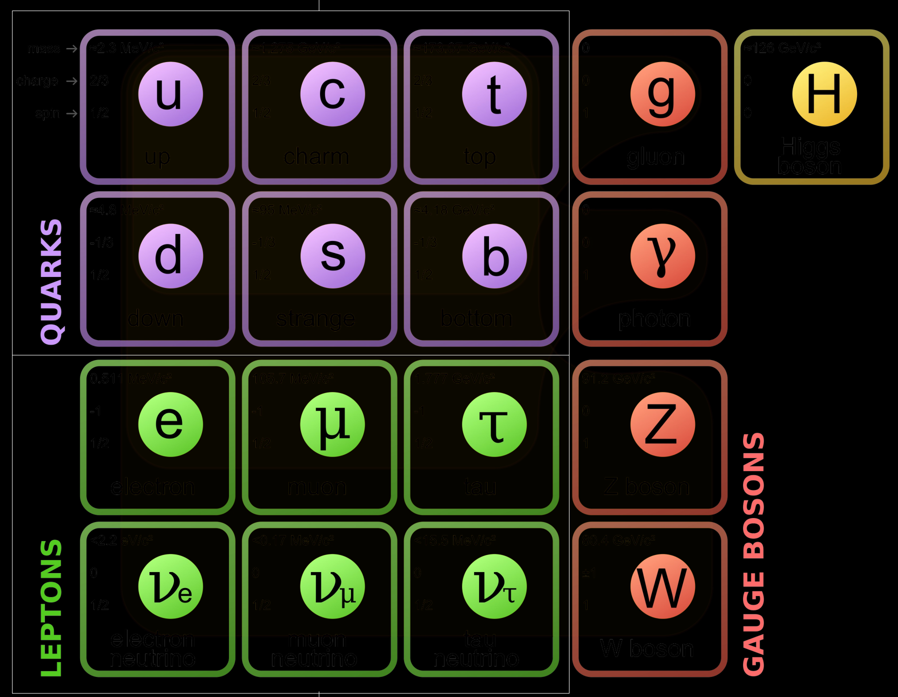




By Rainer Klute/Arpad Horvath/MissMJ FNAL

Quarkonic CPV insufficient



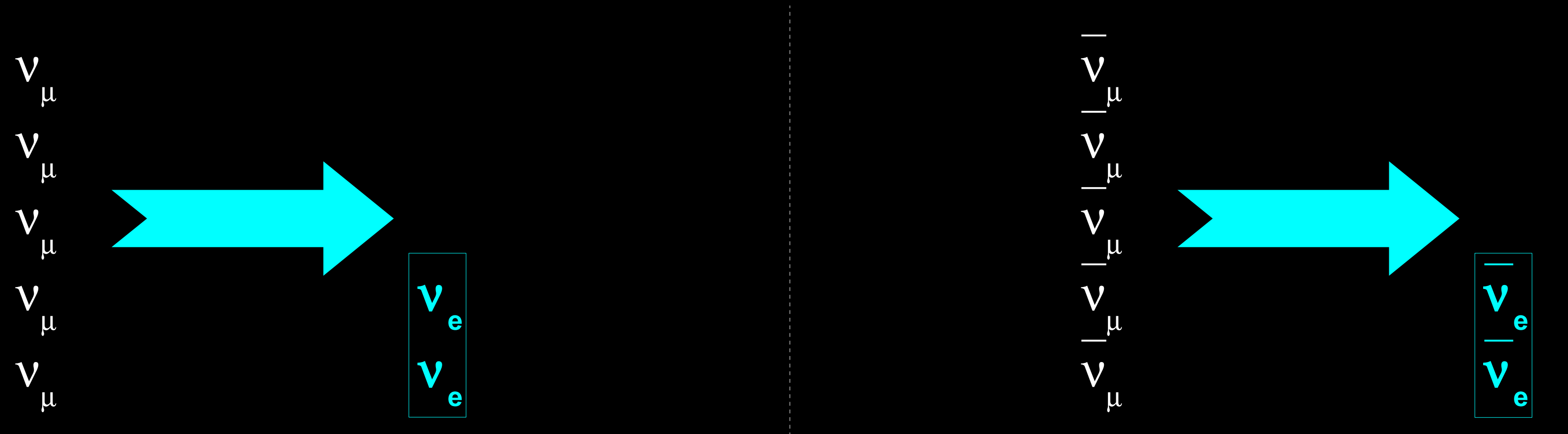


By Rainer Klute/Arpad Horvath/MissMJ FNAL

Leptonic CPV (LCPV) *unknown*

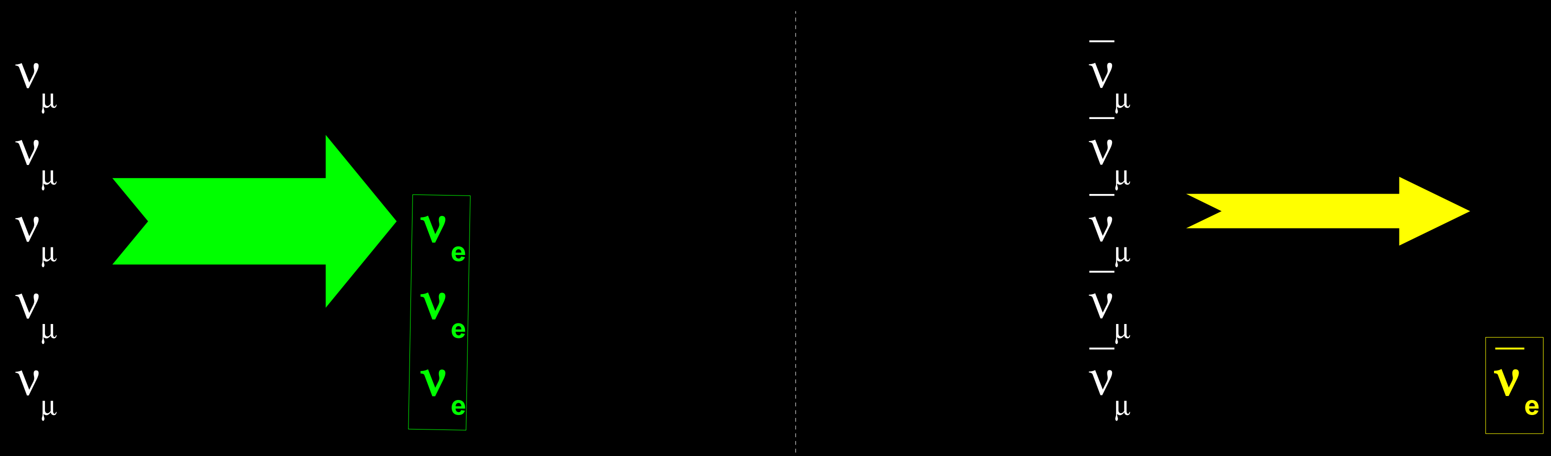
Material World **Antimaterial World**

Leptonic CP Symmetry



*no matter effect

LCPV



Neutrino Oscillations

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

Pontecorvo–Maki–Nakagawa–Sakata

PMNS matrix

Neutrino Oscillations

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

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

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{12} \neq 0$

Neutrino Oscillations

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

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

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$\theta_{23} \neq 0$

$\theta_{12} \neq 0$

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

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PMNS matrix

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

$\theta_{ij} \neq 0$, δ_{CP}-phase irreducible → leptonic CP violation

Neutrino Oscillations

Neutrino (flavor) oscillations depend on mixing angles, δ_{CP}-phase and mass differences.

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

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

PMNS matrix

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

$\theta_{ij} \neq 0$, δ_{CP}-phase irreducible → leptonic CP violation

With a ν_μ beam

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

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{32}$$

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

"CP-odd term"

Neutrino Oscillations

Neutrino (flavor) oscillations depend on mixing angles, δ_{CP}-phase and mass differences.

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

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

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$\theta_{ij} \neq 0$, δ_{CP}-phase irreducible → leptonic CP violation

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

flip sign

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

$P(\bar{\nu}_\mu \to \bar{\nu}_\mu) = P(\nu_\mu \to \nu_\mu)$ by CPT symmetry

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

CP-odd term in appearance channels allow extraction of δ_{CP} using neutrino and anti-neutrino beams

Neutrino Oscillations

Neutrino (flavor) oscillations depend on mixing angles, δ_{CP}-phase and mass differences.

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

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$\theta_{ij} \neq 0$, δ_{CP}-phase irreducible → leptonic CP violation

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

flip sign

solar + KamLAND *et al.*

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

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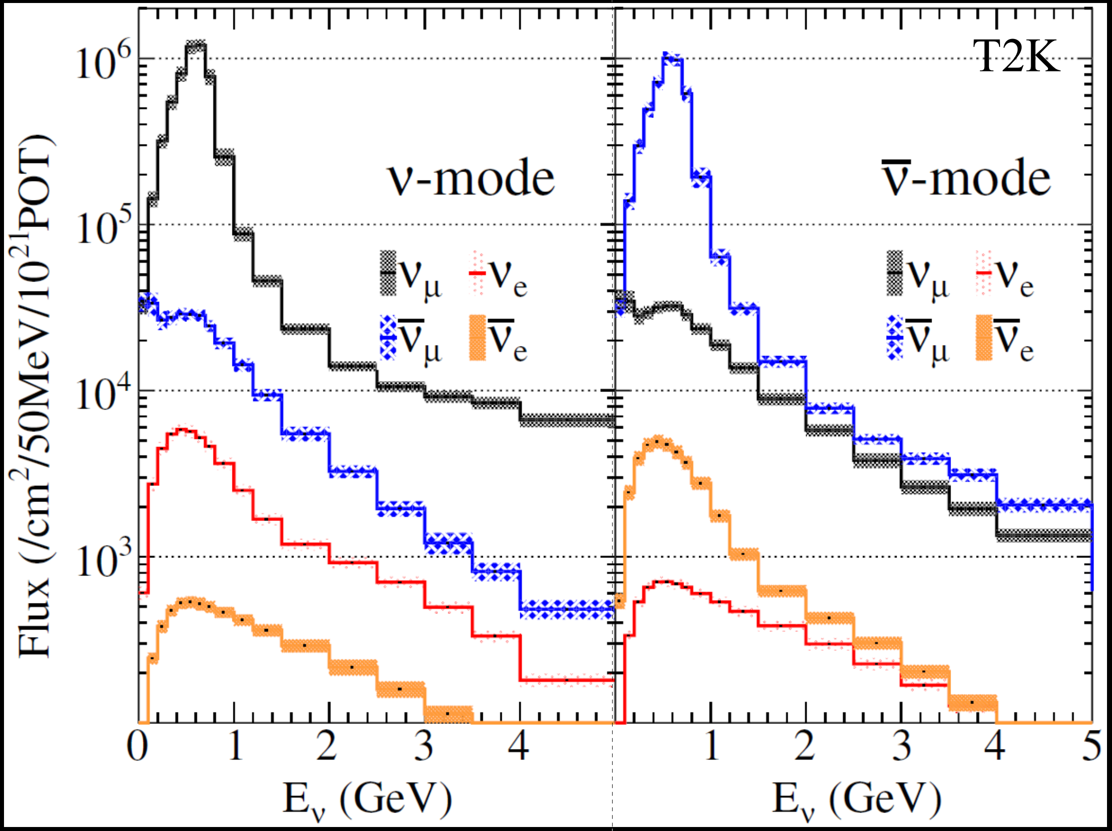
$$\Delta_{ij} \equiv \frac{\Delta m^2_{ij} L}{4E}$$

CP-odd term in appearance channels allow extraction of δ_{CP} using neutrino and anti-neutrino beams – unique opportunities with accelerator neutrinos

Material World **Antimaterial World**

Accelerator

ν_μ $\bar{\nu}_\mu$



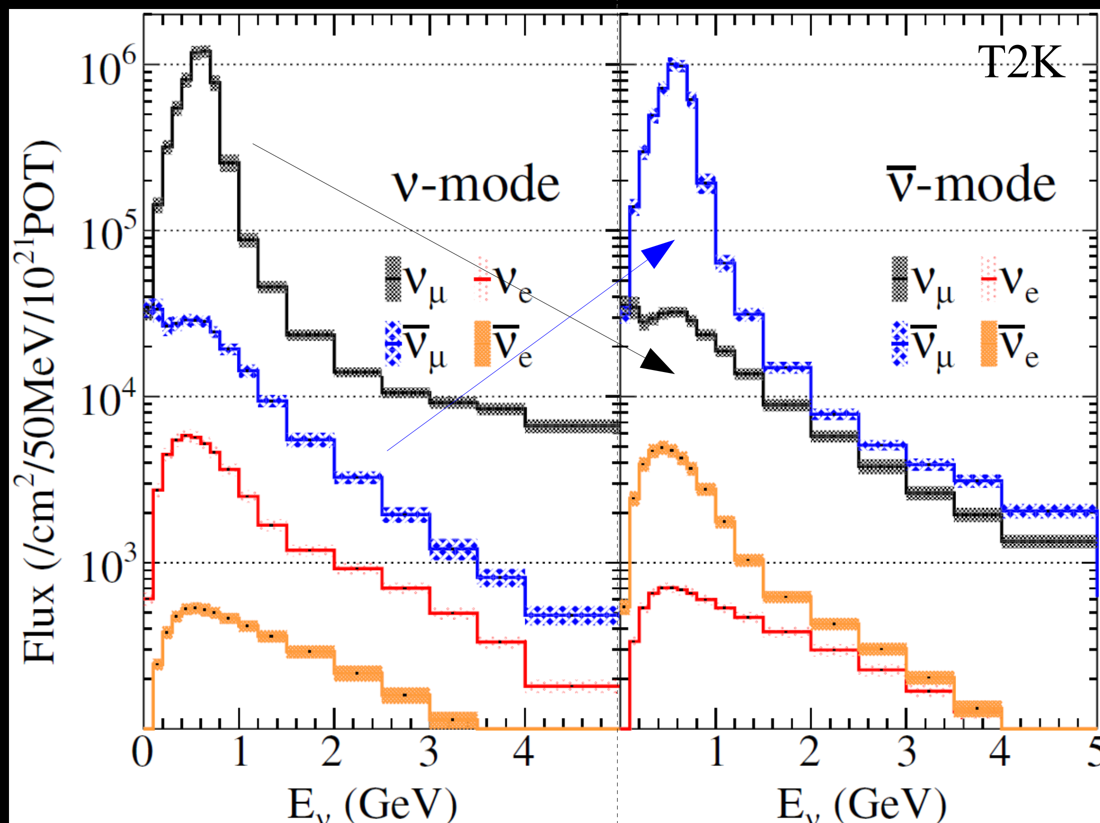
Phys.Rev.Lett. 116 (2016) no.18, 181801

Material World **Antimaterial World**

Accelerator

ν_μ

$\bar{\nu}_\mu$



Phys.Rev.Lett. 116 (2016) no.18, 181801

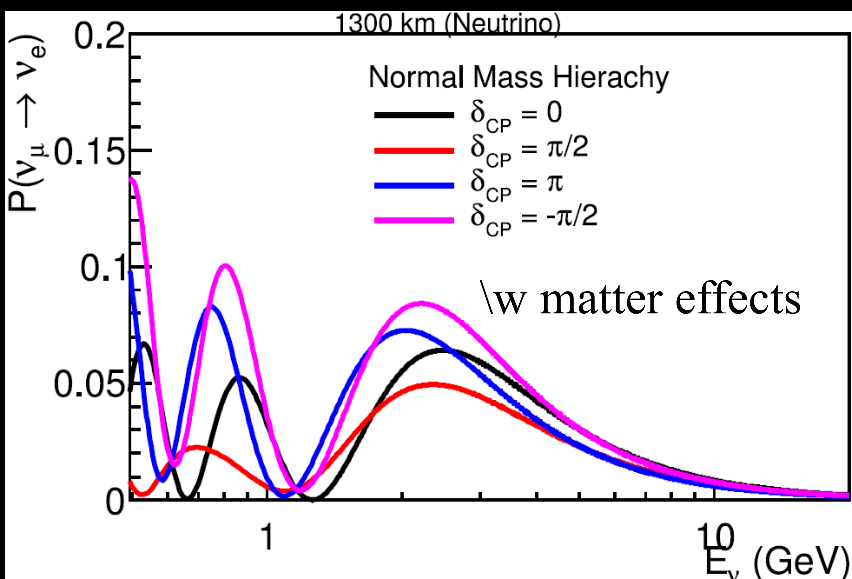
Material World

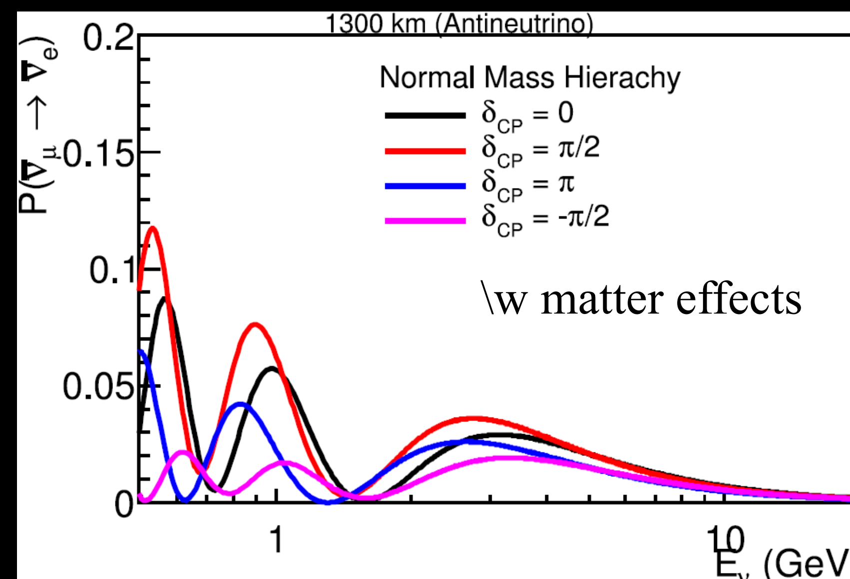
Antimaterial World

Accelerator

ν_μ → $P(\nu_\mu \to \nu_e, E_\nu)$ → ν_e

$\bar{\nu}_\mu$ → $P(\bar{\nu}_\mu \to \bar{\nu}_e, E_{\bar{\nu}})$ → $\bar{\nu}_e$

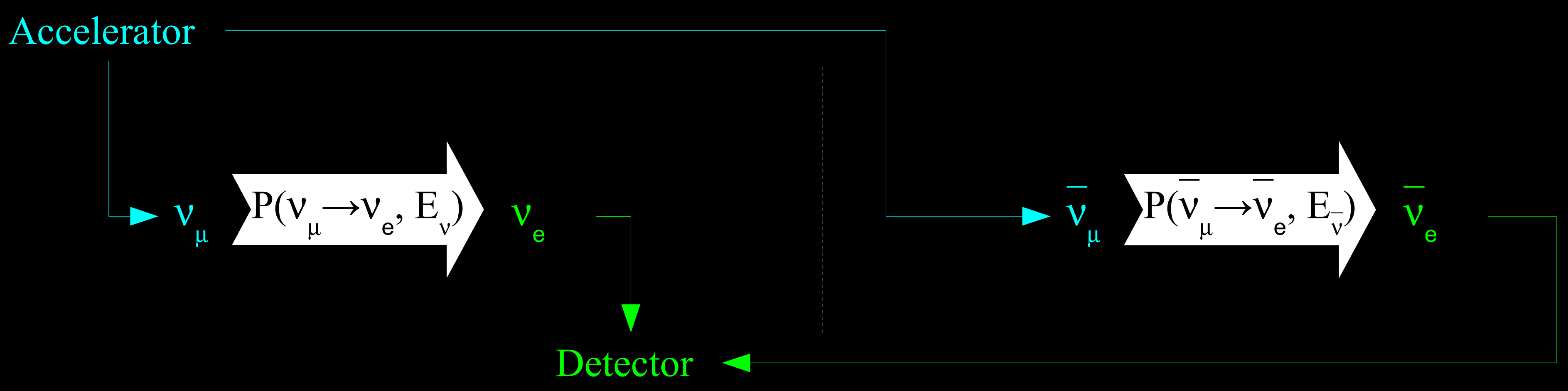


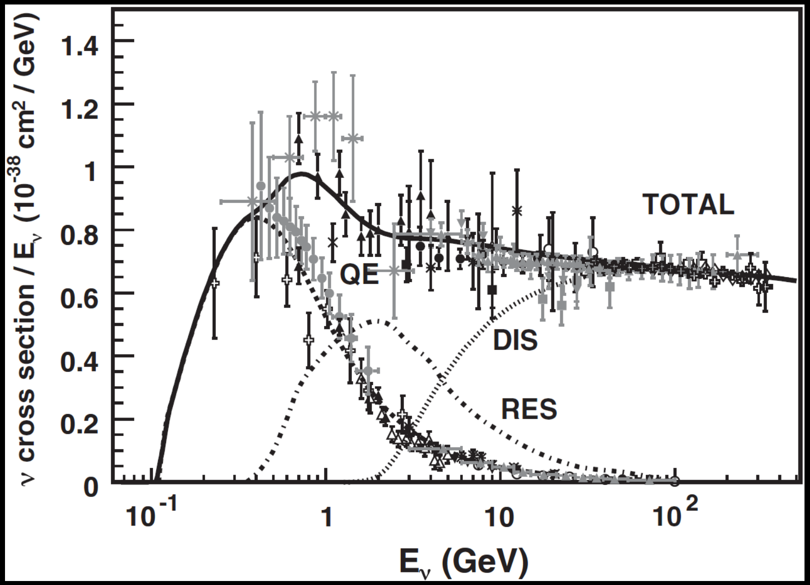


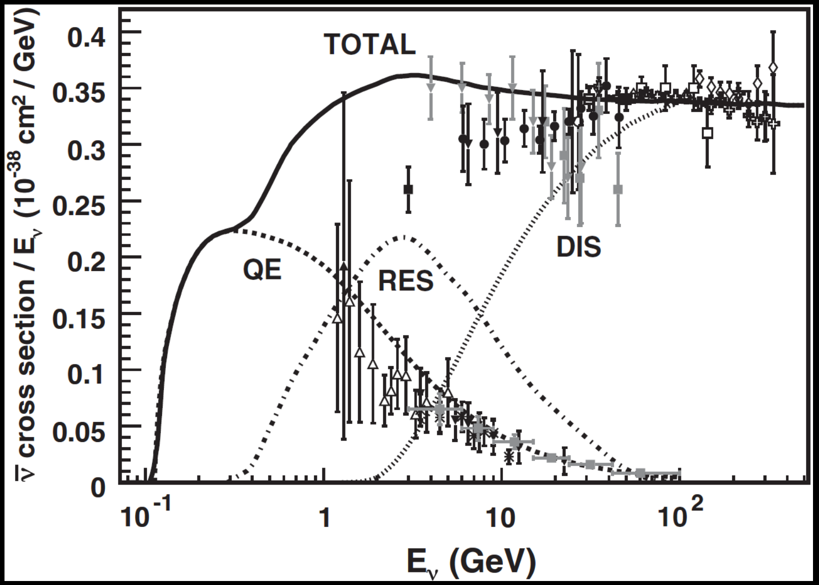
Prog.Part.Nucl.Phys. 83 (2015) 1-30

Material World

Antimaterial World





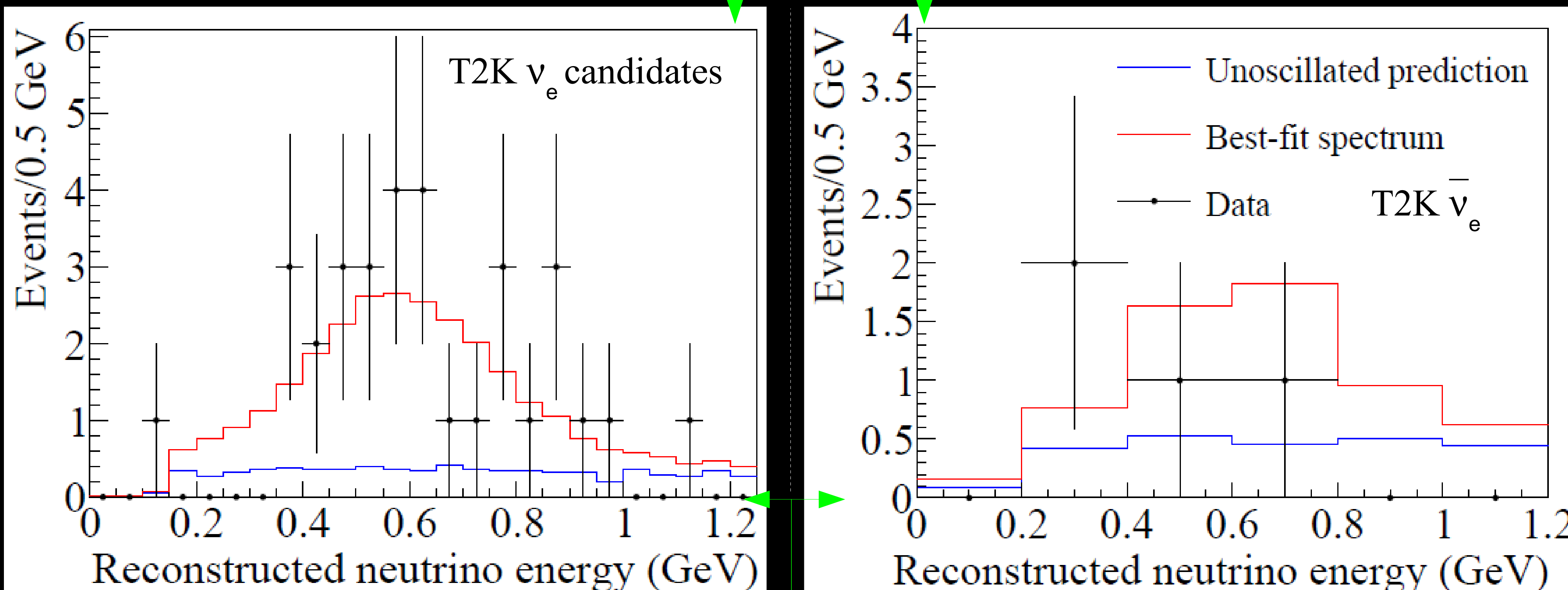


Rev.Mod.Phys. 84 (2012) 1307

Material World **Antimaterial World**

Convert to flux
via
cross section measurement

$P(\nu_\mu \rightarrow \nu_e, E_\nu)$ $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e, E_{\bar{\nu}})$



arXiv:1701.00432

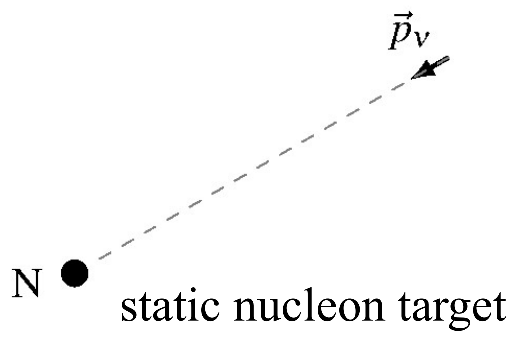
Neutrino energy reconstruction

Outline

1. Understanding matter-antimatter asymmetry with neutrinos
2. Nuclear effects in neutrino-nucleus interactions
3. Measuring neutrino interactions
4. A neutrino shadow play

   Act One: Neutrino energy independent measurement of nuclear effects

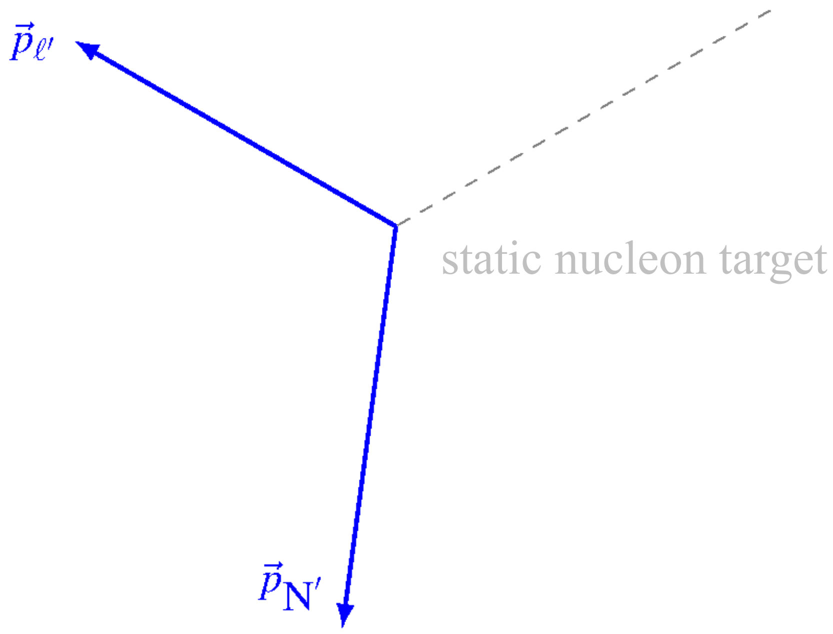
   Act Two: Nuclear effect independent measurement of neutrino energy spectra
5. Summary


$\vec{p}_\nu$
N
static nucleon target

Quasi-elastic scattering (QE)

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

charged current (CC) ν → *l′*



quasi-elastic (QE) N → N'

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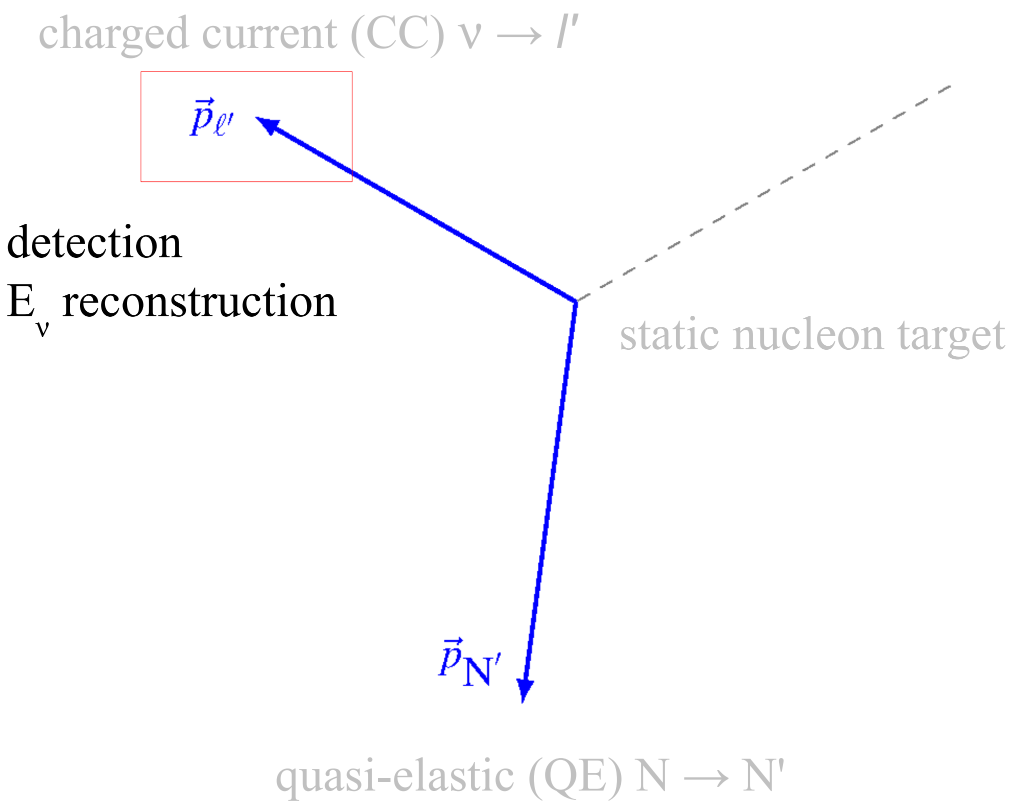
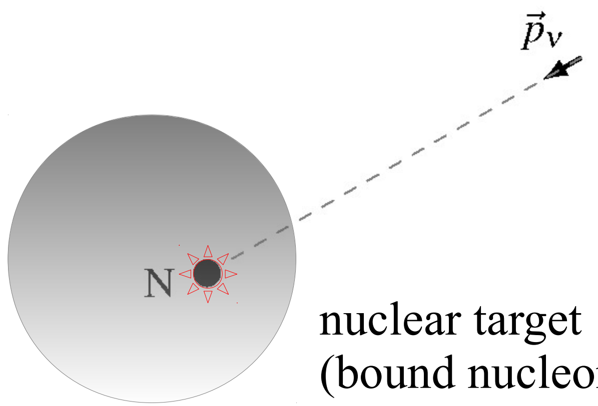


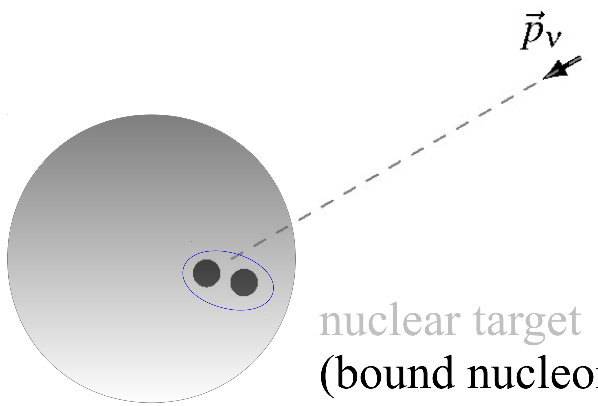
Fermi motion (FM) biases E_ν reconstruction



nuclear target
(bound nucleon)

Fermi motion (FM) biases E_ν reconstruction

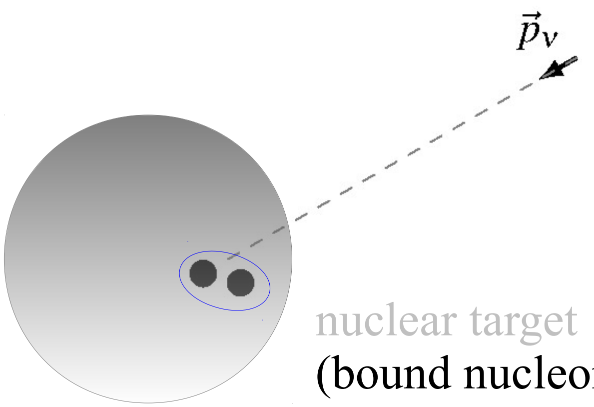
Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics



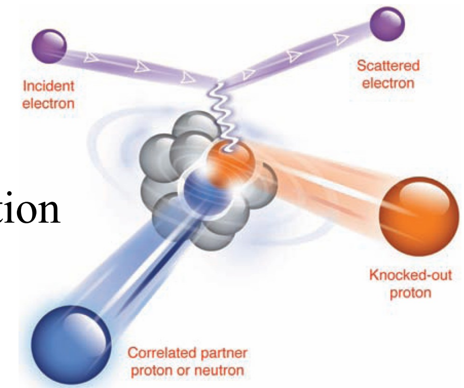
- Impulse approximation: independent particles
- In particle-hole excitation:
  - RPA (random phase approximation): sum of 1p1h excitation (over all pairs) ~ ground state correlations (long range)
  - npnh (n≥2): sub-leading terms in ph expansion ~ multinucleon correlations (short range)

Fermi motion (FM) biases E_ν reconstruction

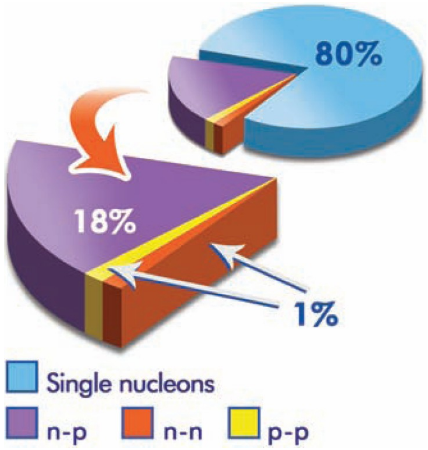
Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics



initial correlation
large relative motion



Science 320 (2008) 1476-1478



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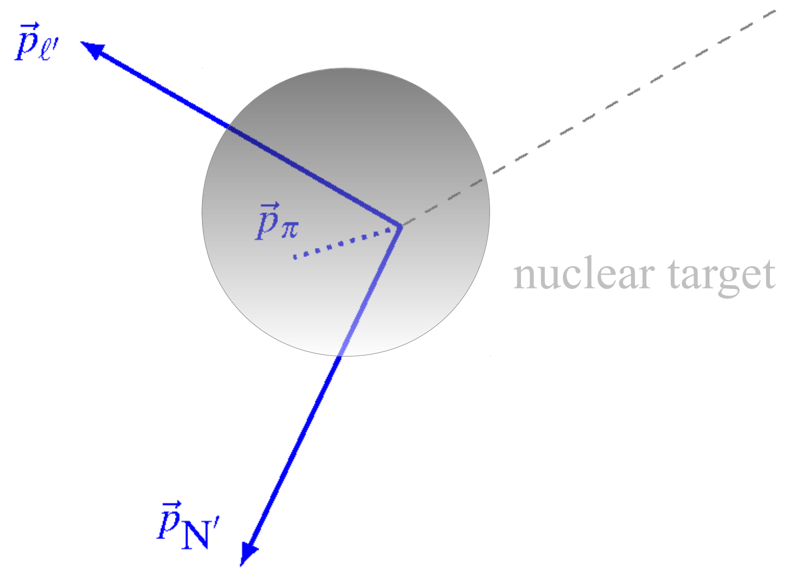
QE-like: π absorbed in nucleus ← final-state interaction (FSI)

charged current (CC) ν → *l'*



Resonance production (RES)

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

QE-like N → N'
including resonance production (RES) Δ → N'π followed by π absorption

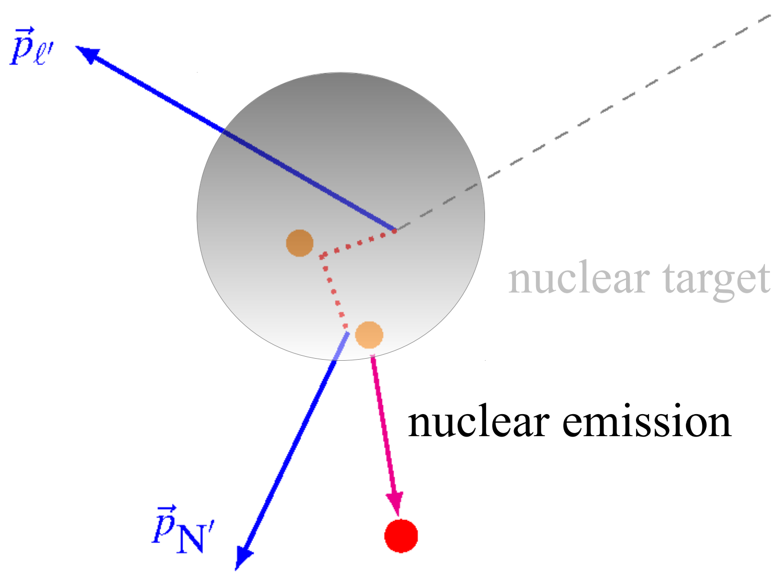
Fermi motion (FM) biases E_ν reconstruction

Multinucleon correlations:
cross section unknown, strong bias to *all* final-state kinematics

QE-like: π absorbed in nucleus ← final-state interaction (FSI)

FSI → energy-momentum transferred in nucleus, possible nuclear emission

charged current (CC) ν → *l′*



QE-like N → N'
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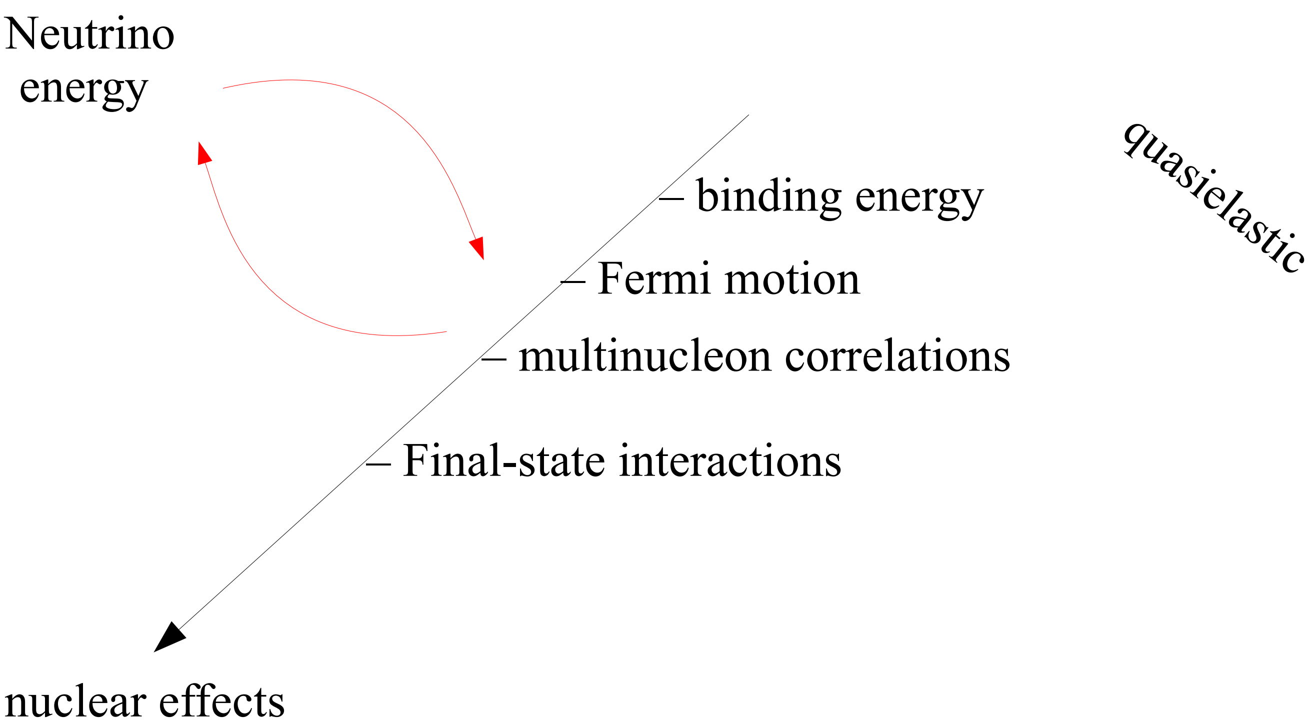
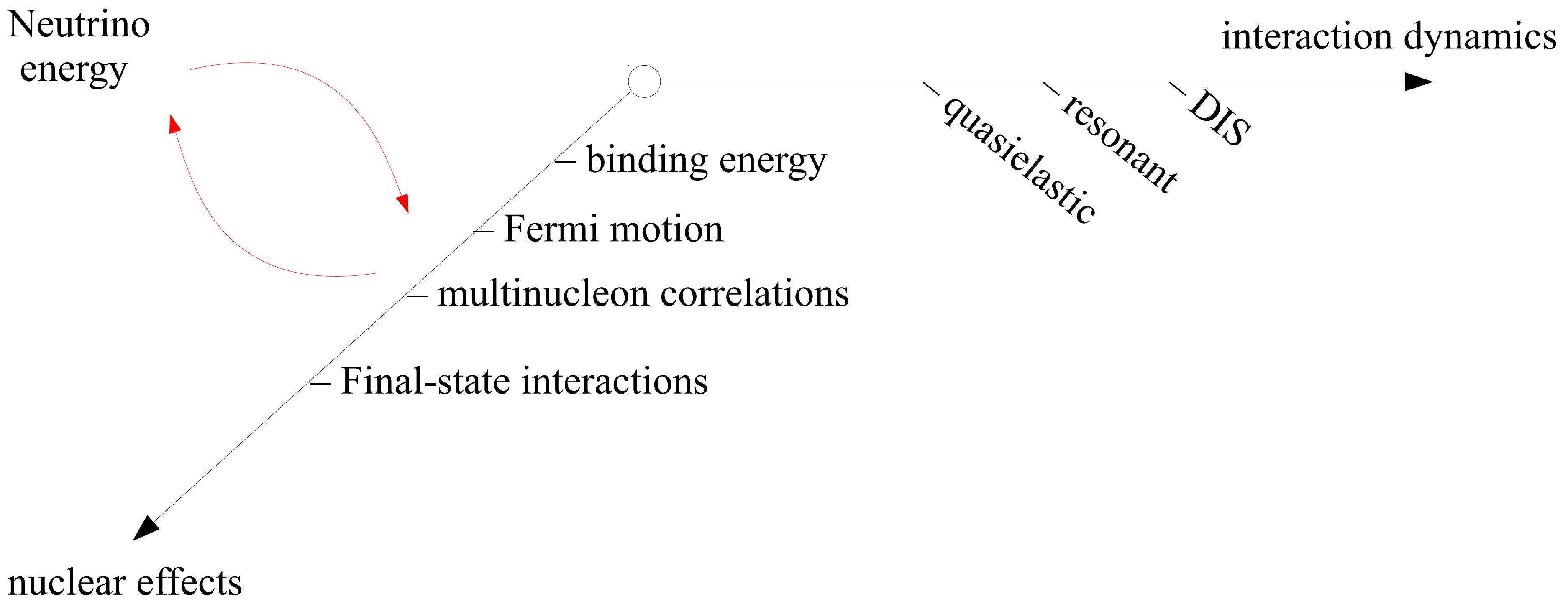
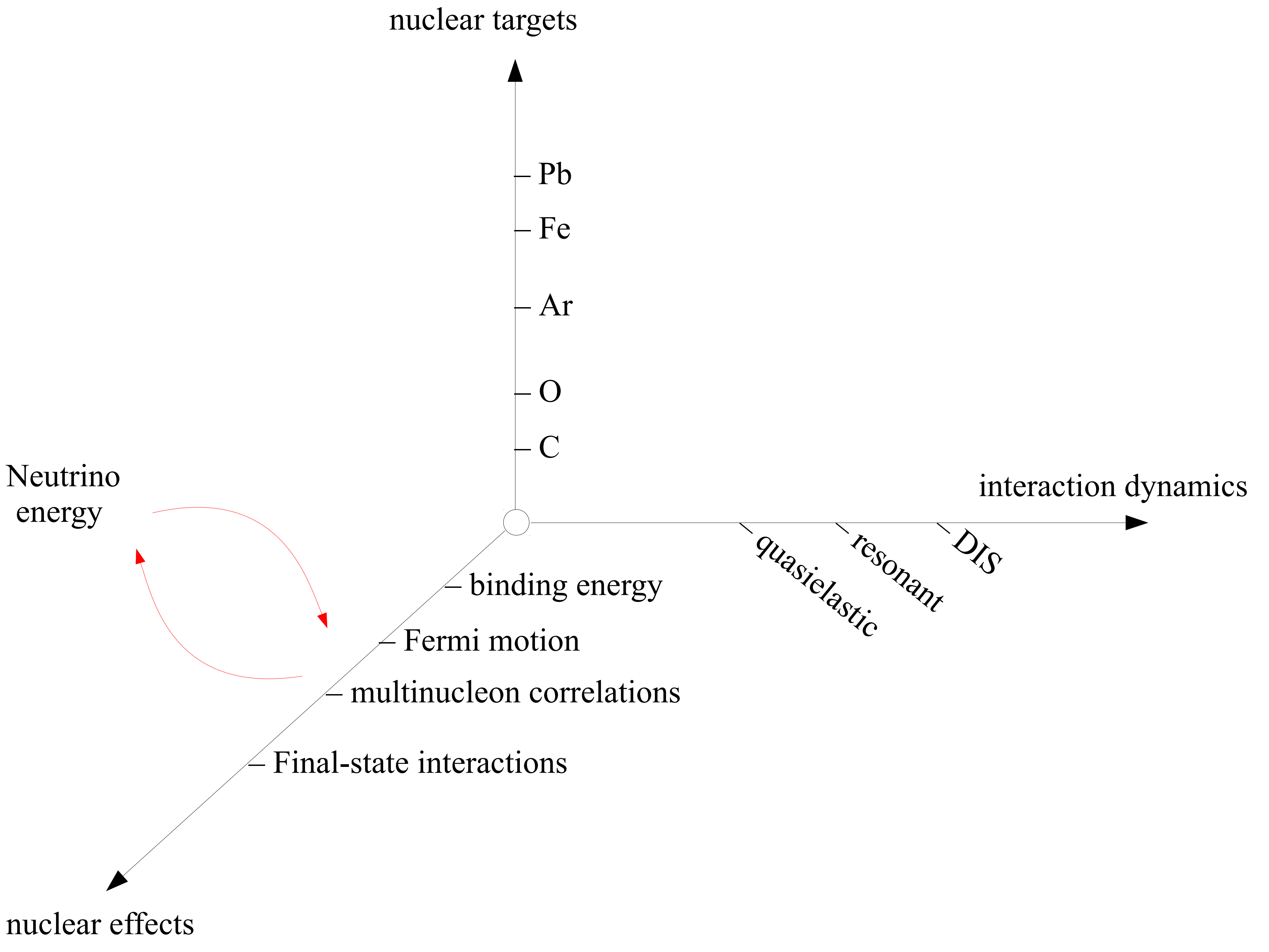

Neutrino energy
quasielastic
– binding energy
– Fermi motion
– multinucleon correlations
– Final-state interactions
nuclear effects


Neutrino
energy
interaction dynamics
quasielastic
resonant
DIS
binding energy
Fermi motion
multinucleon correlations
Final-state interactions
nuclear effects


nuclear targets
Pb
Fe
Ar
O
C
Neutrino energy
interaction dynamics
quasielastic
resonant
DIS
binding energy
Fermi motion
multinucleon correlations
Final-state interactions
nuclear effects

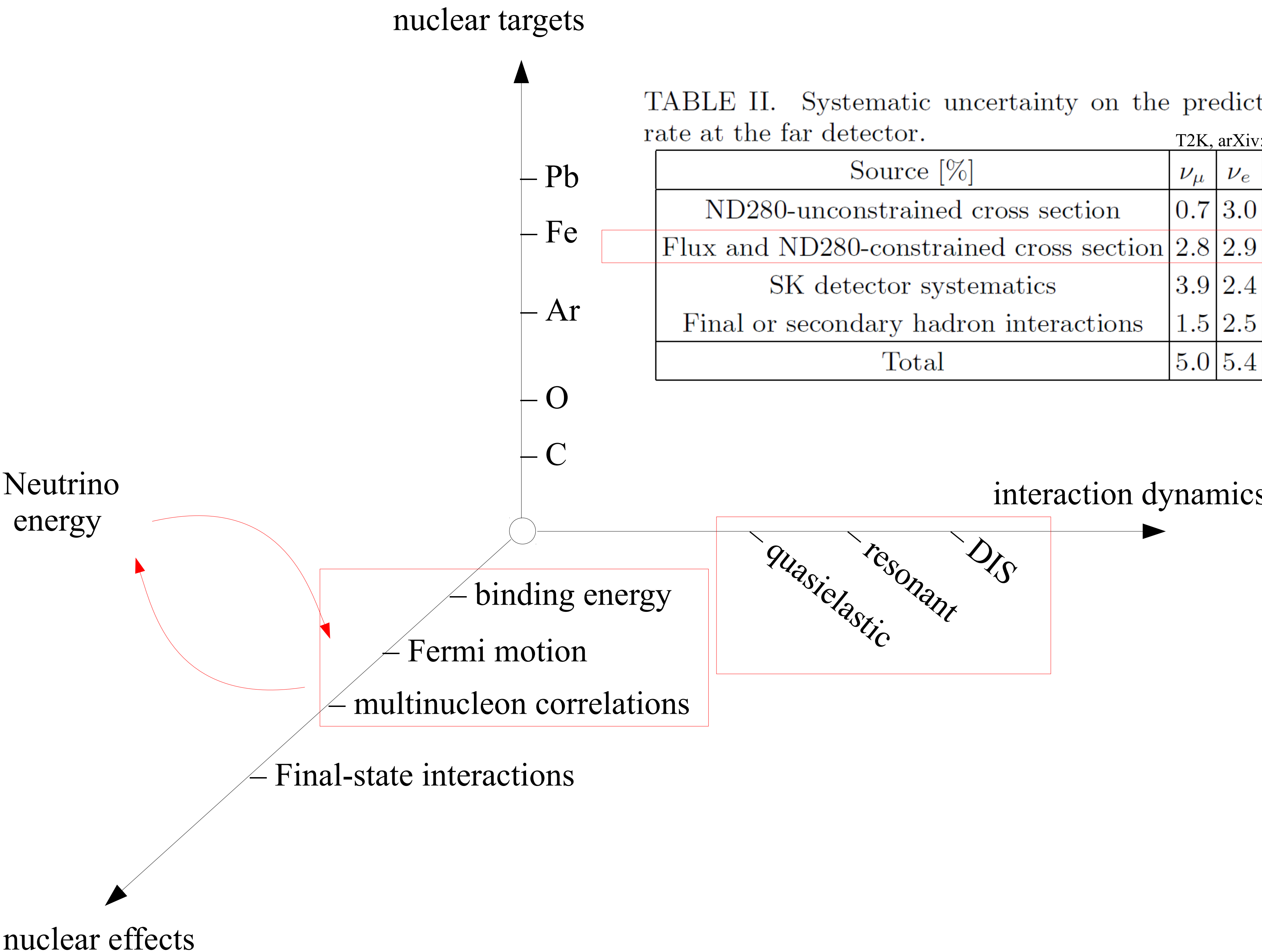
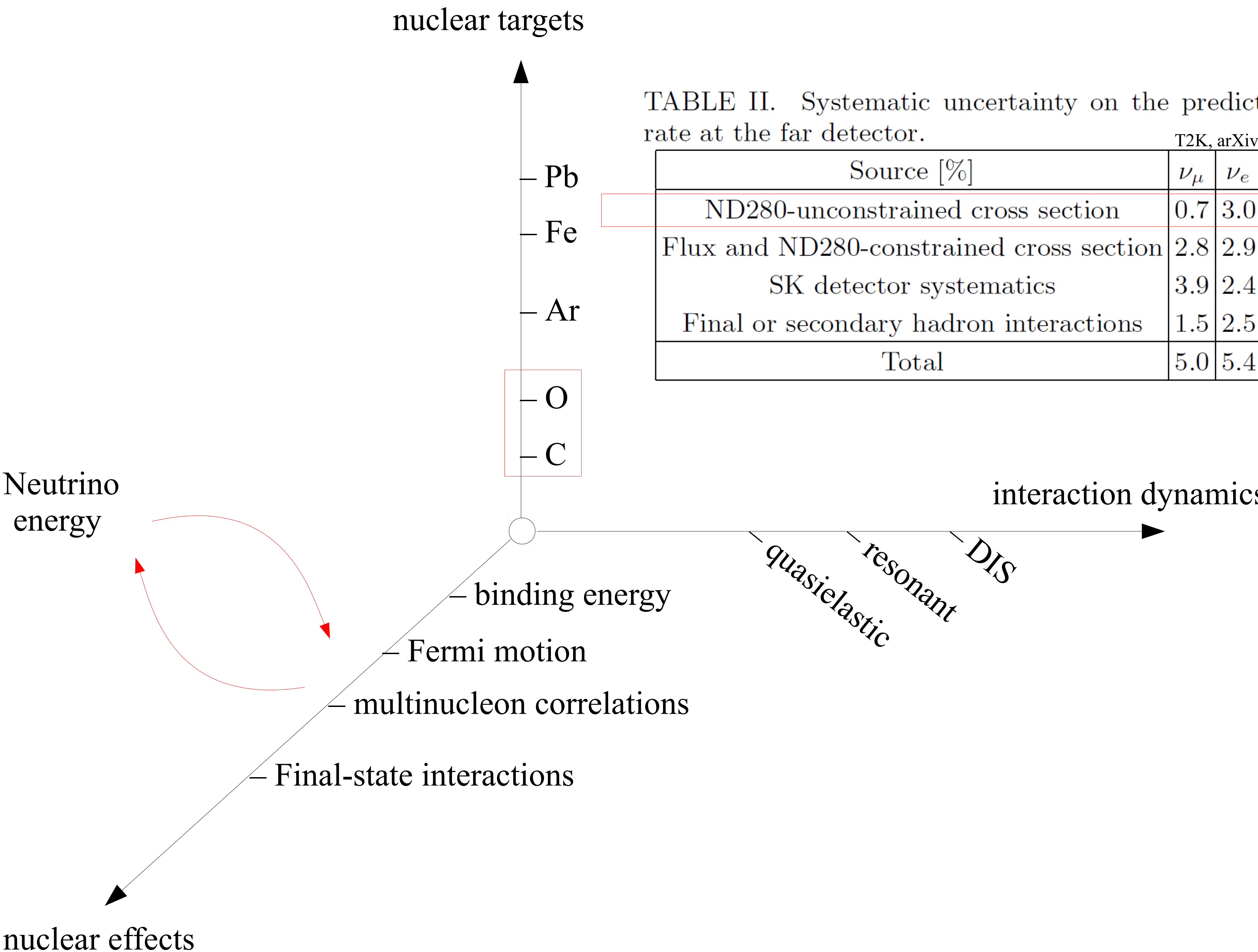


TABLE II. Systematic uncertainty on the predicted event rate at the far detector.

T2K, arXiv:1701.00432

Source [%]	ν_μ	ν_e	$\overline{\nu}_\mu$	$\overline{\nu}_e$
ND280-unconstrained cross section	0.7	3.0	0.8	3.3
Flux and ND280-constrained cross section	2.8	2.9	3.3	3.2
SK detector systematics	3.9	2.4	3.3	3.1
Final or secondary hadron interactions	1.5	2.5	2.1	2.5
Total	5.0	5.4	5.2	6.2



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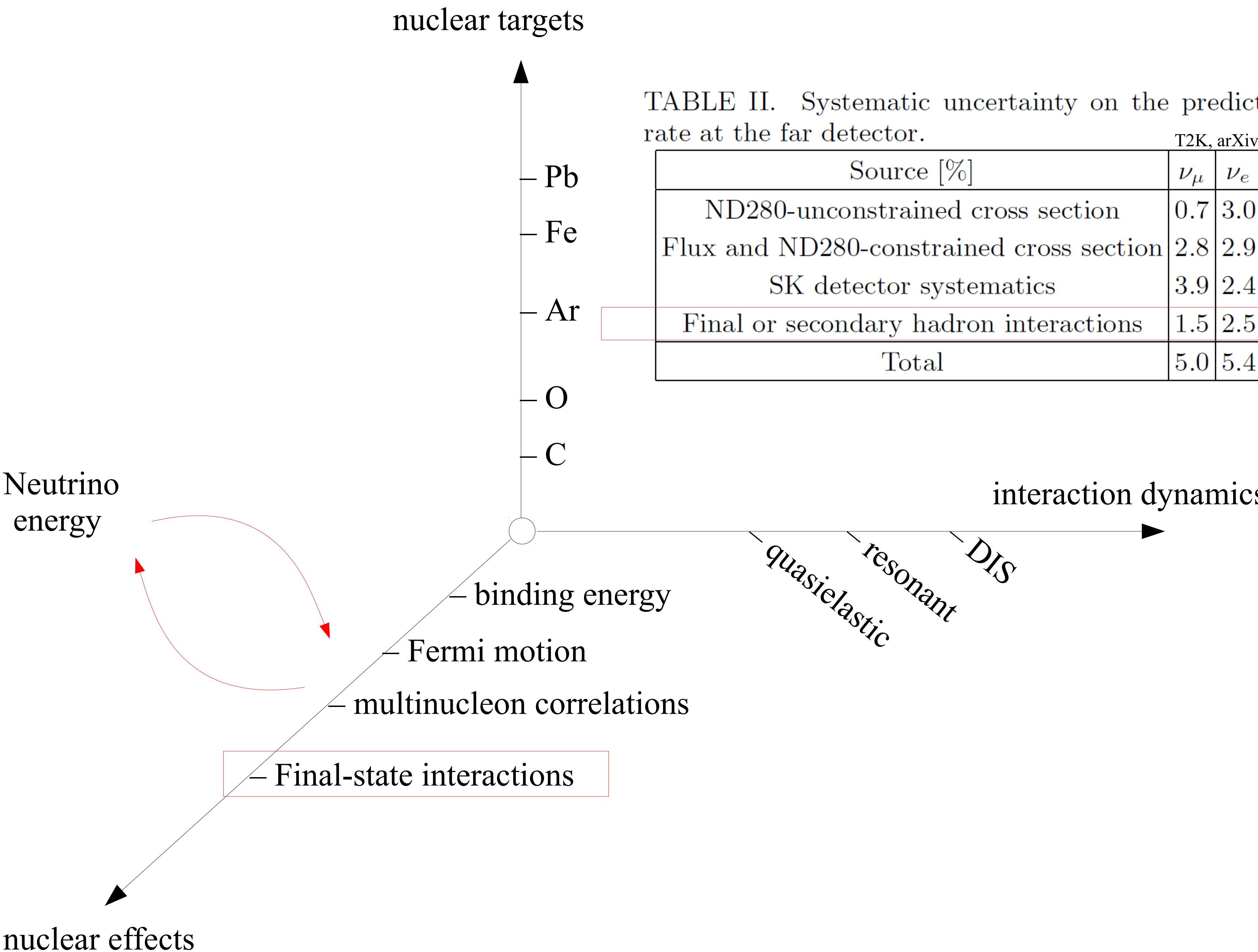

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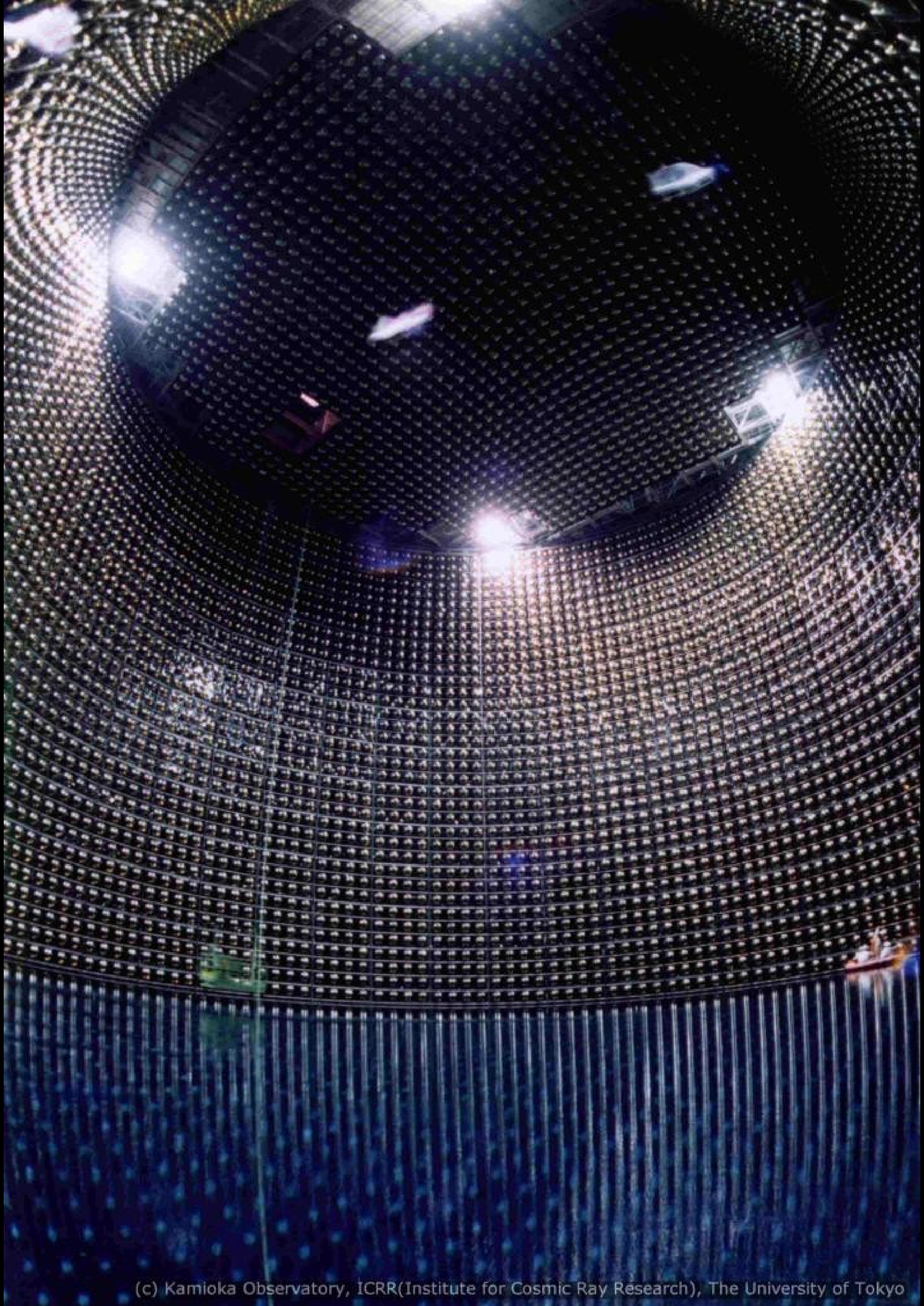
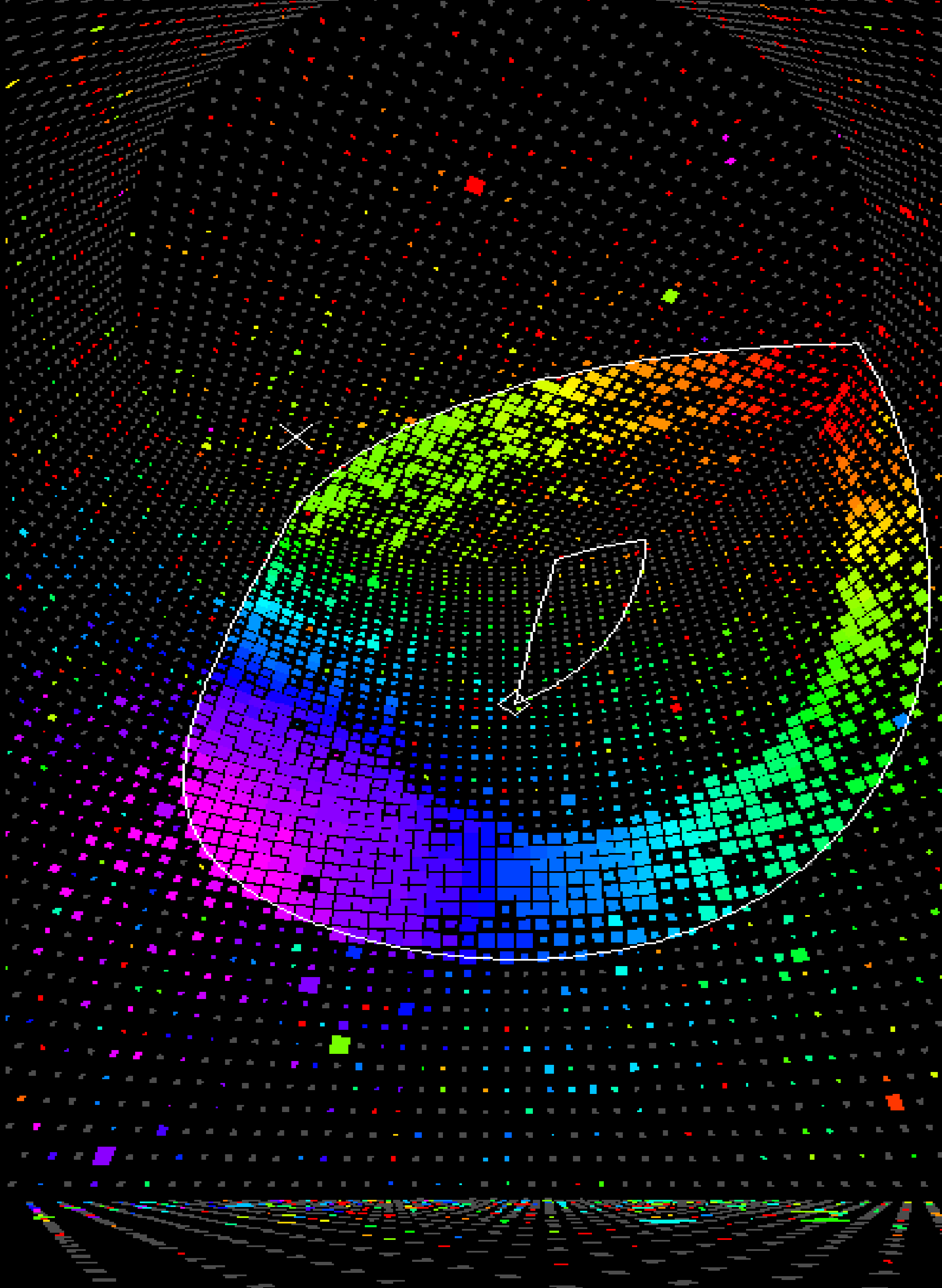


Super-Kamiokande

- 50 kt water Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector
  → time and amplitude of Cherenkov light

Source: http://www-sk.icrr.u-tokyo.ac.jp/sk/detector/image-e.html



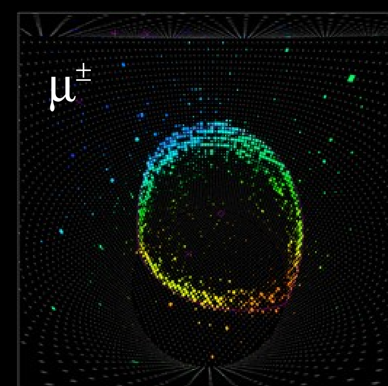
Source: http://www.ps.uci.edu/~tomba/sk/tscan/th

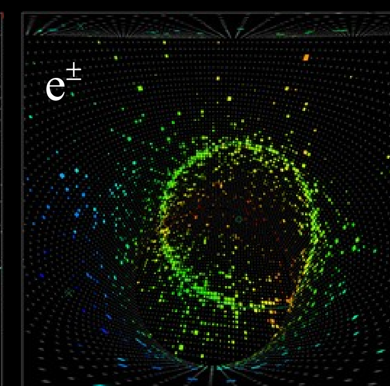
Super-Kamiokande

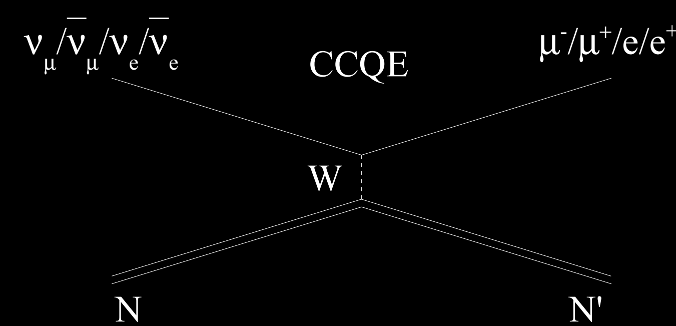
- 50 kt water Cherenkov
- 11129 20-inch PMTs in inner detector; 1885 8-inch PMTs in outer veto detector
  → time and amplitude of Cherenkov light

→ E_ν rec. from μ/e kinematics

→ proton not seen



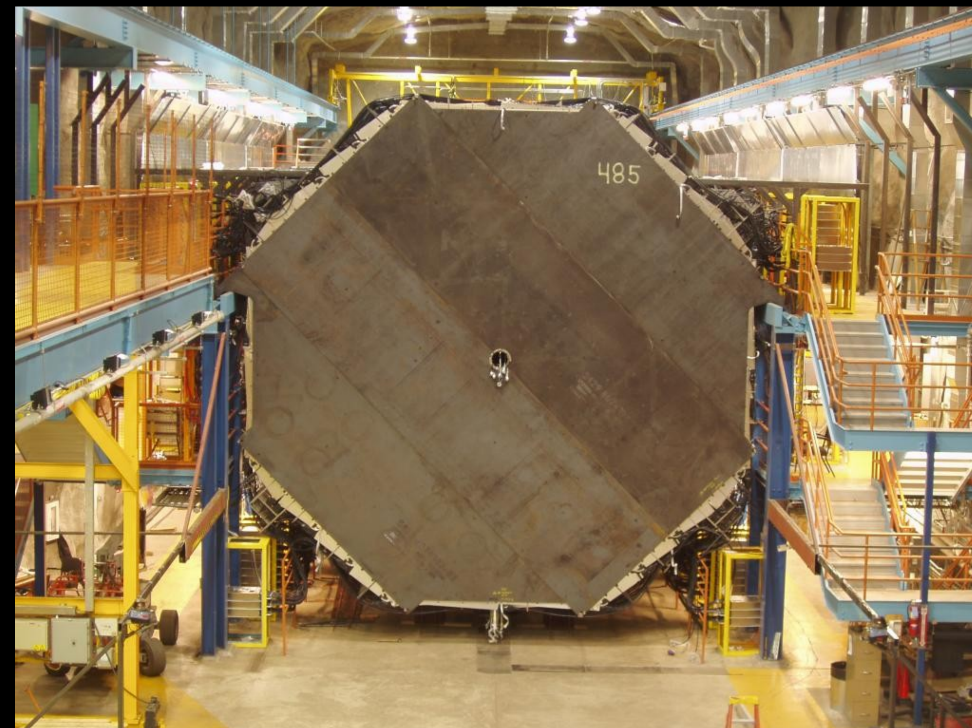




MINOS

Near detector

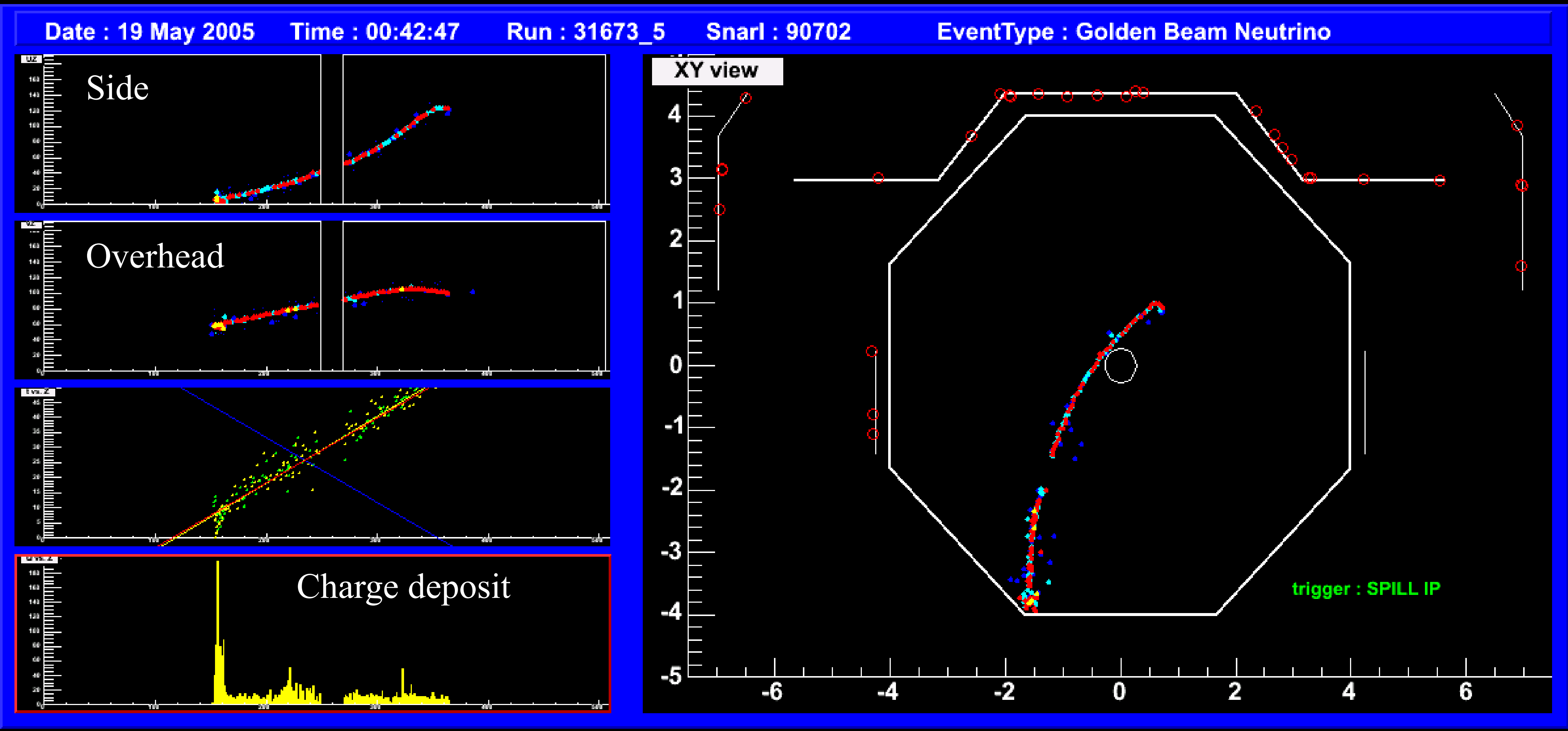
Source: http://www.fnal.gov/pub/today/archive/archive_2004/today04-09-13.html



Far detector

Source: http://www.interactions.org/cms/?pid=2100&image_no=FN0095

MINOS



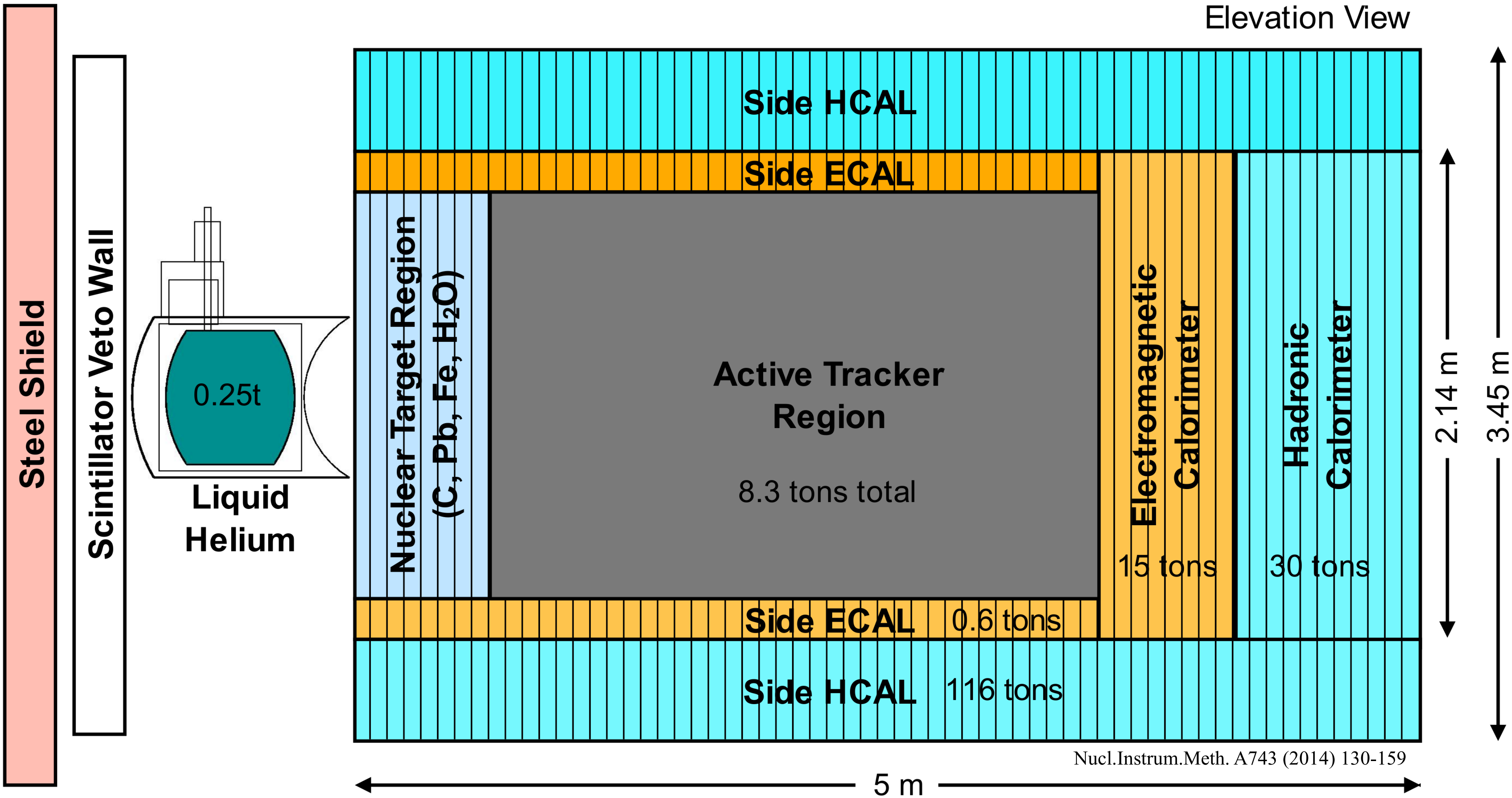
Source: http://www.hep.phy.cam.ac.uk/~thomson/gallery.html

Steel-Scintillator Sampling Calorimeters:
Charged lepton: full kinematics
Proton: energy deposit

MINERvA

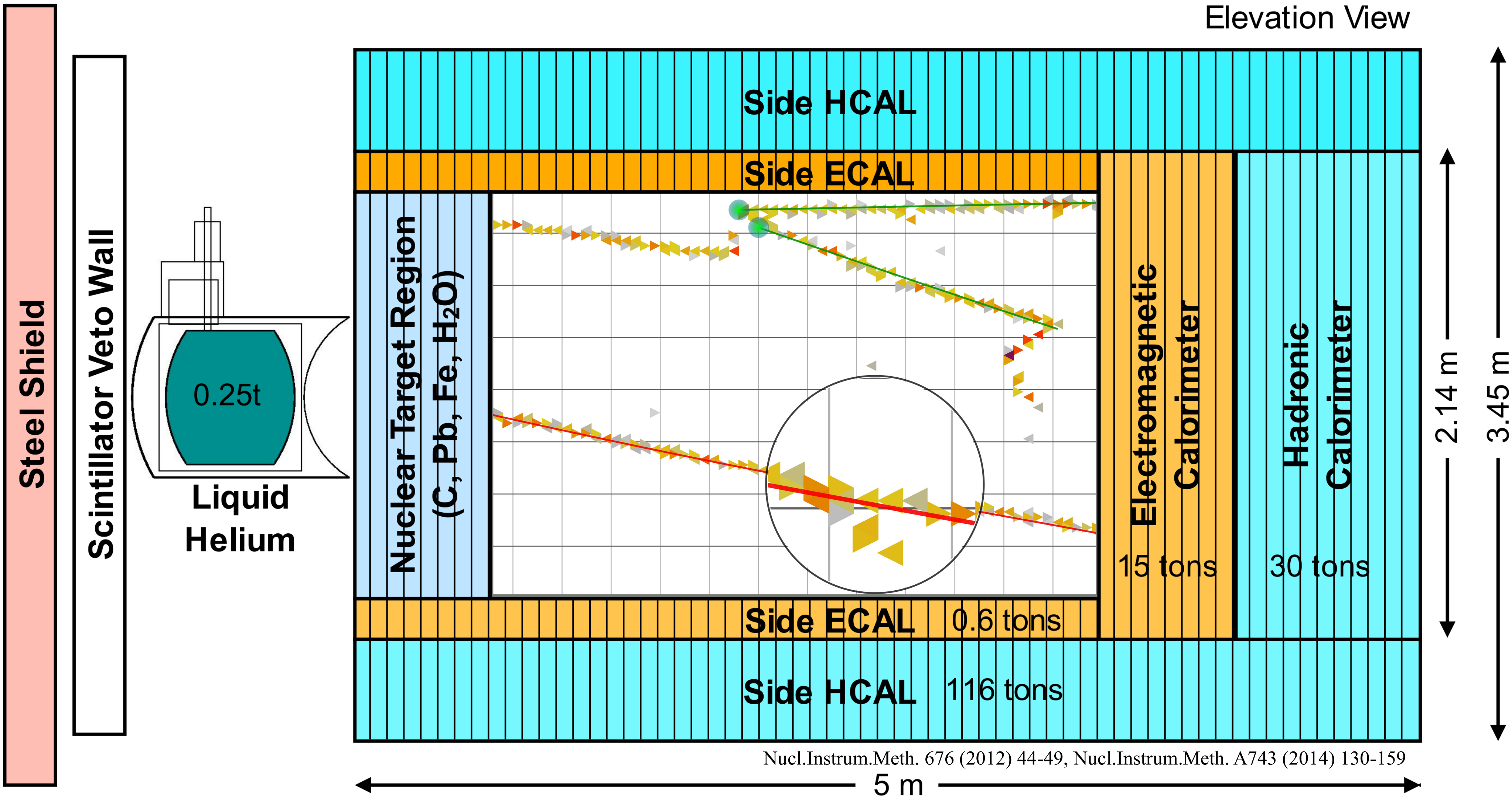
Source: http://vmsstreamer1.fnal.gov/VMS_Site_03/VMSFlash/090924Minerva/index.htm

MINERvA



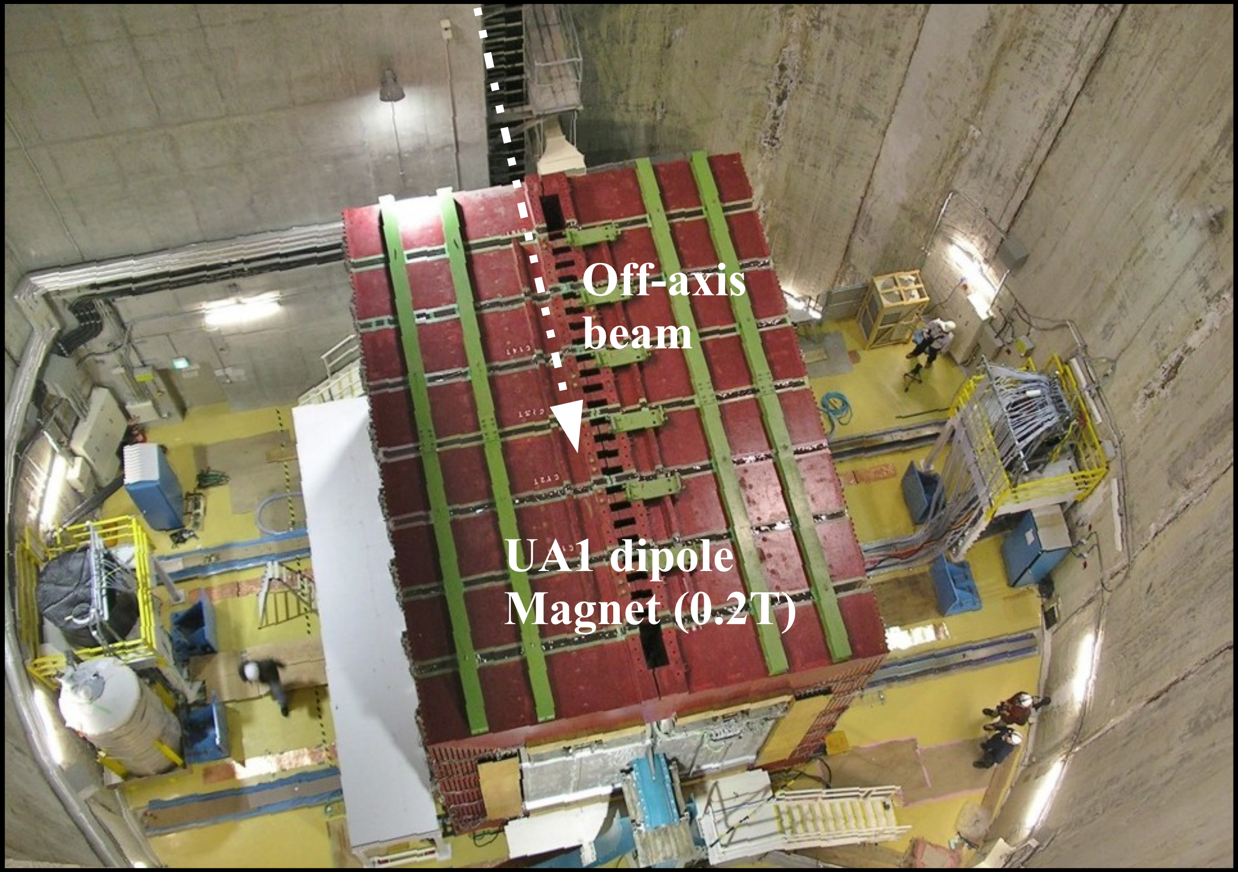
Scintillator tracker

MINERvA

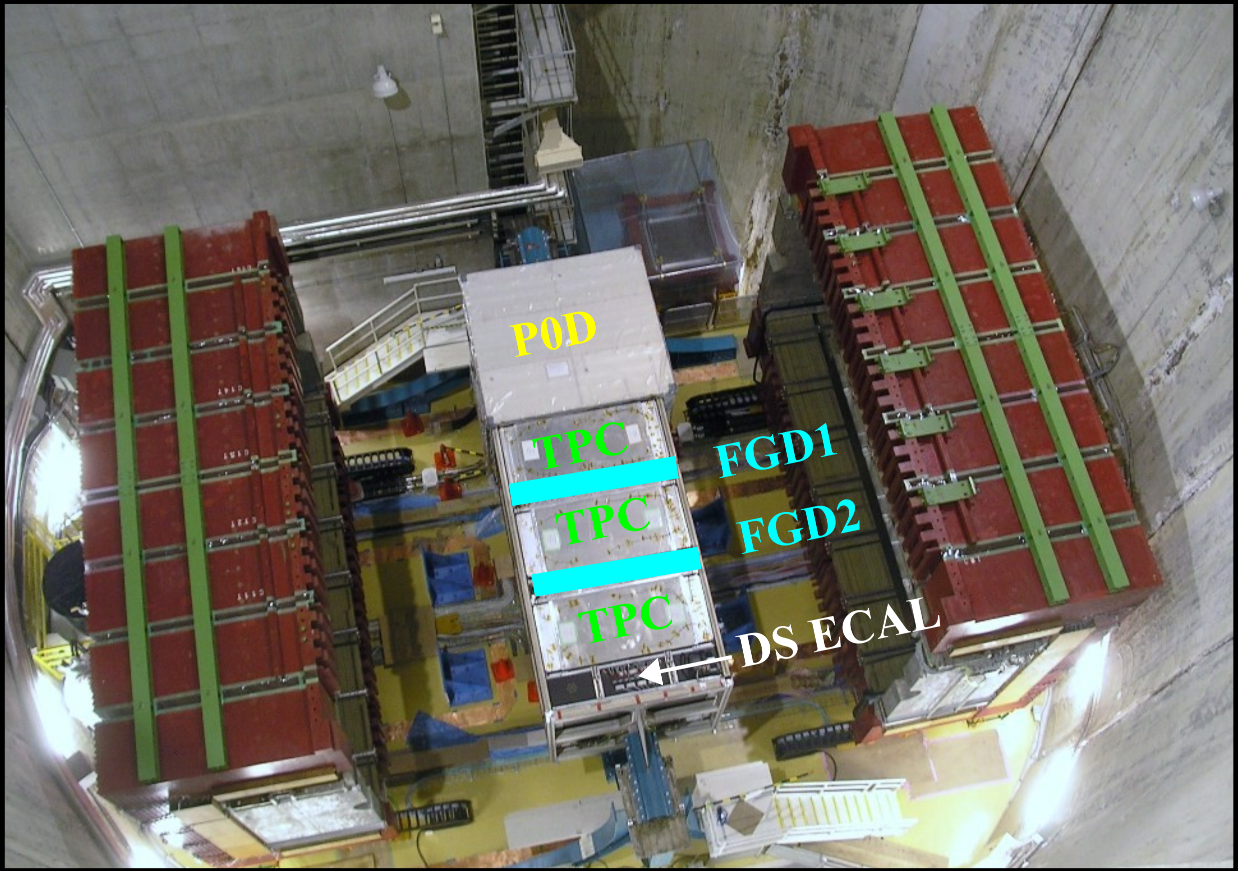


Scintillator tracker:
Charged lepton: full kinematics
Proton: full kinematics (full acceptance)

T2K off-axis near detector (ND280)



T2K off-axis near detector (ND280)



P0D: Pi0 Detector
contains H_2O targets

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

ECAL:
surrounding P0D and tracker

Side Muon Range Detector:
in magnet yokes

→

- Charged lepton: full kinematics
- Proton: full kinematics (high resolution, partial acceptance)

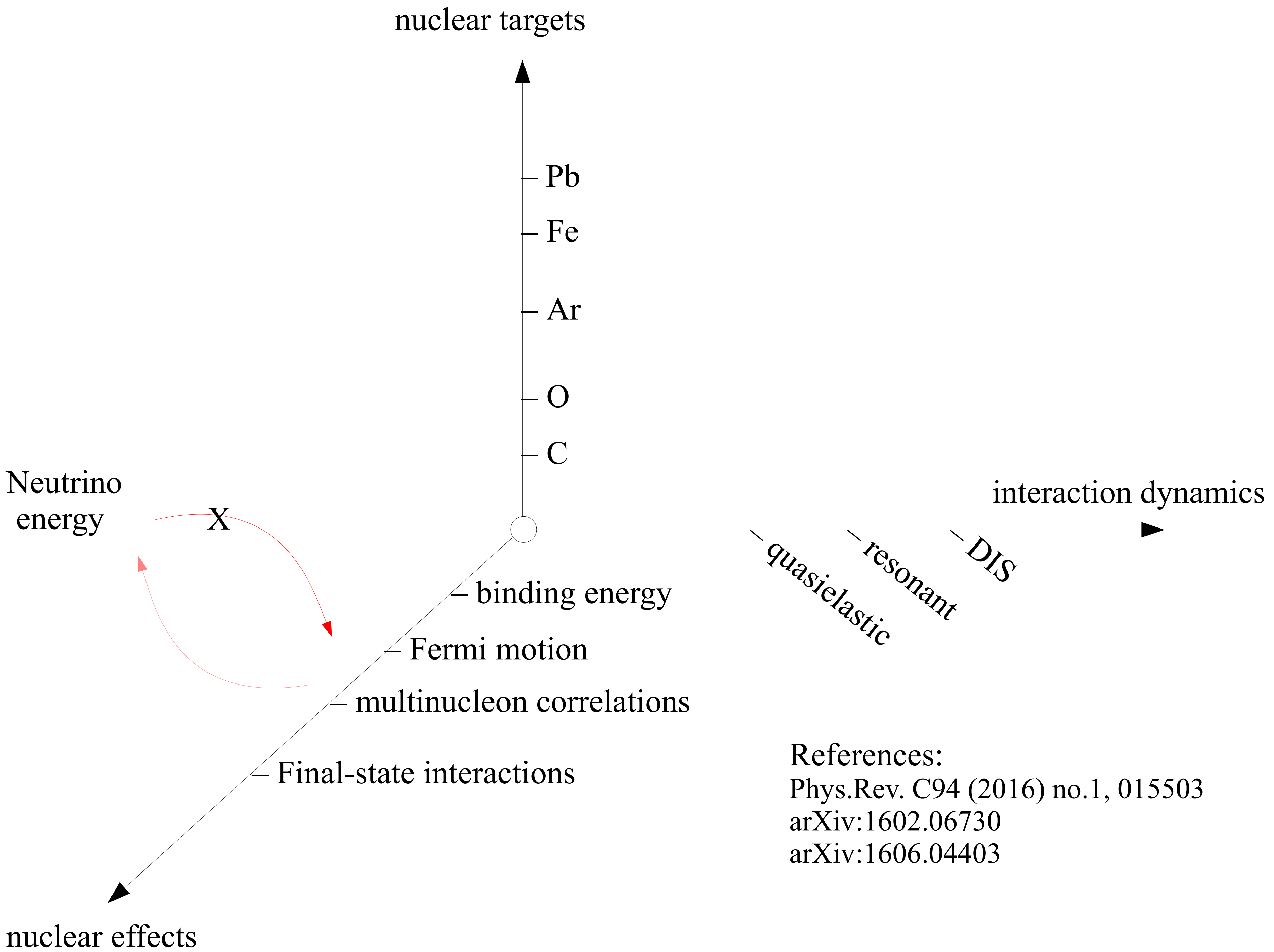
Outline

1. Understanding matter-antimatter asymmetry with neutrinos
2. Nuclear effects in neutrino-nucleus interactions
3. Measuring neutrino interactions
4. A neutrino shadow play

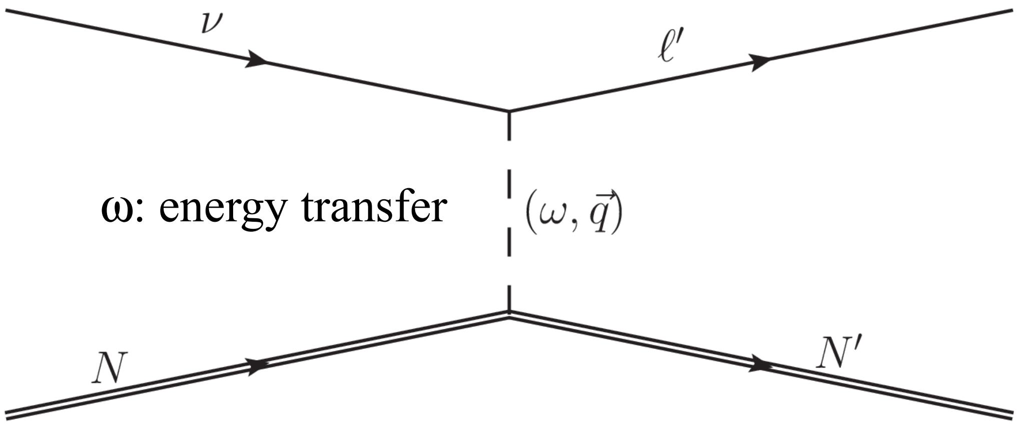
    Act One: Neutrino energy independent measurement of nuclear effects

    Act Two: Nuclear effect independent measurement of neutrino energy spectra

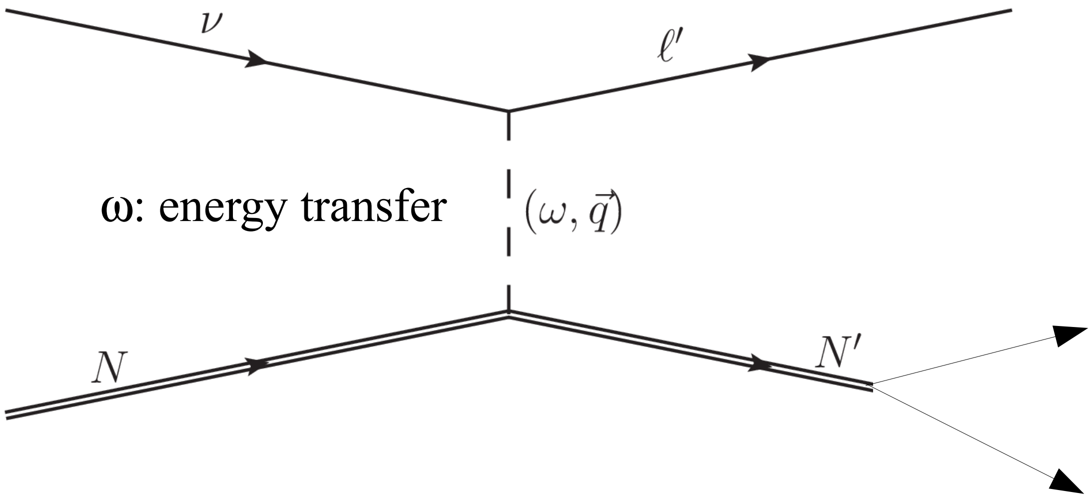
5. Summary



References:
Phys.Rev. C94 (2016) no.1, 015503
arXiv:1602.06730
arXiv:1606.04403

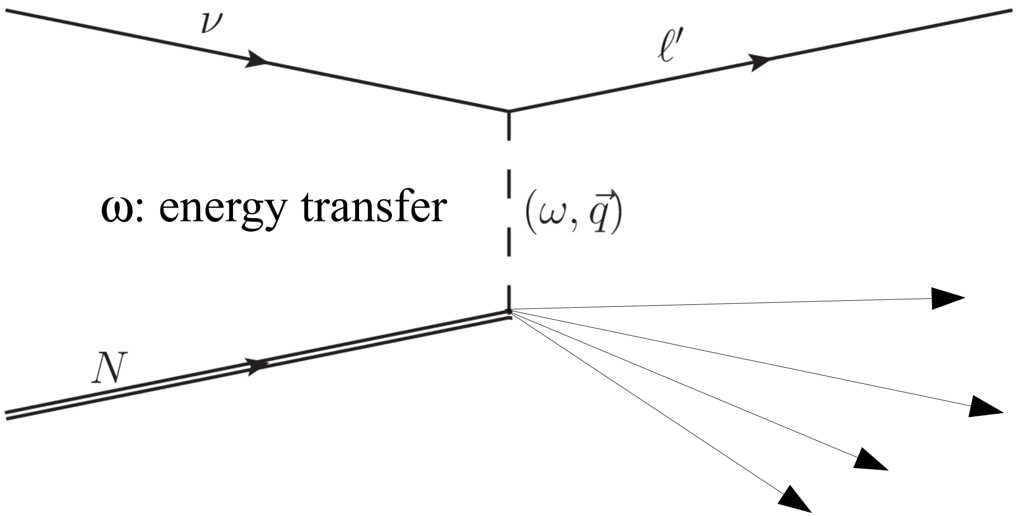


Quasi-elastic scattering (QE): $\nu \mathrm{n} \to \ell^- \mathrm{p}$

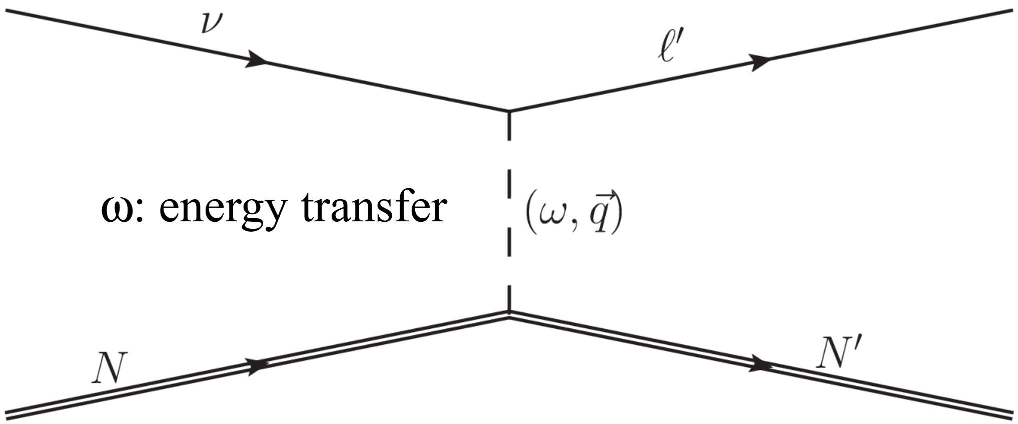


ω: energy transfer

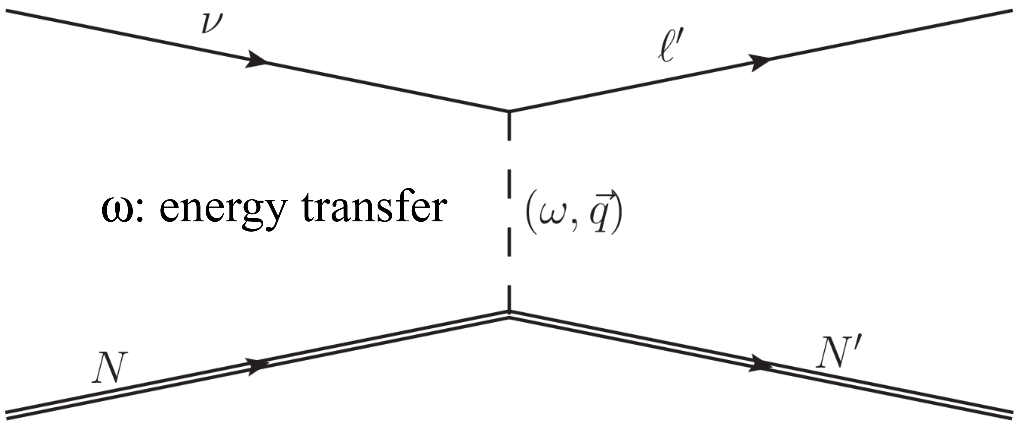
Resonance production (RES): $\nu \mathrm{p} \to \ell^- \Delta^{++} \to \ell^- \mathrm{p} \pi^+$

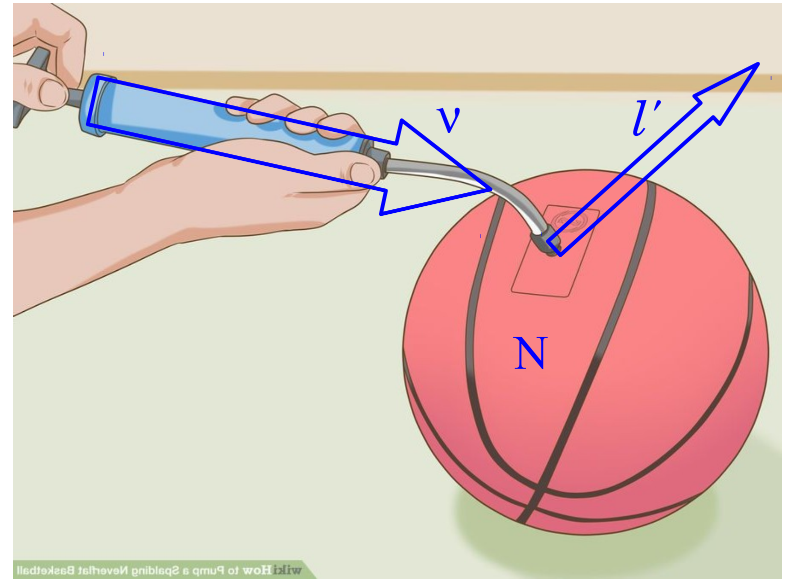


Deep inelastic scattering (DIS): nucleon breaks up



For QE and RES (nucleon not breaking up),
ω “saturates” when E_ν > 0.5 GeV
[Phys.Rev. C94 (2016) no.1, 015503]





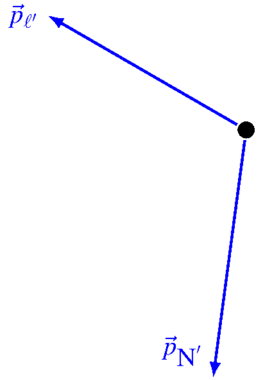
Source: http://www.wikihow.com/Pump-a-Spalding-Neverflat-Basketball

For QE and RES (nucleon not breaking up),
ω "saturates" when $E_\nu > 0.5$ GeV
[Phys.Rev. C94 (2016) no.1, 015503]

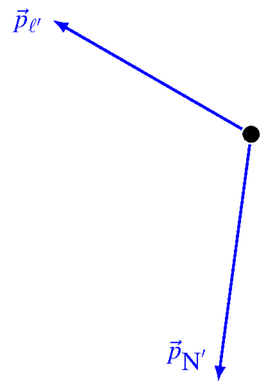
In QE and RES

- Lepton retains most of the increase of E_ν
- Leptonic kinematics much more E_ν-dependent than hadronic ones

Transverse kinematic imbalances
– *a neutrino shadow play*



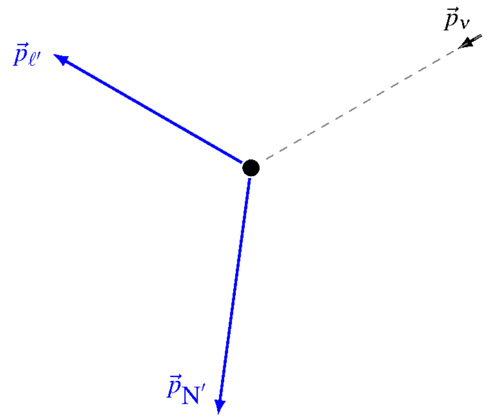
Transverse kinematic imbalances
– *a neutrino shadow play*



Source: http://zhejiangpiying.sokutu.com/tupian.html

To make *Neutrino Shadow Play*, we need
- ✓ beam of light
- ✓ screen

Transverse kinematic imbalances – *a neutrino shadow play*



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To make *Neutrino Shadow Play*, we need
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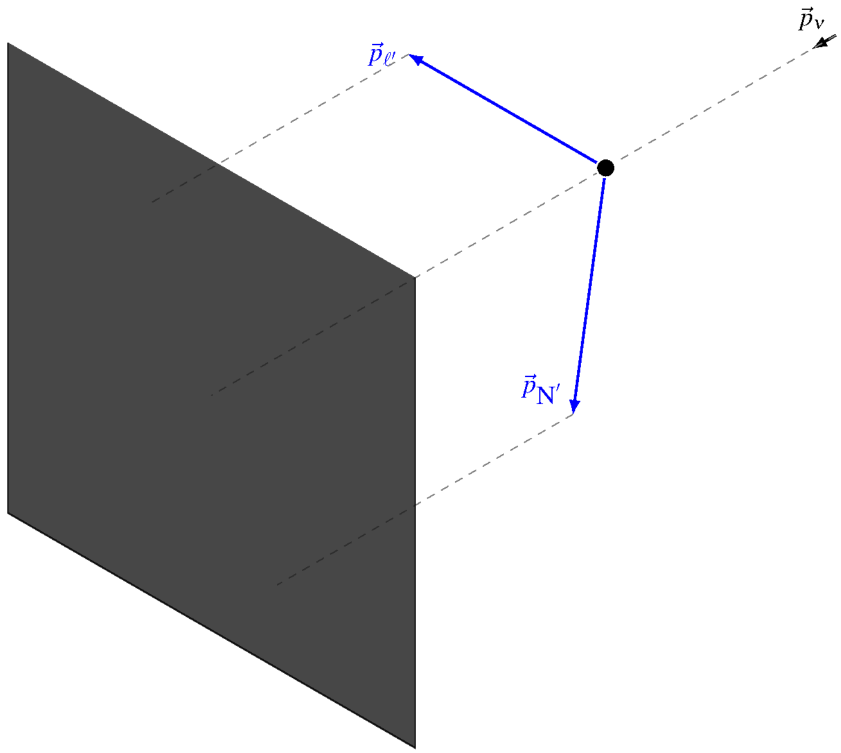
- ✓ screen

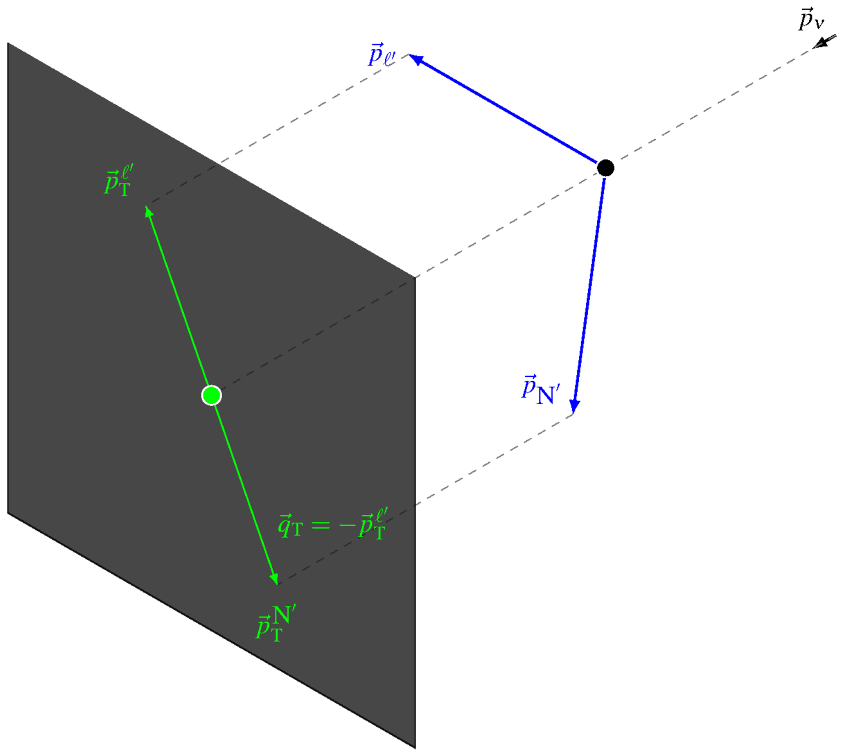
Transverse kinematic imbalances – *a neutrino shadow play*



Source: http://zhejiangpiying.sokutu.com/tupian.html

To make *Neutrino Shadow Play*, we need
- ✓ beam of light → accelerator
- ✓ screen → transverse plane

Transverse kinematic imbalances
– *a neutrino shadow play*



Static nucleon target

Source: http://zhejiangpiying.sokutu.com/tupian.html

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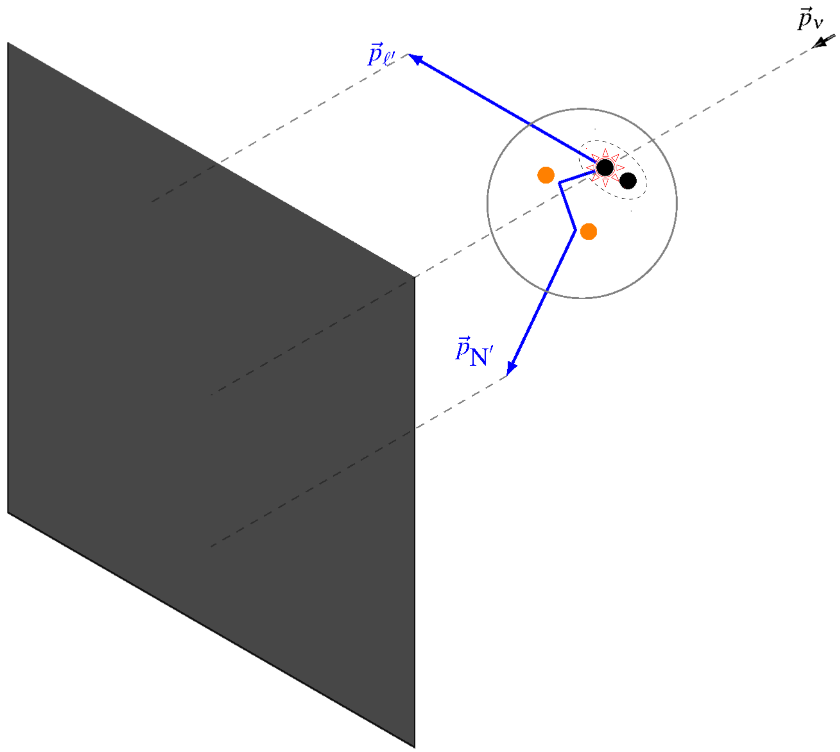

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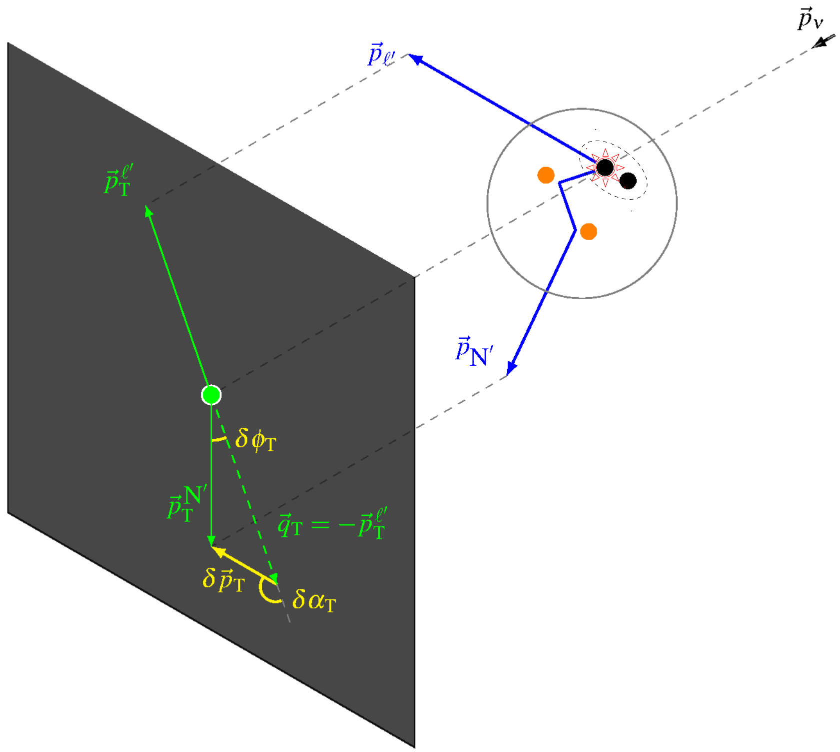
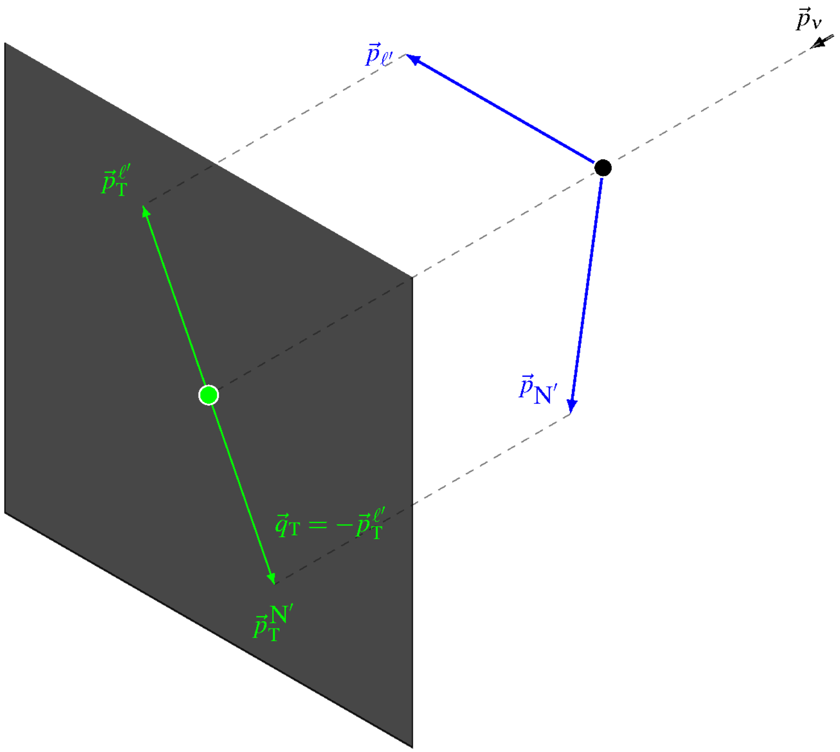


Nuclear target

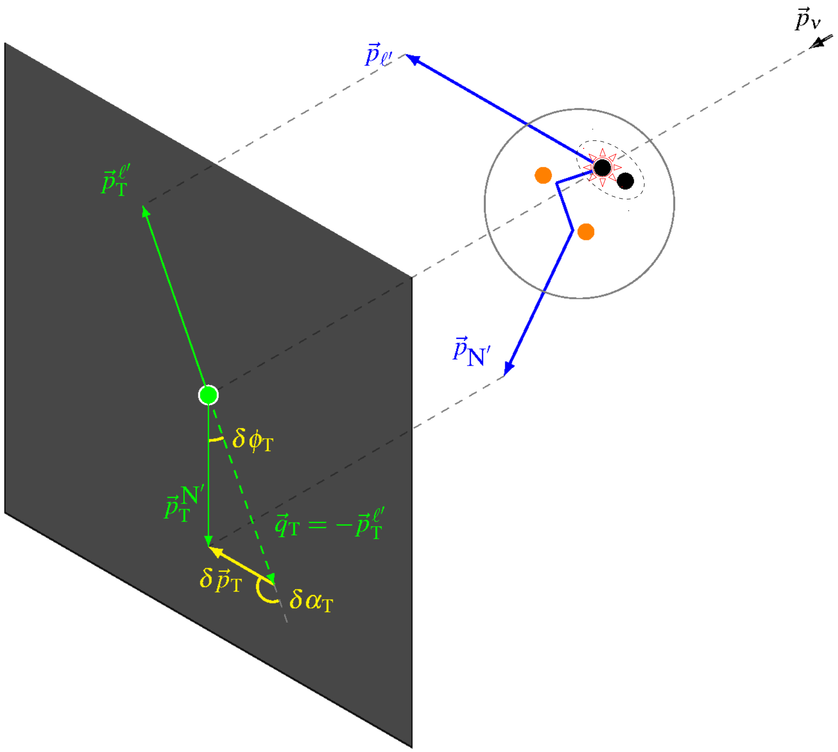
Source: http://zhejiangpiying.sokutu.com/tupian.html

To make *Neutrino Shadow Play*, we need
- ✓ beam of light ⟶ accelerator
- ✓ screen ⟶ transverse plane

Transverse kinematic imbalances
– *a neutrino shadow play*

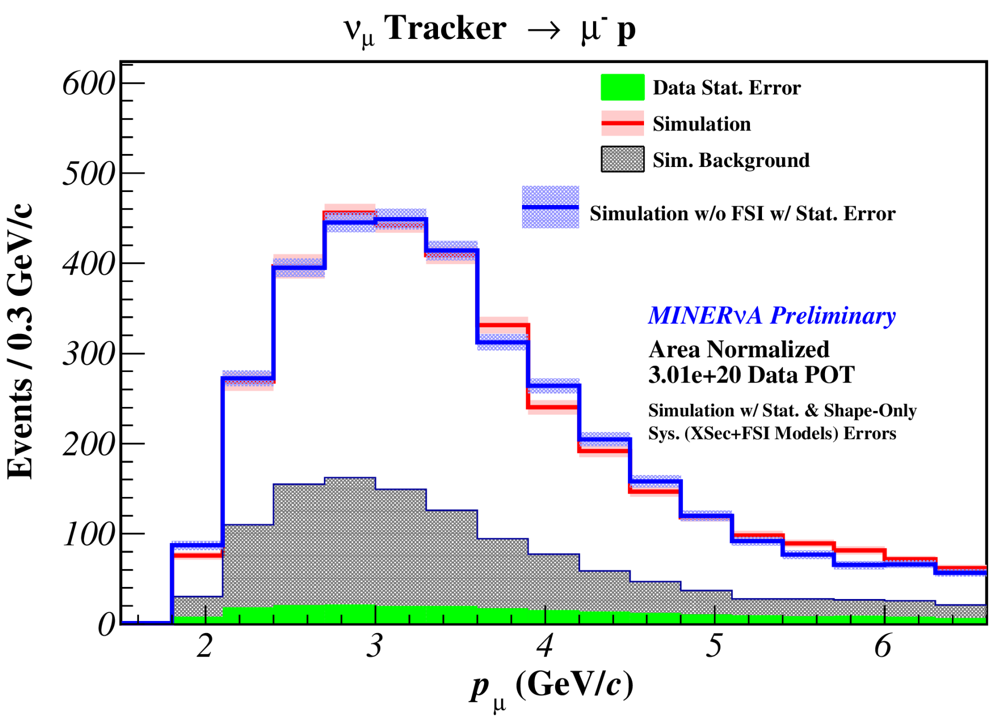


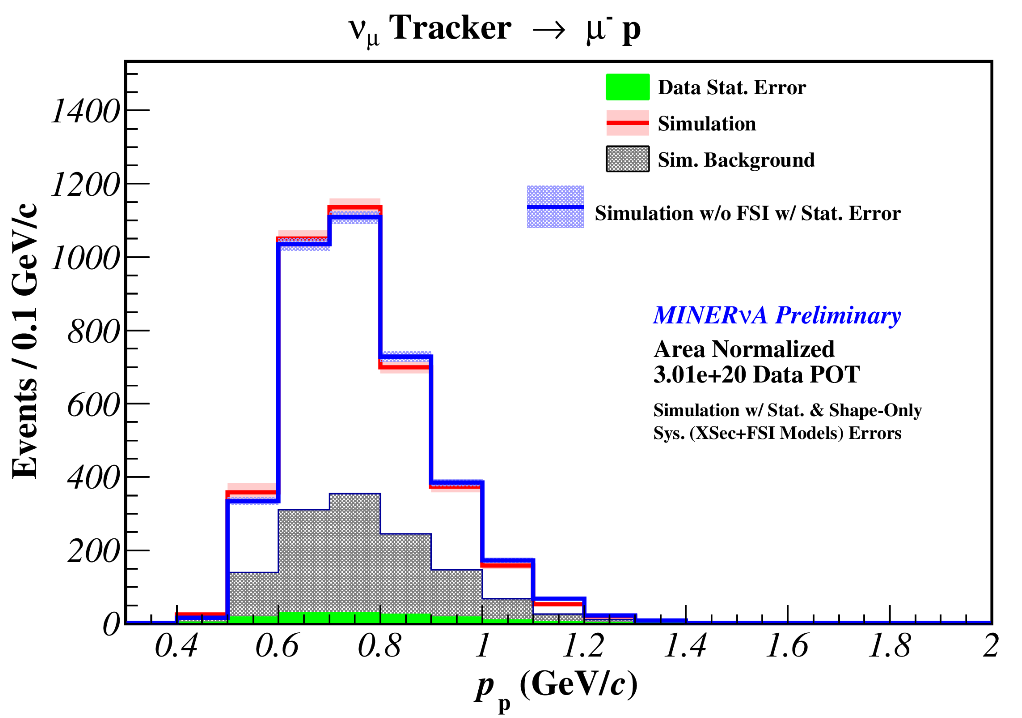
Static nucleon target



Nuclear target

MINERνA measurement of single-transverse kinematic imbalances

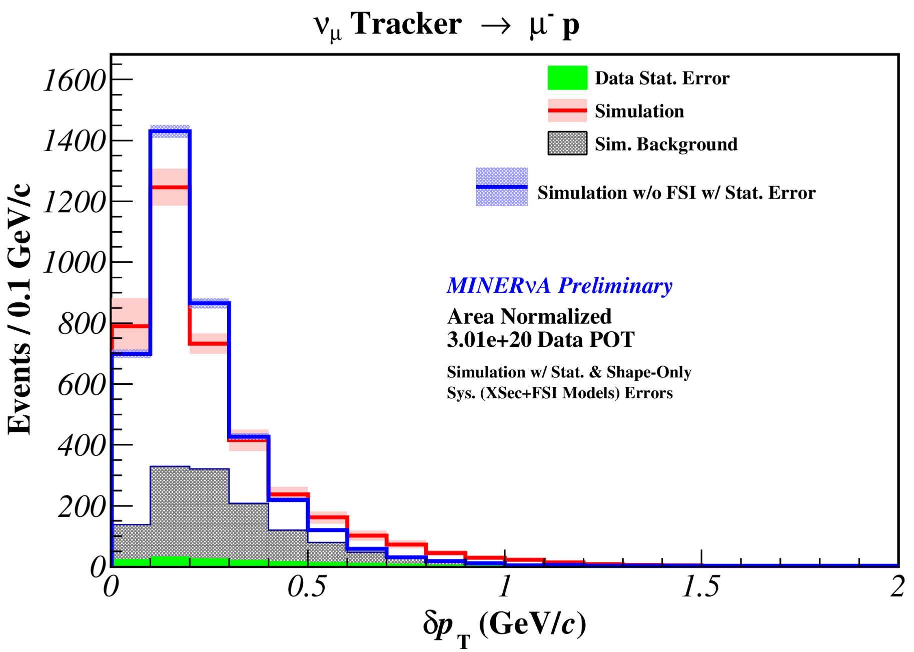


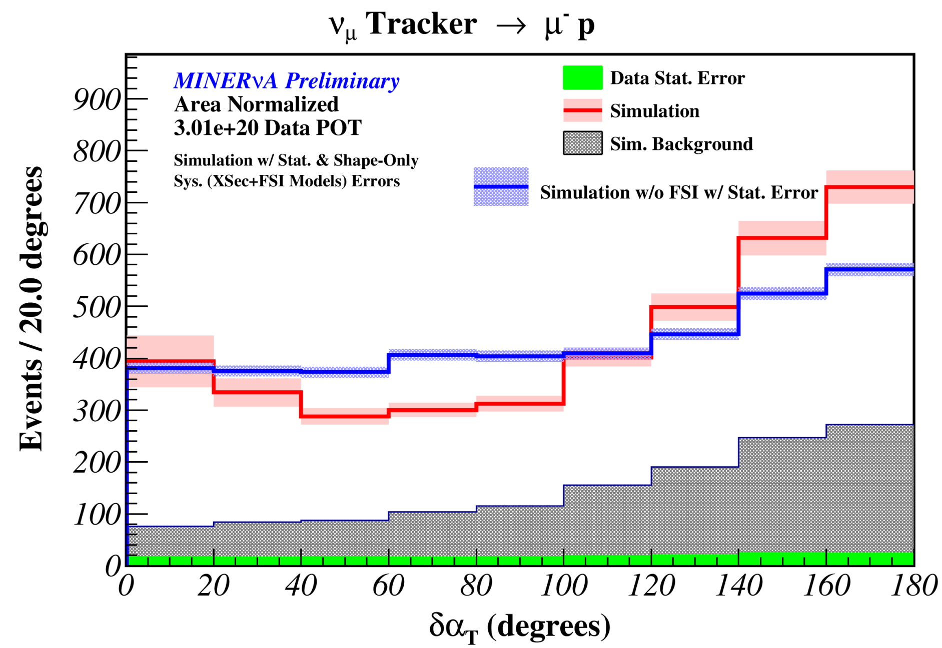


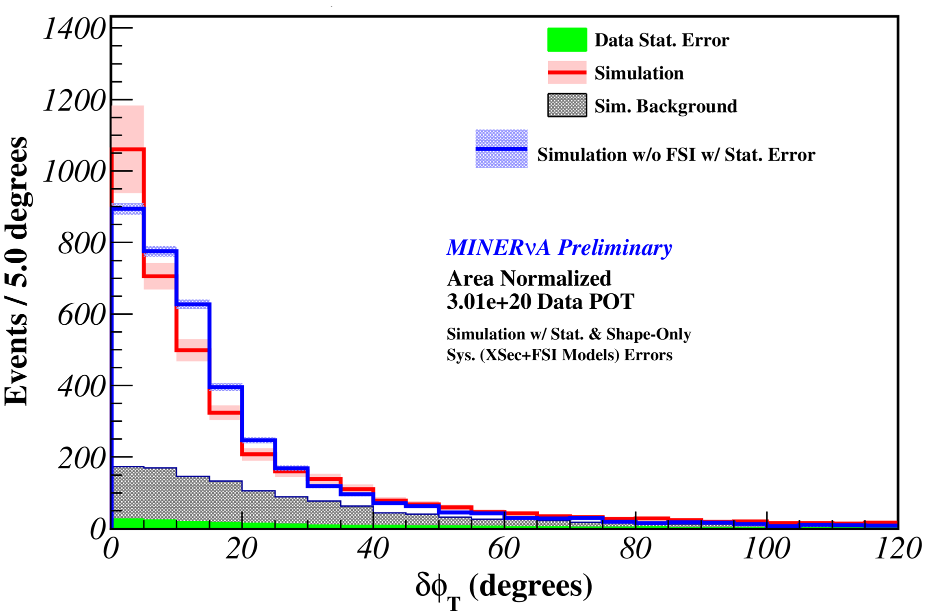
- In given acceptance, overall spectral shapes not sensitive to FSIs.
- Nuclear effects difficult to observe on top of neutrino-nucleon kinematics.

[arXiv:1608.04655]

MINERvA measurement of single-transverse kinematic imbalances





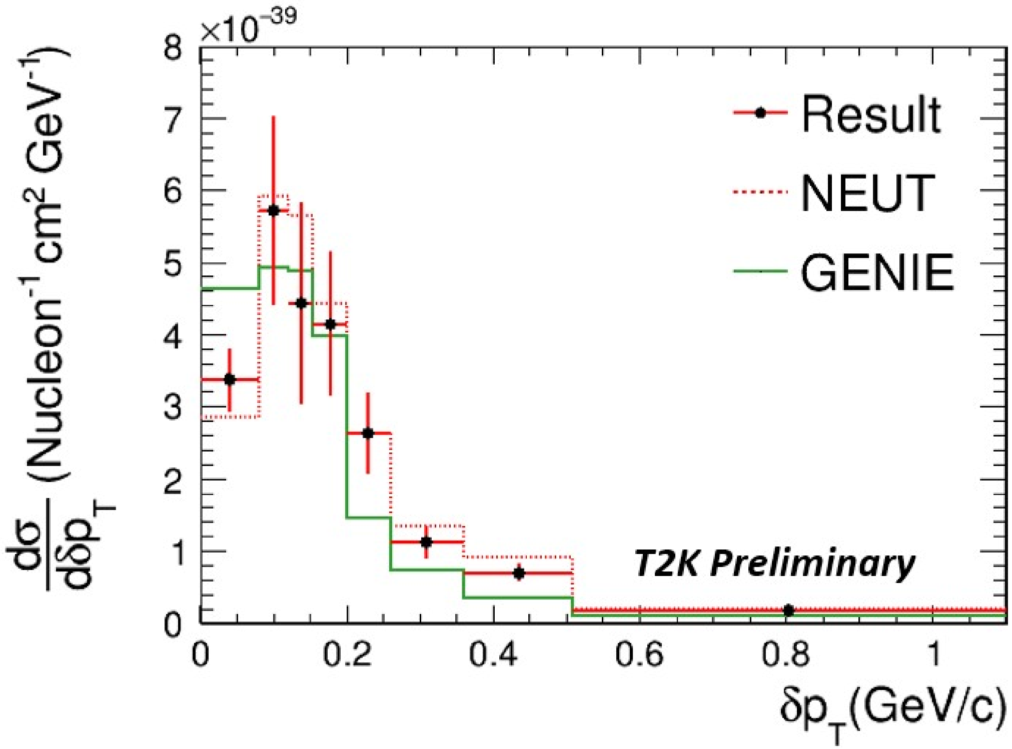


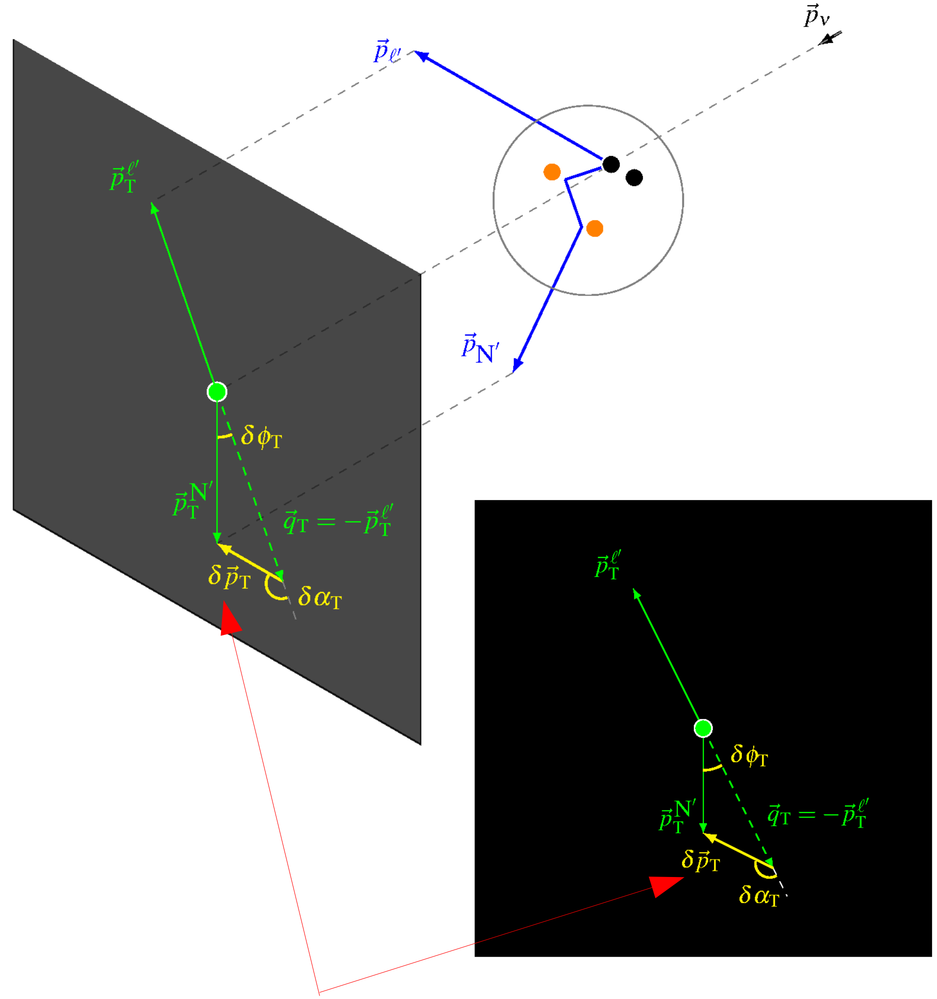
- More sensitive to FSIs
- Sensitivity achieved by dedicated momentum cuts and corrections.

[arXiv:1608.04655]

T2K measurement of single-transverse kinematic imbalances

Preliminary, Progress reports: arXiv:1605.00179, 1610.05077





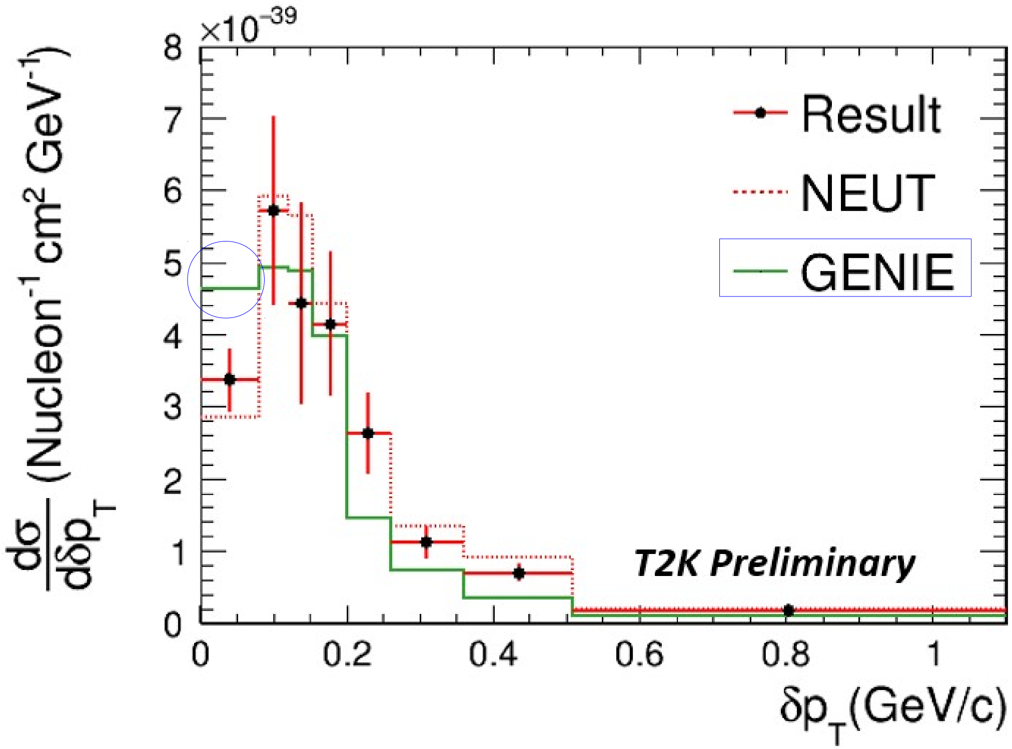
$$\delta\vec{p}_{\rm T} = \vec{p}_{\rm T}^{\rm N} - \Delta\vec{p}_{\rm T}$$

Transverse Fermi motion

(transverse projected) momentum transfer in
- initial-state multinucleon correlation, and
- final-state interaction

T2K measurement of single-transverse kinematic imbalances

Preliminary, Progress reports: arXiv:1605.00179, 1610.05077



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

Transverse Fermi motion

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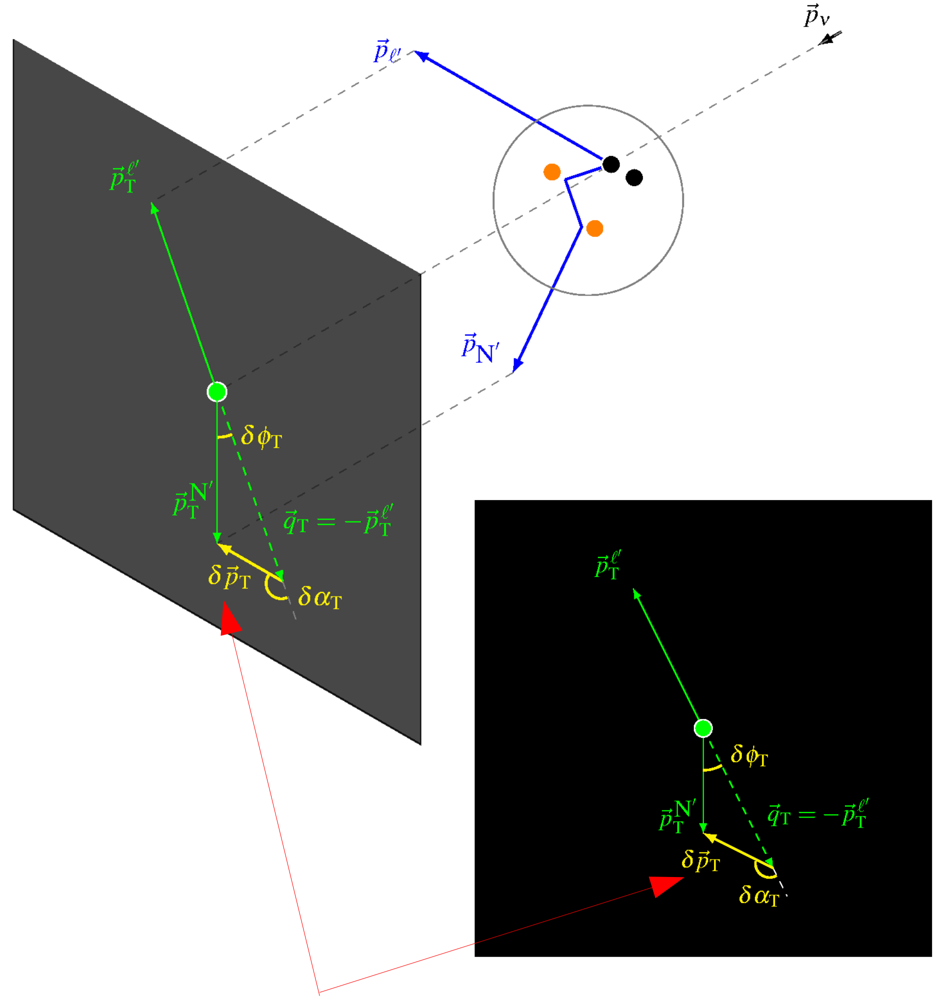

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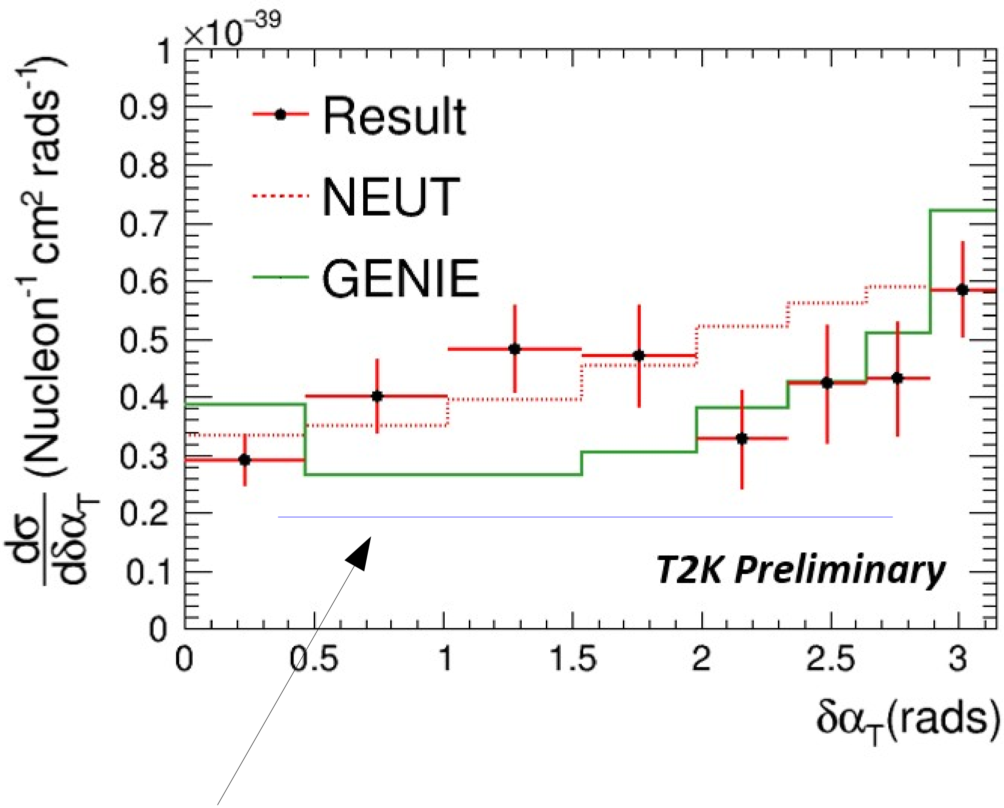
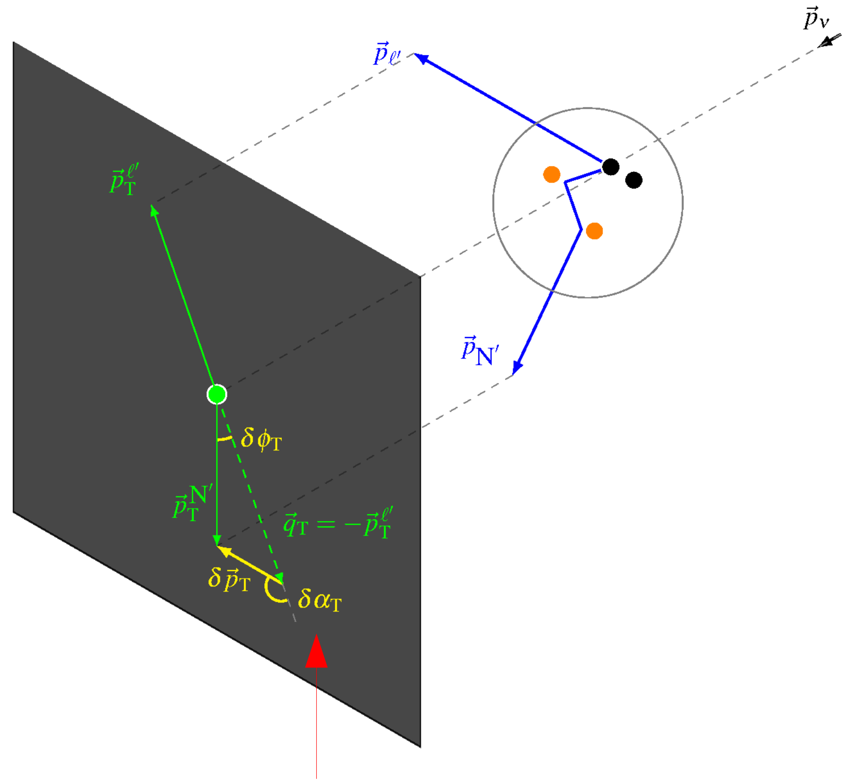
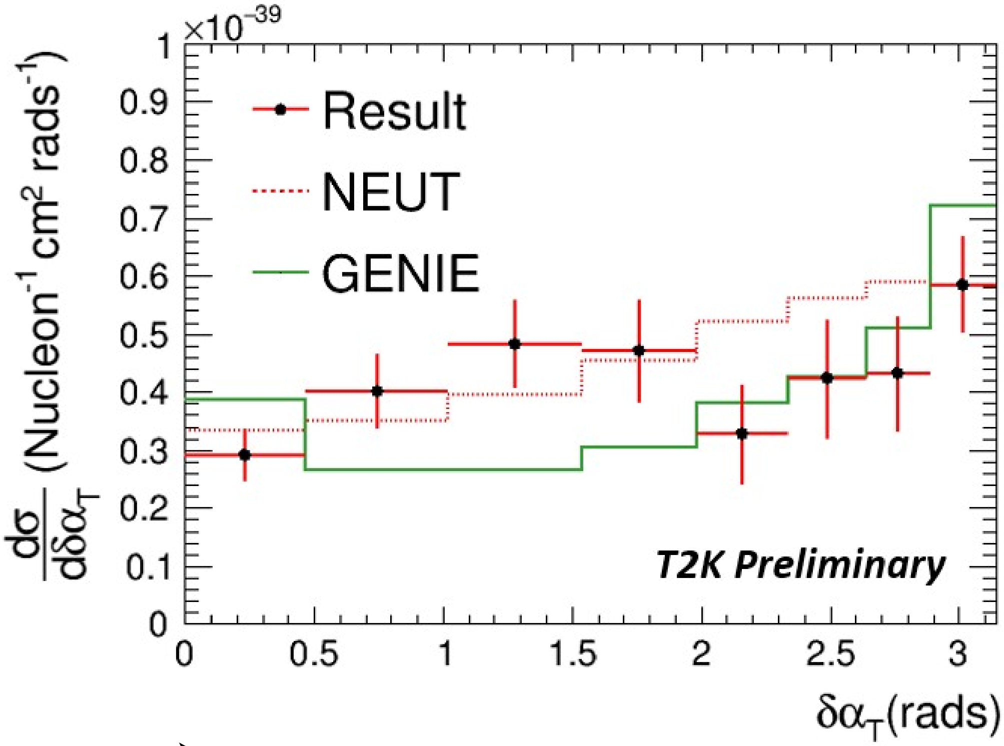


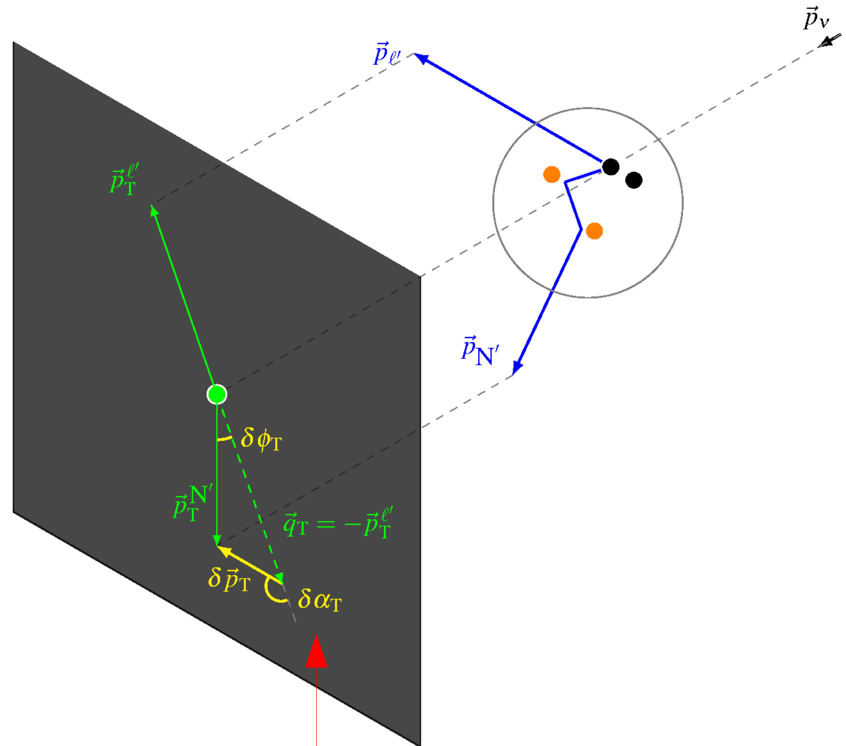


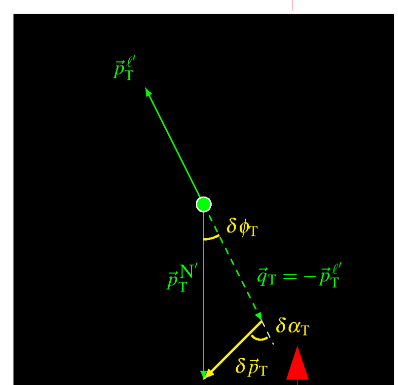
Fermi motion: flat

T2K measurement of single-transverse kinematic imbalances

Preliminary, Progress reports: arXiv:1605.00179, 1610.05077







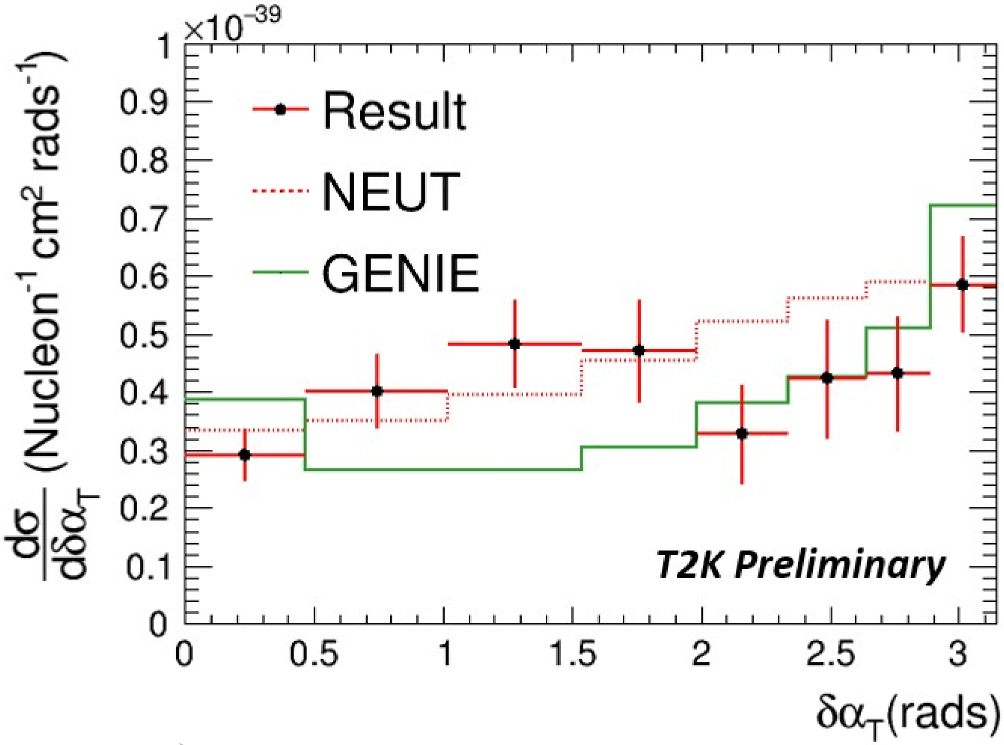
"acceleration"

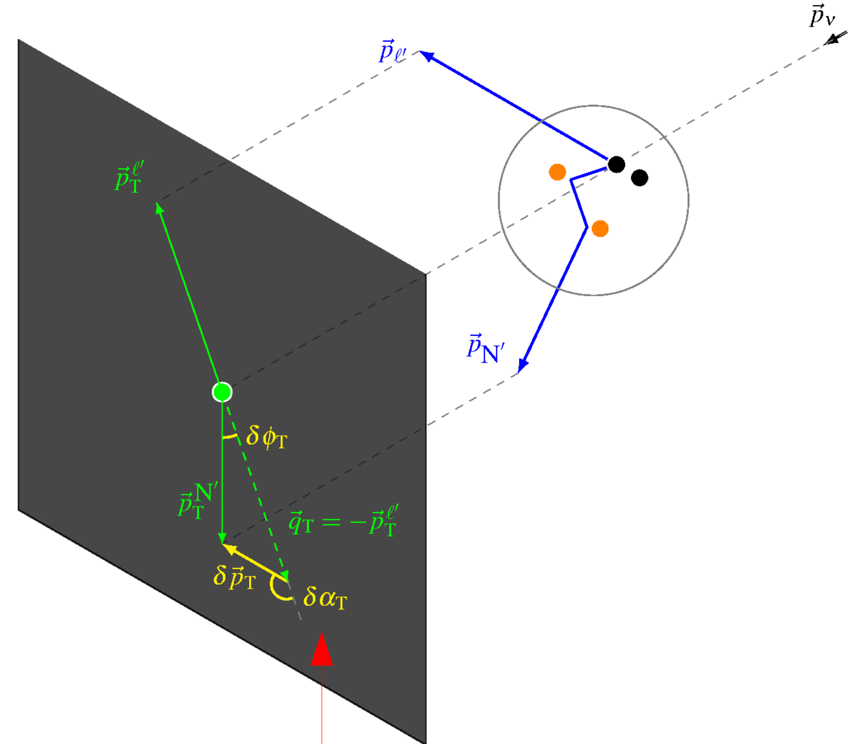
FSI dynamics

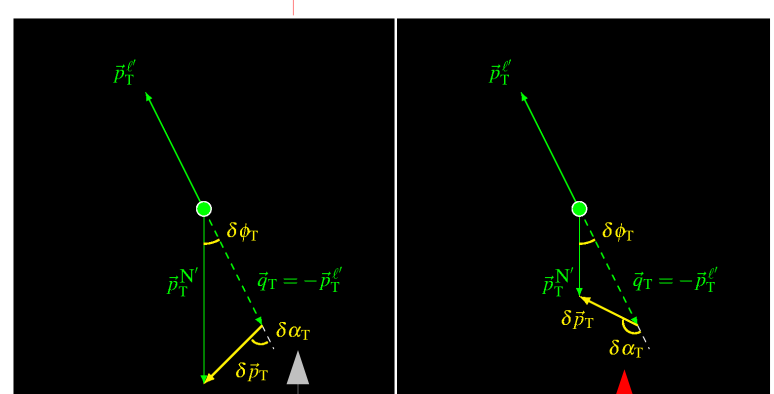
Transversely "accelerated"

T2K measurement of single-transverse kinematic imbalances

Preliminary, Progress reports:
arXiv:1605.00179, 1610.05077







"acceleration"

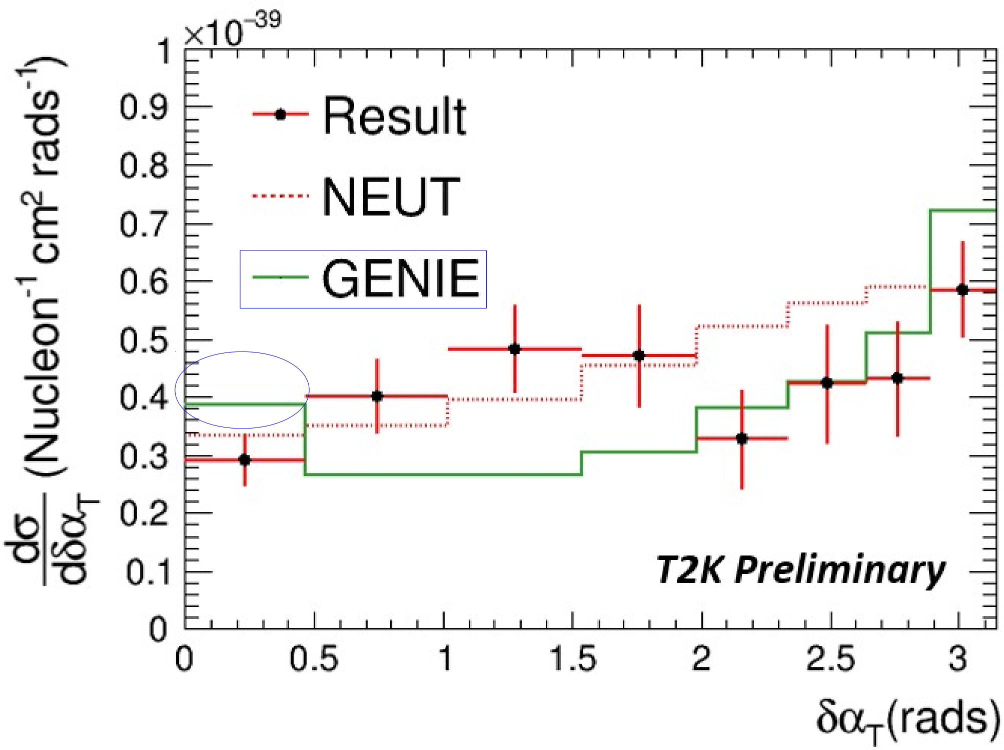
"deceleration"

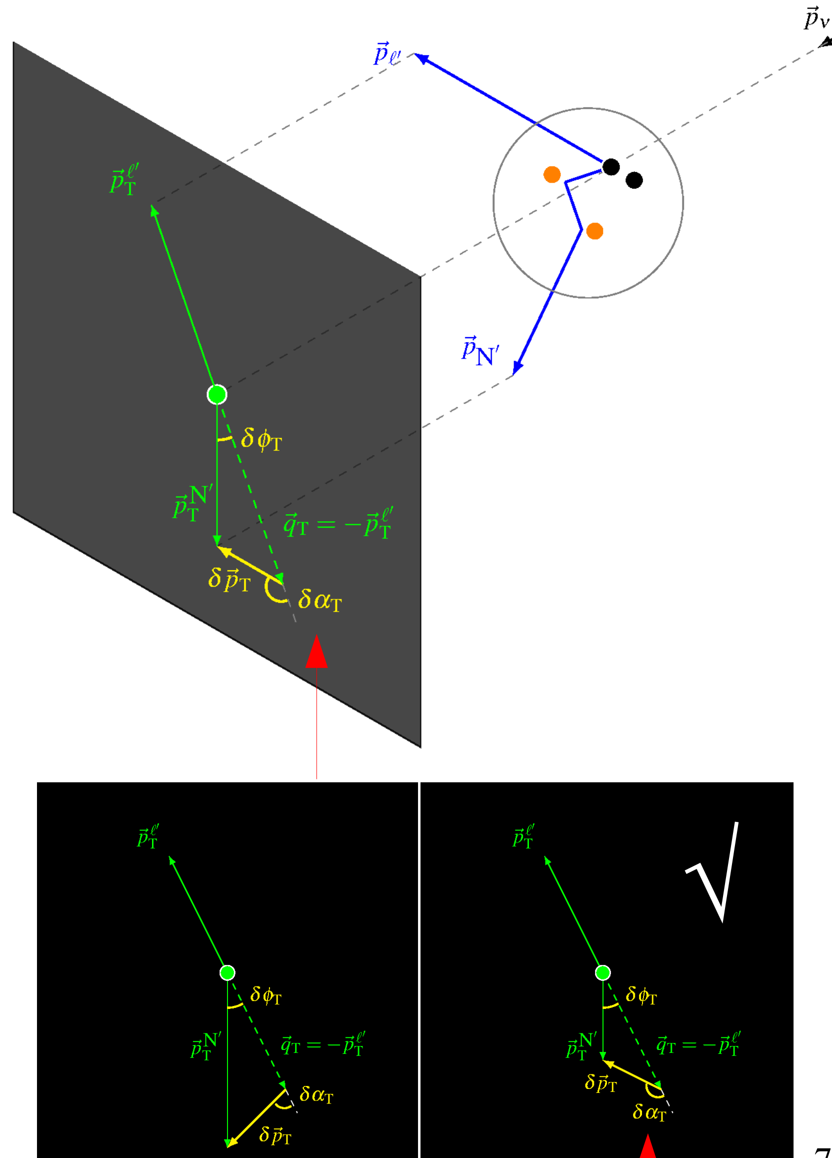
FSI dynamics

Transversely "accelerated" or "decelerated"

T2K measurement of single-transverse kinematic imbalances

Preliminary, Progress reports: arXiv:1605.00179, 1610.05077





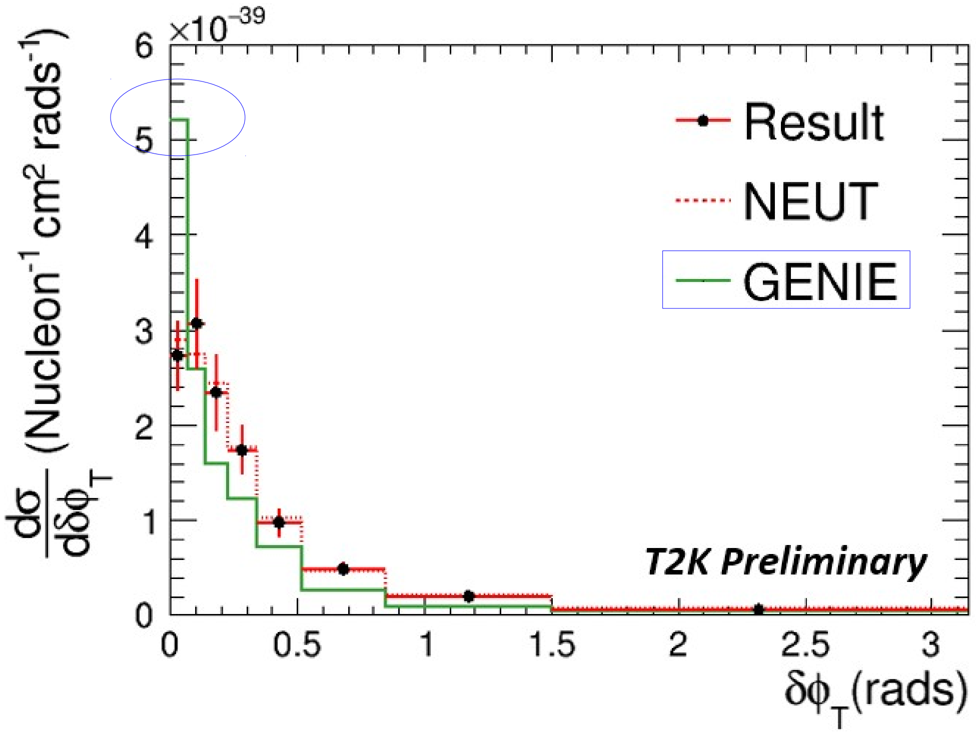
"deceleration"

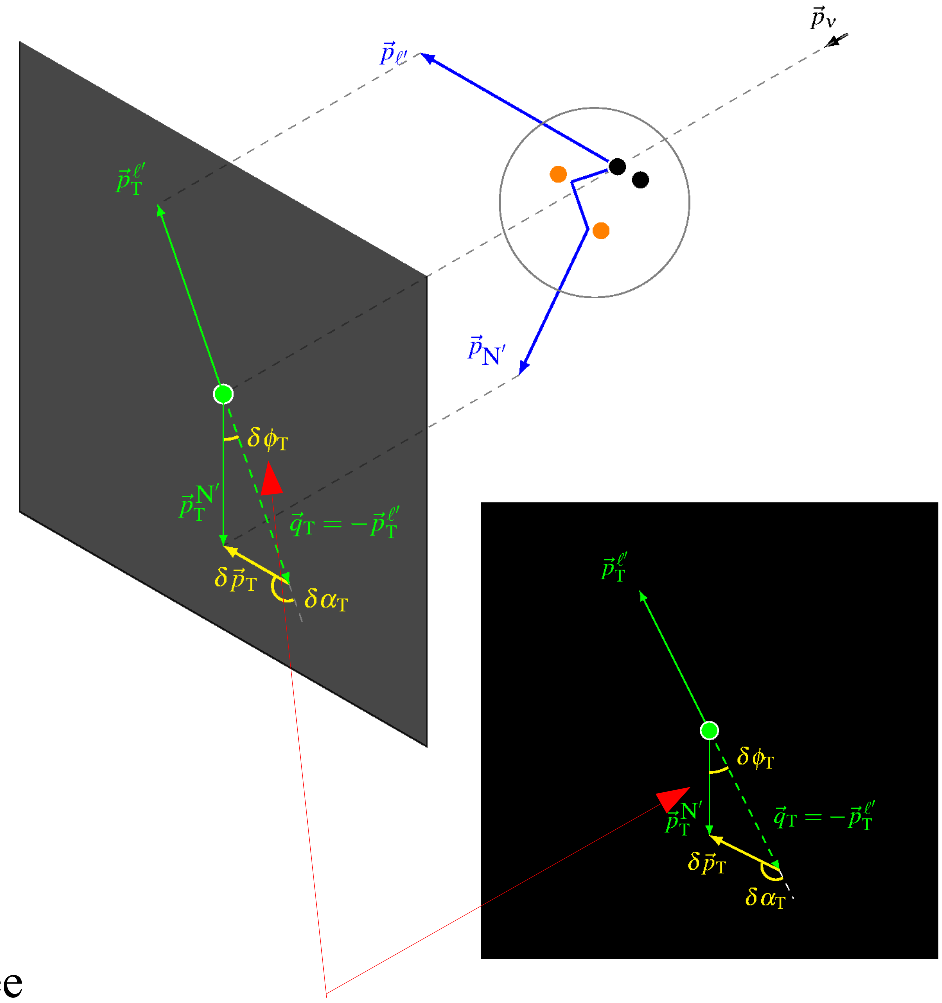
FSI dynamics

Transversely "decelerated"

T2K measurement of single-transverse kinematic imbalances

Preliminary, Progress reports: arXiv:1605.00179, 1610.05077





- Large discrepancy between NEUT and GENIE
  - not seen in single-particle kinematics.

- Highlighted GENIE features ("collinear enhancement") all originate from its FSI model, see discussions in [Phys.Rev. C94 (2016) no.1, 015503]:
  "the GENIE Collaboration suggested to investigate the effect of the elastic interaction of the hA FSI model."

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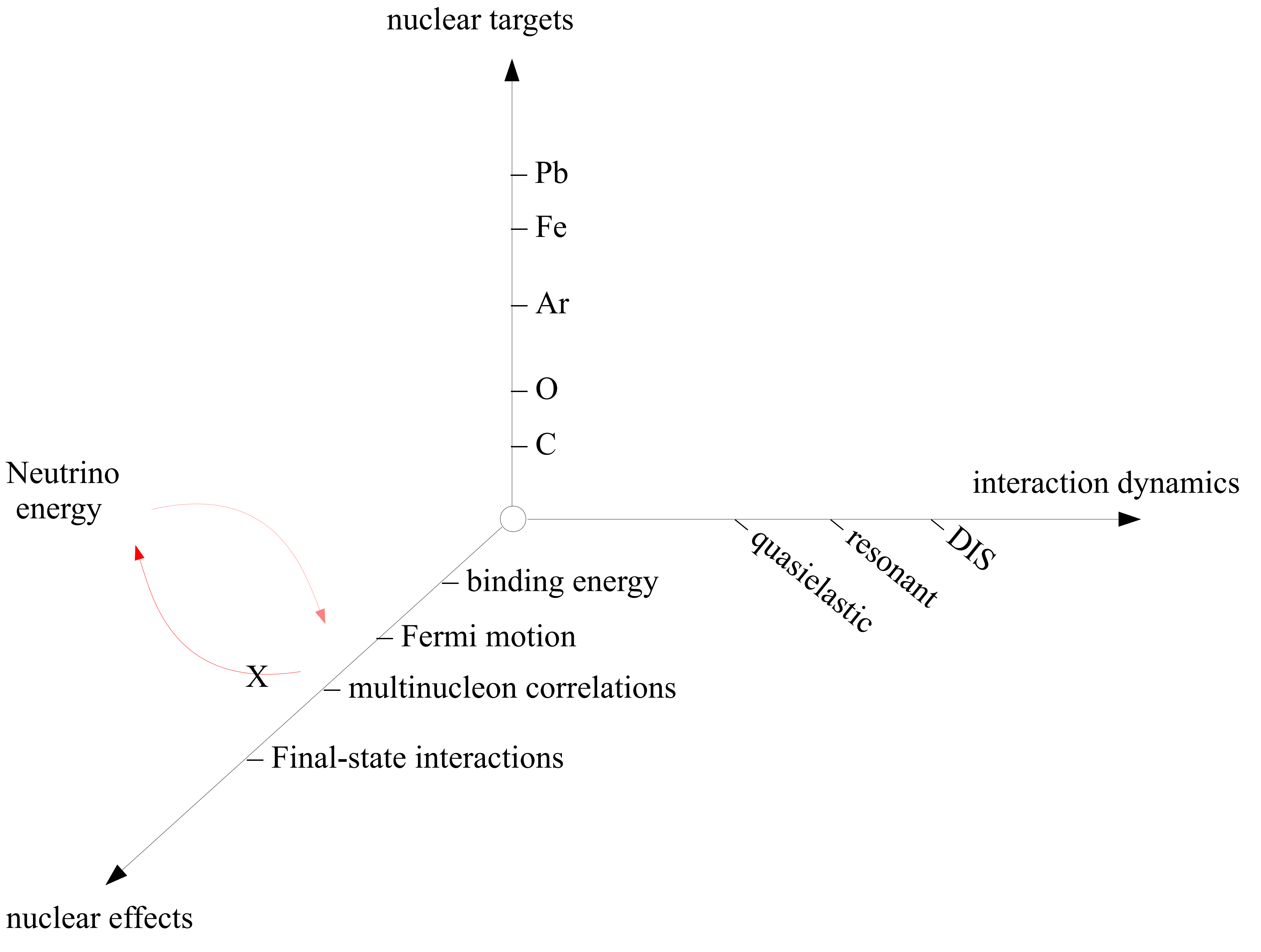
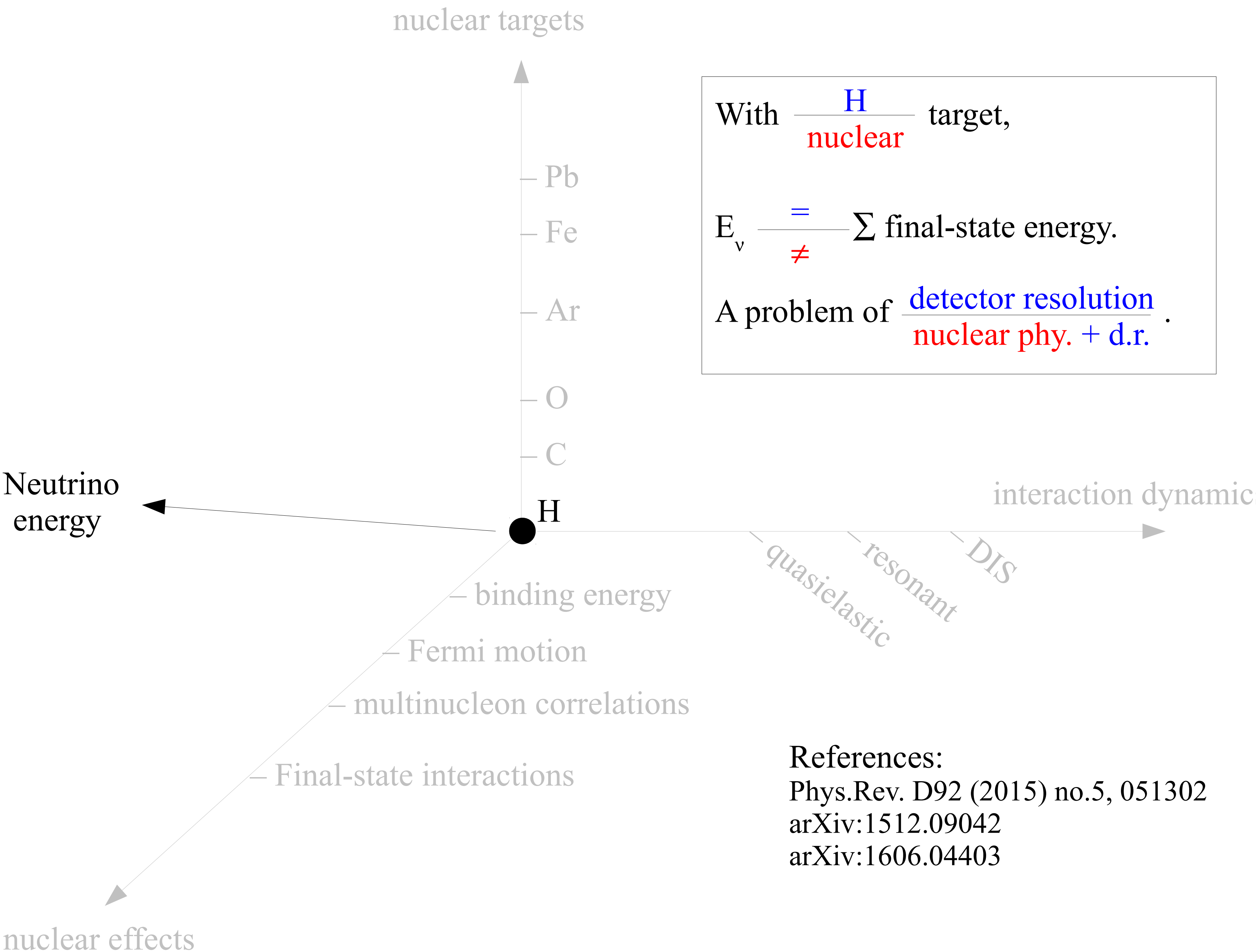

nuclear targets
Pb
Fe
Ar
O
C
Neutrino
energy
interaction dynamics
quasielastic
resonant
DIS
binding energy
Fermi motion
X
multinucleon correlations
Final-state interactions
nuclear effects



With $\frac{\text{H}}{\text{nuclear}}$ target,

$E_\nu \; \frac{=}{\neq} \; \sum$ final-state energy.

A problem of $\frac{\text{detector resolution}}{\text{nuclear phy. + d.r.}}$.

References:

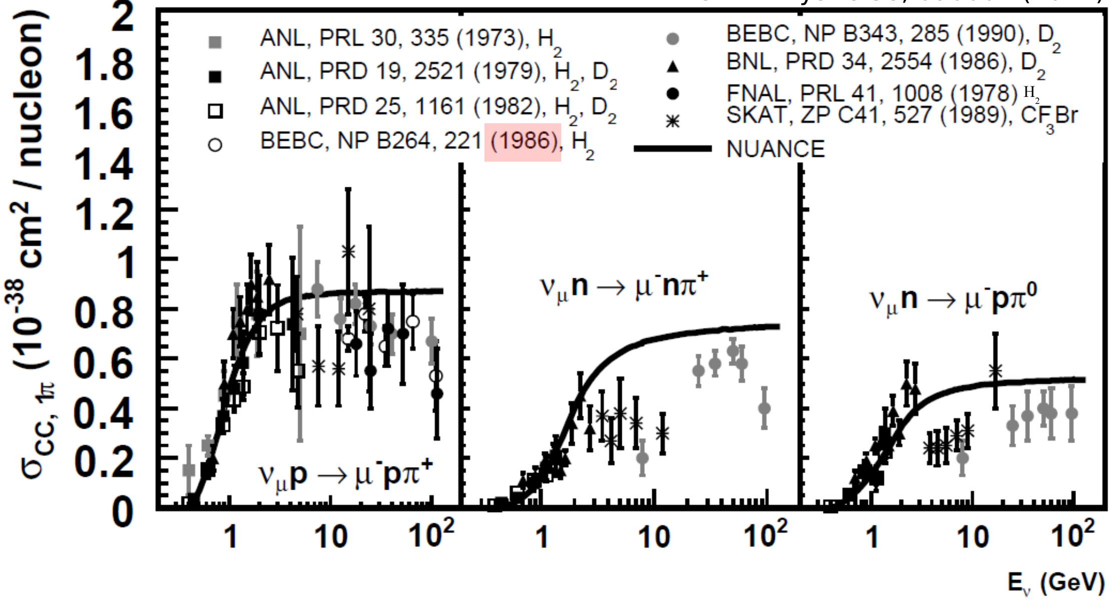
Phys.Rev. D92 (2015) no.5, 051302

arXiv:1512.09042

arXiv:1606.04403

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

Chin. Phys. C 38, 090001 (2014)



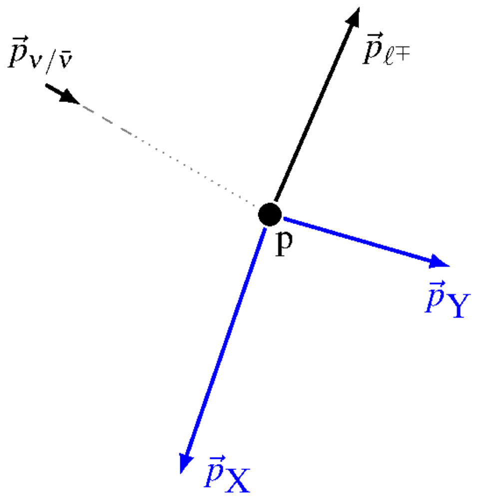
  - Safety issue: explosive
    - "*Since the use of a liquid H2 bubble chamber is excluded in the ND hall* ***due to safety concerns****, ...*" [FERMILAB-PUB-14-022]
- In the last ~30 years there has been no new measurement of neutrino interactions on pure hydrogen.

Double-Transverse kinematic imbalance

Lepton-proton interaction → 3 charged particles: l p → l' X Y

- Leading order realization in standard model:

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



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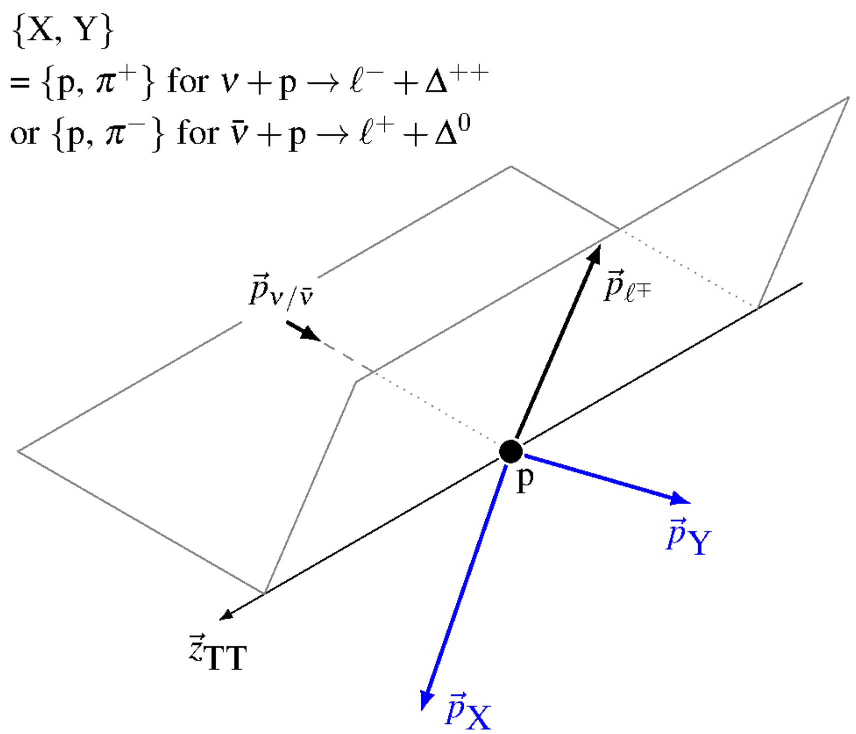

Double-Transverse kinematic imbalance

Lepton-proton interaction → 3 charged particles: l p → l' X Y

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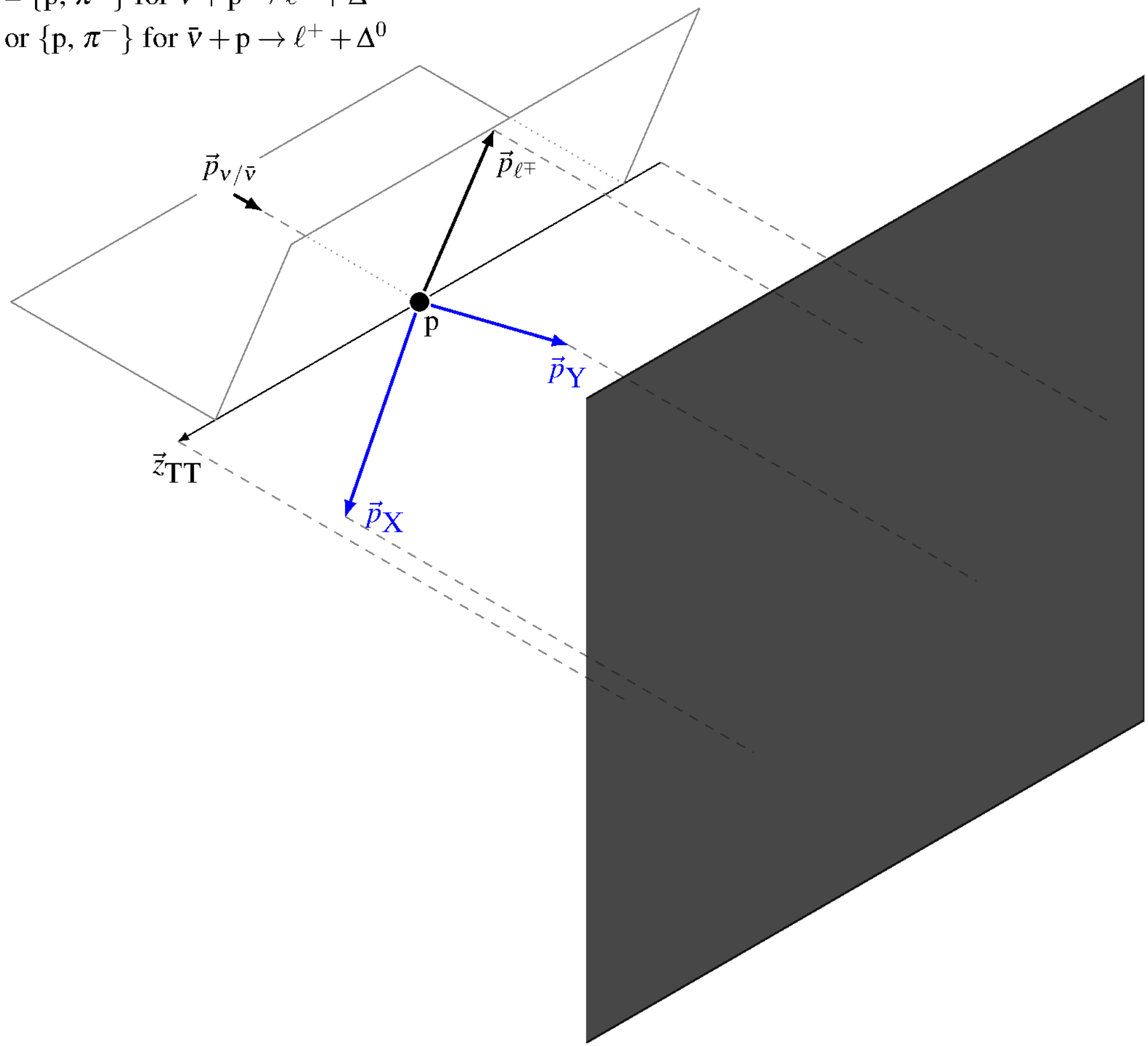
{X, Y}
= {p, π^+} for $\nu + \mathrm{p} \rightarrow \ell^- + \Delta^{++}$
or {p, π^-} for $\bar{\nu} + \mathrm{p} \rightarrow \ell^+ + \Delta^0$

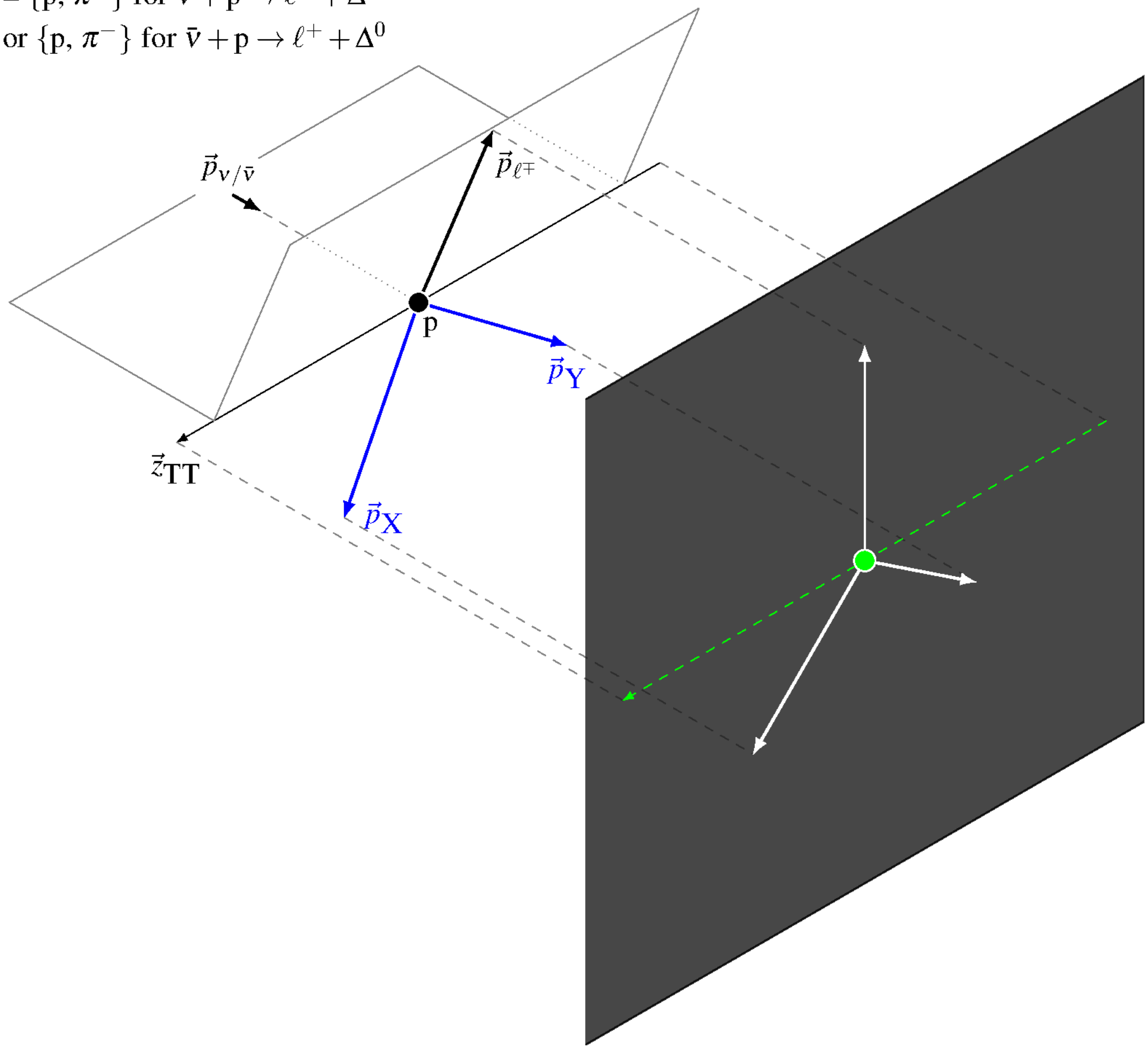


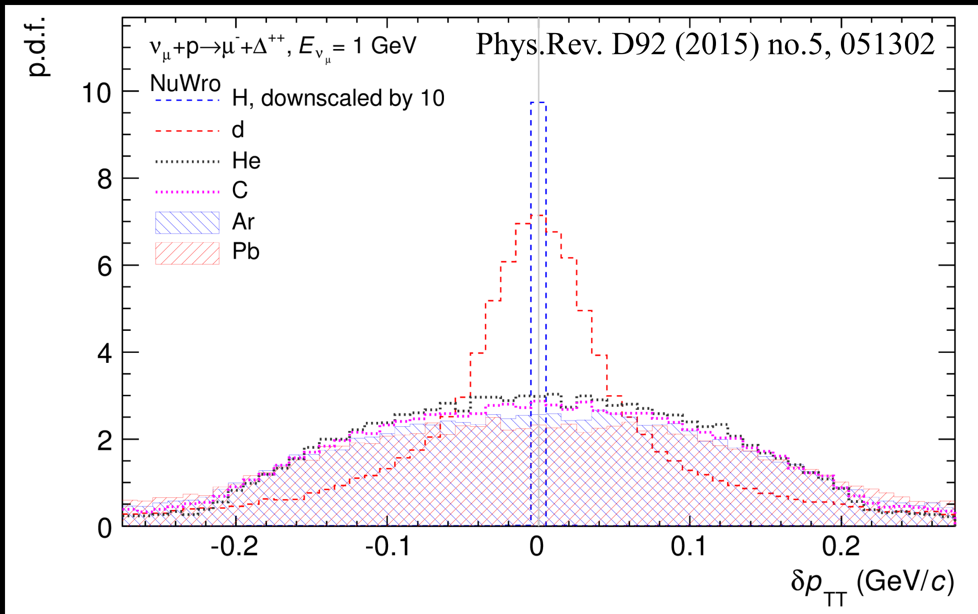
Double-Transverse kinematic imbalance

Lepton-proton interaction → 3 charged particles: $l\,\mathrm{p} \rightarrow l'\,\mathrm{X}\,\mathrm{Y}$

- Leading order realization in standard model:

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





$\{X, Y\}$
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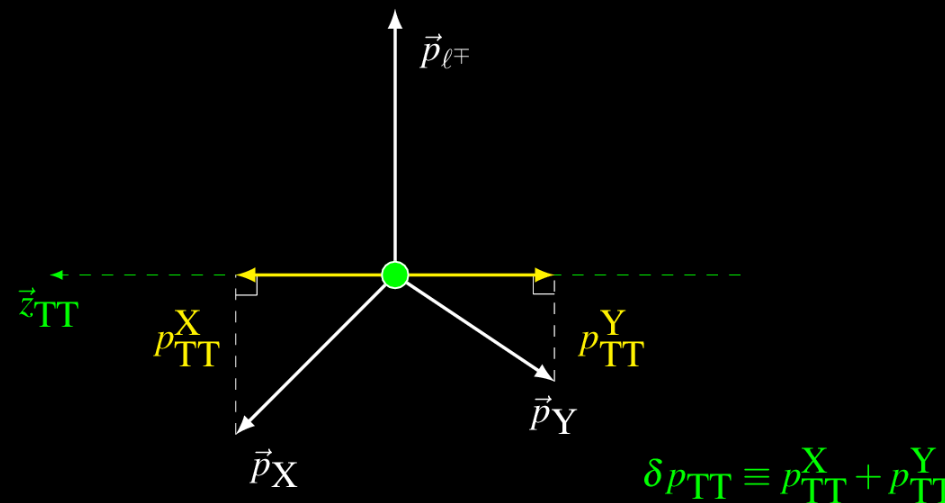
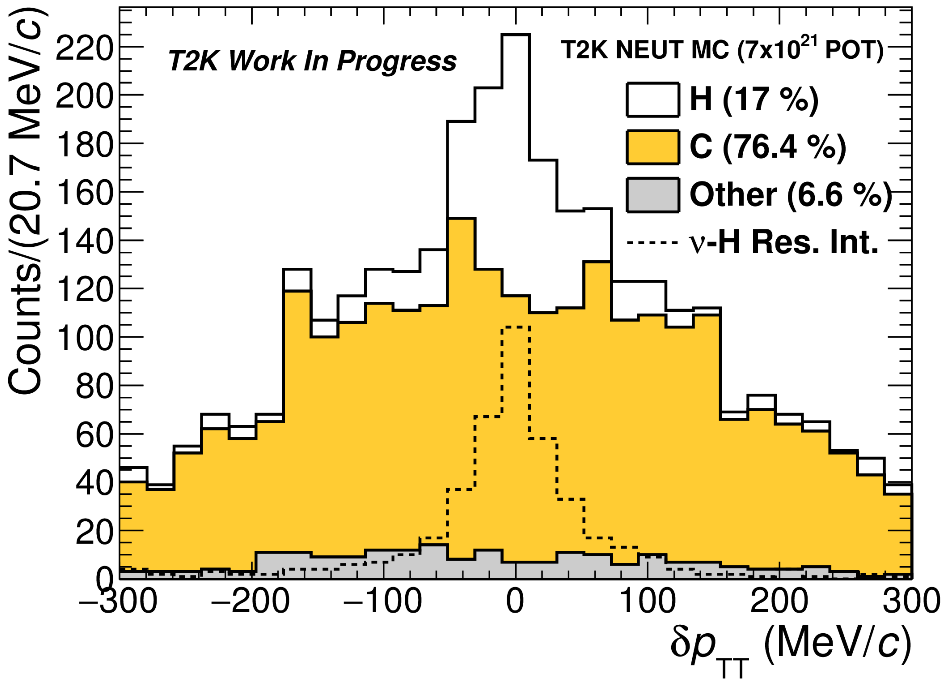


Double-transverse momentum imbalance δp_{TT}

- H: 0
- Heavier nuclei: irreducible symmetric broadening
  - by Fermi motion O(200 MeV)
  - further by FSI
- Hydrogen shape is only detector smearing.
  - With good detector resolution, hydrogen yield can be extracted.
  - With very good res., event-by-event selection of ν-H interaction is possible.

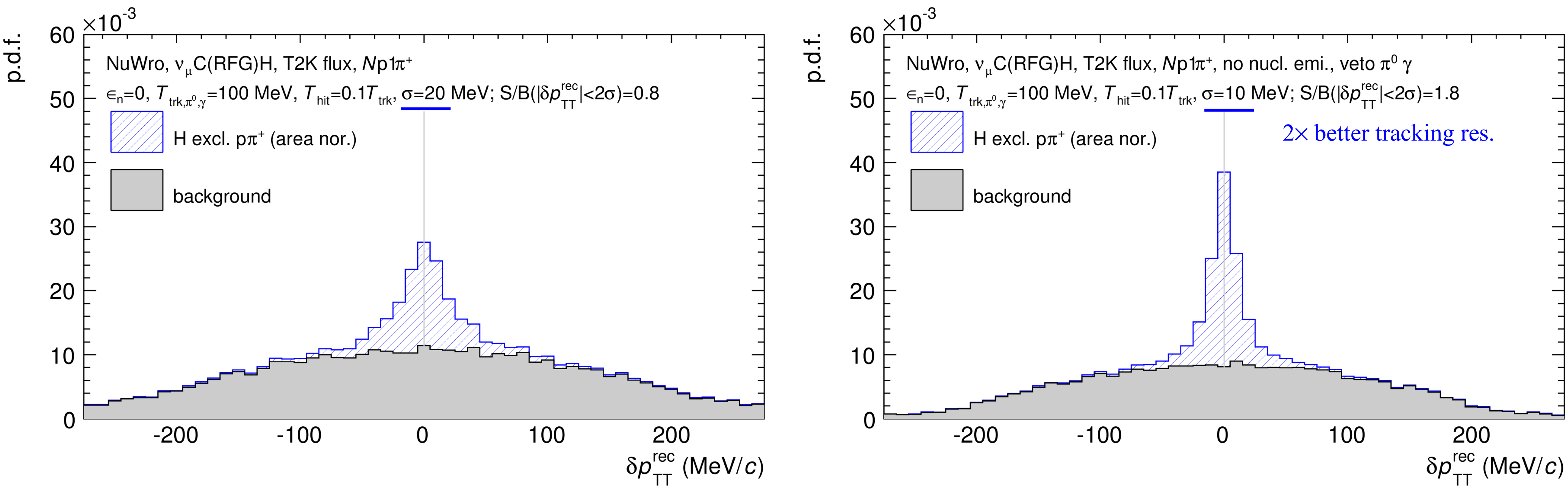
T2K measurement of double-transverse kinematic imbalances

Work in progress, Progress reports:
arXiv:1605.00154, 1610.06244



- Aim at first neutrino-pure hydrogen cross section measurement since 1986
  - ✓ Signal shape well known from detector simulation.
  - ✓ Background can be further constrained by single-transverse kinematic imbalances and measurements w/ pure nuclear target, e.g. graphite.
- Precise probe of nuclear effects in pion production via H/C cross section ratio: detector systemic uncertainties largely canceled (as C, H in same molecule).

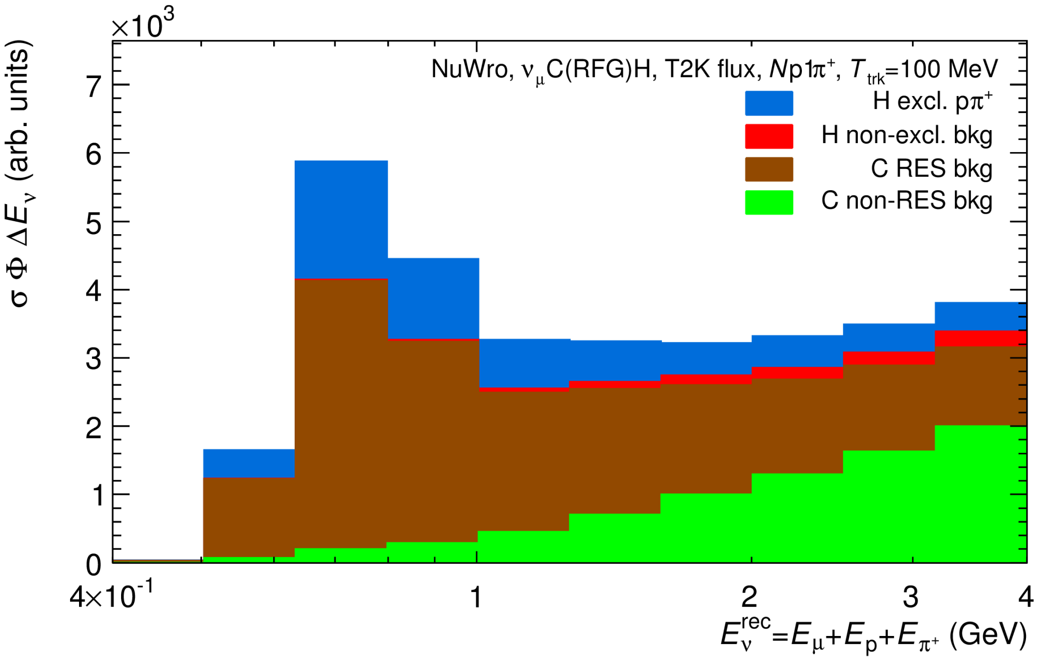
T2K performance projection

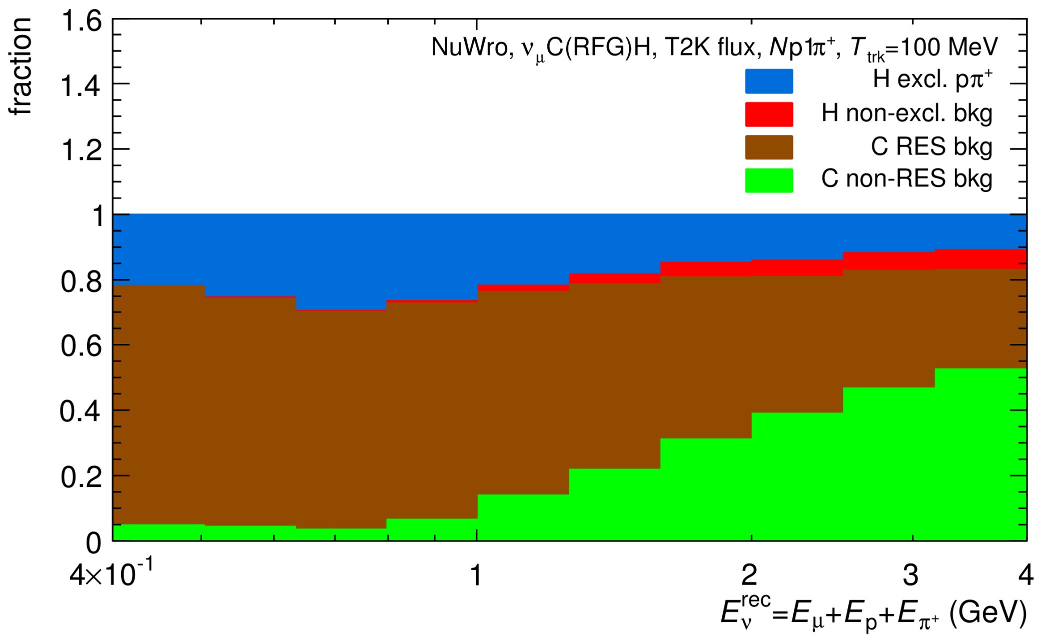


arXiv:1512.09042

- Requirement on nuclear physics decreases as resolution improves! Only need to look at $|\delta p_{TT}|<O(10\ \mathrm{MeV})$ region.

Recipe for nuclear-free neutrino energy spectra





Ideal acceptance w/ ideal tracking+PID

3-particle final state: μ, p, π^+

E_ν reconstructed as sum of final-state energy

H excl. pπ^+ signal

- Fraction: ~ 20% (blue-shifted peak) – 10% (tail)

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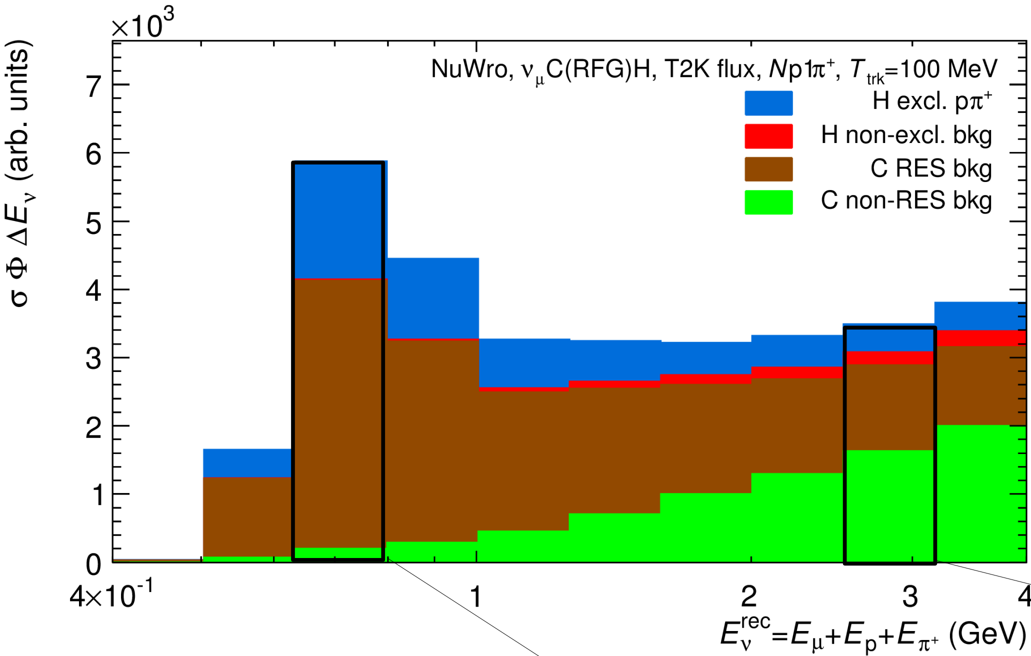

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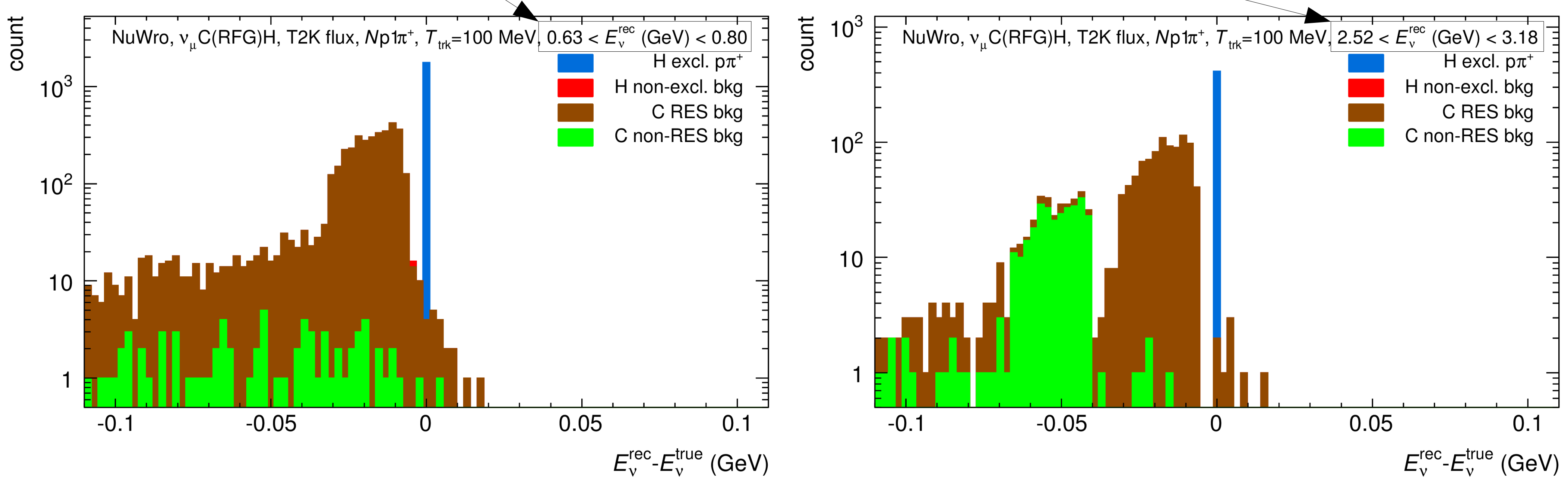

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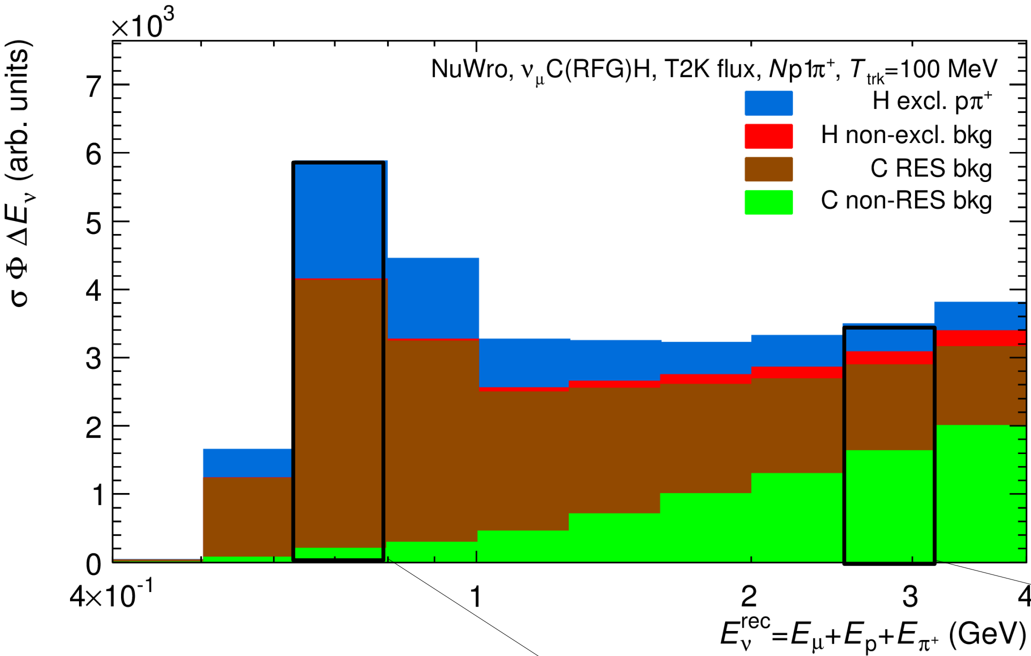

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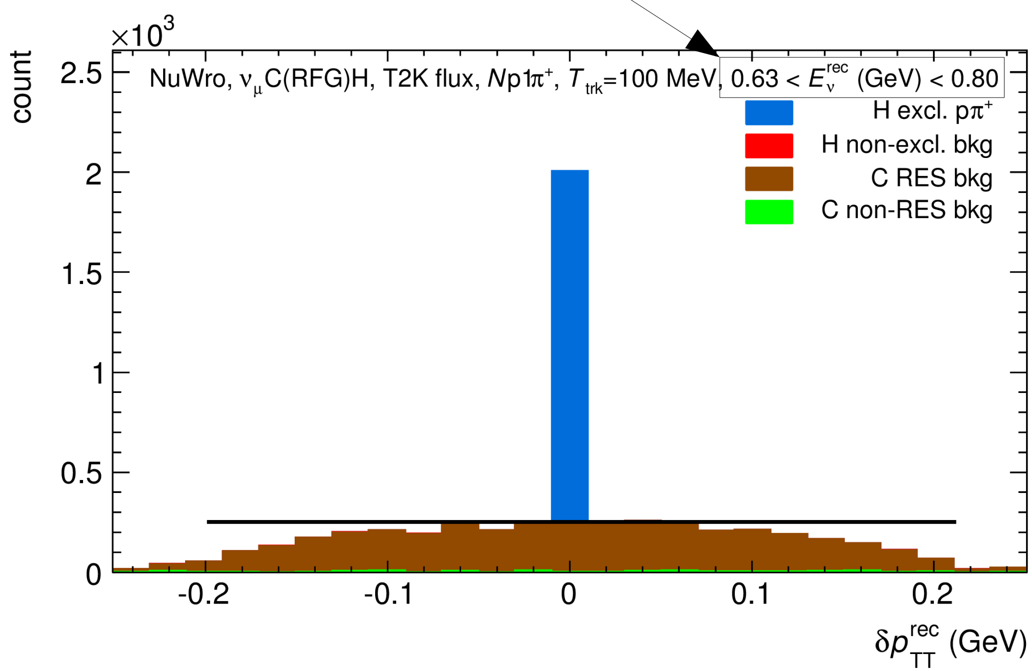

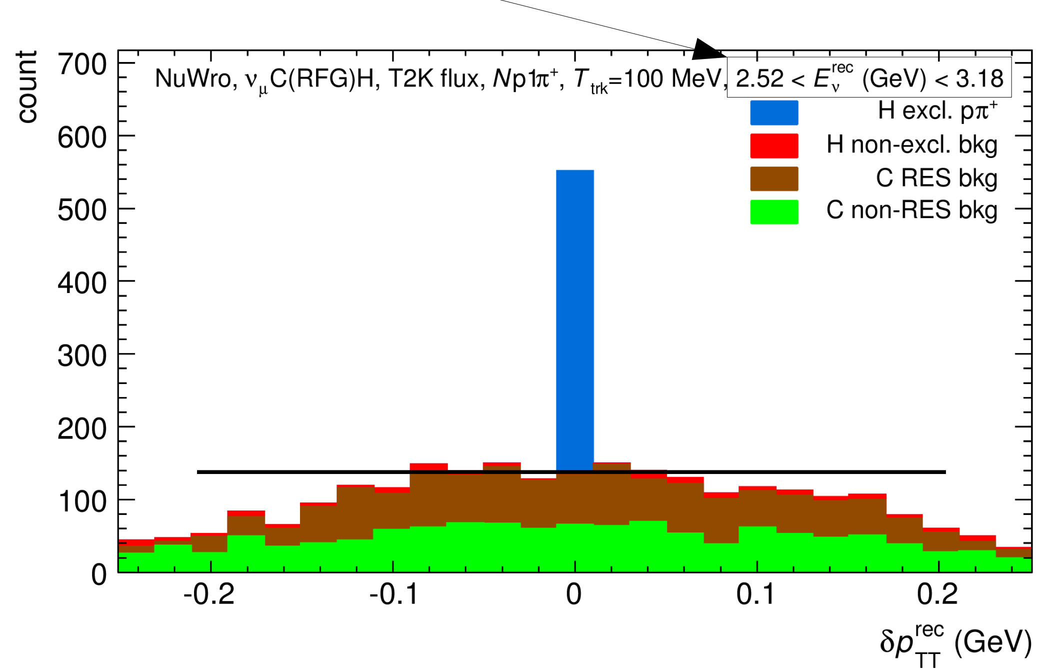

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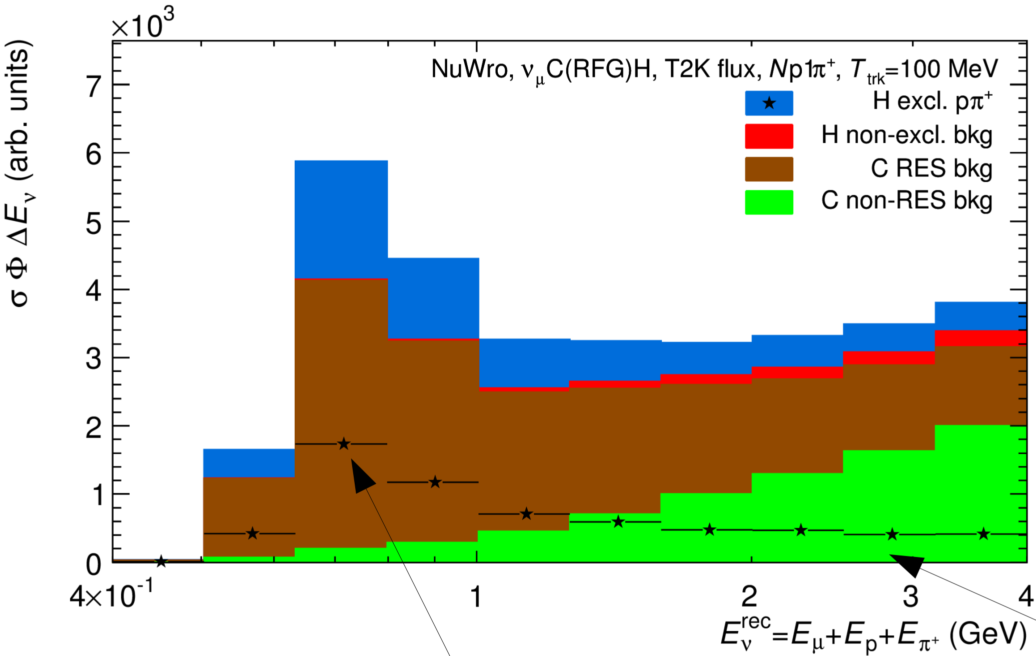


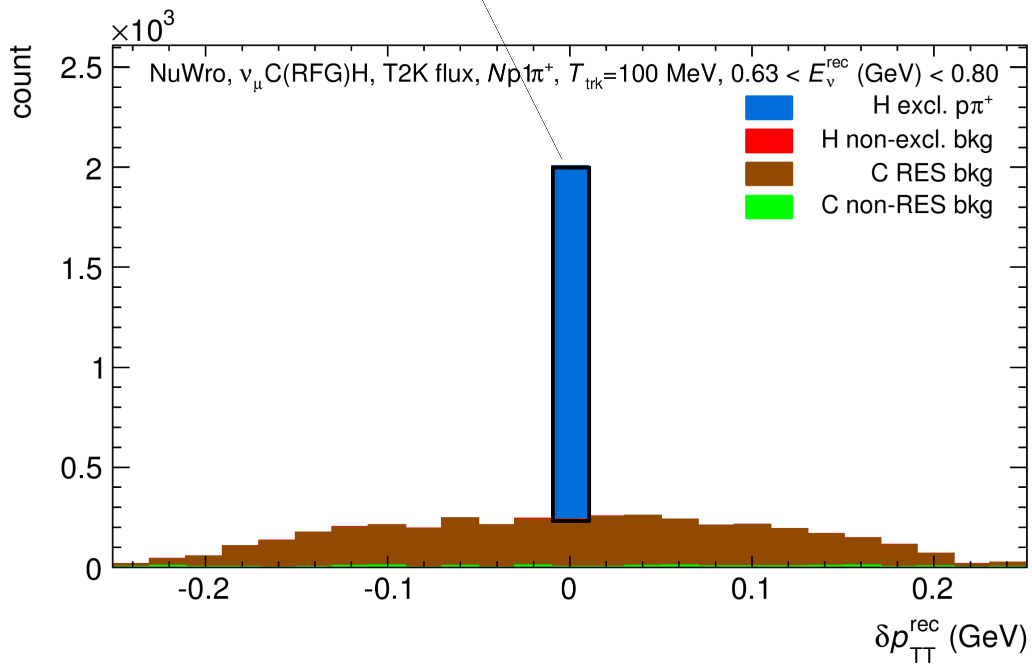
Ideal acceptance w/ ideal tracking+PID

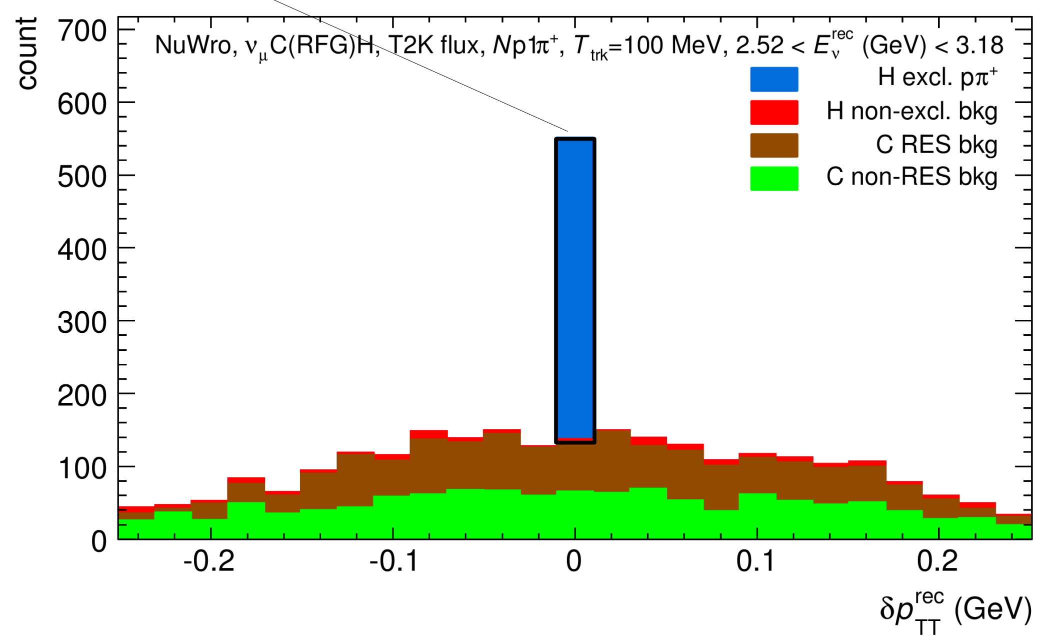
3-particle final state: μ, p, π^+

E_ν reconstructed as sum of final-state energy

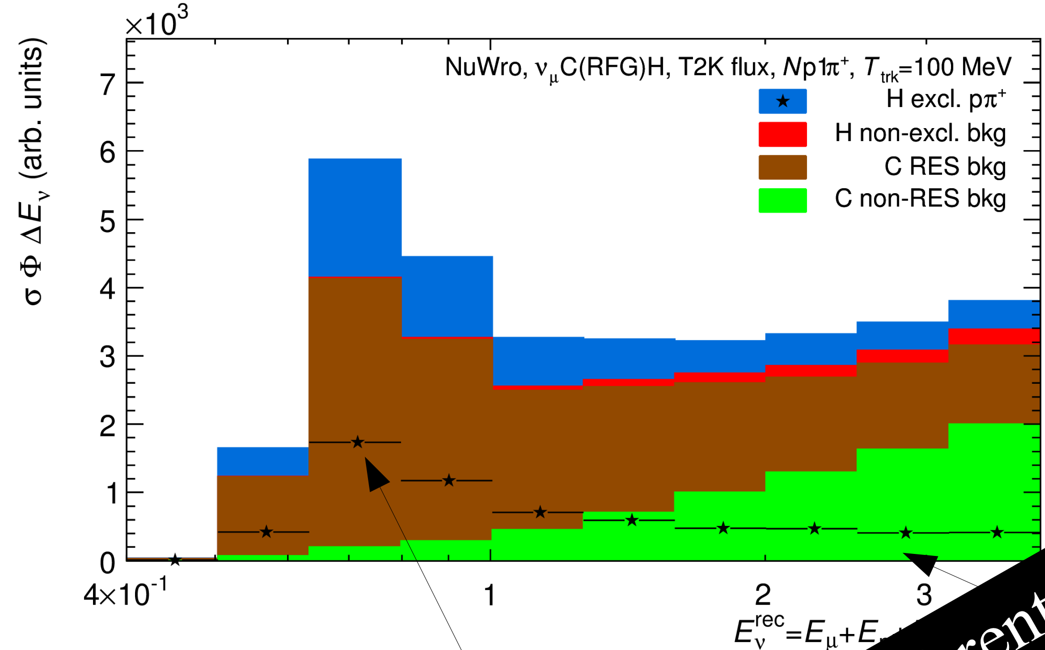
H excl. pπ^+ signal

- Fraction: ~ 20% (blue-shifted peak) – 10% (tail)
- No (nuclear) bias in reconstructed E_ν
- Can be extracted (statistically in realistic case)
- σ only nucleon cross section, Φ=N/(σ ΔE_ν)
  - both Φ and E_ν ***nuclear-free***
  - require tracking, PID (only needed for E_ν calculation), νH excl. pπ^+ x-sec





Recipe for nuclear-free neutrino energy spectra



Ideal acceptance w/ ideal tracking+PID

3-particle final state: μ, p, π^+

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H excl. pπ^+ signal

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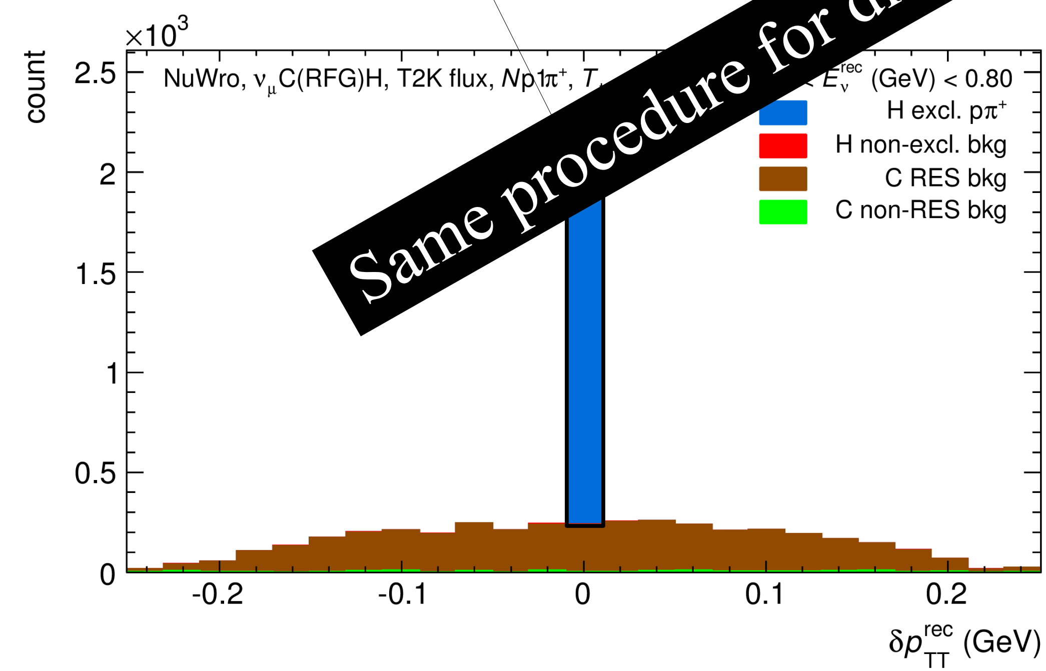
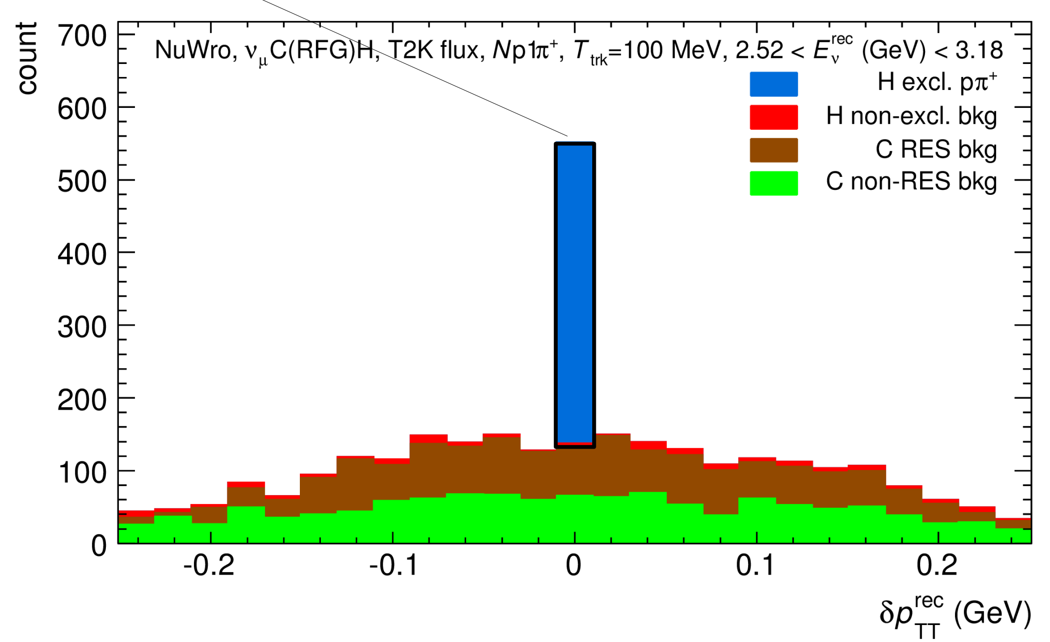
Same procedure for differential cross sections on W, Q^2, *etc.*





Outline

1. Understanding matter-antimatter asymmetry with neutrinos
2. Nuclear effects in neutrino-nucleus interactions
3. Measuring neutrino interactions
4. A neutrino shadow play

   Act One: Neutrino energy independent measurement of nuclear effects

   Act Two: Nuclear effect independent measurement of neutrino energy spectra
5. Summary

Summary

- Transverse kinematic imbalance = nuclear effects
  - A correlation between final-state lepton and hadrons:
    - In the transverse plane, lepton kinematics is used to cancel out nucleon level hadron kinematics; the rest is nuclear effects.
    - Least susceptible to neutrino energy and therefore flux uncertainty.
  - Single transverse kinematic imbalances: separate initial- and final-state nuclear effects
  - Double transverse kinematic imbalance:
    - Revive ν-H interaction measurements
    - Modern measurement of ν-nucleon fundamental interaction
    - Nuclear-free neutrino beam flux determination
- New trend in neutrino cross section measurements
  - Explore different interaction channels with various final-state kinematics
  - More precise probe of nuclear effects with semi-inclusive, exclusive variables
  - Final-state correlations

Source: http://www.cnhubei.com/ztmjys-pyts

BACKUP

The T2K Experiment

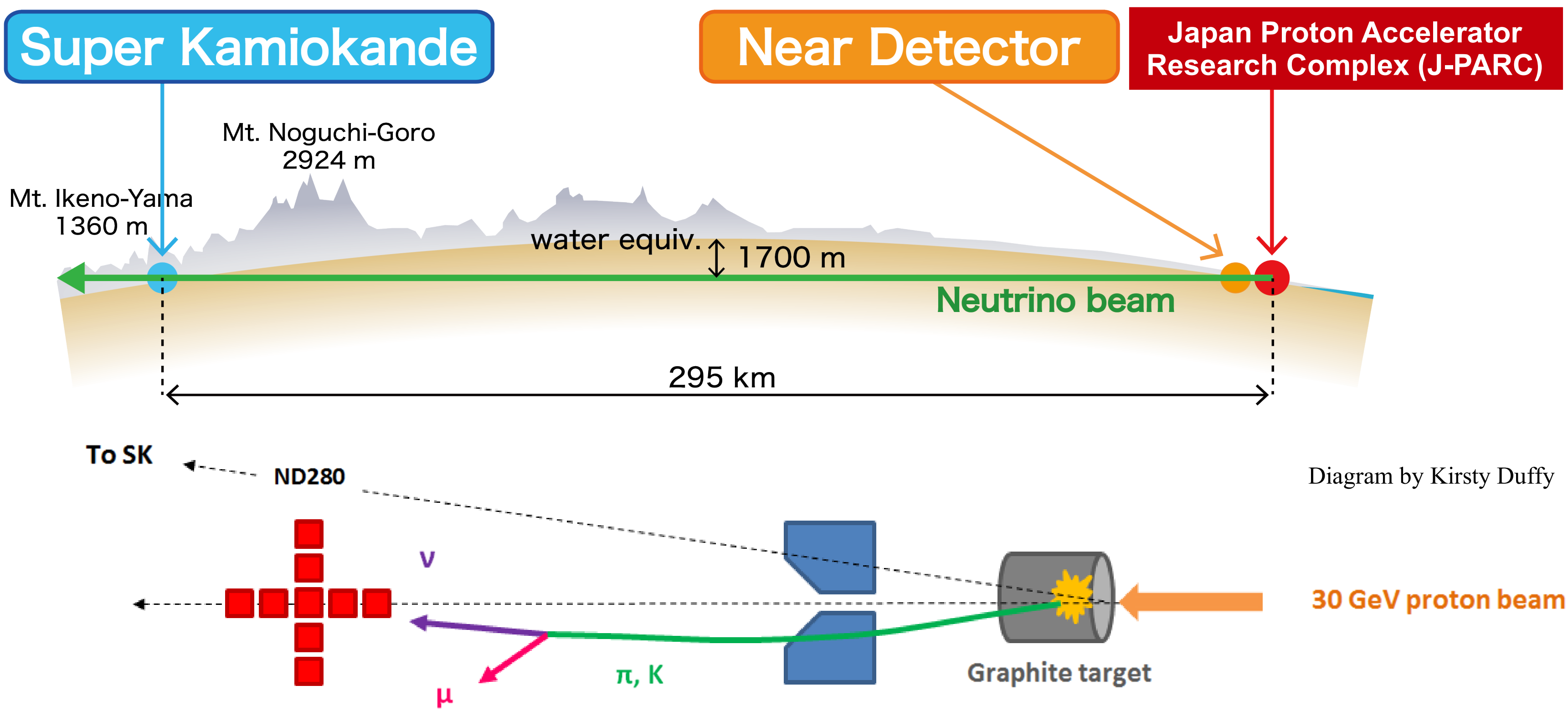
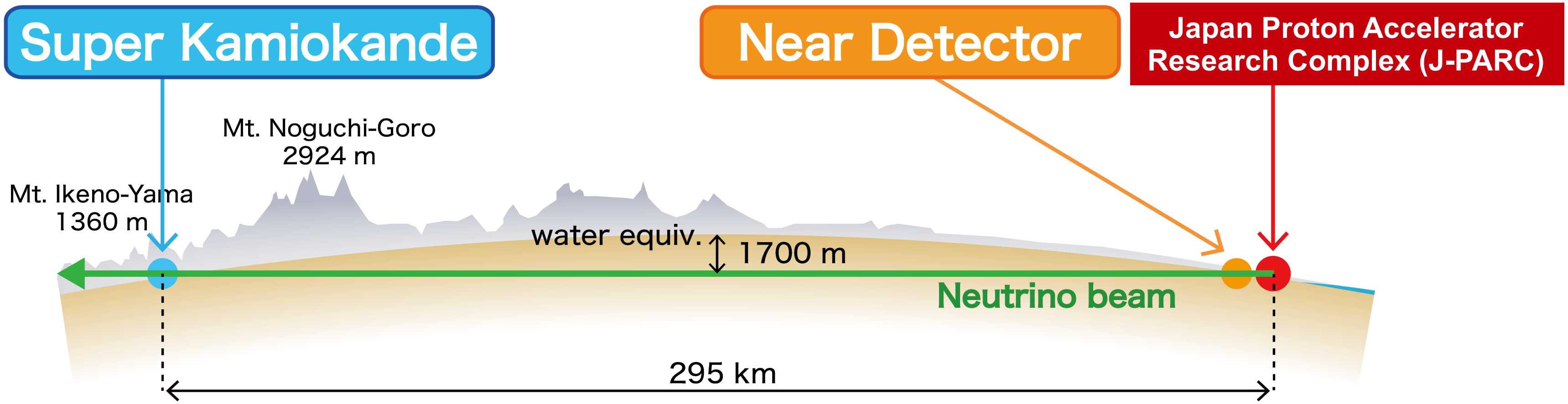
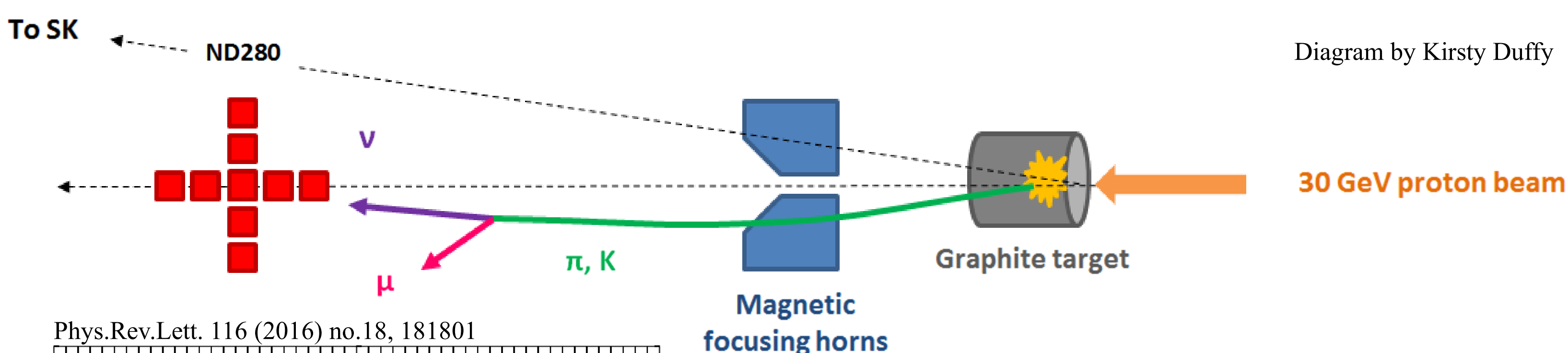


Diagram by Kirsty Duffy

The T2K Experiment





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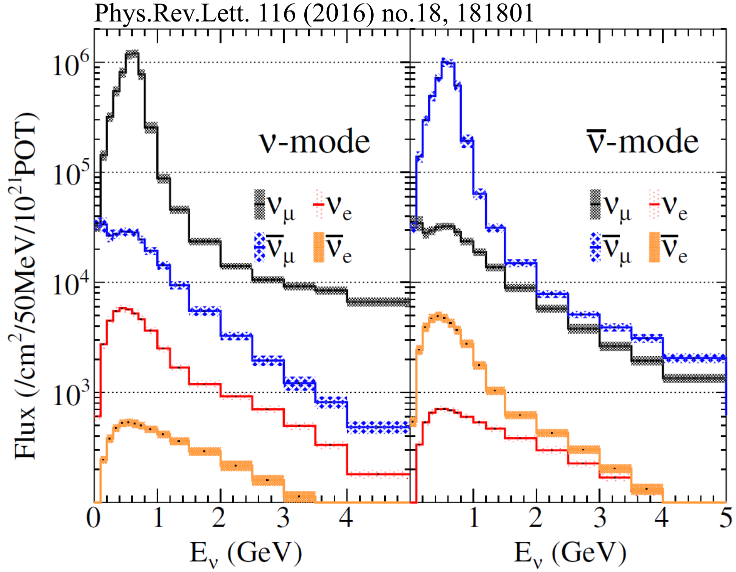
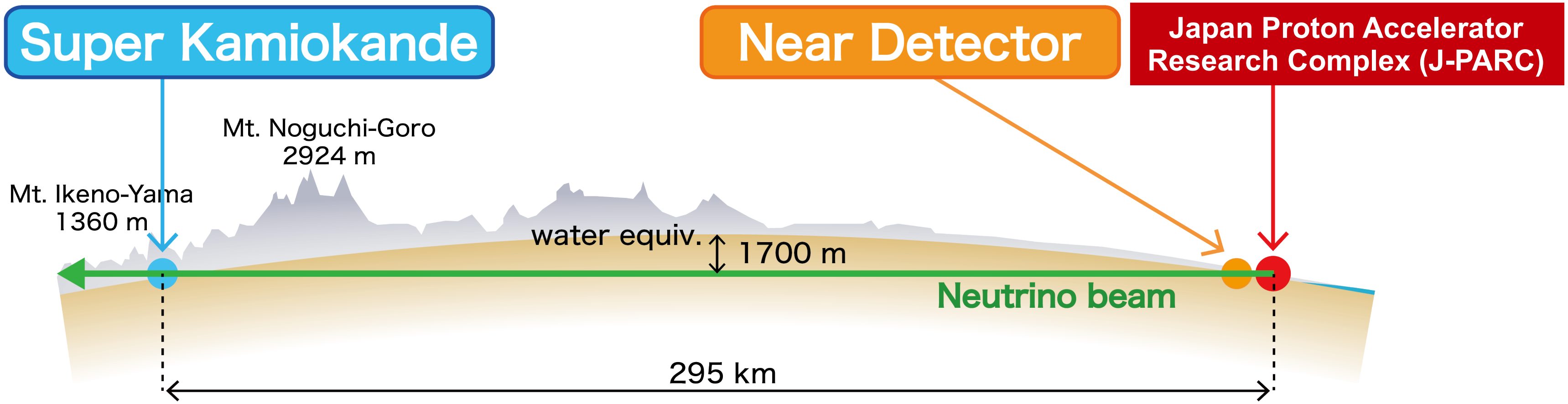
Phys.Rev.Lett. 116 (2016) no.18, 181801

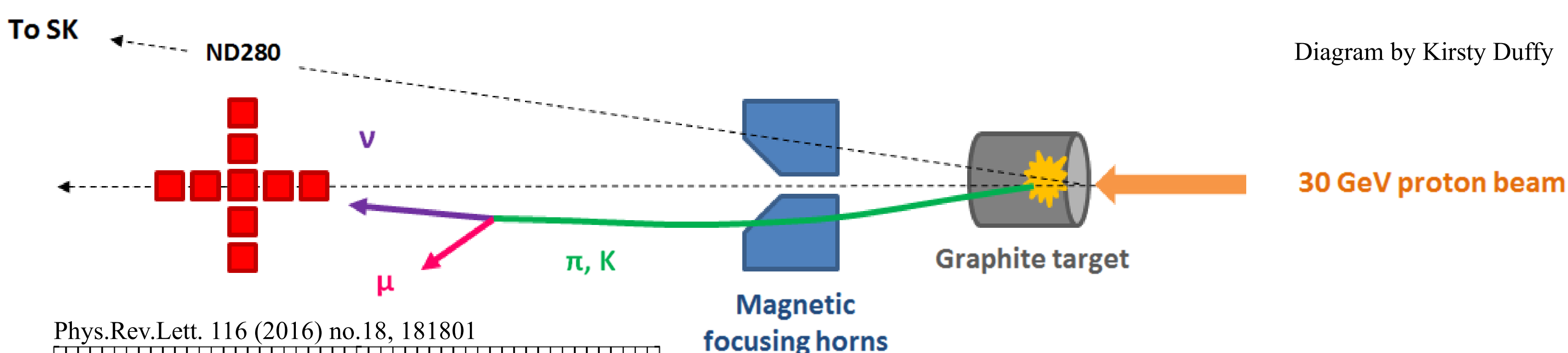


Charge selection on neutrino parents

→ ν or $\bar{\nu}$ mode

The T2K Experiment





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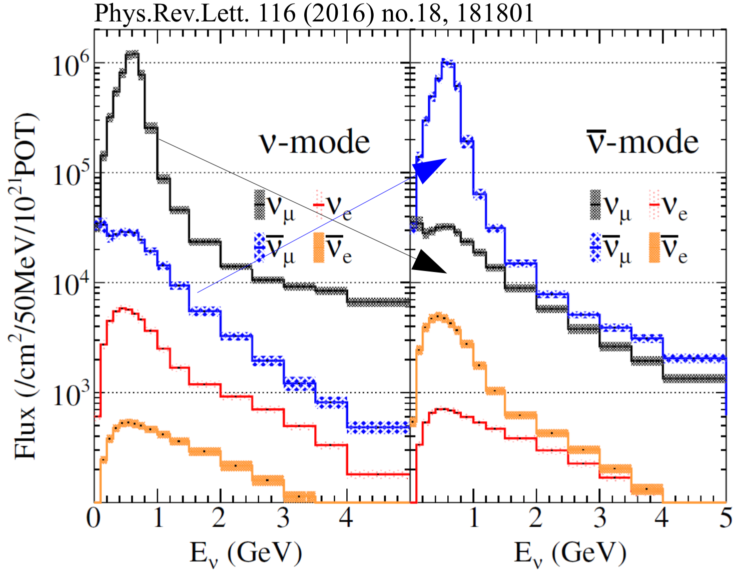

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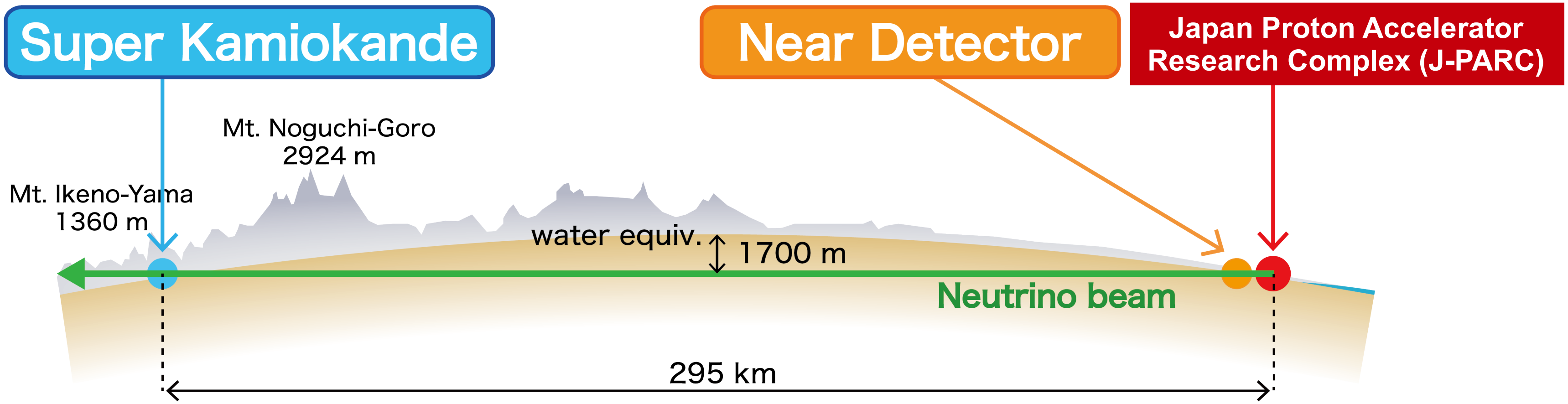

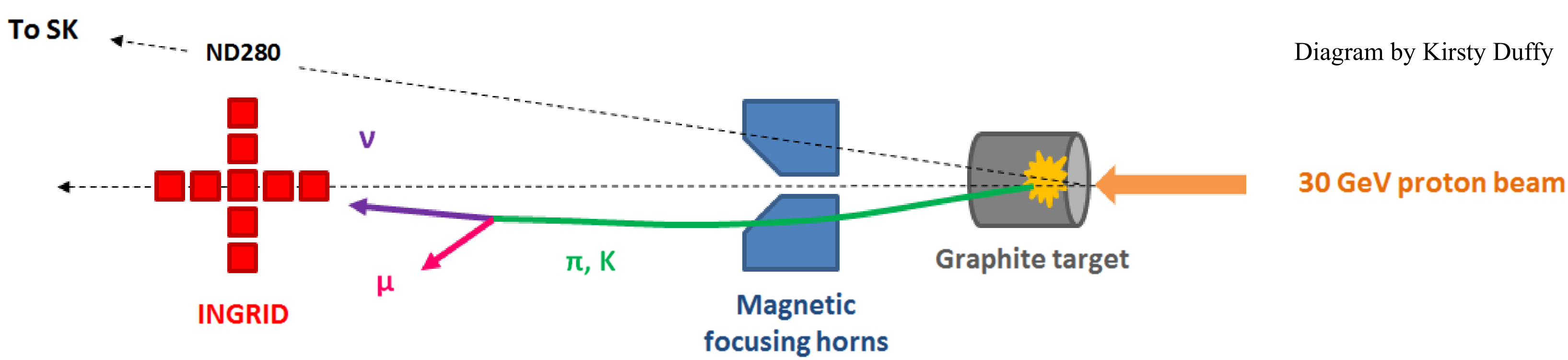

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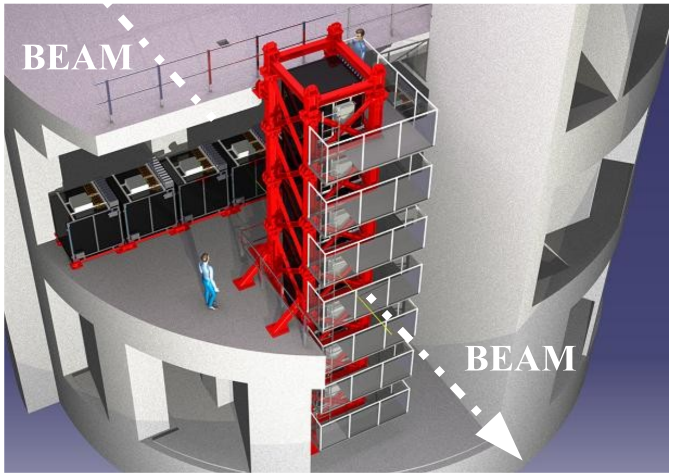
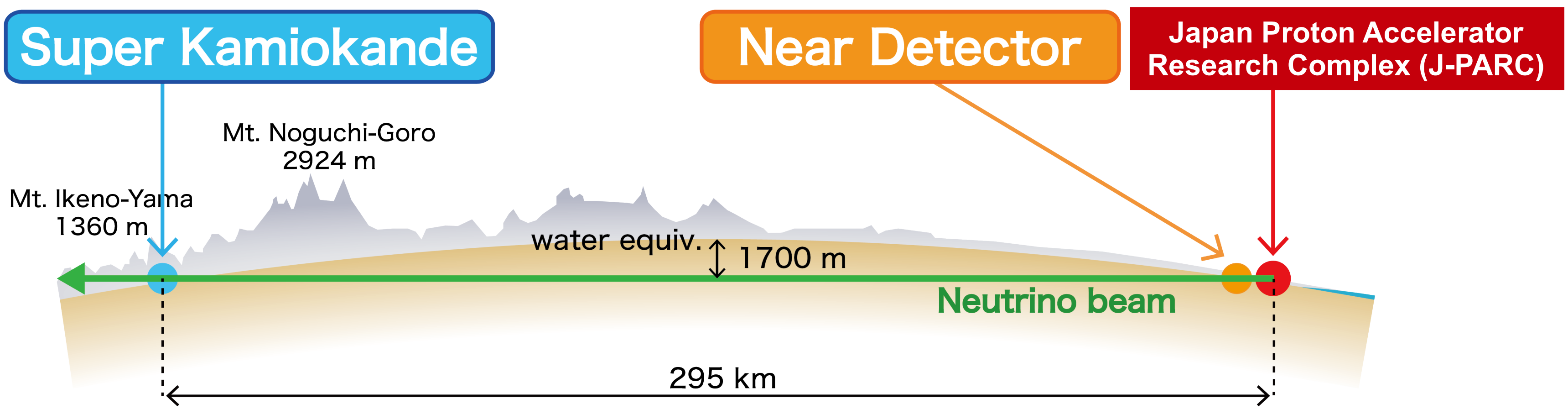


Crossed arrays of 9-ton iron-scintillator detectors

- Monitor neutrino beam stability and beam spatial profile
- estimate beam flux uncertainty
- stand-alone cross-section measurements

The T2K Experiment



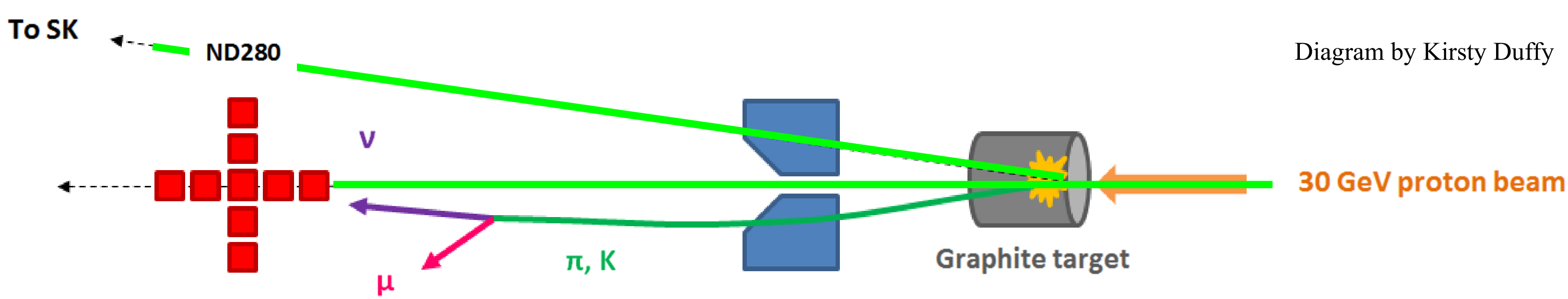
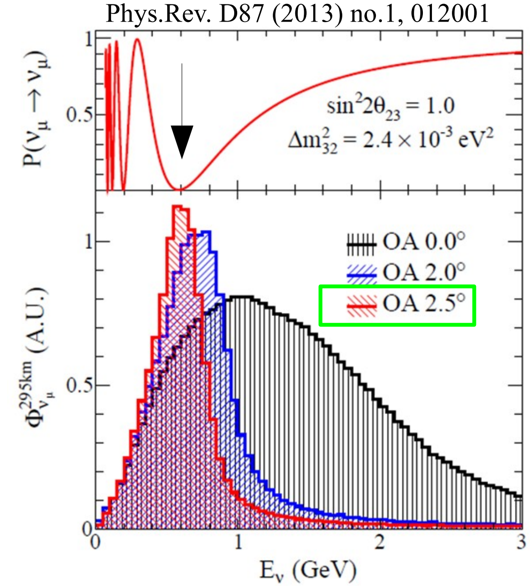


Diagram by Kirsty Duffy

Off-axis neutrino beams:
Reduce dependence on pion energy → narrow-band

Spectrum peak at maximum disappearance @SK

Phys.Rev. D87 (2013) no.1, 012001



END

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