Neutrino cross sections for future oscillation experiments

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based on A.M.A. & C. Mariani, J. Phys. G 44 (2017) 054001

Nuclear *ab initio* Theories and Neutrino Physics,
INT, University of Washington, Feb 26–Mar 30, 2018

Outline

1) **Introduction**
- Neutrino oscillations in a nutshell
- Near to far event-spectra ratio

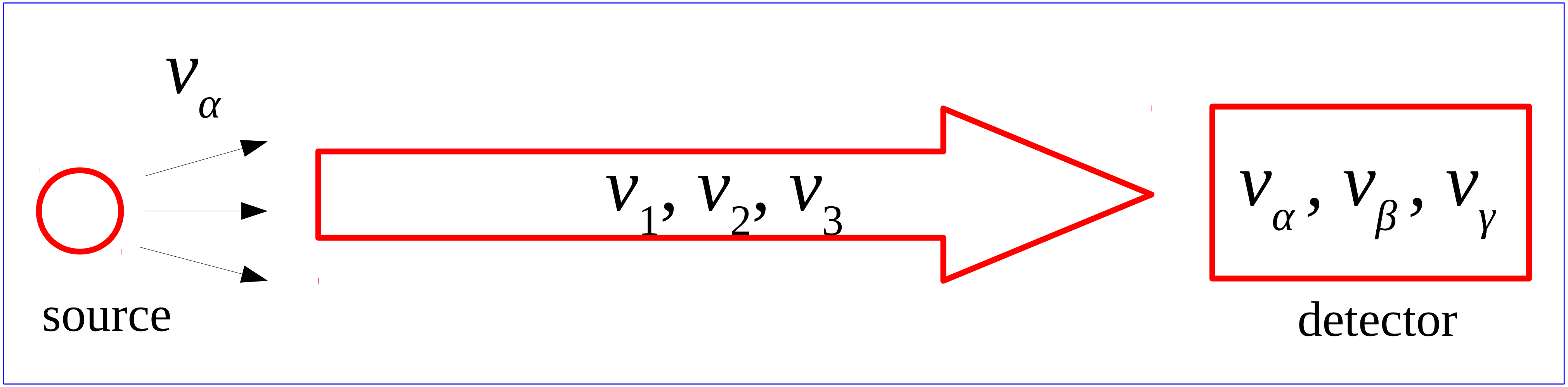
2) **Energy reconstruction**
- Kinematic and calorimetric methods
- Challenges

3) **Systematic uncertainties**
- Extrapolation between nuclei
- Cross section in the dip region
- Missing energy and nuclear effects in calorimetric energy reconstruction

4) **Summary**

Neutrino oscillations

Neutrino oscillations in a nutshell



- ν's produced in a given flavor α, **mixture of mass eigenstates**
- different masses propagate with **different phases**, e^{-itE_i}

$$tE_i = t\sqrt{m_i^2 + \mathbf{p}^2} = t|\mathbf{p}|\left(1 + \frac{m_i^2}{2|\mathbf{p}|^2}\right) = |\mathbf{p}|t + \frac{m_i^2 L}{2E_\nu}$$

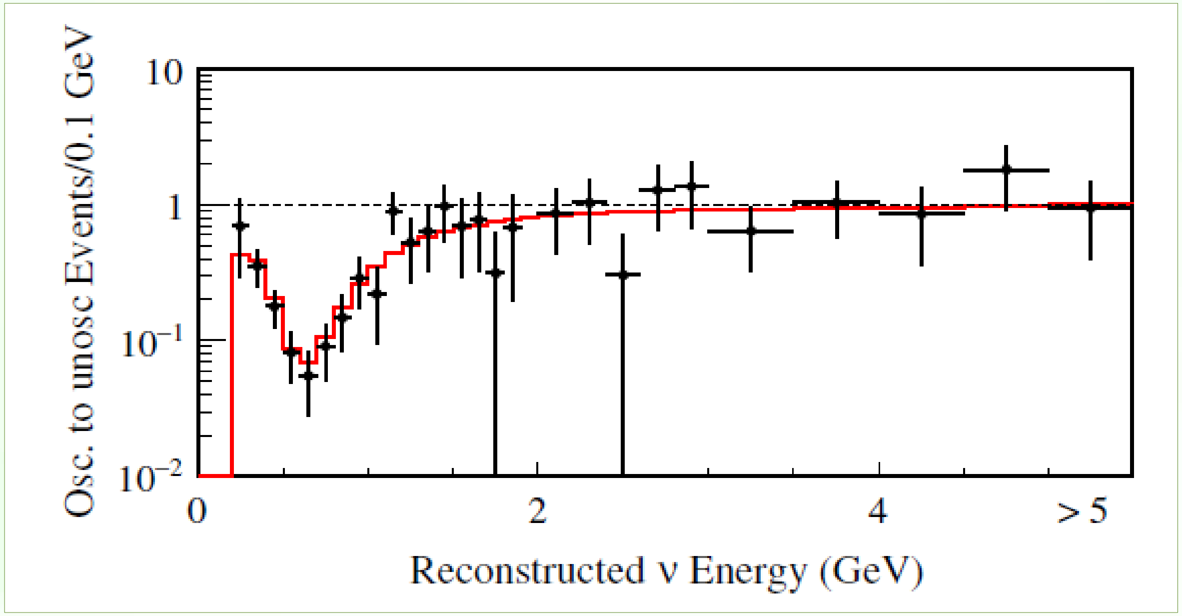
- detected mixture of mass eigenstates is, in general, different; appearance of **another flavors**, β and γ

Neutrino oscillations in a nutshell

In the simplest case of 2 flavors

$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Example [K. Abe *et al.* (T2K Collaboration), PRD 91, 072010 (2015)]



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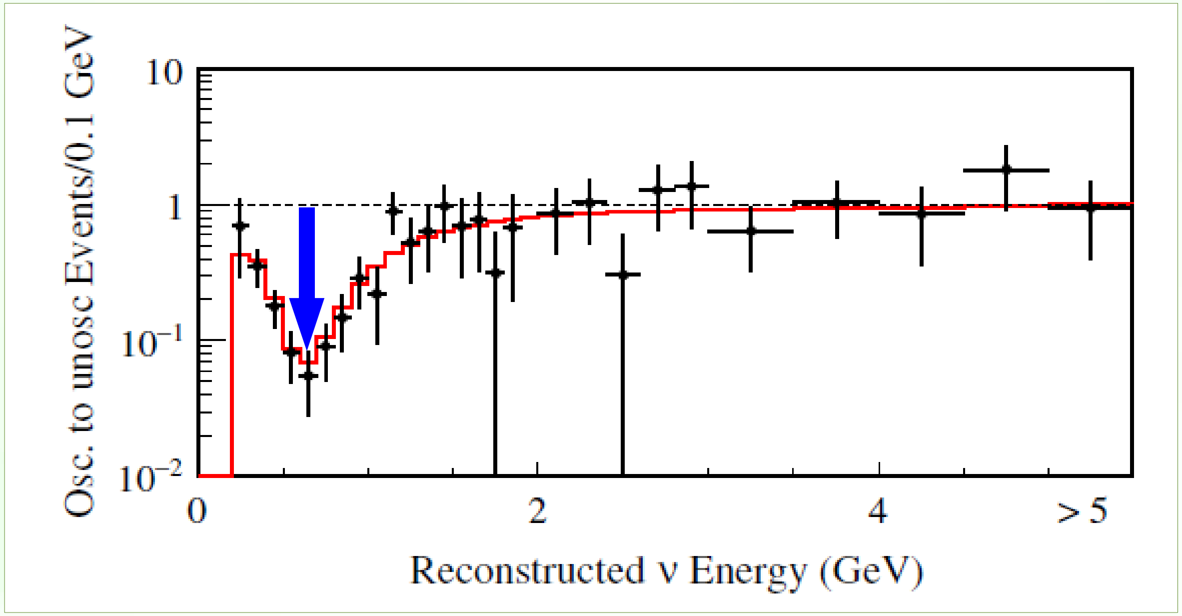

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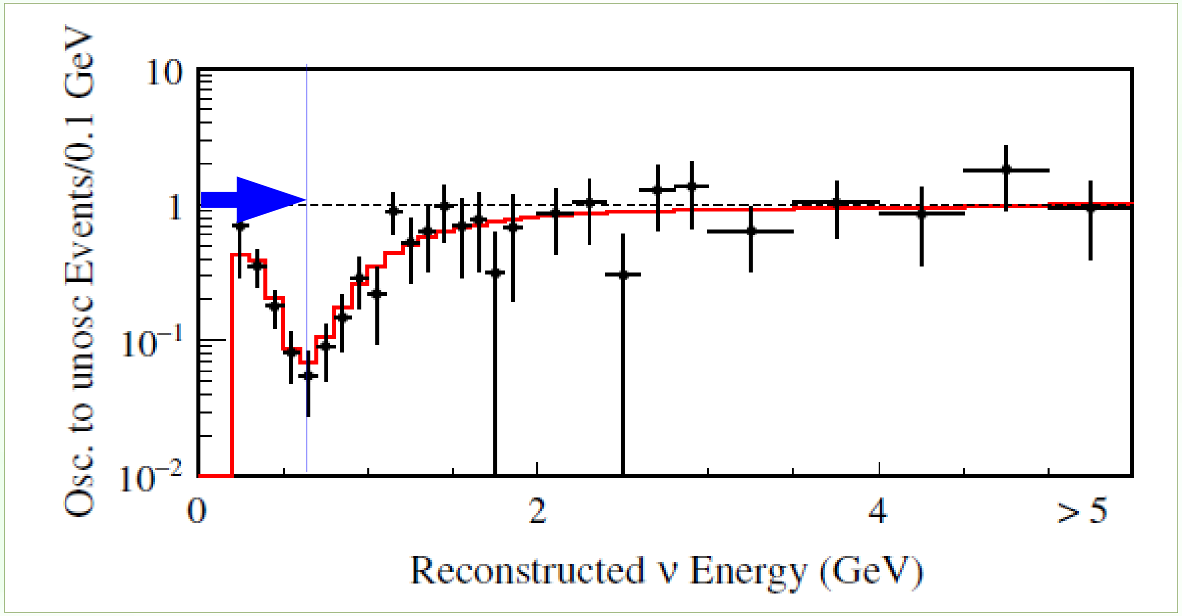
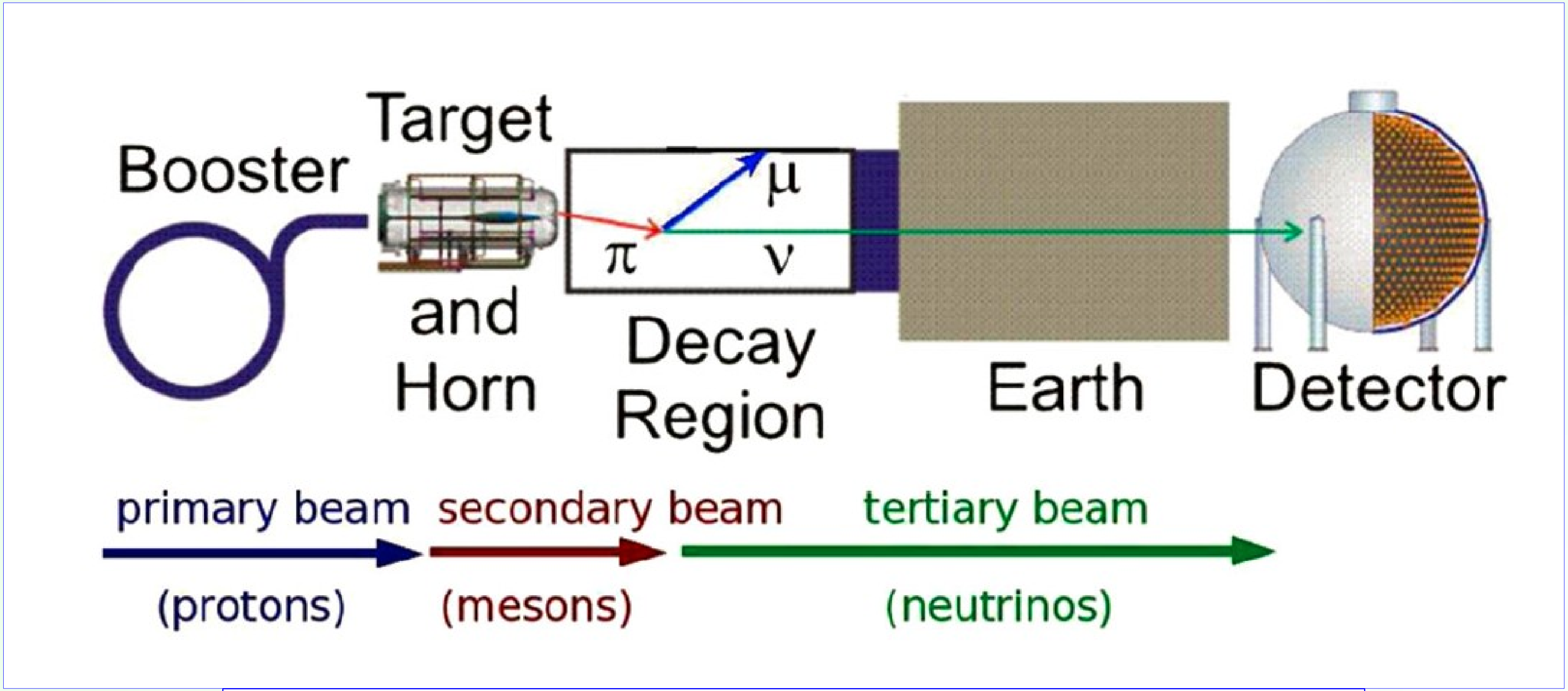
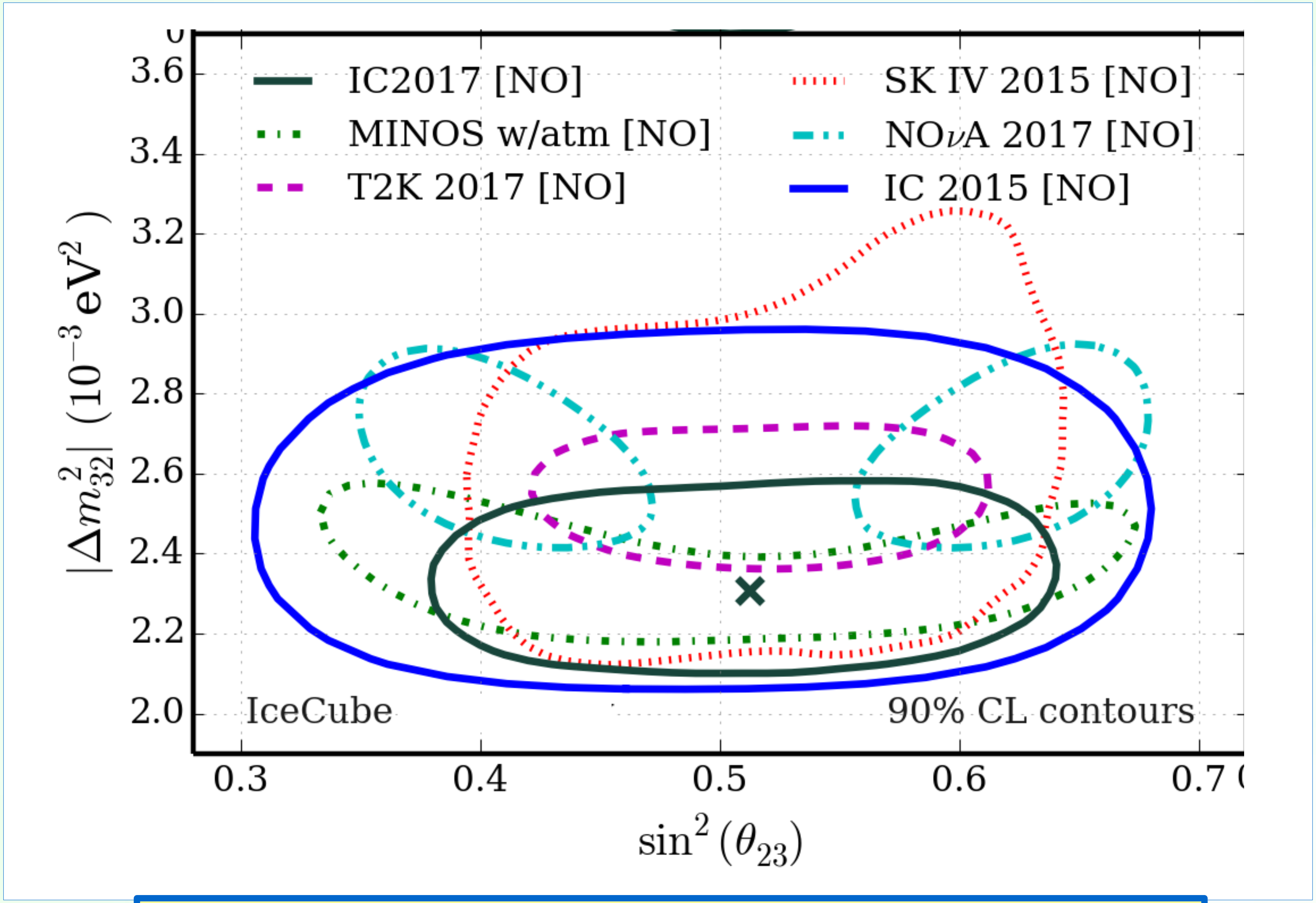


Neutrino beams



Aguilar-Arevalo et al. (MiniBooNE), D 81, 092005 (2010)

What precision are we achieving?



J. Hignight (IceCube), APS April Meeting, 2017
Aartsen *el al.*, PRL 120, 071801 (2018)

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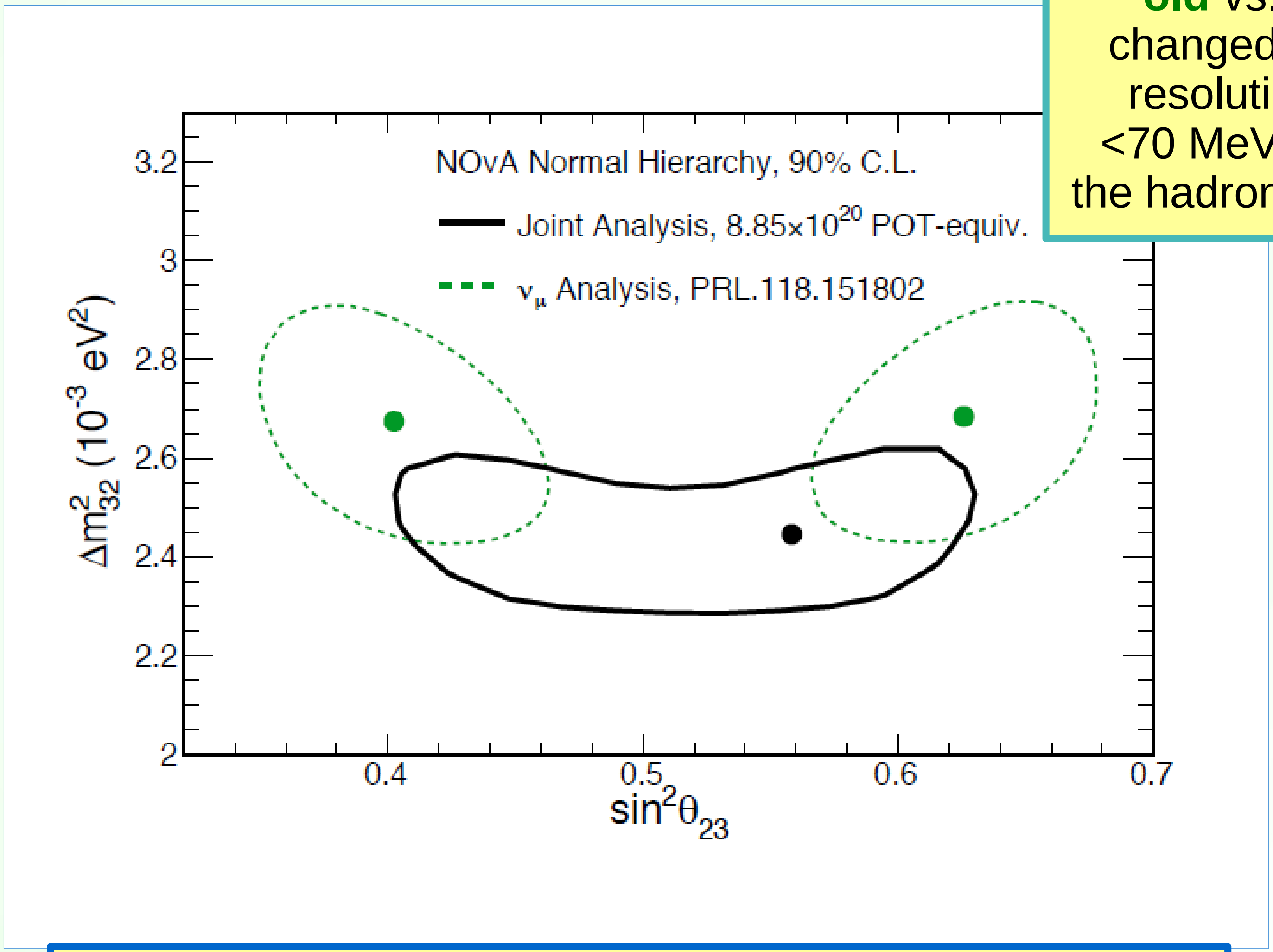
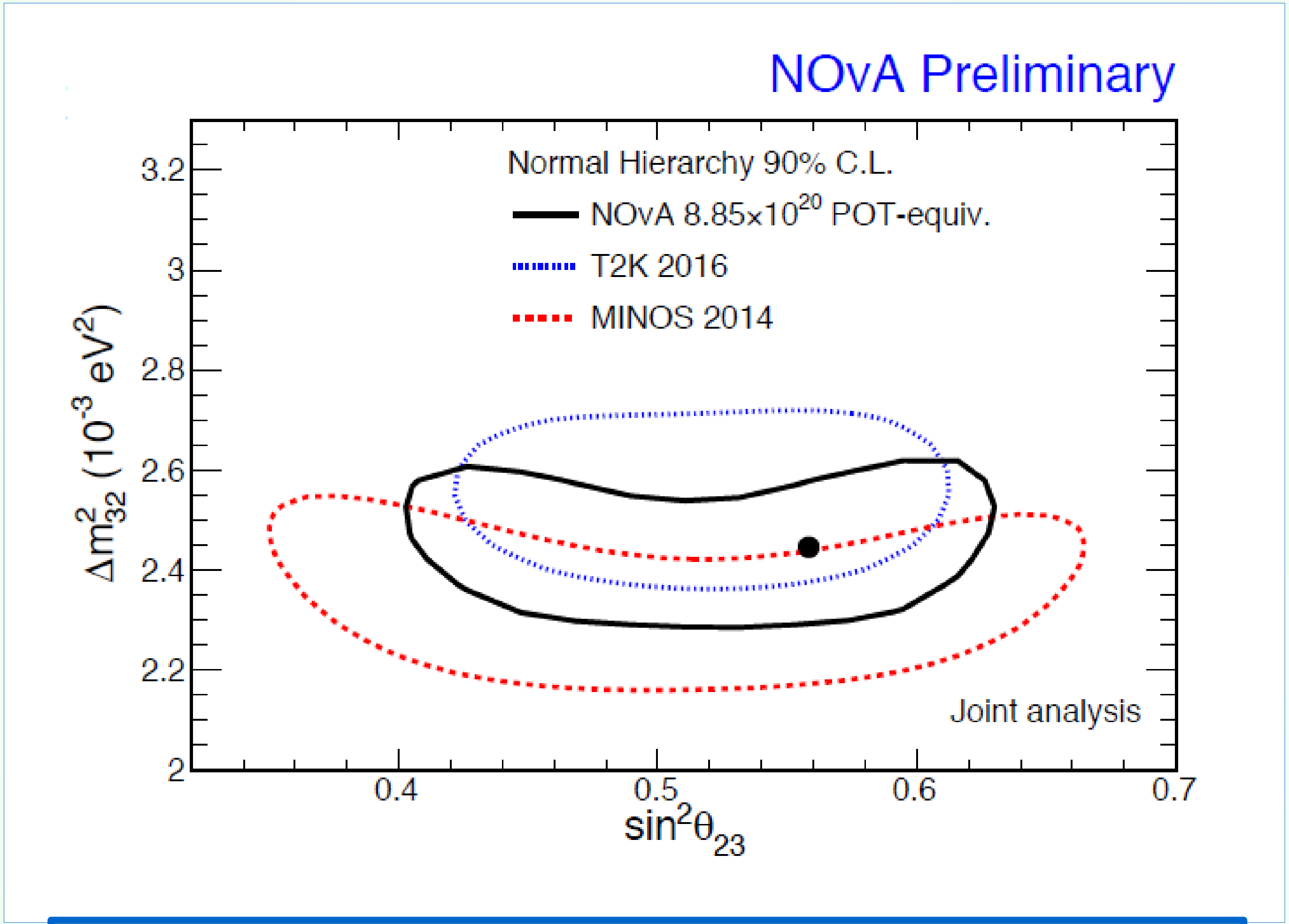


old vs. **new**: changed energy resolution and <70 MeV> shift in the hadronic energy

A. Radovic (NOvA), JETP Jan 12, 2018

What precision are we achieving?



A. Radovic (NOvA), JETP Jan 12, 2018

What precision are we achieving?

At neutrino energy ~600 MeV (T2K kinematics),

- 10% uncertainty (current T2K), ~60 MeV
- 2% uncertainty (current global fits), ~10 MeV

At the NOvA and DUNE kinematics, values x4−5.

DUNE and **T2HK** aim at uncertainties < 1%,
requiring ~**25 MeV** and ~**5 MeV** precision.

Effects considered to be “small” need to be accounted for accurately to avoid biases.

Near to far event spectra ratio

Aims of near and far detectors

Far detector

- Maximize (minimize) the statistics of signal (background) events

Near detector is necessary to measure

- Flux
- Beam-related backgrounds (wrong sign μ and ν_e)
- Cross sections (input to Monte Carlo simulations and energy reconstruction)

Example of T2K

Determination of a number of the flux and cross-section parameters and their covariance reduces the uncertainties

in **disappearance channel** $\nu_\mu \rightarrow \nu_\mu$

- From 21.6% to 2.7% [Phys. Rev. Lett. 112, 181801 (2014)]

in **appearance channel** $\nu_\mu \rightarrow \nu_e$

- From 25.9% to 2.9% [Phys. Rev. Lett. 112, 061802 (2014)]

Unrealistic case

Assumption: 1:1 correspondence between the observed kinematics of events and neutrino energy.

The observed event distribution, $\mathcal{X} = \{\cos\theta, E_\alpha, \ldots\}$

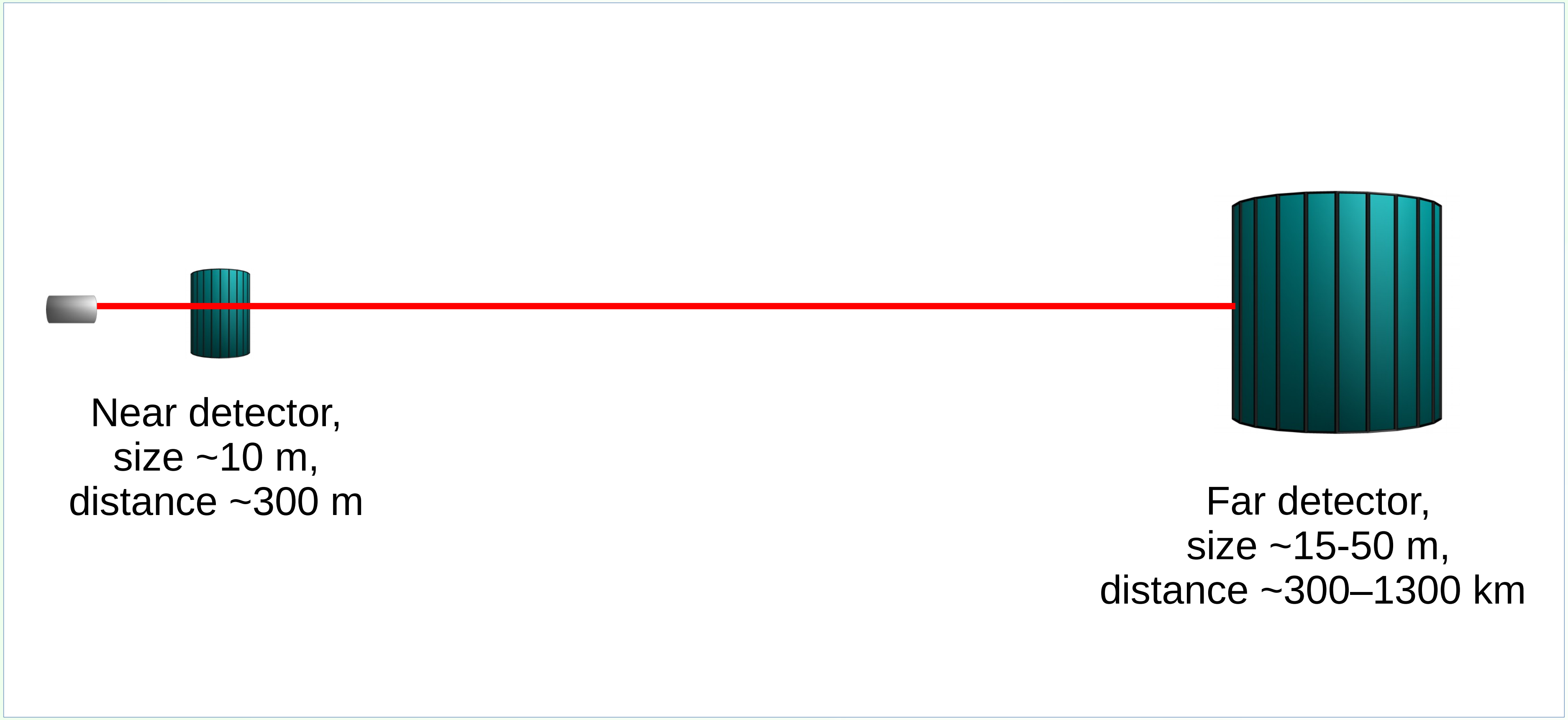
$$R_{\alpha\to\alpha}(\mathcal{X}) = \mathcal{N} \int dE_\nu \Phi_\alpha(E_\nu) P(\nu_\alpha \to \nu_\alpha) \frac{d\sigma_\alpha}{d\mathcal{X}} \epsilon_\alpha(\mathcal{X})$$

gives the E_ν distribution and the oscillation probability

$$R_{\alpha\to\alpha}(E_\nu) = \mathcal{N} \Phi_\alpha(E_\nu) P(\nu_\alpha \to \nu_\alpha) \sigma_\alpha \epsilon_\alpha(E_\nu)$$

$$\frac{R^{\rm far}_{\alpha\to\alpha}(E_\nu)}{R^{\rm near}_{\alpha\to\alpha}(E_\nu)} \approx \frac{\mathcal{N}_{\rm far} \Phi^{\rm far}_\alpha(E_\nu) P(\nu_\alpha \to \nu_\alpha)}{\mathcal{N}_{\rm near} \Phi^{\rm near}_\alpha(E_\nu)} \approx \frac{\mathcal{N}_{\rm far} L^2_{\rm far}}{\mathcal{N}_{\rm near} L^2_{\rm near}} P(\nu_\alpha \to \nu_\alpha)$$

Flux differences: angular dependence



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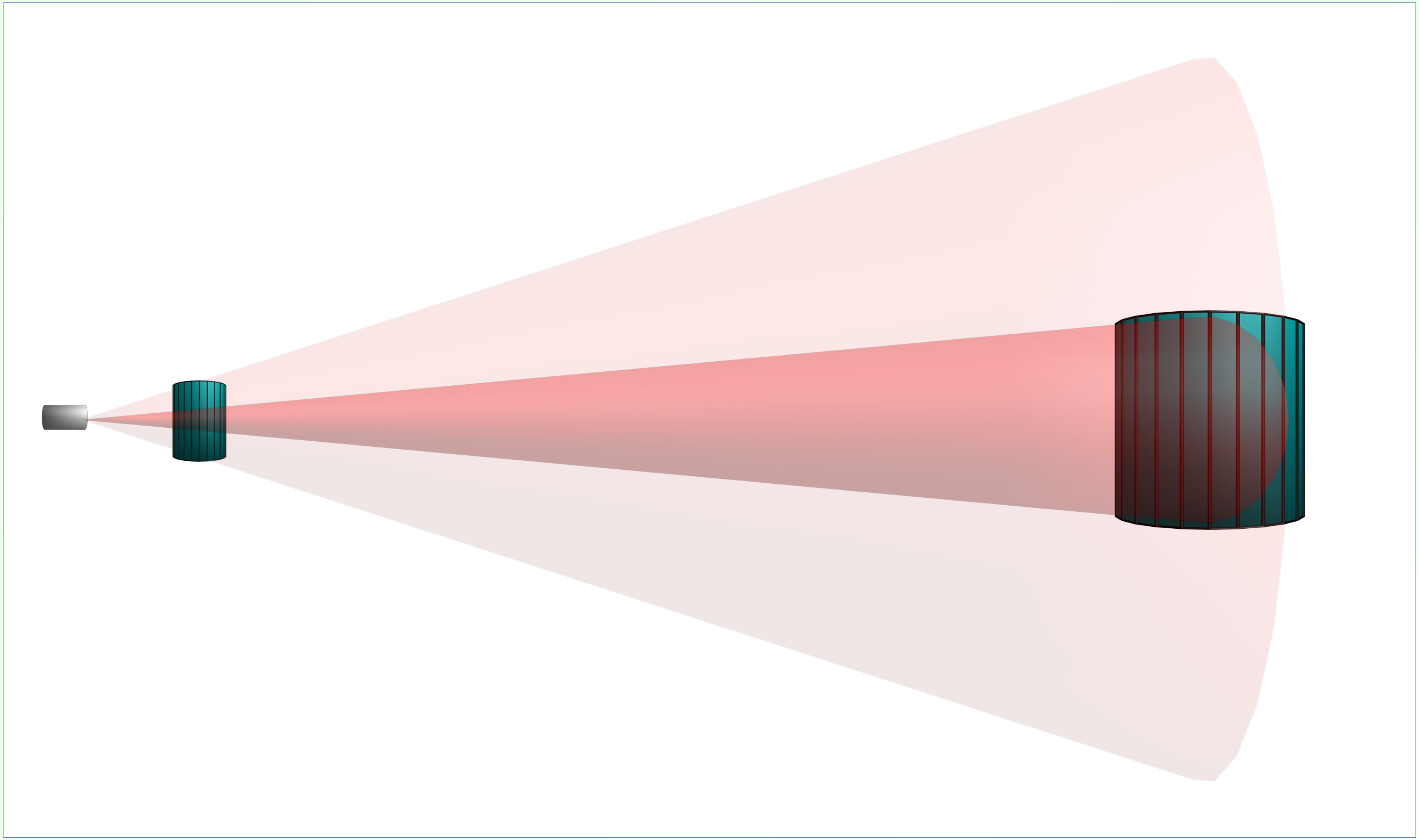
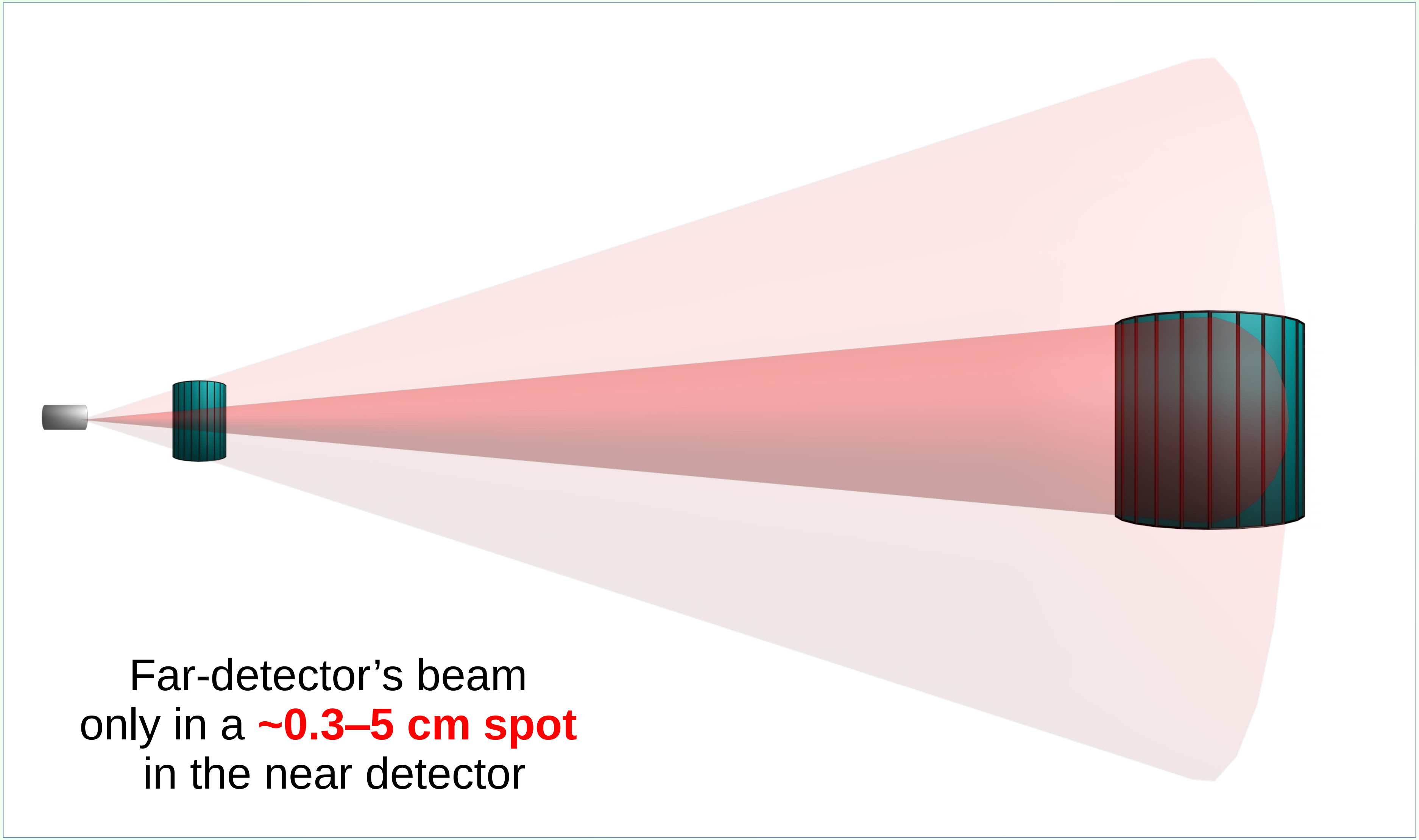
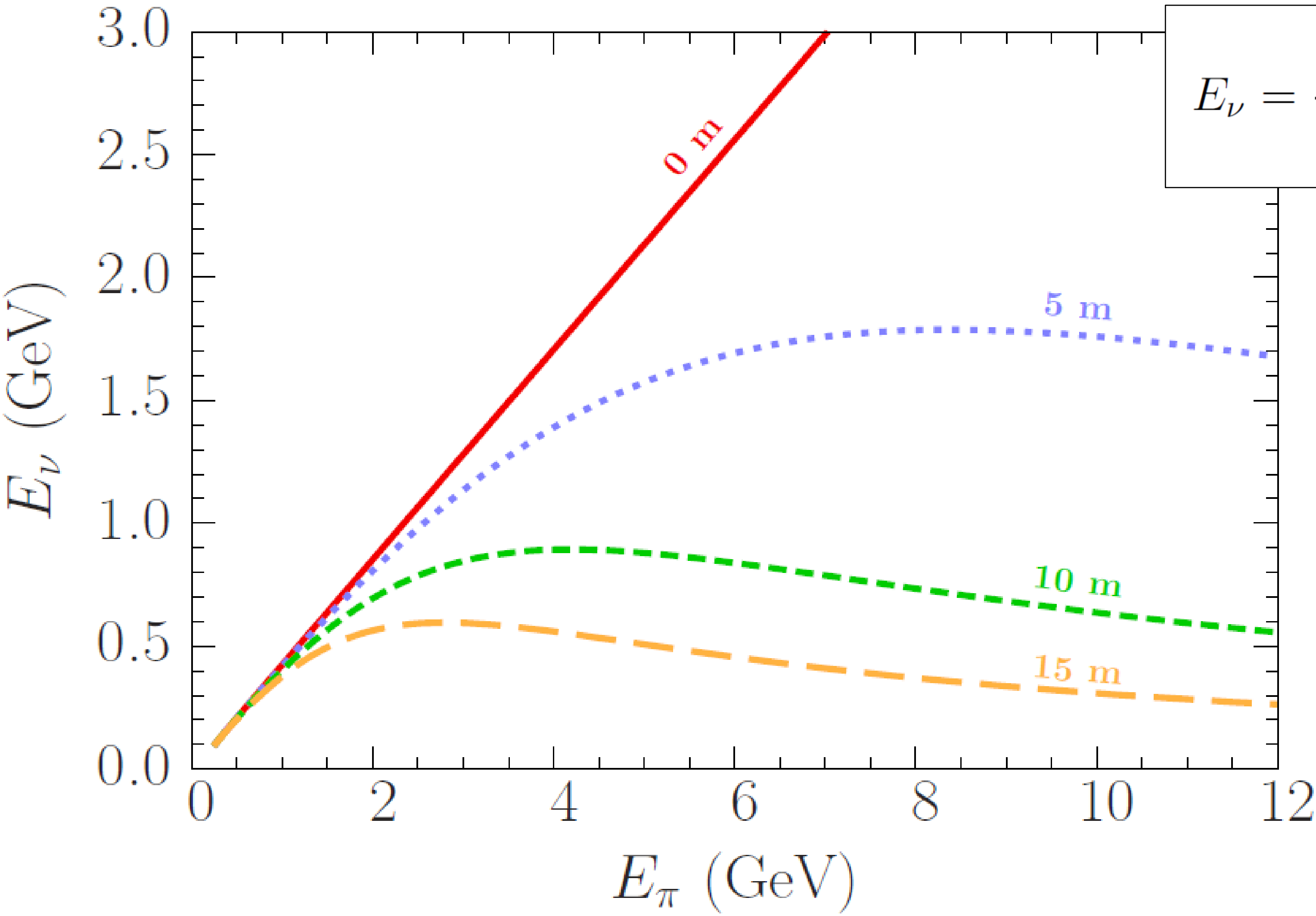


Flux differences: angular dependence



Flux's angular dependence @ ND

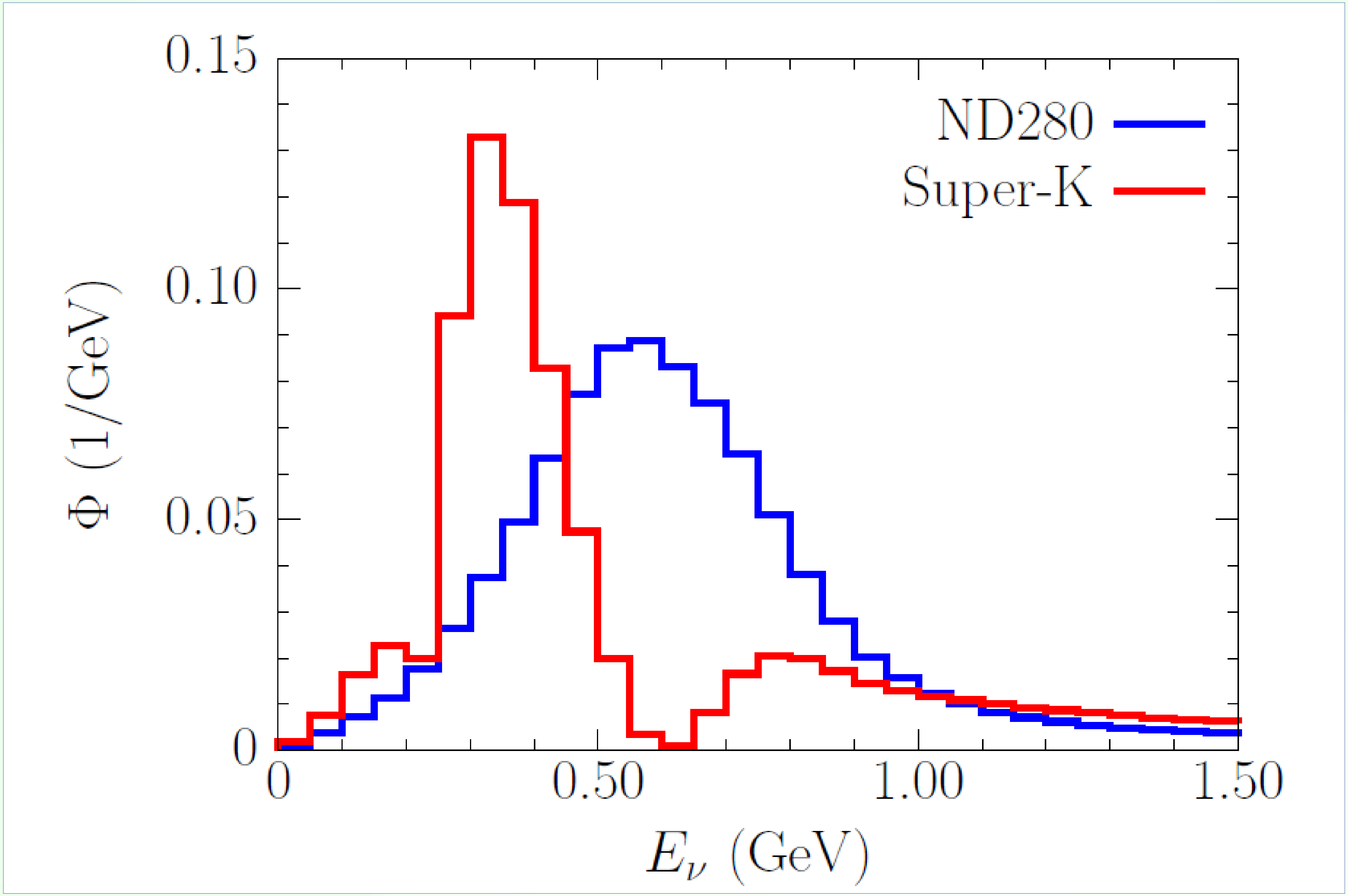


$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{2(E_\pi - |\mathbf{p}_\pi| \cos\theta)}$$

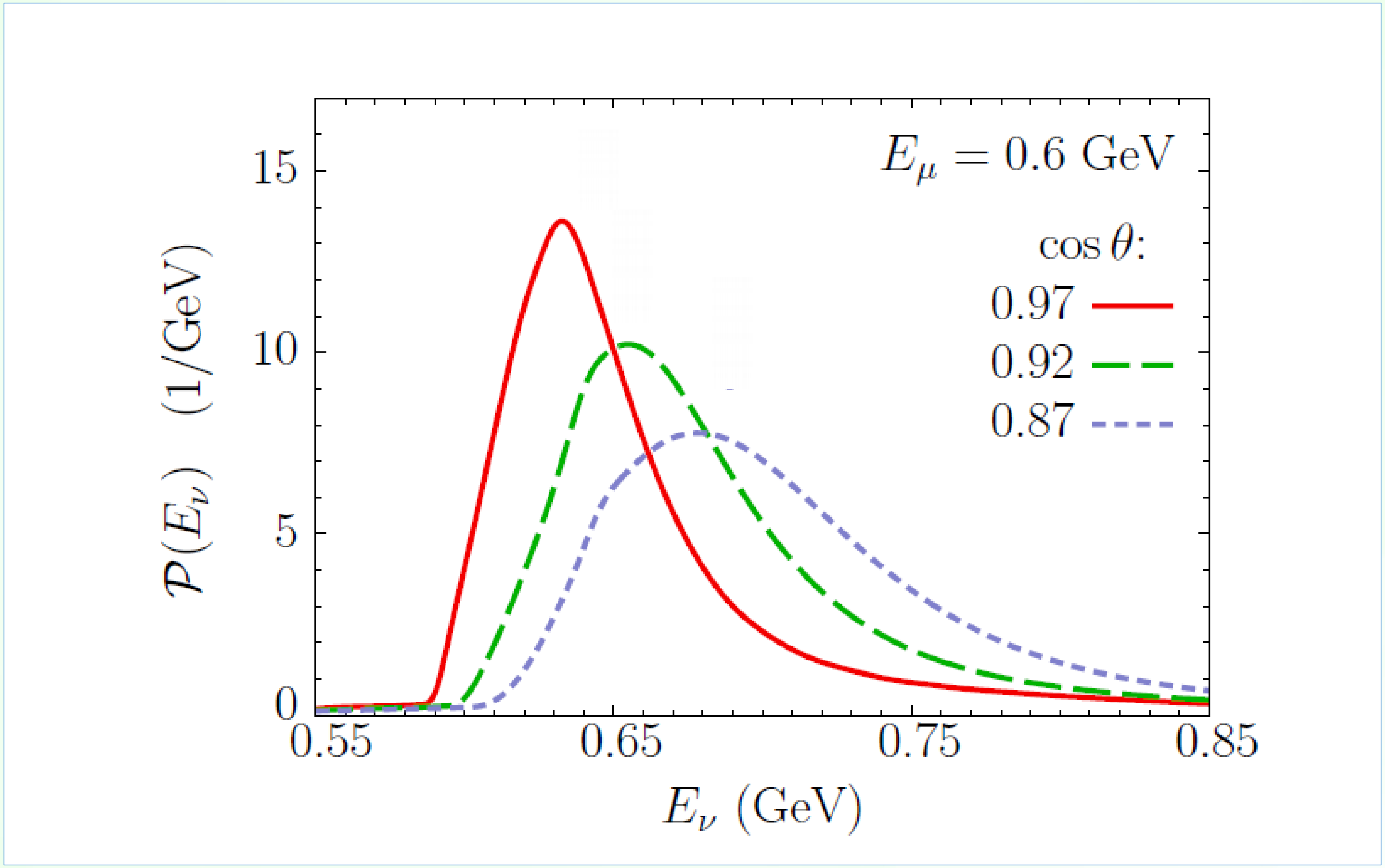
ND @ 300 m,
off-axis distance

0 m → 0.00º
5 m → 0.96º
10 m → 1.91º
15 m → 2.87º

Flux differences: oscillations



Realistic case

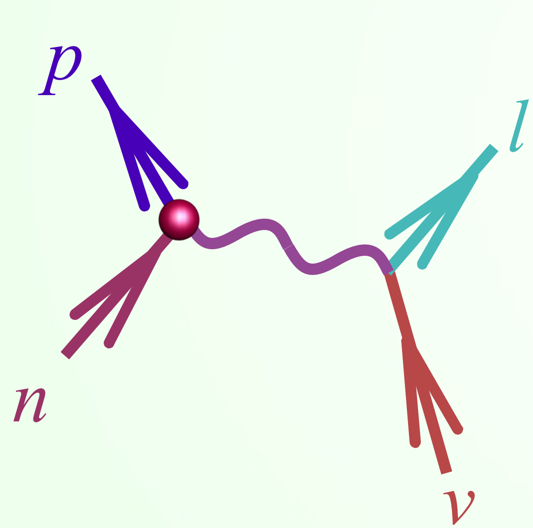


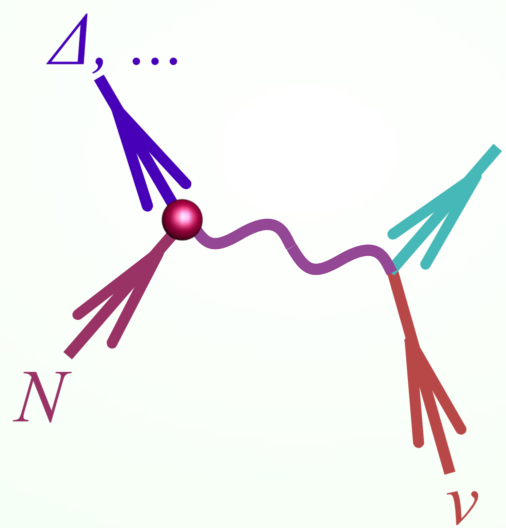
No 1:1 correspondence between muon kinematics and E_ν, even in simple cases

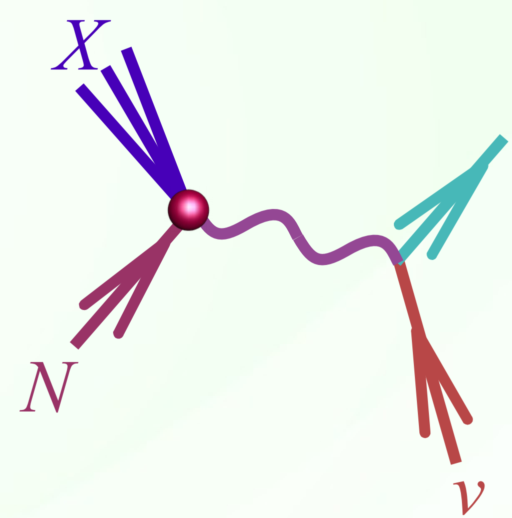
Energy reconstruction

Neutrino CC scattering on a free nucleon

quasielastic scattering	resonance excitation	deep inelastic scattering





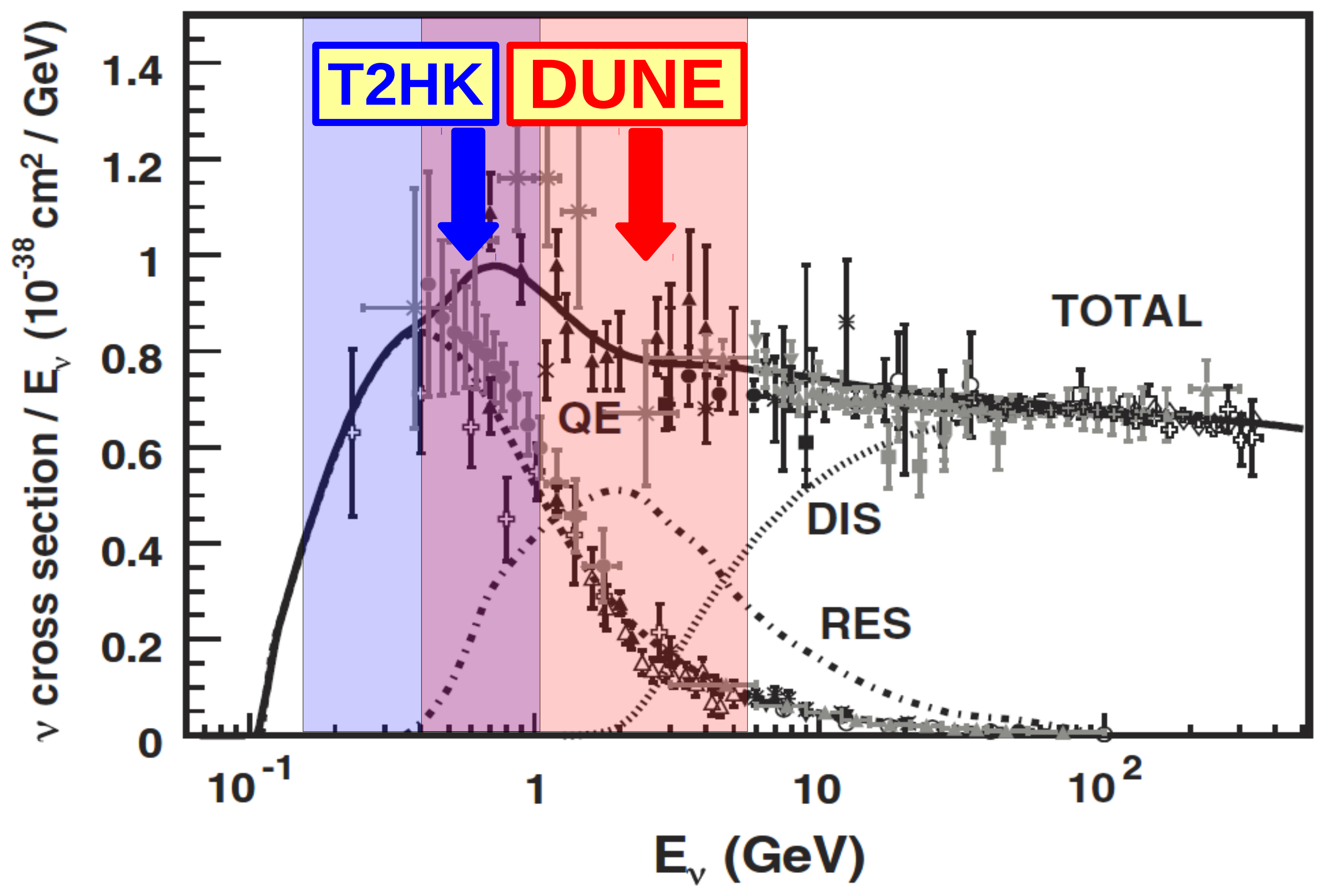


$x = 1$

energy transfer ~300 MeV

$x \ll 1$

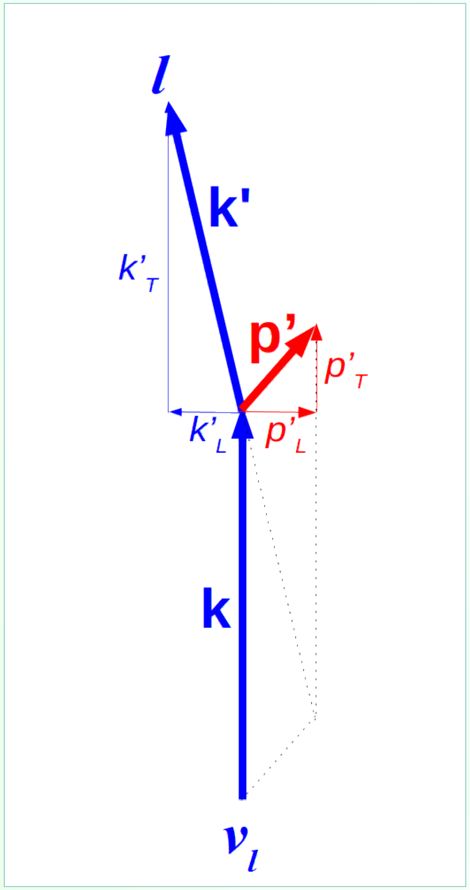
Neutrino scattering



adopted from
Formaggio & Zeller, RMP 84, 1307 (2013)

Kinematic reconstruction

In quasielastic scattering off free nucleons, $\bar{\nu} + p \rightarrow l + n$ and $\nu + n \rightarrow l + p$, we can deduce the neutrino energy from the charged lepton's kinematics.



Energy conservation

$$E + M = E' + \sqrt{M^2 + p_L'^2 + p_T'^2}$$

Momentum conservation

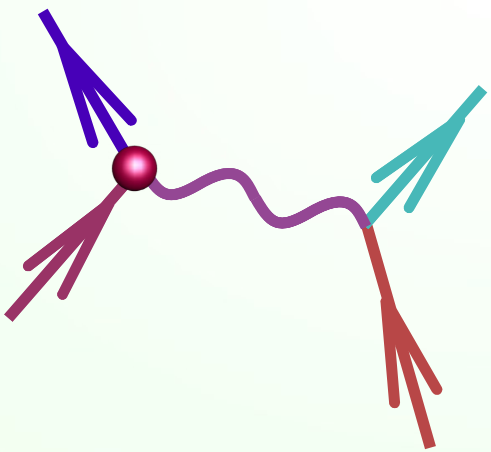
$$E = |k'| \cos\theta + p_L'$$

$$0 = |k'| \sin\theta + p_T'$$

Kinematic reconstruction

In quasielastic scattering off free nucleons, $\bar{\nu} + p \rightarrow l + n$ and $\nu + n \rightarrow l + p$, we can deduce the neutrino energy from the charged lepton's kinematics.

No need to reconstruct the nucleon kinematics.

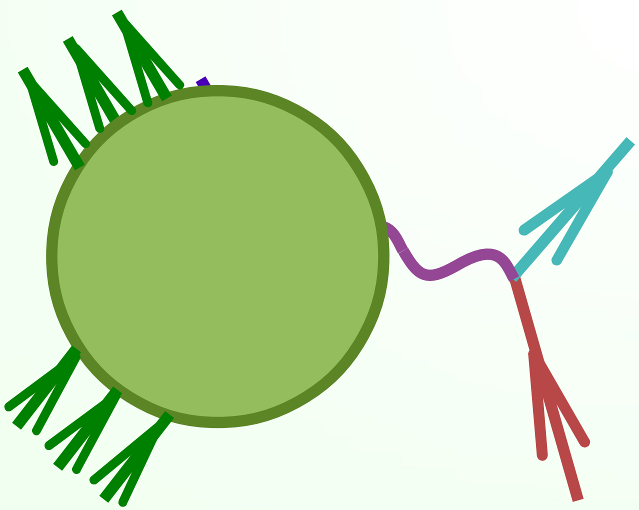


E' and θ known

$$E = \frac{ME' + \text{const}}{M - E' + |\boldsymbol{k}'| \cos\theta}$$

Kinematic reconstruction

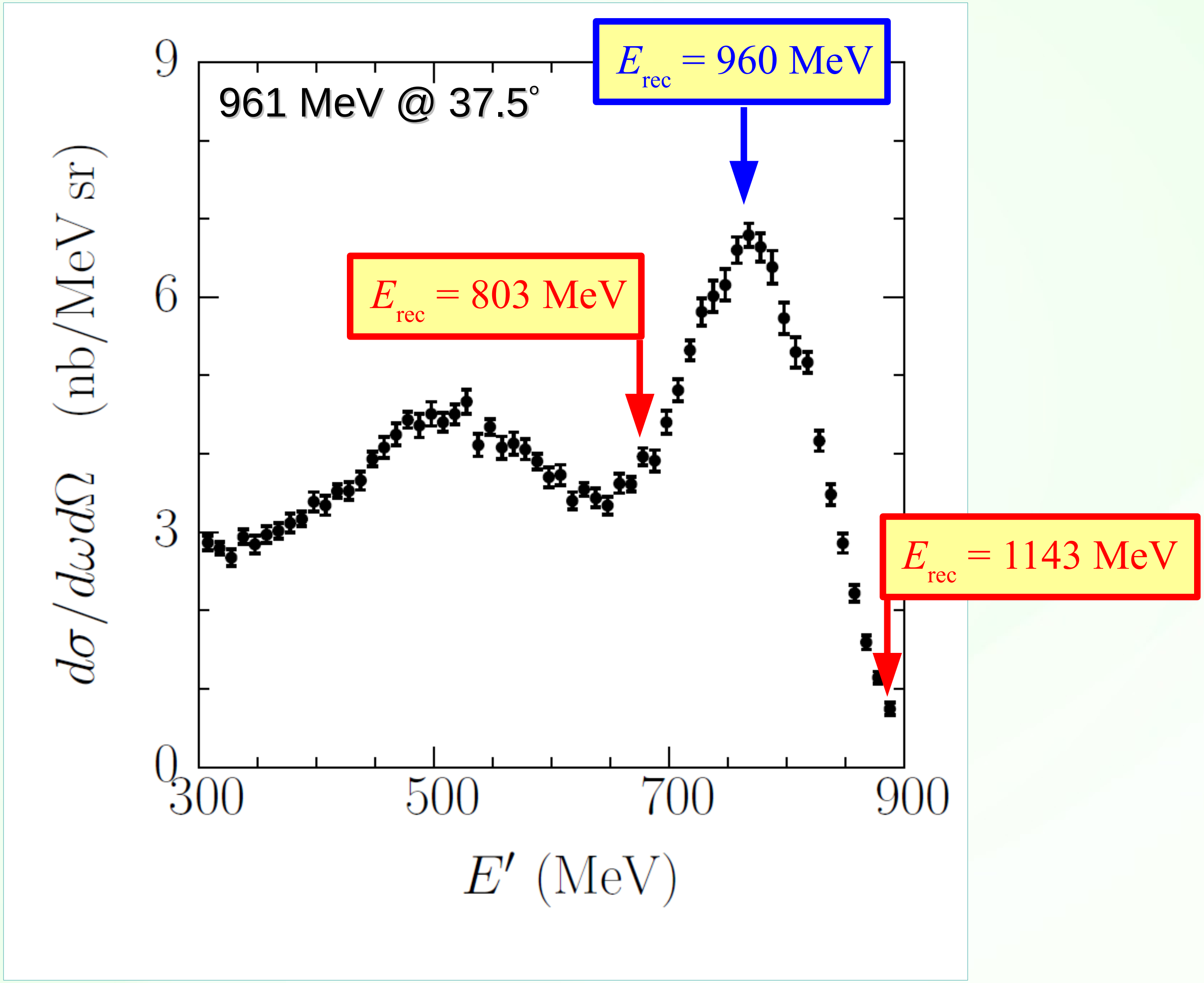
In nuclei the reconstruction becomes an approximation due to the binding energy, Fermi motion, final-state interactions, two-body interactions etc.



E' and θ known

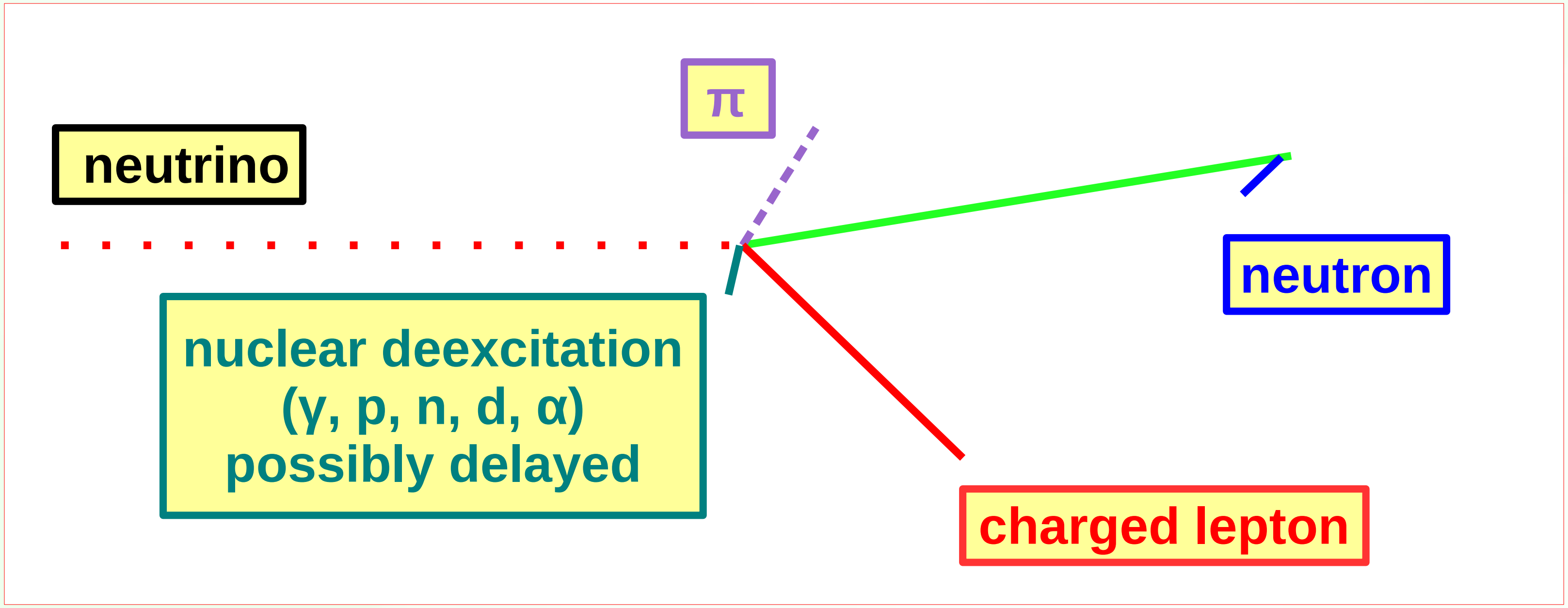
$$E \simeq \frac{(M-\epsilon)E' + \text{const}}{M-\epsilon-E' + |\boldsymbol{k}'|\cos\theta}$$

"Unknown" monochromatic e^- beam



Calorimetric energy reconstruction

- Seemingly simple procedure: add all energy depositions in the detector related to the neutrino event
- Advantages: (i) applicable to any final states, (ii) in an ideal detector, the reconstruction would be exact and insensitive to nuclear effects



Calorimetric energy reconstruction

- In a real detector the method is only insensitive to nuclear effects when

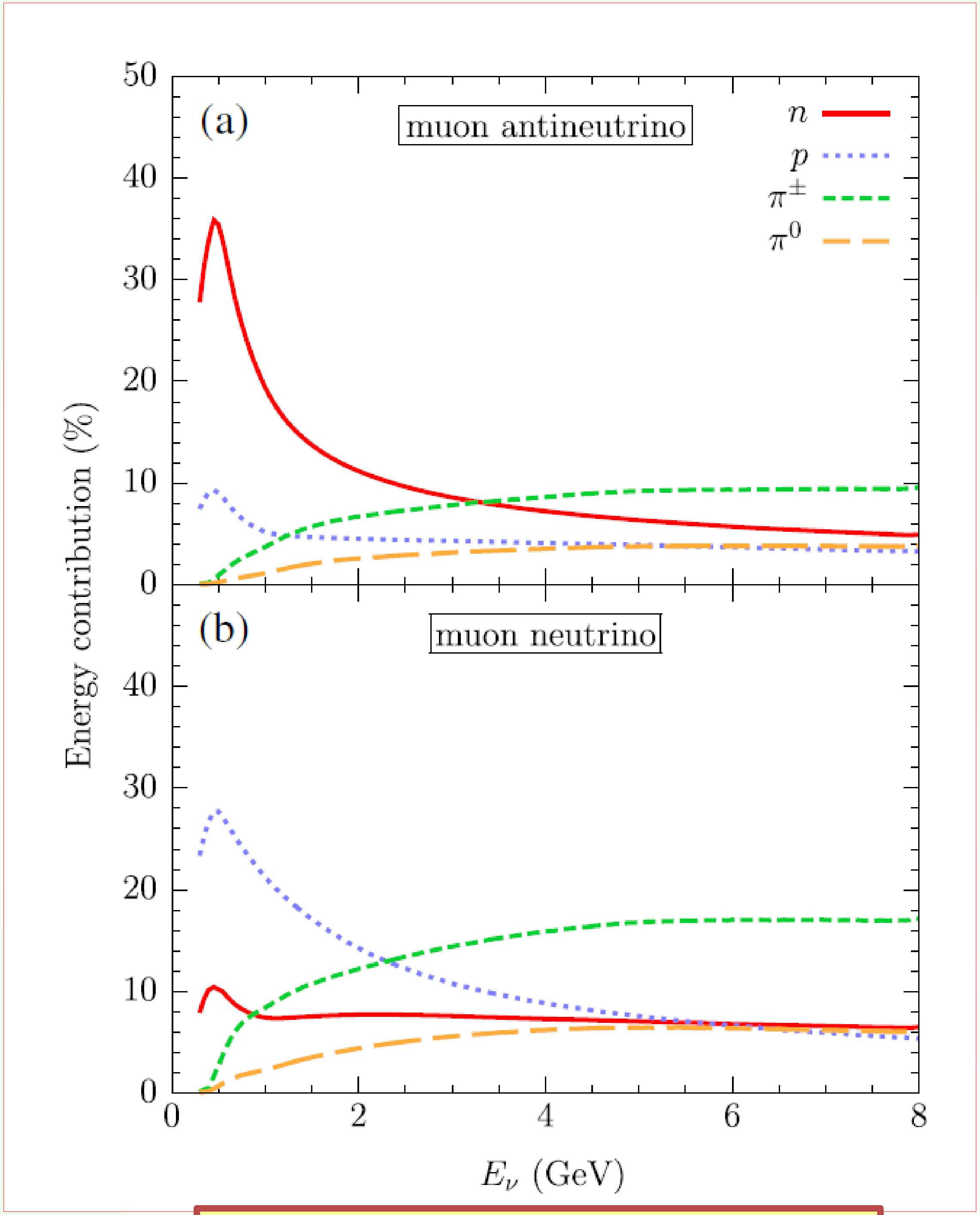
missing energy « neutrino energy

- Otherwise, requires input from nuclear models

A.M.A.,arXiv: 1704.07835

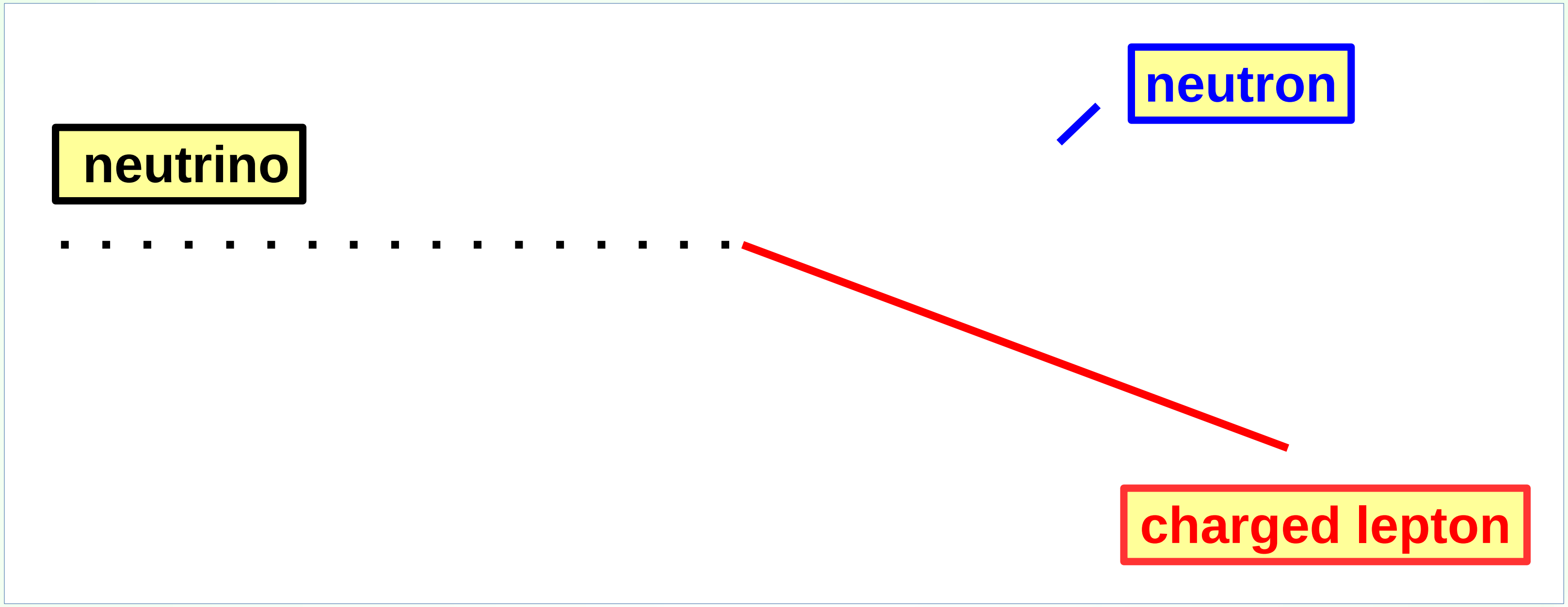
- Correction for the missing energy **may be significant**:
  - undetected pion at least m_π = 140 MeV
  - neutrons are hard to associate with the event

To achieve ~25 MeV accuracy in DUNE, accurate predictions of exclusive cross sections are required.



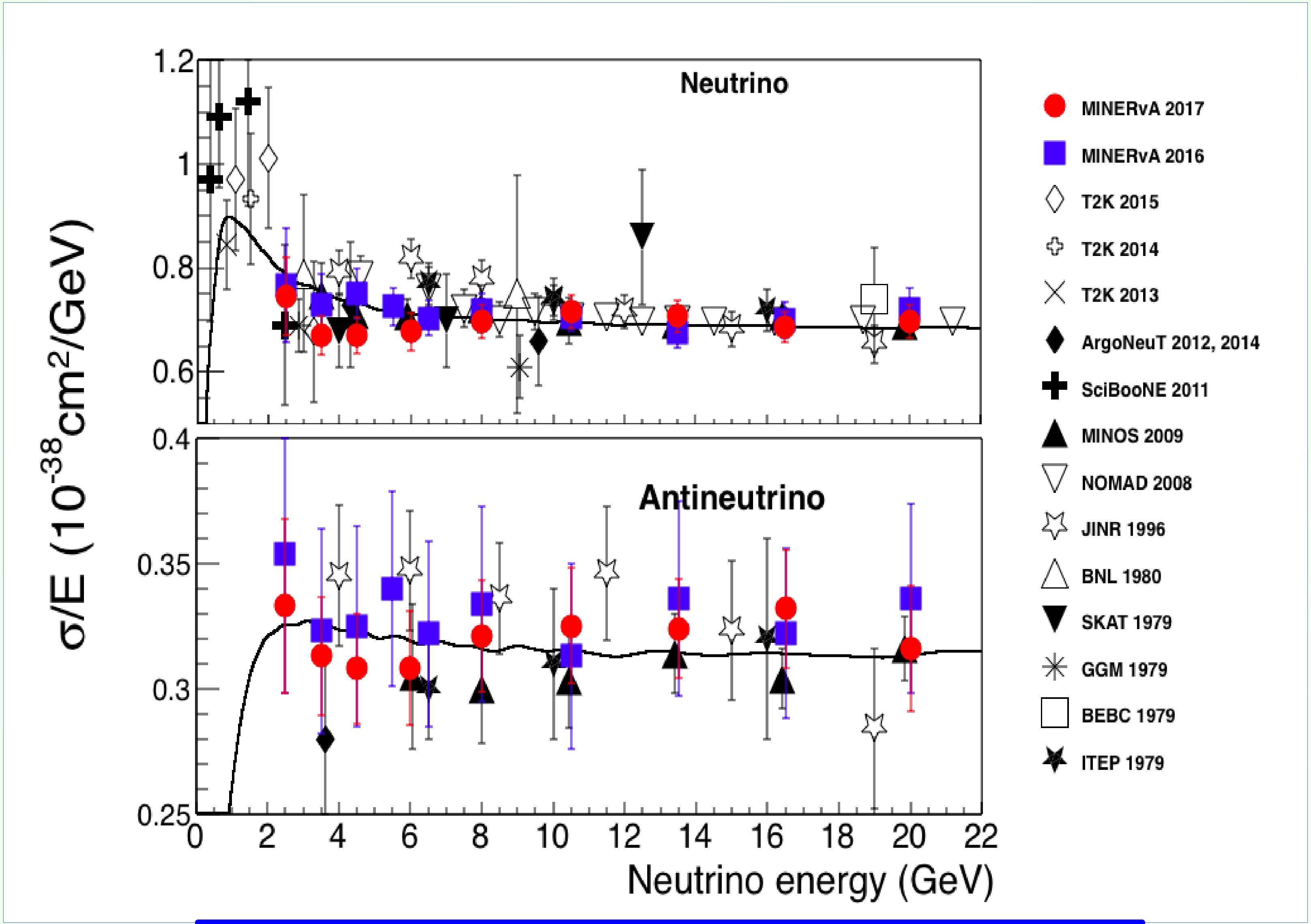
AMA *et al.* PRD 92, 073014 (2015)

Neutrino events



- Unknown probe energy
- Final state not fully known (nuclear deexcitations, undetected particles)
- Interaction dynamics uncertain

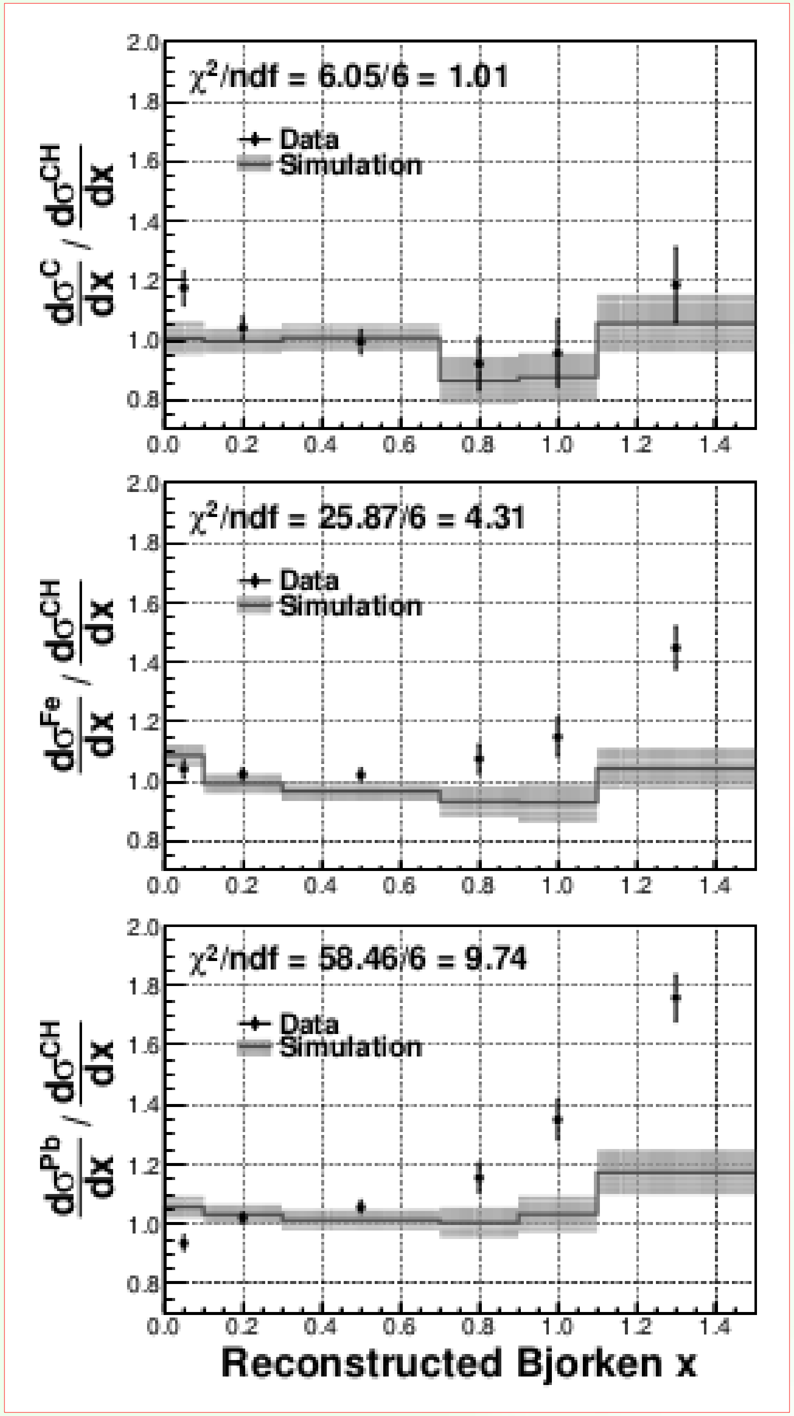
Reduction of uncertainties



Ren et al. (MINERvA), PRD 95, 072009 (2017)

Ratios of ν_μ CC cross sections on C, Fe, and Pb to CH at $2 < E_\nu < 20$ GeV

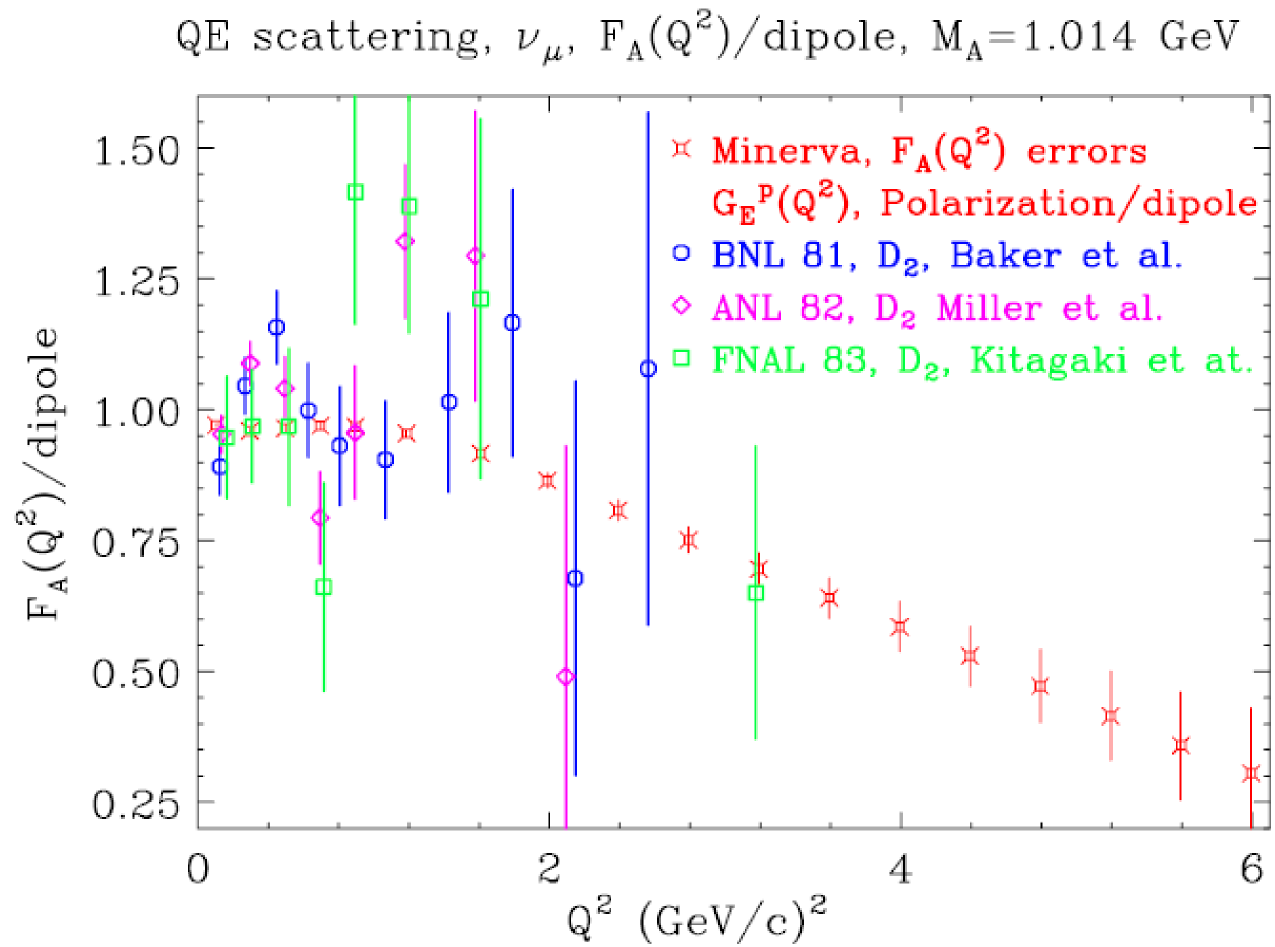
Tice et al. (MINERvA), PRL 112, 231801 (2014)



"The array of nuclear models available to modern neutrino experiments give similar results for these cross section ratios, none of which is confirmed by the data."

"More theoretical work is needed to correctly model nuclear effects in neutrino interactions, from the quasielastic to the deep inelastic regime."

Still a long way to go



Drakoulakos et al. (MINERvA), arXiv:hep-ex/0405002

Systematic uncertainties

Extrapolation to a different nucleus

- Available cross sections or their ratios
(# articles in the last 10 years):
C or CH (**31**), Fe (**8**), Ar (**3**), H_2O (**3**), Pb (**3**)

- If the near and far detectors use **different targets**, the extrapolation is necessary

Extrapolation to a different nucleus

Coloma *et al.*, PRD 89, 073015 (2014)

Considered a T2K-like $\nu_\mu \rightarrow \nu_\mu$ disappearance experiment

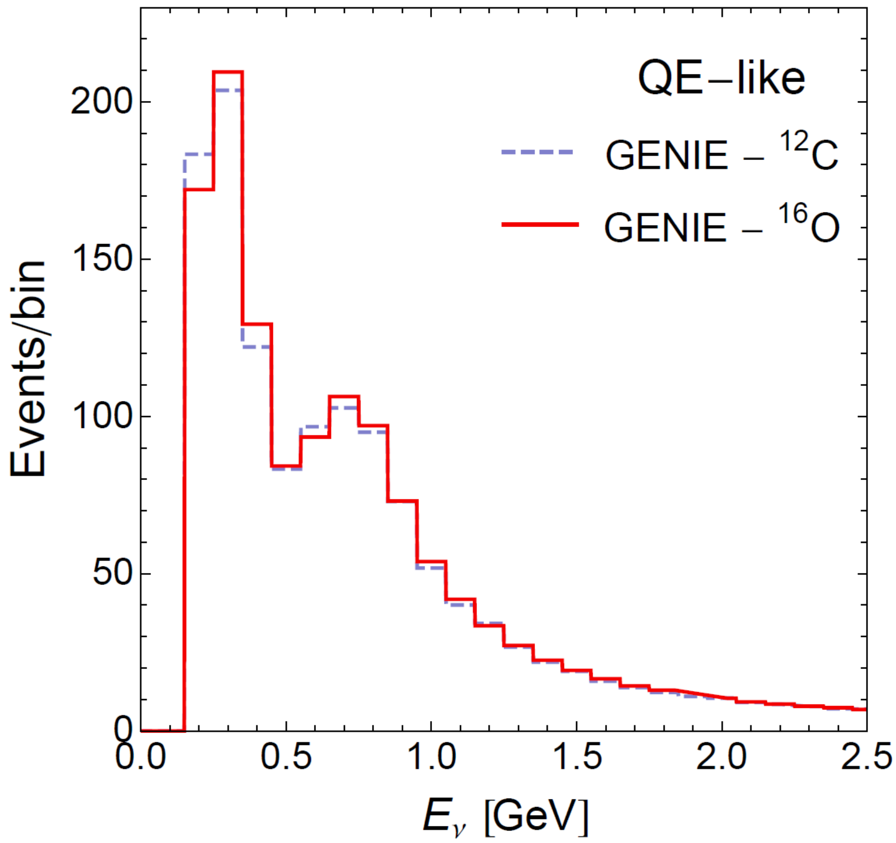
- water Cherenkov near (**1 kt fiducial mass at 1 km**) and far (**22.5 kt at 295 km**) detectors
- beam peaked at **600 MeV**, primary beam power **750 kW**
- running time **5 years**

Assumed **20%** systematic uncertainties for the **shape** and for the overall **normalization**.

True event rates for ^{16}O. Fitted rates for **^{16}O or ^{12}C**.

All migration matrices from the **RFG model in GENIE**.

^{12}C-^{16}O extrapolation



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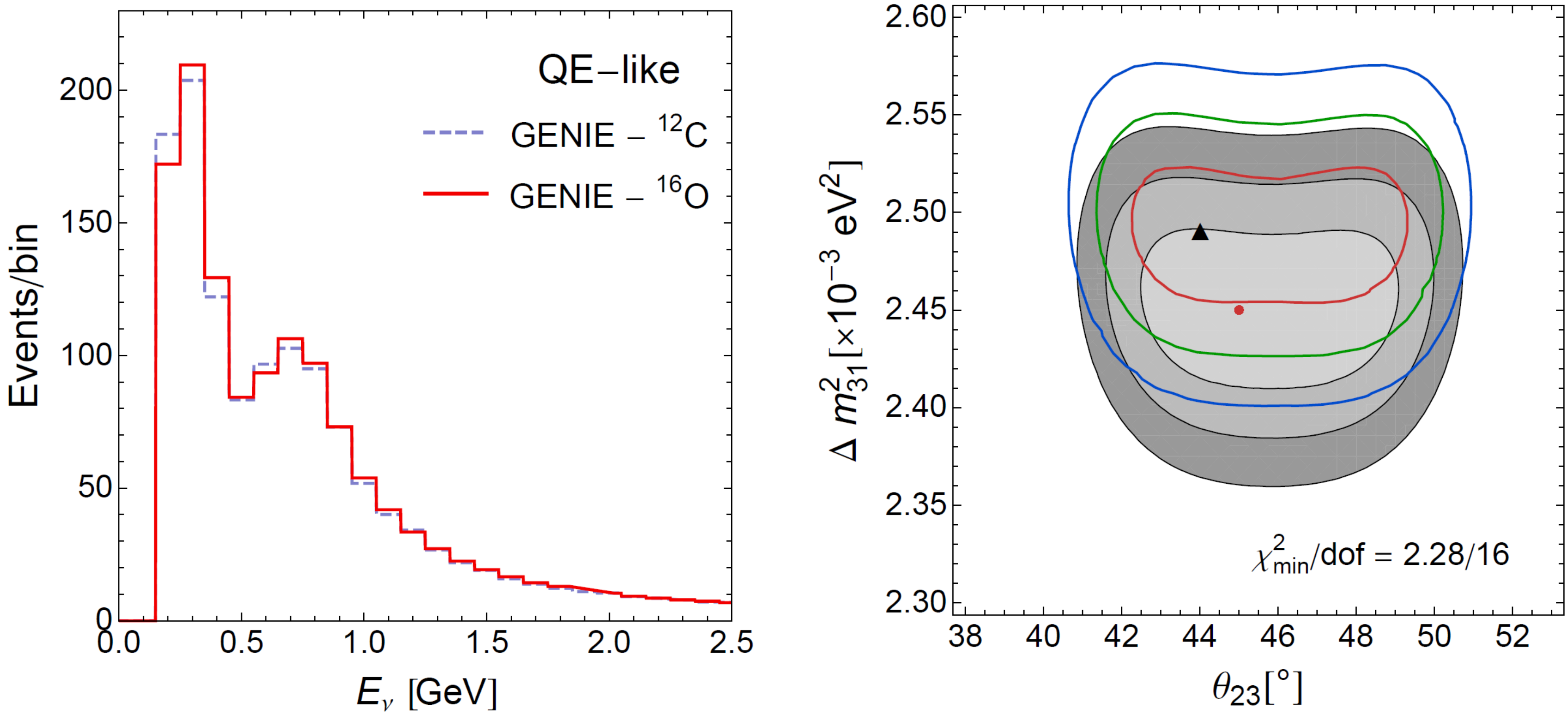


Coloma *et al.*, PRD 89, 073015 (2014)

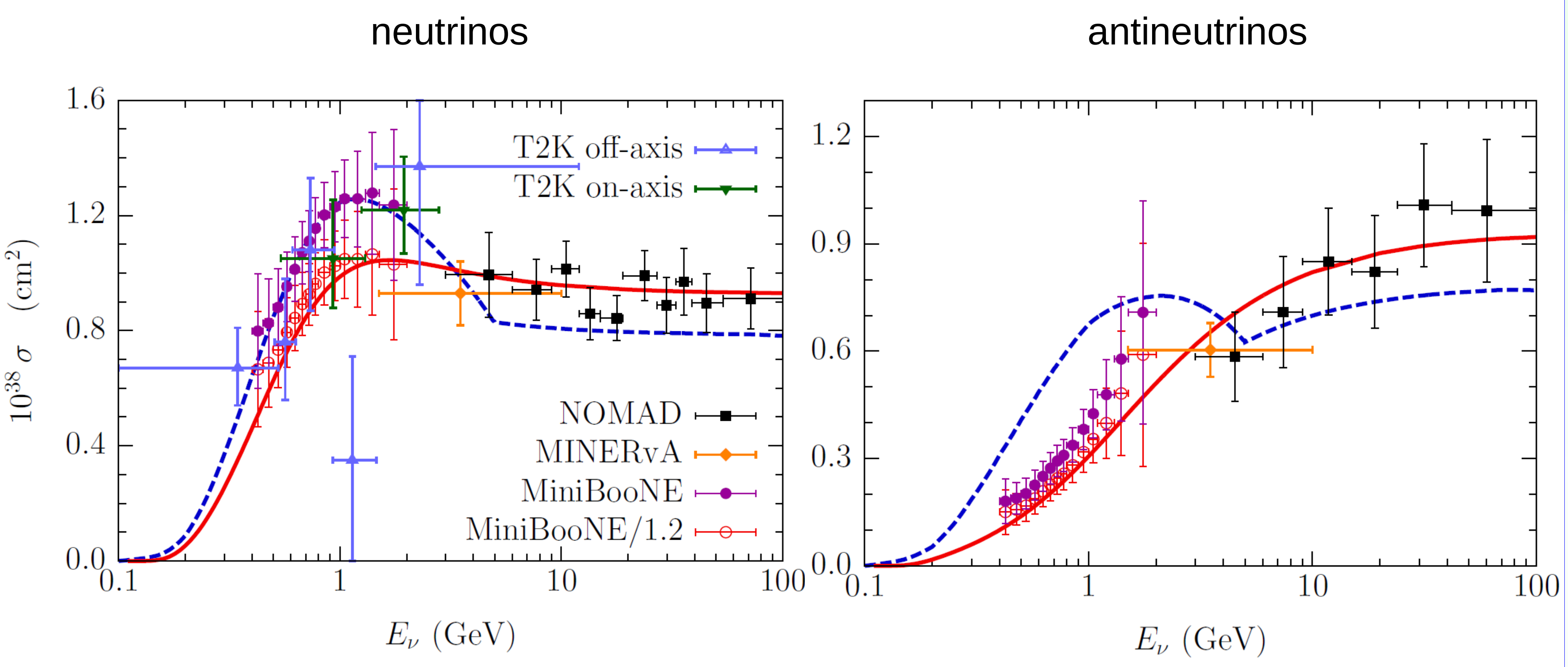
Extrapolation to a different nucleus

Lower limit of the effect:

- crude description of nuclei (neglected shell-structure, differences in density distributions, C is non-spherical)
- extrapolation only between A = 12 and A = 16

The same target material in the near and far detectors is the best way to reduce the systematic uncertainties.

QE with any number of nucleons



AMA *et al.*, PRD 93, 113004 (2016)

2*p*2*h* processes

AMA *et al.*, PRD 93, 113004 (2016)

Compared two **purely phenomenological** approaches

- **effective** SF calculations with the axial mass 1.2 GeV [suggested by K2K, MiniBooNE, MINOS, T2K]
- **GENIE + νT** calculations–QE within the SF approach and multinucleon contribution from the Dytman model [Katori, AIP Conf. Proc. 1663, 030001 (2015)]

Importance of 2*p*2*h* description

AMA *et al.*, PRD 93, 113004 (2016)

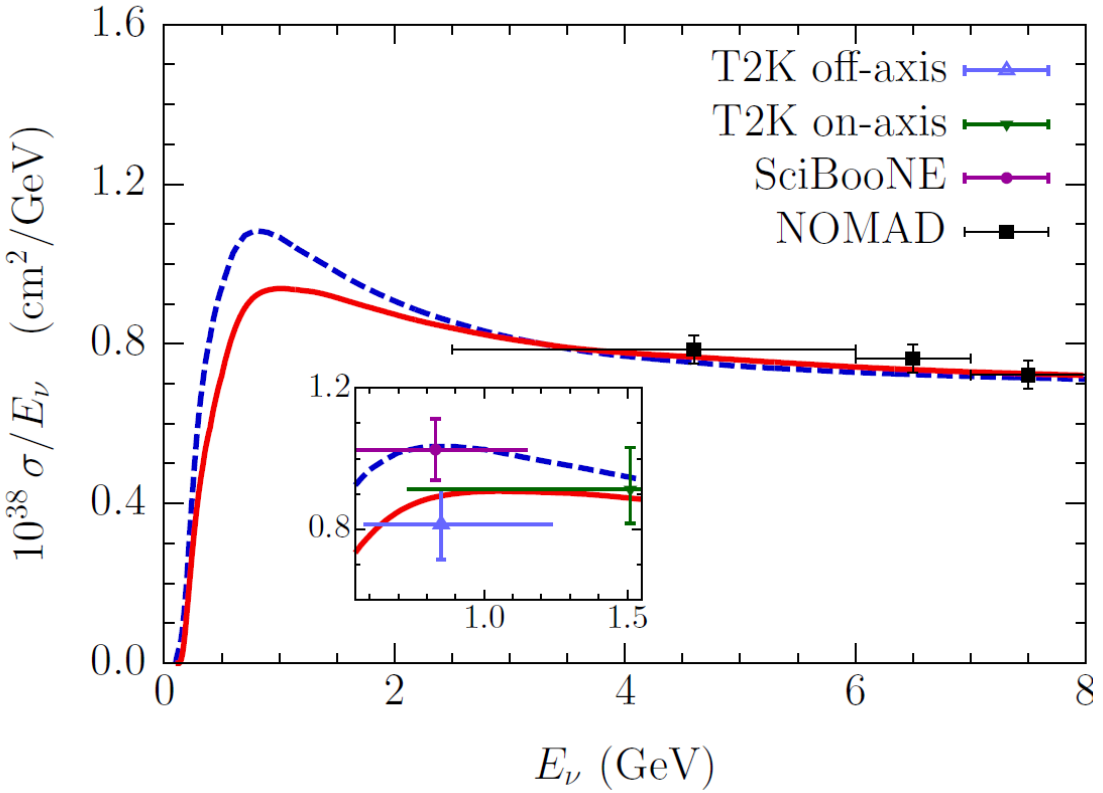
Considered a T2K-like $\nu_\mu \to \nu_\mu$ disappearance experiment

- Cherenkov detectors: near (**1 kt fiducial mass at 1 km**) and far (**22.5 kt at 295 km**) with **the carbon target**
- beam peaked at **600 MeV**, primary beam power **750 kW**
- number of unoscillated events **~6000**

Assumed **20%** systematic uncertainties for the **shape** and for the overall **normalization**.

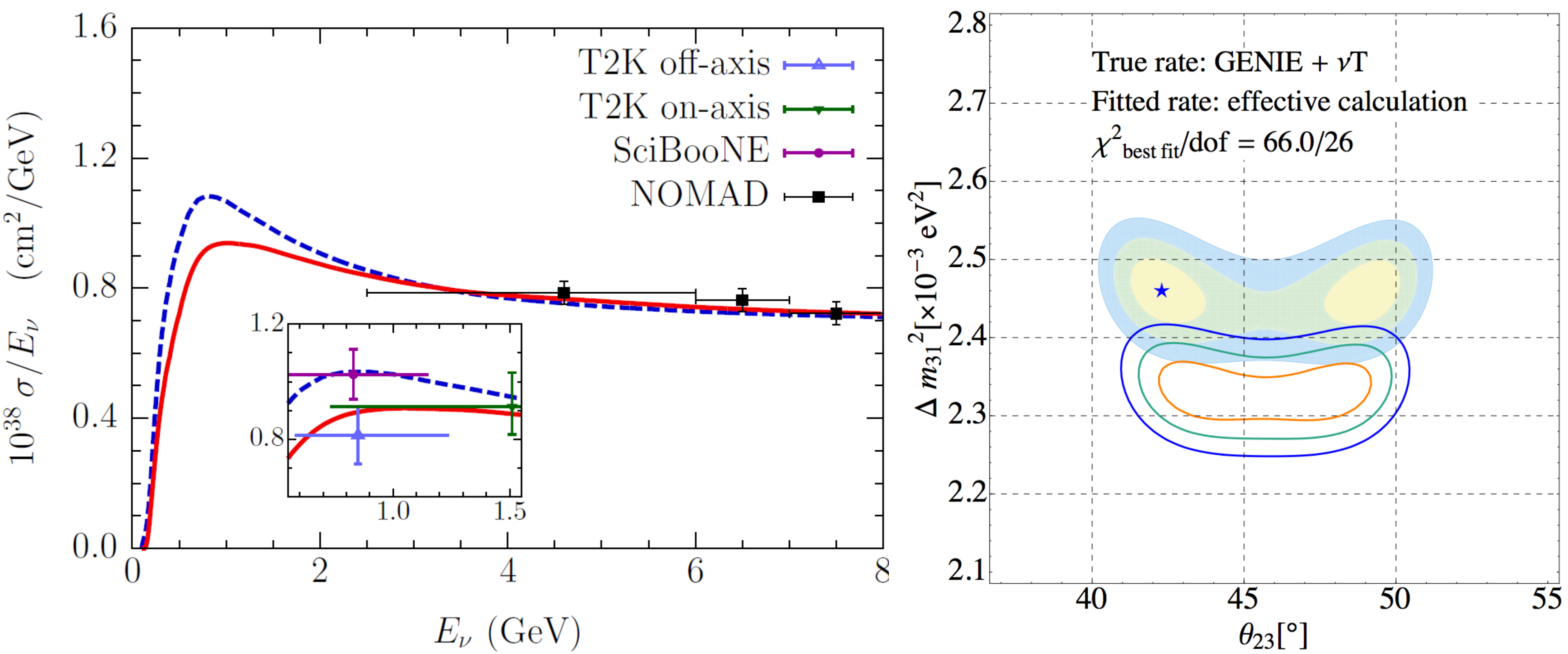
True event rates from the **GENIE + νT** approach. Fitted rates from the **effective** or **GENIE + νT** approaches.

Importance of 2*p*2*h* for neutrinos



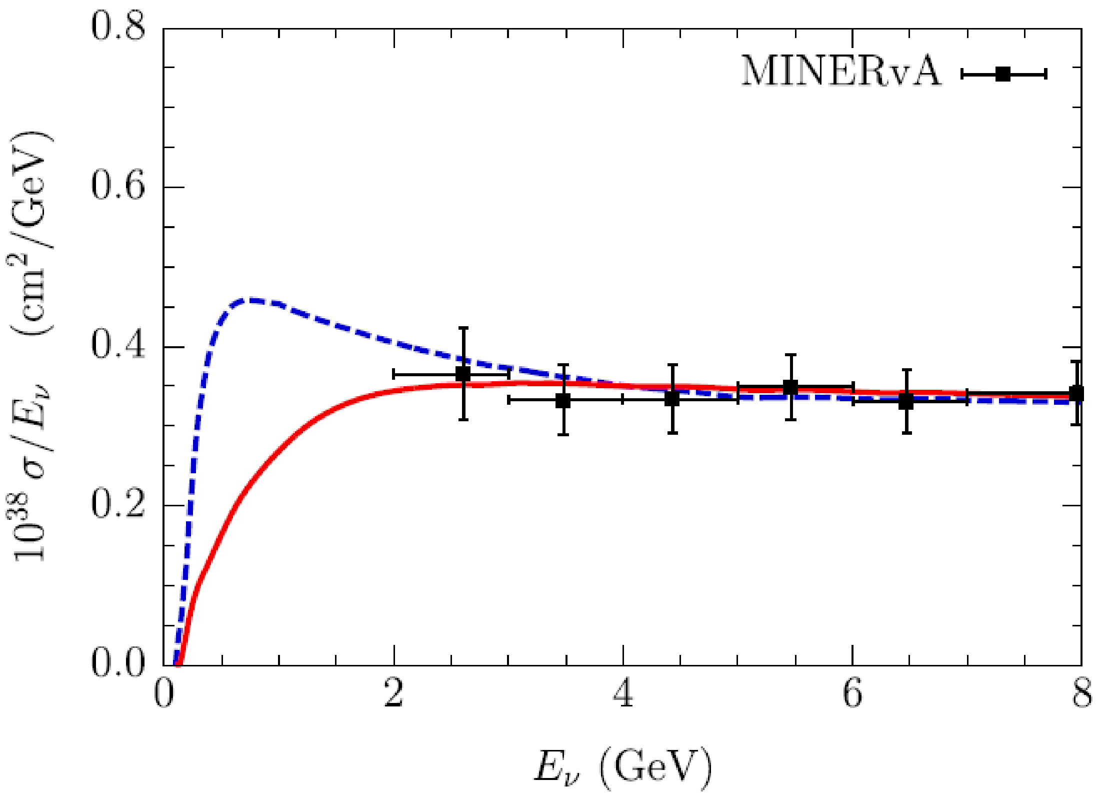
AMA *et al.*, PRD 93, 113004 (2016)

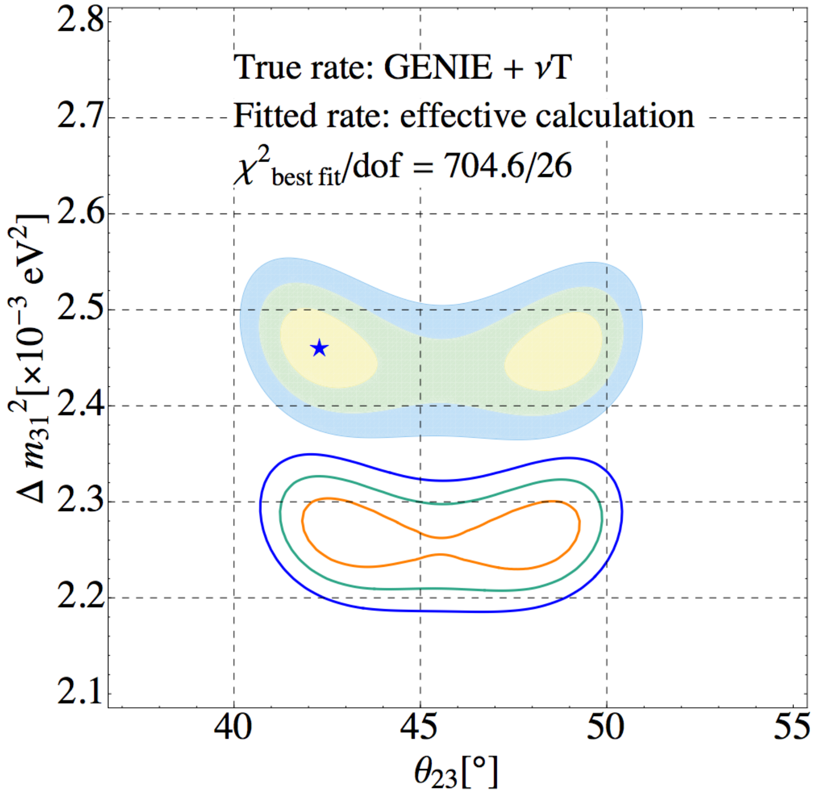
Importance of 2*p*2*h* for neutrinos



AMA *et al.*, PRD 93, 113004 (2016)

Importance of 2*p*2*h* for antineutrinos





AMA *et al.*, PRD 93, 113004 (2016)

Missing energy

AMA *et al.*, PRD 92, 091301 (2015)

In an ideal detector, the calorimetric energy reconstruction would be **perfect for any event type**.

$$E_\nu^{\mathrm{cal}} = E_\ell + \sum_i T_i^N + \epsilon_n + \sum_j E_j ,$$

In a real detector, thresholds and efficiencies affect the reconstruction, introducing sensitivity to event composition. For example, 100 MeV proton may give a reconstructed energy different than two 50-MeV neutrons.

Missing energy

AMA *et al.*, PRD 92, 091301 (2015)

Detector effects

- thresholds: **20 MeV** for mesons and **40 MeV** for protons
- energy-independent efficiencies: **60%** for π^0's, **80%** for other mesons, **50%** for protons, neutrons undetected
- finite energy resolutions

Missing energy

AMA *et al.*, PRD 92, 091301 (2015)

Considered a DUNE-like $\nu_\mu \rightarrow \nu_e$ appearance experiment

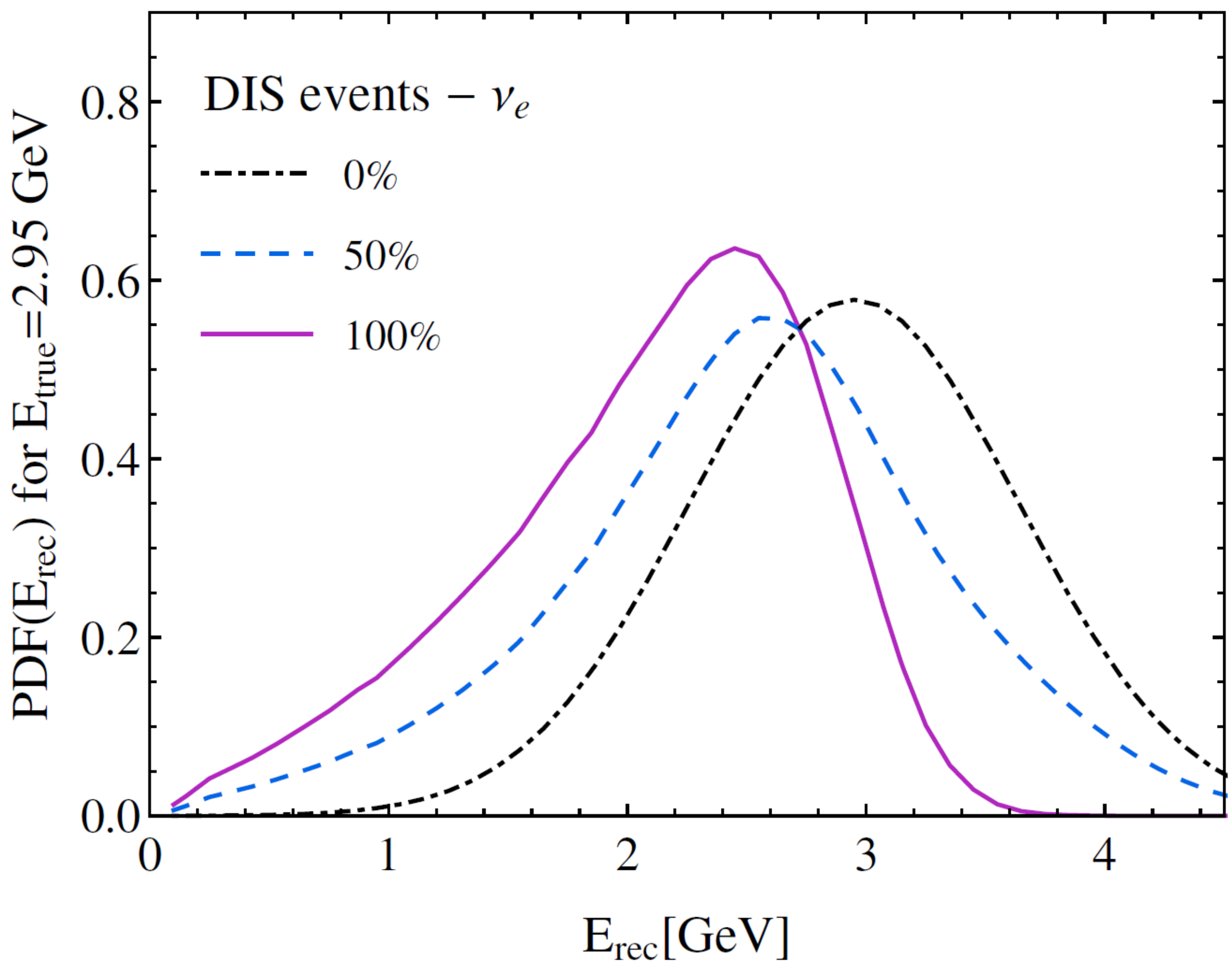
- far detector (**40 kt at 1300 km**) with **the carbon target**
- beam peaked at **2.5 GeV**, primary beam power **1.08 MW**
- running time **6 years (3 + 3)**

Assumed **2%** systematic uncertainties for the **shape** and for **normalization**; **5% bkgd normalization** uncertainty

True event rates with all **detector effects**.

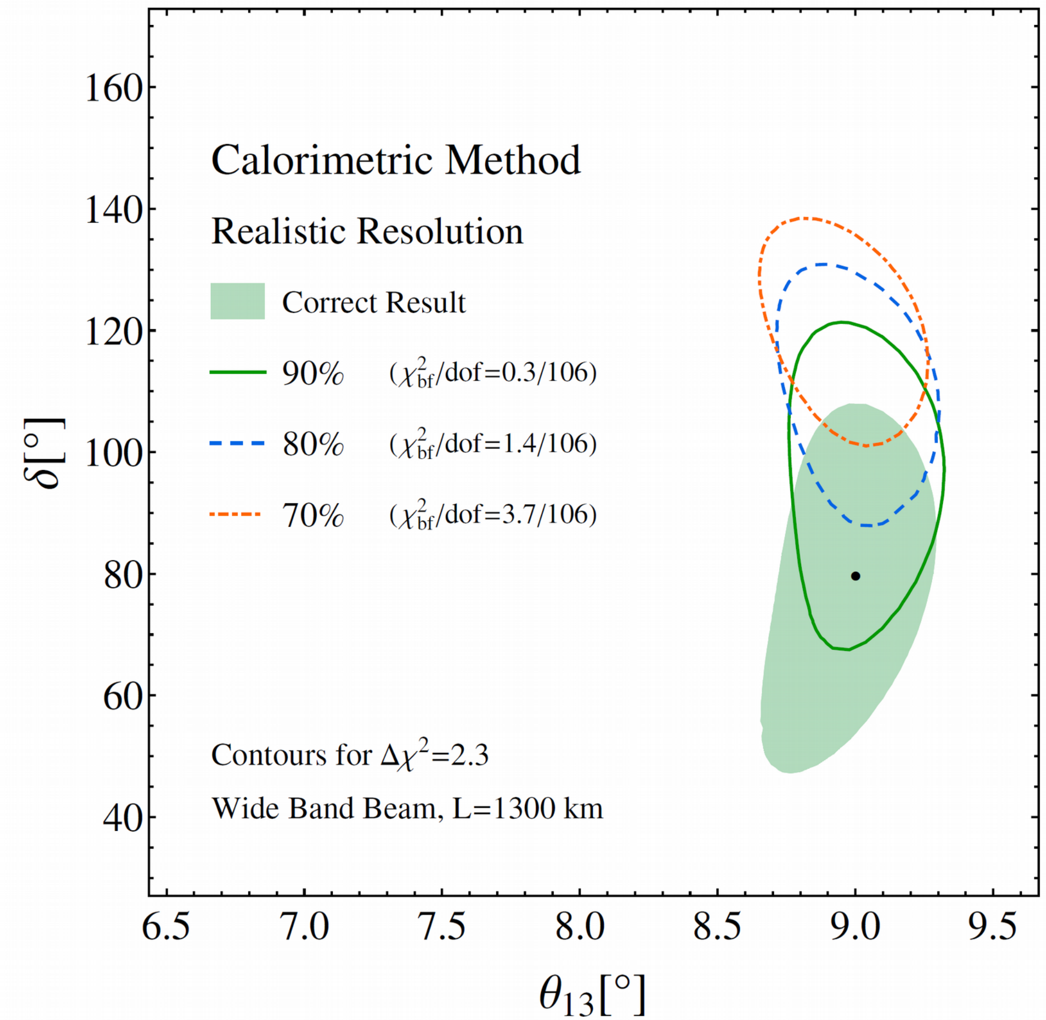
Fitted rates **partly neglect** the missing energy.

Missing energy



AMA *et al.*, PRD 92, 091301 (2015)

Missing energy



AMA *et al.*, PRD 92, 091301 (2015)

Sensitivity to nuclear effects

Nuclear effects (e.g. FSI) redistribute the energy transferred to the nucleus, but they don't change the total amount. In an ideal detector they are irrelevant for the oscillation analysis using E_{cal}.

Does this picture change for a realistic detector?

Sensitivity to nuclear effects

AMA, arXiv:1704.07835

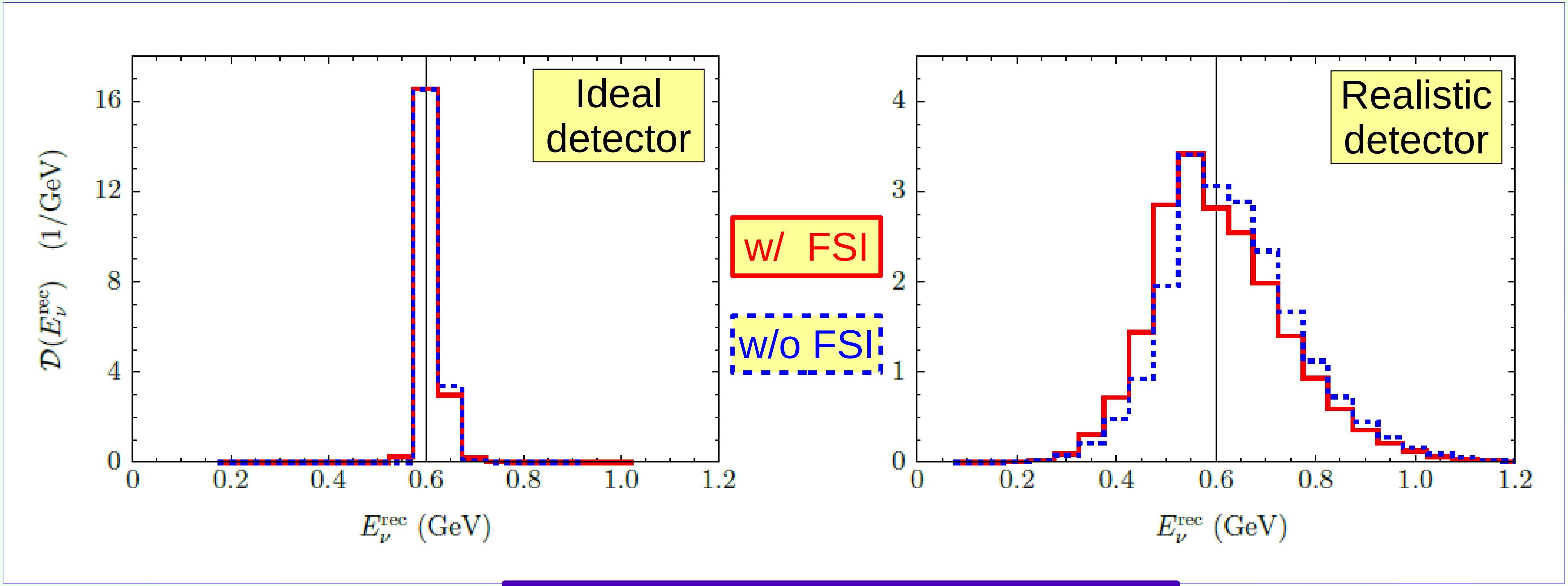
Considered a T2K-like $\nu_\mu \to \nu_\mu$ disappearance experiment

- data collected for **5 years**
- **calorimetric energy reconstruction**
- thresholds: **100 MeV** for mesons and **50 MeV** for nucleons. Realistic energy resolutions.

Assumed **20%** systematic uncertainties for the **shape** and for the overall **normalization**.

True event rates **w/ FSI**, fitted event rates **w/o FSI**.

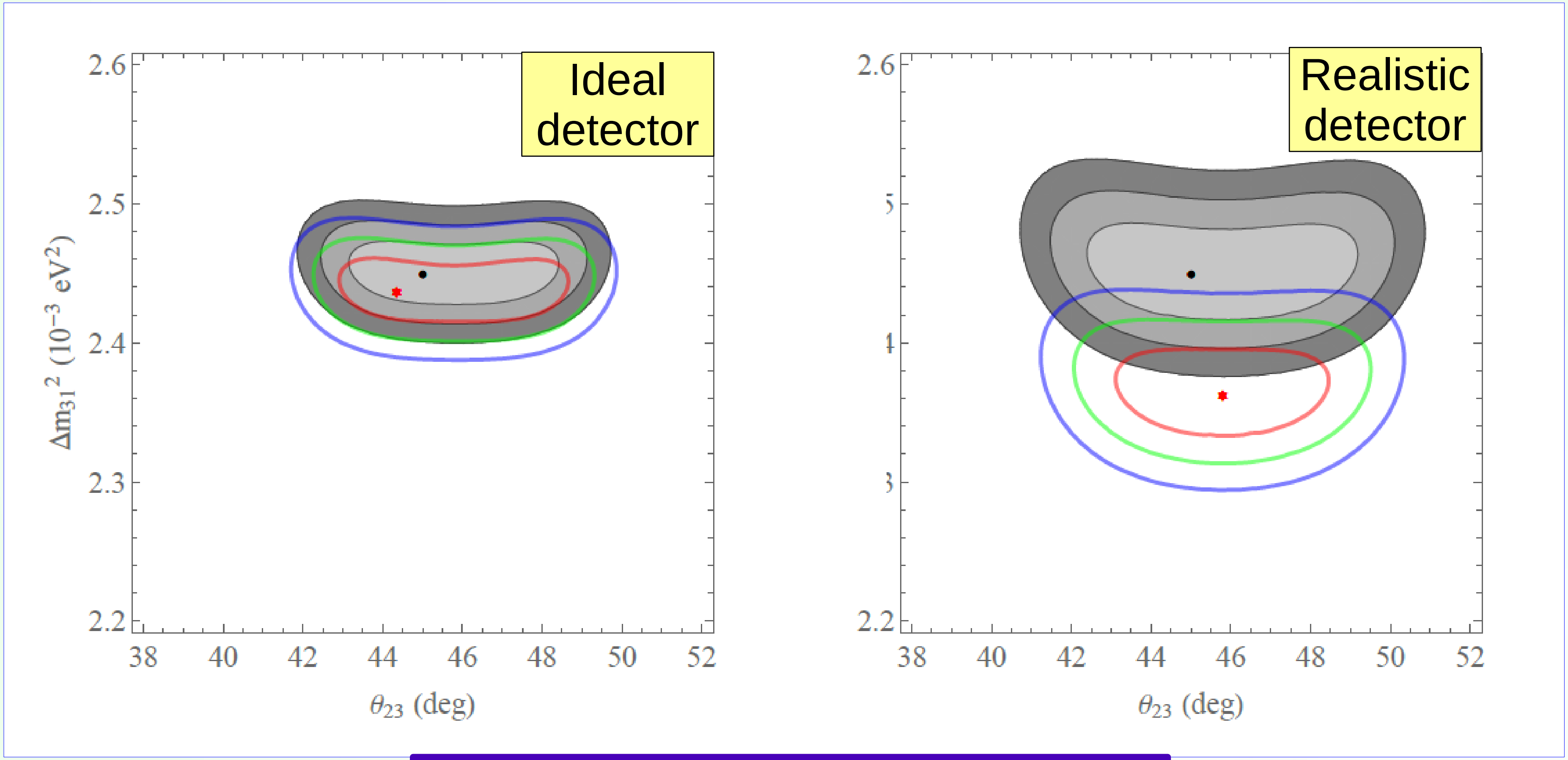
Sensitivity to nuclear effects



AMA, arXiv:1704.07835

Sensitivity to nuclear effects

True event rates w/ FSI, fitted event rates w/o FSI



AMA, arXiv:1704.07835

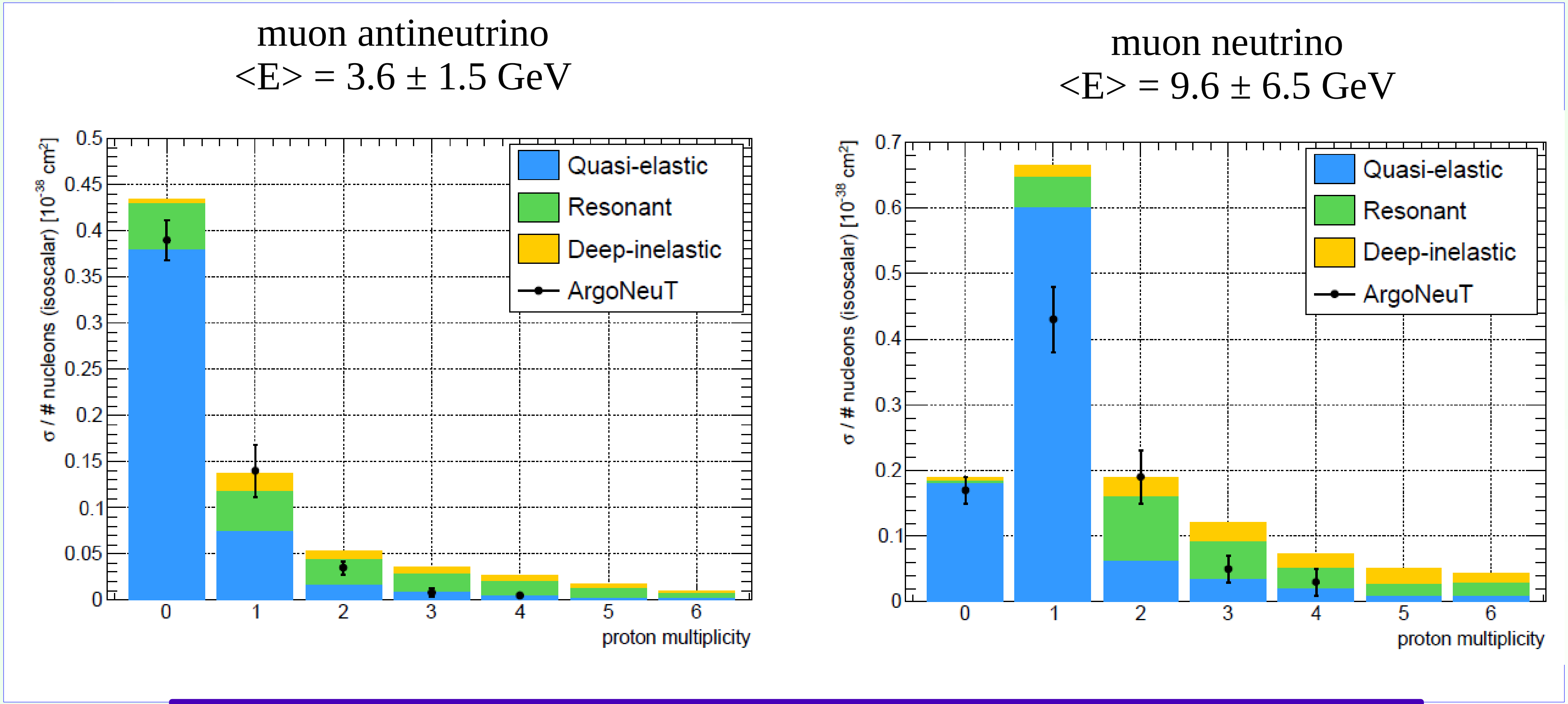
Calorimetric reconstruction

An accurate calorimetric energy reconstruction requires

- an accurate and detailed determination of **detector response** in test-beam exposures
- a realistic simulation of nuclear effects, including intranuclear cascade. **Event composition and spectra of all hadrons become fundamental**.

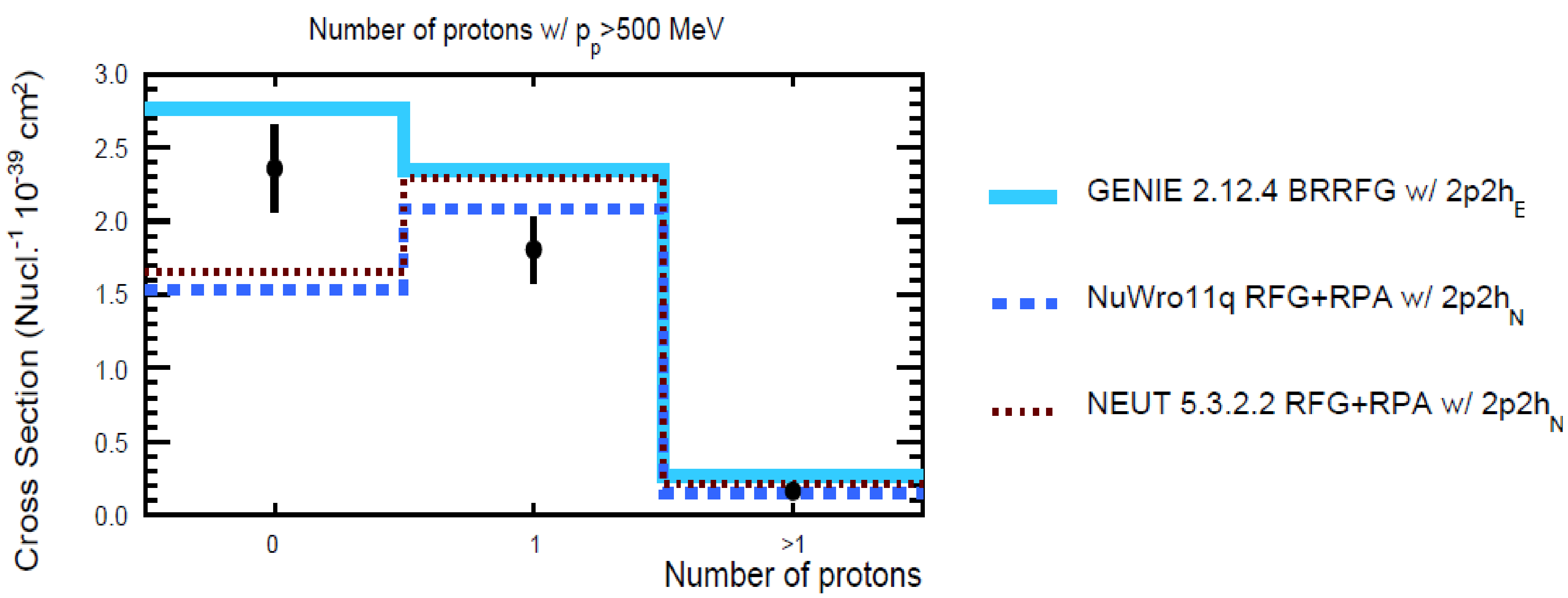
Accurate exclusive cross sections play pivotal role.

Proton multiplicities in CC 0pi events



O. Palamara (ArgoNEUT), JPS Conf. Proc. , 010017 (2016)

Proton multiplicities in CC 0pi events



K. Abe at al. (T2K), arXiv:1802.05078

Summary

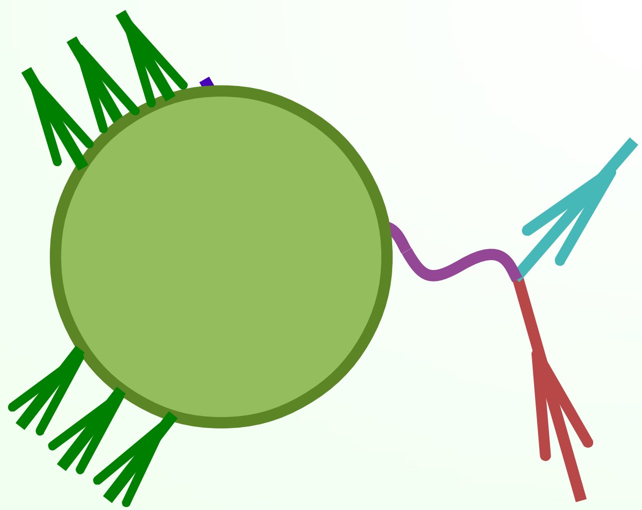
- Experiments of next generation require challenging accuracy for energy reconstruction.
- Near detectors are fundamental to reduce uncertainties, but won’t solve all problems. The lower the thresholds, the better.
- Especially for DUNE, precise and accurate theoretical predictions for spectra of hadrons in the final state are pivotal in energy reconstruction.
- Available data clearly show that more theoretical work is needed. The lower the uncertainties, the more challenges.

Backup slides

Unknown monochromatic beam

Consider the simplest (unrealistic) case:

the beam is monochromatic but its energy is unknown and has to be reconstructed

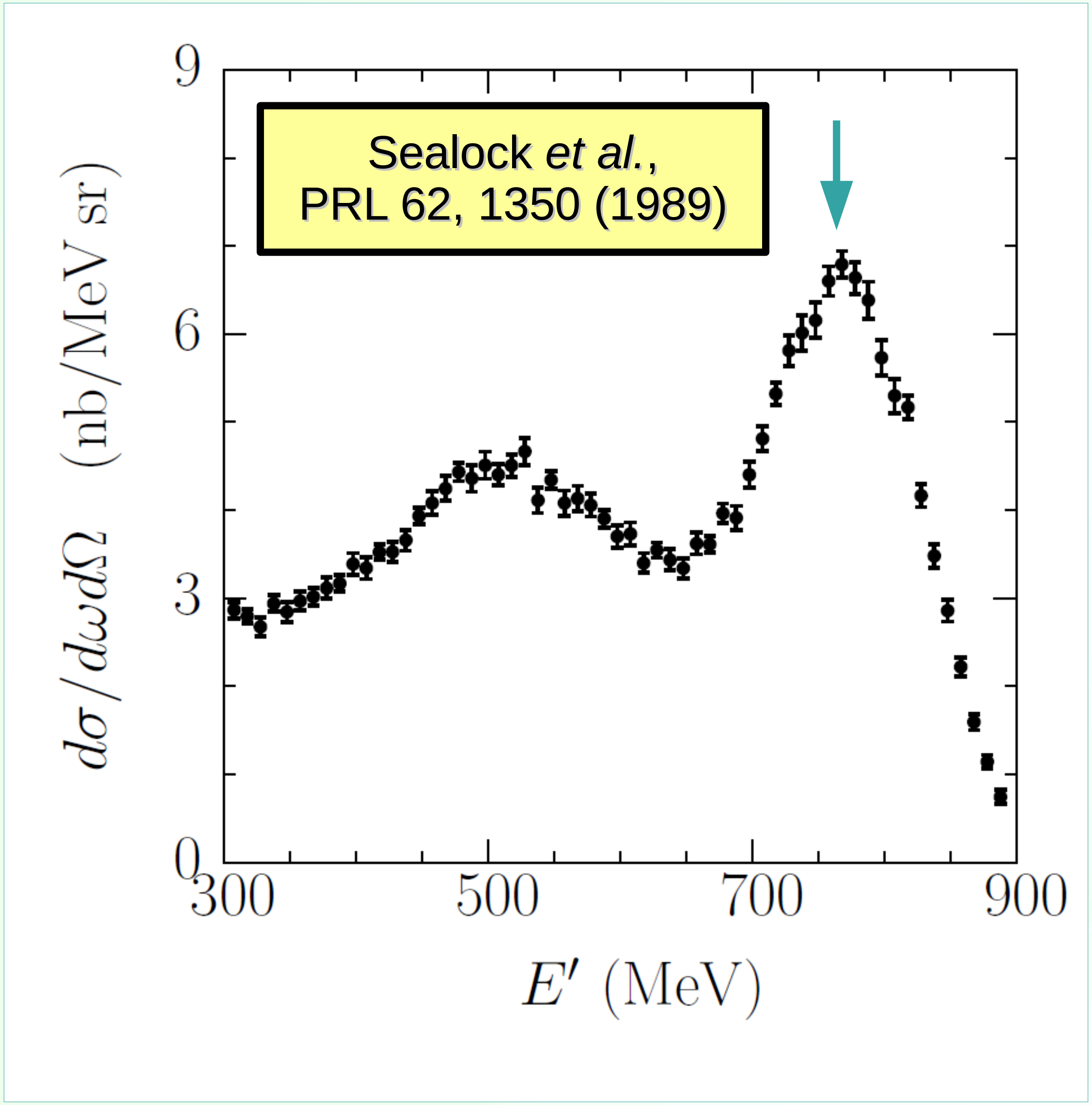


E' and θ known

$E = ?$

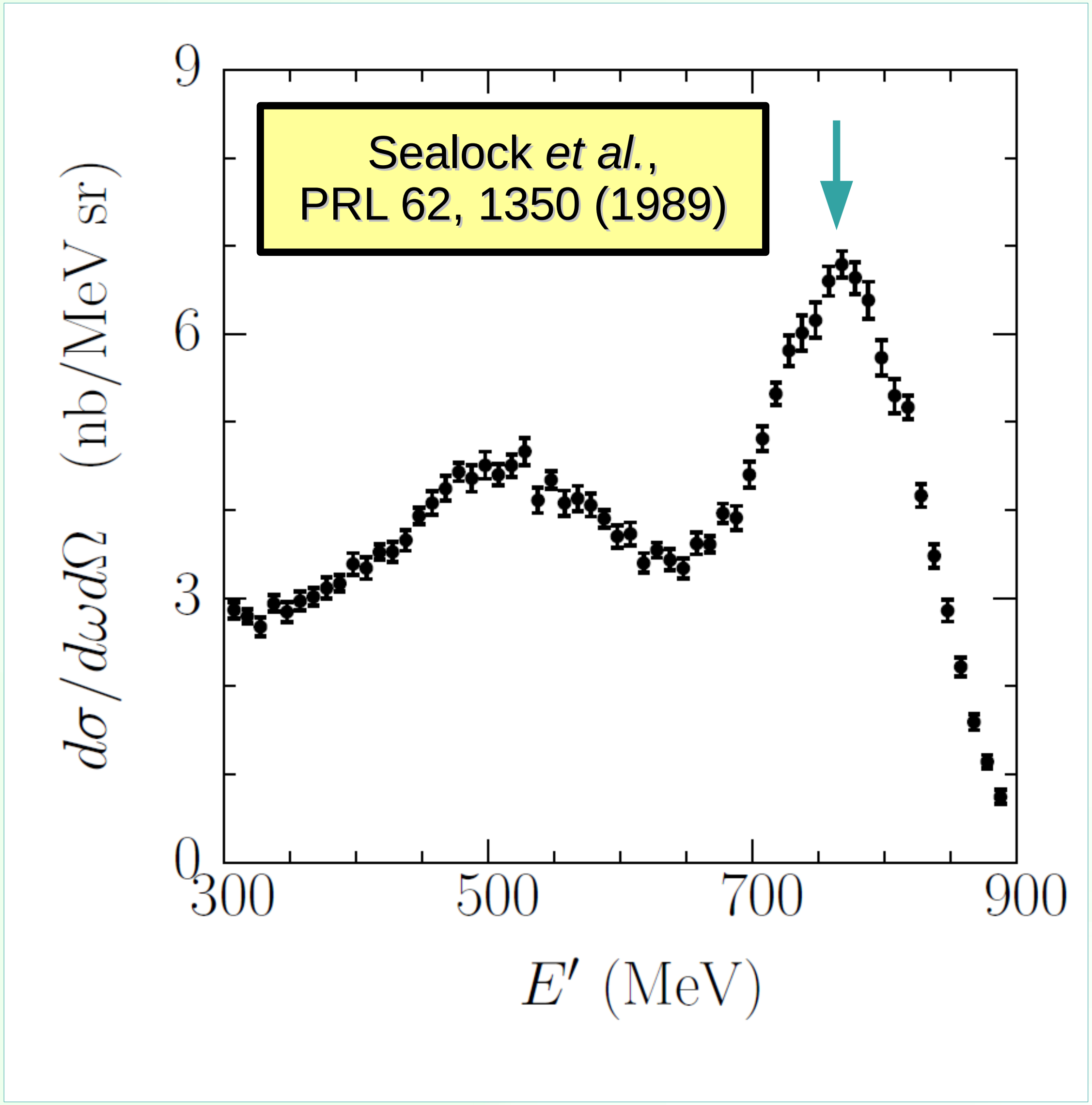
PoS(NuFact2014)004

“Unknown” monochromatic e^- beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 5$ MeV

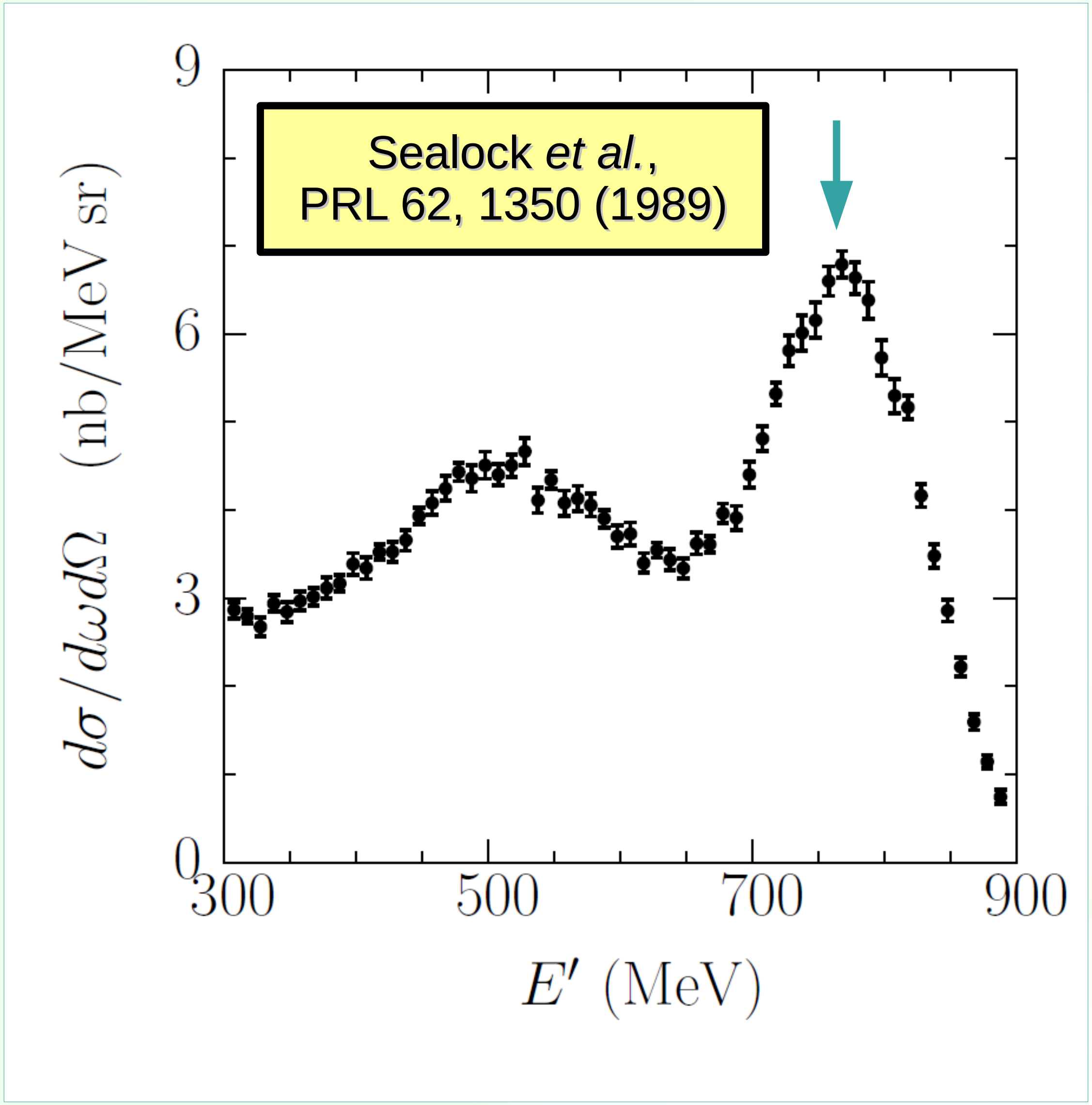
“Unknown” monochromatic e^- beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 5$ MeV

for $\epsilon = 25$ MeV
$E = 960$ MeV
$\Delta E = 7$ MeV

“Unknown” monochromatic e^- beam



$E' = 768$ MeV
$\theta = 37.5$ deg
$\Delta E' = 5$ MeV

for $\epsilon = 25$ MeV
$E = 960$ MeV
$\Delta E = 7$ MeV

true value
$E = 961$ MeV

“Unknown” monochromatic e^- beam

θ (deg)	37.5	37.5	37.1	36.0	36.0
E' (MeV)	976	768	615	487.5	287.5
$\Delta E'$ (MeV)	5	5	5	5	2.5

Assuming $\epsilon = 25$ MeV

rec. *E*	**1285 ± 8**	**960 ± 7**	**741 ± 7**	**571 ± 6**	**333 ± 3**
true *E*	**1299**	**961**	**730**	**560**	**320**

“Unknown” monochromatic e^- beam

θ (deg)	37.5	37.5	37.1	36.0	36.0
E' (MeV)	976	768	615	487.5	287.5
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Appropriate ϵ value?

true E	**1299**	**961**	**730**	**560**	**320**
ϵ	**33 ± 5**	**26 ± 5**	**16 ± 5**	**16 ± 3**	**13 ± 3**

Sealock et al., PRL 62, 1350 (1989)

O'Connell *et al.*, PRC 35, 1063 (1987)

Barreau *et al.*, NPA 402, 515 (1983)

“Unknown” monochromatic e^- beam

θ (deg)	37.5	37.5	37.1	36.0	36.0
E' (MeV)	976	768	615	487.5	287.5
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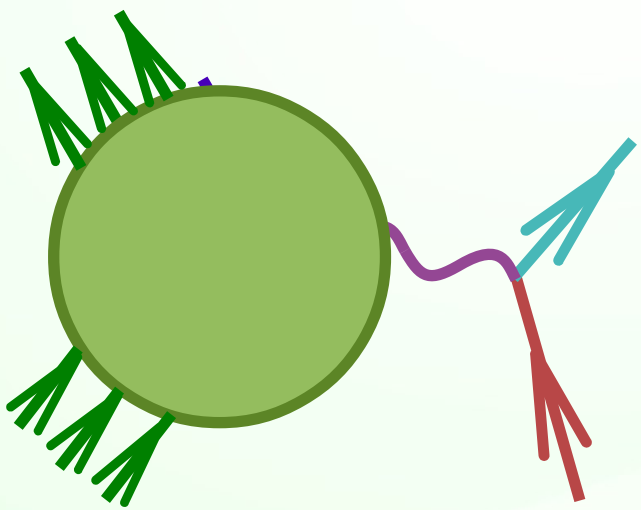
Appropriate ϵ value?

true E	**1299**	**961**	**730**	**560**	**320**
ϵ	**33 ± 5**	**26 ± 5**	**16 ± 5**	**16 ± 3**	**13 ± 3**

different $E \equiv$ different $Q^2 \equiv$ different θ
$\rightarrow$ different ϵ

Polychromatic beam

In modern experiments, the neutrino beams are not monochromatic, and the energy must be reconstructed from the observables, typically E' and $\cos\theta$ under the CCQE event hypothesis.



E' and θ known

$E = ?$

CC0π events

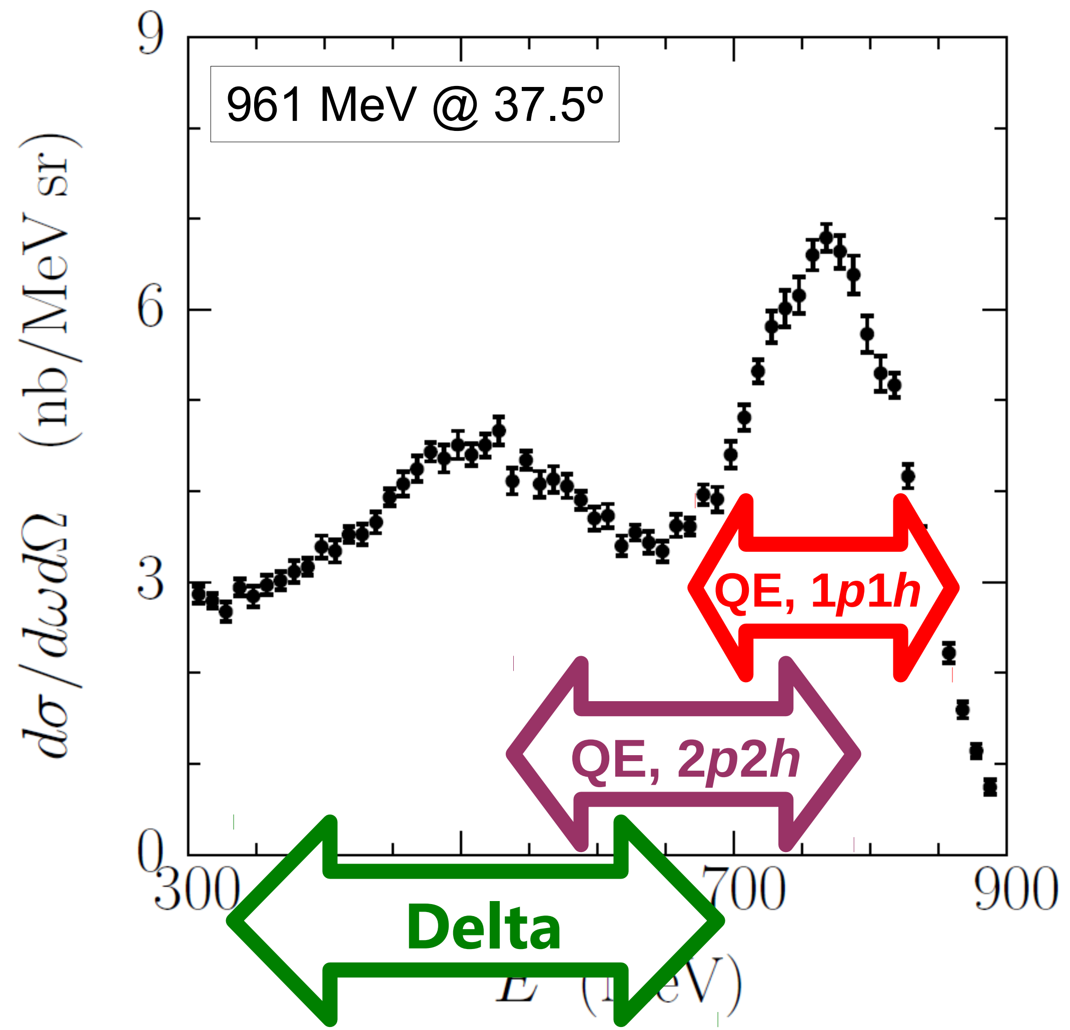
In practice, CCQE energy reconstruction is applied to all events not containing **observed pions**.

CCQE (any number of nucleons)
\+ pion production and followed by absorption
undetected pions

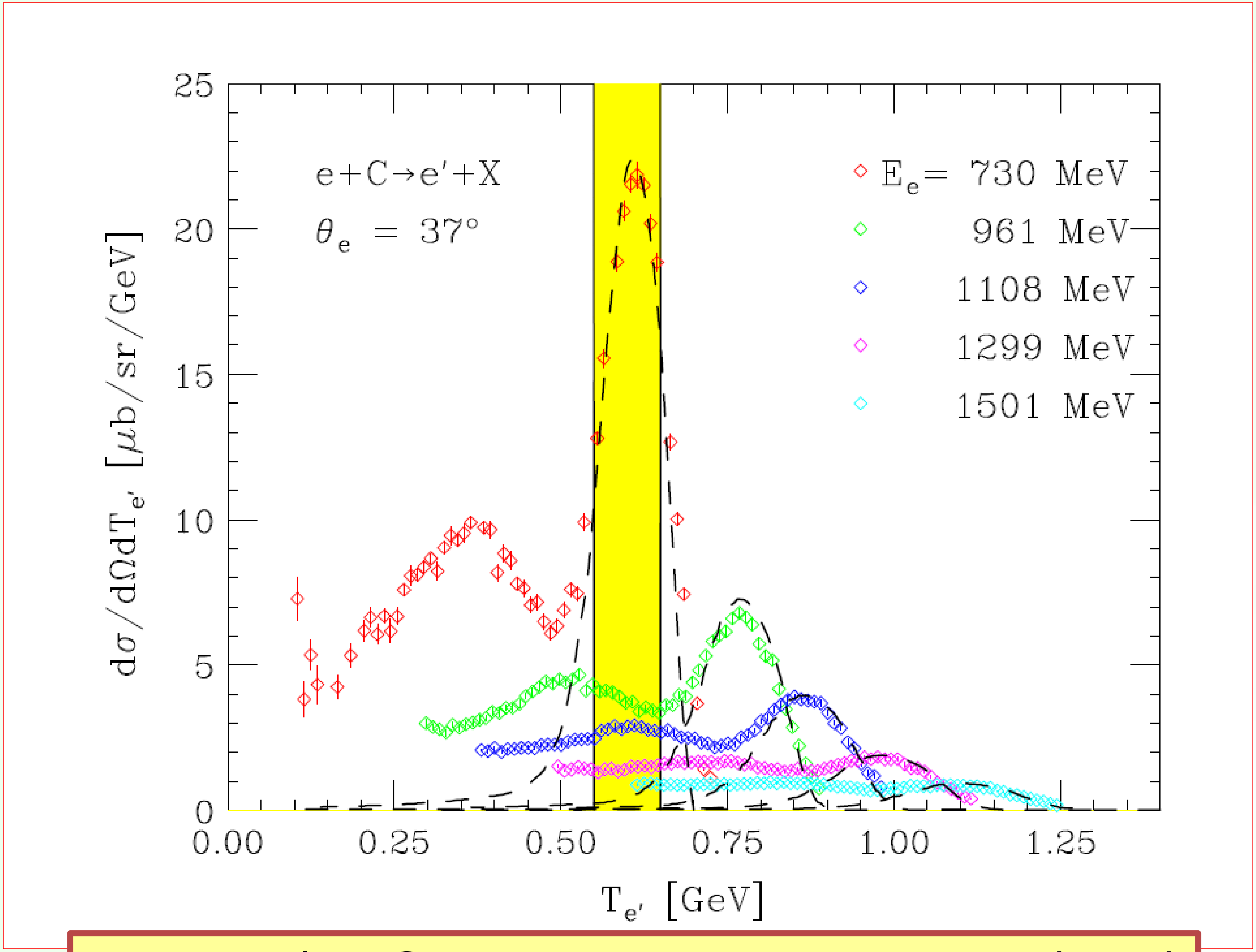
— CCQE with pions from FSI

0π events

Recall the monochromatic-beam case



CCQE events of given $l^{\pm}$ kinematics



Omar Benhar @ NuFact11, PRL 105, 132301 (2010)

CCQE events of given $l^{\pm}$ kinematics

Very different **processes** and **neutrino energies** contribute to CCQE-like events of a given E' and $\cos\theta$.

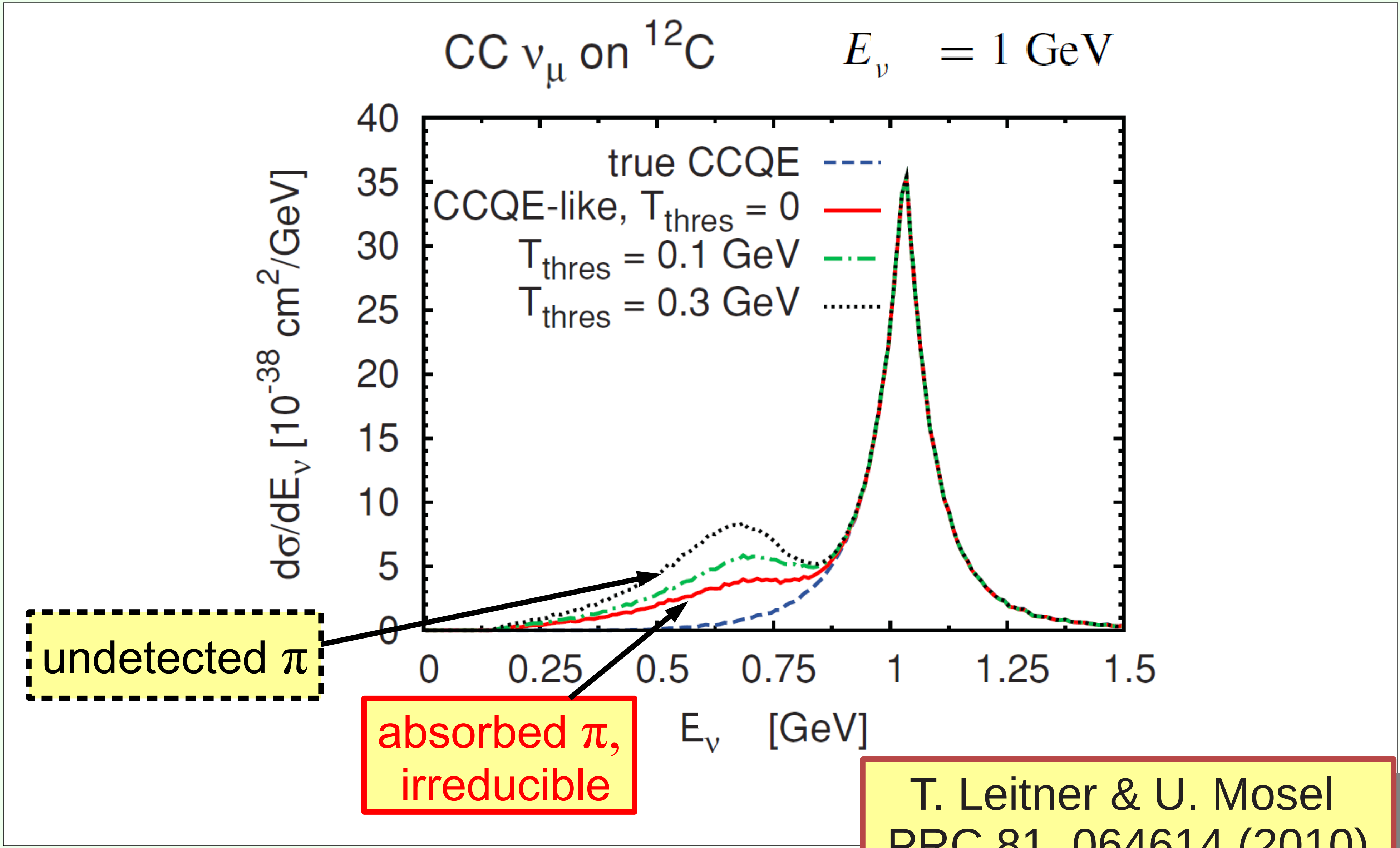
An undetected pion typically lowers the reconstructed energy by **~300–350 MeV**.

Note that in the reconstruction formula, $M_{\Delta} = 1232$ MeV would be more suitable than $M' = 939$ MeV.

$$E_{\nu}^{\rm rec} = \frac{2(M-\varepsilon)E_{\ell} + M'^2 - (M-\varepsilon)^2 - m_{\ell}^2}{2(M-\varepsilon-E_{\ell}+|\mathbf{k}_{\ell}|\cos\theta)}.$$

$$\frac{M_{\Delta}^2 - M'^2}{2M} \approx 340 \text{ MeV}$$

Absorbed or undetected pions



T. Leitner & U. Mosel
PRC 81, 064614 (2010)

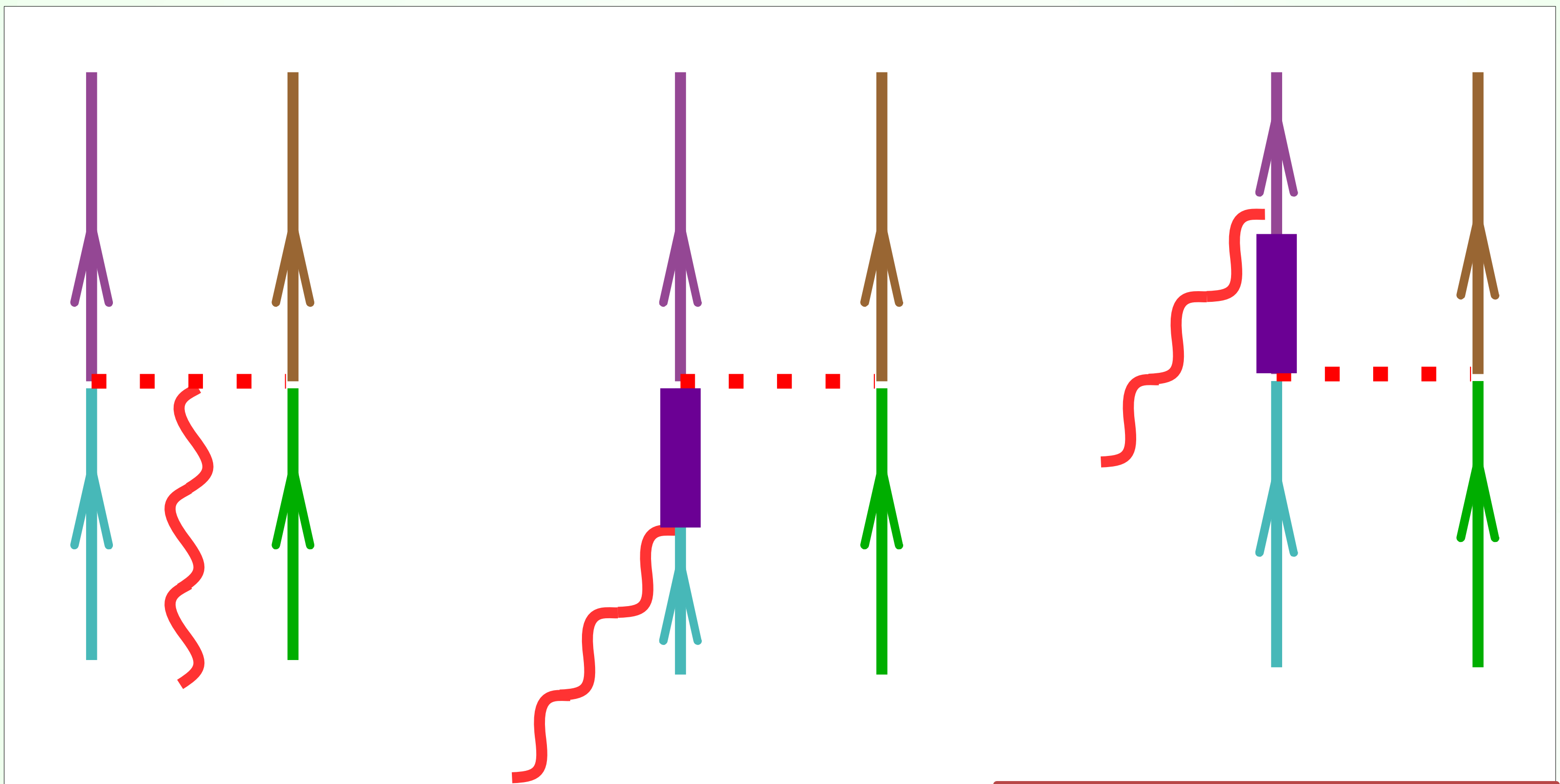
$2p2h$ final states

Final states involving two (or more) nucleons may come from

- **initial-state correlations**: ~20% of nucleons in nucleus strongly interact, typically forming a deuteron-like *np* pair of high relative momentum
- **final-state interactions**
- **2-body reaction mechanisms**, such as by meson-exchange currents

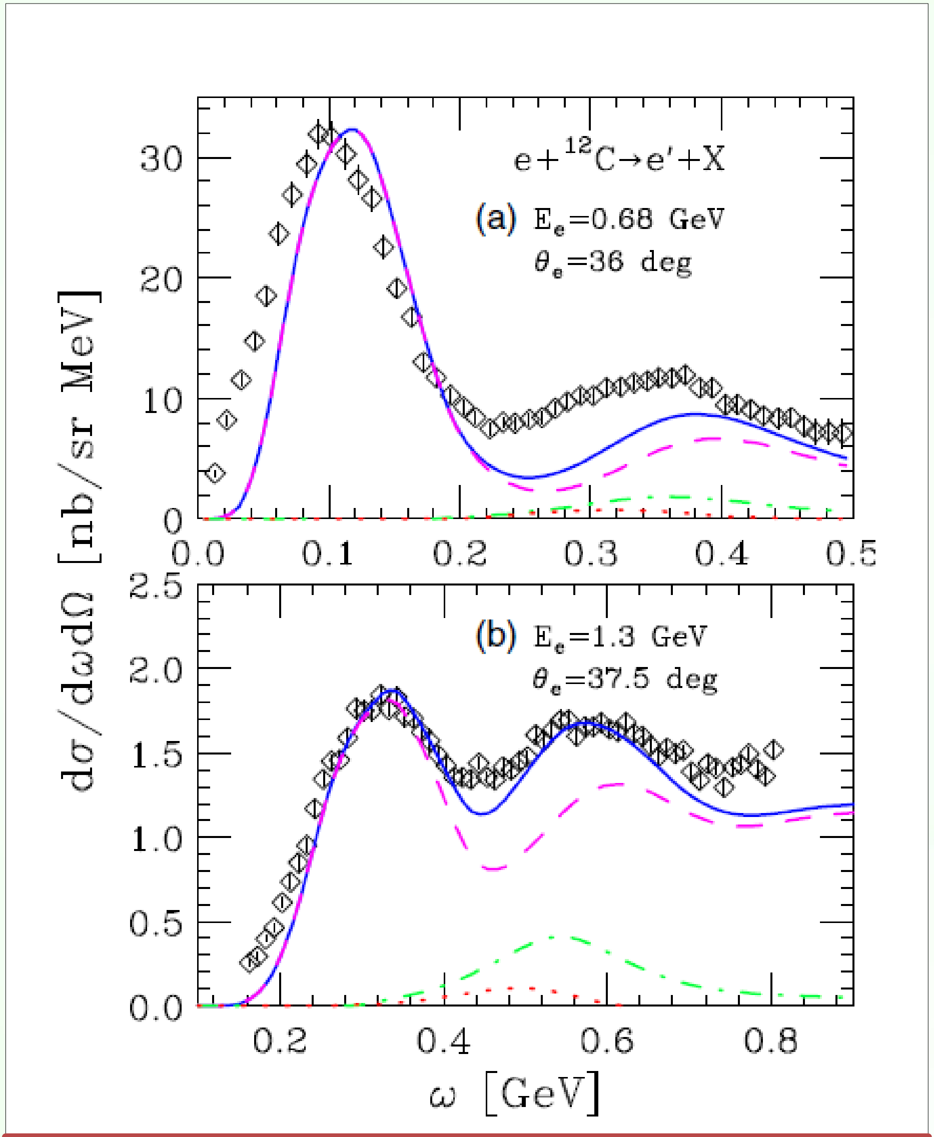
Alberico *et al.*
Ann. Phys. 154, 356 (1984)

2-body reaction mechanisms



Donnelly *et al.*
PLB 76, 393 (1978)

2*p*2*h* contribution to the cross section

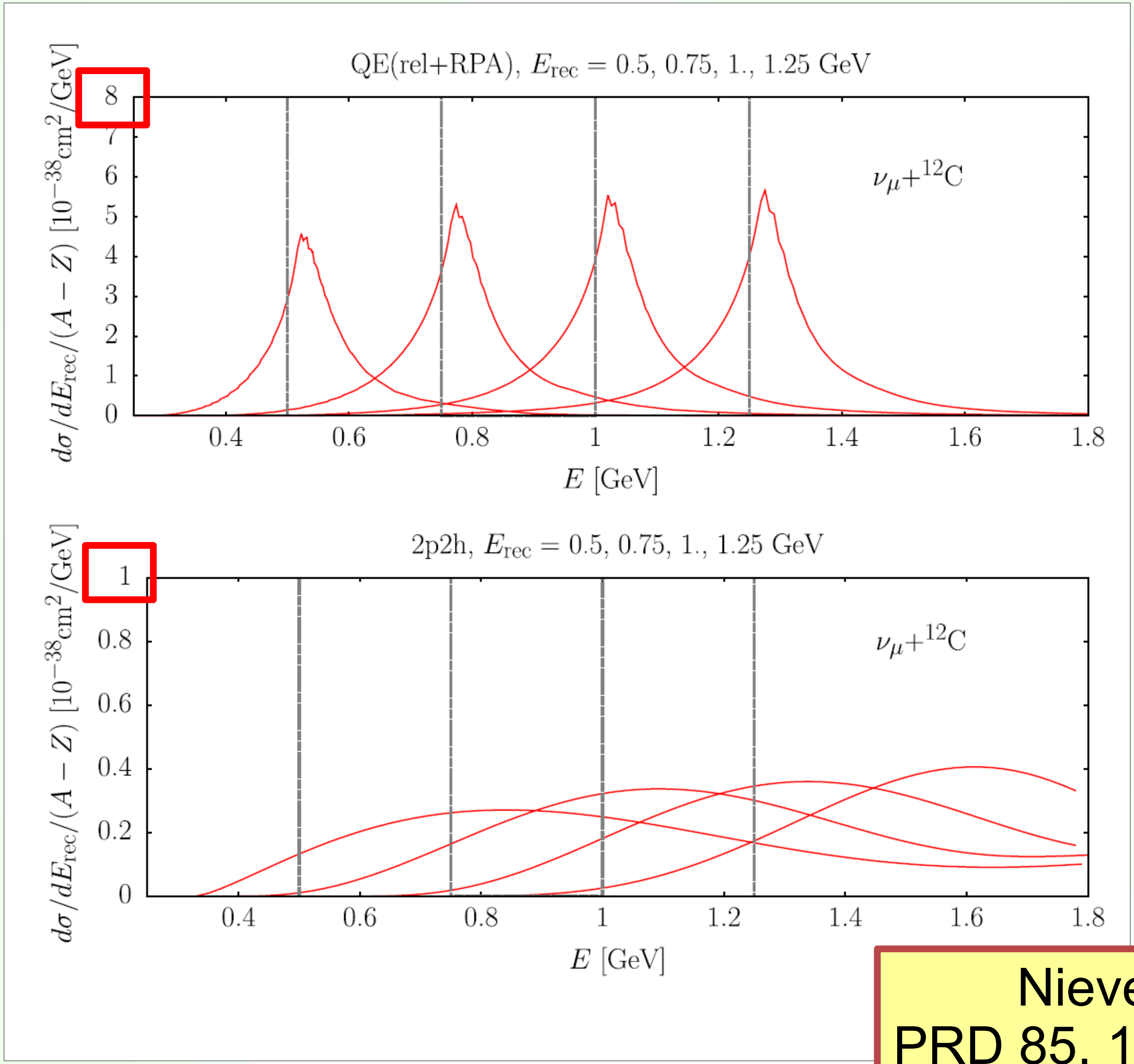


Rocco *et al.*, PRL 116, 192501 (2016)

2*p*2*h* effect on energy reconstruction

1*p*1*h*

2*p*2*h*



Nieves *et al.*,
PRD 85, 113008 (2012)