Electron scattering in NEUT neutrino event generator

S. Abe, PRD 111, 033006 (2025)

Seisho Abe
seisho@icrr.u-tokyo.ac.jp
Kamioka Obs., ICRR, the University of Tokyo

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ICRR
Institute for Cosmic Ray Research
University of Tokyo

KAMIOKA OBSERVATORY

Contents

- Electron scattering for neutrinos
- NEUT neutrino event generator
- Implementation of electron scattering to NEUT
- Prospects and summary

Open questions in neutrino oscillation

Discovery of neutrino oscillation

ν_μ → Propagation (Vaccum/matter) → ν_e, ν_μ, ν_τ

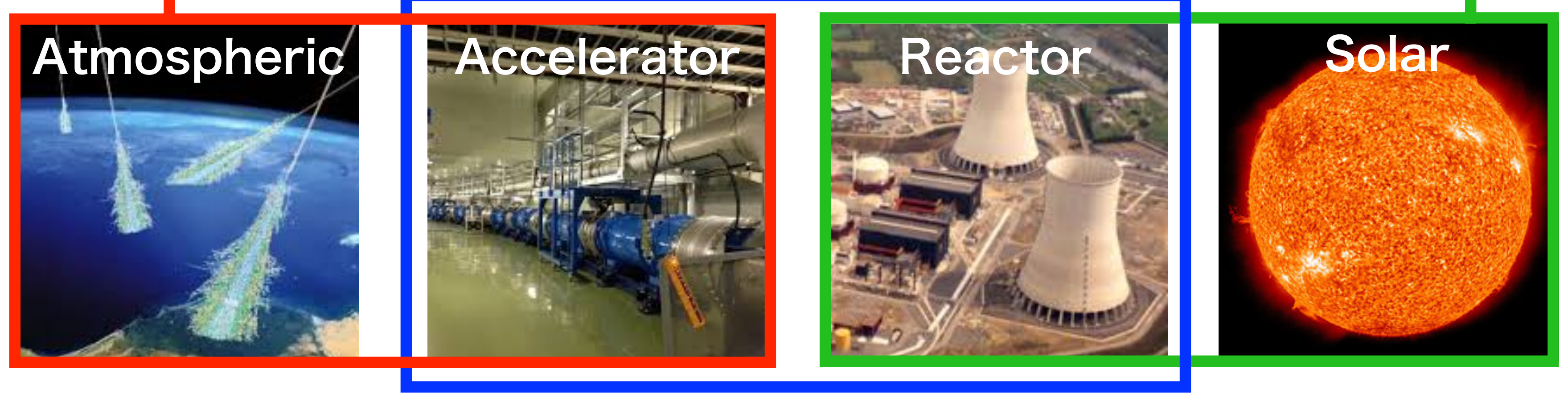
Appearance
Disappearance

Discovery ➡ Assumption in the standard model:
~~"Massless neutrinos"~~
Beyond the Standard Model

PMNS matrix

Flavor · Mass

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



$c_{ij}=\cos\theta_{ij}$
$s_{ij}=\sin\theta_{ij}$
$\Delta m_{ij}^2=m_i^2-m_j^2$

CP-phase (δ_{CP})

$\sin\delta_{CP}\neq 0$?

$$P(\nu_\mu\to\nu_e)\neq P(\bar{\nu}_\mu\to\bar{\nu}_e)$$

Magnitude of CP violation (Jarlskog invariant)

$$J_{CP}\equiv\frac{1}{8}\cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\delta_{CP}$$

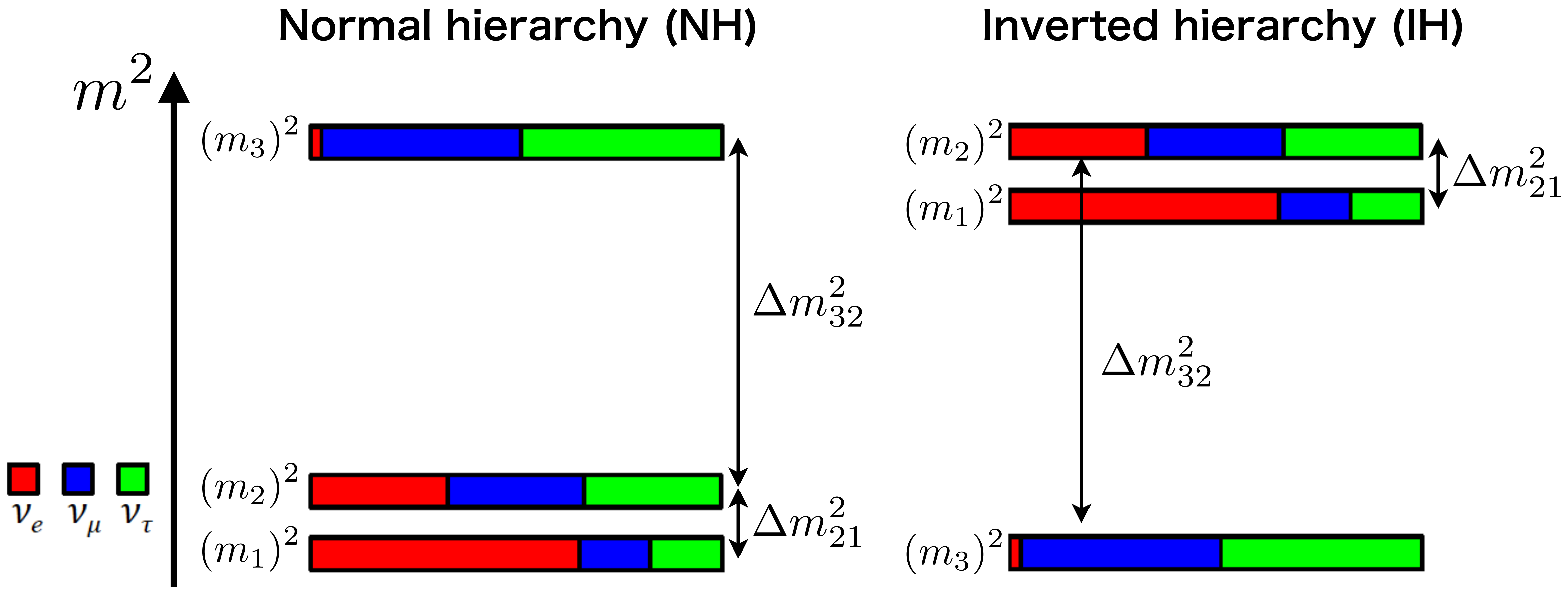
Quarks ↔ Neutrinos

$J_{CP}^{CKM}\sim 3\times 10^{-5}$ ⟷ $J_{CP}^{PMNS}\simeq 0.033\sin\delta_{CP}$ Large?!

Too small to explain our matter-dominant universe···

Neutrino CP-violation could be a hint to reveal the mysteries of the universe.

Mass hierarchy



→ **More precise measurements!**

Long-baseline neutrino oscillation experiment

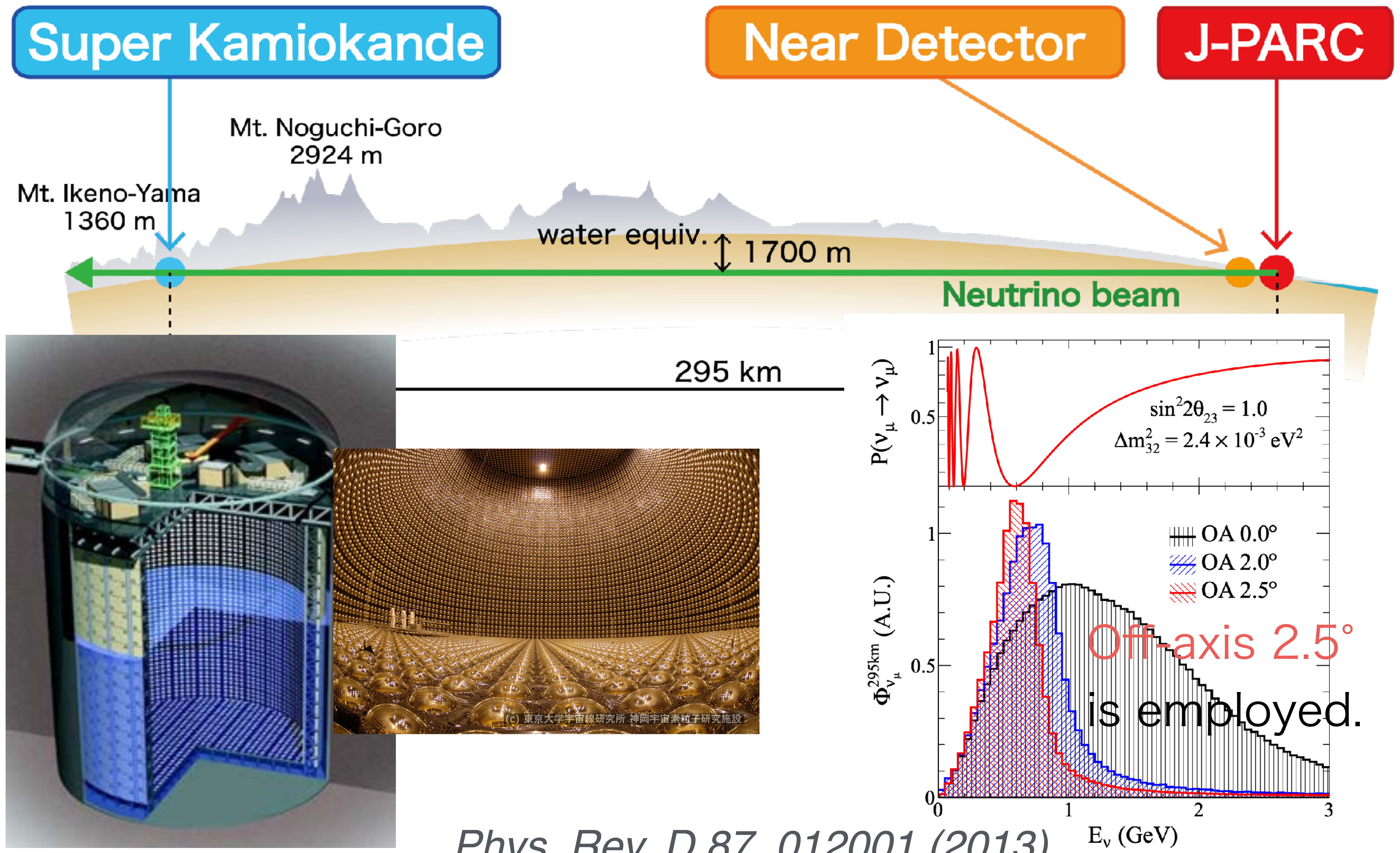
$$P(\nu_\alpha(\bar{\nu}_\alpha) \rightarrow \nu_\beta(\bar{\nu}_\beta)) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E_\nu}\right)$$

Oscillation probability

$$\pm 2\sum_{i>j} \mathrm{Im}(U_{\beta i}U^*_{\alpha i}U^*_{\beta j}U_{\alpha j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E_\nu}\right).$$

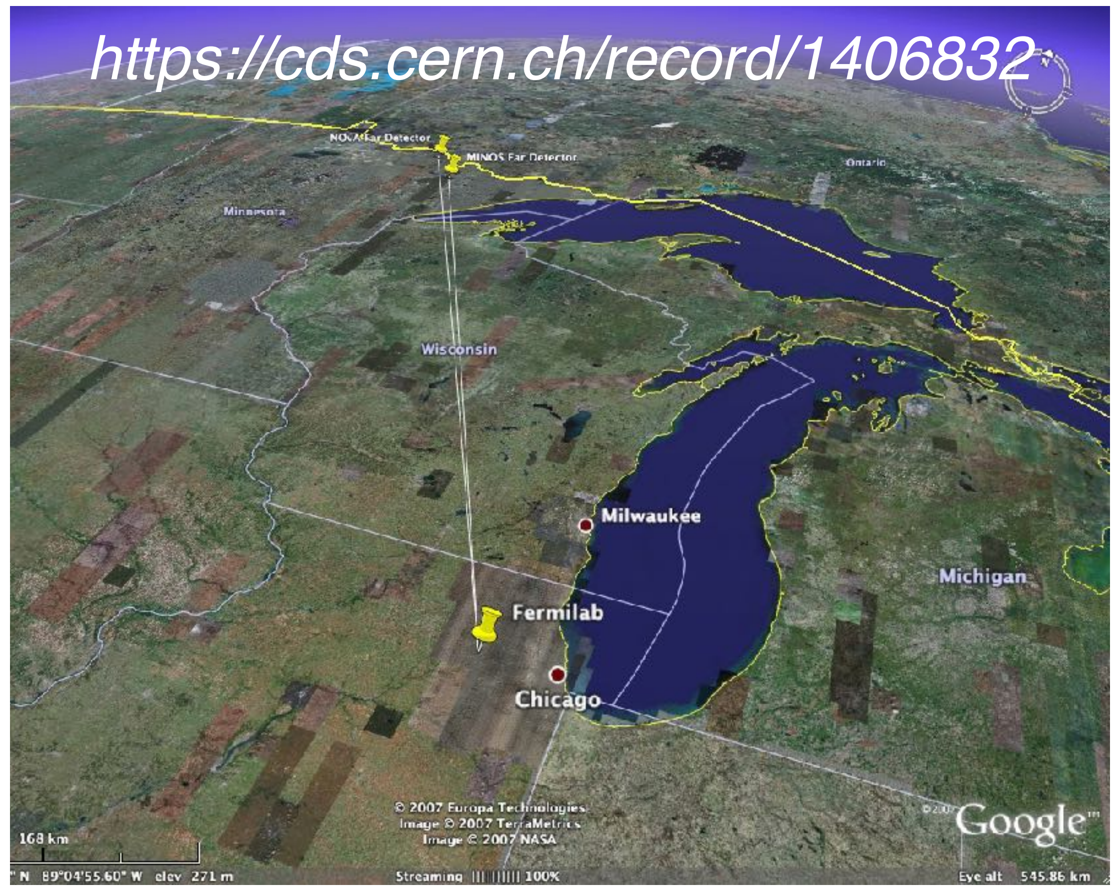
- L: Baseline (fixed).
- **E_ν: Neutrino energy.**

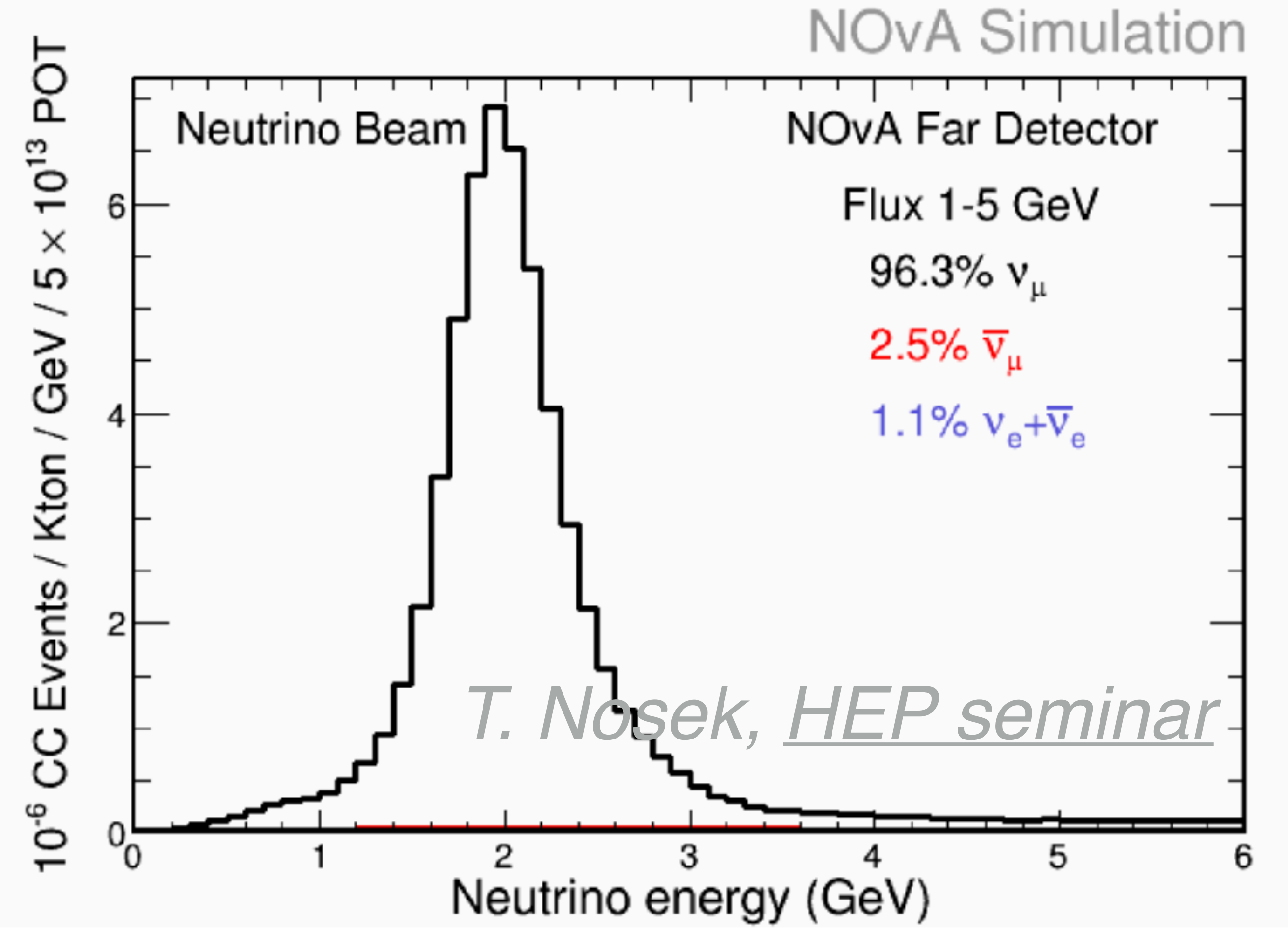
T2K L = 295 km, <Ev> = 0.6 GeV



Phys. Rev. D 87, 012001 (2013)

NOvA L = 810 km, <Ev> = 1.8 GeV





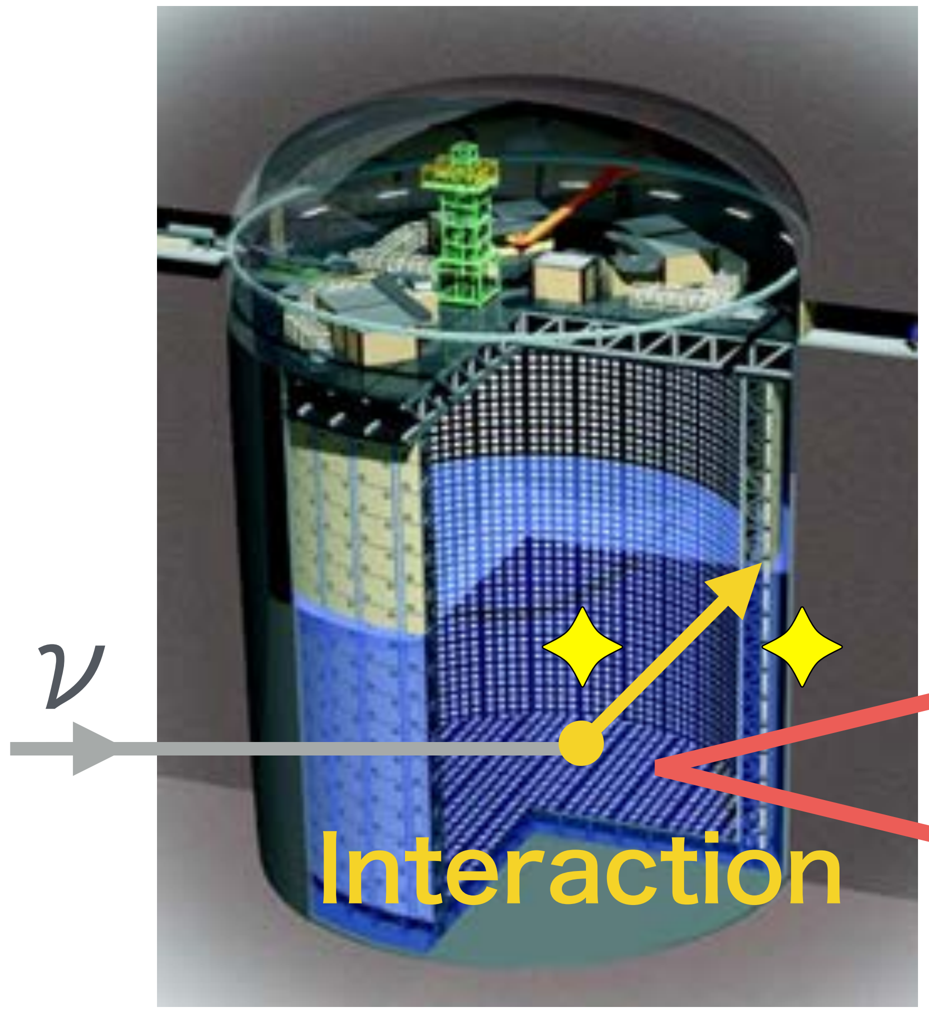
Essential challenge: Neutrino energy reconstruction

* **Broad energy spectra** due to π/K decay in flight.

Neutrino energy reconstruction

Super-Kamiokande (SK)

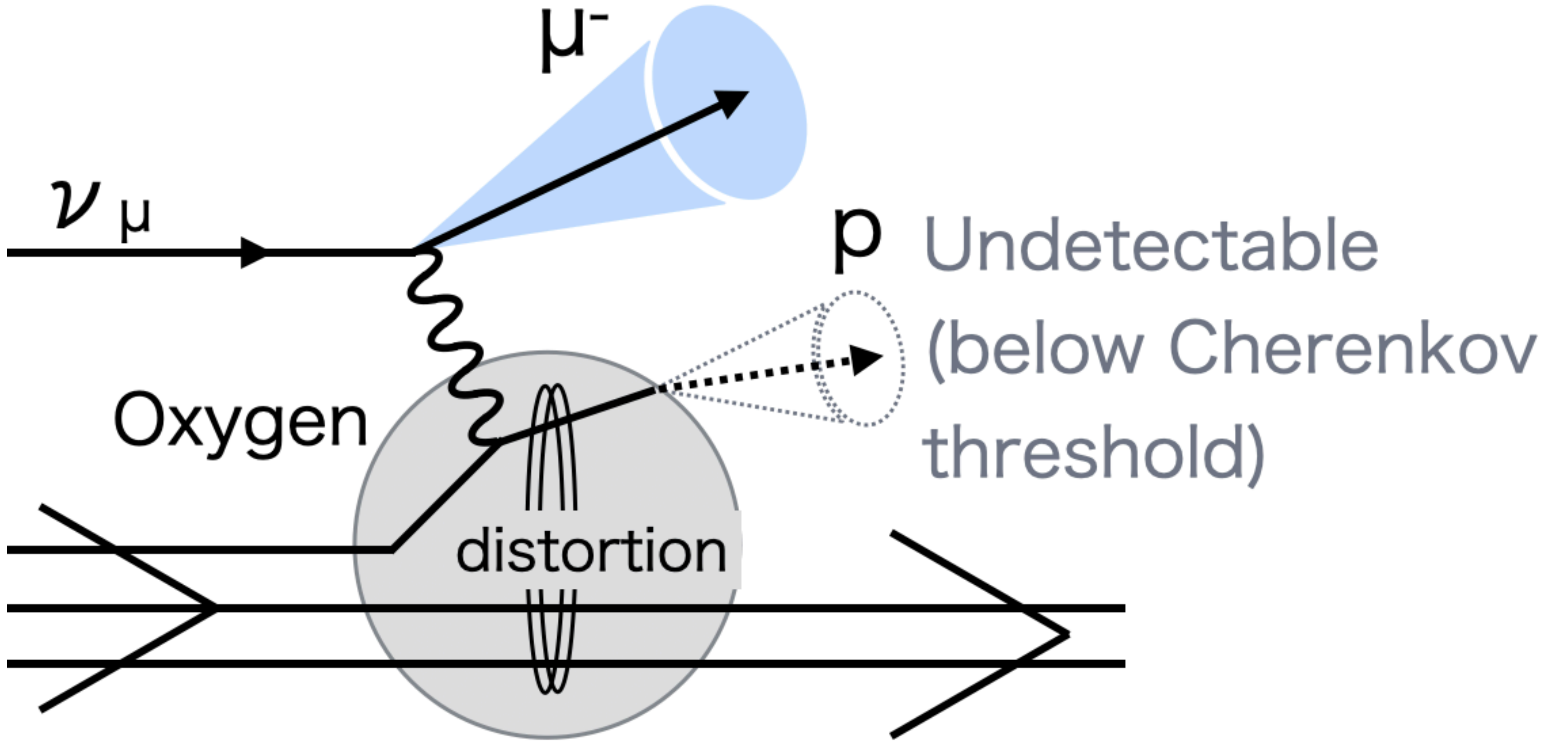
50 kt Water Cherenkov



Neutrino-nucleus interaction

Many body

Main signal: CCQE Charged-Current Quasi-Elastic



Reconsturcted neutrino energy:

$$E_\nu^{rec} = \frac{2E_l\tilde{M} - (m^2 + \tilde{M}^2 - M_f^2)}{2(\tilde{M} - E_l + p_l\cos\theta_l)},$$

$$\tilde{M} = M_i - E_b,$$

Nucleon mass — Binding energy

Charged lepton kinematics

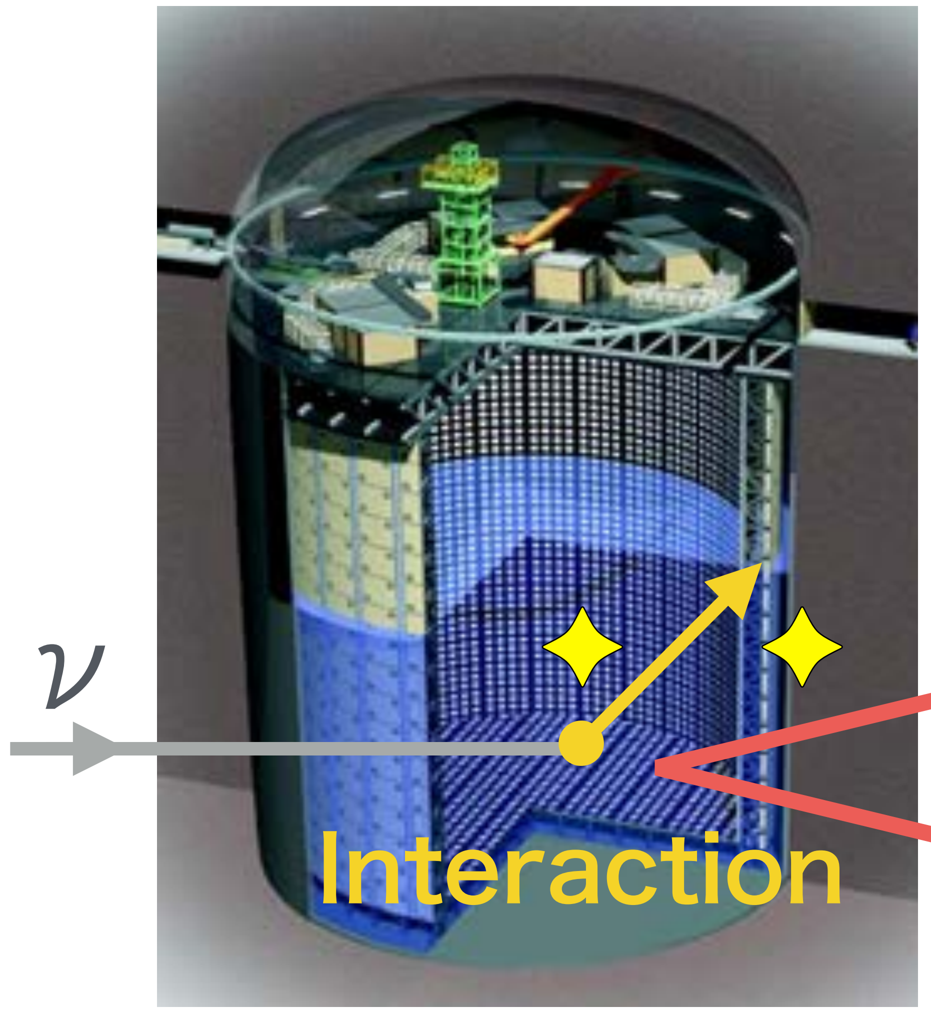
Key: Nuclear effects

Precise modeling of charged lepton response in many-body neutrino-nucleus interactions.

Neutrino energy reconstruction

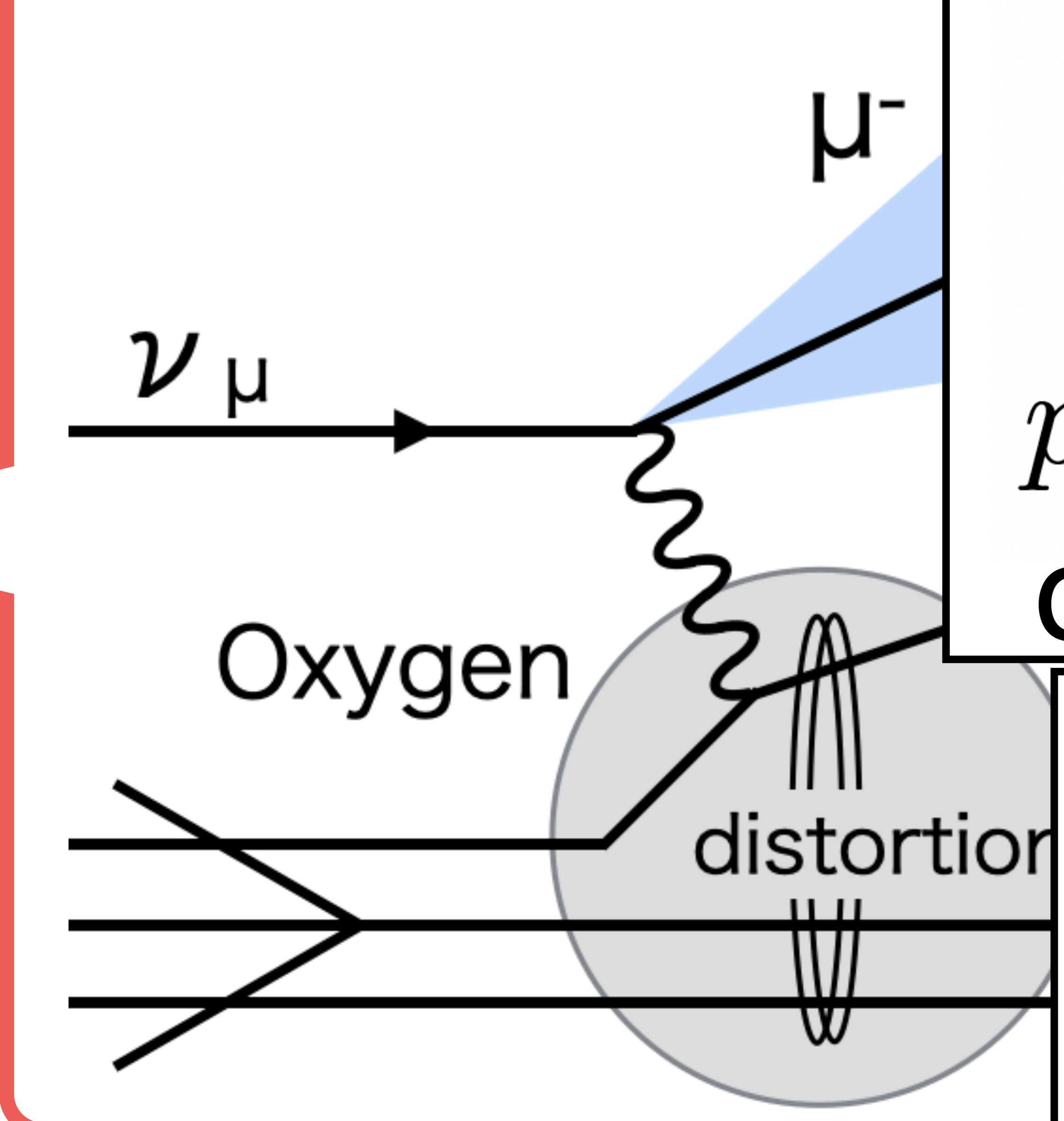
Super-Kamiokande (SK)

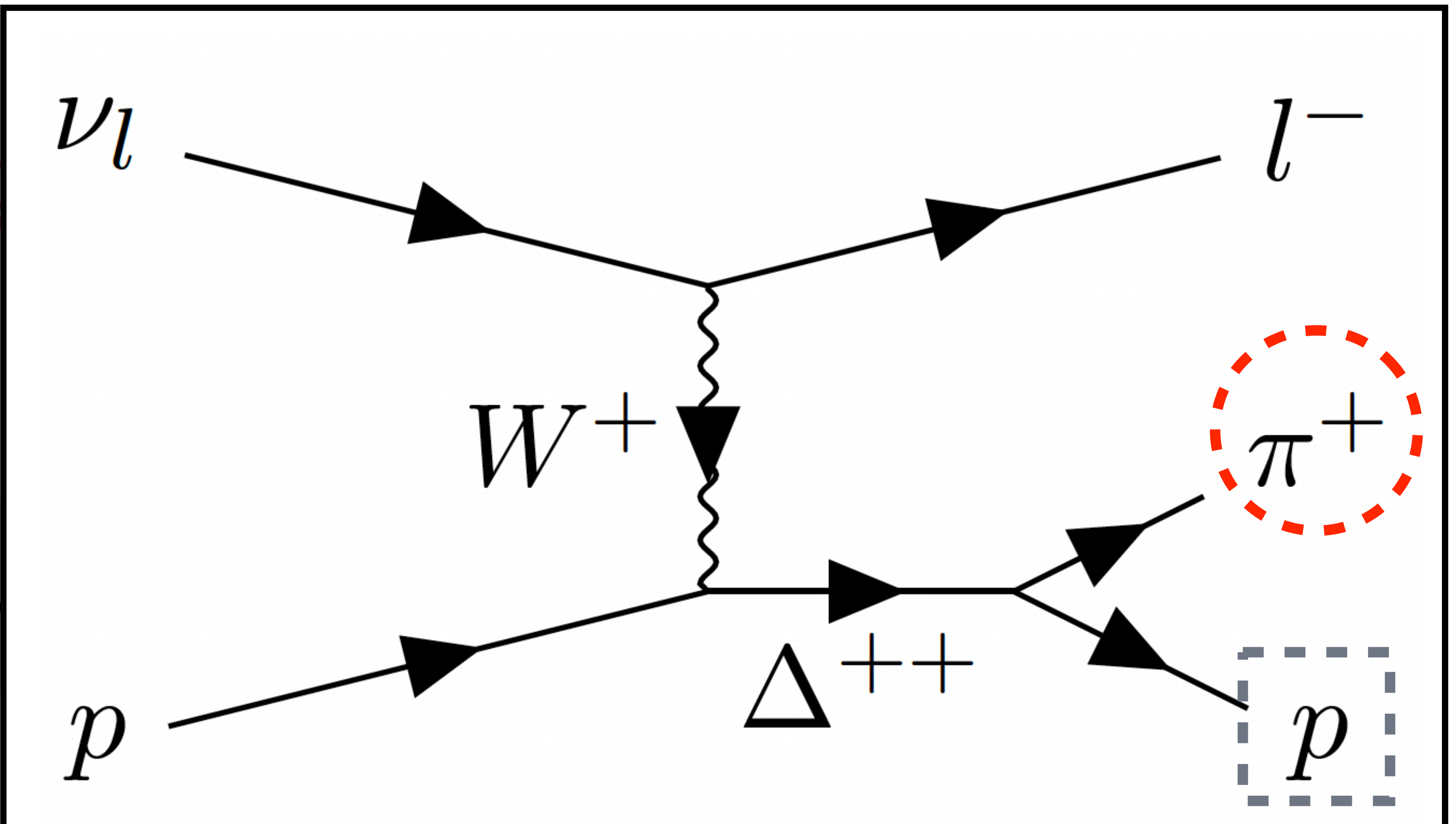
50 kt Water Cherenkov



Neutrino-nuc

Main signal: CC





CCRES (resonant pion production)

could be undetected. (below threshold, absorbed)

undetectable (below threshold)

- Non-CCQE is sometimes categorized as CCQE.
- It biases energy reconstruction.
- Nuclear effects are matter!

Reconsturcted neutrino energy:

$$E_\nu^{rec} = \frac{2E_l\tilde{M} - (m^2 + \tilde{M}^2 - M_f^2)}{2(\tilde{M} - E_l + p_l\cos\theta_l)},$$

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Nucleon mass Binding energy

Charged lepton kinematics

Key: Nuclear effects

Precise modeling of charged lepton response in many-body neutrino-nucleus interactions.

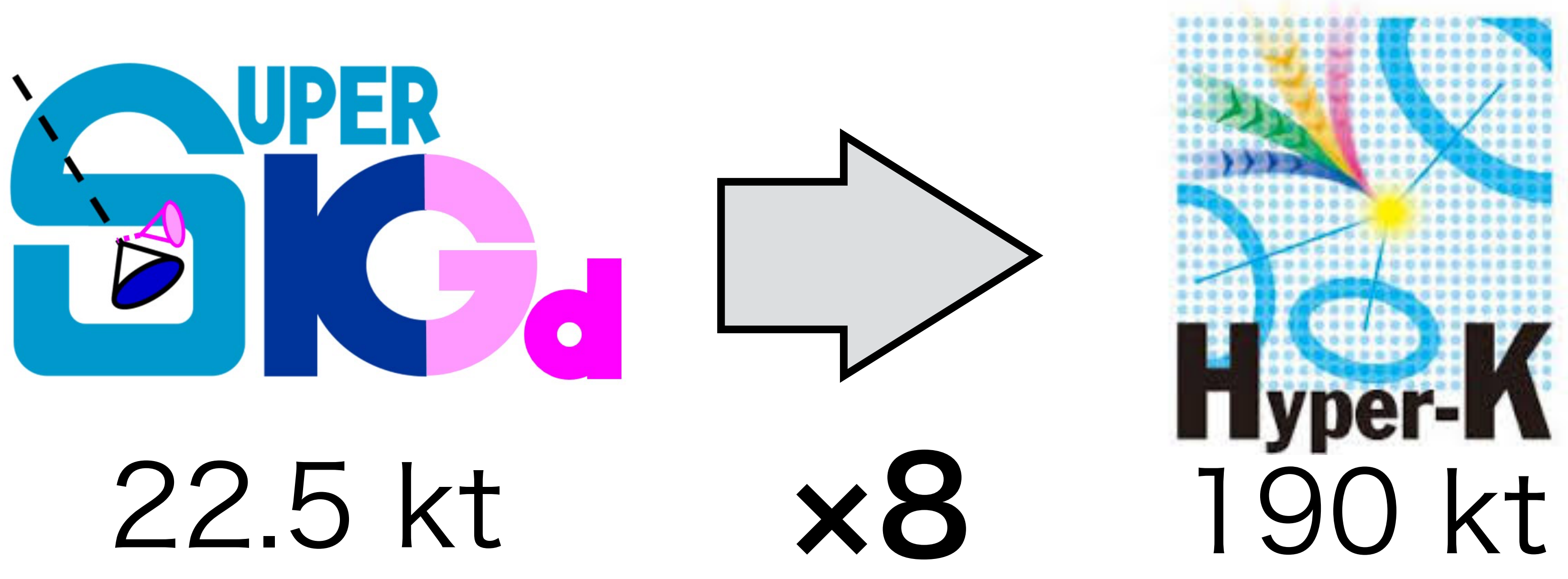
Impact on ν oscillation measurements

- ν interactions are the dominant systematic uncertainty.
  - Currently dominated by stat. unc.

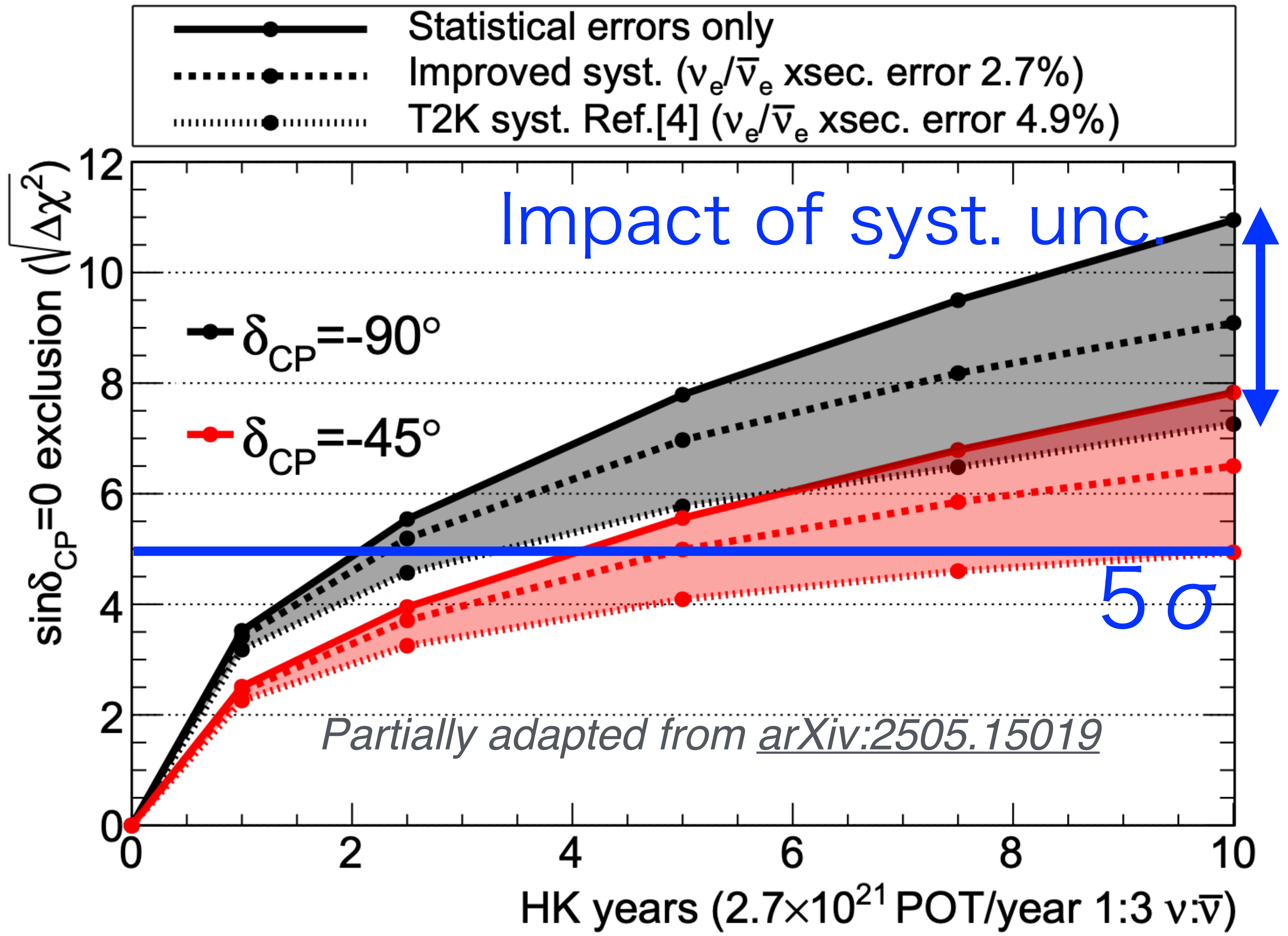
- In the next-generation experiment, syst. unc. will be dominant.

- **Toward Hyper-K in 10 Years: Confronting Neutrino Interaction Systematics Now.**

Fiducial volume



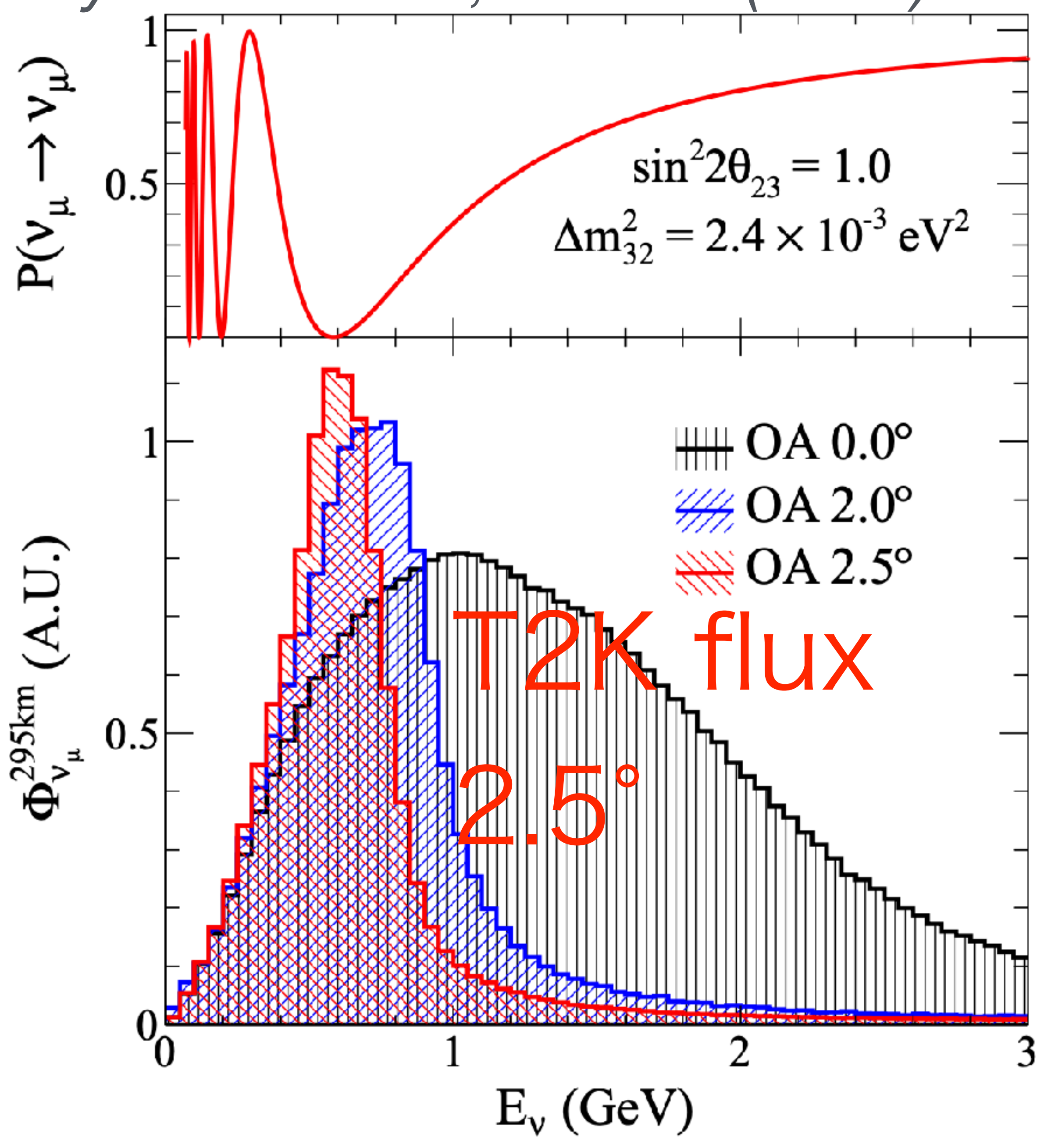
Hyper-K sensitivity on CP-violation



Difficulties in measuring ν interactions

Flux: Broad energy spectra.

Phys. Rev. D 87, 012001 (2013)

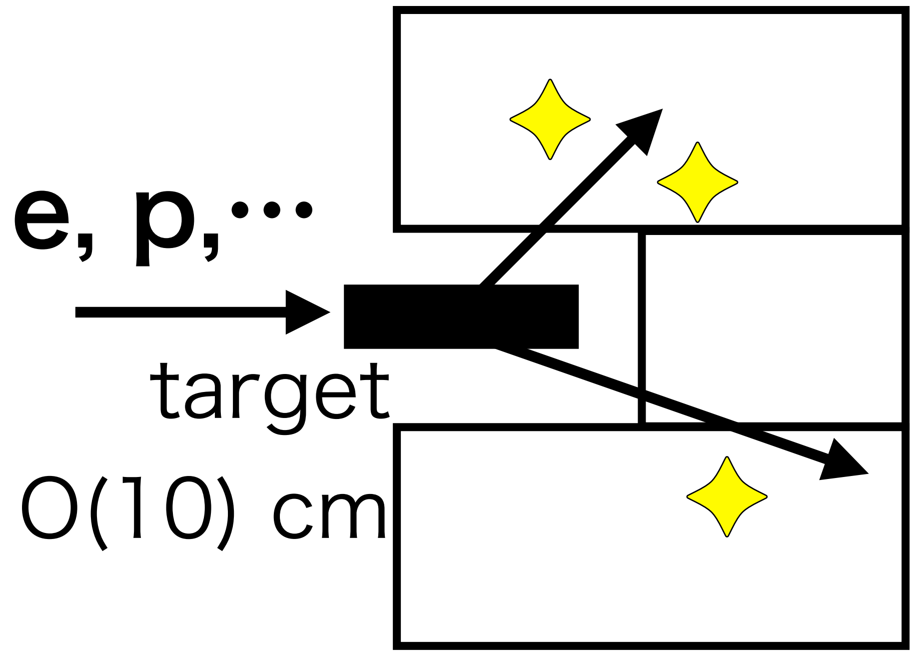


Broad energy spectra due to decay in flight of π/K.

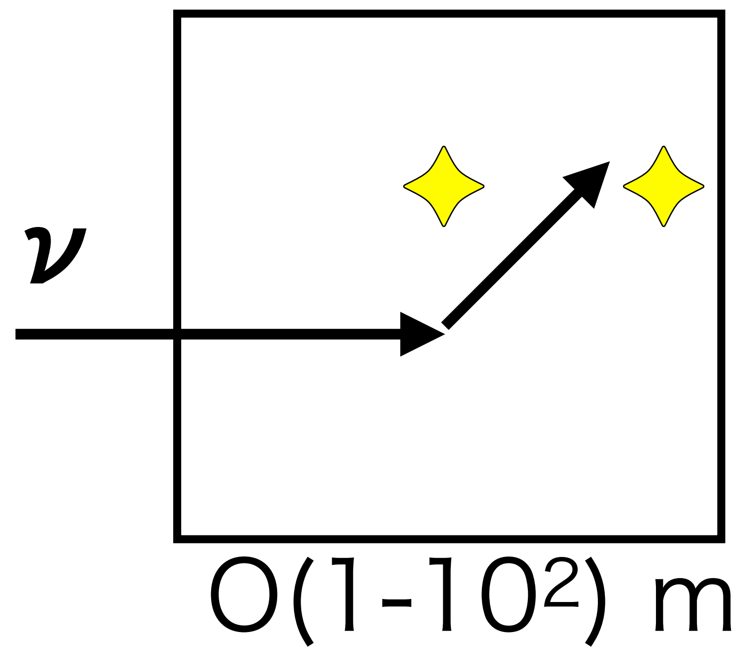
Except for several decay-at-rest sources.

No calibration sources with known true neutrino energy.

Target: To be large.



- Small target.
- Suitable for precise measurement around the target.



- Large target to accumulate statistics, even with a small cross section.

Limited performance on resolutions and threshold.

Difficulties in measuring ν interactions

Flux: Broad energy spectra.

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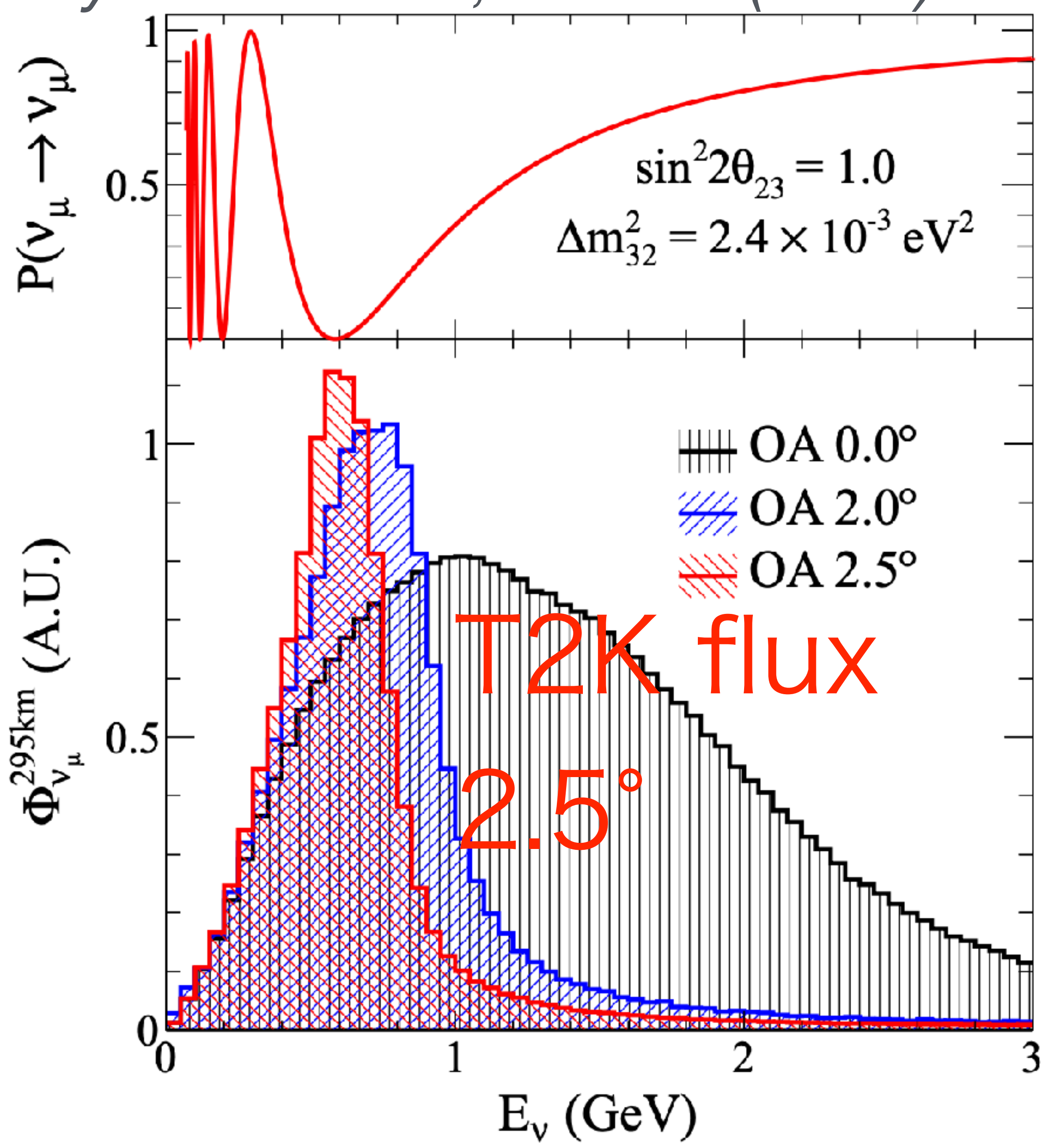

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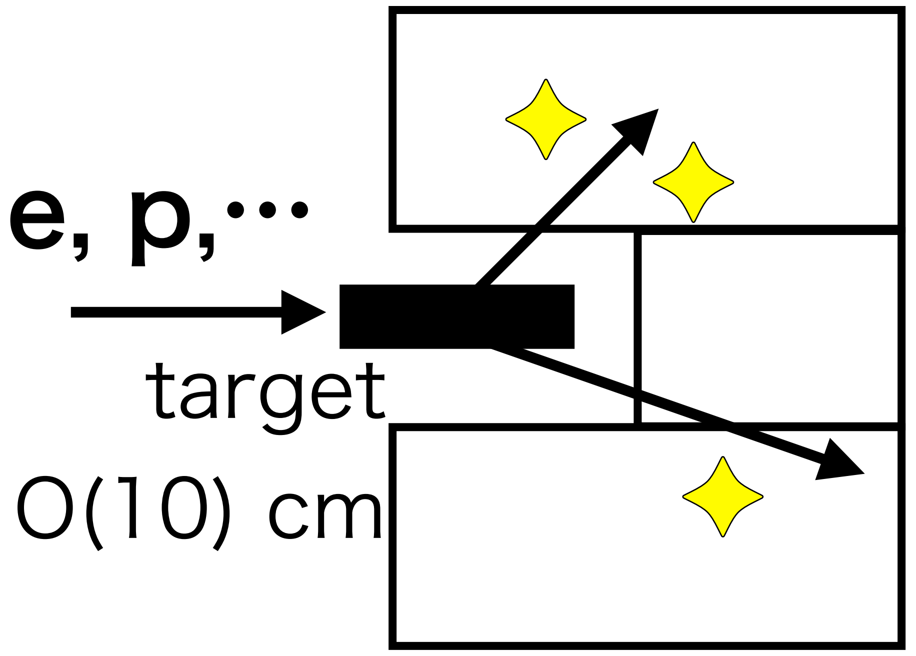

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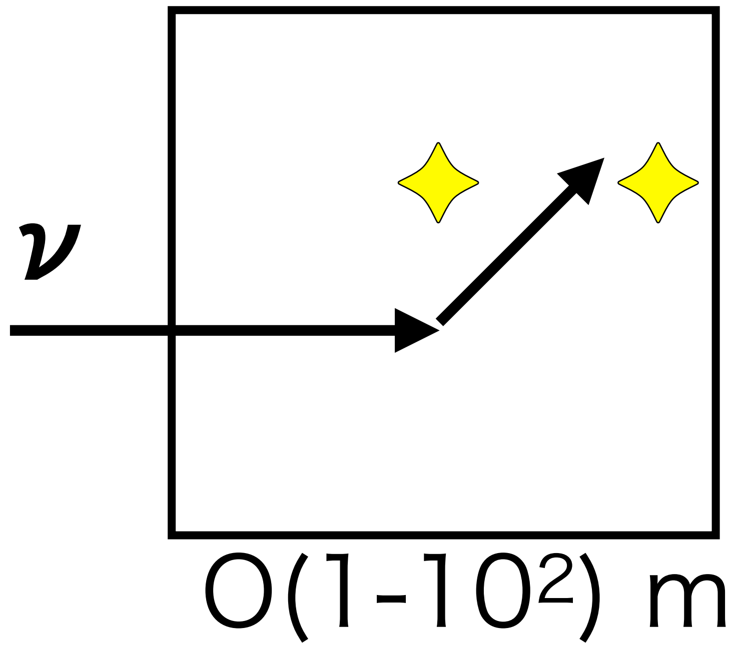


- Large target to accumulate statistics, even with a small cross section.

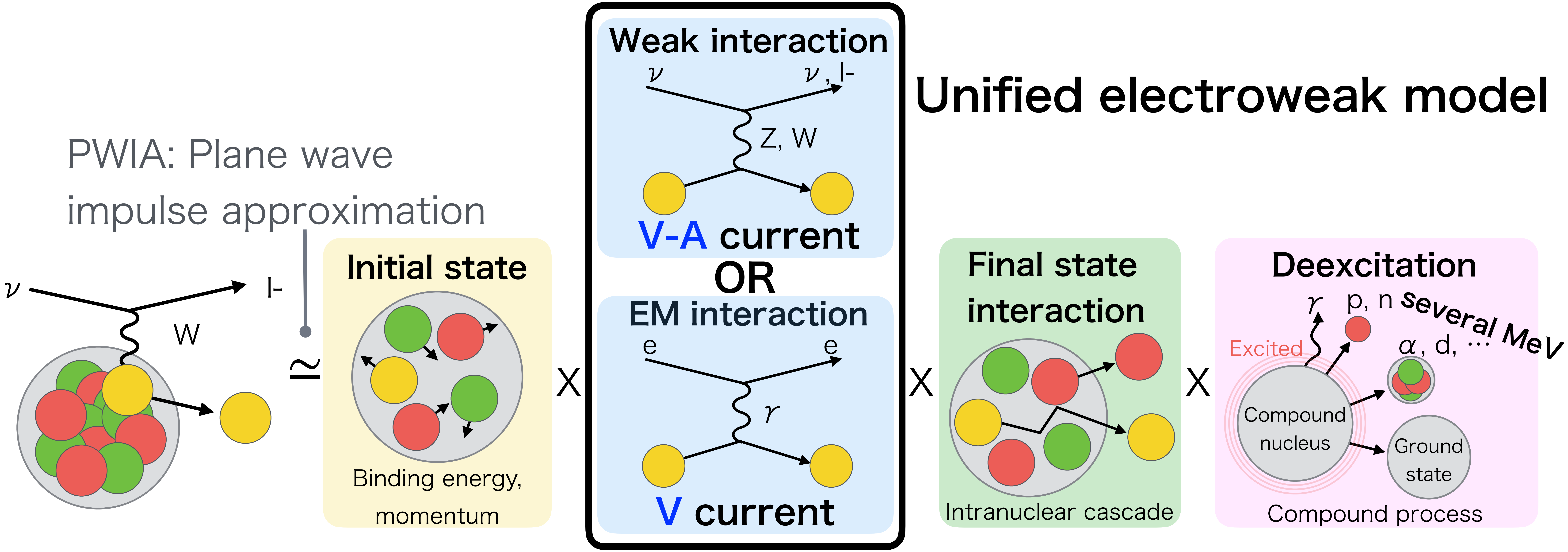
Limited performance on resolutions and threshold.

Approach using "surrogate" reaction, e, p, etc., is effective.

→ Electoweak. Electron scattering!

Electron scattering for neutrino

- **We can evaluate our nuclear model with abundant & high-precision electron scattering data.**
  - Various monochrome electron energies and scattering angles.
- **Extend neutrino event generators to electron scattering.**



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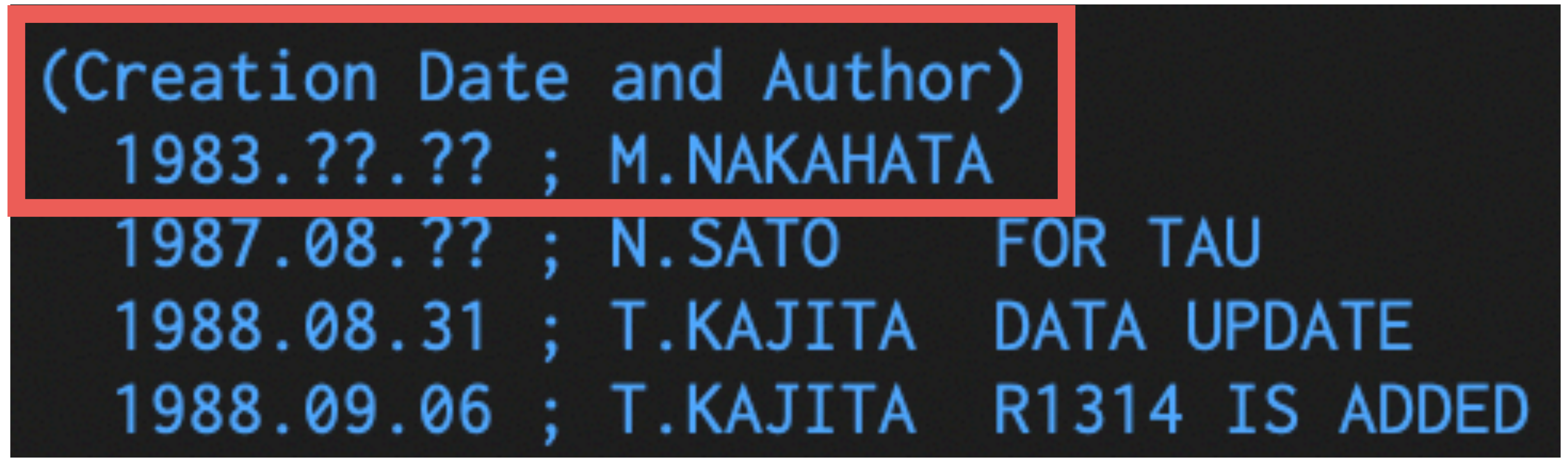
NEUT: A neutrino event generator

- Born for the Kamiokande experiment in the 1980s.



```
(Creation Date and Author)
  1983.??.?? ; M.NAKAHATA
  1987.08.?? ; N.SATO      FOR TAU
  1988.08.31 ; T.KAJITA    DATA UPDATE
  1988.09.06 ; T.KAJITA    R1314 IS ADDED
```

Source code comment.

- Mainly used in experiments in Japan: **Super-Kamiokande (SK), T2K**
  - The primary target is **water**, but it can be used for carbon, iron, etc.

Hayato

- Not open to the public, but distributed upon request.
  - e.g.) KamLAND, JUNO

- Recently developed by T2K NIWG members, mainly.

UK: Luke, Kamil, Patrick, Jake
Japan: Hayato, Abe
+ other contributors

T2K NIWG conveners (Neutrino Interaction Working Group)

Luke

Kevin

Kamil

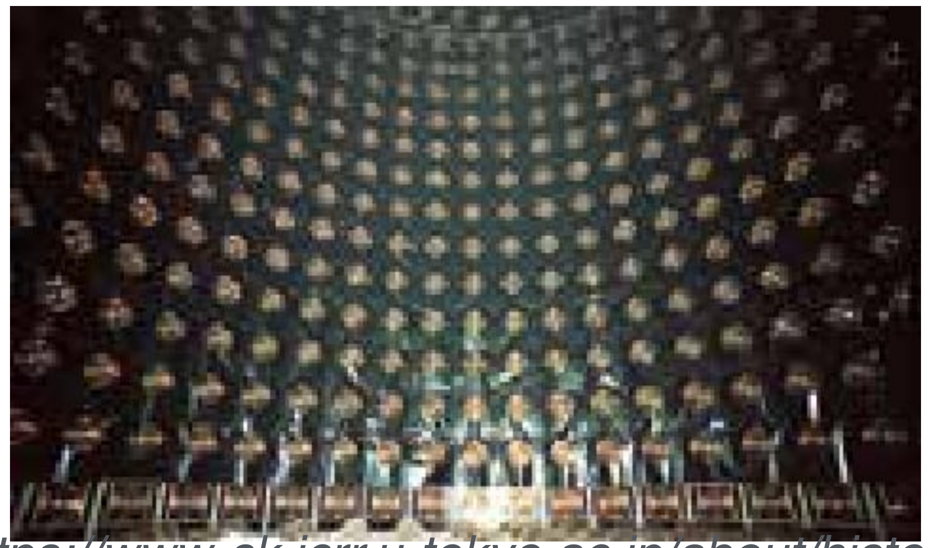
Patrick

Abe

NEUT is in transition period

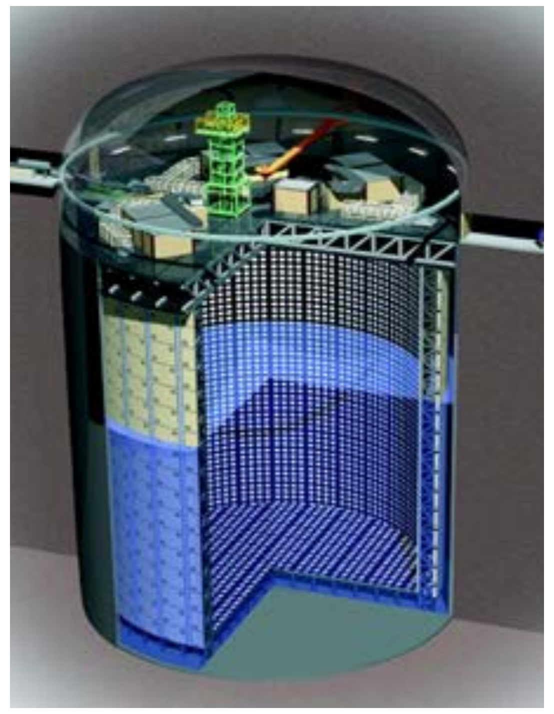
Passed 1983-1996

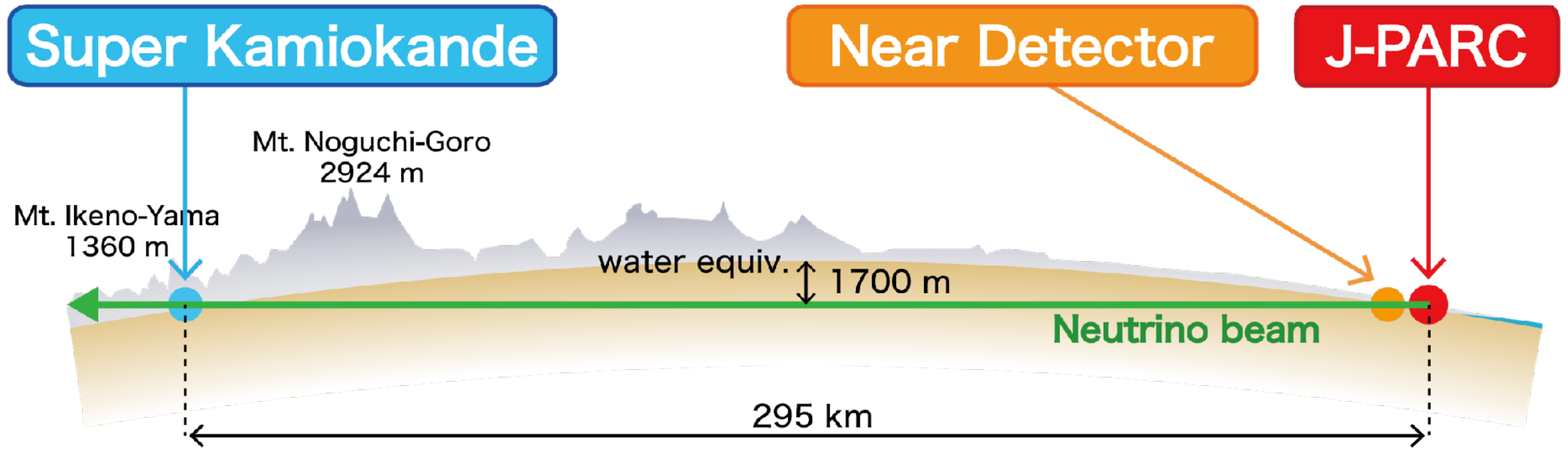
Kamiokande



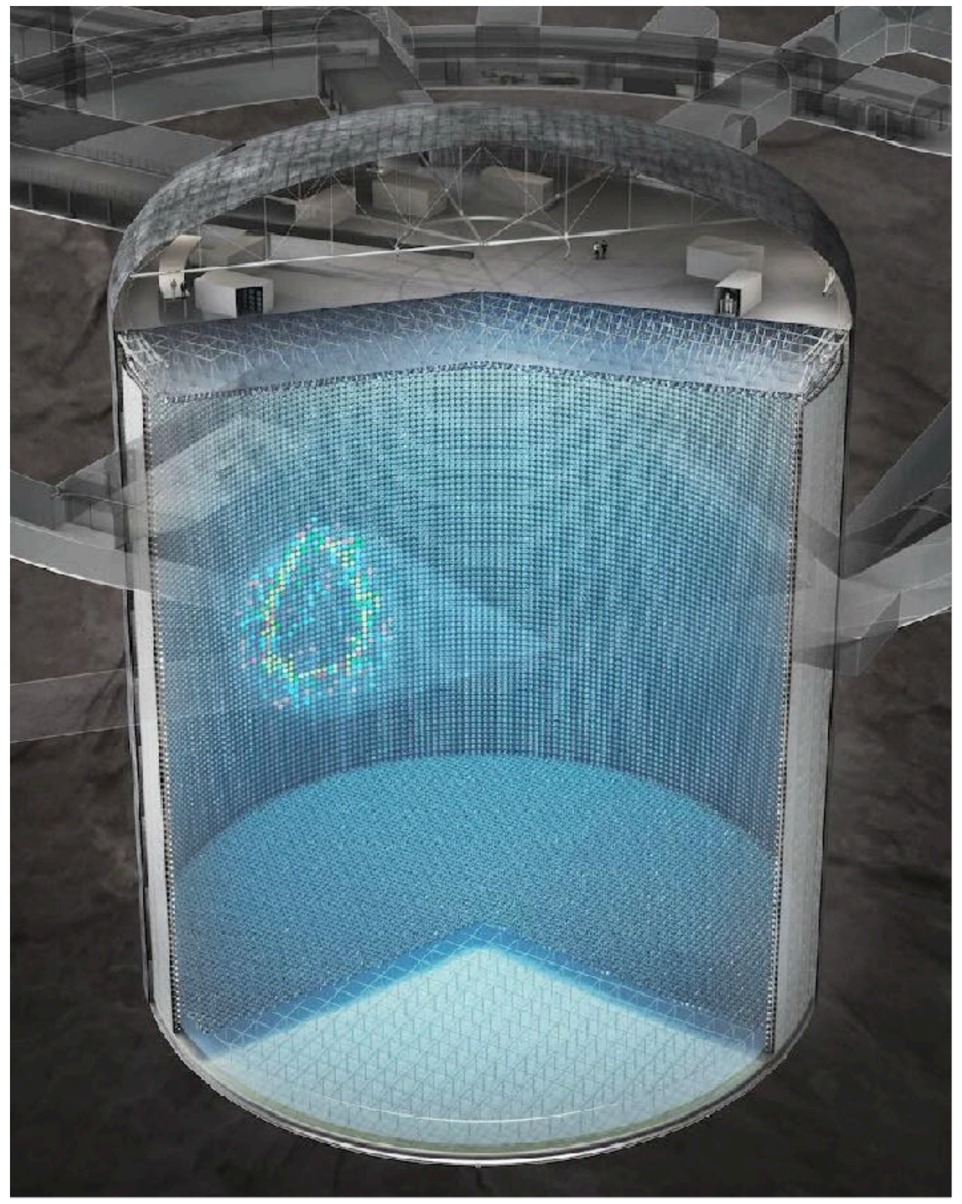
https://www-sk.icrr.u-tokyo.ac.jp/about/history/

Running 1996-





Coming 2027-



https://www-sk.icrr.u-tokyo.ac.jp/hk/

NEUT is in a transition period!

- Keep updating NEUT as well.
- NEUT6 project:
  - Fortran77 → Fortran90.
  - Minimize dependence on CERNLIB.
  - NuHepMC format.
- v6.0.0 was released!

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Extension to electron scattering of NEUT

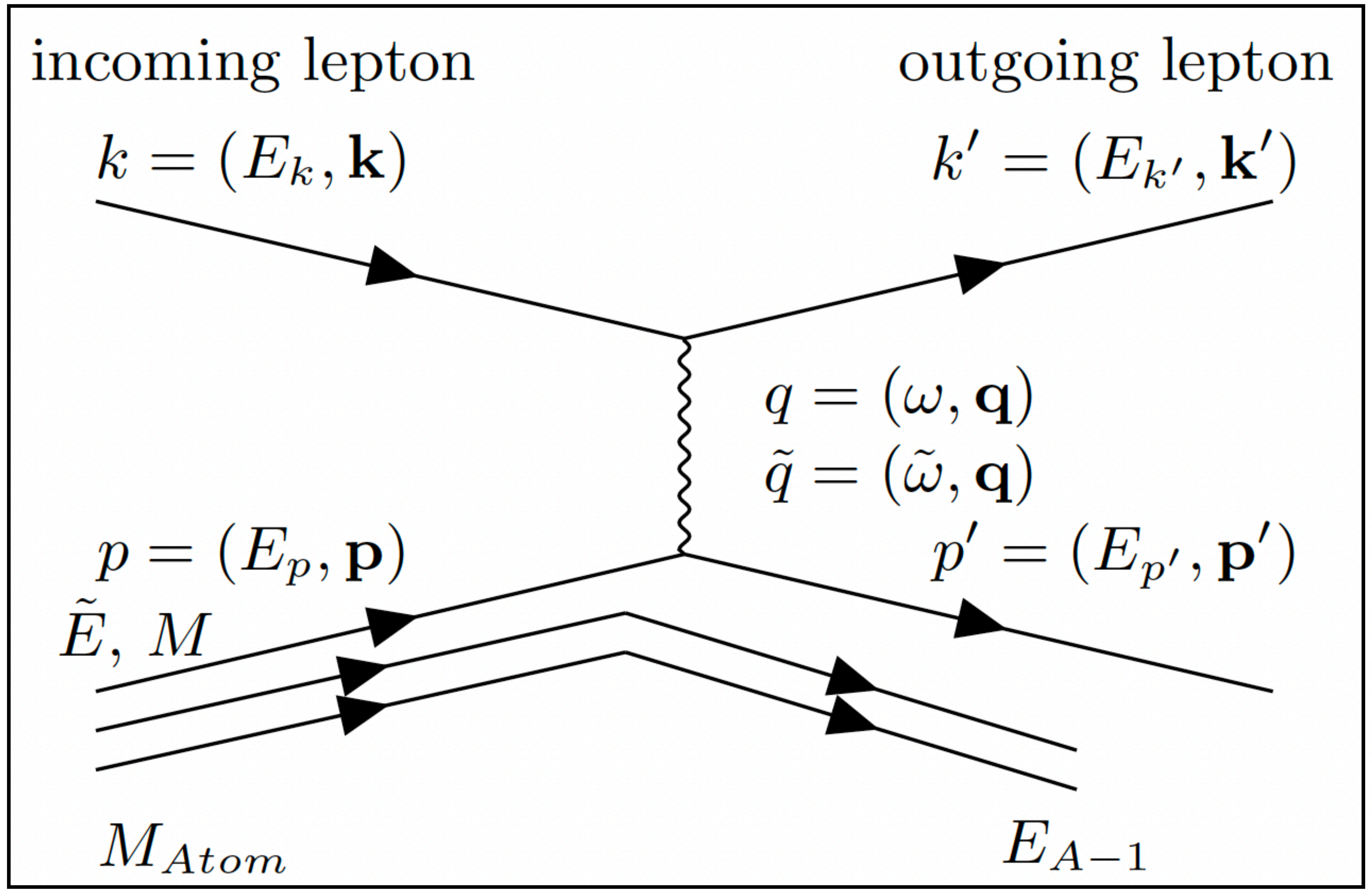
- **Newly implemented electron scattering to be compliant with the NEUT framework.**
  - S. Abe, PRD 109, 036009 (2024)
  - Included from version 5.9.0.
  - Two interaction modes (other modes are future tasks).
    - QE: Spectral Function [1-6].
    - 1 π: DCC (dynamical coupled-channels) [7-8].

- It undergoes FSI cascade and deexcitation in the same way as neutrino scattering.

[1] O. Benhar et al., Nucl. Phys. A579, 493 (1994).
[2] O. Benhar et al., Phys. Rev. D 72, 053005 (2005).
[3] C. Juszczak et al., Nucl. Phys. B, Proc. Suppl. 159, 211 (2006).
[4] A. P. Furmanski, Ph.D. thesis, University of Warwick, 2015.
[5] J. McElwee, Ph.D. thesis, University of Sheffield, 2022.
[6] S. Dolan et al., Phys. Sci. Forum 8, 5 (2023).
[7] S. X. Nakamura et al, Phys. Rev. D 92, 074024 (2015).
[8] K. Yamauchi et al., Proc. Sci. TAUP2023 (2024) 30.

QE: Spectral function (SF) model

- **Extend SF-based model used in T2K to electron scattering.**



Spectral function (SF) by Benhar et al.

Total cross section — Elementary cross section

$$\frac{d\sigma_{\mathrm{tot}}}{dQ^2} = \int d^3p\, d\tilde{E}\; P_{\mathrm{hole}}(\mathbf{p}, \tilde{E}) \frac{d\sigma}{dQ^2},$$

$$\frac{d\sigma}{dQ^2} = \frac{C}{E_k} \int d^3k'\, \delta(\omega + M - \tilde{E} - E_{p'}) \frac{L_{\mu\nu} H^{\mu\nu}}{E_p E_{p'} E_{k'}}.$$

Leptonic/hadronic tensors

FFs appears here.

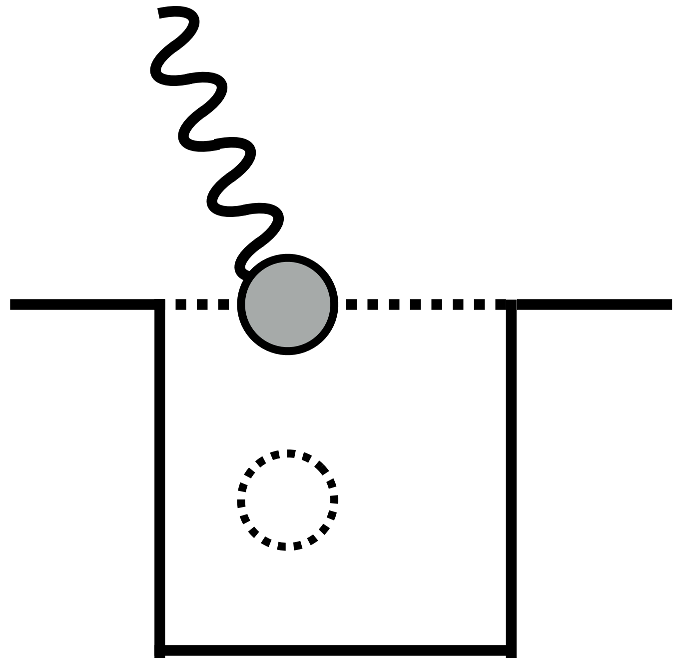
Coupling constant

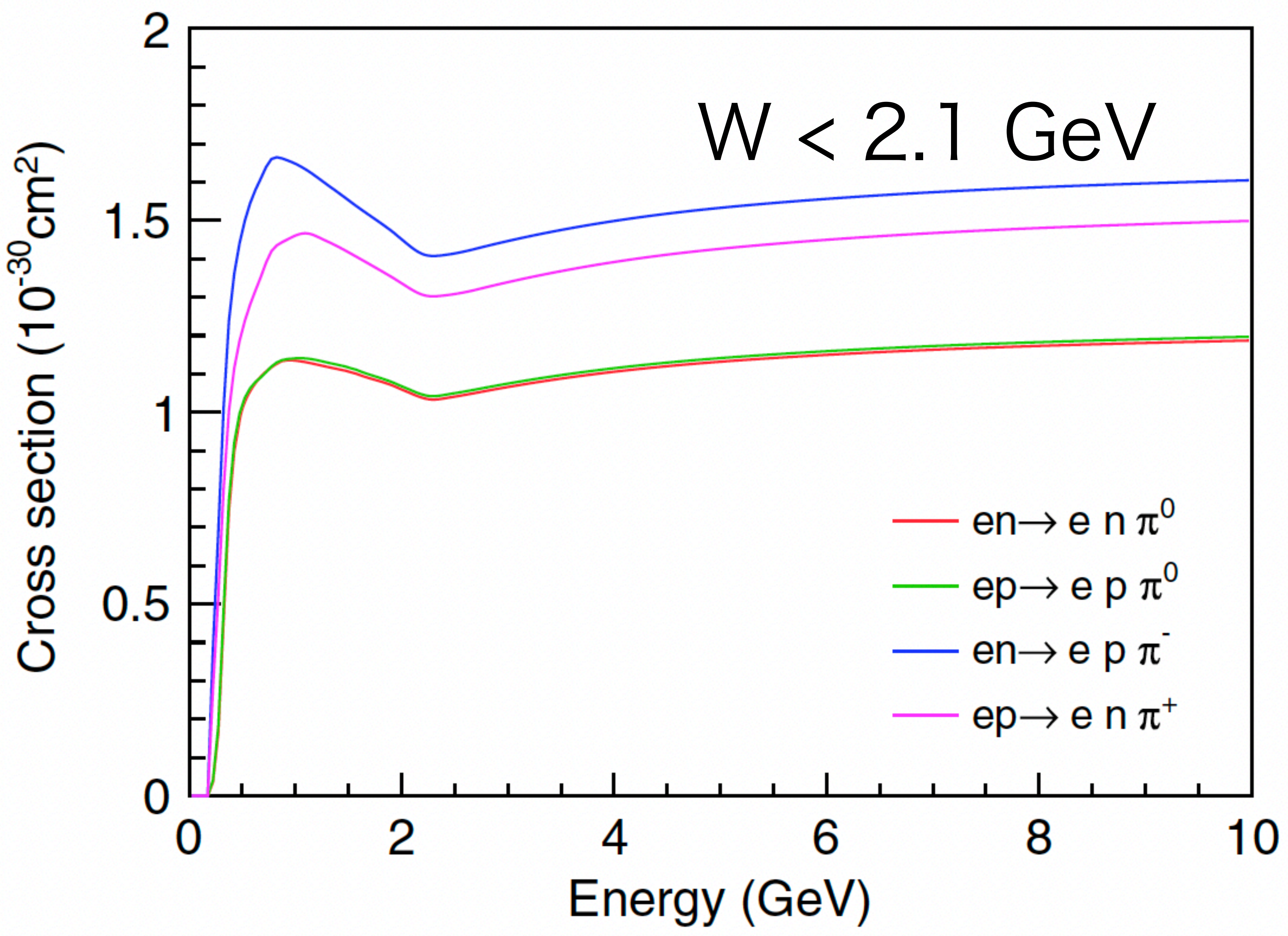
$$C = \begin{cases} \dfrac{G_F^2 \cos^2\theta_C}{8\pi^2} & \text{(CC)}, \\ \dfrac{G_F^2}{8\pi^2} & \text{(NC)}, \\ \dfrac{\alpha^2}{Q^4} & \text{(EM)}, \end{cases}$$

- We can simulate CC, NC, and EM by changing the coupling constant and FFs.
  - The same method as GENIE and NuWro.
- Based on **Plane Wave** Impluse Approx.

Single pion production by DCC

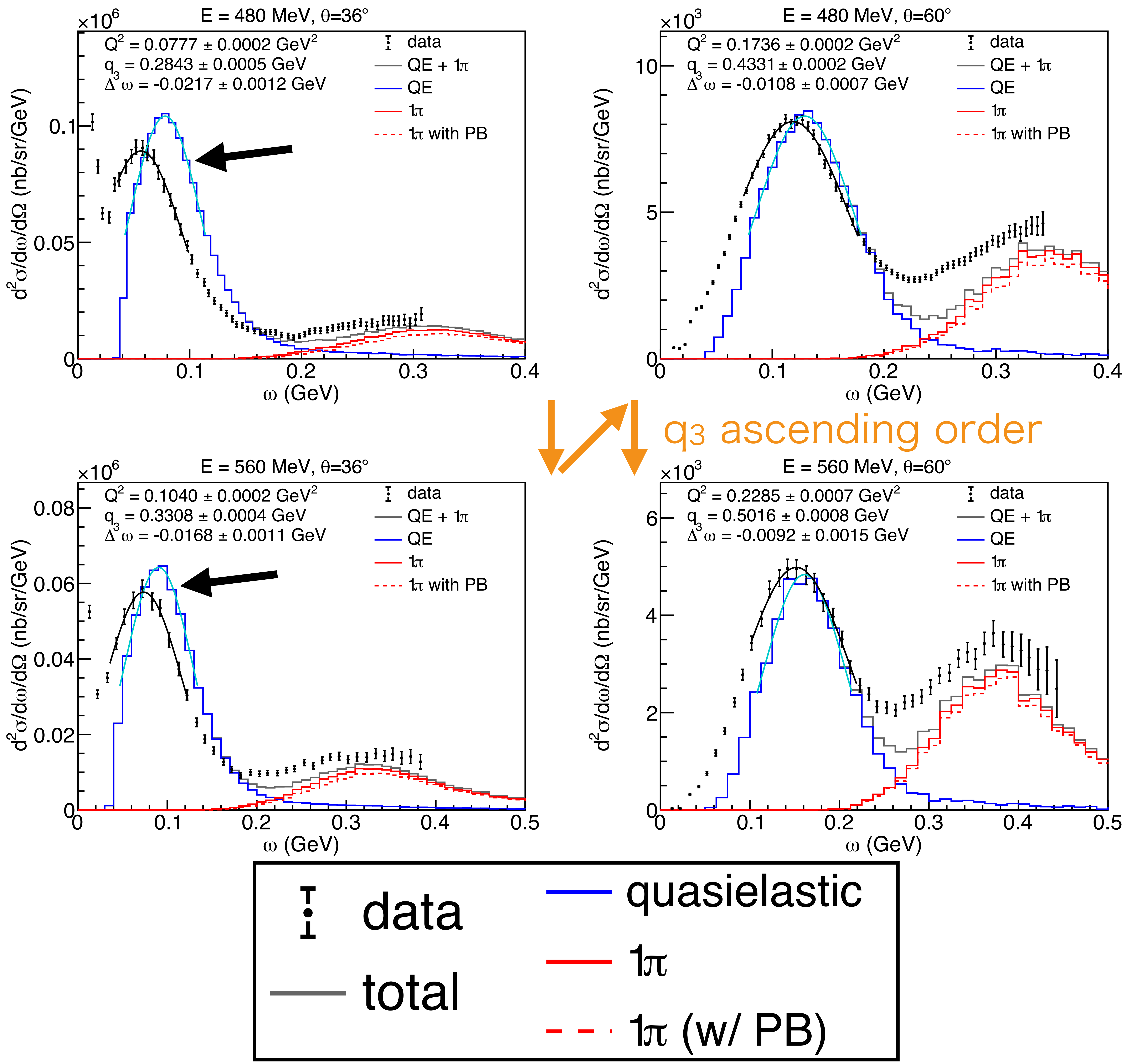
- DCC is an electroweak interaction model.
- Nucleon-level code provided by the authors was implemented [8].
  - Limited to neutrinos.
- It is naturally extended to electrons.





- **All single-pion production models in NEUT do NOT consider binding energy.**
  - **The target nucleon has an on-shell mass with Fermi motion.**
  - The interaction is first described in the nucleon at rest, then boosted to the LAB.
- Implementing the binding energy is one of the important future tasks.

Comparison between NEUT and exp. data



- **QE peak shift is observed.**
- It's known to depend on three-momentum transfer q_3.
  - A smaller q_3 gives a larger peak shift.
  - From effects beyond the PWIA.

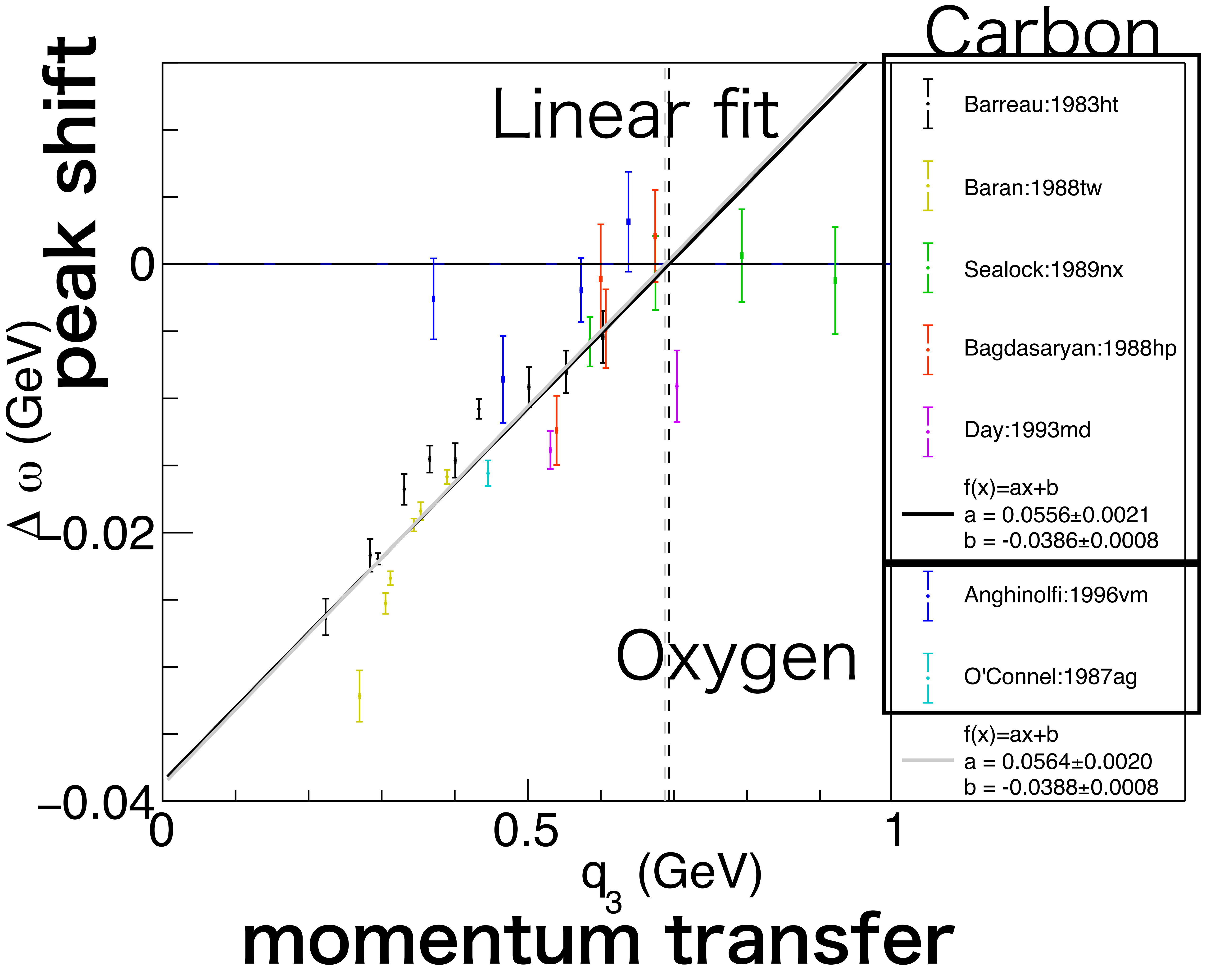
- Analyze the relation between q_3 and peak shift $\Delta\omega$.
- Fit the QE peaks with Gaussian.

peak positions

$$\Delta\omega = \omega_{data} - \omega_{neut}$$

- Calculate q_3 from ω_{data}

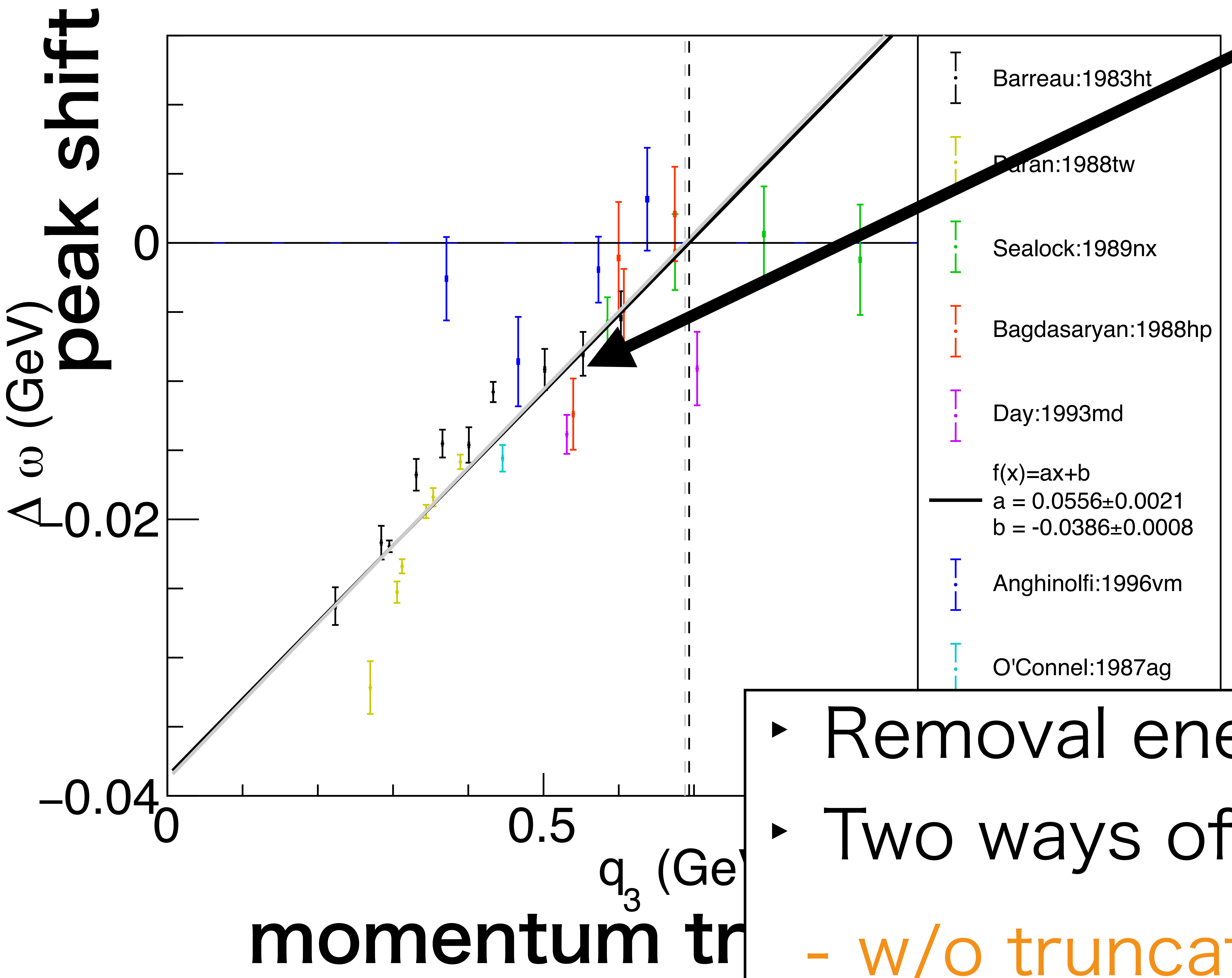
Peak shift vs momentum transfer



- Non-zero $\Delta\omega$ can be interpreted as **an additional term to the removal energy** due to effects beyond the PWIA.
  - Smaller momentum transfer results in smaller effective removal energy.
- Correlation is parameterized by a linear function.

It can be used as **a momentum-dependent correction to the removal energy to empirically introduce "distortion" effects.**

Correction to removal energy $\tilde{E}$



f(q_3): Linear function.

Correction term:

$$\Delta\tilde{E} = \begin{cases} f(q_3) & (f(q_3) \leq 0), \\ 0 & (f(q_3) > 0), \end{cases}$$

truncate to be negative.

$$\tilde{E} \rightarrow \tilde{E} + \Delta\tilde{E}.$$

From SF. From e scat.

- Removal energy can be negative.
- Two ways of correction:
  - w/o truncation: Negative $\tilde{E}$ is allowed.
  - w/ truncation: Negative $\tilde{E}$ is truncated to zero.

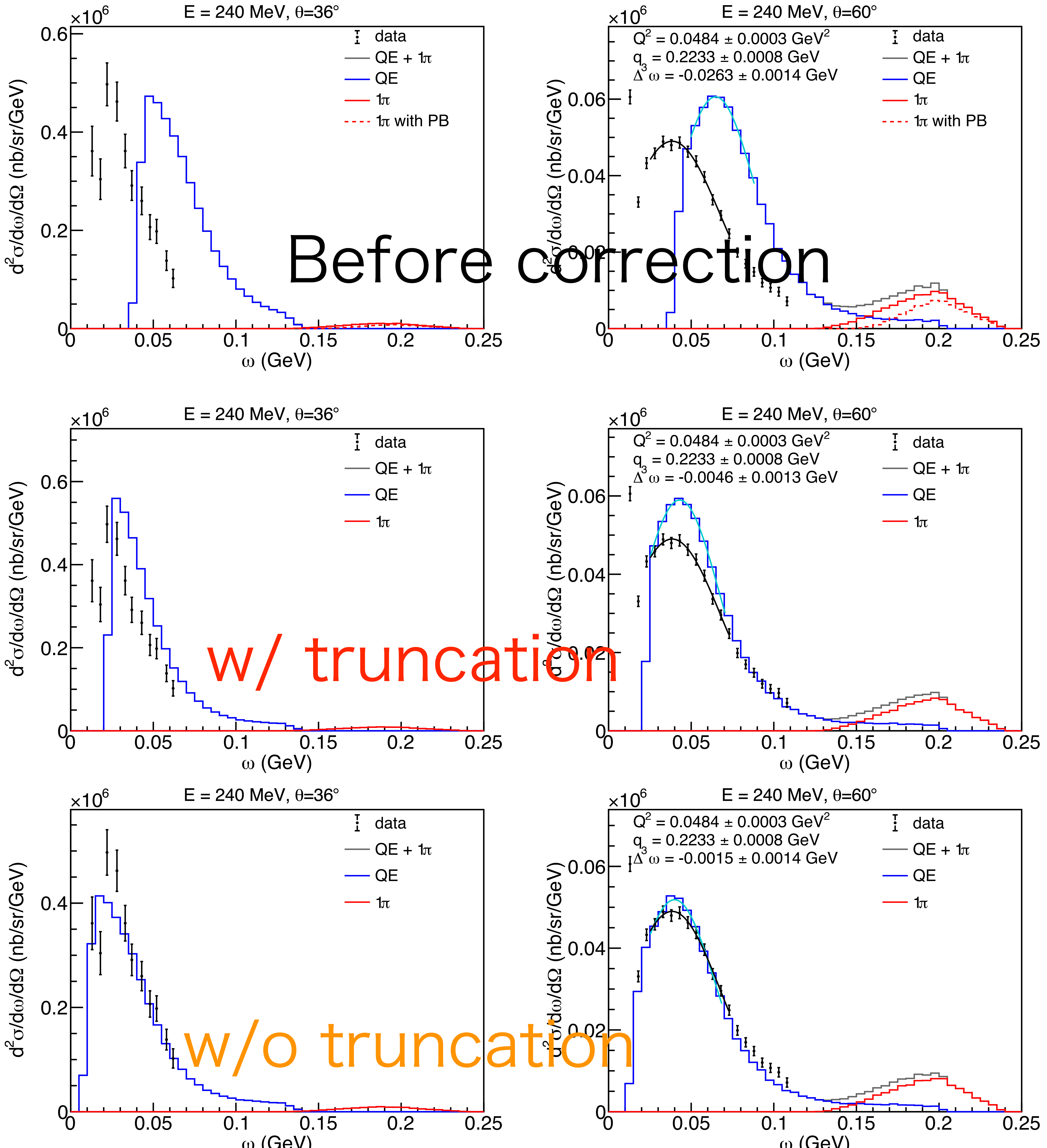
"w/o truncation" should have a stronger correction effect.

Impact of correction

- **“w/o truncation” gives much better agreement.**
  - Both in peak position and height.

- This is an empirical correction.

- **Better to have an alternative way to maintain physics consistency.**
  - e.g.) Theory-driven correction for real optical potential. A. M. Ankowski et al., PRD 91, 033005 (2015)



Impact on neutrino energy reconstruction

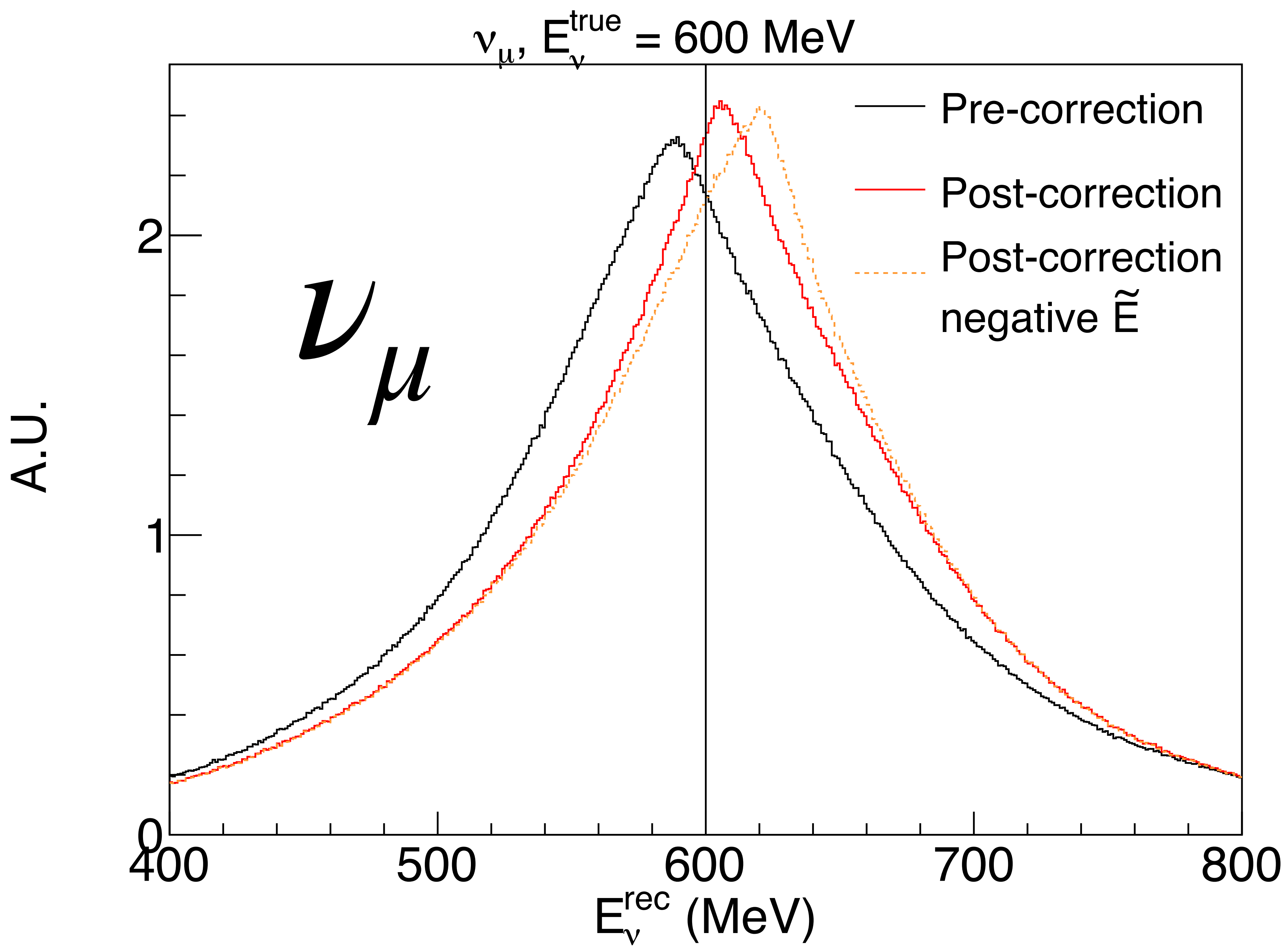
Assuming CCQE — Charged lepton

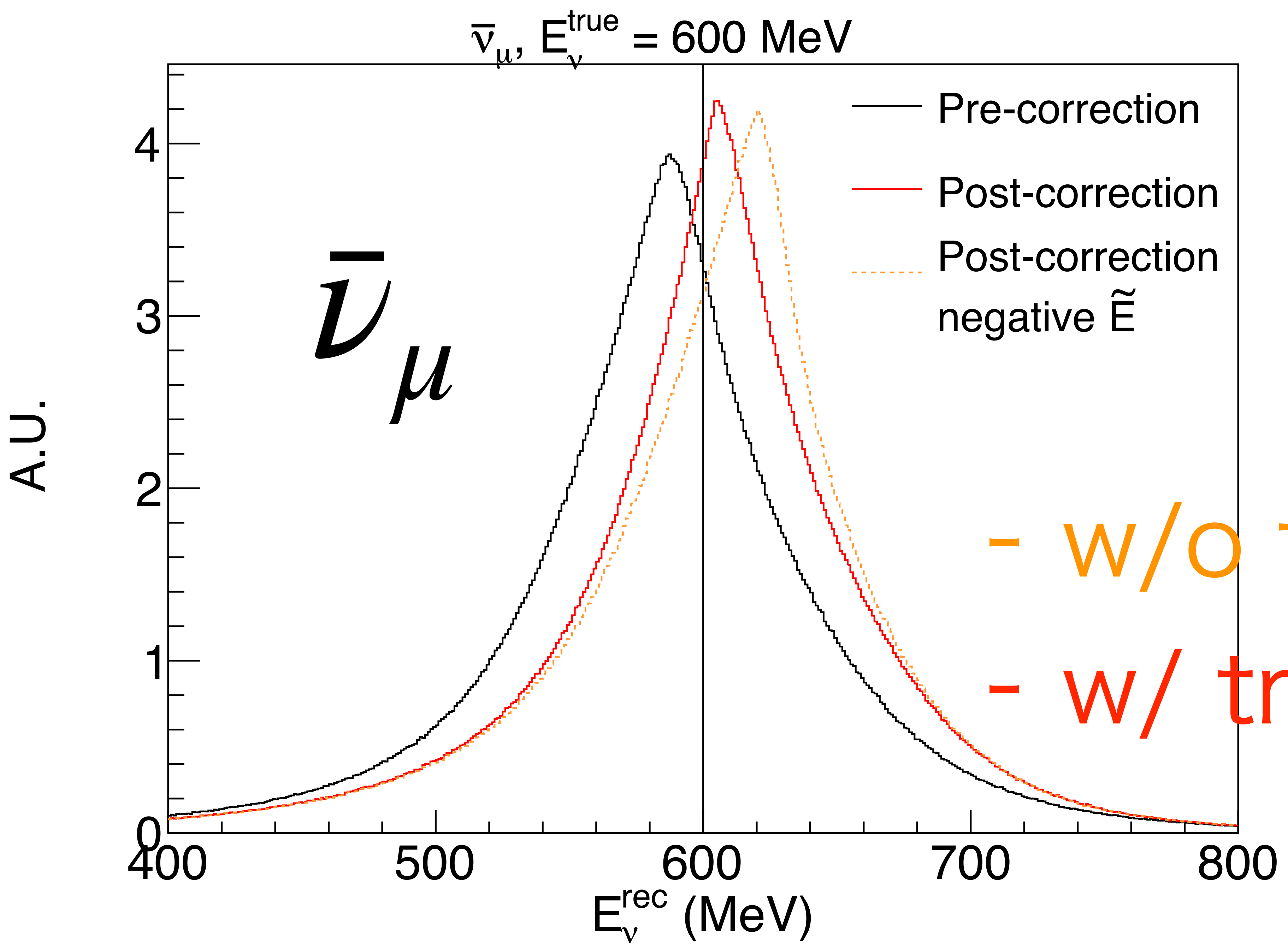
$$E_\nu^{rec} = \frac{2E_l\tilde{M} - (m^2 + \tilde{M}^2 - M_f^2)}{2(\tilde{M} - E_l + p_l\cos\theta_l)},$$

$$\tilde{M} = M_i - E_b, \quad E_b = 27\,\mathrm{MeV}$$

- Shifted by ~20-30 MeV.
- Consistent with similar studies:
  - A. M. Ankowski et al., PRD 91, 033005 (2015)
  - A. Bodek and T. Cai, Eur. Phys. J. C 79, 293 (2019).
- Demonstrated that the “distortion” has a large impact using NEUT.

CCQE @ True E$_\nu$=600 MeV

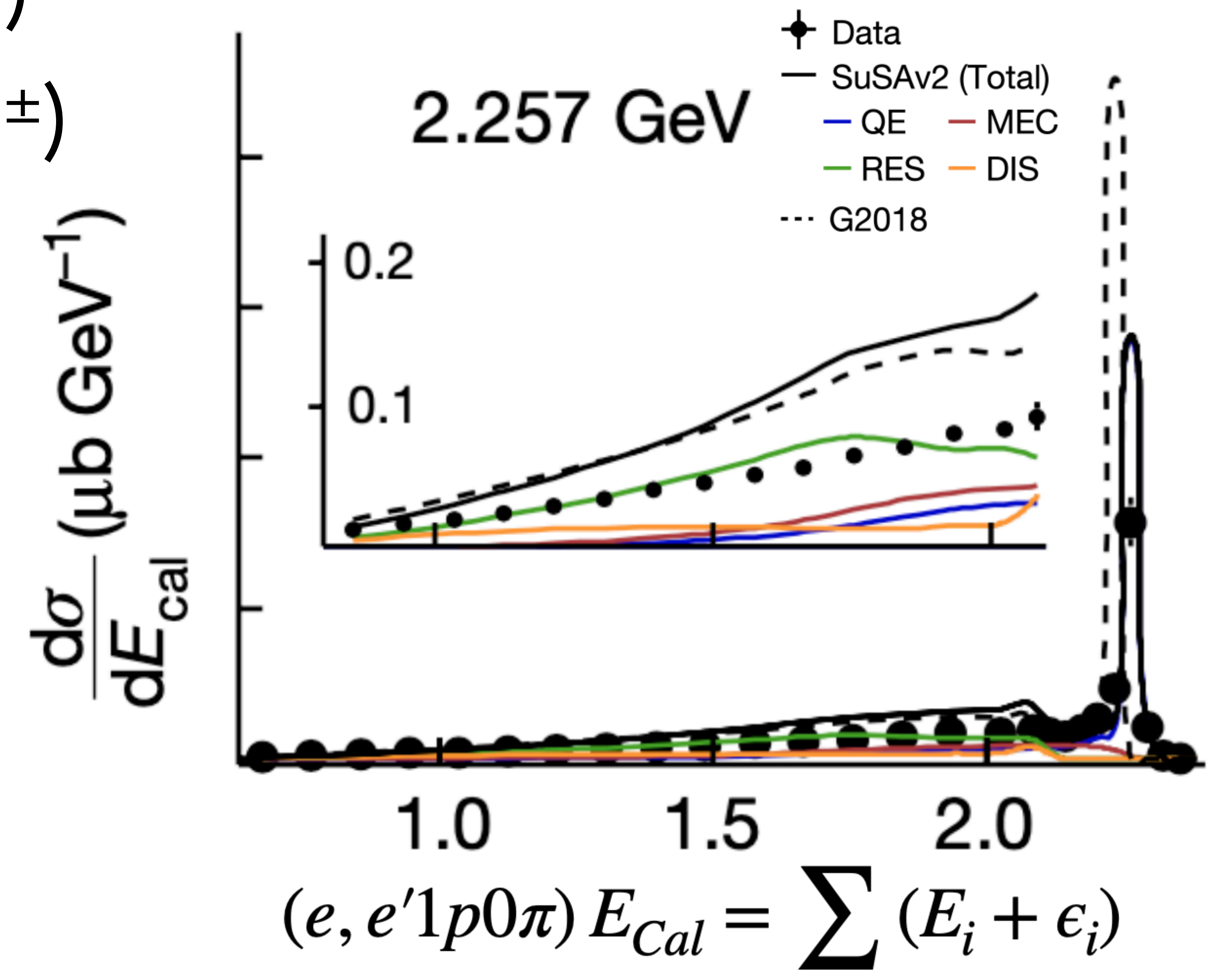




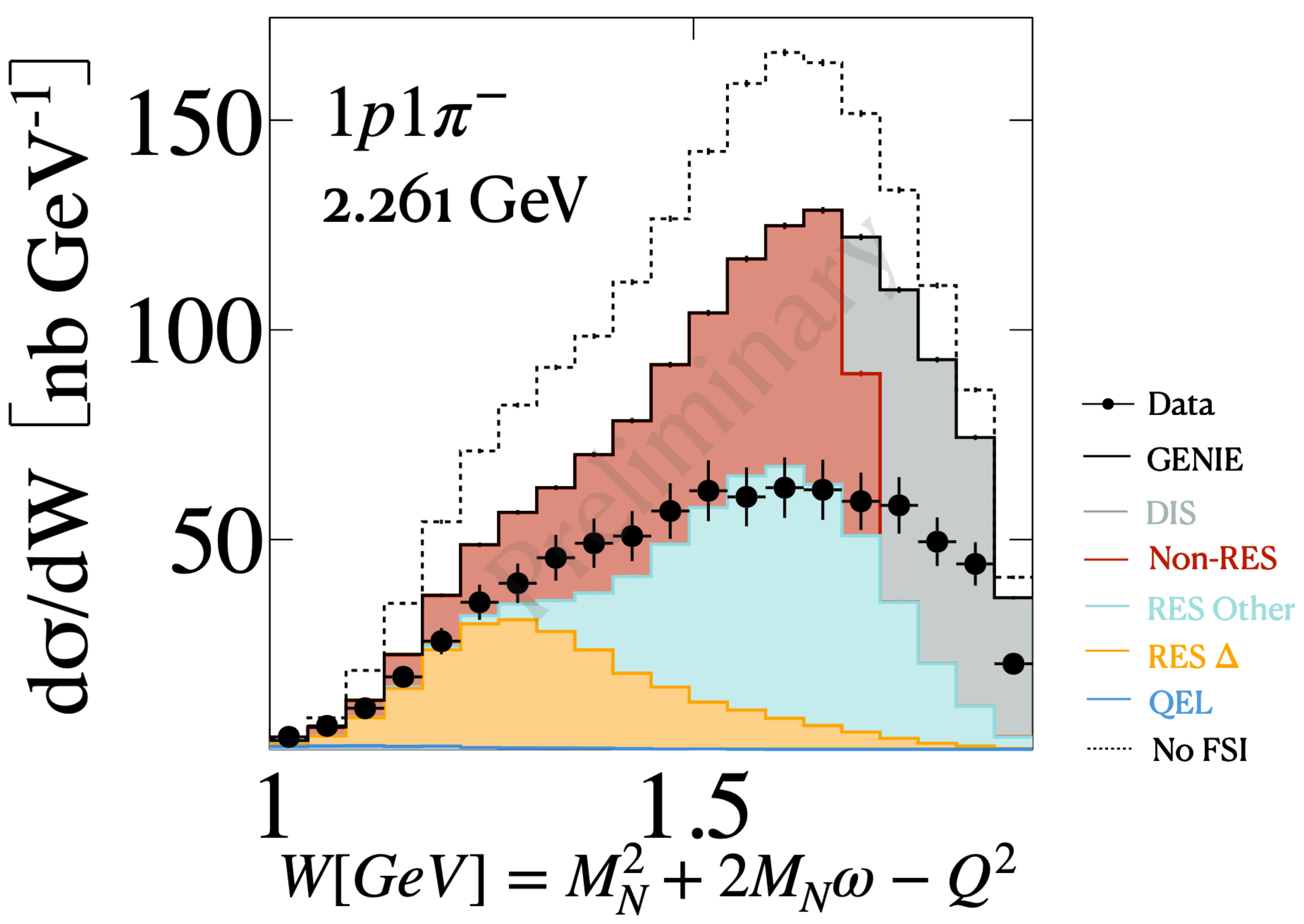
- w/o truncation
- w/ truncation

Further studies: Go to "exclusive"

- **Comparison with e4nu data in JLab.**
  - C(e,e'1p0π)
  - C(e,e'1p1$\pi^{\pm}$)



Julia's talk
Nature volume 599, pages 565–570 (2021)



- Additional topics to be studied:
  - Implement other channels (Multi-nucleon and DIS)
  - Implement binding energy in single π production.

Summary

- Confronting neutrino interaction systematics is important for precise measurements at the next-generation experiments.

- Electron scattering is useful to constrain model uncertainties.
  - Known electron energies, more precise measurement around the target.

- **Electron scattering is newly implemented in NEUT.**
  - **NEUT is now open to electron scattering discussion.**

- **Planning to compare with the “exclusive” data.**

backup

Models in NEUT

Primary	QE	Global Fermi gas, Local Fermi gas (Valencia), Spectral Function, and ED-RMF.
	Multi-nucleon	Valencia
	1π (W < 2 GeV)	Rein(Berger)-Sehgal, DCC, MK, and HNV.
	Multi-π (W < 2 GeV)	GRV98 with Bodek Yang correction + Custom model.
	DIS (W > 2 GeV)	GRV98 with Bodek Yang correction + PYTHIA v5.72
	Coherent π	Rein-Sehgal and Berger-Sehgal
	Diffractive π	Rein
FSI	π cascade	Salcedo et al. + Piozon et al. (tuned to exp. data)
	nucleon cascade	Bertini et al. for MECC-7
Deexcitation	-	Data-driven original model (only oxygen) and NucDeEx.

Y. Hayato and L. Pickering, Eur. Phys. J. Special Topics 230, 4469 (2021).

+ new works (part of them are ongoing)