NSD STAFF MEETING
LBNL - JUNE 2020

JAVIER CARAVACA (SNO COLLABORATION)

RECENT NEWS FROM THE SNO EXPERIMENT

SNO TOOK DATA FROM 1999 TO 2006 TO ADDRESS:

THE SOLAR NEUTRINO PROBLEM

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ν_e

ν_μ

ν_τ

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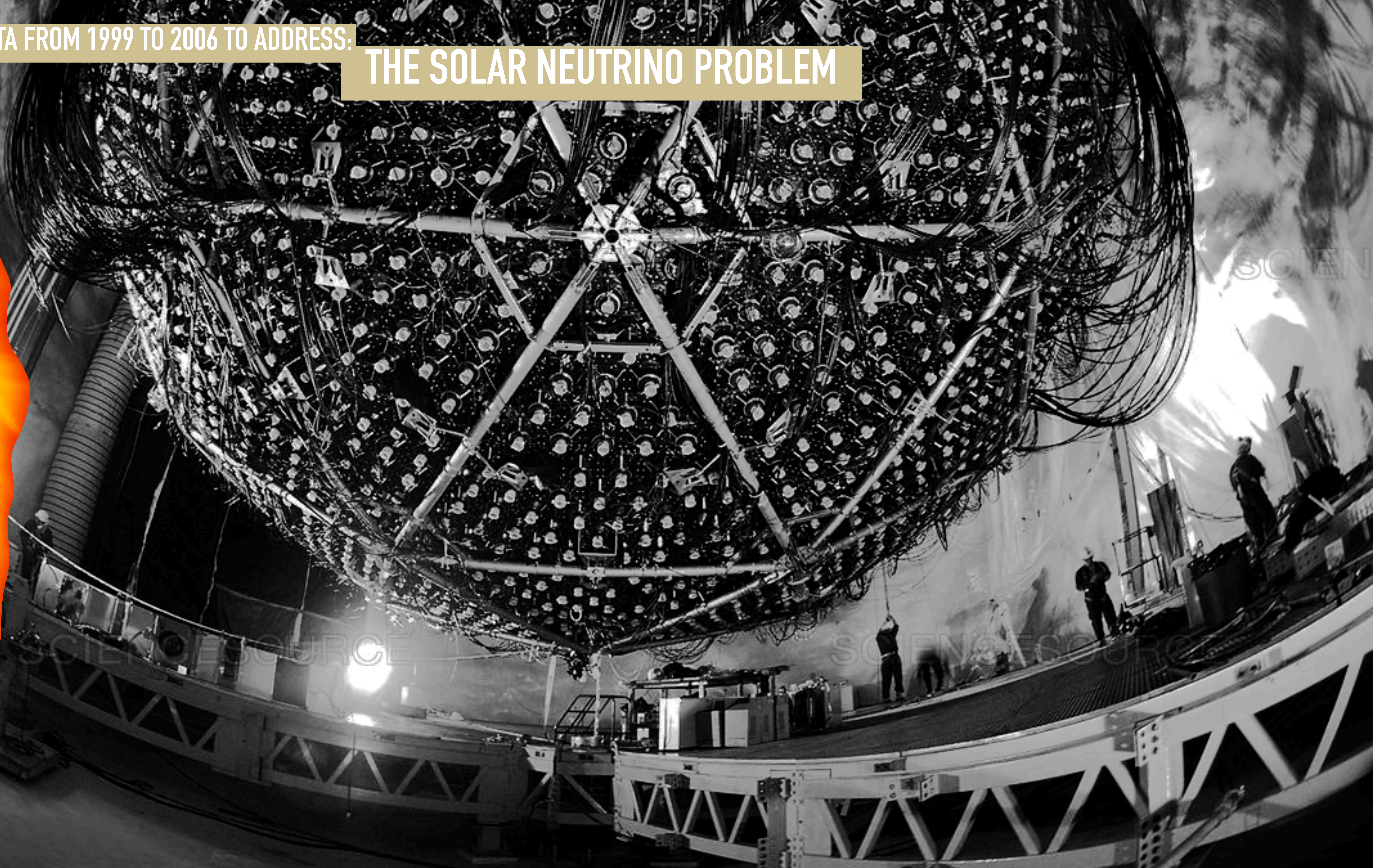


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$\nu + e^- \rightarrow \nu + e^-$
*Cross-section suppressed for non-electron neutrinos

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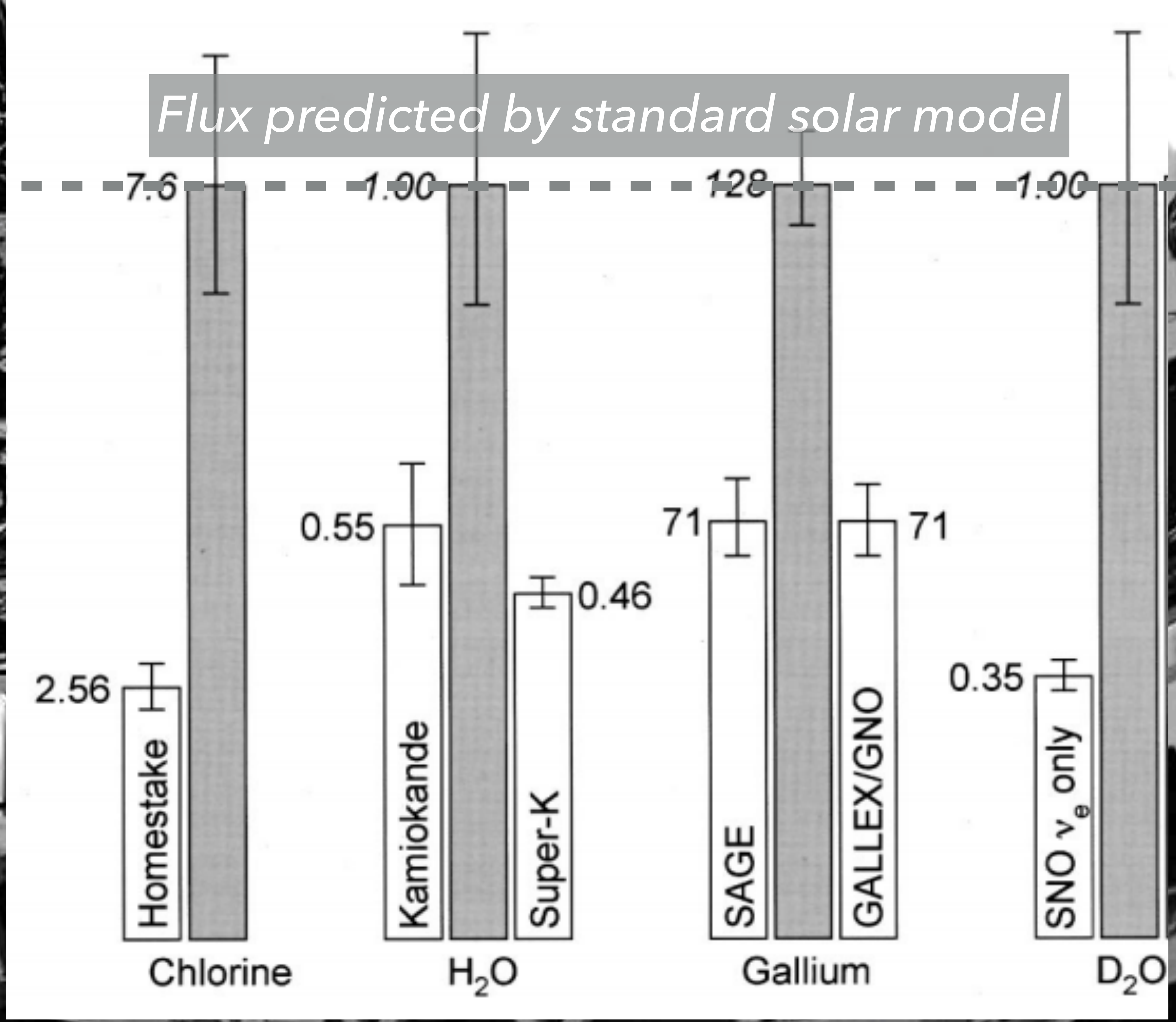

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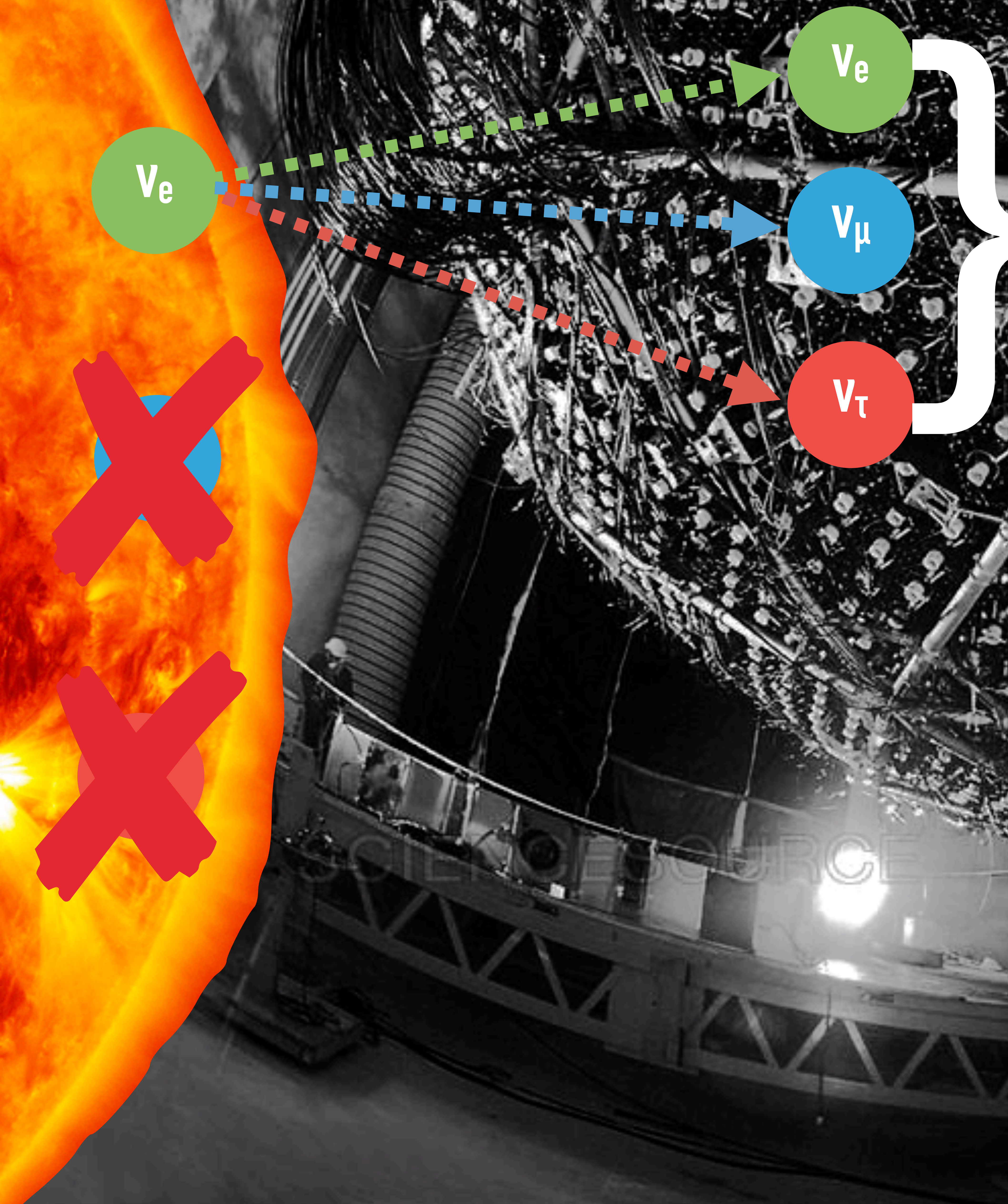


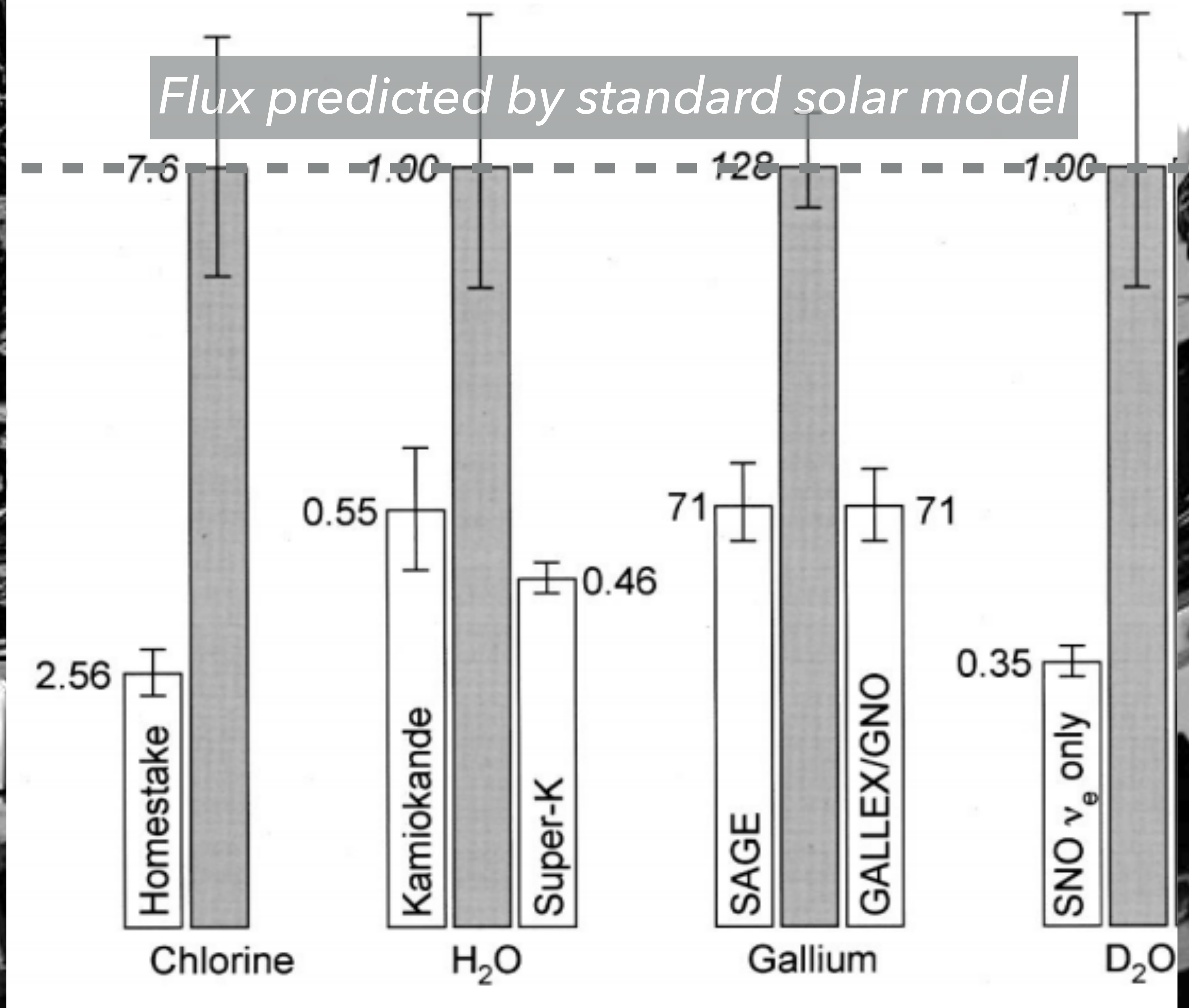
$\nu + e^- \rightarrow \nu + e^-$

**Cross-section suppressed for non-electron neutrinos*

$\nu + d \rightarrow p + n + \nu - 2.22$ MeV

BY USING HEAVY WATER, SNO ENABLED

NEUTRAL CURRENT NEUTRINO INTERACTIONS → SENSITIVE TO ALL SPECIES



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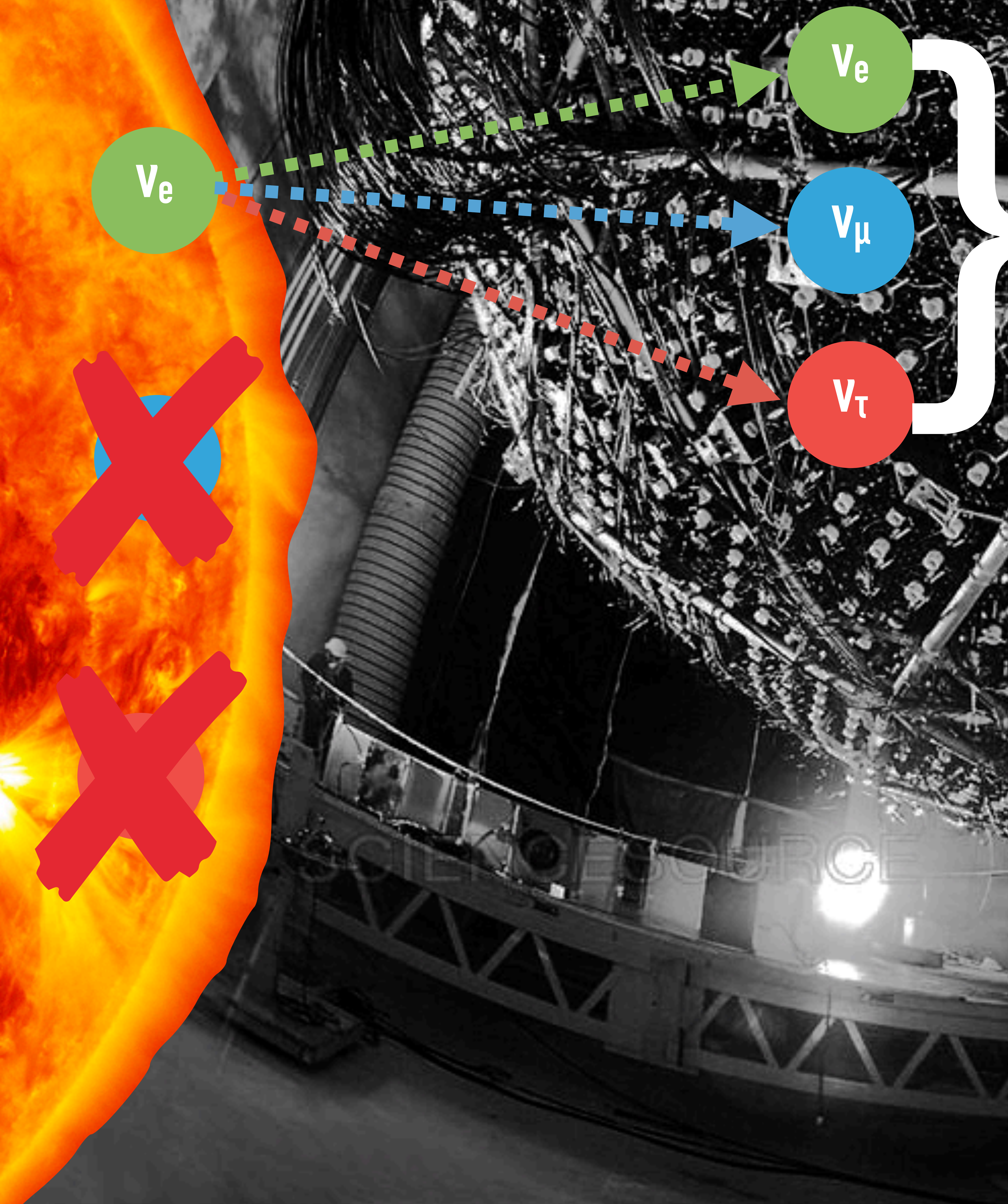

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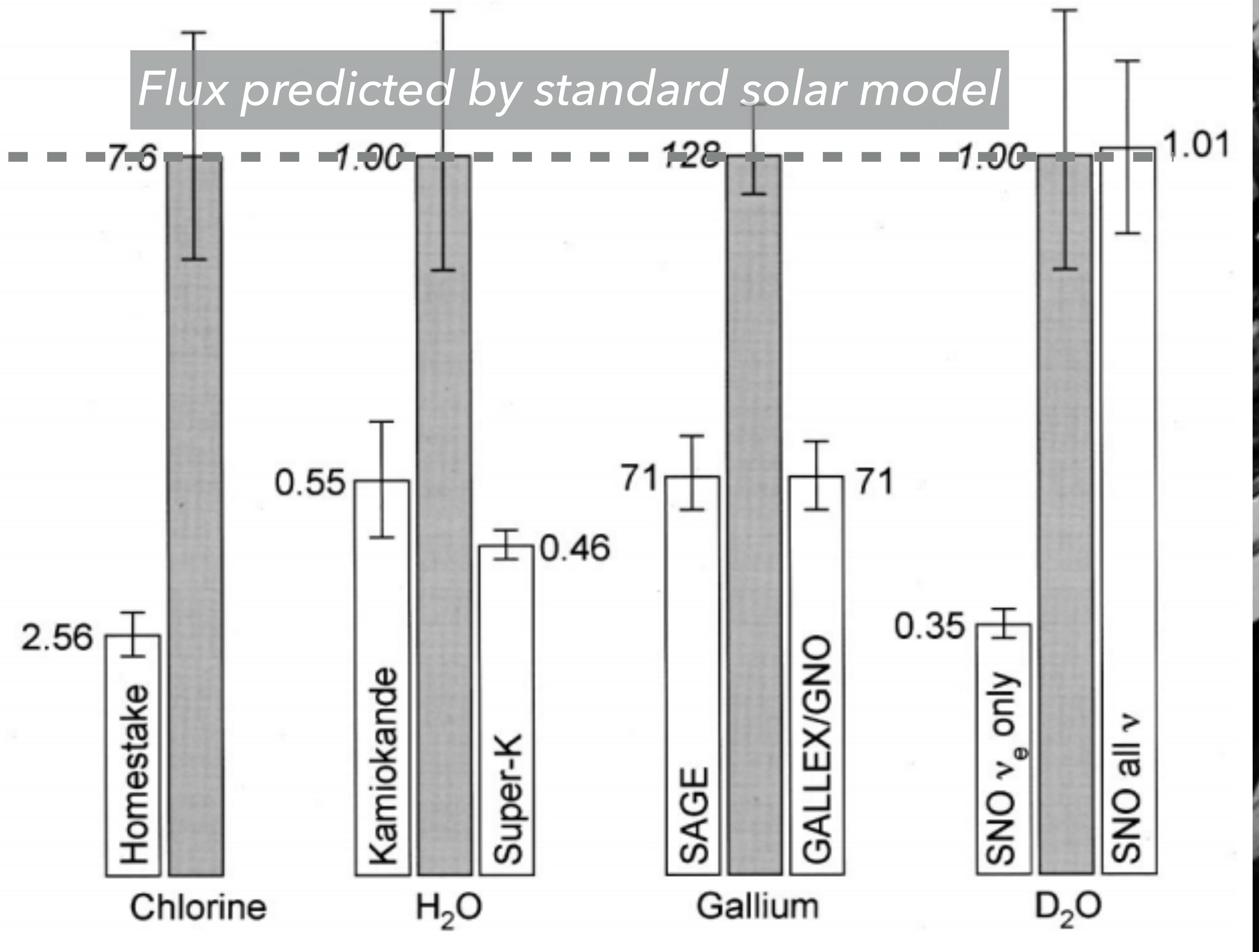

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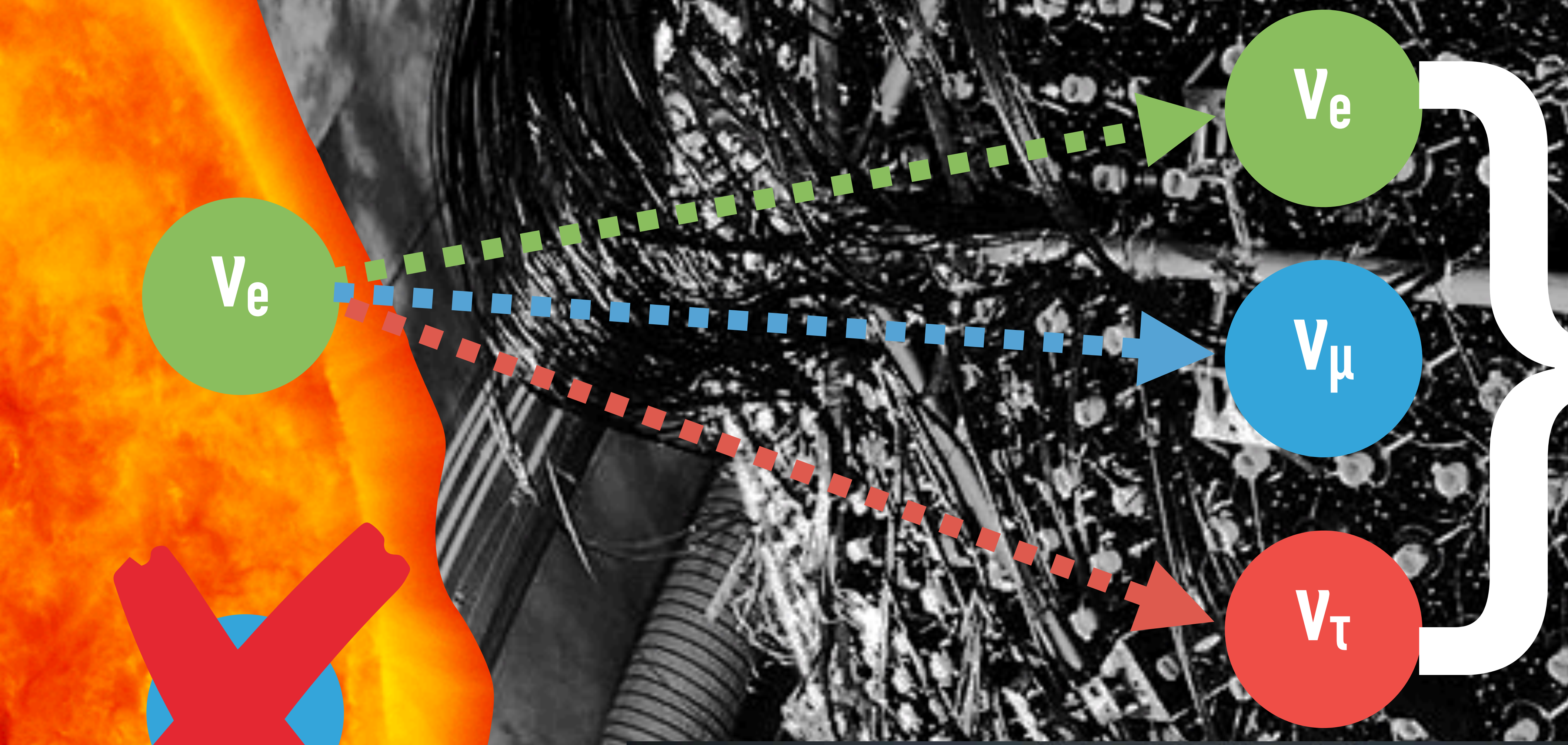

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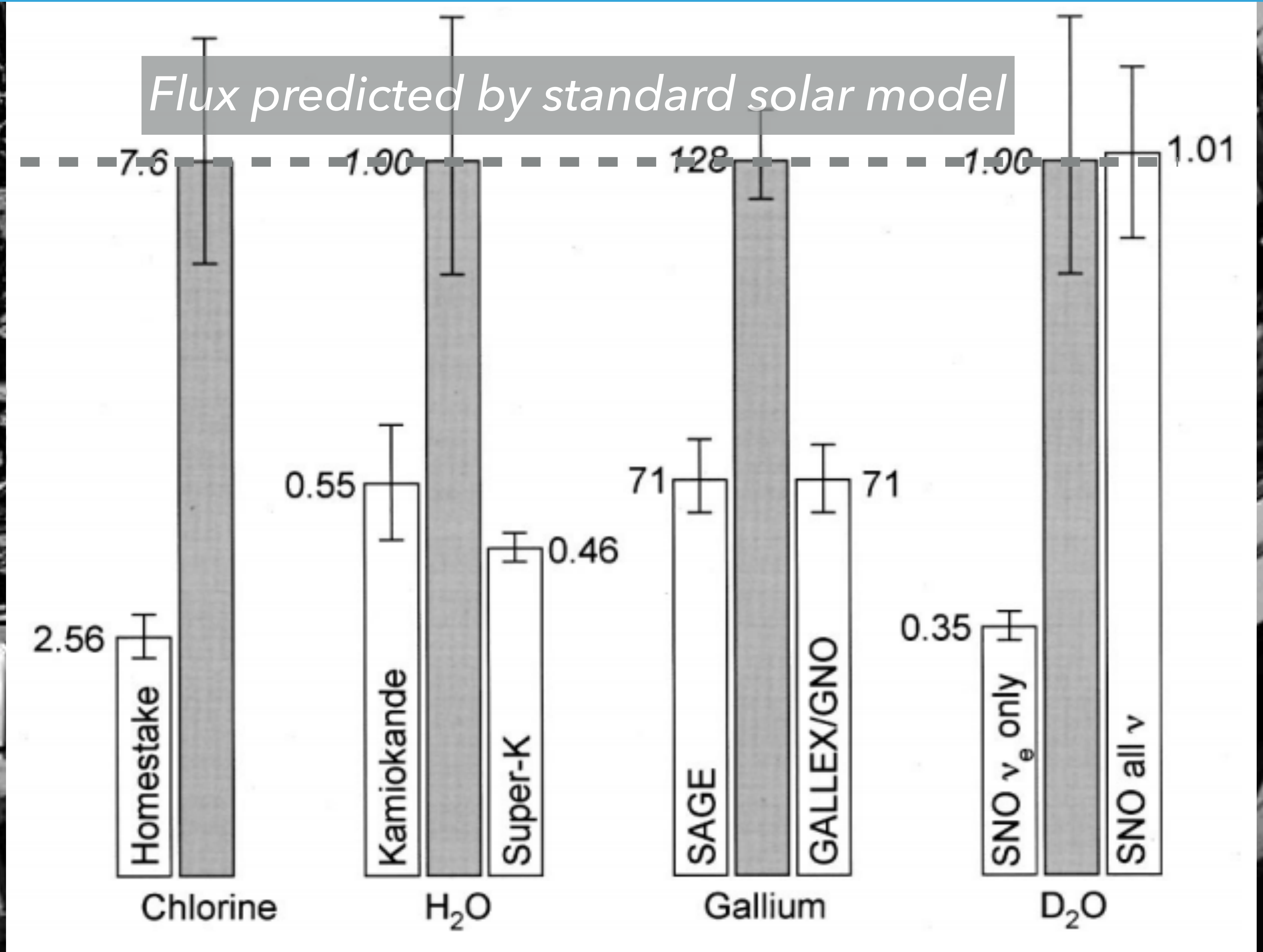

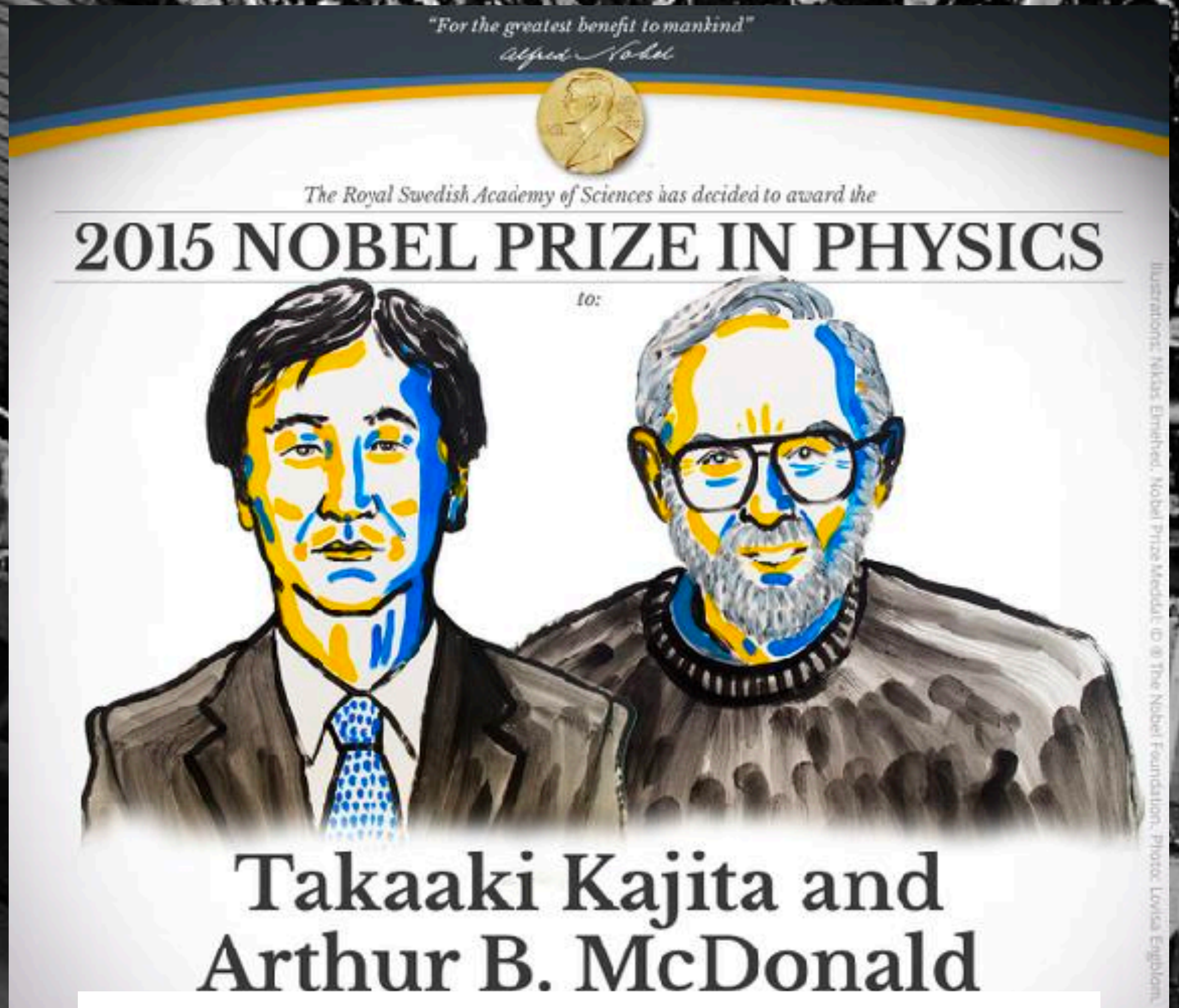

For the discovery of neutrino mixing, showing that neutrinos have mass

SNO ANALYSIS REINVIGORATED IN 2015

NEW COLLABORATORS COMPLETED
NEW ANALYSES USING SNO LEGACY DATA

RECENT ANALYSES (AND OUTLINE OF MY TALK):

- NEUTRON PRODUCTION IN ATMOSPHERIC NEUTRINO INTERACTIONS
- NEUTRON PRODUCTION BY COSMIC MUONS
- NEUTRINO DECAY SEARCH
- LORENTZ SYMMETRY VIOLATION SEARCH
- SOLAR HeP NEUTRINO SEARCH
- SELF-INTERACTING DARK MATTER SEARCH

THE SNO DETECTOR IN A NUTSHELL

~9500 PMTS
(54% OPTICAL COVERAGE)

~100 EXTERNAL
VETO PMTS

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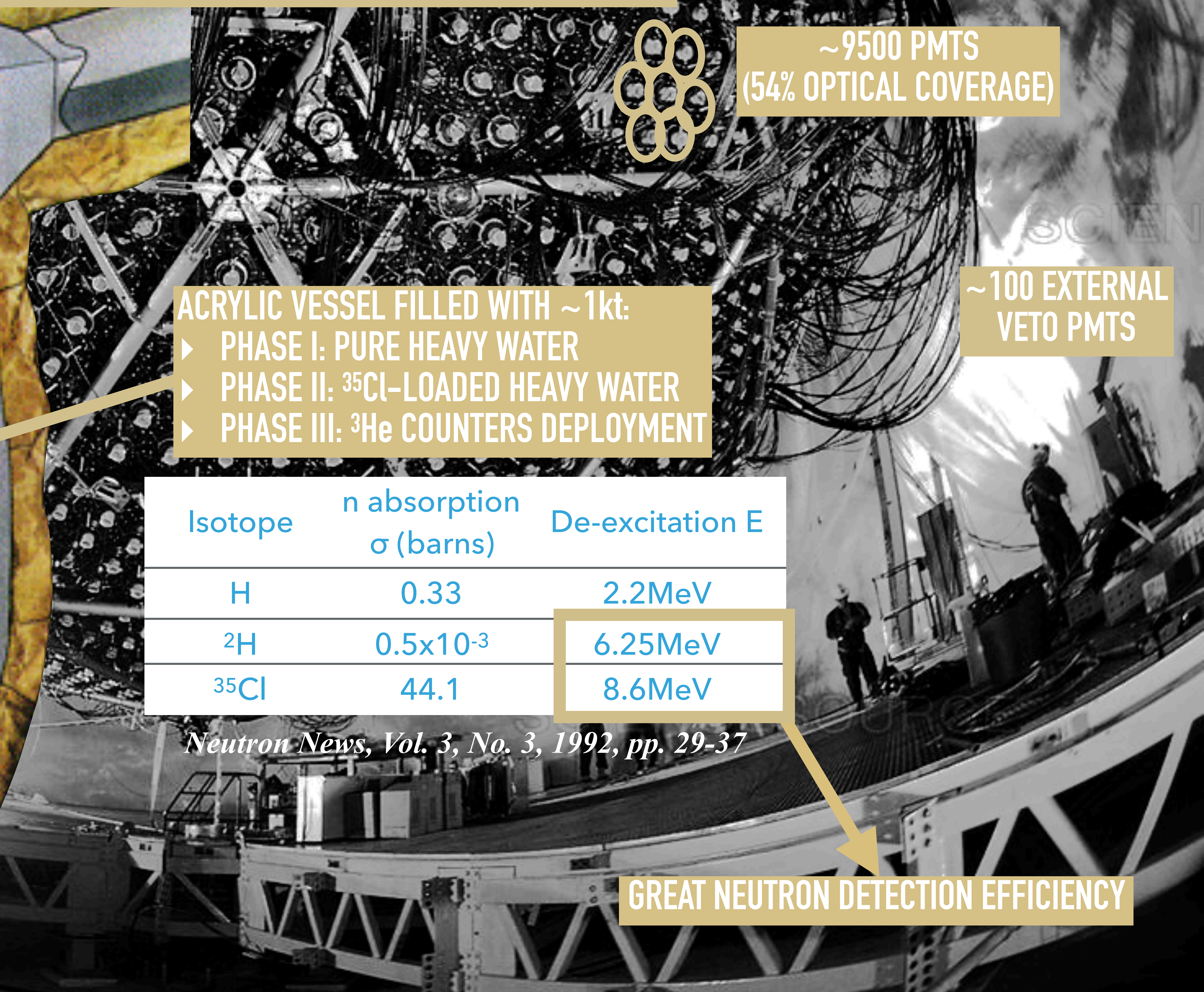


~9500 PMTS
(54% OPTICAL COVERAGE)

~100 EXTERNAL VETO PMTS

ACRYLIC VESSEL FILLED WITH ~1kt:

- PHASE I: PURE HEAVY WATER
- PHASE II: ^{35}Cl–LOADED HEAVY WATER
- PHASE III: ^{3}He COUNTERS DEPLOYMENT

Isotope	n absorption σ (barns)	De-excitation E
H	0.33	2.2MeV
^{2}H	0.5x10^{-3}	6.25MeV
^{35}Cl	44.1	8.6MeV

Neutron News, Vol. 3, No. 3, 1992, pp. 29-37

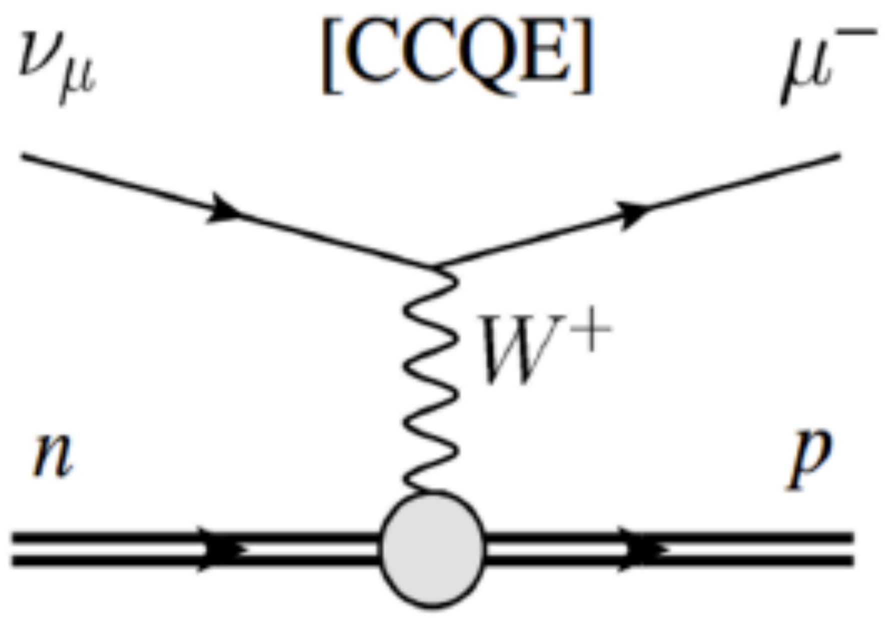
GREAT NEUTRON DETECTION EFFICIENCY

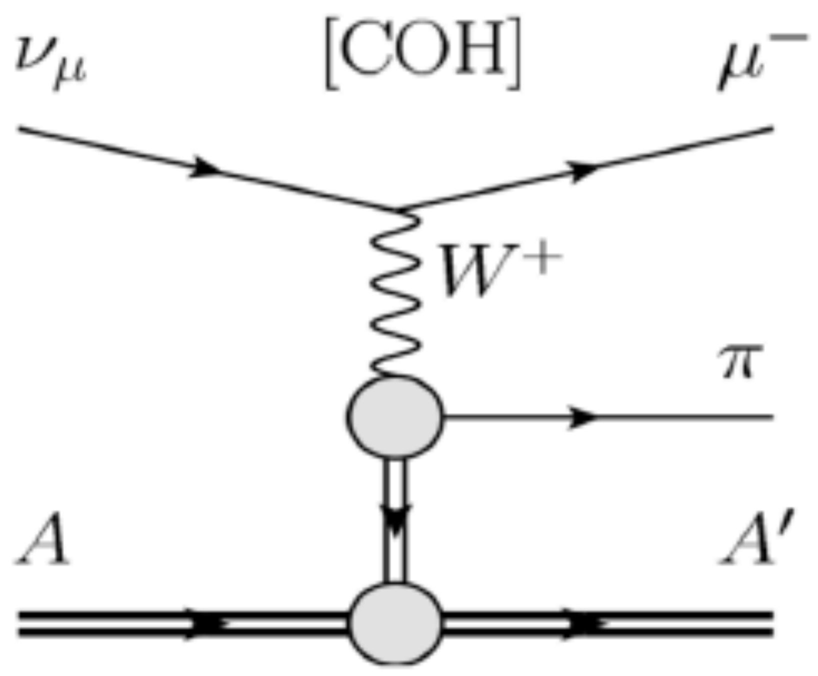
PHYS. REV. D 99, 112007 (2019)

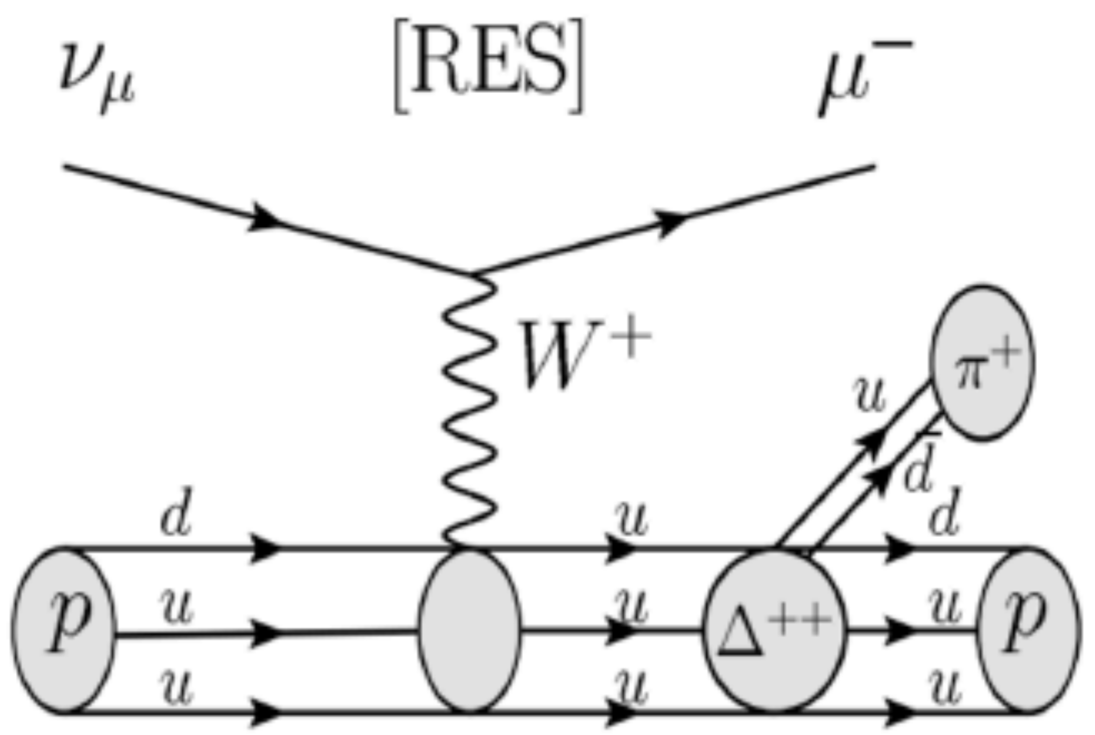
NEUTRON PRODUCTION IN ATMOSPHERIC NEUTRINO INTERACTIONS

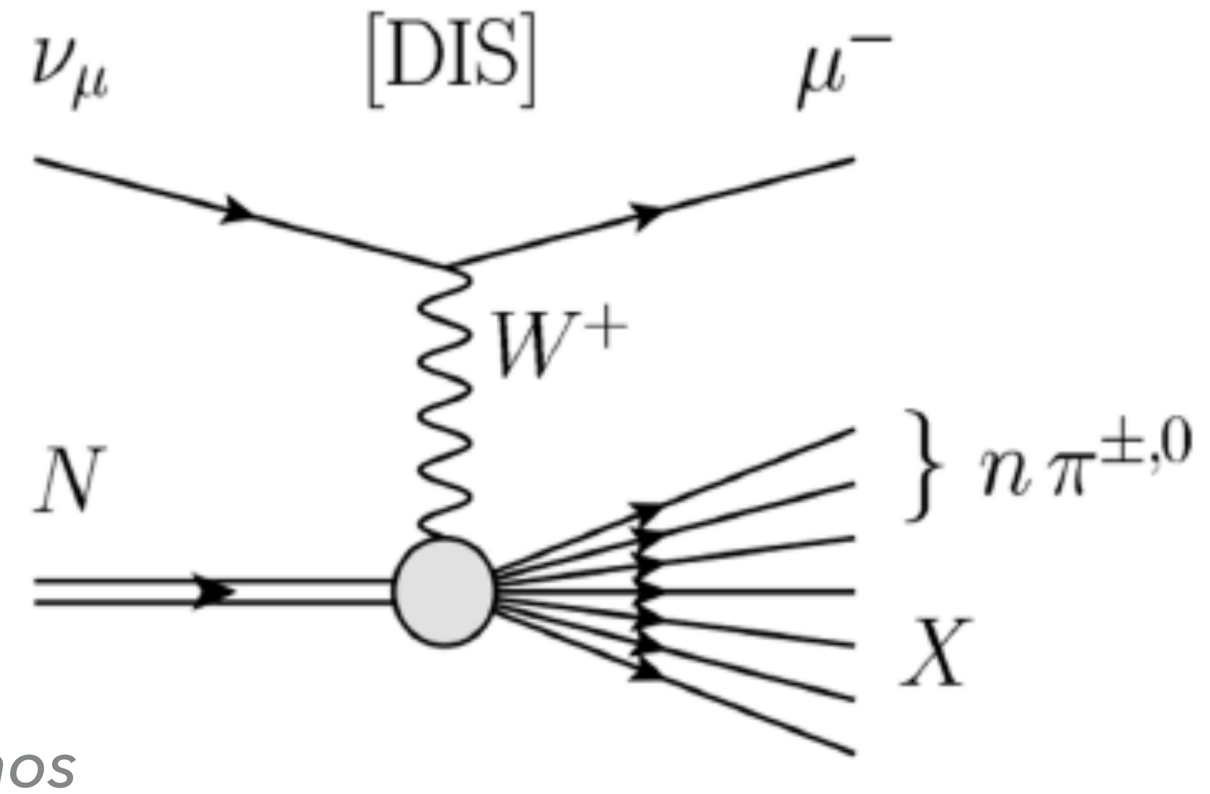
ATMOSPHERIC NEUTRINOS

THE ATMOSPHERE IS A CONSTANT SOURCE OF ~GEV NEUTRINOS AND ANTI-NEUTRINOS









**Same for electron/tau-neutrinos and anti-neutrinos*

ATMOSPHERIC NEUTRINOS ARE A BACKGROUND FOR NUCLEON DECAY (ND) SEARCHES

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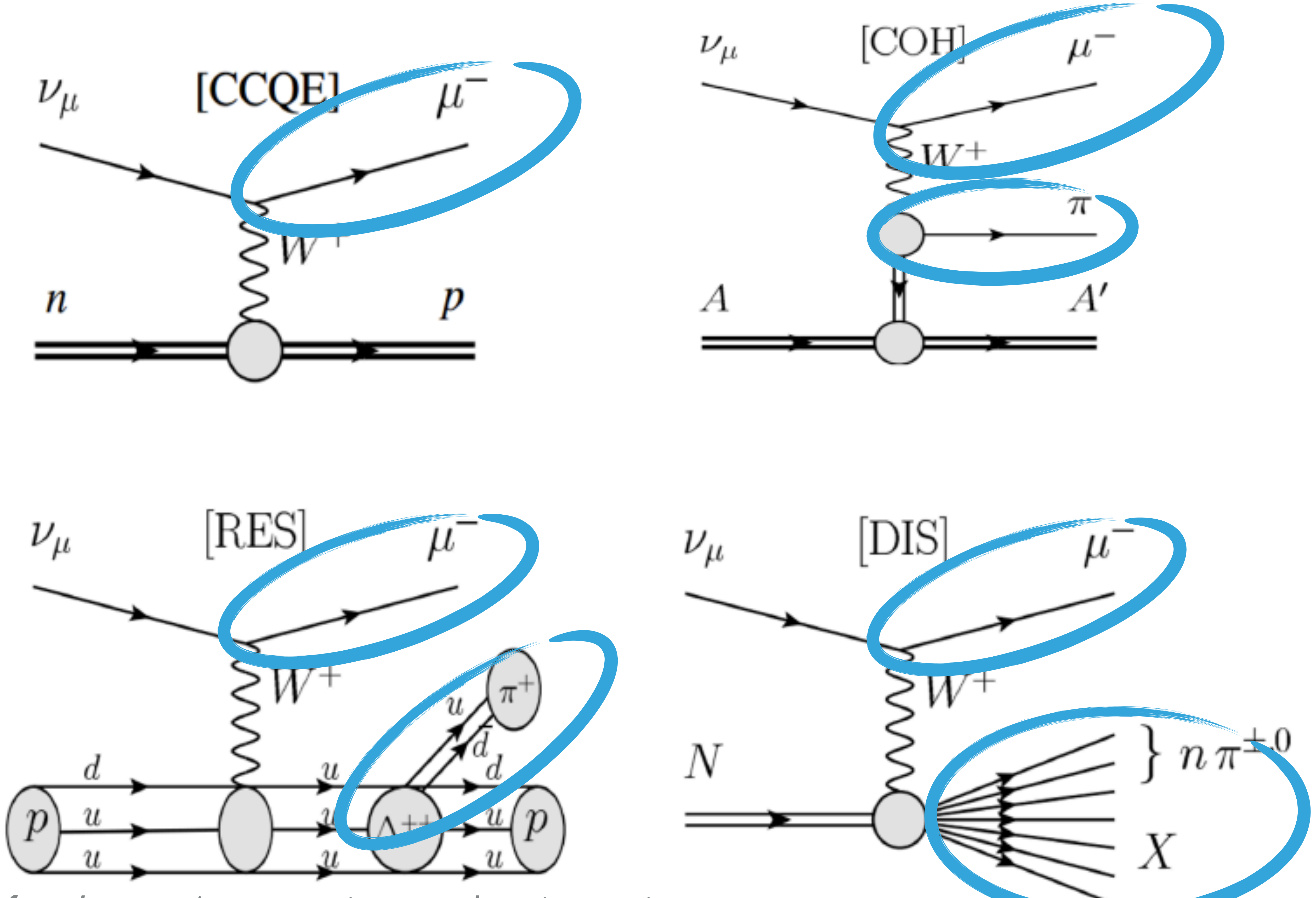

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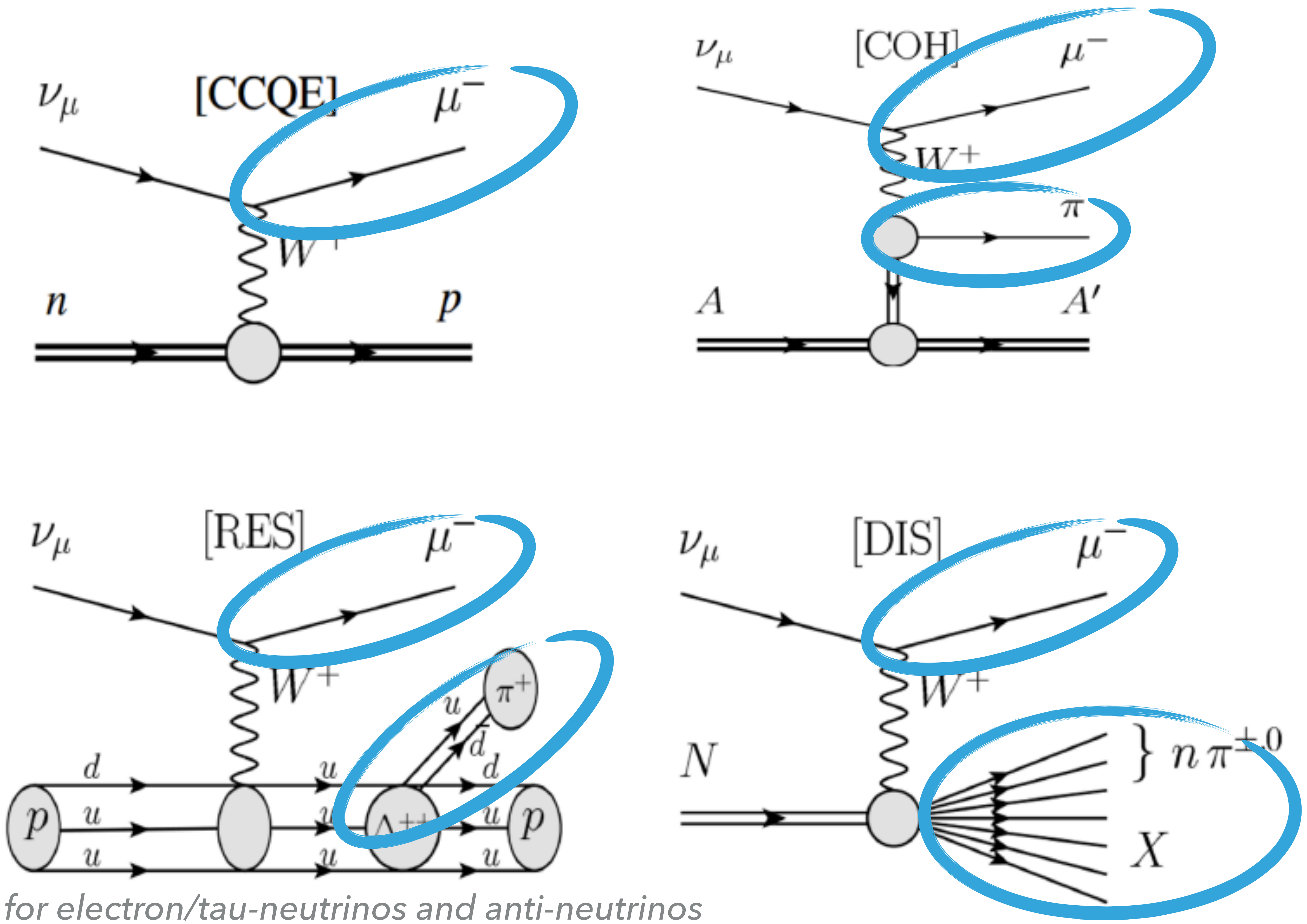

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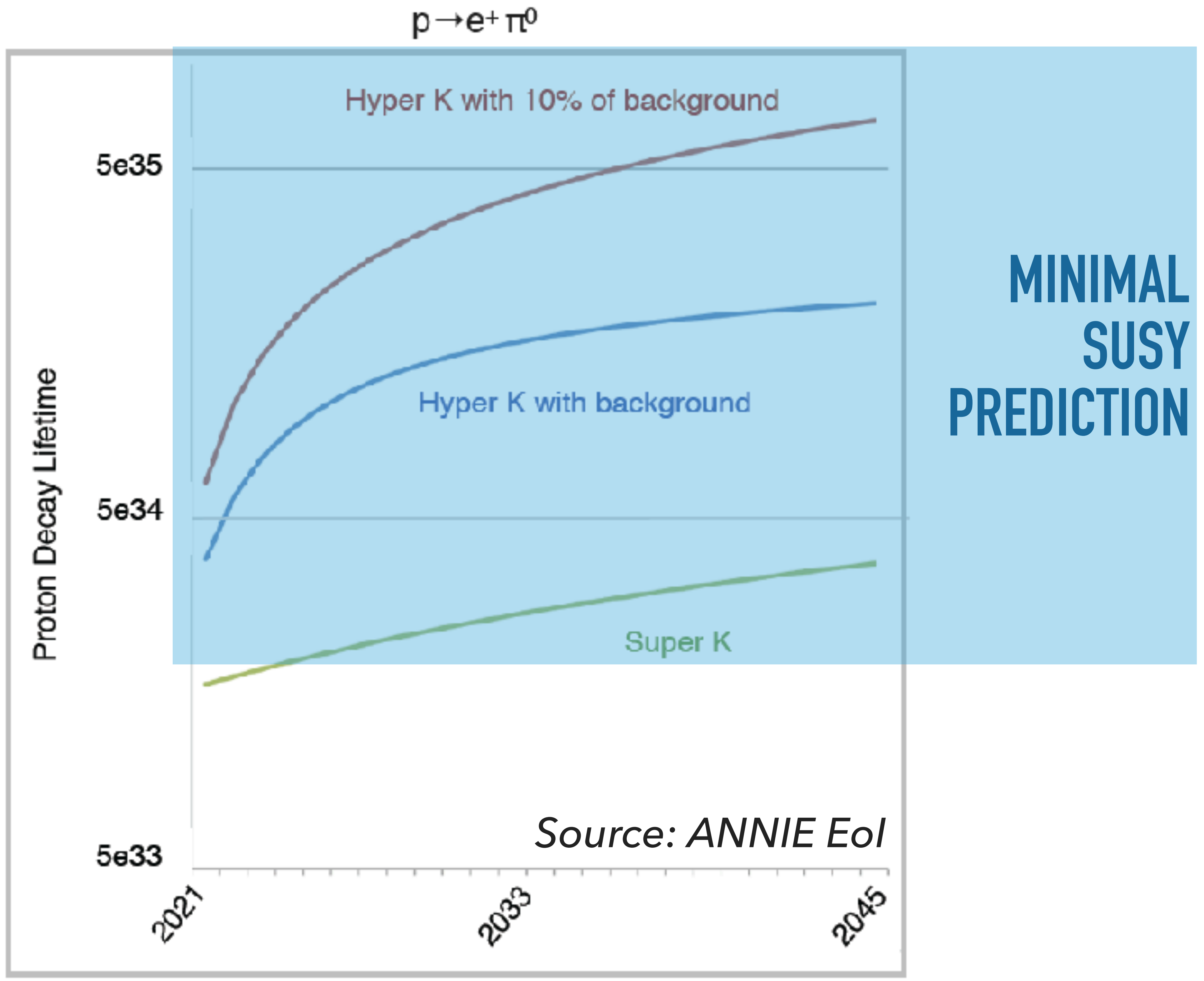

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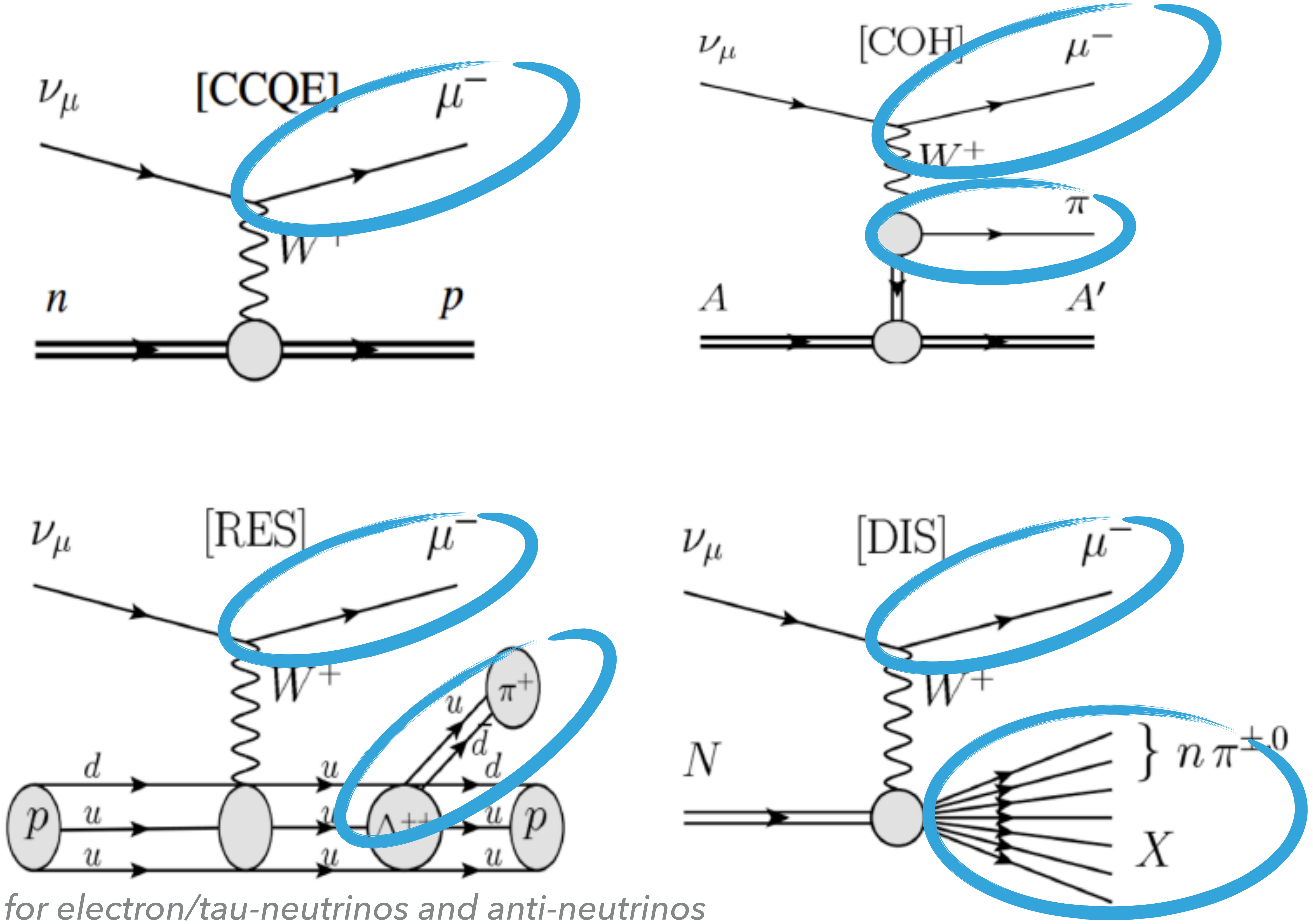

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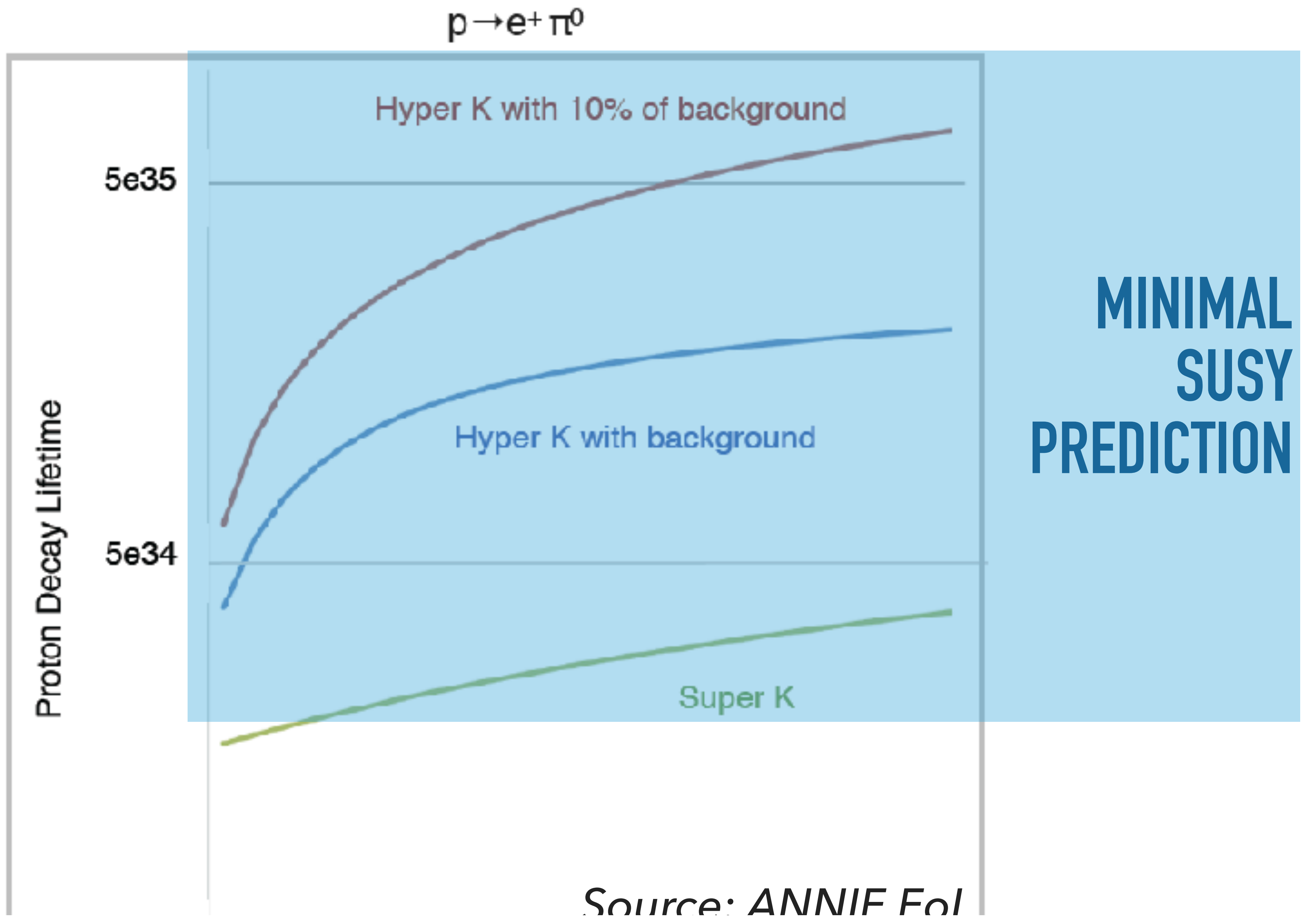

Process	Fraction with at least one neutron produced
ν CCQE	38.4(2.2)%
$\bar{\nu}$ CCQE	99.9(0.1)%
ν CCOther	88.8(2.0)%
$\bar{\nu}$ CCOther	94.7(2.1)%
ν NC	84.8(1.8)%
$\bar{\nu}$ NC	82.4(2.3)%
ν total	61.5(1.1)%
$\bar{\nu}$ total	95.6(0.6)%
Total	69.5(0.8)%

PROTON DECAY → TYPICALLY NO NEUTRONS

ATMOSPHERIC NEUTRINOS → 70% PRODUCE AT LEAST ONE

NEUTRON PRODUCTION IN GeV NEUTRINO INTERACTIONS IS VERY IMPORTANT FOR DIFFERENT REASONS

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1. PROTON DECAY TYPICALLY DOES NOT PRODUCE NEUTRONS: BACKGROUND REJECTION POTENTIAL

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2. NEUTRONS FROM ANTI-ν CCQE
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NEUTRONS FROM ν CCQE

1. PROTON DECAY TYPICALLY
DOES NOT PRODUCE NEUTRONS:
BACKGROUND REJECTION POTENTIAL

NEUTRON PRODUCTION IN GeV NEUTRINO INTERACTIONS IS VERY IMPORTANT FOR DIFFERENT REASONS

3. STUDYING CROSS-SECTION MODELS

Process	Fraction with at least one neutron produced
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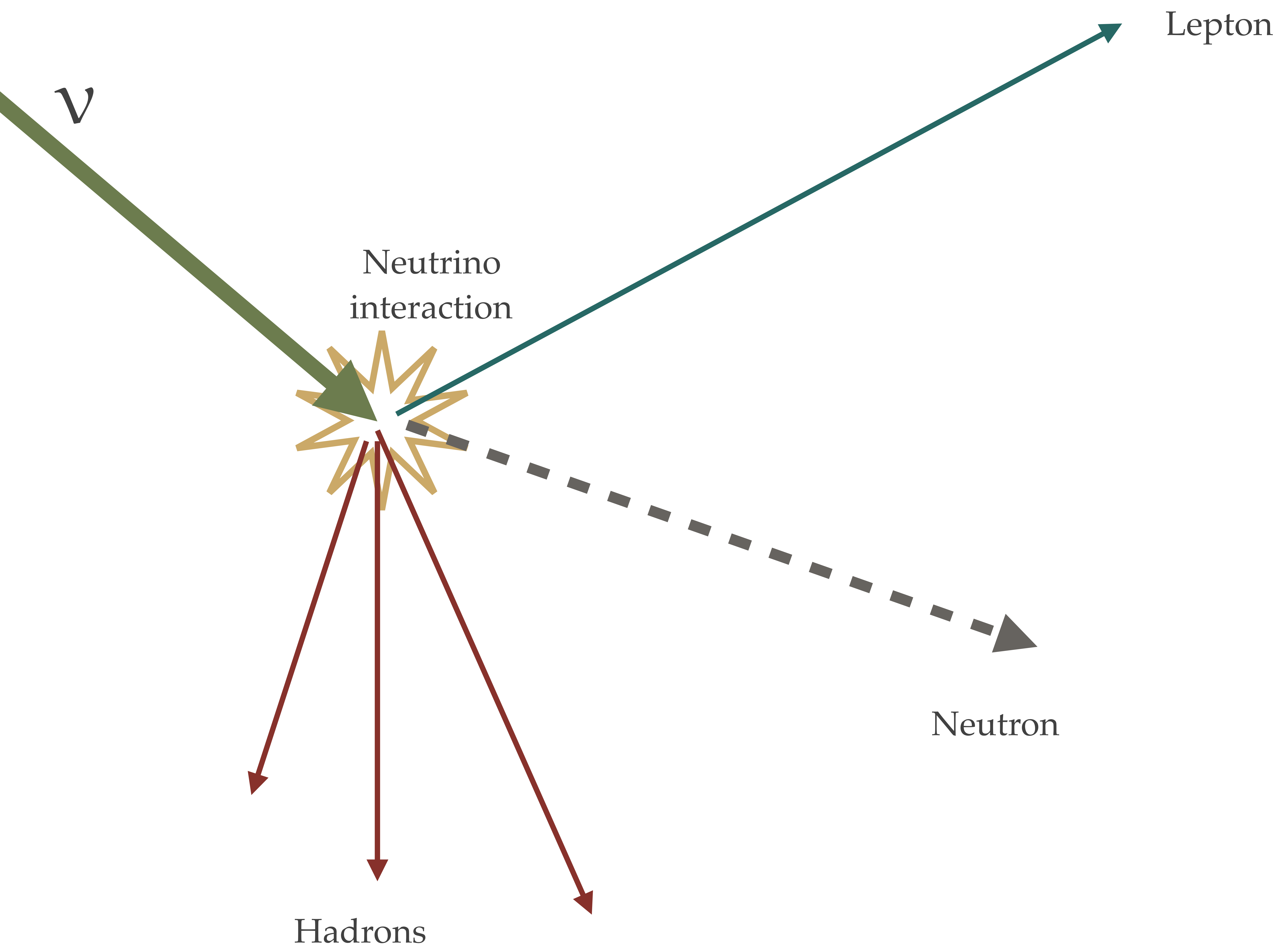
1. PROTON DECAY TYPICALLY DOES NOT PRODUCE NEUTRONS: BACKGROUND REJECTION POTENTIAL

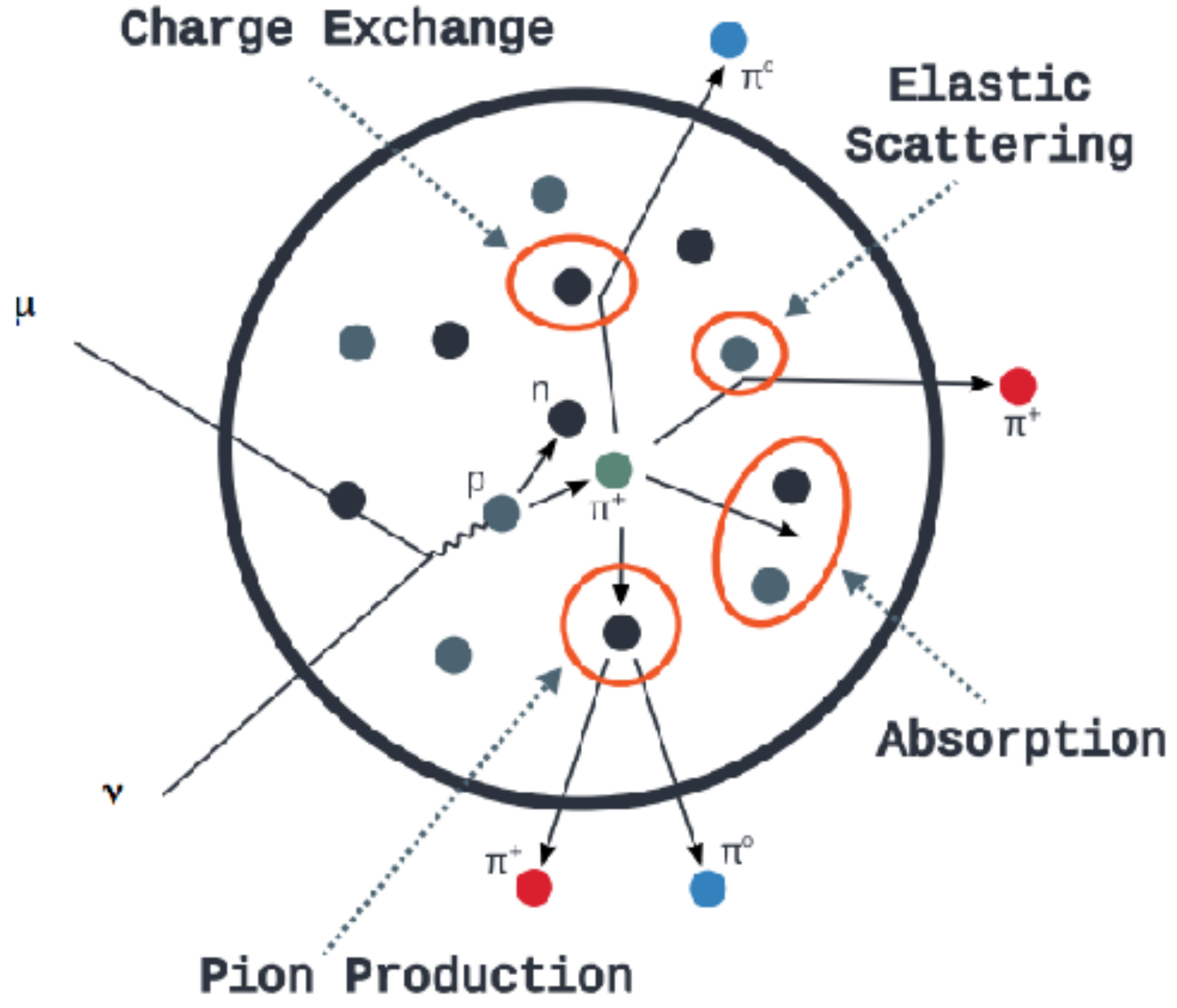
NEUTRON PRODUCTION MECHANISM IS COMPLICATED



NEUTRON PRODUCTION MECHANISM IS COMPLICATED

ν

Final State Interactions



Lepton

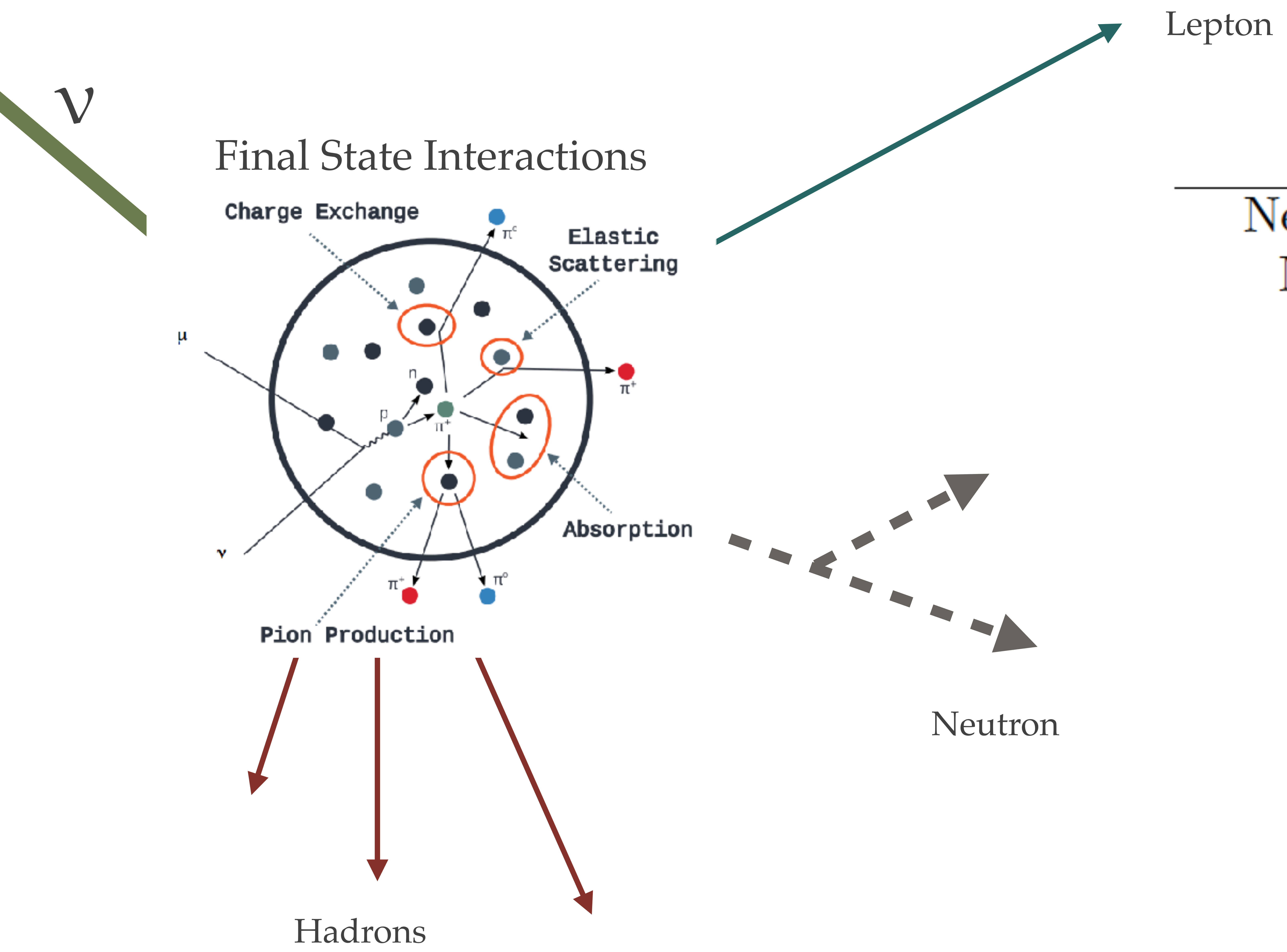
Neutron

Hadrons

GENIE + GEANT4 simulation of atmospheric neutrinos in heavy water

Origin	Fraction
Neutrino Interaction	33.49%

NEUTRON PRODUCTION MECHANISM IS COMPLICATED



GENIE + GEANT4 simulation of atmospheric neutrinos in heavy water

Origin	Fraction
Neutrino Interaction	33.49%
Neutron Inelastic	34.76%

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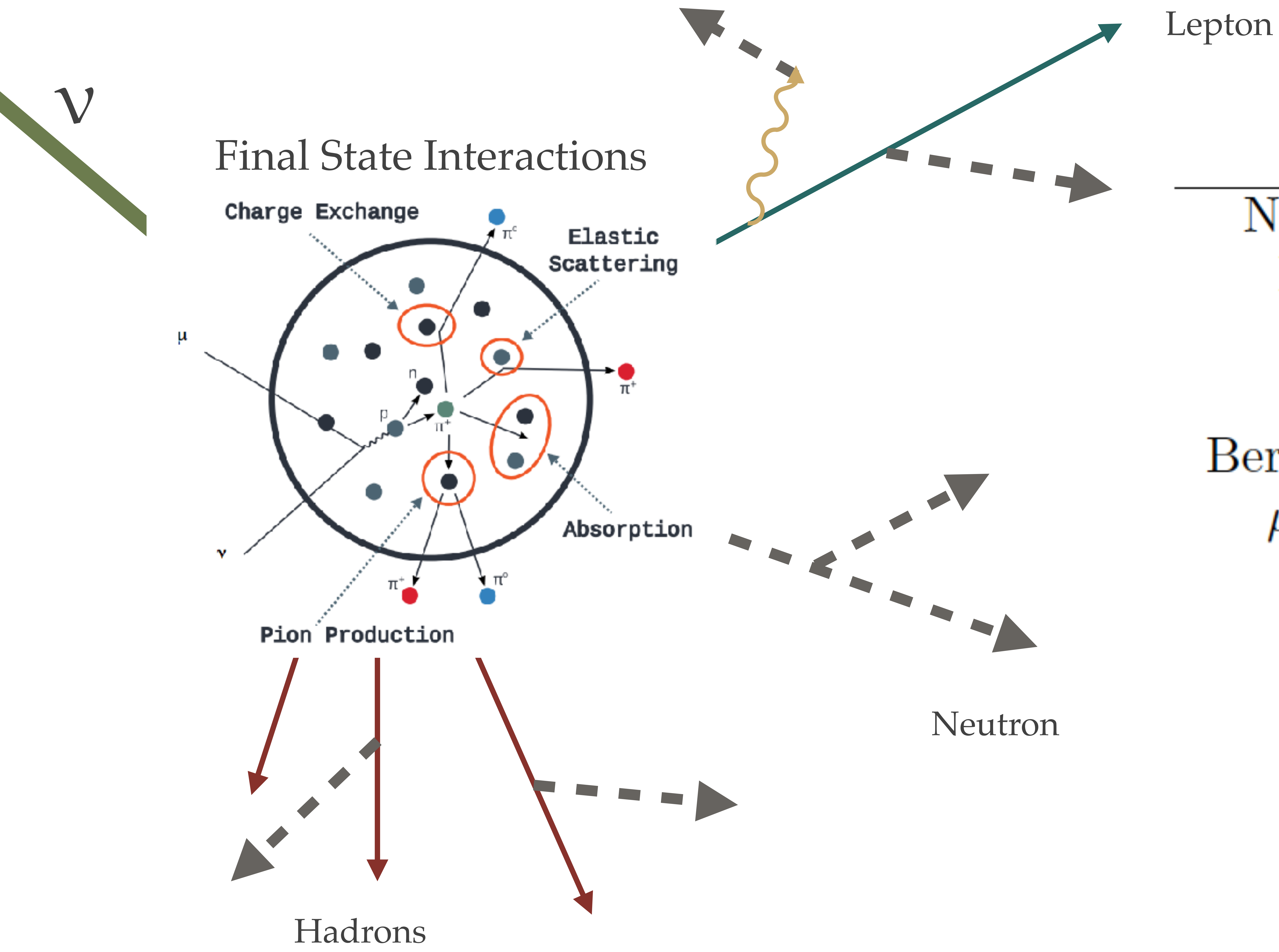


GENIE + GEANT4 simulation of atmospheric neutrinos in heavy water

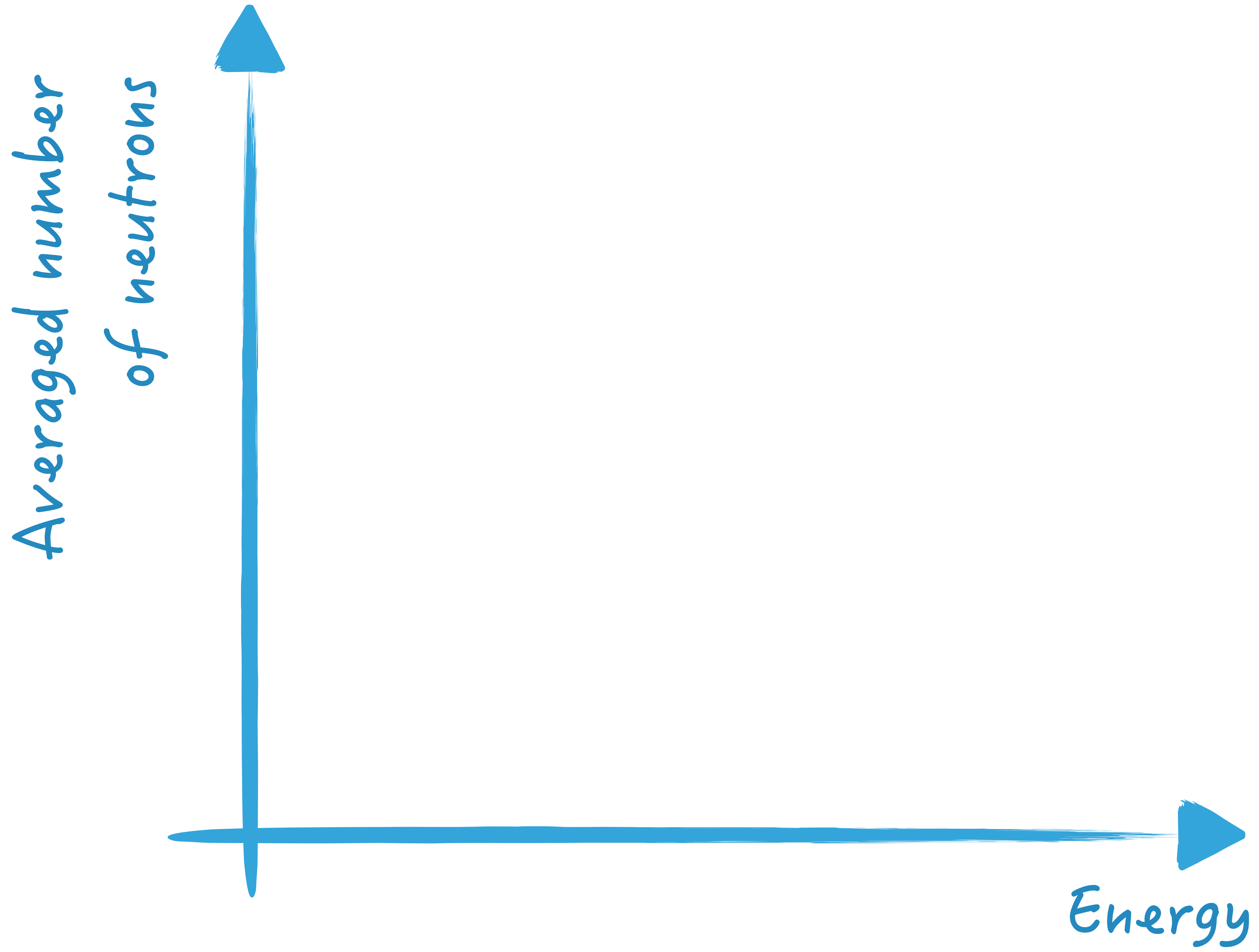
Origin	Fraction
Neutrino Interaction	33.49%
Neutron Inelastic	34.76%
pi/K Inelastic	14.56%
Proton Inelastic	7.90%
Bertini Capture at Rest	6.11%
μ Capture at Rest	2.14%
Photo-nuclear	0.76%
Other	0.28%

GOALS

1) MEASURING THE NEUTRON PRODUCTION FROM ATMOSPHERIC NEUTRINO INTERACTIONS AS A FUNCTION OF ENERGY

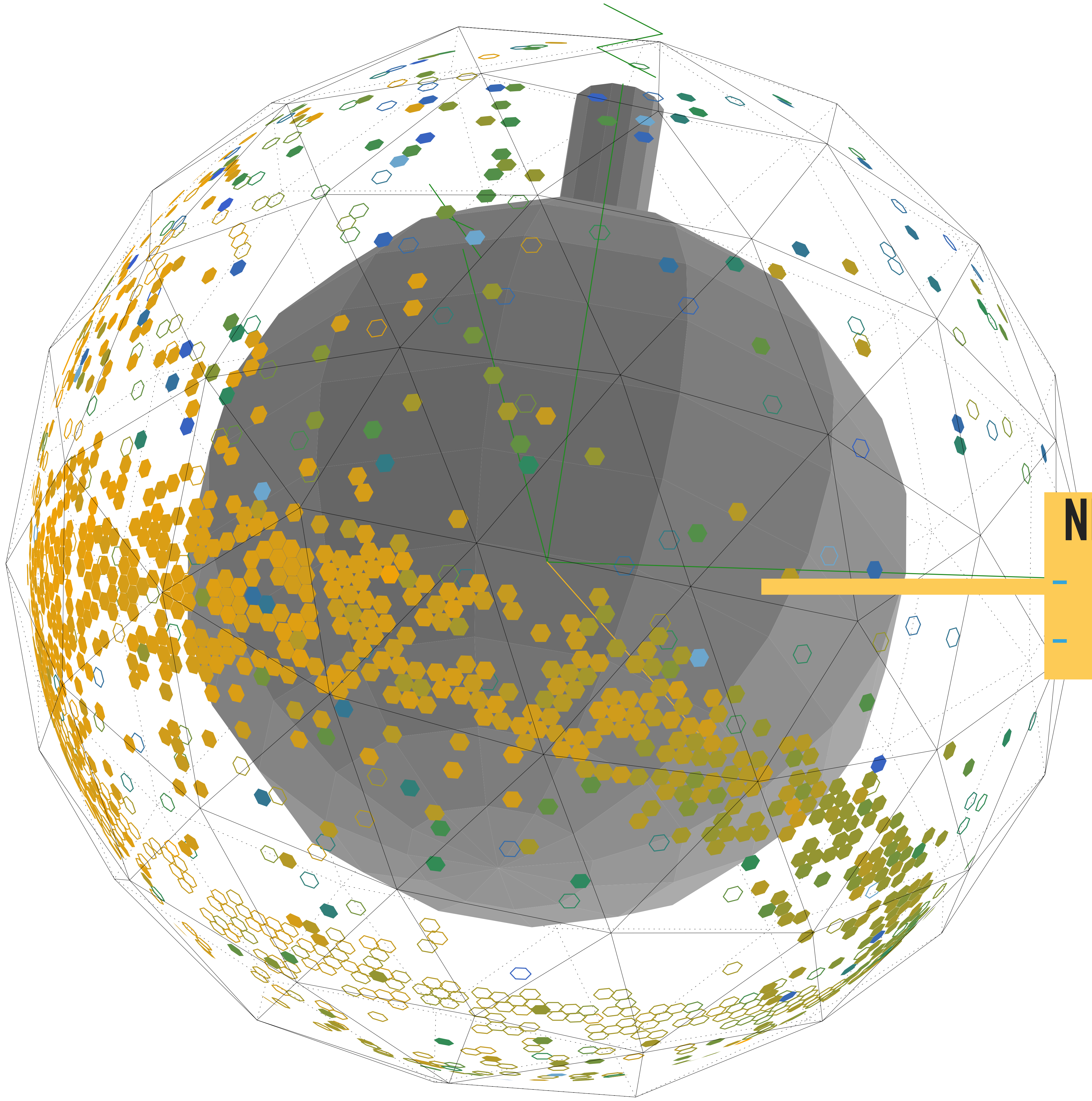
2) PROVIDE FIRST VALIDATION OF MONTE CARLO MODEL

3) EXPLORE NEUTRON DETECTION IMPACT IN NEUTRINO/ANTINEUTRINO SEPARATION

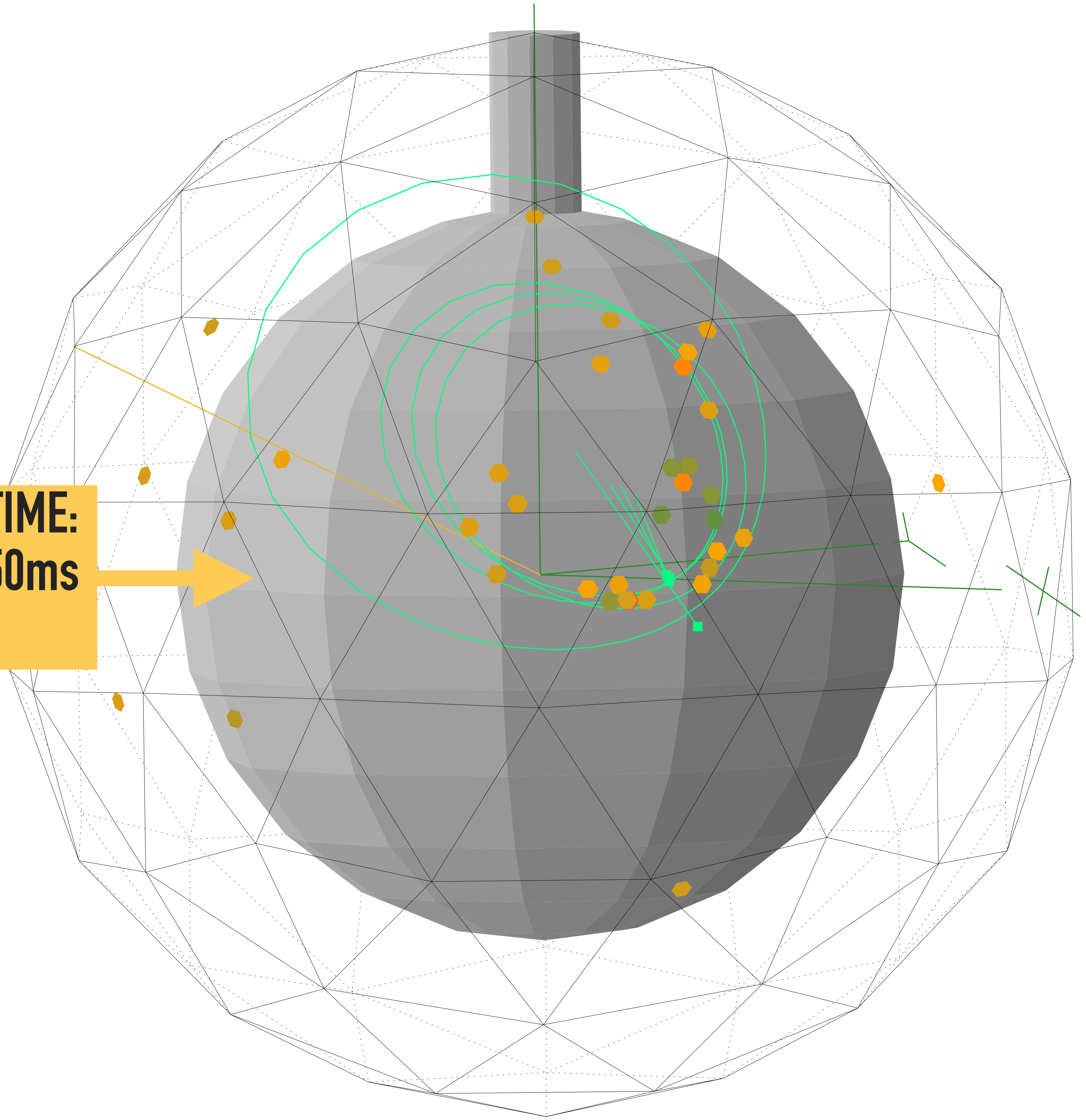


SELECT ATMOSPHERIC NEUTRINO INTERACTIONS AND LOOK FOR NEUTRON CAPTURES IN COINCIDENCE

ATMOSPHERIC EVENT



NEUTRON CAPTURE CANDIDATE



NEUTRON CAPTURE TIME:

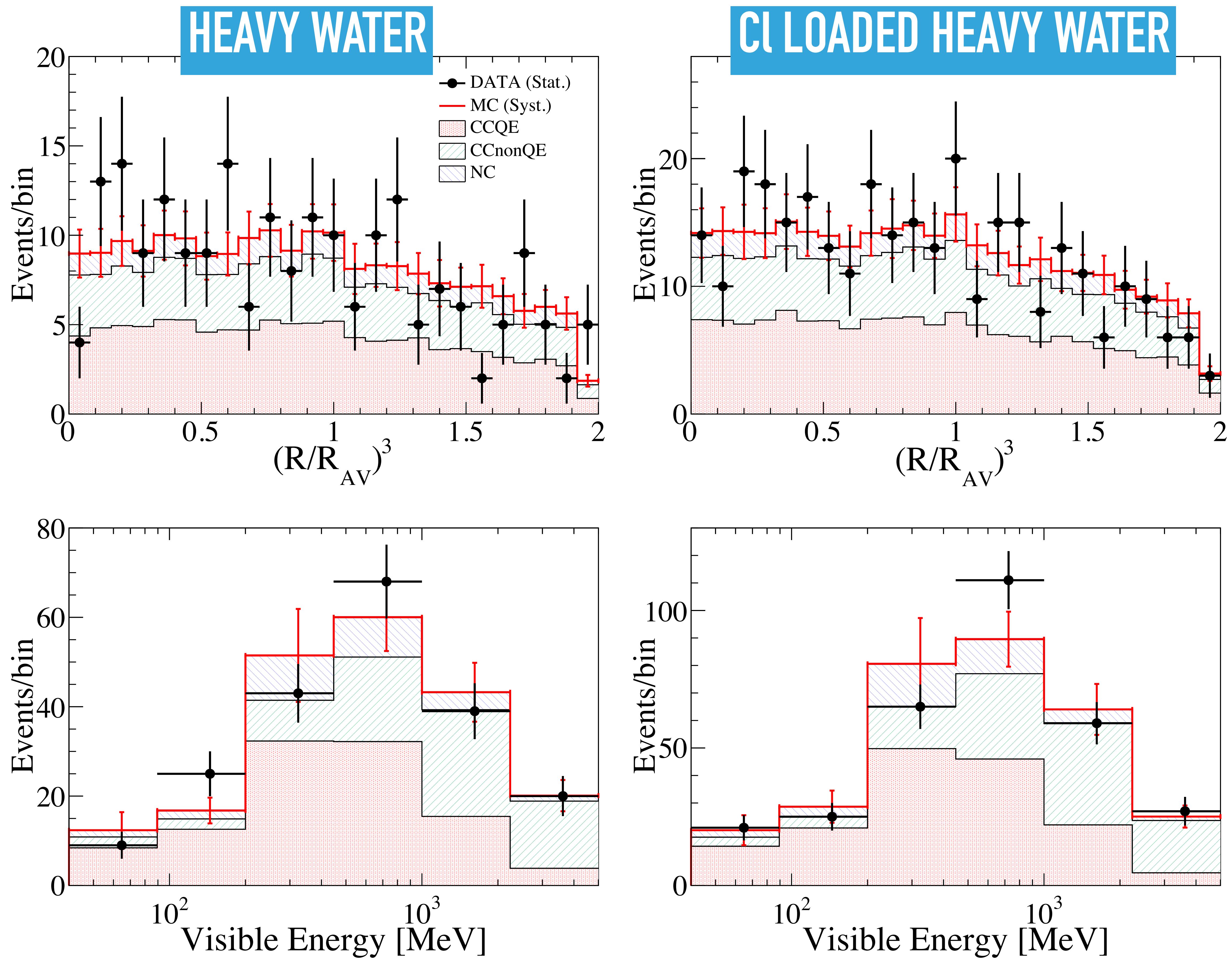
- HEAVY WATER: ~50ms
- ^{35}Cl: ~5ms

SELECT ATMOSPHERIC NEUTRINO INTERACTIONS AND LOOK FOR NEUTRON CAPTURES IN COINCIDENCE

ATMOSPHERIC EVENT

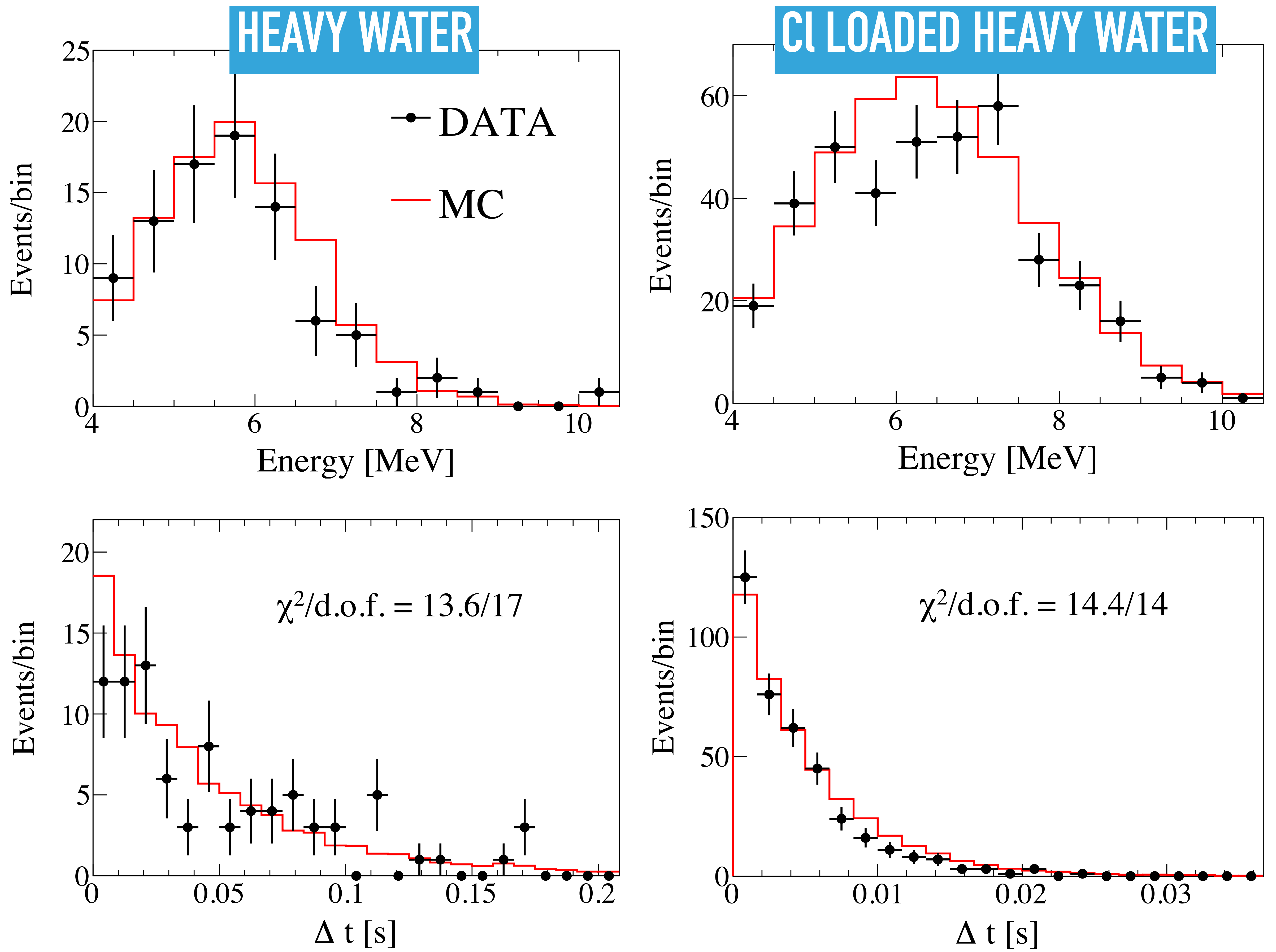
Developed algorithm based on SK and MiniBooNE to reconstruct:

- Lepton position and direction
- Particle type: electron or muon
- Multiplicity: single particle or multi-particle

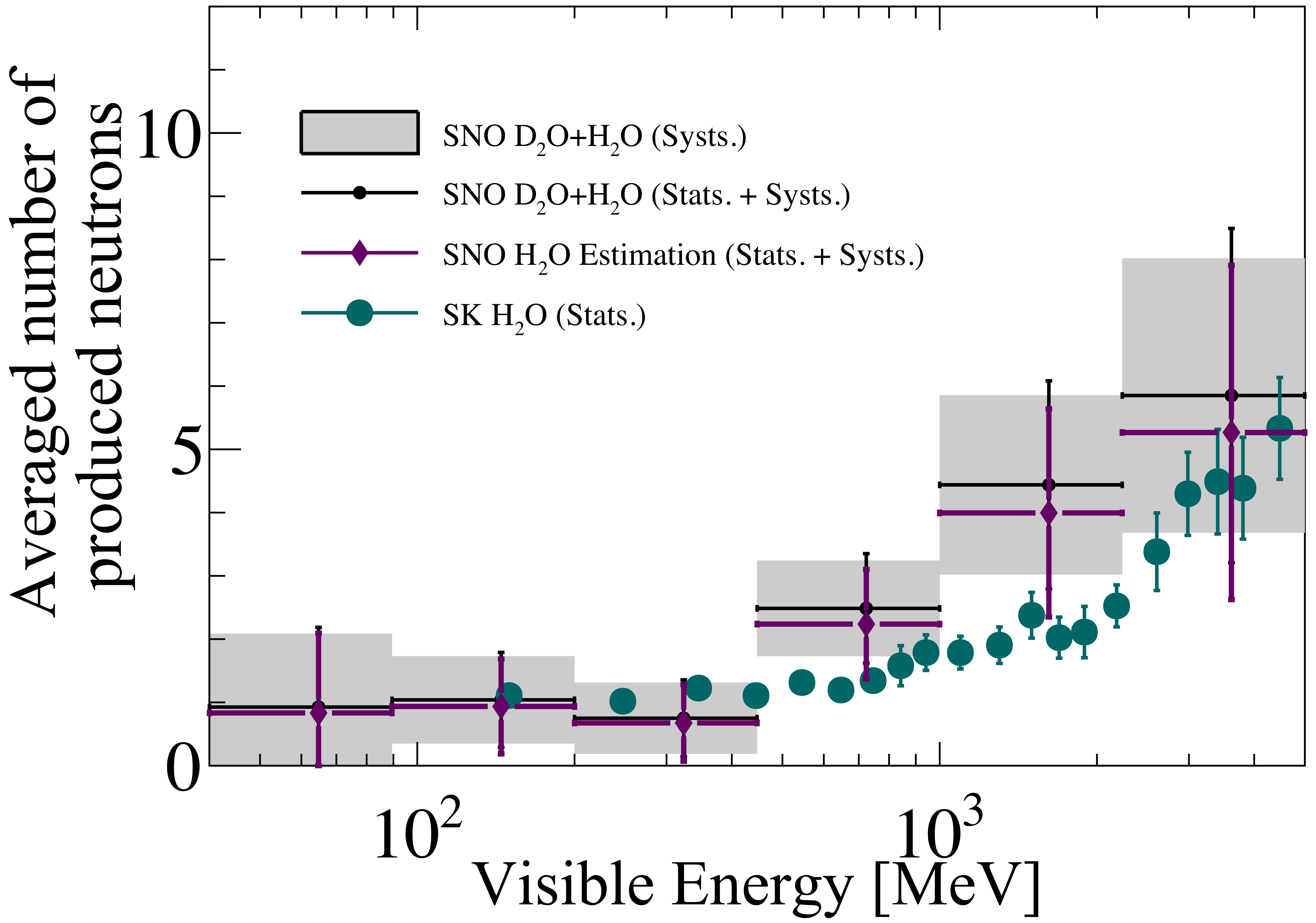


NEUTRON CAPTURE CANDIDATE

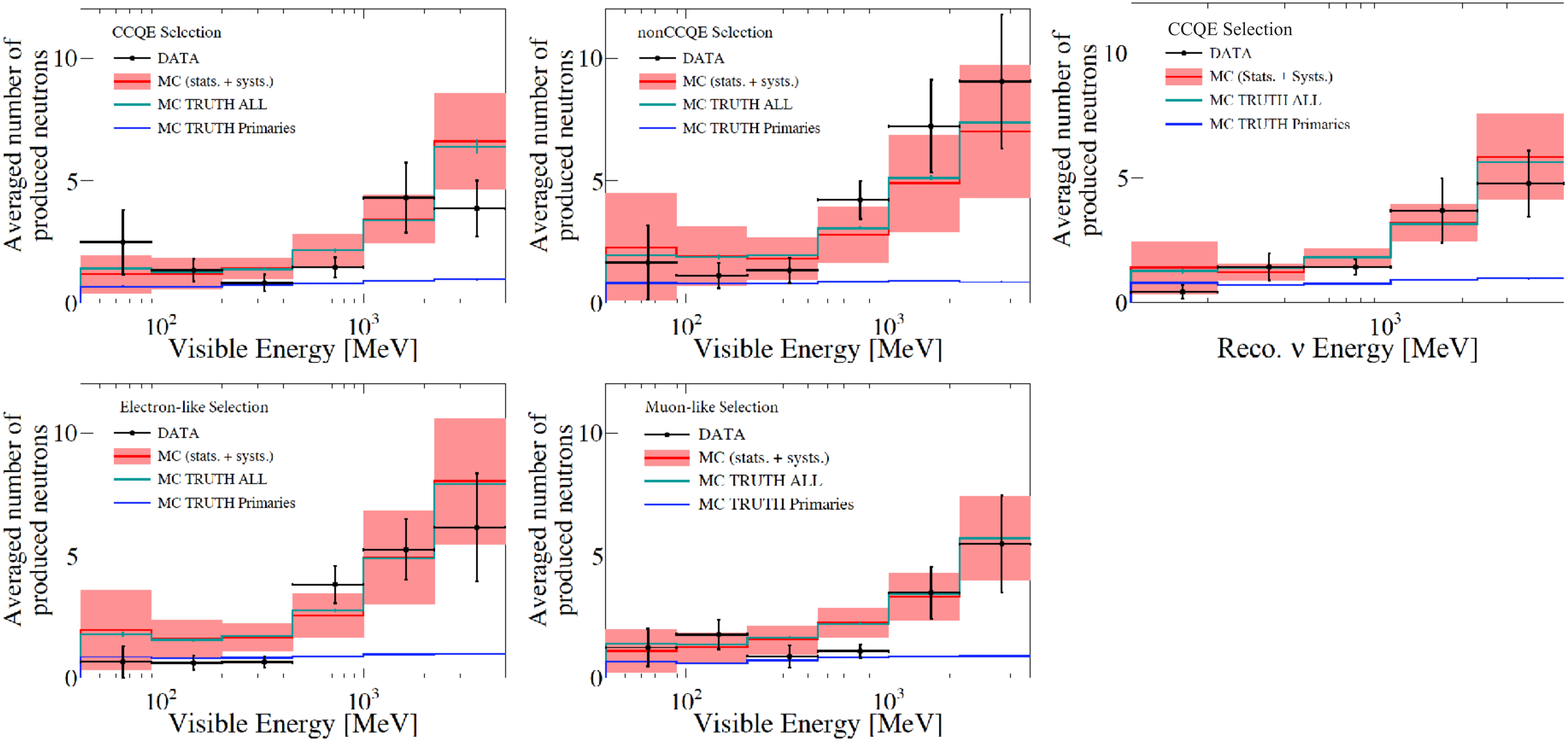
Used original SNO algorithms:



MEASURED NEUTRON PRODUCTION COMPATIBLE WITH SK RESULTS



MEASURED NEUTRON PRODUCTION COMPATIBLE WITH GENIE/GEANT4 MC



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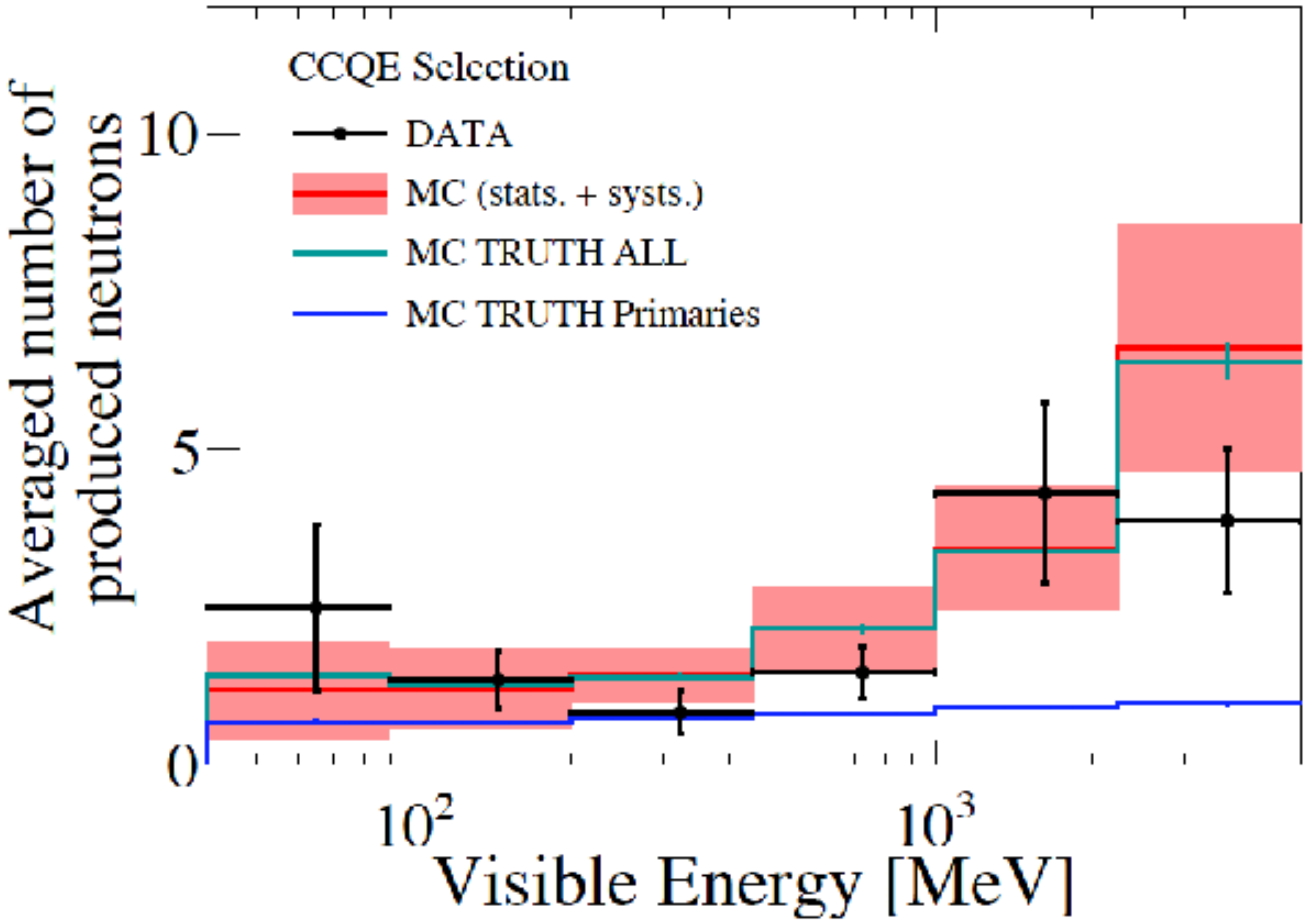
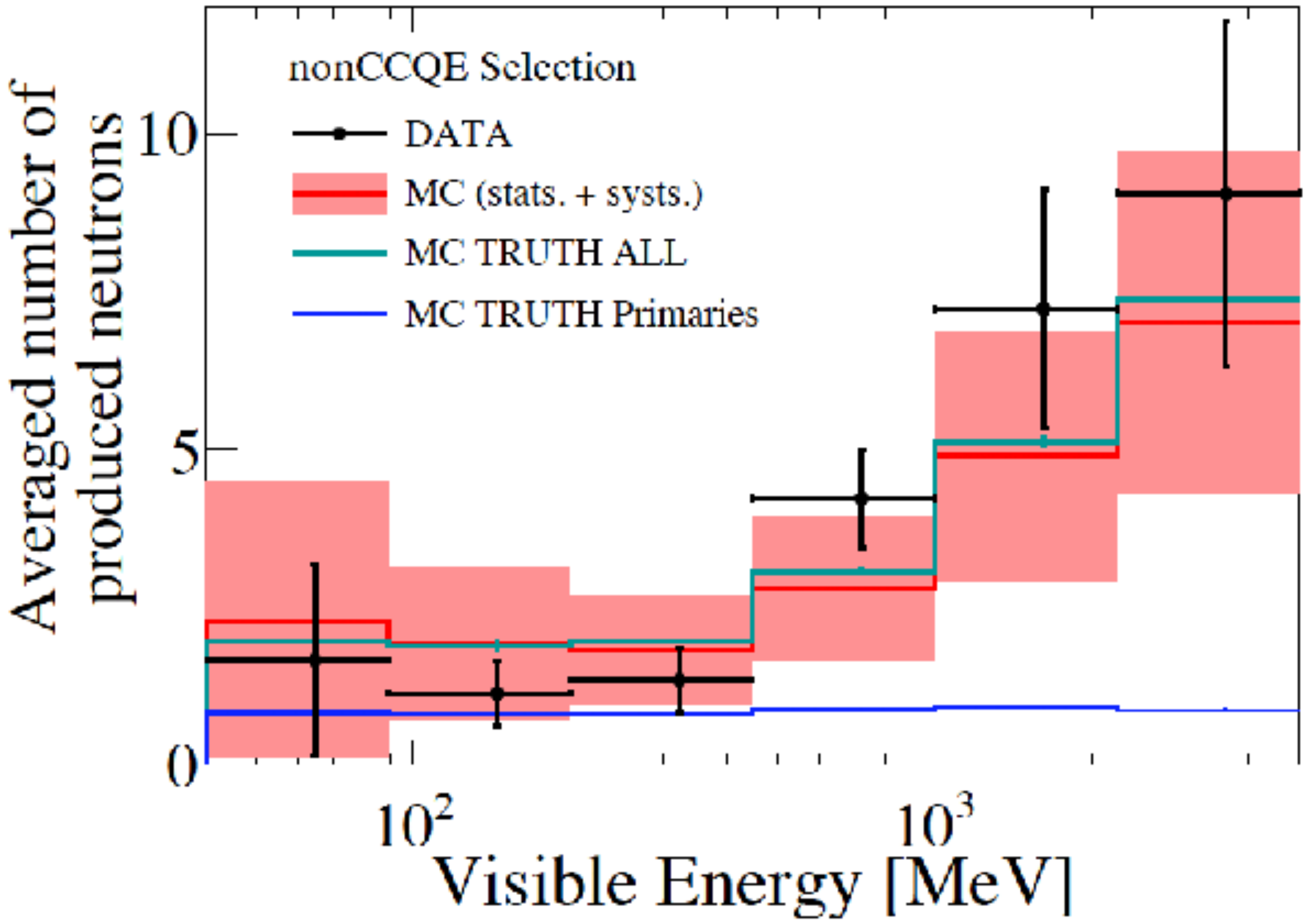
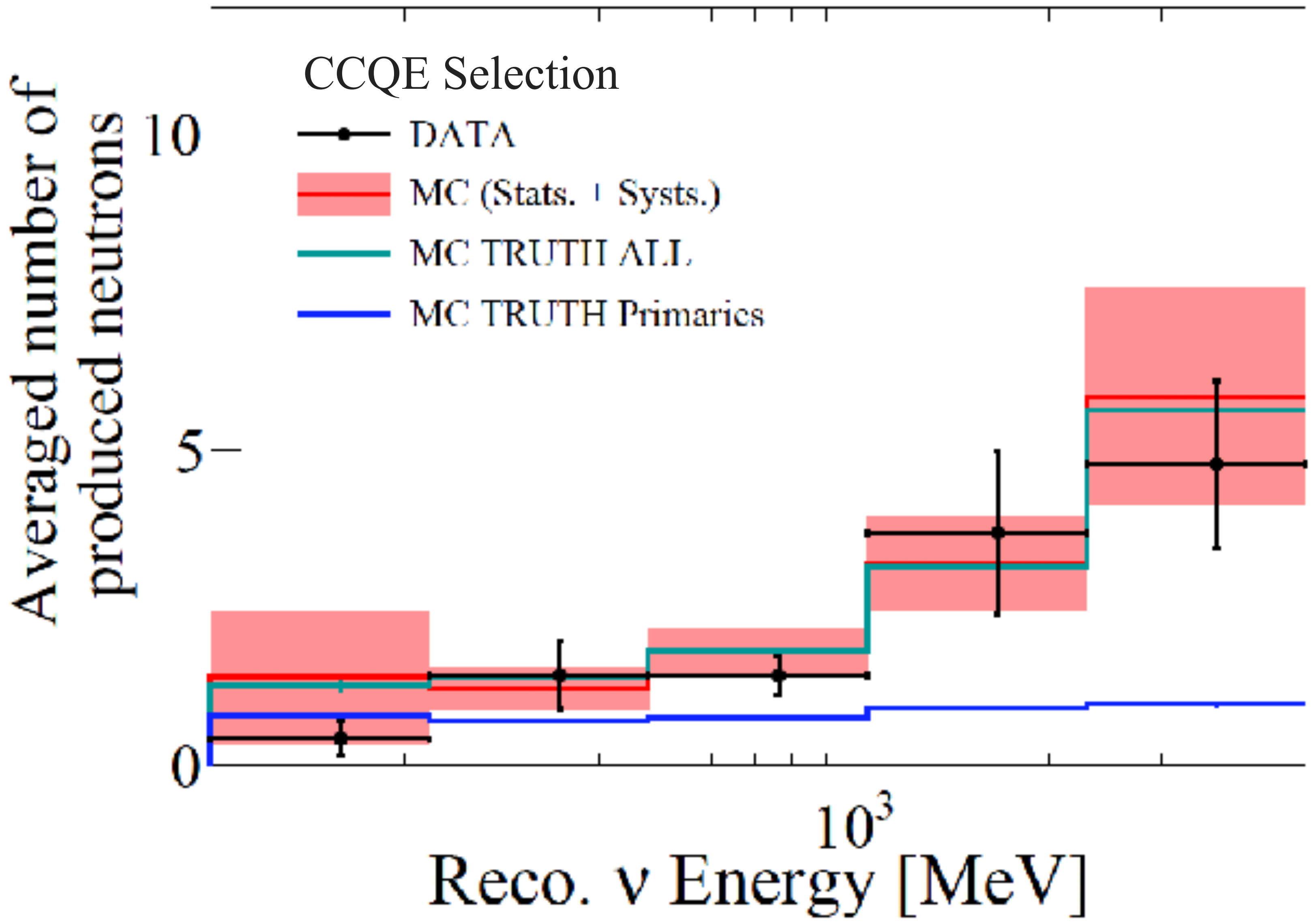
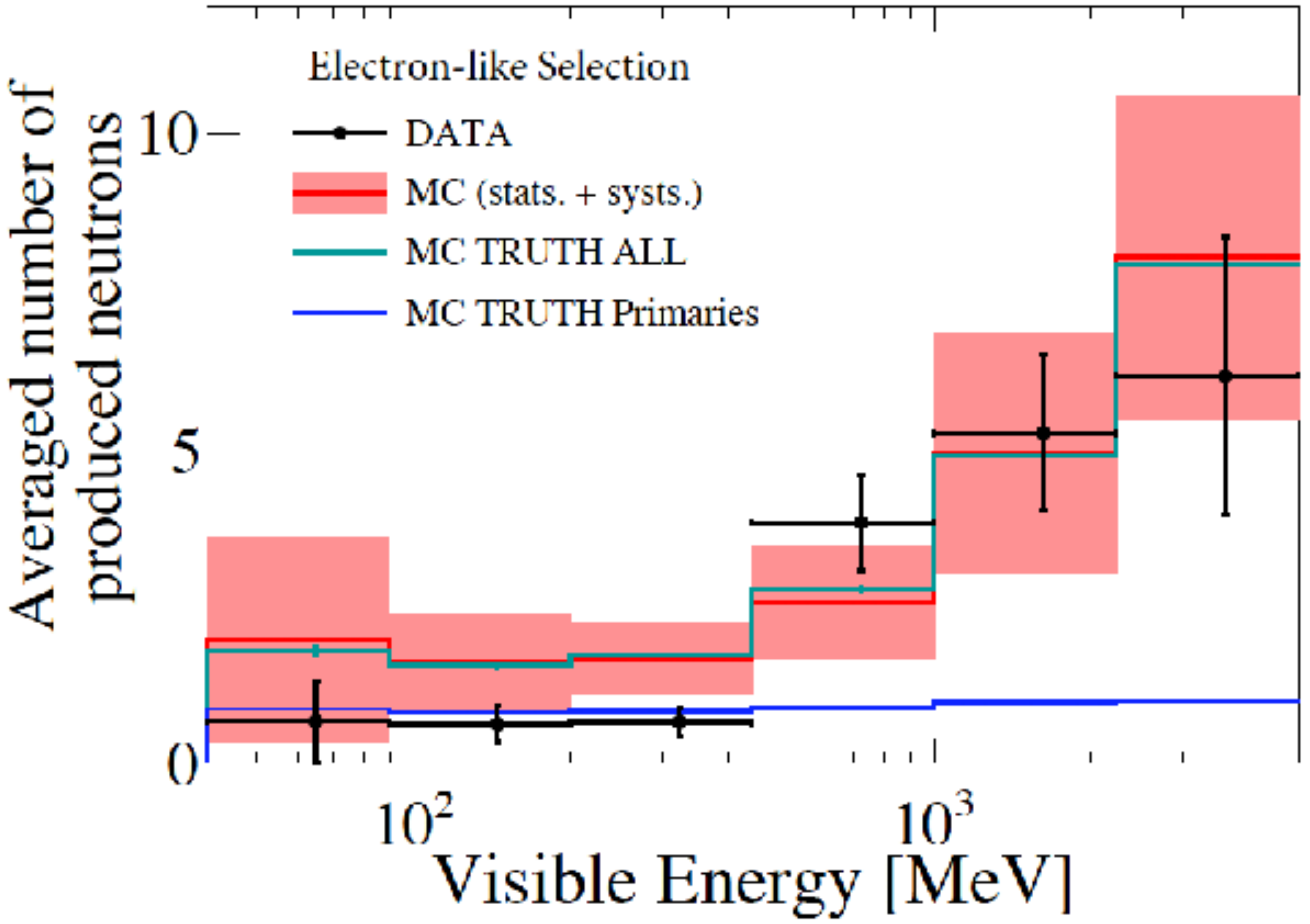
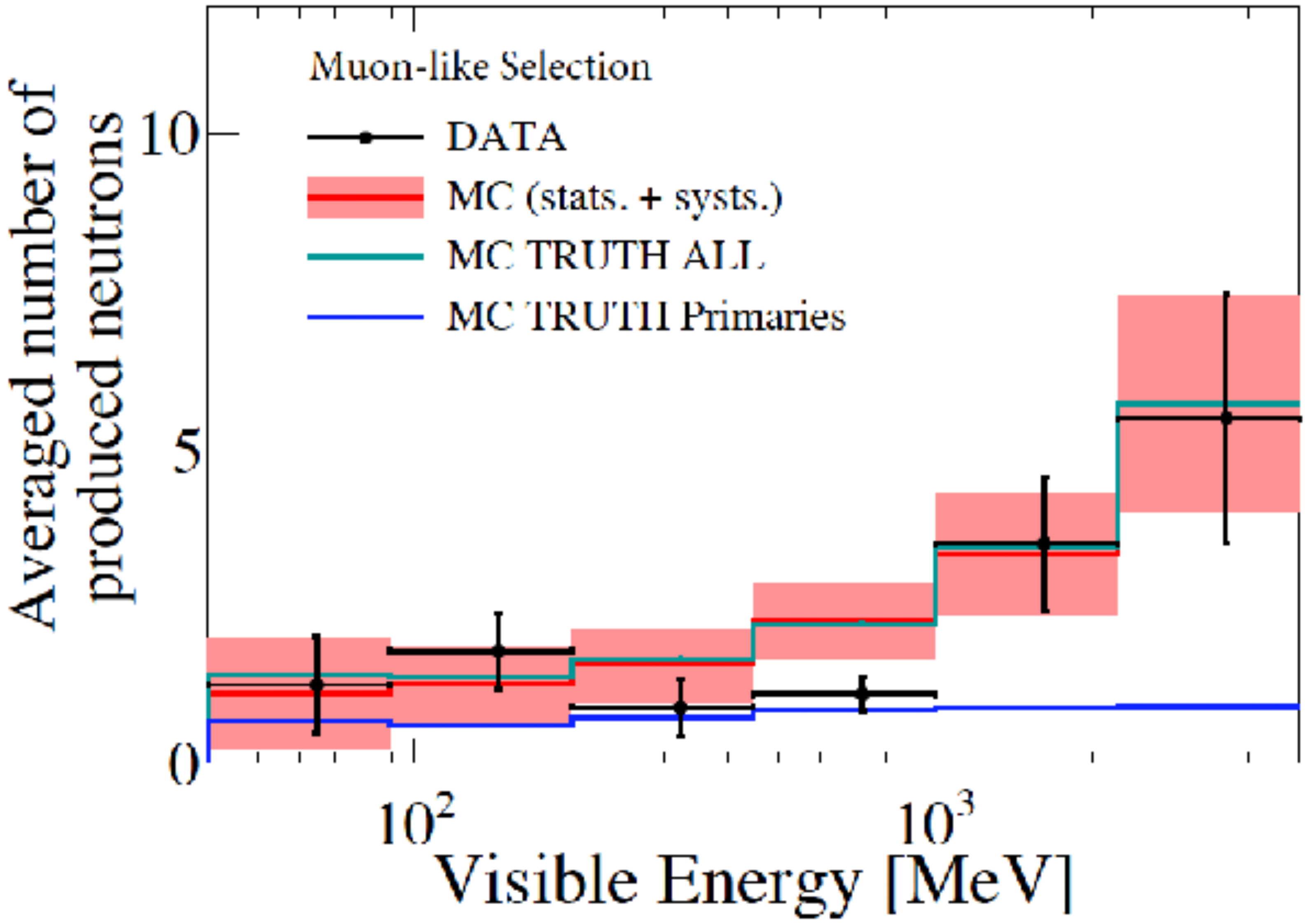






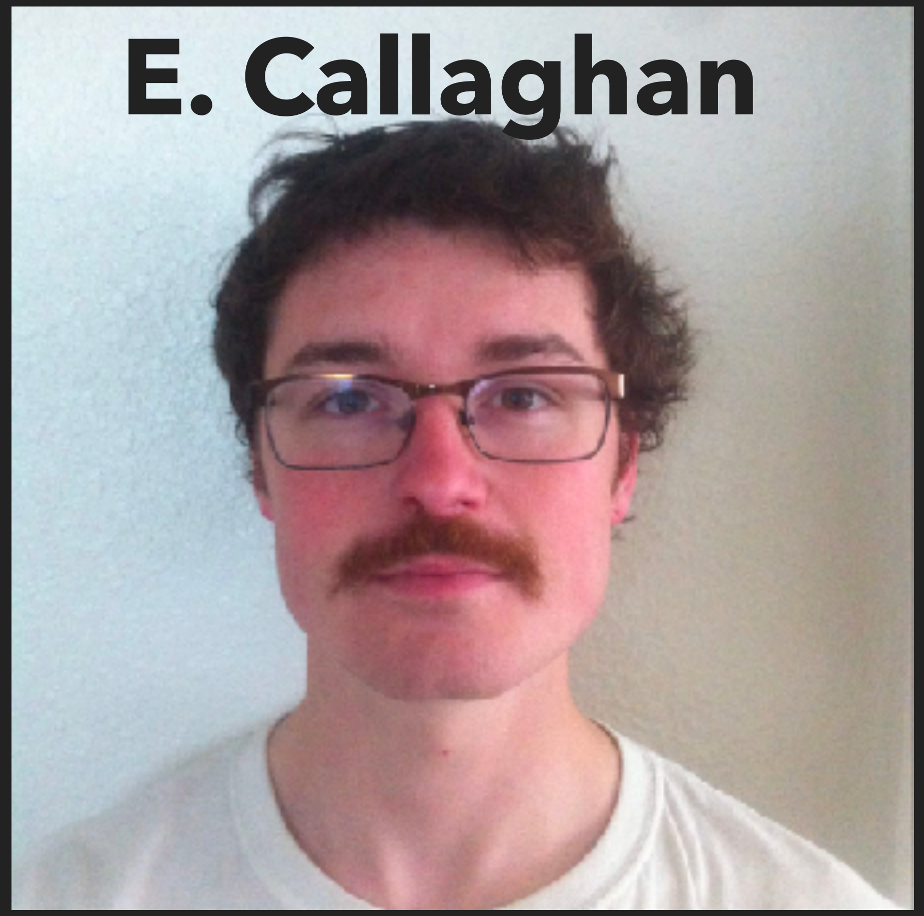




DATA AND MC AGREE AT 2σ IN THE ENTIRE ENERGY RANGE AND FOR ALL SAMPLES

ANTI-ν COMPONENT CAN BE CONSTRAINED AT THE 46% LEVEL

A #NEUTRON CUT CAN ENHANCE THE ANTI-ν COMPONENT BY 10%

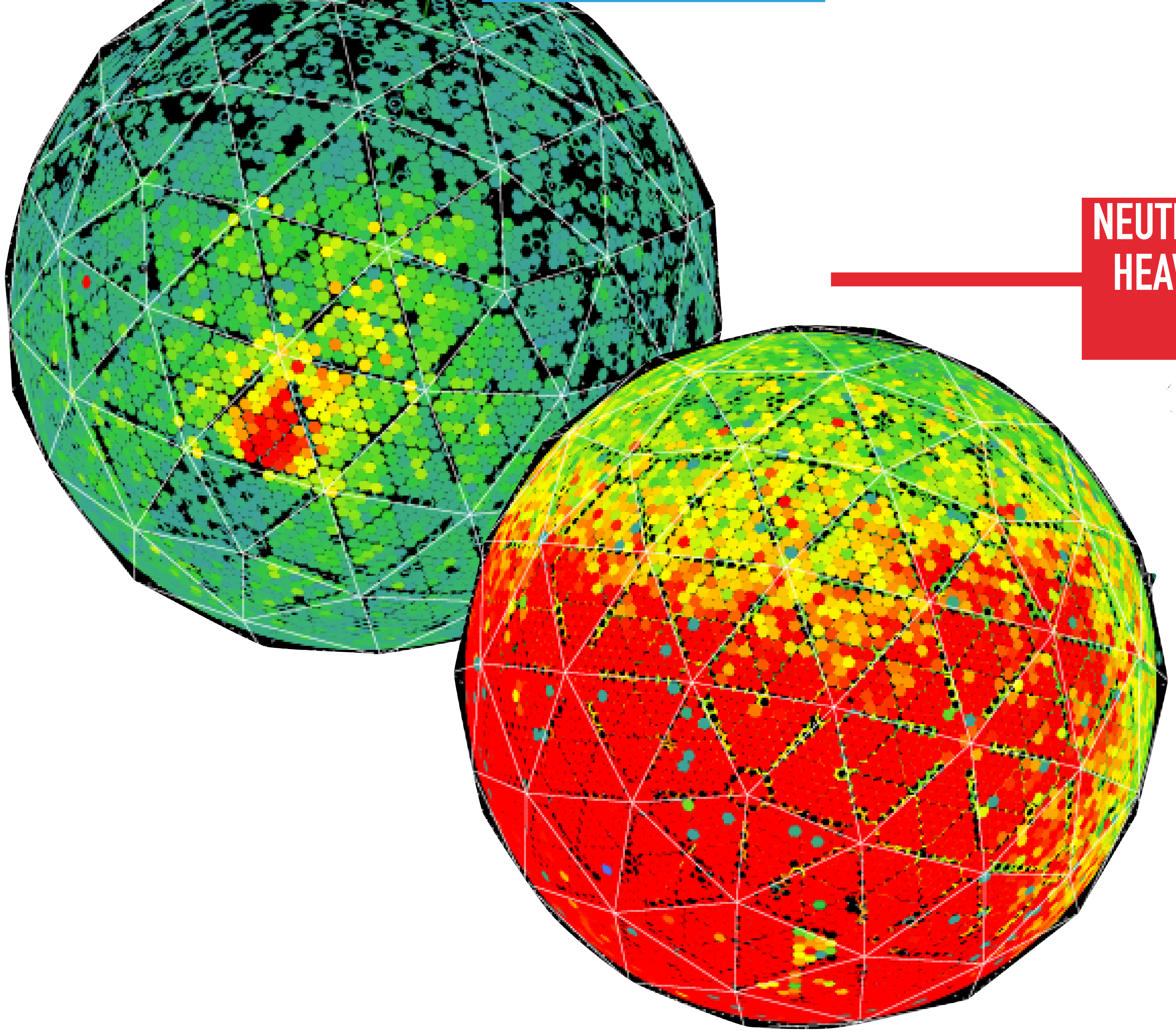


PHYS. REV. D 100, 112005 (2019)

NEUTRON PRODUCTION BY COSMIC MUONS

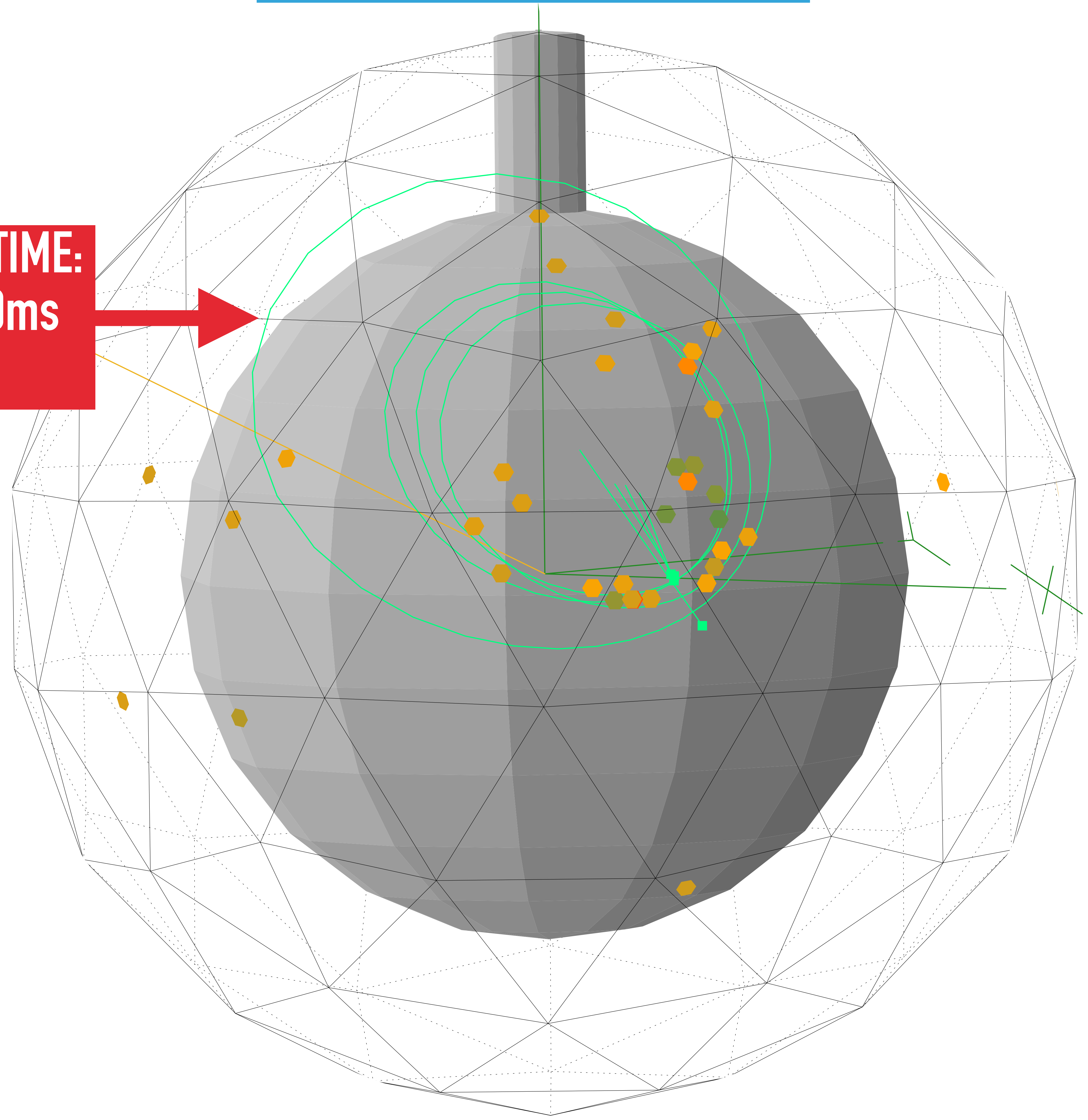
NEUTRONS PRODUCED BY COSMIC MUONS IS A BACKGROUND FOR A NUMBER OF ANALYSES

COSMIC MUON EVENT

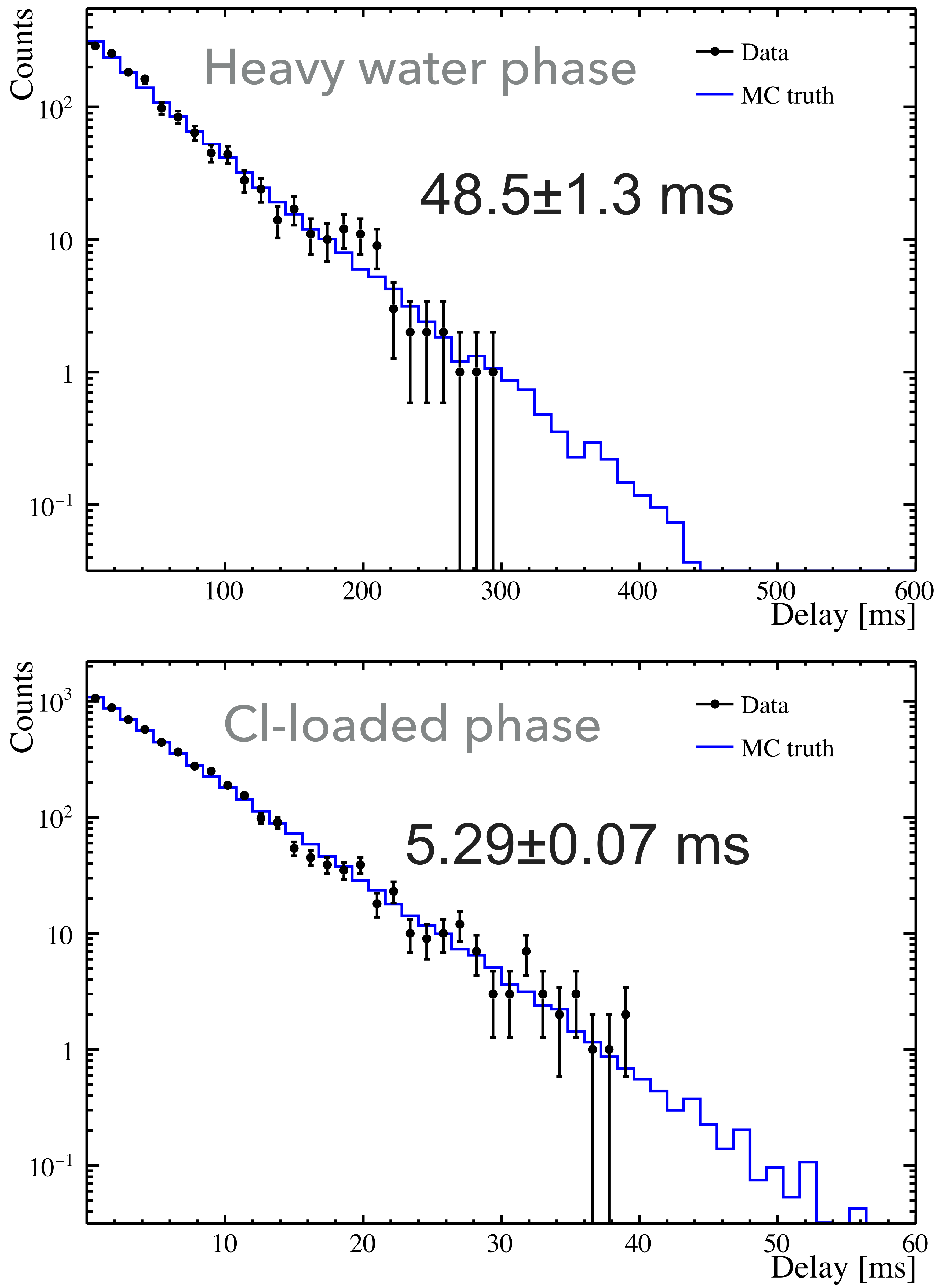


NEUTRON CAPTURE TIME:
HEAVY WATER: ~50ms
^{35}Cl: ~5ms

NEUTRON CAPTURE CANDIDATE



SNO CAN IDENTIFY NEUTRONS AFTER COSMIC MUON EVENTS



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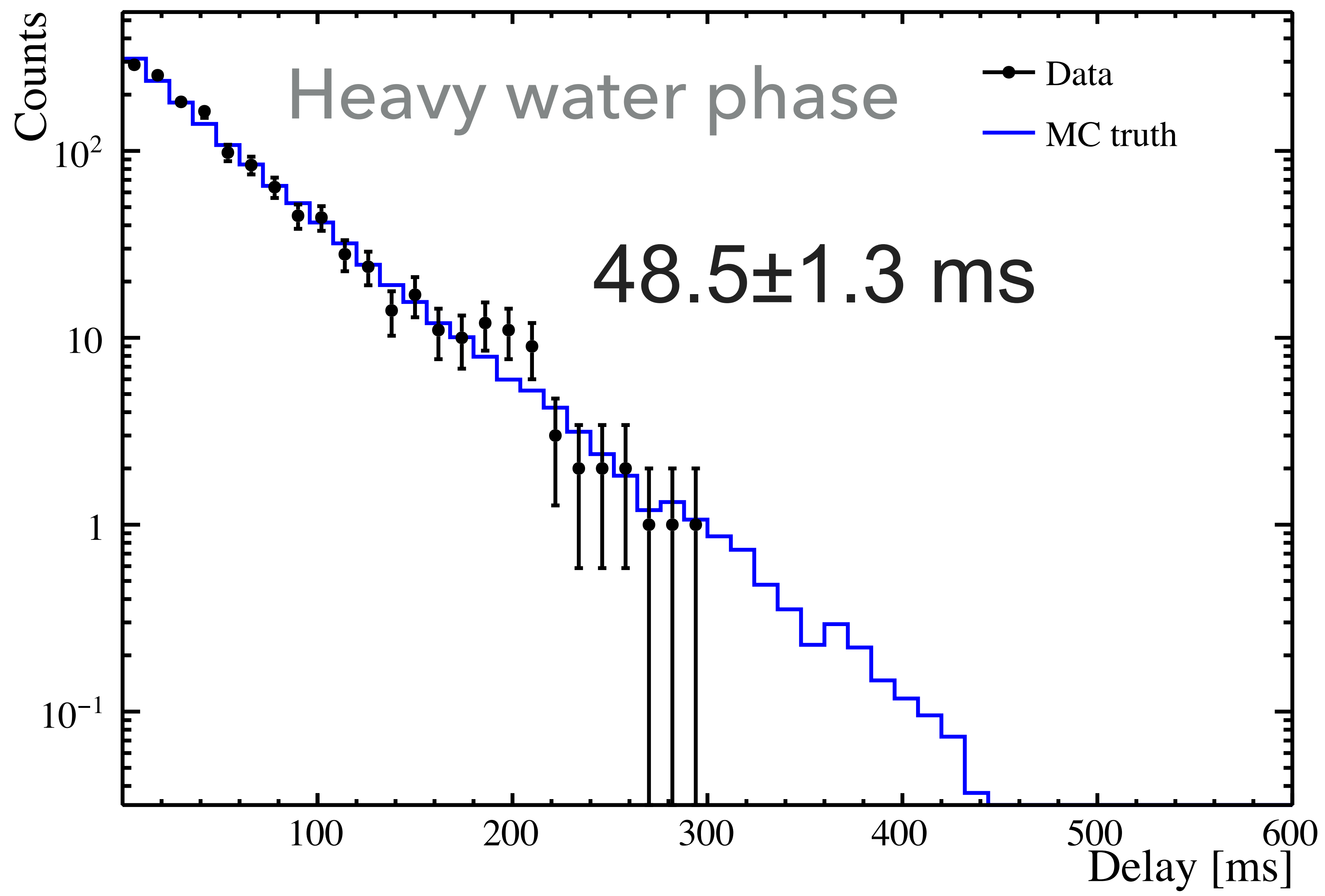
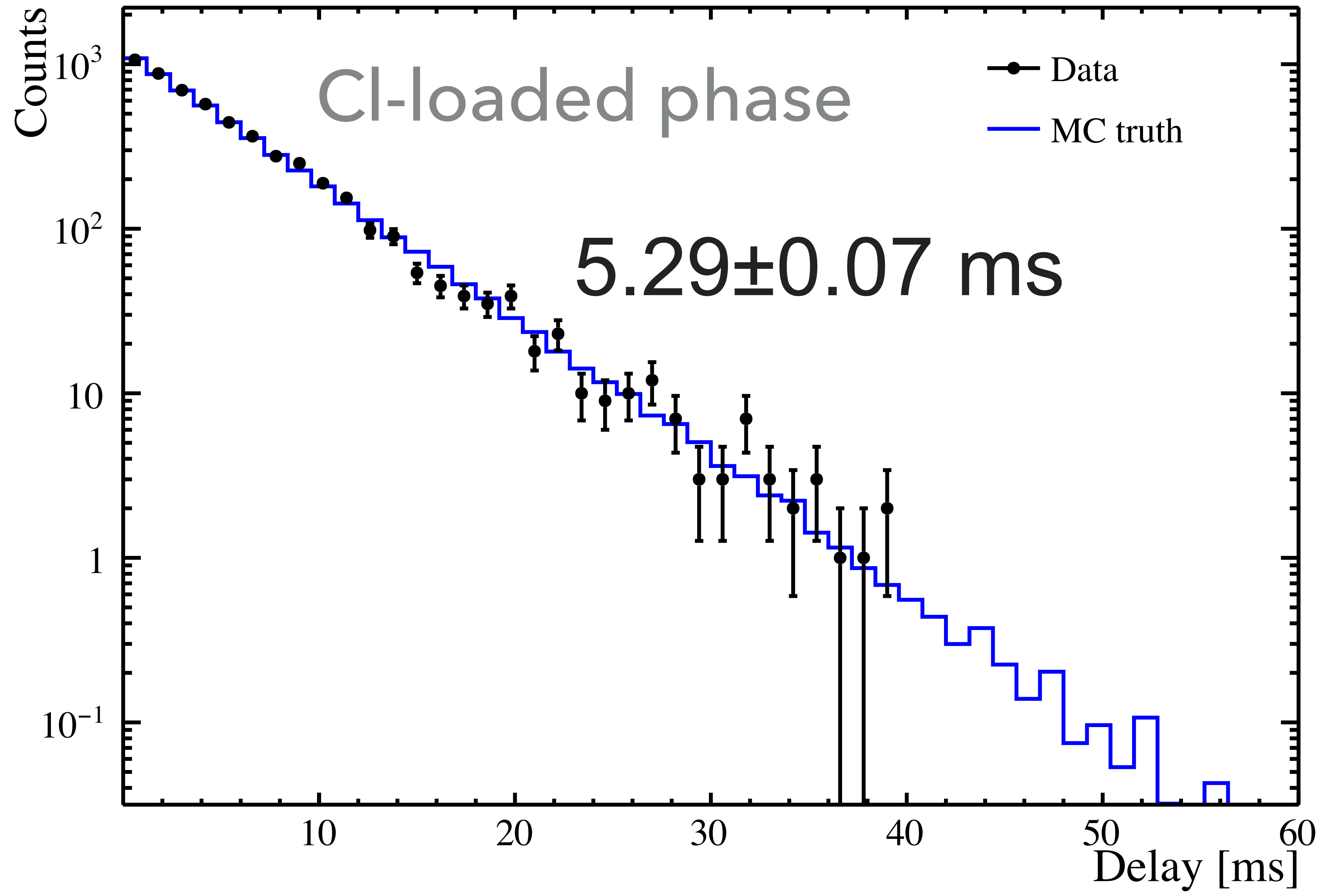
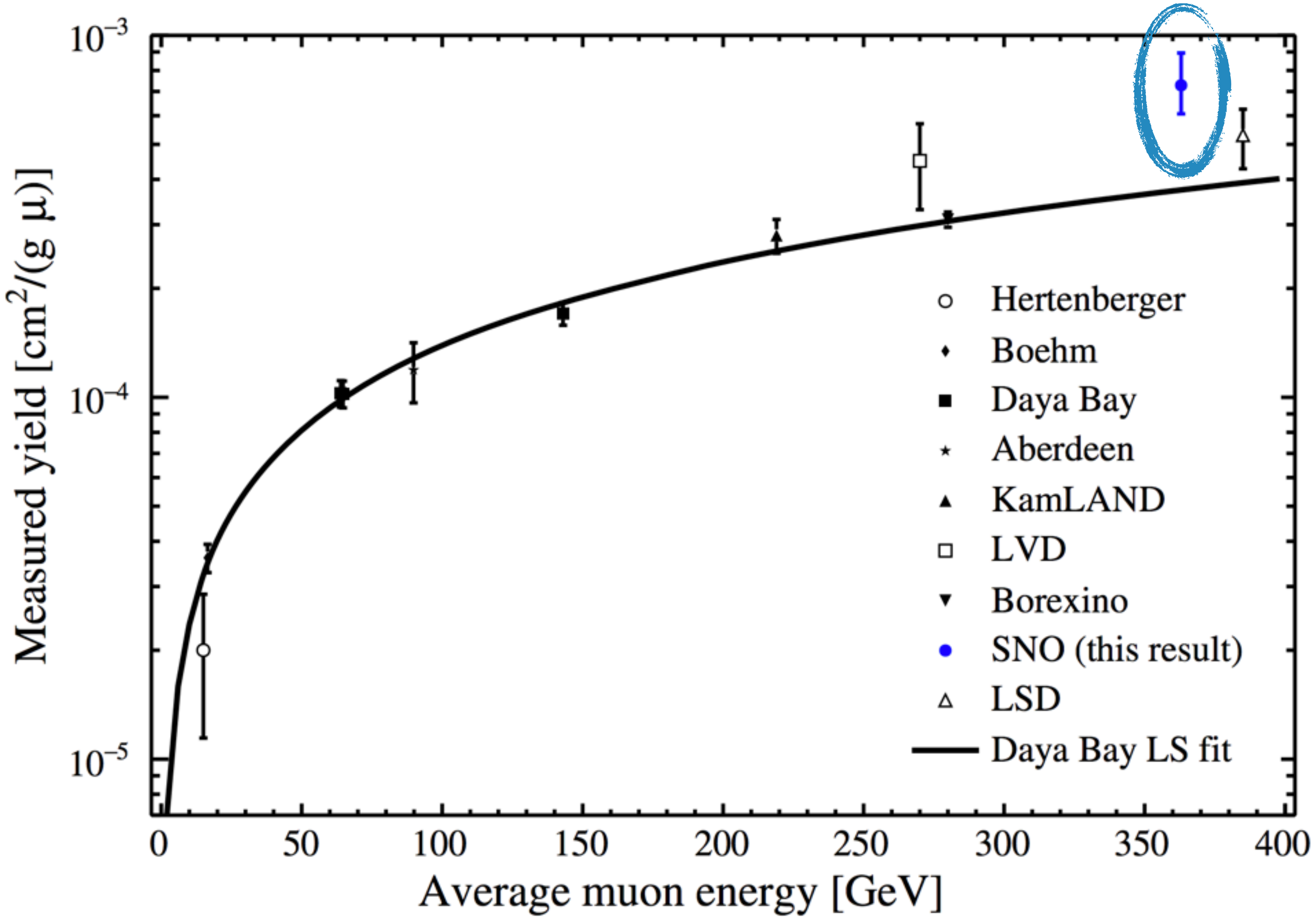




First measurement of this kind in heavy water



Dr. B. Land

PHYS. REV. D 99, 032013 (2019)

NEUTRINO LIFETIME

NEUTRINO OSCILLATION BASICS

Neutrino flavors are linear combination of 3 mass states:

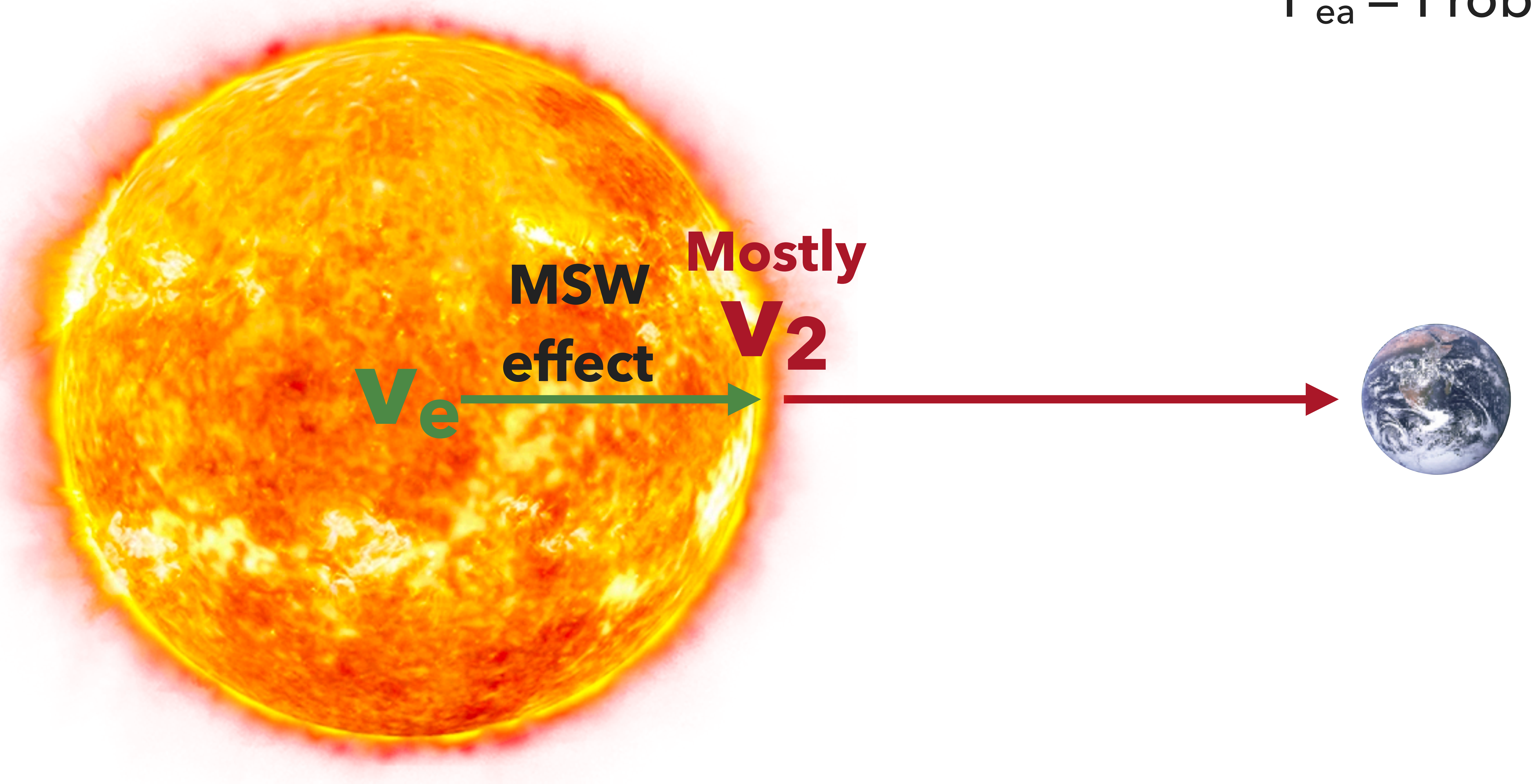
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

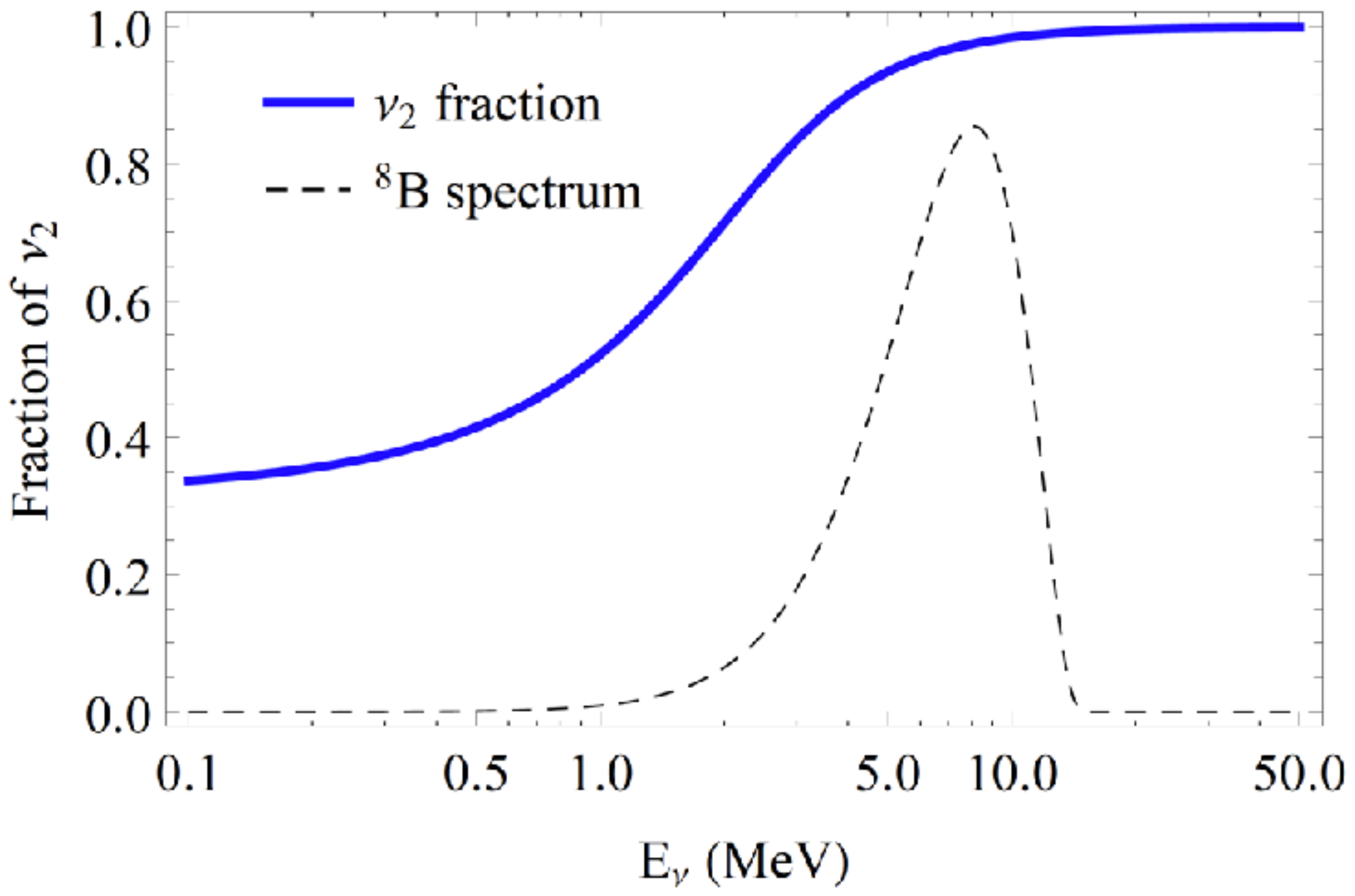
Oscillation probability from neutrino flavor α to β:

$$P_{\alpha\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/(2E)} \right|^2$$

P_{ee} = Probability of an **ve** being detected as **ve**

P_{ea} = Probability of an **ve** being detected as **va**





SINCE NEUTRINOS HAVE MASS, THEY COULD POTENTIALLY DECAY SOLAR NEUTRINOS PROVIDE A LONG BASELINE TO STUDY THIS DECAY

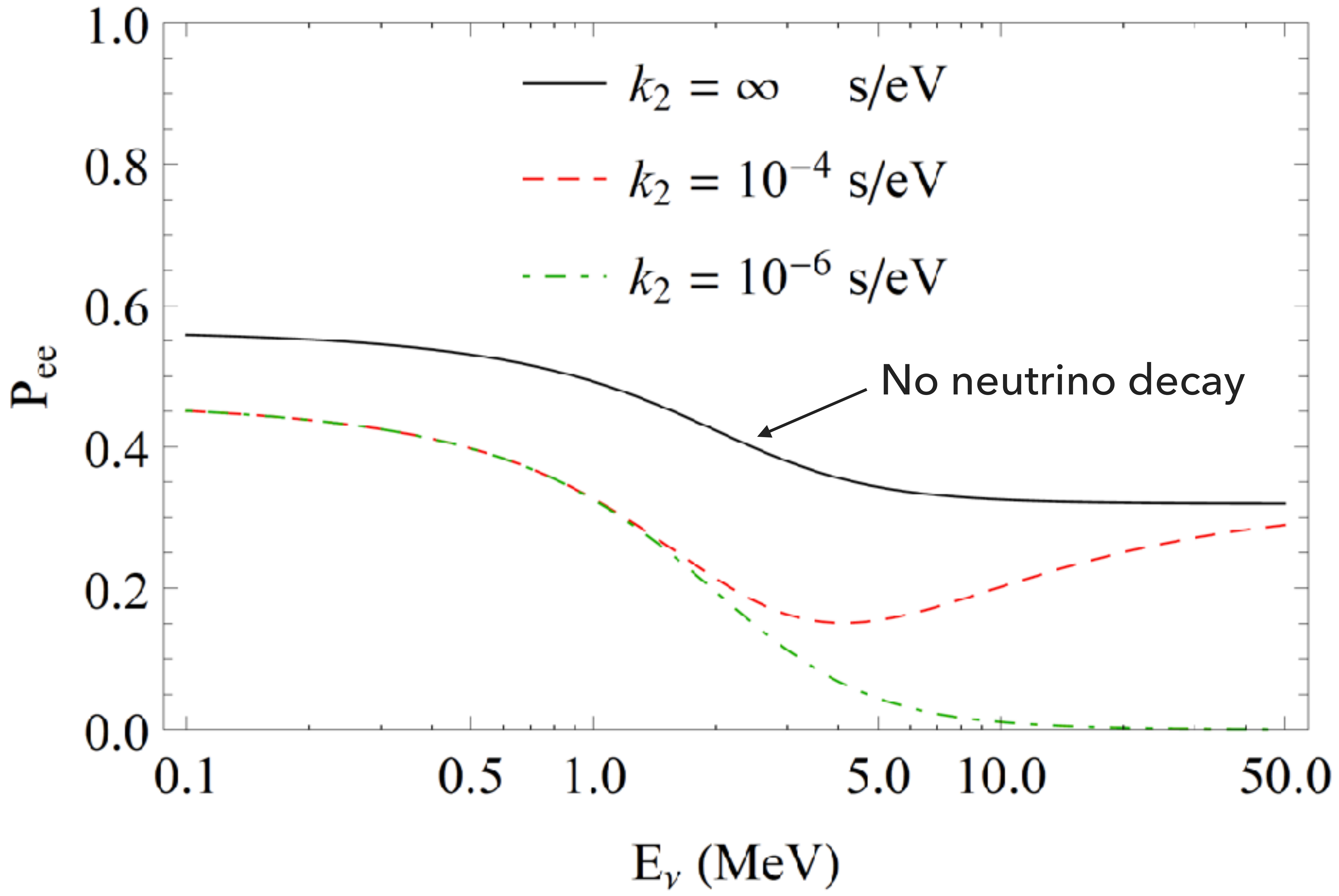
Disappearance and appearance probabilities:

$$P_{ee} = \sum_i \psi_i |U_{ie}|^2$$
$$P_{ea} = \sum_i \psi_i |U_{i\mu}|^2 + \psi_i |U_{i\tau}|^2$$

$$\psi_i \approx e^{-L/(Ek_i)} \phi_i = e^{-L/(Ek_i)} |\langle \nu_{mi}(V_e)|\nu_e\rangle|^2$$

Neutrino decay factor

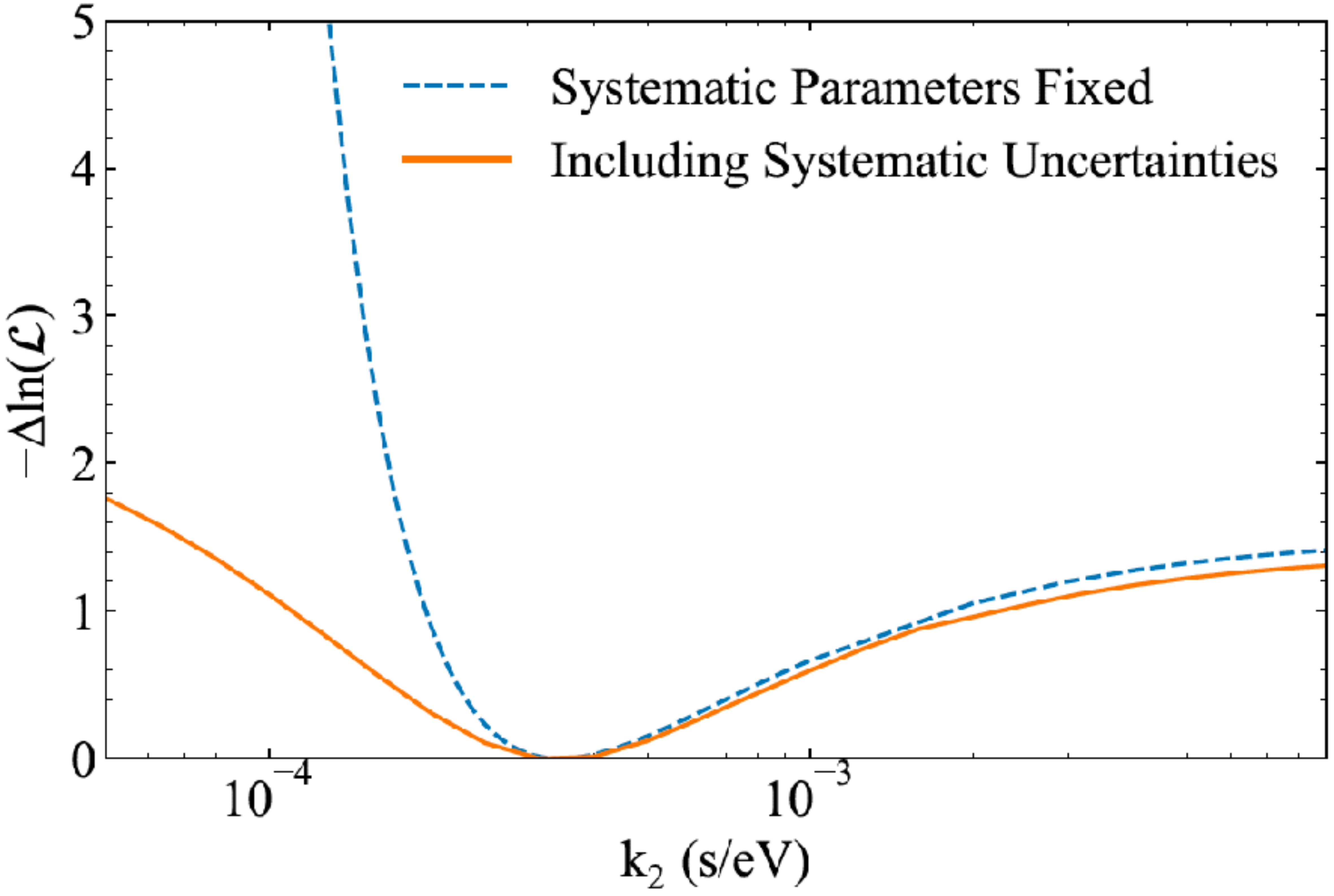
Defined mass-scaled lifetime k_2



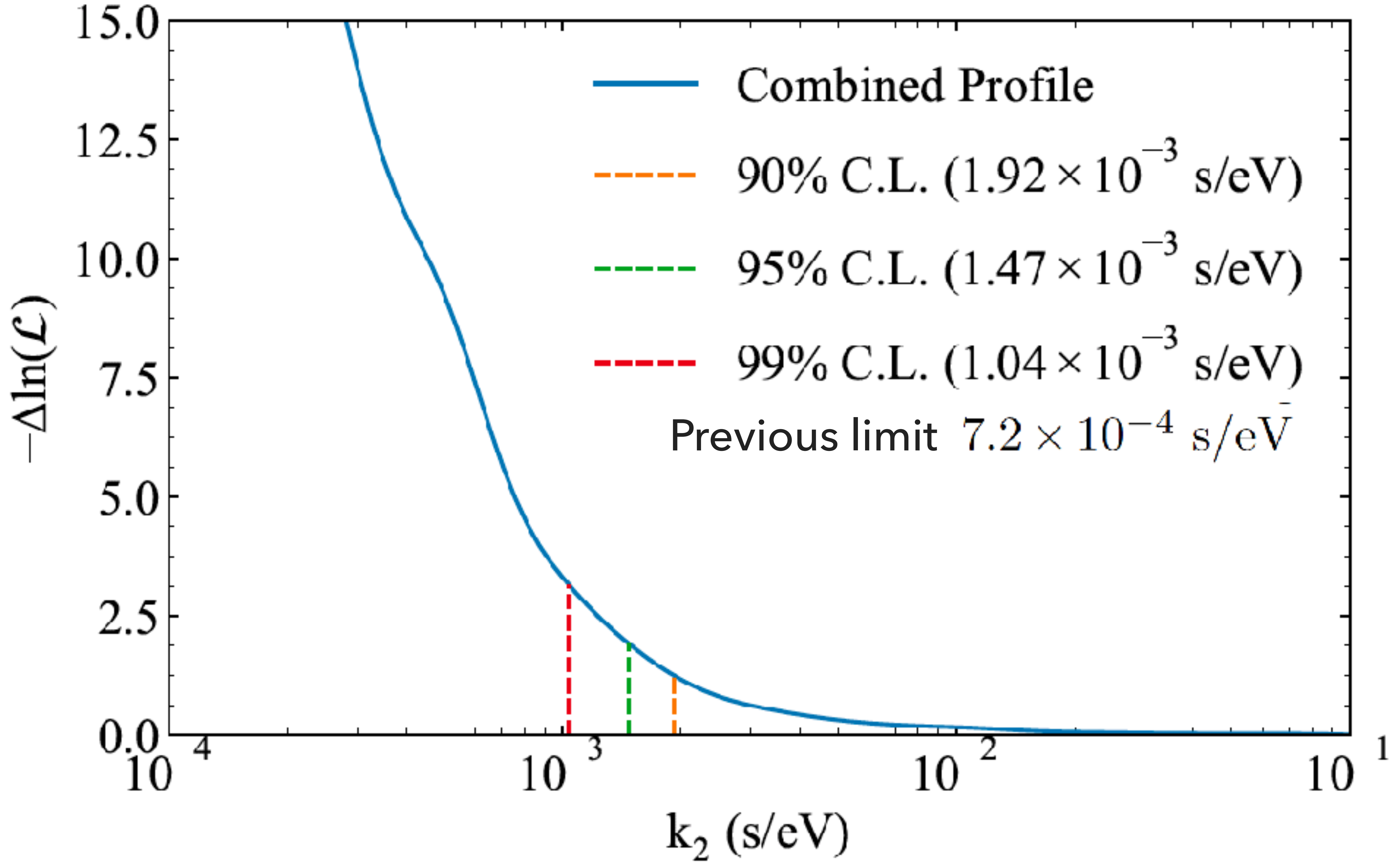
GOAL: MEASURE LIFETIME OF ν_2 MASS STATE BY MEASURING P_{EE} AND P_{EA} SHAPES

DEVELOPED MULTIVARIATE LIKELIHOOD FIT TO EXTRACT k_2 PARAMETER

SNO standalone



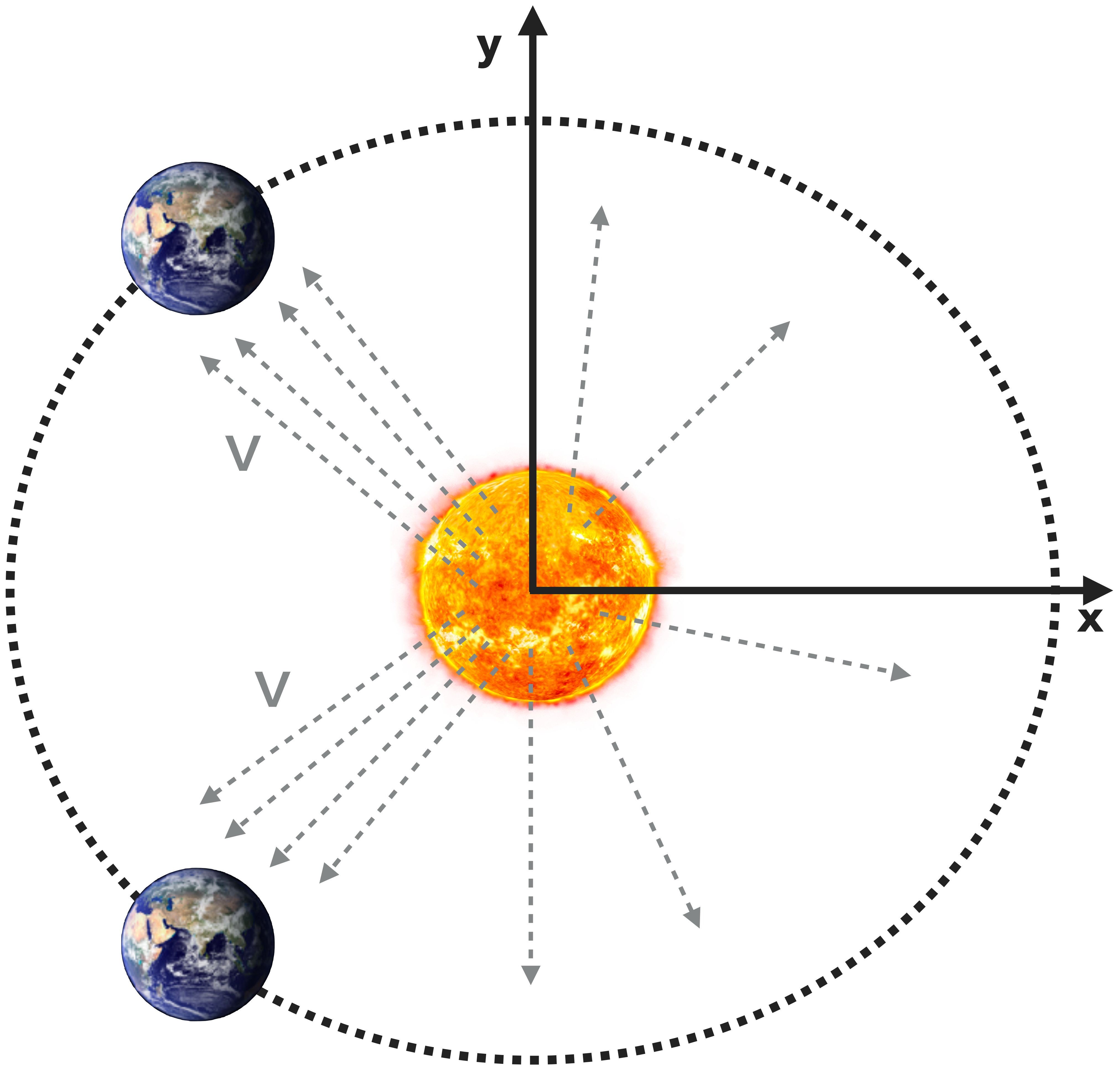
SNO + KamLAND + Borexino +
SAGE + GALLEX +GNO + Homestake



PHYS. REV. D 98, 112013 (2018)

LORENTZ SYMMETRY VIOLATION

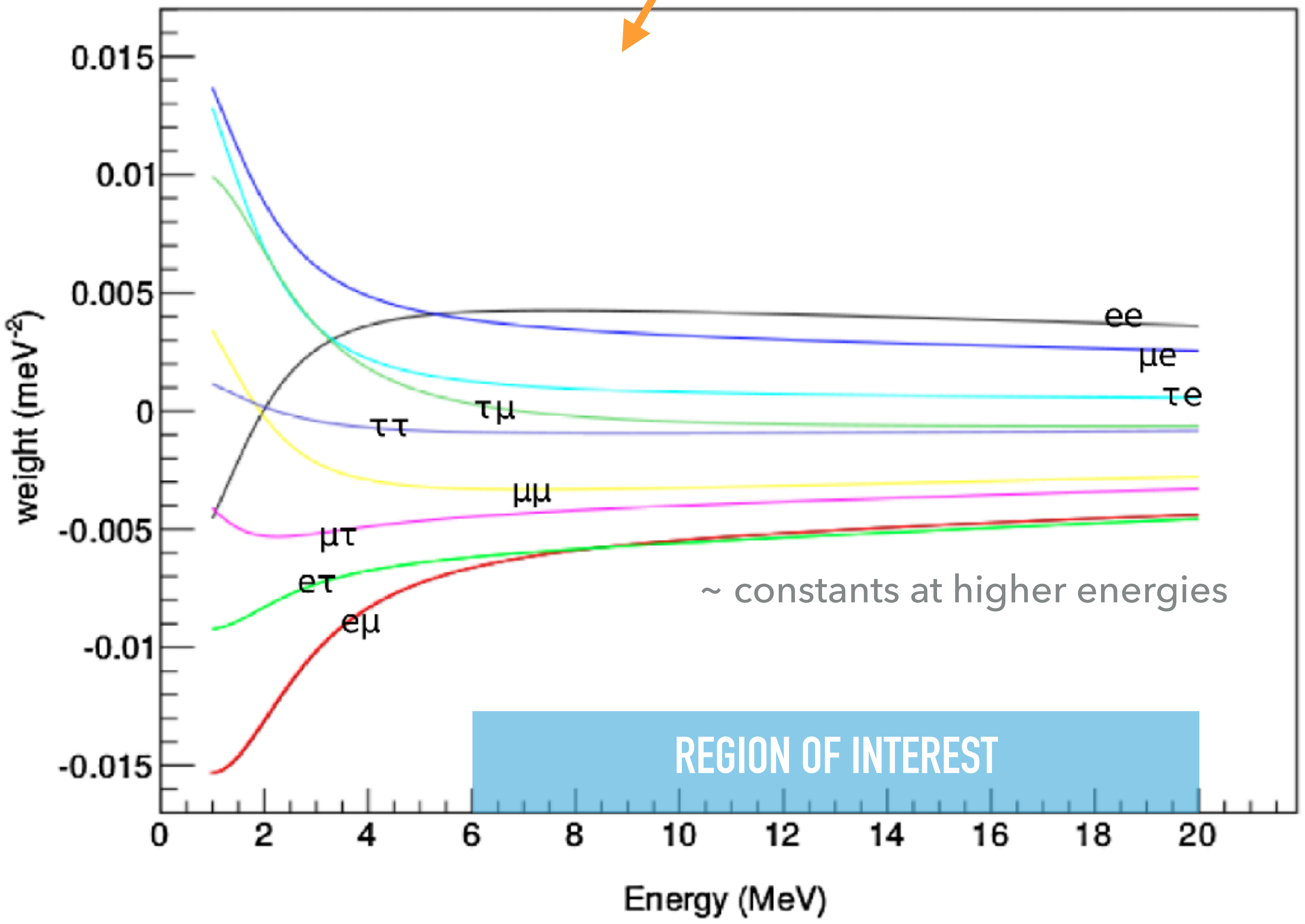
LORENTZ VIOLATION IN SOLAR NEUTRINO OSCILLATIONS



Lorentz violation could result in annual modulation of the solar neutrino survival probability

Lorentz violation introduces correction factors into the solar neutrino survival probability

$$\delta P^{(1)}_{\beta\alpha} = \Re e \sum_{jm\gamma\delta} Y_{jm}(\hat{p}) w^{\beta\alpha}_{\gamma\delta} \left(E (a^{(3)}_{\text{eff}})^{\gamma\delta}_{jm} - E^2 (c^{(4)}_{\text{eff}})^{\gamma\delta}_{jm} \right)$$

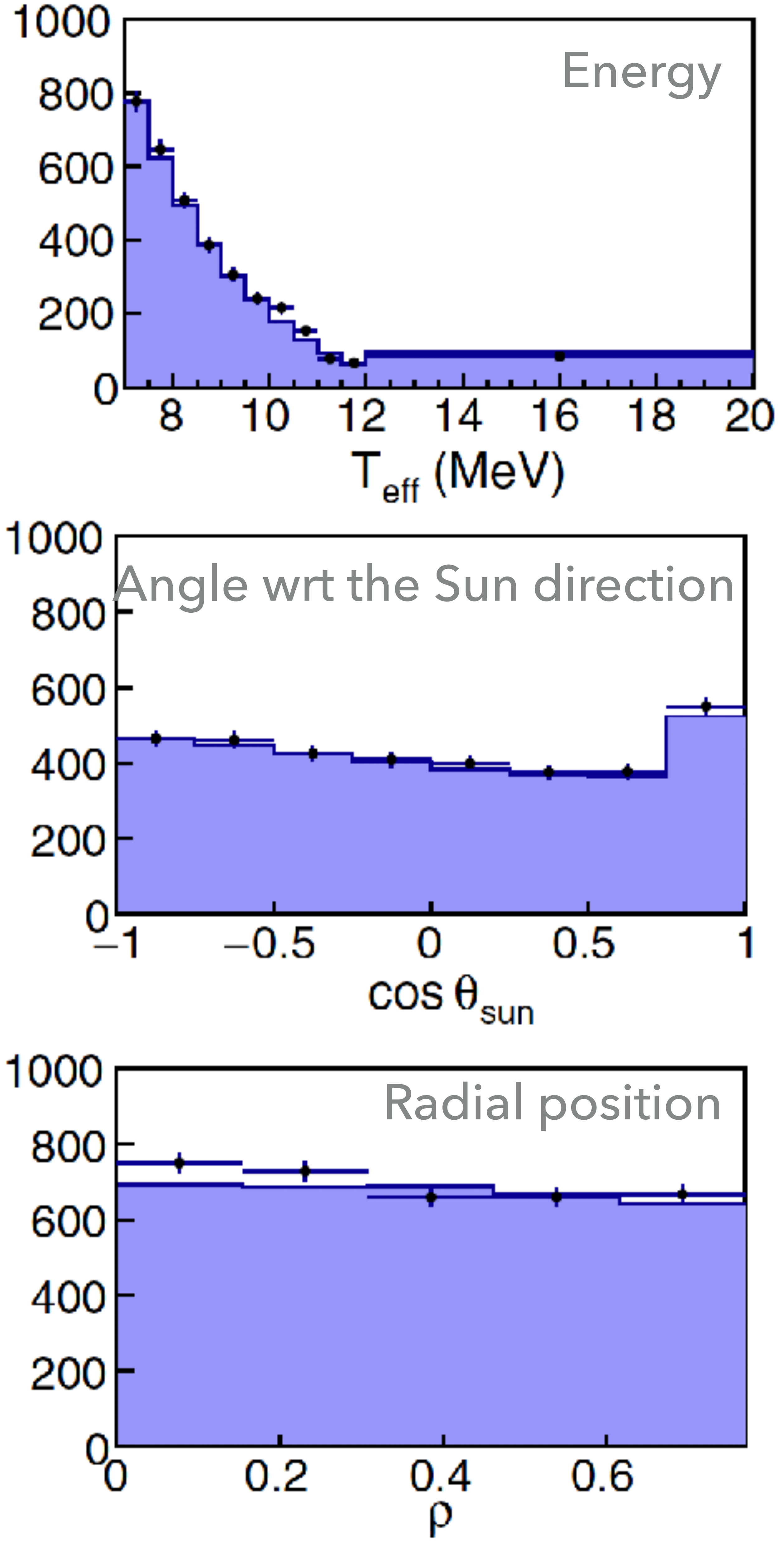


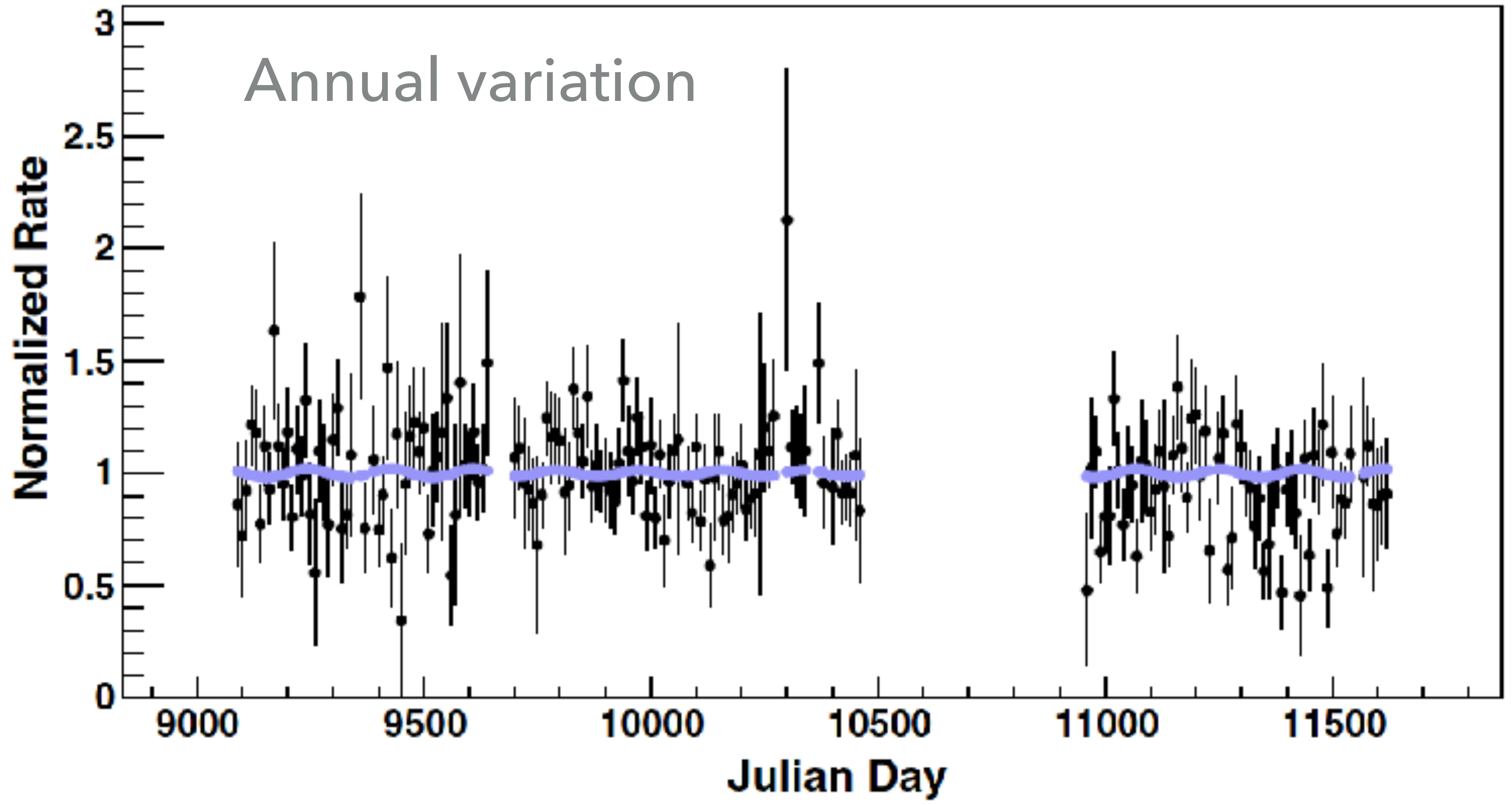
~ constants at higher energies

INDIVIDUAL LIKELIHOOD FIT

In practice, we fit for: $c^{(4)}_{\text{SNO}} = \sum_{\alpha\beta} w^{ee}_{\alpha\beta} \left(c^{(4)}_{\text{eff}}\right)^{\alpha\beta}$

and analogously for: $a^{(3)}_{\text{SNO}}$





Mode	LV signal	Solar flux (10^6 cm^{-2} s^{-1})	$\sin\theta_{12}$
E	$7.0^{+7.2+5.9}_{-7.5-6.7}$ GeV^{-1}	$5.22 \pm 0.27^{+0.17}_{-0.22}$	$0.497\ ^{+0.088+0.078}_{-0.098-0.078}$
$E \sin\omega t$	$0.0^{+7.2+2.1}_{-7.3-2.2} \times 10^{-1}$ GeV^{-1}	$5.15 \pm 0.26^{+0.14}_{-0.17}$	$0.577\ ^{+0.019+0.010}_{-0.018-0.009}$
$E \cos\omega t$	$0.2^{+7.3+2.2}_{-7.4-2.3} \times 10^{-1}$ GeV^{-1}	$5.15 \pm 0.26^{+0.14}_{-0.17}$	$0.577\ ^{+0.019+0.010}_{-0.018-0.009}$
E^2	$3.0^{+3.3+2.7}_{-3.4-3.1} \times 10^{2}$ GeV^{-2}	$5.22 \pm 0.27^{+0.17}_{-0.22}$	$0.537\ ^{+0.048+0.042}_{-0.049-0.037}$
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$E^2 \sin 2\omega t$	$5.8^{+6.5+1.6}_{-6.4-1.8} \times 10^{1}$ GeV^{-2}	$5.15 \pm 0.26^{+0.14}_{-0.17}$	$0.577\ ^{+0.019+0.010}_{-0.018-0.009}$
$E^2 \cos 2\omega t$	$-4.4^{+6.5+1.7}_{-6.6-1.8} \times 10^{1}$ GeV^{-2}	$5.15 \pm 0.26^{+0.14}_{-0.17}$	$0.577\ ^{+0.019+0.010}_{-0.018-0.009}$

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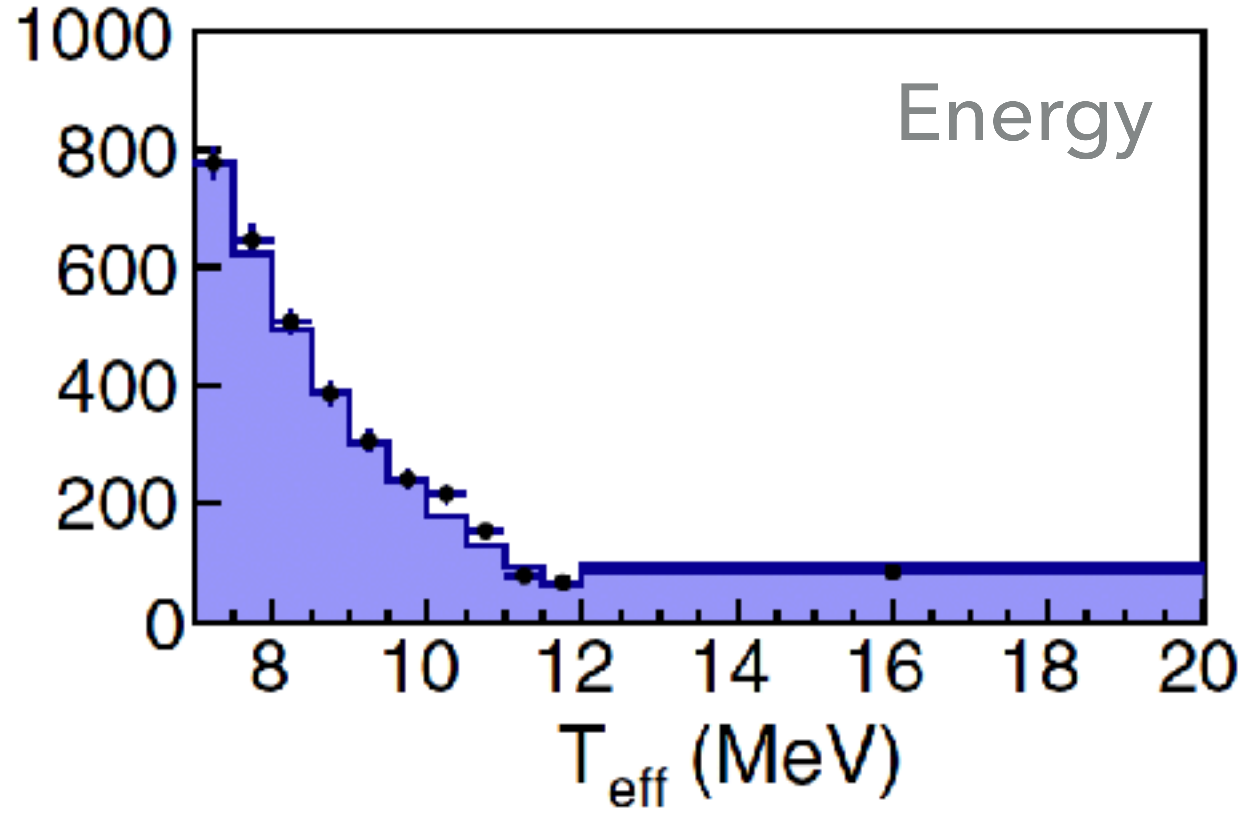

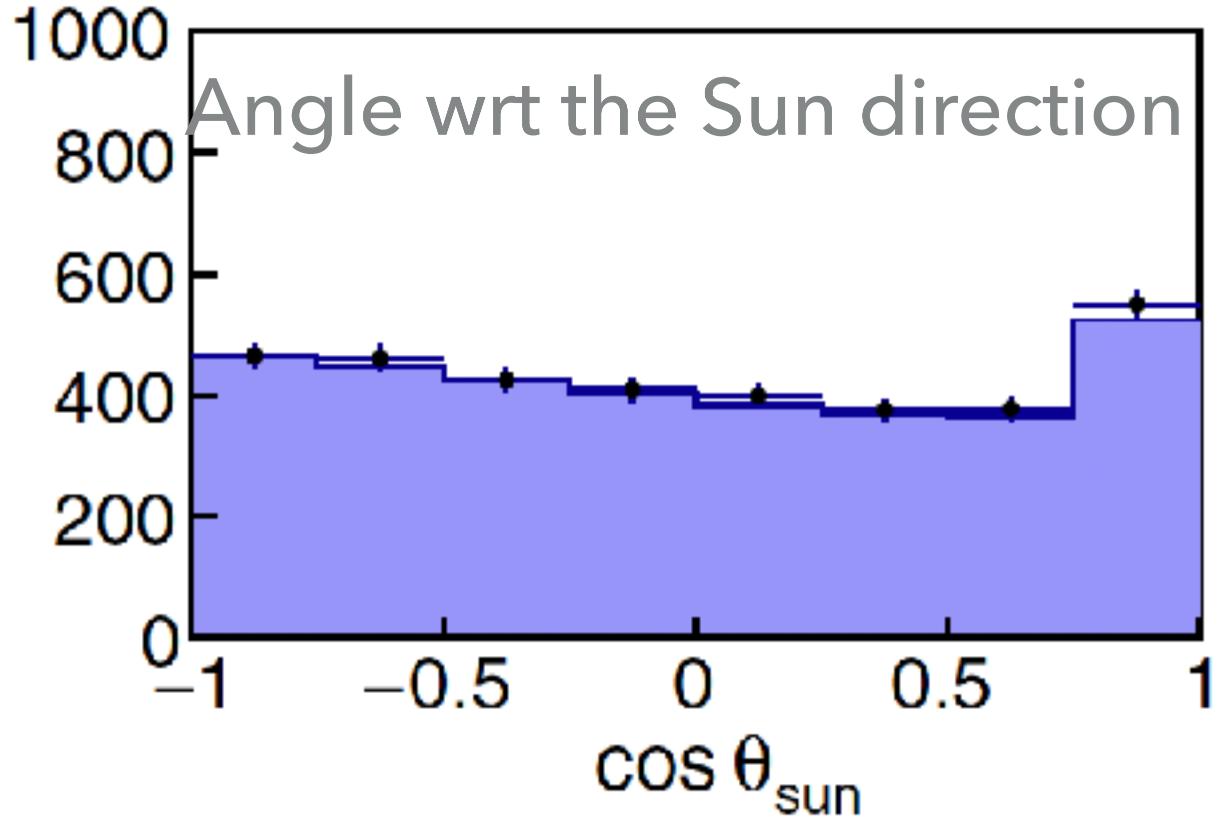

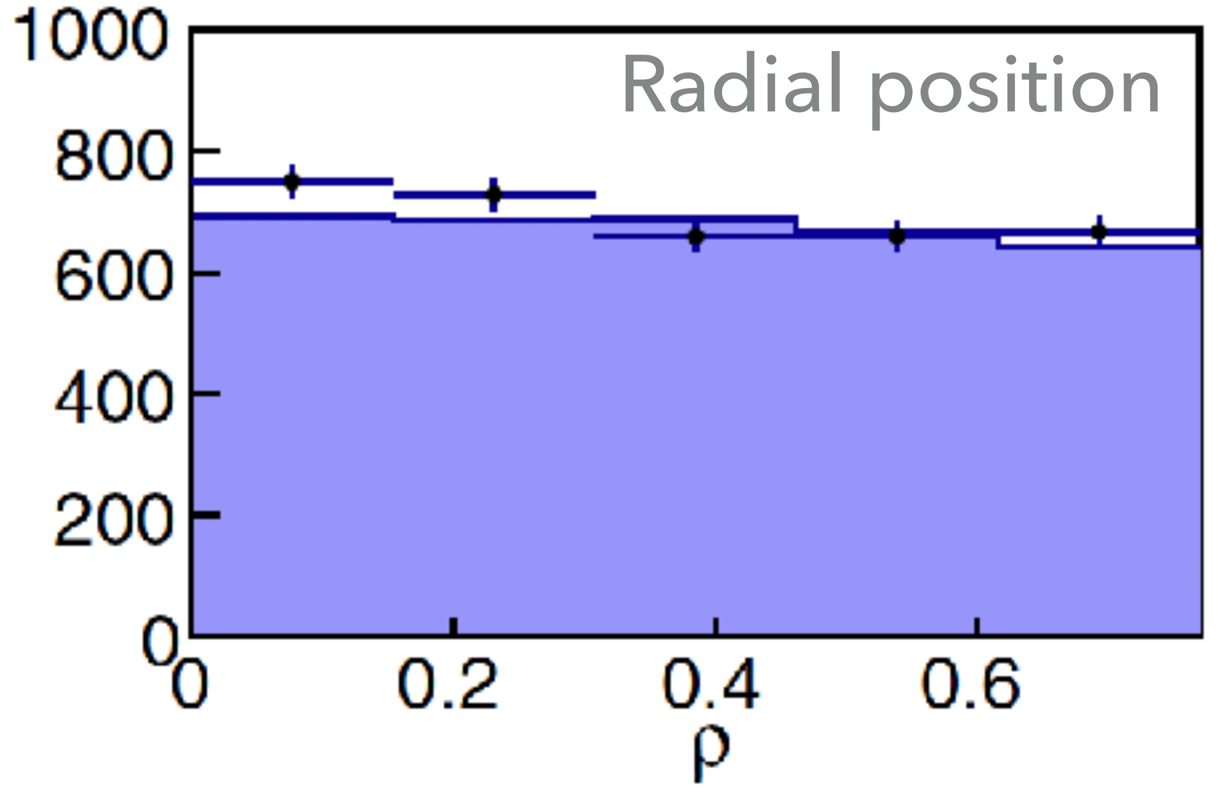

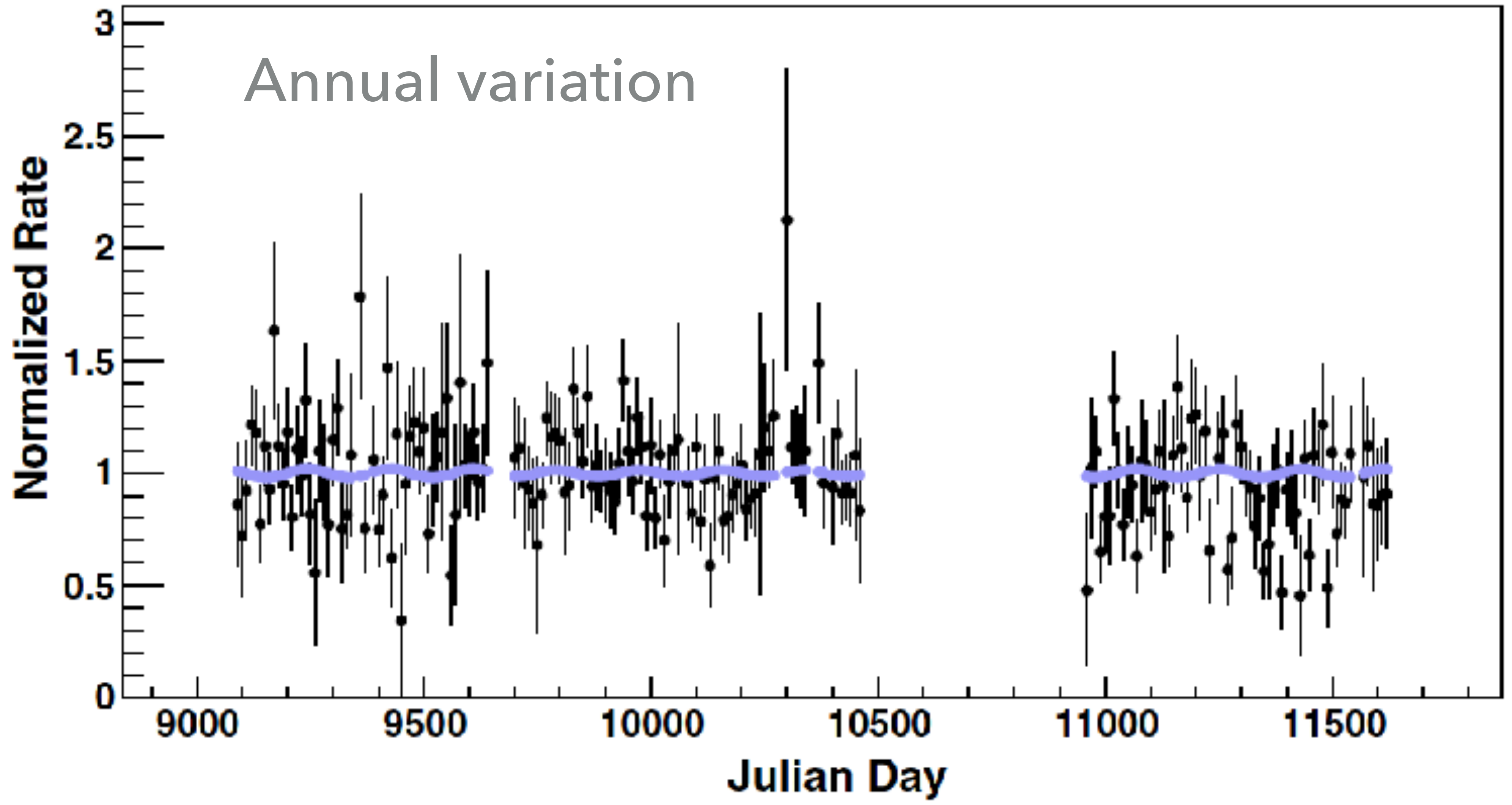

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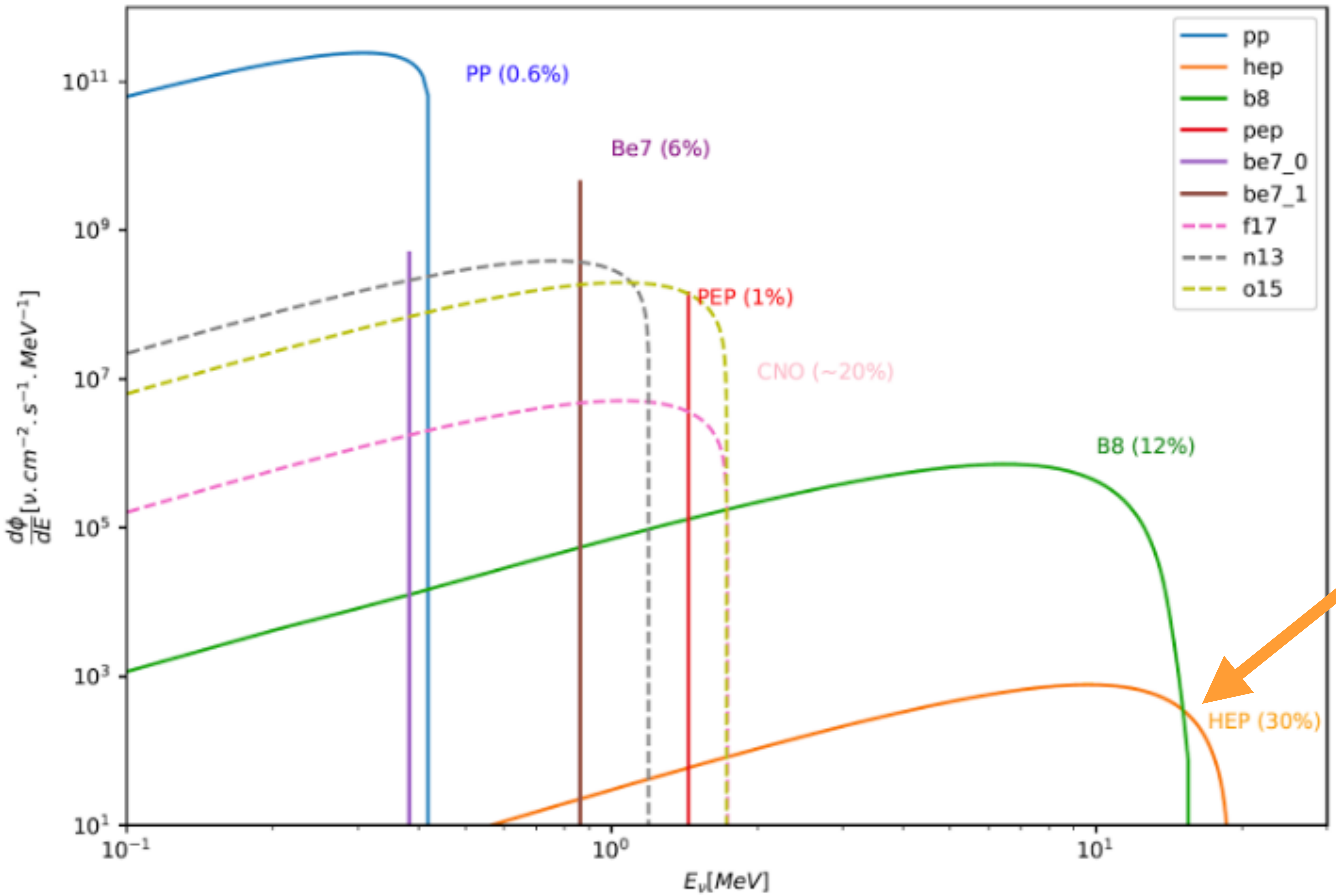
NO LORENTZ SYMMETRY VIOLATION OBSERVED
SET LIMITS IN 78 PARAMETERS: 38 PREVIOUSLY UNCONSTRAINED AND 16 IMPROVED

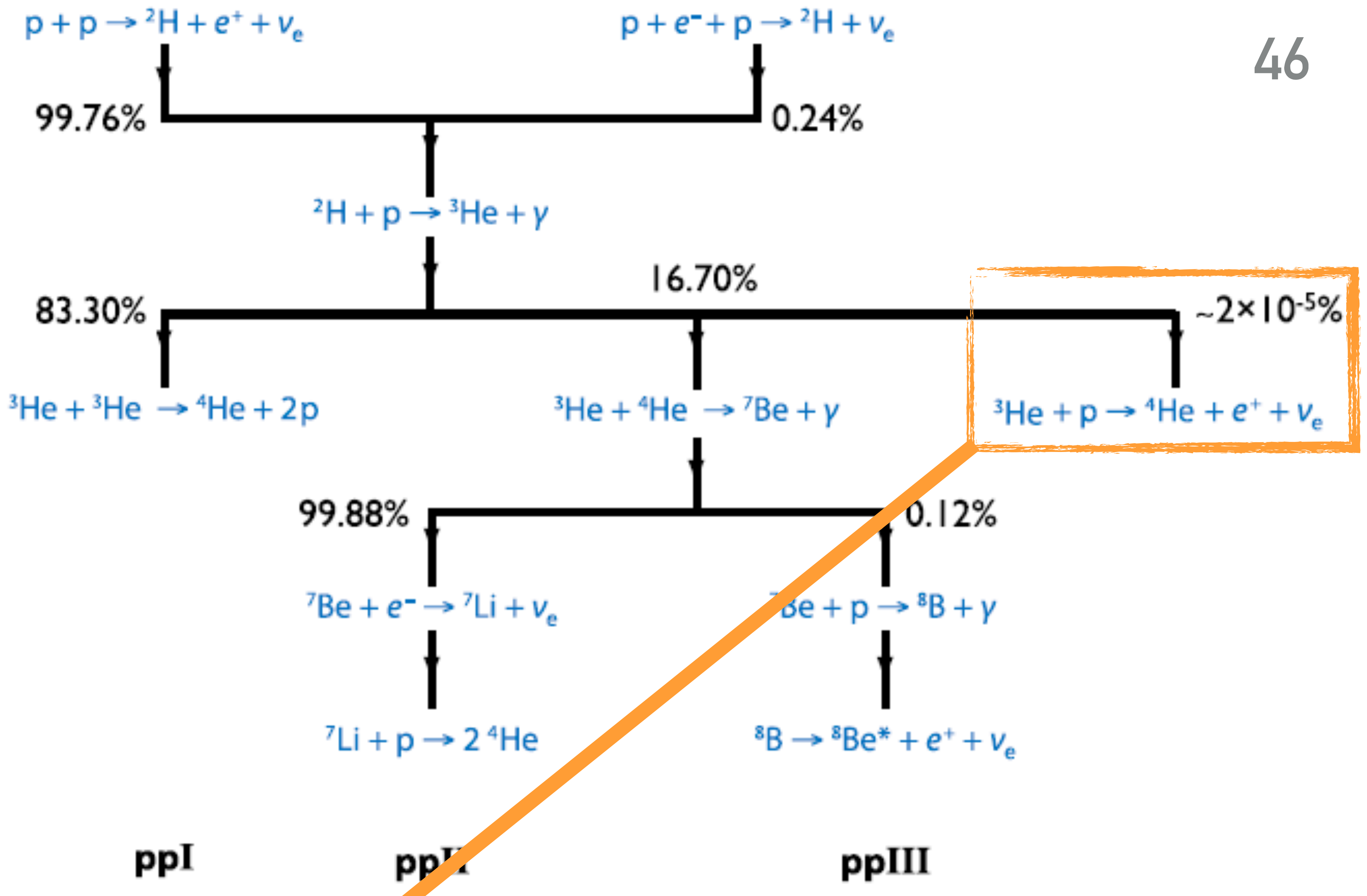
PAPER UNDER INTERNAL REVIEW

HEP NEUTRINOS

HEP NEUTRINO SEARCH

- Last unobserved branch of PP-chain neutrinos
- SNO enables hep-ν CC on deuterium
- Main backgrounds are ^8B and atmospheric neutrinos





SNO IS EXPECTED TO REACH WORLD LEADING SENSITIVITY

PAPER UNDER INTERNAL REVIEW

SUMMARY

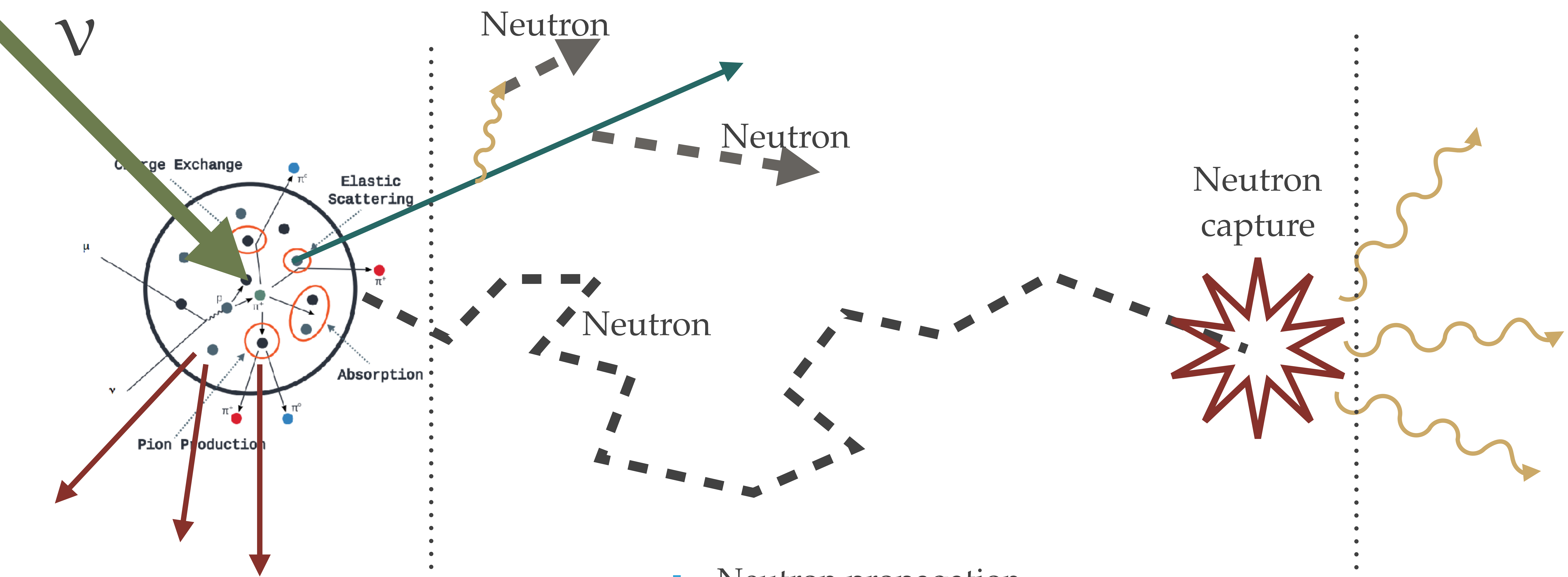
SNO IS STILL PRODUCING QUALITY PHYSICS

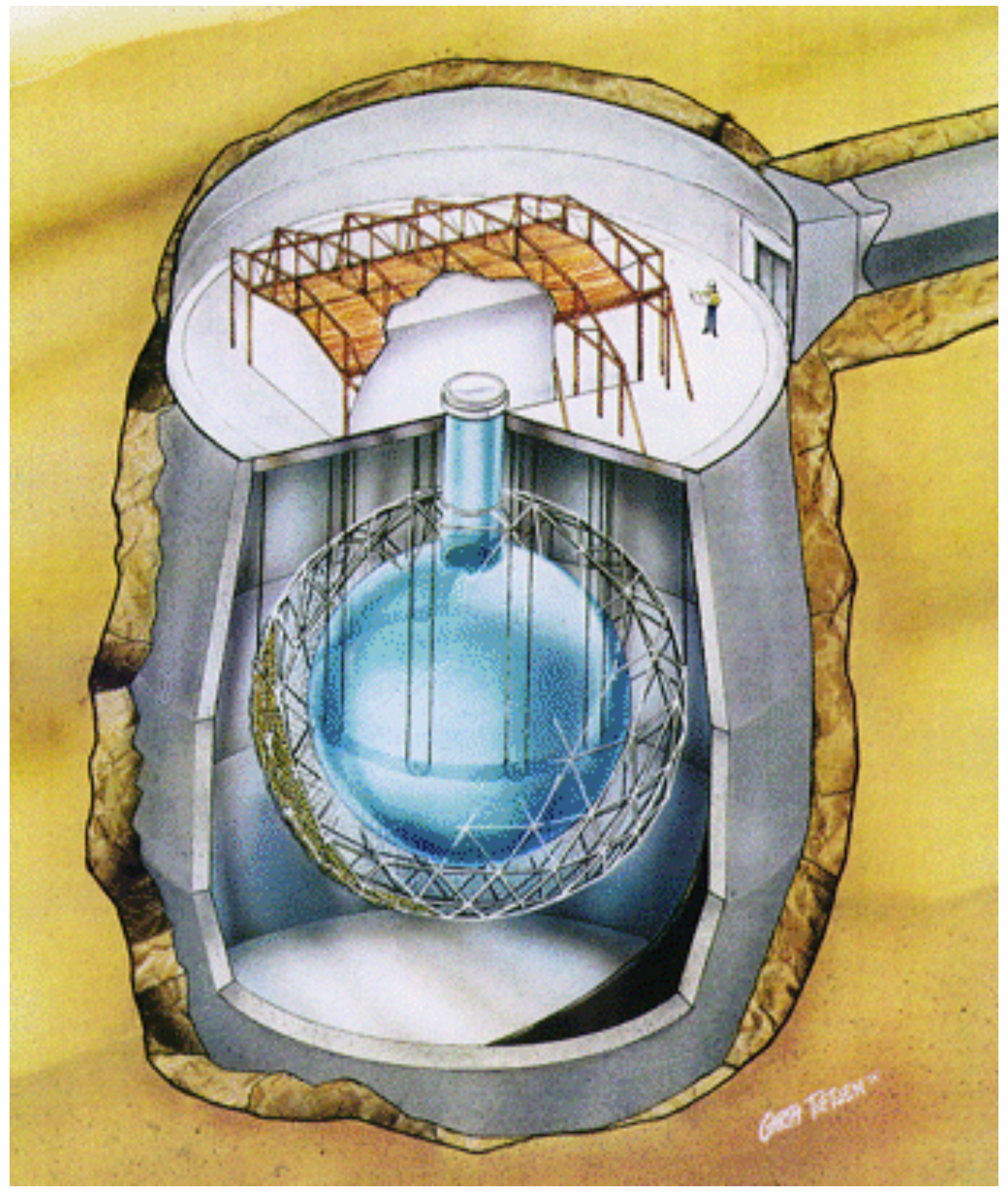
STAY TUNED!

- NEUTRON PRODUCTION IN ATMOSPHERIC NEUTRINO INTERACTIONS — PHYS. REV. D 99, 112007 (2019)
- NEUTRON PRODUCTION BY COSMIC MUONS — PHYS. REV. D 100, 112005 (2019)
- NEUTRINO DECAY SEARCH — PHYS. REV. D 99, 032013 (2019)
- LORENTZ SYMMETRY VIOLATION SEARCH — PHYS. REV. D 98, 112013 (2018)
- SOLAR HEP NEUTRINO SEARCH — PAPER UNDER INTERNAL REVIEW
- SELF-INTERACTING DARK MATTER SEARCH — ANALYSIS ONGOING

BACKUP

NEUTRON PROCESSES MONTE CARLO MODEL





- Neutrino interaction
- Final State Interactions

- Neutron propagation
- Secondary neutron production
- Neutron capture
- De-excitation gamma emission

*NeutronHP model

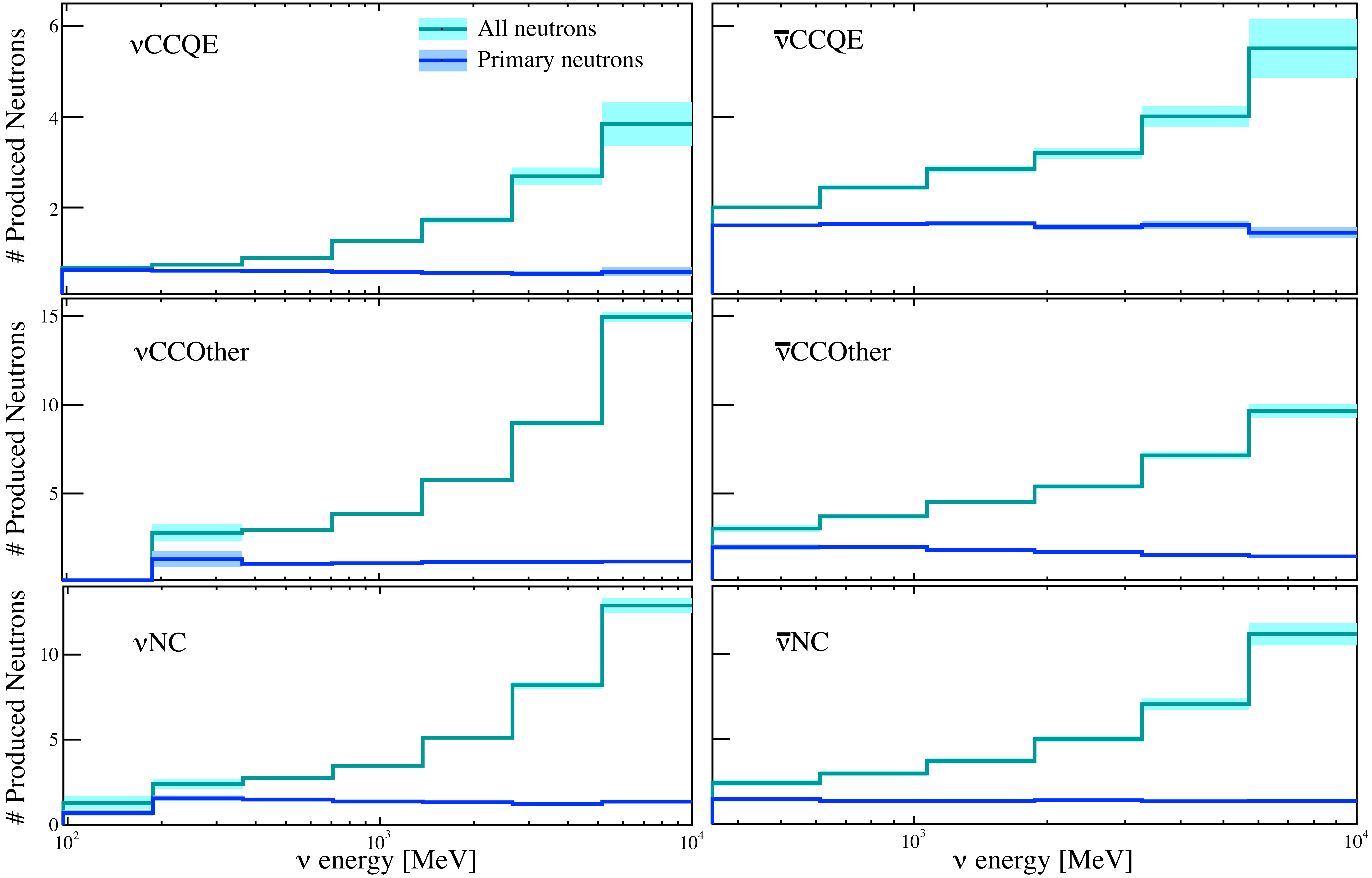
Official SNO package: Cherenkov production and detector response

SNOMAN

PRIMARY NEUTRONS

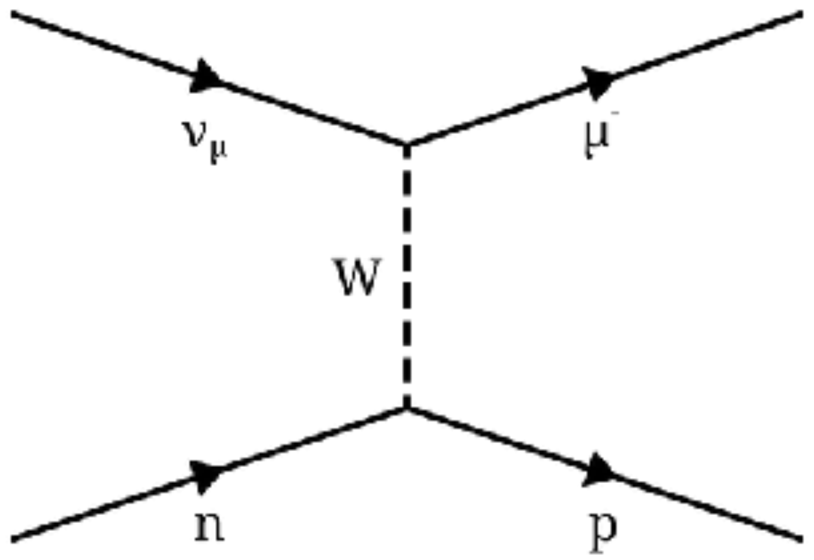
SECONDARY NEUTRONS

ESTIMATED NEUTRON PRODUCTION FROM ATMOSPHERIC NEUTRINOS IN SNO

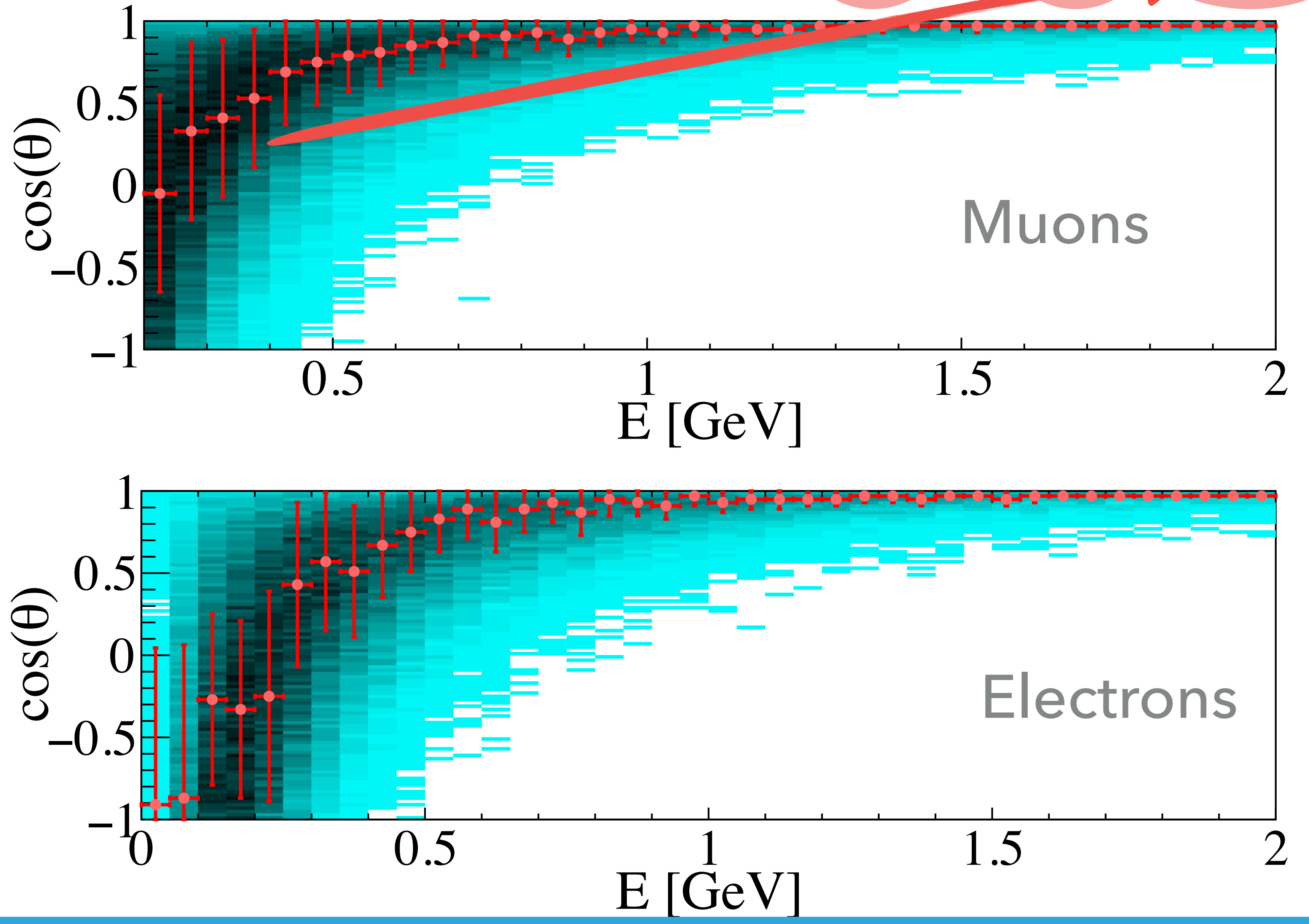


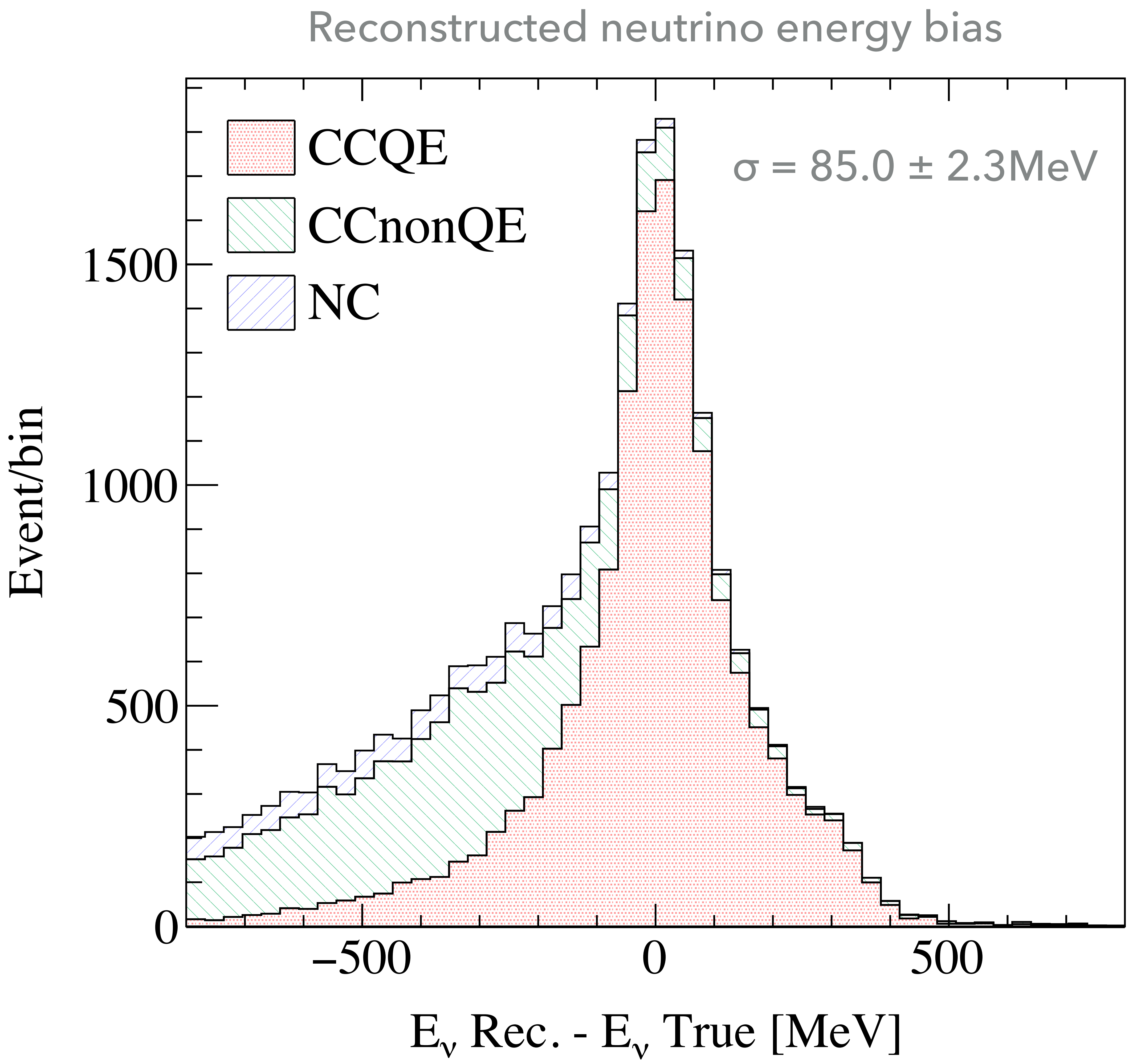
NEUTRINO ENERGY ESTIMATION

RECONSTRUCT NEUTRINO ENERGY UNDER CCQE HYPOTHESIS



$$E_r^{\nu} = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)}$$

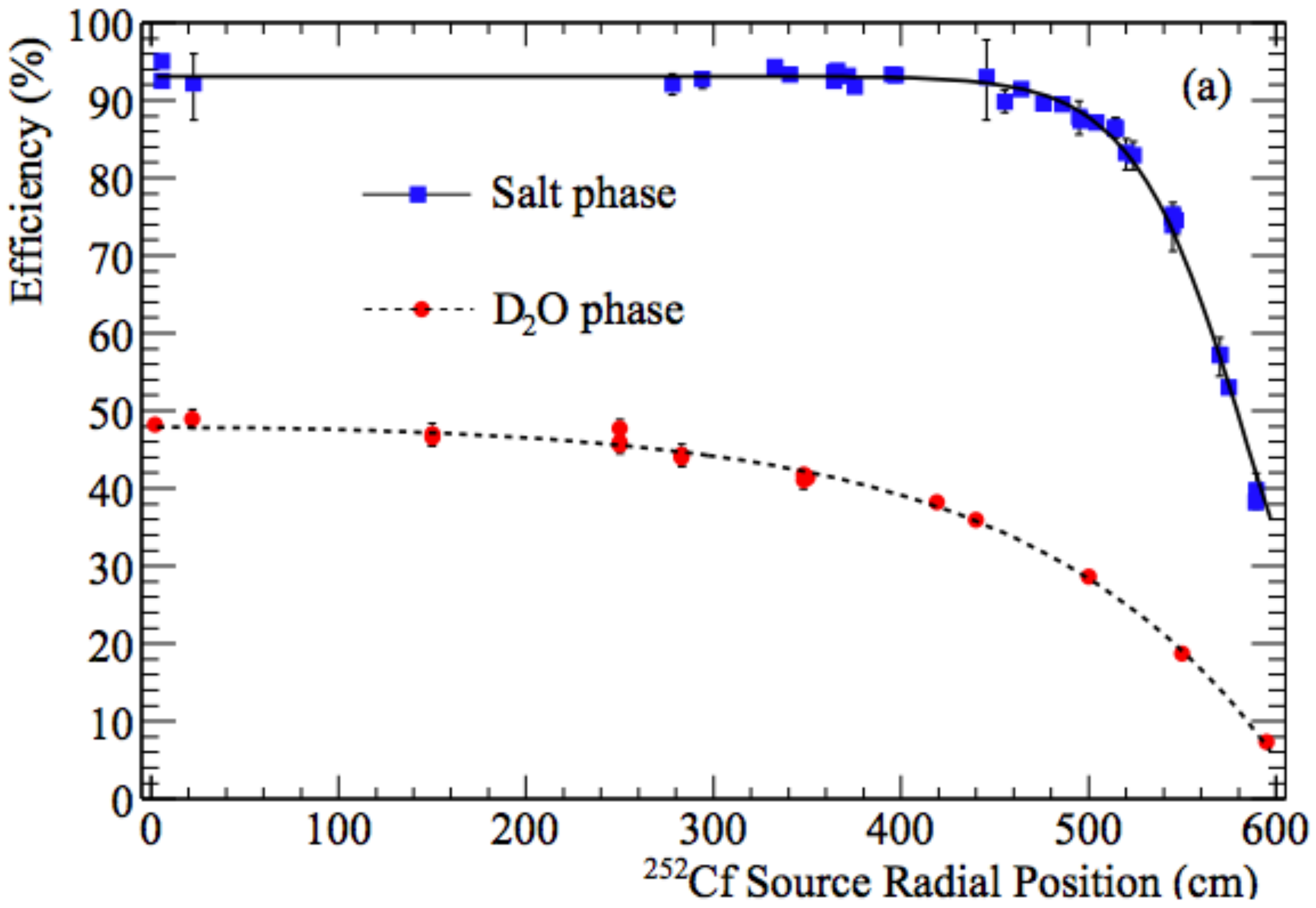




NO ATMOSPHERIC NEUTRINO DIRECTION → GET COS(Θ)/E DEPENDENCY FROM MC

NEUTRON DETECTION EFFICIENCY MODEL VALIDATED WITH A ^{252}Cf SOURCE

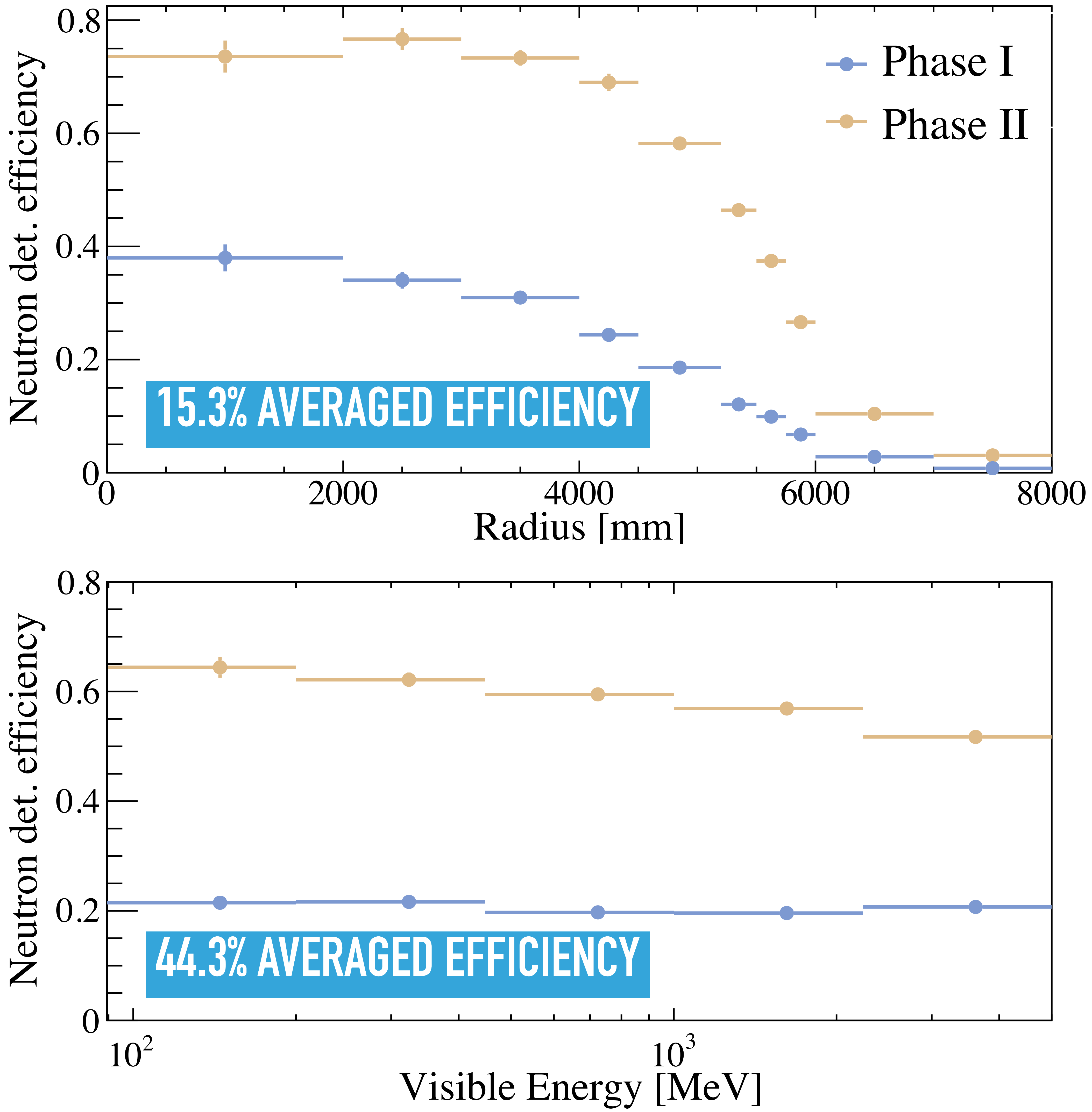
^{252}Cf source deployed at different radial positions and compared data and Monte Carlo



Phase I → Agreement @1.9% level

Phase II → Agreement @1.4% level

As calculated from Monte Carlo



CROSS-SECTION SYSTEMATICS

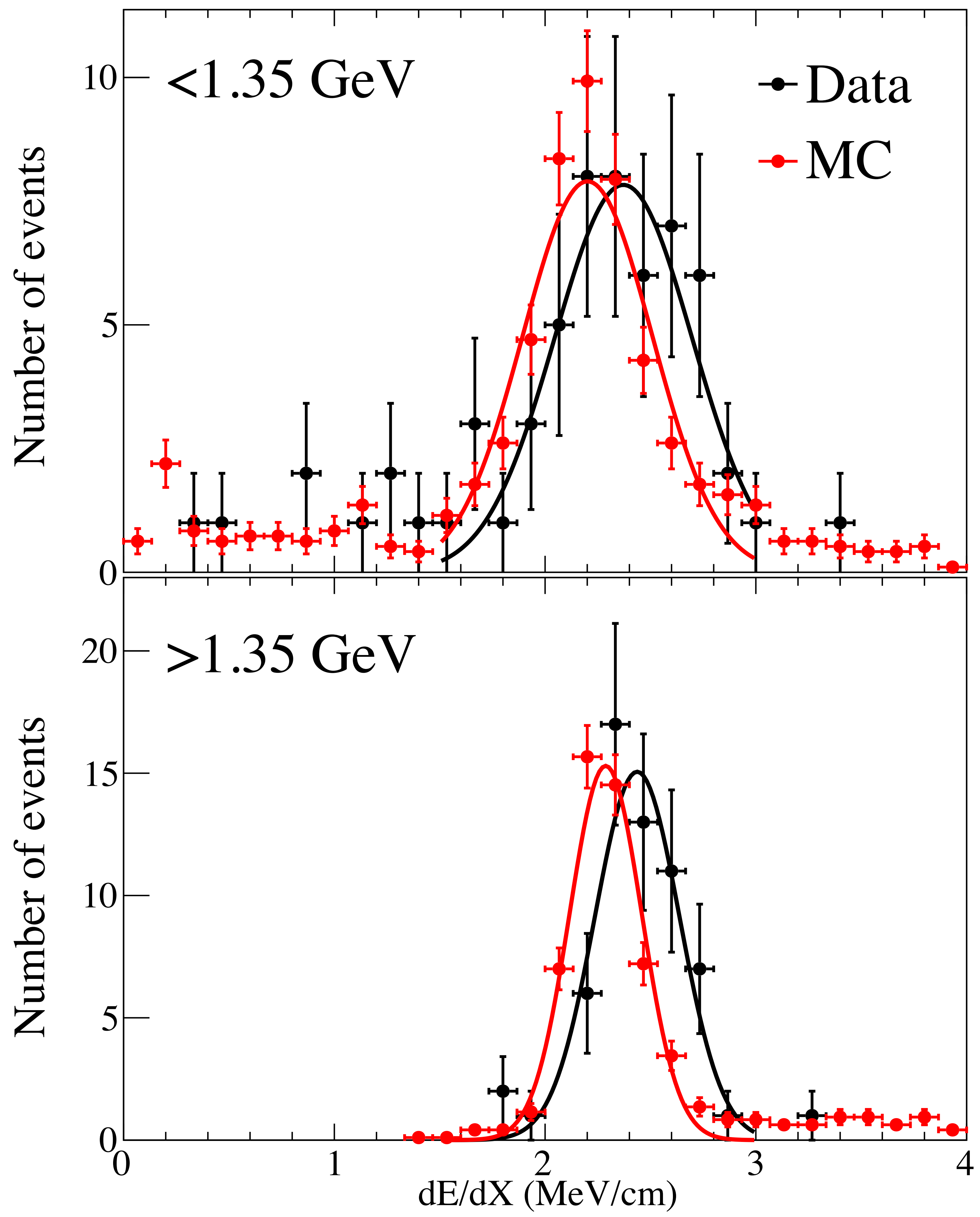
GENIE label	Physical parameter	Nominal value	1σ uncertainty
	Cross sections		
MaCCQE	CCQE axial mass	0.990 GeV	$-15\% + 25\%$
MaCCRES	CC and NC resonance axial mass	1.120 GeV	$\pm 20\%$
MaCOHpi	CC and NC coherent pion production axial mass	1.000 GeV	$\pm 50\%$
MvCCRES	CC and NC resonance vector mass	0.840 GeV	$\pm 10\%$
R0COHpi	Nuclear size controlling pion absorption in Rein-Sehgal model	1.000 fm	$\pm 10\%$
CCQEPauliSupViaKF	CCQE Pauli suppression via changes in Fermi level	0.225 GeV	$\pm 35\%$
AhtBY, BhtBY	Higher-twist parameters in Bodek-Yang model scaling	$A = 0.538$, $B = 0.305$	$\pm 25\%$
CV1uBY	GRV98 PDF correction parameter in Bodek-Yang model	0.291	$\pm 30\%$
CV2uBY	GRV98 PDF correction parameter in Bodek-Yang model	0.189	$\pm 30\%$
	Hadronization		
AGKYxF1pi	Pion transverse momentum in AGKY model [31]	See Appendix C of Ref. [9]	See Appendix C of Ref. [9]
AGKYpT1pi	Pion Feynman x for Nπ states in AGKY model [31]	See Appendix C of Ref. [9]	See Appendix C of Ref. [9]
FormZone	Hadron formation zone	See Appendix C of Ref. [9]	$\pm 50\%$
	Hadron transport		
MFP_pi, MFP_N	Pion and nucleon mean free path	See Appendix C of Ref. [9]	$\pm 20\%$
FrCEx_pi, FrCEx_N	Pion and nucleon charge exchange probability	See Appendix C of Ref. [9]	$\pm 50\%$
FrAbs_pi, FrAbs_N	Pion and nucleon absorption probability	See Appendix C of Ref. [9]	$\pm 20\%$

SYSTEMATIC UNCERTAINTIES SUMMARY

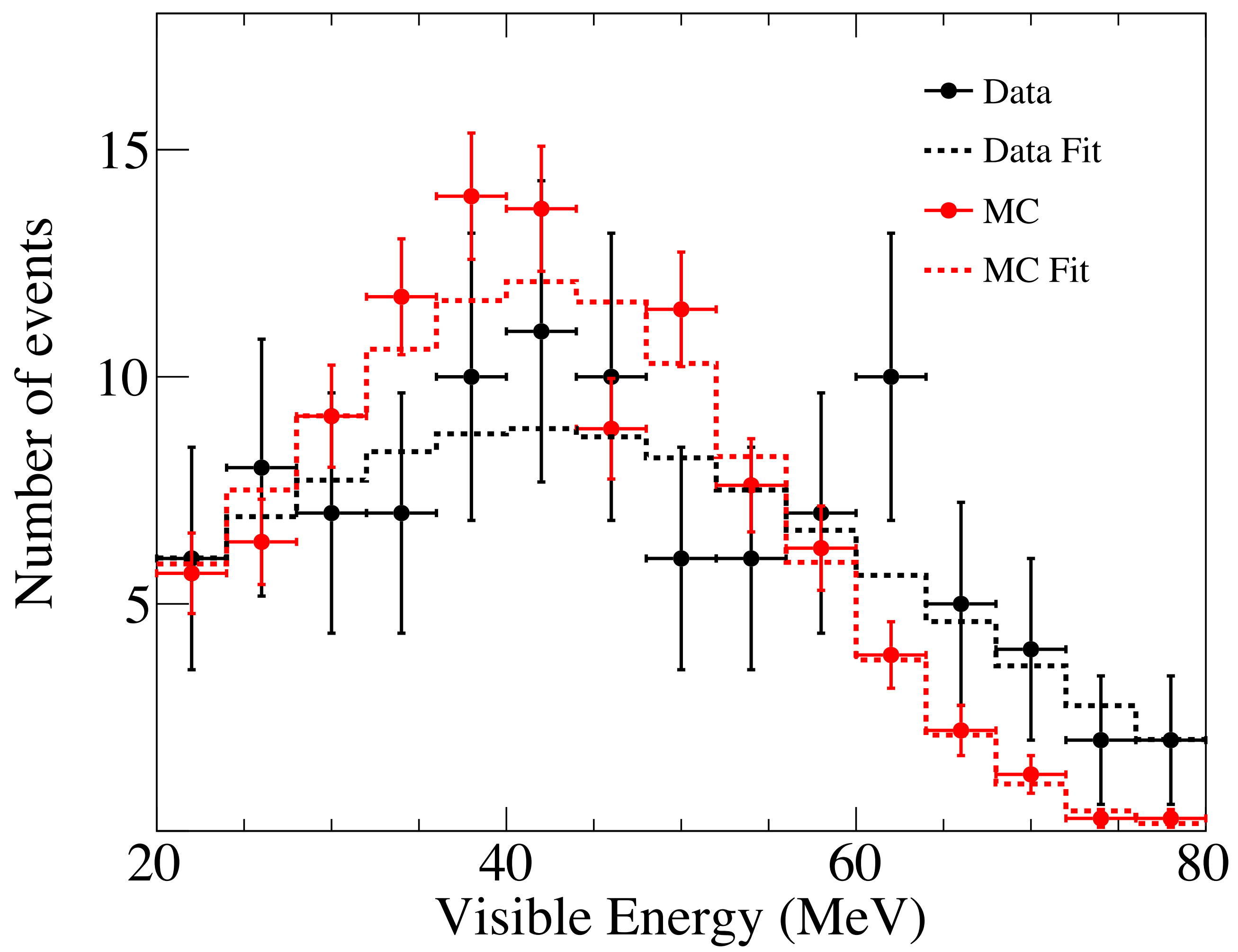
Systematic parameter	$\pm 1\sigma$ uncertainty	1σ fractional effect	Type
High-energy scale	See Fig. 12	0.7%	Shift
High-energy resolution			Smearing
Assumed $\cos\theta$ in E_ν reconstruction	See Fig. 5	$< 0.1\%$	Shift
Particle misidentification	$e = 0 \pm 5\%$, $\mu = 4 \pm 5\%$	$< 0.1\%$	Shift
Ring miscounting	$e = 14 \pm 14\%$, $\mu = 11 \pm 9\%$	$< 0.1\%$	Shift
High-energy radial bias	28 mm	$< 0.1\%$	Shift
High-energy radial resolution	160 mm		Smearing
Quality cuts efficiency	1.47%	1.5%	Reweight
Neutron capture reconstruction	See Sec. VII A 5	$< 0.1\%$	Shift, smearing, & reweight
Neutron detection efficiency	See Sec. VII A 6	15.9%	Reweight
Atmospheric neutrino flux	$\sim$15%	1.5%	Reweight
Neutrino interaction model	See Table. IV	12.5%	Reweight
MC statistical error	...	1.9%	Reweight
Total	...	24.9%	...

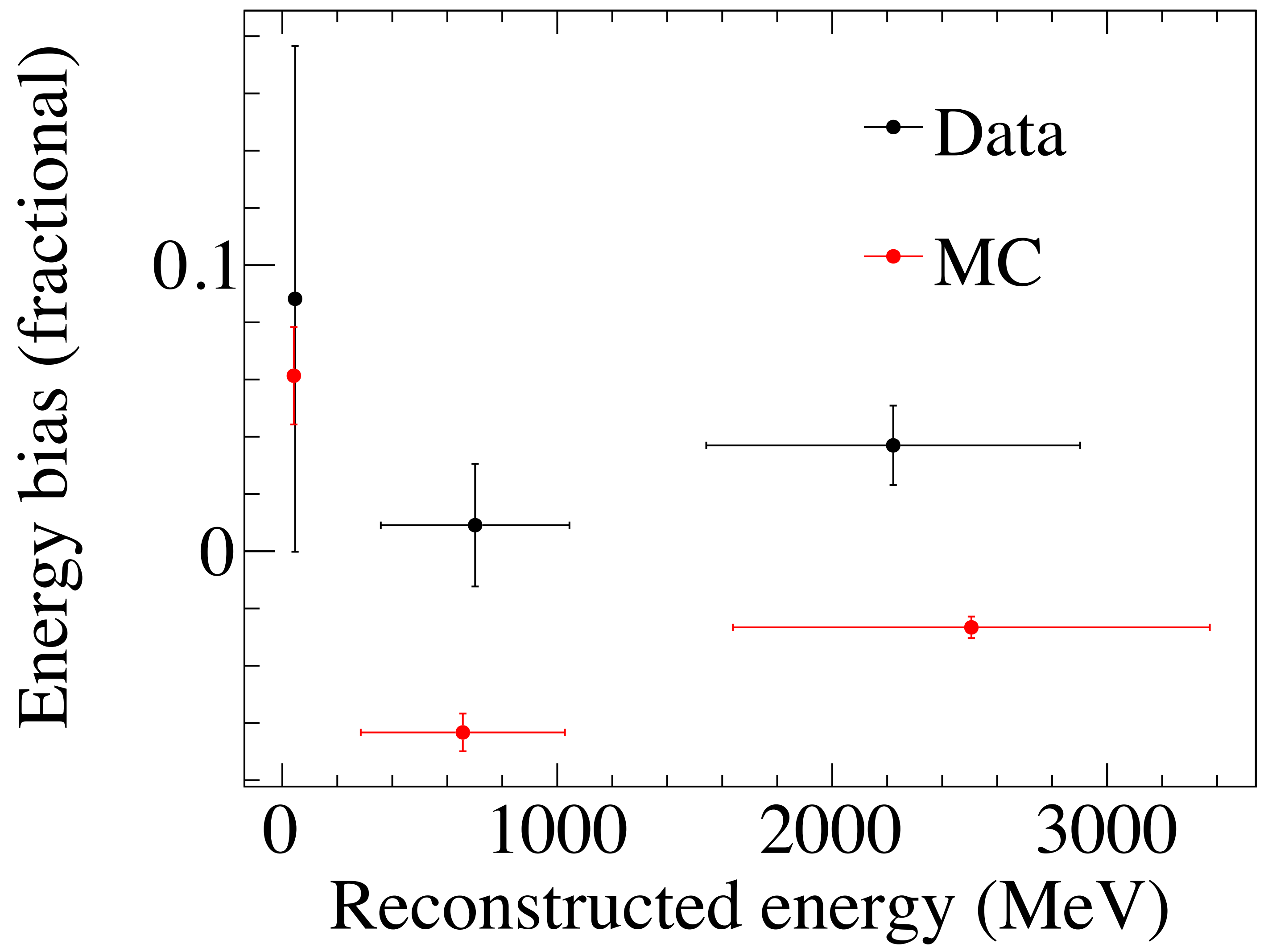
RINGFITTER CALIBRATION

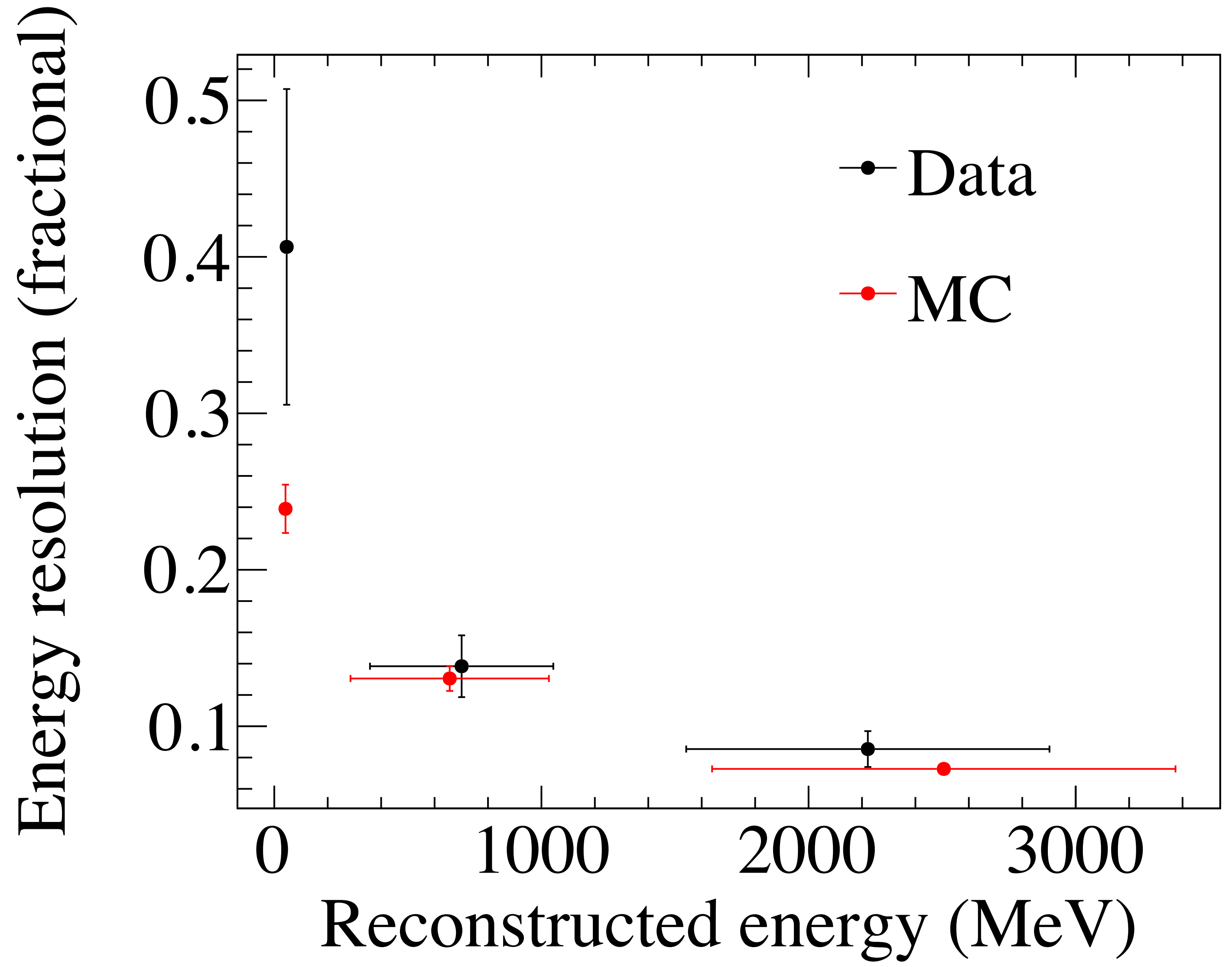
Stopping muons



Michel electrons



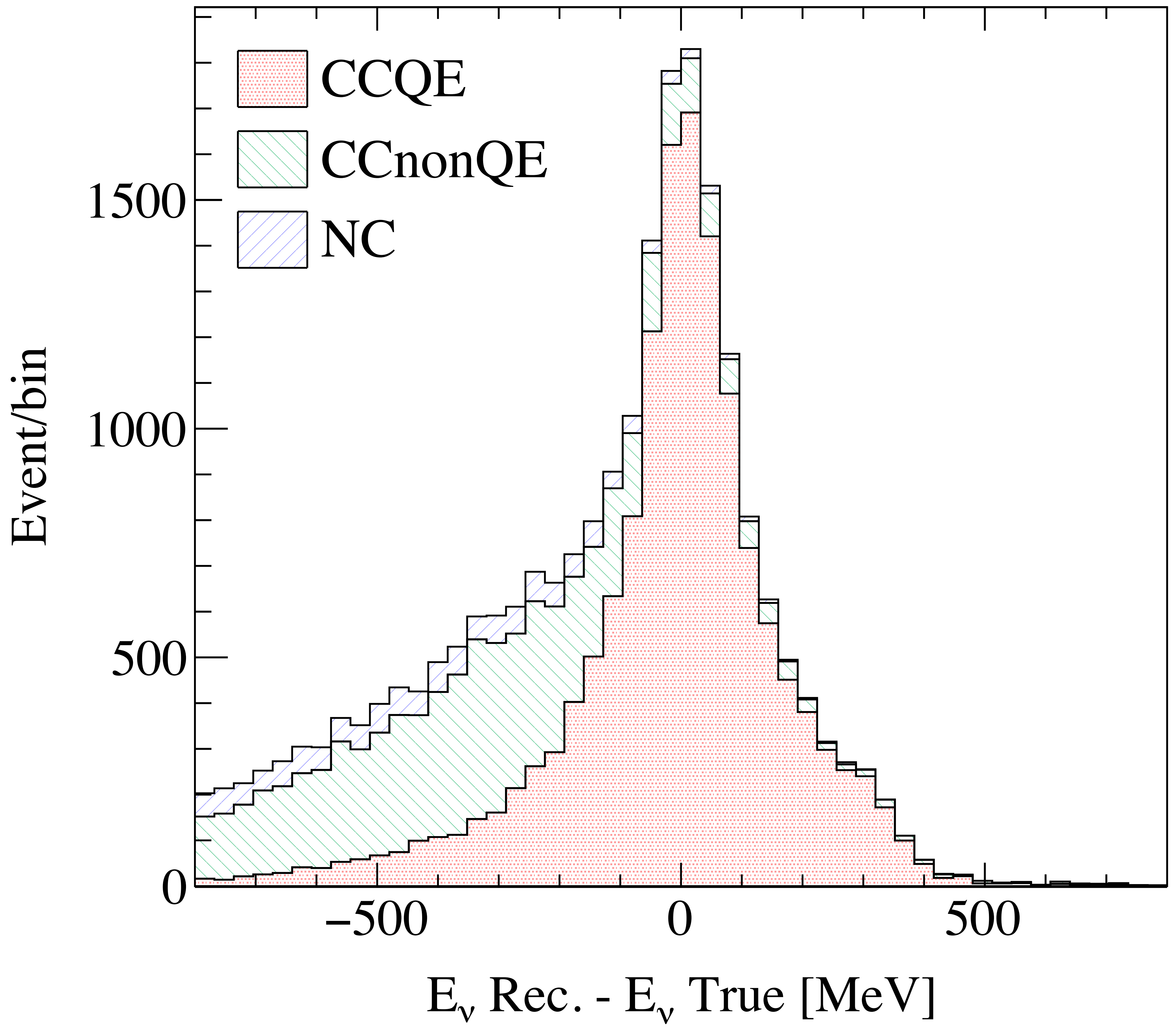


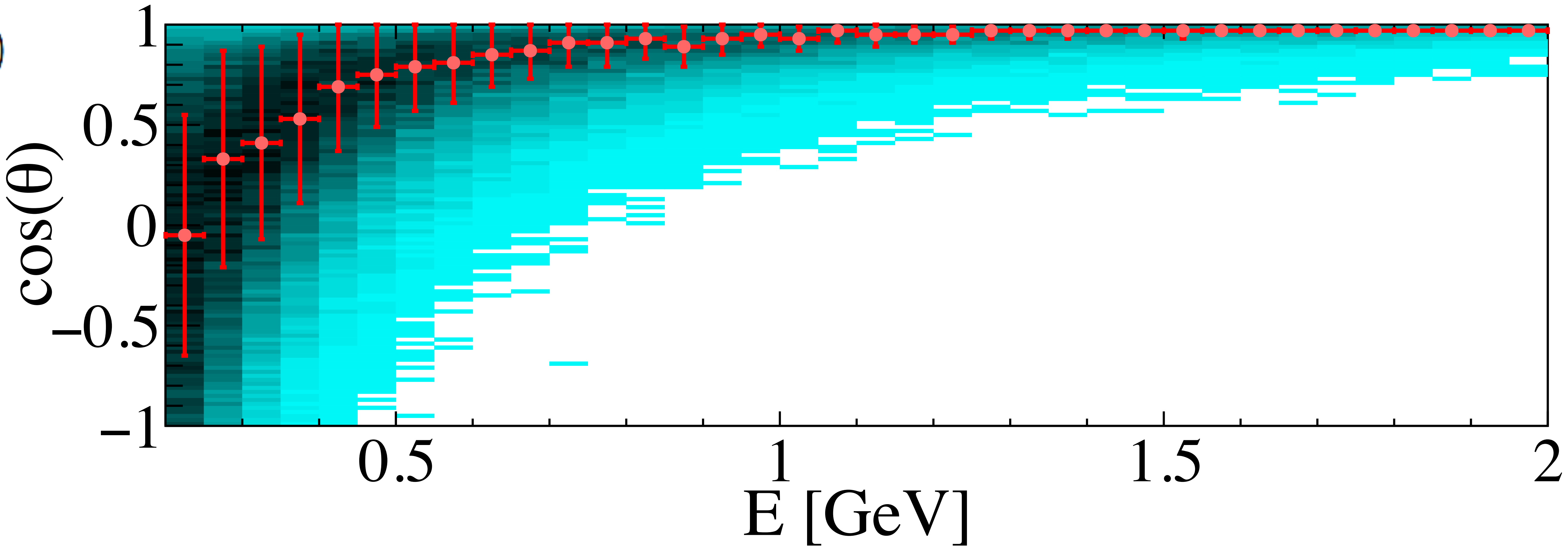


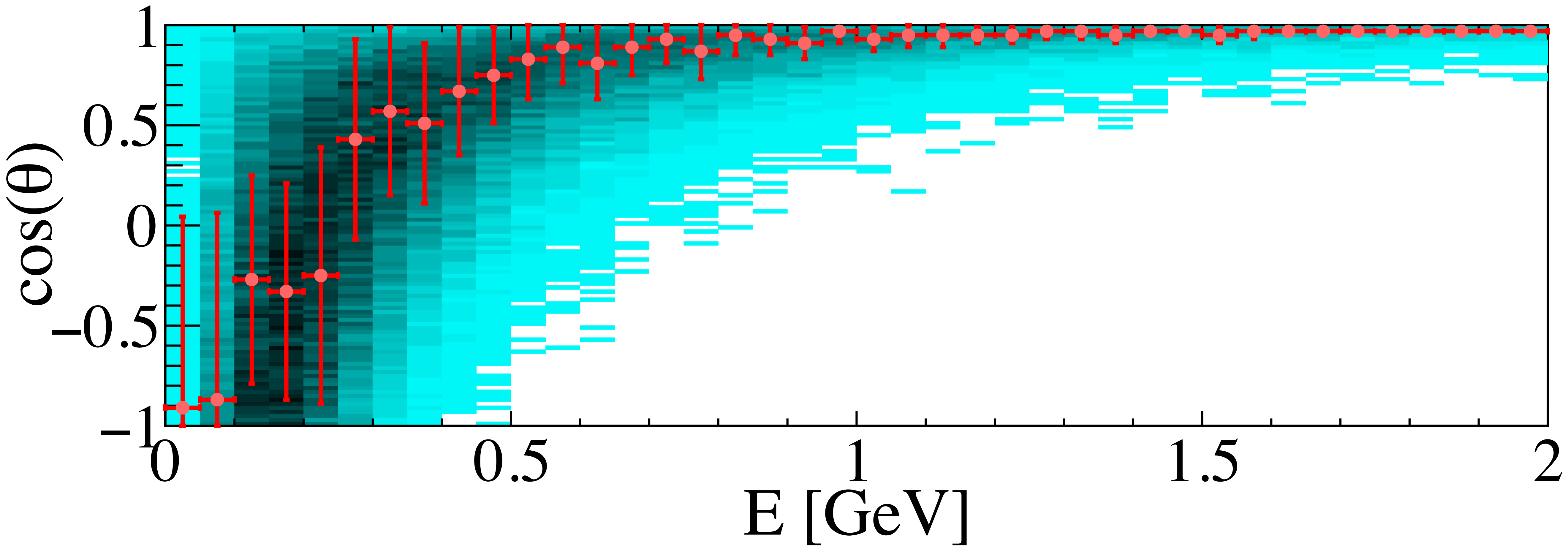
NEUTRINO ENERGY RECONSTRUCTION

The neutrino energy is reconstructed according to the CCQE hypothesis,

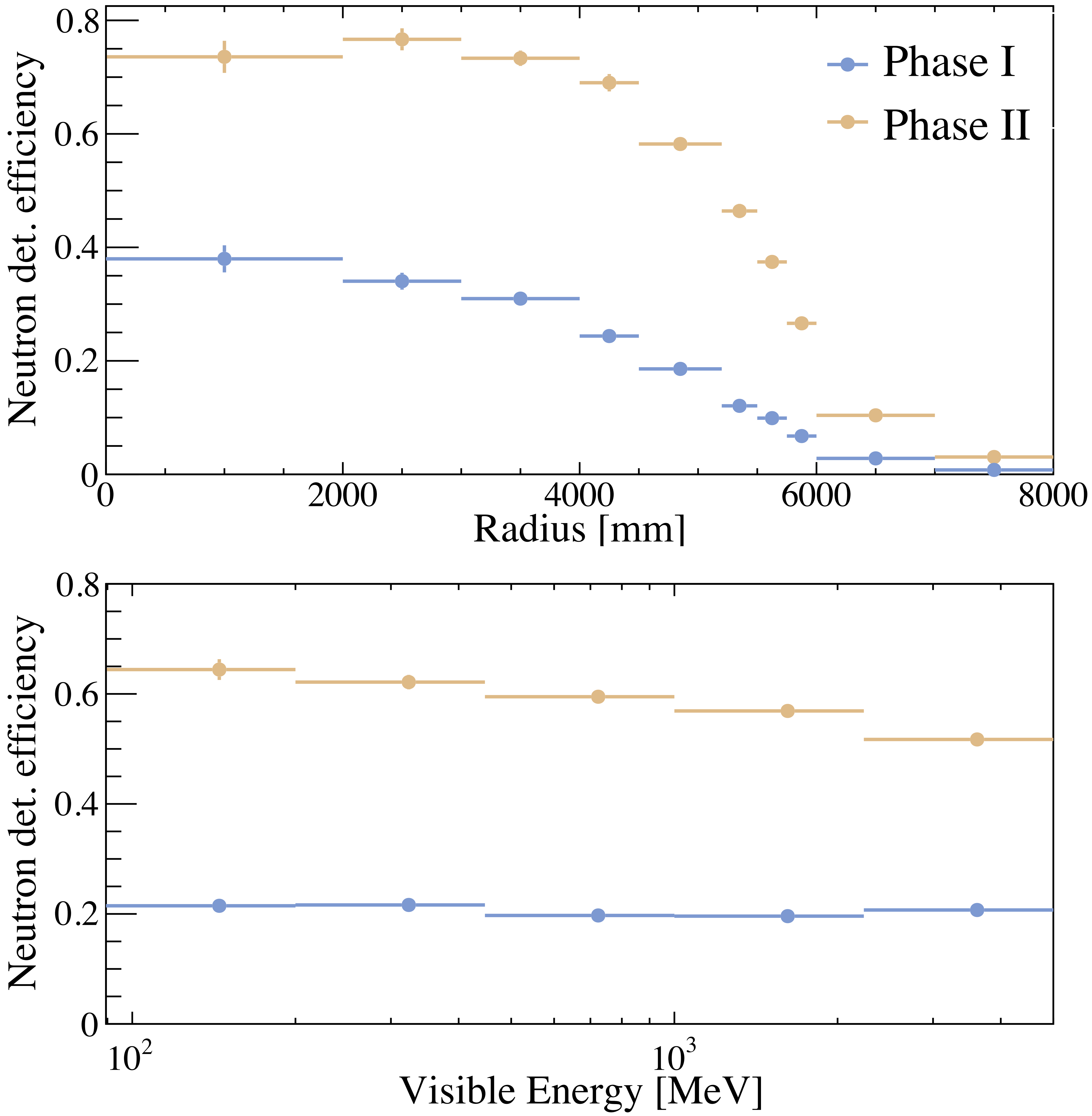
$$E_r^\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_l^2 + 2(m_n - E_b)E_l}{2(m_n - E_b - E_l + p_l \cos\theta_l)} \quad (7)$$



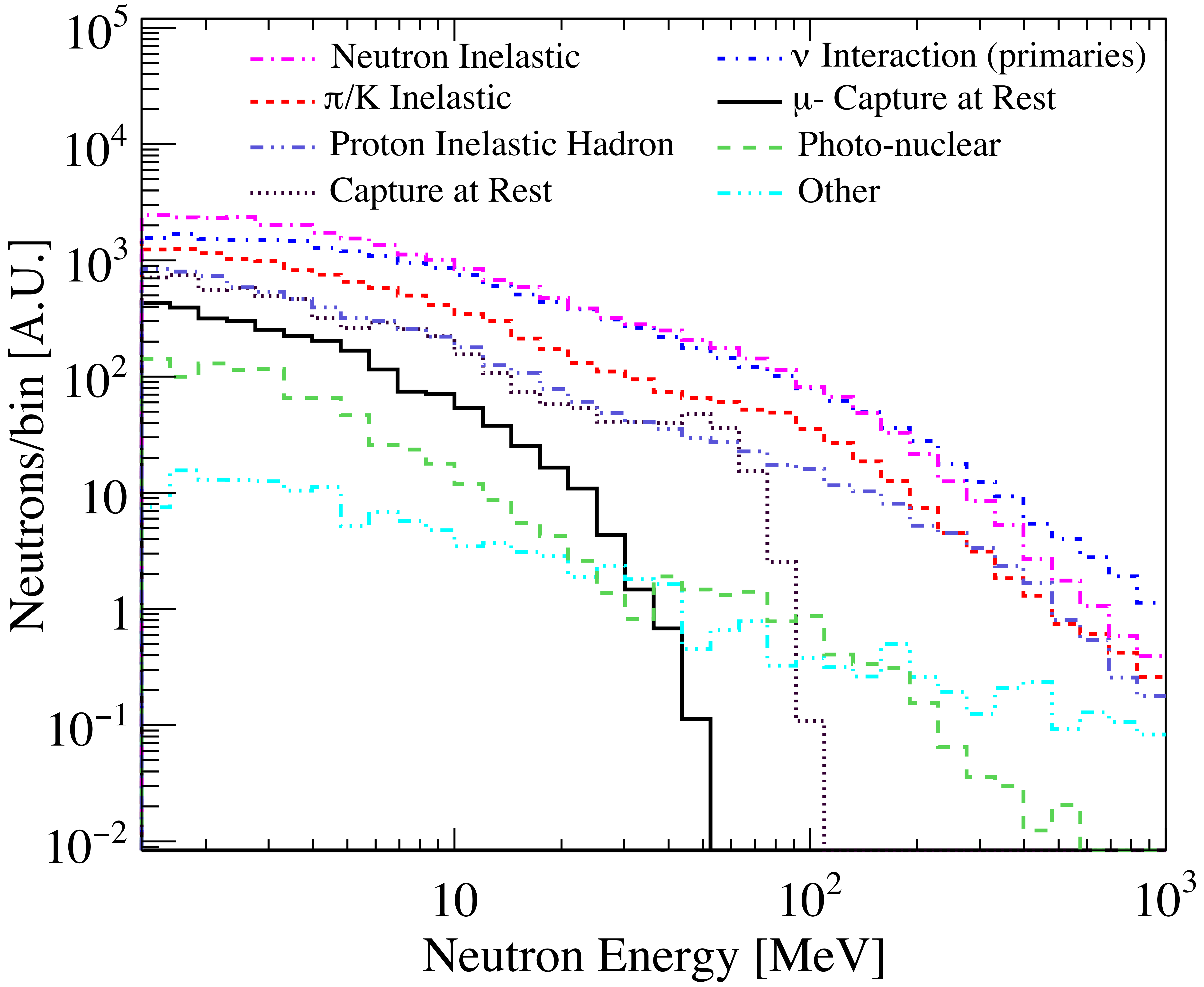




NEUTRON DETECTION EFFICIENCY

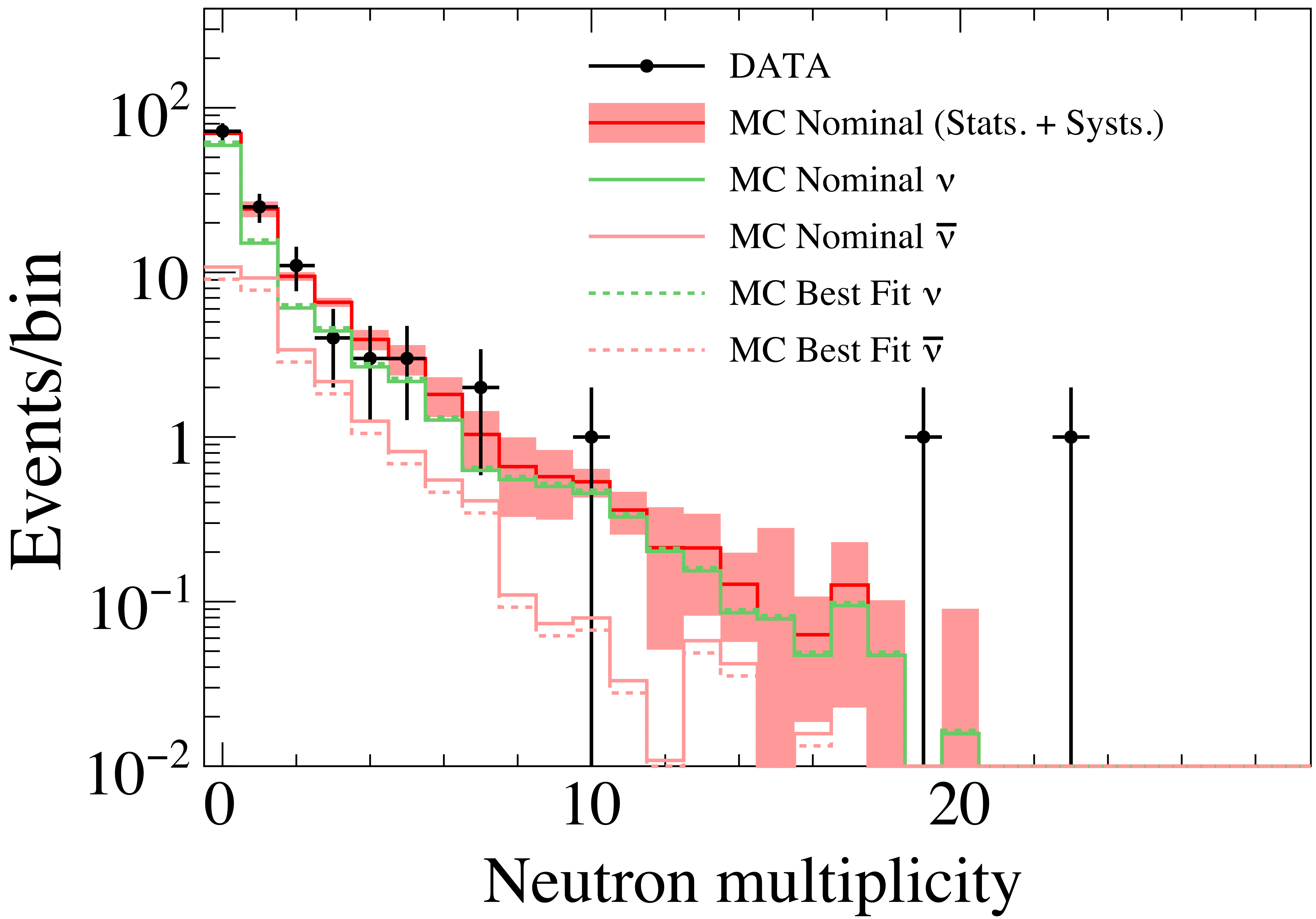


NEUTRON PRODUCTION



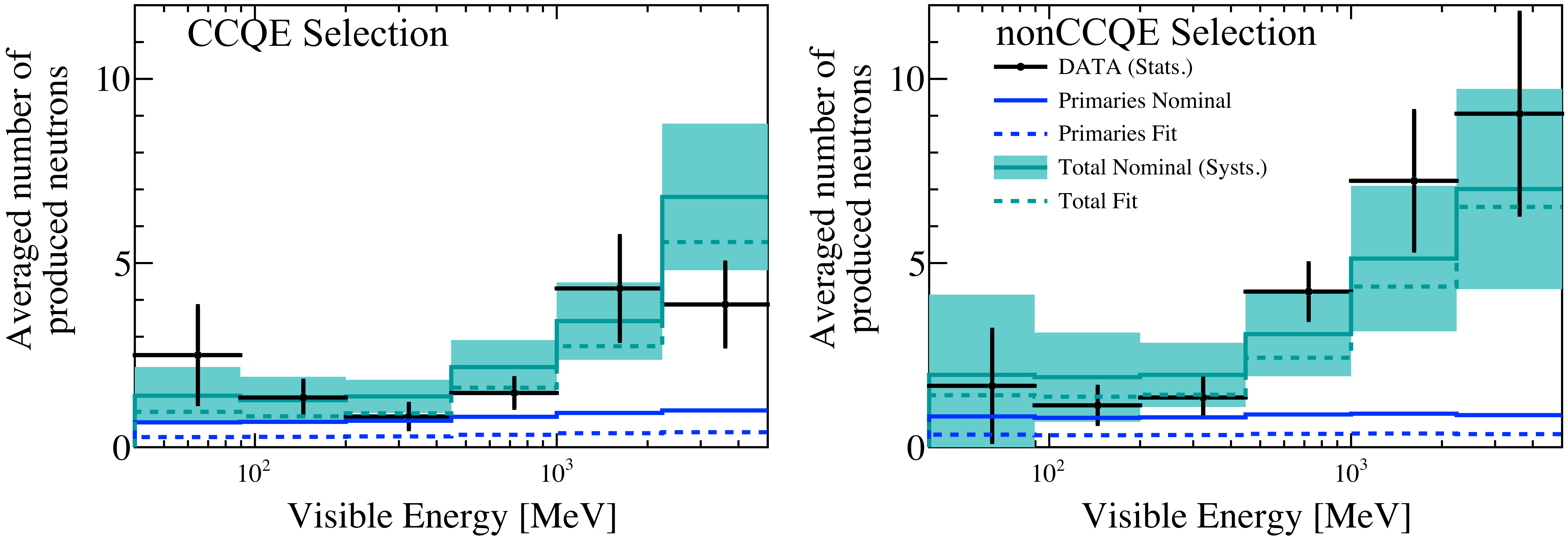
Neutron origin	Fraction
Neutrino interaction	33.0(0.2)%
Neutron inelastic	34.9(0.2)%
π/K inelastic	15.0(0.1)%
Proton inelastic	7.3(0.1)%
Hadron capture at rest	6.4(0.1)%
μ capture at rest	2.20(0.04)%
Photonuclear	0.90(0.02)%
Other	0.29(0.01)%

ν/anti-ν STATISTICAL SEPARATION



PRIMARY/SECONDARY NEUTRONS FIT

PRIMARY/SECONDARY NEUTRON COMPONENTS ARE DIFFERENT FOR CCQE AND NON-CCQE INTERACTIONS → HELP DISENTANGLING DIFFERENT NEUTRON ORIGIN THROUGH SHAPE LIKELIHOOD FIT



Best fit

- Primary neutrons: Best fit MC/Nominal MC = 0.41 ± 0.50
- Secondary neutrons: Best fit MC/Nominal MC = 0.95 ± 0.25
- χ^2/dof = 14.4/12

SNO TOOK DATA FROM 1999 TO 2006 TO ADDRESS:

THE SOLAR NEUTRINO PROBLEM

ν_τ

ν_μ

ν_e

$$\nu + d \rightarrow p + n + \nu - 2.22\ \text{MeV} \quad \text{(NC)}$$

$$\nu + e^- \rightarrow \nu + e^- \quad \text{(ES)}$$

ν_e