BERKELEY LAB

UC DAVIS – OCTOBER 1st, 2019

JAVIER CARAVACA

NEUTRON PRODUCTION IN ATMOSPHERIC NEUTRINO INTERACTIONS WITH SNO

PHYS. REV. D 99, 112007 (2019)

OUTLINE

MOTIVATION

- PROTON DECAY
- ν/ANTI-ν DISCRIMINATION
- NEUTRINO CROSS-SECTIONS

THE SNO DETECTOR

ANALYSIS METHODS

RESULTS

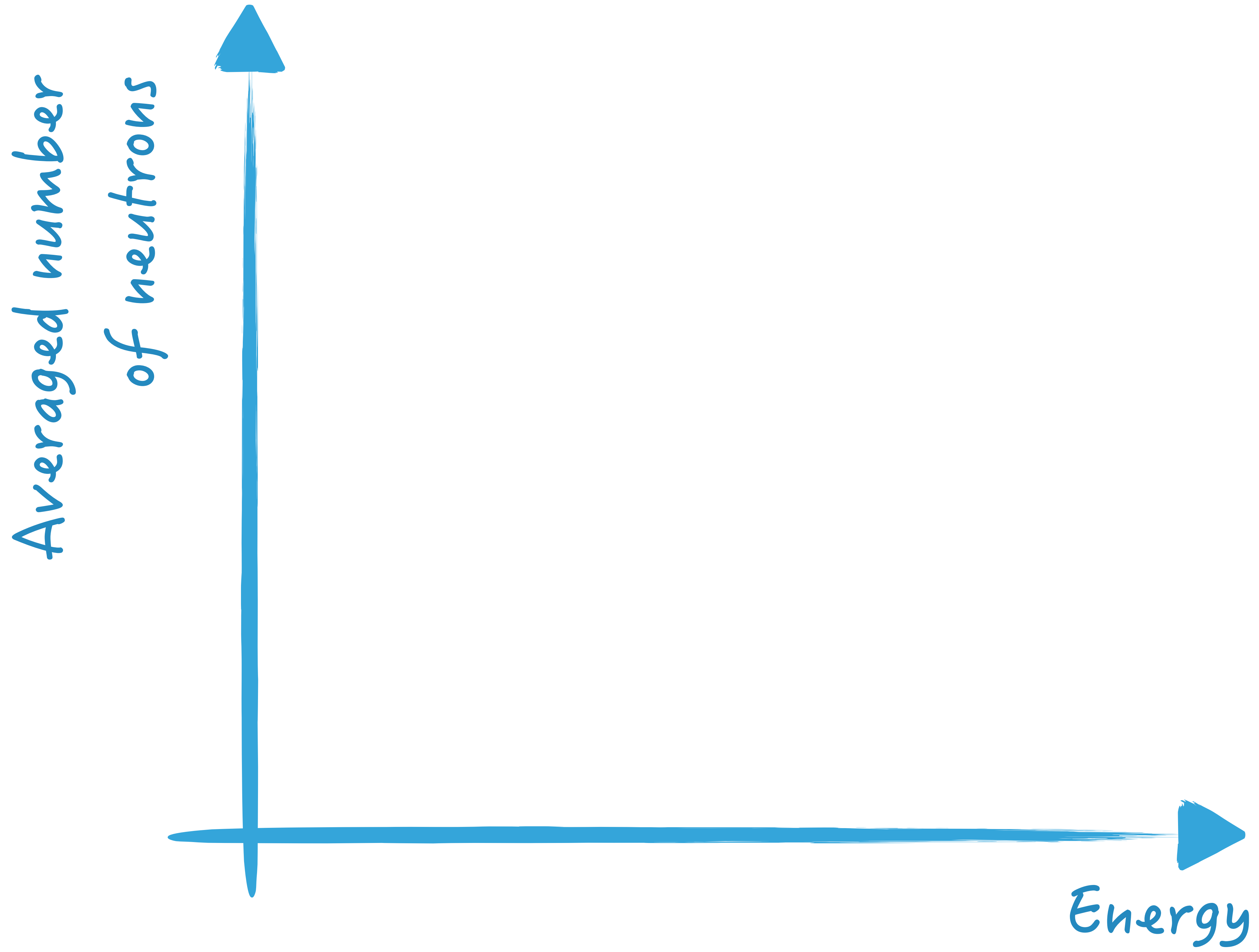
- NEUTRON PRODUCTION MEASUREMENT
- DATA/MC COMPARISON
- NEUTRINO/ANTI-NEUTRINO DISCRIMINATION

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



NUCLEON DECAY (ND)

GUT THEORIES ($10^{15\text{-}16}$ GEV) PREDICT NUCLEON DECAY

↓

A WAY TO PROBE THOSE THEORIES IS LOOKING FOR ND

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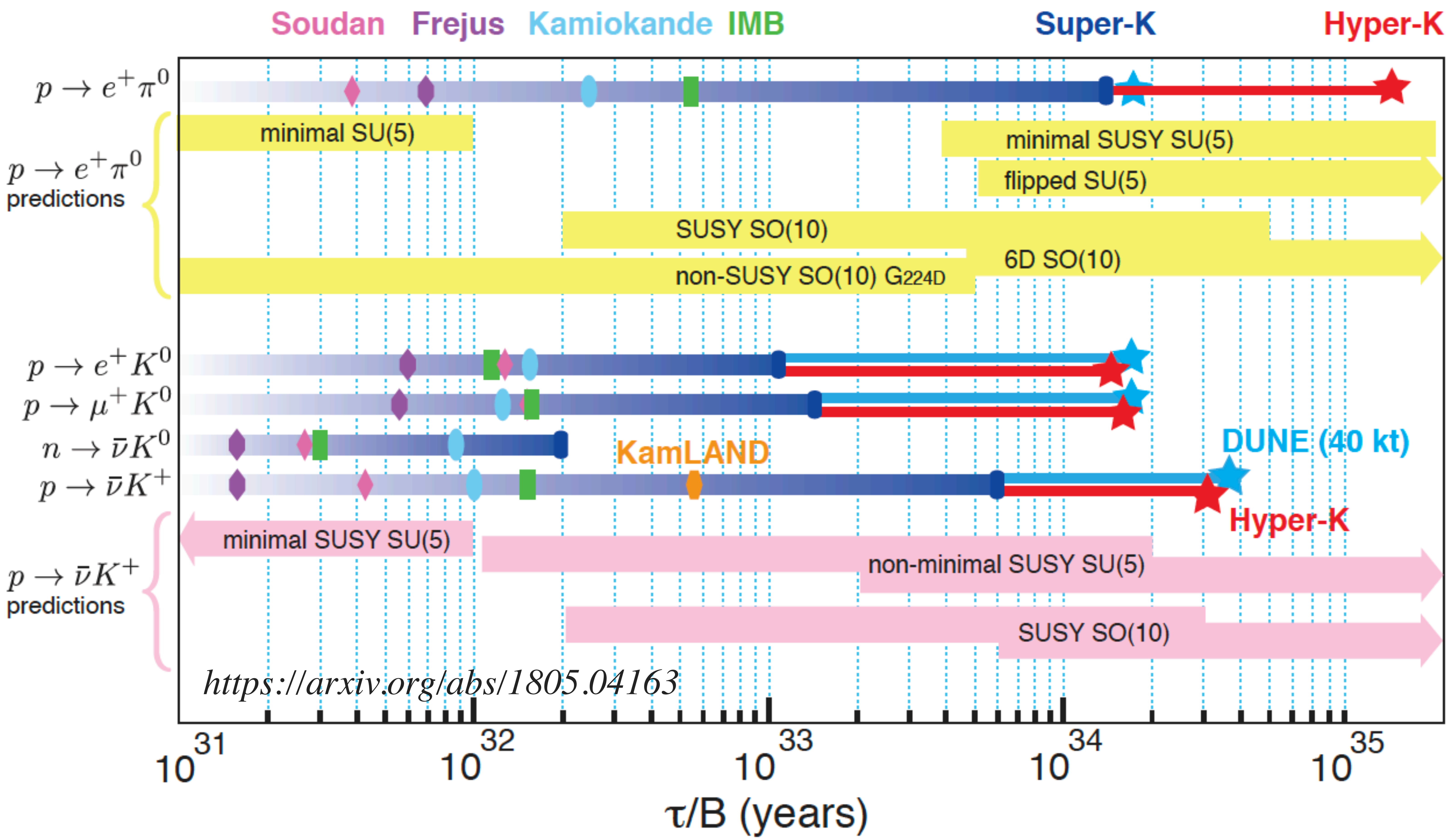

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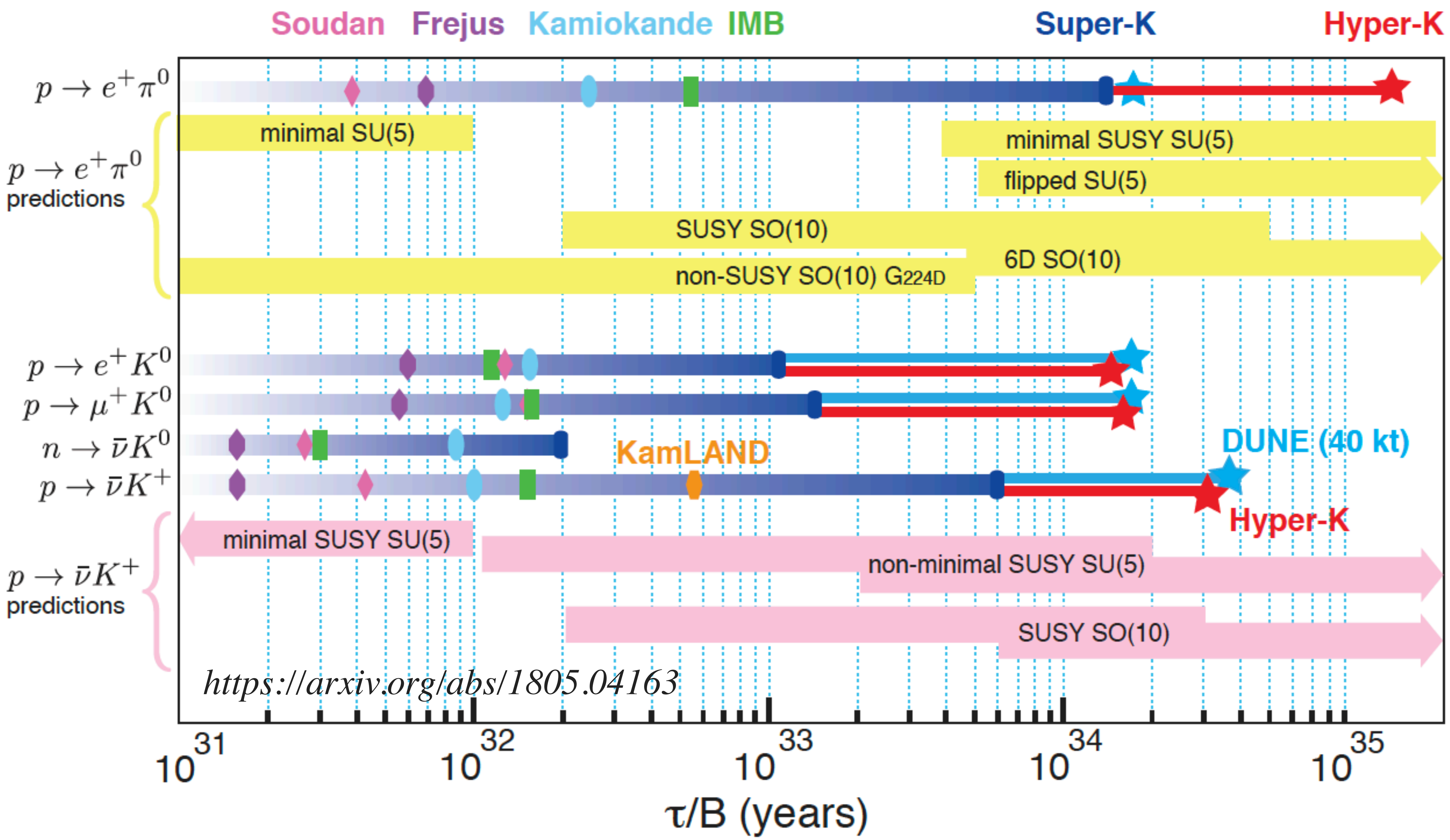
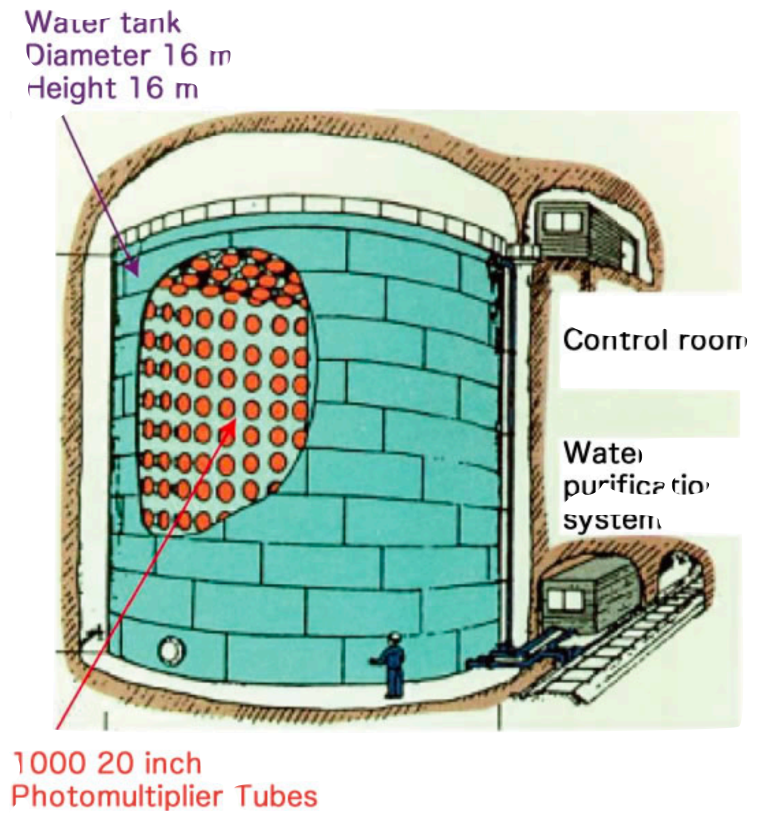
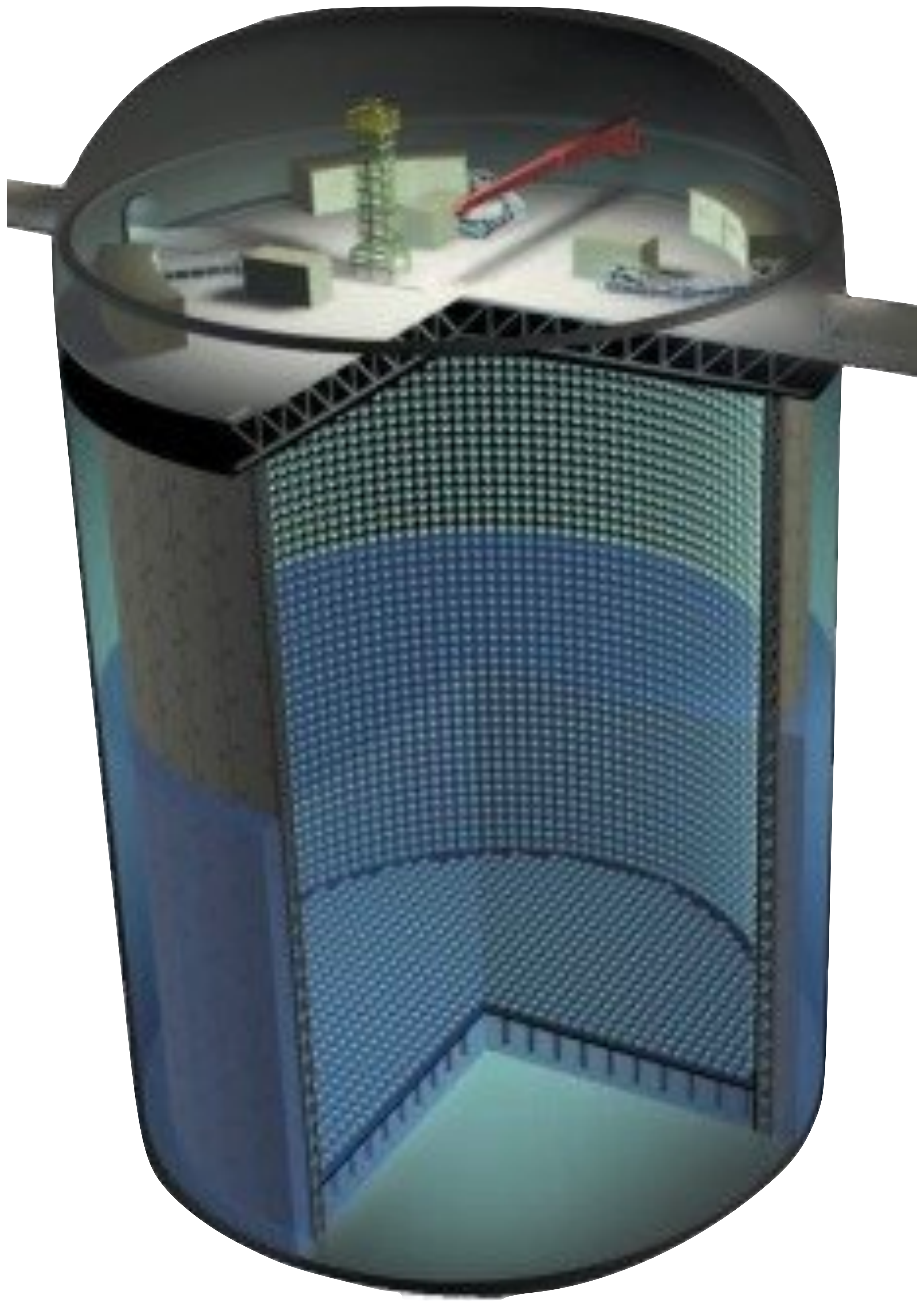


KamiokaNDE



Super-Kamiokande



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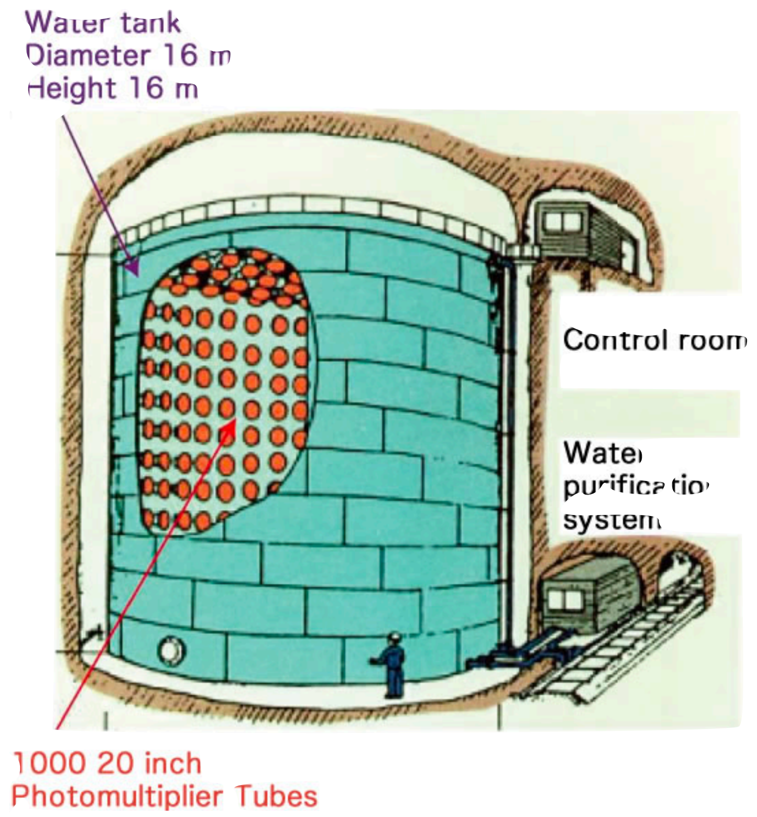

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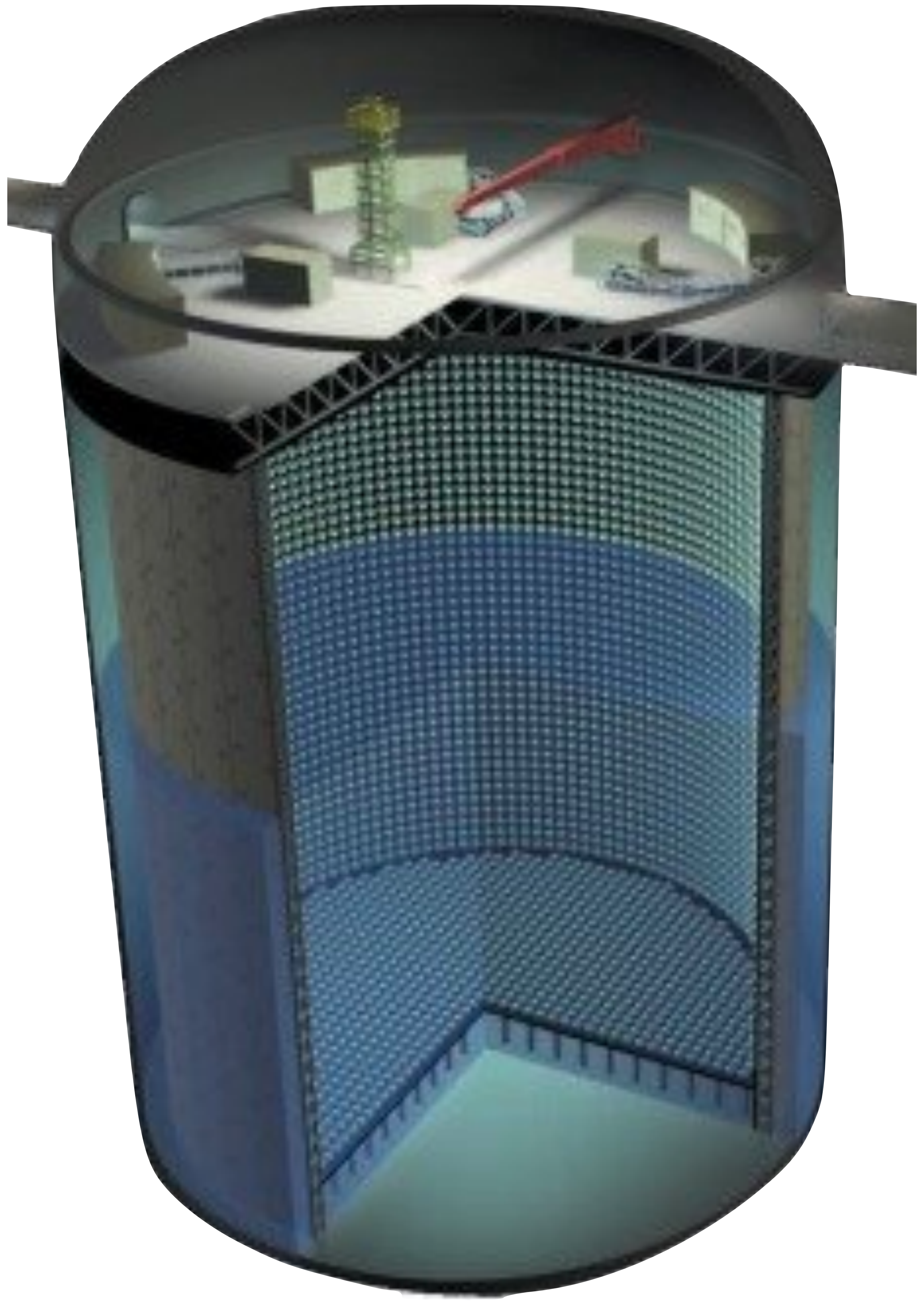
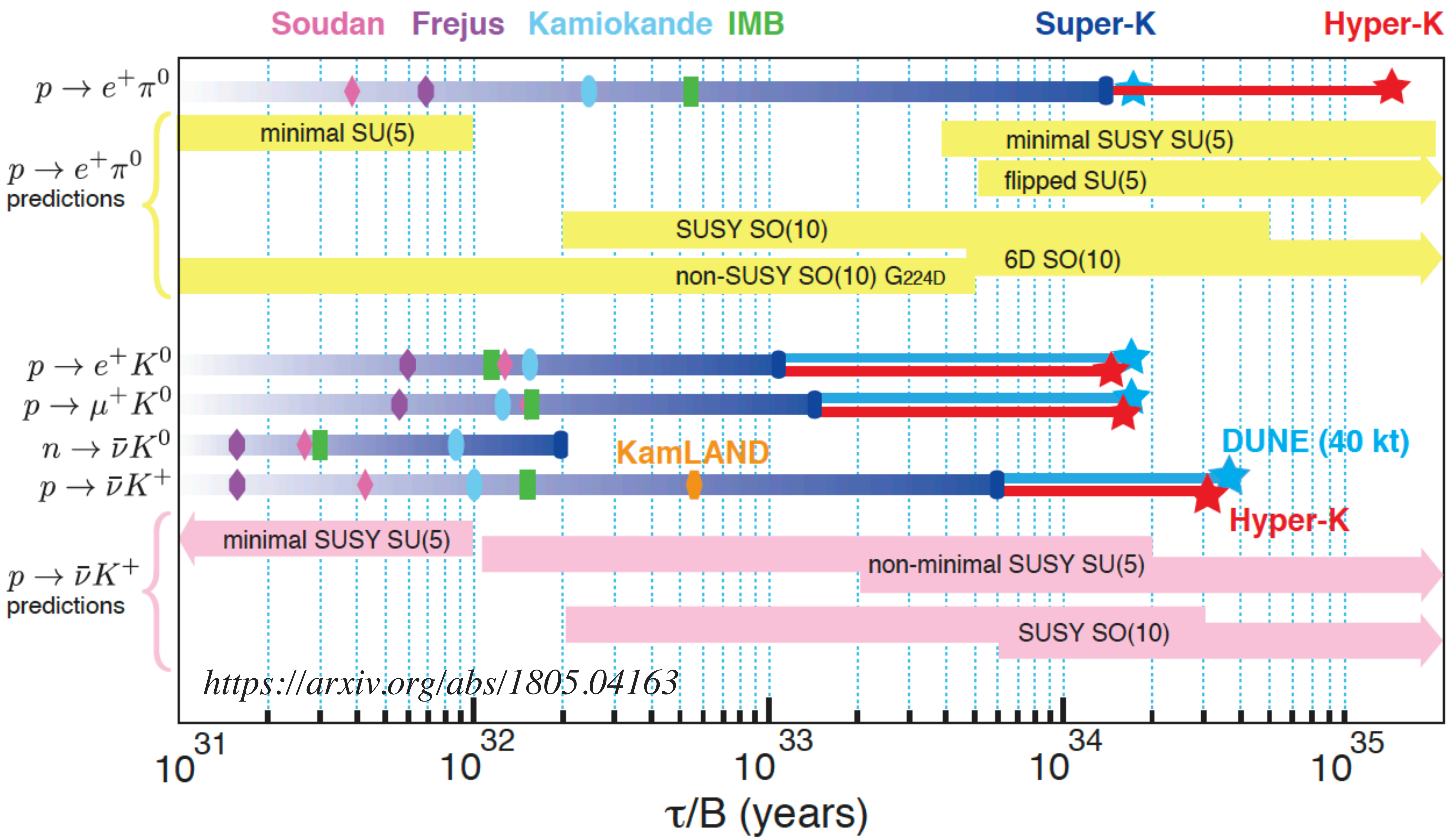
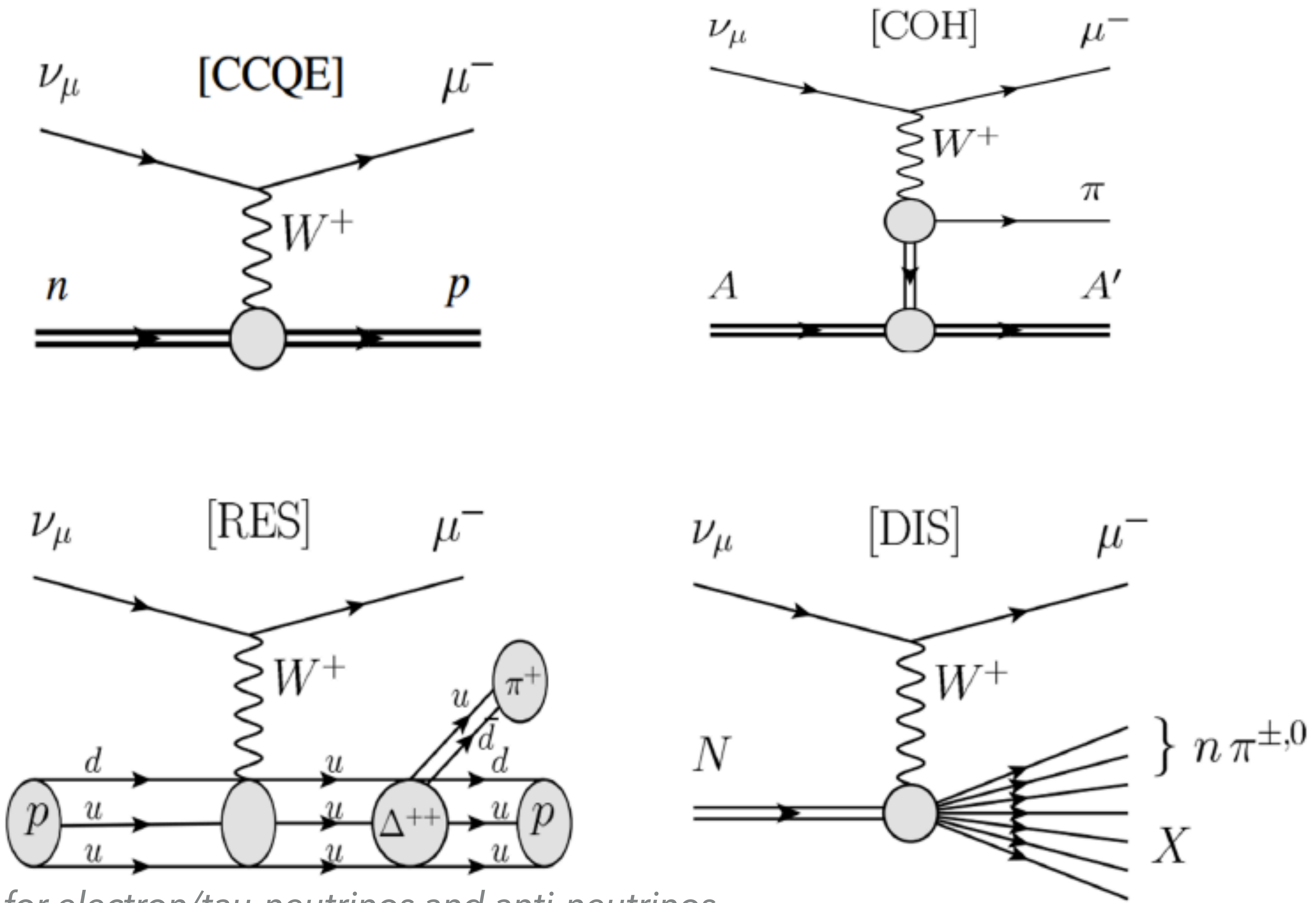




ATMOSPHERIC NEUTRINOS

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



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ATMOSPHERIC NEUTRINOS ARE A BACKGROUND FOR NUCLEON DECAY SEARCHES

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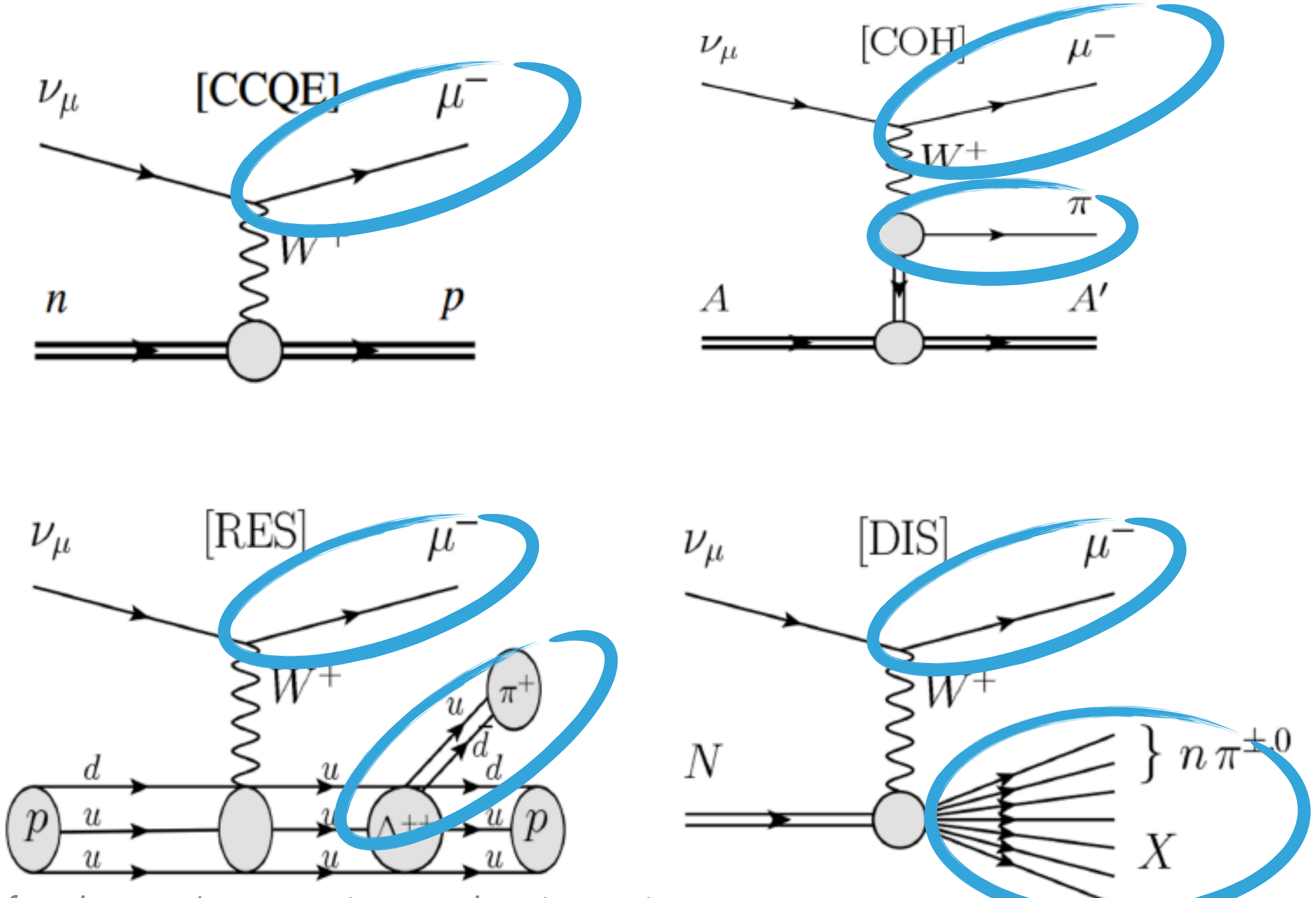

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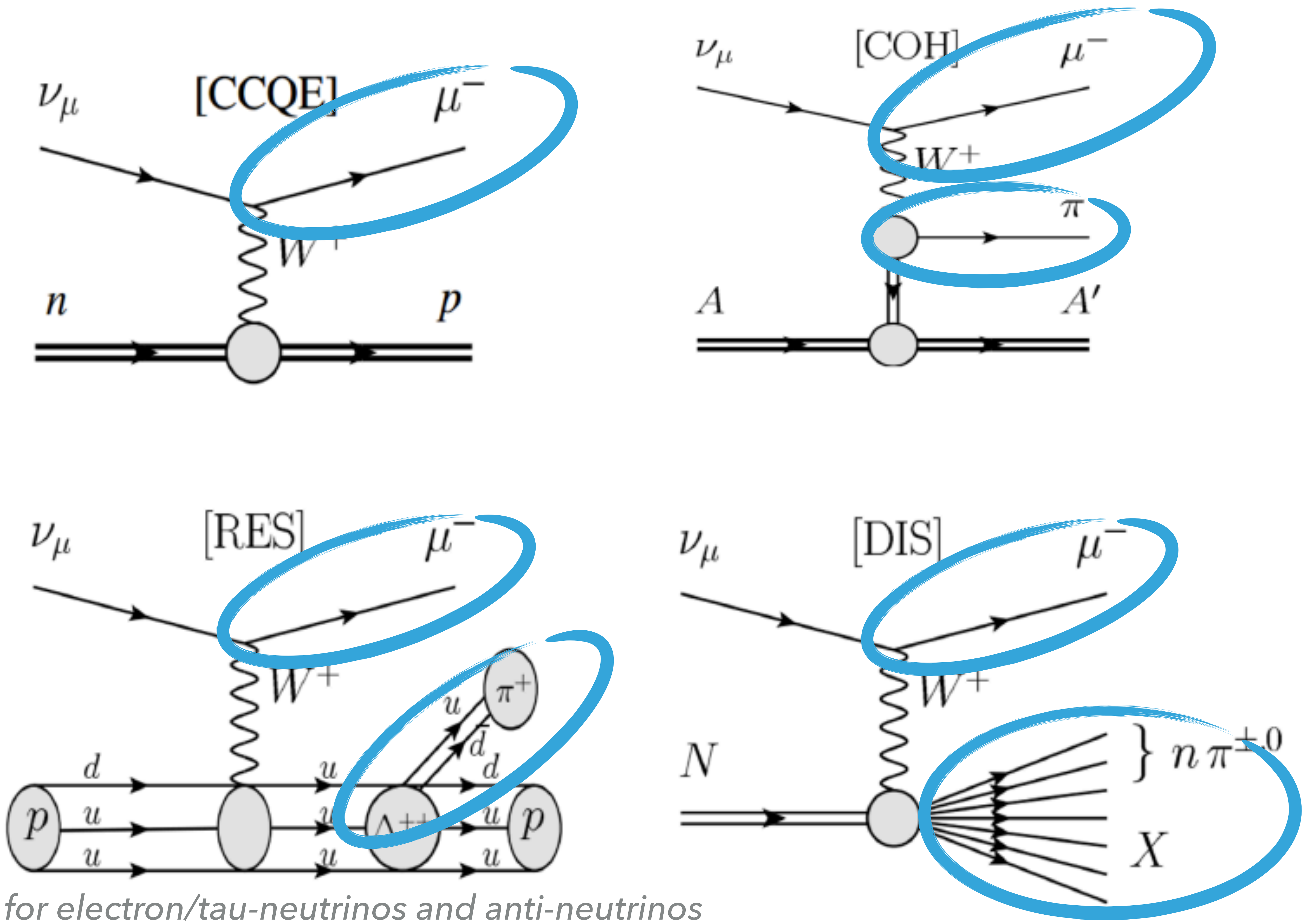

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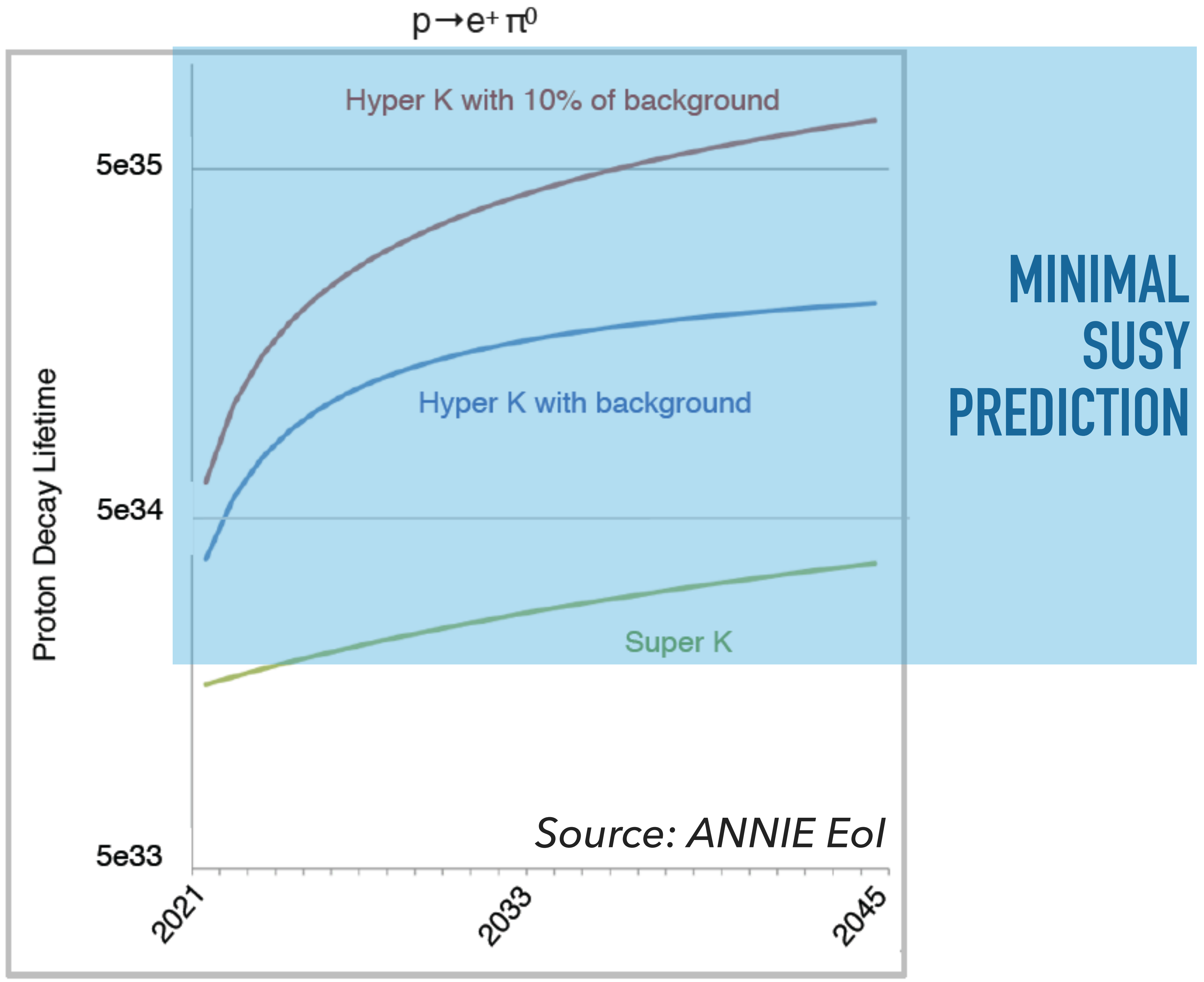

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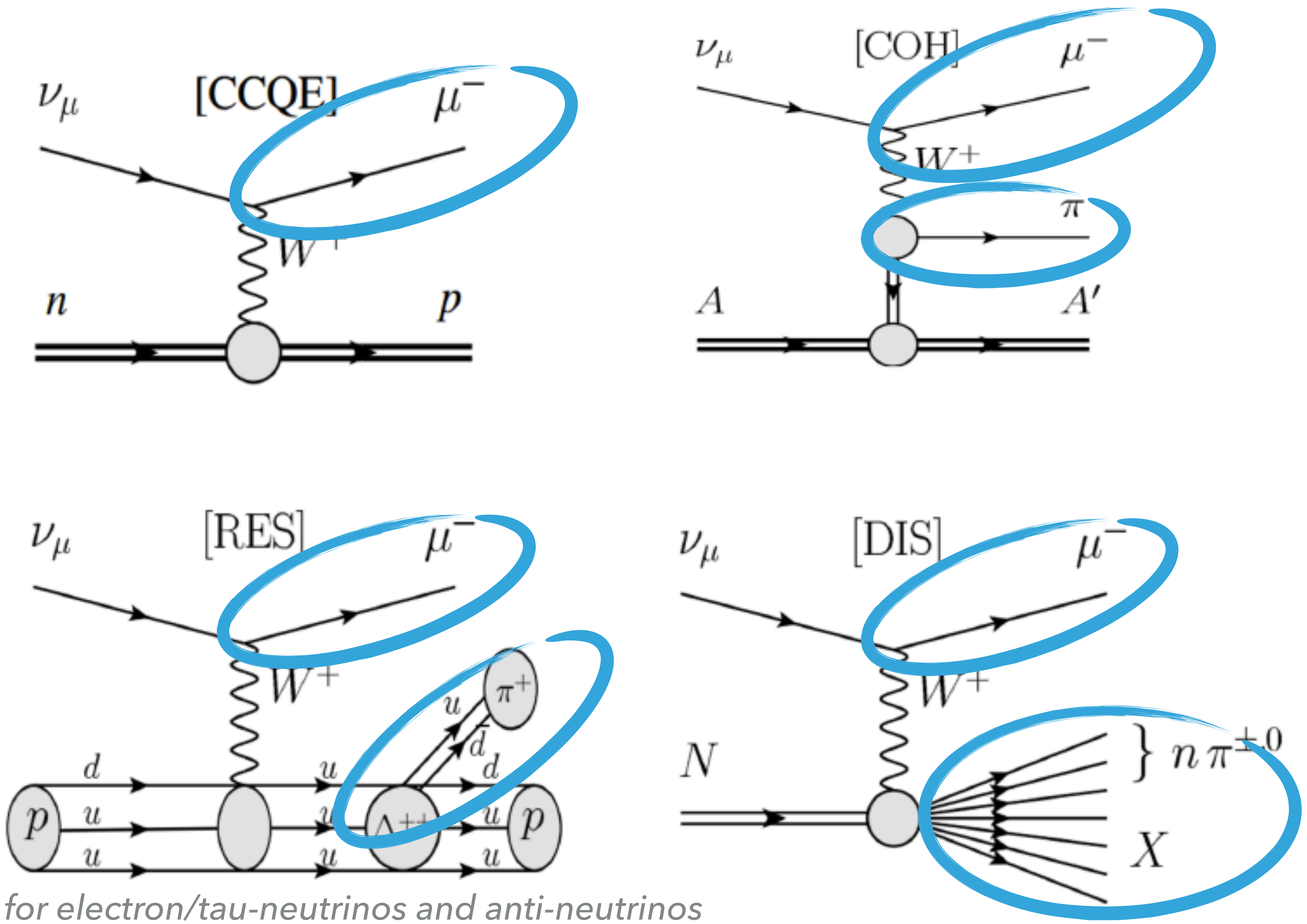

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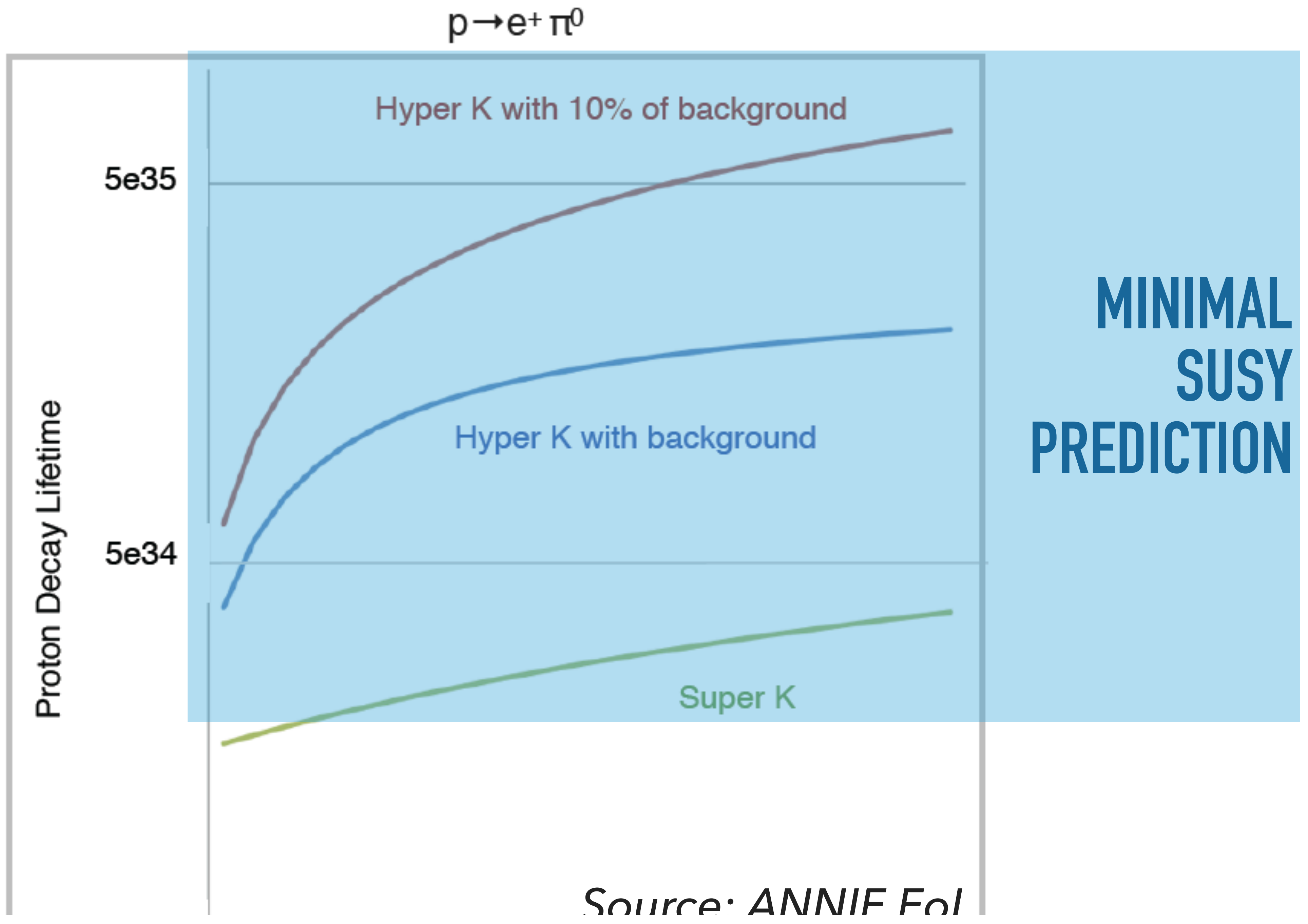
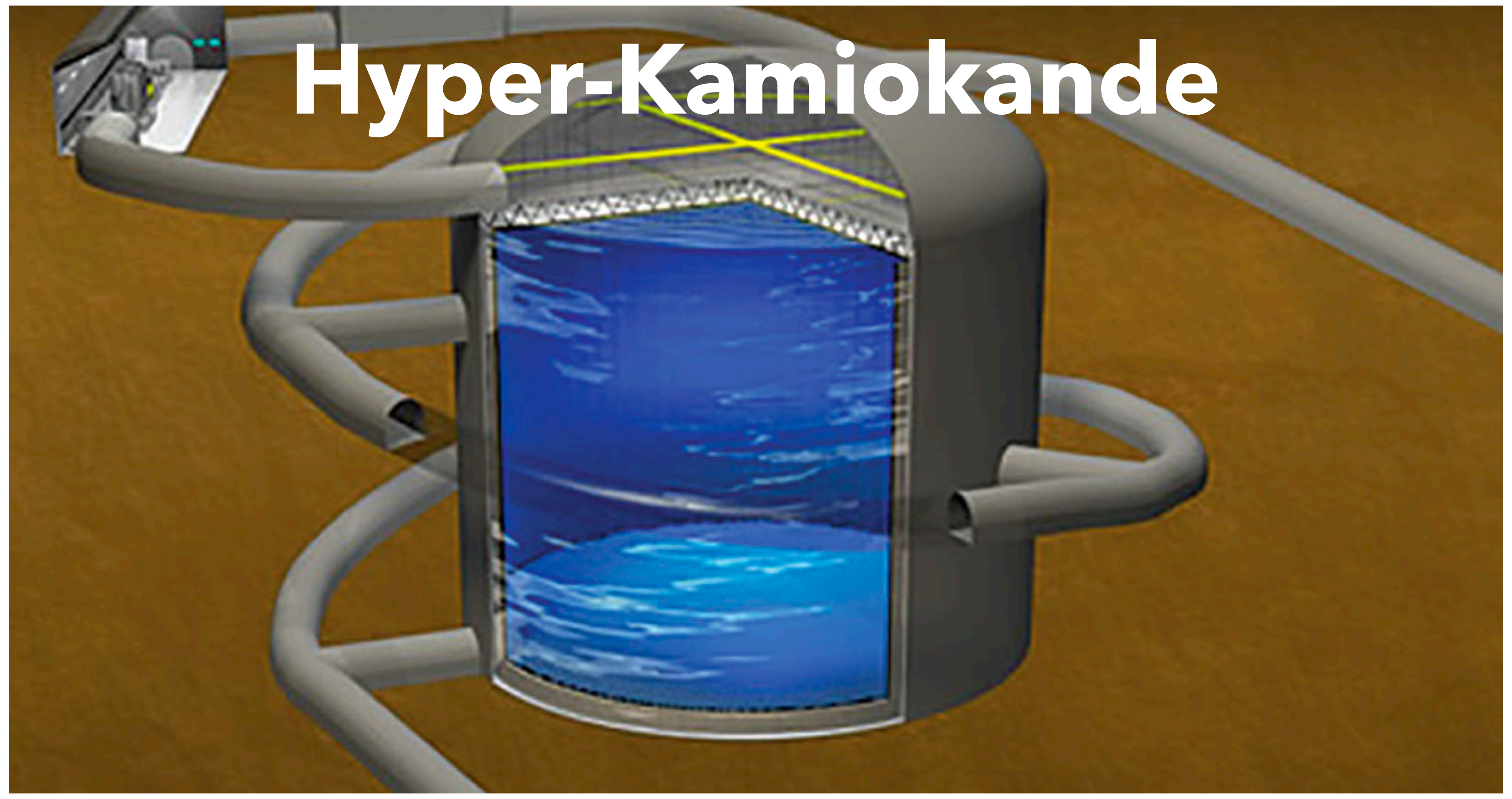


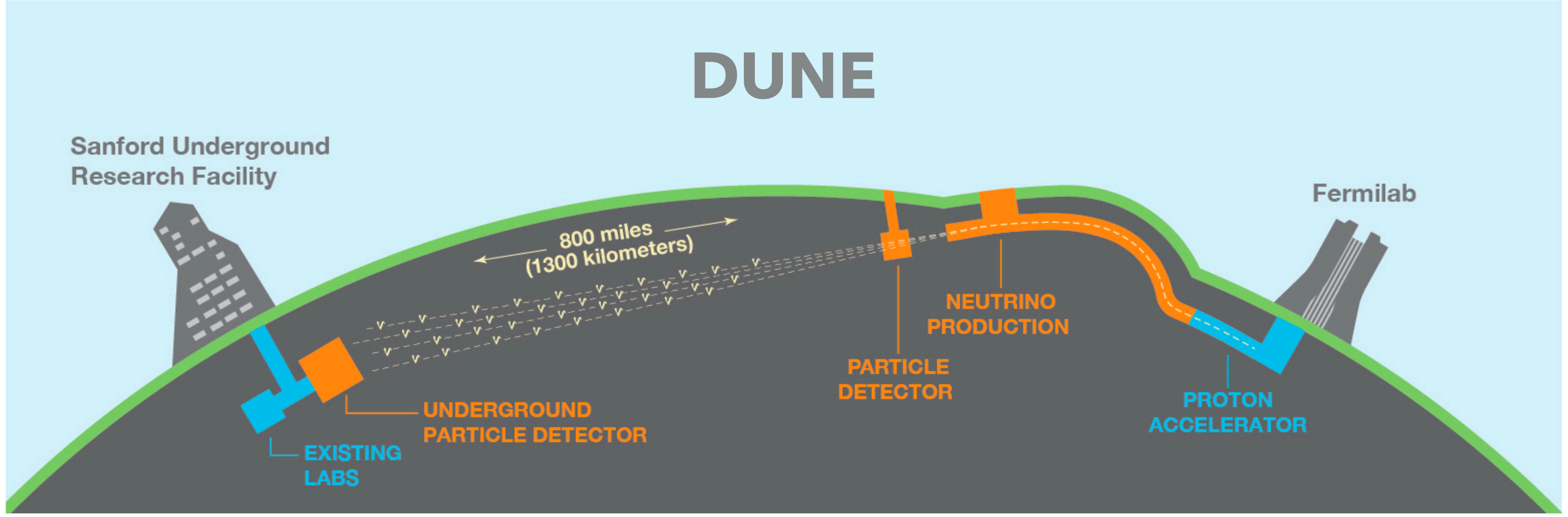
Process	Fraction with at least one neutron produced
ν CCQE	38.4(2.2)%
$\bar{\nu}$ CCQE	99.9(0.1)%
ν CCOther	88.8(2.0)%
$\bar{\nu}$ CCOther	94.7(2.1)%
ν NC	84.8(1.8)%
$\bar{\nu}$ NC	82.4(2.3)%
ν total	61.5(1.1)%
$\bar{\nu}$ total	95.6(0.6)%
Total	69.5(0.8)%

PROTON DECAY → TYPICALLY NO NEUTRONS
ATMOSPHERIC NEUTRINOS → 70% PRODUCE AT LEAST ONE

NEUTRINO/ANTI-NEUTRINO SEPARATION

CP VIOLATION DETECTION IS THE CORNERSTONE OF THE FUTURE BEAM NEUTRINO PROGRAM





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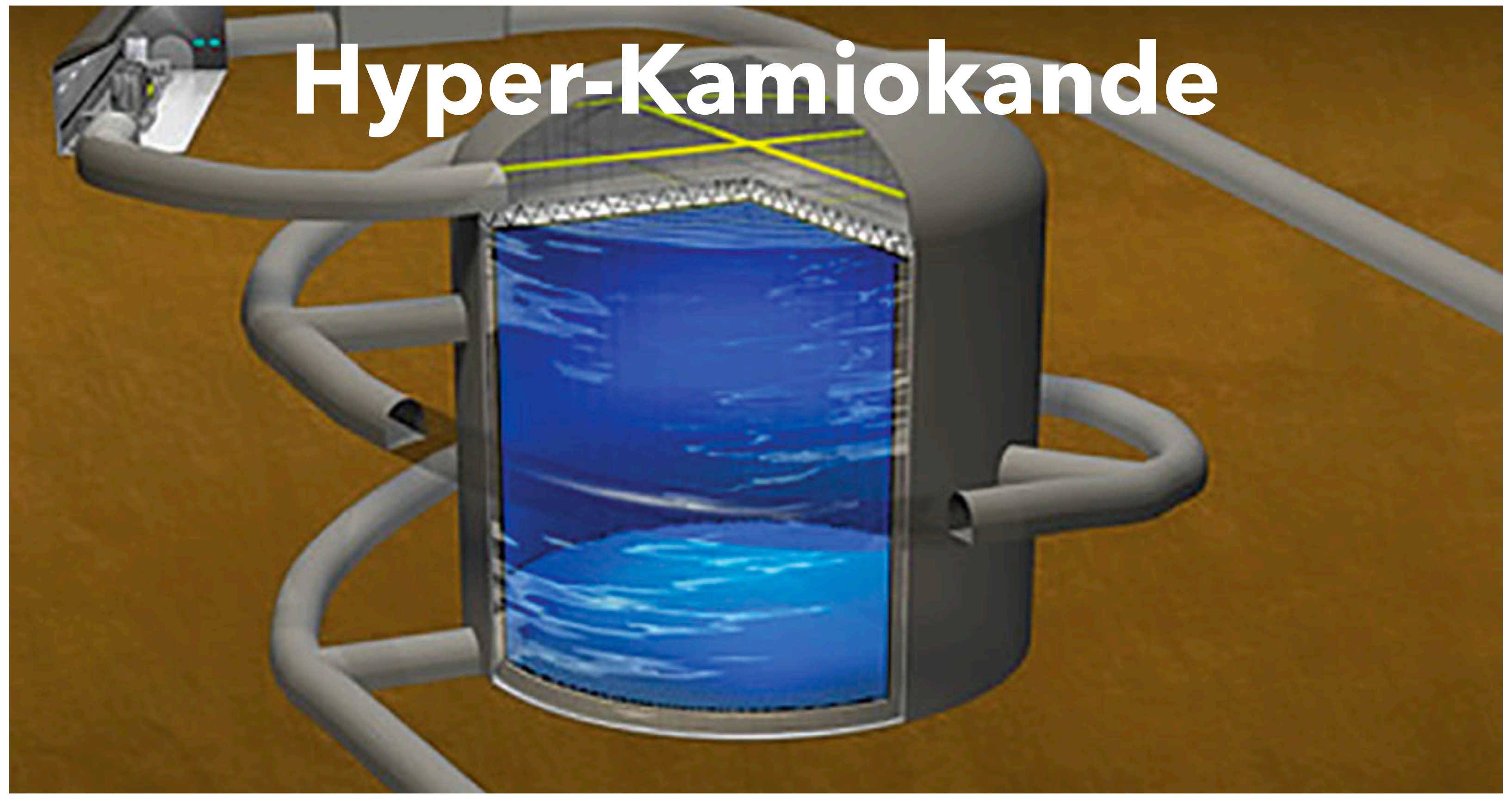

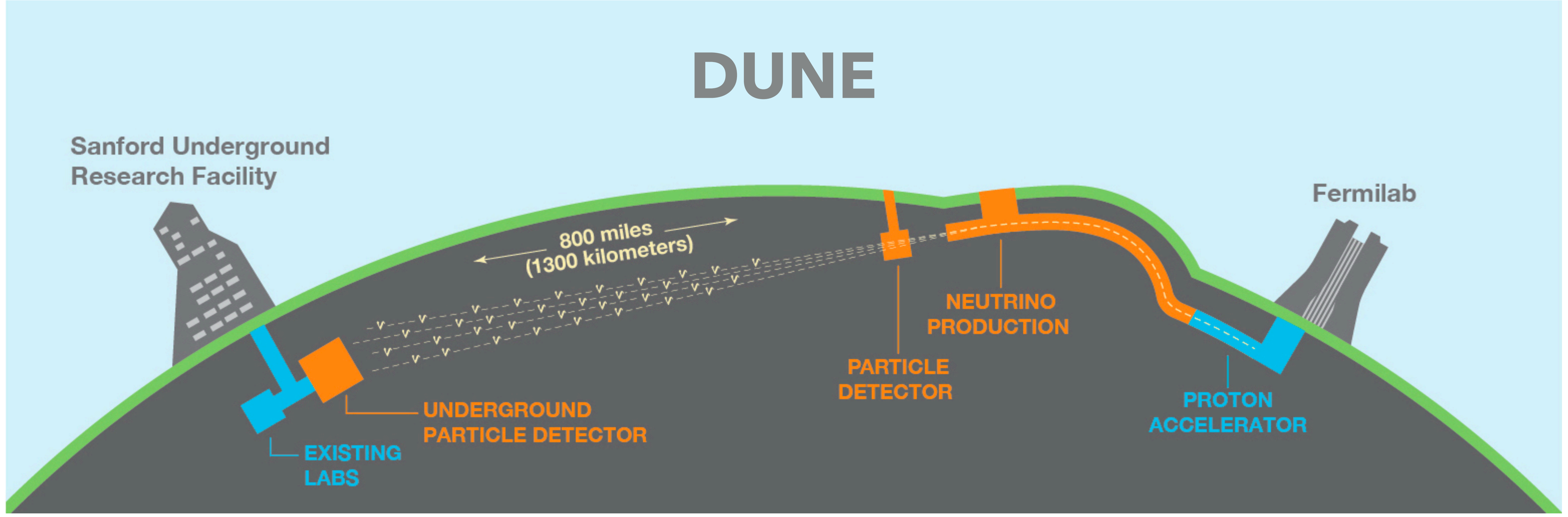

PMNS MATRIX

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP VIOLATION DETECTION IMPLIES DEMONSTRATION OF THE FACT THAT NEUTRINOS AND ANTI-NEUTRINOS OSCILLATE DIFFERENTLY

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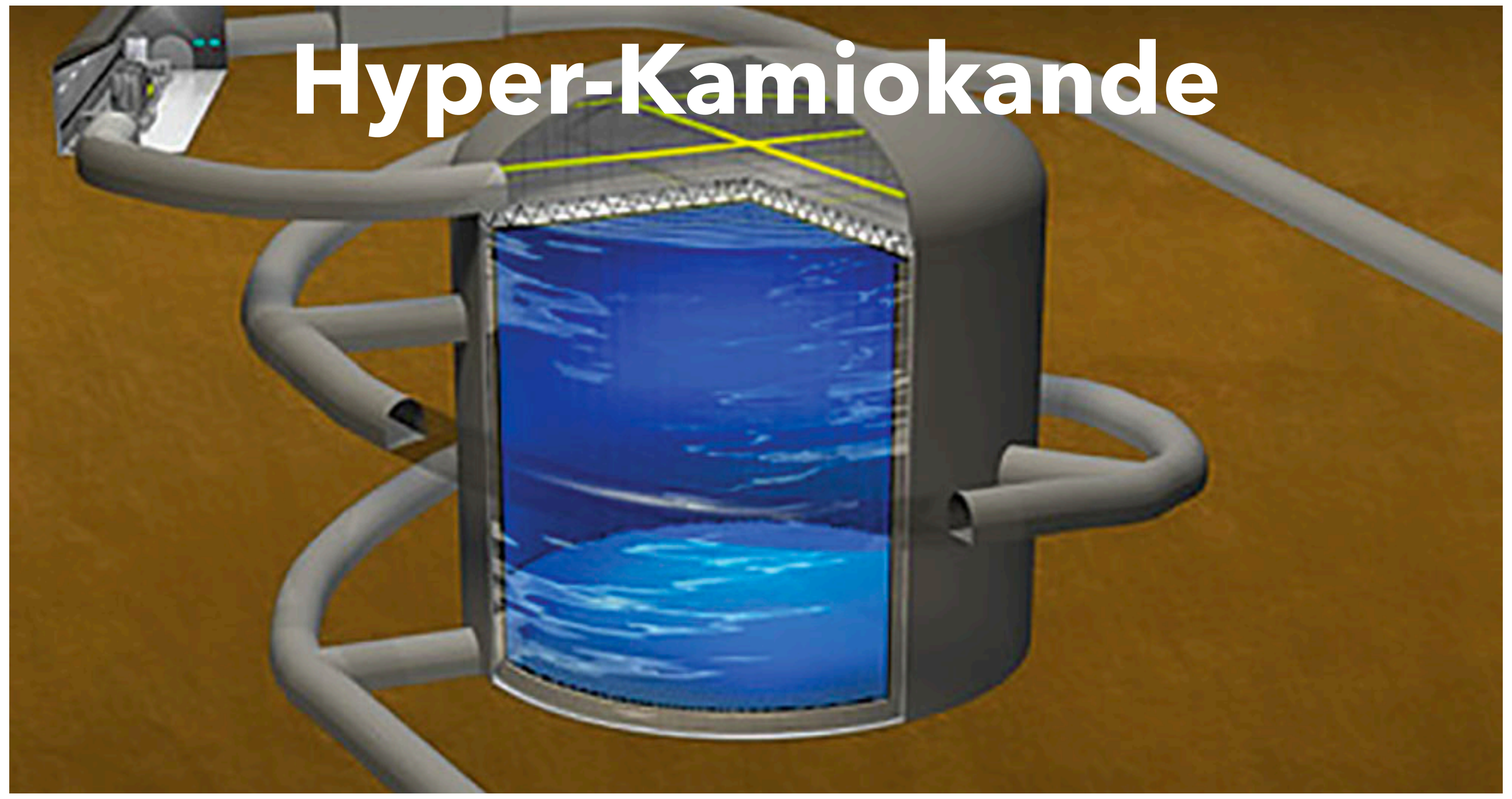

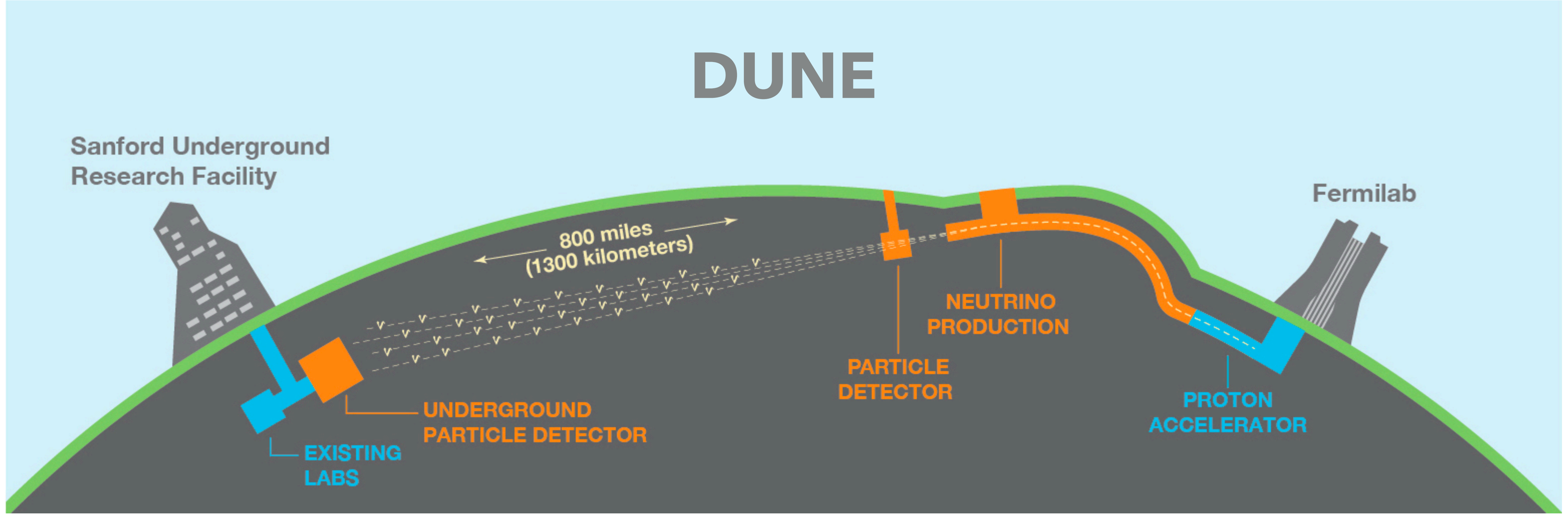

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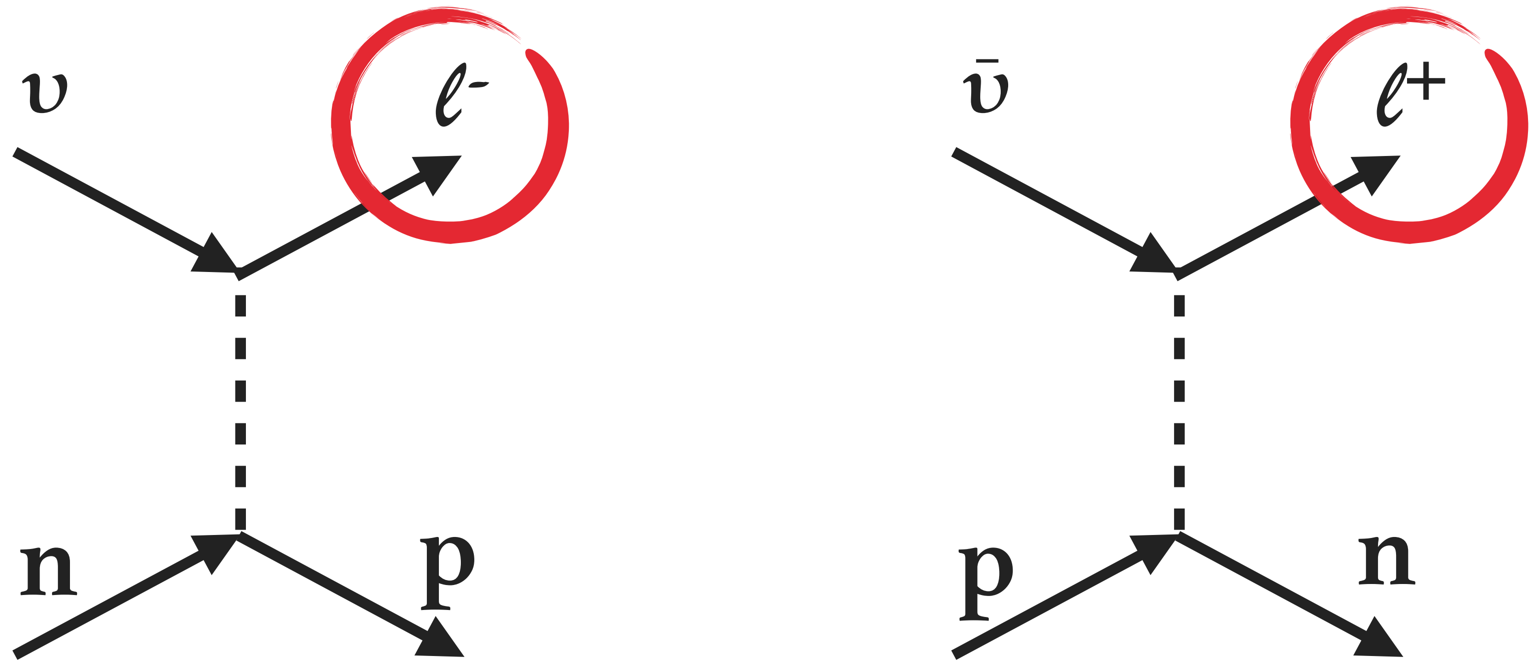
NEUTRINO BEAM EXPERIMENTS CAN RUN IN NEUTRINO OR ANTI-NEUTRINO MODES

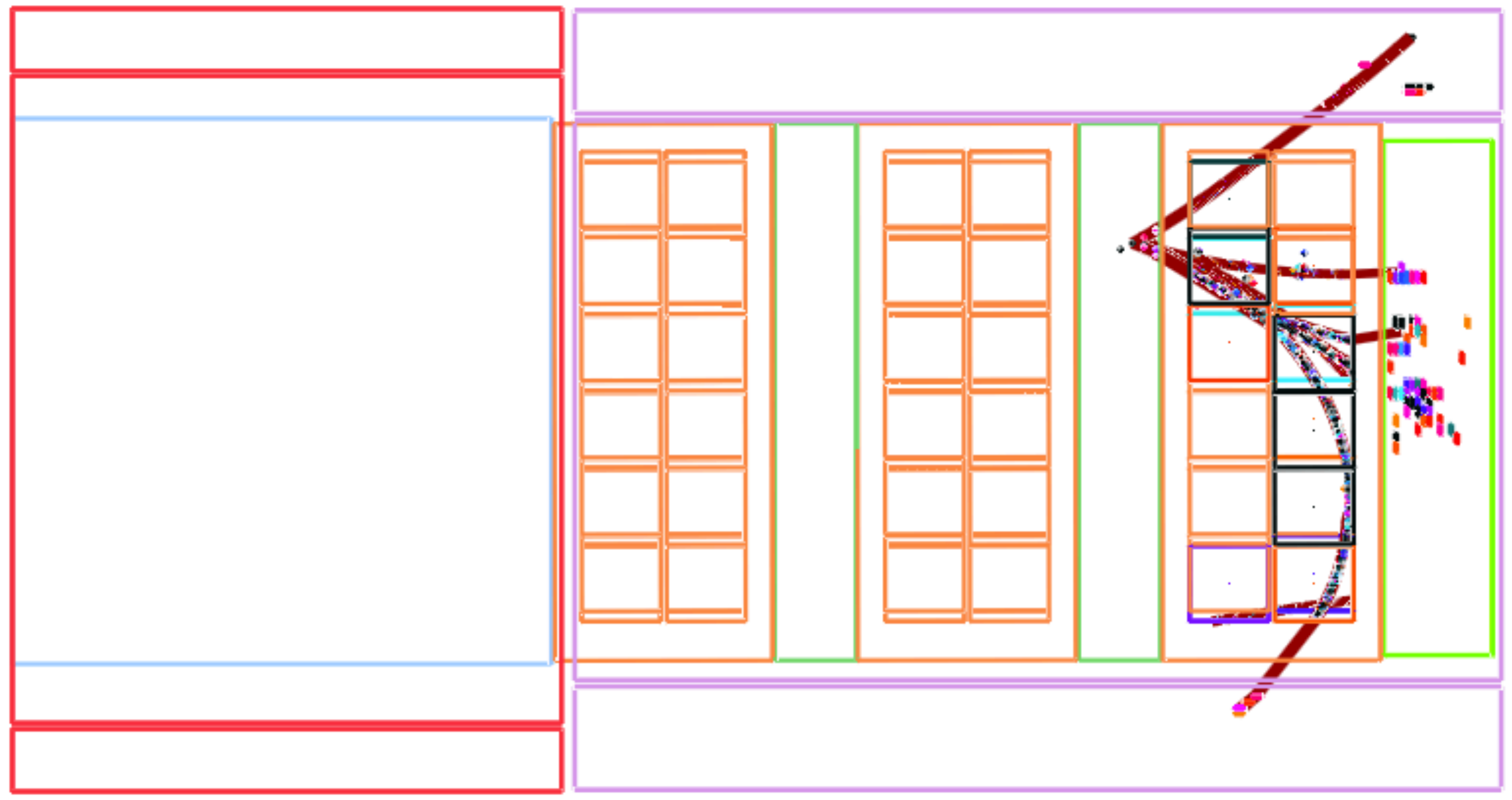
FOR ATMOSPHERIC NEUTRINOS THIS IS NOT POSSIBLE…

CP VIOLATION DETECTION IMPLIES DEMONSTRATION OF THE FACT THAT NEUTRINOS AND ANTI-NEUTRINOS OSCILLATE DIFFERENTLY

NEUTRINO/ANTI-NEUTRINO SEPARATION IN NON-MAGNETIZED DETECTORS



Example of magnetized detector [T2K Tracker]



IN MAGNETIZED DETECTORS WE DETERMINE NEUTRINO LEPTON NUMBER BY MEASURING THE CHARGE OF THE PRODUCED LEPTON

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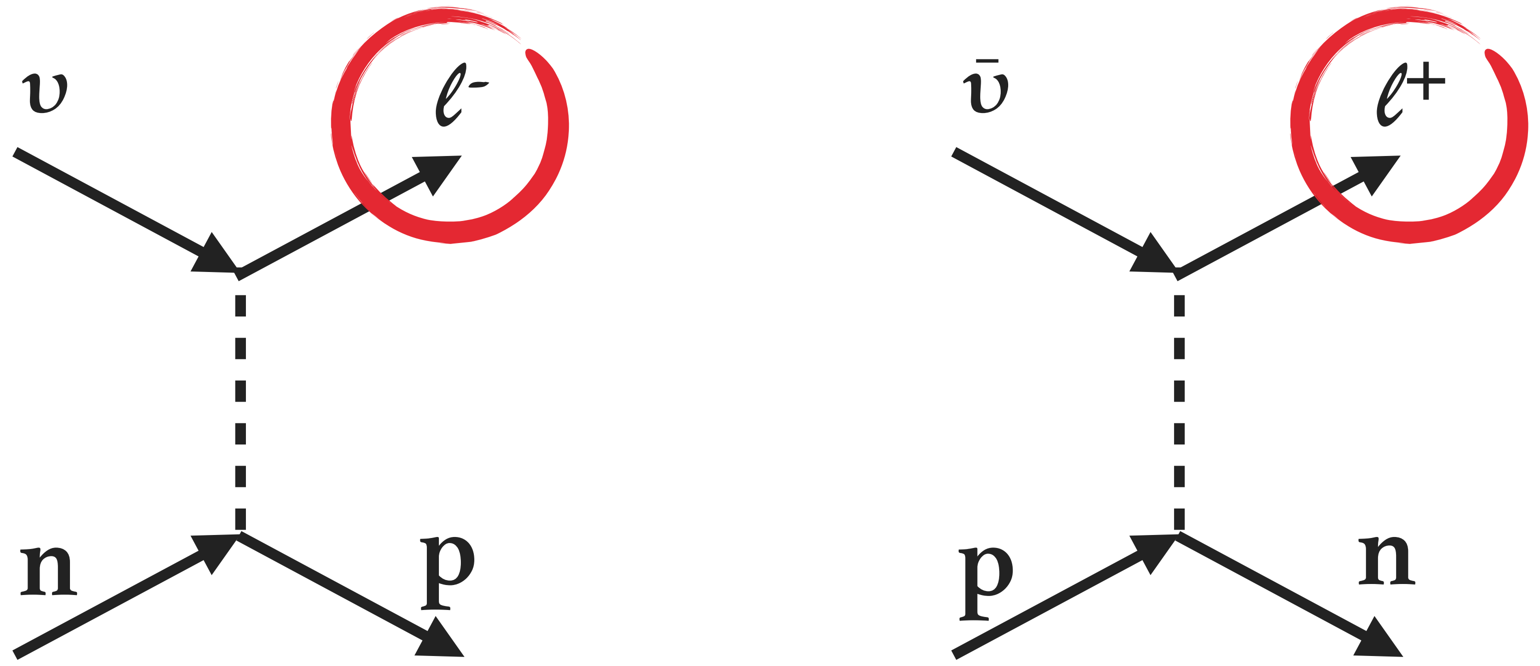

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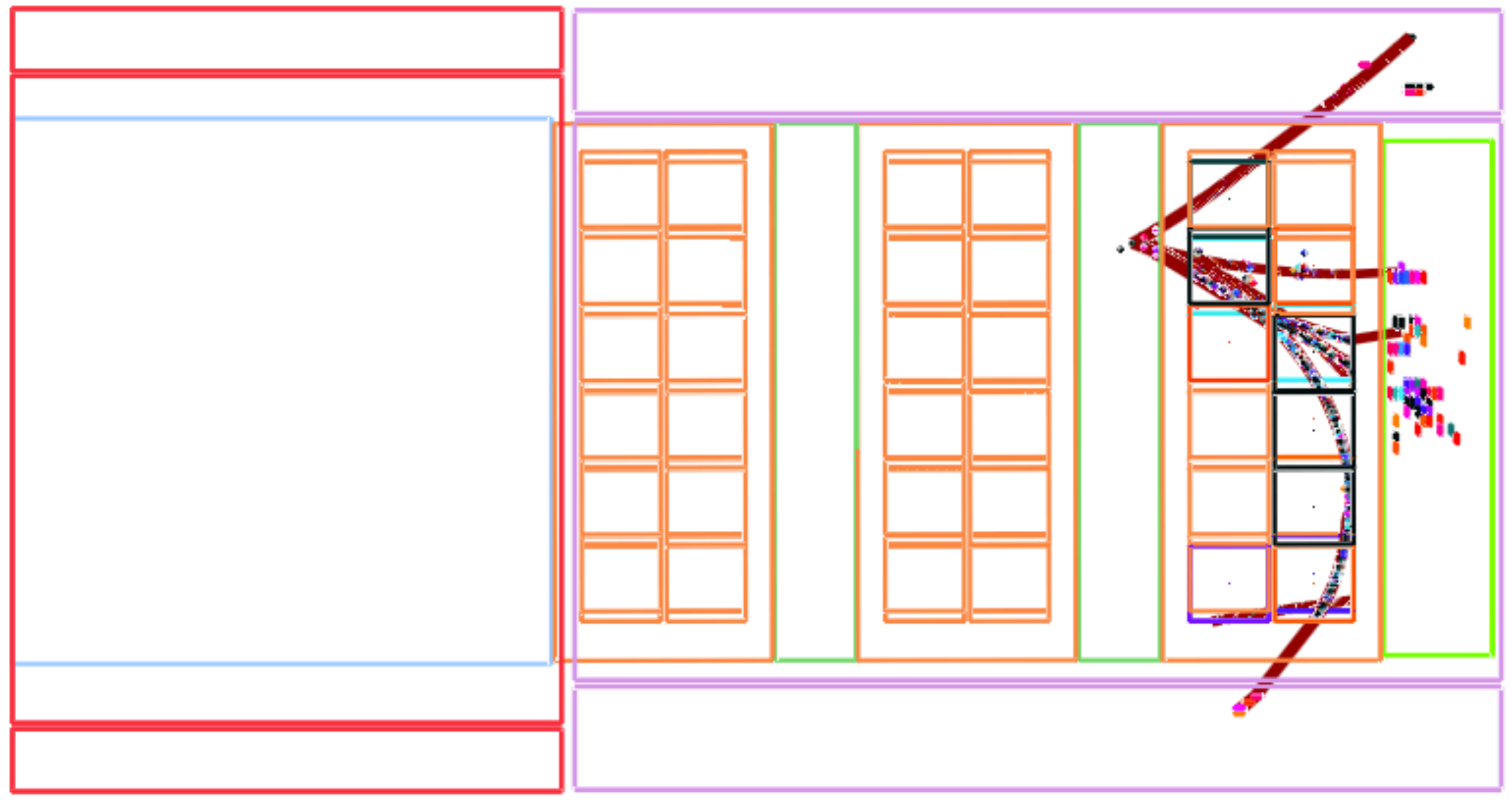

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IN A NON-MAGNETIZED DETECTOR (SK) THIS DOES NOT WORK…

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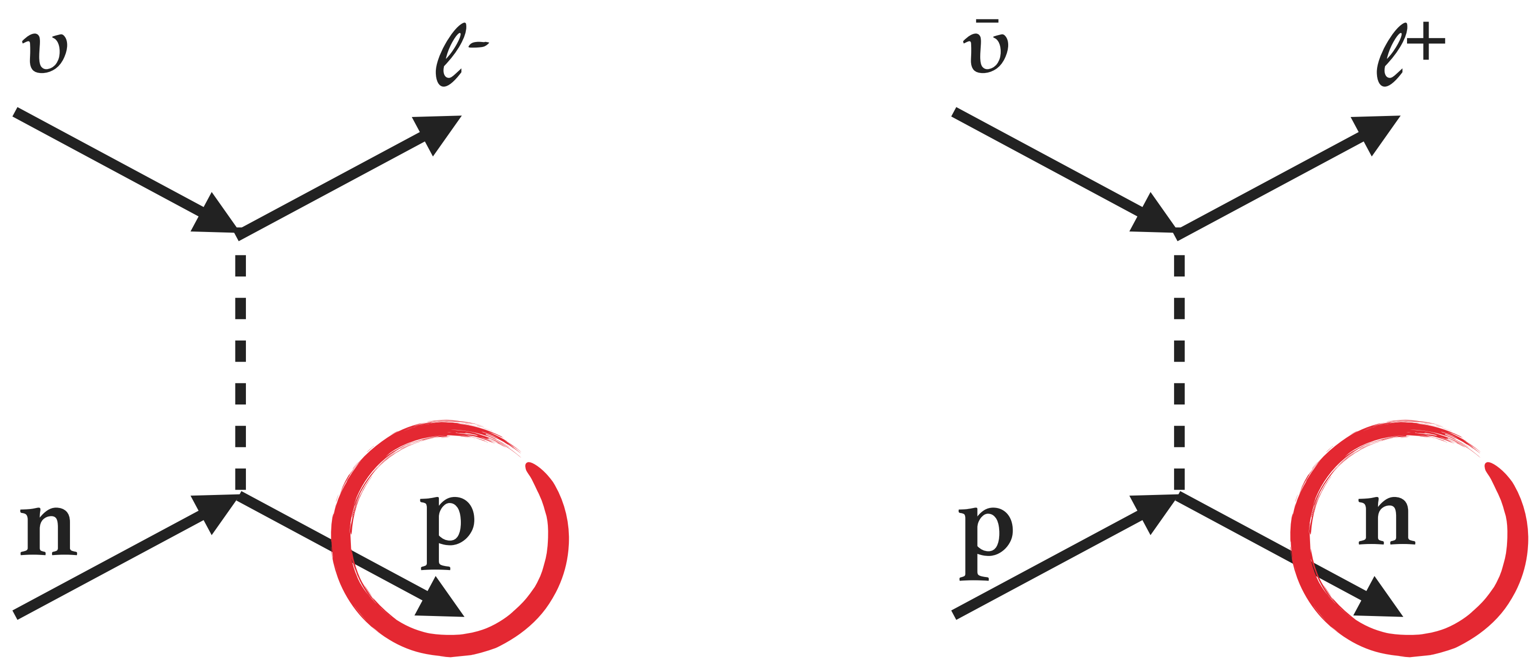

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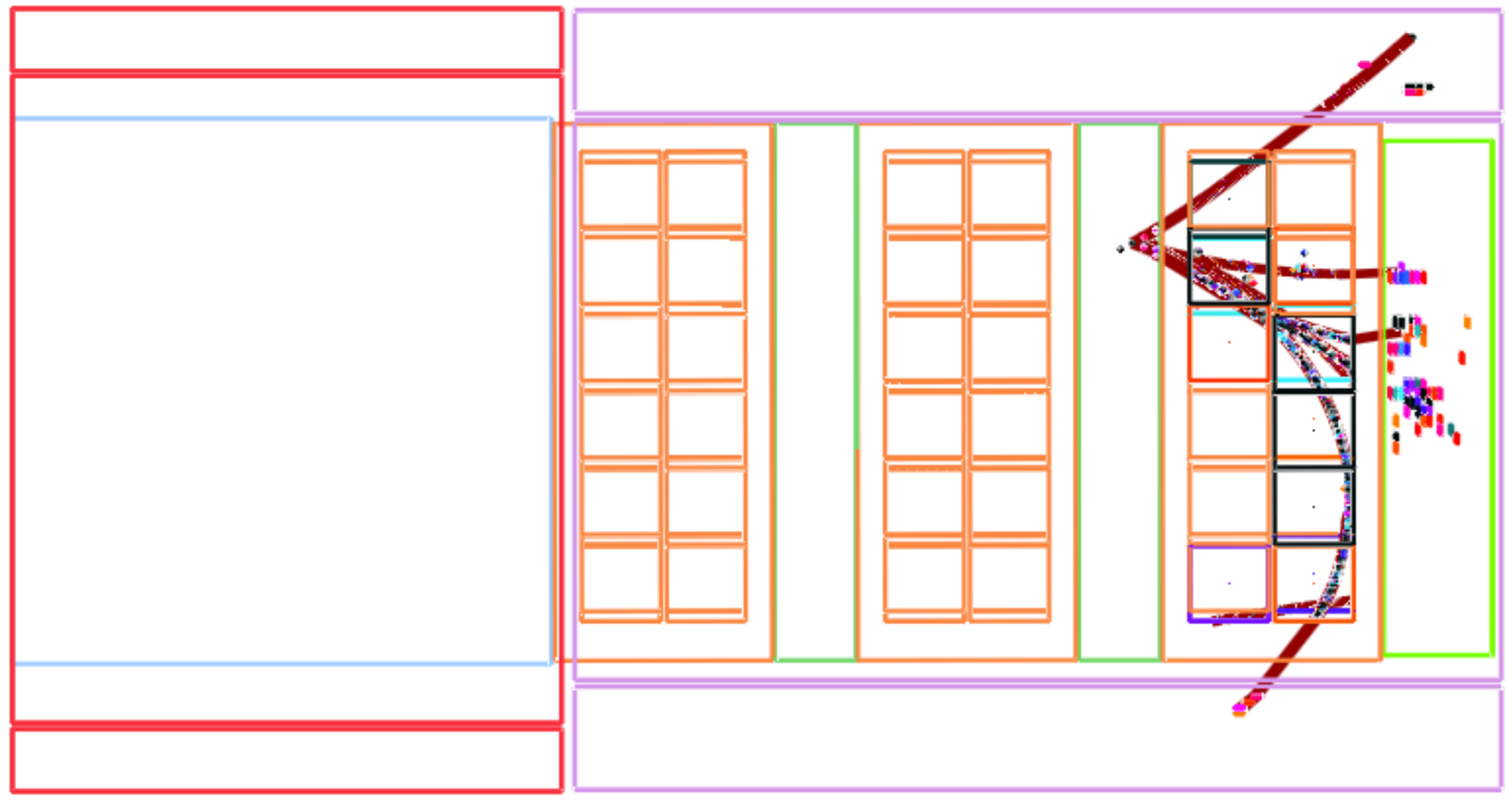

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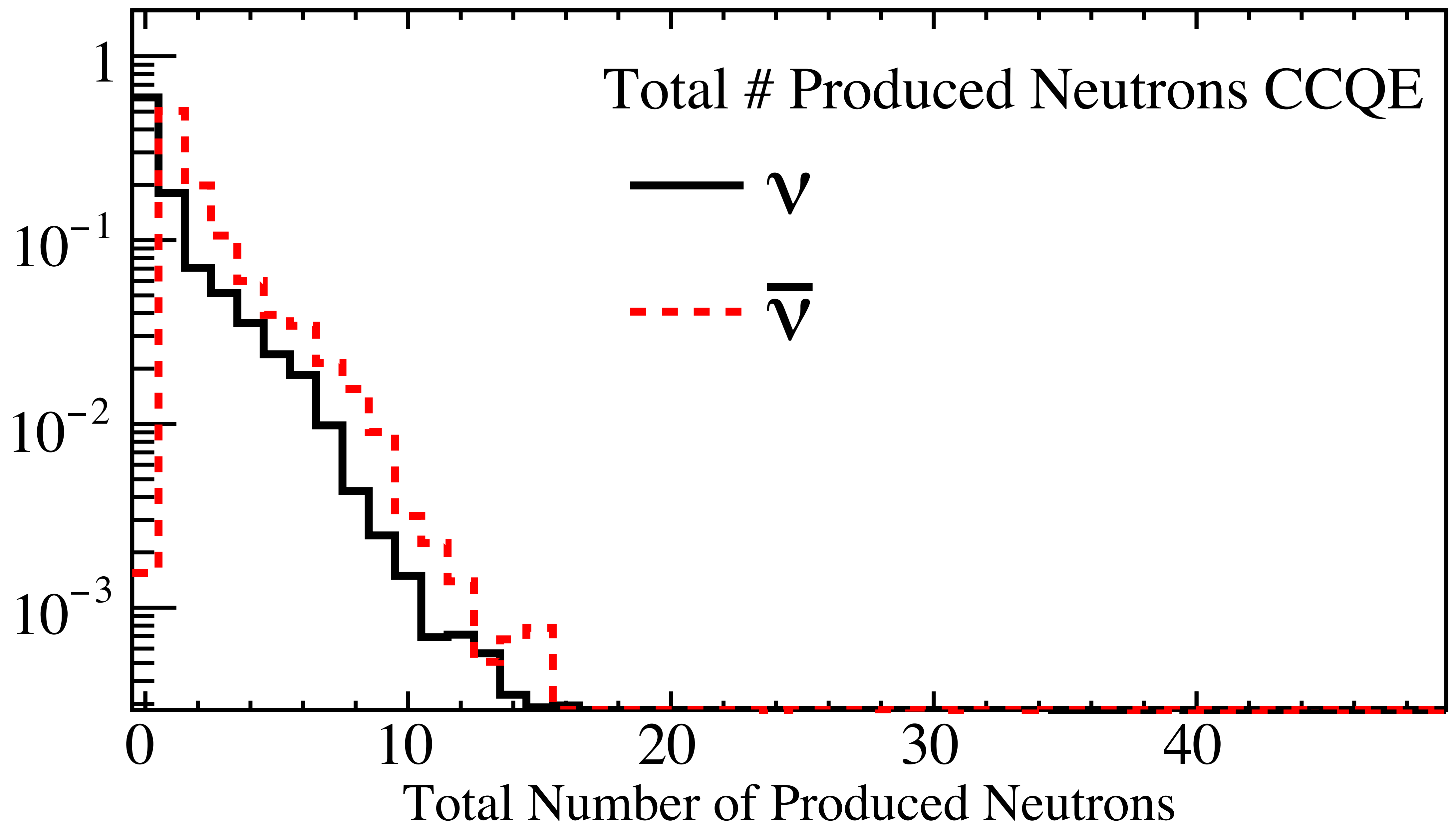

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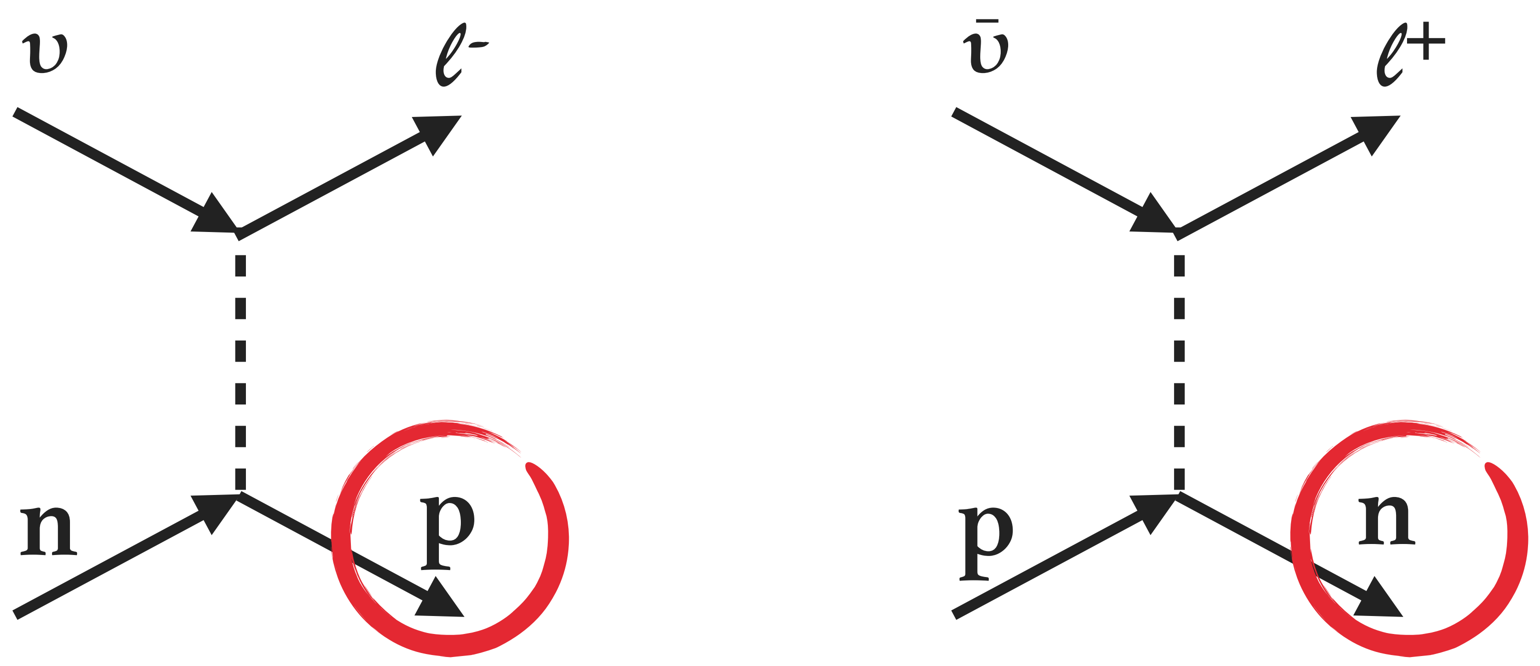

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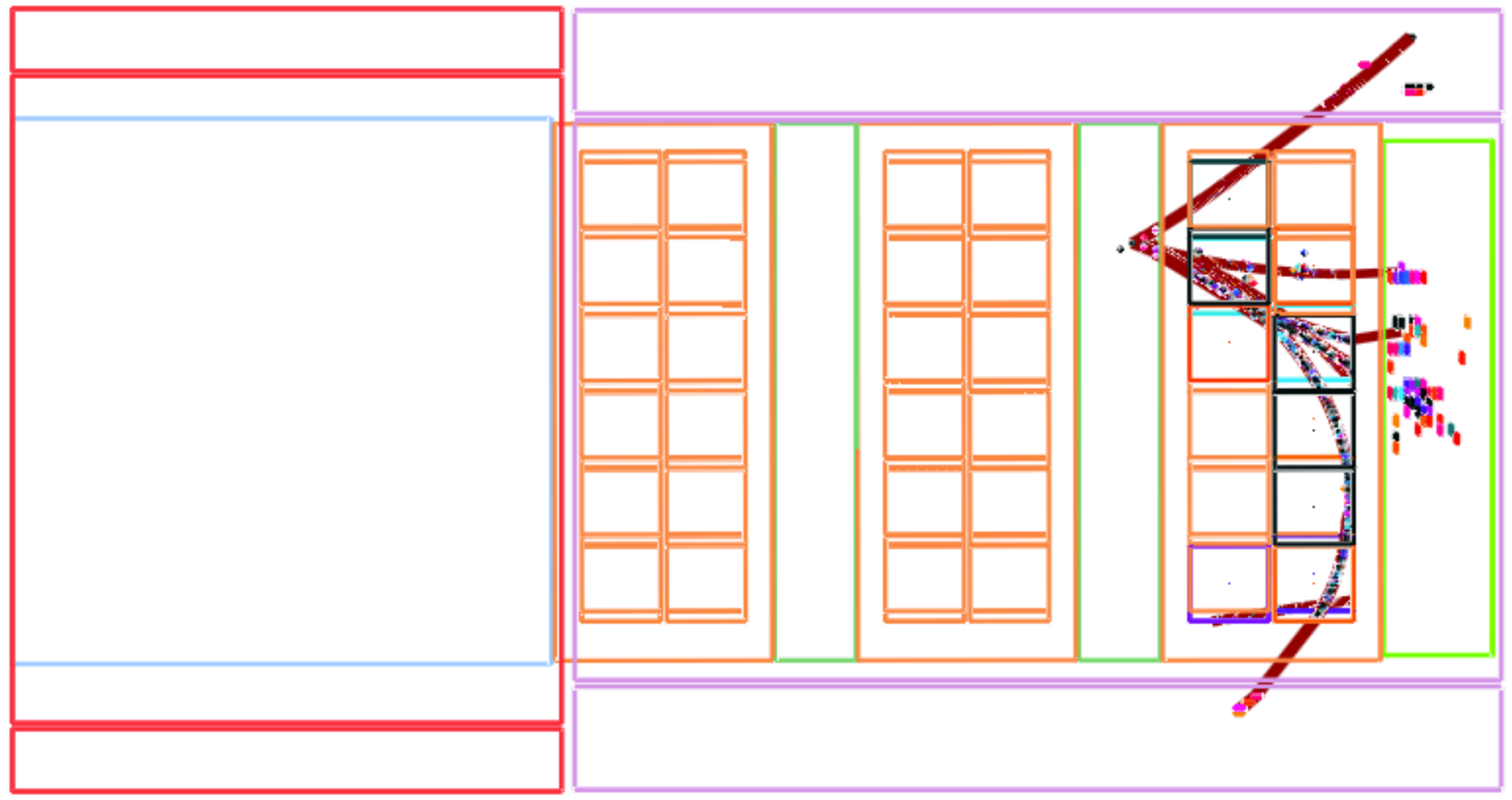

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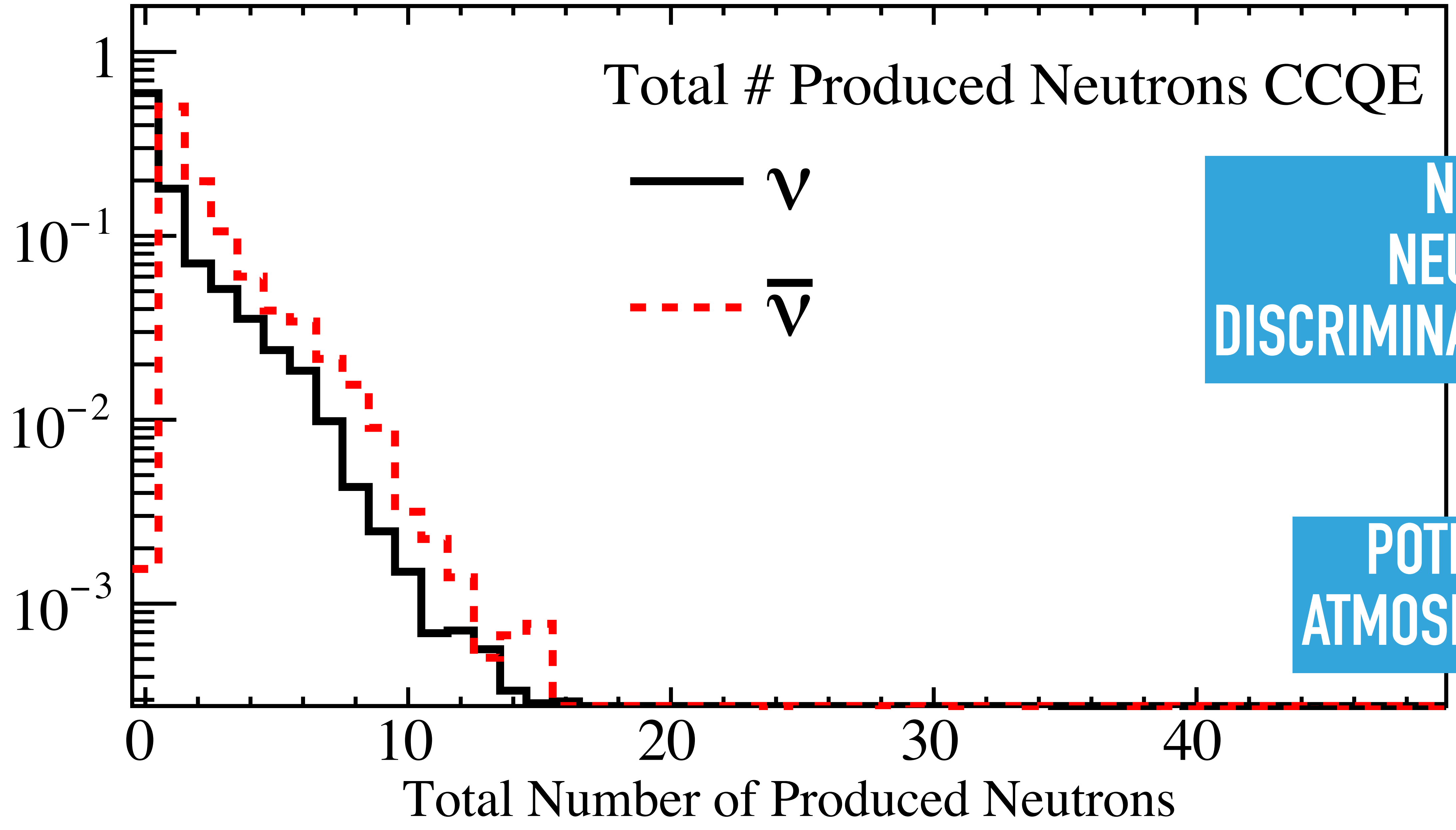
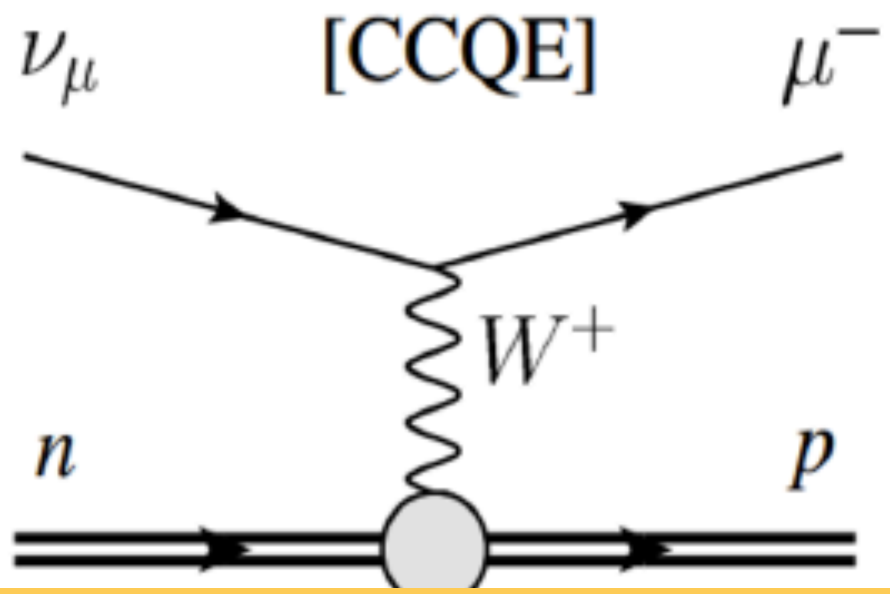
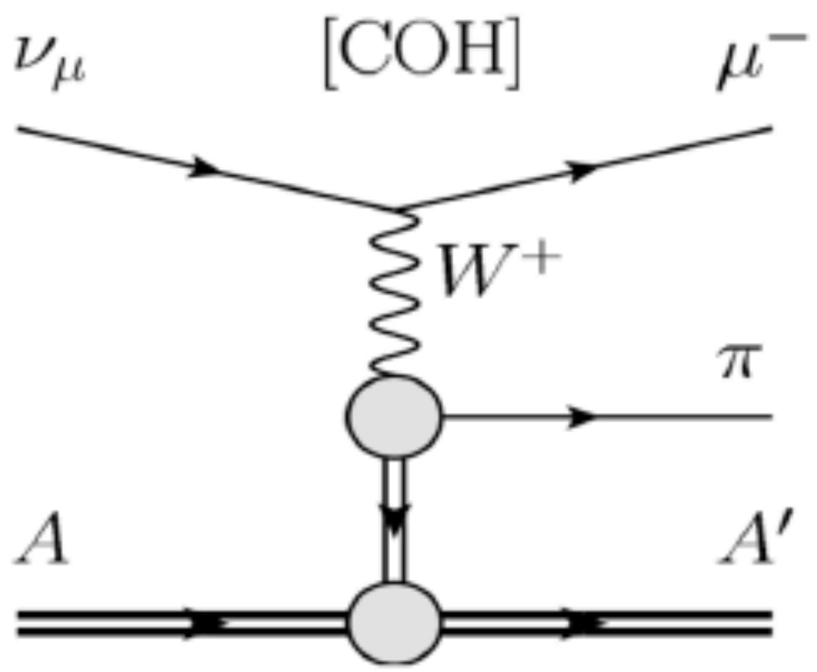


NEUTRON DETECTION ENABLES NEUTRINOS AND ANTI-NEUTRINOS DISCRIMINATION IN NON-MAGNETIZED DETECTORS

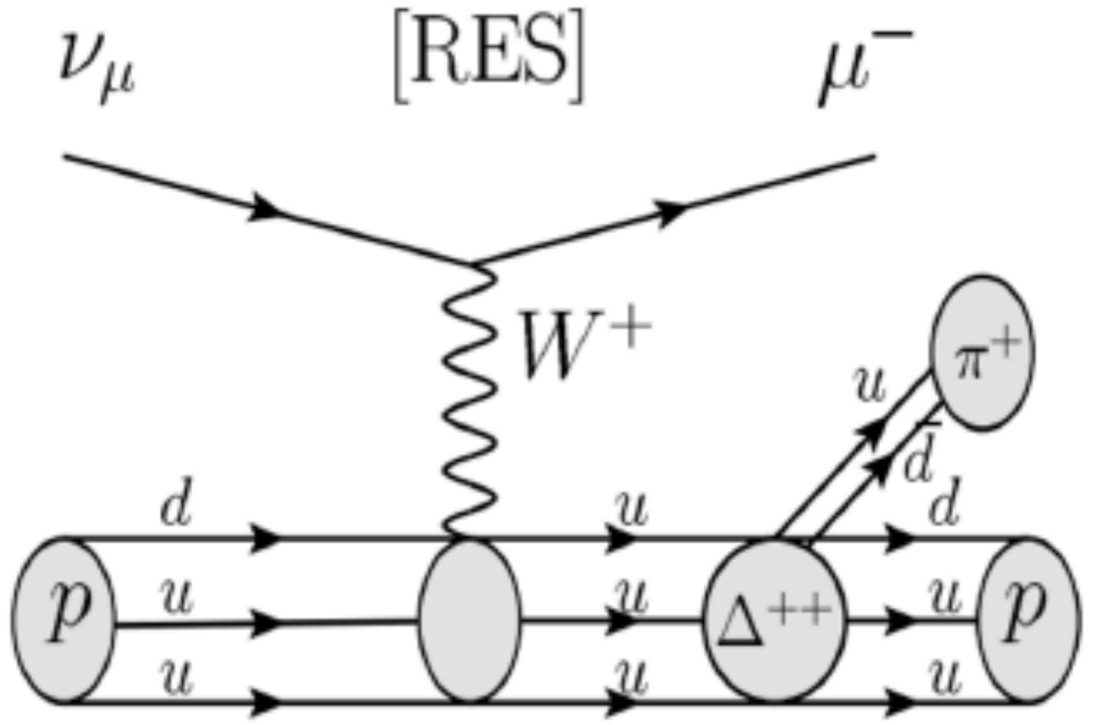
POTENTIAL FOR CP VIOLATION FROM ATMOSPHERIC NEUTRINO MEASUREMENTS

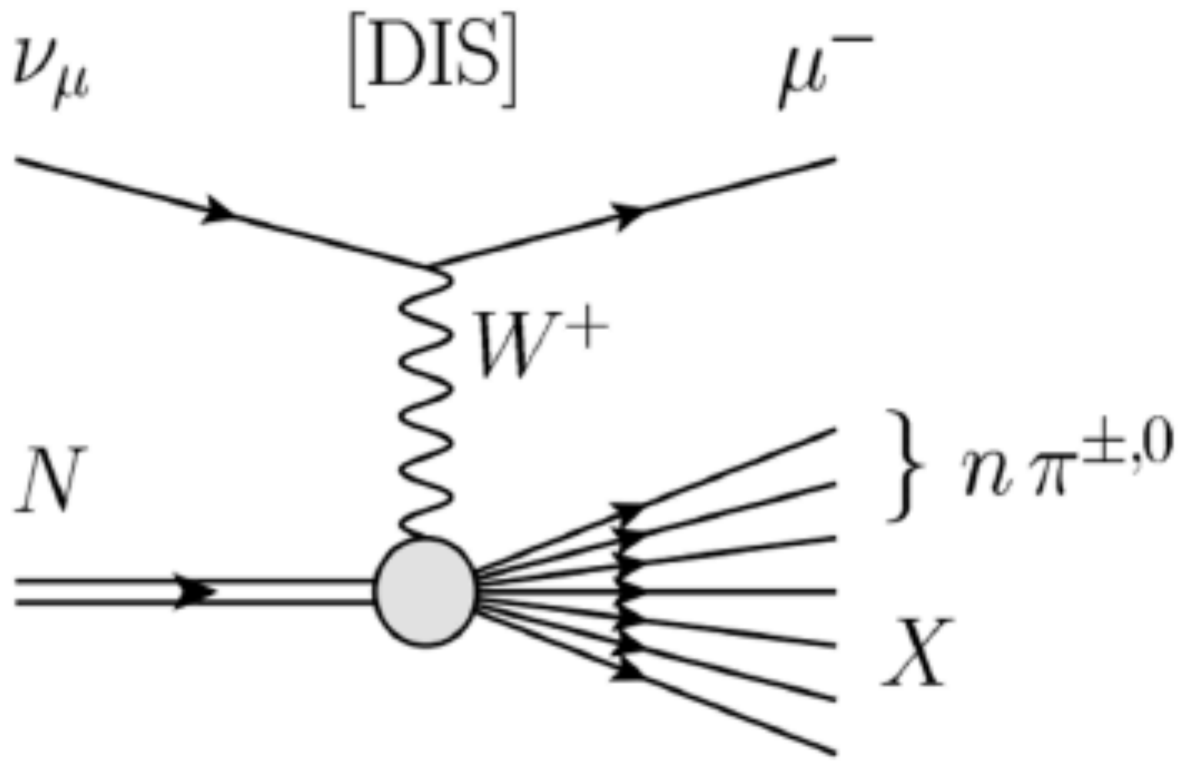
POTENTIAL FOR NEUTRINO INTERACTION CLASSIFICATION





CCQE IS A VERY IMPORTANT CHANNEL FOR NEUTRINO ENERGY RECONSTRUCTION AND HENCE NEUTRINO OSCILLATION MEASUREMENTS





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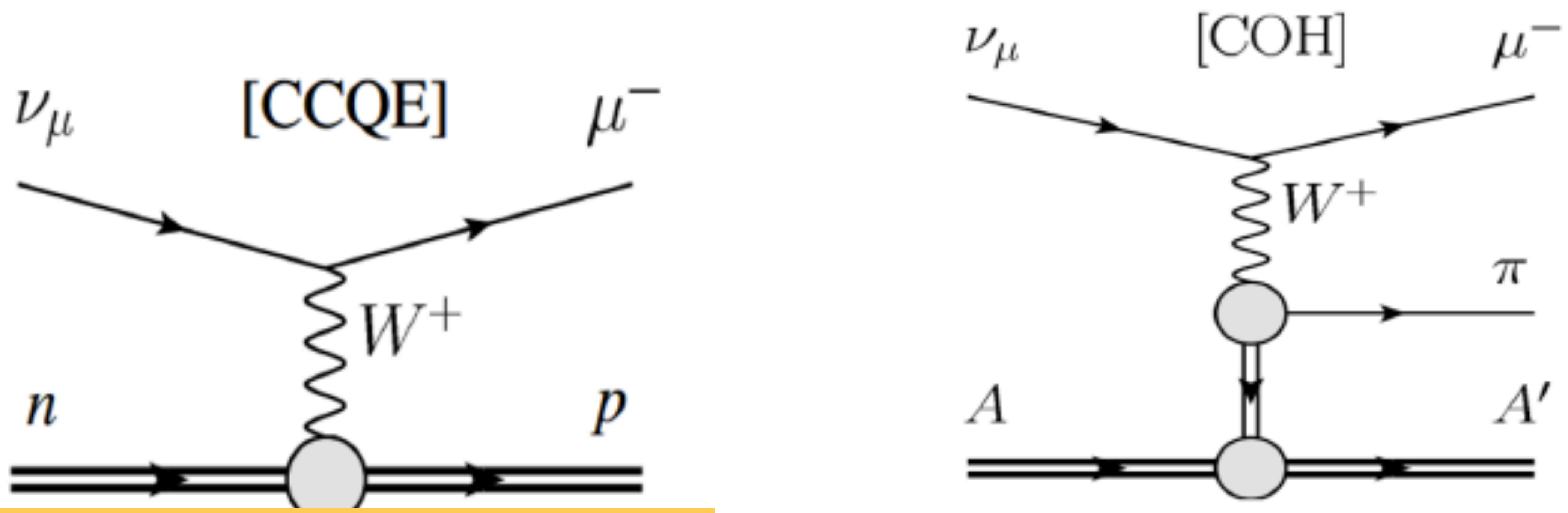

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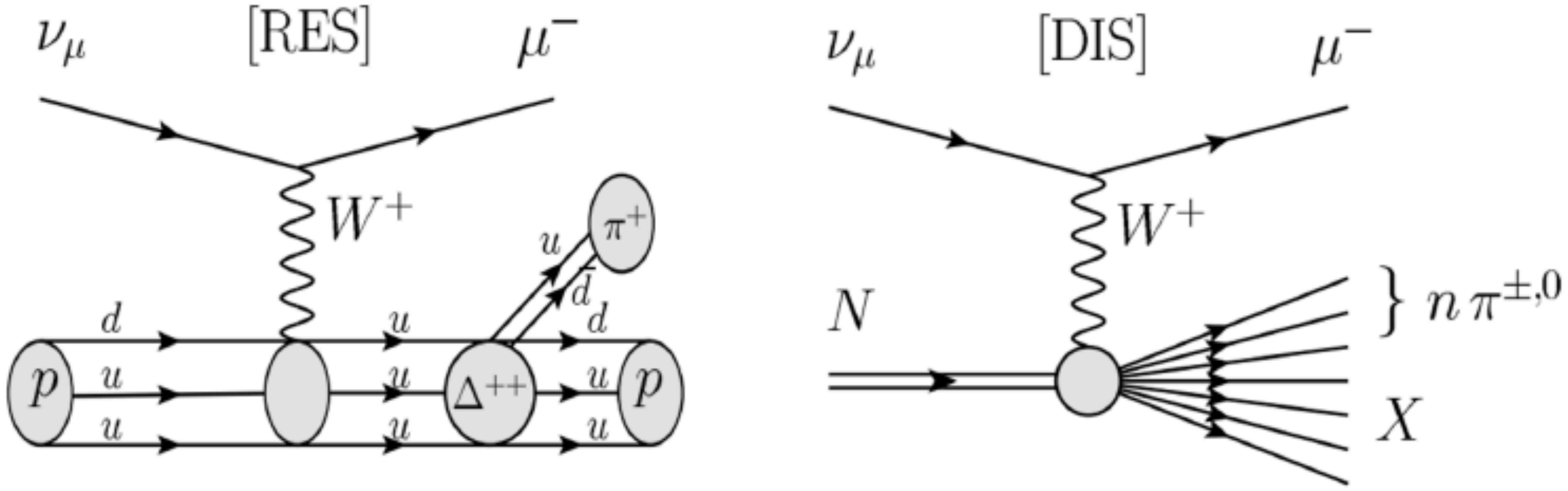
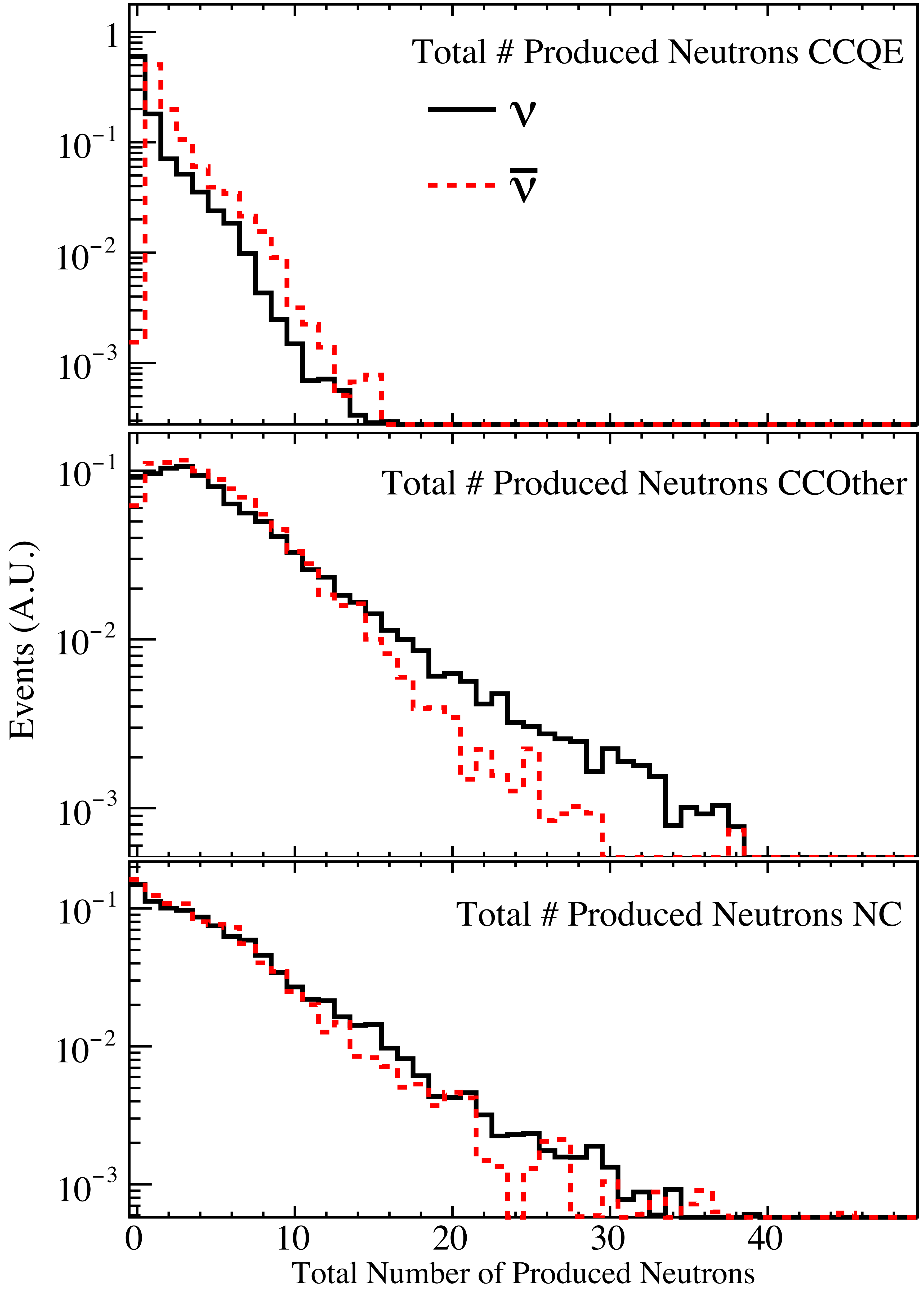
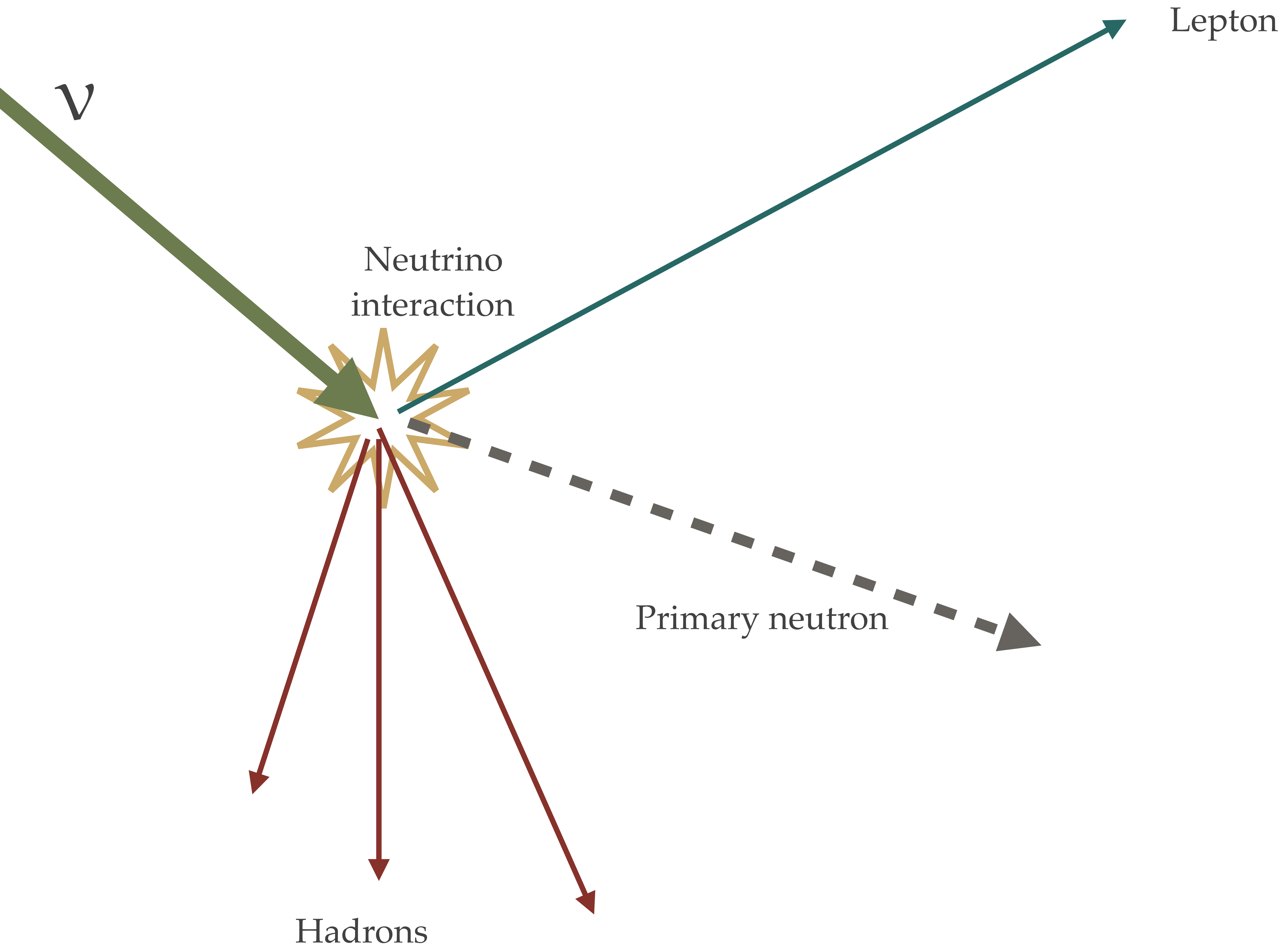




DIFFERENT NEUTRINO INTERACTION MODES PRODUCE DIFFERENT NUMBER OF NEUTRONS

CLEARLY DISTINGUISH BETWEEN CCQE AND OTHERS

NEUTRON PRODUCTION MECHANISM IS COMPLICATED



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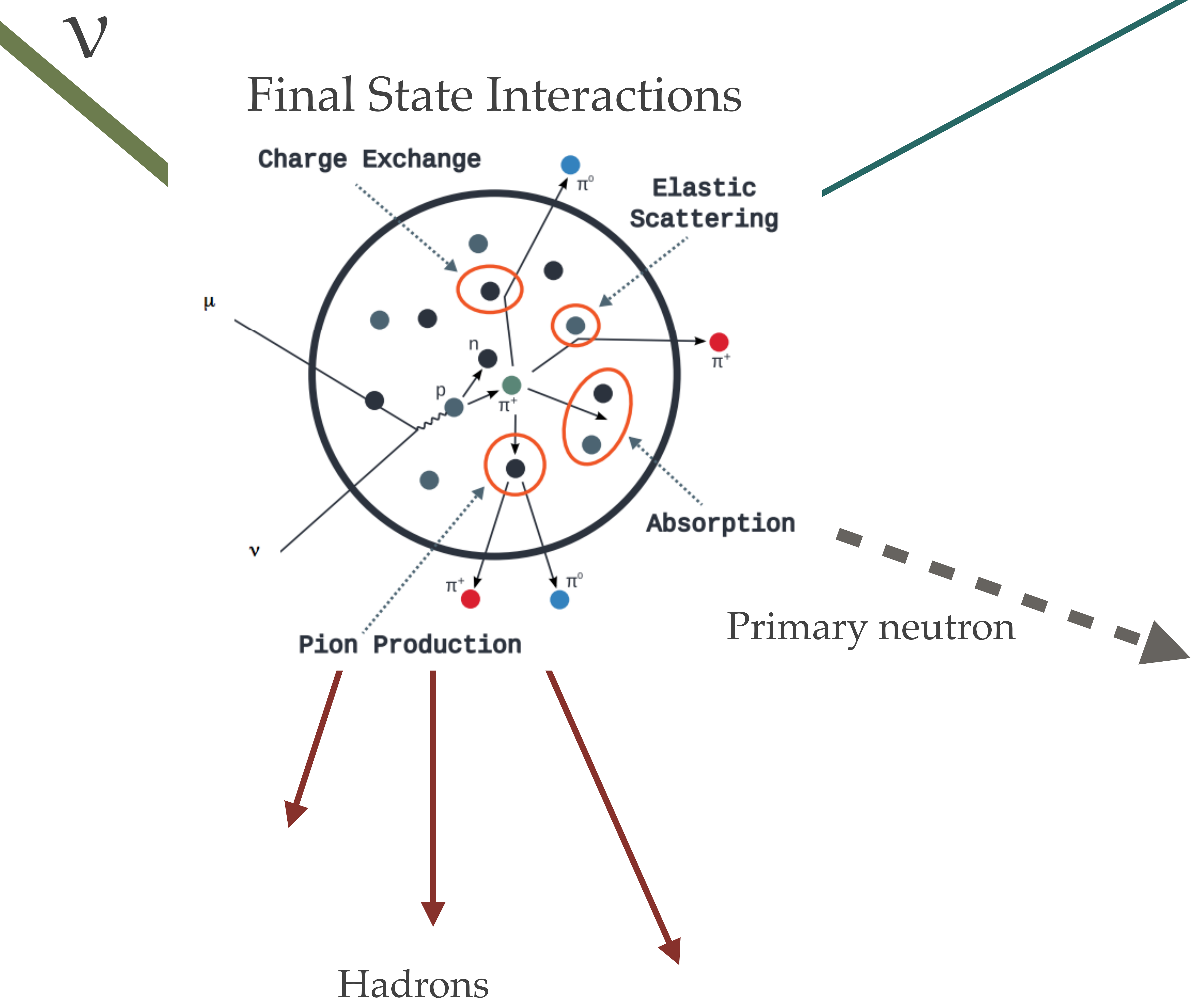

GENIE + GEANT4 simulation of atmospheric neutrinos in heavy water

Neutron origin	Fraction
Neutrino interaction	33.0(0.2)%

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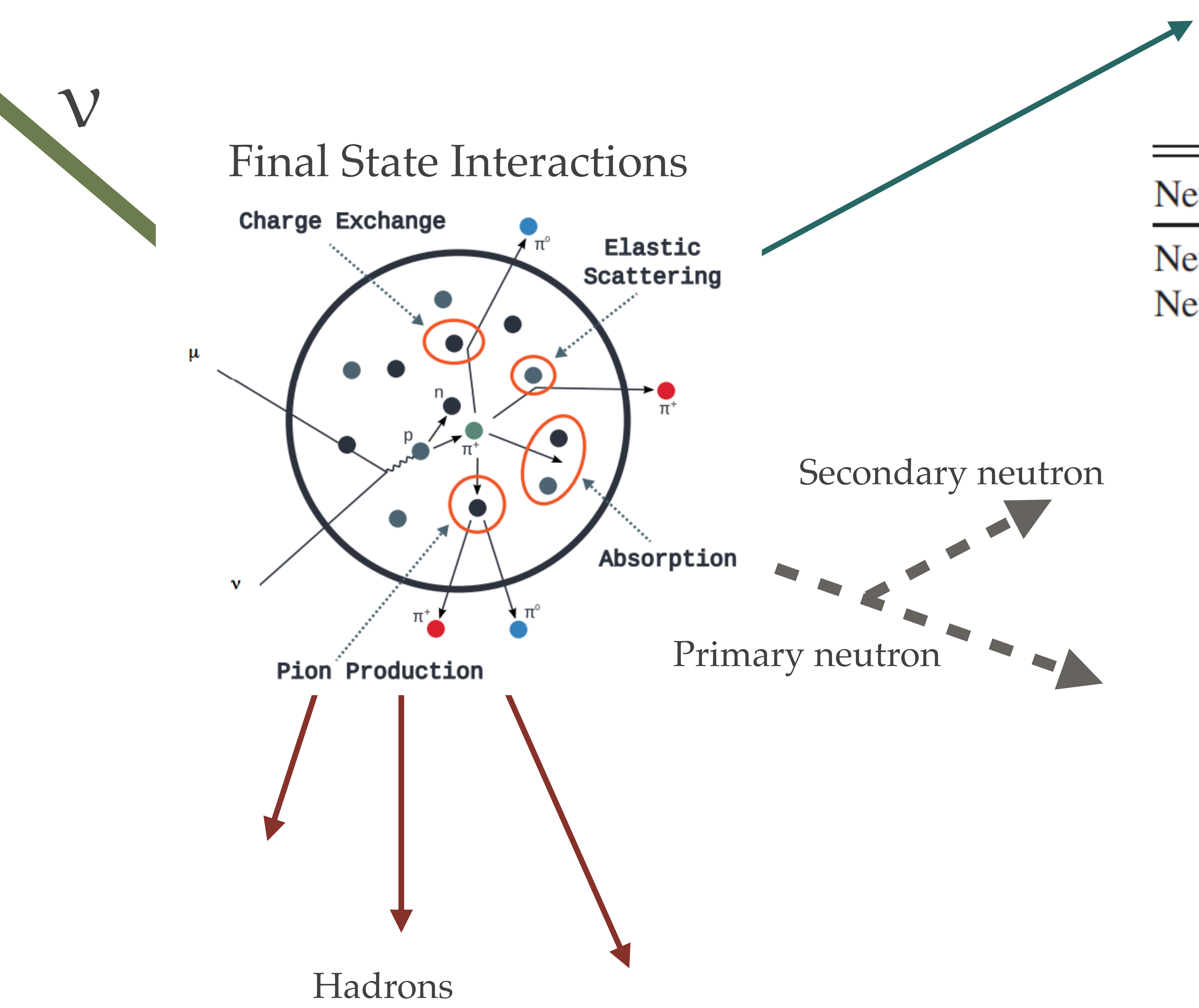

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Neutron inelastic	34.9(0.2)%

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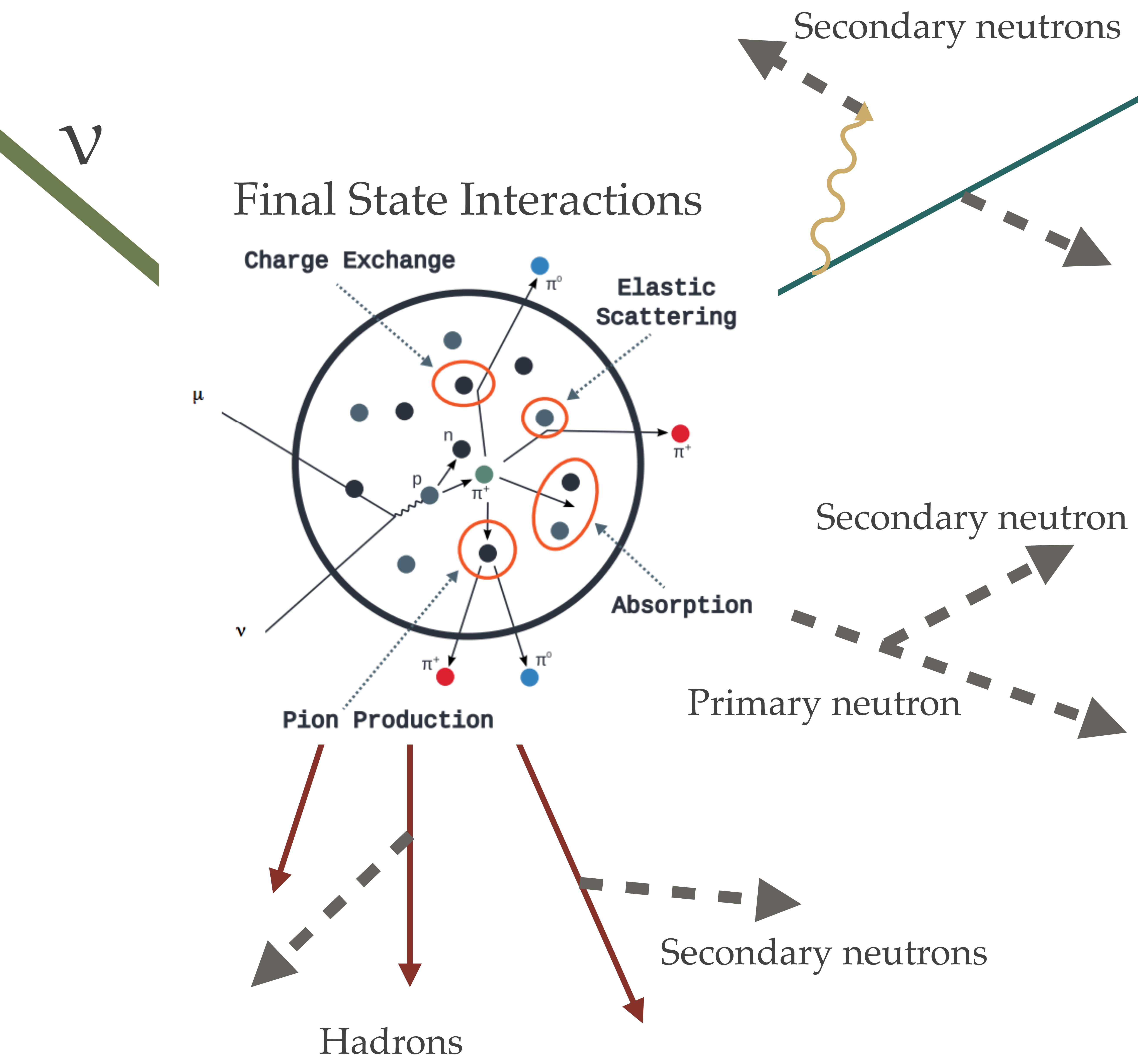

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π/K inelastic	15.0(0.1)%
Proton inelastic	7.3(0.1)%
Hadron capture at rest	6.4(0.1)%
μ capture at rest	2.20(0.04)%
Photonuclear	0.90(0.02)%
Other	0.29(0.01)%

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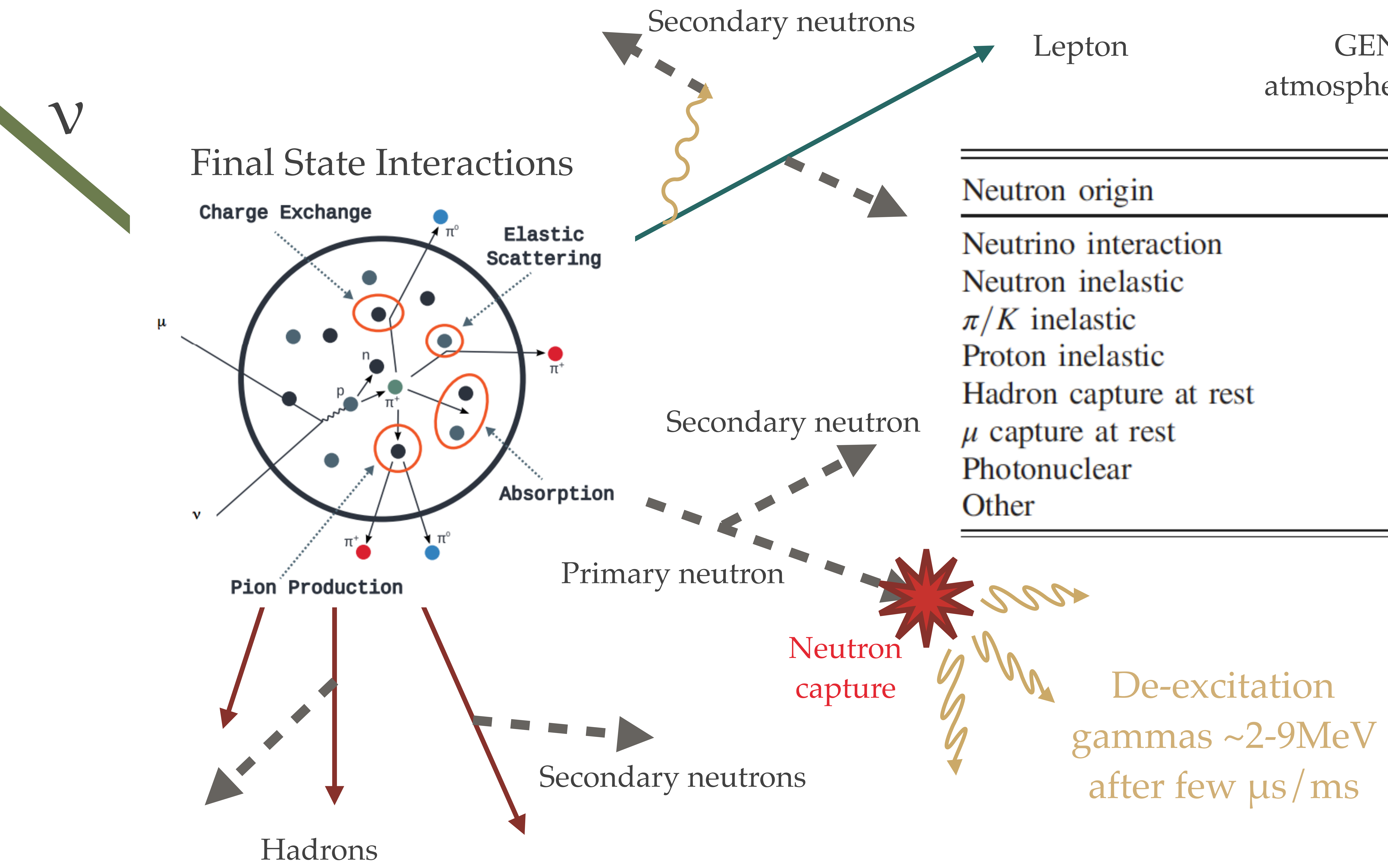

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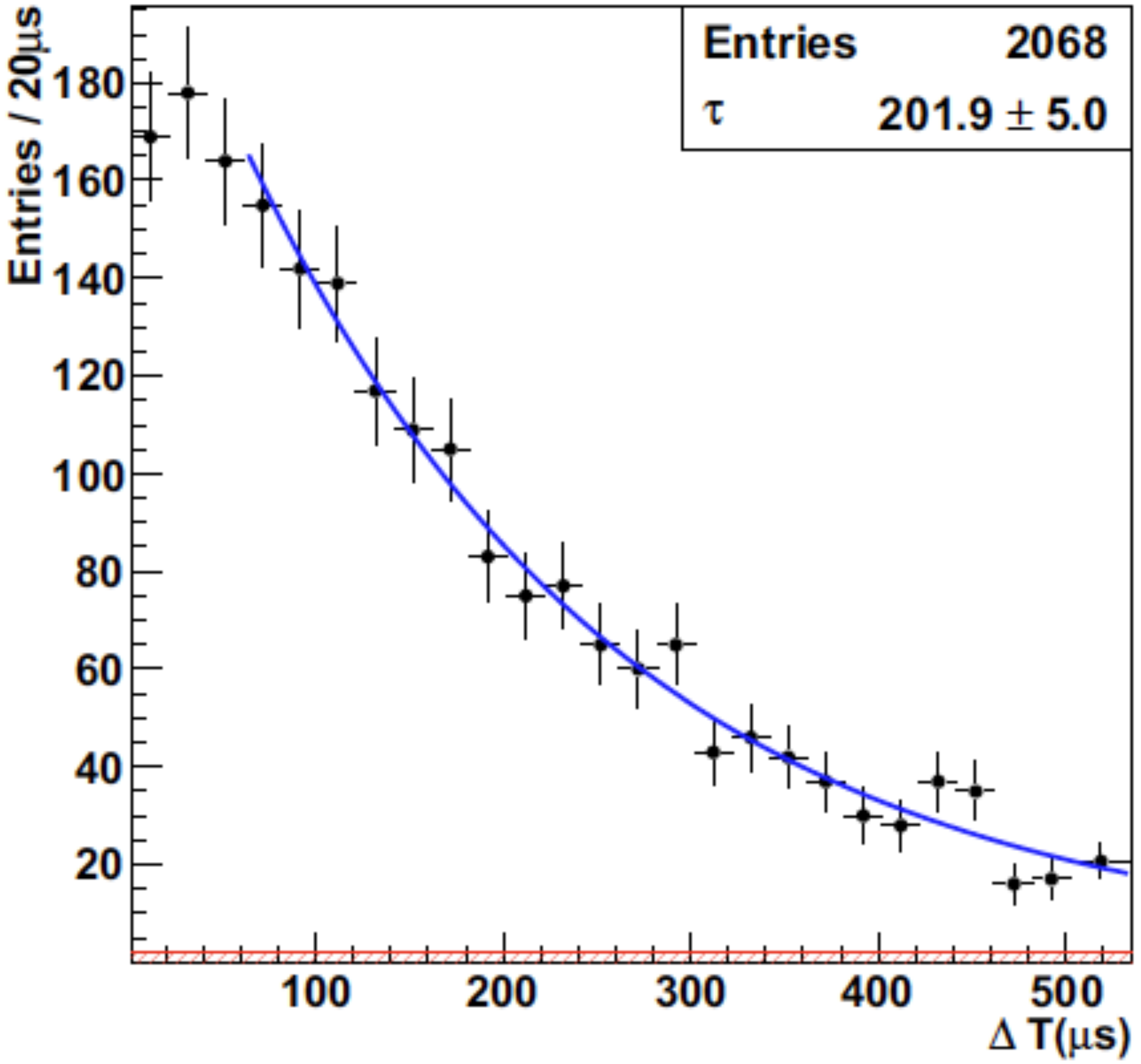
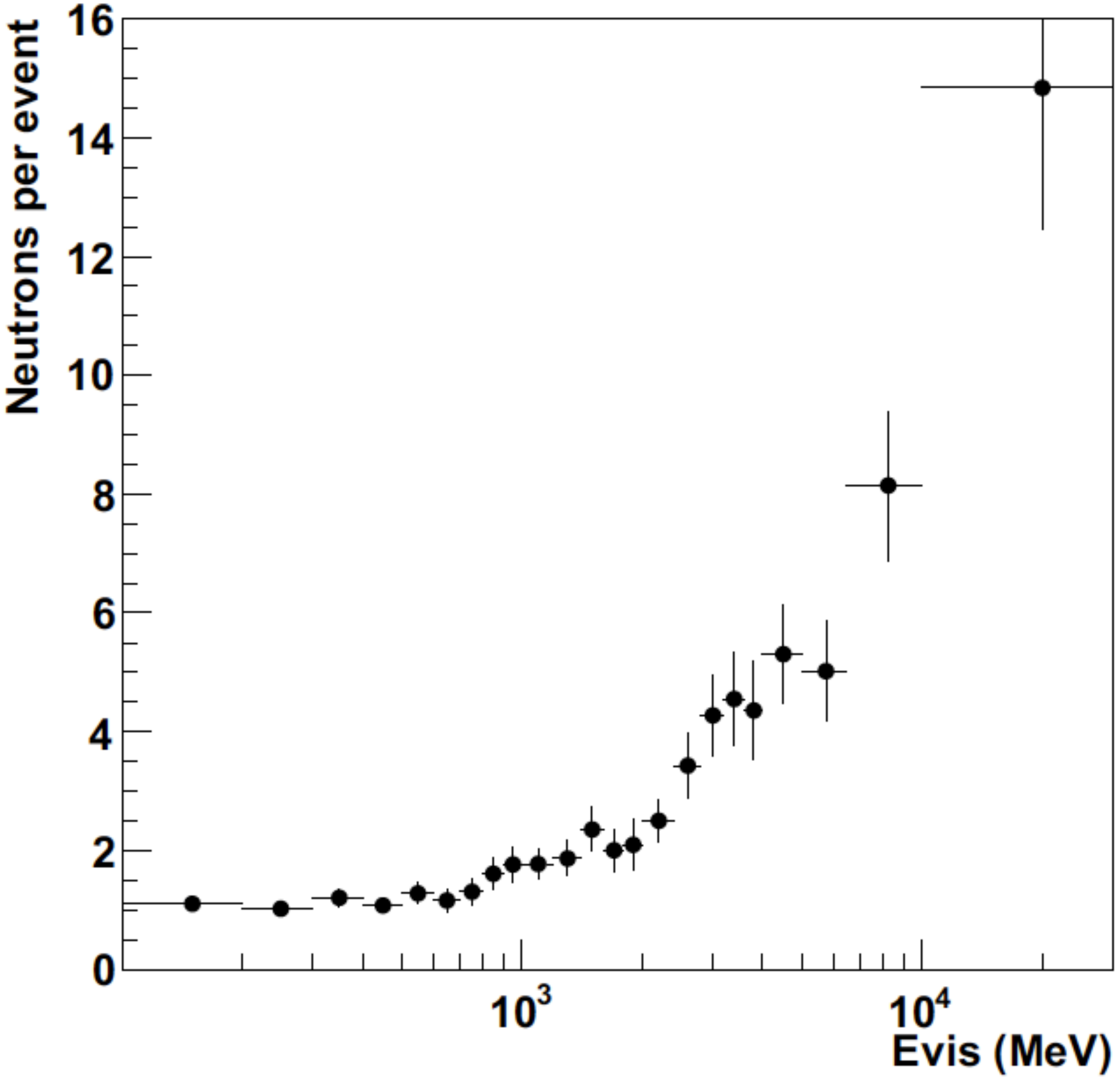
SUPER-KAMIOKANDE DEMONSTRATED NEUTRON DETECTION IN LIGHT WATER

Time difference between atmospheric event and neutron capture in light water



Averaged number of neutrons vs atmospheric neutrino visible energy



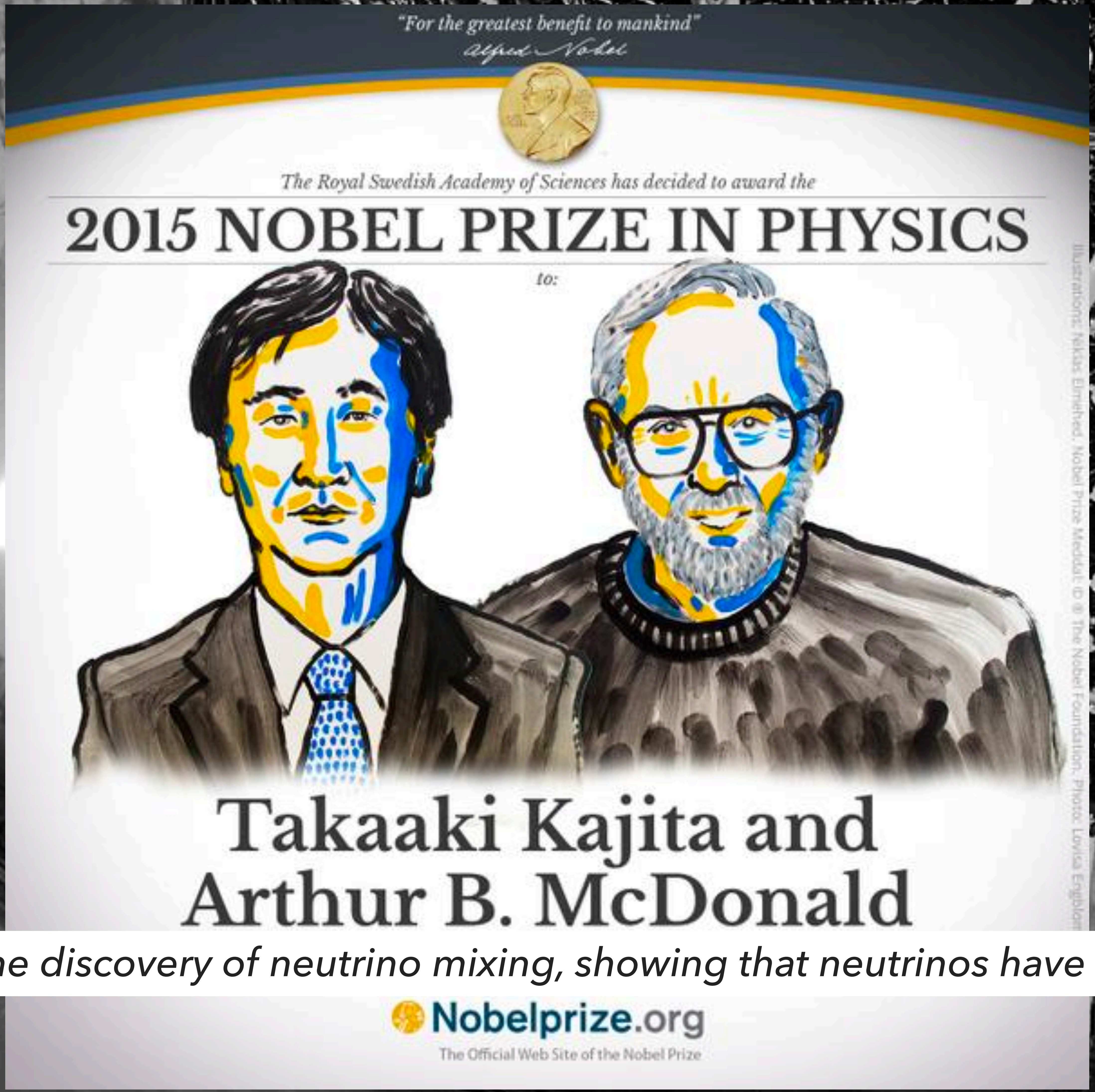
Source: Proceedings of the 32nd International Cosmic Ray Conference, Beijing, 2011

http://inspirehep.net/record/1343280/files/v4.pdf

SNO ANALYSIS:

WE HAVE MEASURED NEUTRON PRODUCTION FROM ATMOSPHERICS IN SNO AND COMPARED IT TO THE MONTE CARLO MODEL

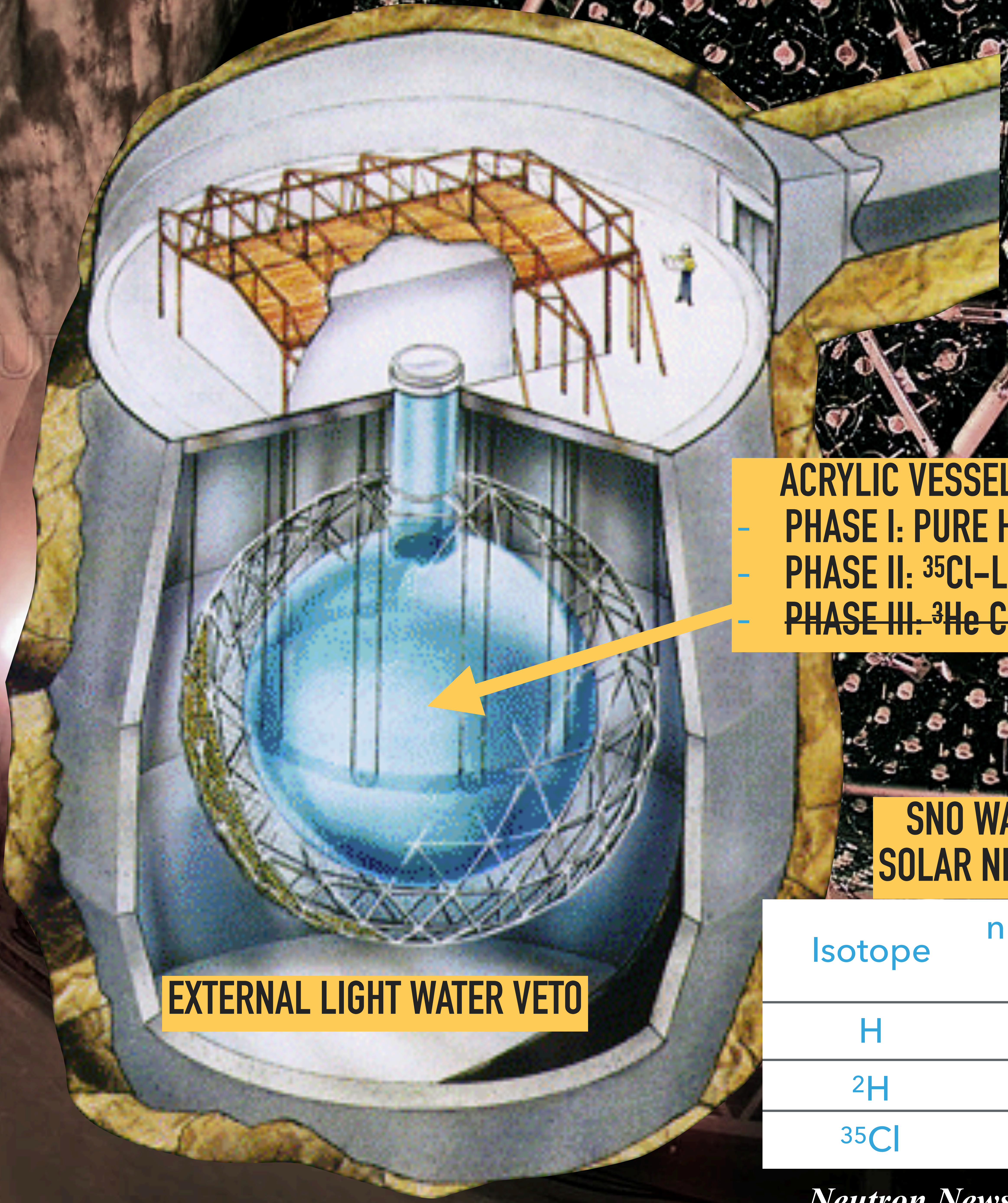
SNO TOOK DATA FROM 1999 TO 2006

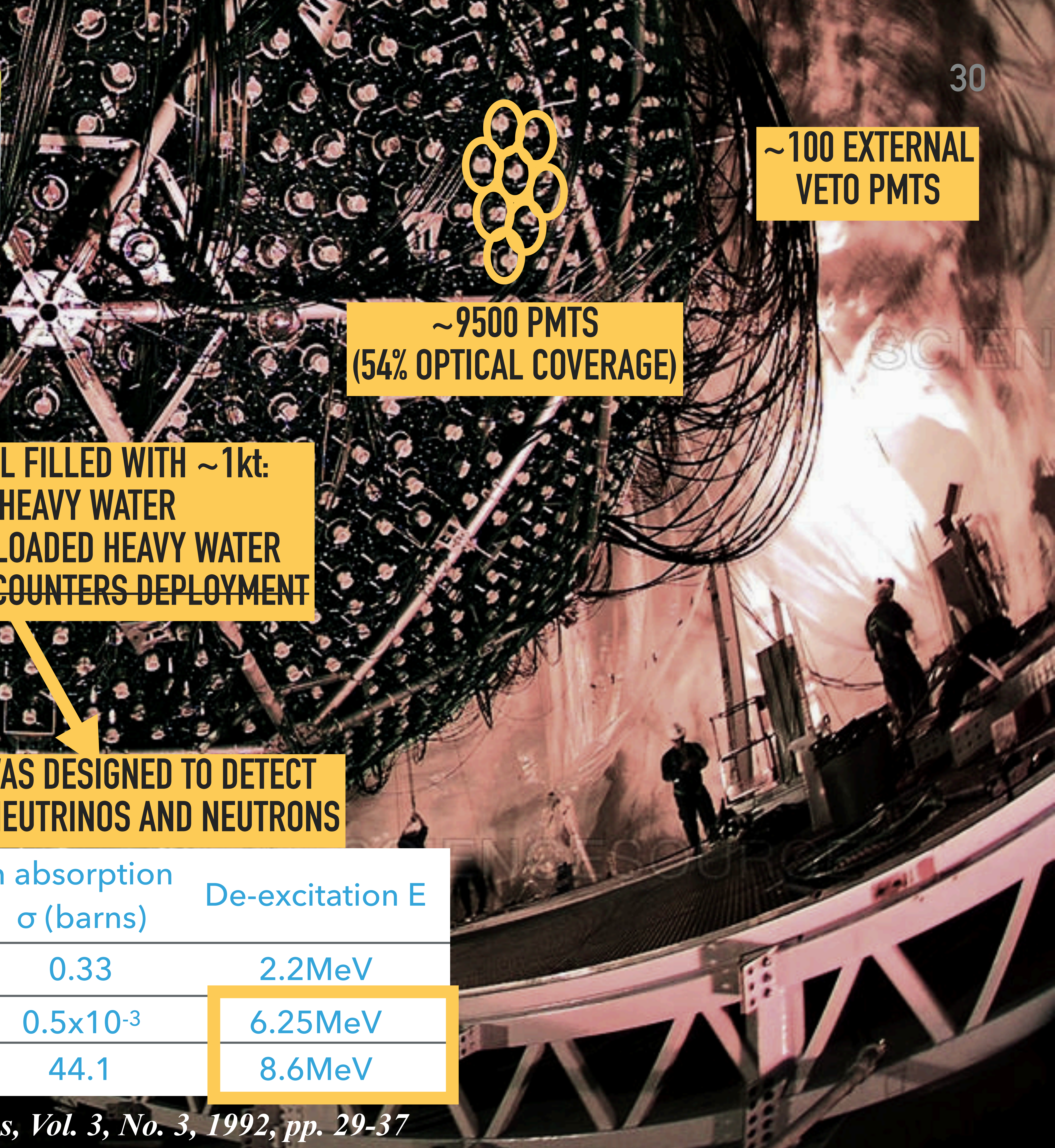


For the discovery of neutrino mixing, showing that neutrinos have mass

SNO ANALYSIS REINVIGORATED IN 2015.
NEW COLLABORATORS TOOK ON
NEW ANALYSES USING SNO LEGACY DATA


~100 EXTERNAL VETO PMTS
~9500 PMTS
(54% OPTICAL COVERAGE)
ACRYLIC VESSEL FILLED WITH ~1kt:
- PHASE I: PURE HEAVY WATER
- PHASE II: ^{35}Cl-LOADED HEAVY WATER
- ~~PHASE III: ^{3}He COUNTERS DEPLOYMENT~~
EXTERNAL LIGHT WATER VETO





~100 EXTERNAL VETO PMTS

~9500 PMTS (54% OPTICAL COVERAGE)

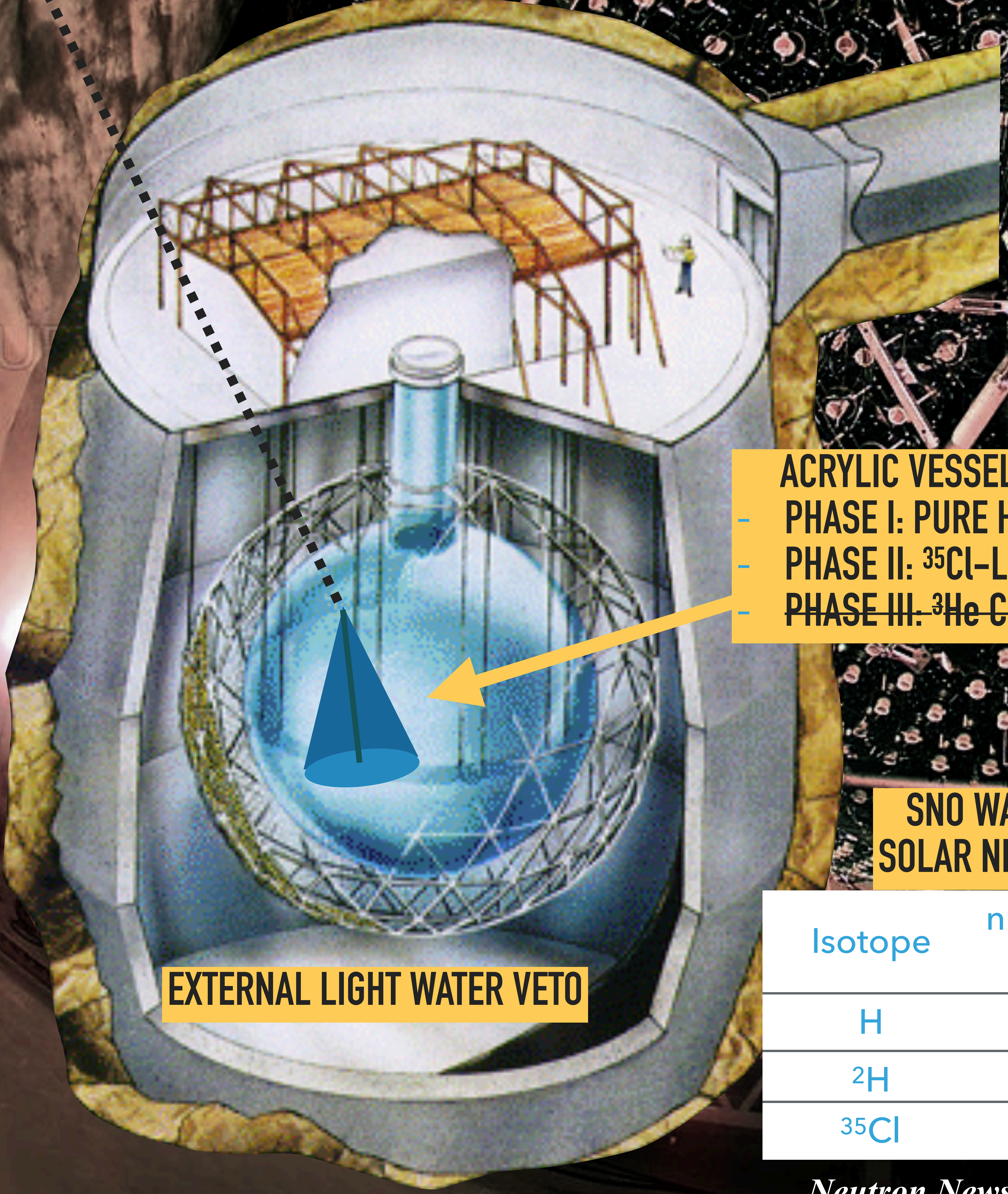
ACRYLIC VESSEL FILLED WITH ~1kt:

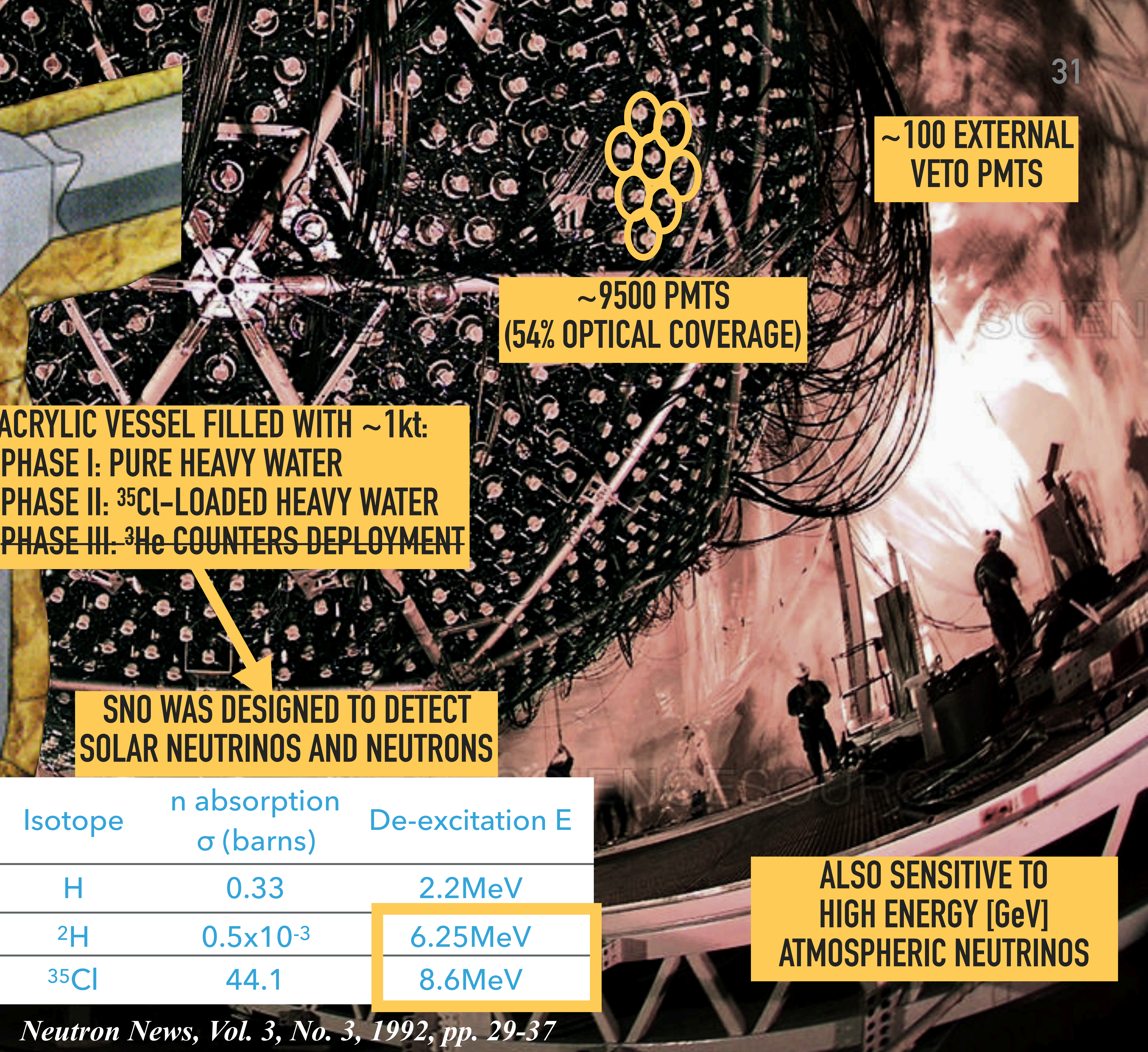
- PHASE I: PURE HEAVY WATER
- PHASE II: ^{35}Cl-LOADED HEAVY WATER
- ~~PHASE III: ^{3}He COUNTERS DEPLOYMENT~~

SNO WAS DESIGNED TO DETECT SOLAR NEUTRINOS AND NEUTRONS

Isotope	n absorption σ (barns)	De-excitation E
H	0.33	2.2MeV
^{2}H	0.5×10^{-3}	6.25MeV
^{35}Cl	44.1	8.6MeV

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

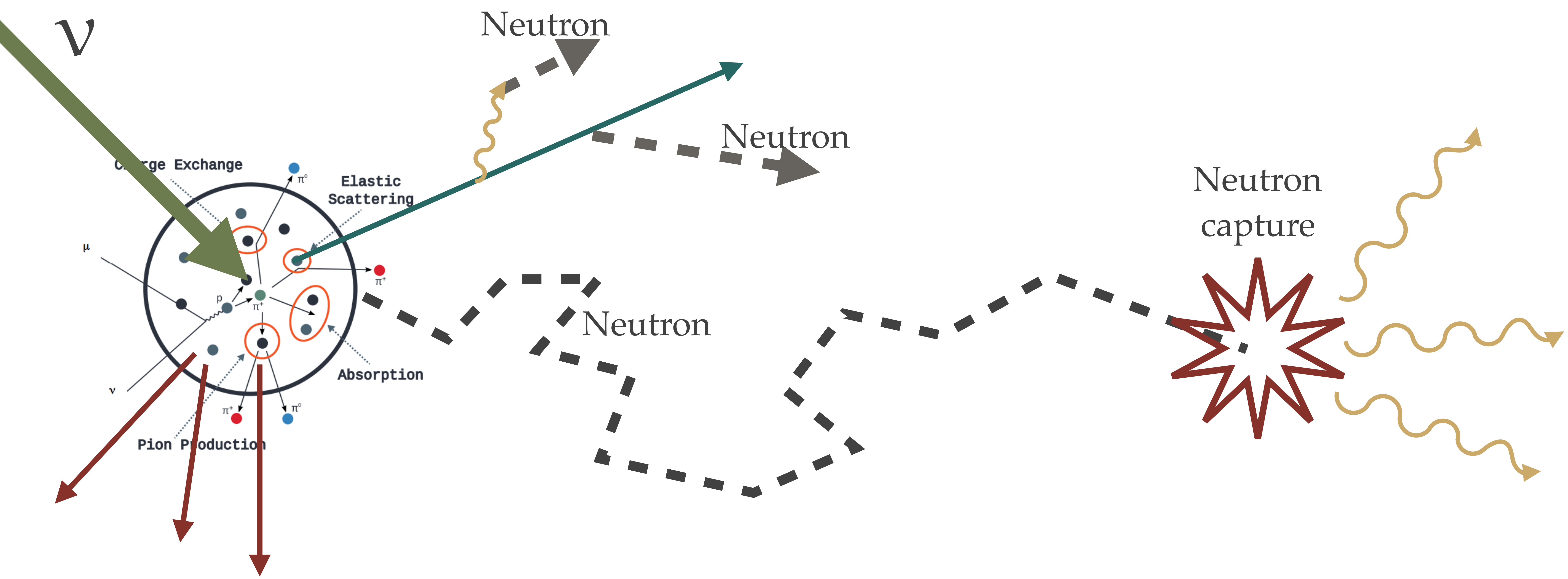




Isotope	n absorption σ (barns)	De-excitation E
H	0.33	2.2MeV
^{2}H	0.5×10^{-3}	6.25MeV
^{35}Cl	44.1	8.6MeV

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

NEUTRON PROCESSES MONTE CARLO MODEL



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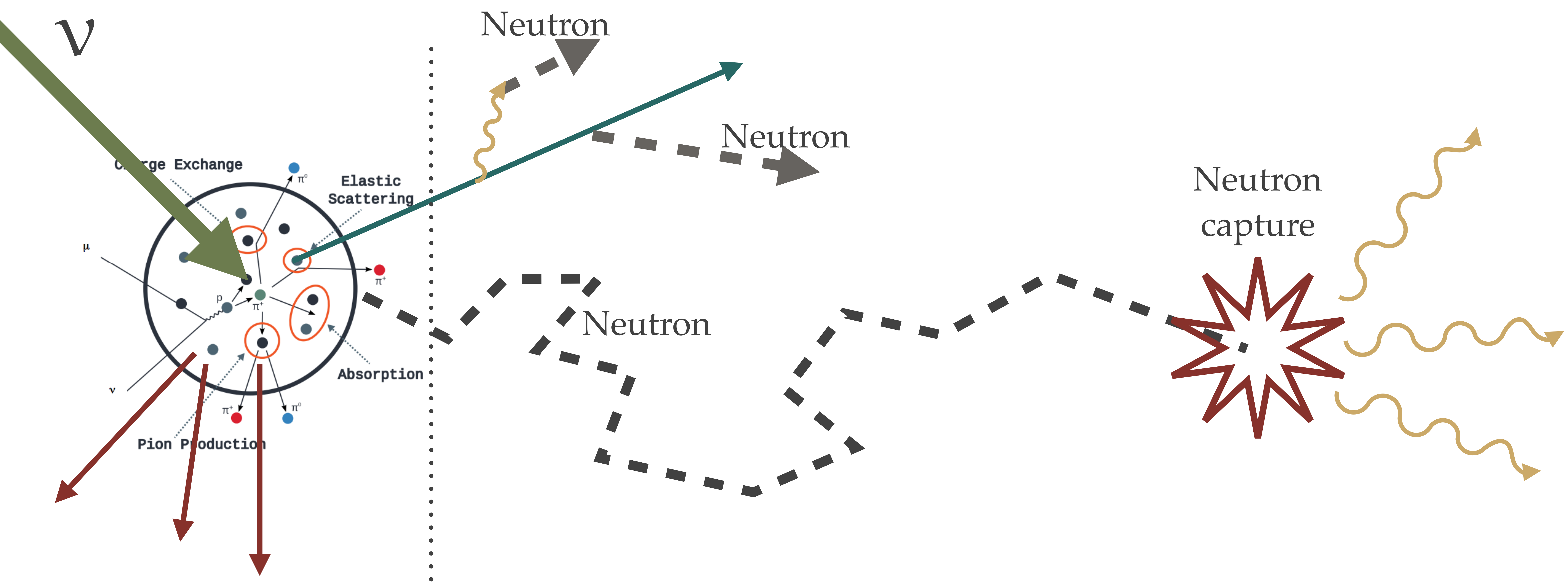
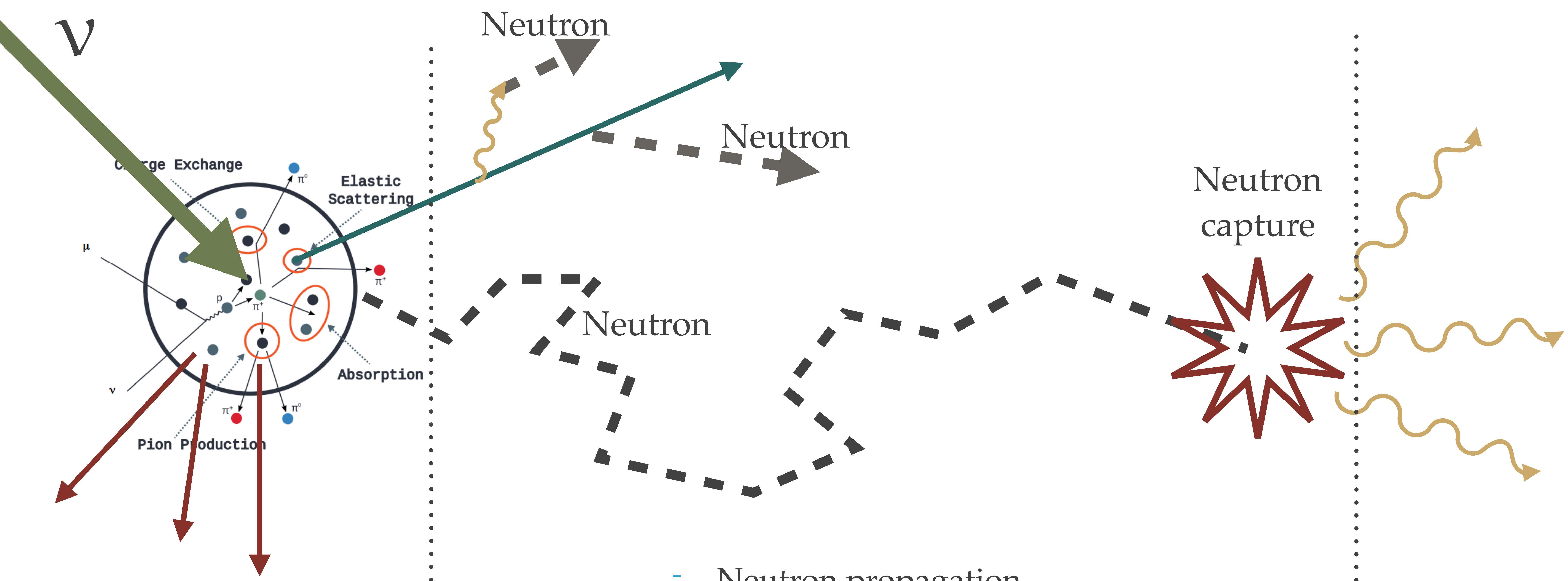


- Neutrino interaction
- Final State Interactions

PRIMARY NEUTRONS

NEUTRON PROCESSES MONTE CARLO MODEL



- Neutrino interaction
- Final State Interactions

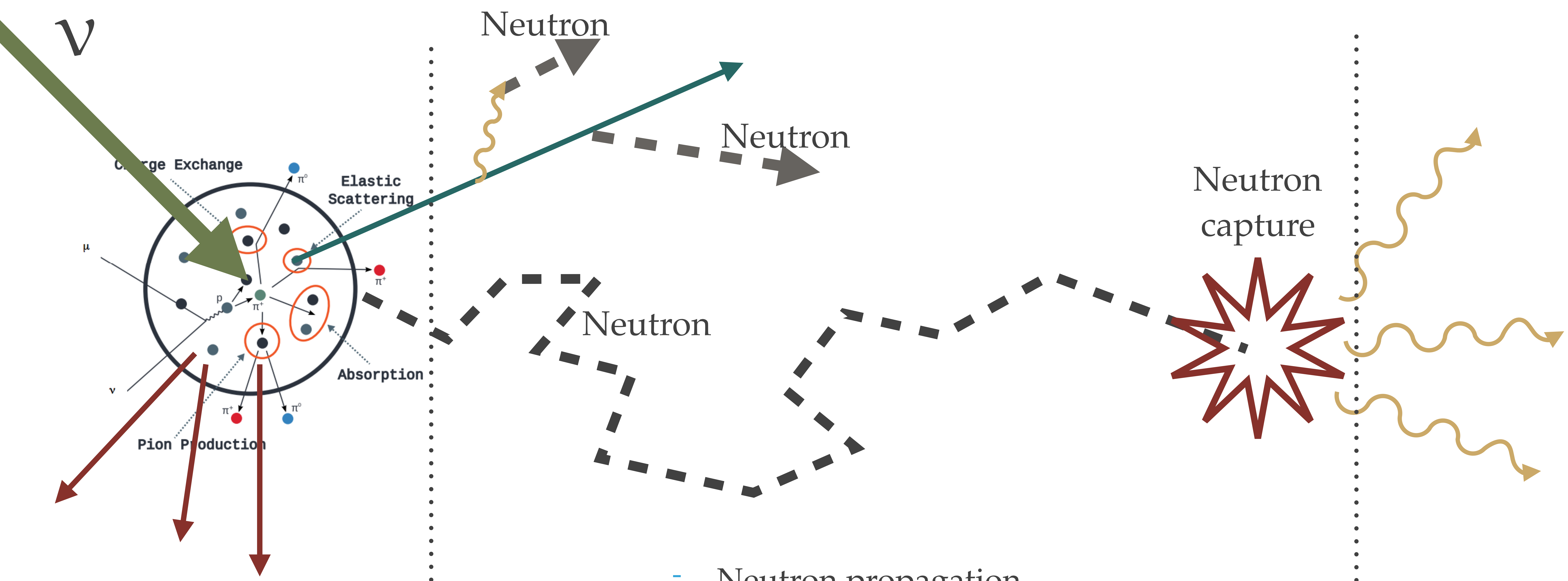
- Neutron propagation
- Secondary neutron production
- Neutron capture
- De-excitation gamma emission

*NeutronHP model

PRIMARY NEUTRONS

SECONDARY NEUTRONS

NEUTRON PROCESSES MONTE CARLO MODEL



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Genie

PRIMARY NEUTRONS

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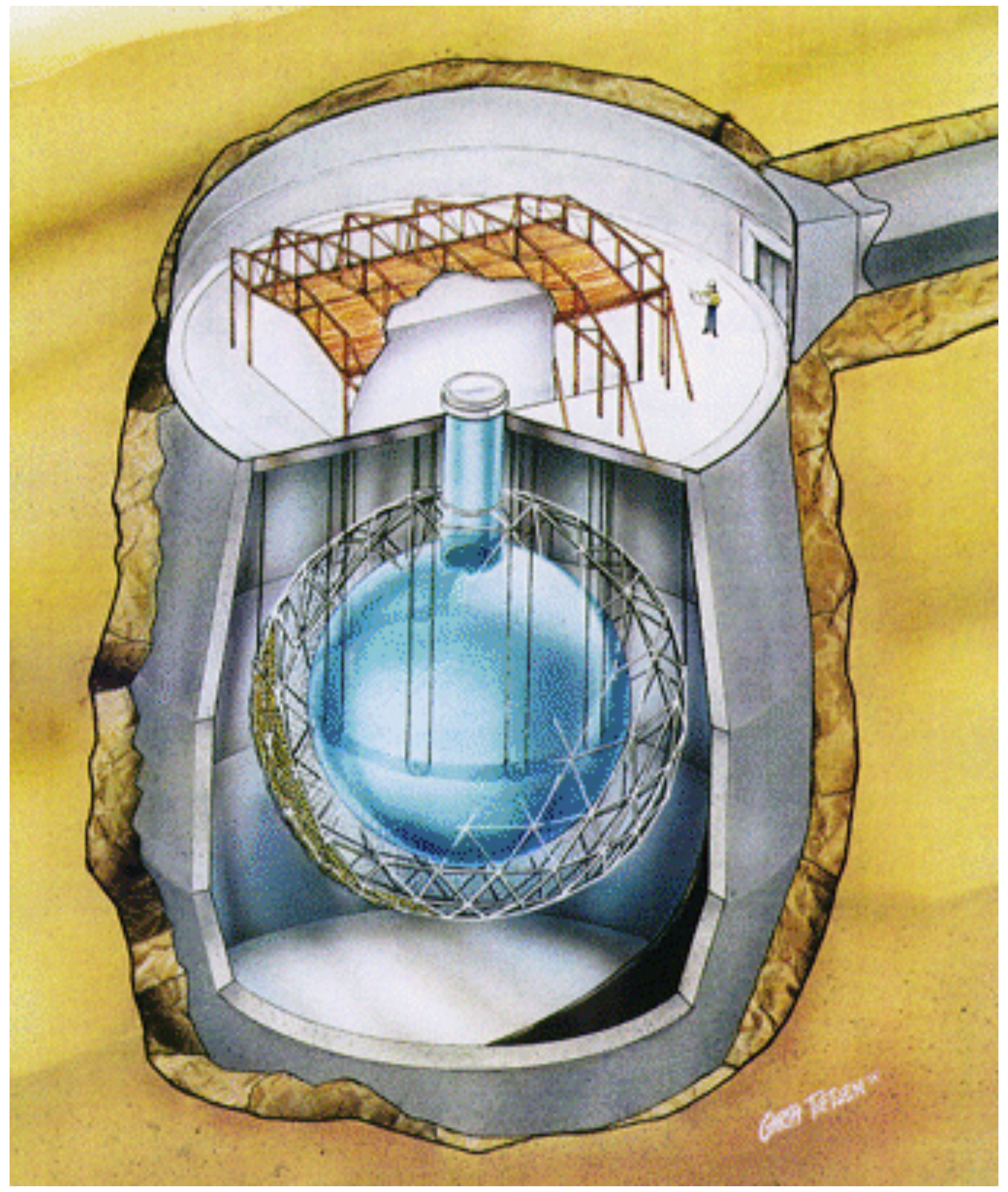
GEANT4 A SIMULATION TOOLKIT

**NeutronHP model*

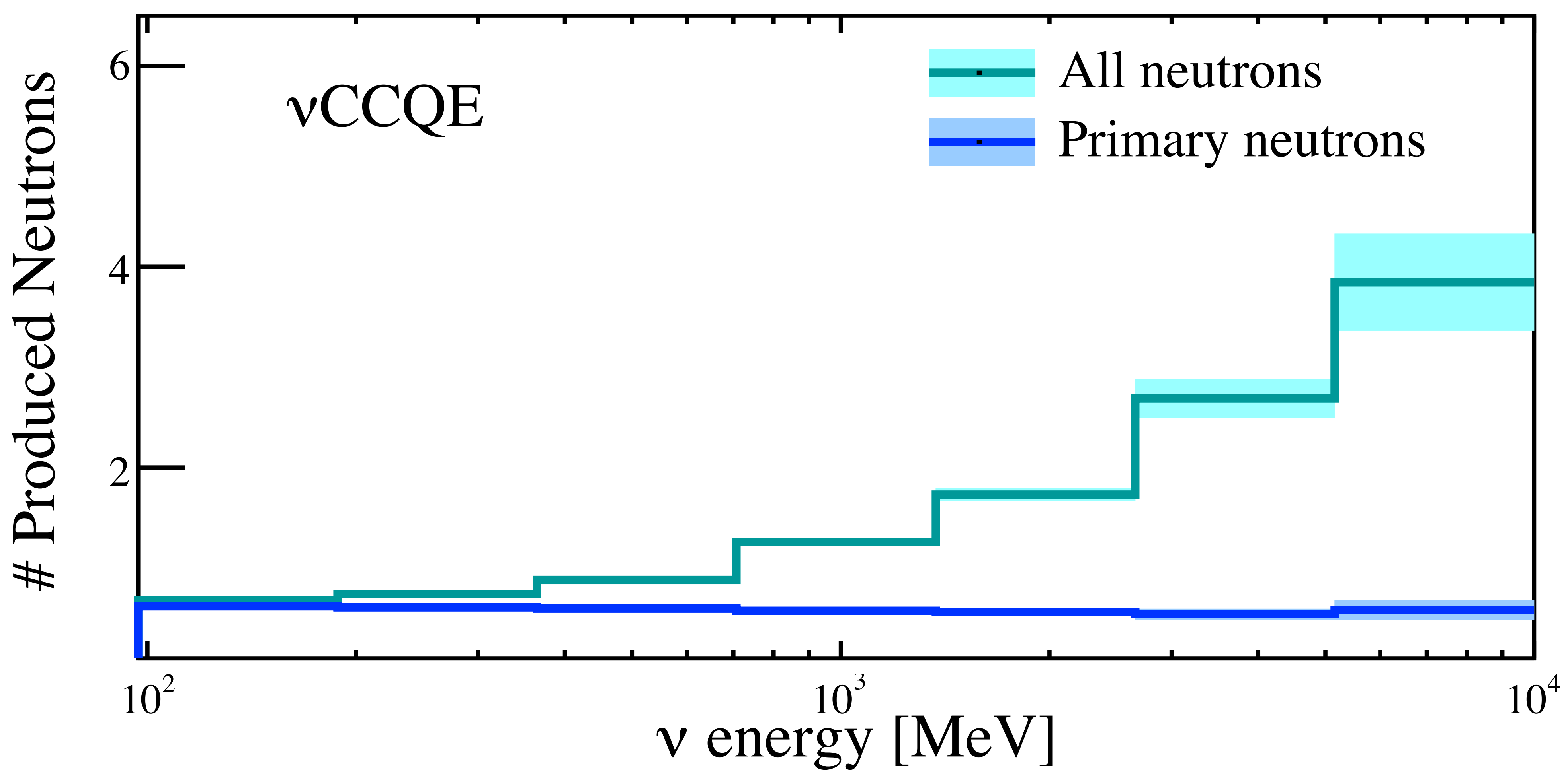
SECONDARY NEUTRONS



Official SNO package: Cherenkov production and detector response

SNOMAN

ESTIMATED NEUTRON PRODUCTION FROM ATMOSPHERIC NEUTRINOS IN SNO



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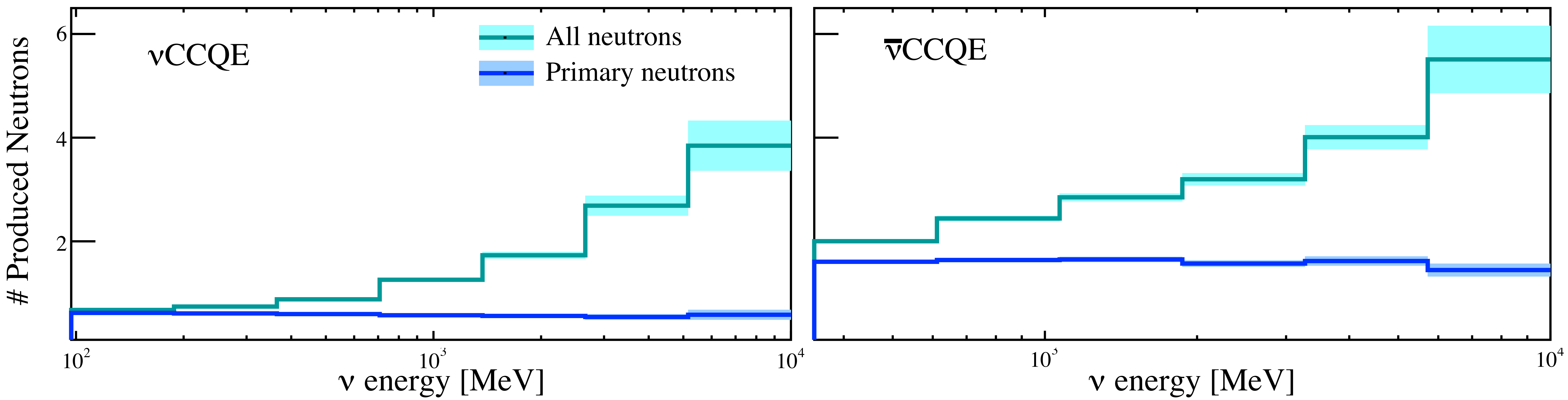

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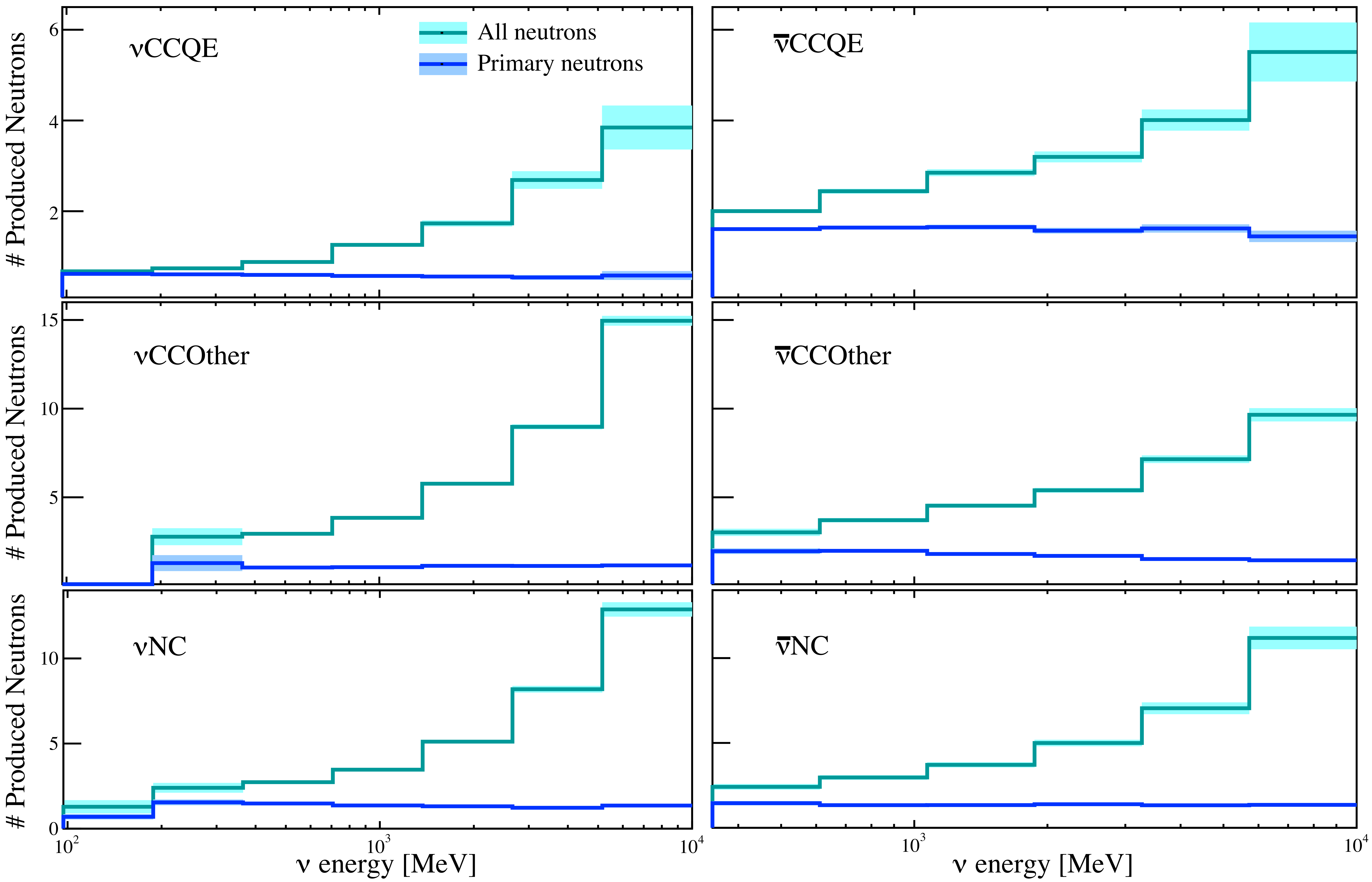
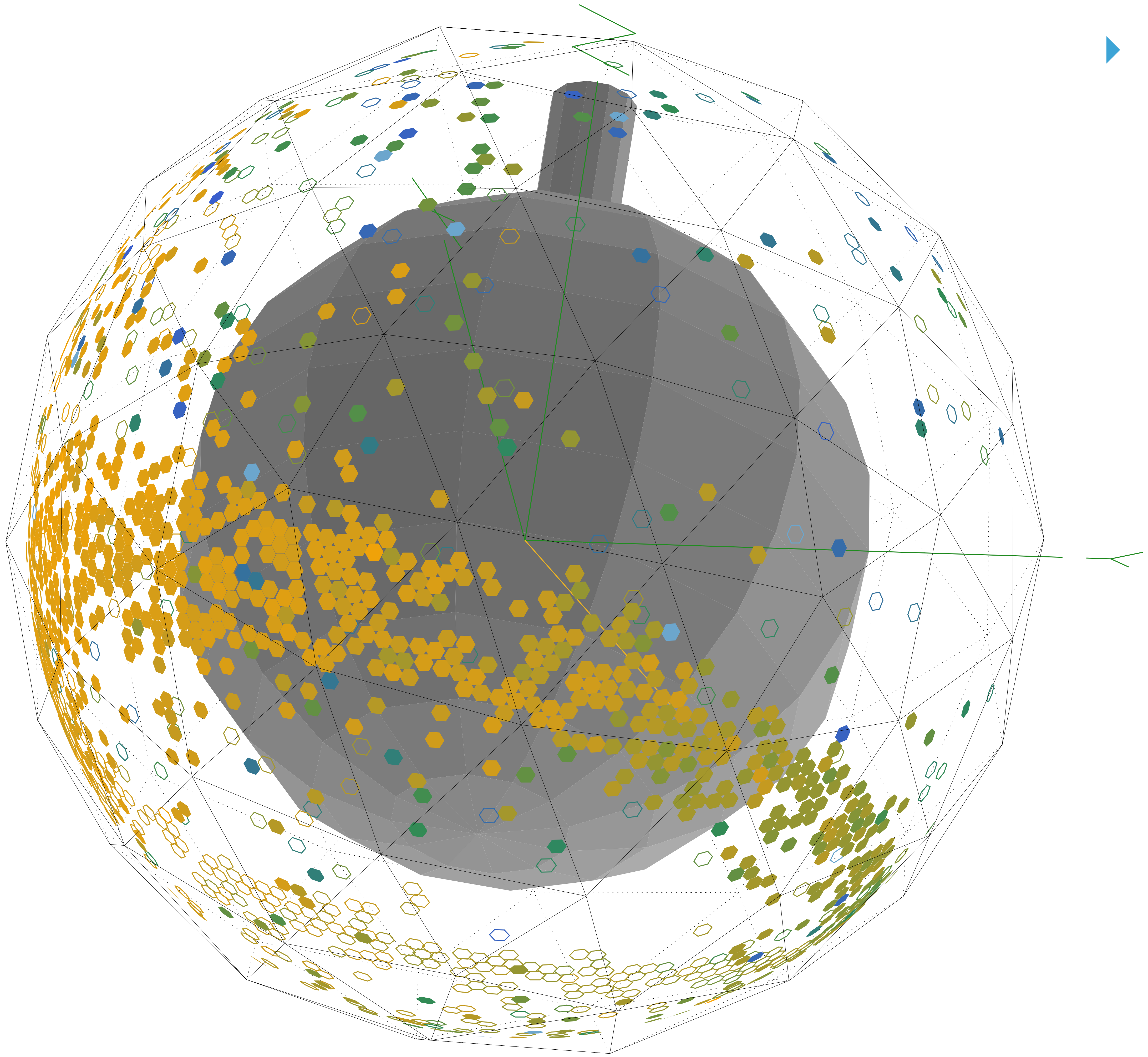


ATMOSPHERIC NEUTRINO EVENTS ARE EASILY IDENTIFIED BY THE CHERENKOV CONE PRODUCED BY THE CHARGED PARTICLES

Atmospheric neutrino interaction candidate



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  - Determines interaction position and direction of most energetic charged particle

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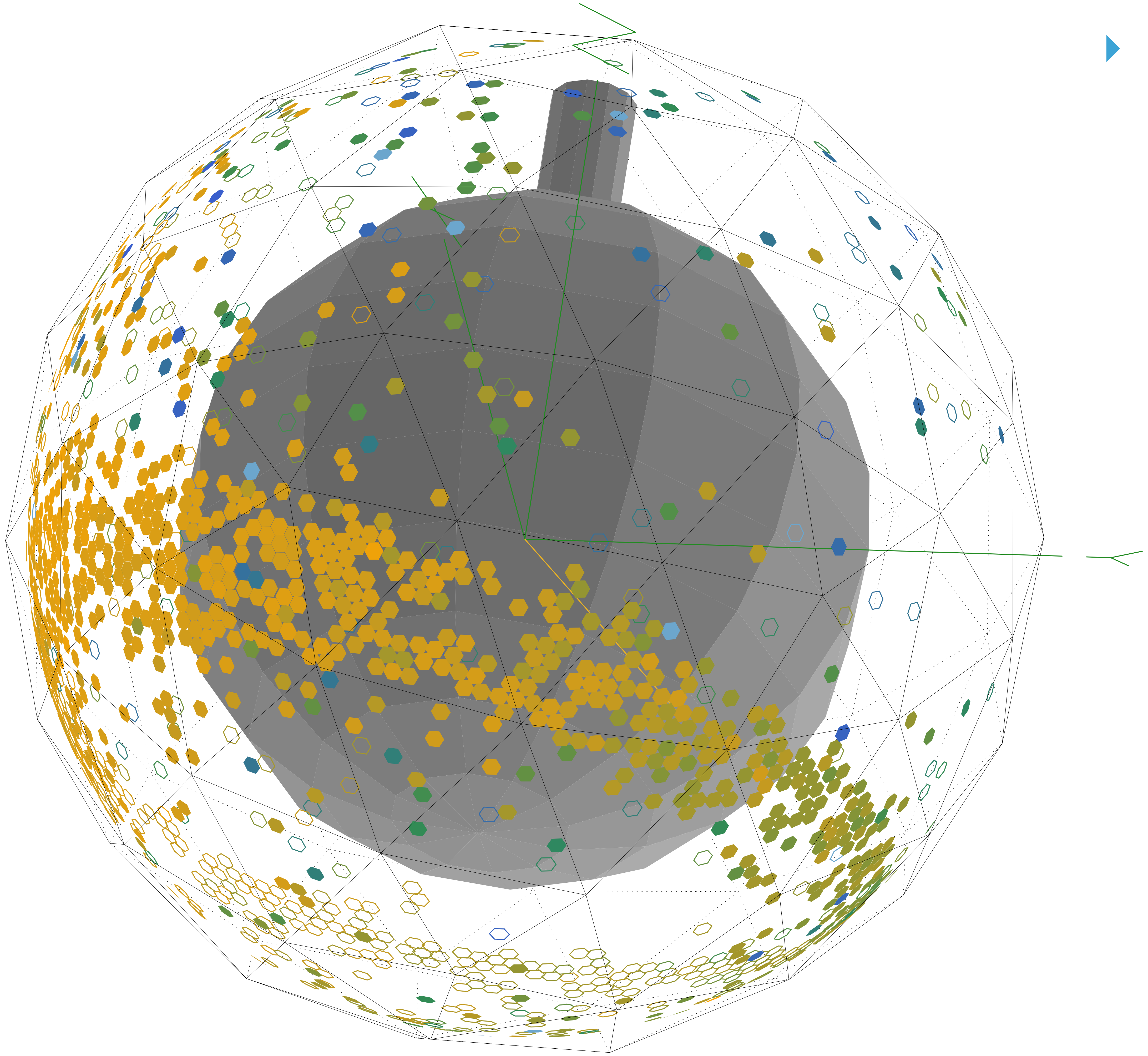

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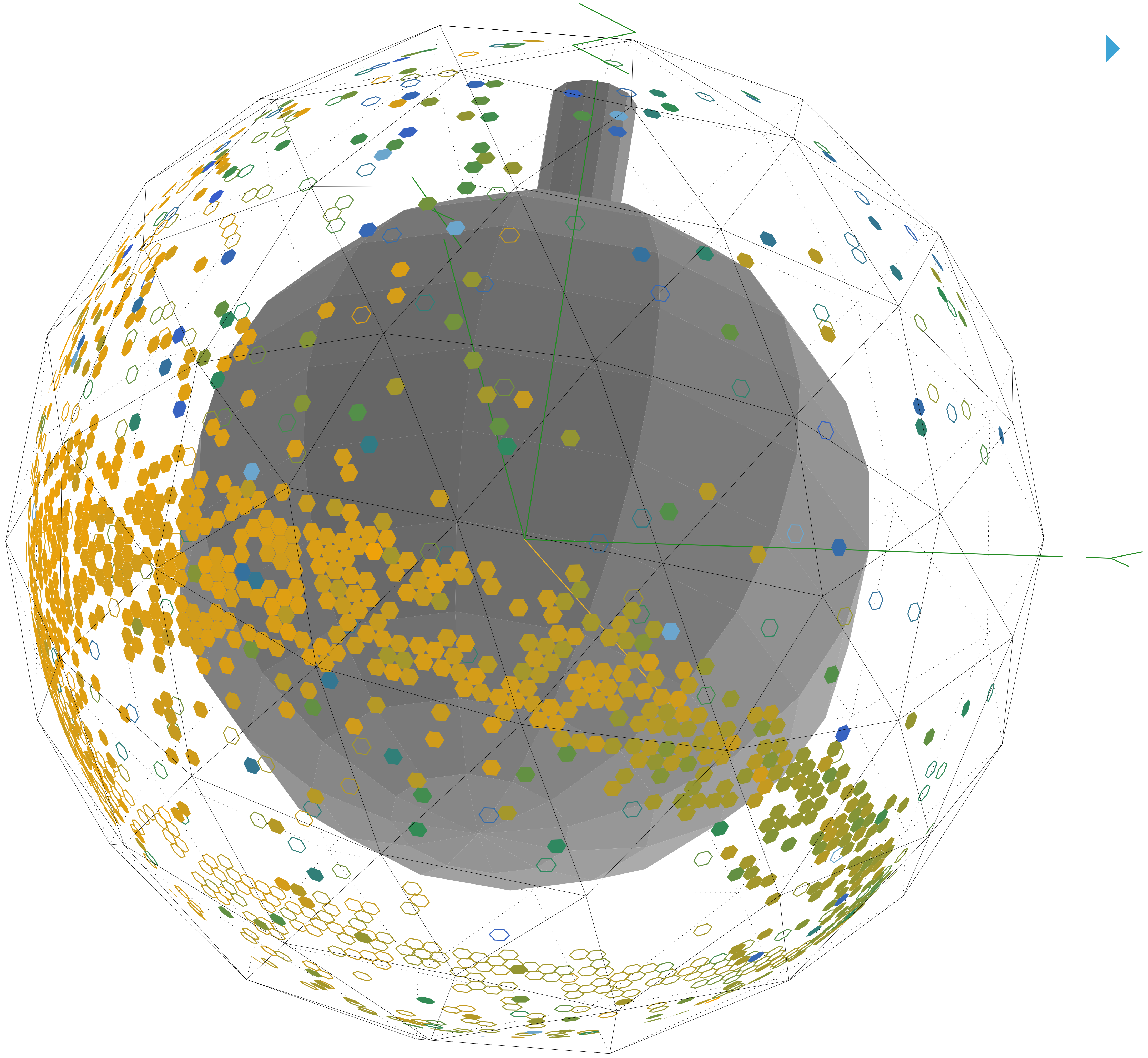

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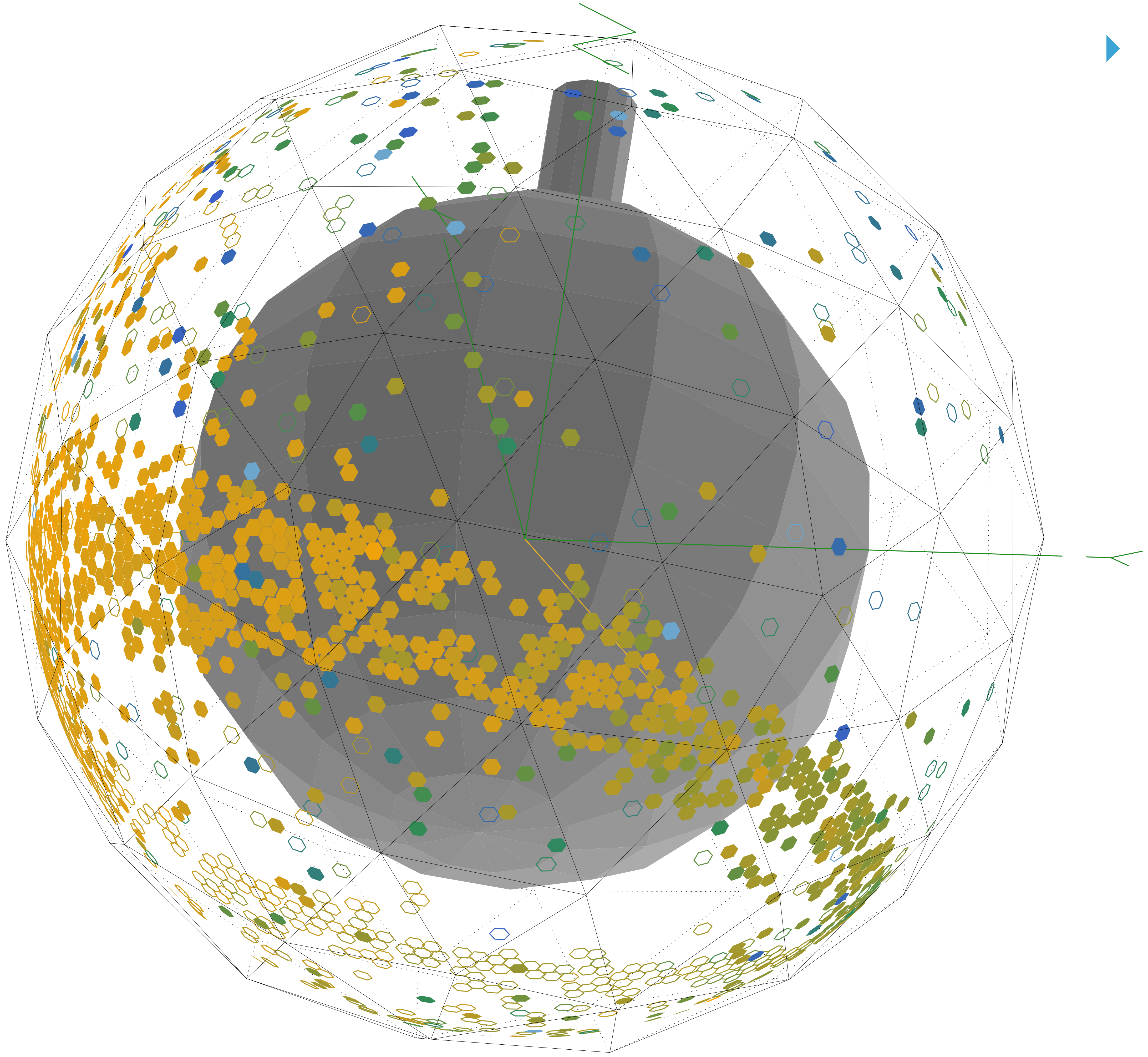

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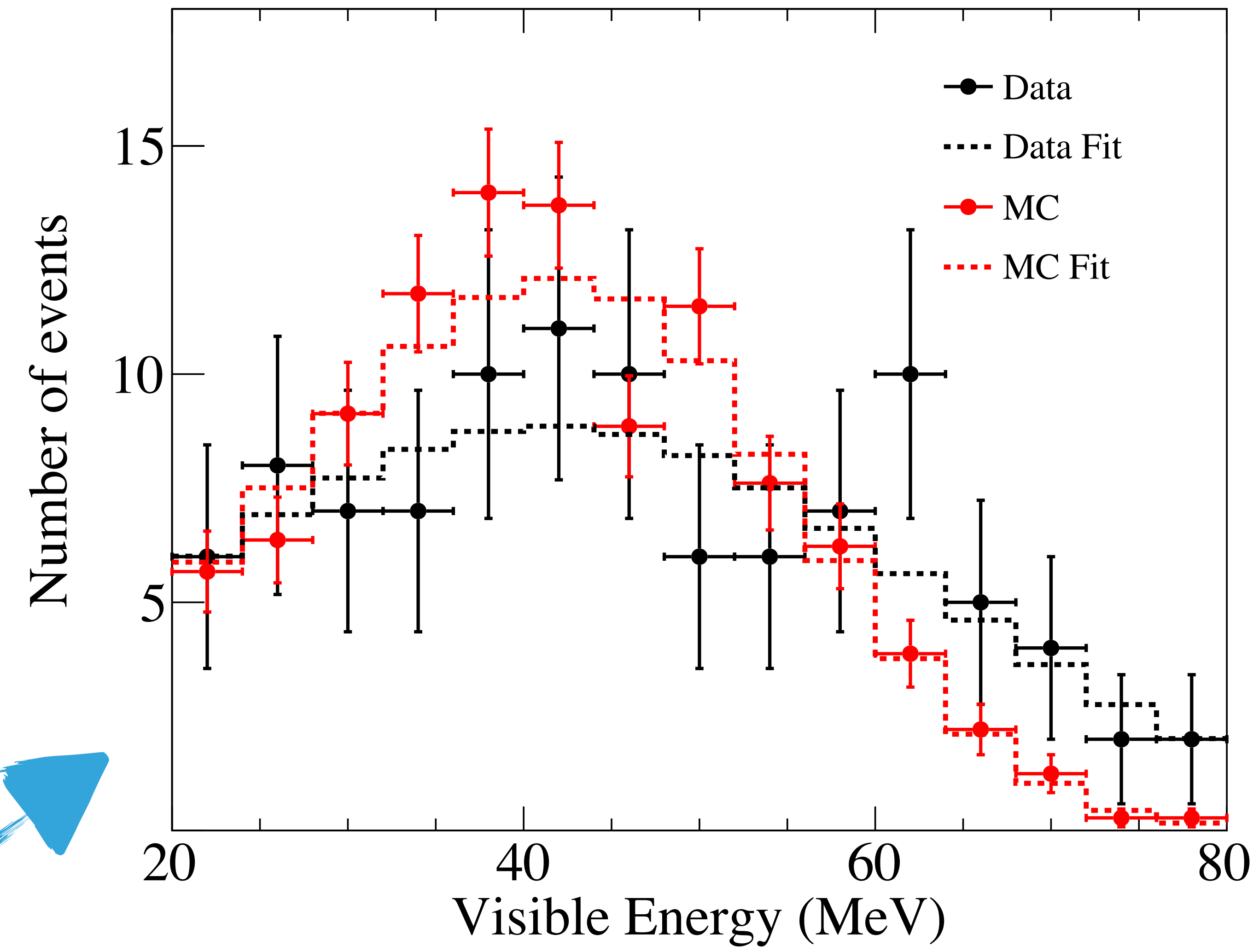
  - Classifies main charged particle into electrons (shower-like) or muons (MIP-like)
  - Determines whether secondary Cherenkov rings are present → single-particle vs multi-particle events

RING FITTER ENERGY CALIBRATION



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    - Michel electron → ~50MeV end point

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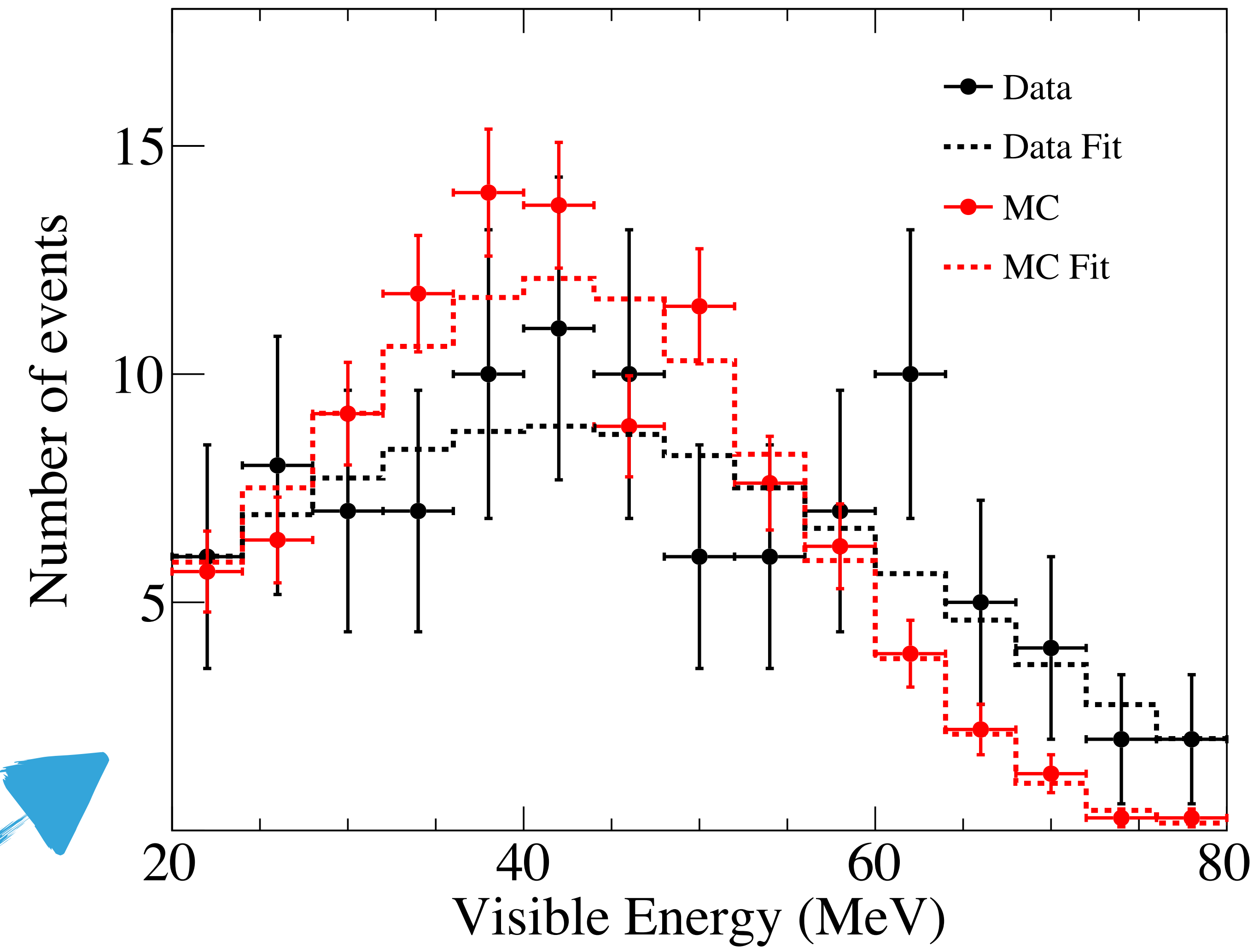

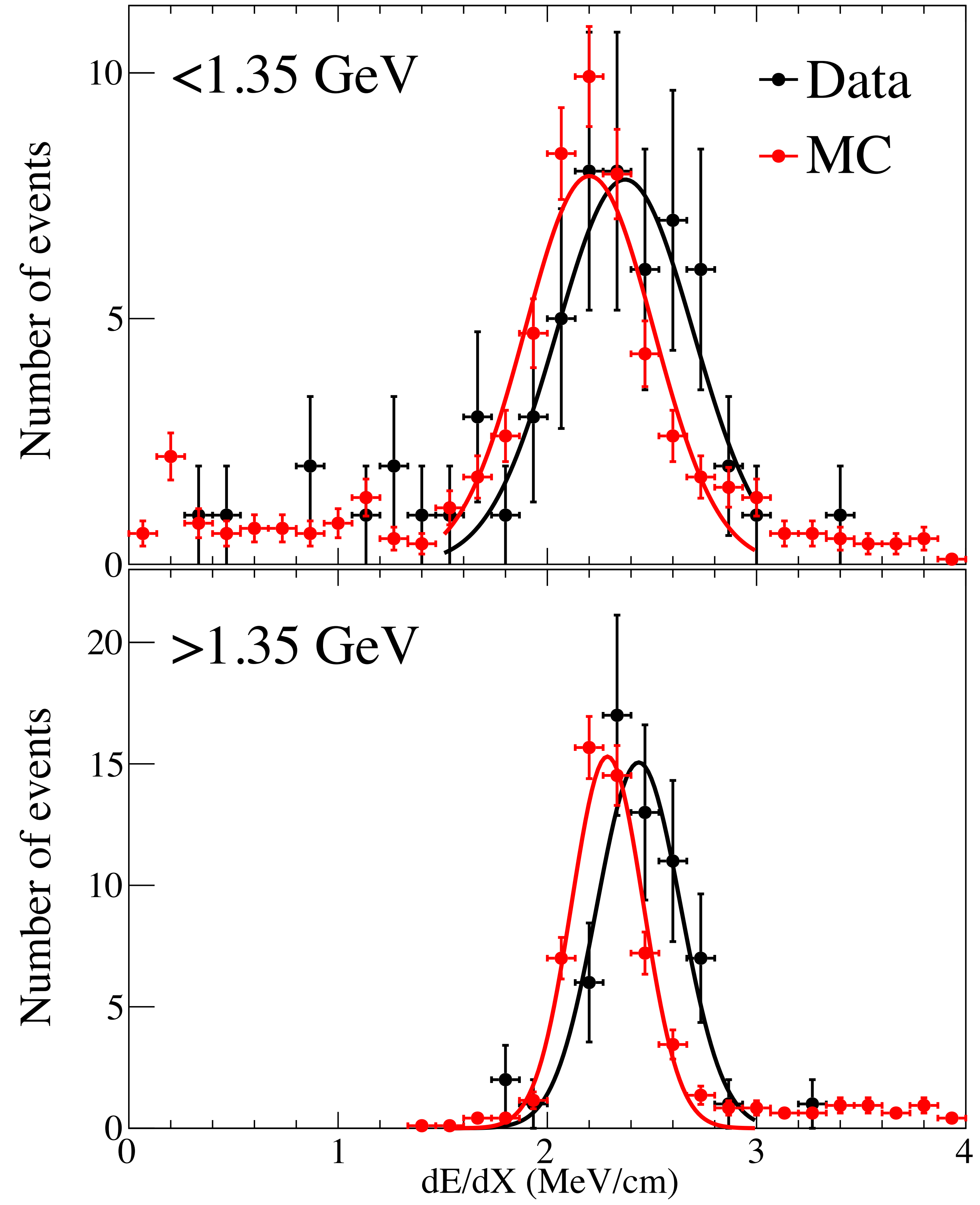

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    - Michel electron → ~50MeV end point
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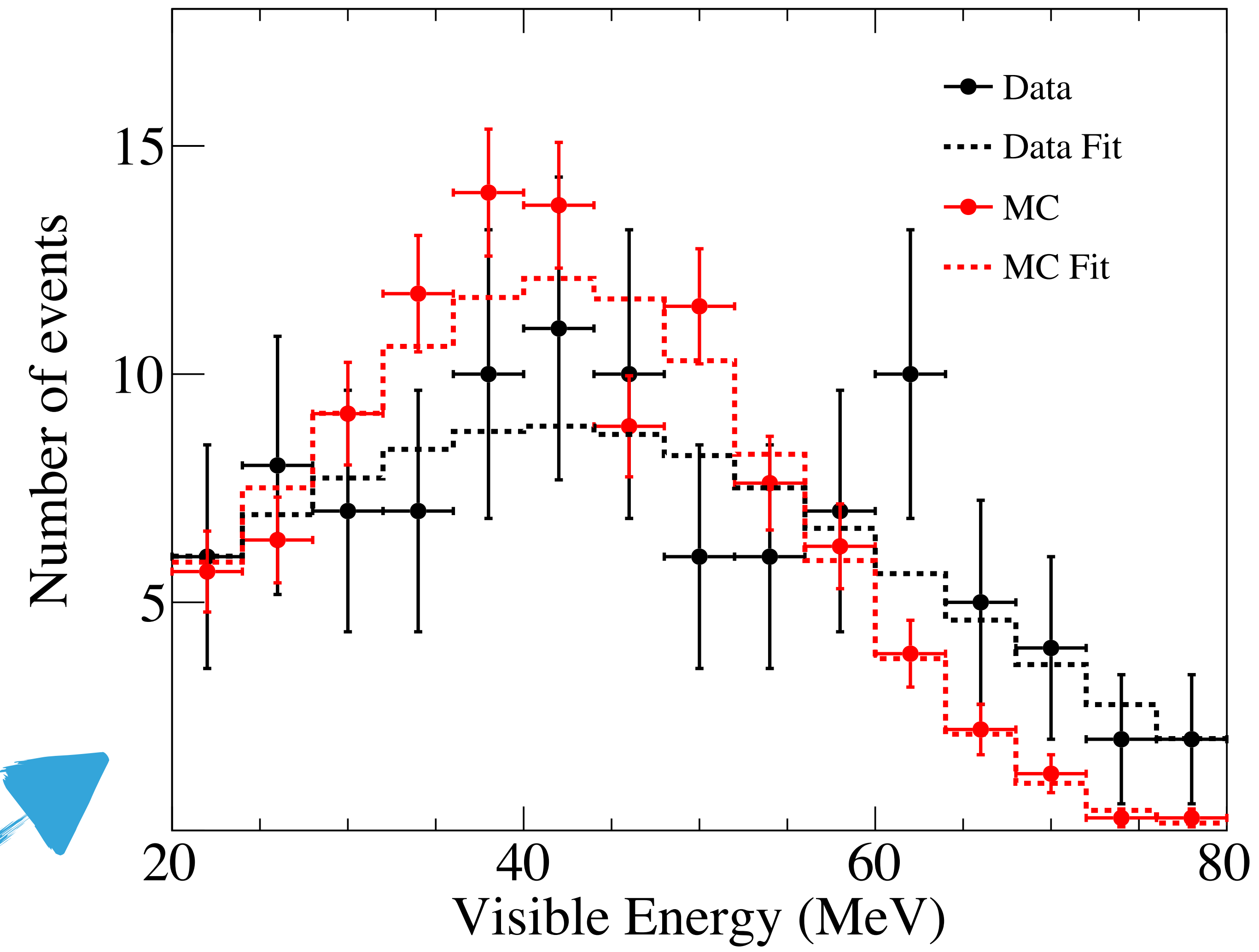
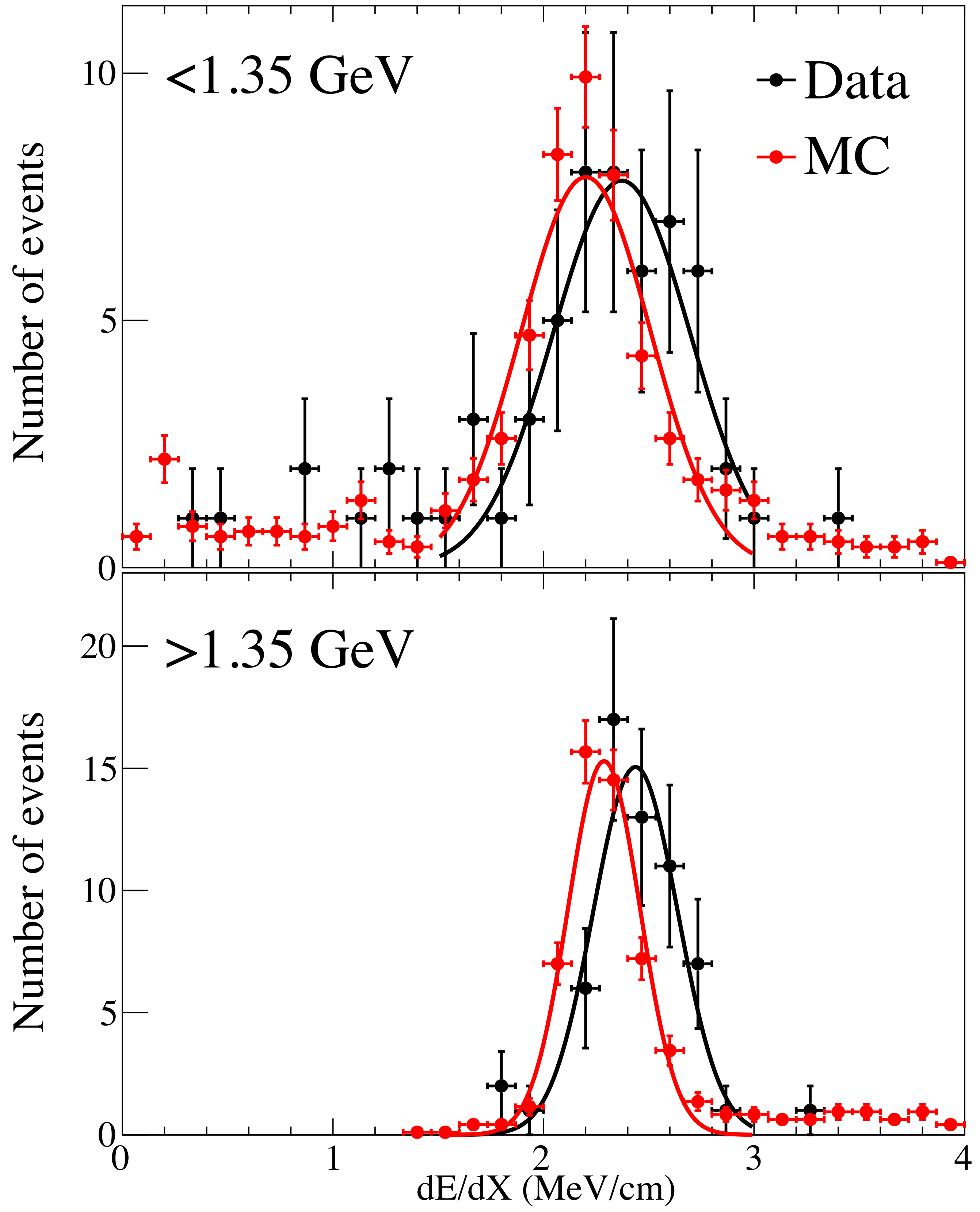
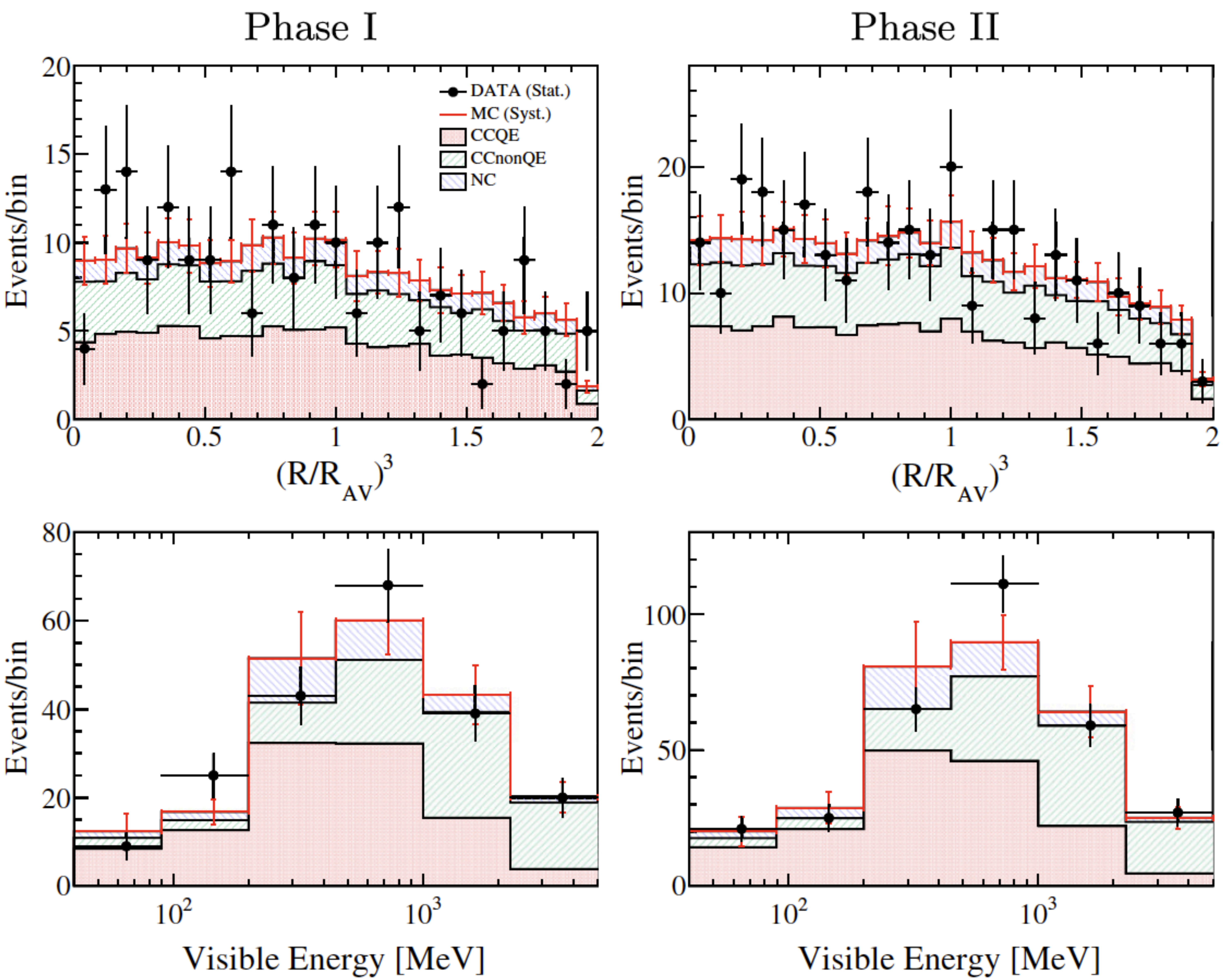
- Calculate bias and resolution correction factors and energy systematic uncertainties





ATMOSPHERIC NEUTRINO INTERACTION CANDIDATES

- Focus on events with more than 200 PMT hits
- Select fully contained events by requiring less than 3 external veto PMTs hits
- Designed low level cuts to remove instrumental backgrounds (mainly flashers)
- Fiducial volume cut of 7.5m

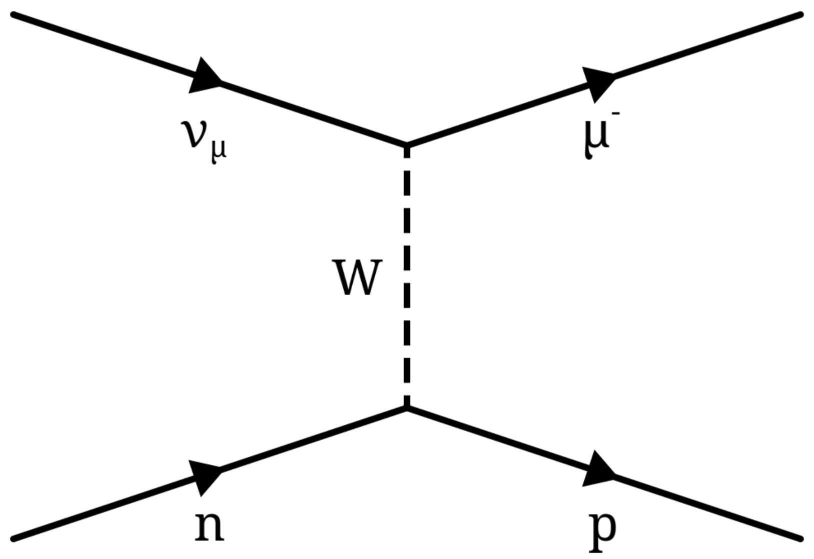


337 DAYS → 204 EVENTS

499 DAYS → 308 EVENTS

NEUTRINO ENERGY ESTIMATION

RECONSTRUCT NEUTRINO ENERGY UNDER CCQE HYPOTHESIS



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

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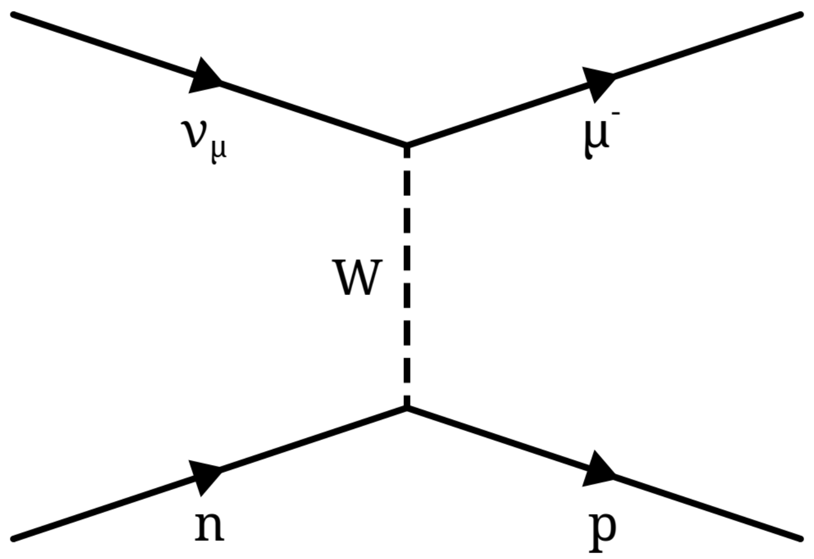

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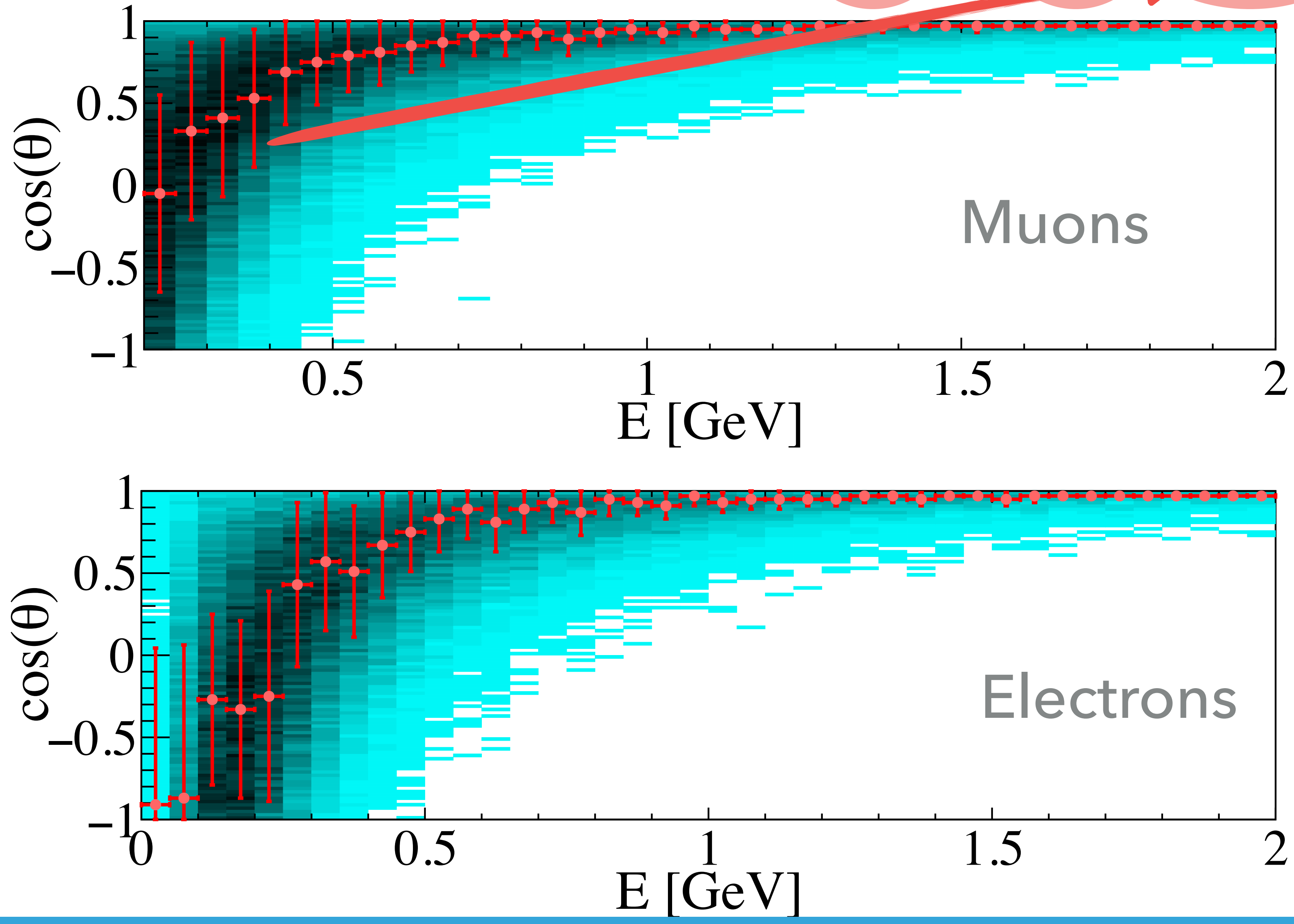

NO ATMOSPHERIC NEUTRINO DIRECTION → GET COS(Θ)/E DEPENDENCY FROM MC

NEUTRINO ENERGY ESTIMATION

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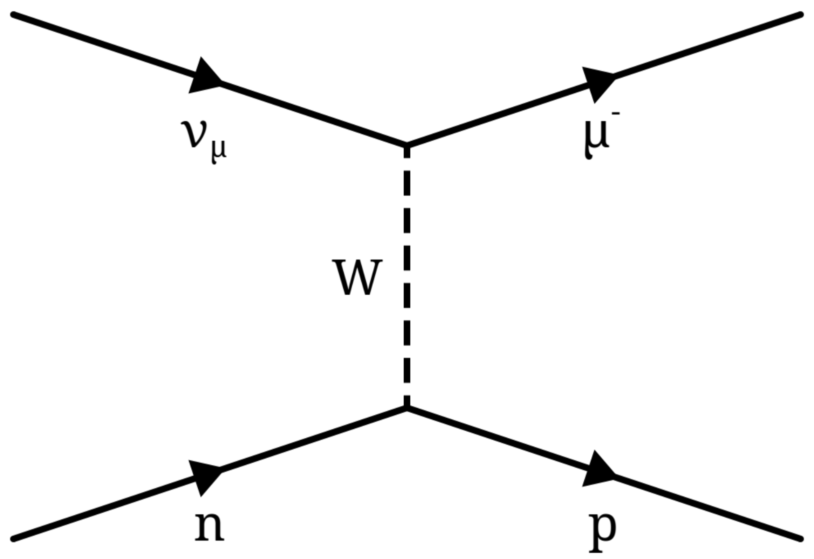

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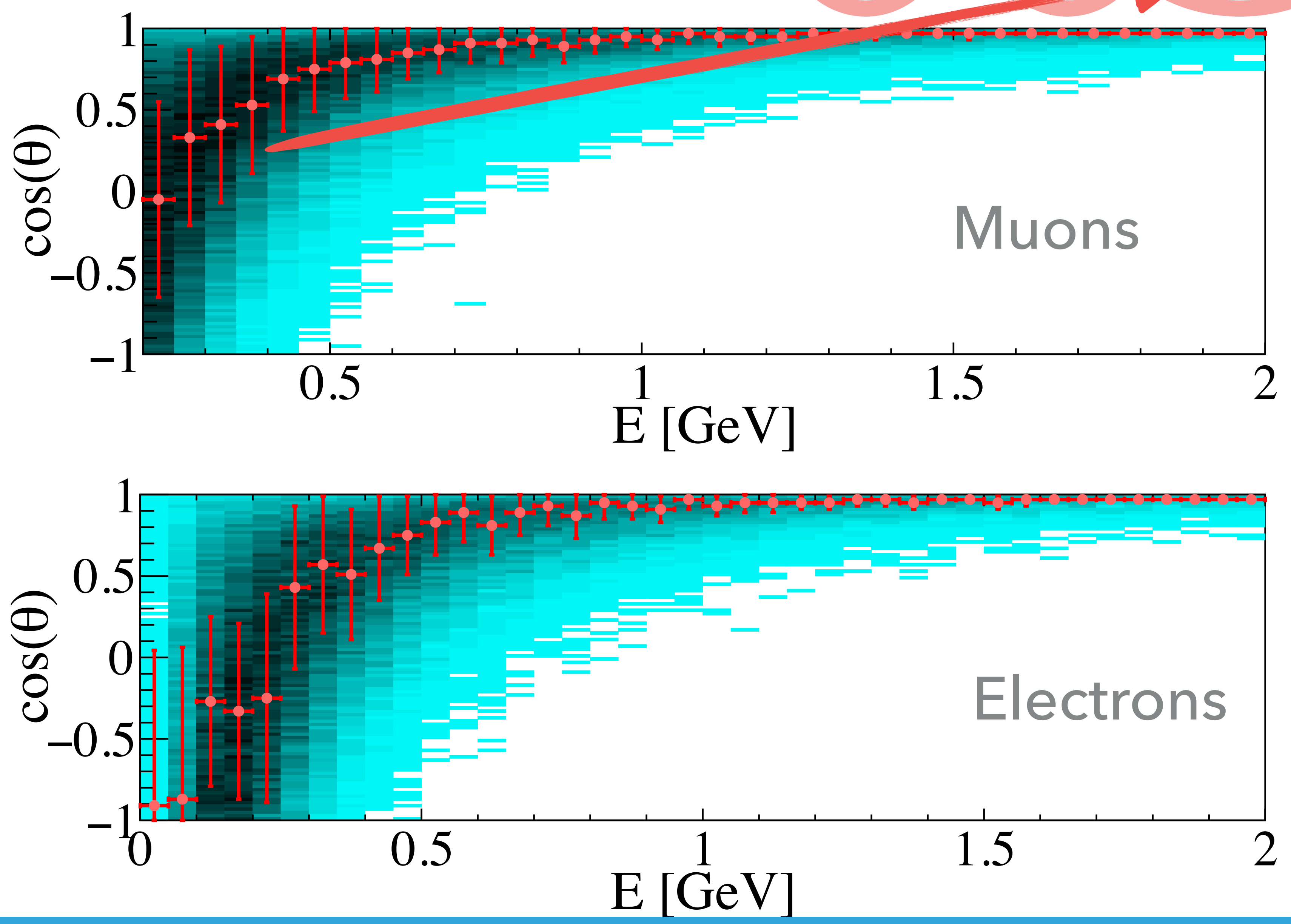
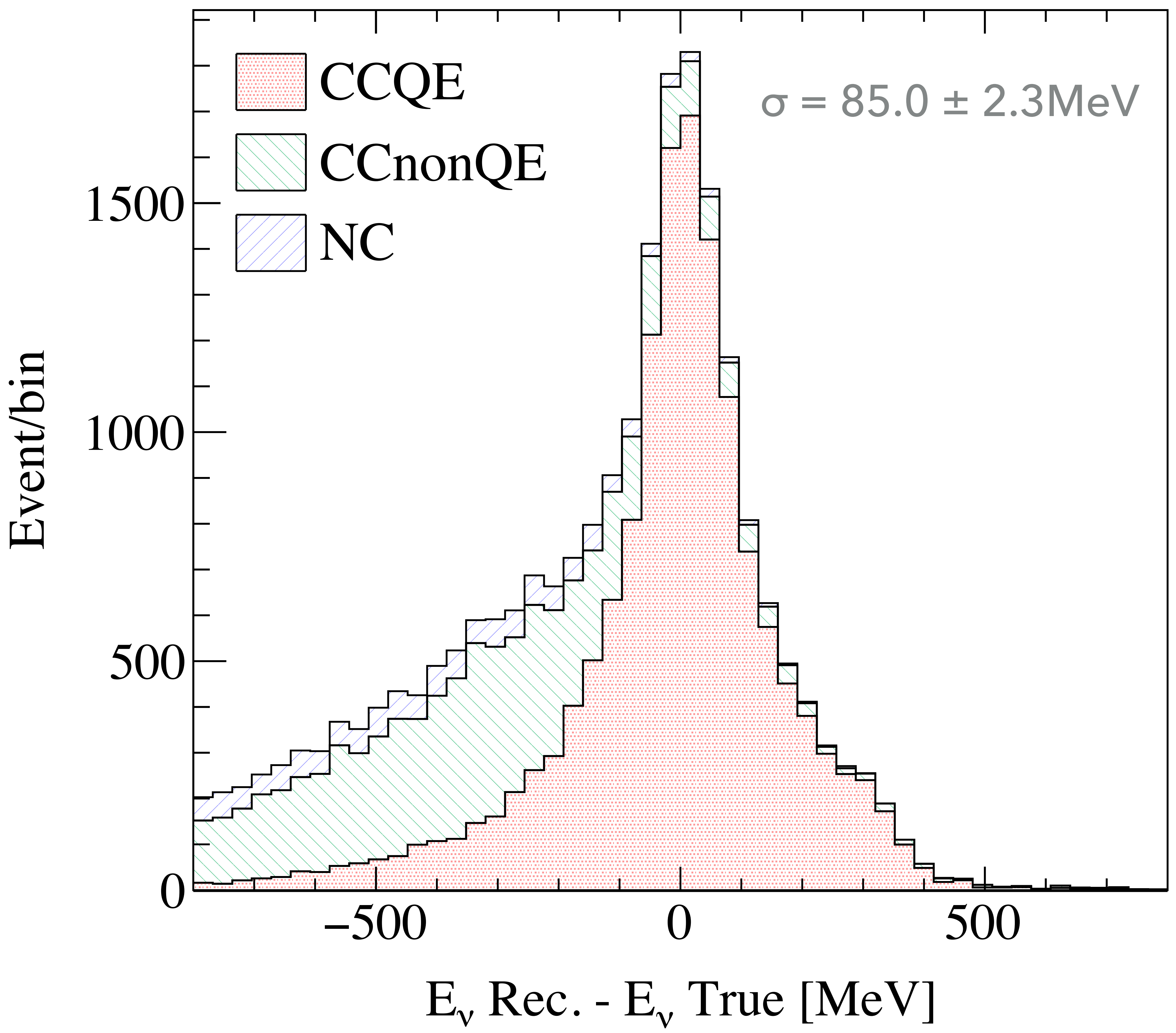


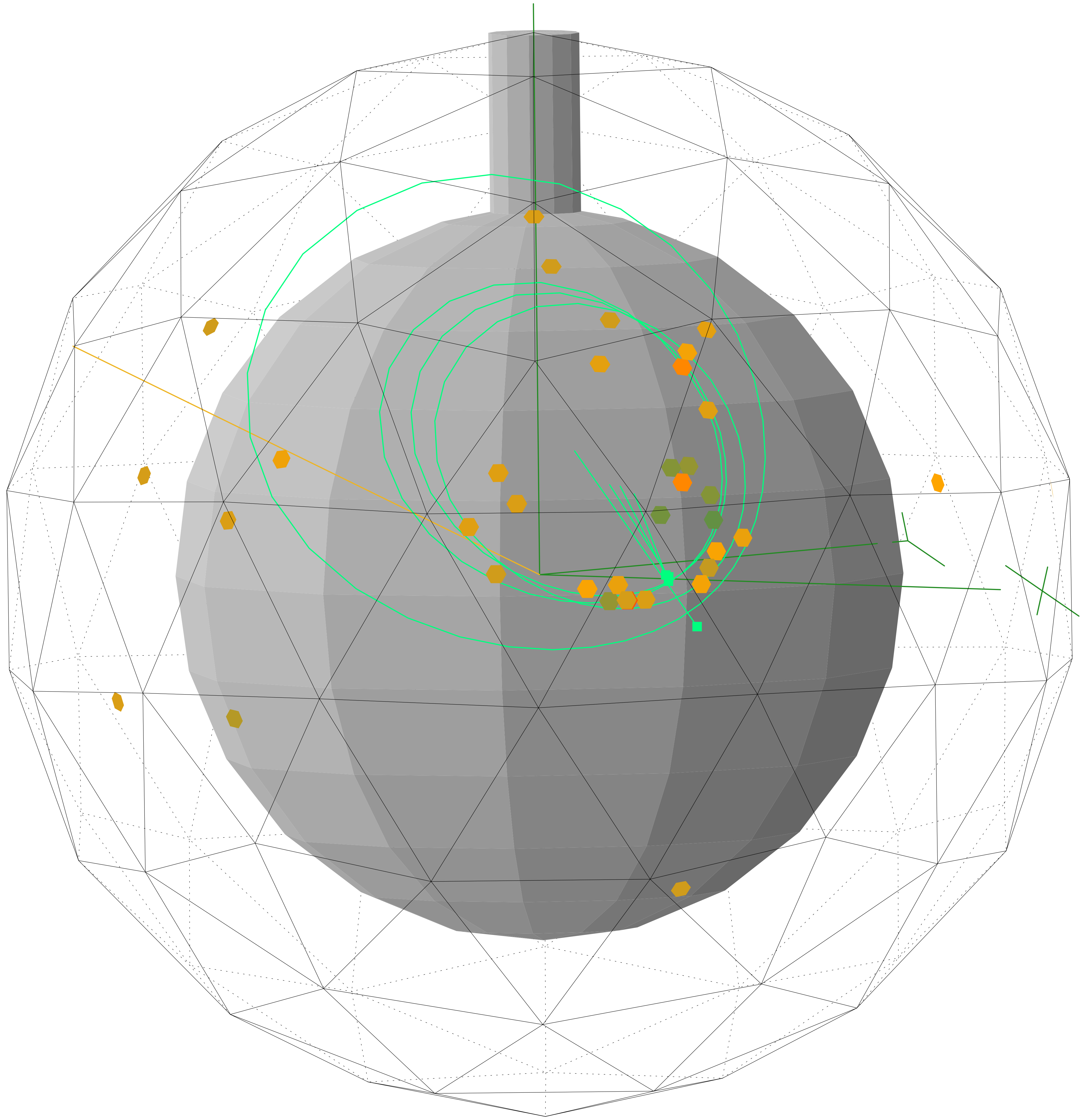
Reconstructed neutrino energy bias



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

NEUTRON CAPTURES ON DEUTERIUM AND ^{35}Cl IDENTIFIED BY COINCIDENCE

Neutron capture candidate



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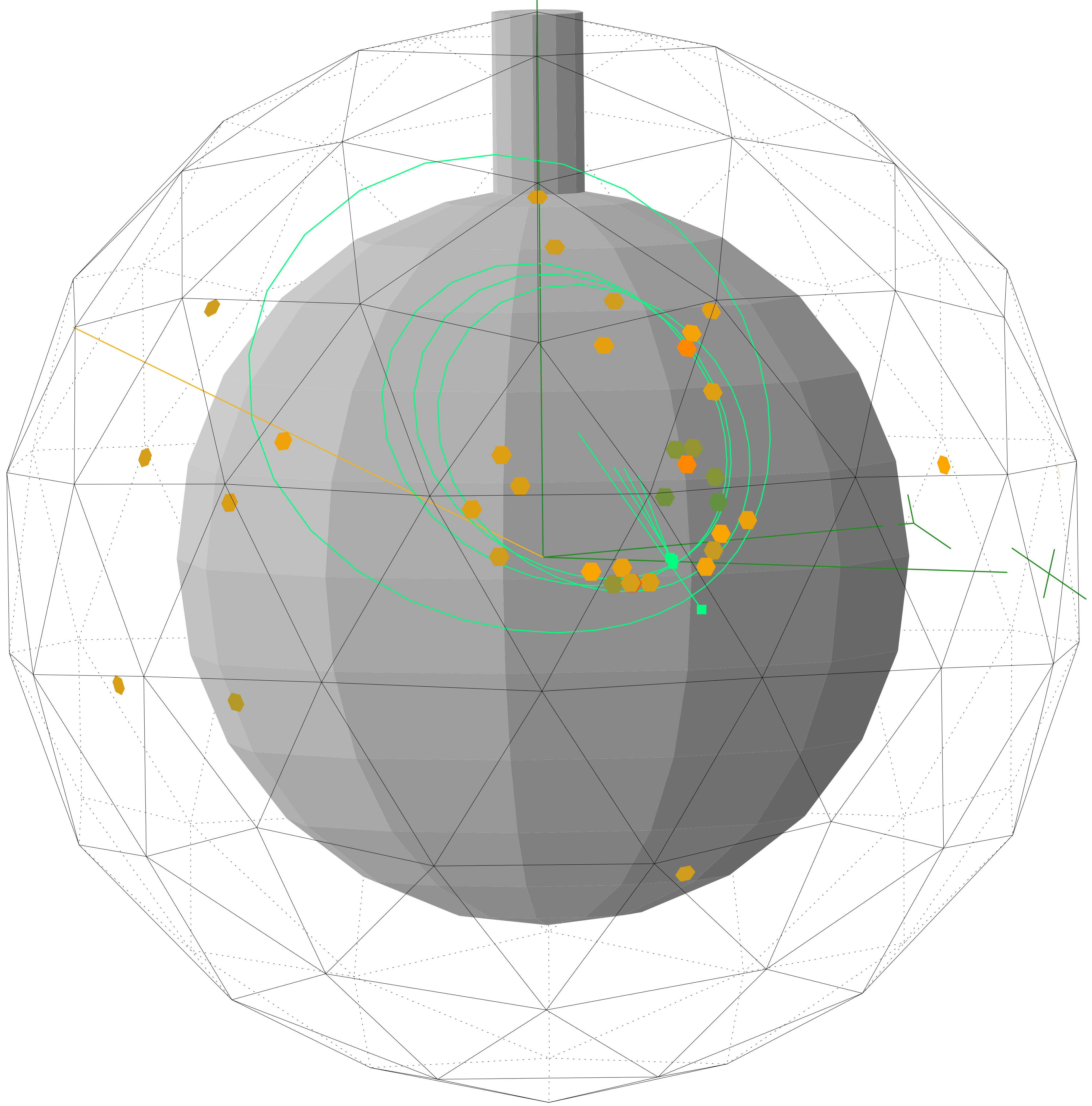
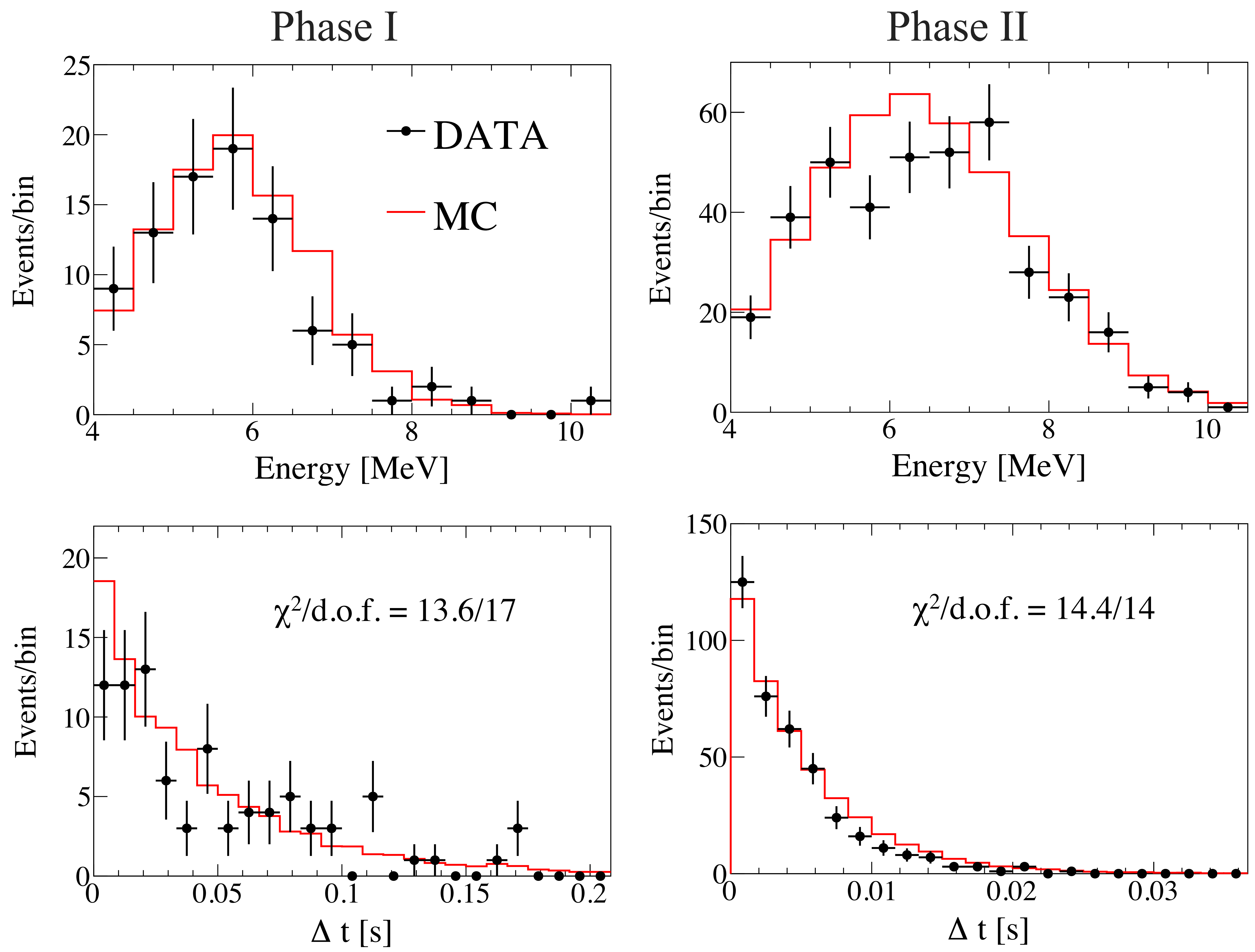


Using original SNO reconstruction tools identified neutrons capturing within the acrylic vessel



Time from neutrino interaction

NEUTRON CAPTURES ON DEUTERIUM AND ^{35}Cl IDENTIFIED BY COINCIDENCE

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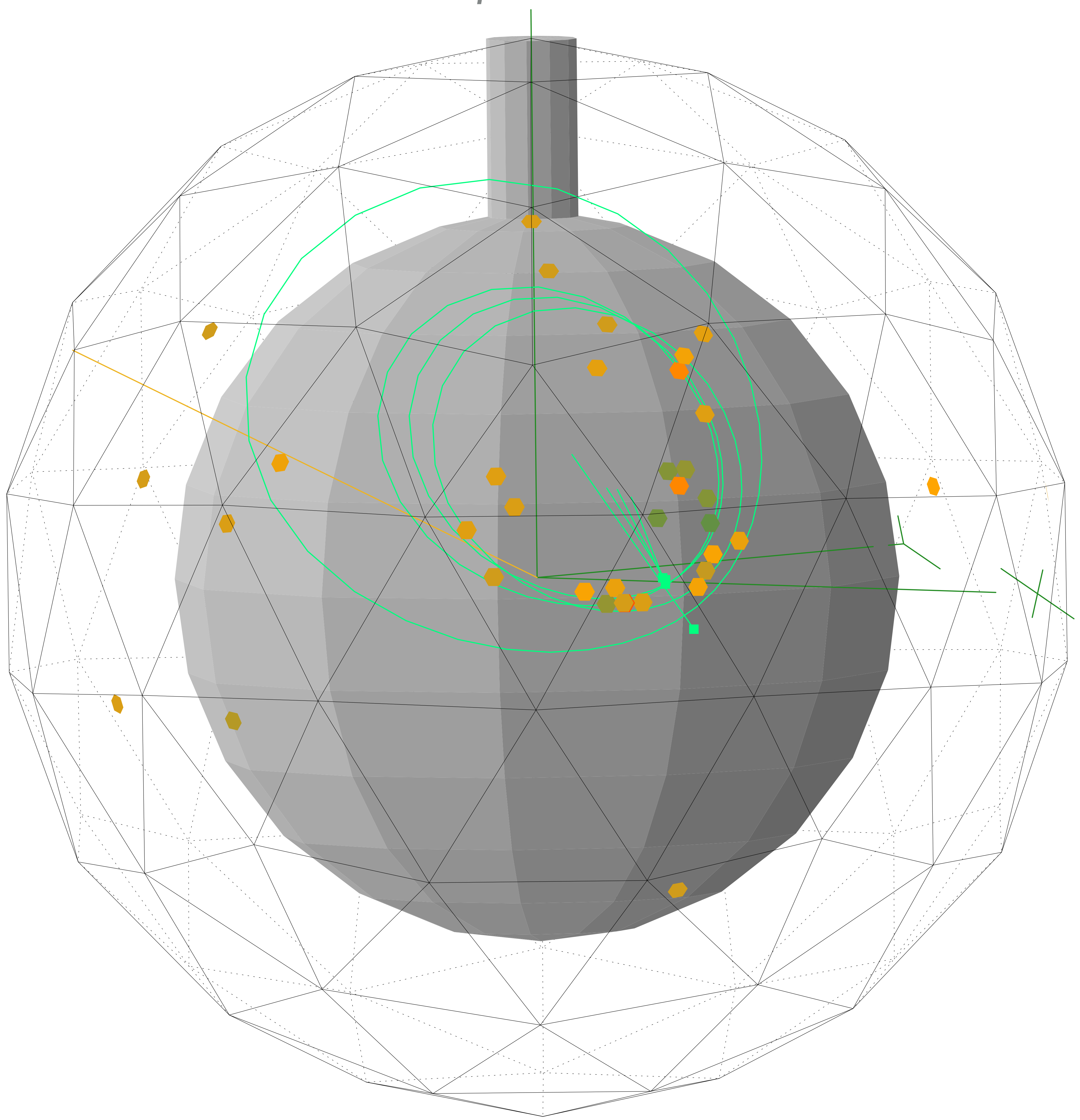
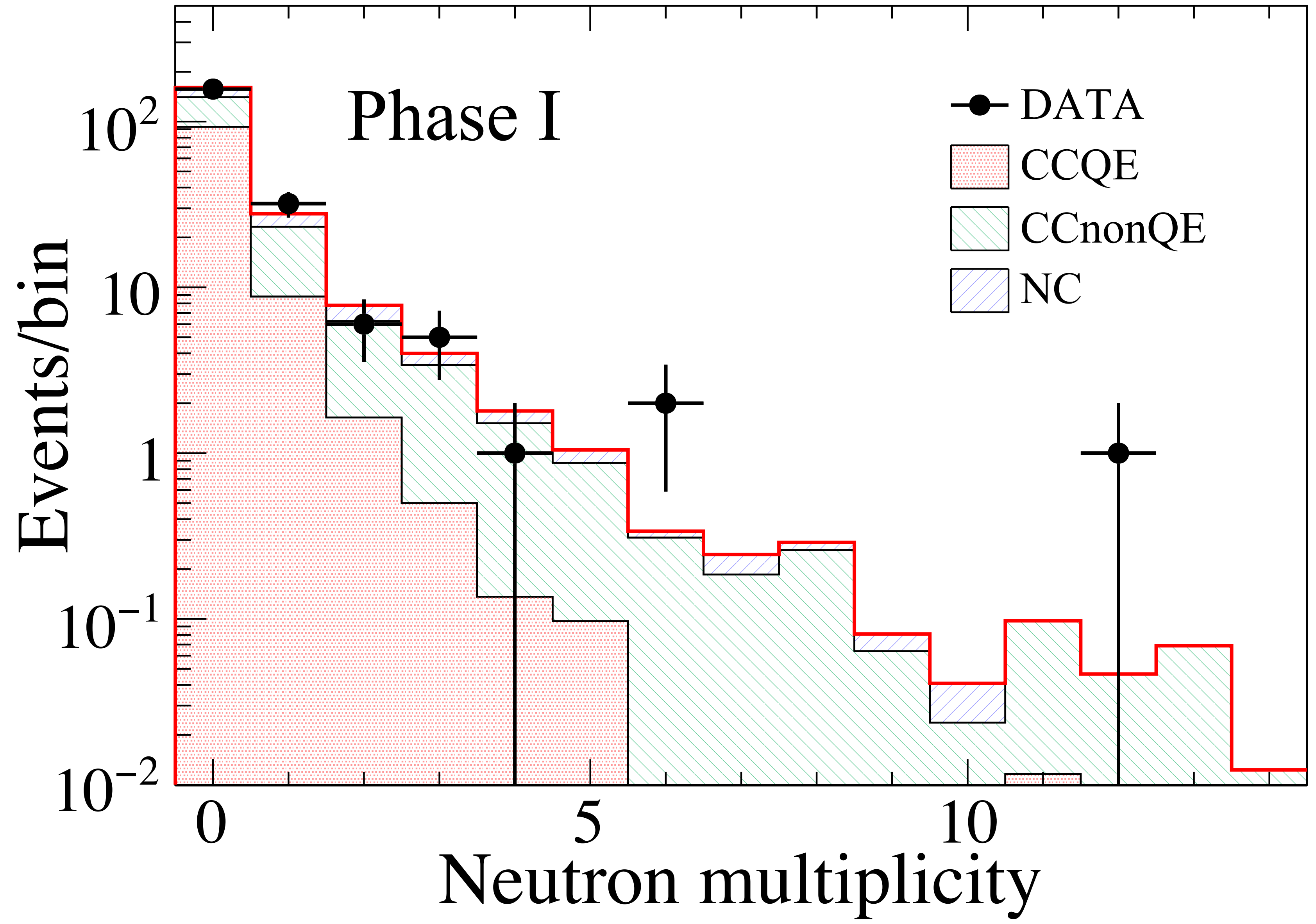


88 neutron capture candidates



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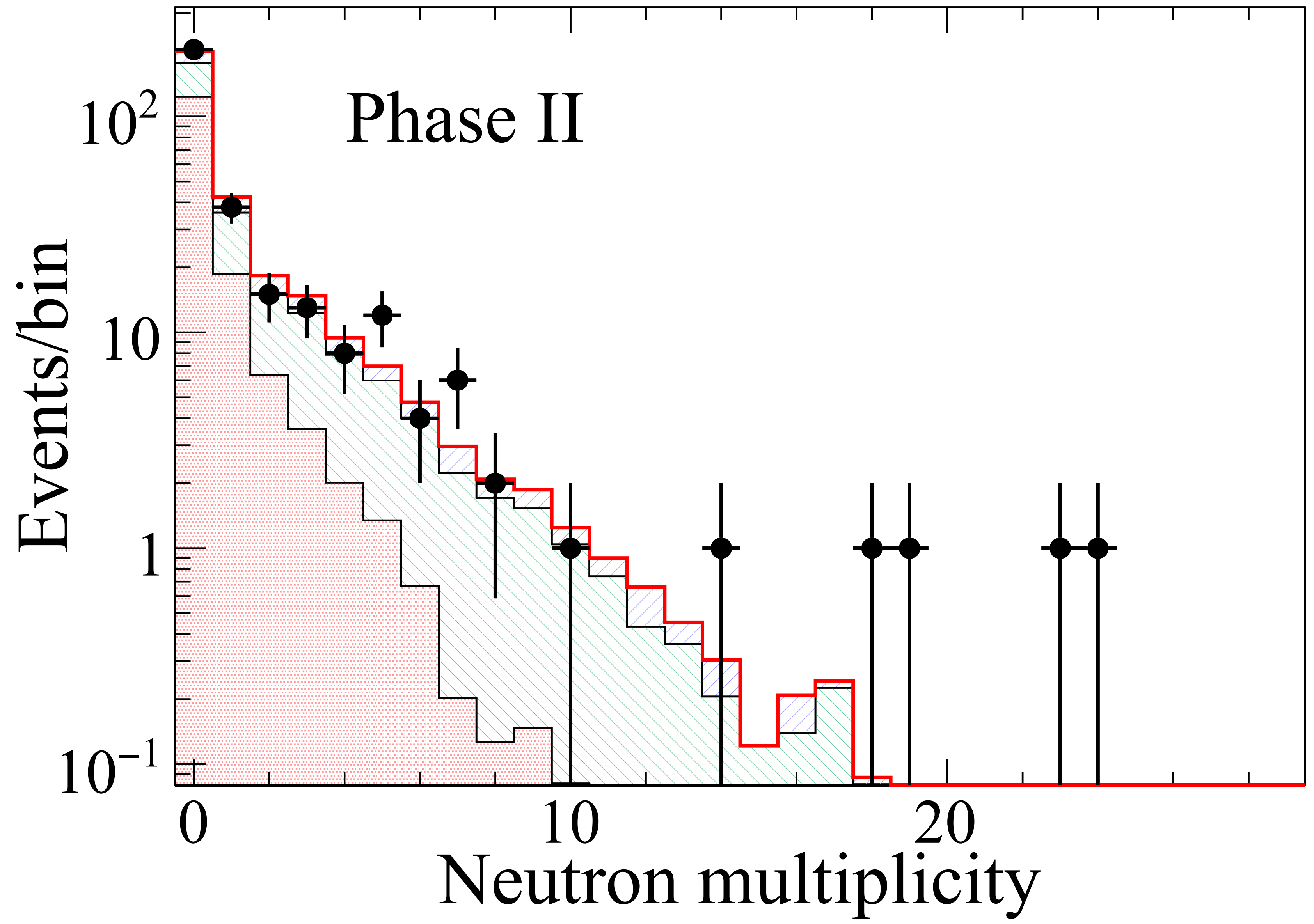
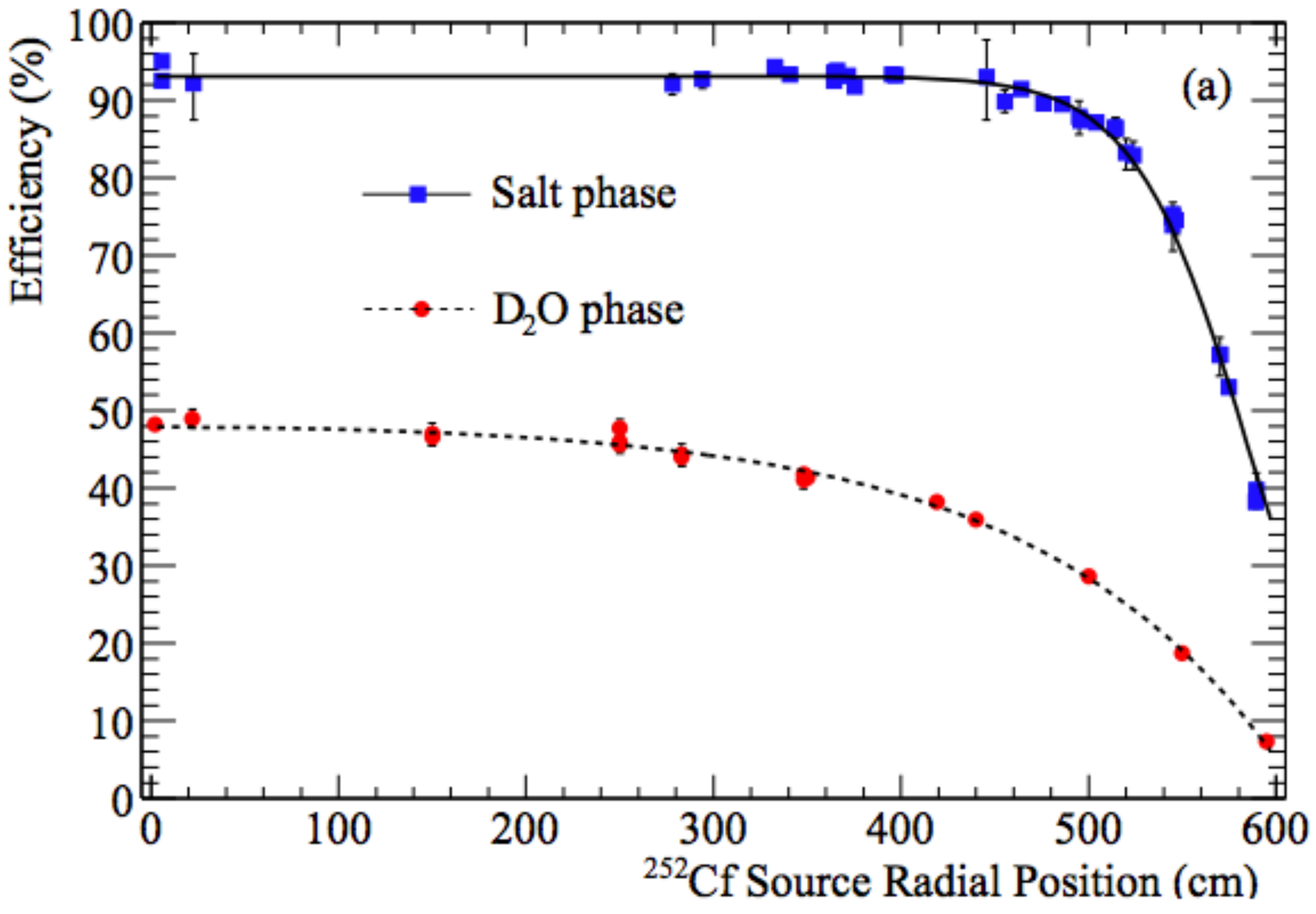


NEUTRON DETECTION EFFICIENCY MODEL VALIDATED WITH A ^{252}Cf SOURCE

^{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

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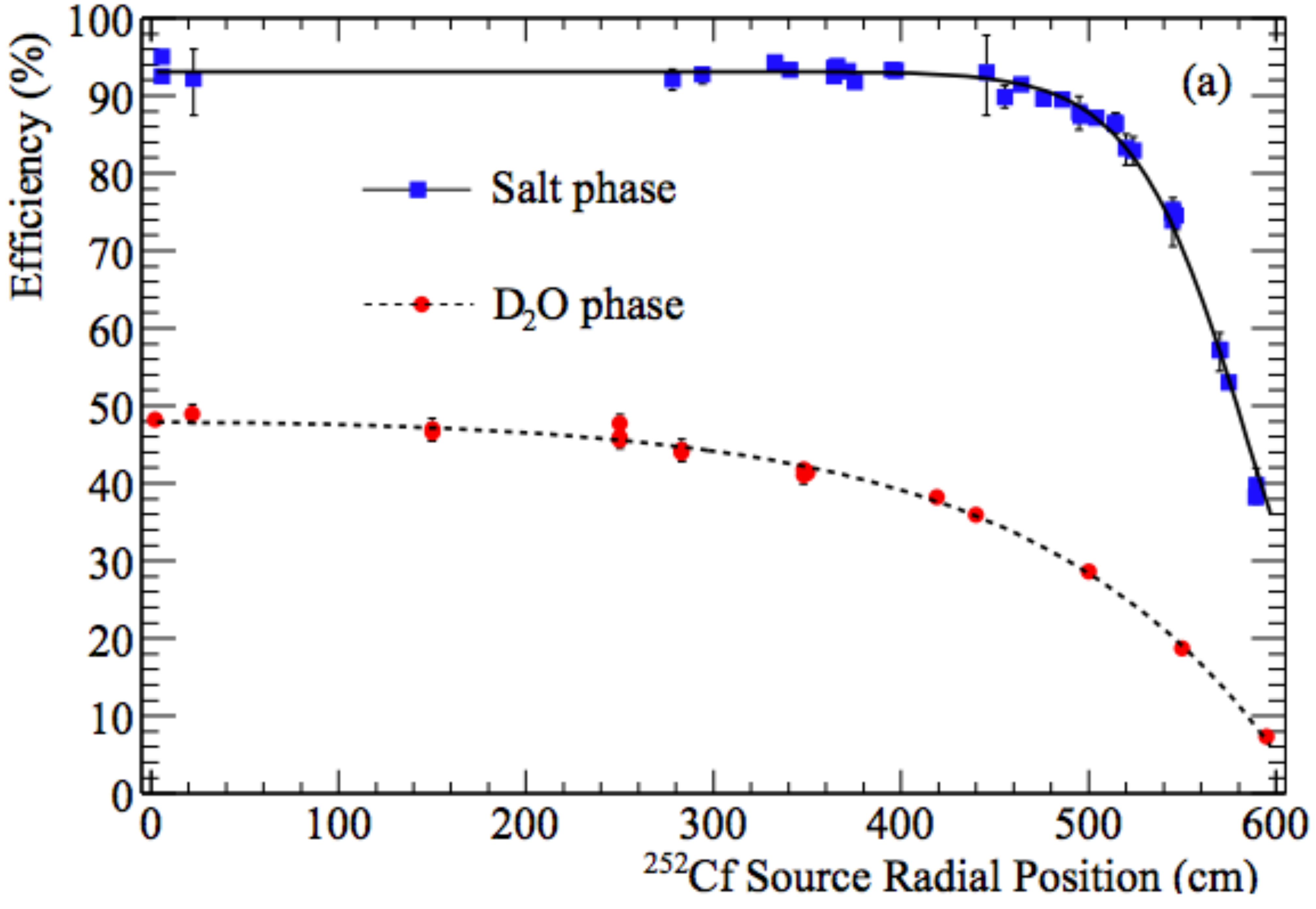

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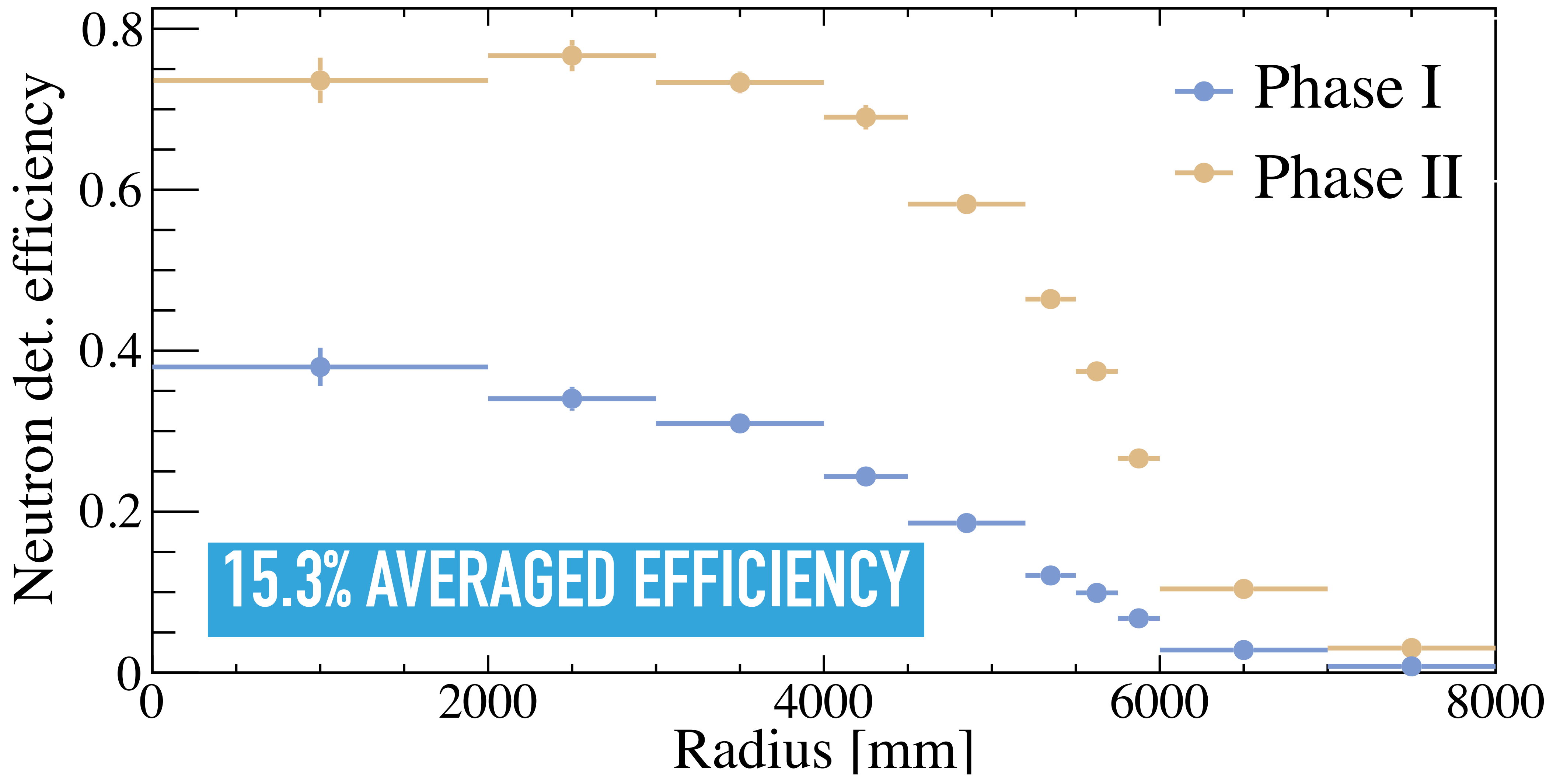
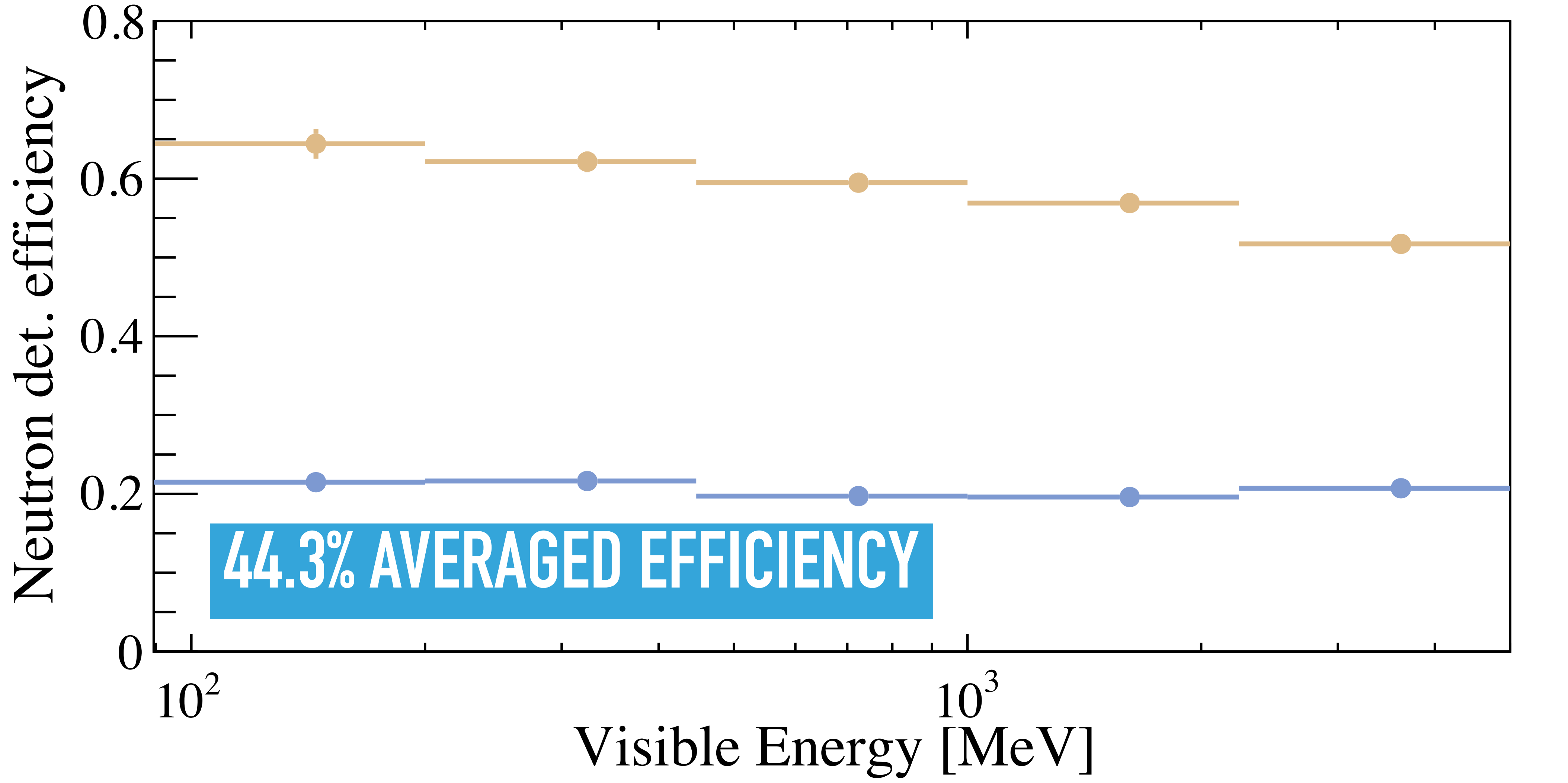
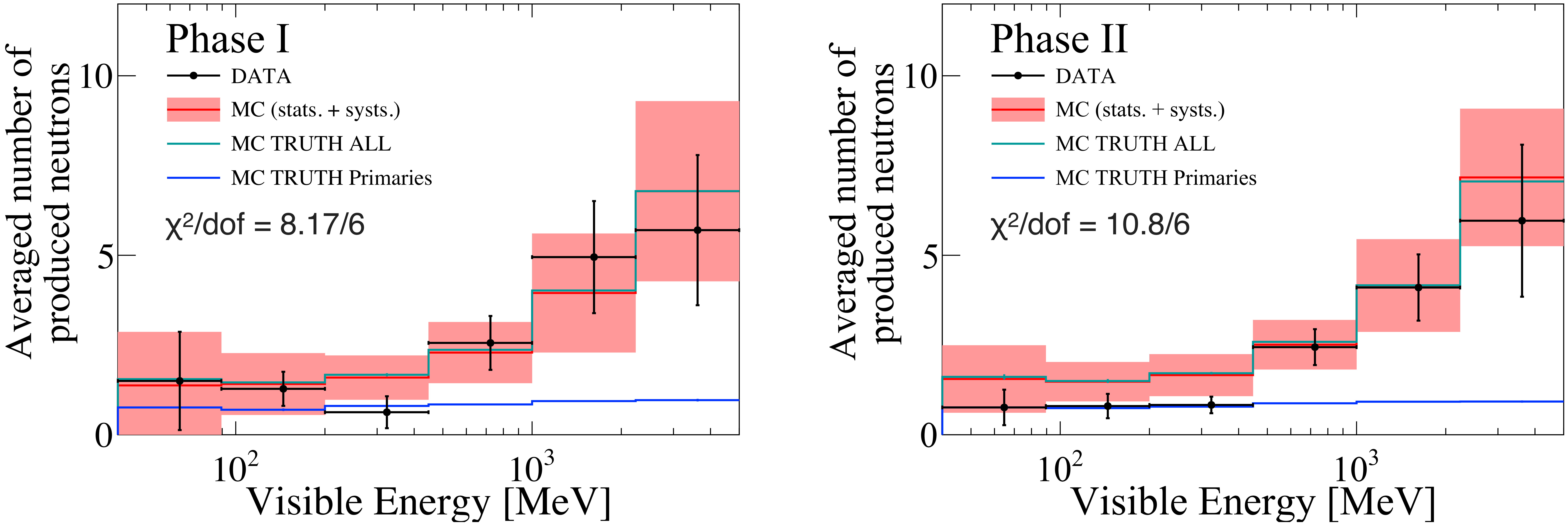
As calculated from Monte Carlo





RESULTS

INCLUSIVE RESULTS AND MONTE CARLO COMPARISON

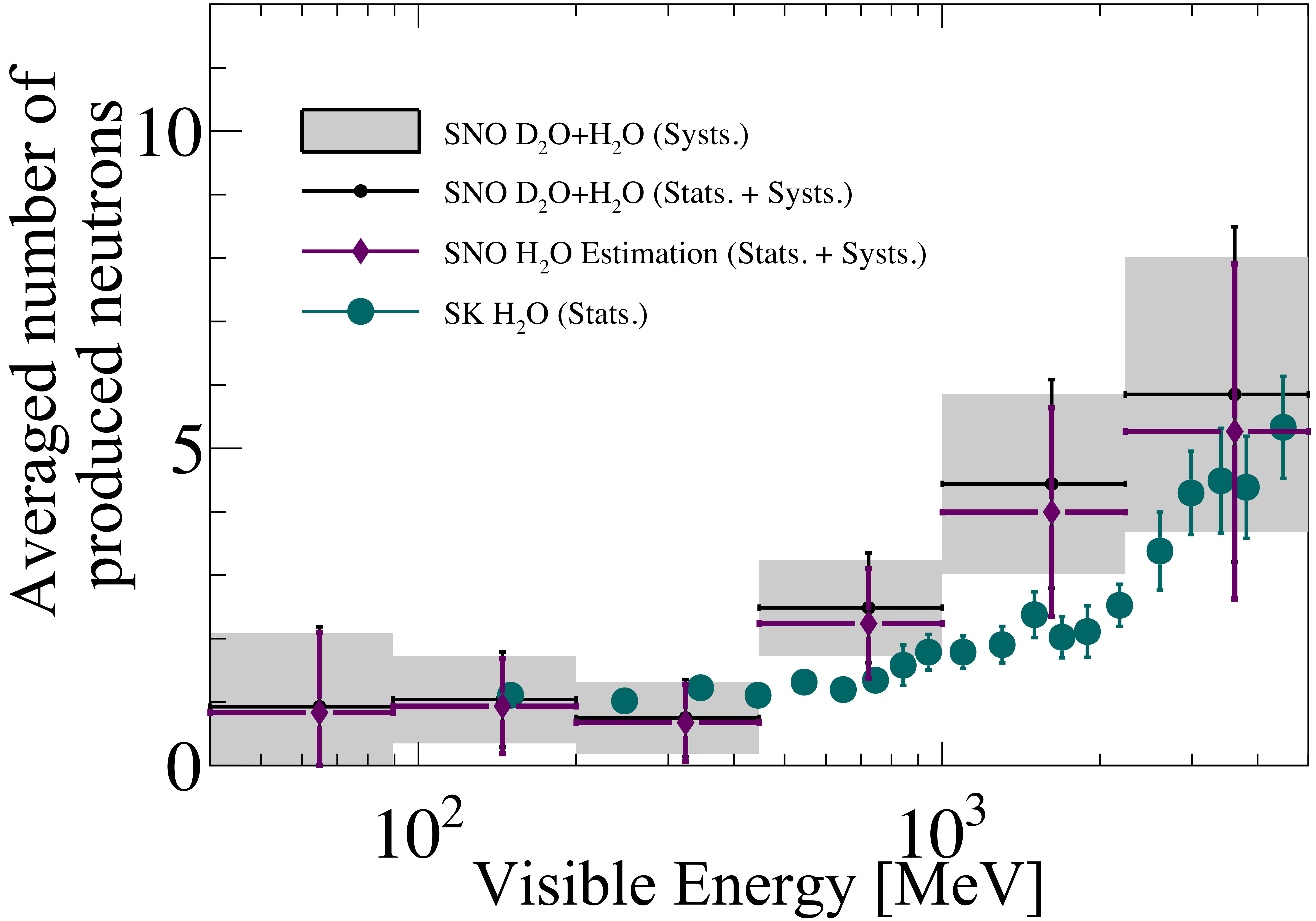


**Visible Energy = electron-equivalent energy*

SNO/SK COMPARISON

NEUTRON PRODUCTION IN HEAVY WATER IS 9.8±2.8% LARGER THAN IN LIGHT WATER ACCORDING TO OUR MC MODEL

→ ESTIMATE NEUTRON PRODUCTION IN LIGHT WATER VERSION OF SNO AND COMPARE TO SK

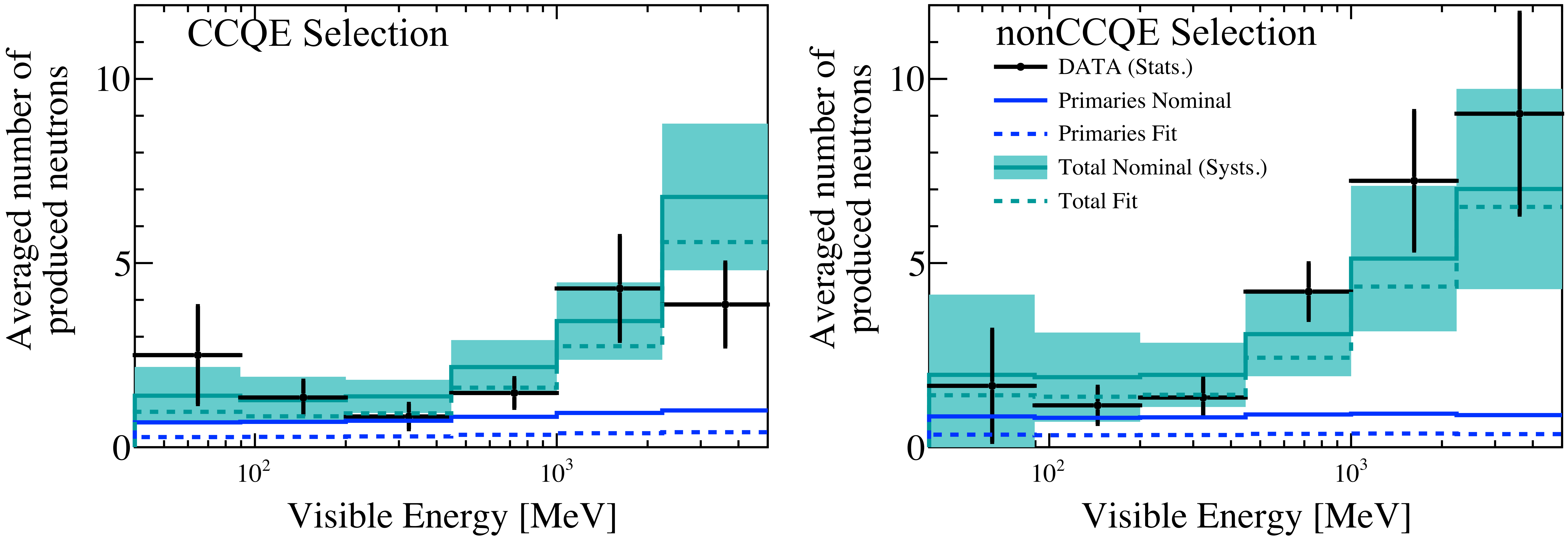


SK source: *Proceedings of the 32nd International Cosmic Ray Conference, Beijing, 2011* *http://inspirehep.net/record/1343280/files/v4.pdf*

COMPARISON BY INTERACTION CHANNELS

PRIMARY/SECONDARY NEUTRONS FIT

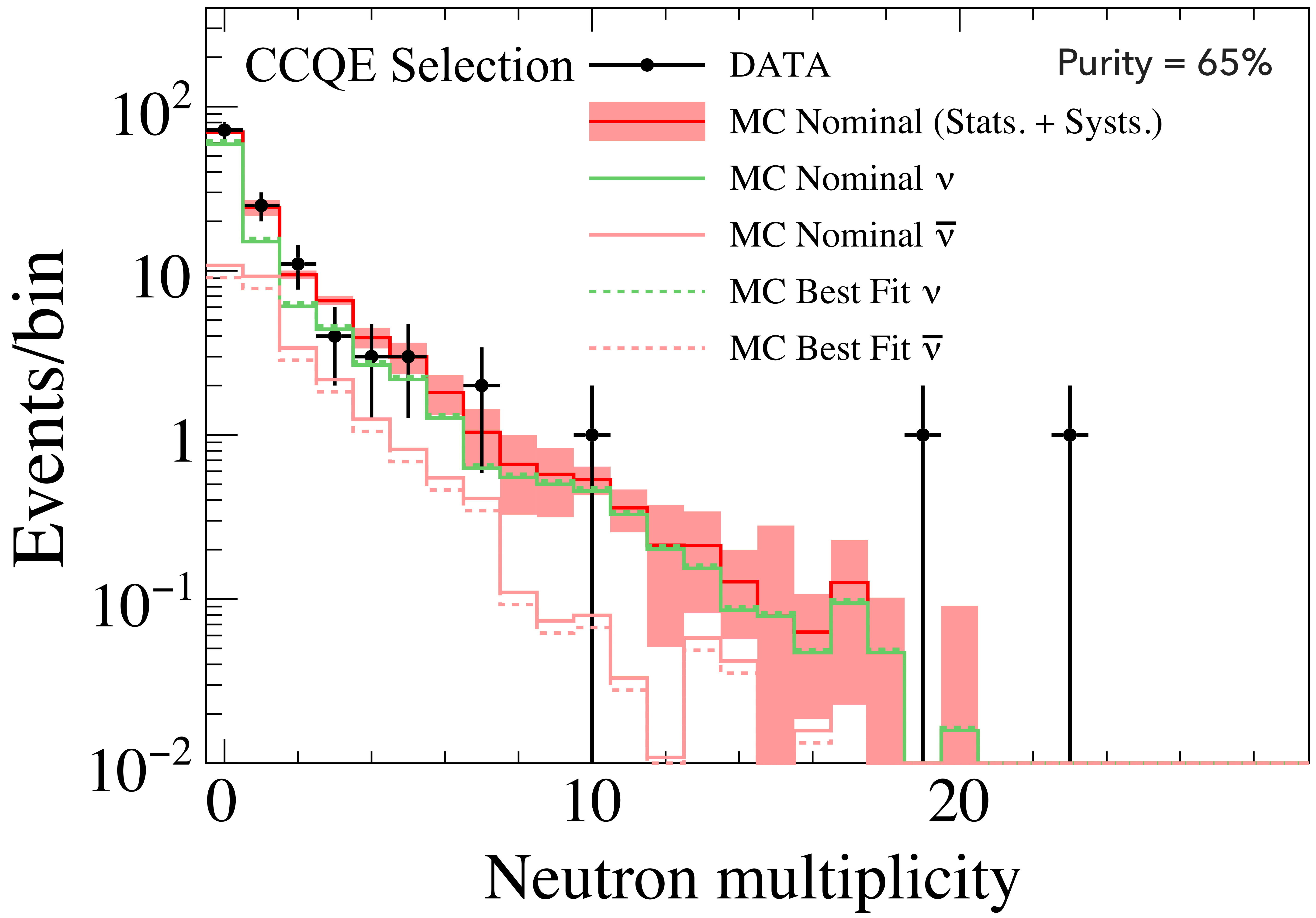
PRIMARY/SECONDARY NEUTRON COMPONENTS ARE DIFFERENT FOR CCQE AND NON-CCQE INTERACTIONS → HELP DISENTANGLING DIFFERENT NEUTRON ORIGIN THROUGH SHAPE LIKELIHOOD FIT



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

NEUTRINO/ANTI-NEUTRINO SEPARATION



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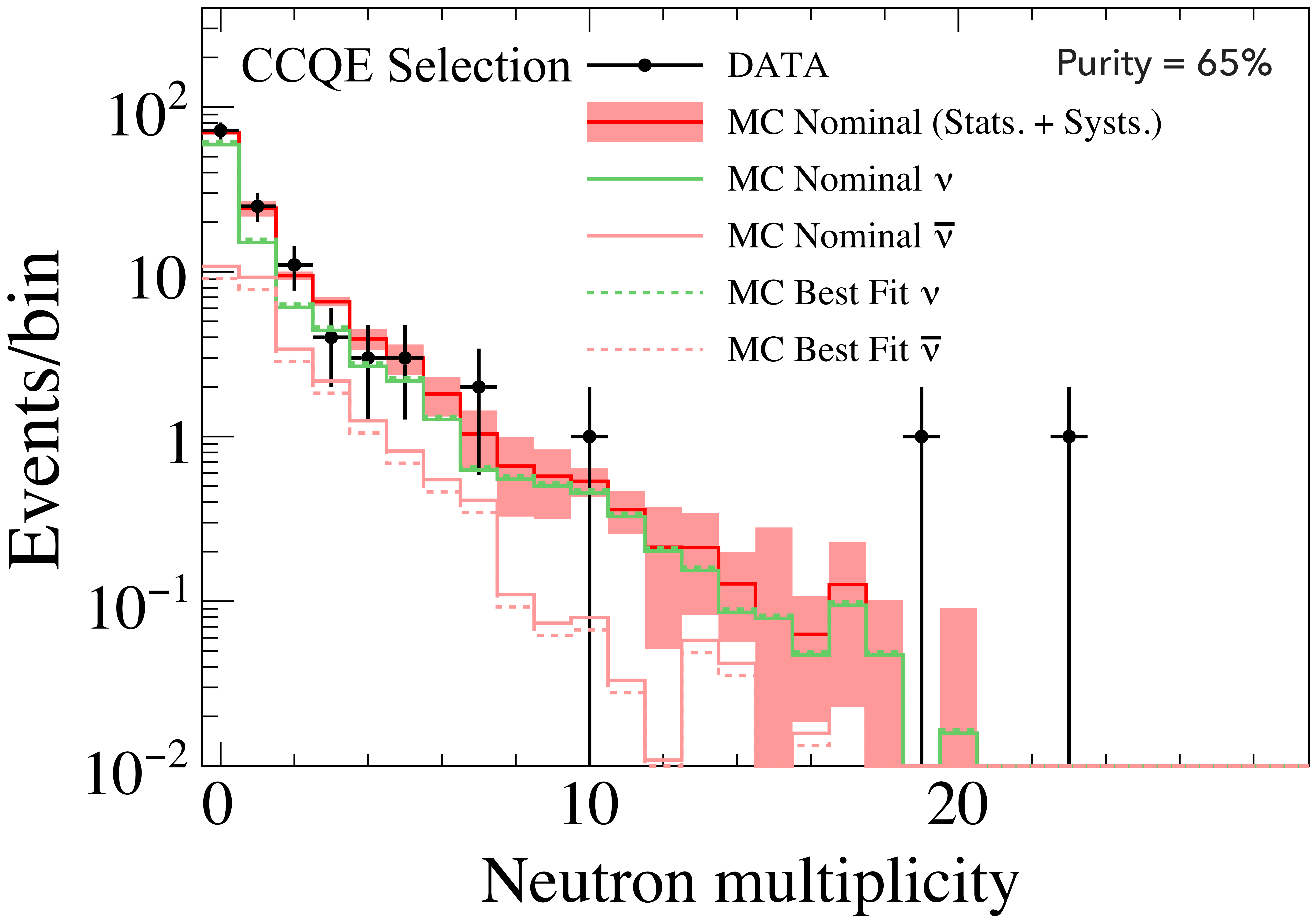

Best fit

- Anti-neutrino normalization = 0.81 ± 0.37
- Constrains anti-neutrino component **at the 46% level**

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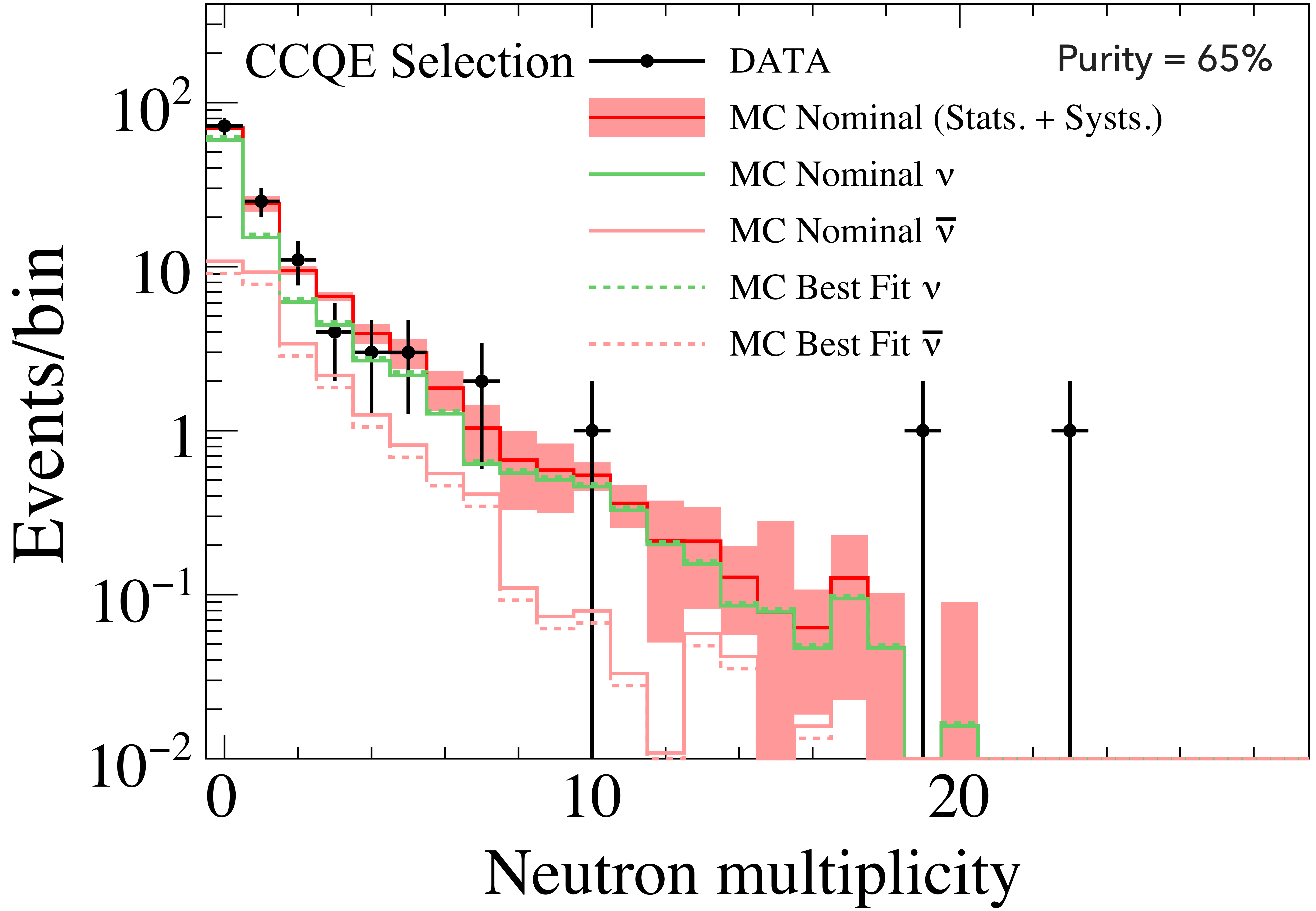

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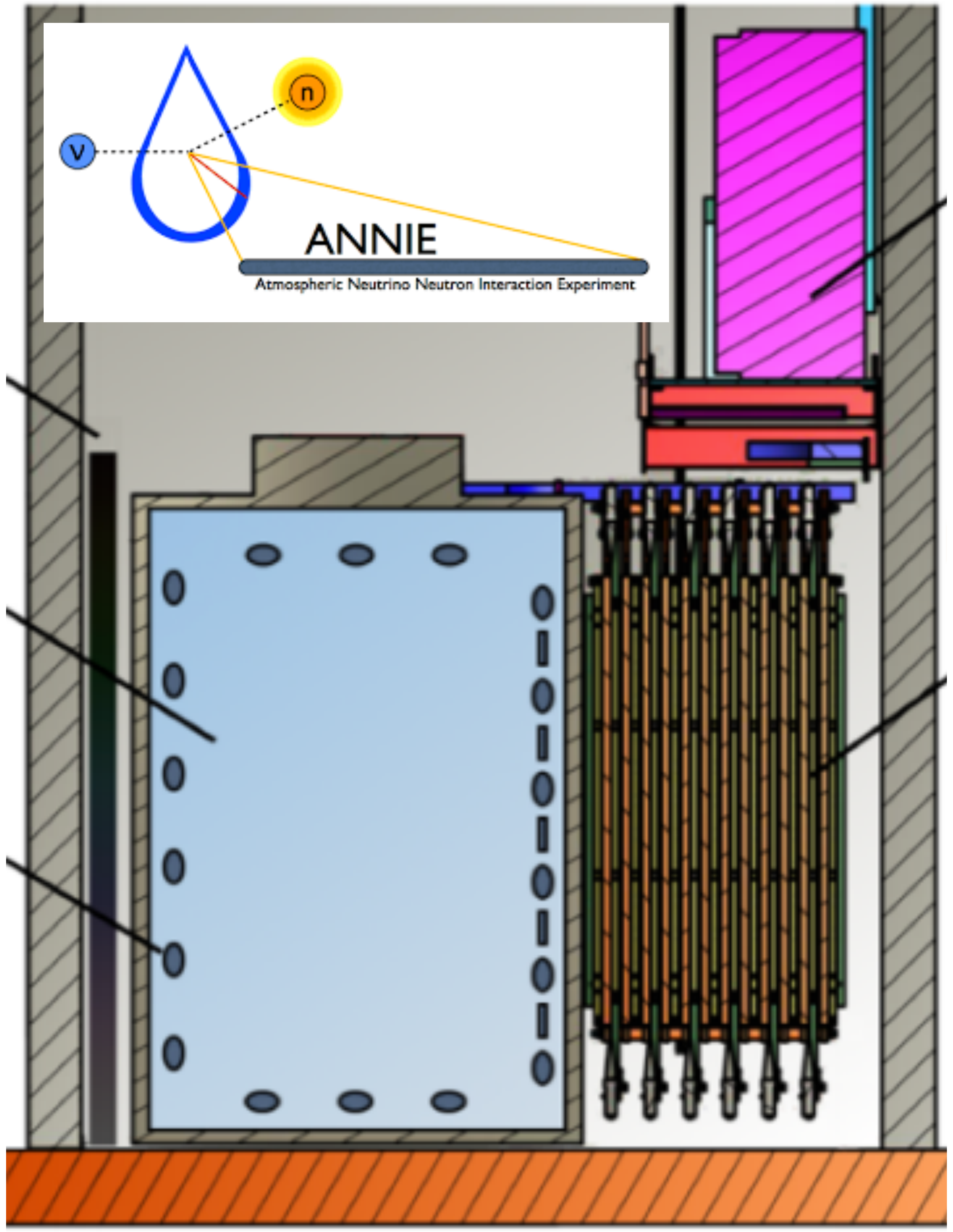
SELECTING EVENTS WITH 1 OR MORE NEUTRONS INCREASES ANTI-NEUTRINO COMPONENT FROM 23.6% TO 34.4%

PROMISING WITH A HIGHER CCQE PURITY AND LARGER NEUTRON DETECTION EFFICIENCY

ANNIE WILL MEASURE NEUTRON PRODUCTION FROM BEAM NEUTRINO INTERACTIONS AS A FUNCTION OF KINEMATICS



- The ANNIE approach:
  - Water Cherenkov detector deployed in a neutrino beam (FERMILAB) → Provides fixed neutrino direction, enabling calculation of kinematic variables
  - First physics use of Gd-doped water → Excellent neutron detection efficiency
- ANNIE will provide a calibration of neutron processes

SUMMARY

- UNDERSTANDING NEUTRON PROCESSES IN NEUTRINO INTERACTIONS IS CRUCIAL FOR NUCLEON DECAY SEARCHES AND FUTURE NEUTRINO OSCILLATION EXPERIMENTS
- SNO HAS PUBLISHED A MC VALIDATION OF NEUTRON PRODUCTION VERSUS ENERGY AND INTERACTION CHANNELS
- GOOD AGREEMENT BETWEEN DATA AND MODELS WITHIN UNCERTAINTIES
- PROMISING RESULTS FOR NEUTRINO/ANTI-NEUTRINO SEPARATION USING NEUTRON TAGGING IN FUTURE DEDICATED DETECTORS
- EXCITING RESULTS FROM ANNIE WILL COME DURING THE NEXT YEAR

OTHER RECENT SNO ANALYSES

NEUTRON PRODUCTION IN ATMOSPHERIC NEUTRINO INTERACTIONS
PHYS. REV. D 99, 112007 (2019)

NEUTRON PRODUCTION BY COSMIC MUONS
ARXIV:1909.11728 [HEP-EX]

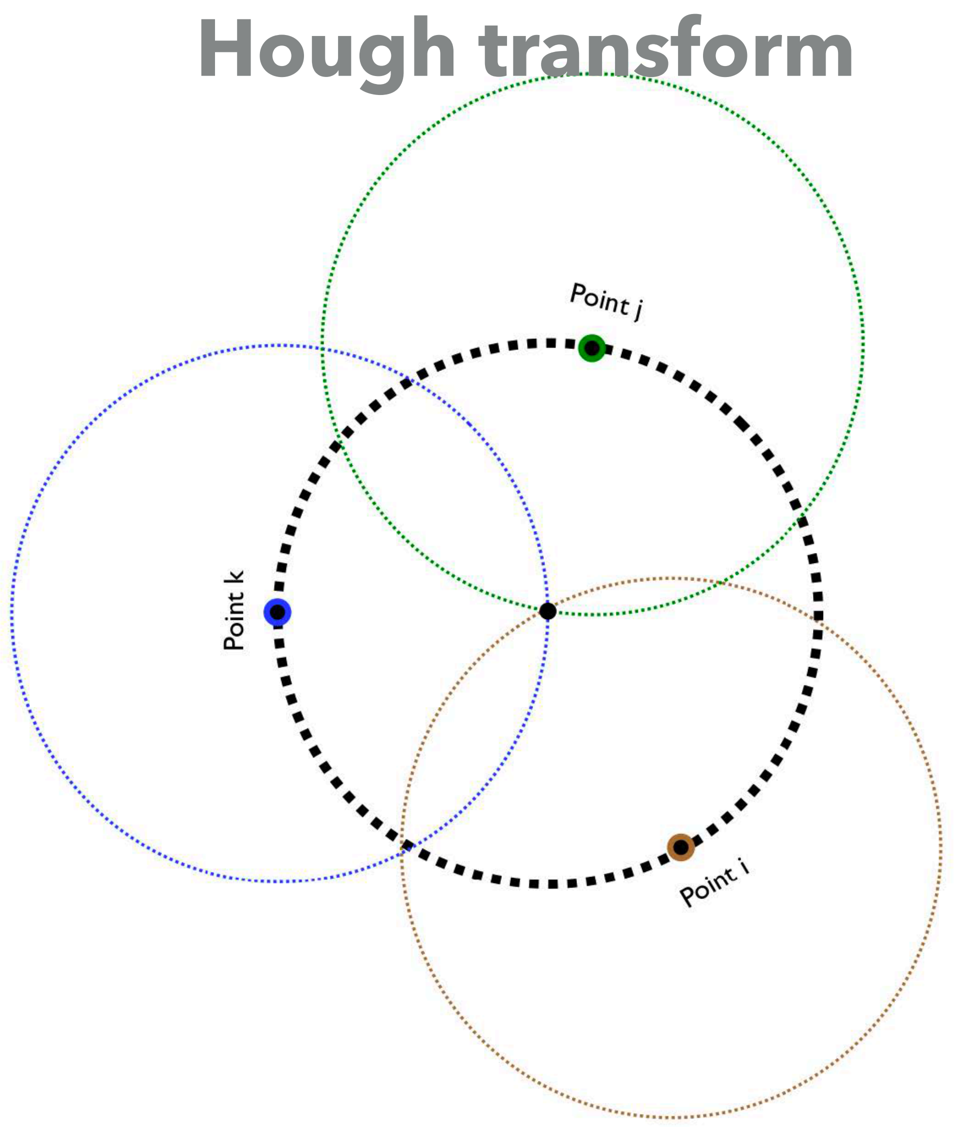
NEUTRINO DECAY SEARCH
PHYS. REV. D 99, 032013 (2019)

LORENTZ VIOLATION SEARCH
PHYS. REV. D 98, 112013 (2018)

SOLAR HEP NEUTRINO SEARCH
PAPER IN PREPARATION

BACKUP

RING FITTER ALGORITHM



1. Seed determination:
    1. Hough transform → Direction seed
    2. SNO+ water fitter → Position seed
    3. Total number of PE → Energy seed
2. Precise event position and direction → Likelihood fit under the single ring hypothesis

$$\mathcal{L}(\vec{x}) = \prod_{i}^{hit} P_i^{hit}(q_i, t_i(\vec{r})|\lambda_i(\vec{x})) \prod_{j}^{unhit} e^{-\lambda_j(\vec{x})}$$

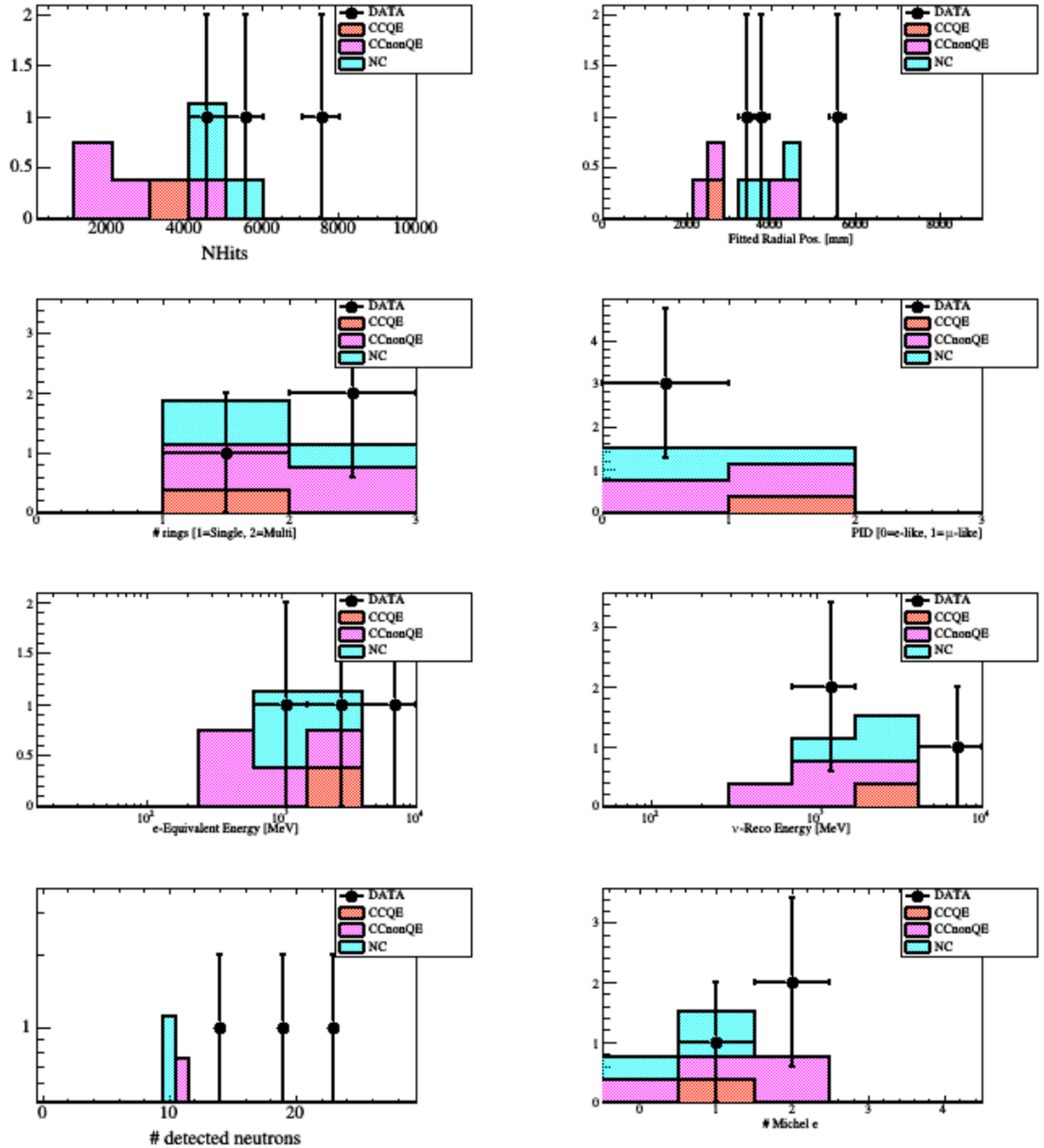
$$P_i^{hit}(q_i, t_i(\vec{r})|\lambda_i) = \sum_{n_i} P_N(n_i|\lambda_i) \times P_Q(q_i|n_i) \times P_T(t_i(\vec{r})|n_i)$$

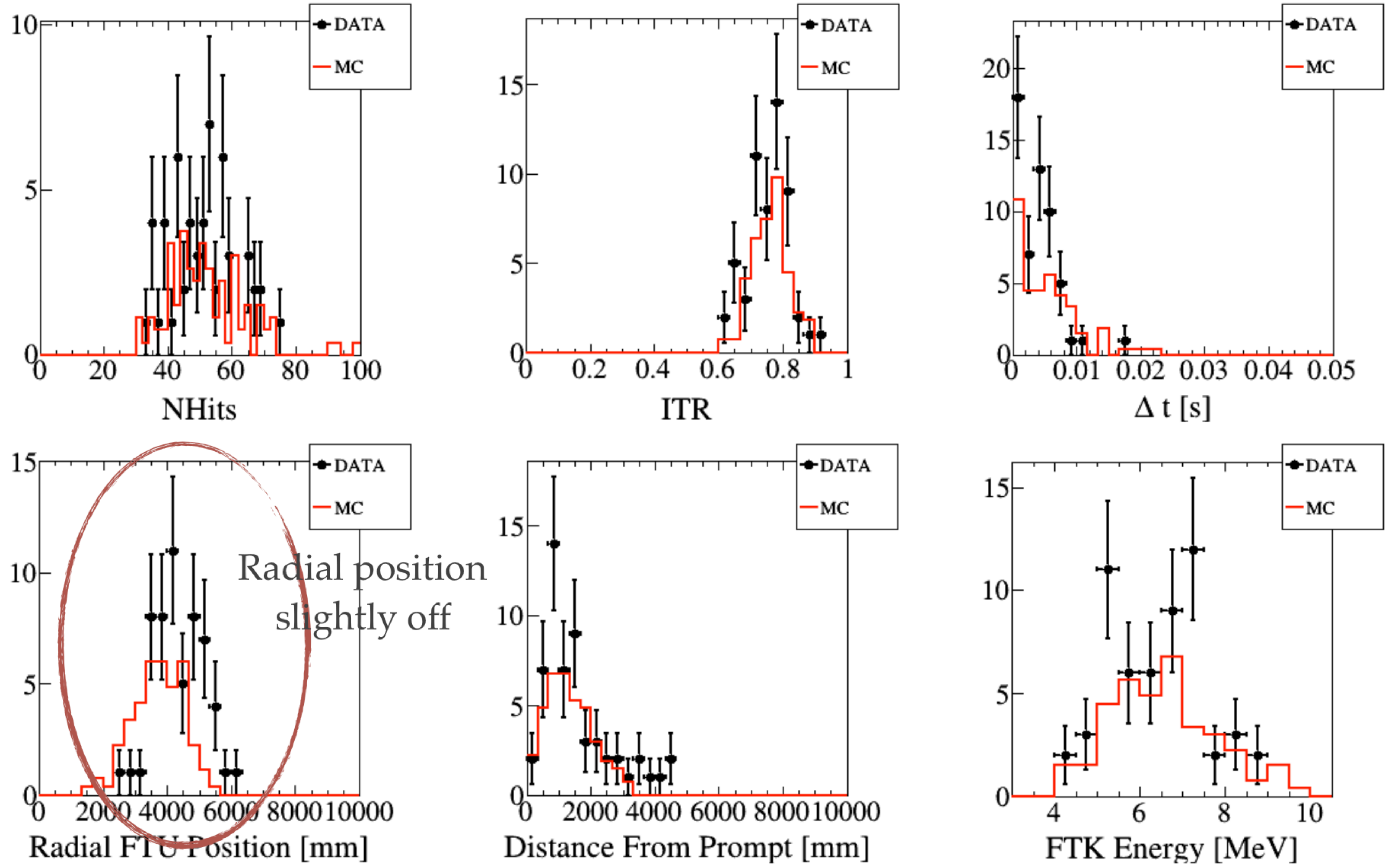
3. Particle identification → Perform likelihood fit under electron and muon hypothesis and calculate ΔL
4. Visible energy reconstruction → Use fit position and total number of PE to get energy from MC lookup tables
5. Ring multiplicity → Subtract main ring and redo Hough transform

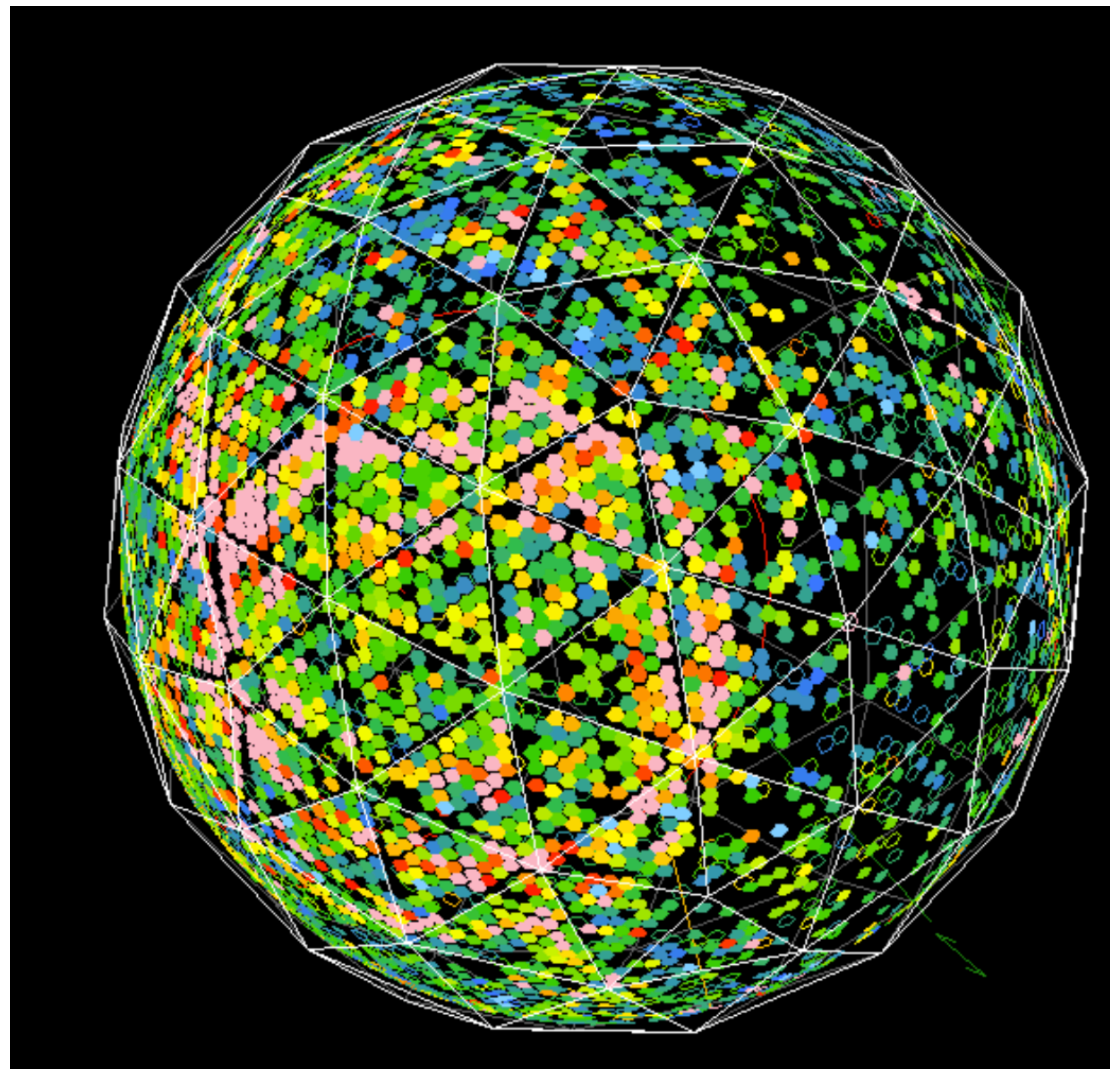
$$\sum_{n_i>0} q_i \times P_N(n_i|\lambda_i) \times P_Q(q_i|n_i)$$

OUTLIERS

Events with more than 10 neutrons





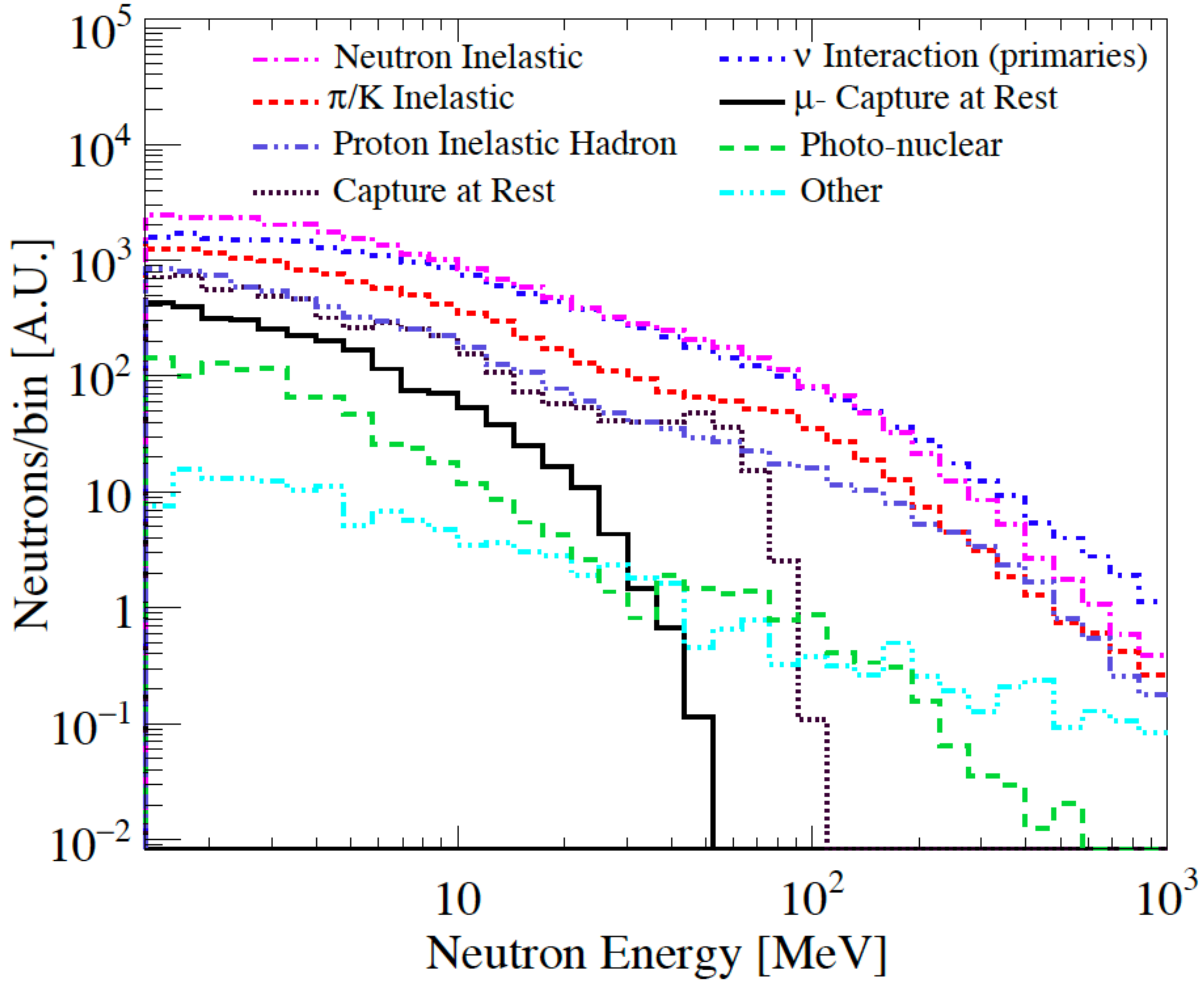


All of them are multi-ring events

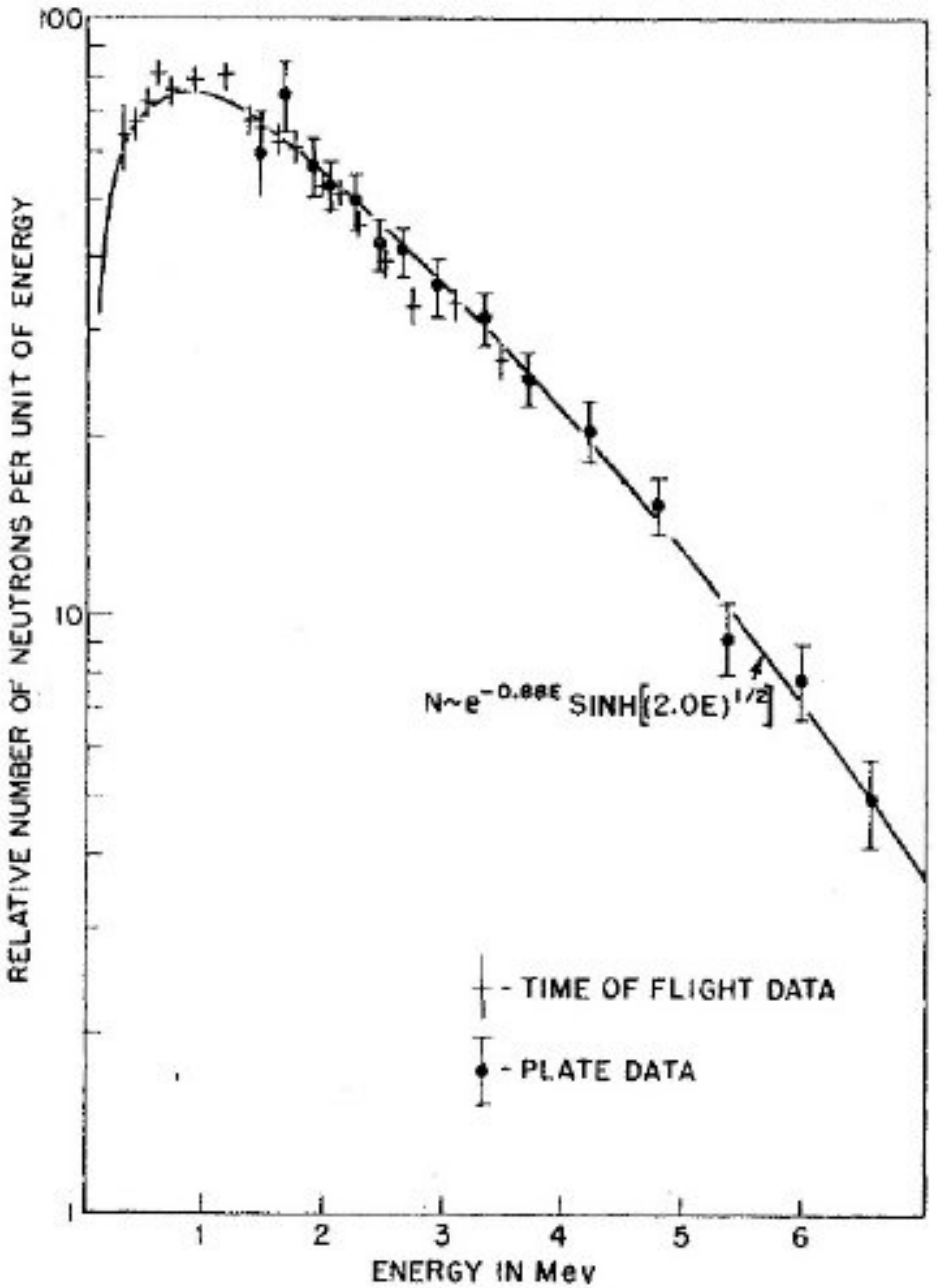
The external veto was definitely working for those runs

NEUTRON ENERGY DISTRIBUTIONS

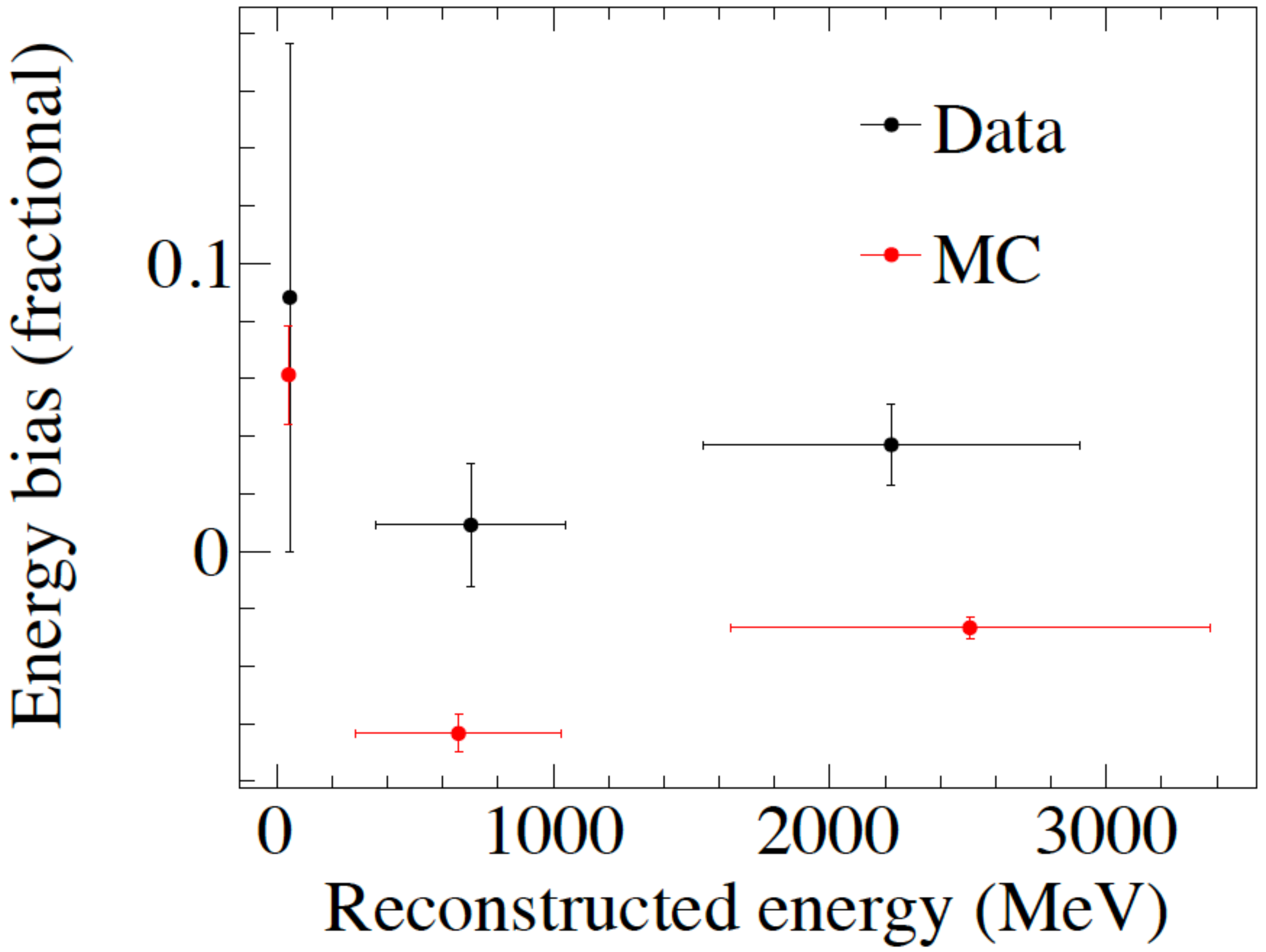
Atmospheric neutrinos

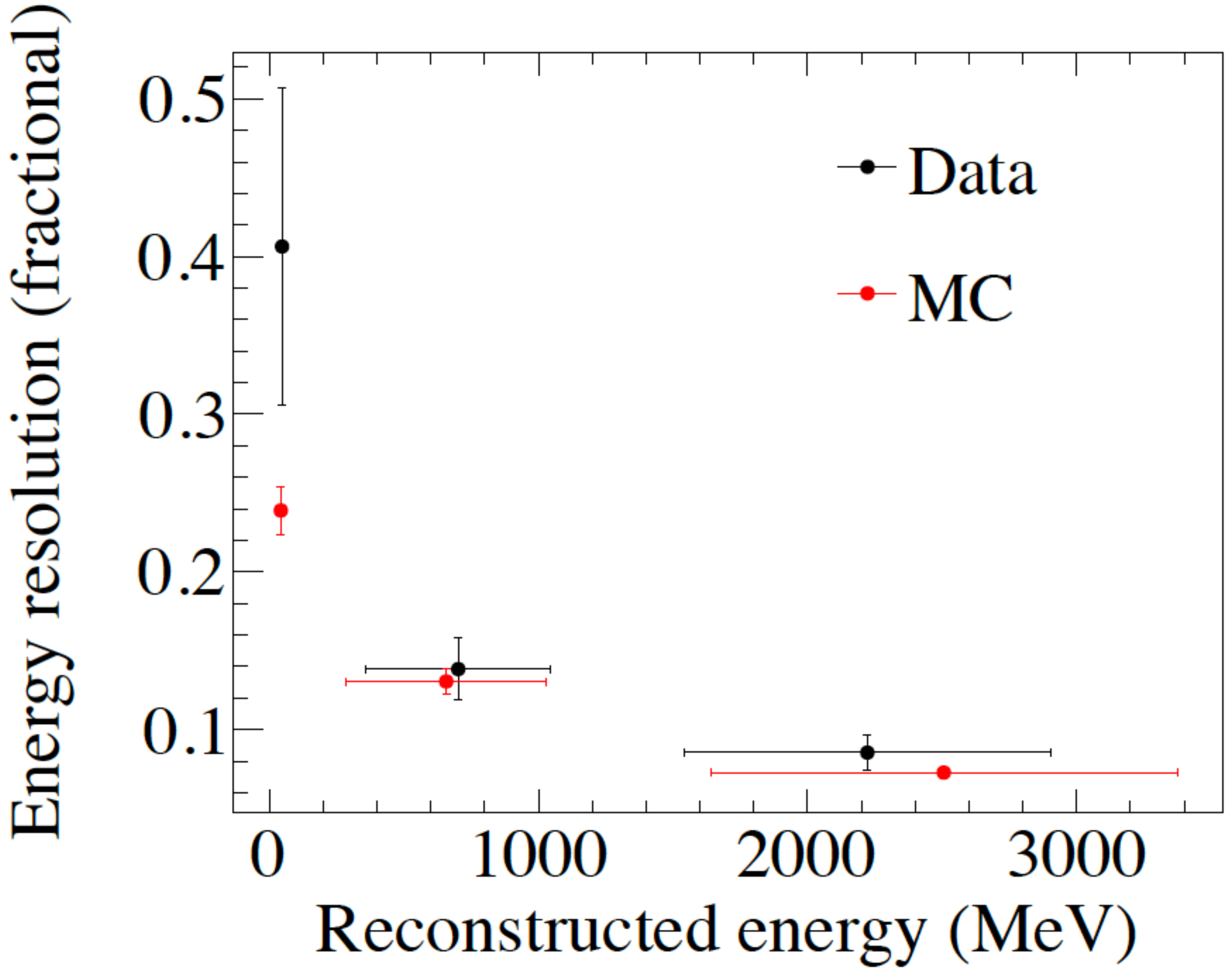


Cf-252

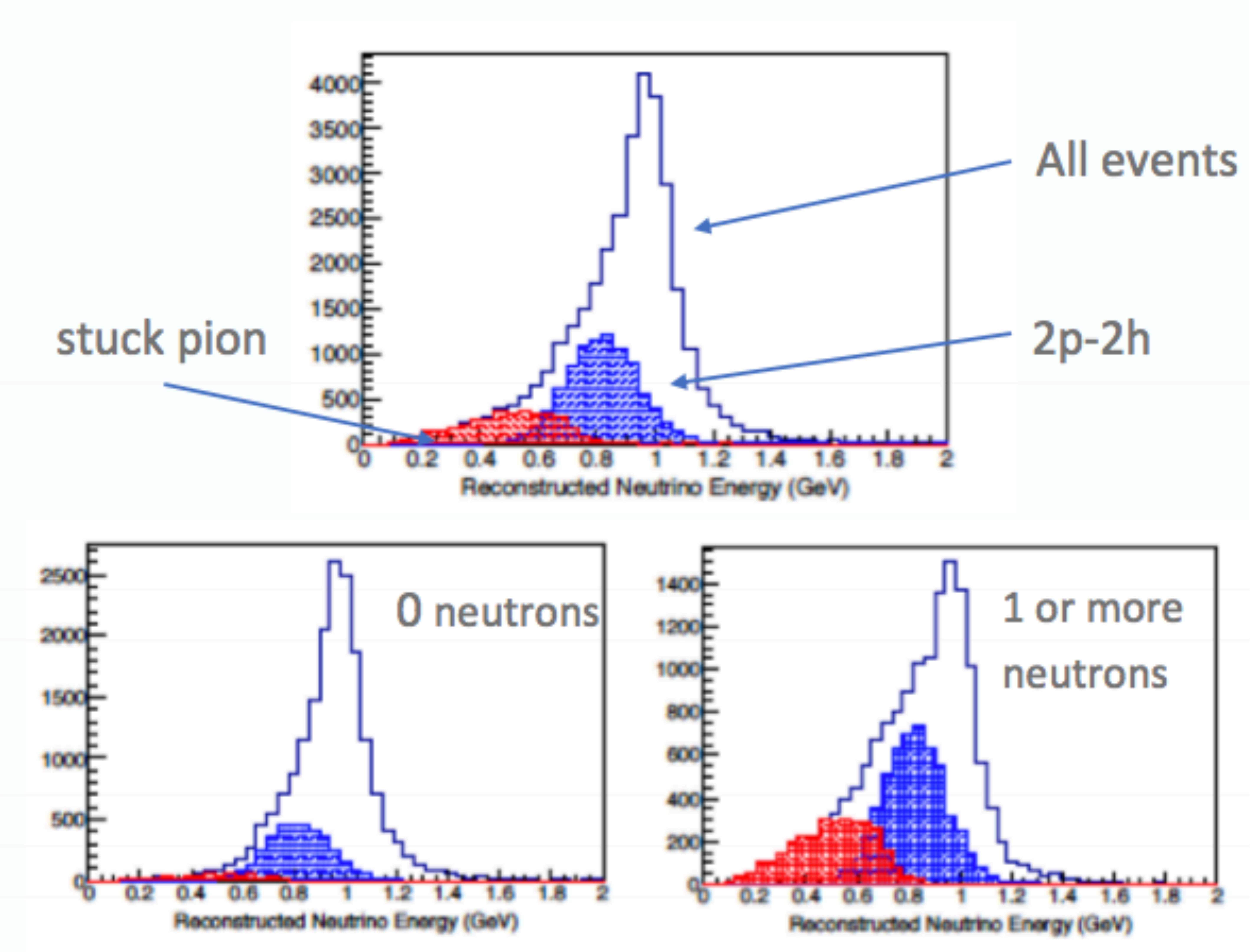


ENERGY SYSTEMATIC UNCERTAINTIES

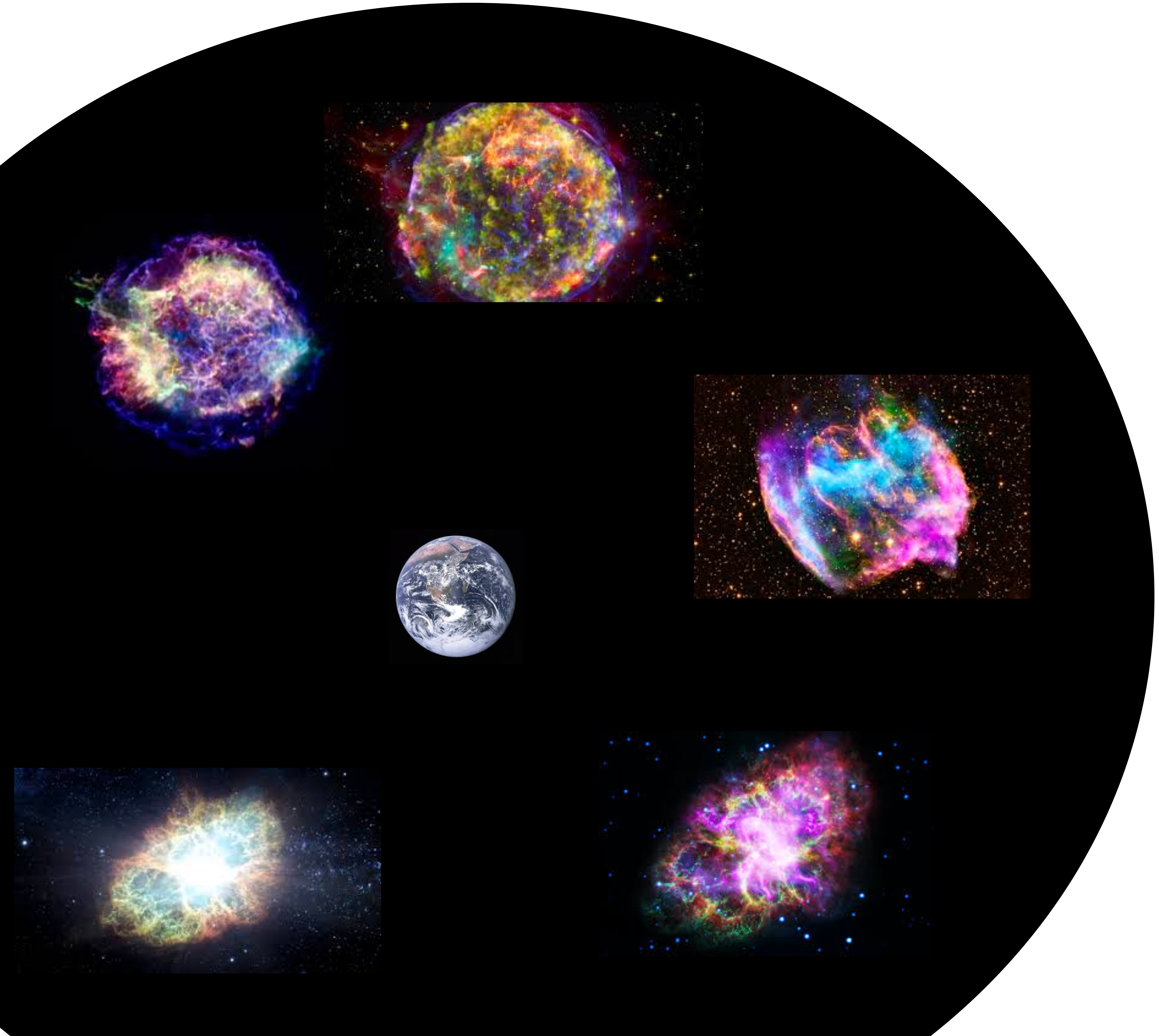


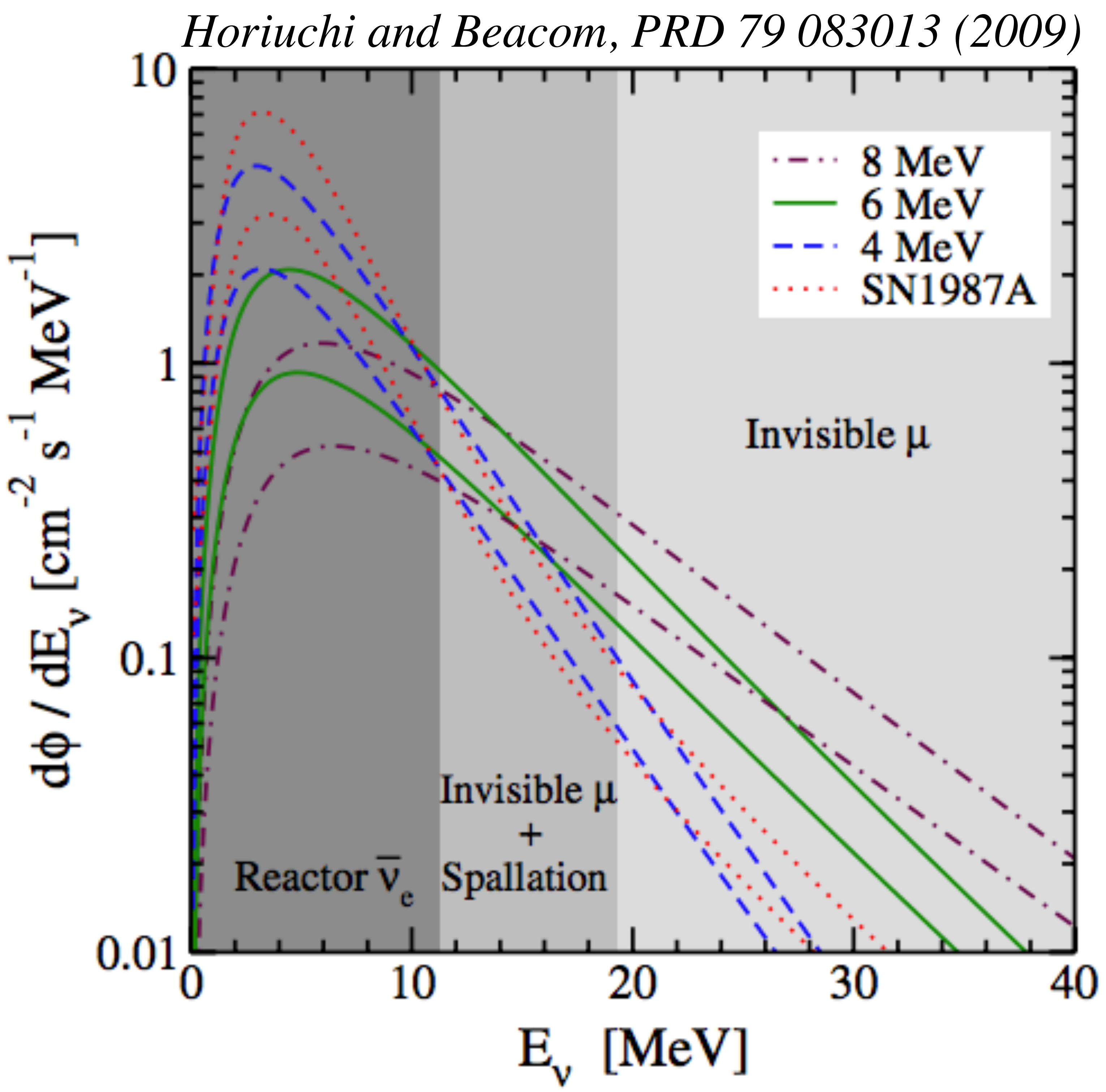


IMPROVEMENT OF ENERGY RESOLUTION

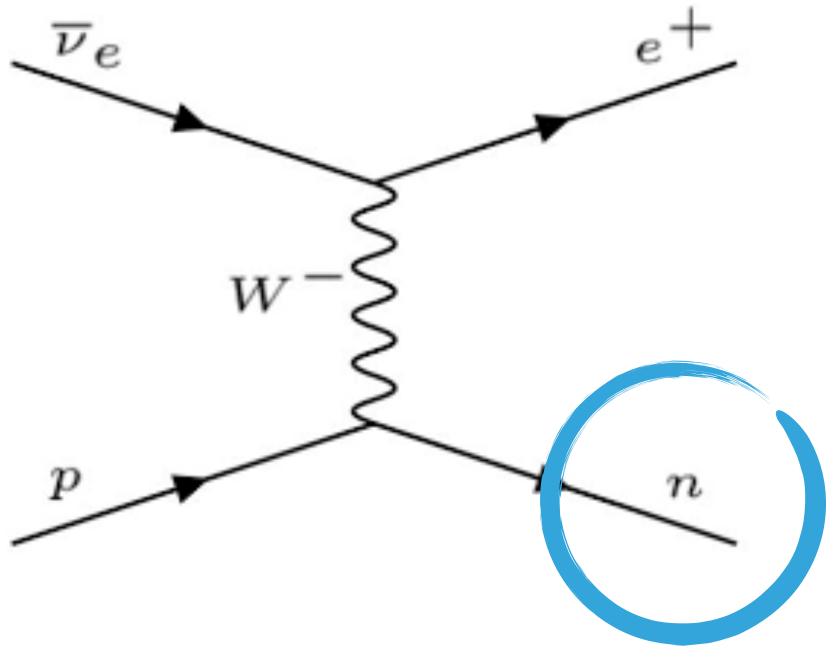


NEUTRON TAGGING CAN HELP DETECTING ANTI-NUE THROUGH INVERSE BETA DECAY PROCESS

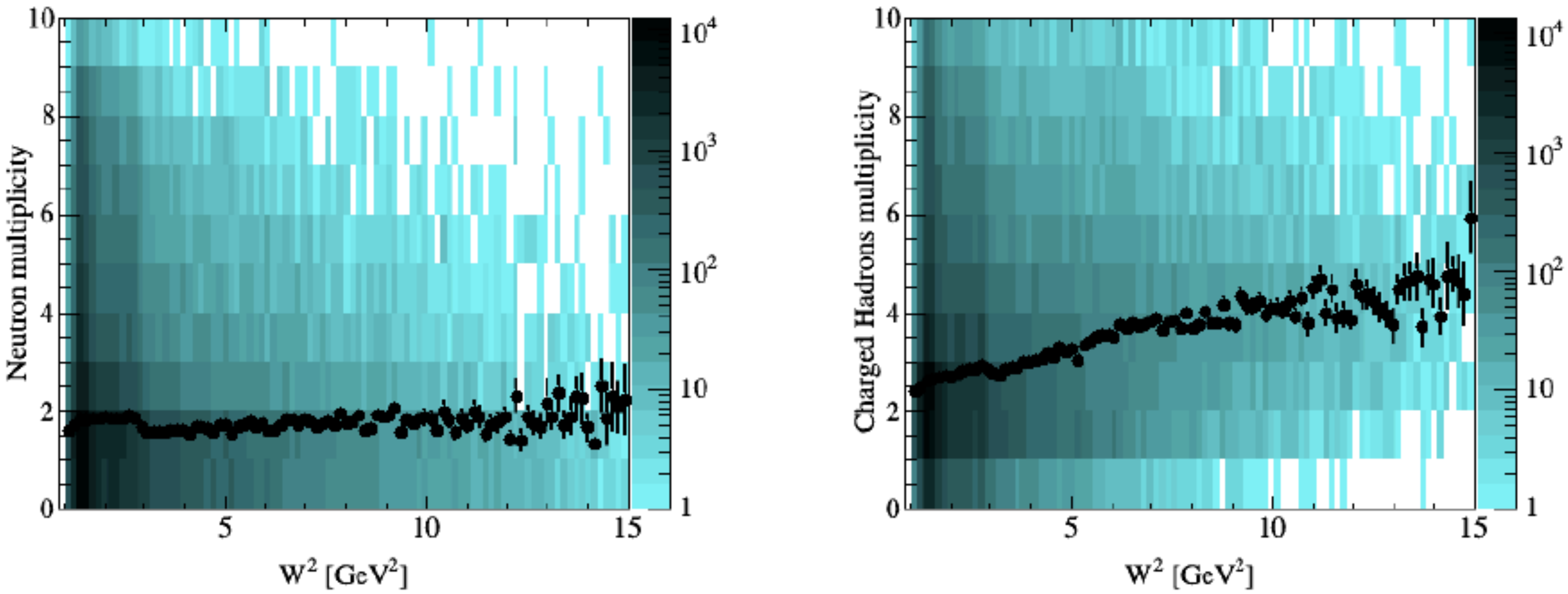




NEUTRON TAGGING ENABLES DETECTION THROUGH IBD



HADRON MULTIPLICITY VS W²



While charged hadron production increases with energy [*Eur.Phys.J.C63:1-10,2009*] that's not the case of neutron production, according to the GENIE hadronization model.

ATMOSPHERIC NEUTRINO SELECTION SUMMARY

Mode	Quality cuts	CCQE selection	Non-CCQE selection	Electronlike	Muonlike
No. events (data)	512	123	208	283	229
CCQES	51.1(0.5)%	64.5(1.2)%	28.7(0.6)%	47.4(0.7)%	55.6(0.8)%
CCRES	22.1(0.3)%	18.0(0.5)%	29.1(0.5)%	20.6(0.4)%	23.9(0.5)%
CCDIS	13.3(0.2)%	9.3(0.4)%	19.9(0.4)%	14.0(0.3)%	12.5(0.3)%
CCOther	0.18(0.02)%	0.15(0.04)%	0.34(0.05)%	0.15(0.03)%	0.21(0.04)%
NCES	0.23(0.03)%	0.20(0.05)%	0.23(0.04)%	0.20(0.03)%	0.26(0.04)%
NCOther	13.1(0.2)%	7.8(0.04)%	21.7(0.4)%	17.7(0.4)%	7.5(0.2)%
ν_e	48.9(0.5)%	50.2(1.0)%	49.4(0.8)%	74.9(0.9)%	17.5(0.4)%
ν_μ	47.6(0.5)%	47.7(1.0)%	44.9(0.7)%	20.5(0.4)%	80.5(1.0)%
ν_τ	3.5(0.1)%	2.1(0.2)%	5.7(0.2)%	4.6(0.2)%	2.1(0.1)%

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]	
AGKYpT1pi	Pion Feynman x for Nπ states in AGKY model [31]	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]	$\pm 20\%$

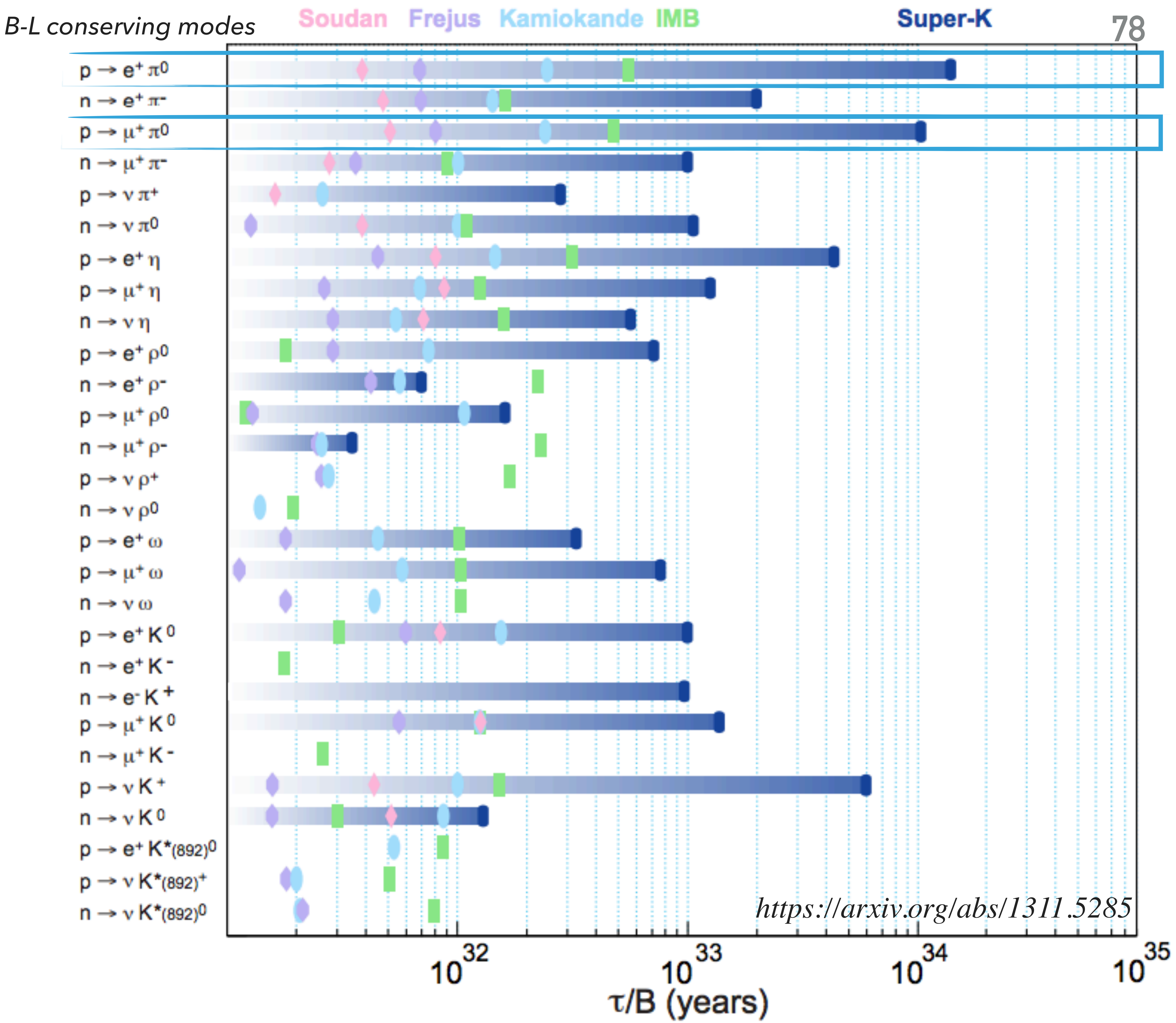
SYSTEMATIC UNCERTAINTIES SUMMARY

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%	...

GEANT4 [RATPAC] — SECONDARY NEUTRONS AND NEUTRON CAPTURES

- Two bugs were found and corrected:
  - De-excitation of ^{36}Cl and ^{17}O not properly treated → Gammas will be extracted randomly from energy levels spectrum without taking into account branching ratios or that even that total sum of the gammas corresponds to the energy available for the de-excitation
  - Deuteron breakup from gammas won't produce an extra neutron, but just a proton

NUCLEON DECAY (ND)



REFERENCES

- Proton decay SK → https://journals.aps.org/prd/pdf/10.1103/PhysRevD.95.012004
- K2K atmospheric neutrino backgrounds → Phys.Rev.D77:032003,2008 [https://arxiv.org/pdf/0801.0182.pdf]
- Super-K first detection of neutrons in water → Astroparticle Physics 31 320-328 (2009)
- Super-K neutron production from atmospherics → Proceedings of the 32 International Cosmic Ray Conference, Beijing (2011)
- ANNIE EoI → arXiv:1402.6411v1 (2014)
- Neutron cross-sections → https://www.nndc.bnl.gov/sigma/
- Neutron production from atmospherics in SNO, R. Bonventre Thesis → Publicly Accessible Penn Dissertations 1213 (2014)