Towards new discoveries with neutrinos (and dark matter)

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Outline

- the discovery of neutrino mass
- open questions
- experimental probes: neutrinoless double beta decay and long baseline neutrino oscillation
- theoretical challenges
- summary

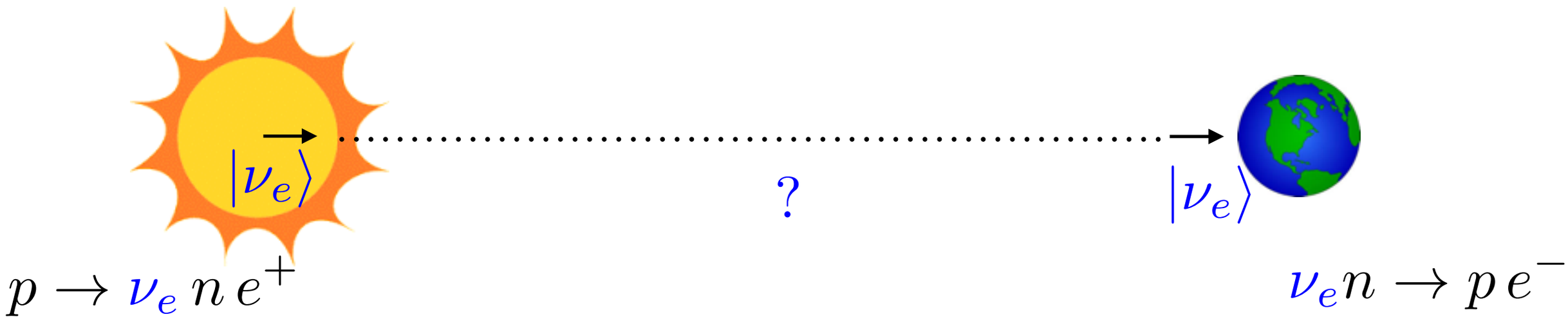
- neutrino mass is physics beyond the standard model

  - fermion mass terms in quantum field theory are constrained by gauge invariance

  - in the renormalizable standard model, there is no mass term for the neutrino

Theory was critical to establishing the solar neutrino puzzle

flux of ν_e produced in Sun > flux of ν_e surviving at Earth



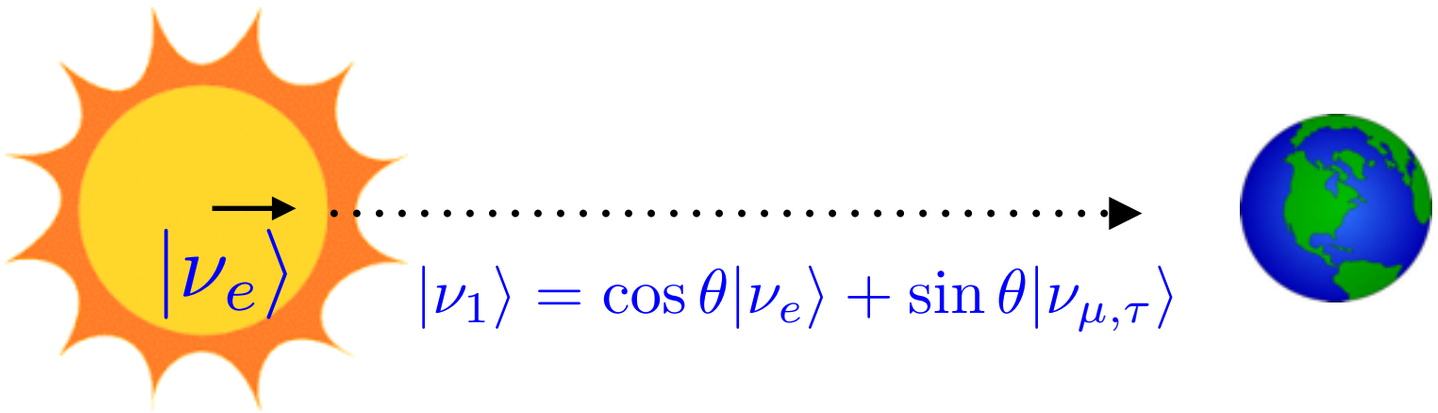
R. Davis, J. Bahcall

standard solar model flux:

$$\phi_{\rm SSM} = 5.05^{+1.01}_{-0.81} \times 10^6 {\rm cm}^{-2}{\rm s}^{-1}$$

$\phi_{\rm observed} \sim$ 1/3 of this

Experiment establishes neutrino flavor conversion



charged current (CC):

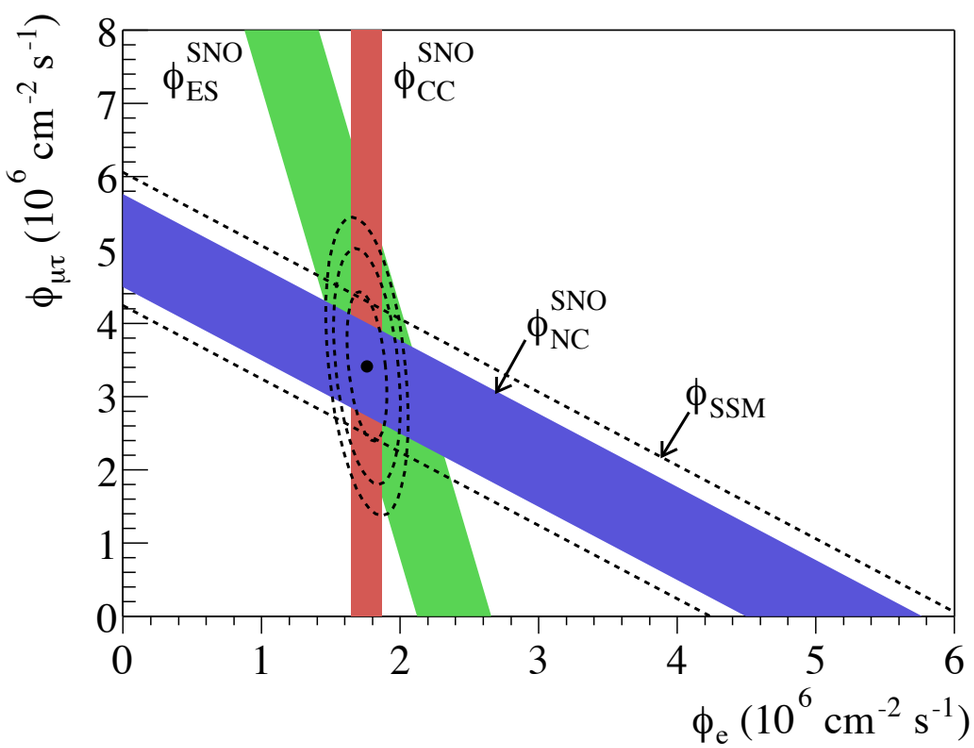
$$\nu_e\, d \to p\, p\, e^-$$

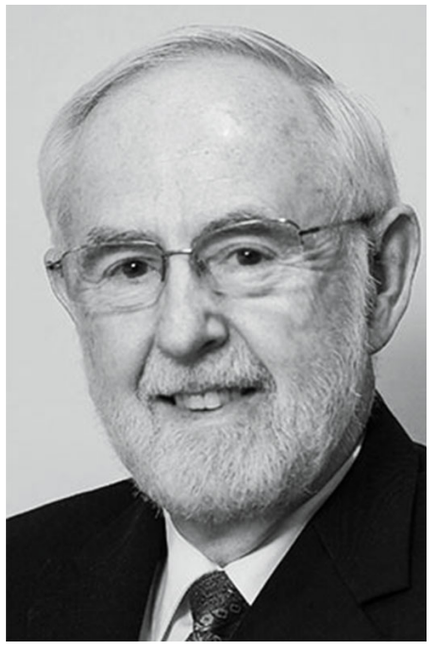
neutral current (NC):

$$\nu_{e,\mu,\tau}\, d \to p\, n\, \nu_{e,\mu,\tau}$$

elastic scattering

$$\nu_{e,\mu,\tau}\, e^- \to \nu_{e,\mu,\tau}\, e^-$$





A. McDonald
Nobel prize 2015

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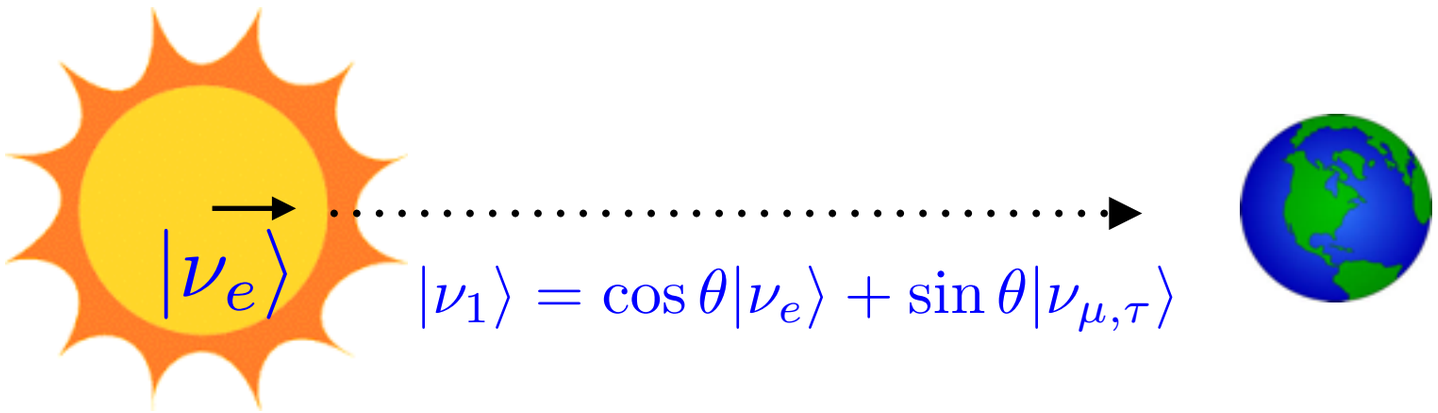

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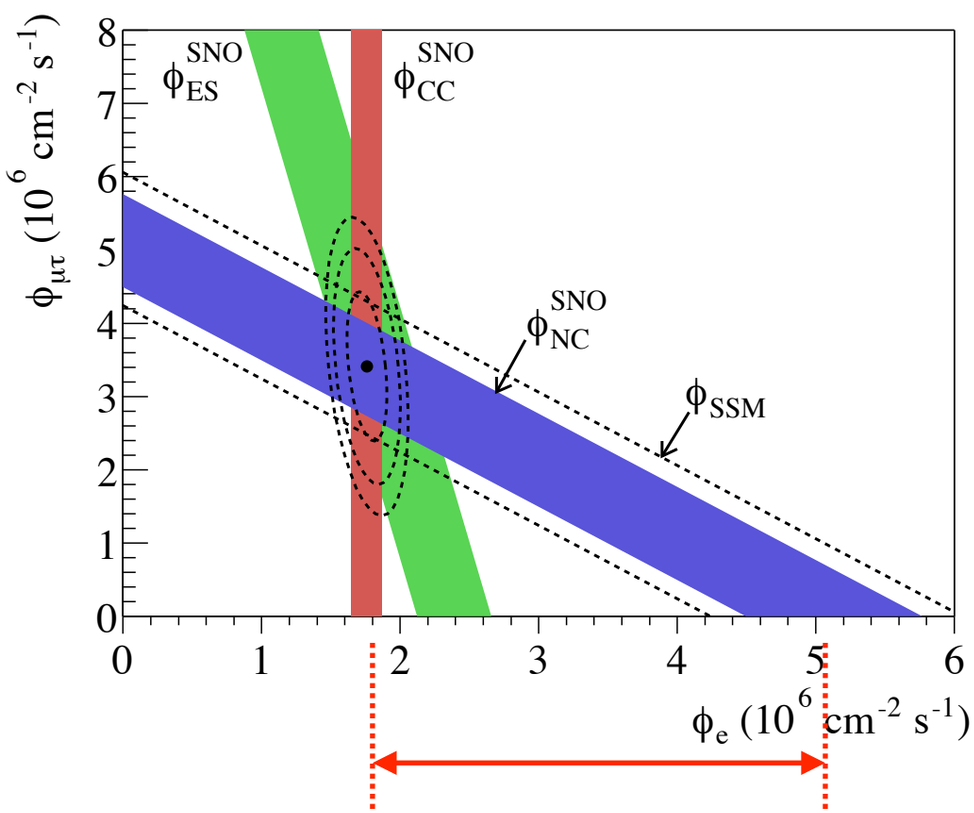
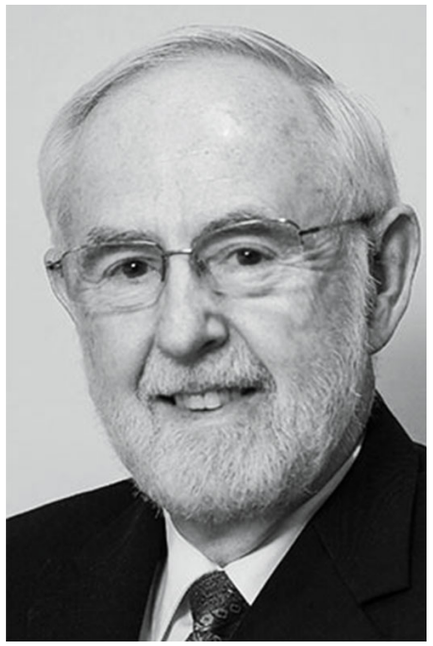


confirms ν_e deficit



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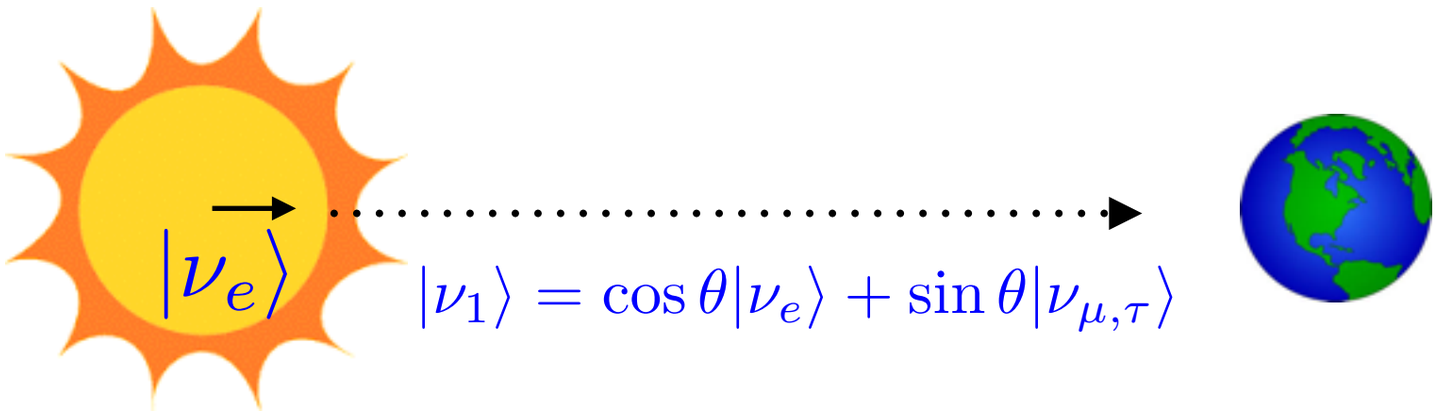

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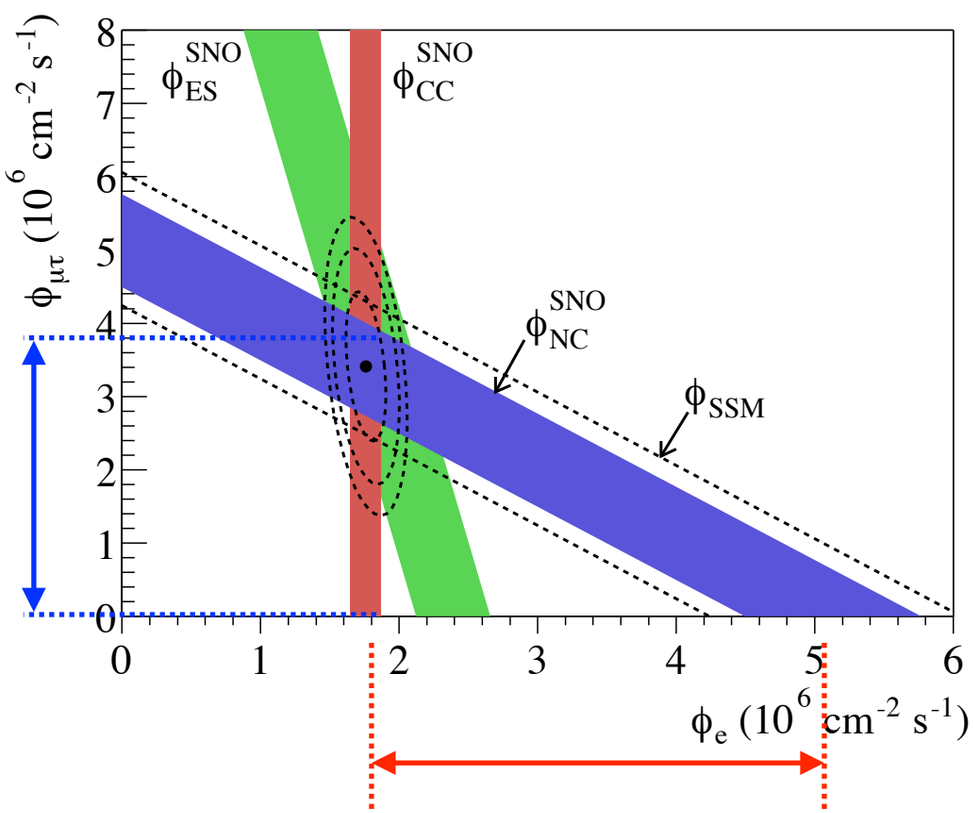
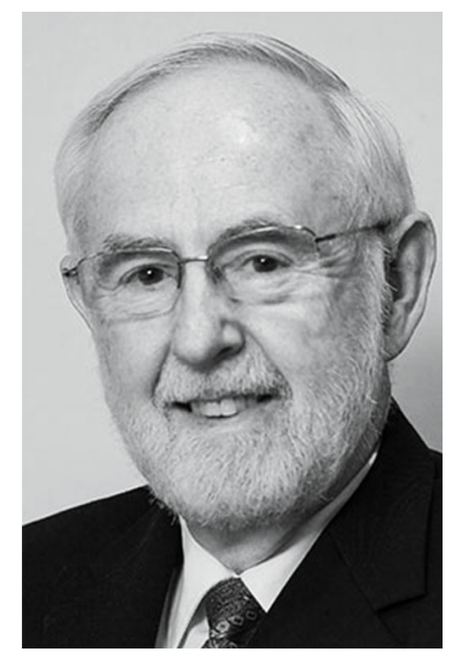


establishes neutrino flavor transformation

confirms ν_e deficit

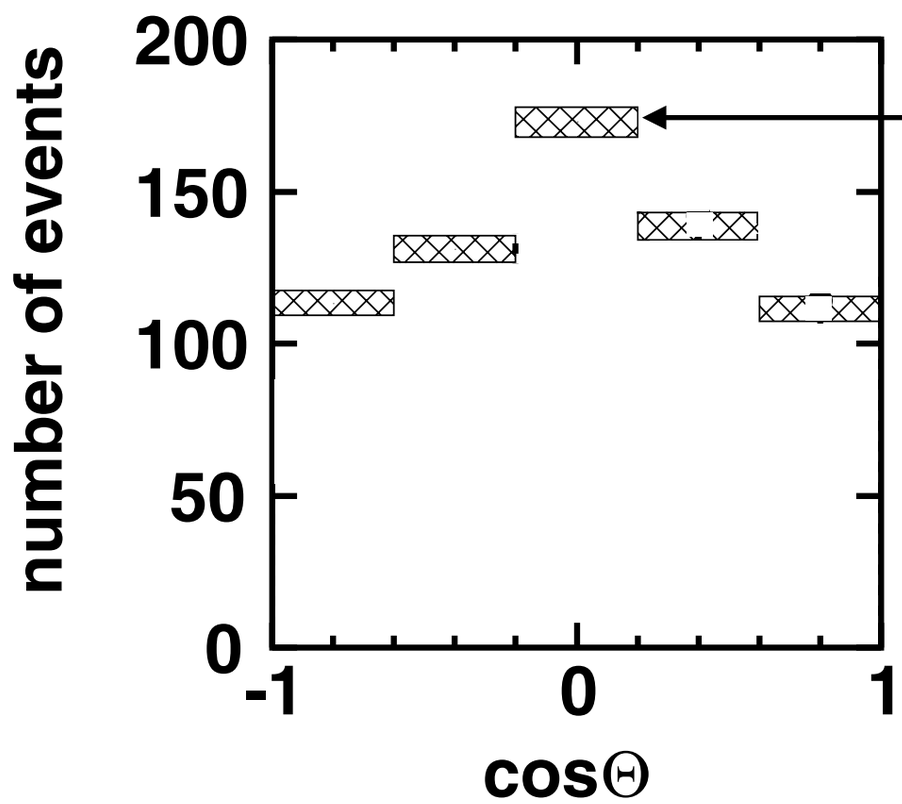


A. McDonald
Nobel prize 2015

Theory and experiment established atmospheric neutrino oscillation

flux of ν_μ produced in atmosphere >

flux of ν_μ surviving at Earth



calculated event rate
(without oscillation)

@ Neutrino 1998 conference

T. Kajita
Nobel prize 2015

Theory and experiment established atmospheric neutrino oscillation

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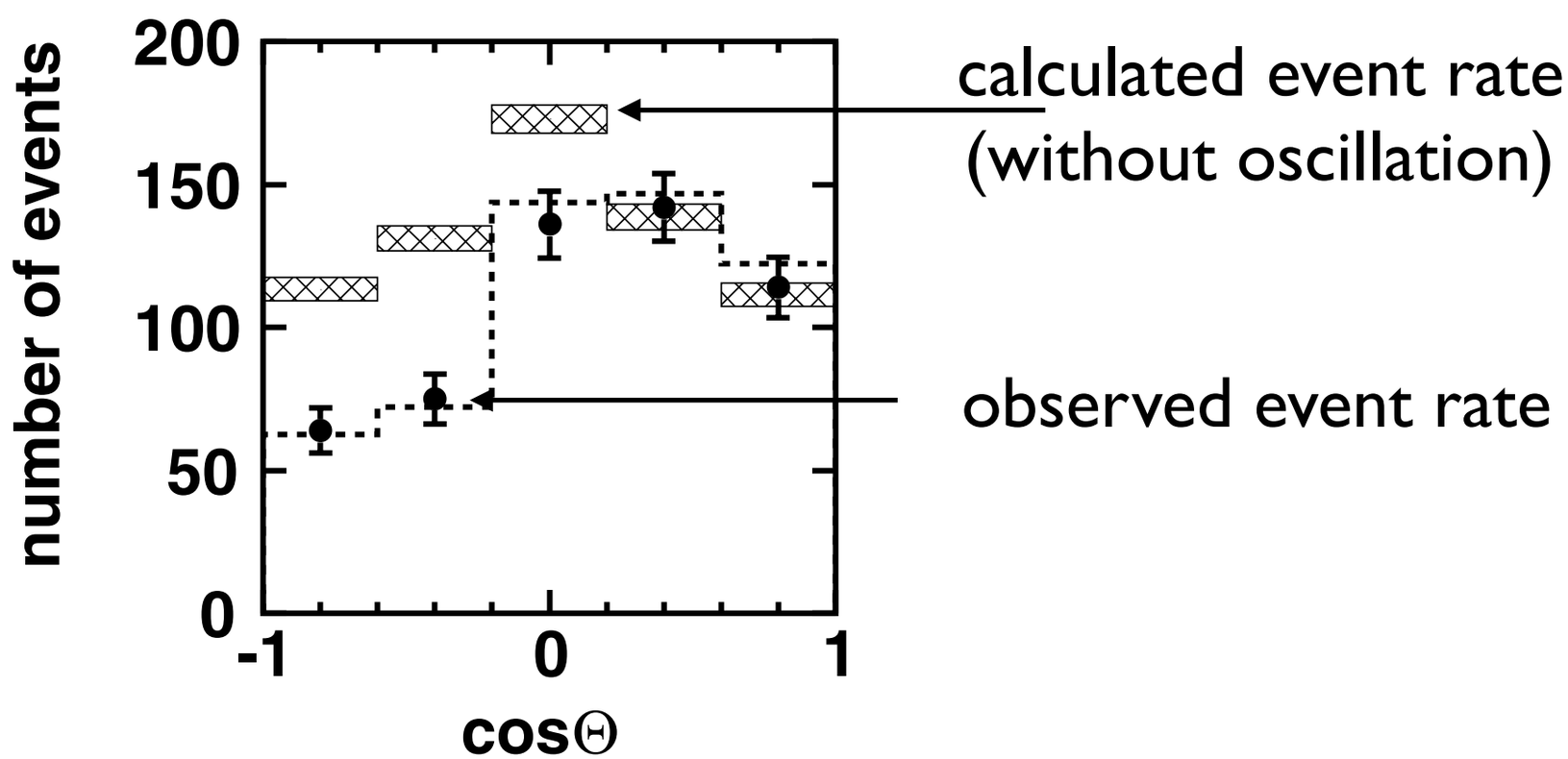

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Flavor transformation is a manifestation of neutrino mass

$$H = \sum_i \sqrt{m_i^2 + p^2}|\nu_i\rangle\langle\nu_i|$$

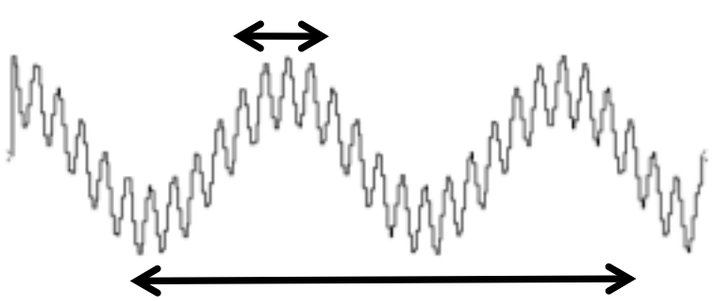
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

charge eigenstates

mass eigenstates

algebra

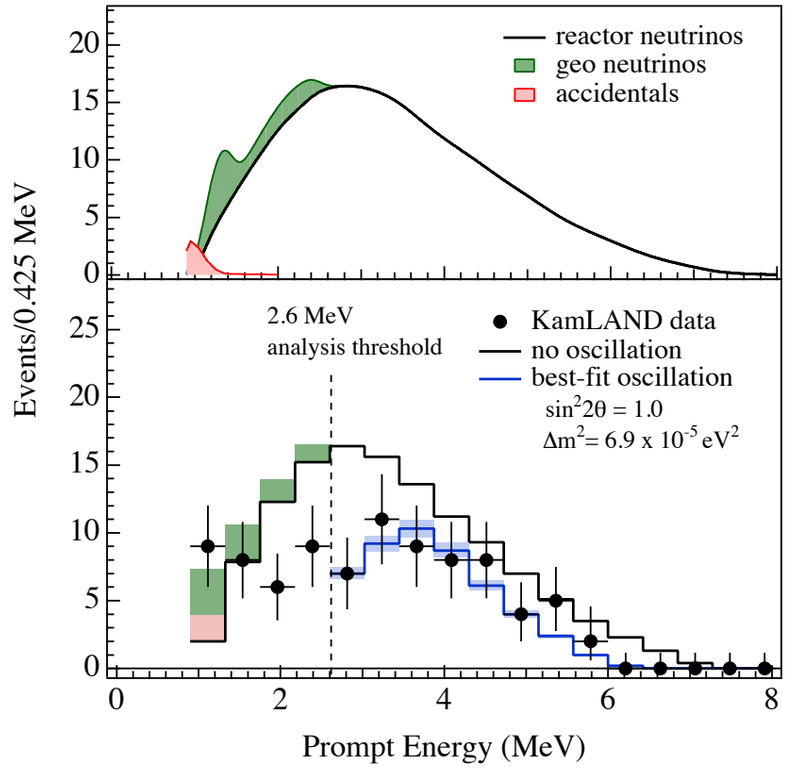
$$P(\nu_\ell \to \nu_{\ell'}) = \delta_{\ell\ell'} - 4\sum_{i>j} \mathcal{R}(U^*_{\ell i}U_{\ell' i}U_{\ell j}U^*_{\ell' j}) \sin^2\left[1.27\Delta m^2_{ij}(\mathrm{eV}^2)\mathrm{L(km)/E(GeV)}\right]$$
$$\pm 2\sum_{i>j} \mathcal{I}(U^*_{\ell i}U_{\ell' i}U_{\ell j}U^*_{\ell' j}) \sin^2\left[2.54\Delta m^2_{ij}(\mathrm{eV}^2)\mathrm{L(km)/E(GeV)}\right]$$



when one mass splitting is relevant:

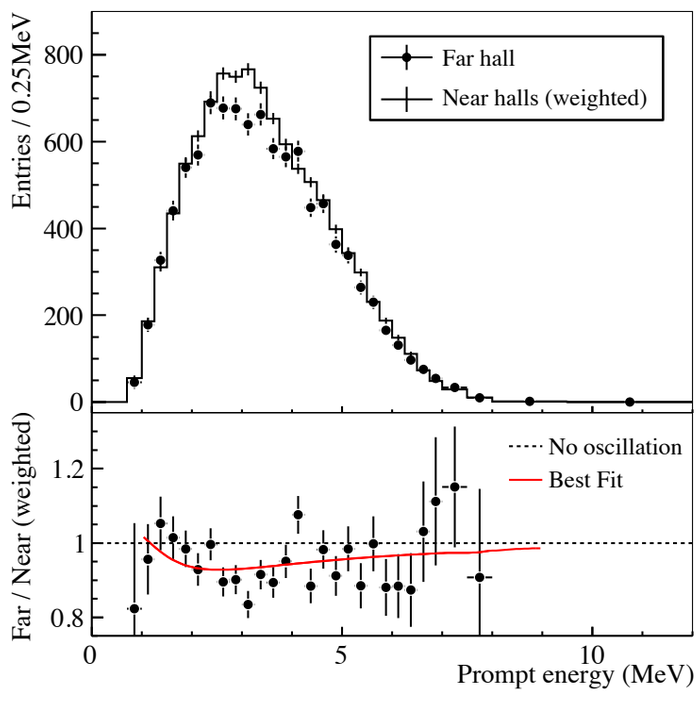
$$P(\nu \to \nu') = \sin^2 2\theta \sin^2\left[1.27\,\Delta m^2(\mathrm{eV}^2)\frac{L(\mathrm{km})}{E(\mathrm{GeV})}\right]$$

Manmade neutrino sources have confirmed the basic picture



Kamland 2002

and established the magnitude of mixing between three different flavors



Daya Bay 2012

Double Chooz 2011, T2K 2011, Reno 2012

- historical recap

  - neutrino transformation firmly established

  - important interplay between theory and experiment

    - <u>theory</u>: predicts flux in absence of oscillation (solar, atmospheric, reactor)

    - <u>experiment</u>: observes flux different from prediction

    theory enters again, providing interaction cross sections to translate event rate to flux

  - same interplay for current and next generation experiments exploring this physics beyond the standard model

- modern theory framework

Having established neutrino mass, revisit the assumptions that caused us to predict its absence

1) renormalizability

in modern understanding, renormalizability is a strange concept (= infinite cutoff energy)

2) absence of "sterile" neutrinos

Violating either of these amounts to physics beyond the standard model. For (1), and in general also for (2), find lepton number violation

A lot of unanswered questions…

- unresolved questions for neutrinos

#1 is lepton number really violated?

The unique first order perturbation to the Standard Model:

$$\mathcal{L} = \frac{1}{\Lambda} L L H H$$

lepton doublet

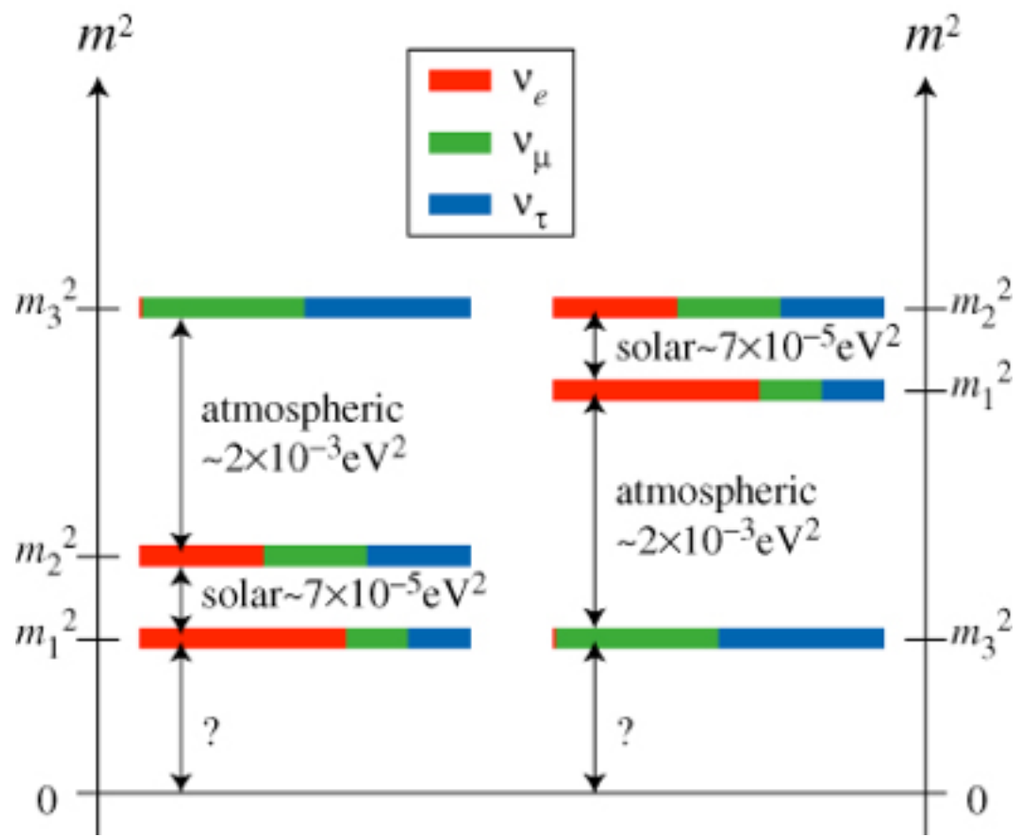
Higgs field

$$L = \begin{pmatrix} \nu \\ \ell \end{pmatrix} \qquad H = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

- Majorana mass term for neutrino
- Lepton number violating
- Nonrenormalizable, mass scale $\Lambda \sim 10^{16}$ GeV (!!!)

- unresolved questions for neutrinos

#2 how are neutrino masses arranged: are they about equal, or hierarchical, and in what order?



- determines observability of lepton number violation, #1

- unresolved questions for neutrinos

#3 how many sterile neutrinos are there?

- with 3, can form lepton-number conserving mass terms for 3 neutrino states

- with more than 3, find new mass splitting and oscillation lengths

- some intriguing hints, and new experimental probes

- unresolved questions for neutrinos

#4 is CP symmetry violated?

- do neutrinos behave differently from anti-neutrinos?

- CP violation a necessary ingredient to generate the baryon asymmetry of the universe.

- known sources of CP violation (quark mixing) cannot account for observed baryon asymmetry

- experimental probes of the open questions

#1 is lepton number really violated? } neutrinoless double beta decay

#2 how are neutrino masses arranged?
#3 how many sterile neutrinos are there?
#4 is CP symmetry violated?
} focus on accelerator based oscillation searches

see talks of: *B. Jamieson* *P. de Perio* *H. Tanaka* *A. Kanaka*

active efforts also with atmospheric, reactor, supernova neutrinos

see talks of: *D. Grant* *C. Bruulsema*

and theoretical interpretation

see talk of: *N. Giasson*

- $0\nu\beta\beta$ experimental searches

11 candidate nuclei with observed double beta decay (single beta decay forbidden):

^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U

fundamental physics

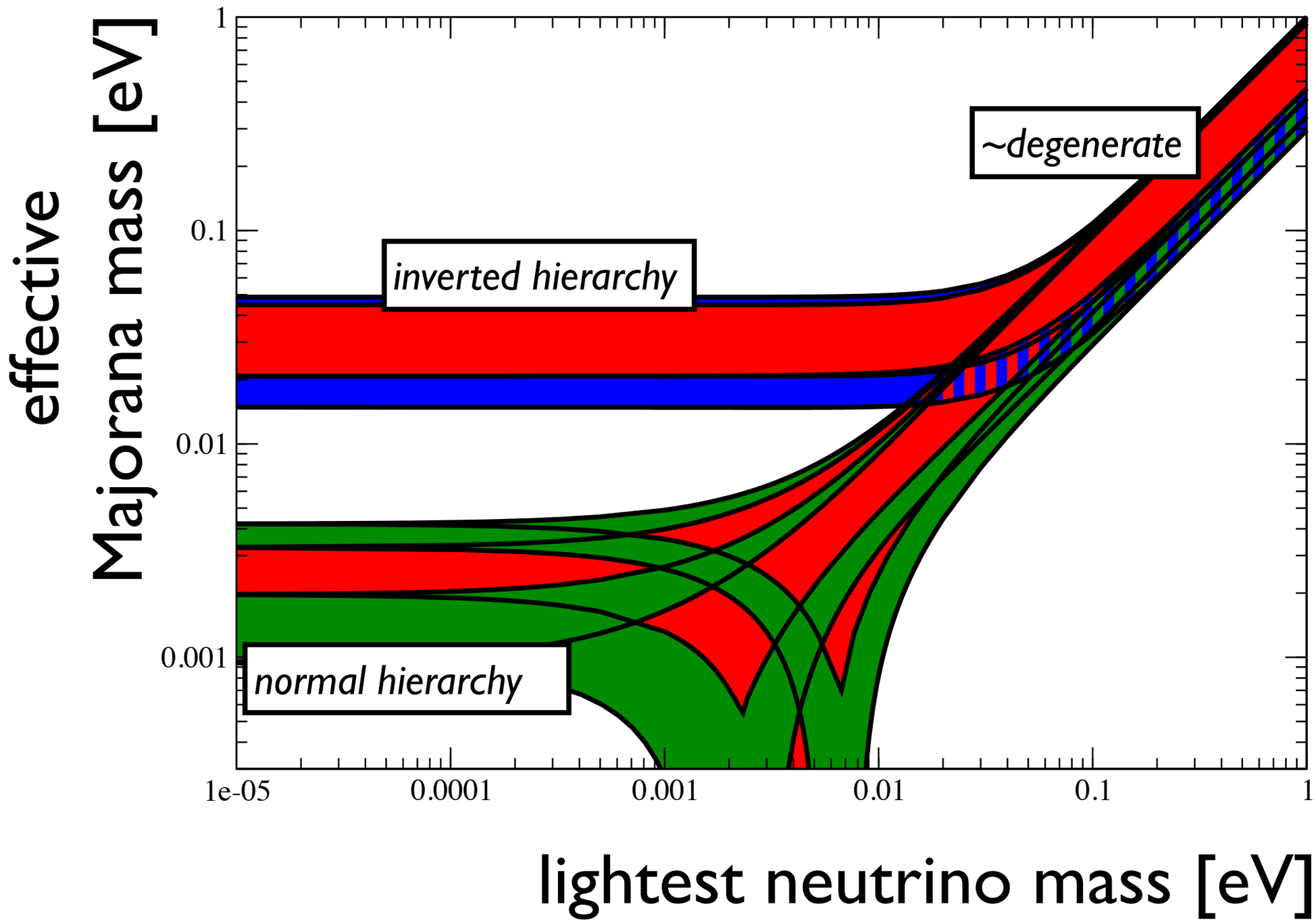
$$(T^{0\nu}_{\frac{1}{2}})^{-1} \propto |M^{0\nu}|^2 \langle m_{\beta\beta}\rangle^2 \qquad \langle m_{\beta\beta}\rangle^2 = \left|\sum_i U^2_{ei} m_{\nu_i}\right|^2$$

experimental rate

theoretical matrix element

- theory is critical to translate event rate to neutrino mass parameter
- O(1-10) uncertainty on matrix element, intense theory effort underway

- interplay of particle, nuclear, astro physics



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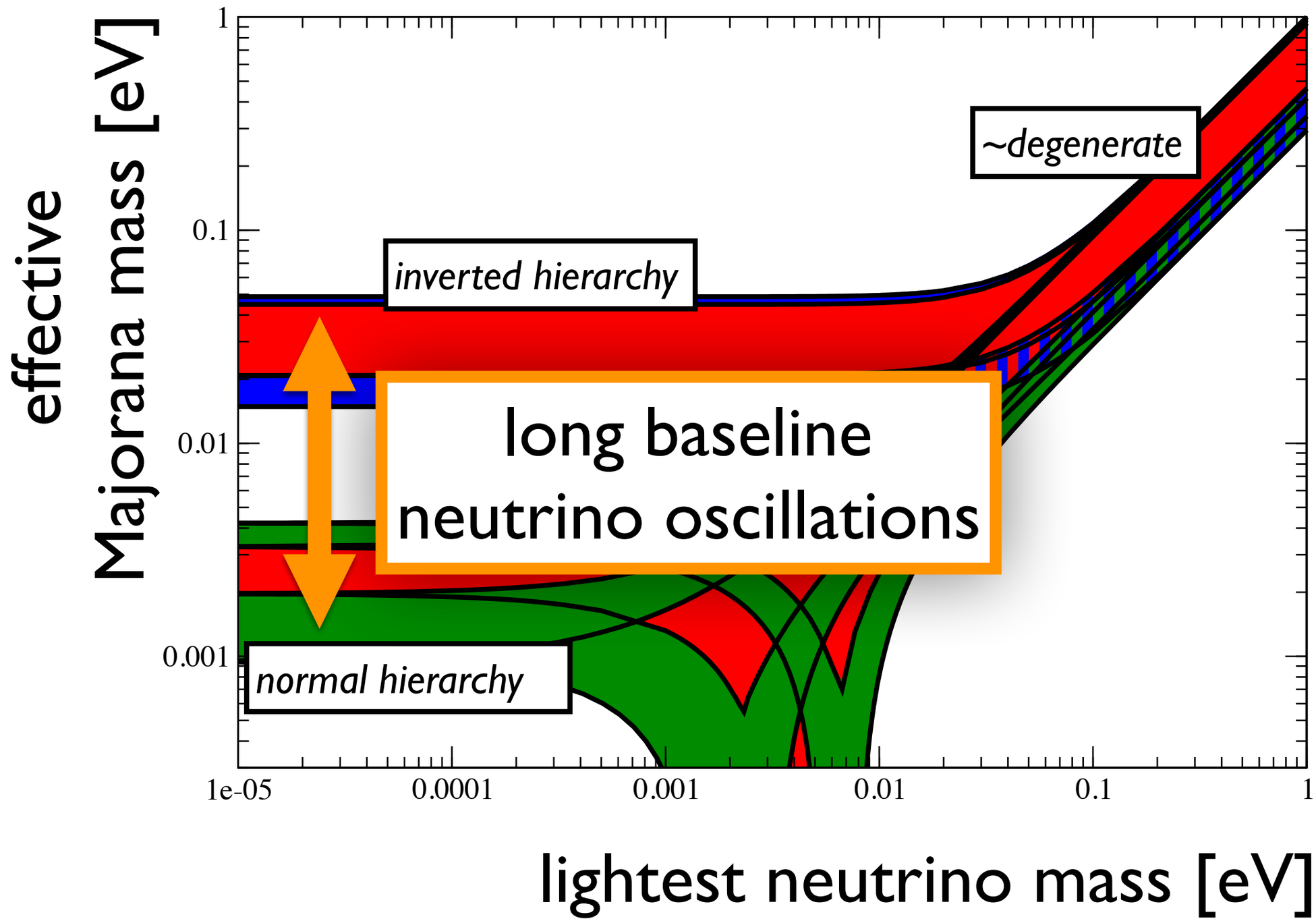

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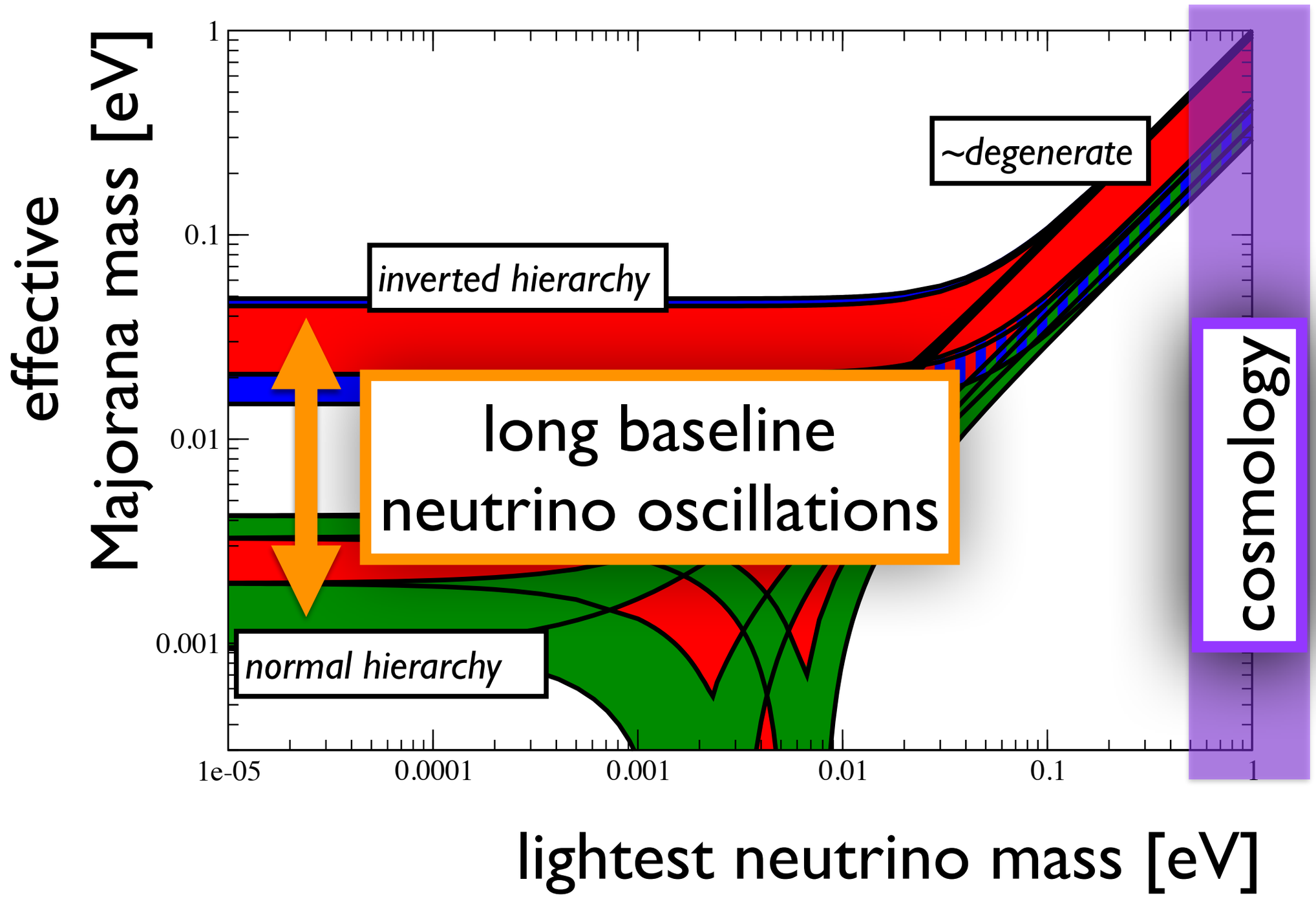
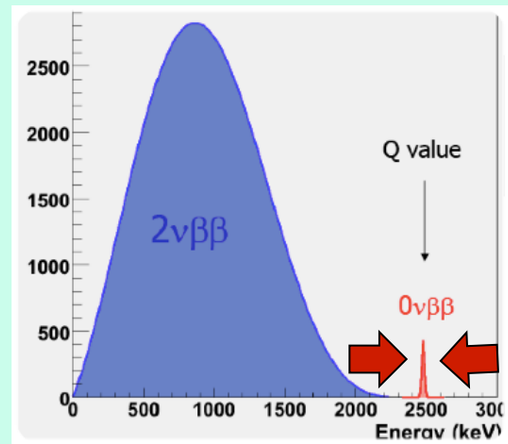
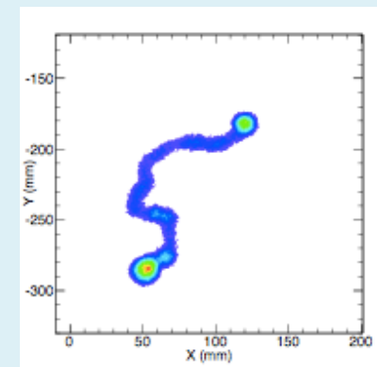
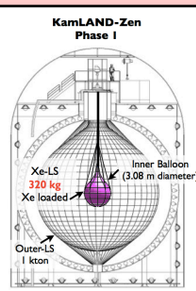


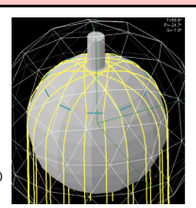
• 0νββ experimental searches

K. Scholberg

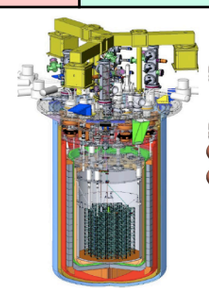
The "Brute Force" Approach	The "Peak-Squeezer" Approach	The "Final-State Judgement" Approach
		



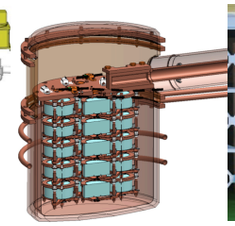
KamLAND-Zen (^{136}Xe)



SNO+ (^{130}Te)

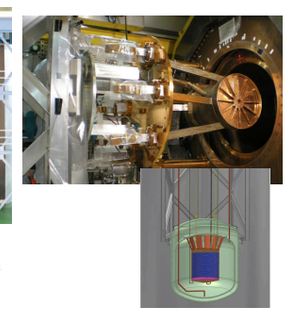


CUORICINO/ CUORE (^{130}Te)

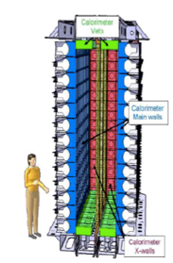


MAJORANA (^{76}Ge)

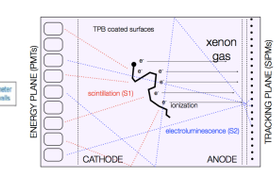
GERDA (^{76}Ge)



EXO/nEXO (^{136}Xe)



NEMO/ SuperNEMO (various/^{82}Se)



NEXT (^{136}Xe)

+more future ideas...

see talks of:

C. Kraus *E. Caden* *T. Brunner*
J. Rumleskie *E. Cudmore* *Y. Lan*
R. Ford *R. Gornea*
F. Retiere

• long baseline neutrino oscillations

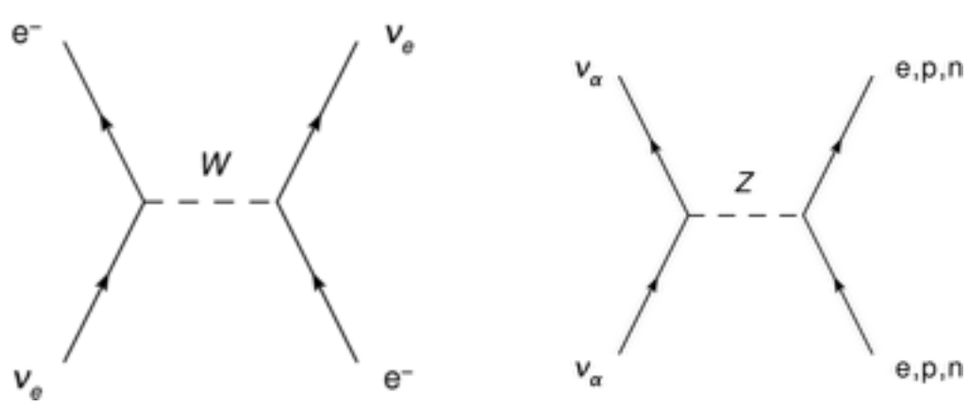
- ν_μ produced by accelerator beams

- Appearance of ν_e as a function of neutrino energy and oscillation length probes underlying neutrino parameters

two important aspects:

1) long baseline to probe matter effect

$$H = \sum_i \sqrt{m_i^2 + p^2}|\nu_i\rangle\langle\nu_i| + V(r)|\nu_e\rangle\langle\nu_e|$$



$$\sqrt{2}G_F N_e$$

2) broad energy range to disentangle ordering, CP violation

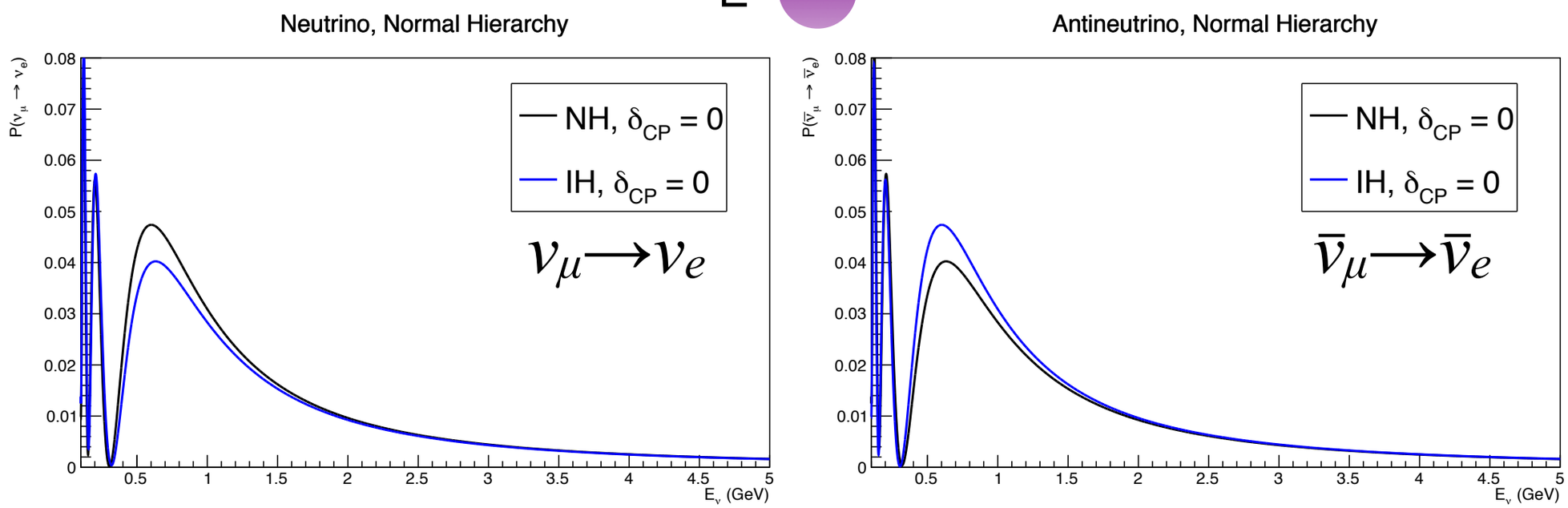
1) long baseline to probe matter effect

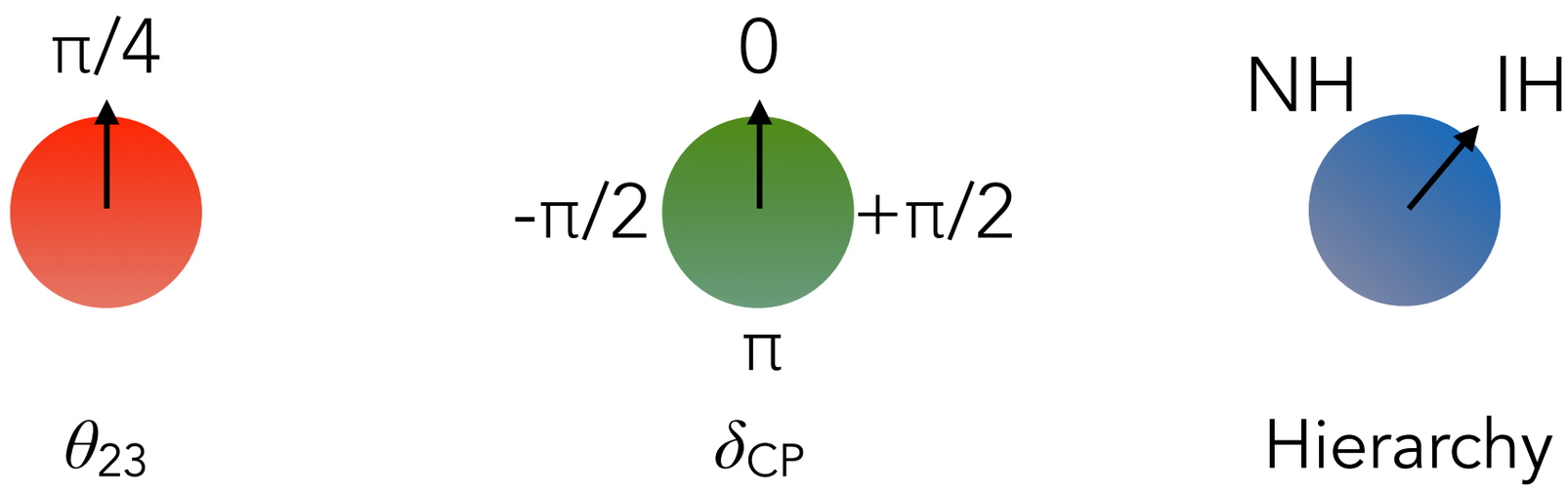
H.Tanaka

$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

295 km

L





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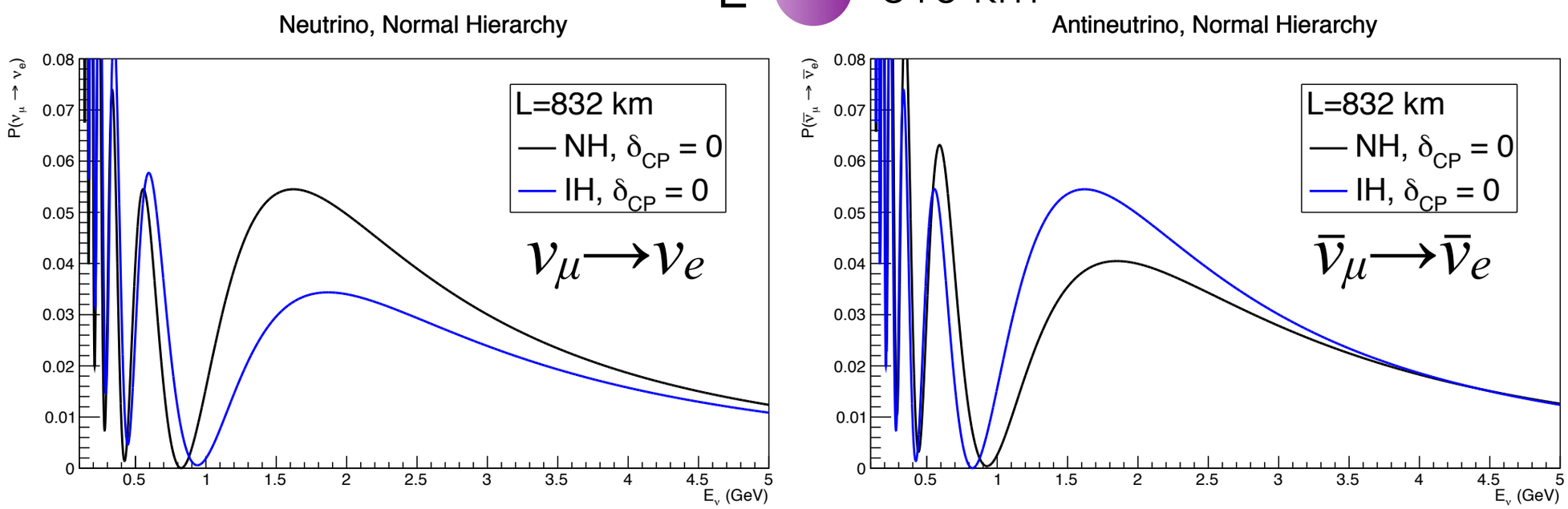
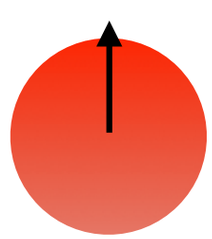
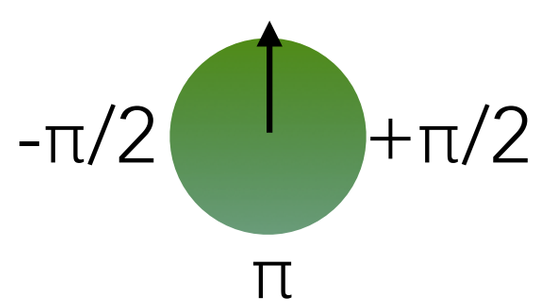
L → 810 km

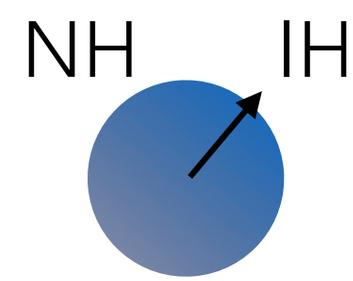




θ_{23}



δ_{CP}



Hierarchy

2) broad energy range to disentangle ordering, CP violation

H.Tanaka

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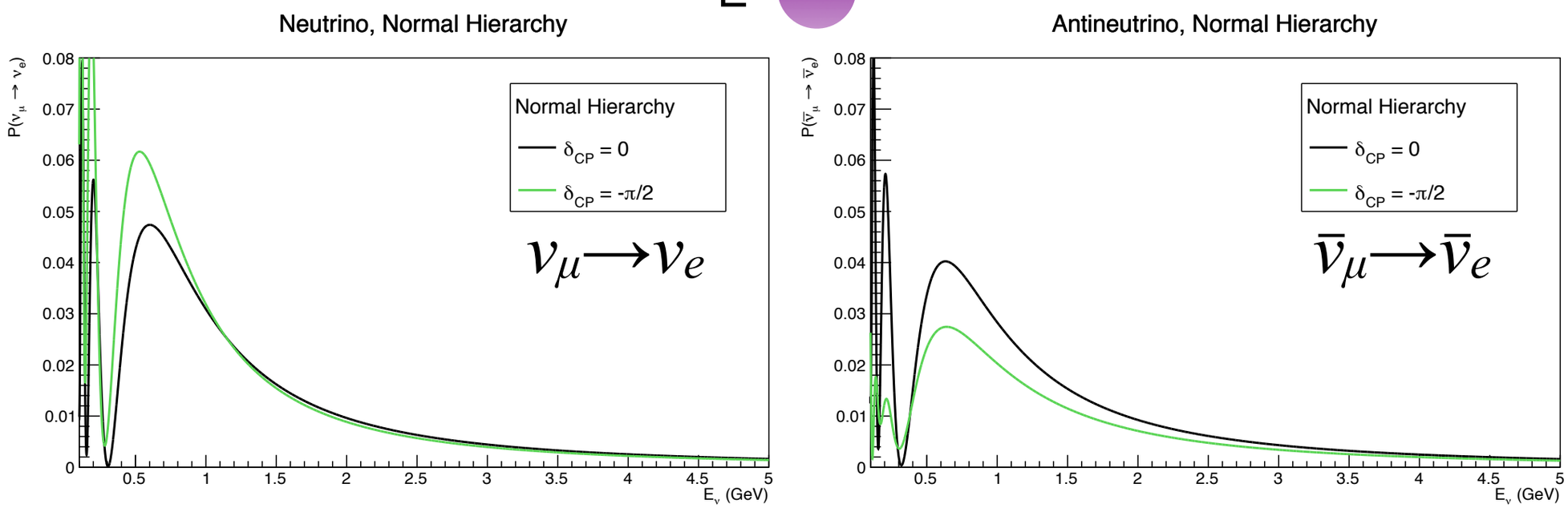

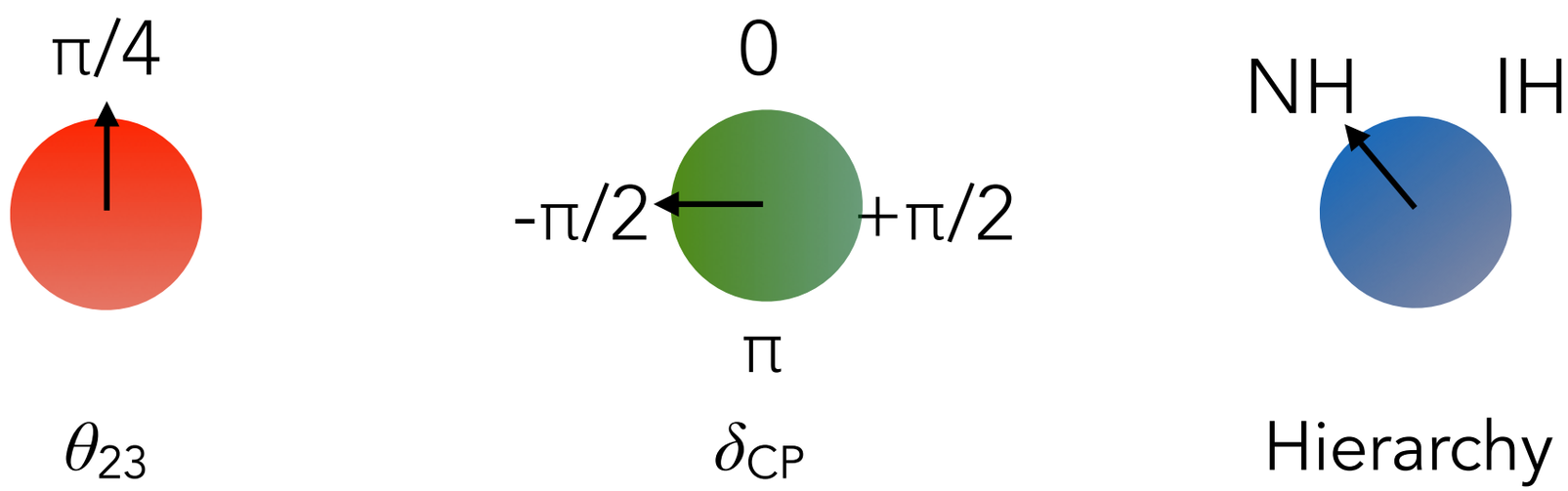

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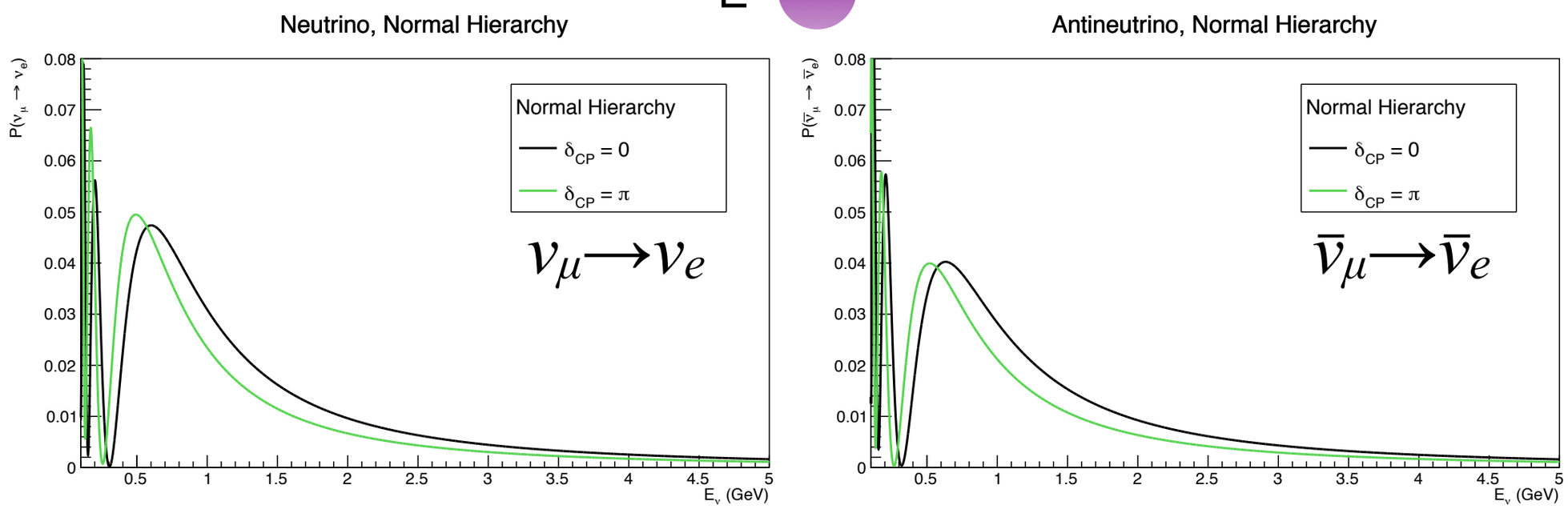

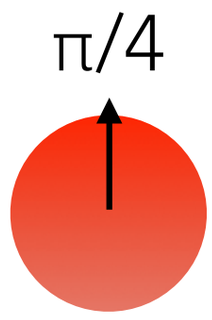

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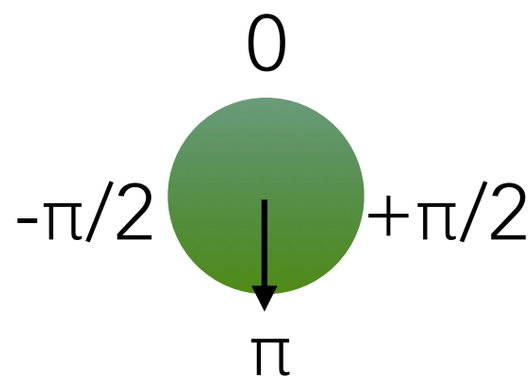

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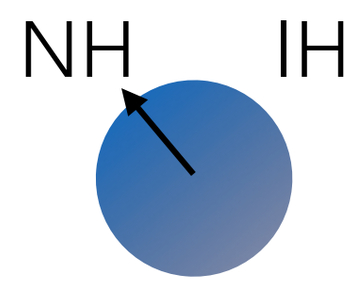

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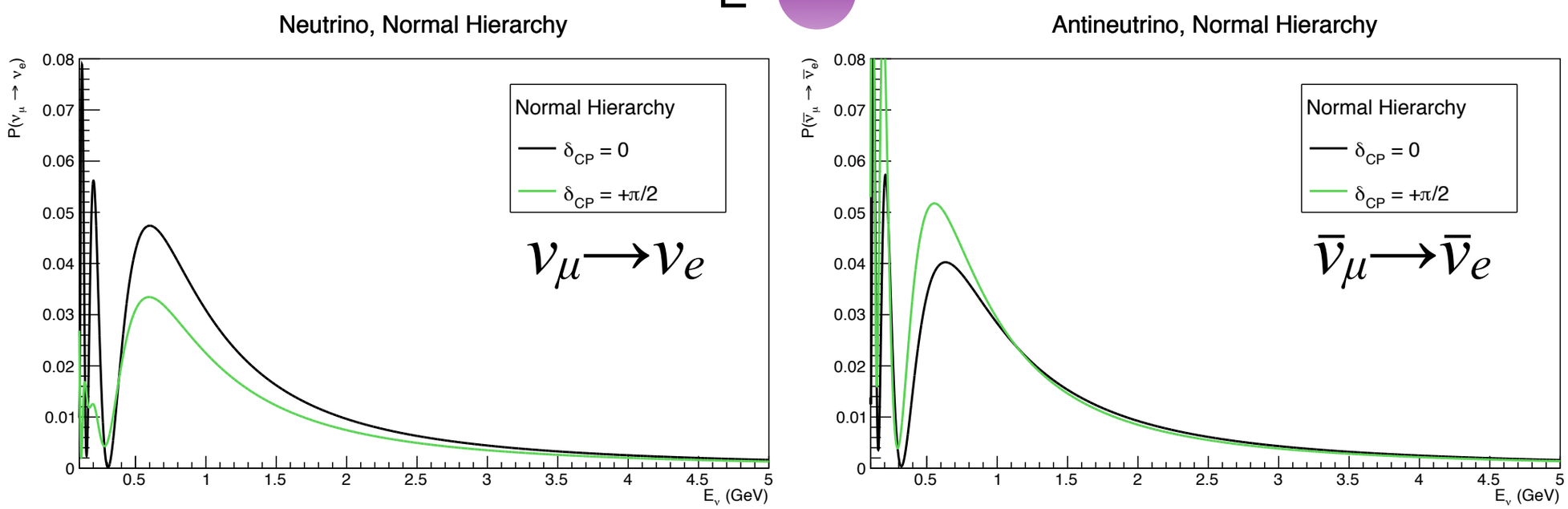
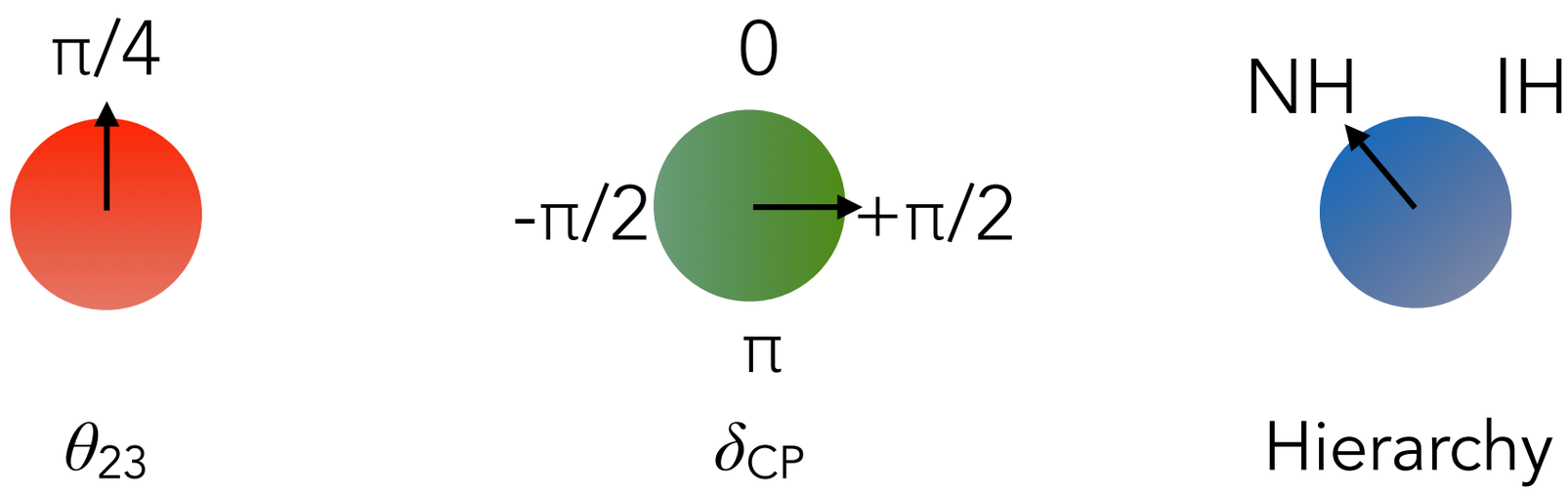
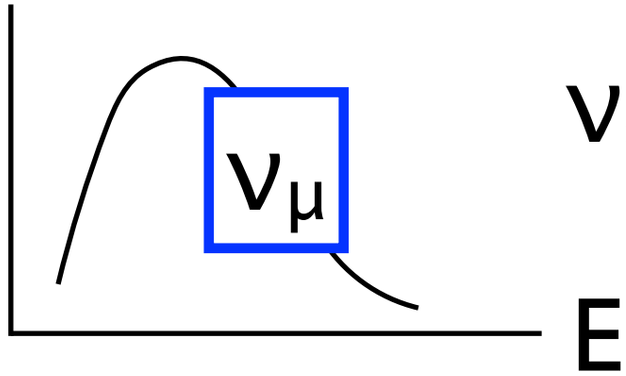


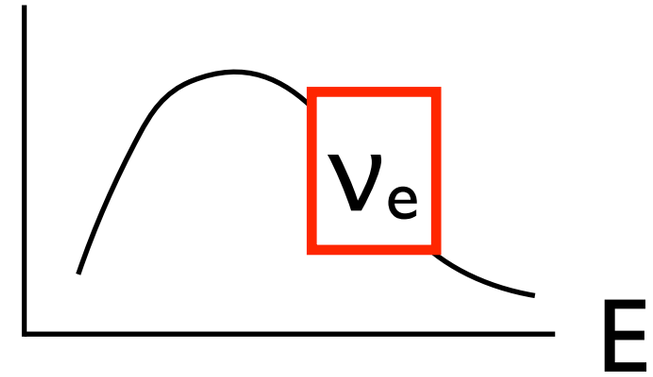


probability of $\nu_\mu \rightarrow \nu_e$ $\Rightarrow$ fundamental neutrino properties

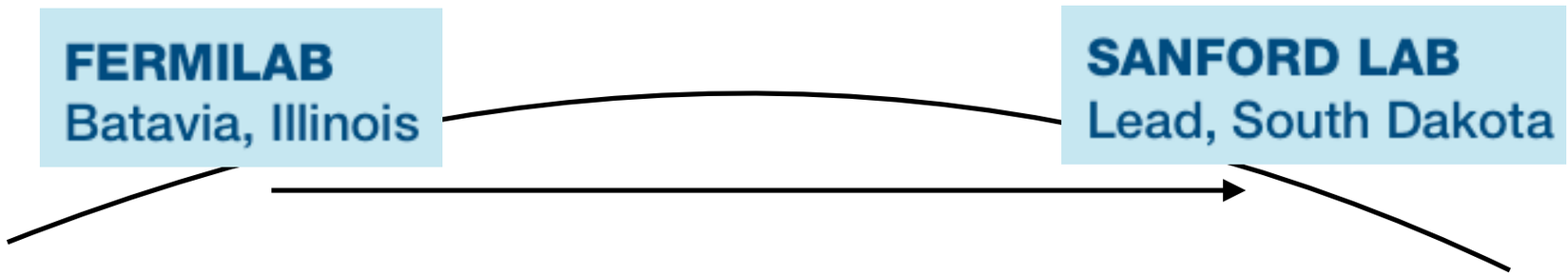
ν_μ flux



$$\nu_e \text{ flux} = \frac{\nu_e \text{ event rate}}{\text{cross section}}$$

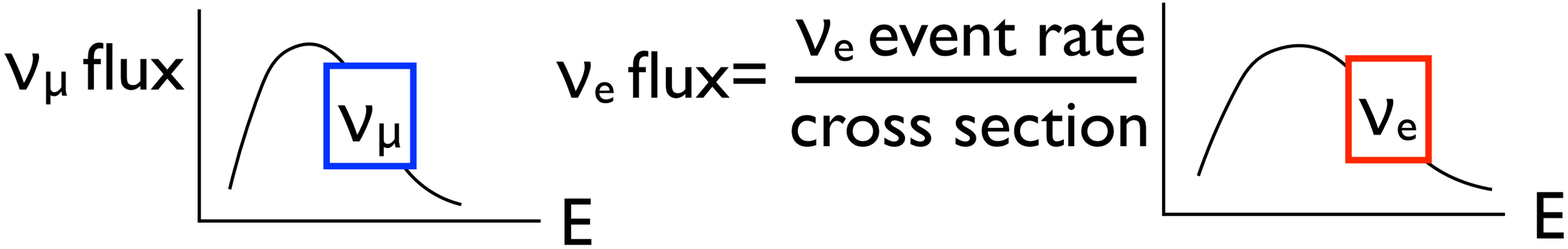


E.g. DUNE

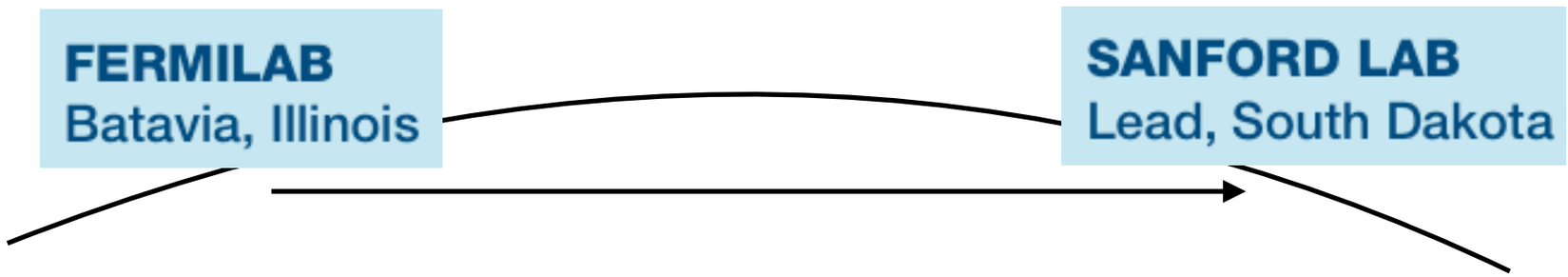


Cross section translates observed event rate to ν_e appearance prob.

probability of $\nu_\mu \to \nu_e$ $\Rightarrow$ fundamental neutrino properties



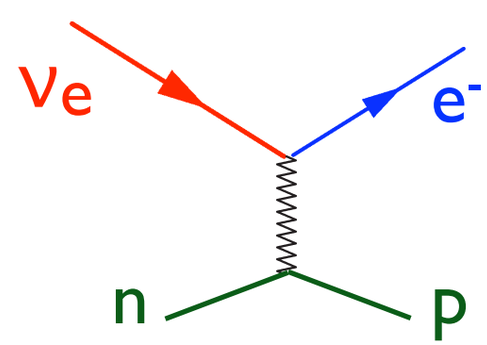
E.g. DUNE



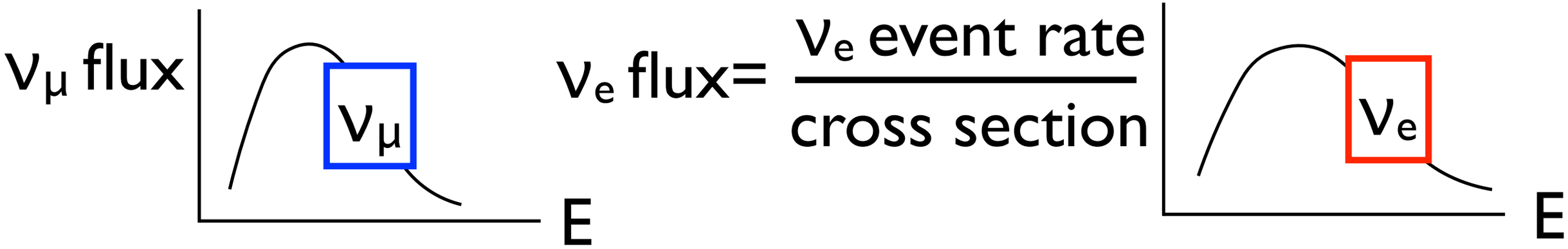
Cross section translates observed event rate to ν_e appearance prob.

Basic signal process: charged current quasi elastic scattering

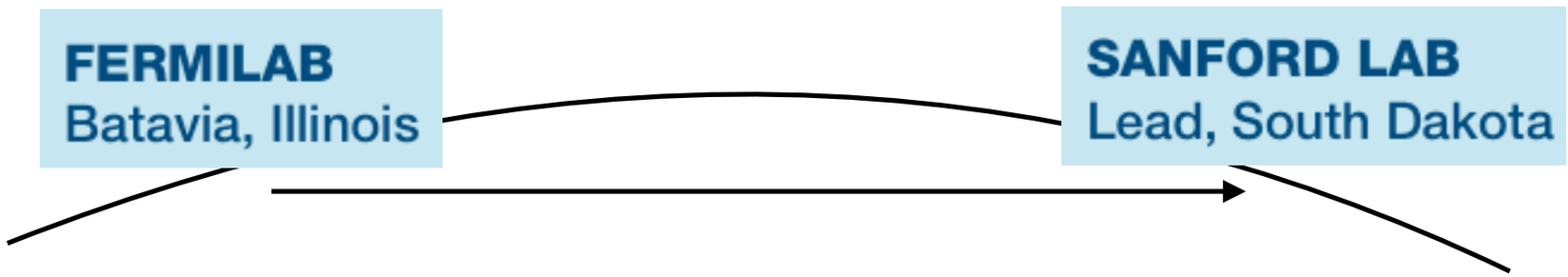
(large event sample, "reconstructible" neutrino energy, theoretically "clean")



probability of $\nu_\mu \to \nu_e$ ⇒ fundamental neutrino properties



E.g. DUNE



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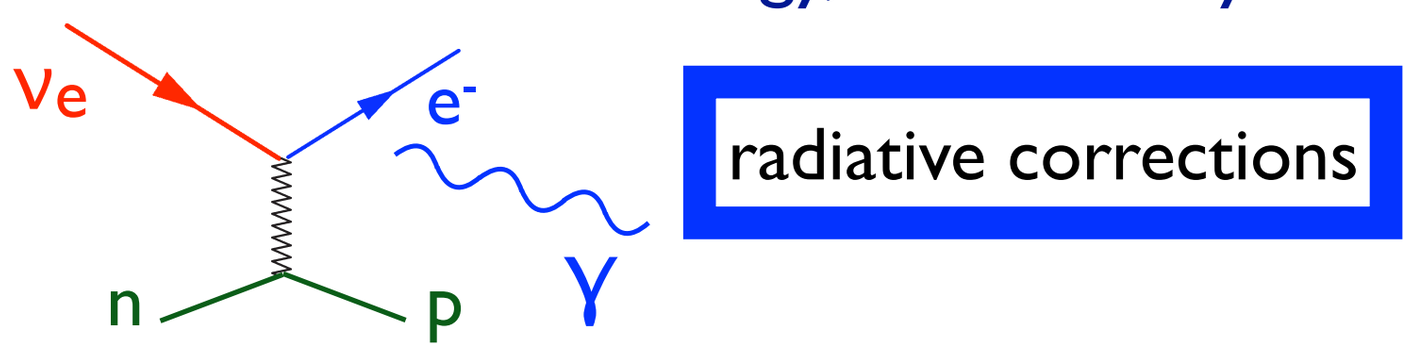
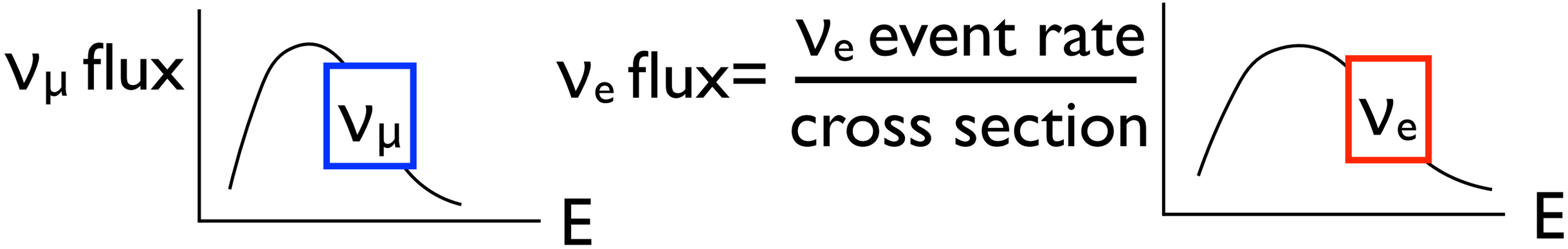


probability of $\nu_\mu \to \nu_e$ $\Rightarrow$ fundamental neutrino properties



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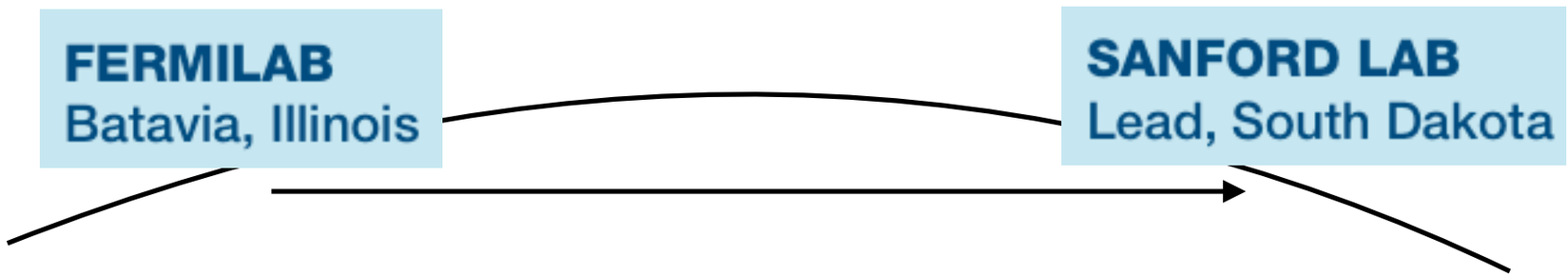

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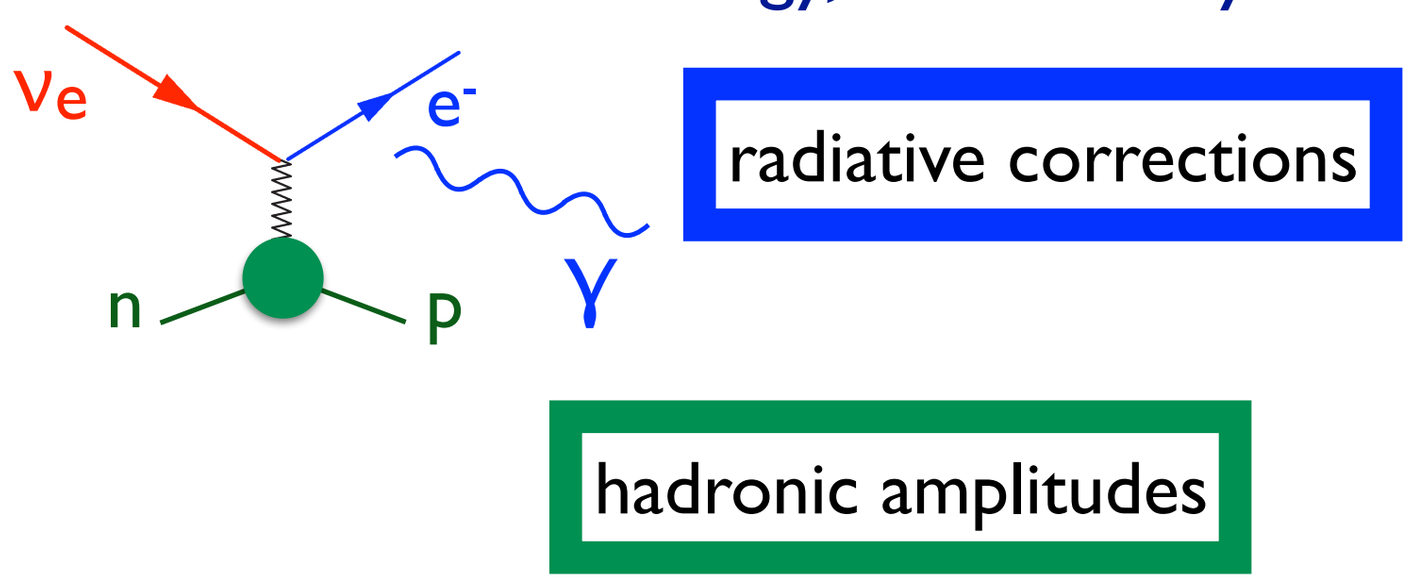
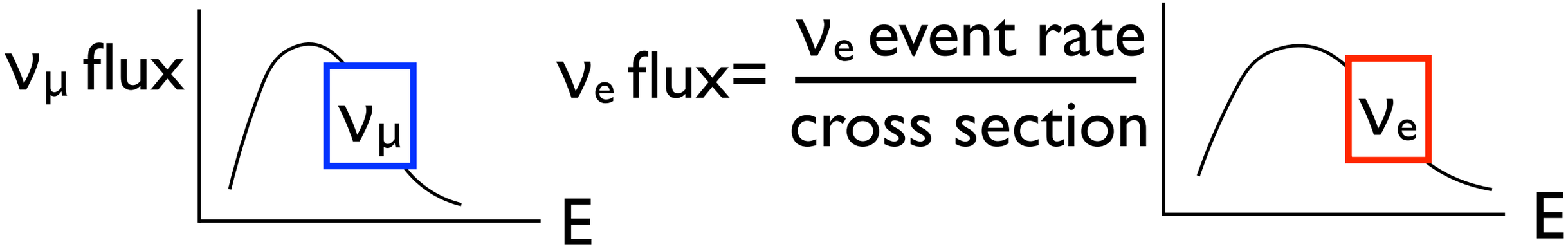


probability of $\nu_\mu \to \nu_e$ ⇒ fundamental neutrino properties



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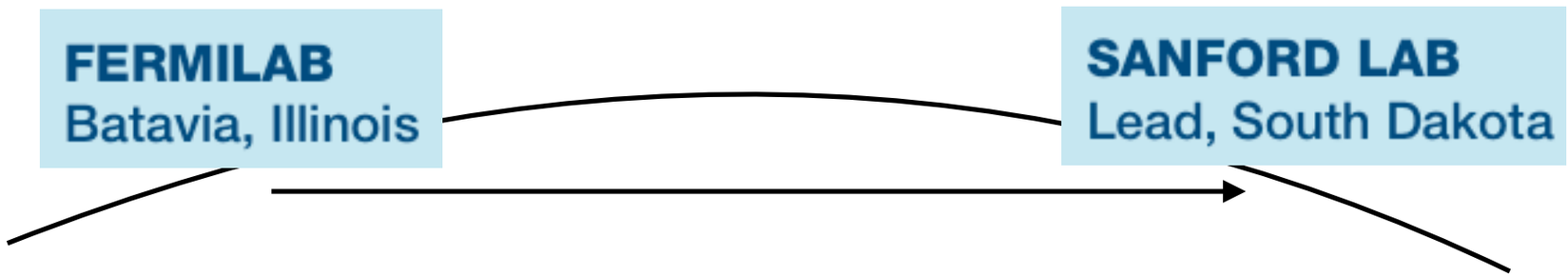

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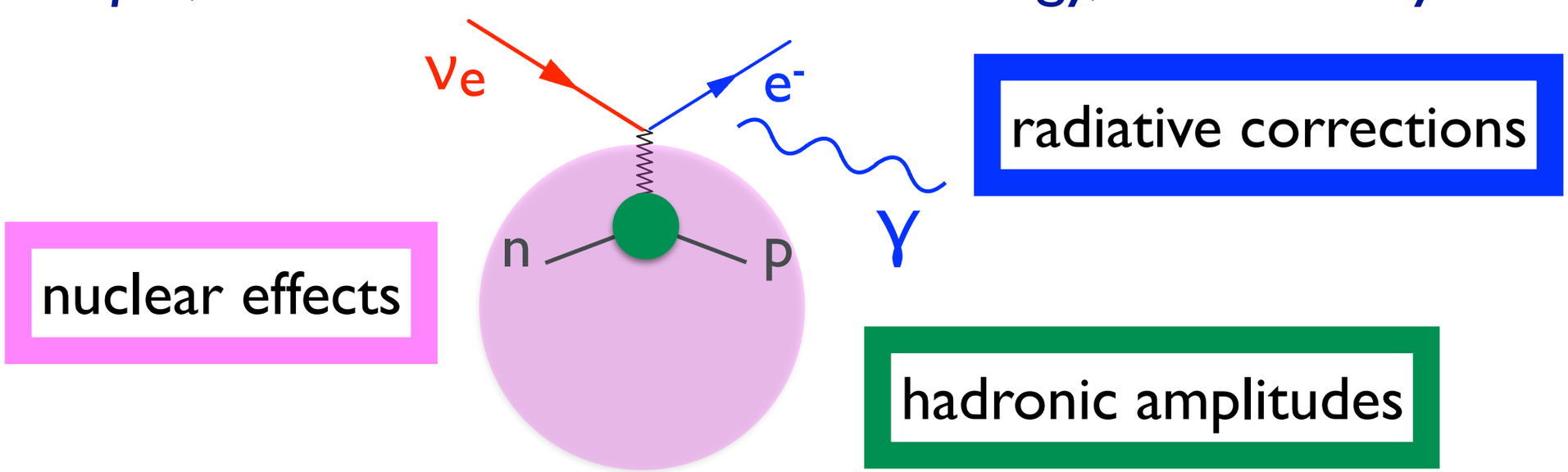
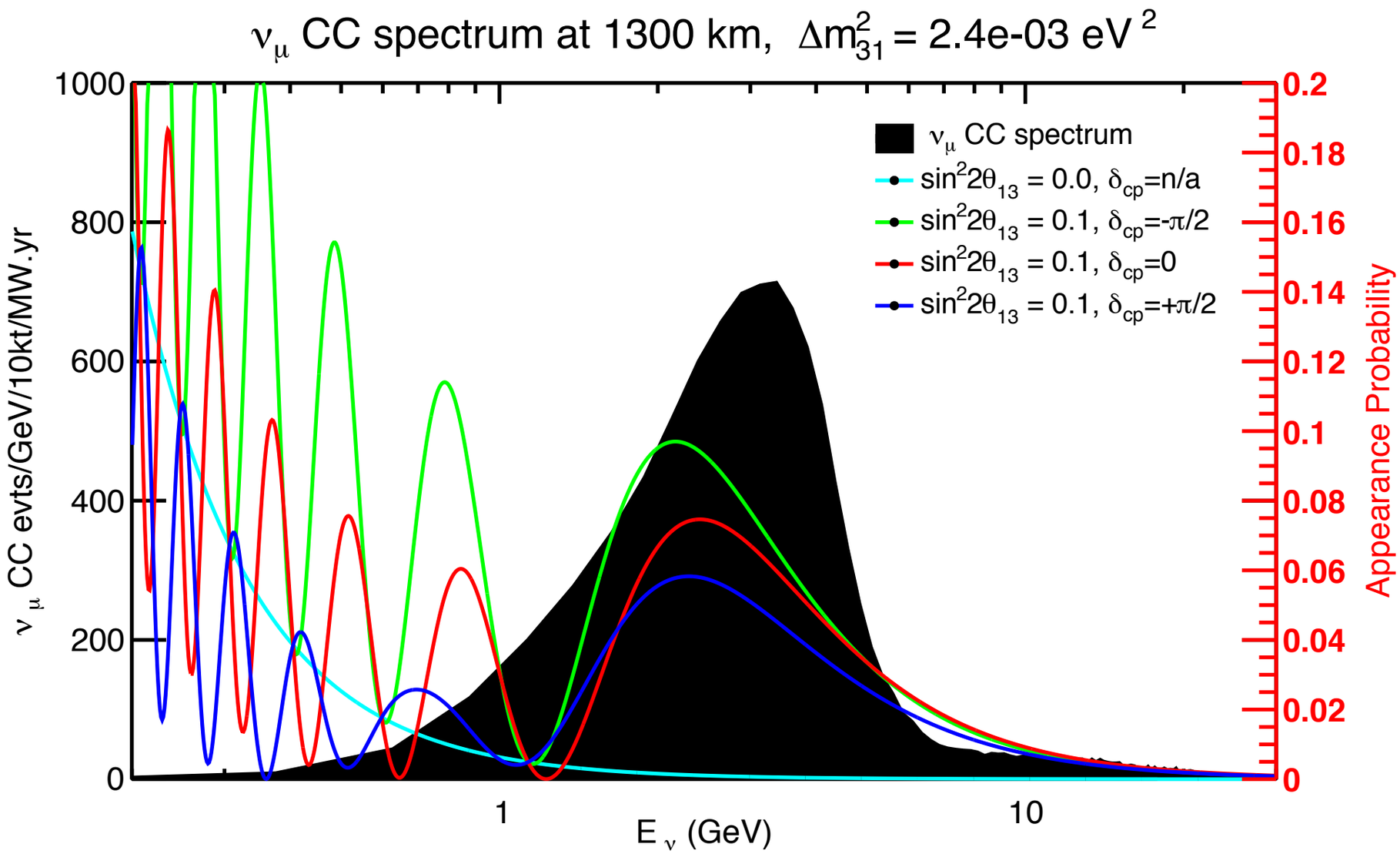
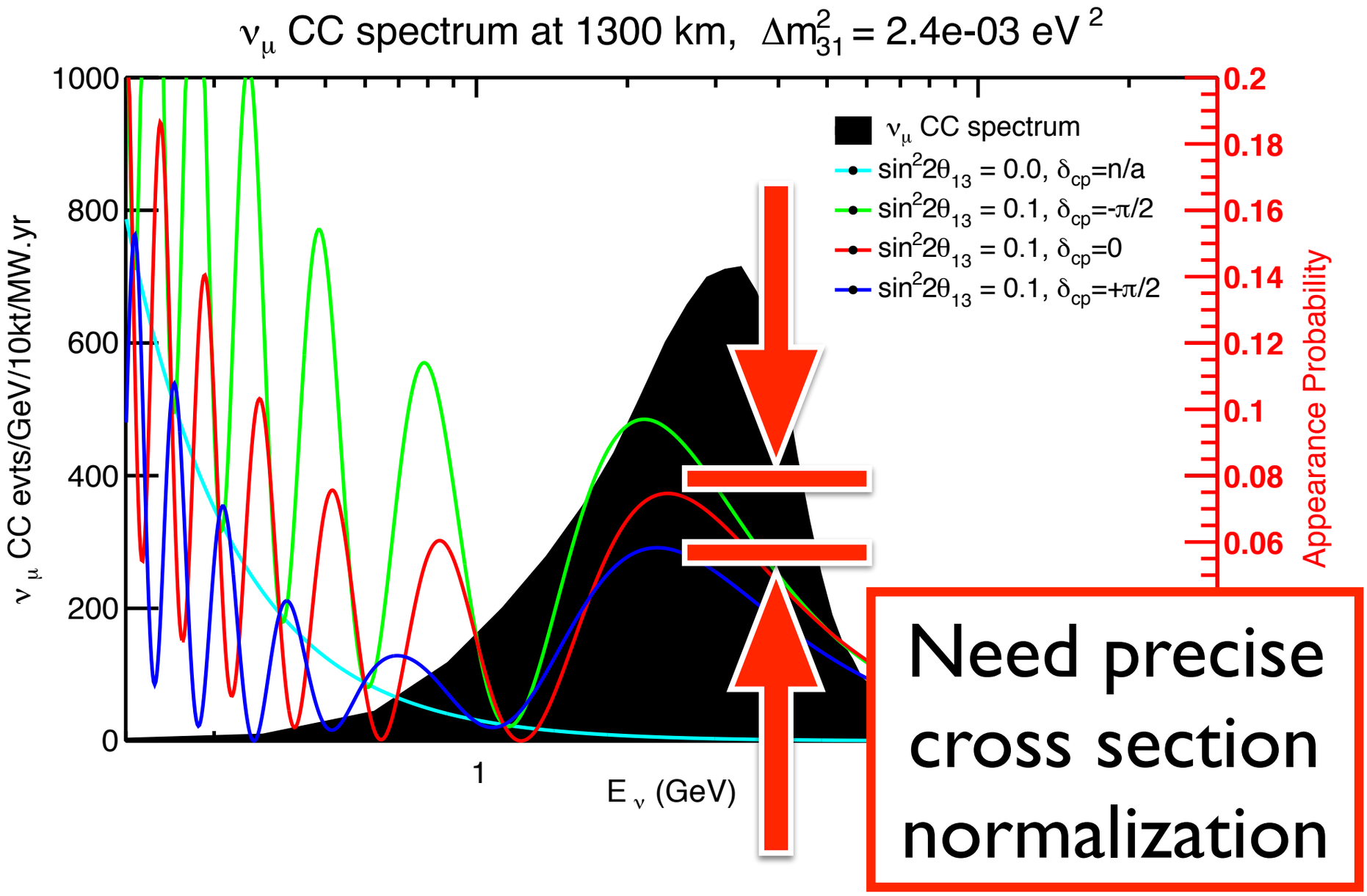




LBNE, 1307.7335
cf. Coloma, Huber et al., 1307.1243, 1311.4506;
Lalakulich and Mosel, 1311.7288



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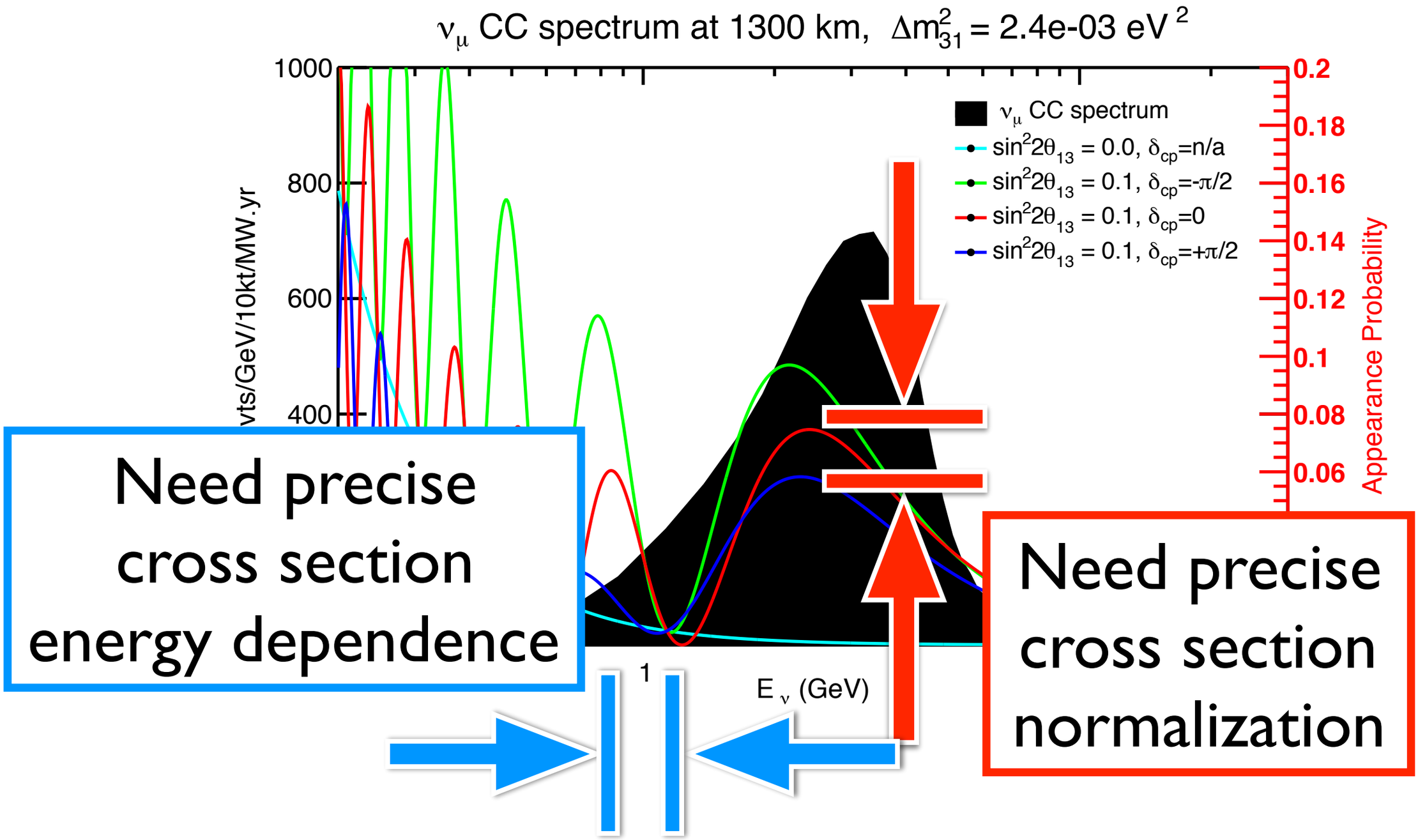

LBNE, 1307.7335
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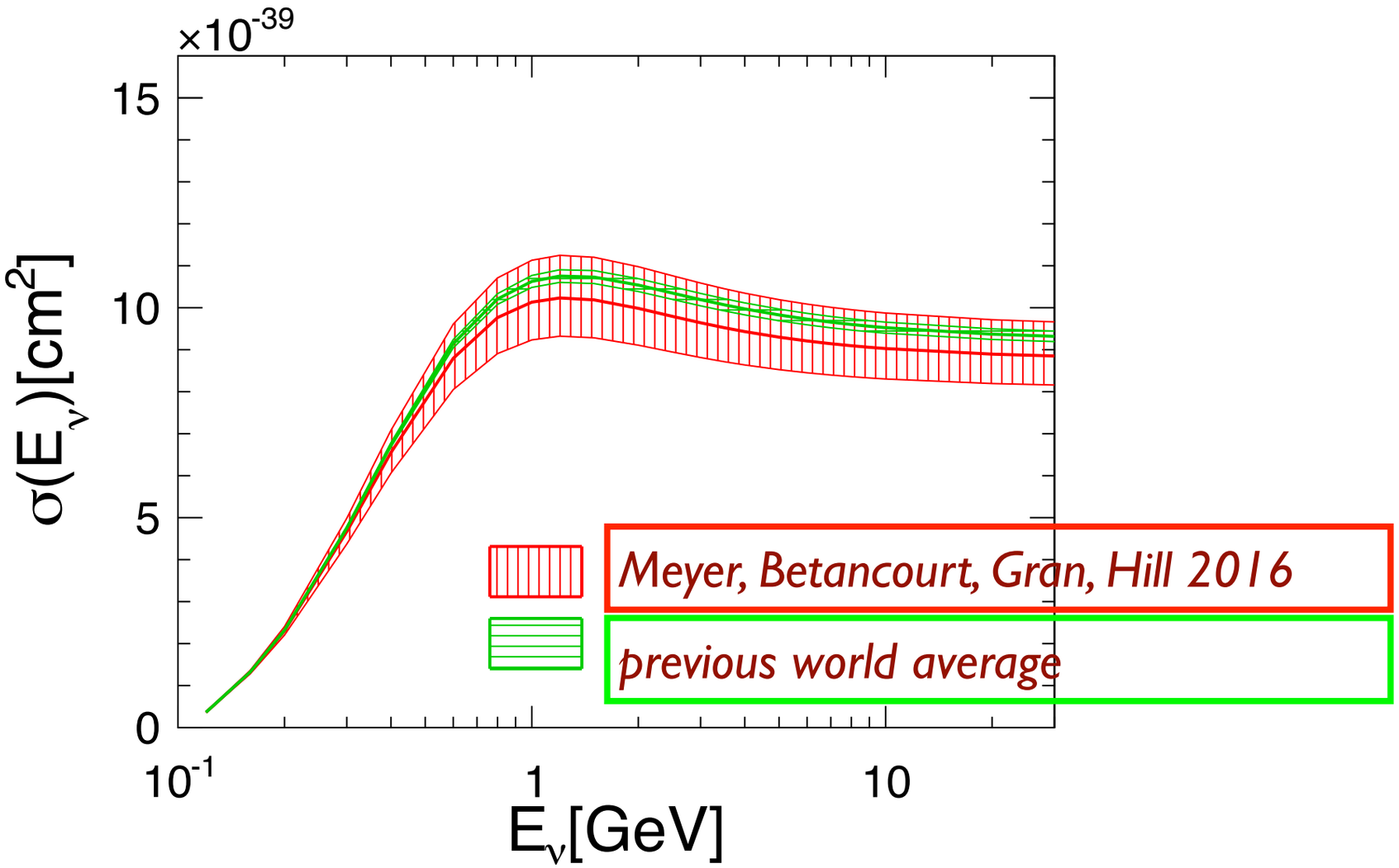
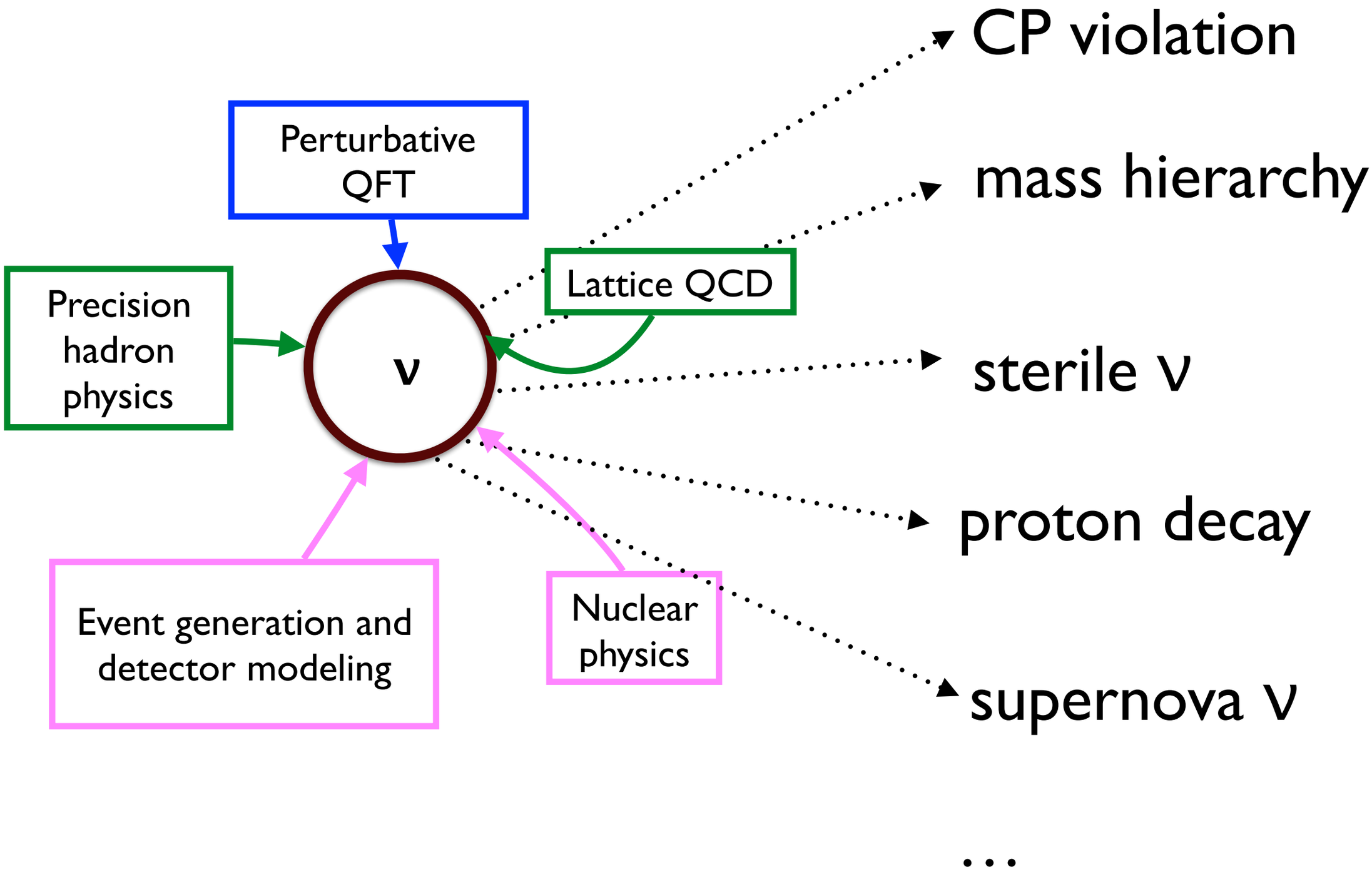
Cross section uncertainties can mimic the effects of CP violation:



- careful analysis of previous elementary target (deuterium) data reveals hadronic uncertainty. Future improvement from lattice QCD.

- intense theoretical effort underway

QCD in many regimes critical to extracting fundamental physics in the neutrino sector



An intense, interdisciplinary effort

Summary

- neutrino mass is physics beyond the standard model
- compelling questions remain unanswered
- theory has a critical role to play
- exciting interplay between particle and astrophysics
- next generation experiments are poised for discovery