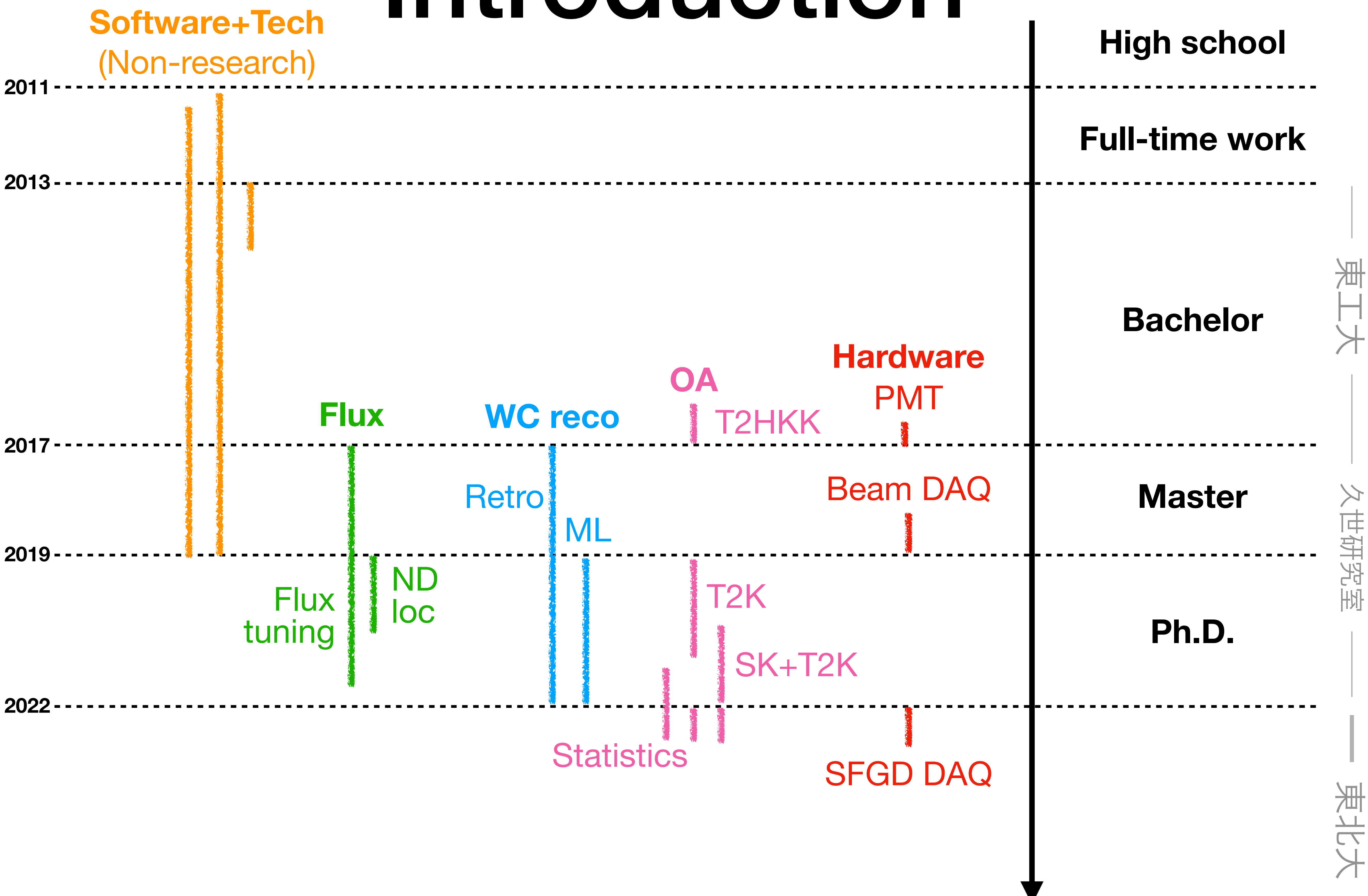
(some aspects of) **Neutrino oscillation experiments**

2022-11-09, Flavor Physics Workshop

Lukas Berns (T2K, HK Collaboration)

Introduction



Overview

- Current 3-flavor picture
- Example: T2K → SK+T2K joint
- Future prospects for 3-flavor
- Sterile neutrinos

Neutrino oscillation

- Production / detection of neutrinos, via charged current in association with charged leptons e, μ, τ
  → **flavor** eigenstates

- Mass/phase evolution of neutrinos controlled by complex Yukawa couplings with Higgs (or any other mechanism)
  → diagonalize to get **Hamiltonian** eigenstates

← only exists if ν_R is introduced (coupling of L and ν_R)

Flavor Eigenstate

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

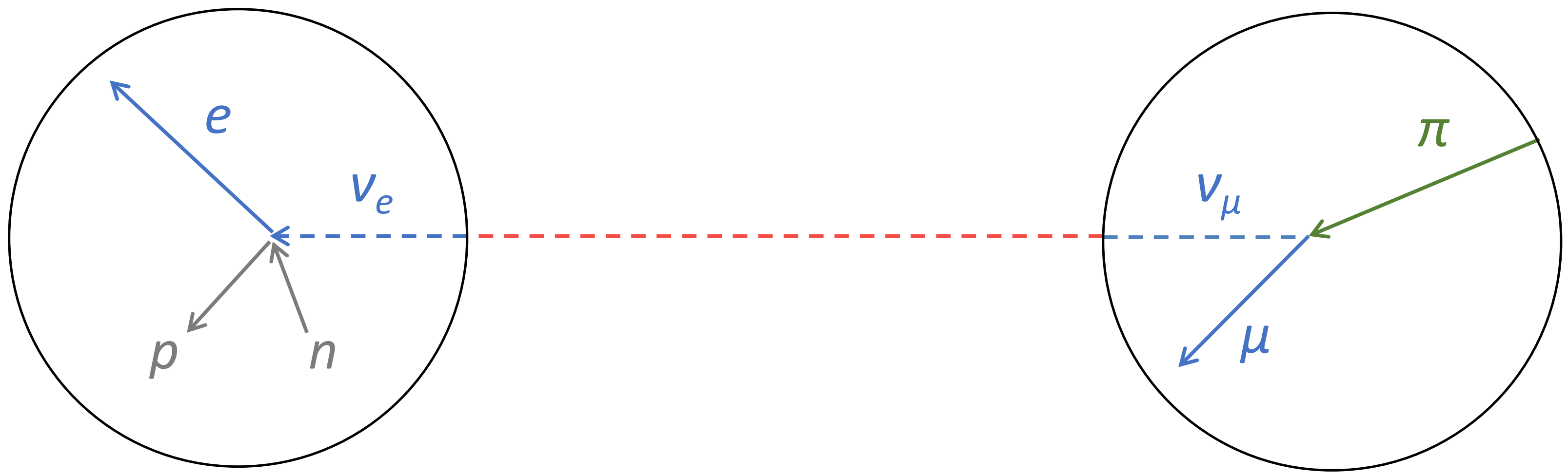
Hamiltonian Eigenstate ν_1, ν_2, ν_3

Superposition (Unitary transf.)

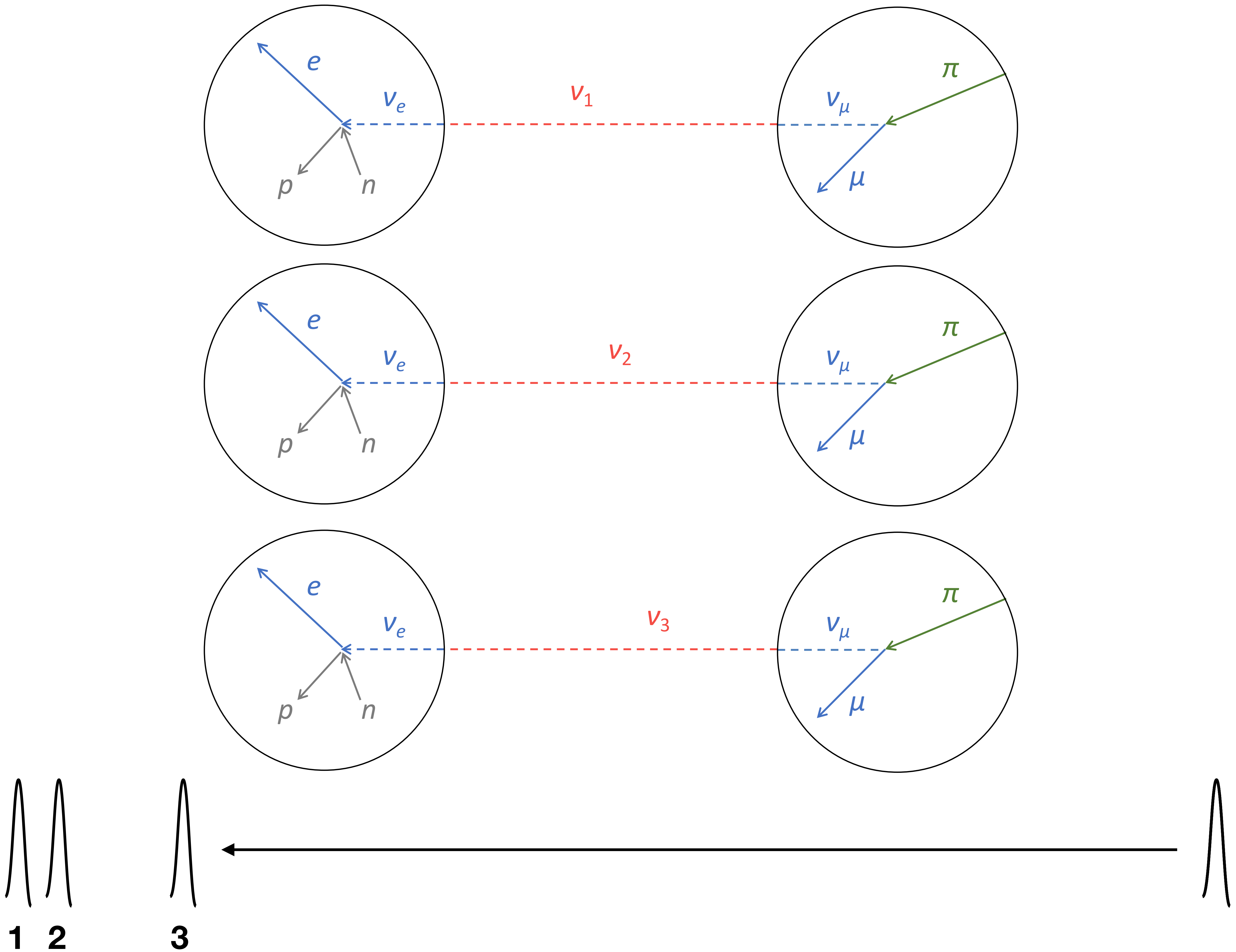
- Neutrinos are very light and also barely interact. **Coherence** preserved over millions of km.

→ flavor **oscillates** in

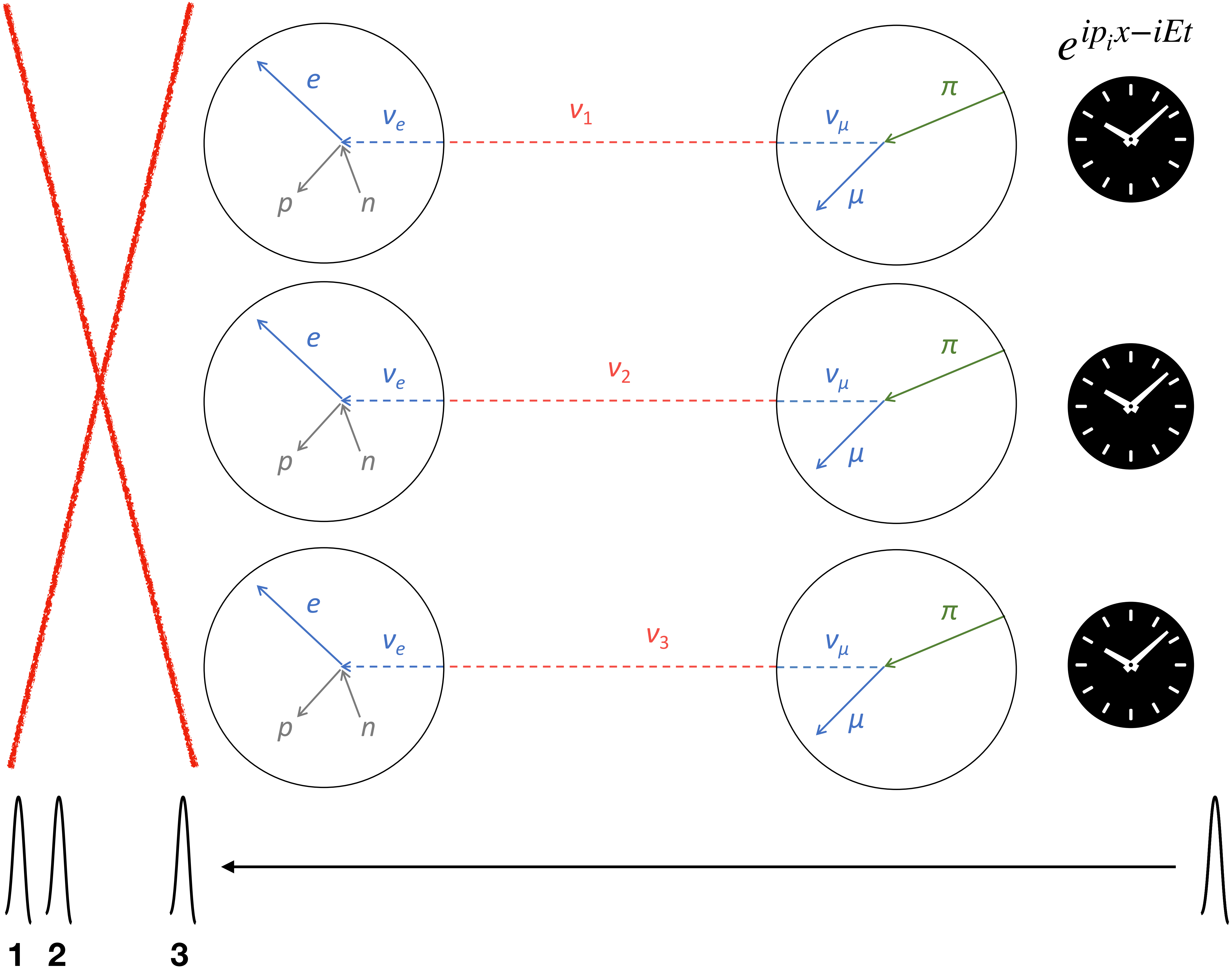
$$L \times \Delta E \propto \frac{\Delta m^2 L}{E}$$



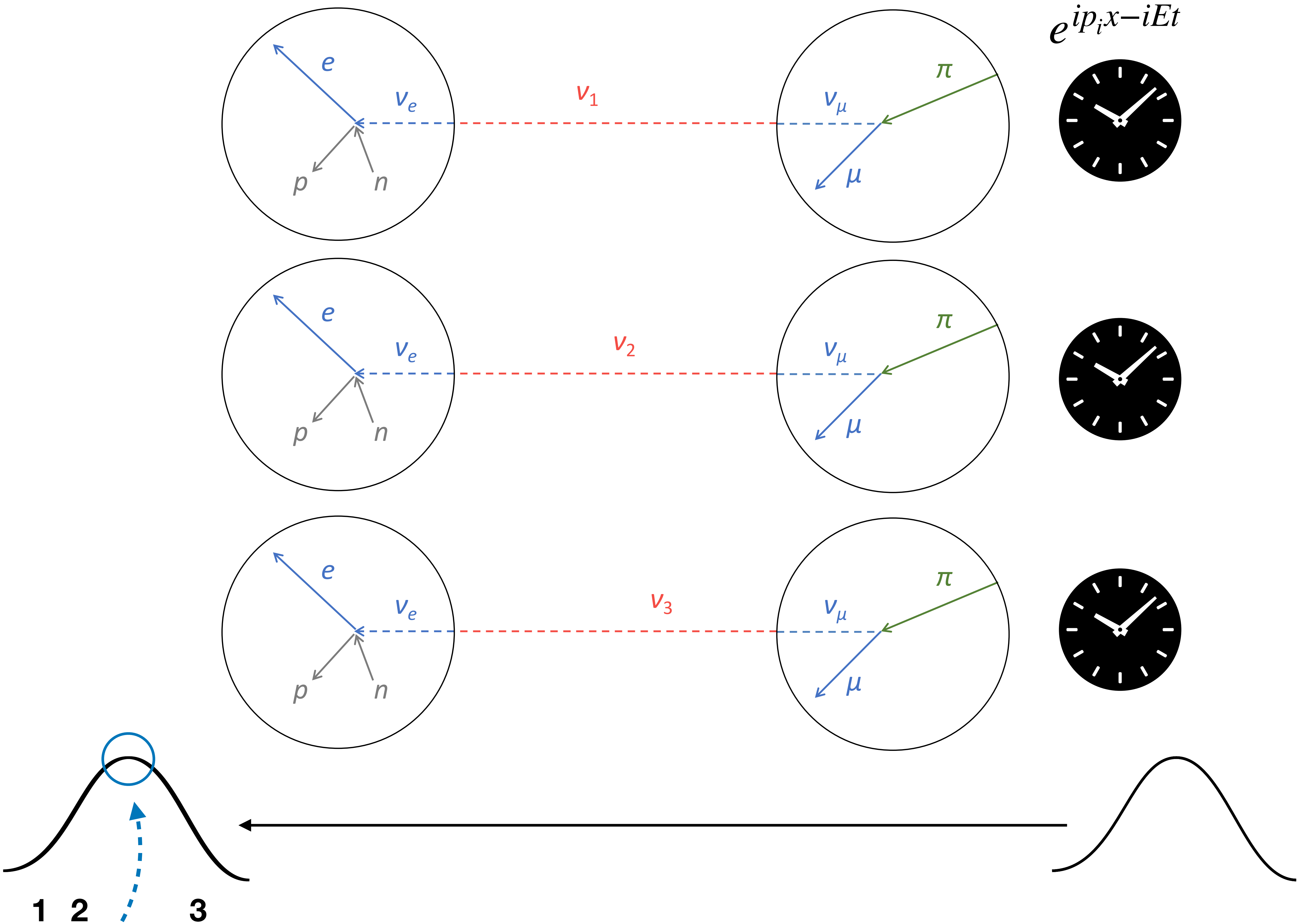
e
ν_e
p
n
π
ν_μ
μ



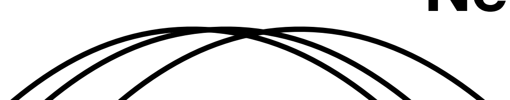
e
νe
ν1
νμ
π
p
n
μ
e
νe
ν2
νμ
π
p
n
μ
e
νe
ν3
νμ
π
p
n
μ
1
2
3

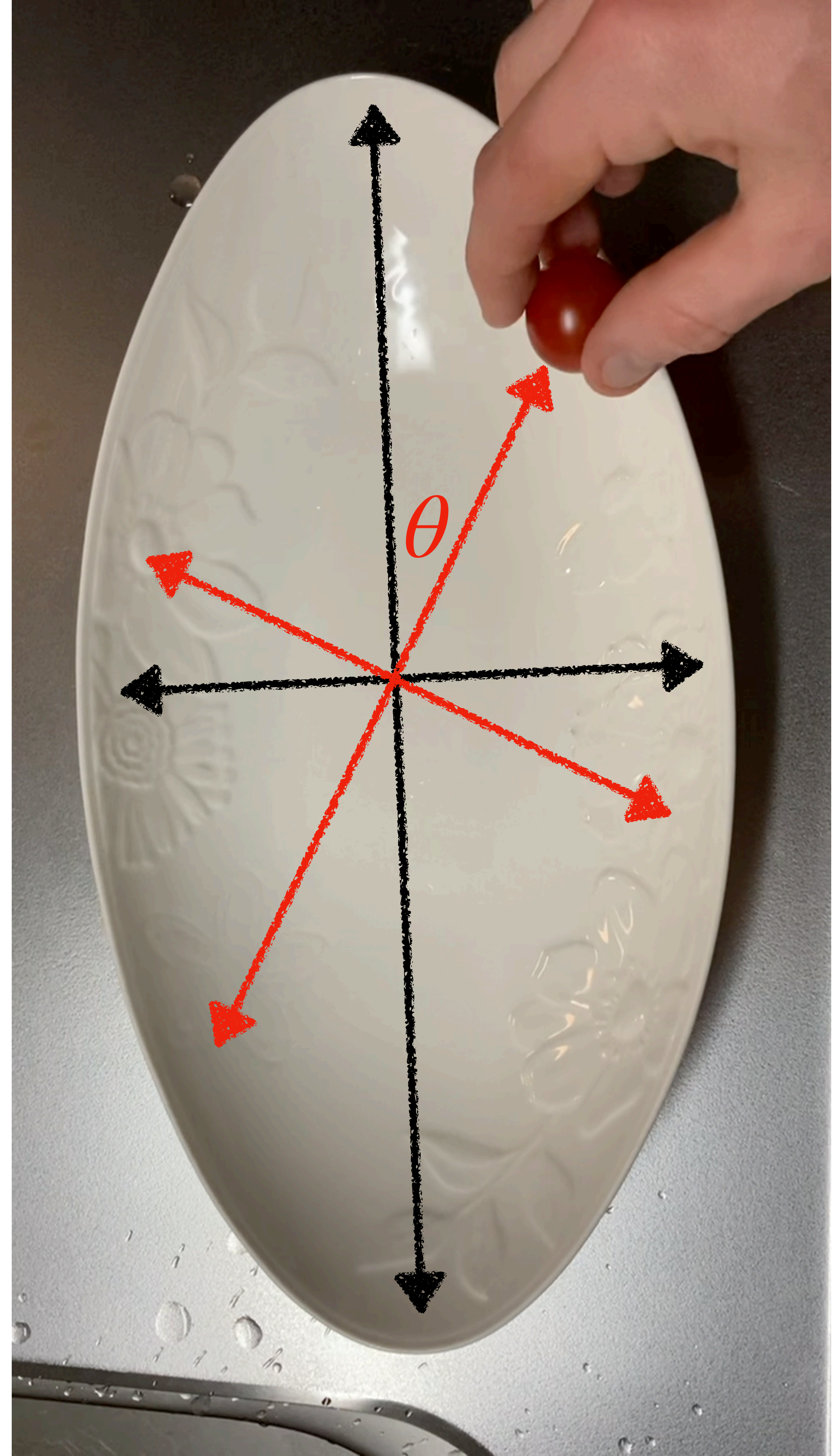


$e^{ip_i x - iEt}$
e
ν_e
p
n
ν_1
ν_2
ν_3
ν_μ
π
μ
1
2
3



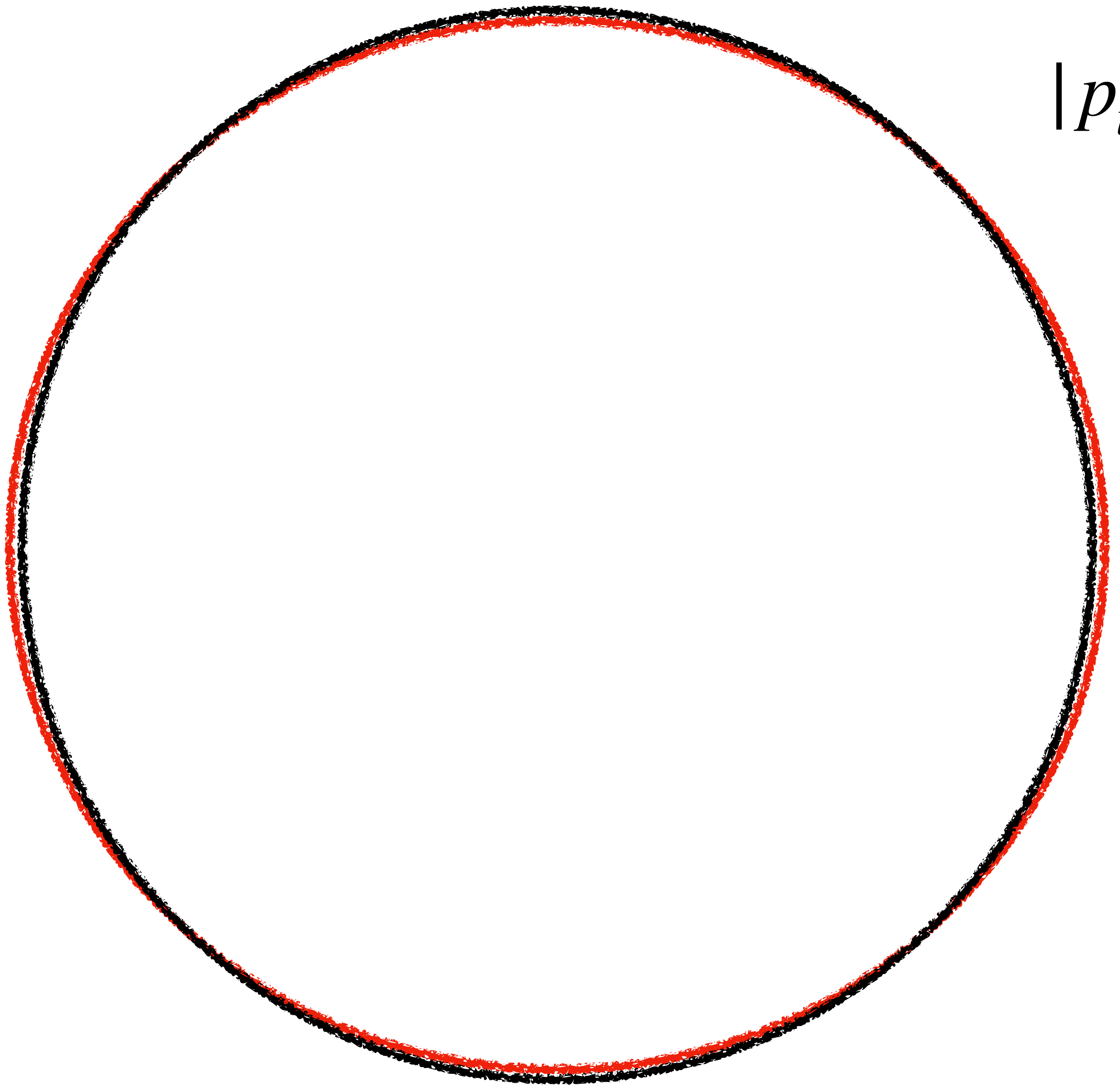
Neutrinos remain coherent!




θ

Perfect plate

Slightly deformed



$$|p_i| = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$$

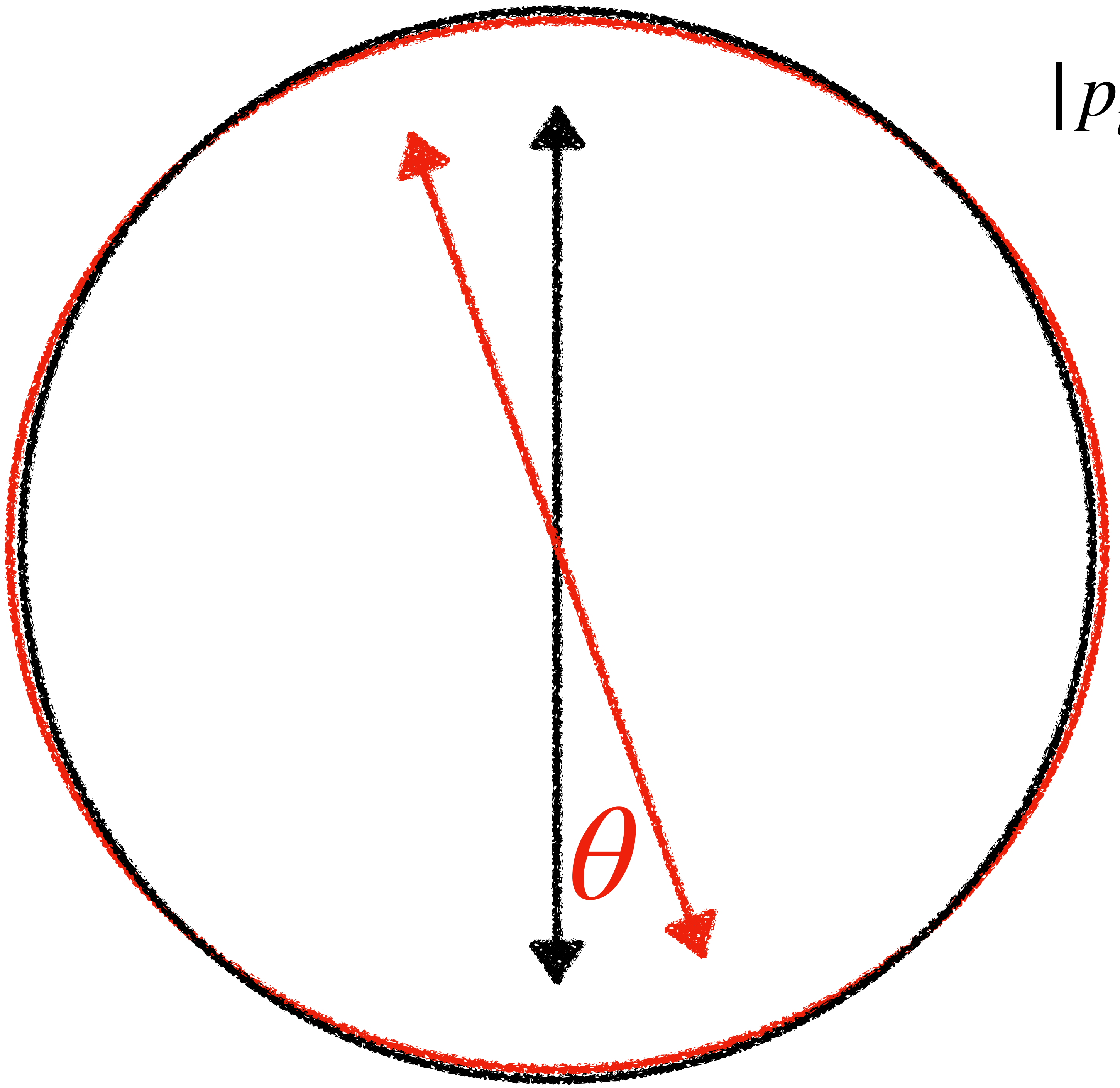
$$\left(E^2 \gg m_i^2\right)$$

→ flavor **oscillates** in

$$L \times \Delta E \propto \frac{\Delta m^2 L}{E}$$

Perfect plate

Slightly deformed



$$|p_i| = \sqrt{E^2 - m_i^2} \approx E - \frac{m_i^2}{2E}$$

$$\left(E^2 \gg m_i^2\right)$$

$$\sin^2 2\theta$$

→ flavor **oscillates** in

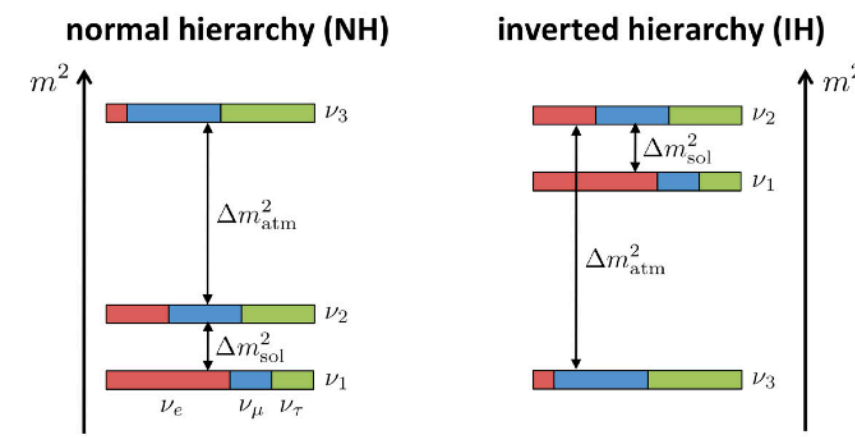
$$L \times \Delta E \propto \frac{\Delta m^2 L}{E}$$

Typical parametrization

$$U = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\text{atmospheric}} \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}^{\text{reactor}} \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\text{solar}}$$

$$c_{ij} \equiv \cos\theta_{ij}$$

$$s_{ij} \equiv \sin\theta_{ij}$$



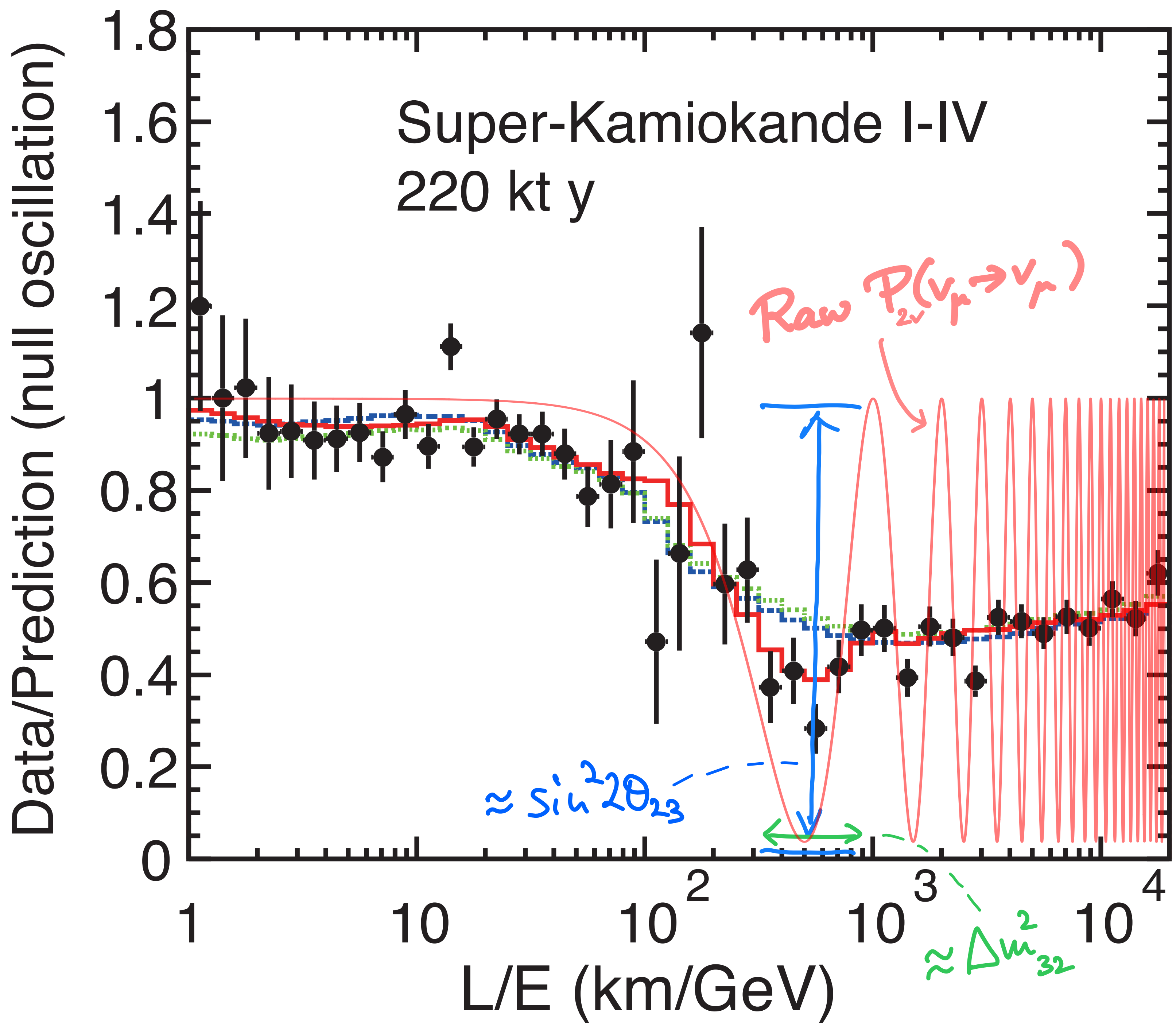
Credit: JUNO Collaboration / JGU-Mainz

- Two mass scales:
  Δm^2_{21} (solar, reactor) typically 32 km / 1 MeV
  Δm^2_{32} (atmospheric, accelerator) typically 1000 km / 1 GeV

- Three mixing angles:
  θ_{12} (solar, long-baseline reactor)
  θ_{23} (atmospheric, accelerator $\nu_\mu \to \nu_\mu$ disappearance)
  θ_{13} (short-baseline reactor $\nu_e \to \nu_e$, accelerator $\nu_\mu \to \nu_e$ appearance)

- One CP-violating phase: δ_{CP} (if Majorana two more, but no effect on oscillation)

Atmospheric neutrinos



- Production in atmosphere $p + A \to N + A' + \pi^{\pm}$

  then
  $\pi^{\pm} \to \mu + \nu_\mu$
  $\mu \to e + \nu_e + \nu_\mu$

- At few-GeV expect $\nu_\mu : \nu_e = 2 : 1$ but ν_μ about half of expectation

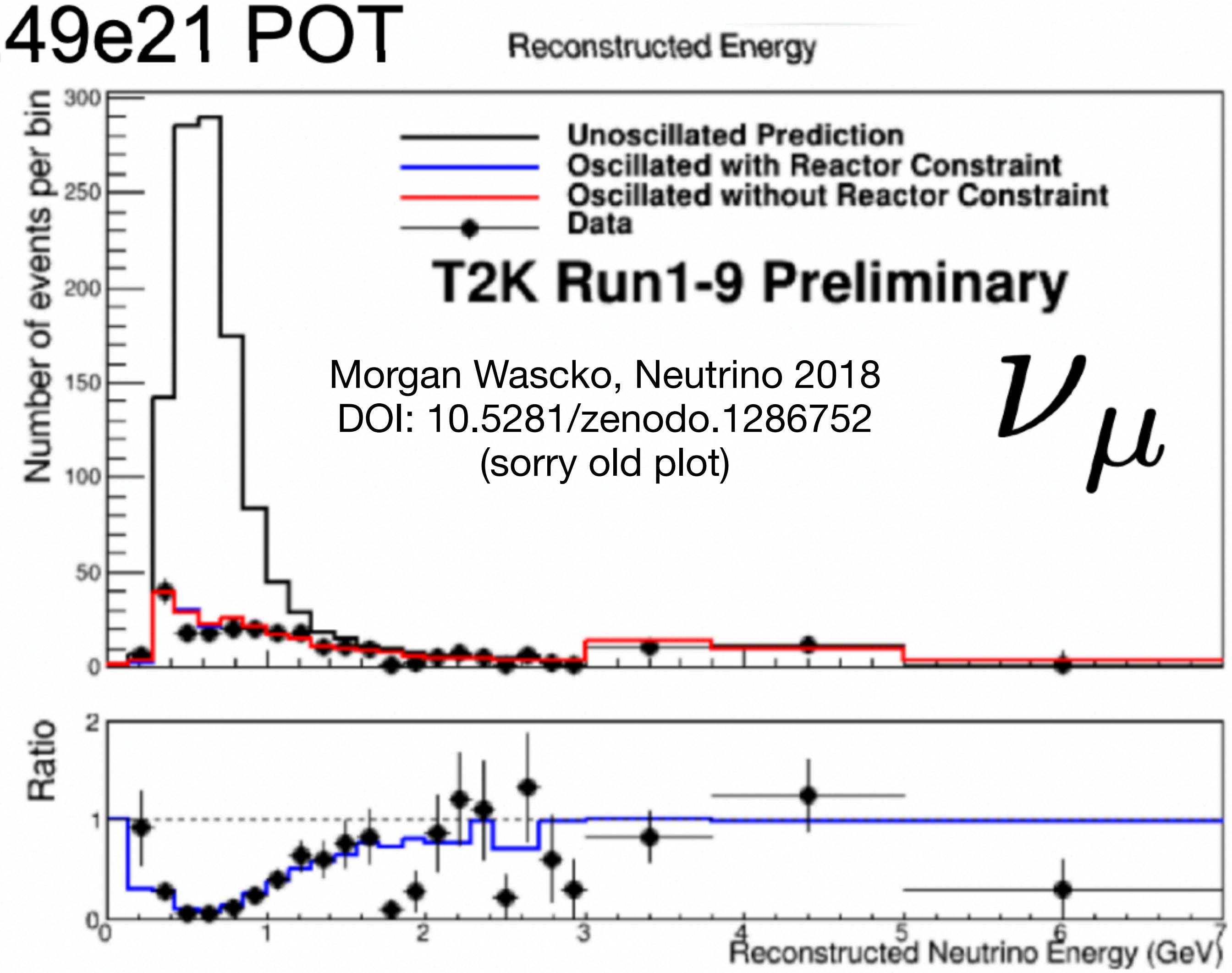
- At > GeV good neutrino direction resolution → baseline L

- Maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing → $\theta_{23} \approx 45^\circ$

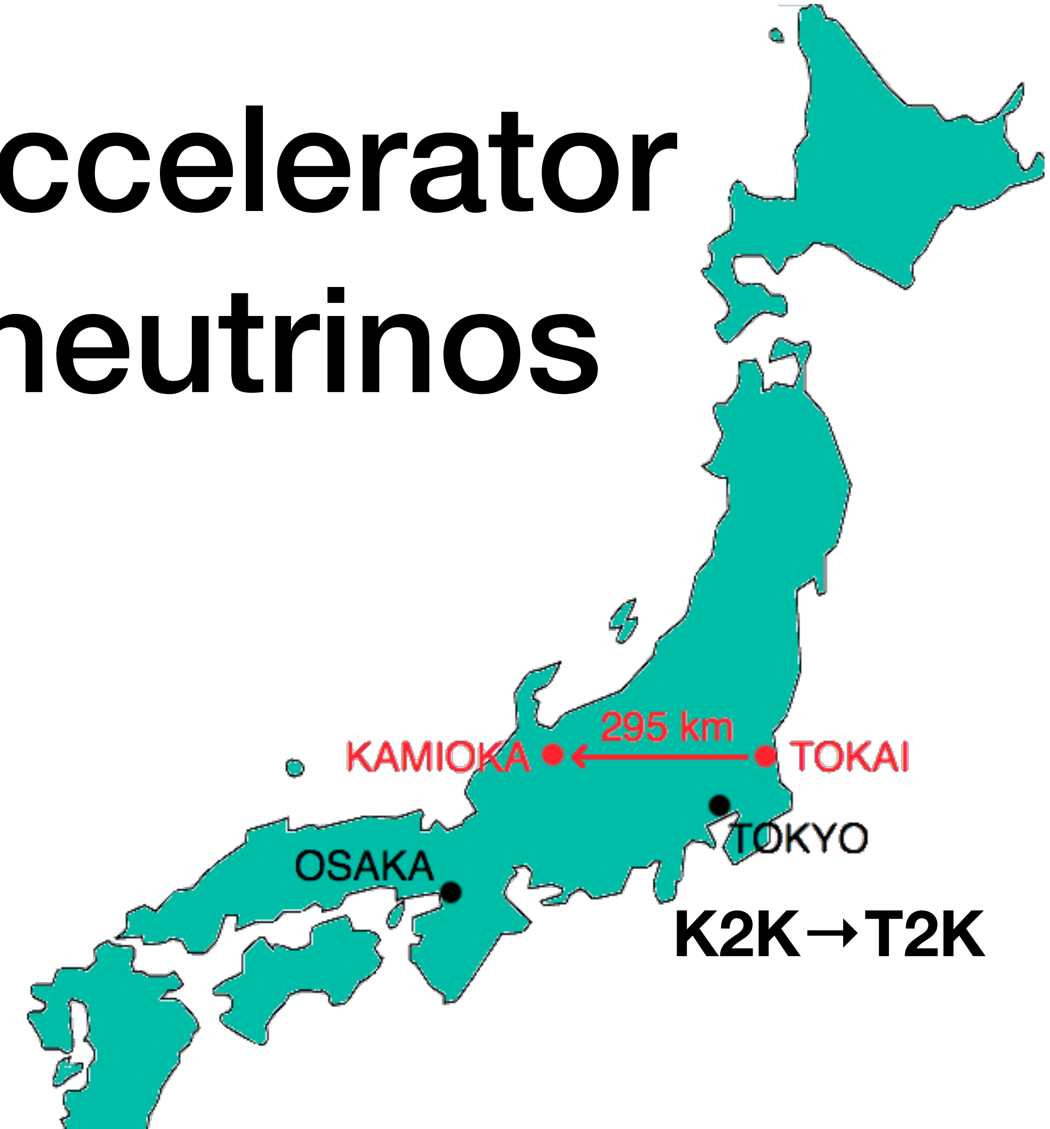
Plots from PDG review, drawings and osc. prob mine

Accelerator neutrinos

1.49e21 POT



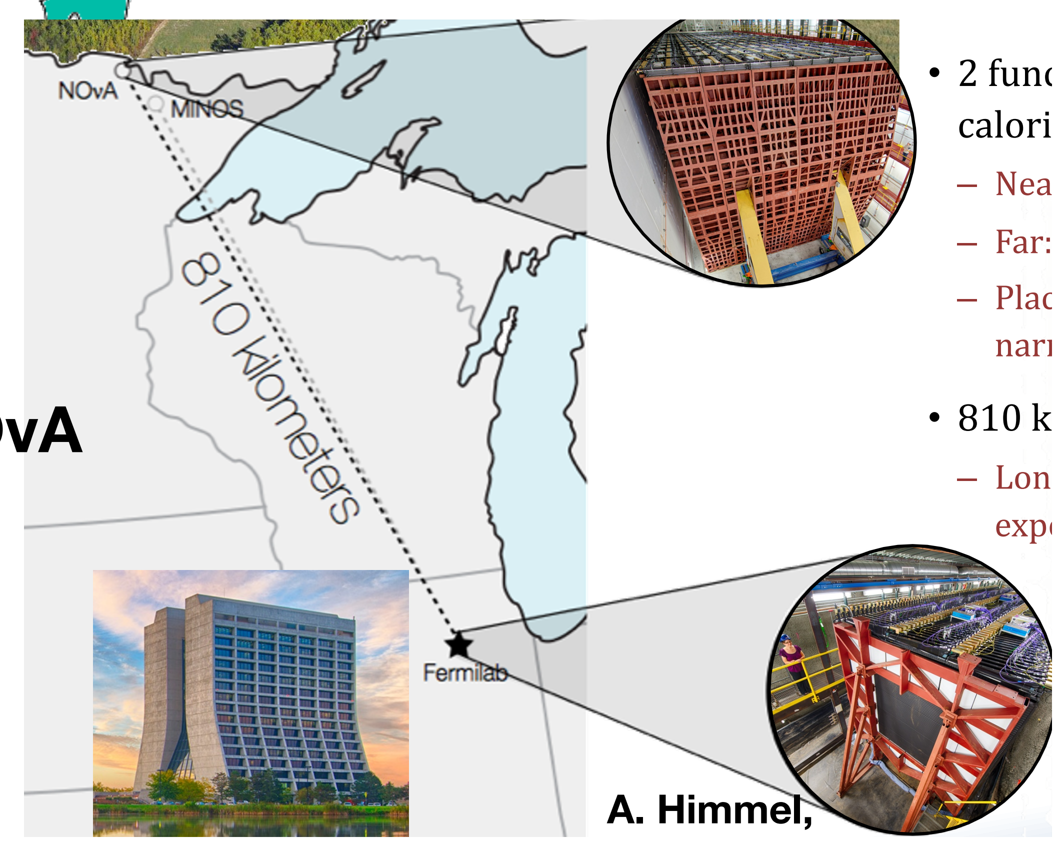
Reconstructed neutrino energy



K2K→T2K

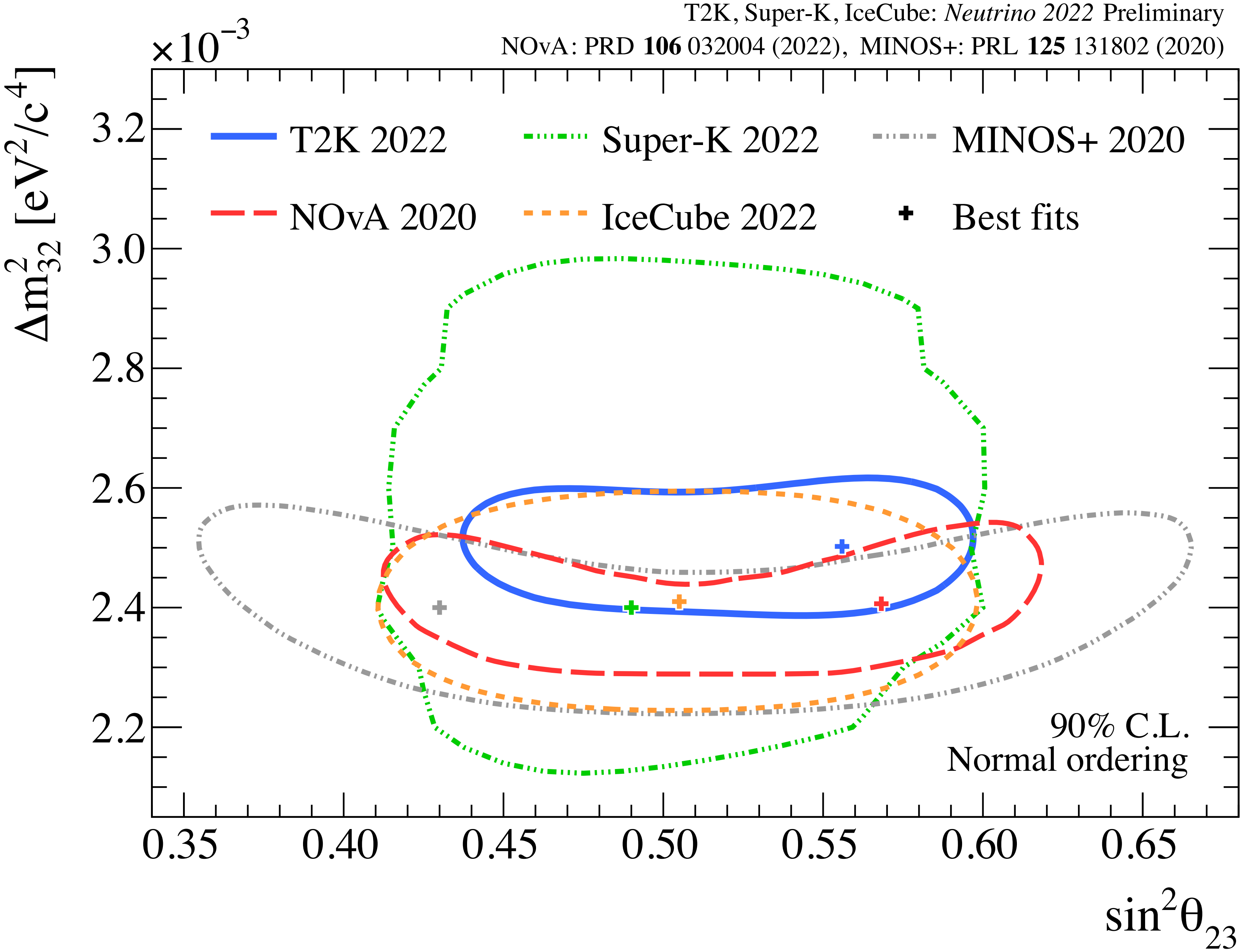
- Accelerate protons and produce pions in fixed target $p + A \rightarrow \pi^{\pm} + \cdots$
- Pions decay in flight to produce $\pi^{\pm} \rightarrow \nu_\mu + \mu$
- "Disappearance" of $\nu_\mu \rightarrow \nu_\mu$
- Fixed L + can reconstruct energy because of known ν direction

MINOS→NOvA

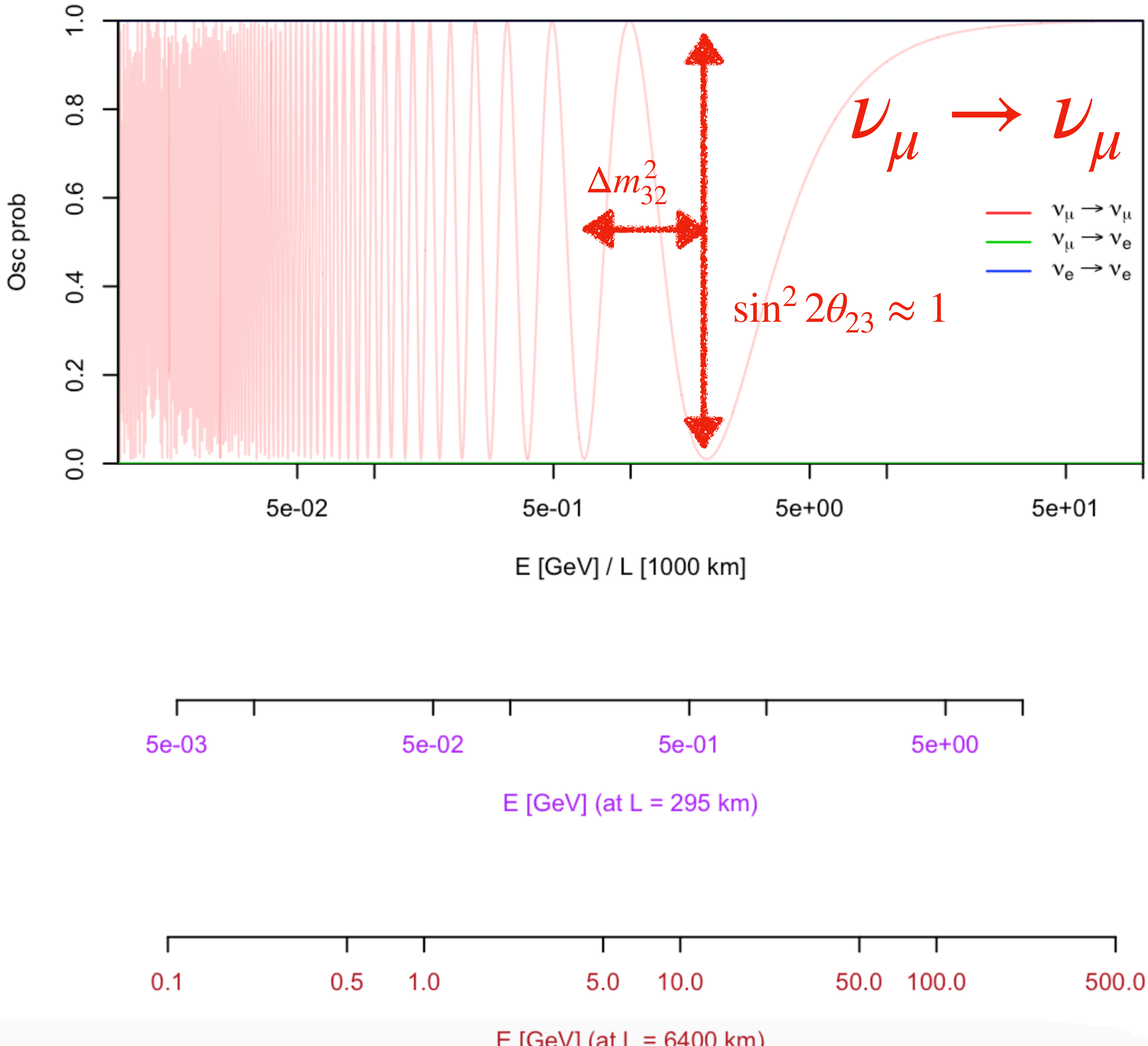


A. Himmel, Neutrino 2020

Atmospheric oscillation parameters



- Accelerator experiments most precise, but all very consistent
- IceCube will significantly improve results soon

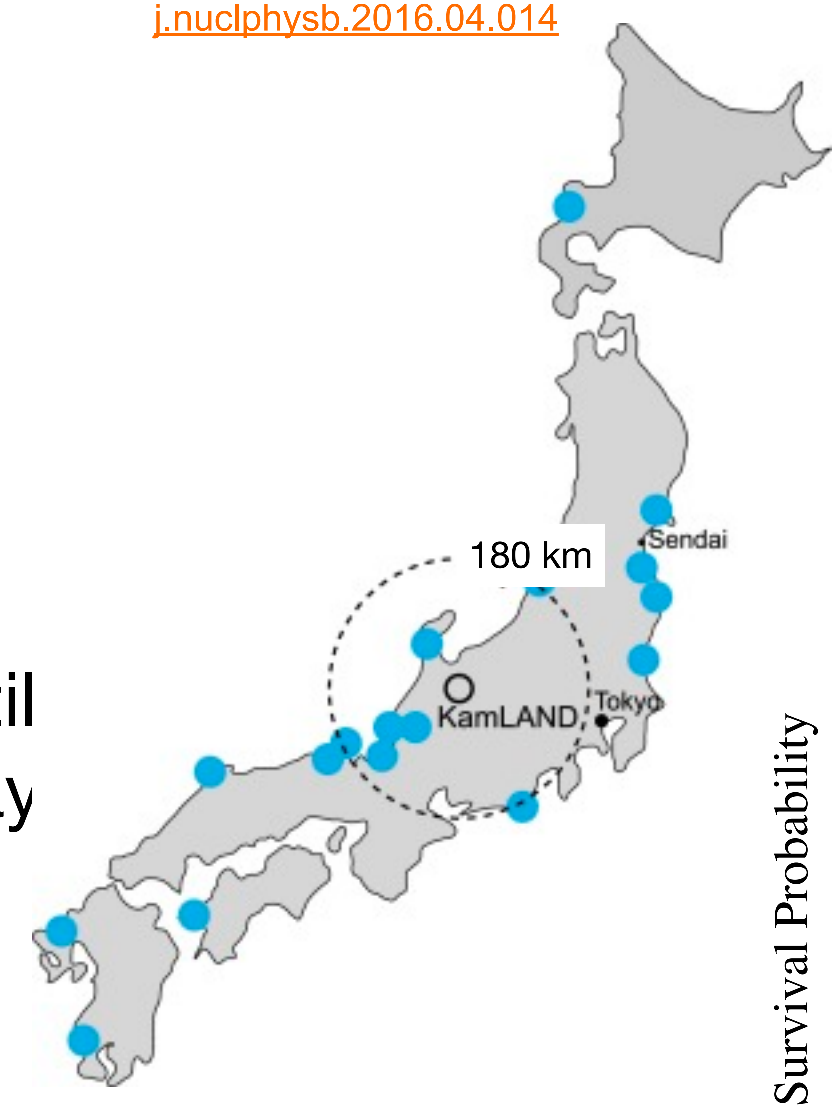


$\nu_\mu \to \nu_\mu$
Δm^2_{32}
$\sin^2 2\theta_{23} \approx 1$
$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_e$
$\nu_e \to \nu_e$
Osc prob
0.0
0.2
0.4
0.6
0.8
1.0
5e-02
5e-01
5e+00
5e+01
E [GeV] / L [1000 km]
5e-03
5e-02
5e-01
5e+00
E [GeV] (at L = 295 km)
0.1
0.5
1.0
5.0
10.0
50.0
100.0
500.0
E [GeV] (at L = 6400 km)

Long-baseline reactor experiments

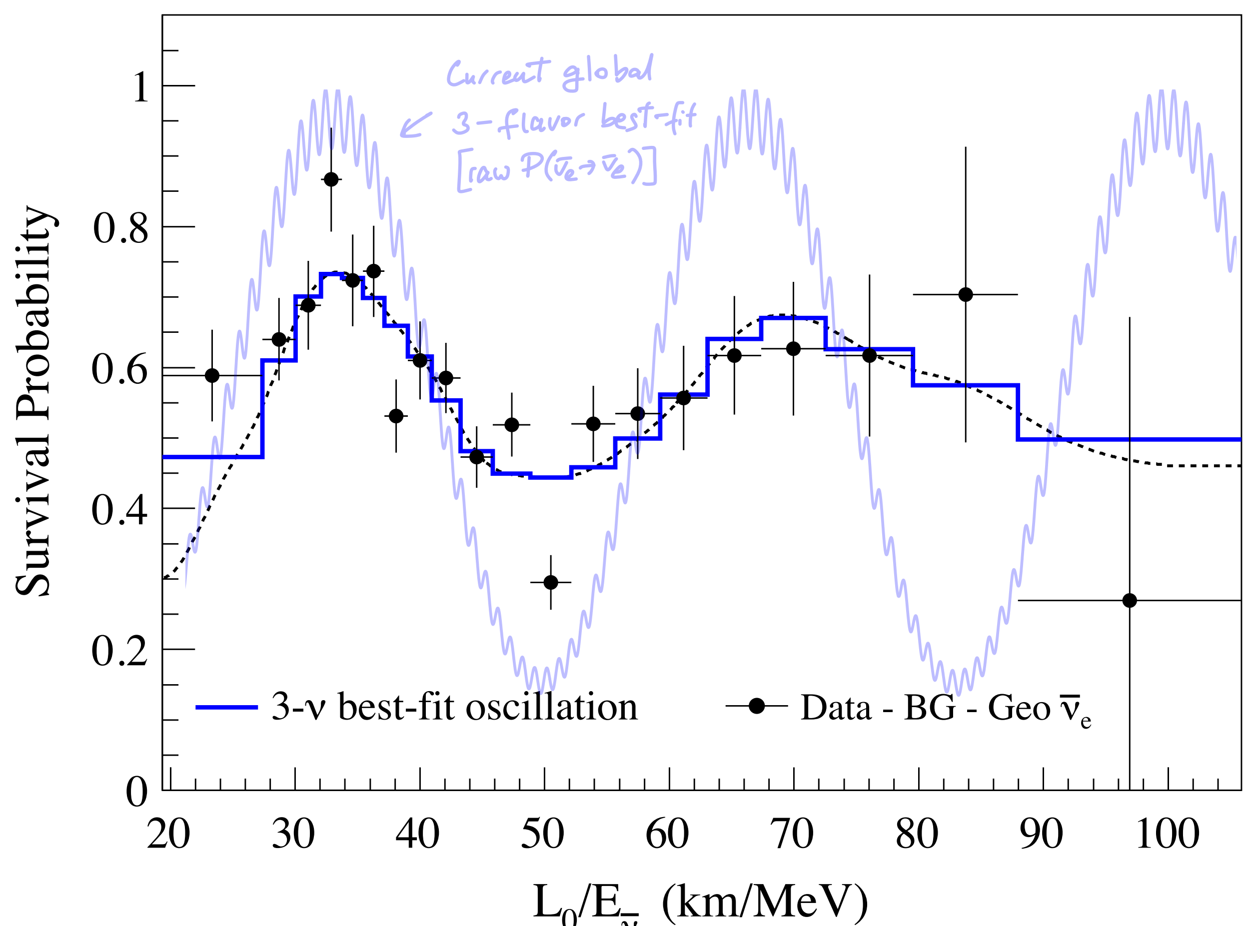
- KamLAND
- Few-MeV $\overline{\nu}_e$ from nuclear reactors (β-chain)
- $L \approx 100\,\mathrm{km}$
- 1000 t liquid scintil inverse beta decay $\overline{\nu}_e + p \rightarrow e^+ + n$
- θ_{12} and Δm^2_{21}

https://doi.org/10.1016/j.nuclphysb.2016.04.014



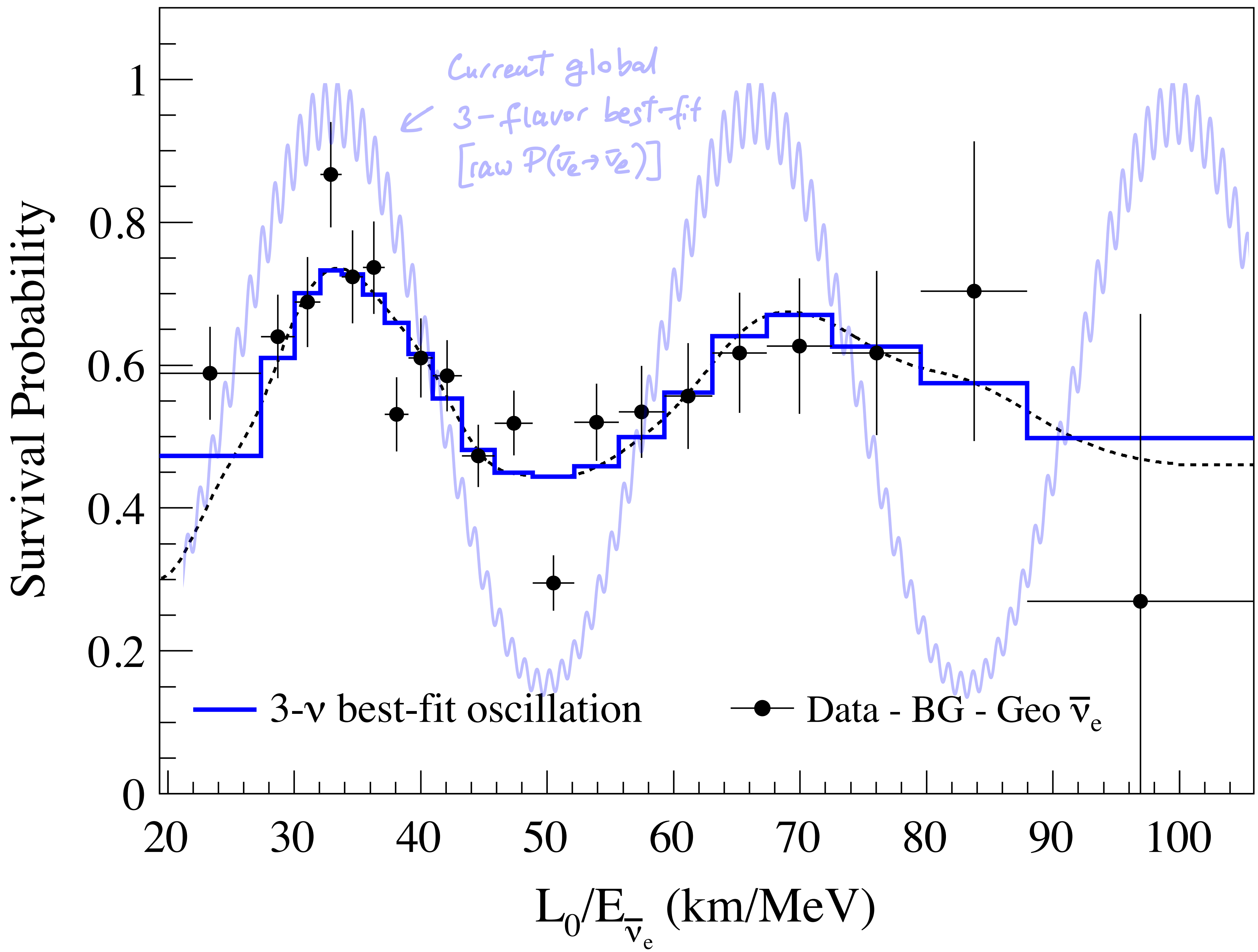
Gando et al. Reactor On-Off Antineutrino Measurement with KamLAND. Phys. Rev. D, 88(3):033001, 2013. doi: 10.1103/PhysRevD.88.033001. arXiv: 1303.4667.

Hand-drawn text / osc prob are mine.



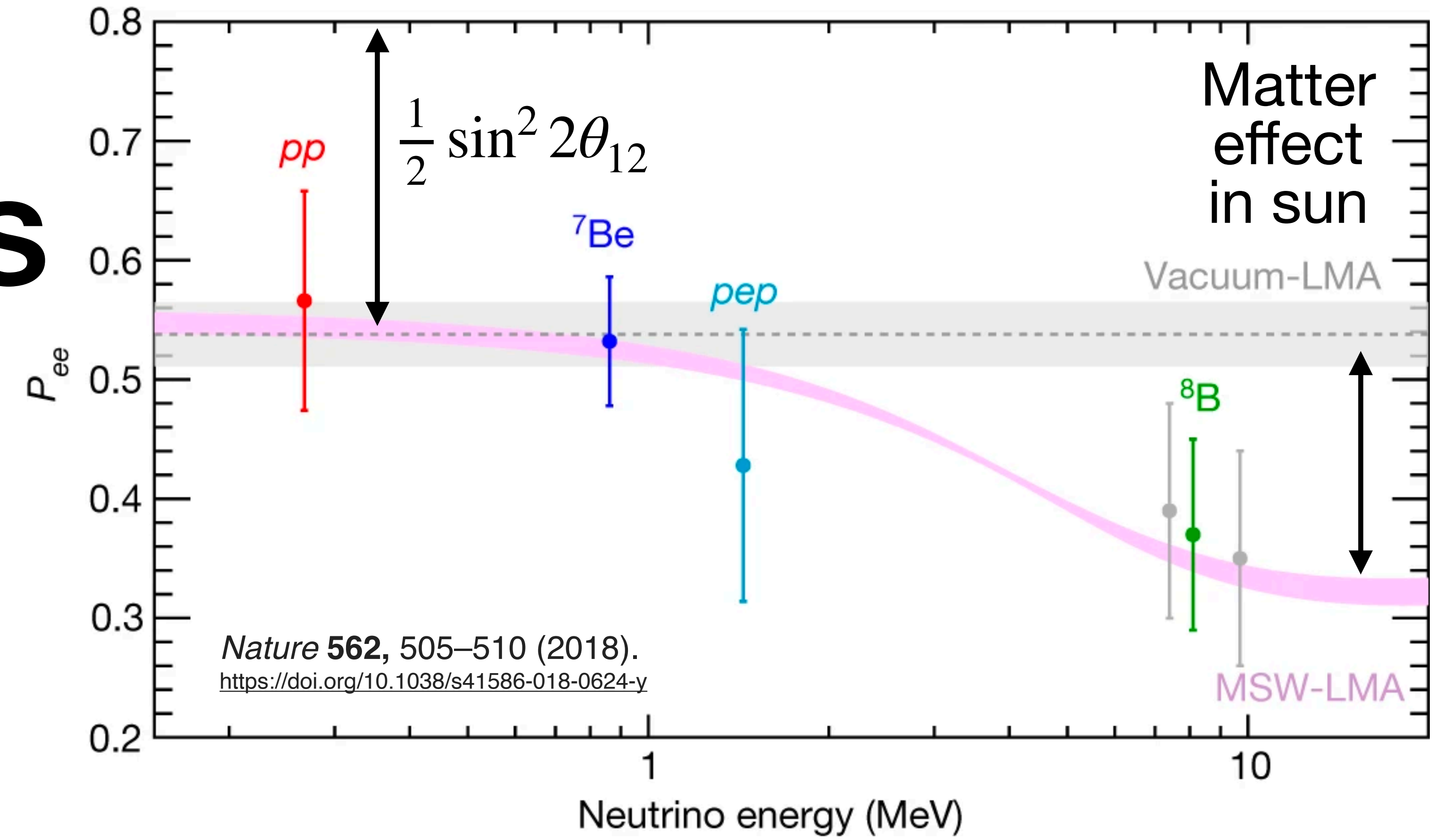
Long-baseline reactor experiments

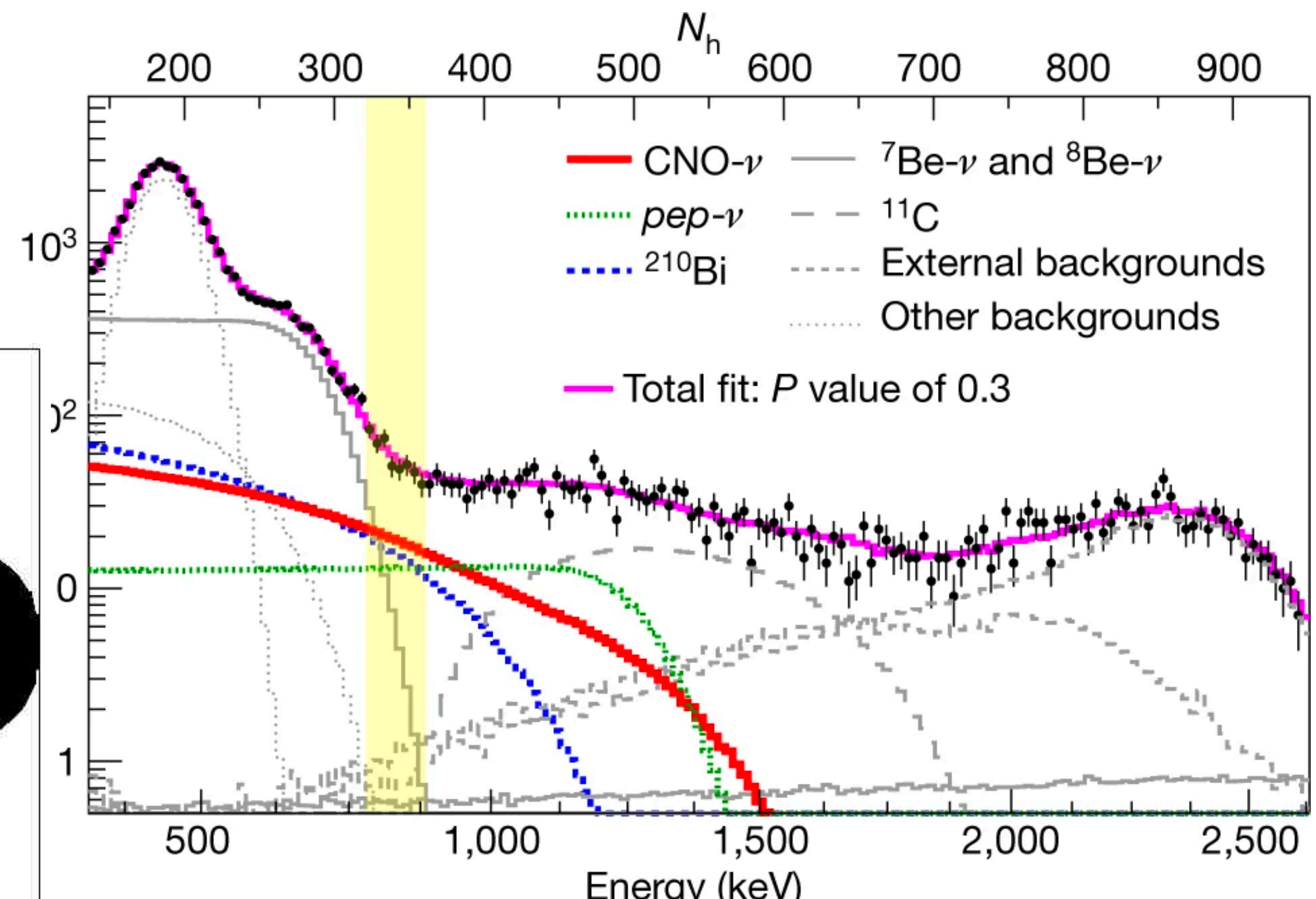
- KamLAND
- Few-MeV $\overline{\nu}_e$ fro[m] nuclear reactors (β-chain)
- $L \approx 100\,\mathrm{km}$
- 1000 t liquid sci[ntillator] inverse beta dec[ay] $\overline{\nu}_e + p \rightarrow e^+ +$
- θ_{12} and Δm^2_{21}



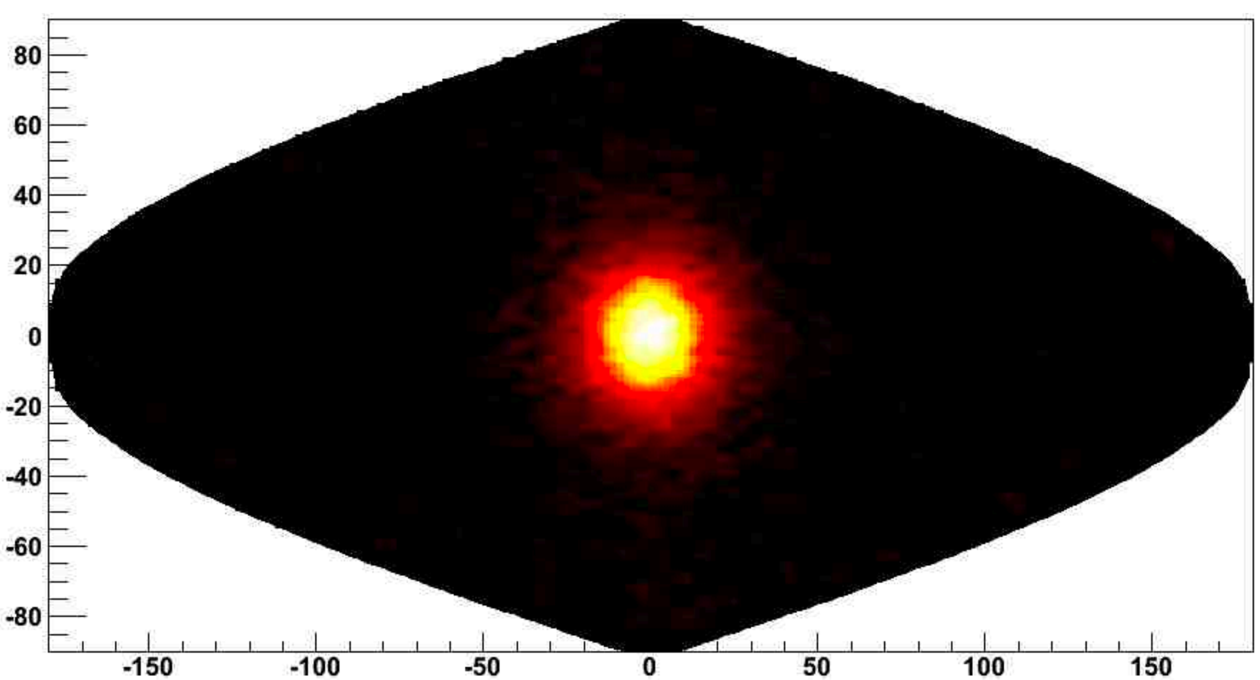
Solar neutrinos

- $E \approx \mathrm{MeV}\ \nu_e$ produced in nuclear fusion cycles in Sun
- SuperK, SNO
  Water / Heavy water
- Borexino
  Liquid scintillator





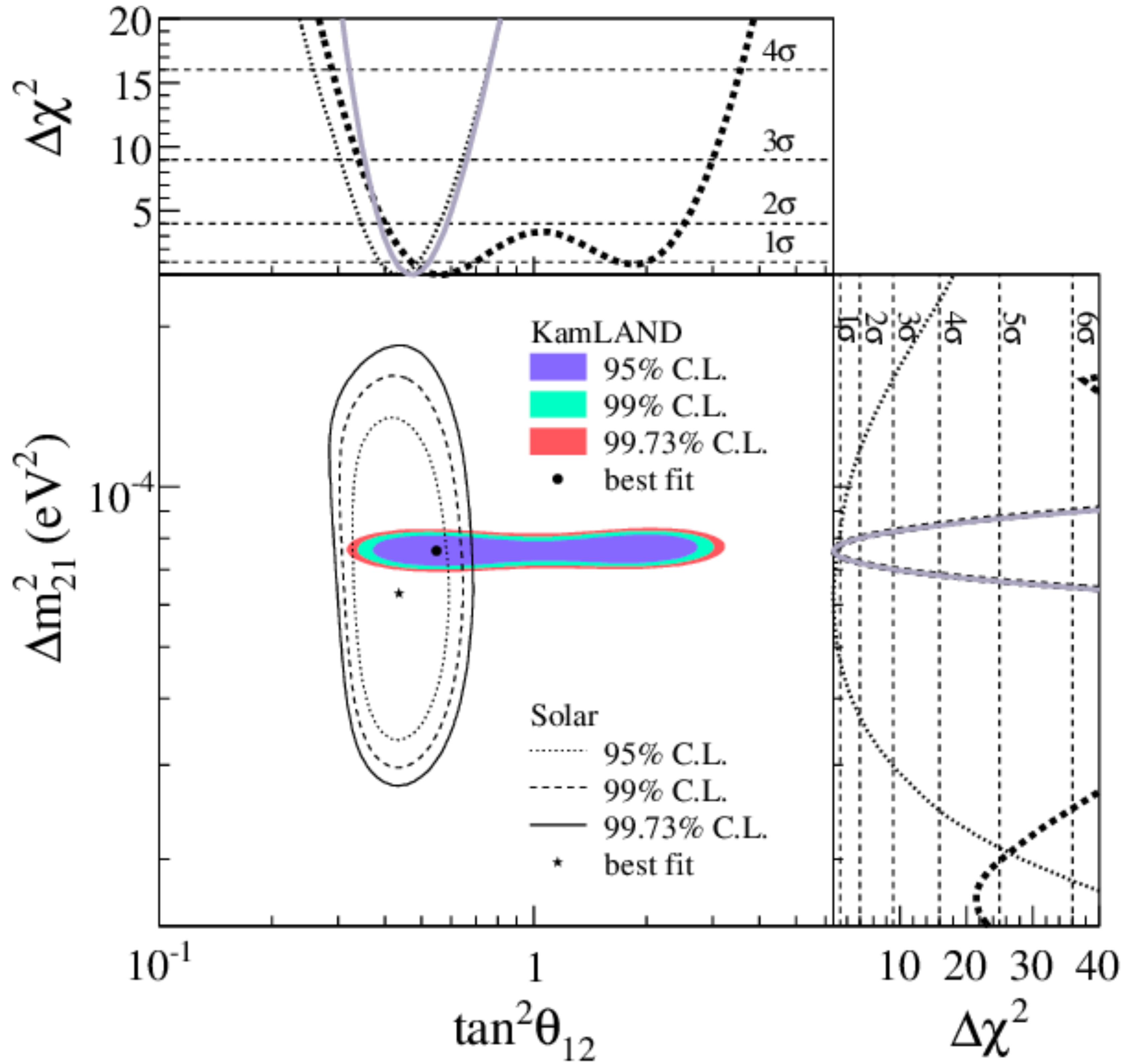
Nature **587**, 577–582 (2020).
https://doi.org/10.1038/s41586-020-2934-0



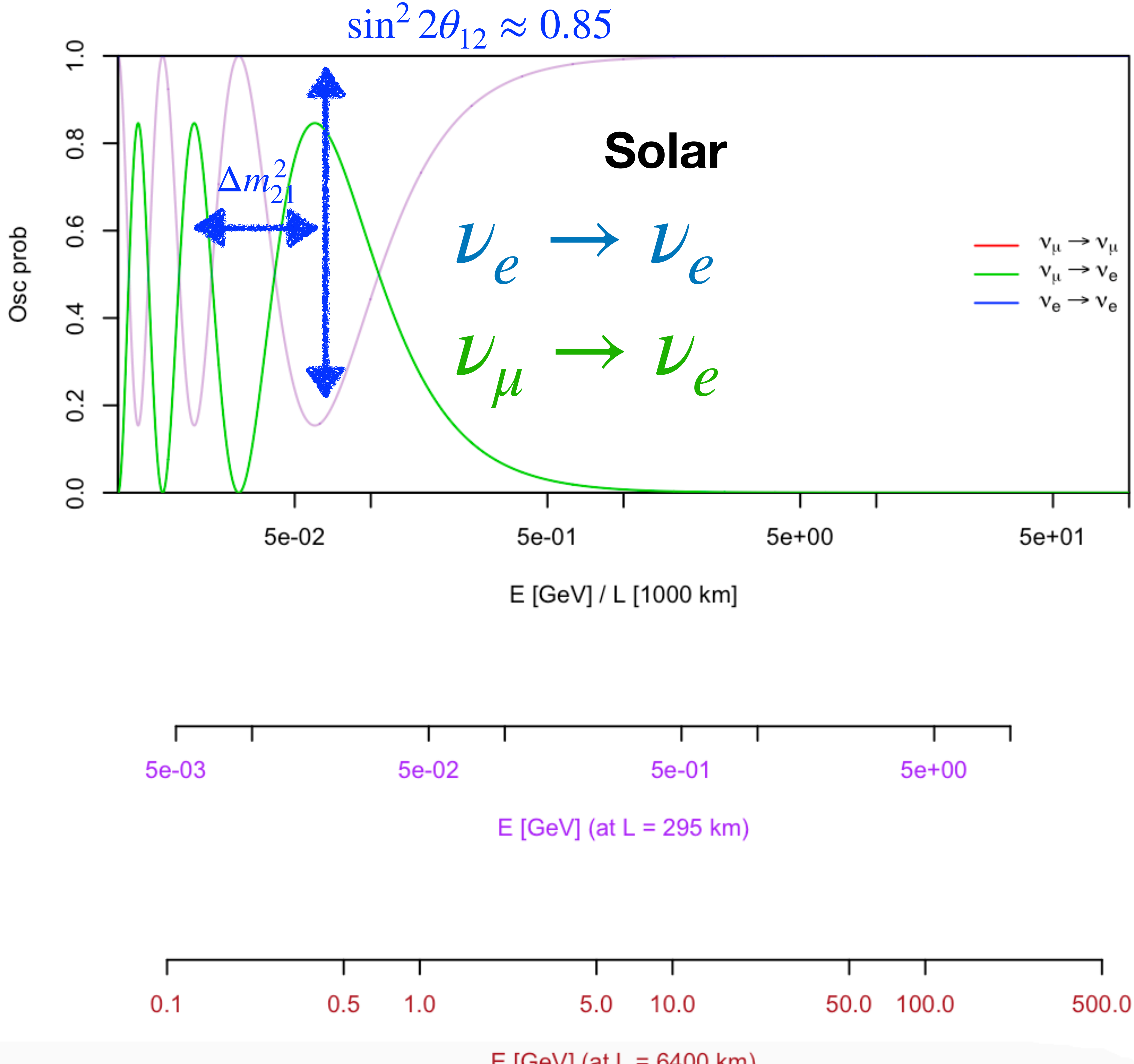
https://www-sk.icrr.u-tokyo.ac.jp/sk/sk/solar-e.html

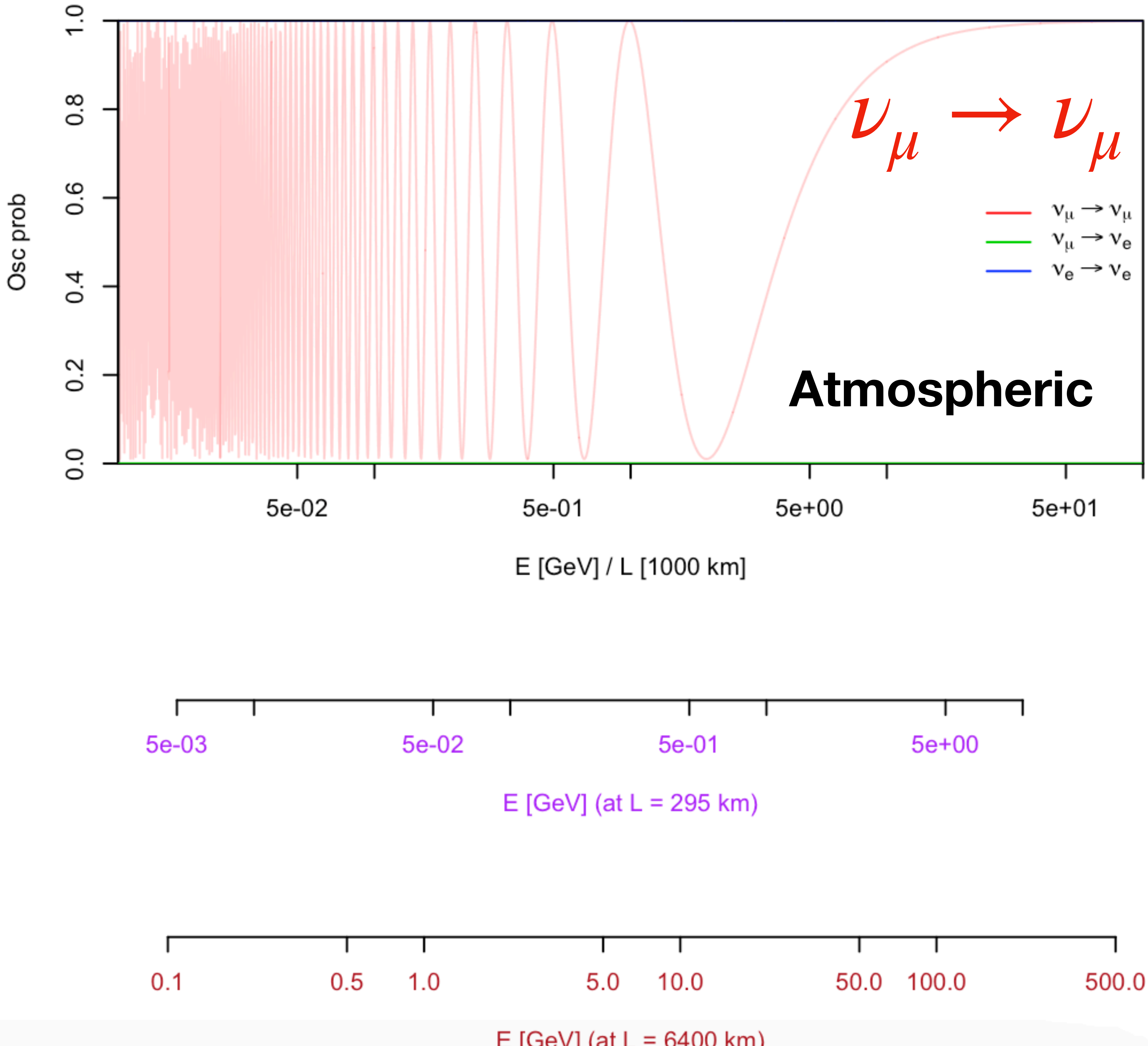
Solar oscillation parameters

- Solar neutrino and reactor neutrino experiments have different strengths.
- Combine to give more complete picture



https://doi.org/10.1103/PhysRevLett.100.221803


$\sin^2 2\theta_{12} \approx 0.85$
Solar
Δm^2_{21}
$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_e$
Osc prob
0.0
0.2
0.4
0.6
0.8
1.0
5e-02
5e-01
5e+00
5e+01
E [GeV] / L [1000 km]
$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_e$
5e-03
5e-02
5e-01
5e+00
E [GeV] (at L = 295 km)
0.1
0.5
1.0
5.0
10.0
50.0
100.0
500.0
E [GeV] (at L = 6400 km)



Osc prob
0.0
0.2
0.4
0.6
0.8
1.0
$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_e$
Atmospheric
5e-02
5e-01
5e+00
5e+01
E [GeV] / L [1000 km]
5e-03
5e-02
5e-01
5e+00
E [GeV] (at L = 295 km)
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0.5
1.0
5.0
10.0
50.0
100.0
500.0
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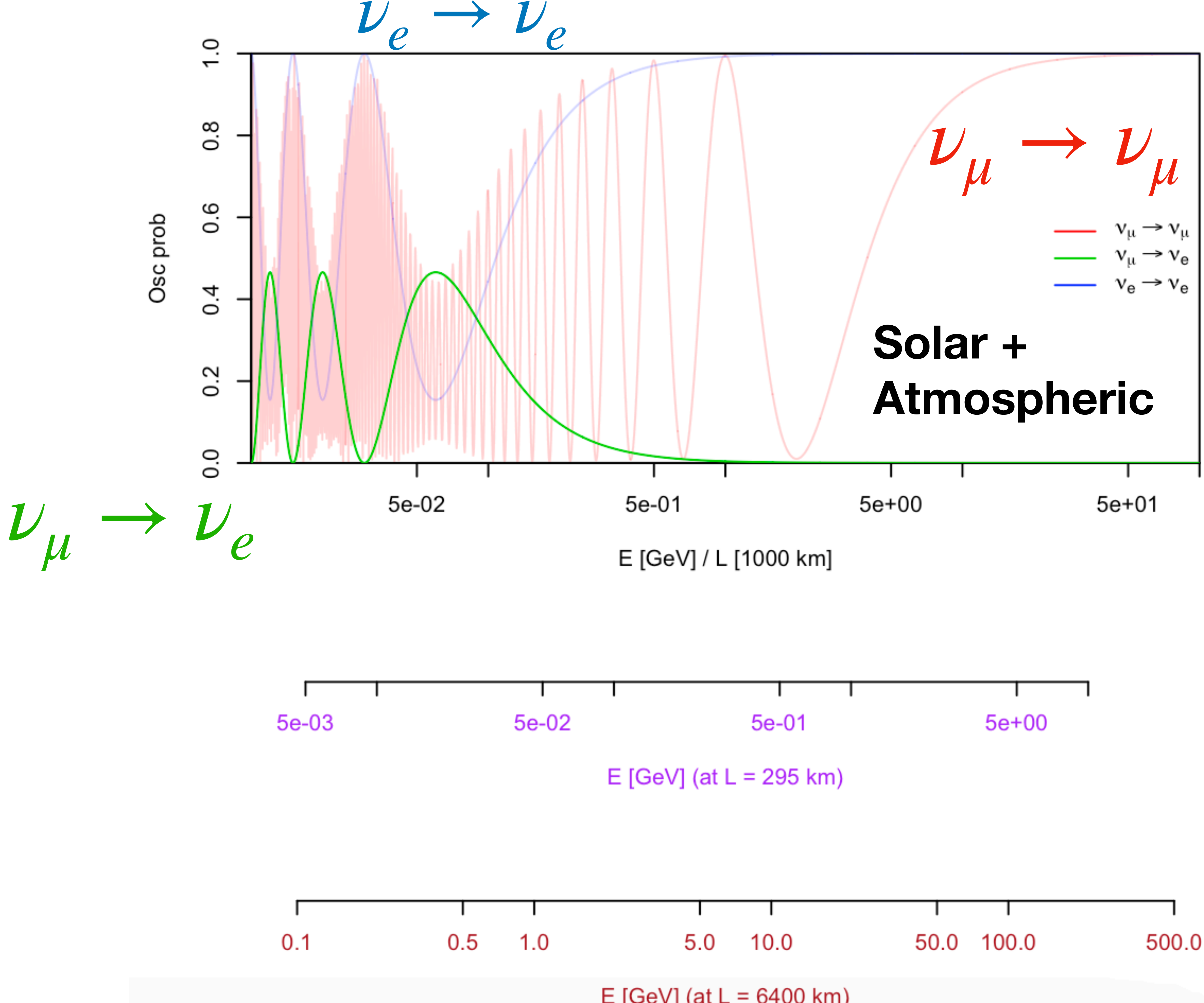
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$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_e$
Solar +
Atmospheric
5e-02
5e-01
5e+00
5e+01
E [GeV] / L [1000 km]
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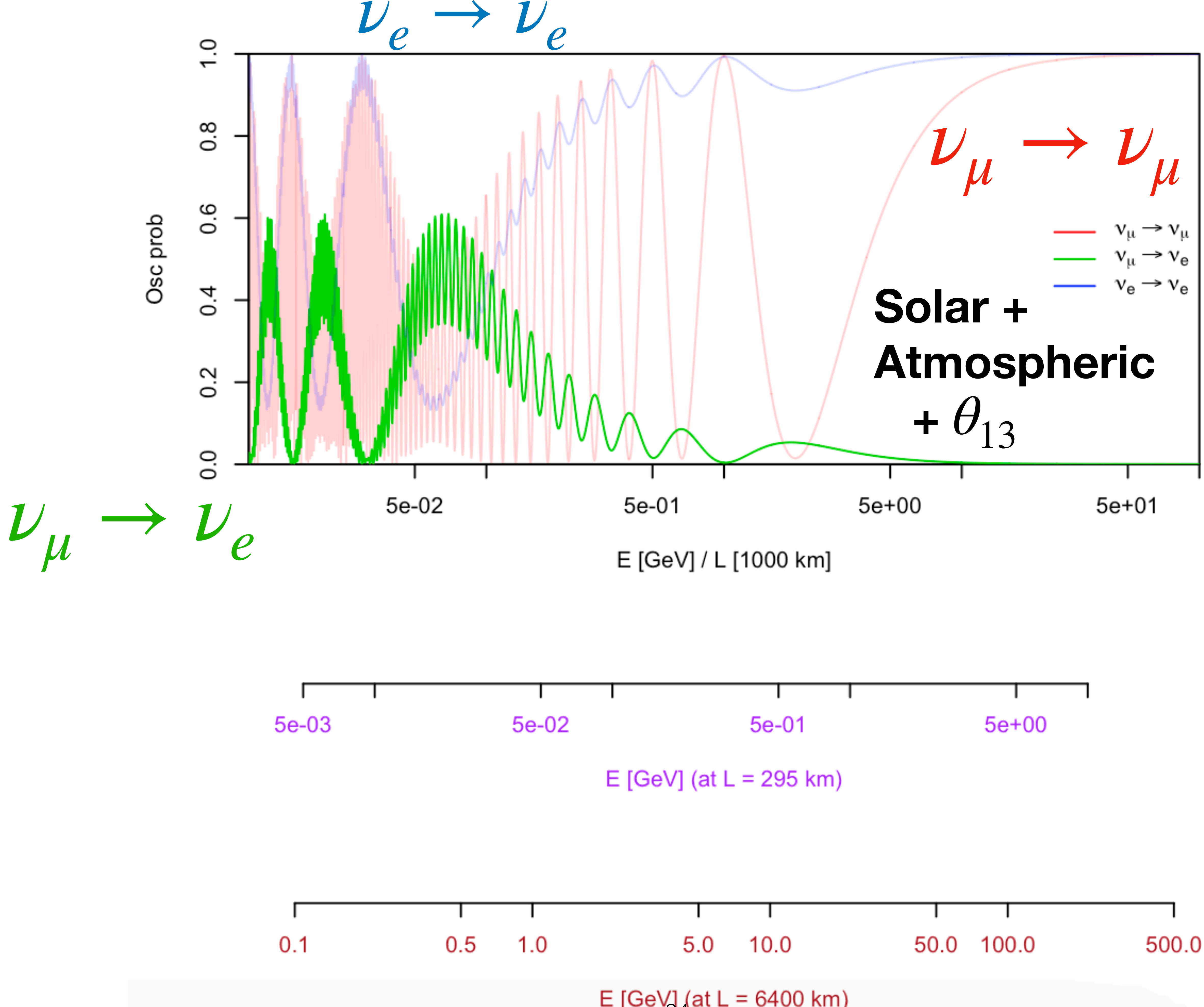

$\nu_e \rightarrow \nu_e$
$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_e$
Osc prob
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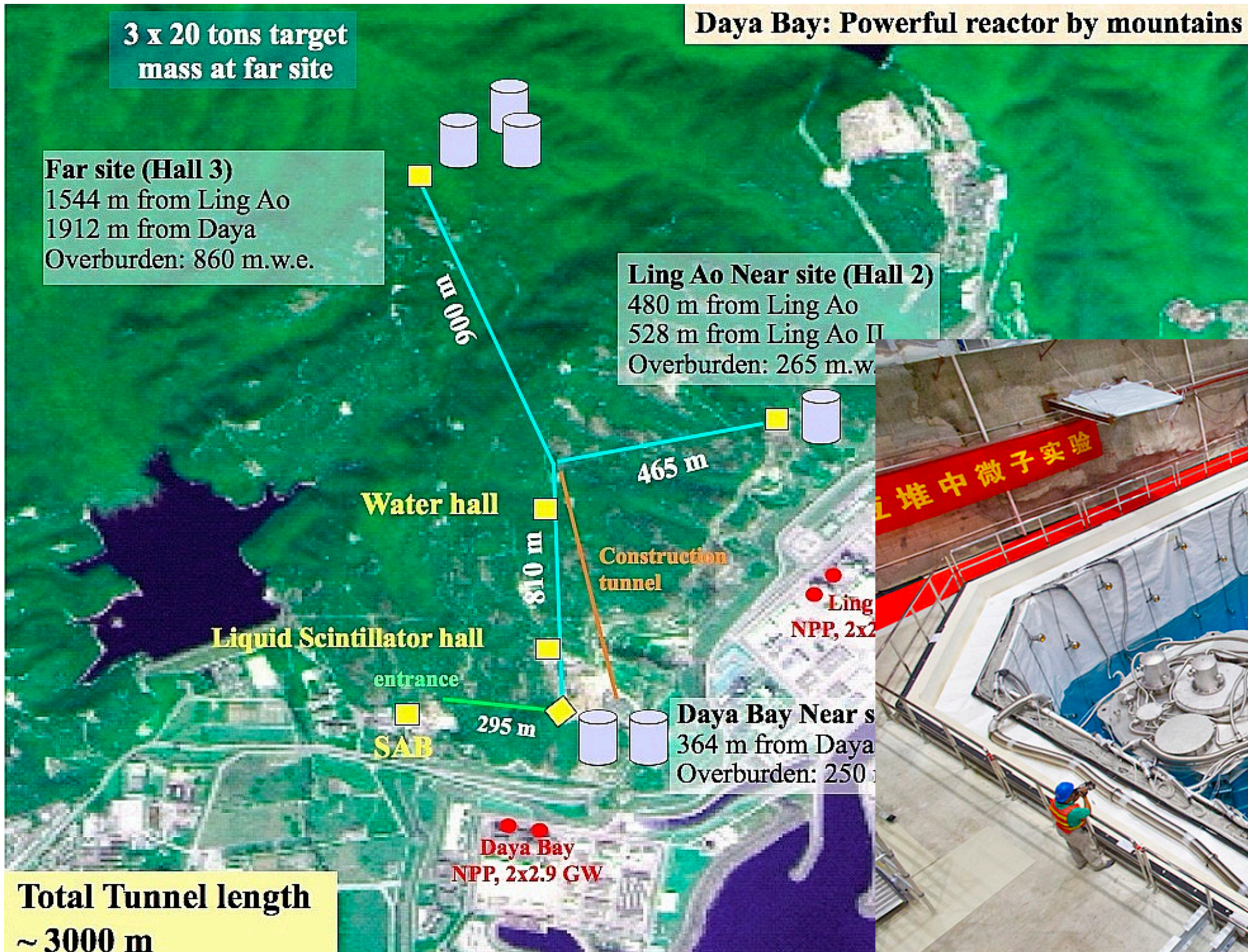
1.0
5e-02
5e-01
5e+00
5e+01
E [GeV] / L [1000 km]
$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_e$
$\nu_e \rightarrow \nu_e$
Solar +
Atmospheric
+ θ_{13}
5e-03
5e-02
5e-01
5e+00
E [GeV] (at L = 295 km)
0.1
0.5
1.0
5.0
10.0
50.0
100.0
500.0
E [GeV] (at L = 6400 km)

Reactor neutrinos



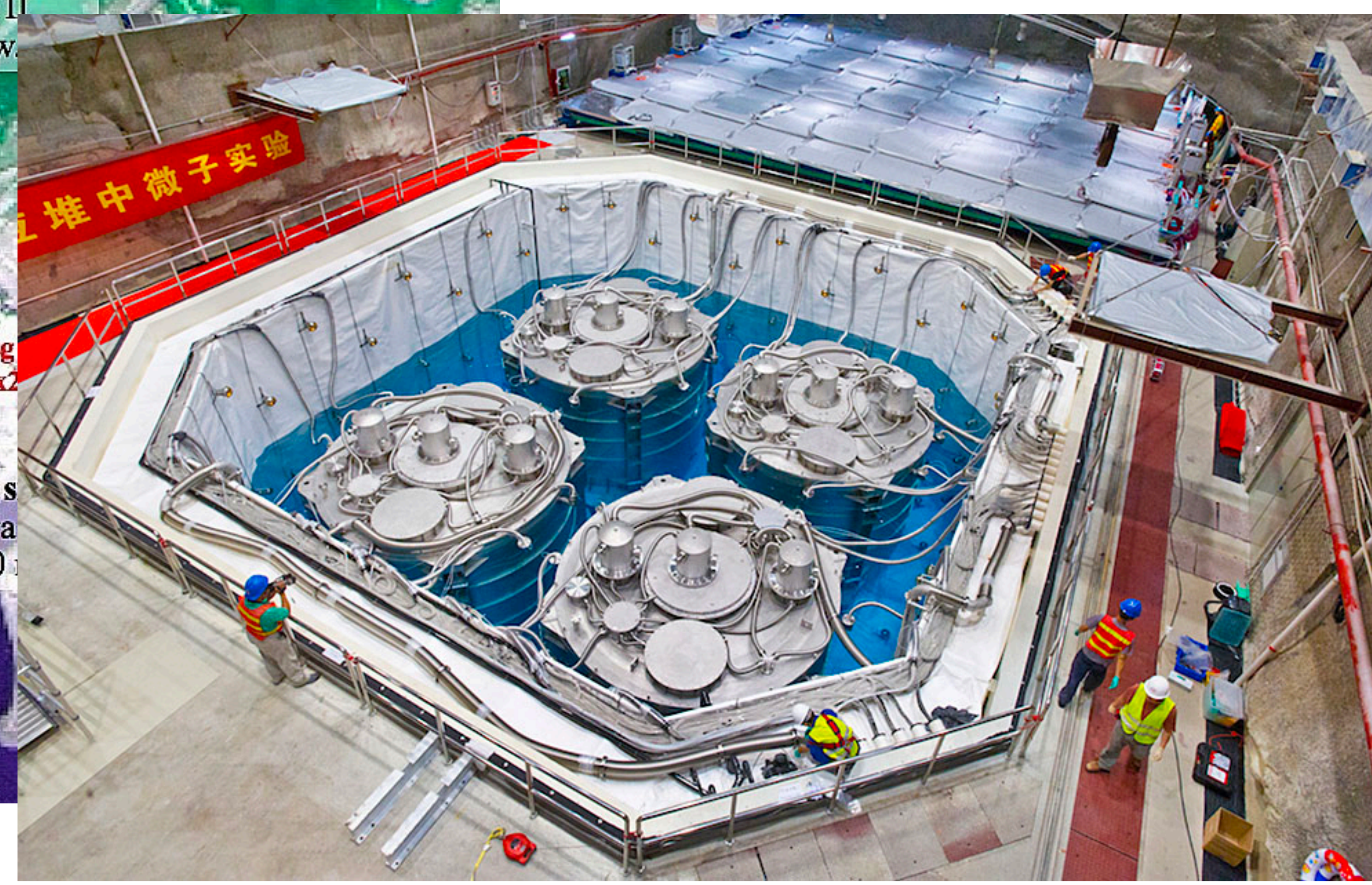


Photo: Roy Kaltschmidt, Berkeley Lab

- Double Chooz, Daya Bay, …

$$L \approx \text{km}$$

Short baseline

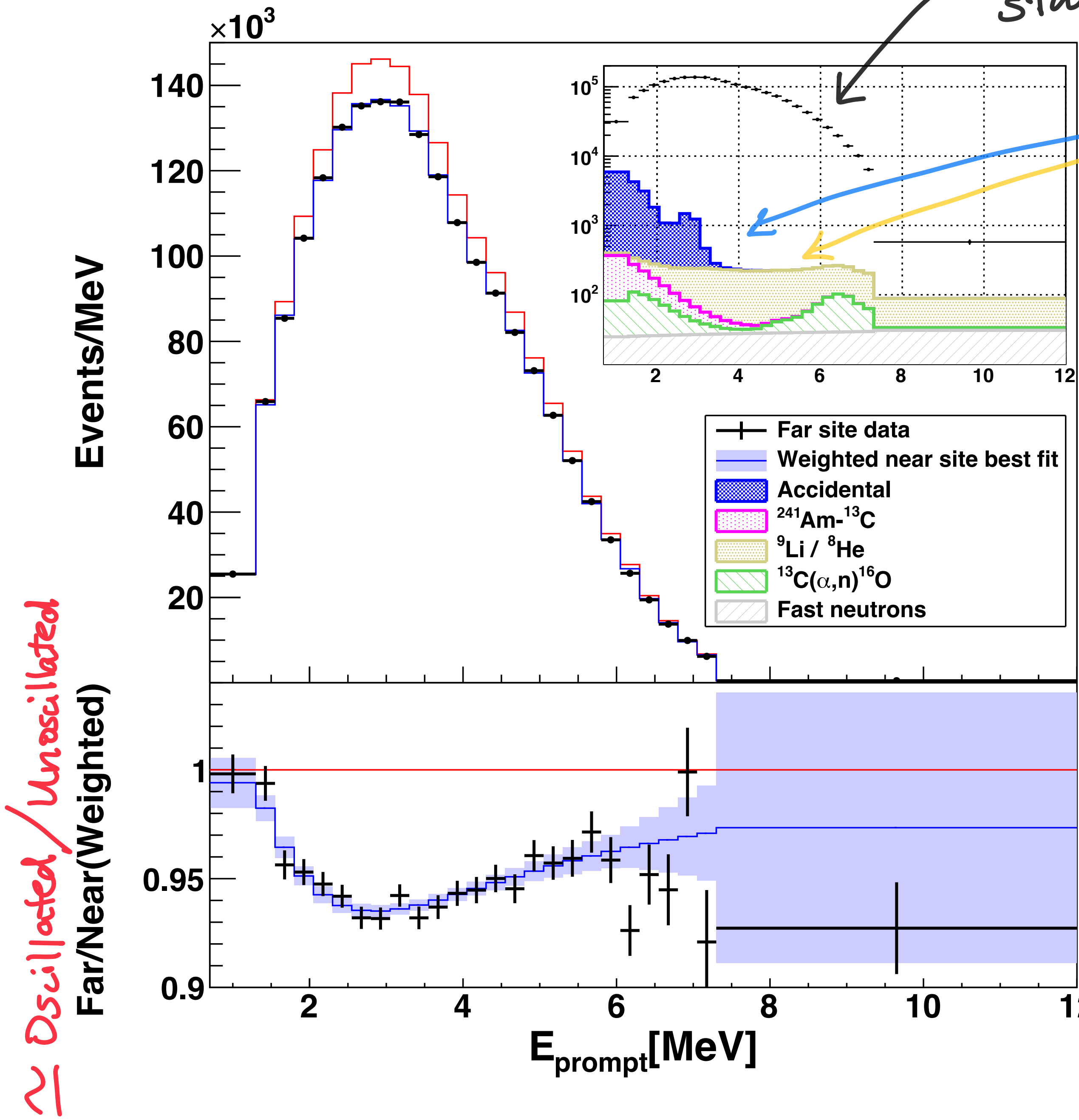
Reactor neutrinos

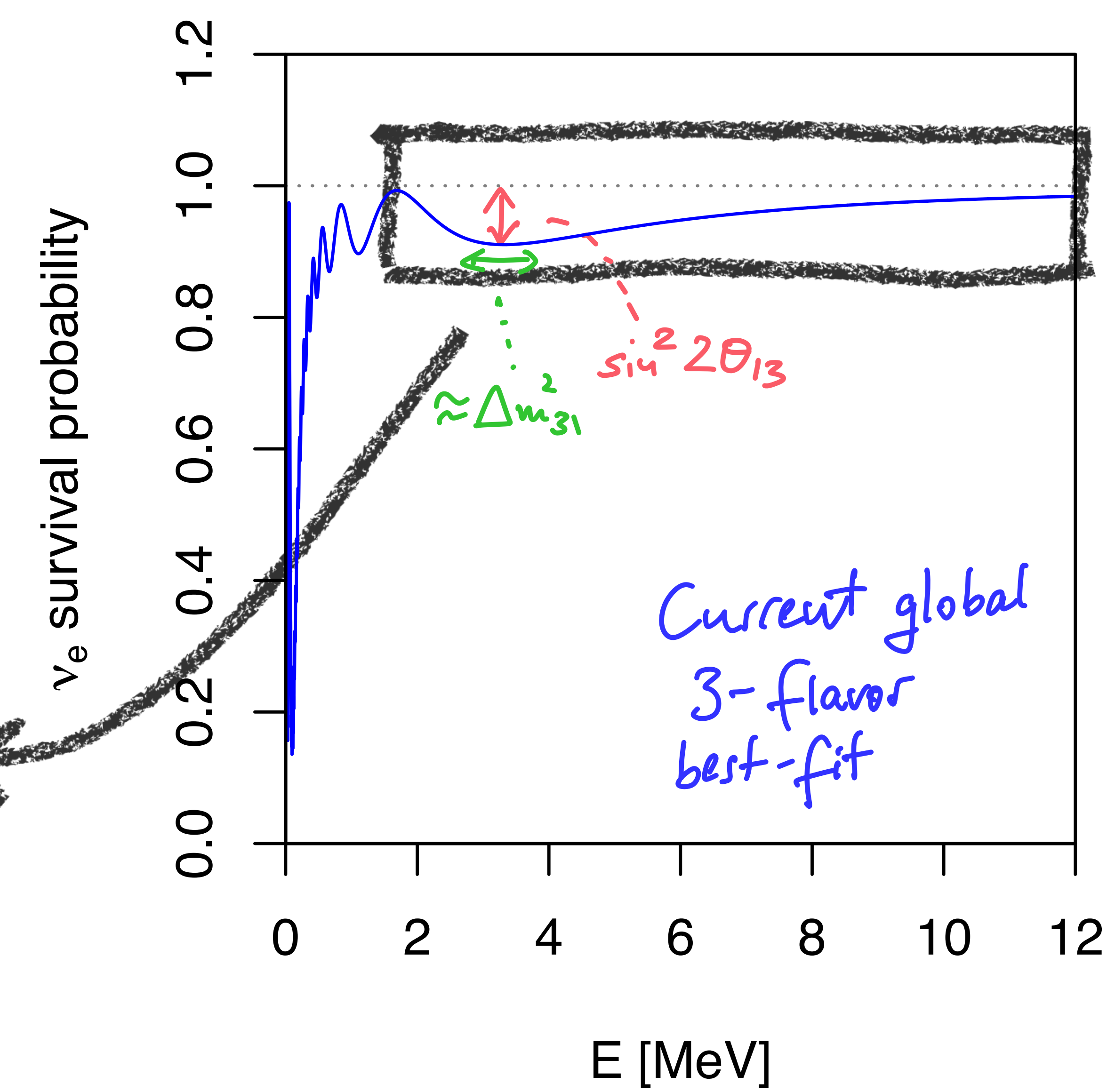
- Double Chooz, Daya Bay, …

high statistics

small backgrounds

$L \approx \text{km}$

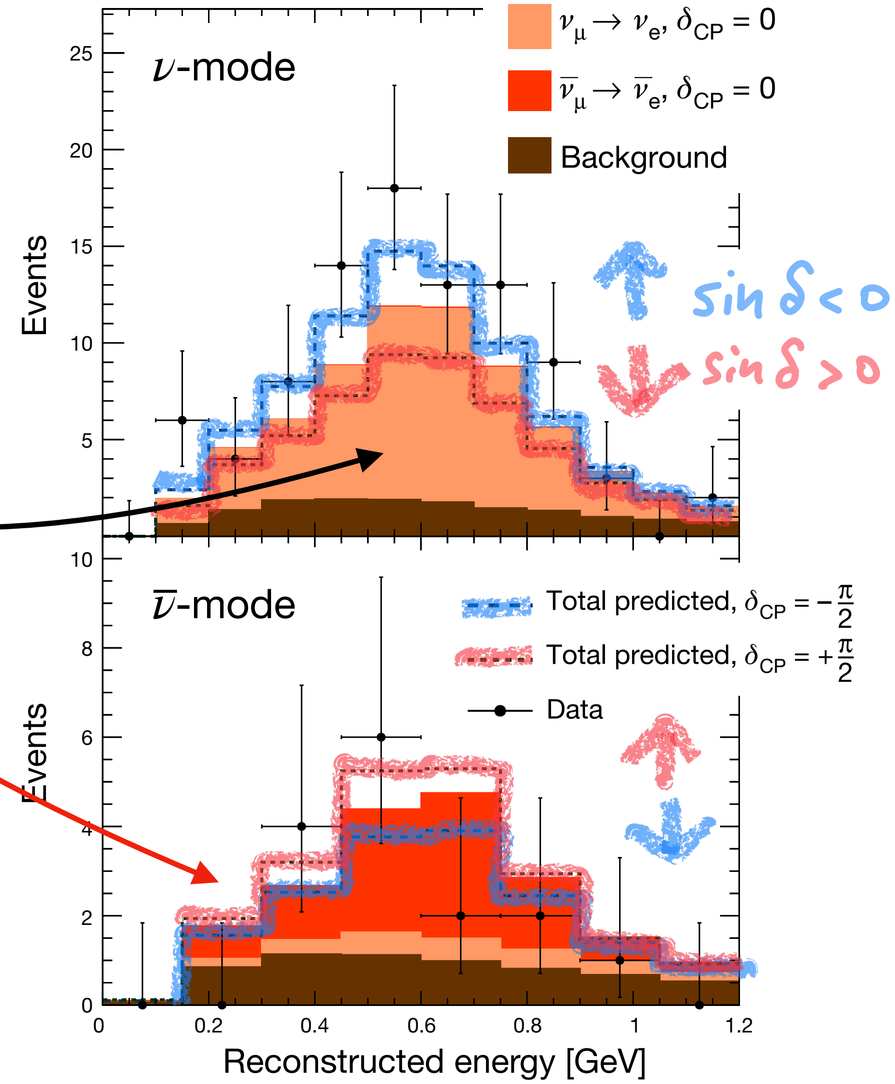




Left plot from PDG review
Hand-written notes and right plot are mine

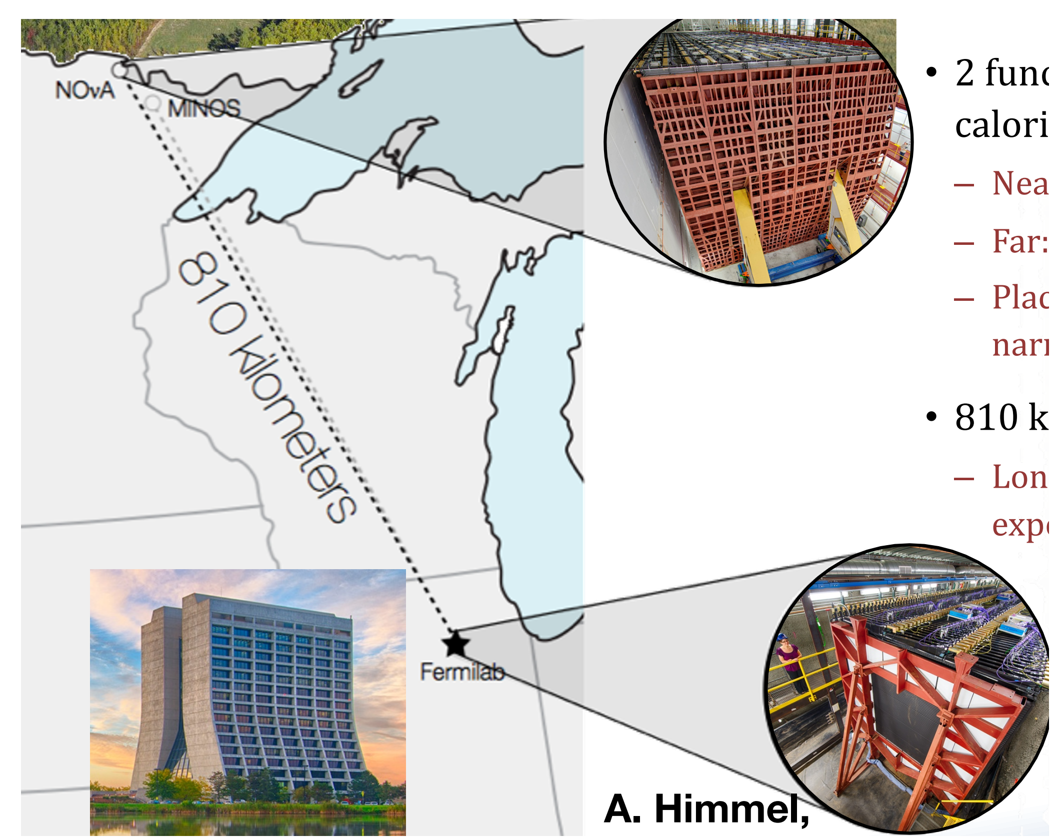
Accelerator neutrinos

$\nu_\mu \rightarrow \nu_e$



K2K→T2K

MINOS→NOvA



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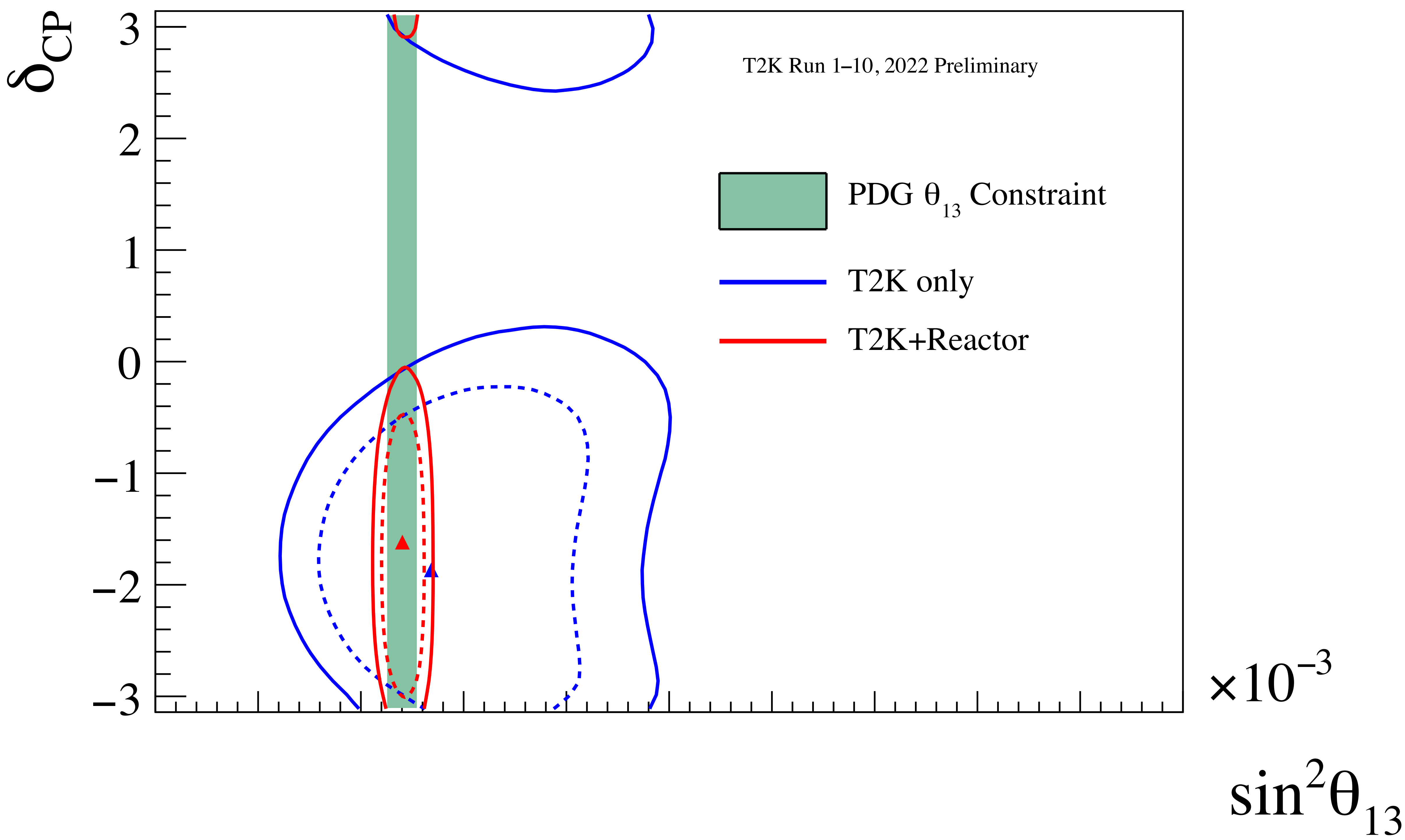
- Tunnel is short = most μ do not decay in flight, so very little ν_e
- "Appearance" of $\nu_\mu \rightarrow \nu_e$
- "Horns" (toroidal electromagnets) used to select ν_μ or $\overline{\nu}_\mu$



δ_{CP}
3
2
1
0
−1
−2
−3
T2K Run 1–10, 2022 Preliminary
PDG θ_{13} Constraint
T2K only
T2K+Reactor
$\times 10^{-3}$
$\sin^2\theta_{13}$

ν-oscillation

(interaction) (propagation)

For neutrinos flavor basis ≠ Hamiltonian basis.

→ Flavor ($\nu_e \mid \nu_\mu \mid \nu_\tau$) oscillates over $L \times \Delta m^2 / E$, amplitude controlled by (PMNS) **mixing matrix** U:

$$
U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}
$$

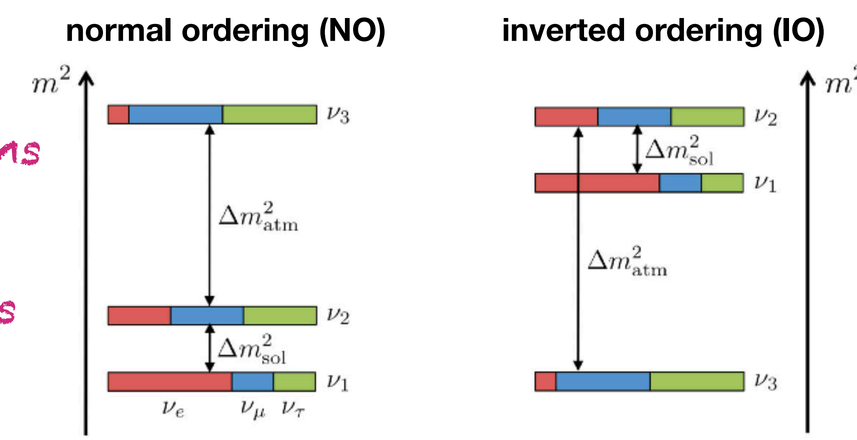
$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Open questions:

- value of δ_{CP} → if $\sin\delta_{\mathrm{CP}} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)
- is θ_{23} maximal? octant? (i.e. $\theta_{23} < \frac{\pi}{4}$ or $\theta_{23} > \frac{\pi}{4}$)

important params for cosmology (leptogenesis...) and 0ν2β searches

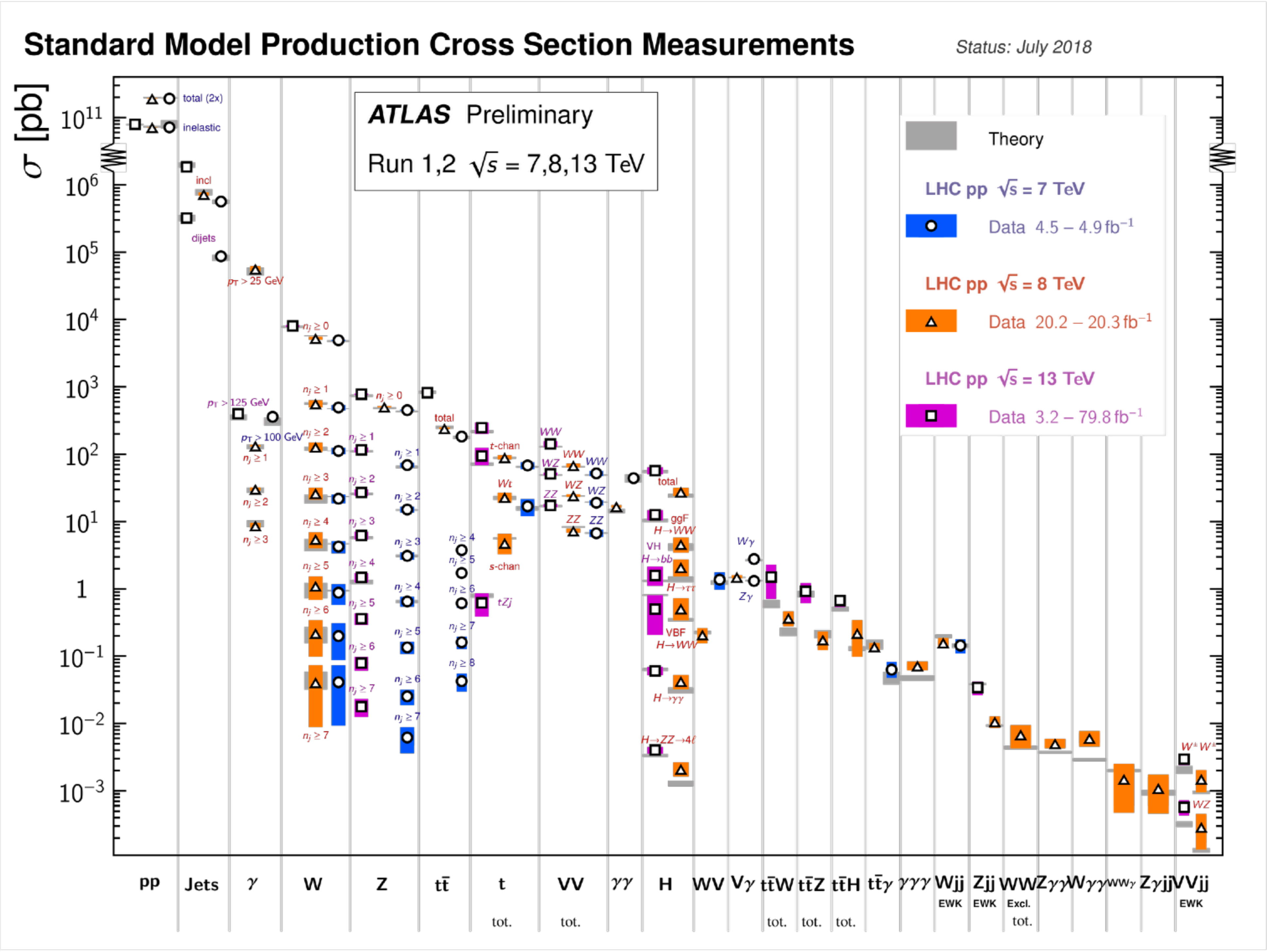
flavor symmetries?



Credit: JUNO Collaboration / JGU-Mainz

The Standard Model

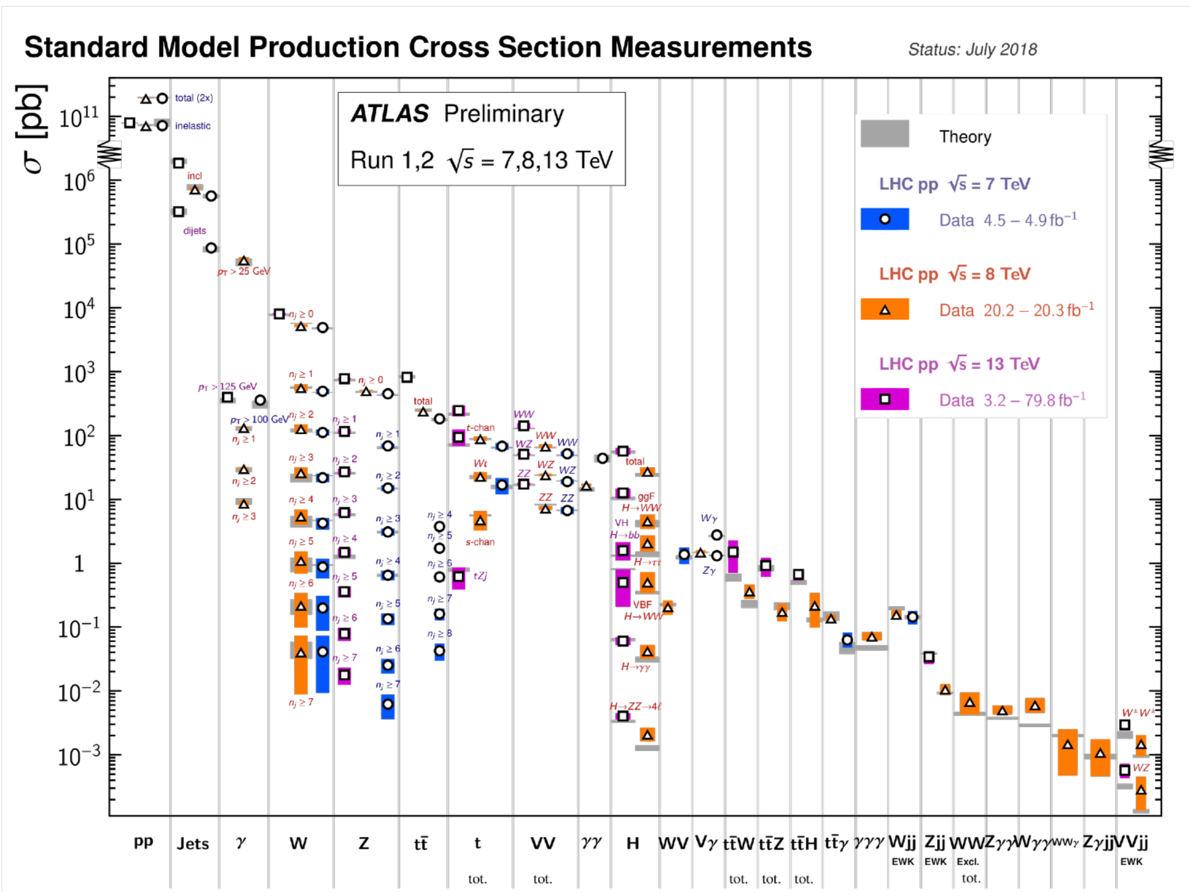
Its success…



http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

The Standard Model

Its success…



http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/

and problems

- Observation:
  - No Graviton string theory?
  - Baryon/anti-baryon asymmetry of universe SUSY, GUT, leptogenesis?
  - Dark matter SUSY WIMP, axion?
  - Dark energy
- Anomalies:
  - Muon g–2 (anomalous magnetic moment)
  - Flavor anomalies (B meson decays, …)
- Theoretical:
  - SUSY? Technicolor? Smallness of Higgs mass (hierarchy problem)
  - Small neutrino masses see-saw?
  - Charge assignment, many parameters, … GUT? Flavor-symmetries?
  - Strong CP problem axion?

Q.1

Image credit: X-ray: NASA/CXC/PSU/L. Townsley et al;
Optical: UKIRT; Infrared: NASA/JPL-Caltech

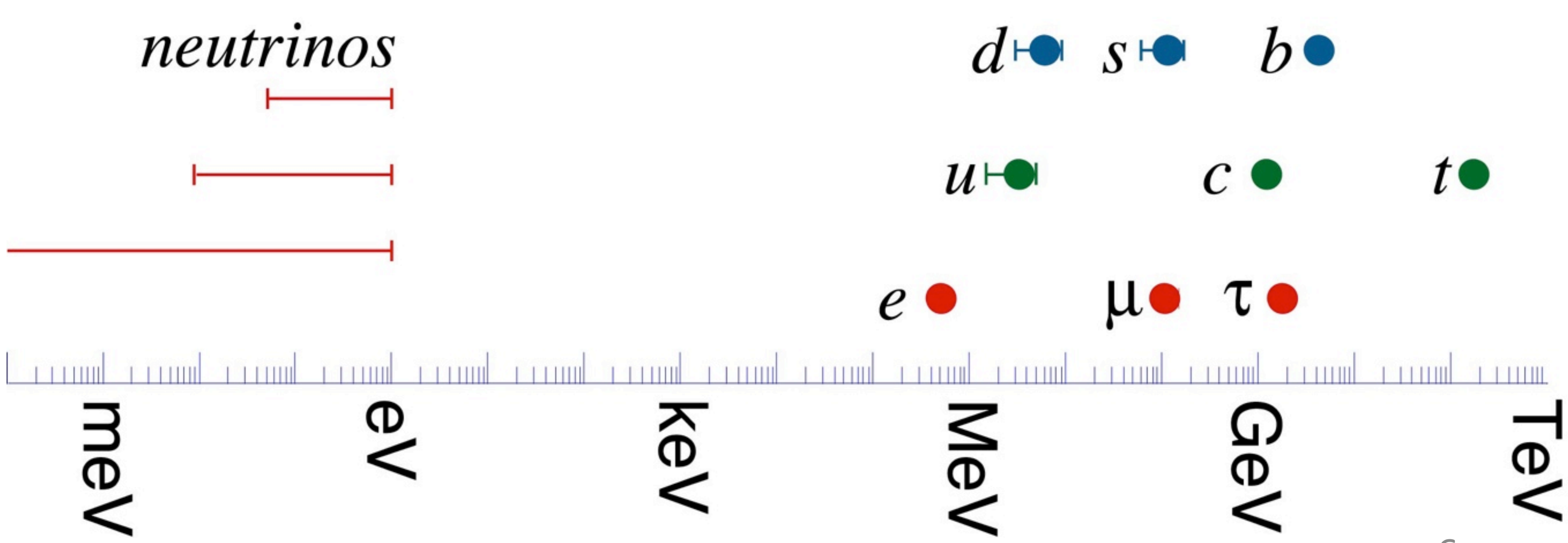
Standard model univ.

Expect 10^{-10} x less matter

Q.2

Extremely small neutrino masses

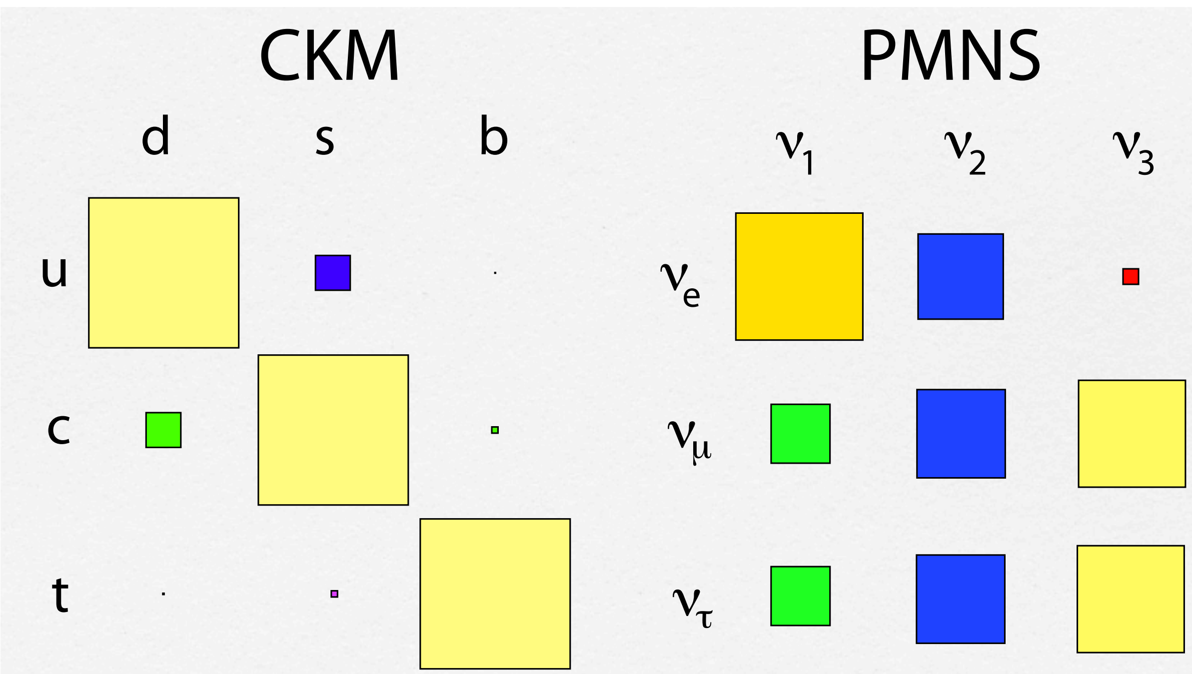
SM: exactly 0

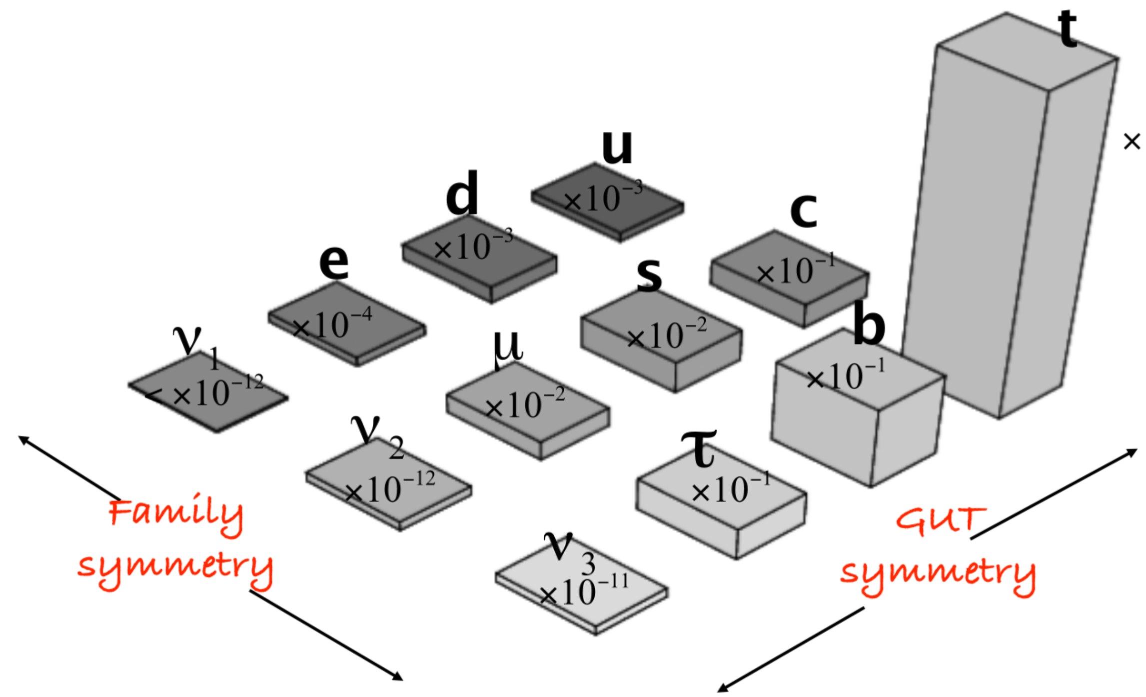


Flavor symmetries?

In SM, the three generations of fermions are exact copies in terms of gauge interactions, and only differ in the Yukawa couplings with Higgs. Or is there more going on? (c.f. flavor anomalies)

quark mixing ↓ **lepton mixing** ↓





Attempts are made to introduce discrete or continuous symmetry structures into the three generations (and break them).

These introduce **relations** among/predictions of neutrino mixing parameters such as δ_{CP}, MO or the θ_{23} octant that can be tested by precise measurement of oscillation parameters.

Unification of leptons and quarks
→ CKM and PMNS matrix are related, and overall less free parameters

c.f. in past many theories predicted a small solar mixing angle θ_{12} and were falsified.

Both figures by S. King.
doi:10.1088/1742-6596/631/1/012005

ν-oscillation

(interaction) (propagation)

For neutrinos flavor basis ≠ Hamiltonian basis.

→ Flavor ($\nu_e \mid \nu_\mu \mid \nu_\tau$) oscillates over $L \times \Delta m^2 / E$, amplitude controlled by (PMNS) **mixing matrix** U:

$$
U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}
$$

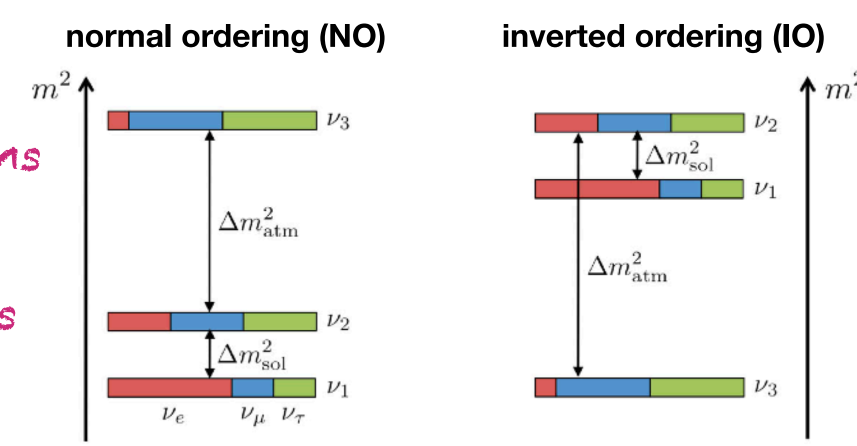
$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

Open questions:

- value of δ_{CP} → if $\sin\delta_{\text{CP}} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)
- is θ_{23} maximal? octant? (i.e. $\theta_{23} < \frac{\pi}{4}$ or $\theta_{23} > \frac{\pi}{4}$)

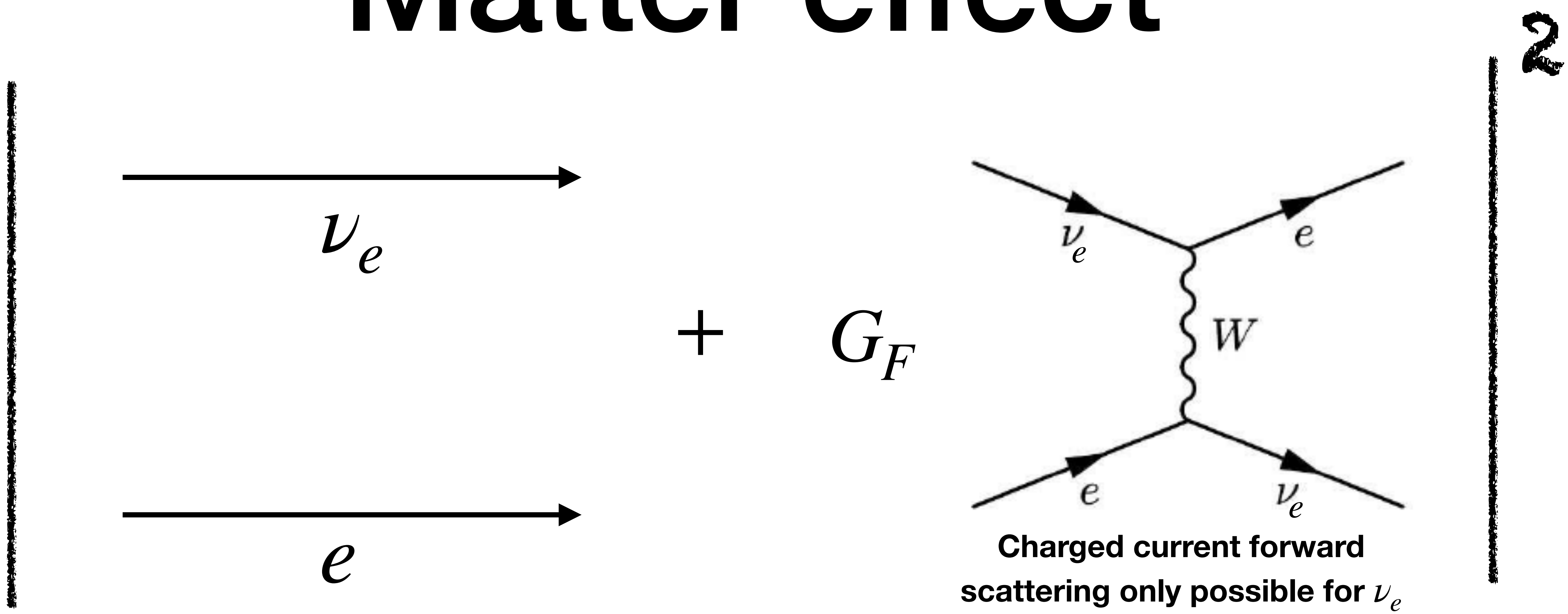
important params for cosmology (leptogenesis...) and 0ν2β searches

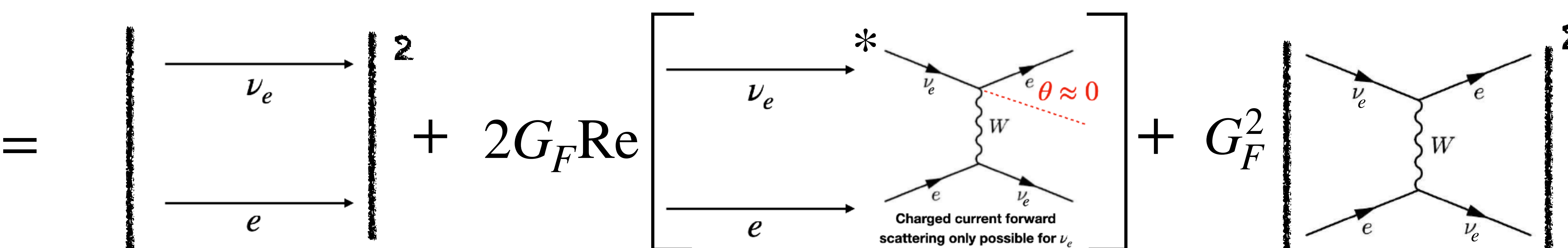
flavor symmetries?



Credit: JUNO Collaboration / JGU-Mainz

Matter effect





Only for $\theta = 0$

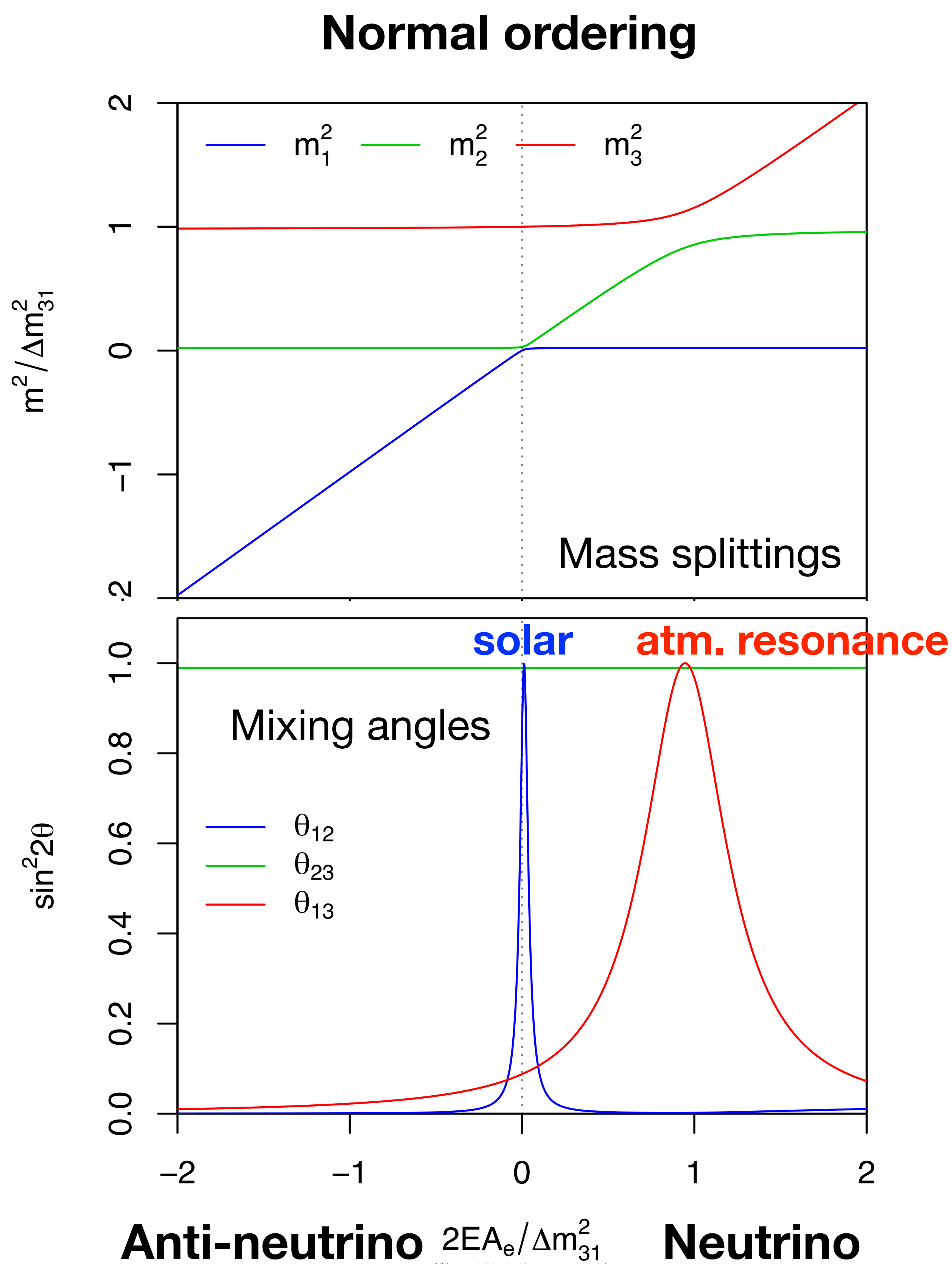
Very small

Matter effect

- Presence of e^- picks out ν_e and acts as effective potential term in Hamiltonian that flips sign for anti-neutrinos

$$H_{\mathrm{matter}}(t) = \underbrace{\frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger}_{\text{Vacuum Hamitonian}} + \underbrace{\begin{pmatrix} A_e(t) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}}_{\text{Matter potential}}$$

Matter effect



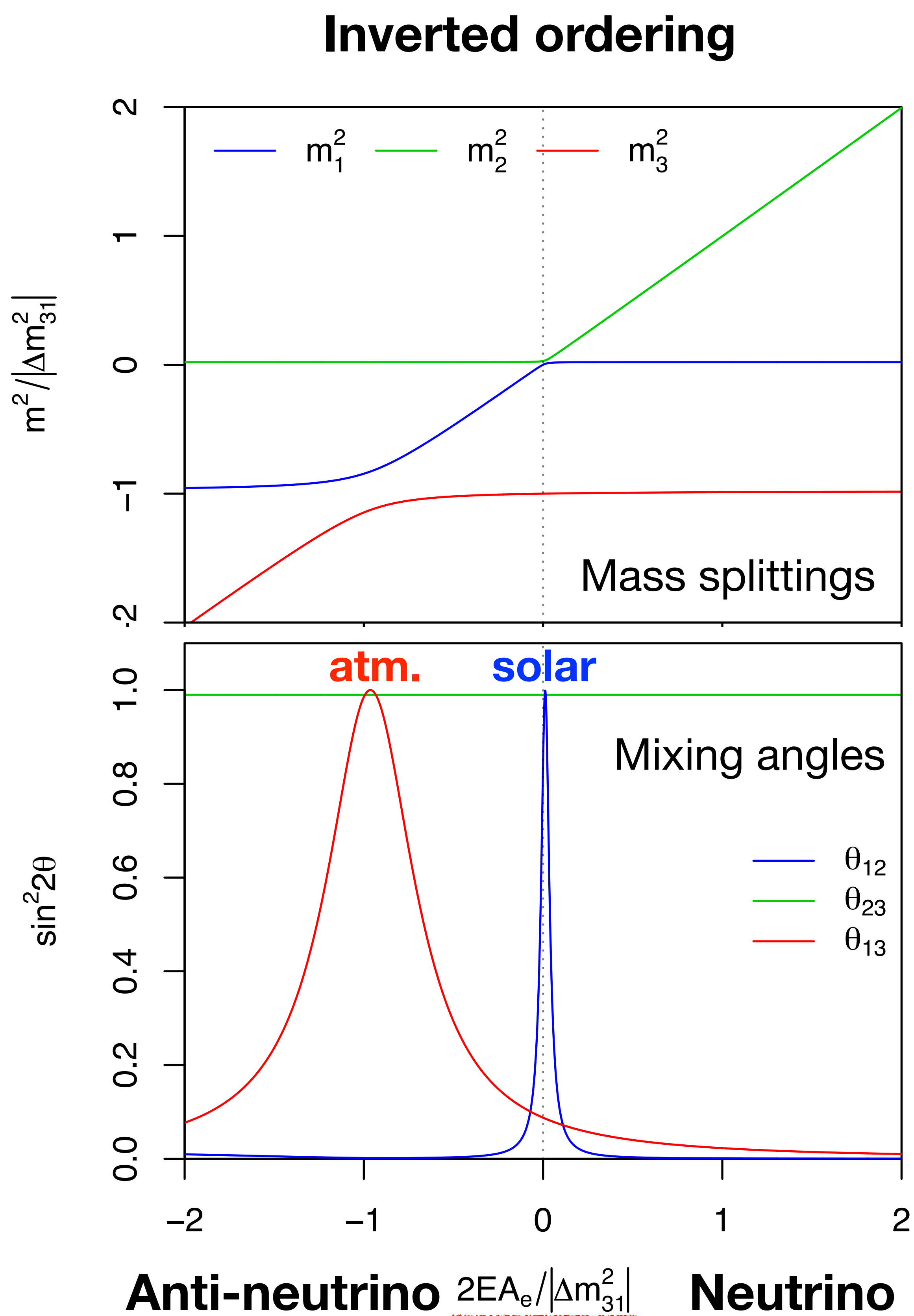
≈ Energy × Density

- Matter effect changes effective mass splittings Δm^2_m and mixing angles θ_m over long distances (e.g. Earth).

- At **resonance**, dramatic consequence — effective mixing $\sin^2 2\theta_m$ in matter can become maximal $= 1$ for *any* vacuum-value of $\sin^2 2\theta > 0$.

- Resonance only appears for neutrinos or anti-neutrinos depending on the sign of Δm^2 → **mass ordering sensitivity**.

$$\sin^2 2\theta_m = \left(\frac{\Delta m^2}{\Delta m^2_m}\right)^2 \sin^2 2\theta = \frac{\left(\sin 2\theta\right)^2}{(\sin 2\theta)^2 + \left(\cos 2\theta - \frac{2EA_e}{\Delta m^2}\right)^2}$$



≈ Energy × Density

Matter effect

- Matter effect changes effective mass splittings Δm_m^2 and mixing angles θ_m over long distances (e.g. Earth).

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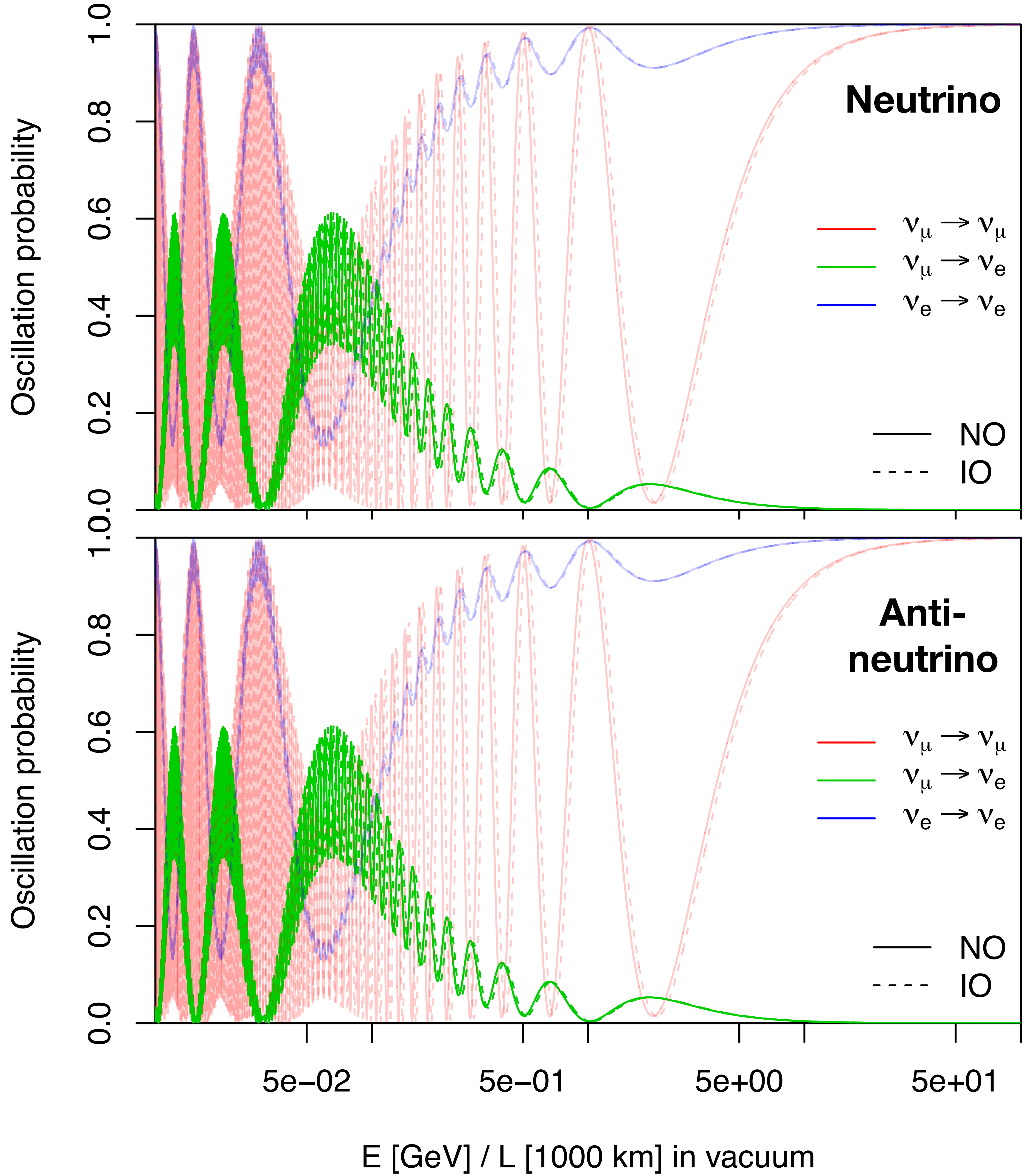
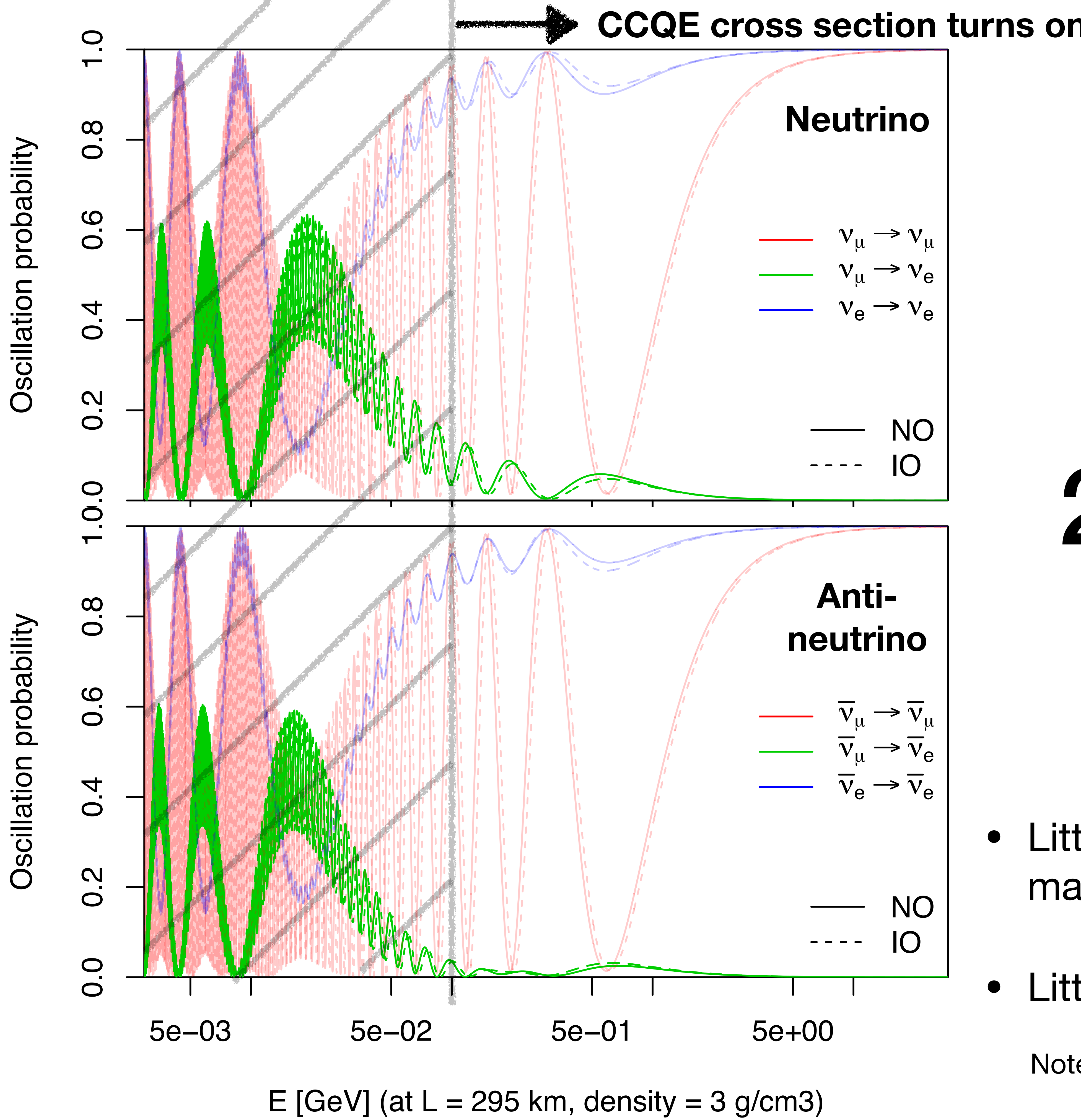

Neutrino
Anti-neutrino
$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_e$
$\nu_e \to \nu_e$
NO
IO
Oscillation probability
0.0
0.2
0.4
0.6
0.8
1.0
5e−02
5e−01
5e+00
5e+01
E [GeV] / L [1000 km] in vacuum

Vacuum

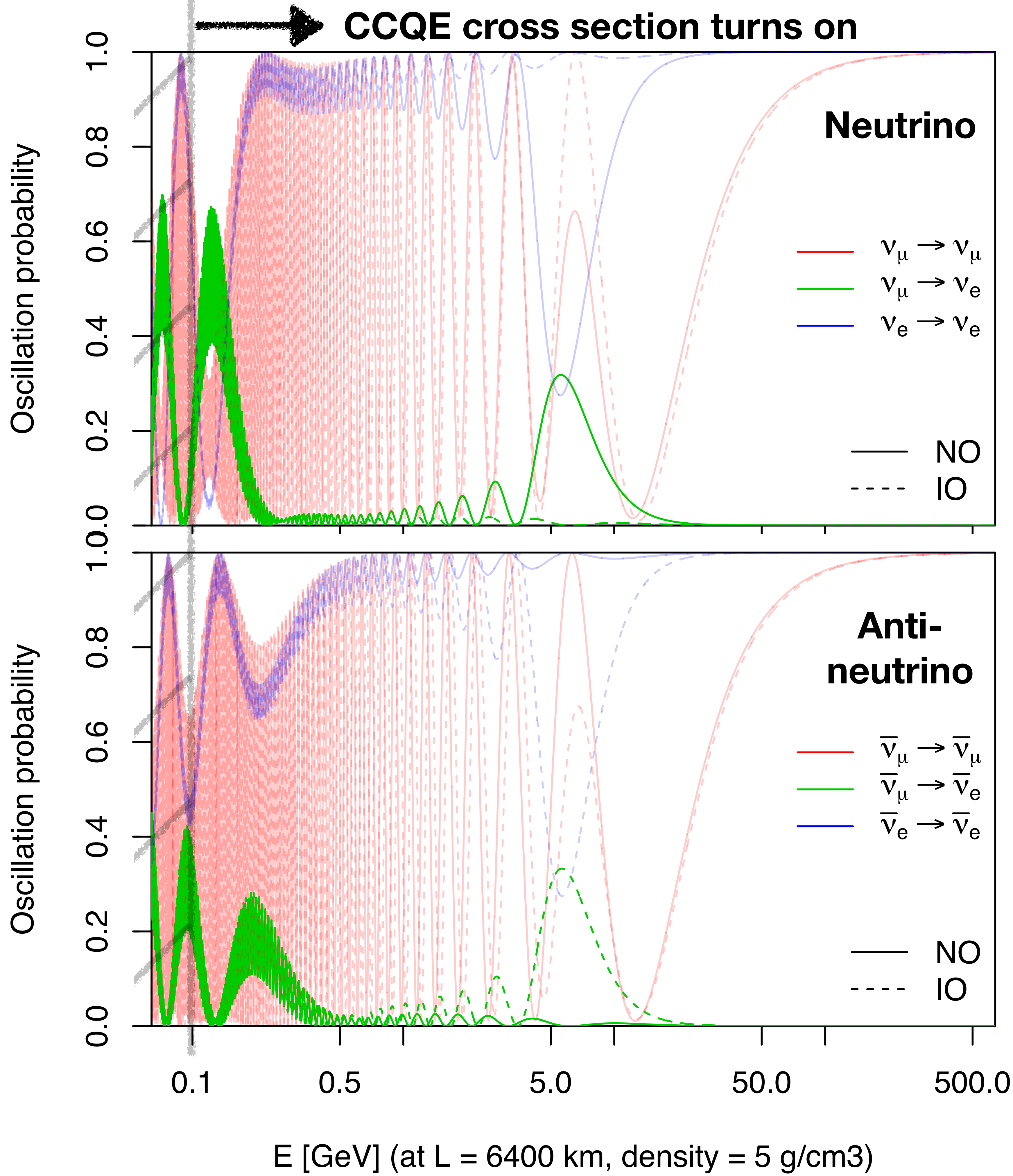


295 km

T2K

- Little impact from matter effect
- Little sensitivity to MO

Note: flux peak at 0.6 GeV

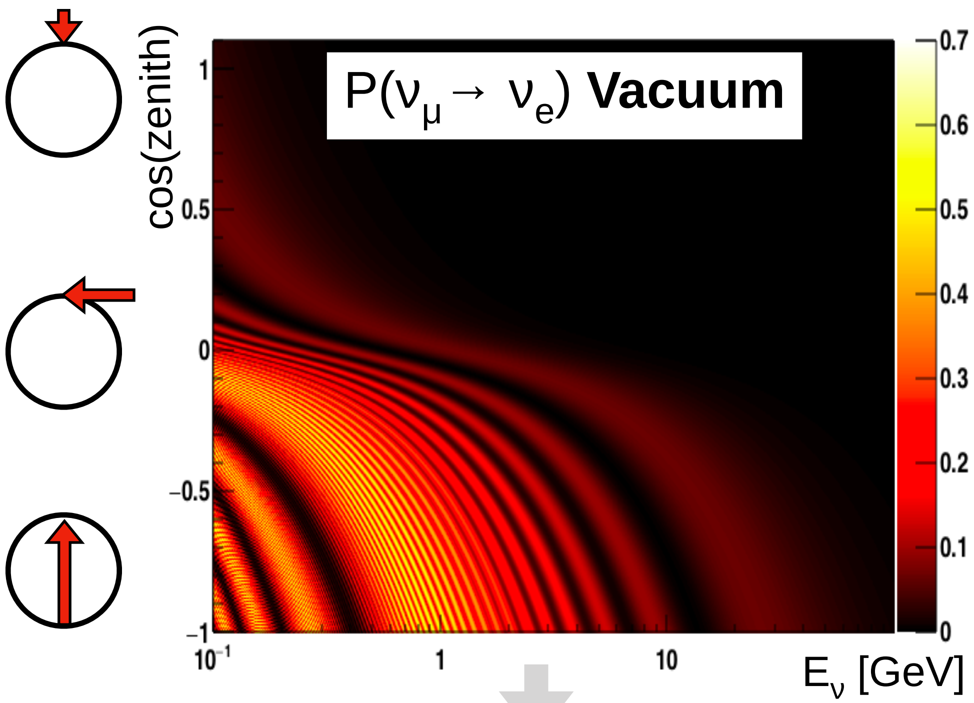


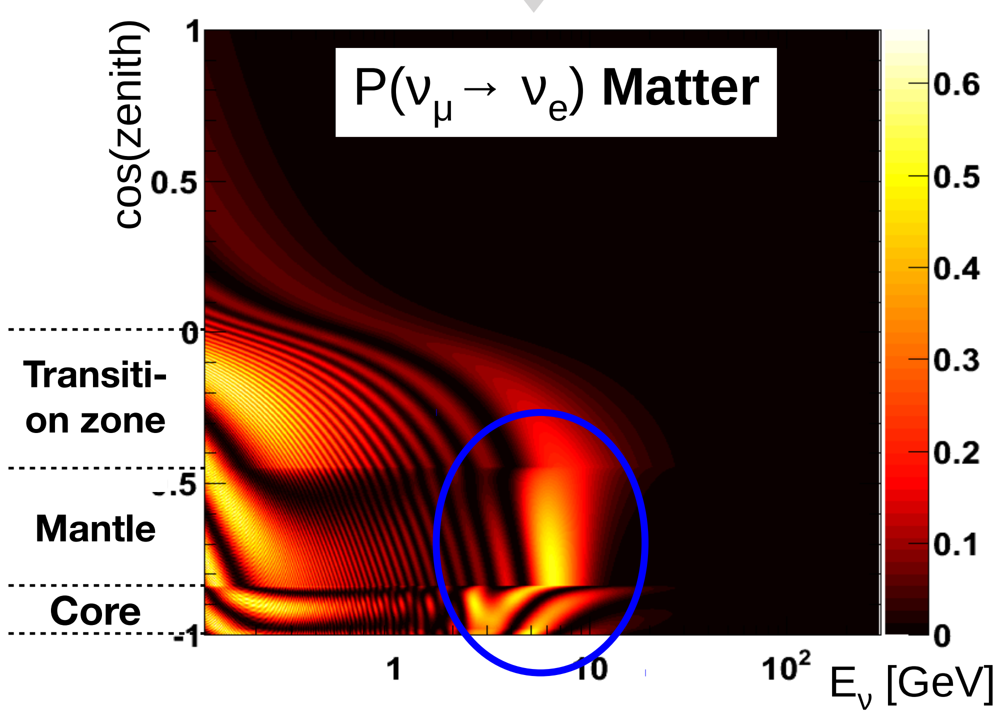
6400 km Earth

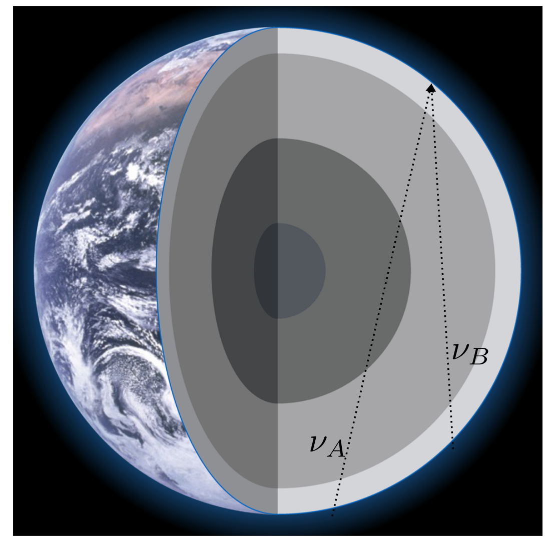
- Core/mantle resonance at few-GeV with sensitivity to MO via $\nu/\overline{\nu}$

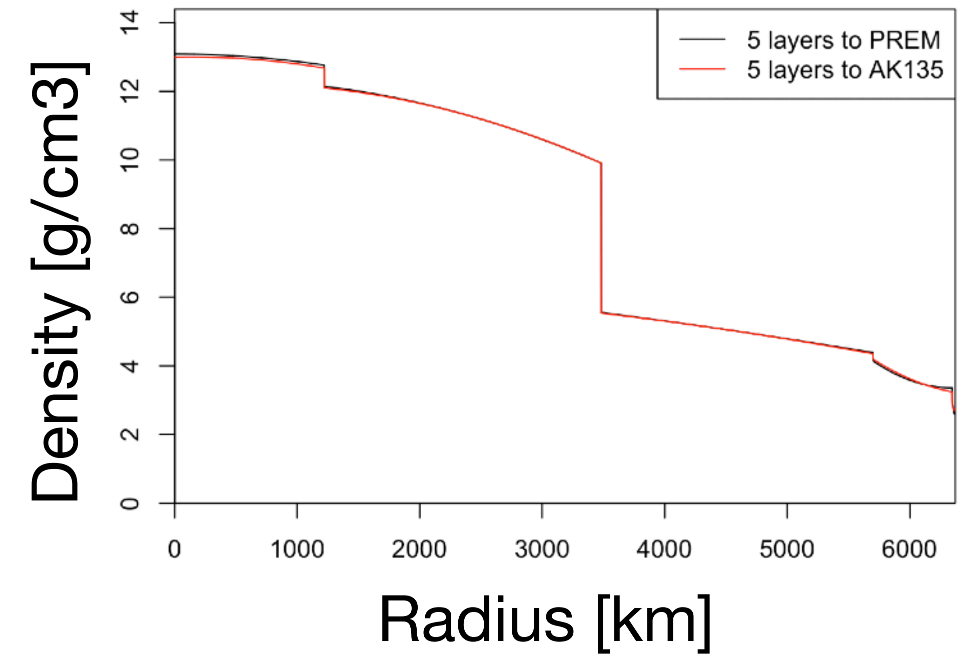
- "Solar" mixing is turned "off" above 0.5 GeV, and below creates $\nu/\overline{\nu}$ asymmetry via solar resonance

Matter effect in Earth









- Resonance in Earth mantle and core in few-GeV region
- Only for ν in normal, and $\bar{\nu}$ in inverted ordering
  → MO sensitivity
- Effect size depends on θ_{23} octant

Oscillograms from:
C. Bronner for SK collaboration, at ICTP Advanced Workshop on Physics of Atmospheric Neutrinos 2018

SuperK experiment

atmospheric neutrinos

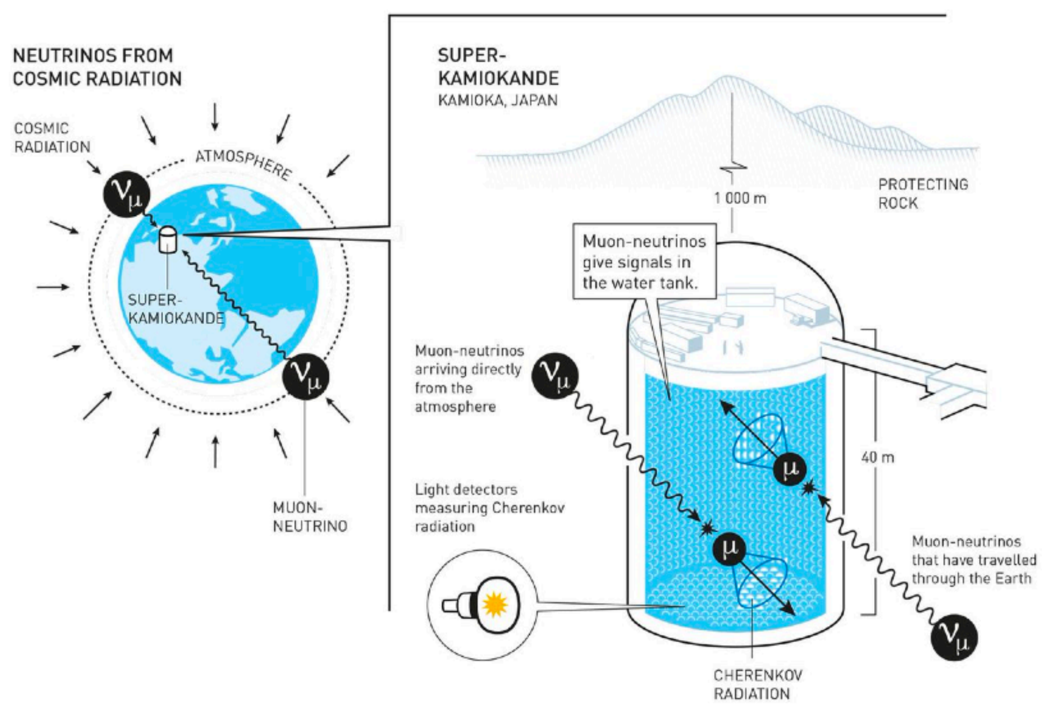
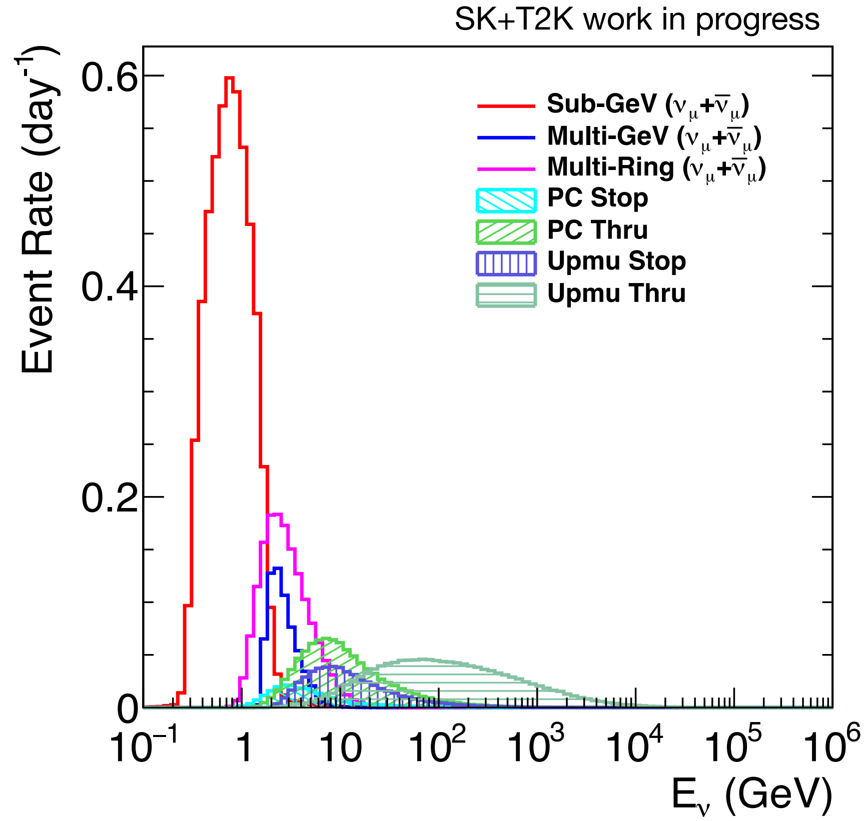
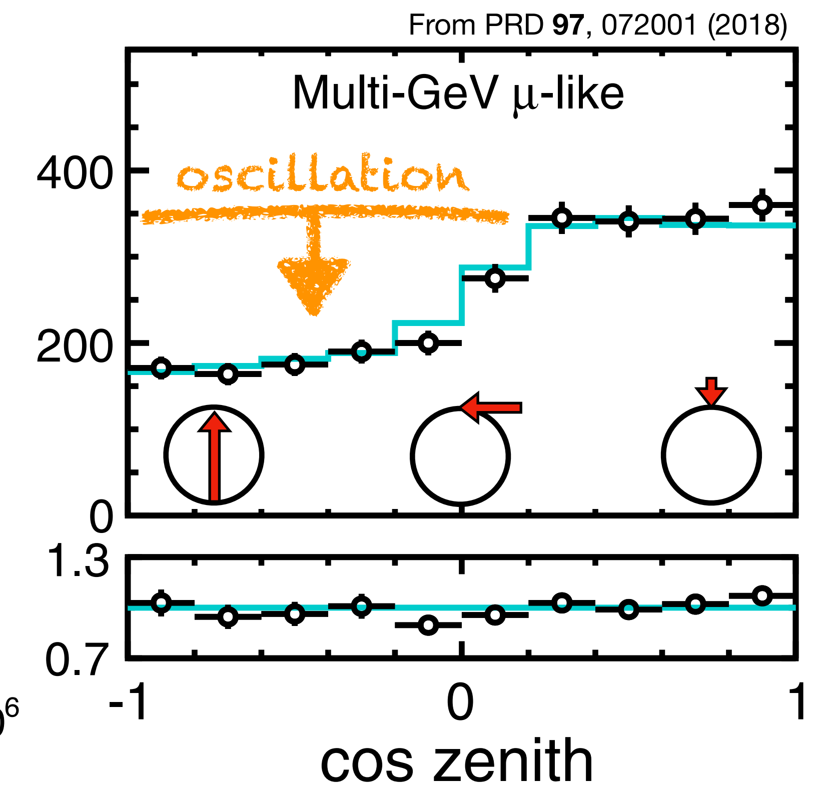


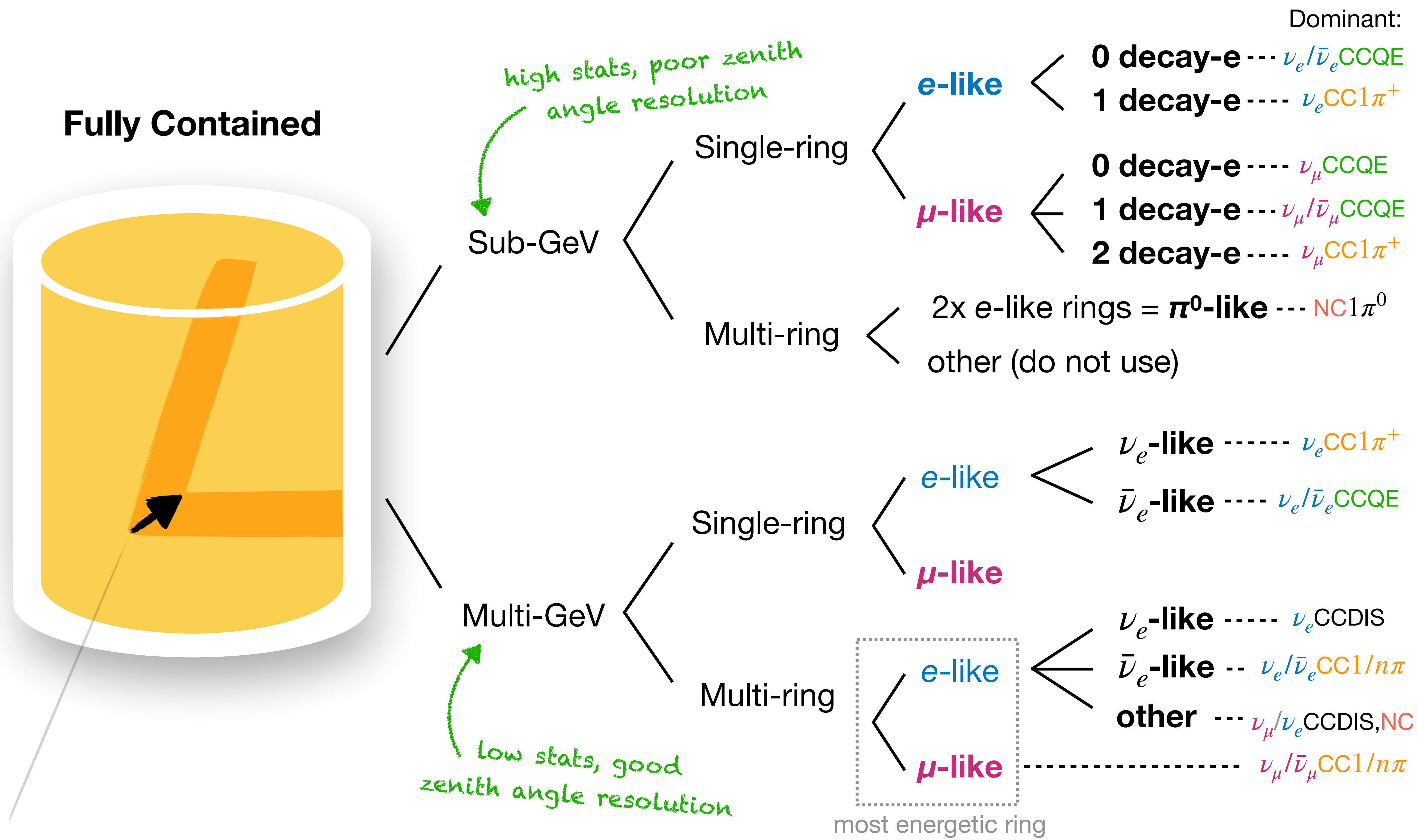
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences





- Neutrinos generated from primary cosmic rays in atmosphere: $p + X \to \pi^{\pm} + \cdots \to \mu^{+} + \overset{(-)}{\nu}_{\mu} + \cdots$
- Many $e/\mu/\pi^0$ samples over large energy range
- Zenith angle ~ propagation length L

SK sample separation



SK sample separation

Partially Contained

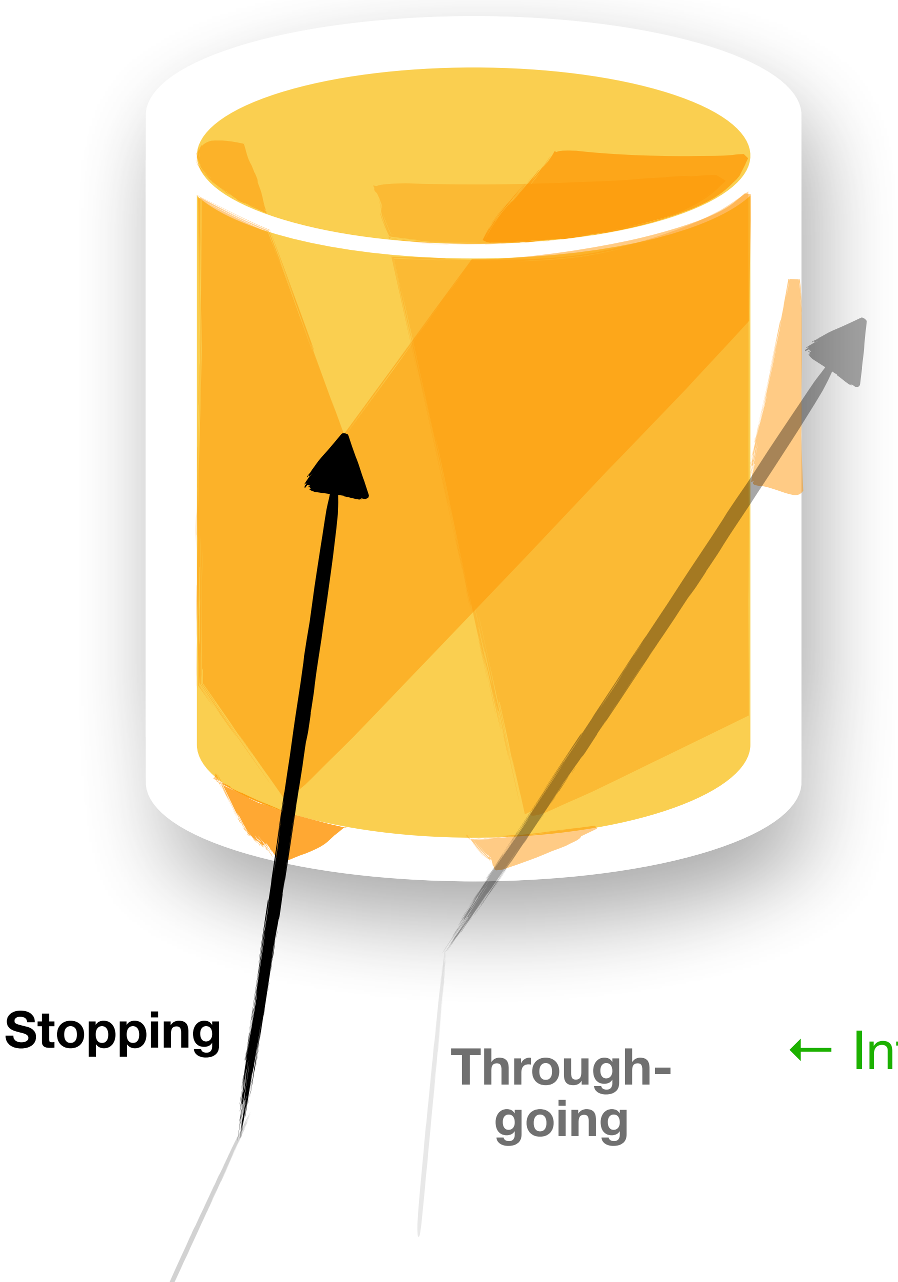
Very simple separation by
charge deposition in OD

Stopping (inside of OD) ------------- Less energetic

Through-going ----- More energetic

SK sample separation

Upward-going μ



peak at true E_ν

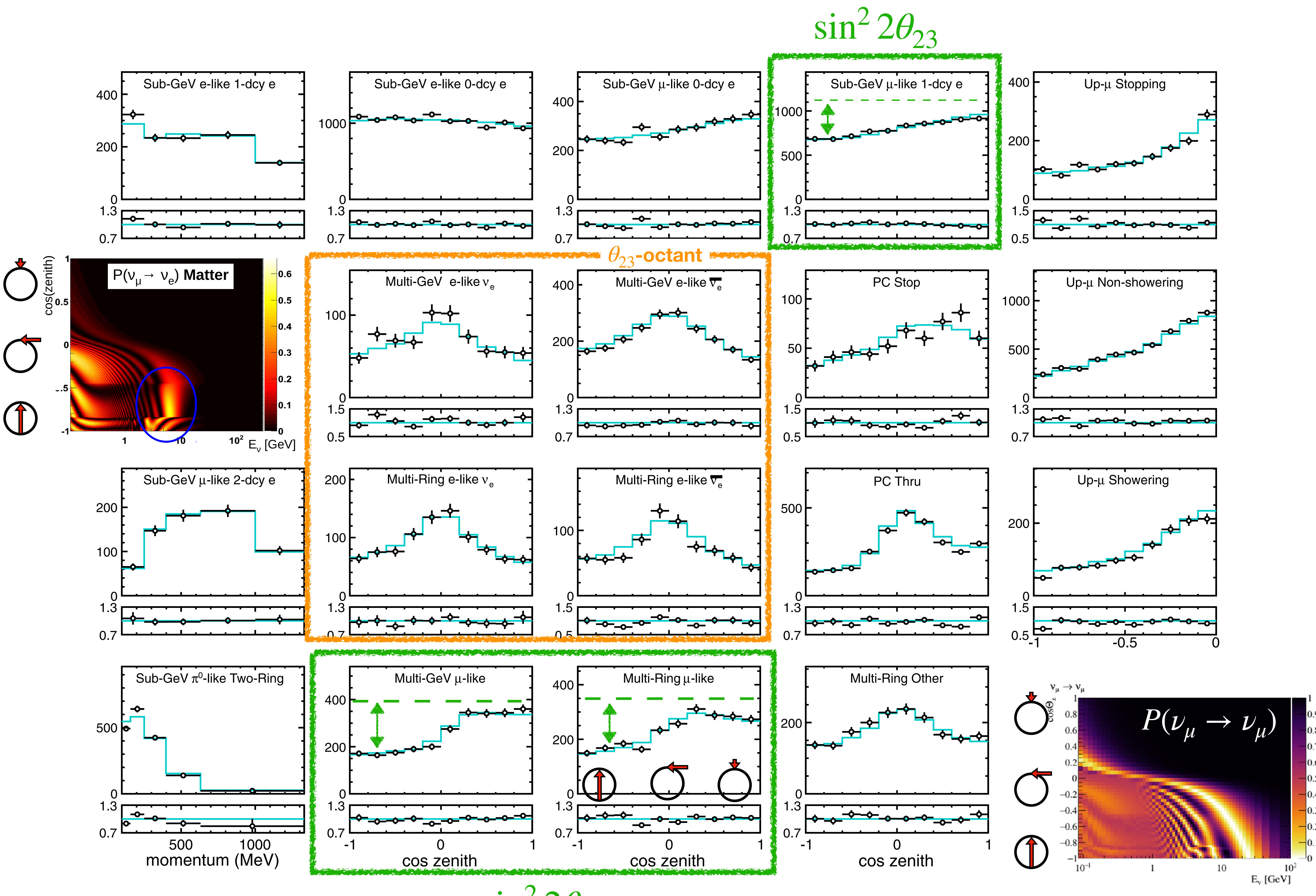
Stopping (inside of SK) ---------- $\approx 10\,\mathrm{GeV}$

Through-going

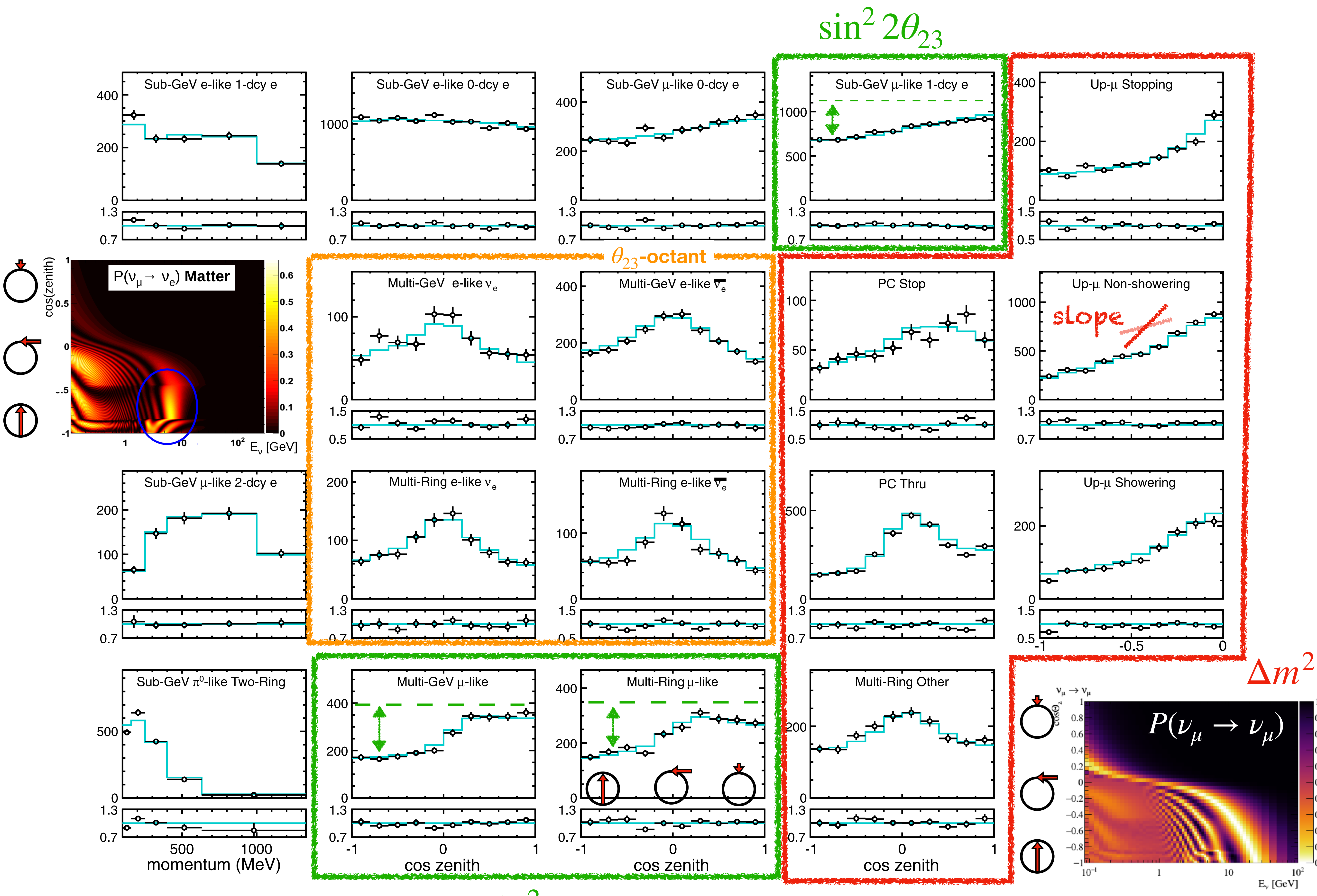
Separation by $\mathrm{d}E/\mathrm{d}x$:

- **Non-showering** (ionization loss) --- $\approx 100\,\mathrm{GeV}$
- **Showering** (radiative loss) -------- $\approx 1\,\mathrm{TeV}$

← Interaction vertex is outside of SK
(in rock surrounding SK)



PRD **97**, 072001 (2018)



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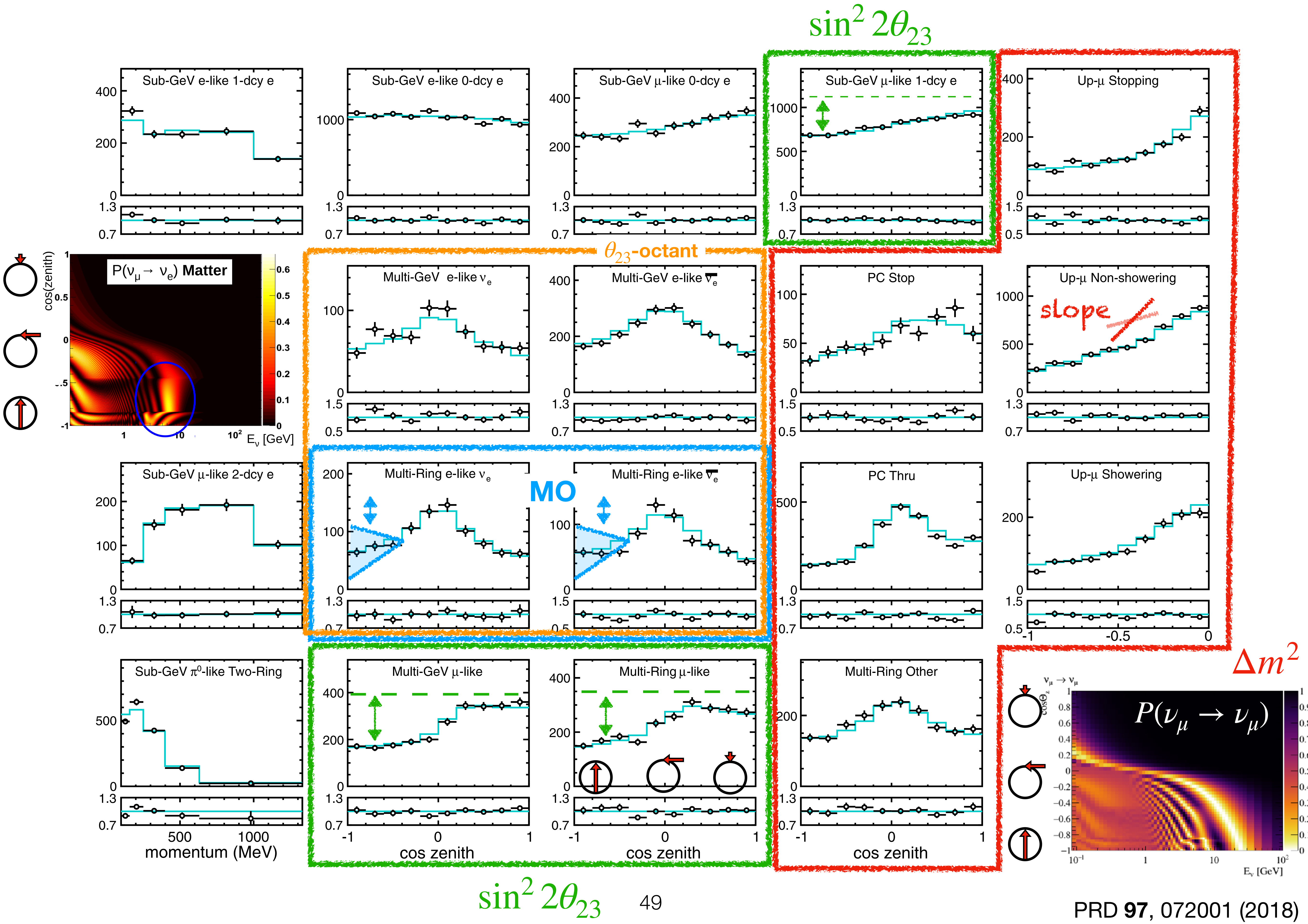

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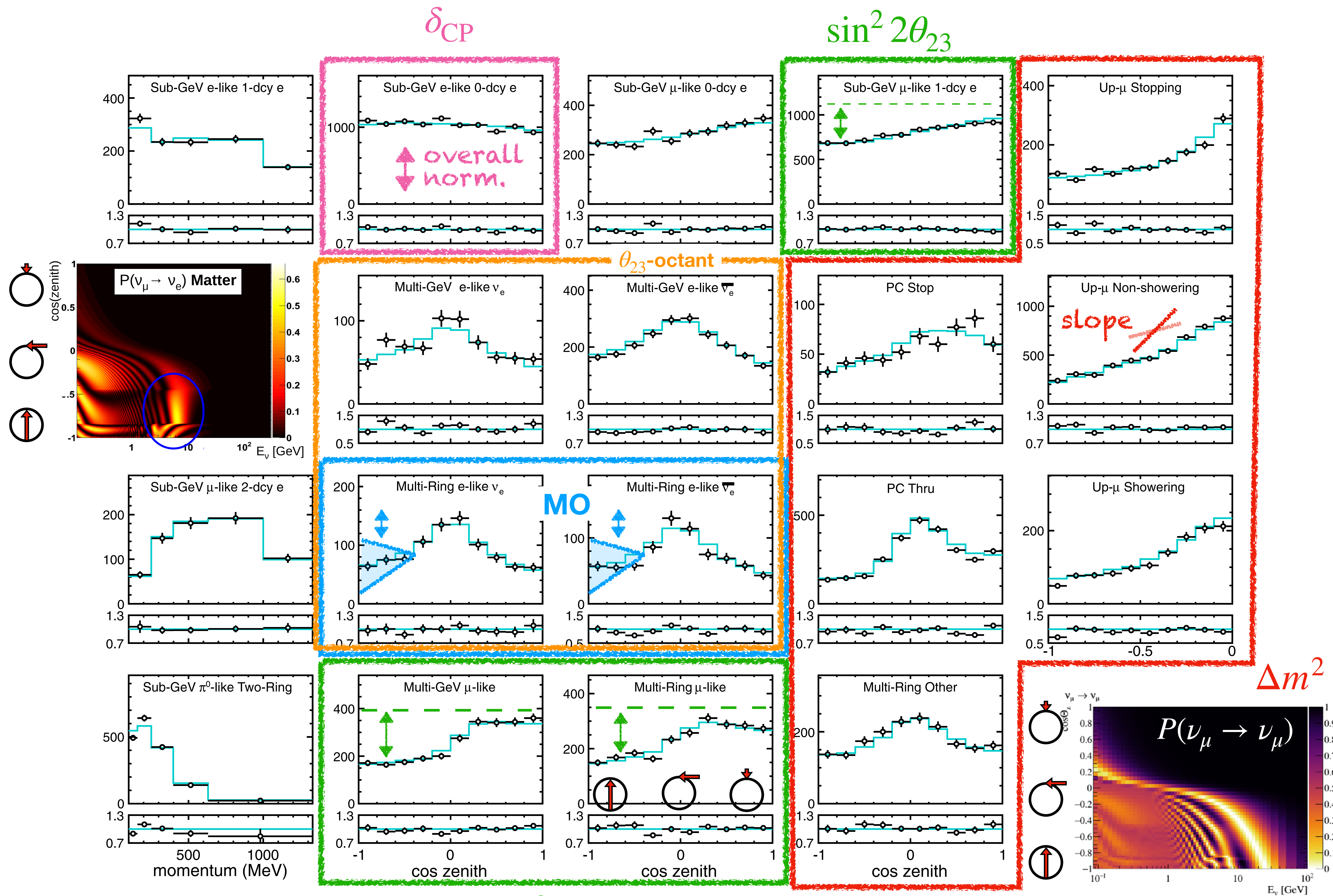
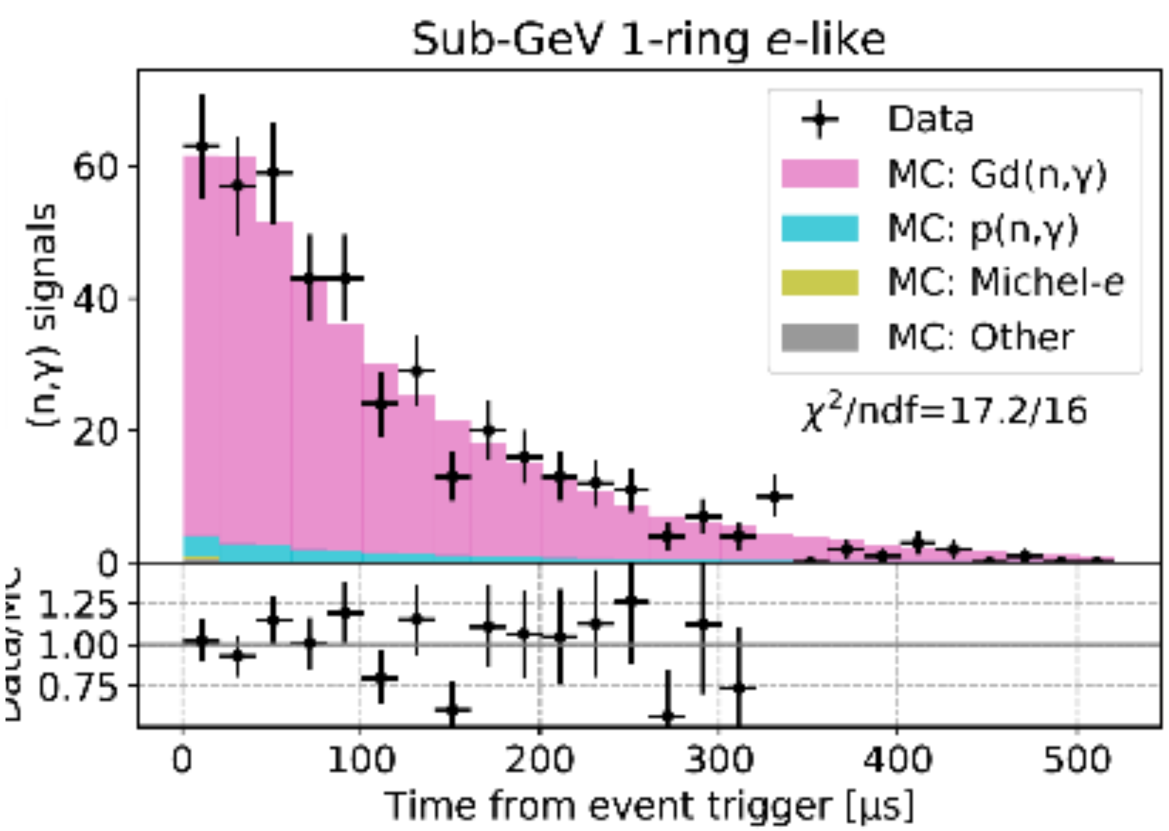


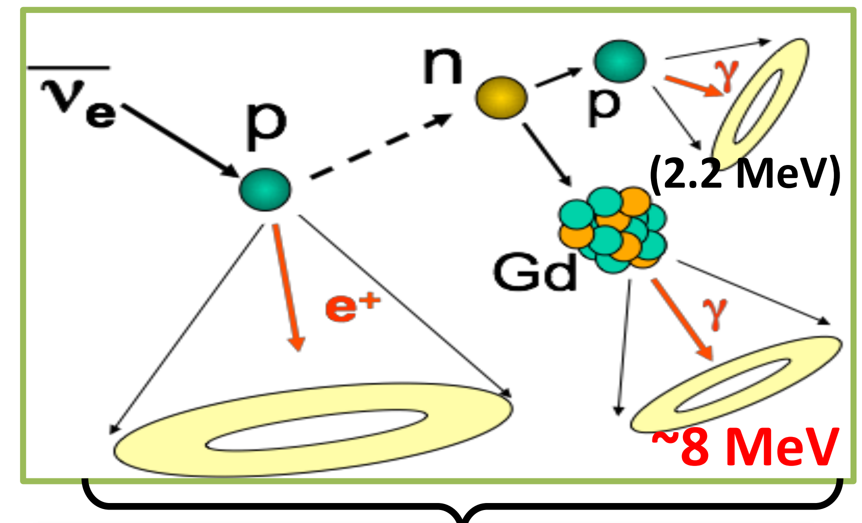
PRD **97**, 072001 (2018)

SK Gd



Preliminary **May 2022**

SK-VI, atmospheric



- Reduce BG of $\bar{\nu}_e$ signal
  - Delayed coincidence
  - ΔT ~ 30 μs (@0.1% Gd)
  - Vertices within ~ 50 cm

Capture efficiencies in water

- 0.01% Gd [$Gd_2(SO_4)_3$ 10t] : ~50%
- 0.03% Gd [$Gd_2(SO_4)_3$ 30t] : ~75%
- 0.1% Gd [$Gd_2(SO_4)_3$ 100t] : ~90%

Gd concentration

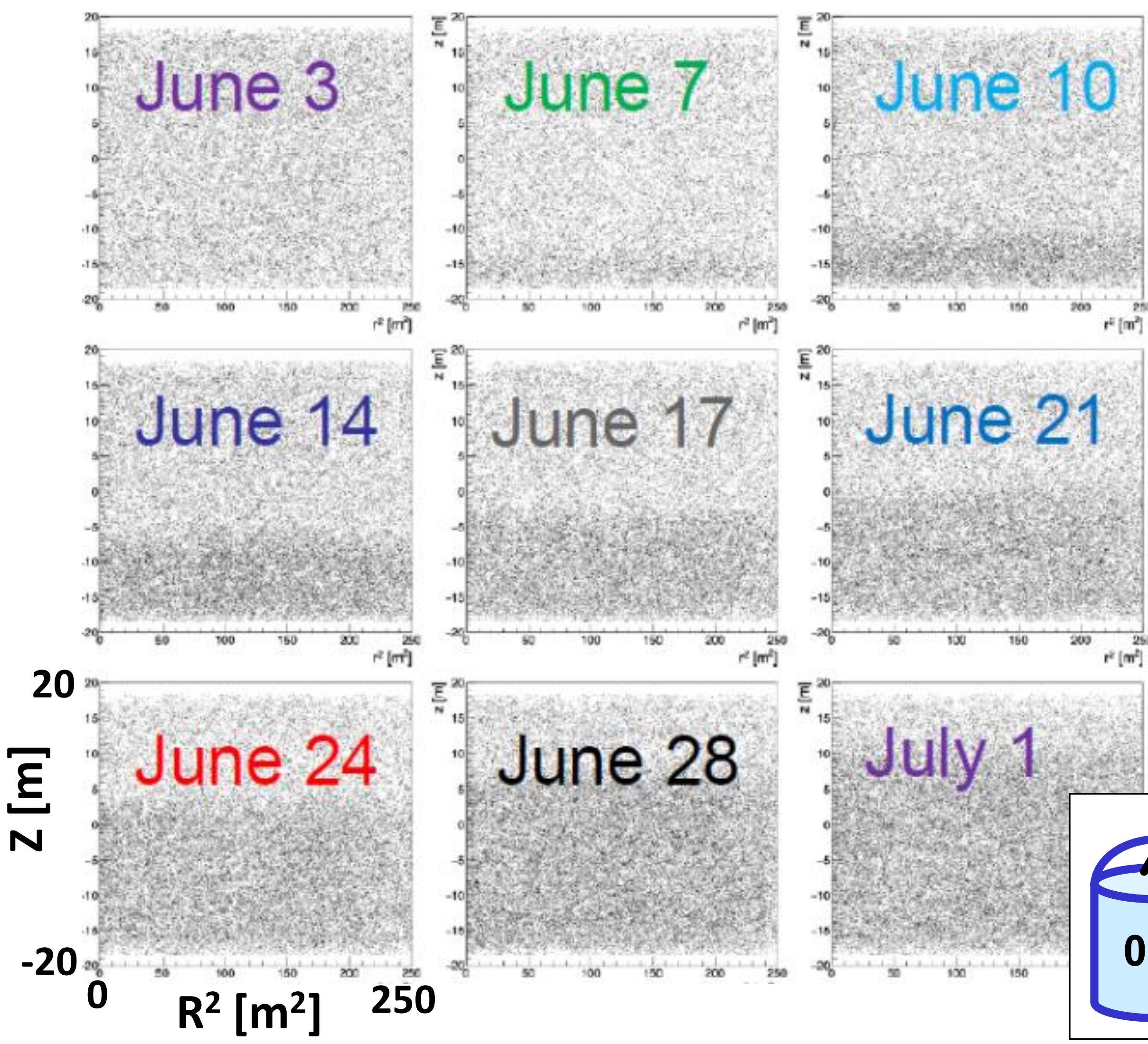
SK-VI: 0.011% (18 Aug. 2020-)

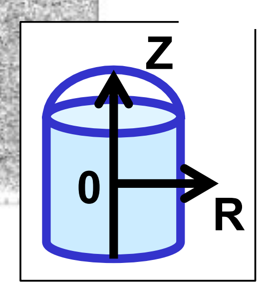
SK-VII: 0.03% (5 Jul. 2022-)

Y. Takeuchi, NOW 2022

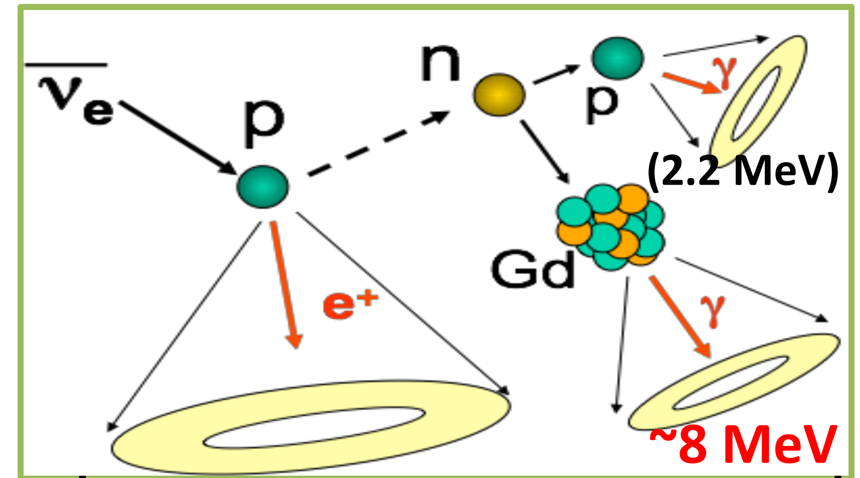
SK Gd

Vertex dist. of cosmogenic neutron candidates





SK-VII, atmospheric



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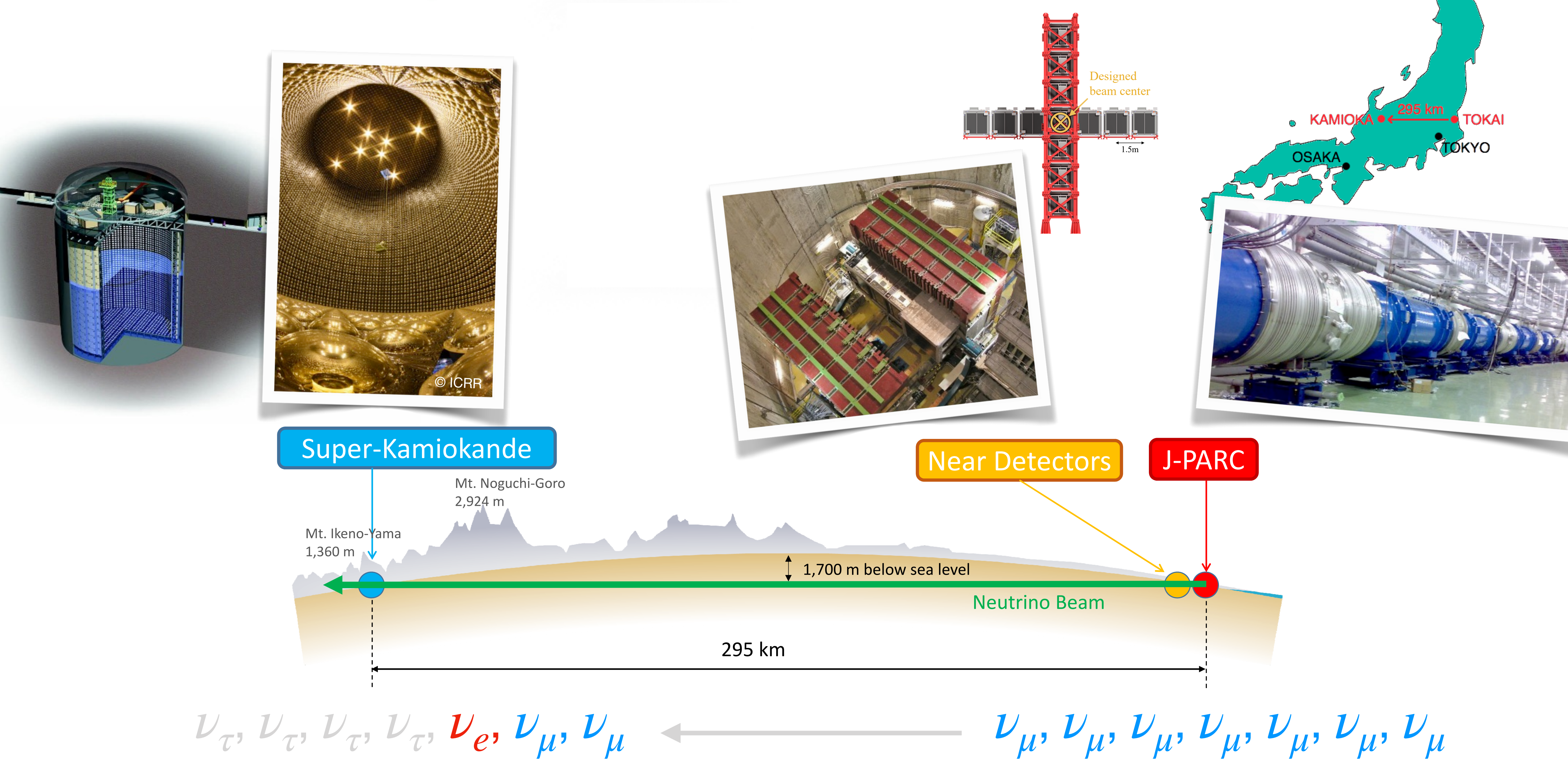
Y. Takeuchi, NOW 2022

T2K experiment



- Study oscillation of neutrino beam from J-PARC accelerator
- ~500 collaborators from institutions in 14 countries

ν-oscillation

(interaction) (propagation)

For neutrinos flavor basis ≠ Hamiltonian basis.

→ Flavor (ν_e | ν_μ | ν_τ) oscillates over $L \times \Delta m^2 / E$,

amplitude controlled by (PMNS) **mixing matrix** U:

atmospheric **reactor** **solar**

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

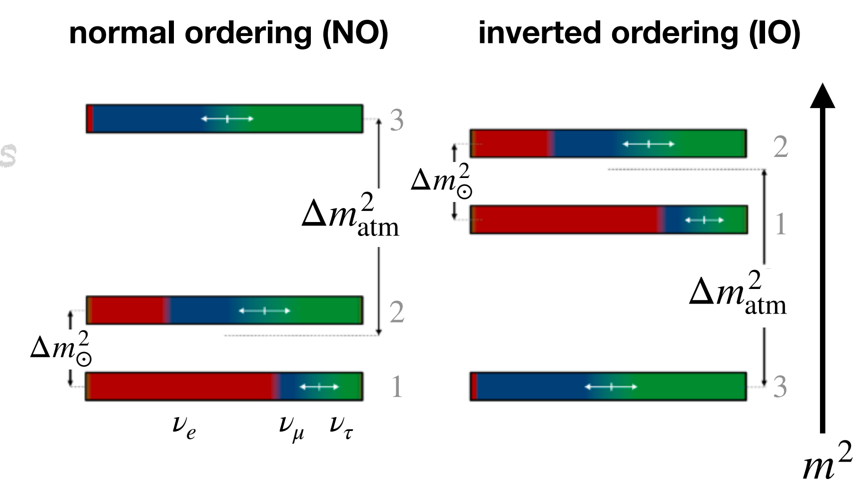
$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

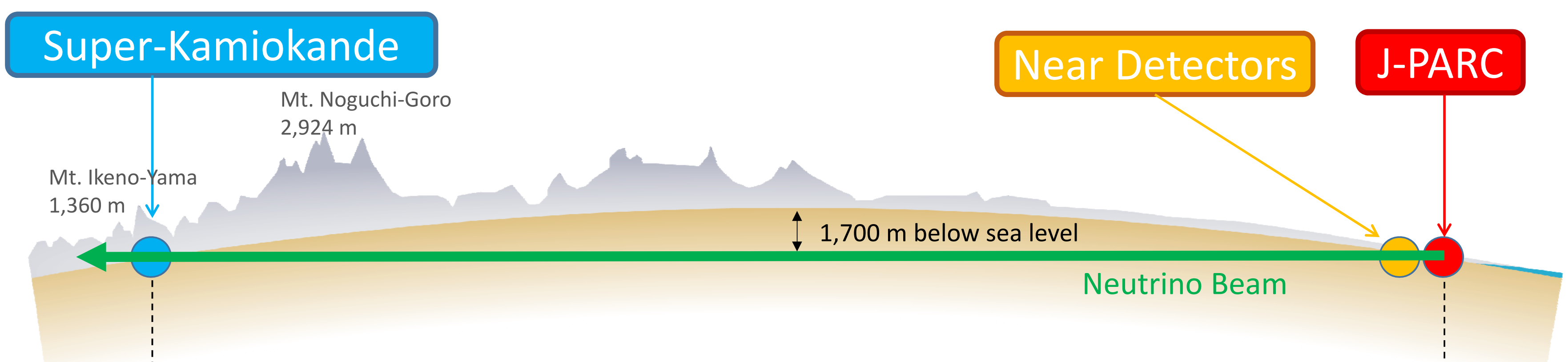
Open questions:

- value of δ_{CP} → if $\sin\delta_{\mathrm{CP}} \neq 0$, CP violation
- sign of Δm^2_{32} (mass ordering)
- is θ_{23} maximal? octant? (i.e. $\theta_{23} < \frac{\pi}{4}$ or $\theta_{23} > \frac{\pi}{4}$)

important params for cosmology (leptogenesis...) and 0ν2β searches

flavor symmetries?





For δ_{CP},MO look for $\nu/\bar{\nu}$ difference of $\nu_\mu \to \nu_e$ appearance

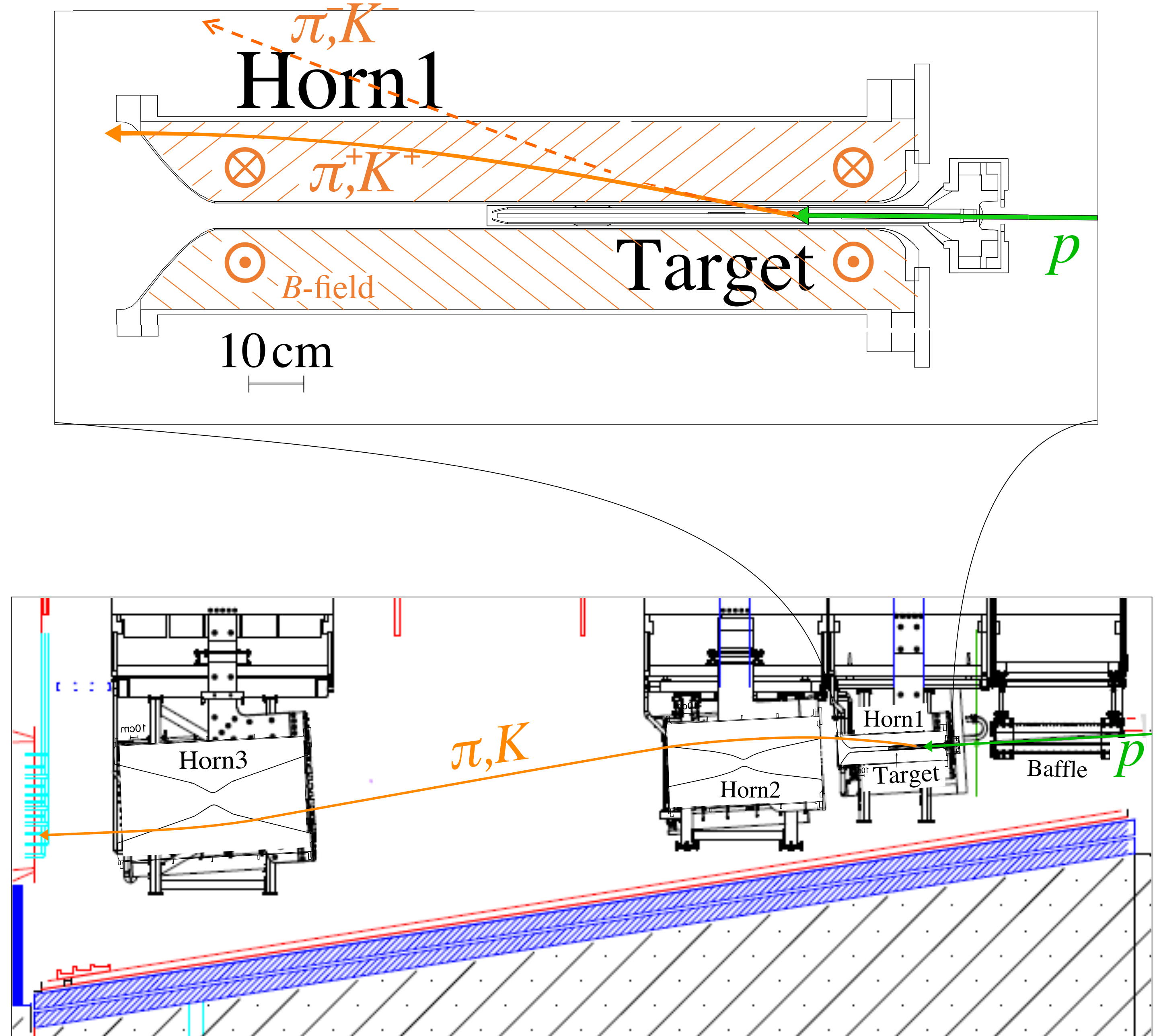
note: wrong-sign ν_μ and intrinsic ν_e backgrounds neglected for illustration

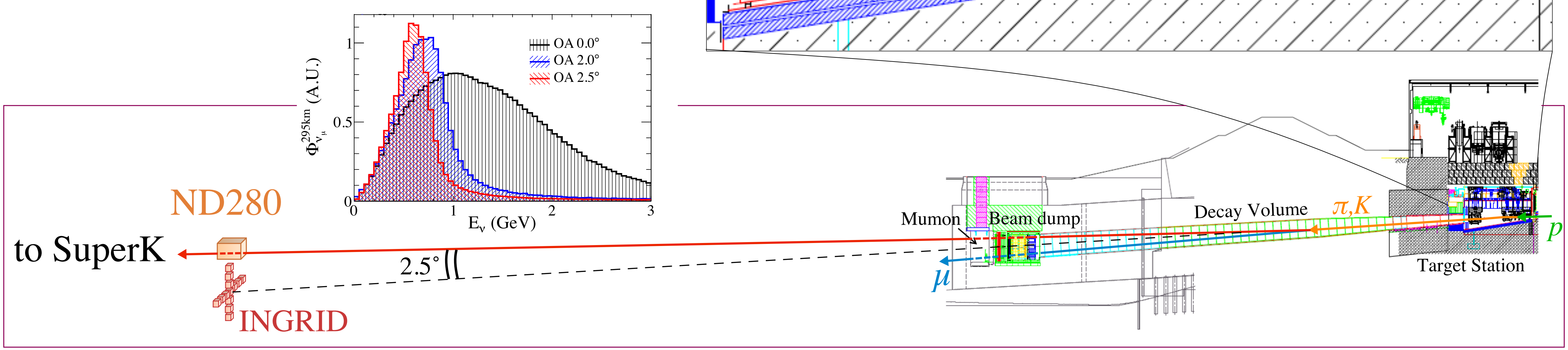
$\nu_\tau, \nu_\tau, \nu_\tau,$ $\boxed{\nu_e,}$ ν_e, ν_μ, ν_μ ← **Neutrino mode** ← $\nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu, \nu_\mu$

$\bar{\nu}_\tau, \bar{\nu}_\tau, \bar{\nu}_\tau,$ $\boxed{\bar{\nu}_\tau,}$ $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\mu$ ← **Anti-neutrino mode** ← $\bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu, \bar{\nu}_\mu$

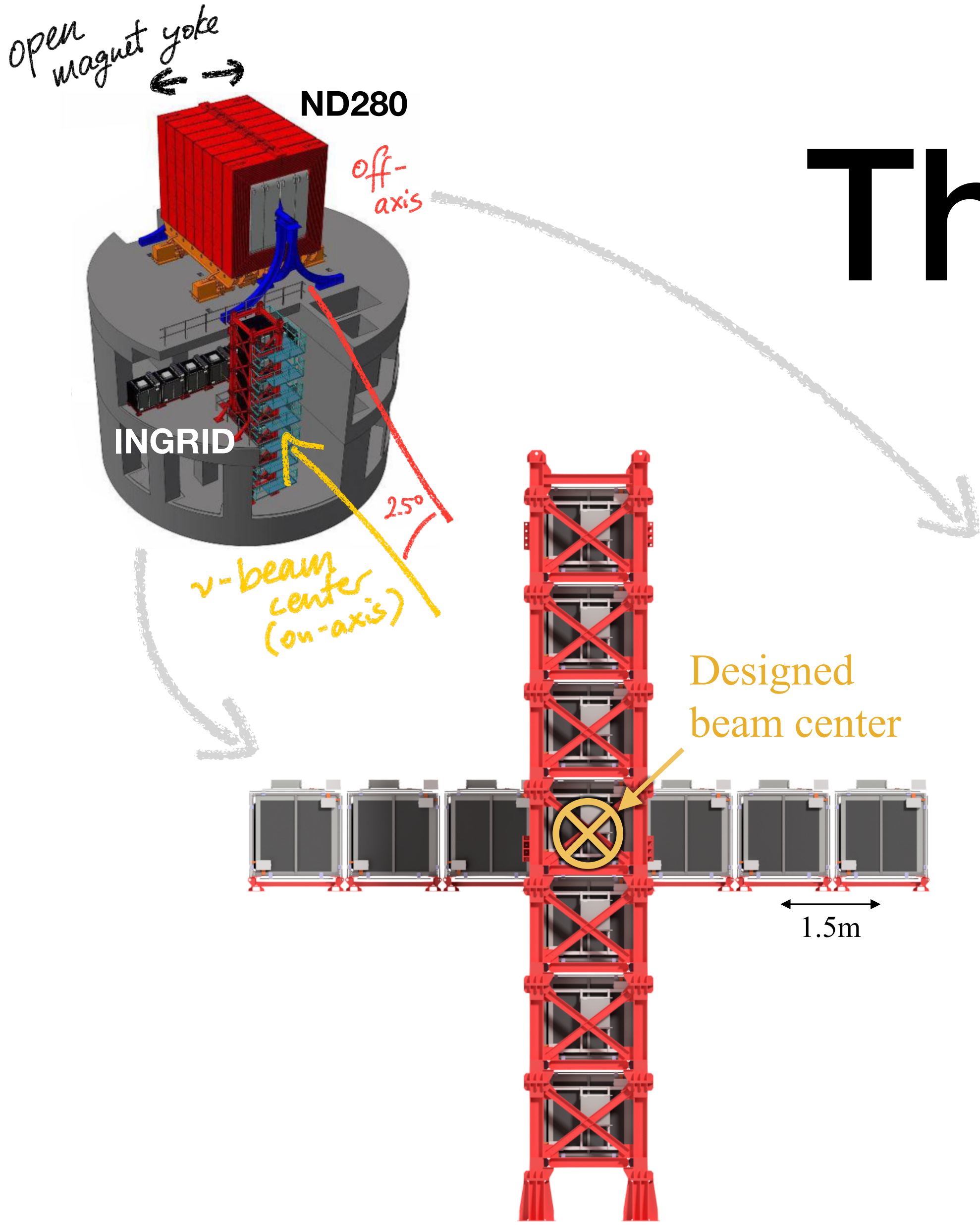
Neutrino beam

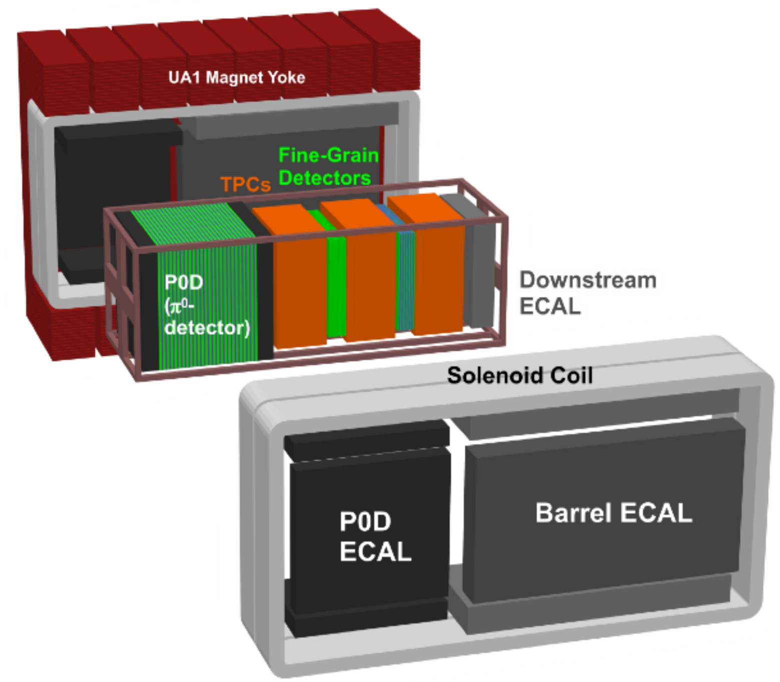
- 30 GeV protons produce π,K in 90 cm graphite target
- Three magnetic horns selectively focus π^+,K^+ or π^-,K^- to produce ν_μ or $\bar{\nu}_\mu$ beam (decay in-flight).
- Narrowband beam thanks to off-axis technique.

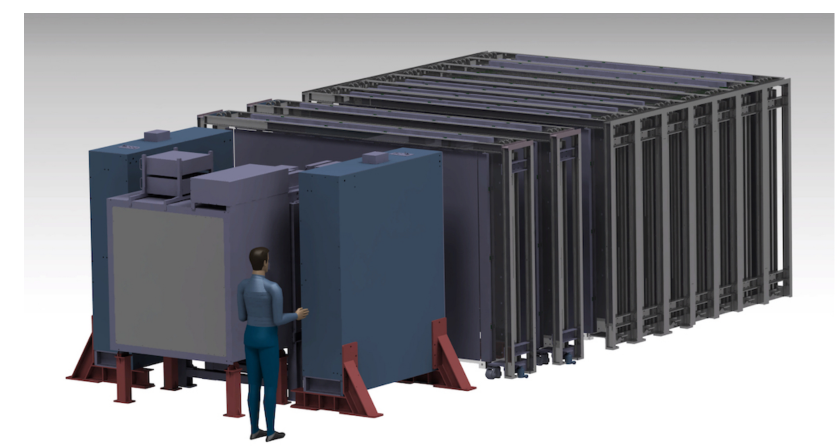




The near detectors







INGRID on-axis detector

- Iron-scintillator sandwich detectors monitor neutrino beam **direction** and intensity

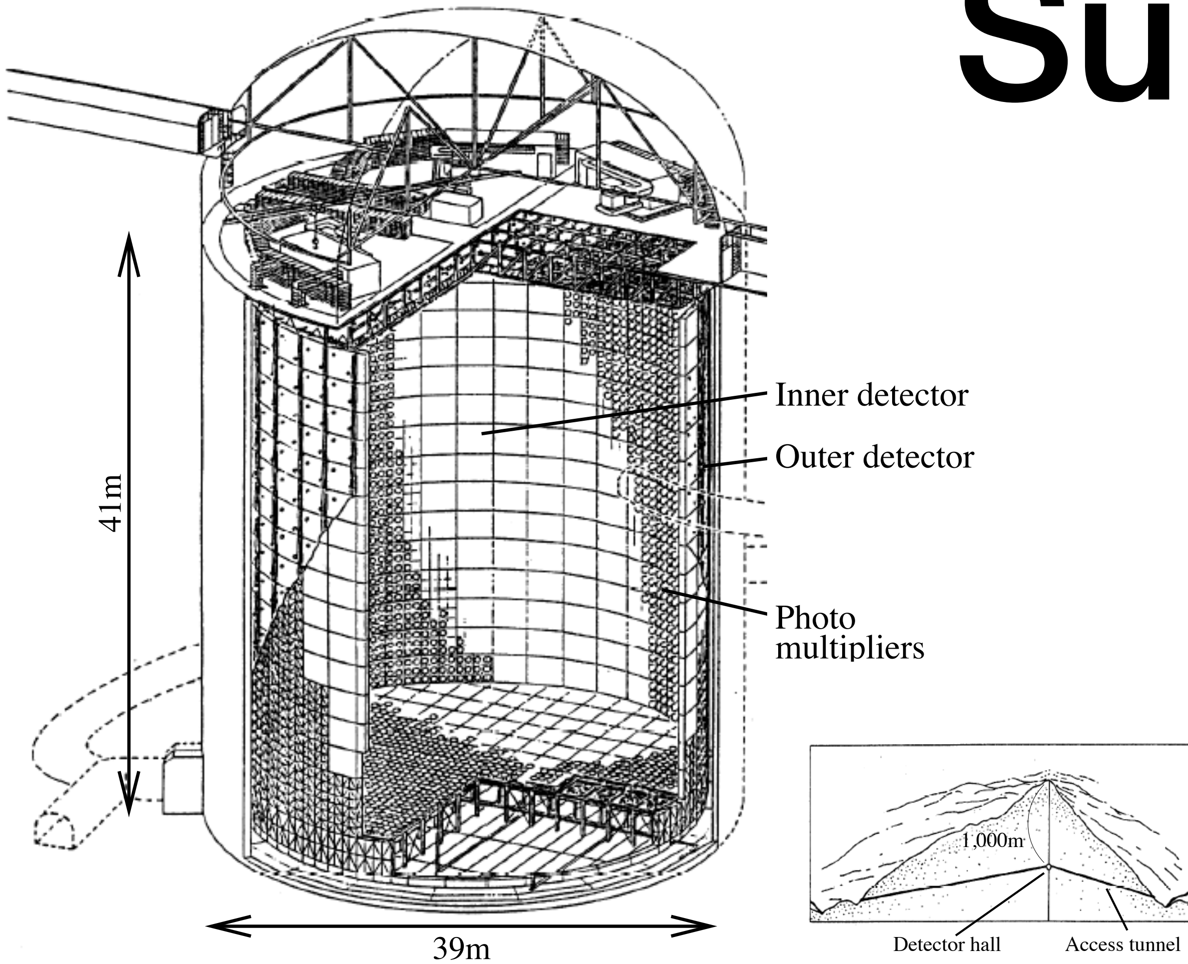
ND280 off-axis detector

- Active **scintillator** + passive **water** targets
- Tracking with **time projection chambers**
- **Magnetized** for charge and momentum measurement

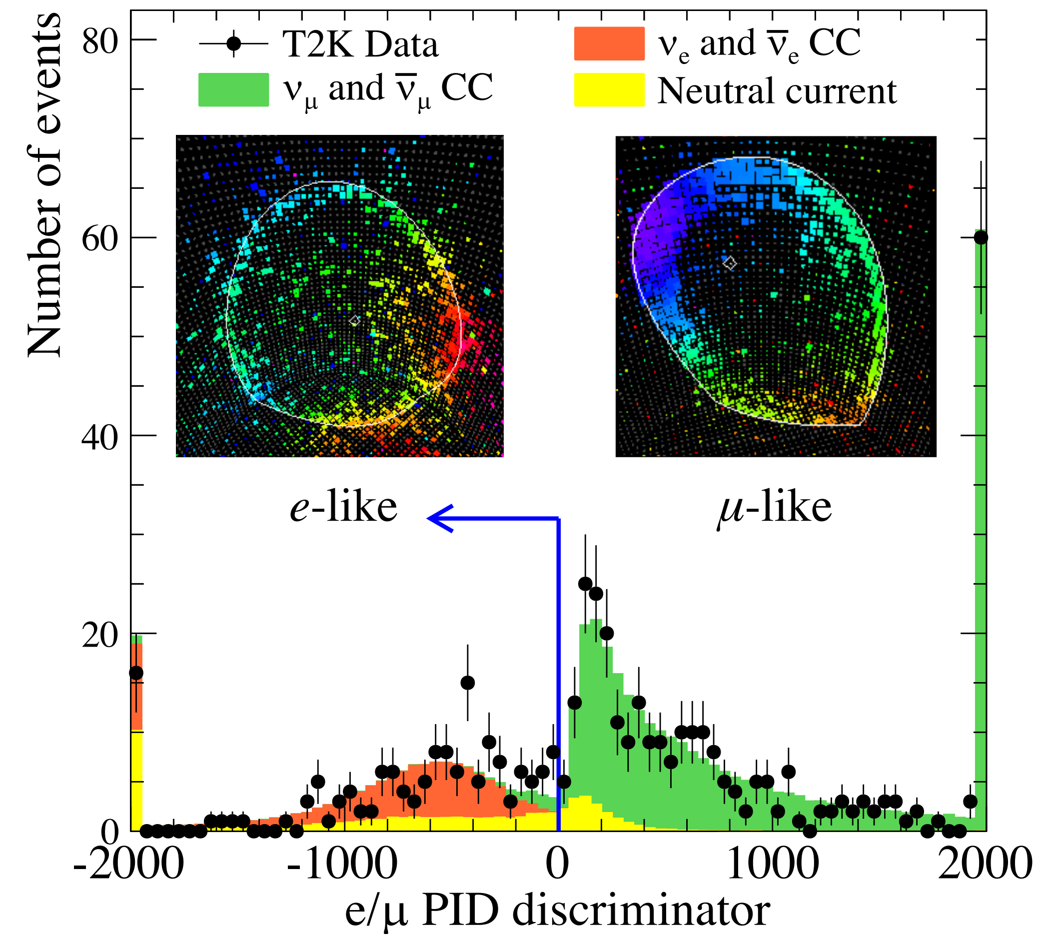
WAGASCI + BabyMIND

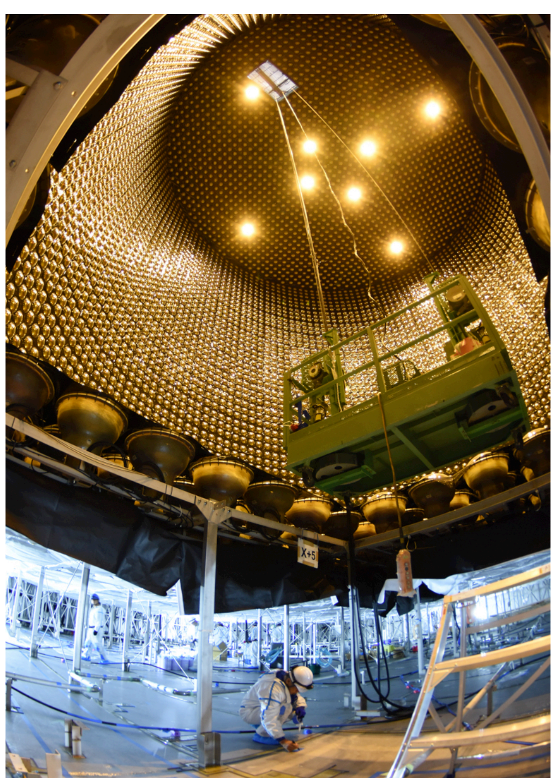
- Latest addition at intermediate **1.5º** off-axis flux
- **Water** target with cuboid lattice scintillators for high angle acceptance
- Compact **magnetized** iron muon range detector
- First xsec meas. published: PTEP, ptab014 (2021)

SuperK – the far detector



Adapted from Nature 580, 339-344 (2020)

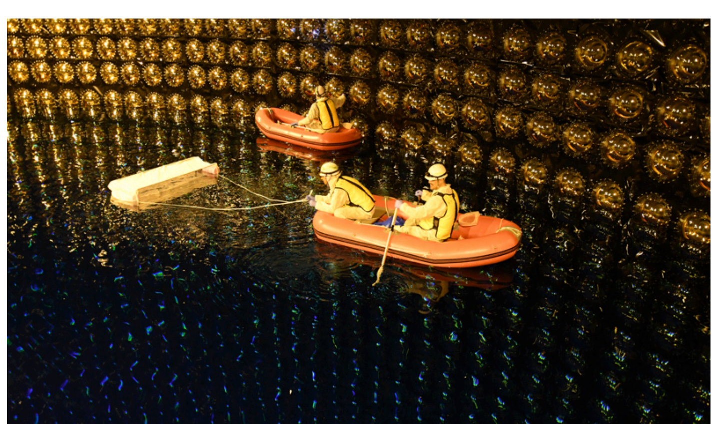




50 kt pure water
~11,000 20 inch PMTs

Now loaded with Gadolinium for improved neutron tagging!

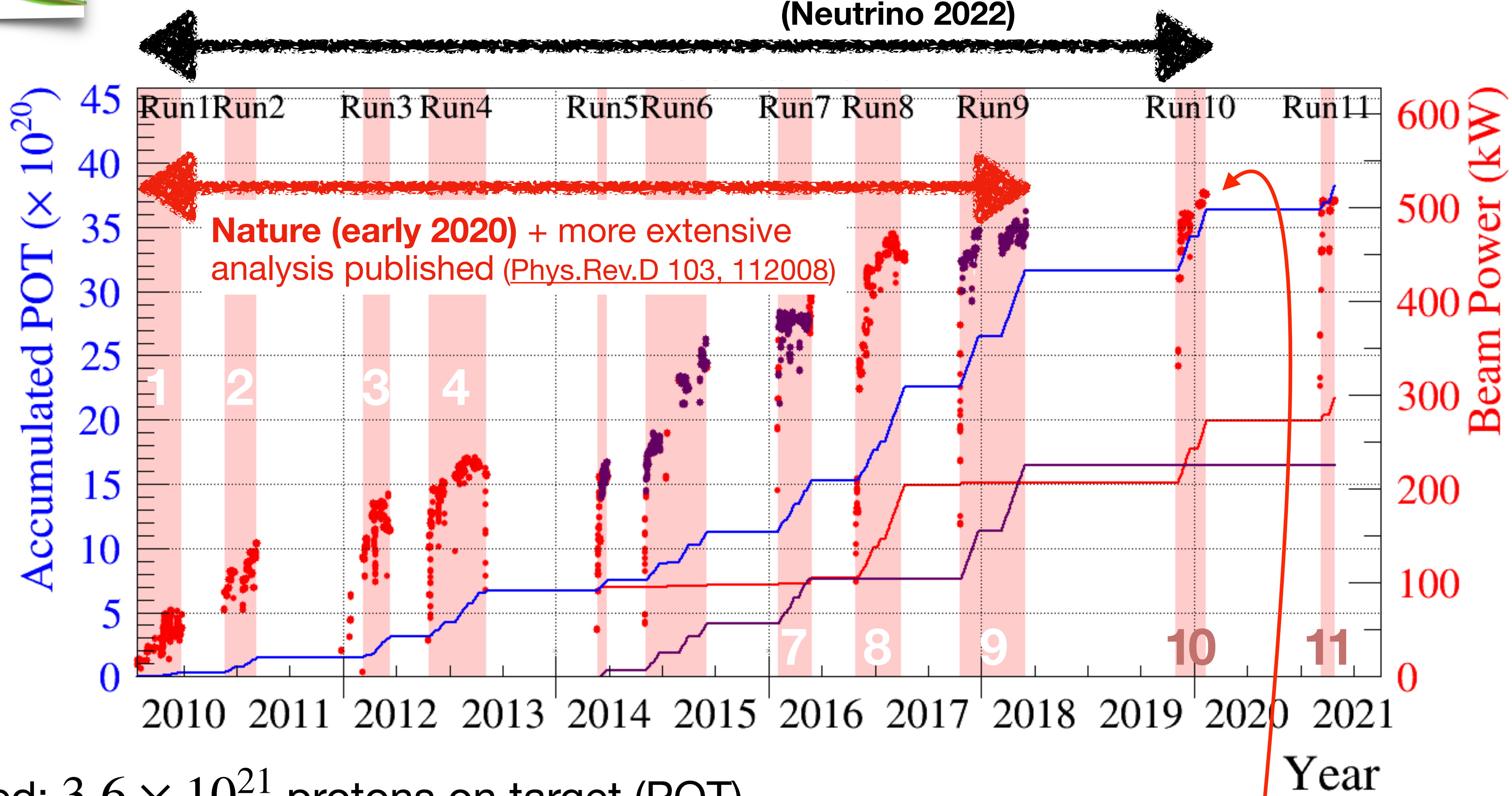
Photos: "Super Kamiokande refurbishment" ICRR (2018)



- Good μ/e PID from ring shape
- Reconstruct neutrino energy from lepton momentum and angle w.r.t. neutrino beam
- Not magnetized, so the beam $\nu/\bar{\nu}$-modes are important. ND280 further constrains the wrong-sign background.

Dataset

Analyzed
(Neutrino 2022)



Analyzed: 3.6×10^{21} protons on target (POT)

ν-mode : $\bar{\nu}$-mode $\sim 6:5$

- Total Accumulated POT for Physics
- ν-Mode Accumulated POT for Physics
- ν̄-Mode Accumulated POT for Physics
- ν-Mode Beam Power
- ν̄-Mode Beam Power

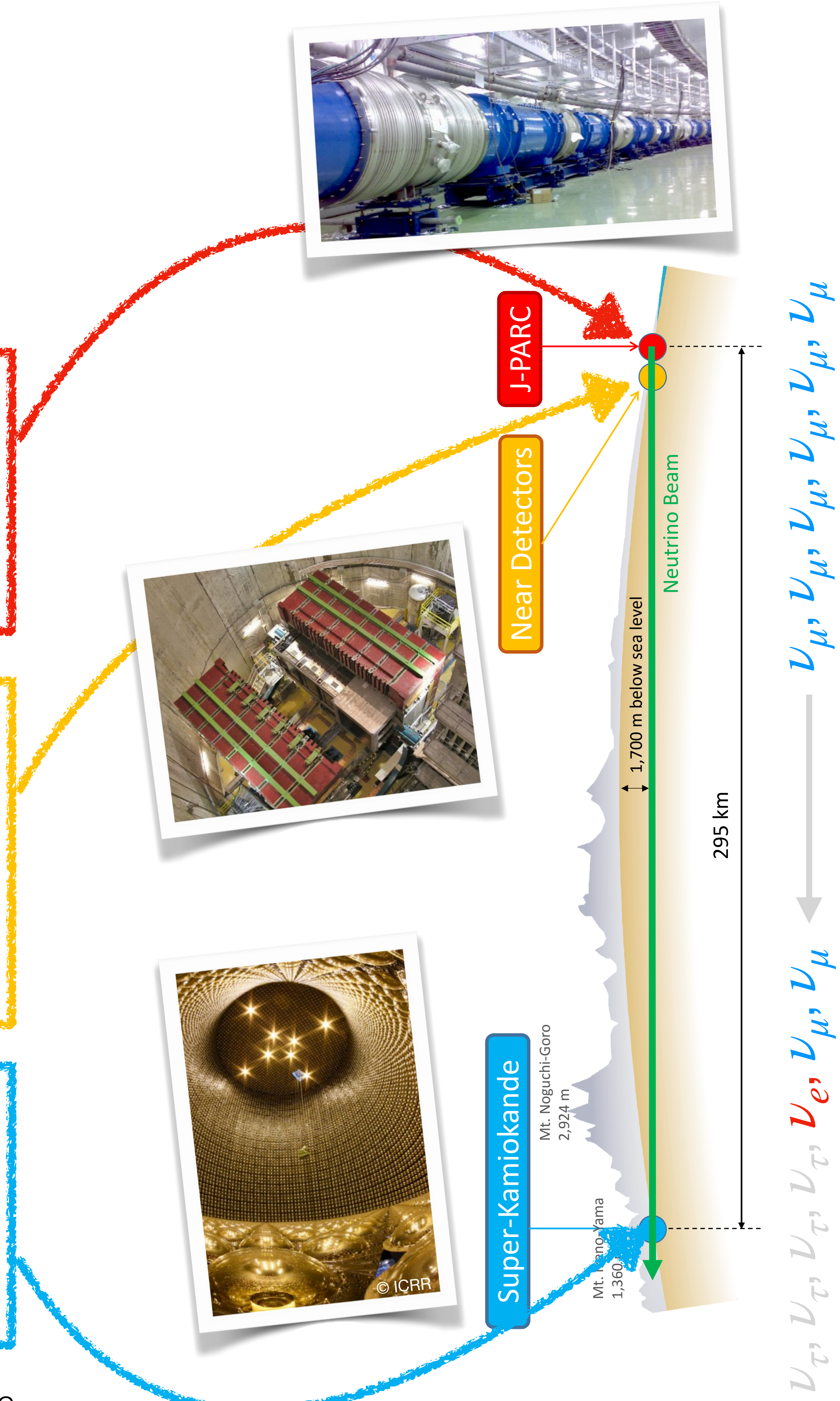
515 kW operation!
Additional run 11 data taken early 2021
(with Gd at SK), not used in this analysis

Analysis strategy

- Beam monitors + hadron production experiments
  → **neutrino flux**

- ND280 measurements
  + interaction model
  + external constraints
  → **unoscillated flux × xsec**

- 6 samples at SK
  → ν_μ **disappearance +**
  ν_e **appearance**



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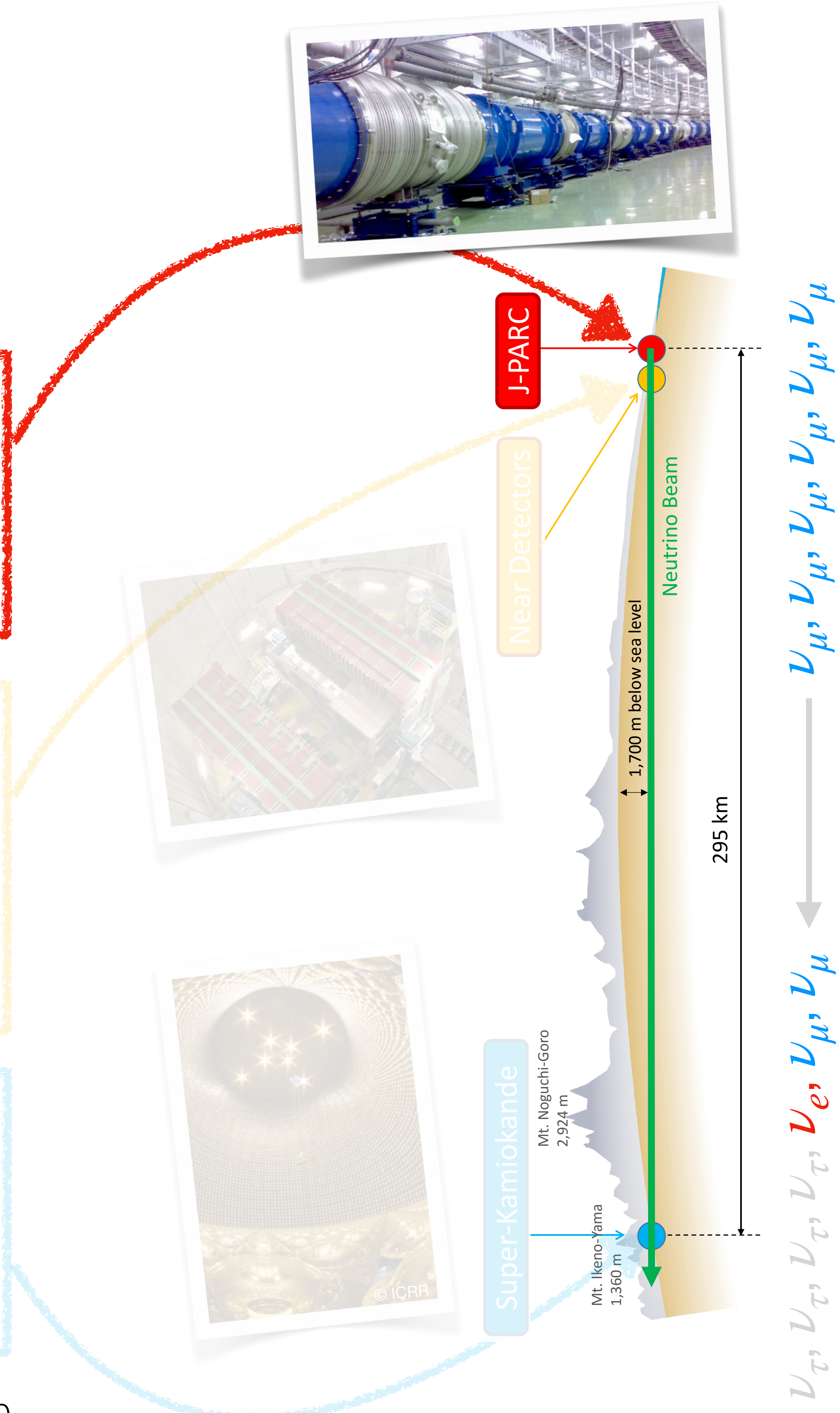
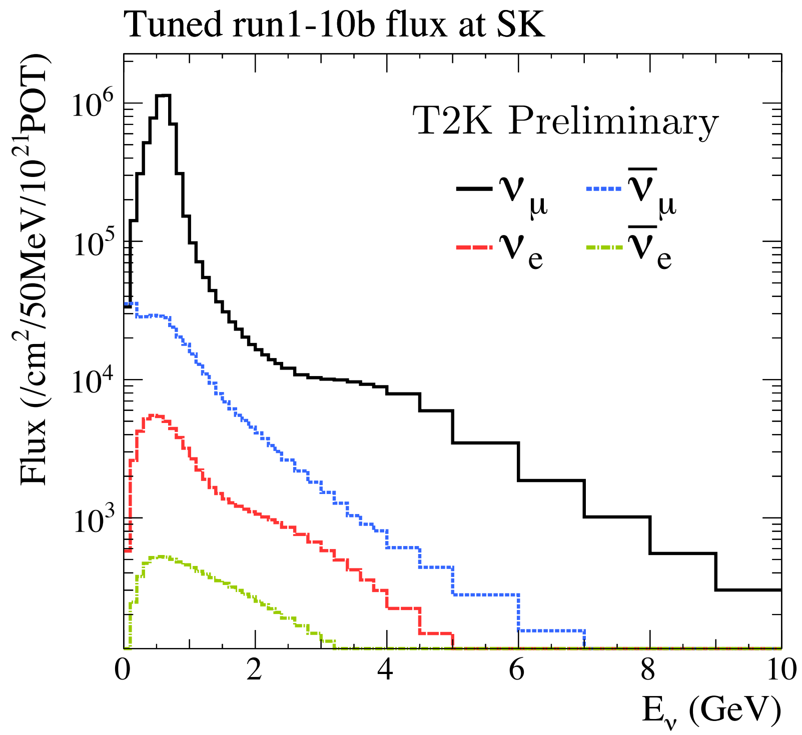


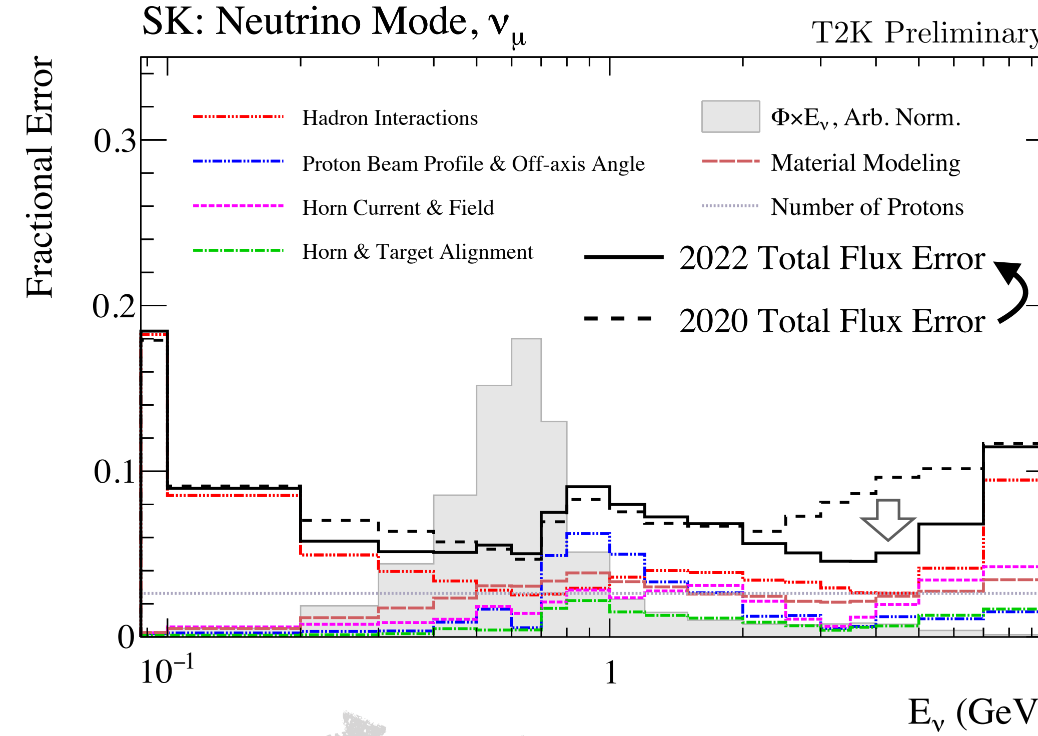
Ana
stra

- Beam monit
production
→ neutrino

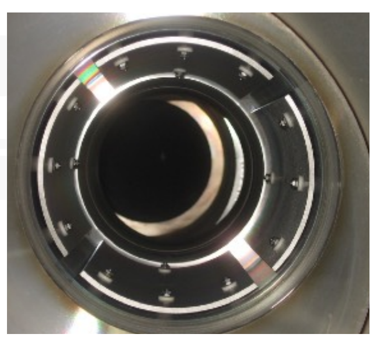
- ND280 me
+ interactio
+ external
→ unosci

- 6 samples
→ ν_μ disap
ν_e appe





Beam line modeling



← Beam monitors

More realistic modeling of cooling water in horns slightly increased uncertainty at flux peak

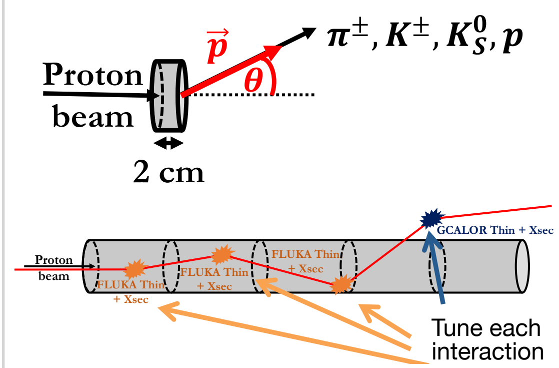
Hadron production experiments

Hadron interaction uncertainty at high-E reduced thanks to higher-statistics **NA61** measurement that includes **kaon** yields from **replica** of T2K target.

K,p in previous analysis

Thin target data

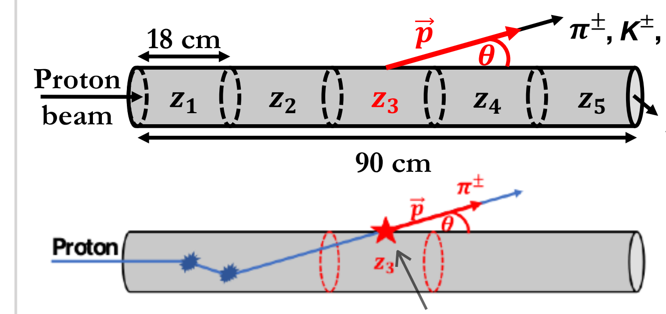
Mainly Eur. Phys. J. C (2016) 76:84



K,p in this analysis

Replica target data

Eur. Phys. J. C (2019) 79:100



An
str

- Beam mc
  productic
  → **neutri**

- ND280 m
  + interac
  + externa
  → **unosc**

- 6 sample
  → ν_μ **dis**
  ν_e **app**

New NA61 measurements are being performed for further reduction in the future!

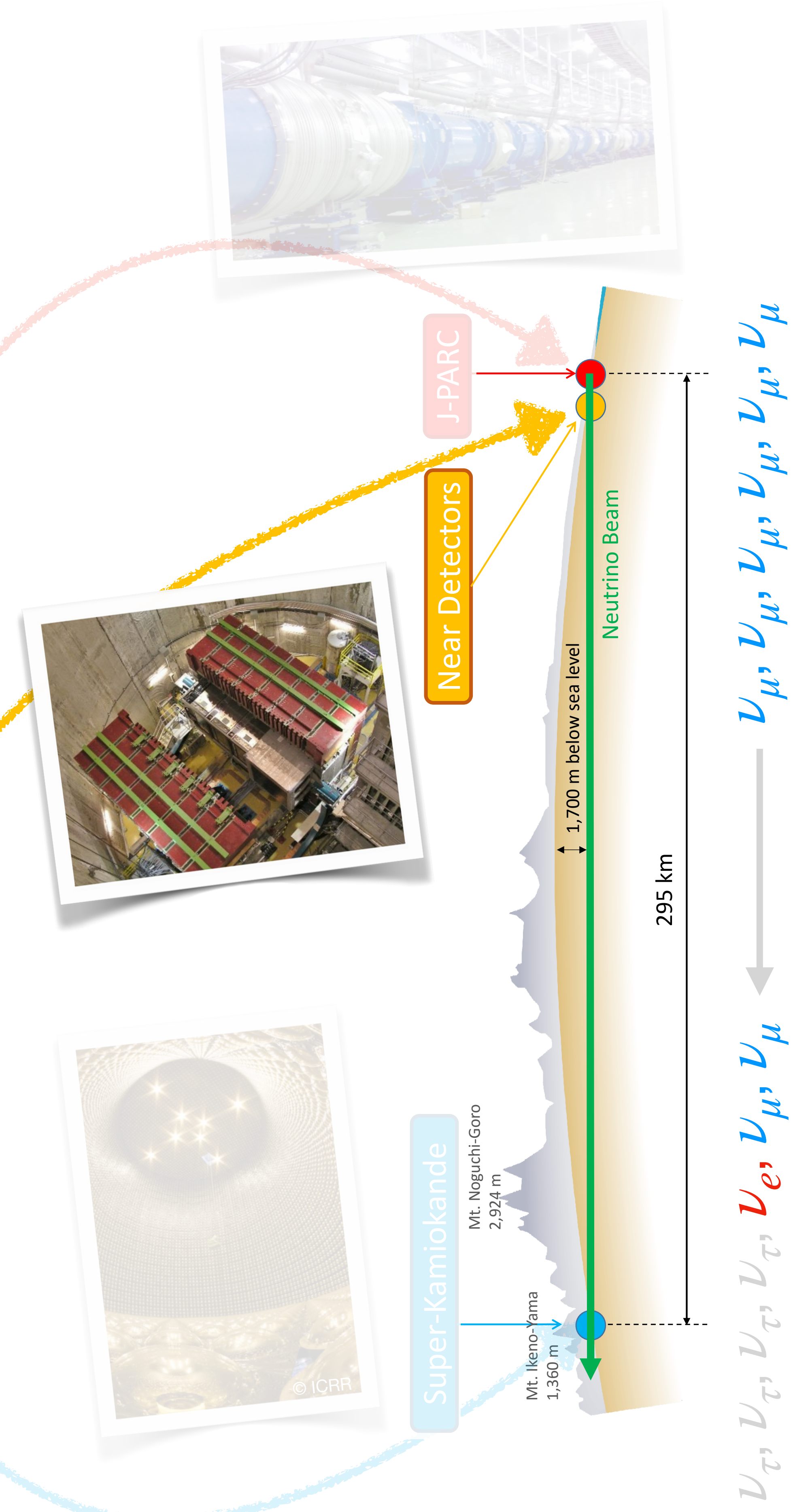
Photos from this summer
(by Y. Nagai, Eric D. Zimmerman, NA61/SHINE)

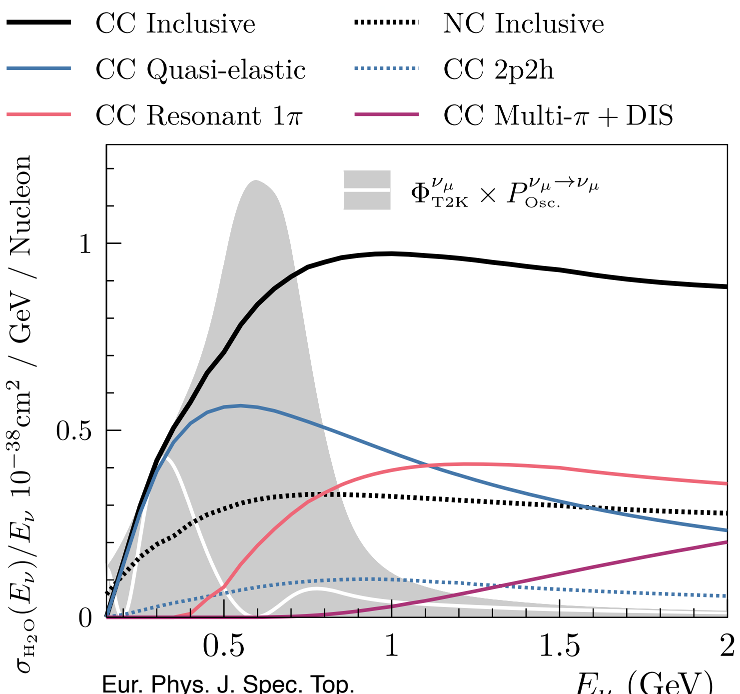
Analysis strategy

- Beam monitors + hadron production experiments
  → **neutrino flux**

- ND280 measurements
  + interaction model
  + external constraints
  → **unoscillated flux × xsec**

- 6 samples at SK
  → ν_μ **disappearance +**
  ν_e **appearance**





Eur. Phys. J. Spec. Top. (2021) 230:4469–4481

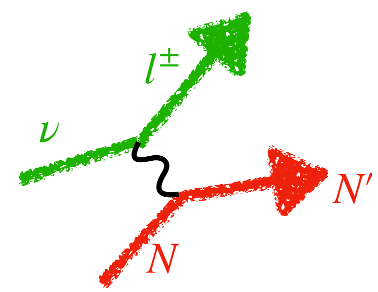
→ neutrin

• ND280 me
+ interactic
+ external
→ unoscil

• 6 samples
→ ν_μ disa
ν_e appe

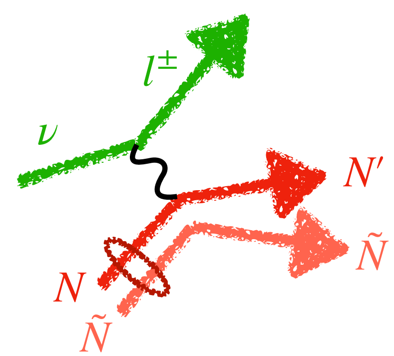
Good E_ν reconstruction

Charged current quasi-elastic (CCQE)

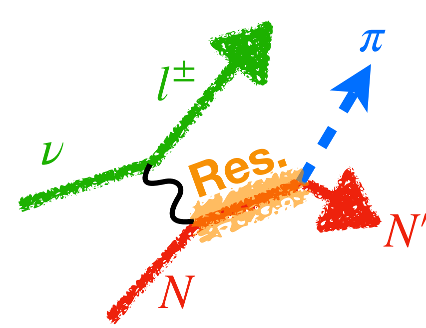


Mis-reconstruction of E_ν (~25% of events)

CC multi-nucleon knock-out (2p2h)



CC Resonant



Significant updates to interaction model

CCQE based on Spectral Function model tuned to e-A scattering data.

- uncertainty on nucl. shell structure
- $|\mathbf{q}|^2$-dependence of removal energy

Replace empirical freedom by physics-motivated low-Q^2 modeling:
- optical potential
- Pauli blocking

Uncertainties for tagging protons
- **2p2h** separation in pp and pn
- nucleon FSI

Resonant based on Rein-Sehgal model with RFG nuclear model.

New tune to bubble chamber data

New uncertainties including effective binding energy.

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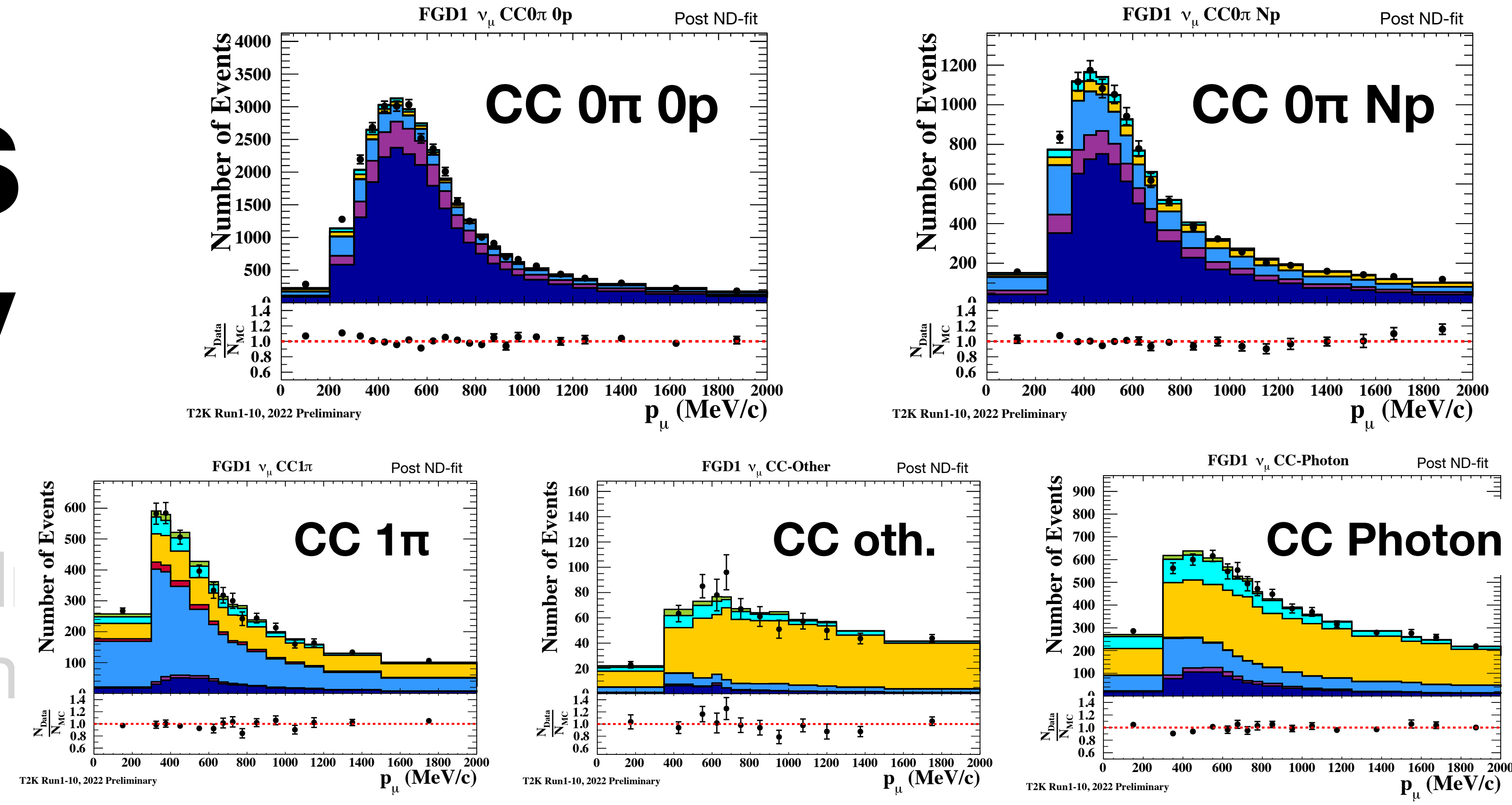
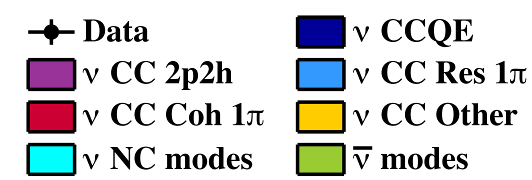
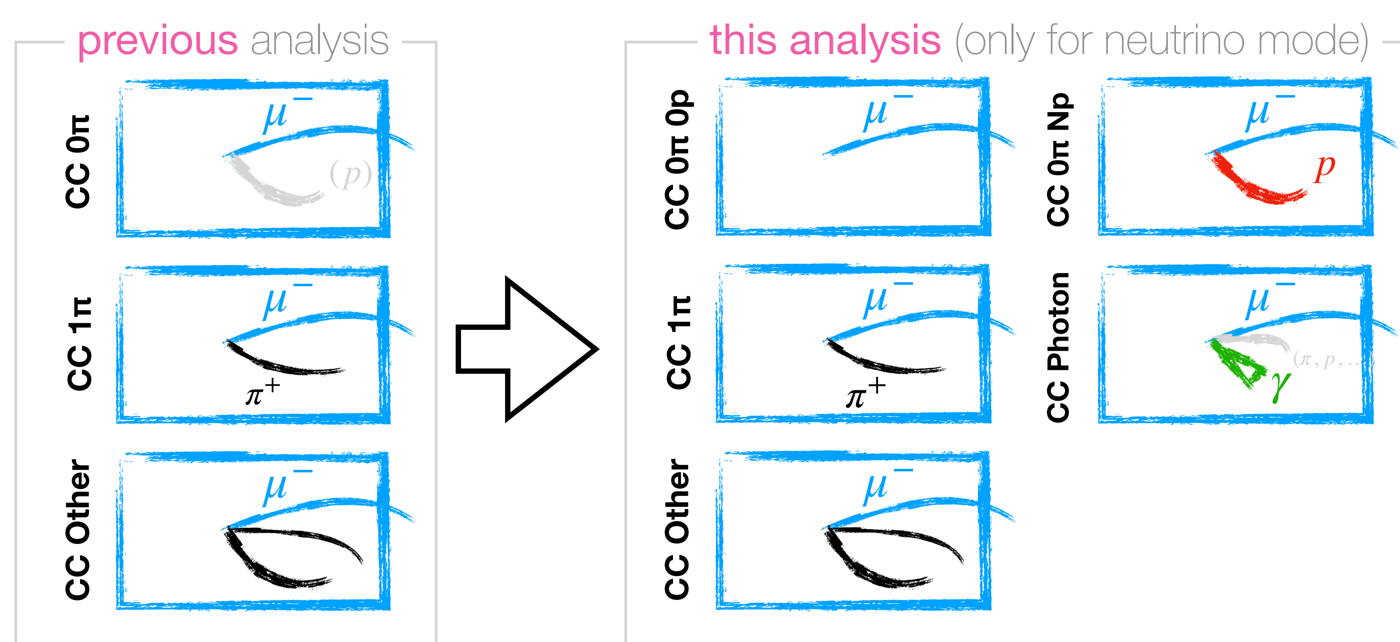


22 samples = (5×1+3×2)×2
separated by



1. π,p,γ multiplicity
   → interaction mode

Finer sample separation in this analysis!



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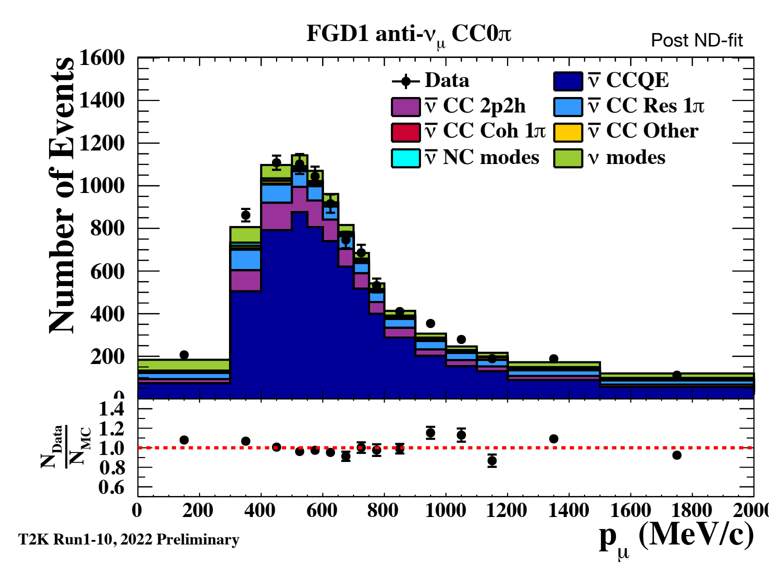
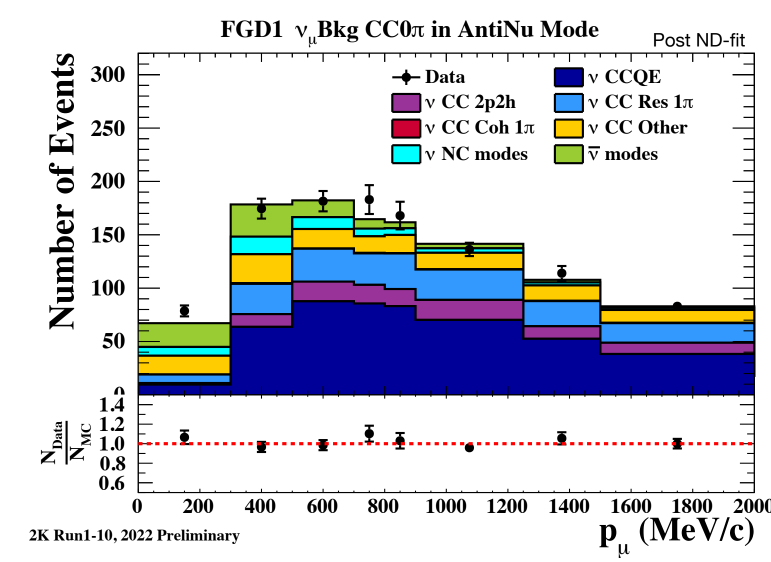
- 6 samples at SK
  → **ν_μ disappearance +**
  ν_e appearance

Right-sign

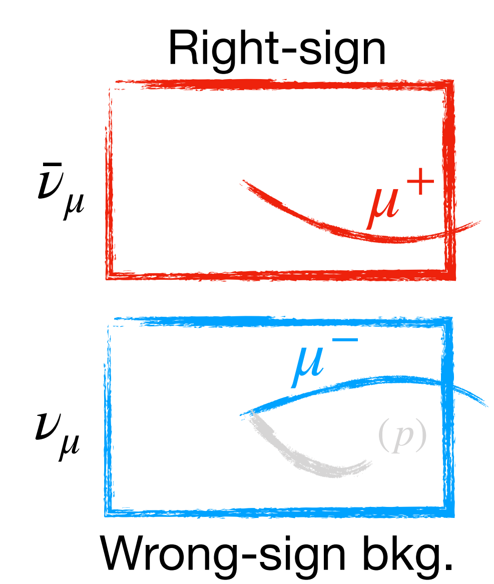


Wrong-sign bkg.



22 samples = (5×1+3×2)×2
separated by

1. π,p,γ multiplicity
   → interaction mode
2. lepton charge
   → wrong-sign bkg
   (in antineutrino mode)
3. C / C+O target
   → ν+O xsec



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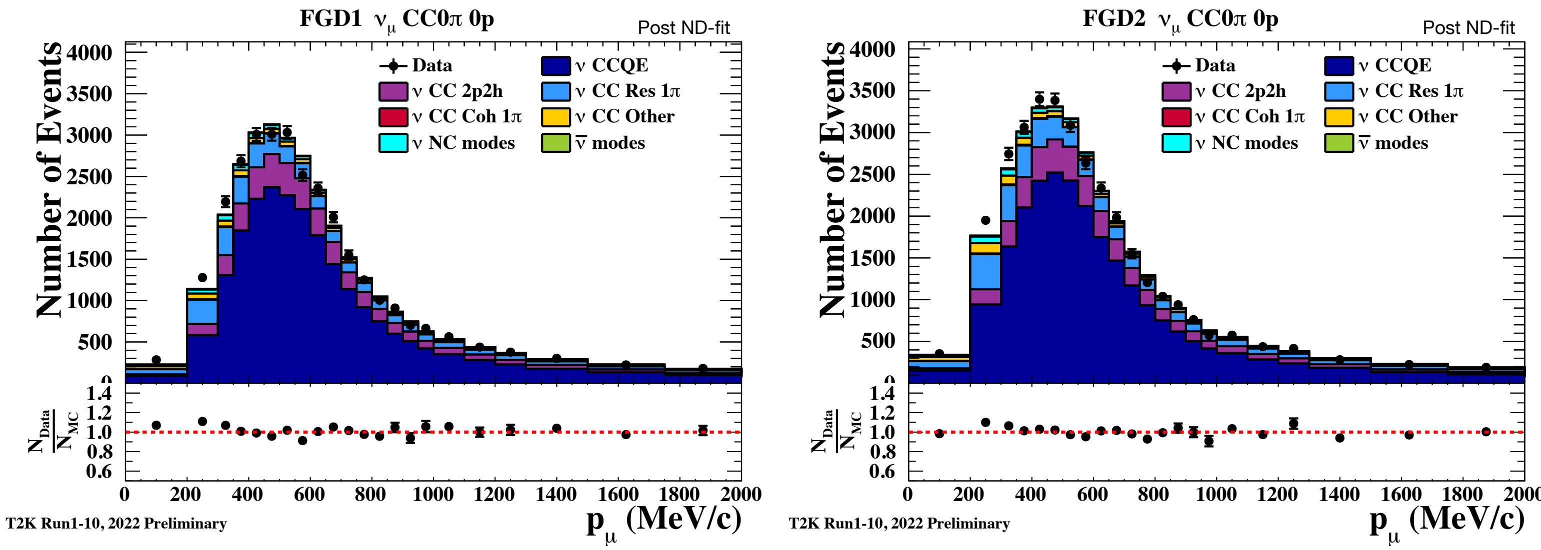
  ν_e **appearance**

C target **C+O target**



22 samples = (5×1+3×2)×2
separated by

1. π,p,γ multiplicity
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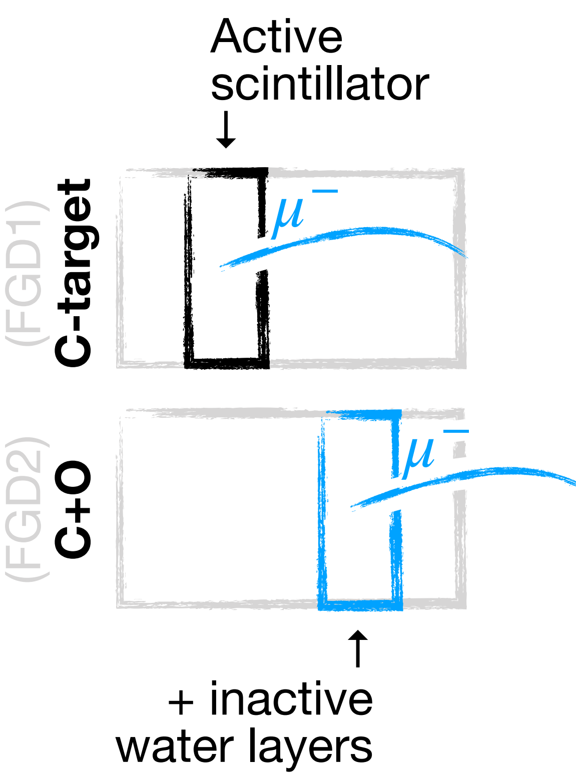

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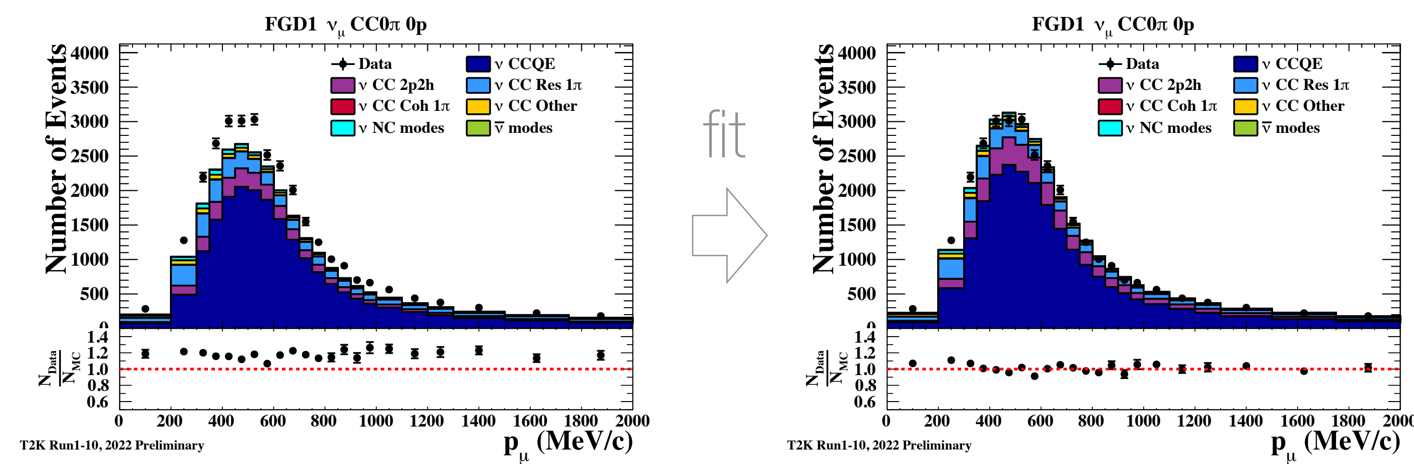
  ν_e appearance

Fit result with correlated flux × xsec propagated to far detector analysis via covariance matrix or joint ND+FD fit.

Both methods give consistent results.

Pre-ND **Post-ND**



ND fit p-value: **10.9%** (> 5% threshold)

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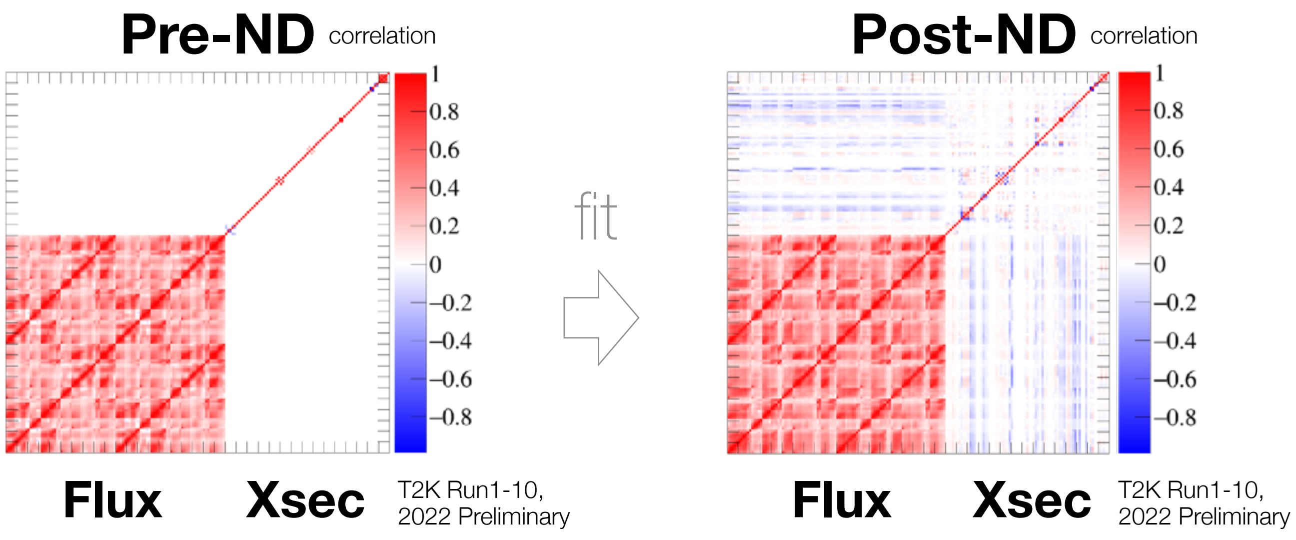

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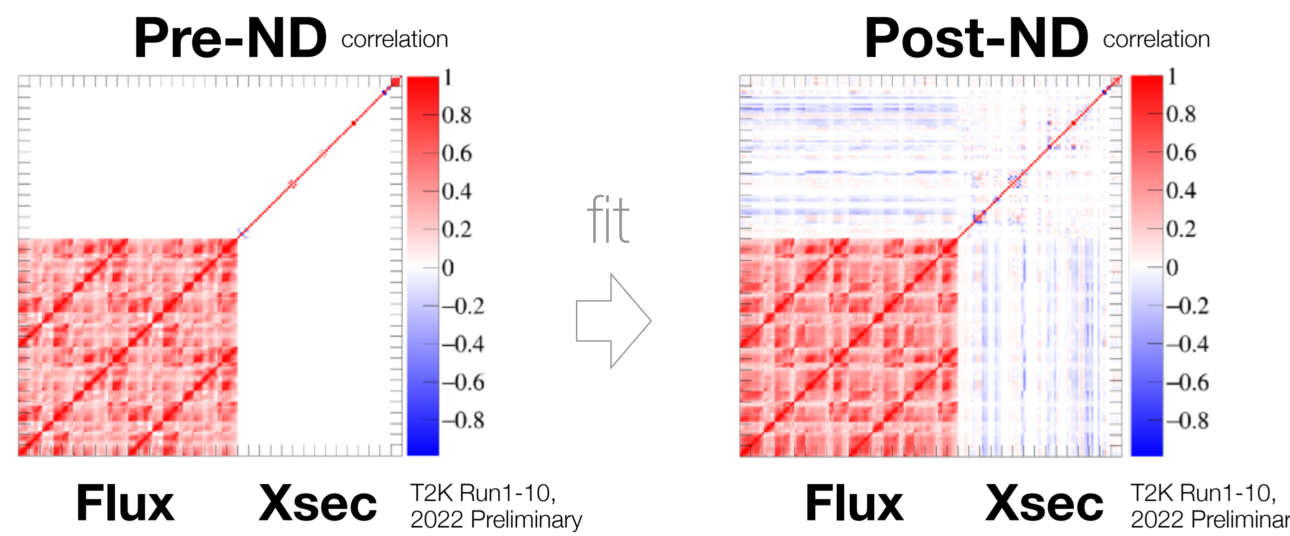
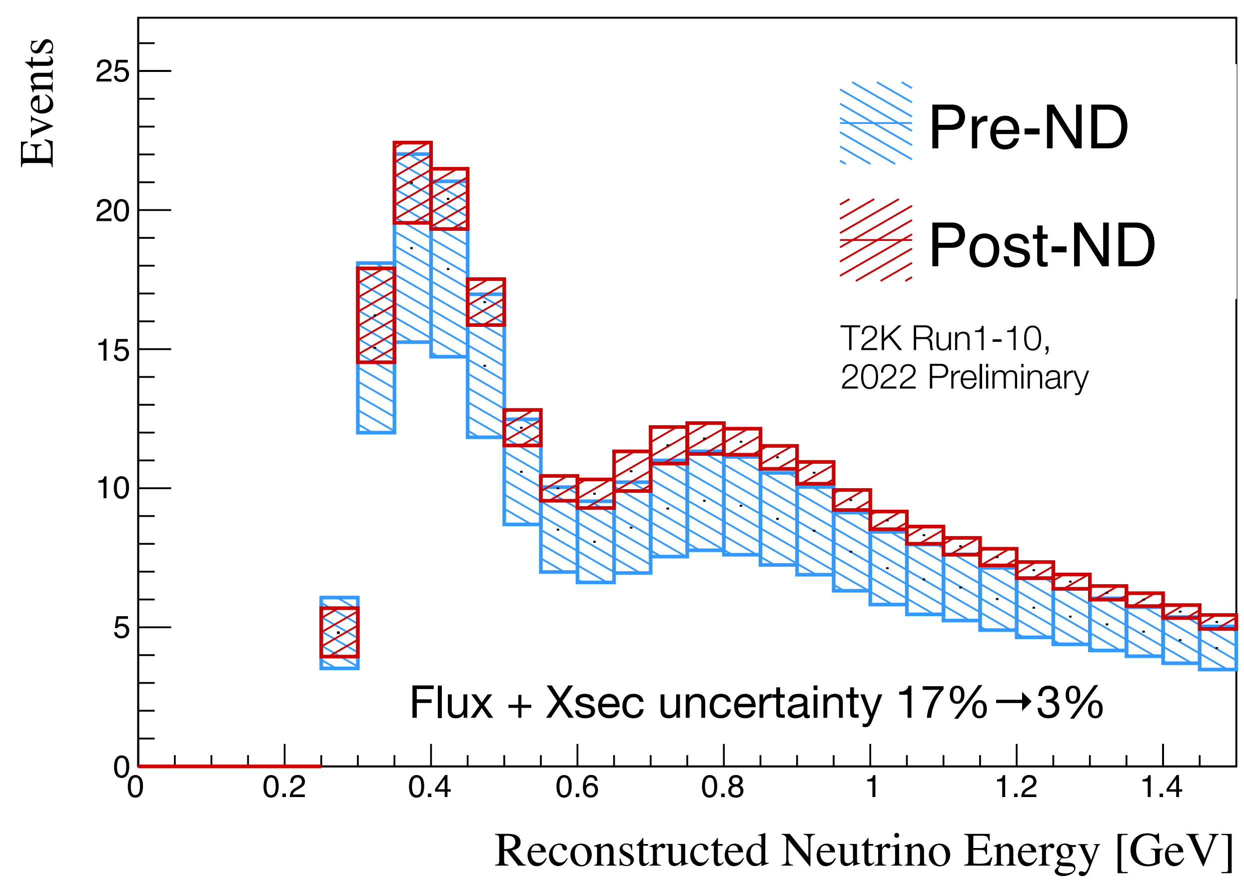


ND fit p-value: **10.9%** (> 5% threshold)

Total syst uncertainty on neutrino mode 1Rμ events at SK



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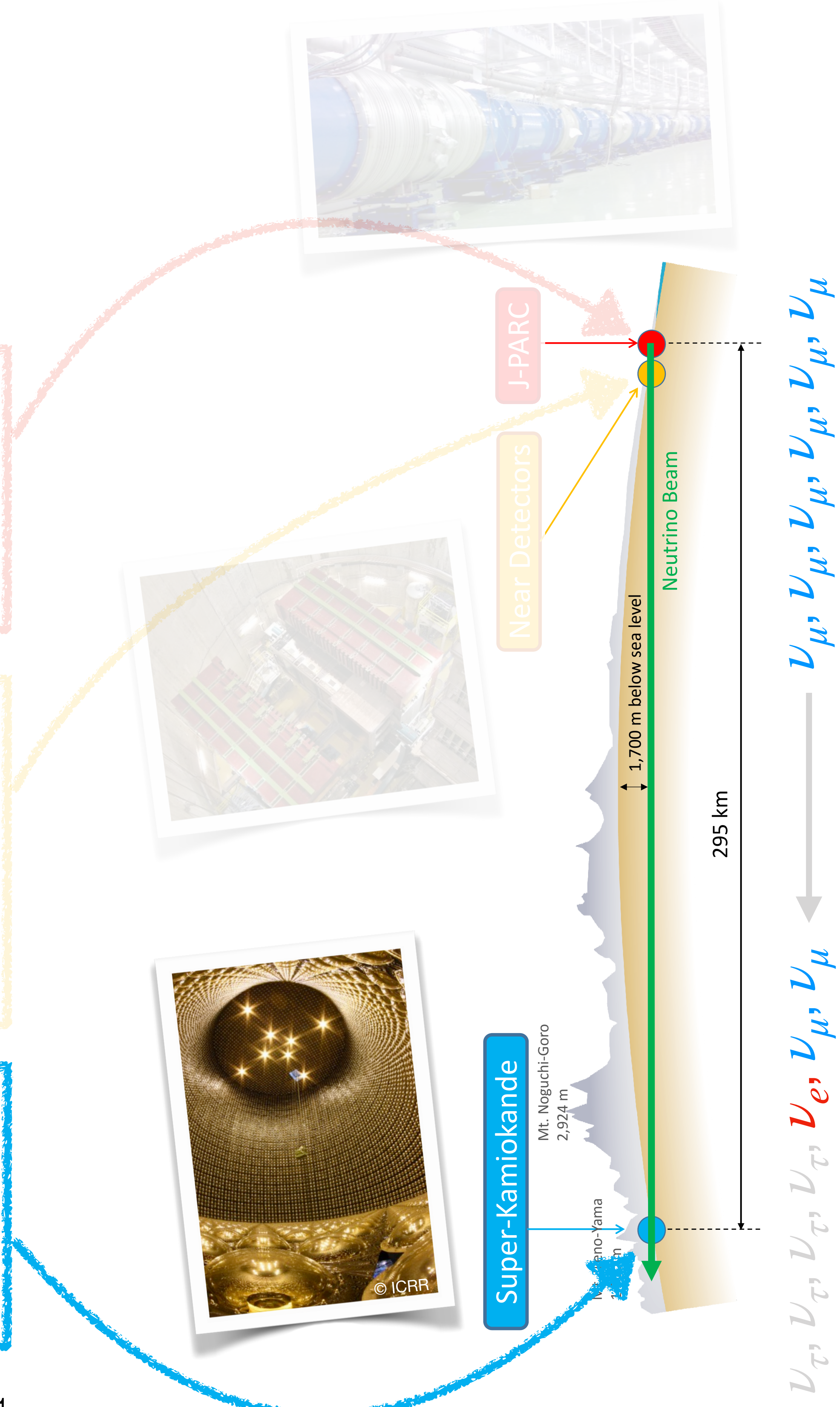

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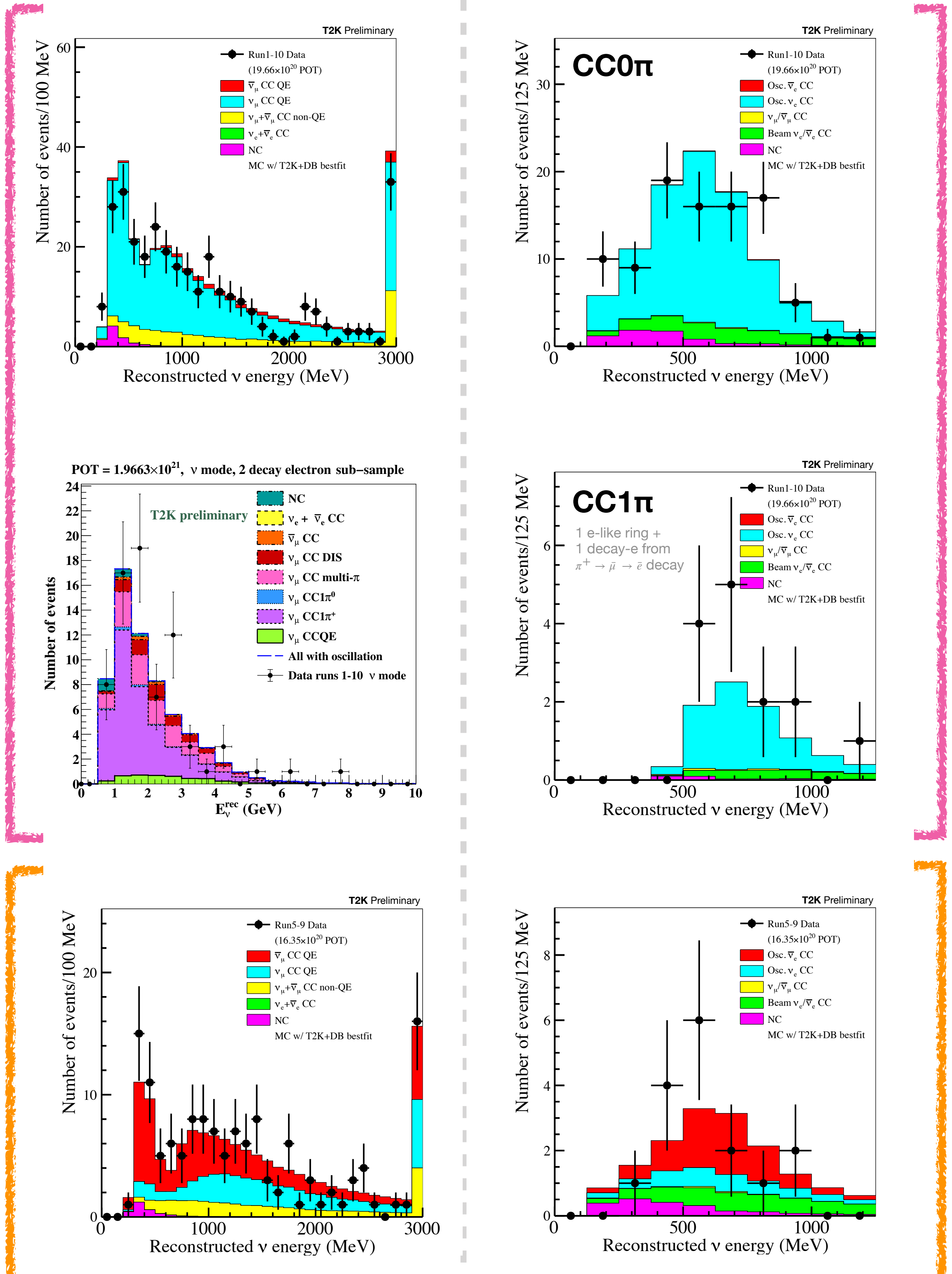
- 6 samples at SK
→ ν_μ **disappearance +**
ν_e **appearance**

μ-like ring | e-like ring

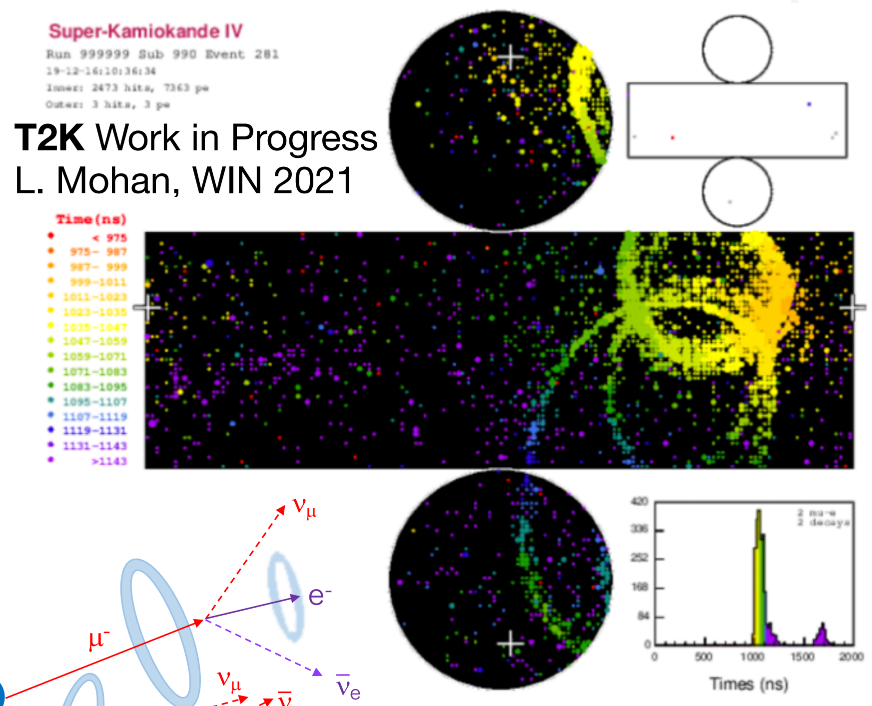
Neutrino mode

Anti-neutrino mode

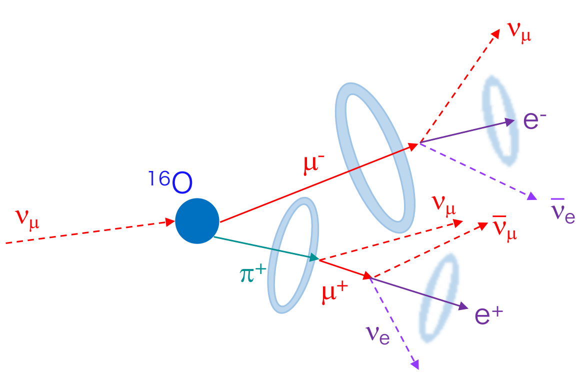


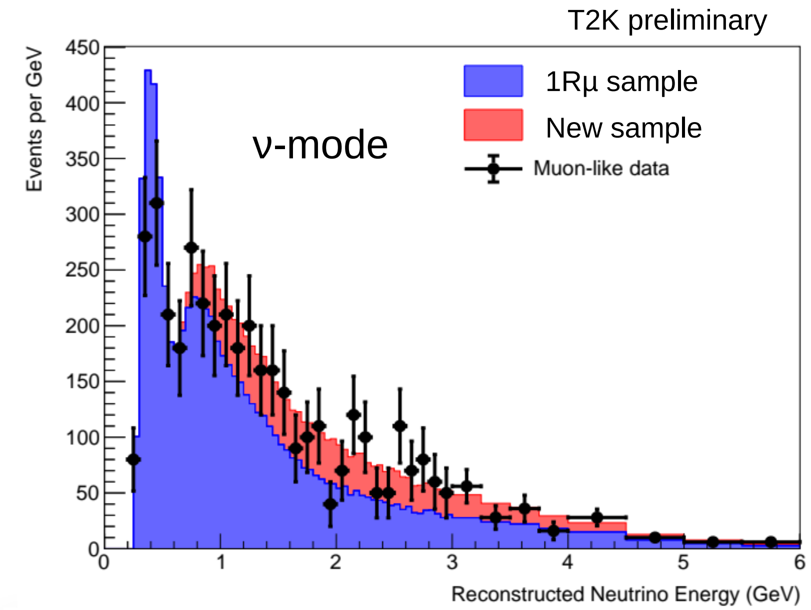
Multi-ring sample added for the first time

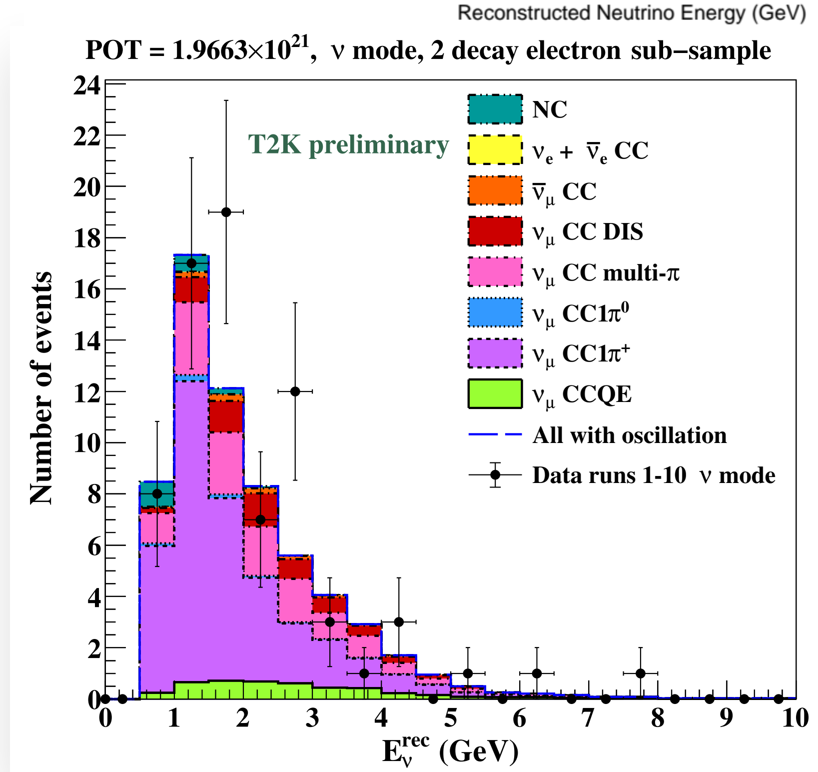
Analysis strategy

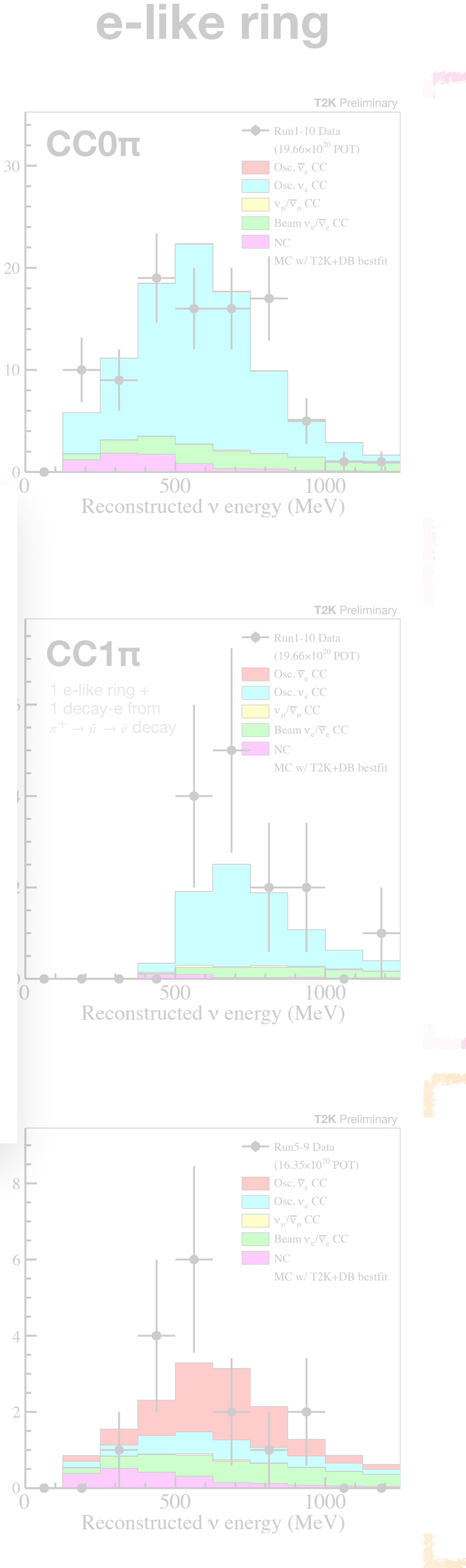


T2K Work in Progress
L. Mohan, WIN 2021









- 6 samples at SK
  → ν_μ **disappearance +**
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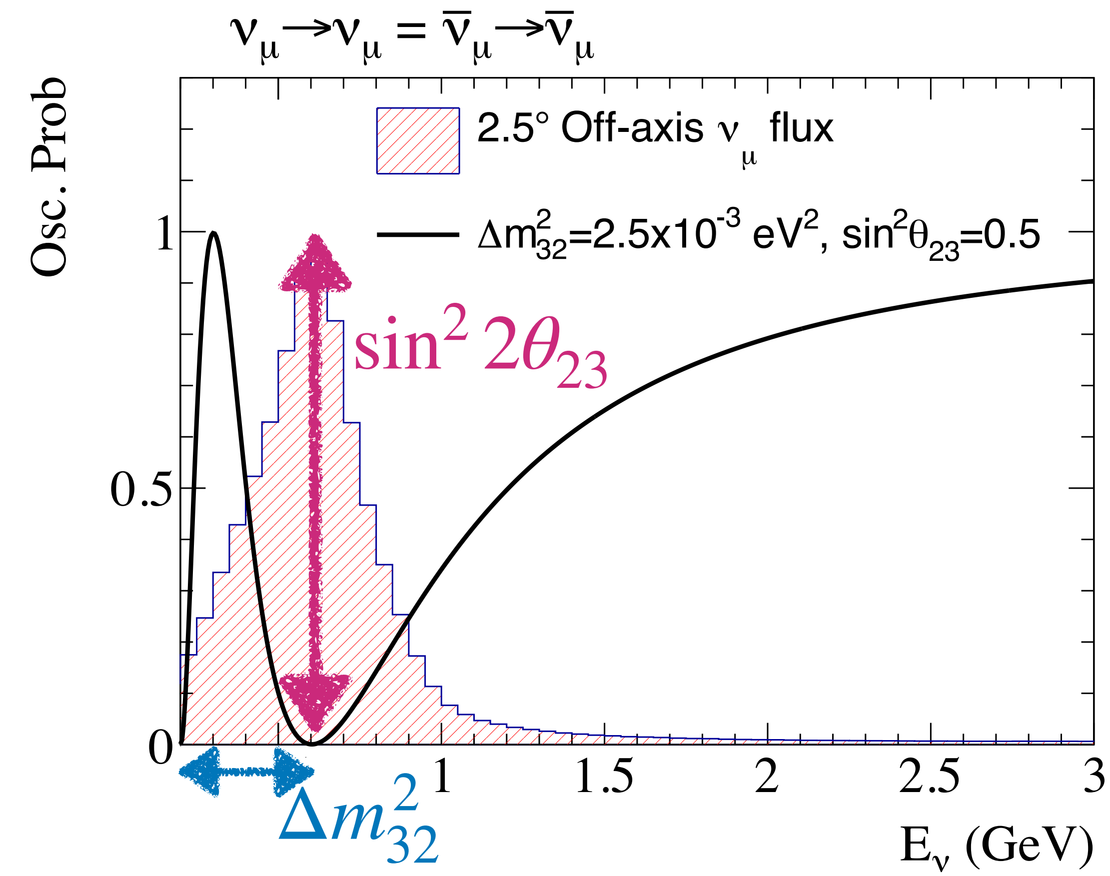
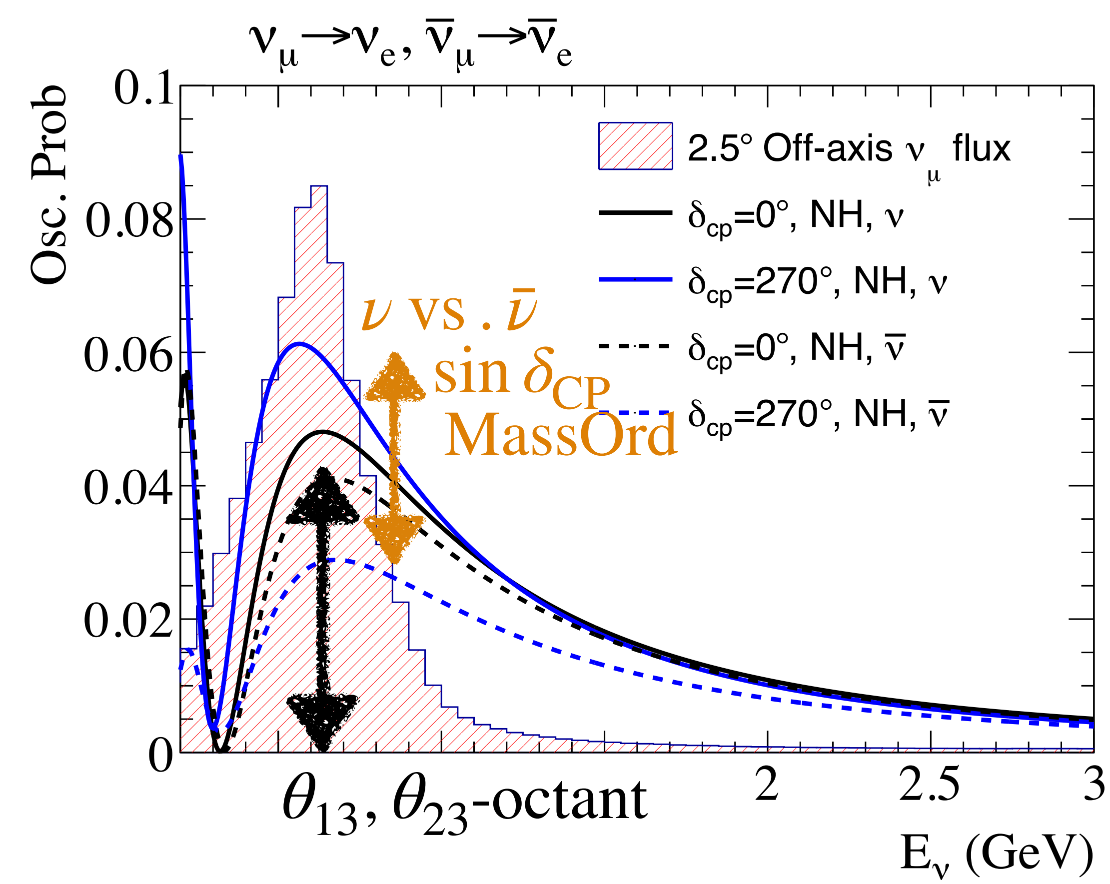
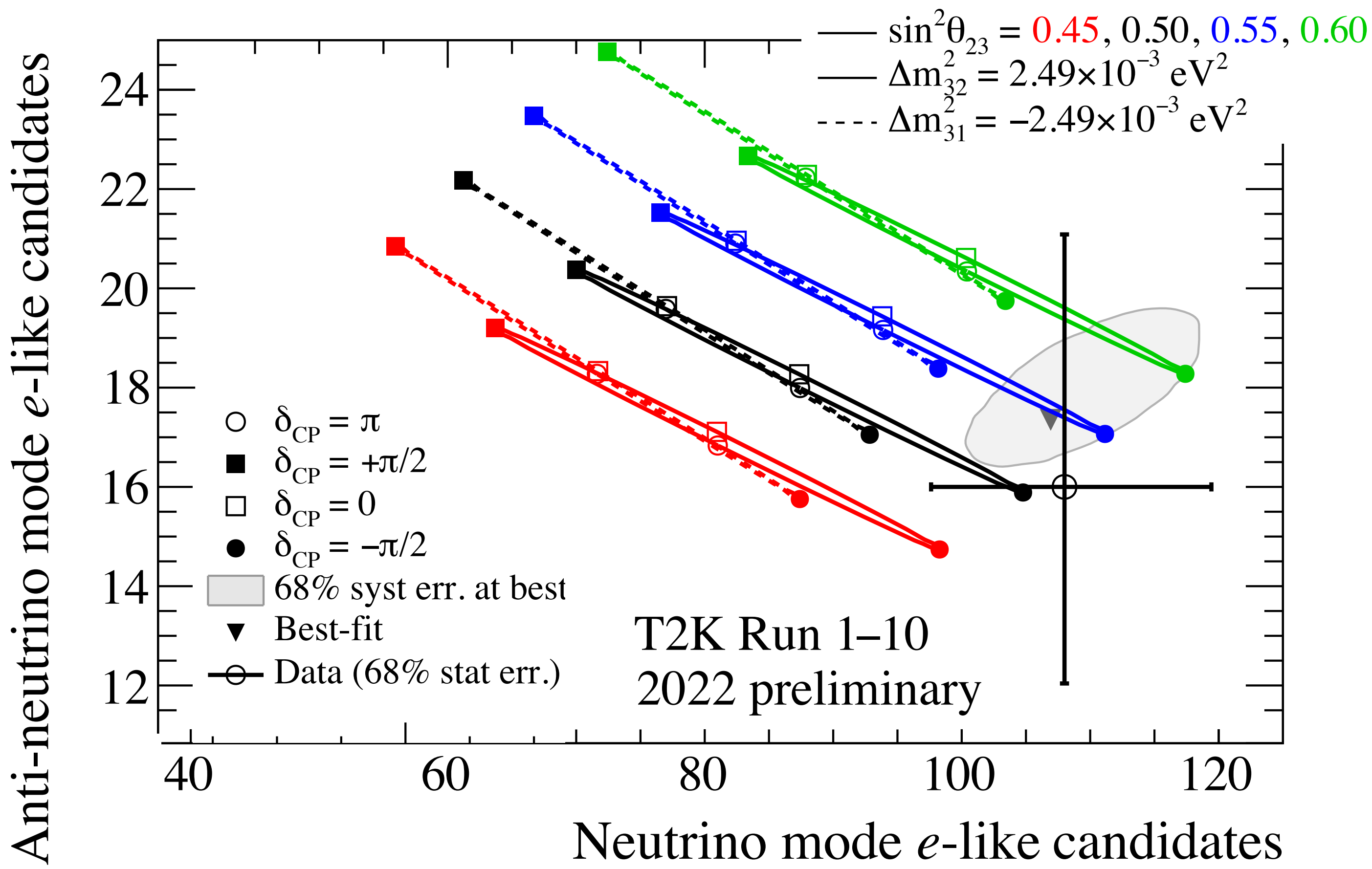
μ-like ring



e-like ring



ν_e vs. $\bar{\nu}_e$ appearance



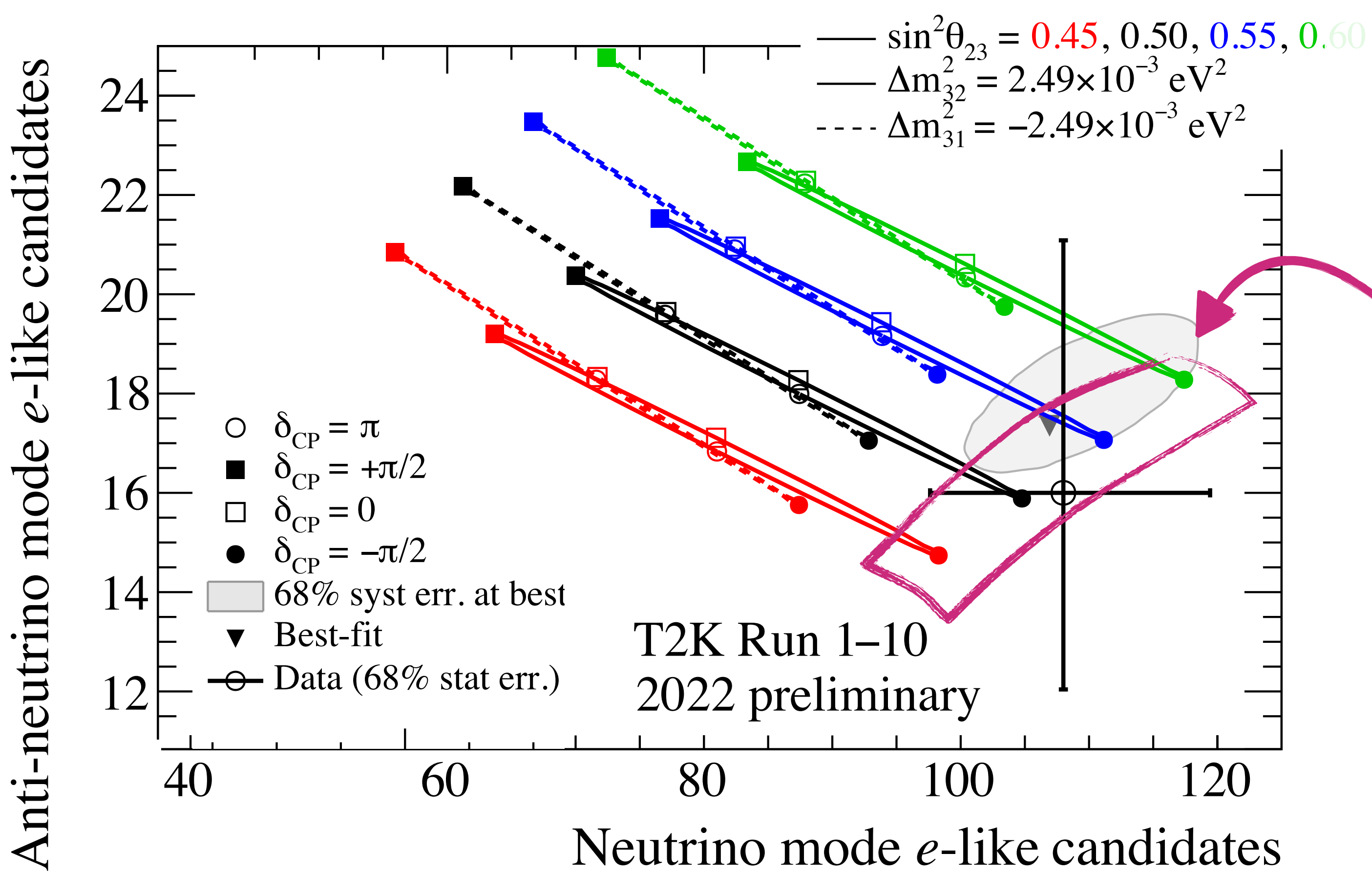
Octant

Mass ordering

Posterior prob.	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NO ($\Delta m^2_{32} > 0$)	0.20	0.54	0.74
IO ($\Delta m^2_{32} < 0$)	0.05	0.21	0.26
Sum	0.25	0.75	1.00

- Bi-event plot illustrates origin of data constraints.
- Best-fit δ_{CP} around **maximal CP-violation** $-\frac{\pi}{2}$
- Weak preference for **Normal ordering** with Bayes factor 2.8 $= P_{\mathrm{NO}}/P_{\mathrm{IO}}$
- Weak preference for **upper octant** with Bayes factor 3.0 $= P_{\mathrm{upper}}/P_{\mathrm{lower}}$

ν_e vs. $\bar{\nu}_e$ appearance



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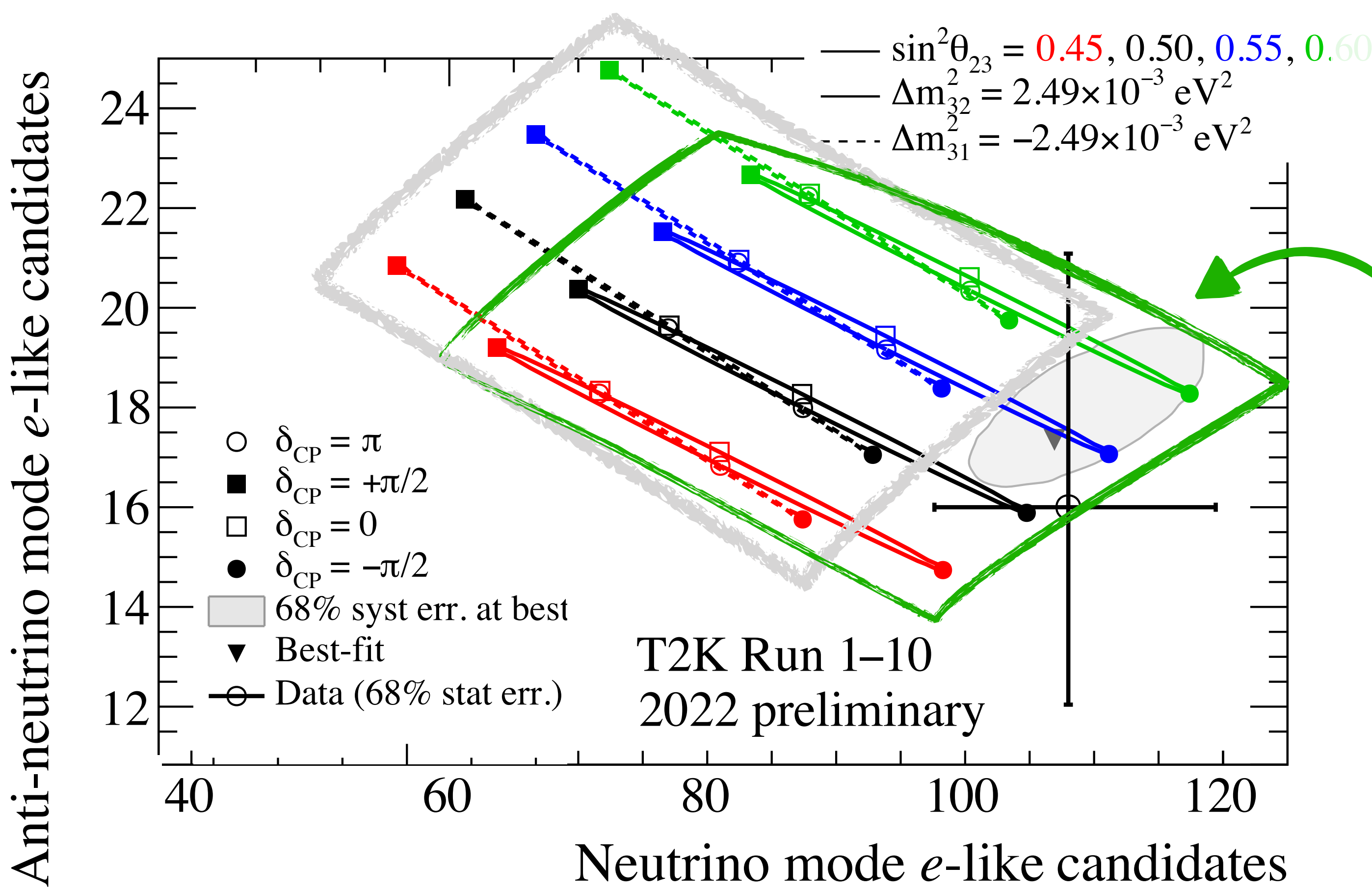

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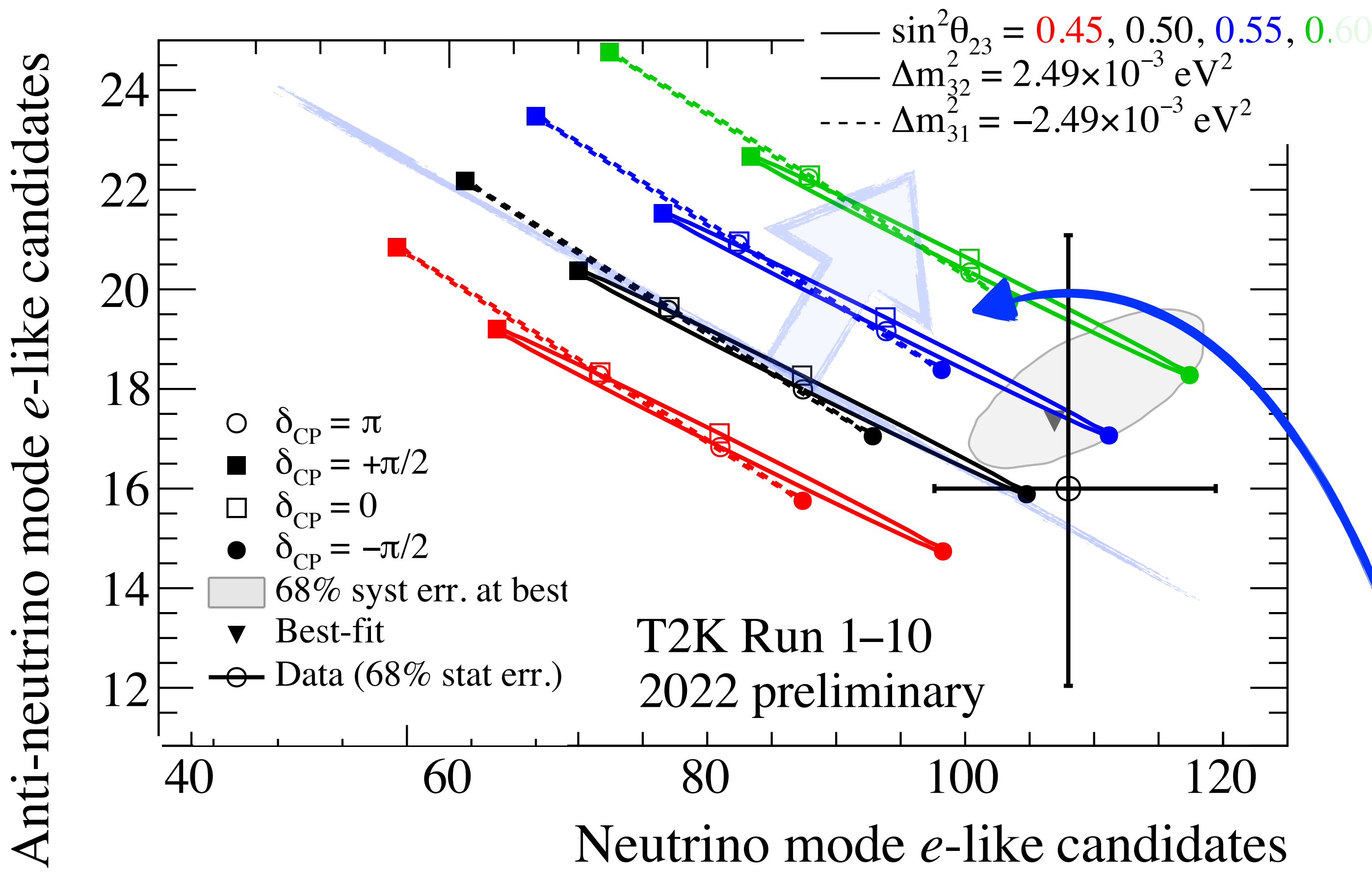
ν_e vs. $\bar{\nu}_e$ appearance



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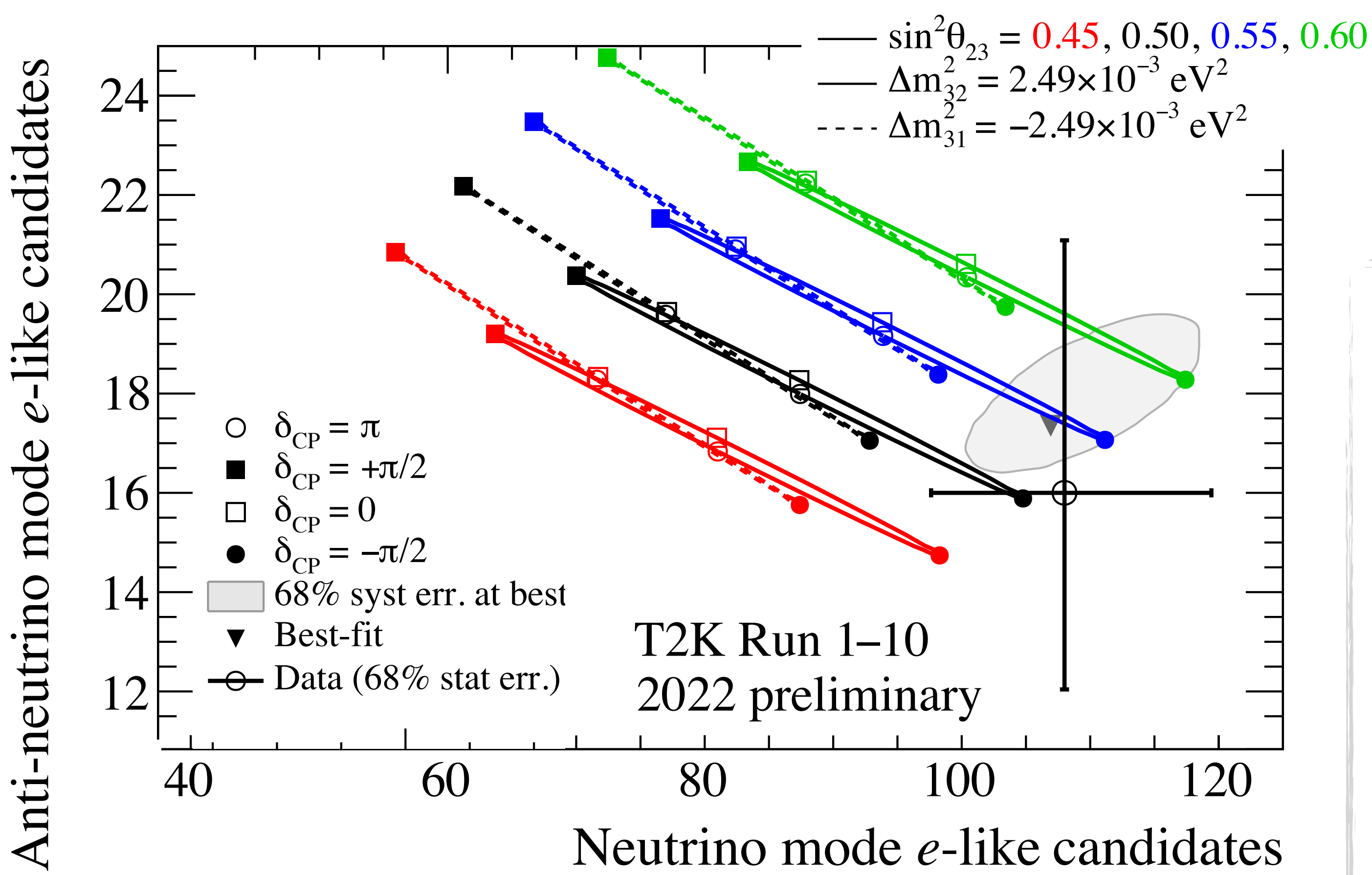
Sum	0.25	0.75	1.00

- Weak preference for **upper octant** with Bayes factor 3.0 $= \dfrac{P_{\text{upper}}}{P_{\text{lower}}} = \dfrac{0.75}{0.25}$

ν_e vs. $\bar{\nu}_e$ appearance



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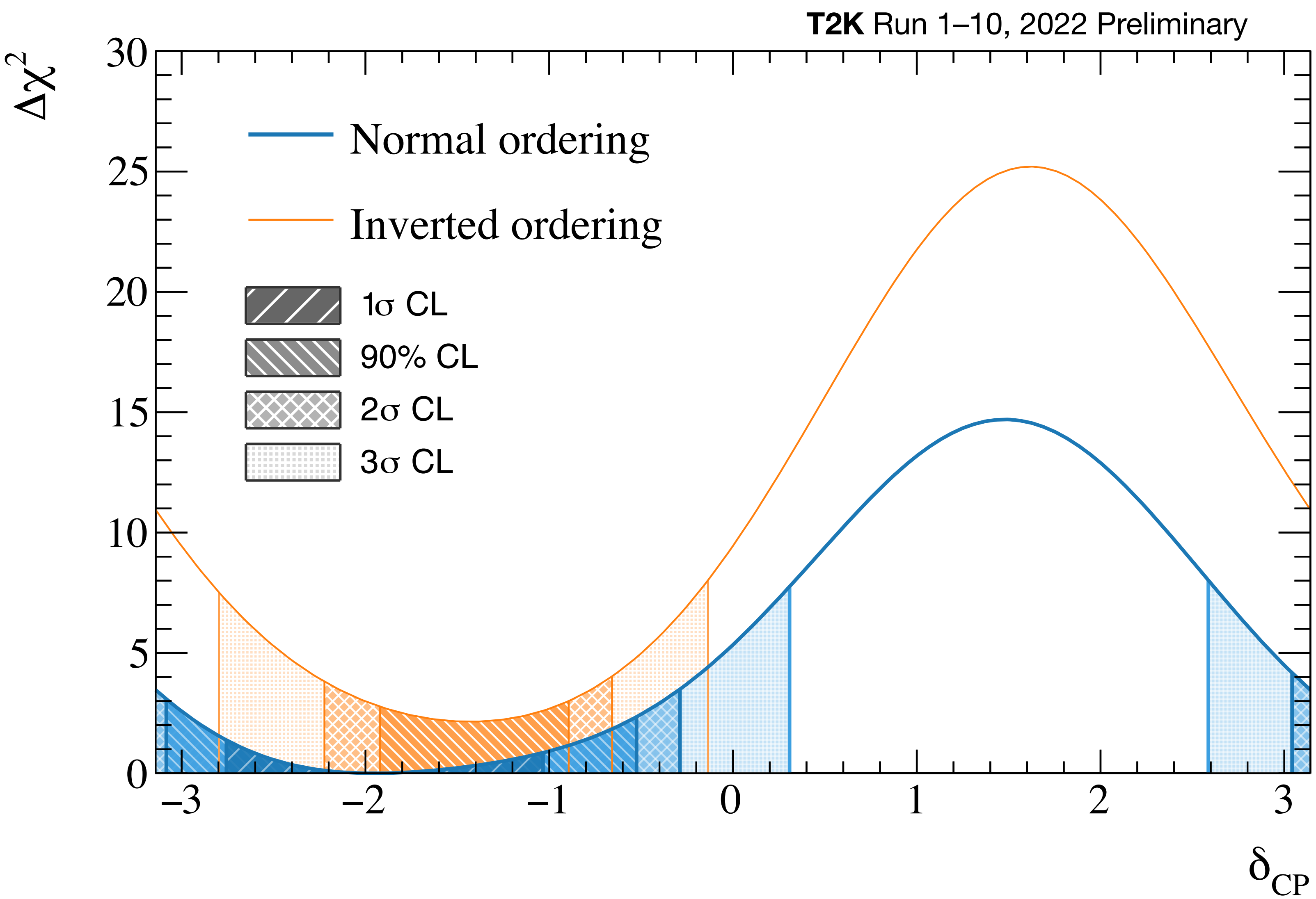
- Weak preference for **Normal ordering** with Bayes factor 2.8 $= P_{\rm NO}/P_{\rm IO}$

- Weak preference for **upper octant** with Bayes factor 3.0 $= P_{\rm upper}/P_{\rm lower}$

Overall less prominent than in previous analysis

Constraints on δ_{CP} and mass ordering



- Large region **excluded at 3σ**
- CP-conservation $\{0, \pi\}$ **excluded at 90%**, π is within 2σ
- Weak preference of **normal ordering**

NOvA + T2K

810 km / 295 km

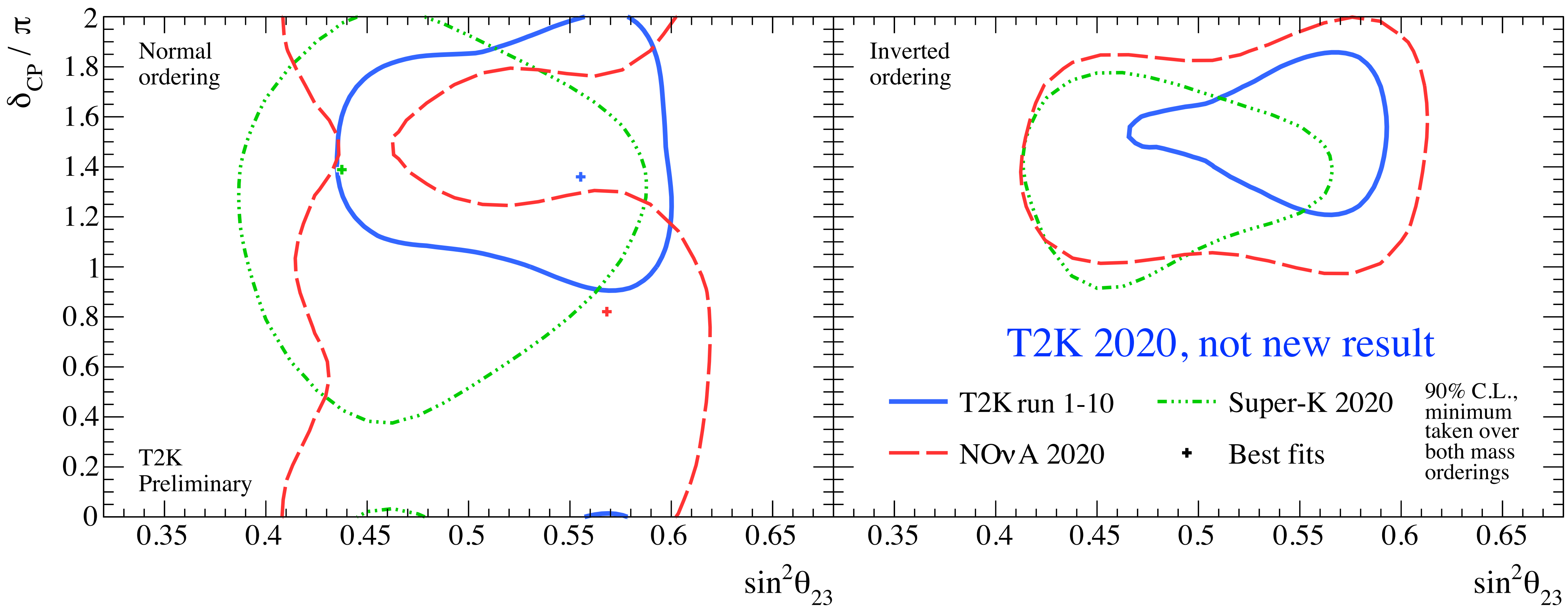
Ongoing joint fits

SK + T2K

atmospheric + accelerator

Comparison of released contours (not joint fit)

NOvA results: A. Himmel (2020) Zenodo, (preliminary)
SK results: Y. Nakajima (2020) Zenodo, (preliminary)
NOvA and T2K use Feldman-Cousins, SK use fixed $\Delta\chi^2$



- Joint fits between experiments with different oscillation baselines/energies and detector technologies

→ expect increased sensitivity in δ_{CP}, mass ordering, θ_{23} octant **beyond** stats increase from resolved degeneracies and syst constraints

- important to understand potentially non-trivial syst. **correlations** between experiments

First results expected soon!

どれが好き？

いろいろなニュートリノを見るスーパーカミオカンデちゃん

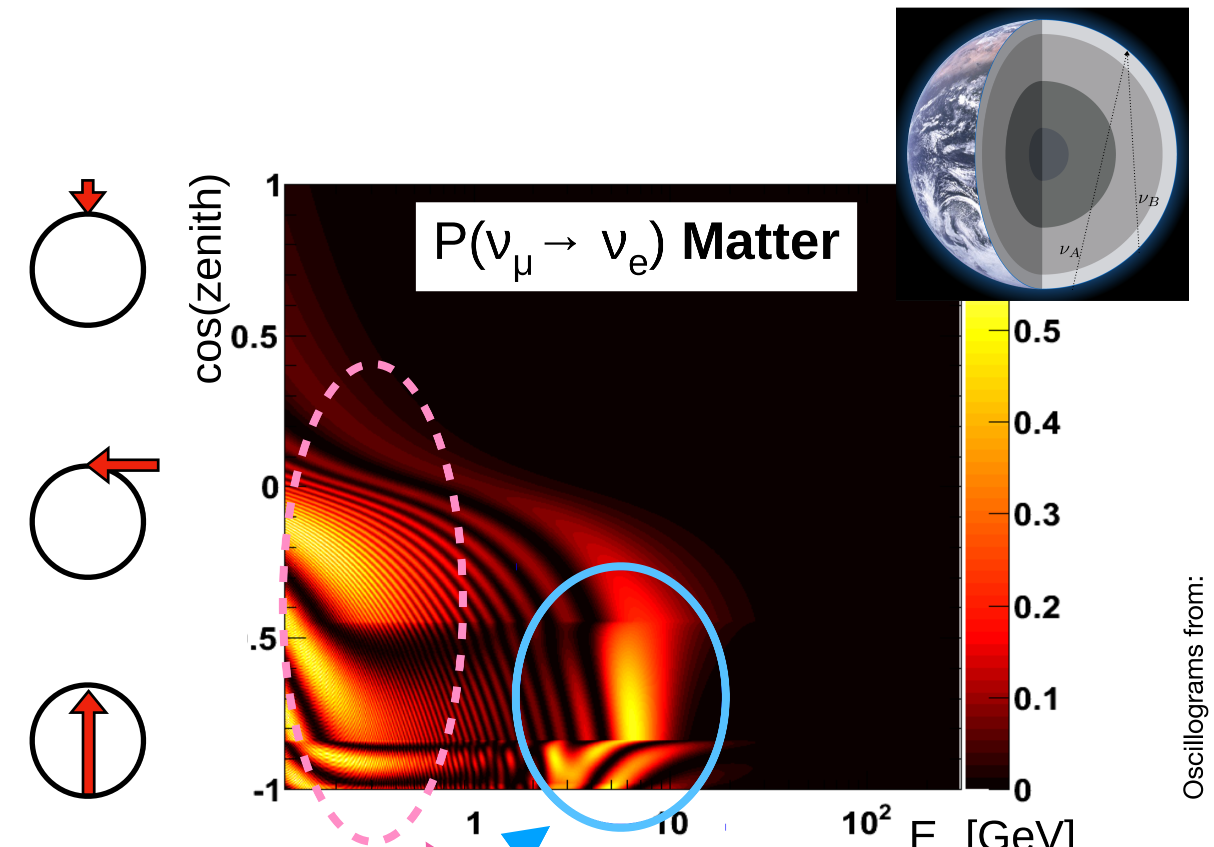
ニュートリノ大好きスーパーカミオカンデちゃん、大気で作られたニュートリノにJ-PARCさんが作ったニュートリノ、超新星爆発で生まれるニュートリノに昔の超新星爆発のなごりのニュートリノ、他にもたくさん見ています。

大気・加速器ニュートリノ振動の同時解析

SK + T2K Joint fit

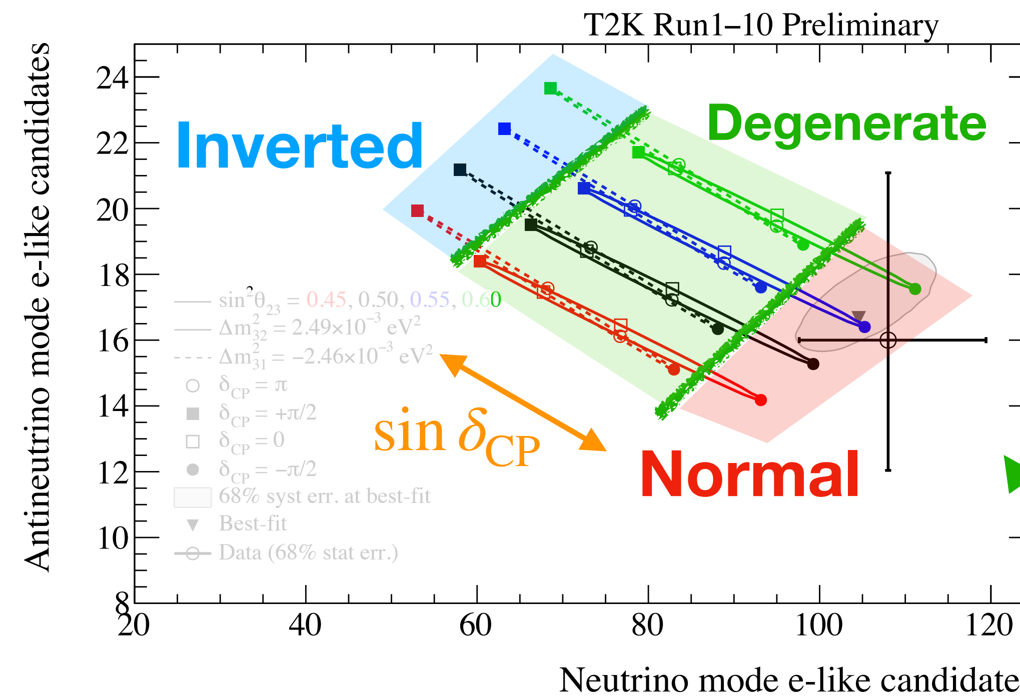
CP and mass ordering sensitivity

SK Atmospheric



- Resonance in Earth mantle & core sensitive to mass ordering
- Weakly sensitive to δ_{CP} via normalization of sub-GeV e-like

T2K Accelerator

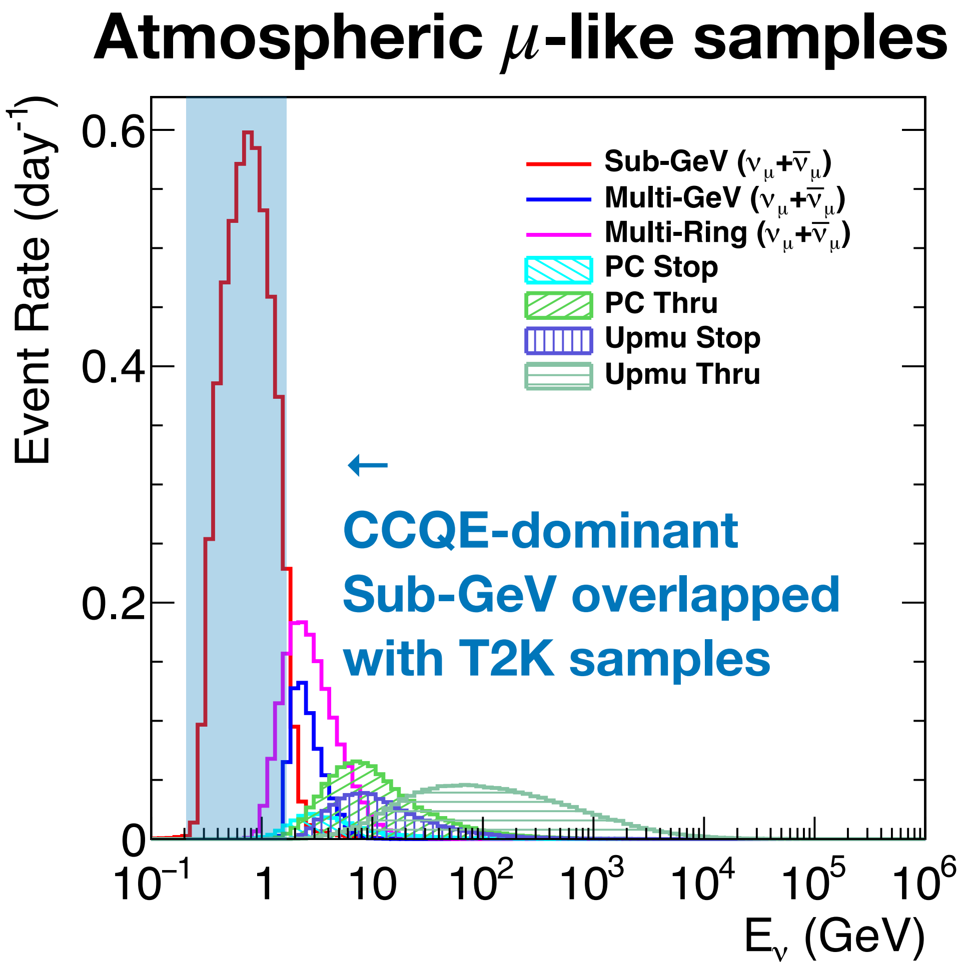


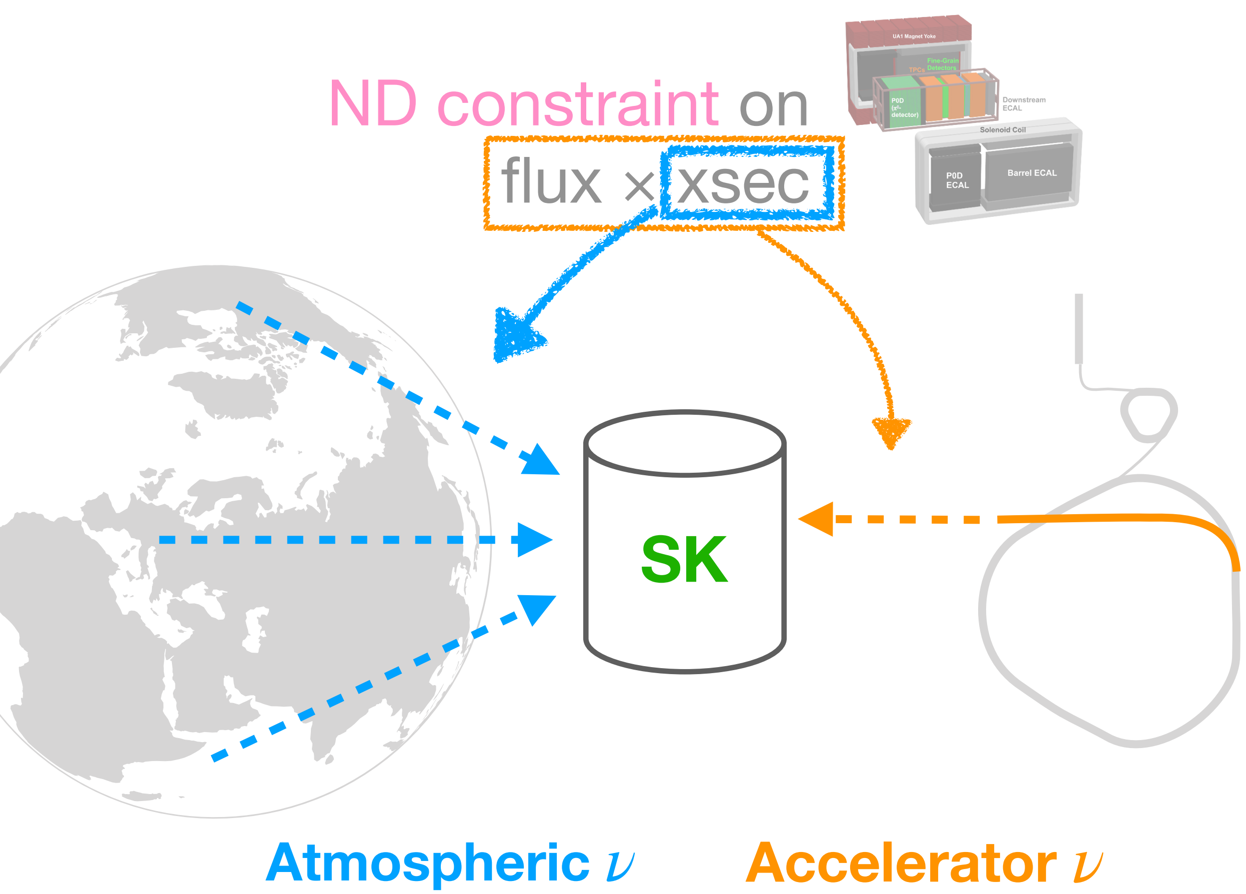
- Anti-correlated change of $\nu_e, \bar{\nu}_e$ appearance probability → δ_{CP}
- For large changes also weakly sensitive to mass ordering

degenerate

When combined, can resolve degeneracy and have better CP violation sensitivity!

Systematic correlations

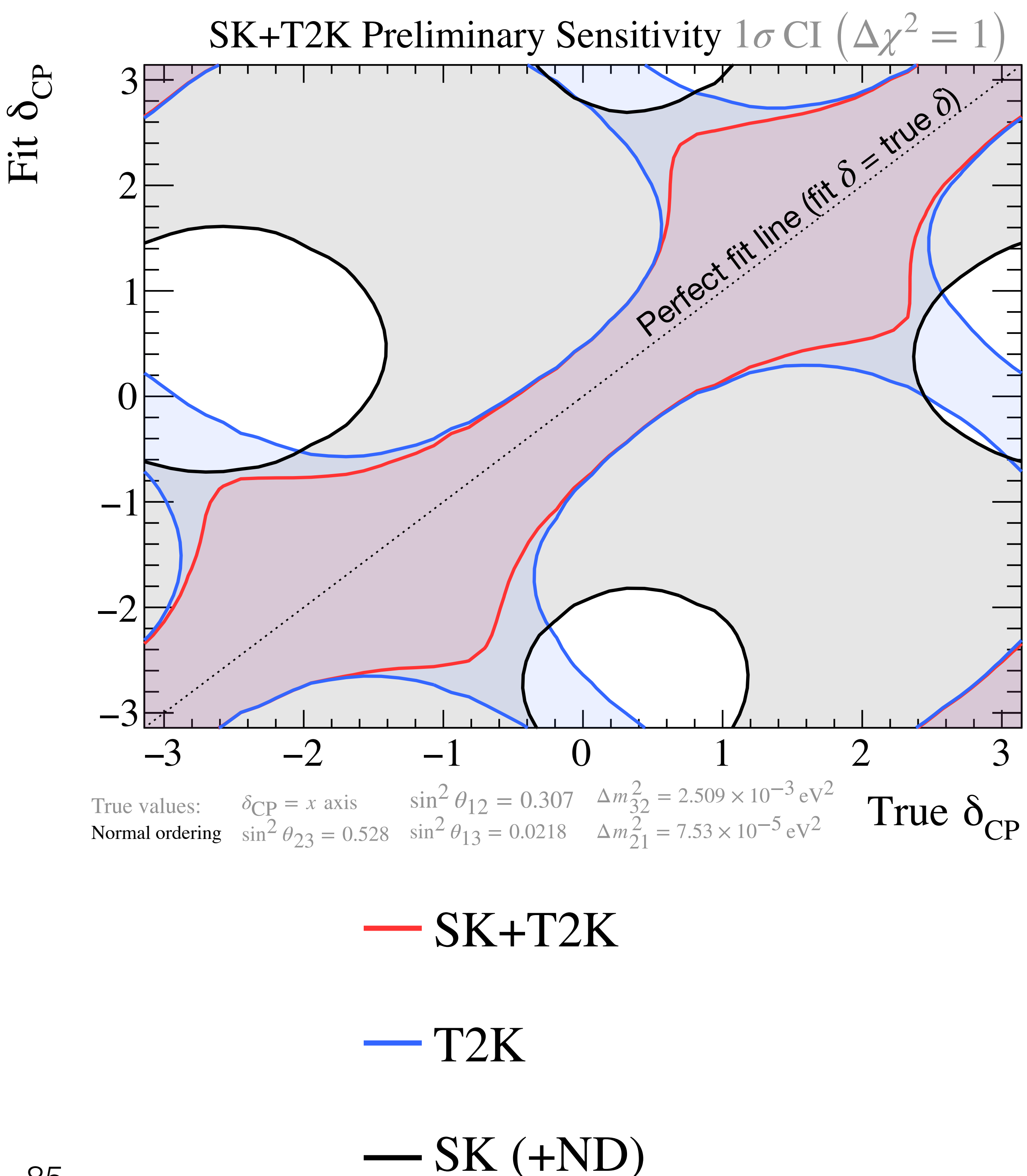




- Overlapped true energy region
  → coherent **interaction model** to capture correlations
  → Bonus: **ND constraint** for atmospherics!
  → developed additional systematics to capture effects important for atm. that ND is insensitive to

- Same Super-K detector used by both experiments
  → estimate contribution from **detector syst.** correlations

Sensitivity for various values of true δ_{CP}

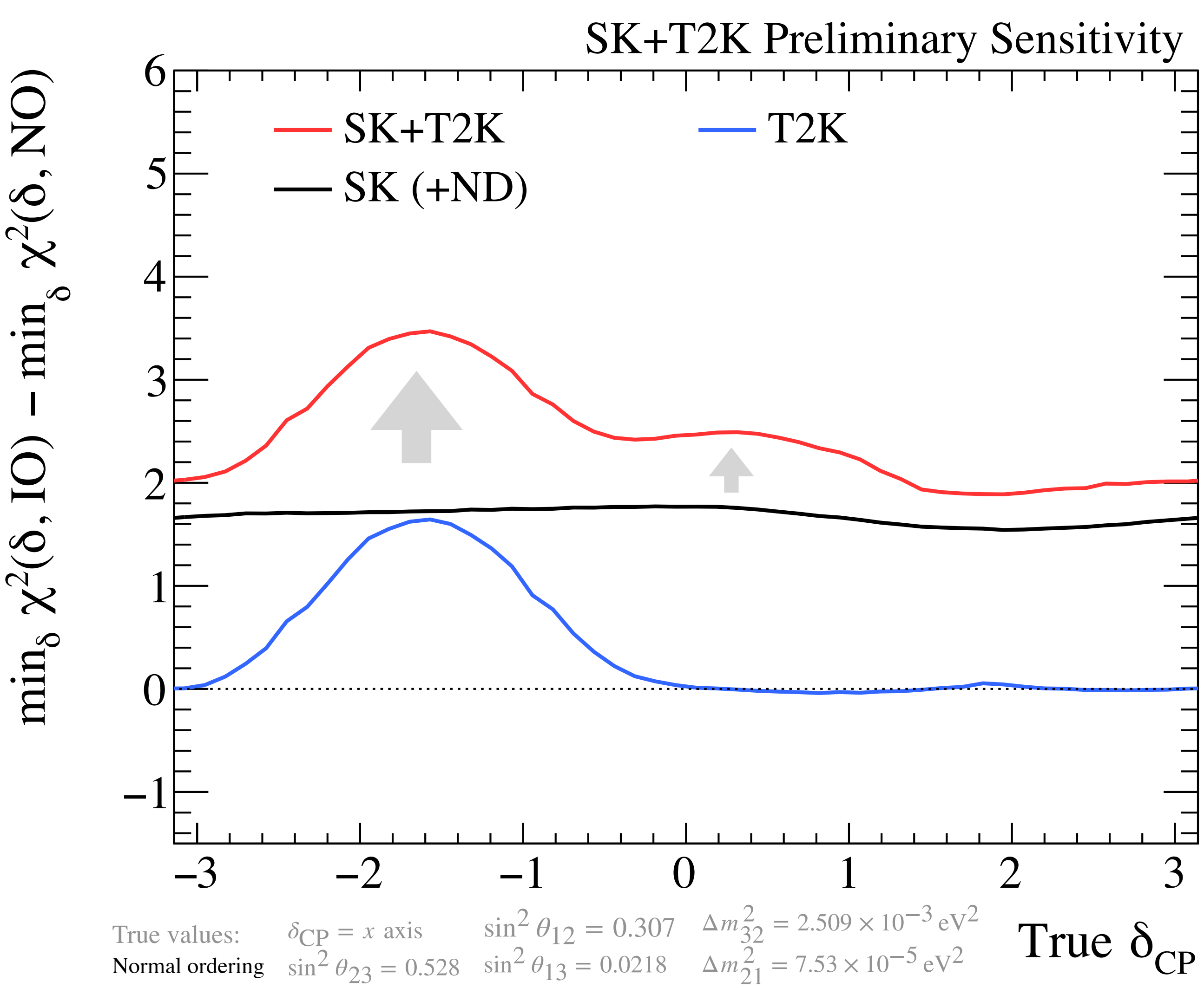


δ_{CP} assuming fixed mass ordering

- T2K is more sensitive, but joint fit with SK can resolve $\text{sign}(\cos\delta_{CP})$ degeneracy due to different sensitive phase
- Little effect from correlations with other parameters (≈ naive sum).

e.g. ND280 systematics constraint has little impact on δ_{CP} for SK results (backup)

Sensitivity for various values of true δ_{CP}



— SK+T2K

— T2K

— SK (+ND)

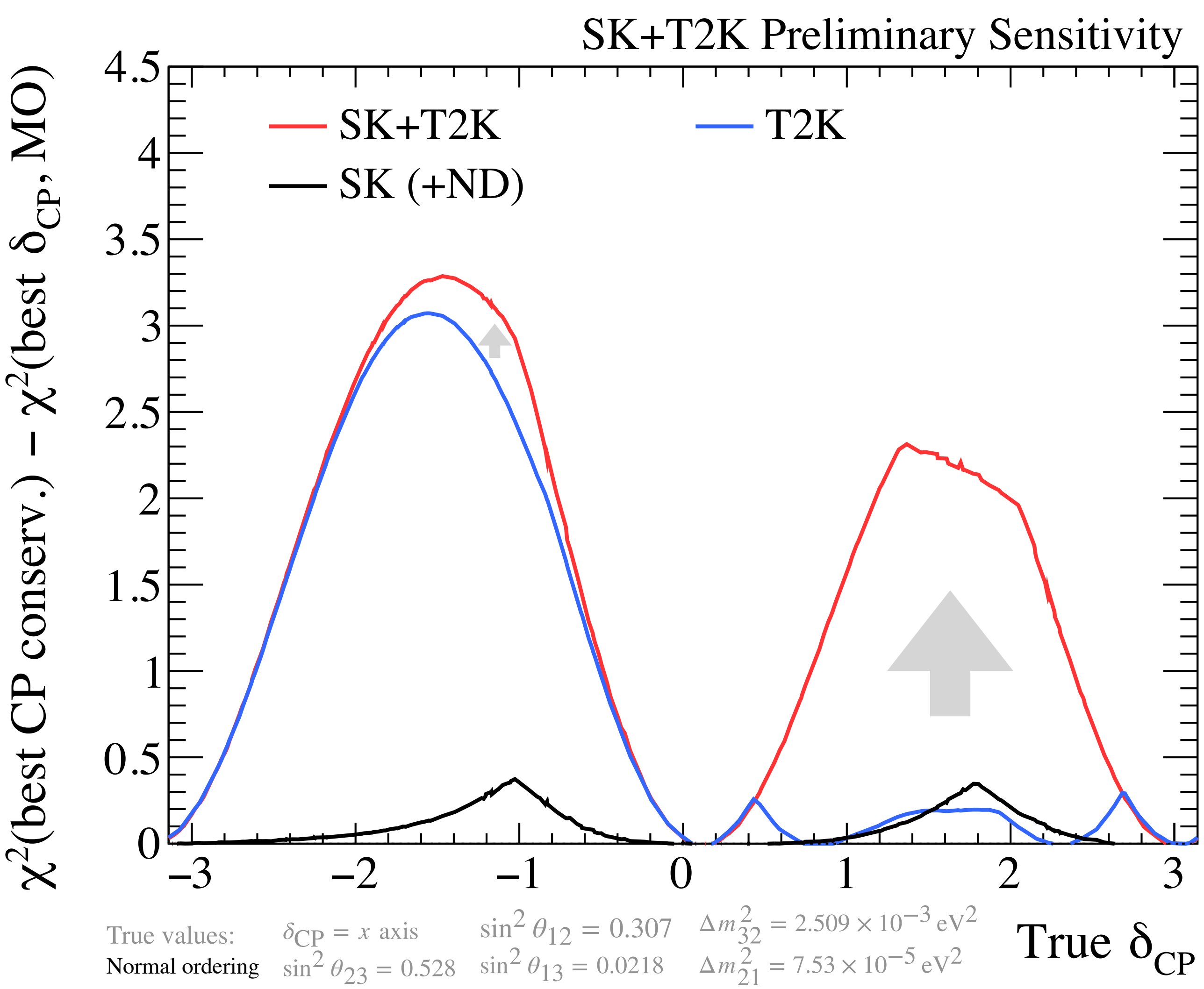
Mass ordering

- Mean sensitivity to reject wrong mass ordering improves with joint fit:

  T2K constraint very dependent on true δ_{CP}, SK atm on $\sin^2\theta_{23}$.

- At currently preferred values $\delta_{CP} \approx -\pi/2$, $\sin^2\theta_{23} \approx 0.56$ expect contribution from both experiments

Sensitivity for various values of true δ_{CP}



SK+T2K

T2K

SK (+ND)

CP violation

- Mean sensitivity to reject the CP conservation hypothesis for various values of true dcp

  CP conservation defined as $\sin\delta_{CP} = 0$ in either MO

- For true $\sin\delta > 0$ in NO (true $\sin\delta < 0$ in IO), T2K cannot exclude CP conservation due to MO-degeneracy

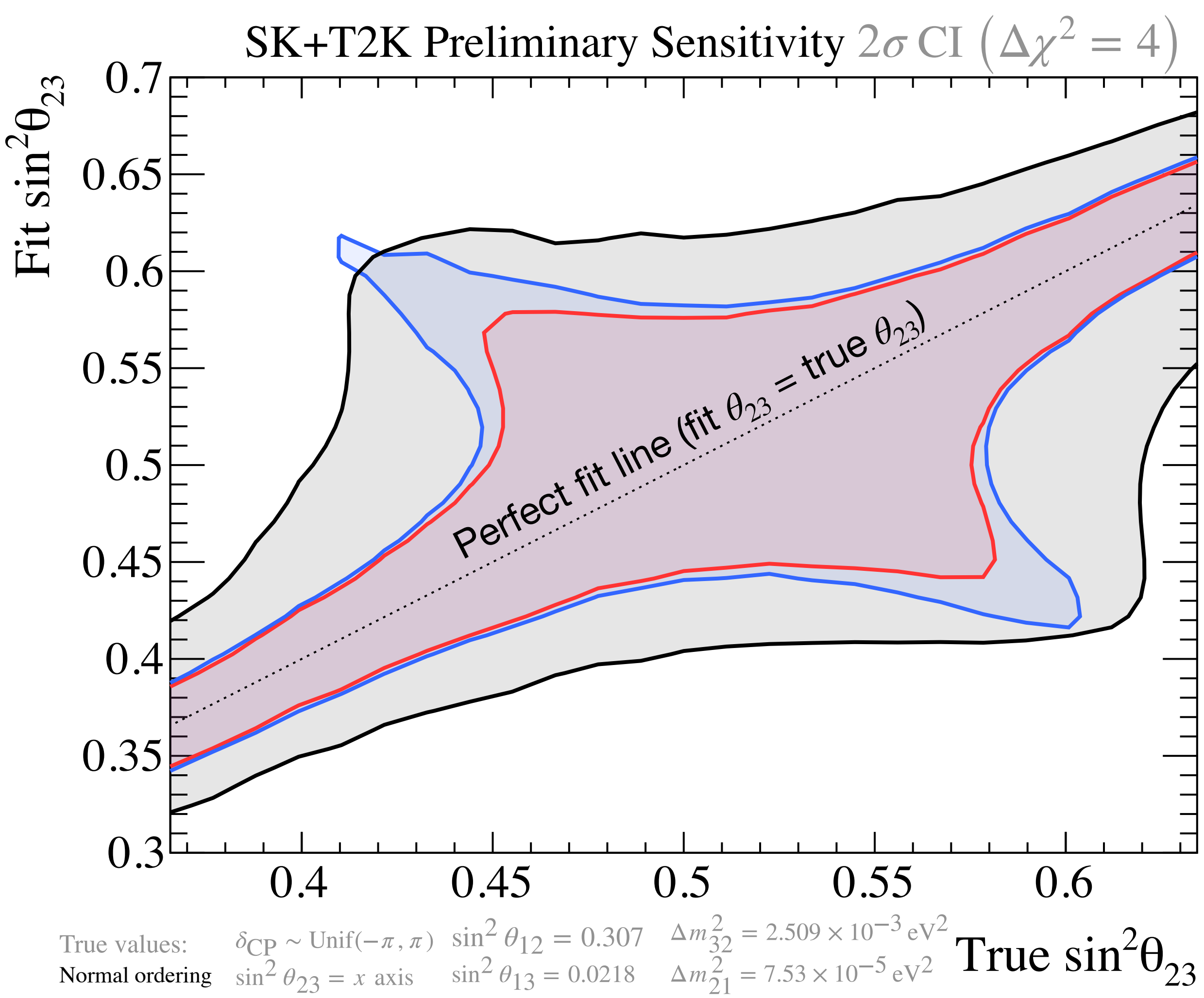
- SK's MO-sensitivity is able to break this degeneracy

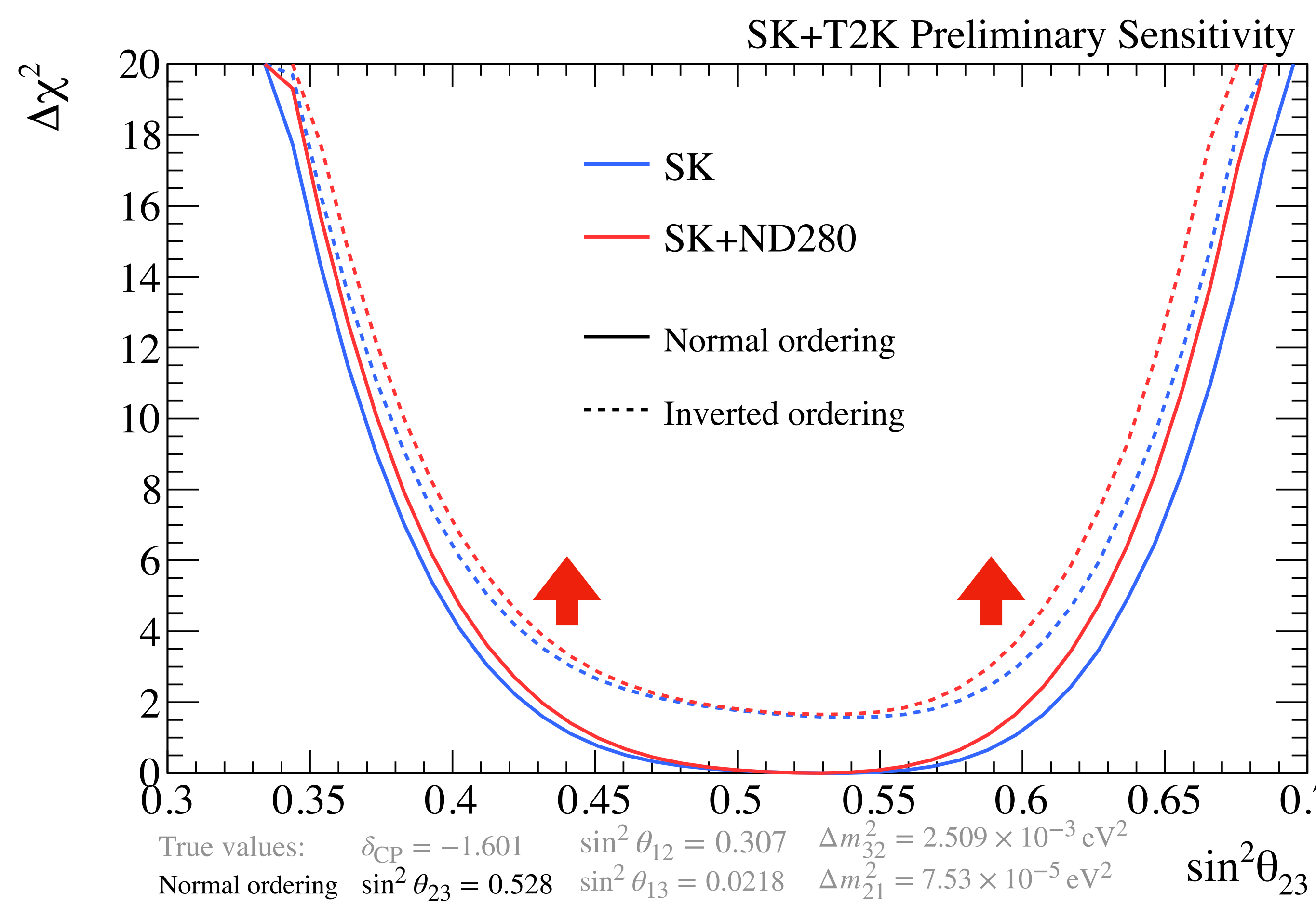
$\sin^2\theta_{23}$

— SK+T2K

— T2K

— SK (+ND)

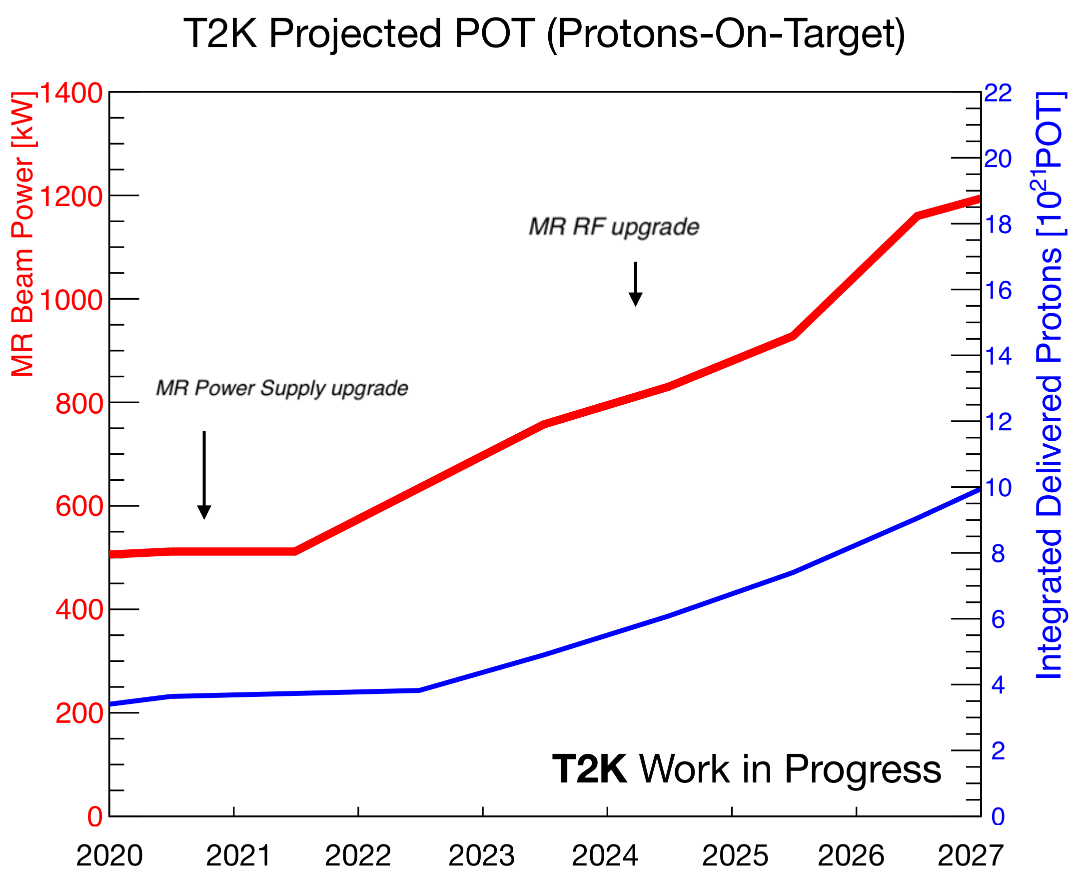




- T2K is more sensitive to $\sin^2 2\theta_{23}$, but joint fit with SK can resolve octant degeneracy $\left(\sin^2\theta_{23} </> 0.5\right)$

- Cross-section constraint from T2K near-detector appears to improve the SK-constraint for $\sin^2\theta_{23}$
- This indirectly also improves the mass ordering constraint

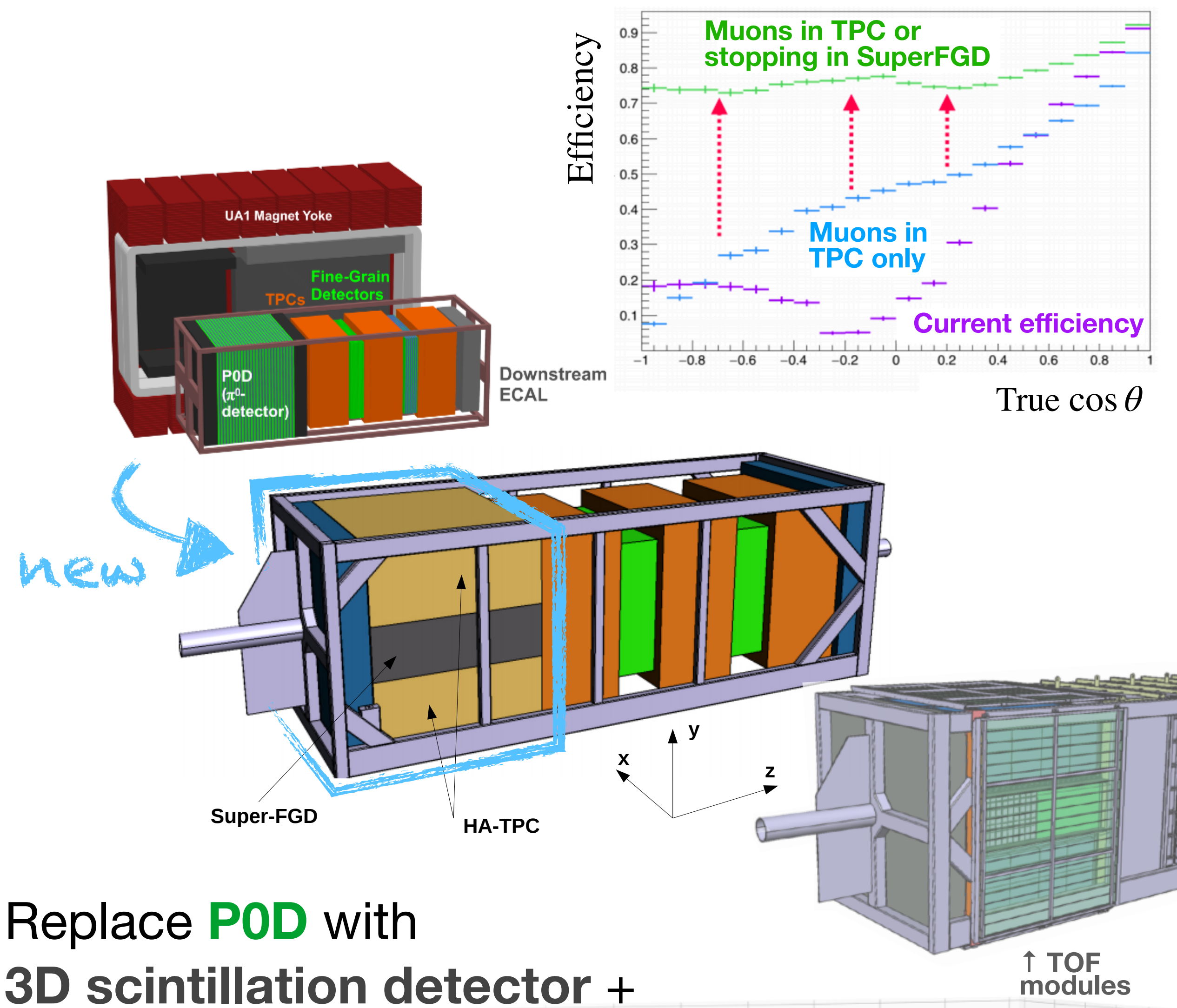
Beam line upgrade



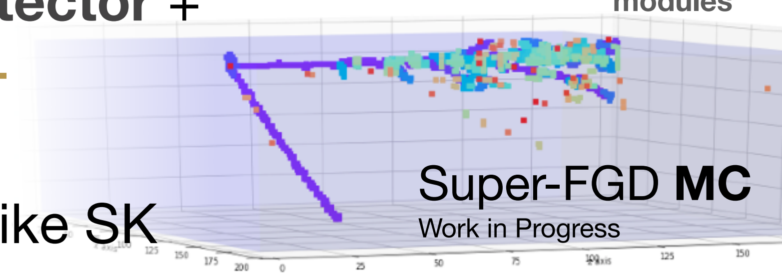
- Increase **beam power** from ~500 kW to 1.3 MW via upgrades to main ring power supply and RF (mostly increased rep rate)
- Many upgrades to neutrino beam line (target, beam monitors, …) ongoing to accept 1.3 MW beam
- Increase **horn current** 250 kA → 320 kA for ~10% more neutrinos/beam-power and reduced wrong-sign background

  Aiming for 320 kA operation in next run!

ND280 upgrade



Replace **P0D** with
3D scintillation detector +
high-angle TPCs +
TOF enclosure



→ 4π acceptance like SK

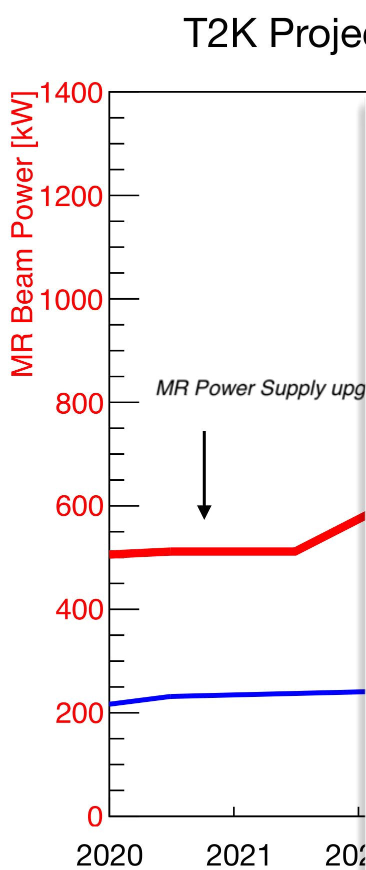
→ lower (proton) mom. threshold

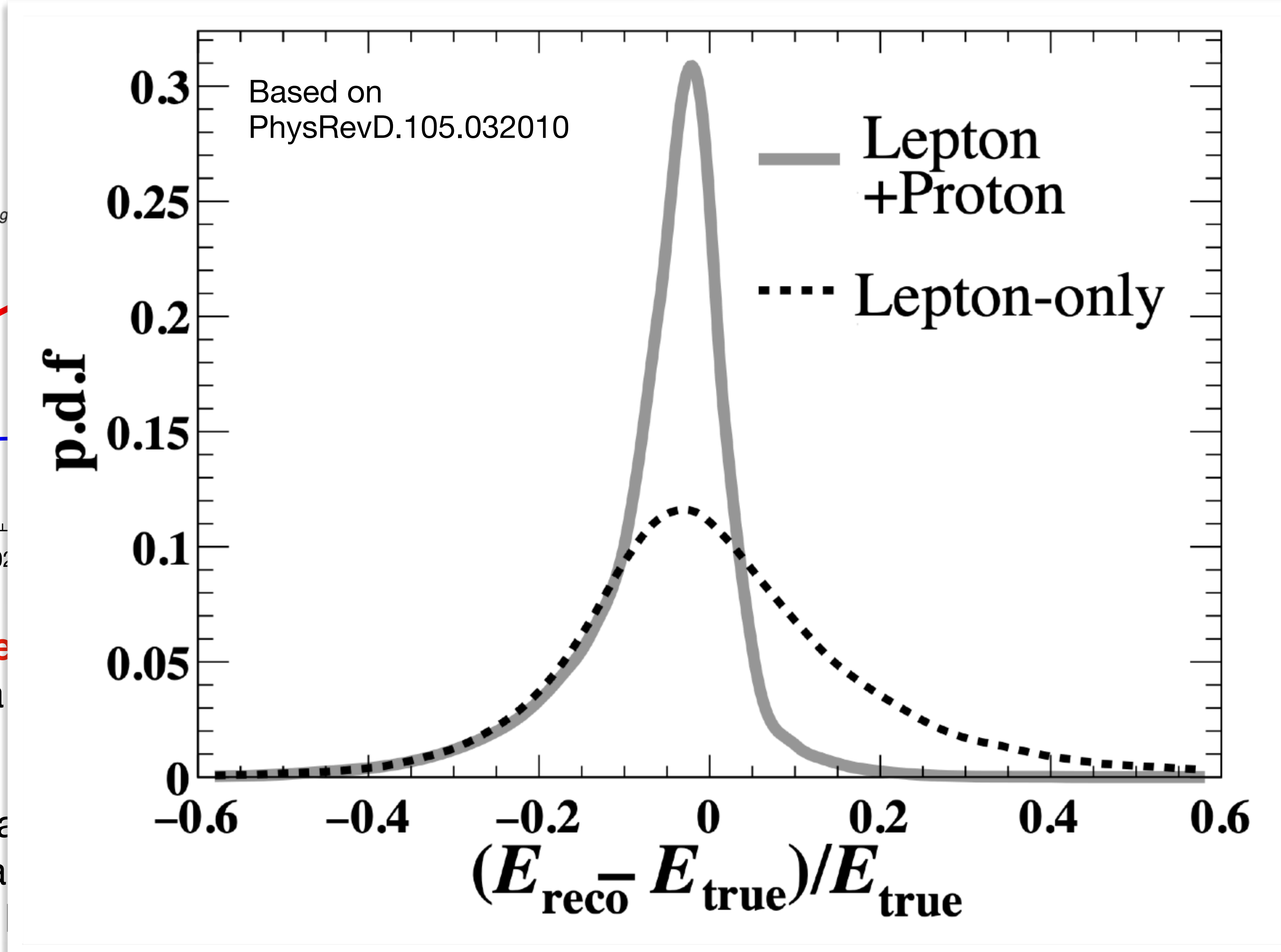
Reduce **xsec systematics** and better understanding of nuclear effects. CERN-SPSC-2019-001 arXiv:1901.03750 [physics.ins-det]

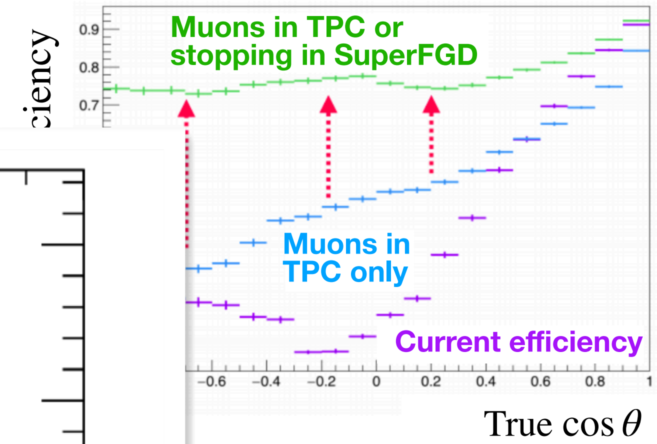
TDR: arXiv:1908.05141 [physics.ins-det]

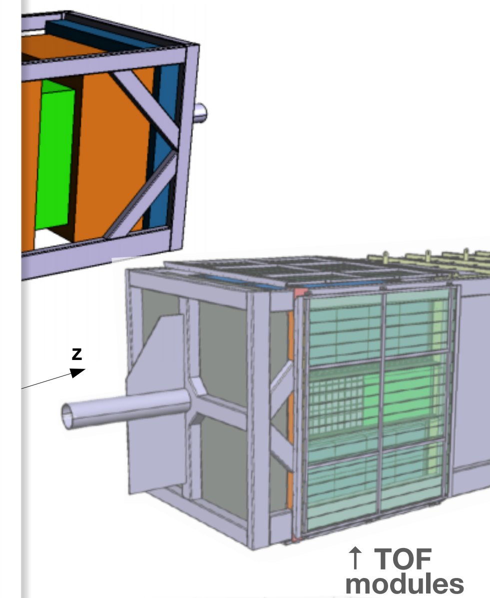
Beam line upgrade

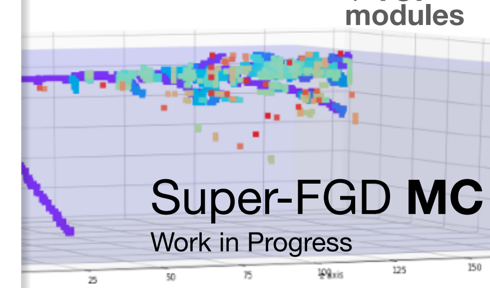
ND280 upgrade











- Increase **be**
  1.3 MW via
  supply and
- Many upgra
  (target, bea
  accept 1.3
- Increase **horn current** 250 kA → 320 kA for ~10% more neutrinos/beam-power and reduced wrong-sign background
  Aiming for 320 kA operation in next run!

old

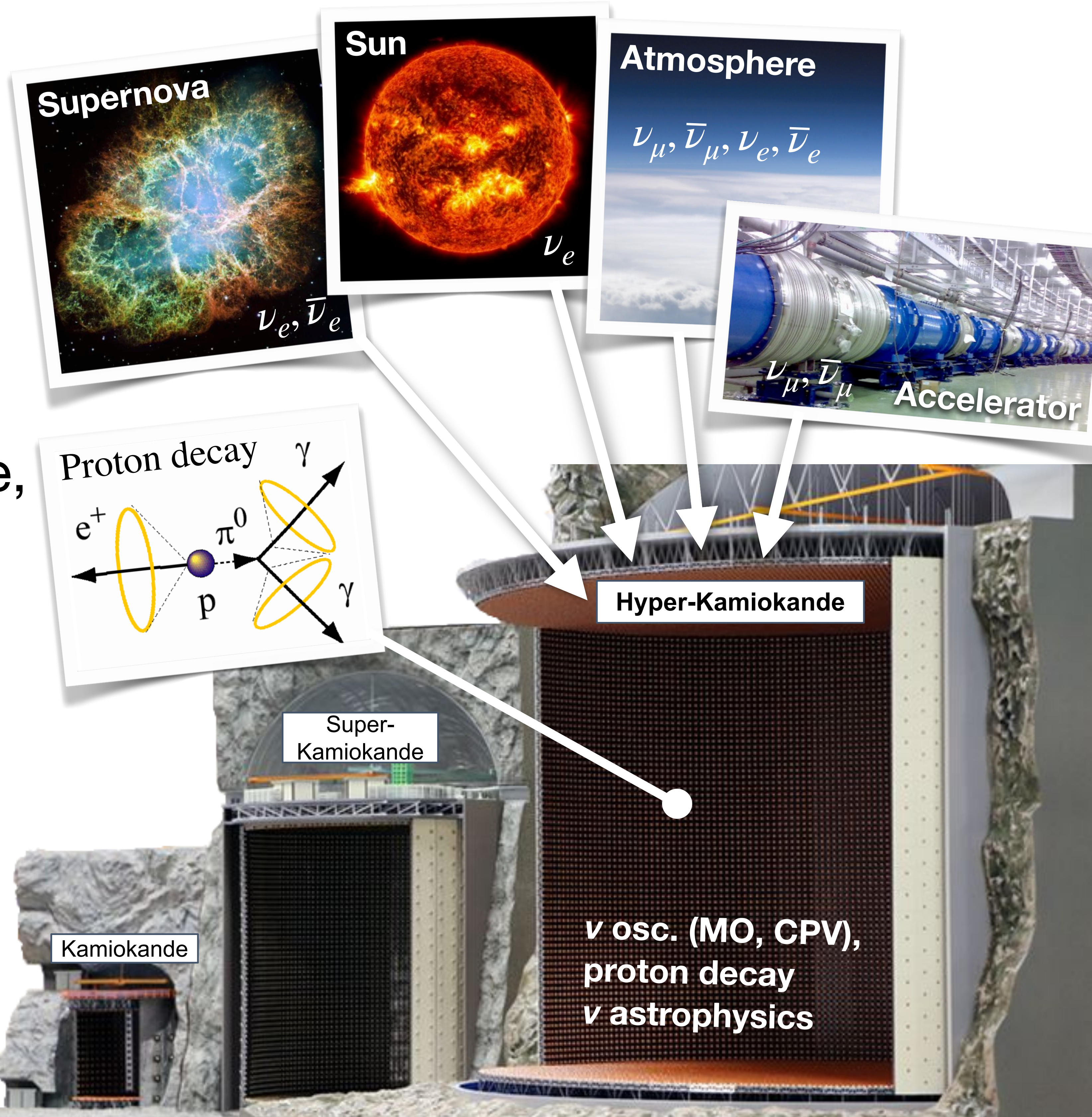
Reduce **xsec systematics** and better understanding of nuclear effects. CERN-SPSC-2019-001 arXiv:1901.03750 [physics.ins-det]

TDR: arXiv:1908.05141 [physics.ins-det]

Hyper-Kamiokande

- Third generation Water-Cherenkov detector in Kamioka, Japan.
- Compared to SuperK, ~8x larger fiducial volume, ~2.6x beam power,

  new PMTs with 2x photon detection and 2x timing resolution.
- Now under construction, operation begin in 2027.



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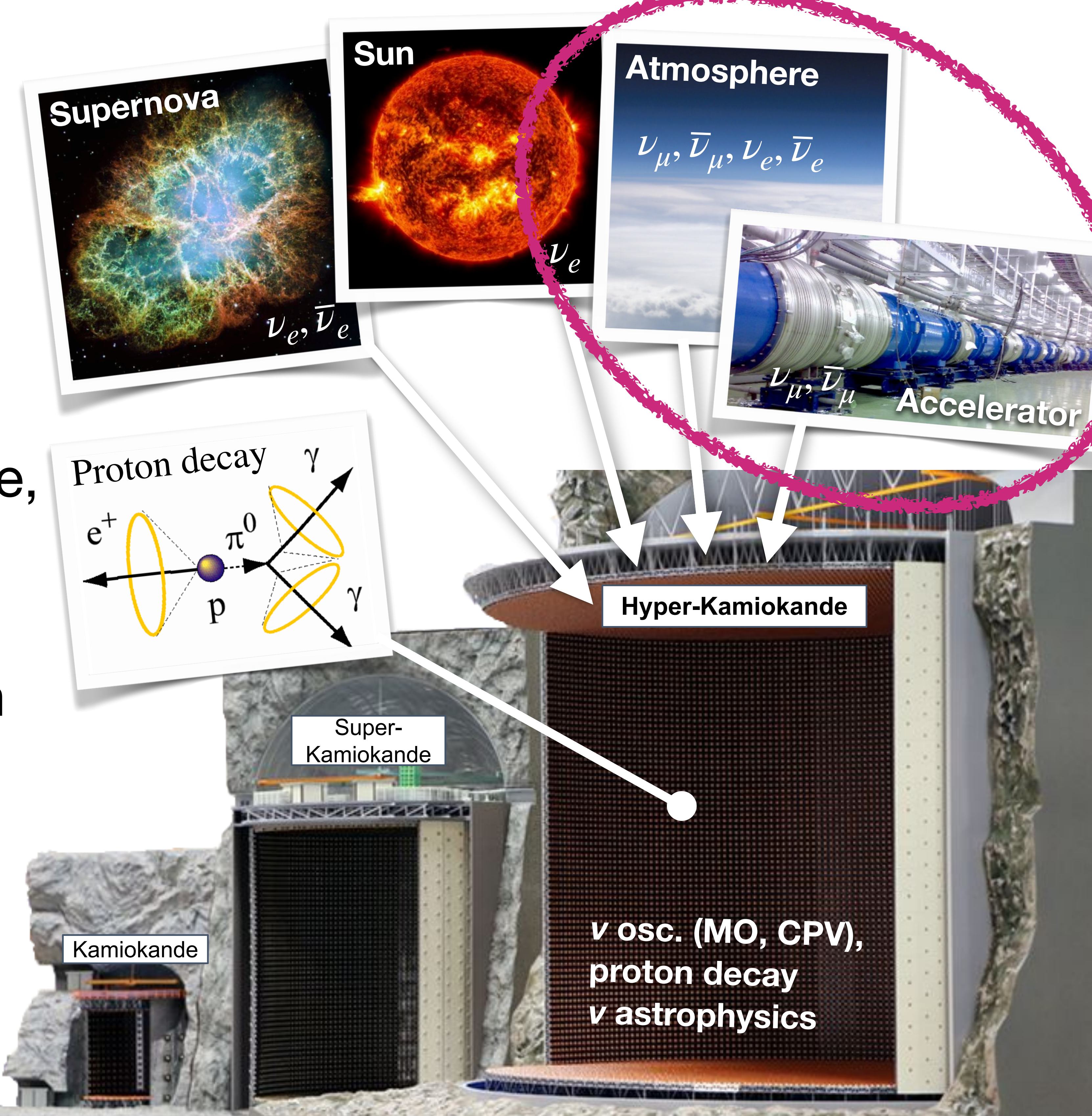
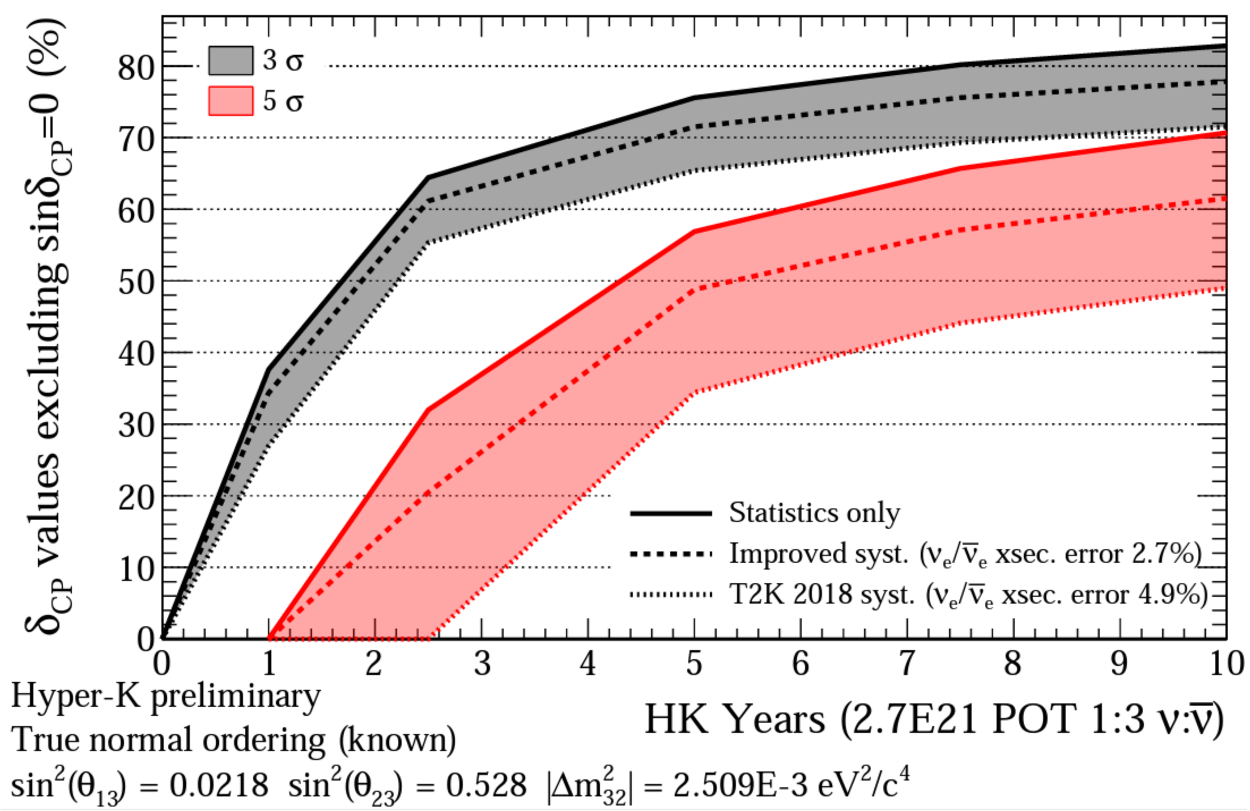
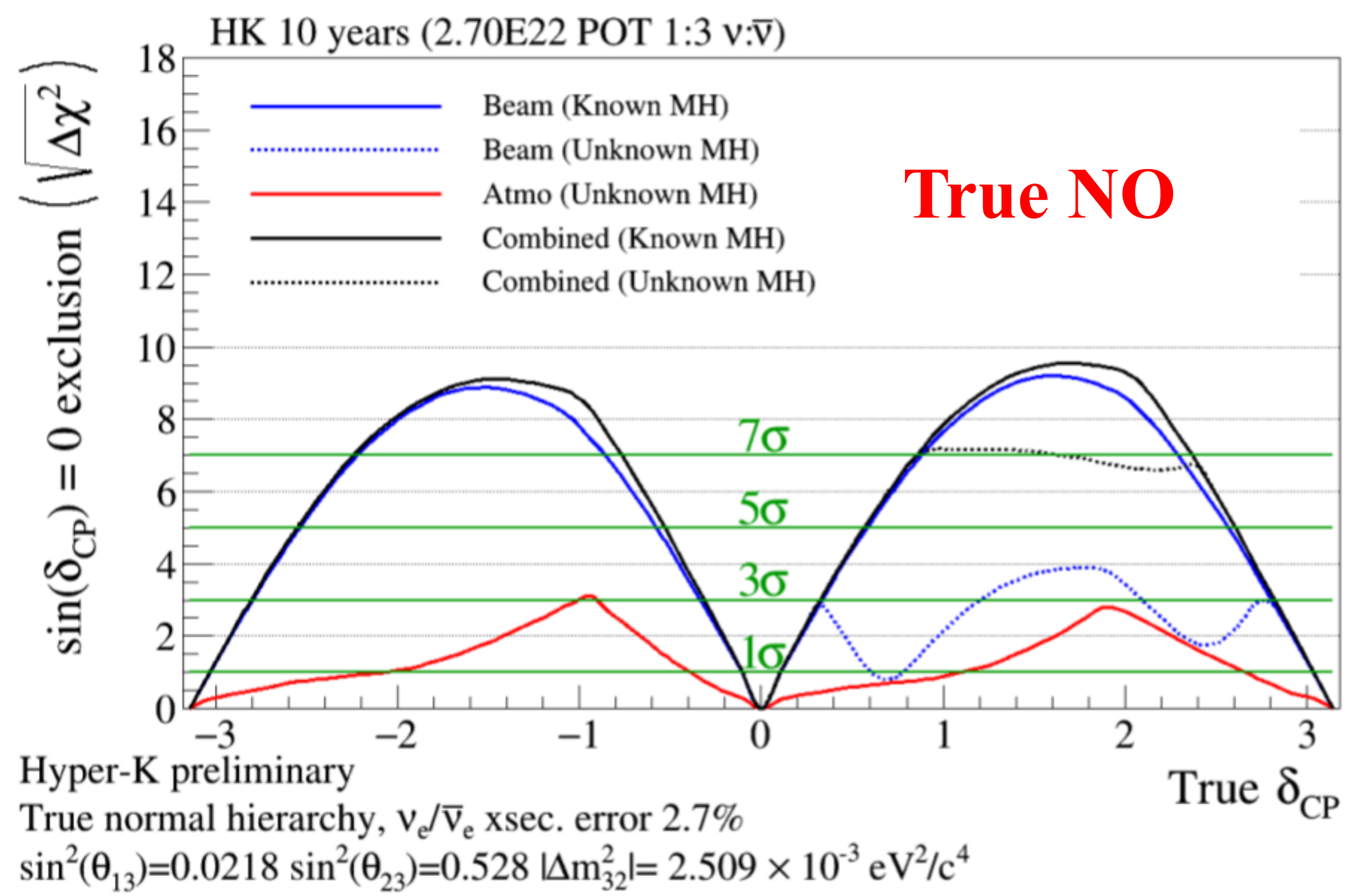


HK physics prospect

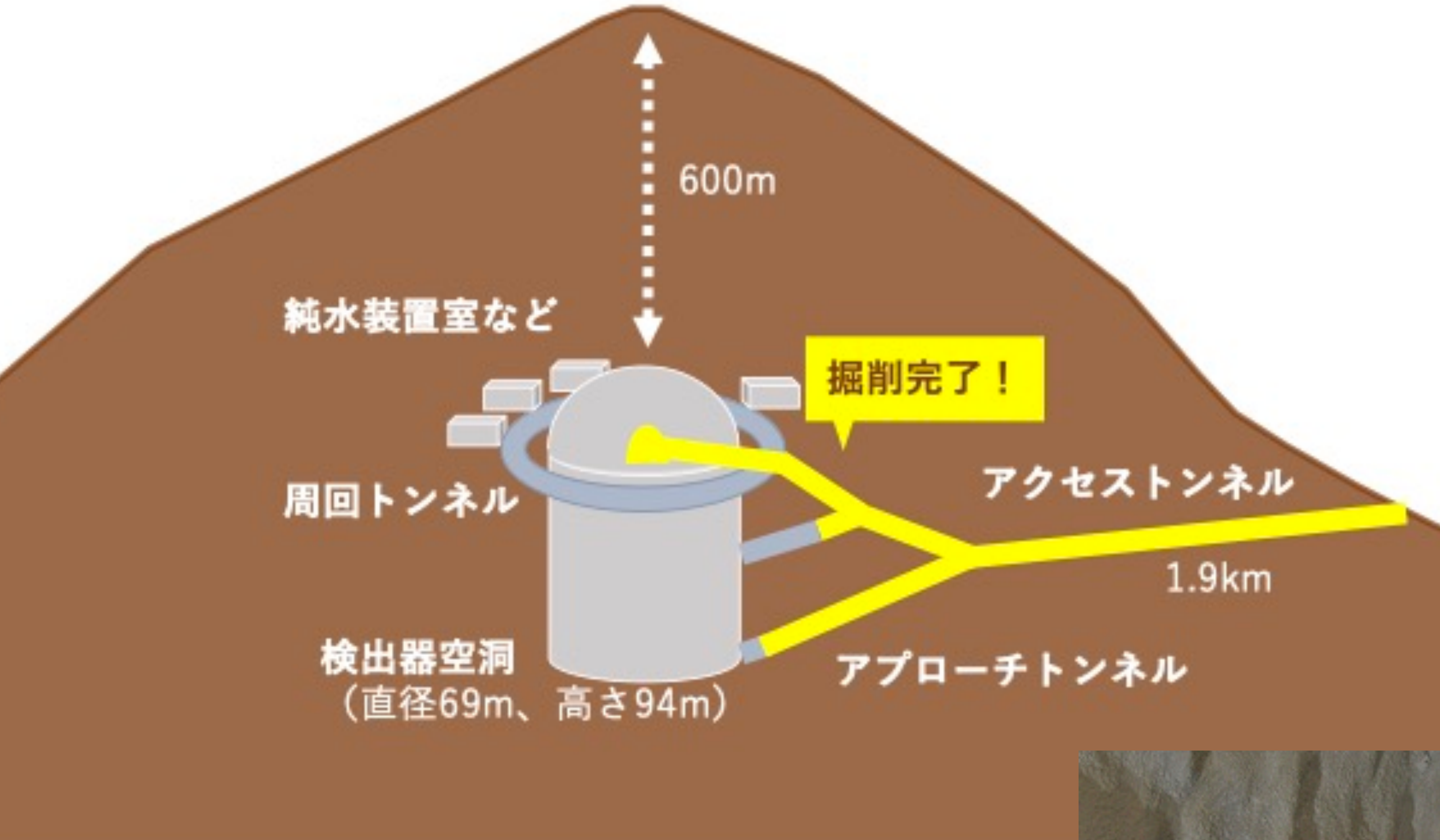
CP with known MO



Beam / atm synergy



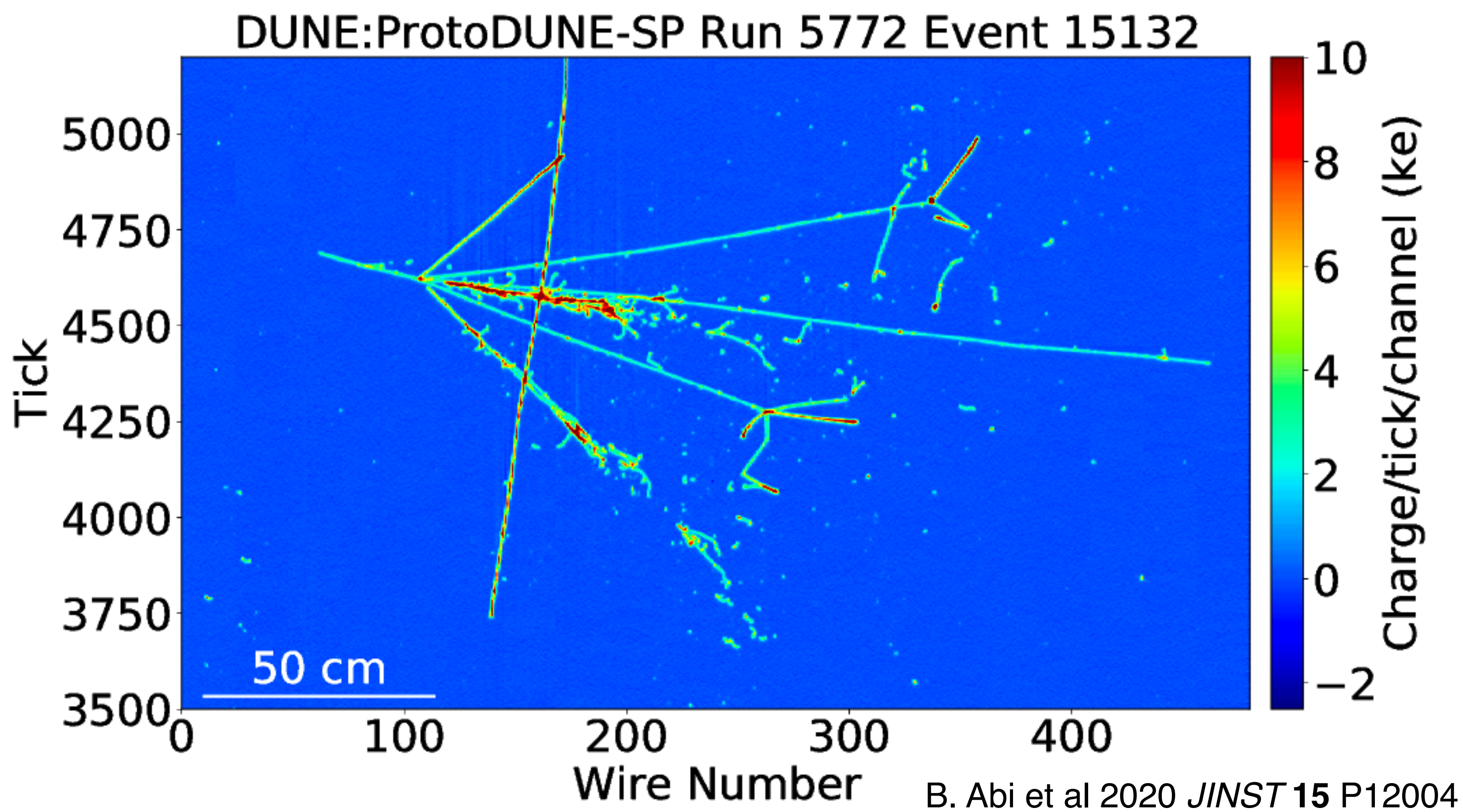
From NOW 2022, Z. Xie



HK status

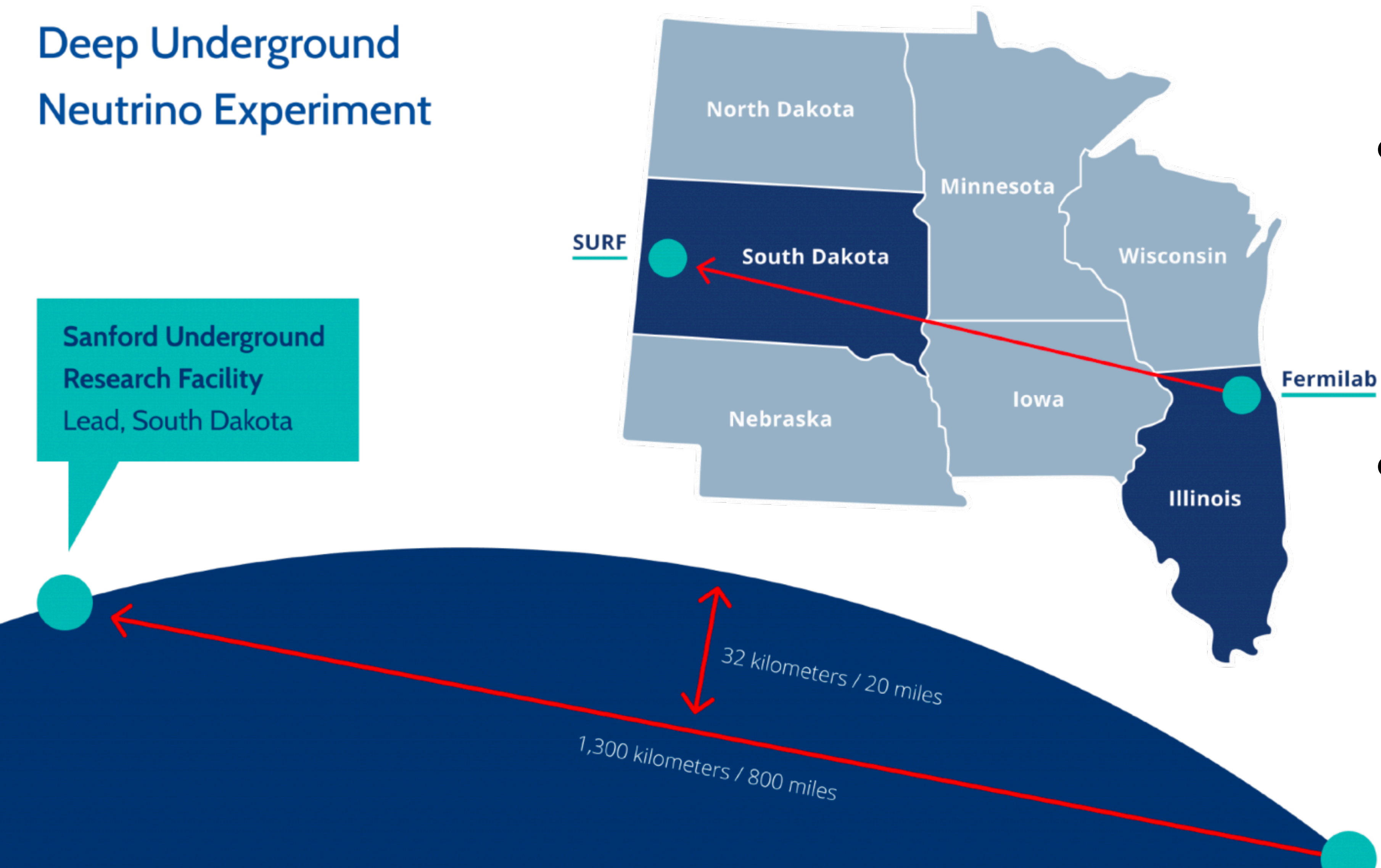
2022-07-25

- Digging
- Mass testing PMTs
- Many other ongoing developments



B. Abi et al 2020 *JINST* **15** P12004

- $L \approx 1300\,\mathrm{km}$
- New detector technology: 70 kton liquid argon TPC
- Physics goals mostly same as HyperK



From https://www.dunescience.org/,
https://lbnf-dune.fnal.gov/

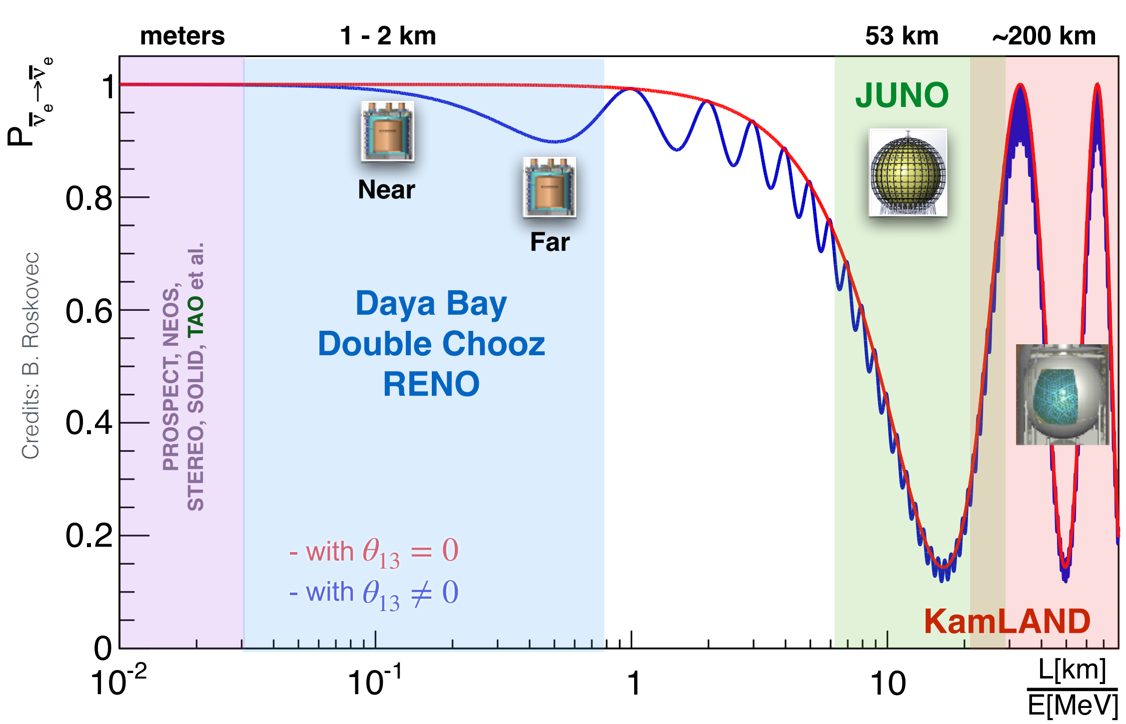
Reactor

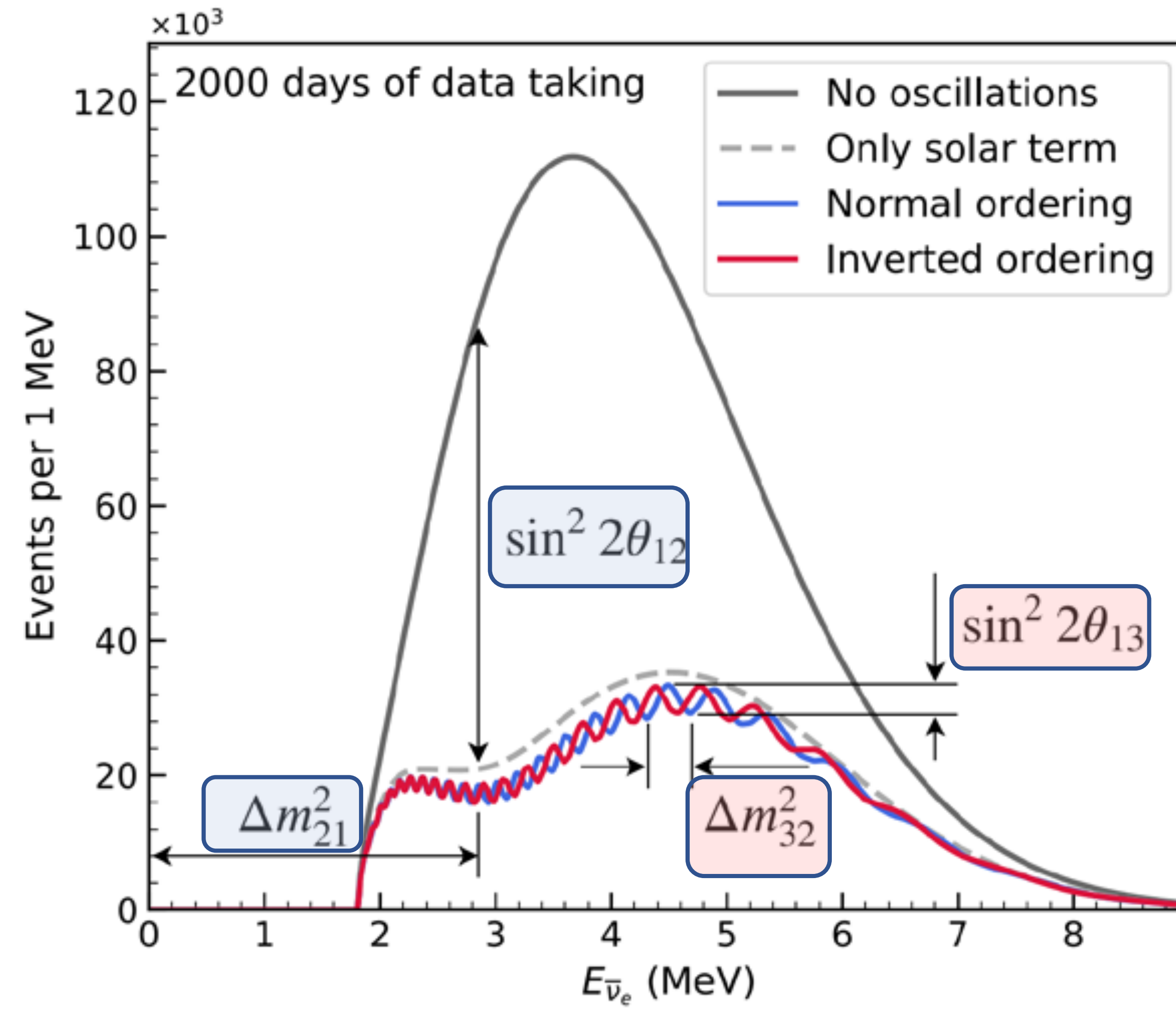
- **JUNO** experiment (China)
  20 kton Liquid Scintillator
  Starting in 2023?

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \cos^4\theta_{13} \boxed{\sin^2 2\theta_{12}} \sin^2 \frac{\boxed{\Delta m^2_{12}} L}{4E}$$
$$- \boxed{\sin^2 2\theta_{13}} \left(\cos^2\theta_{12} \sin^2 \frac{\boxed{\Delta m^2_{31}} L}{4E} + \sin^2\theta_{12} \sin^2 \frac{\boxed{\Delta m^2_{32}} L}{4E} \right)$$

- $L \approx 50\,\mathrm{km}$

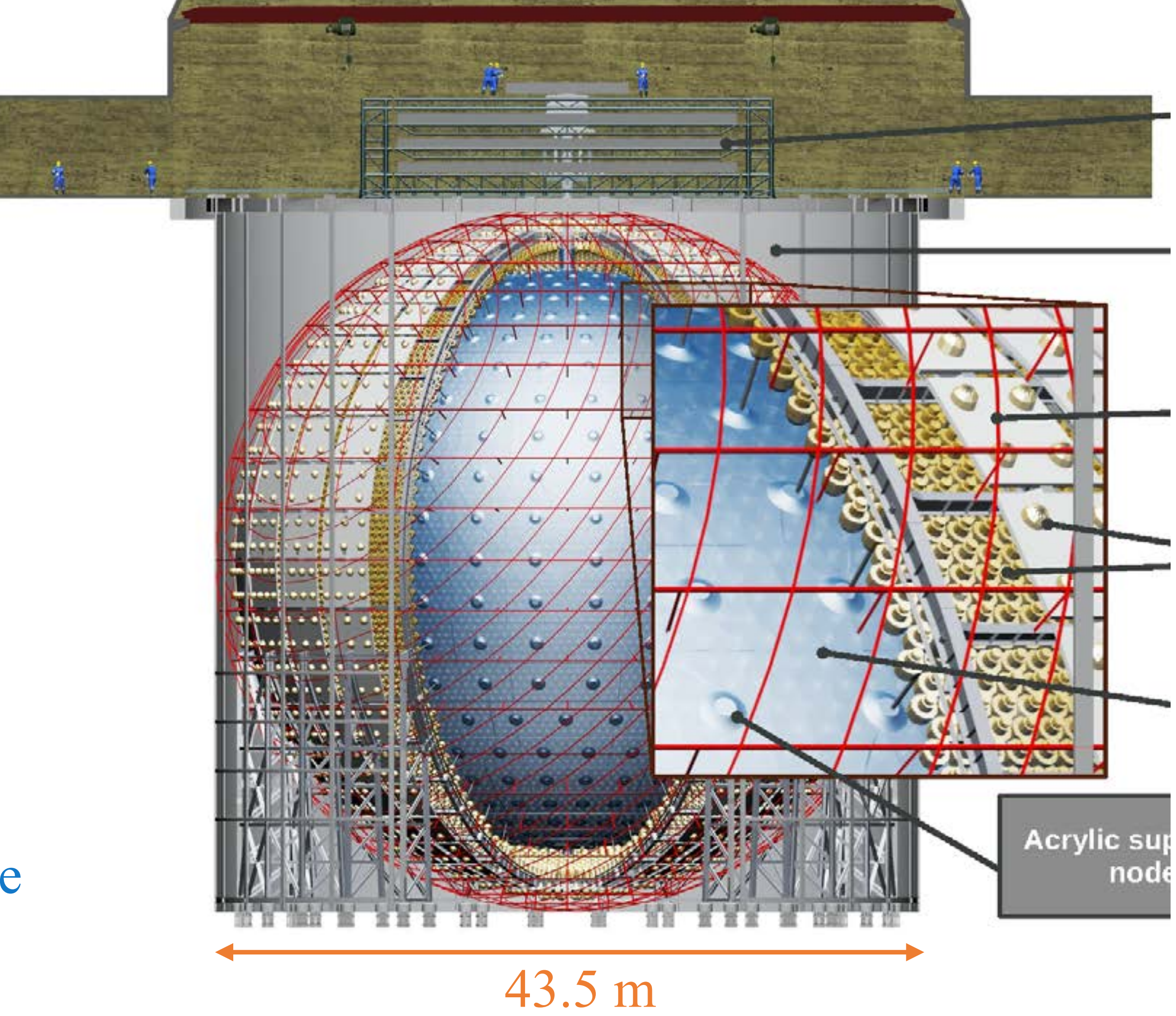
- Precise energy resolution to see small wiggles in $P(\bar{\nu}_e \to \bar{\nu}_e)$ sensitive to mass ordering

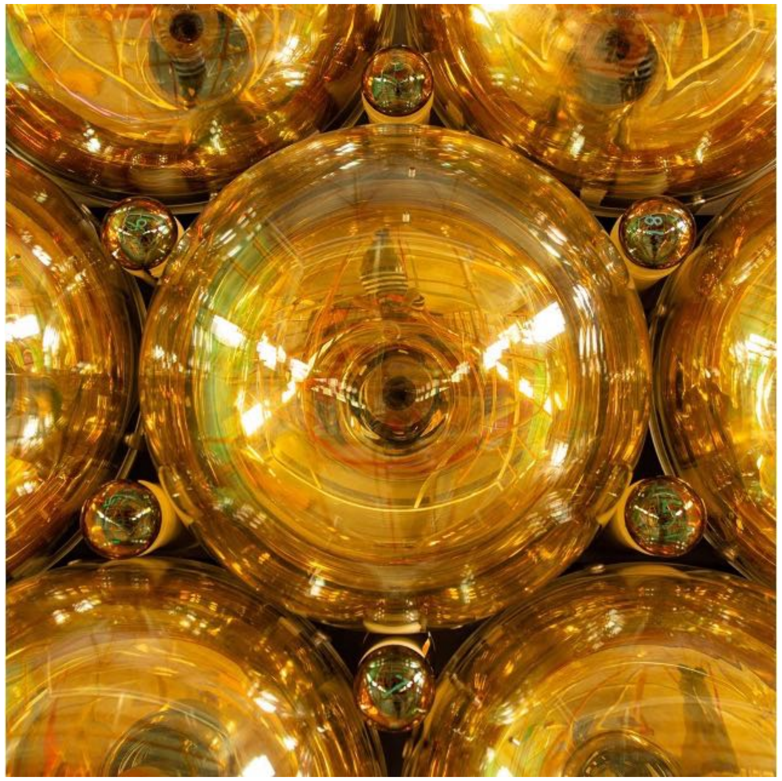


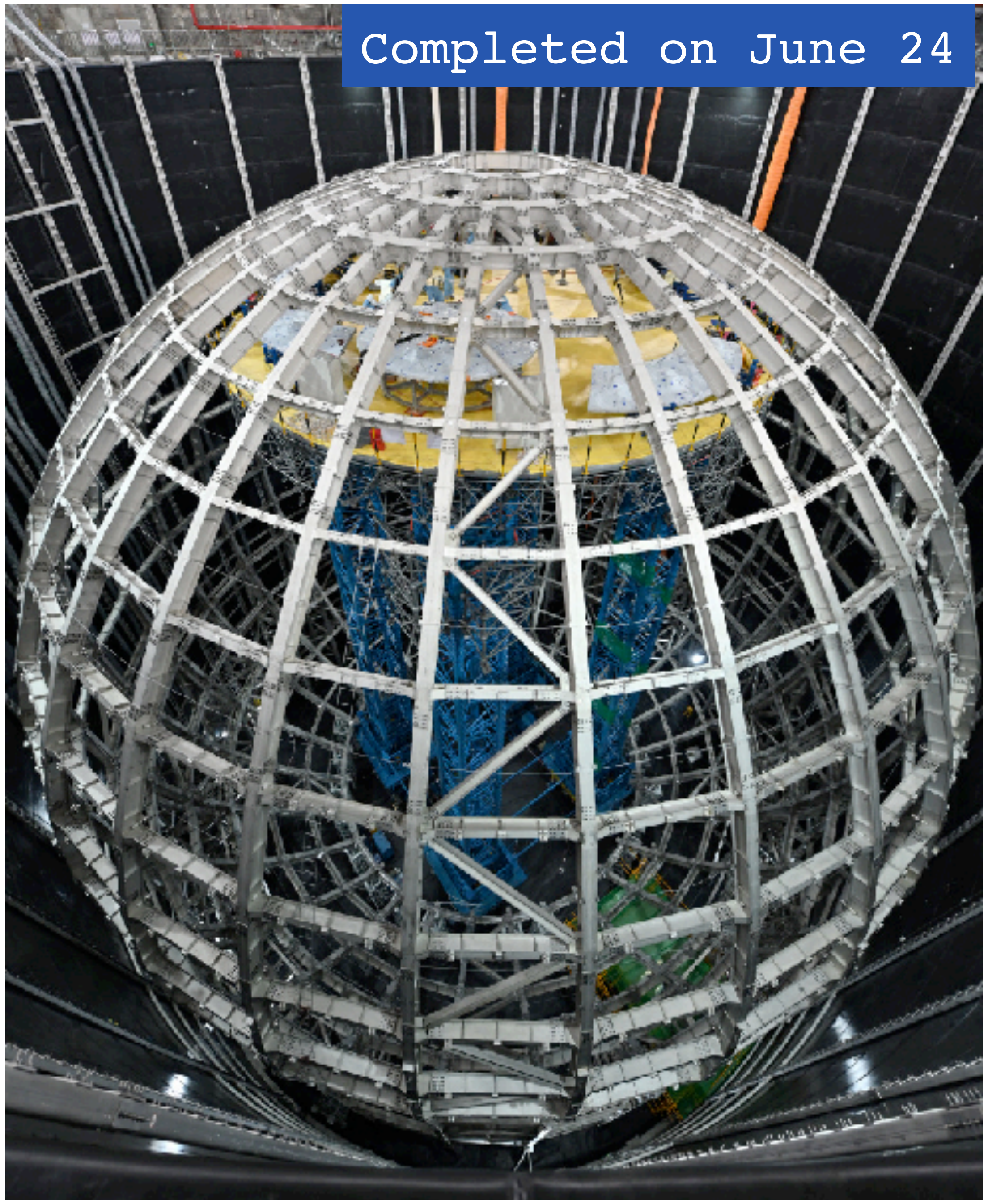


Jinnan Zhang (IHEP) , TAUP 2021

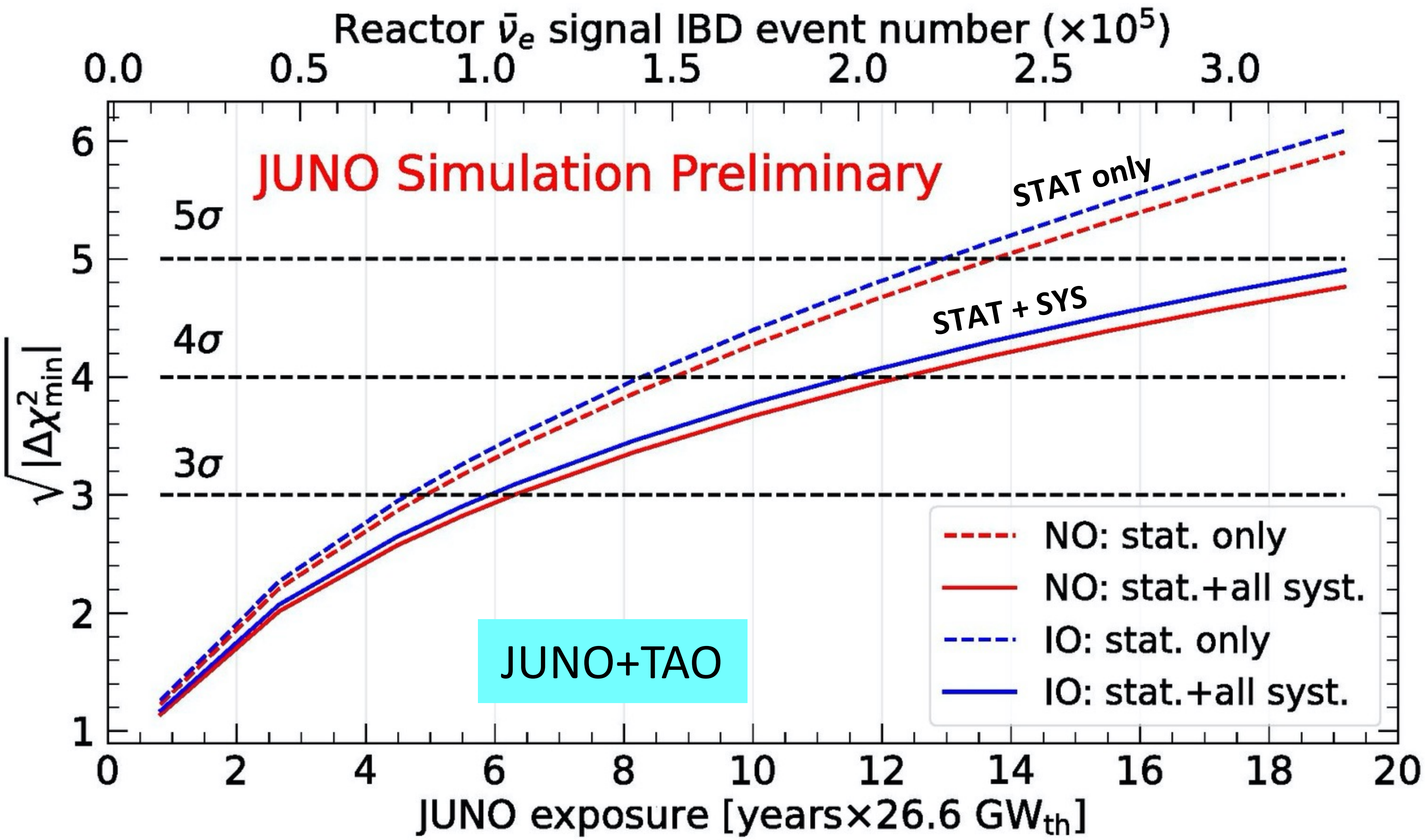
JUNO Status







Mass ordering sensitivity

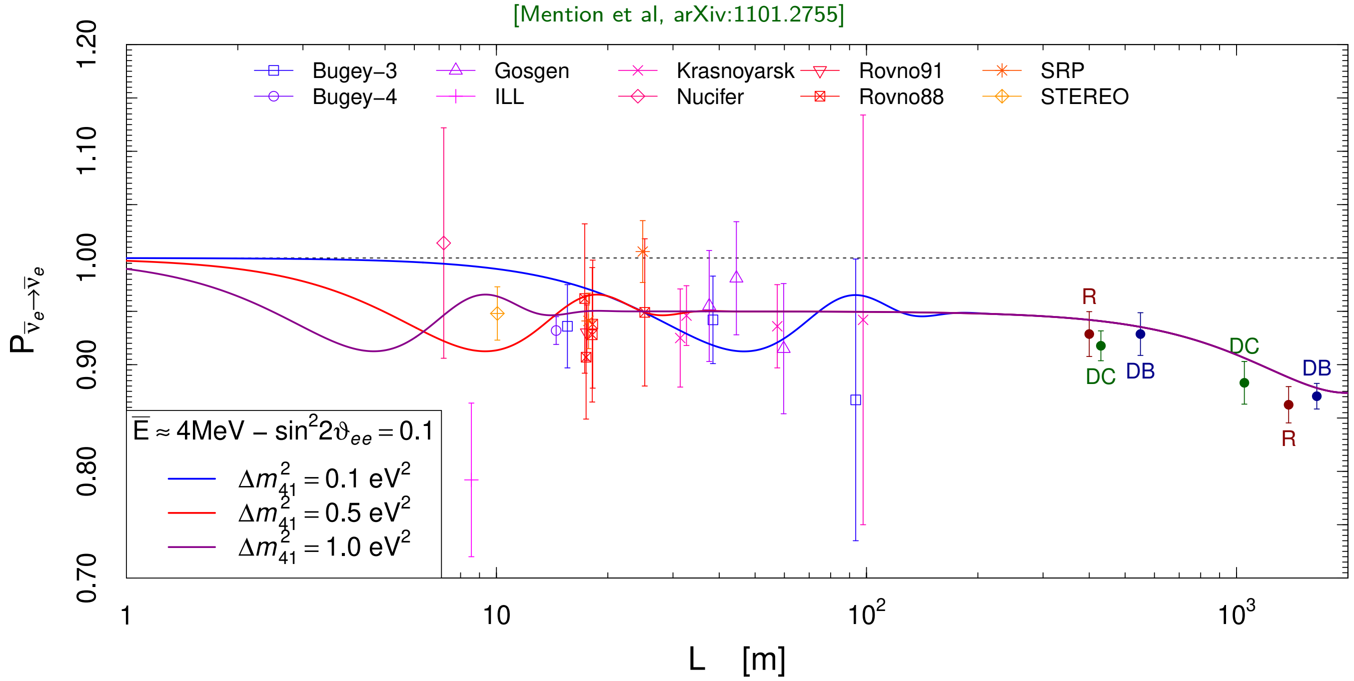


- 3σ in 6 years with JUNO alone, independent of θ_{23}, δ_{CP}
- 5σ in 6 years through joint fit with other experiments (accelerator, atmospheric)

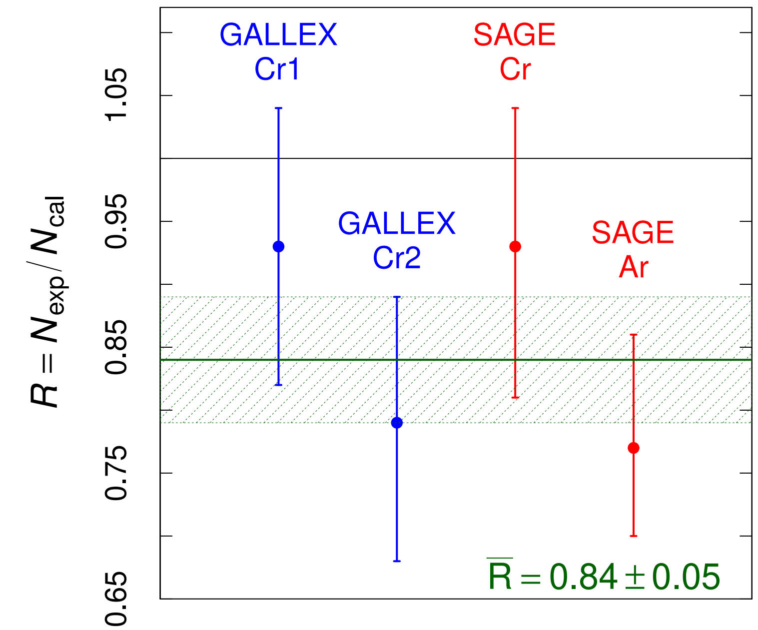
Historical Short-Baseline Anomalies

2011 Reactor Anomaly: $\bar{\nu}_e \to \bar{\nu}_x$ (2.5σ)

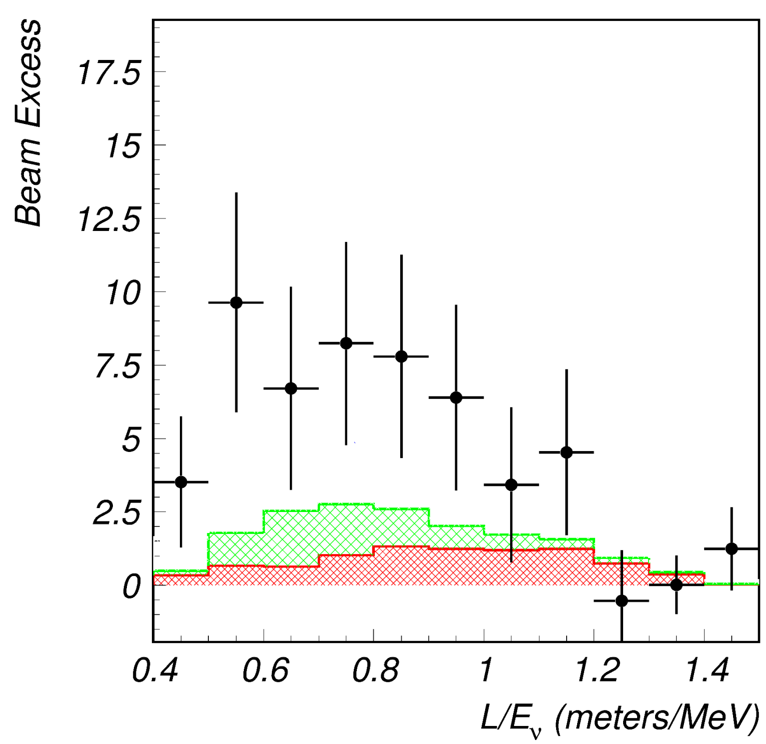
[Mention et al, arXiv:1101.2755]



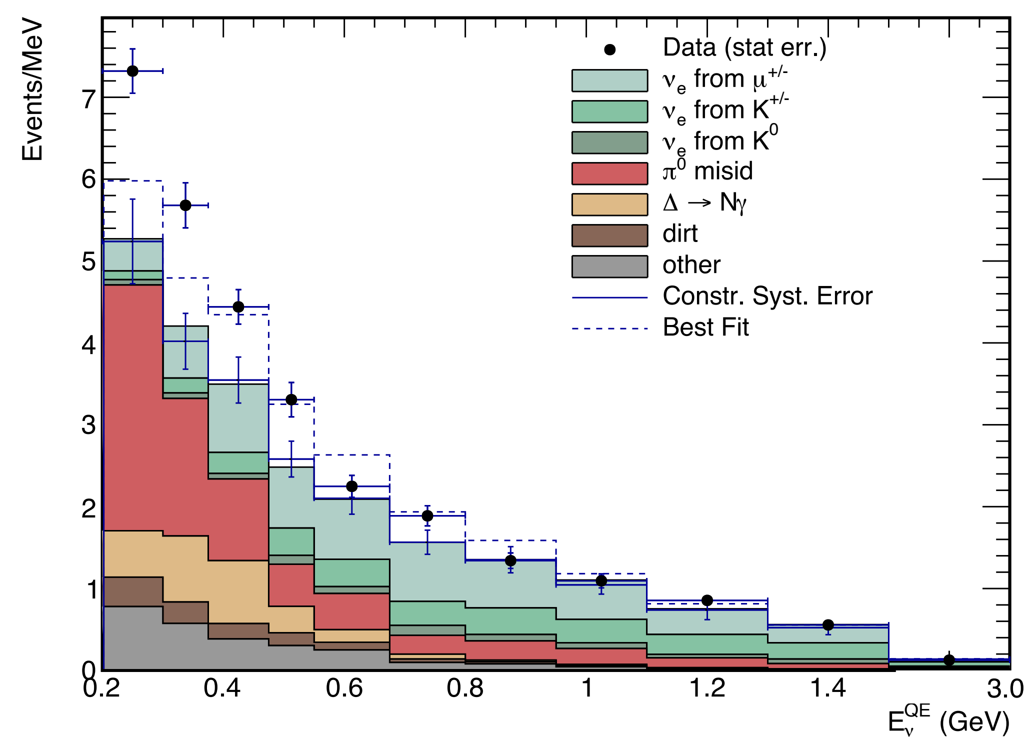
2005 Gallium Anomaly: $\nu_e \to \nu_x$ (2.9σ)



1995 LSND Anomaly: $\bar{\nu}_\mu \to \bar{\nu}_e$ $(\sim 4\sigma)$



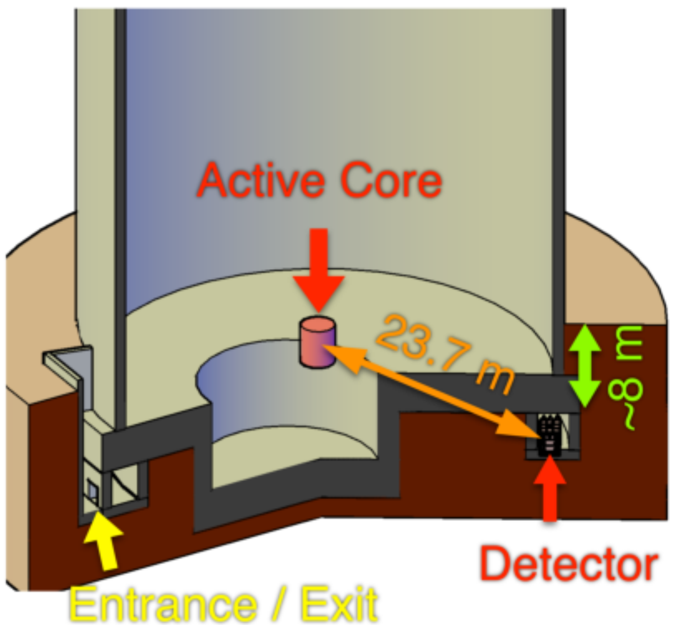
2008 MiniBooNE Anomaly: $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ (4.8σ)



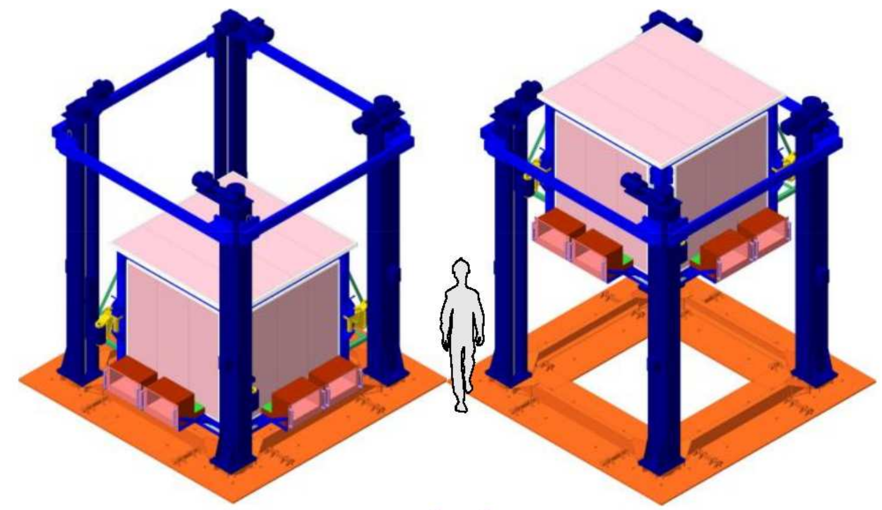
Model Indep. Measurements of Reactor ν Osc.

Ratios of spectra at different distances

NEOS

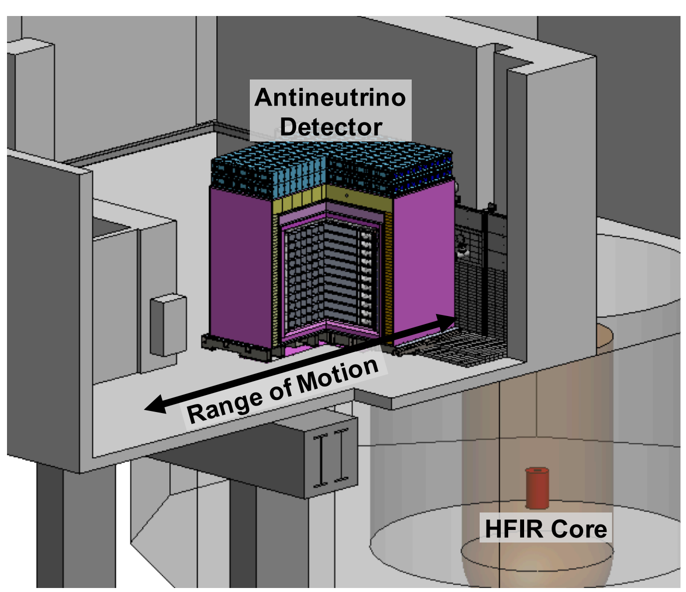


DANSS [Alekseev @ NOW 2022]

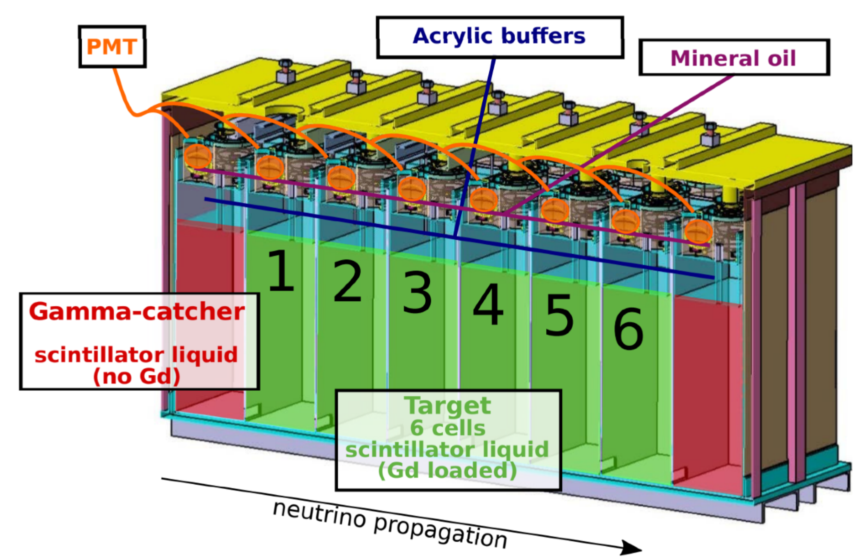


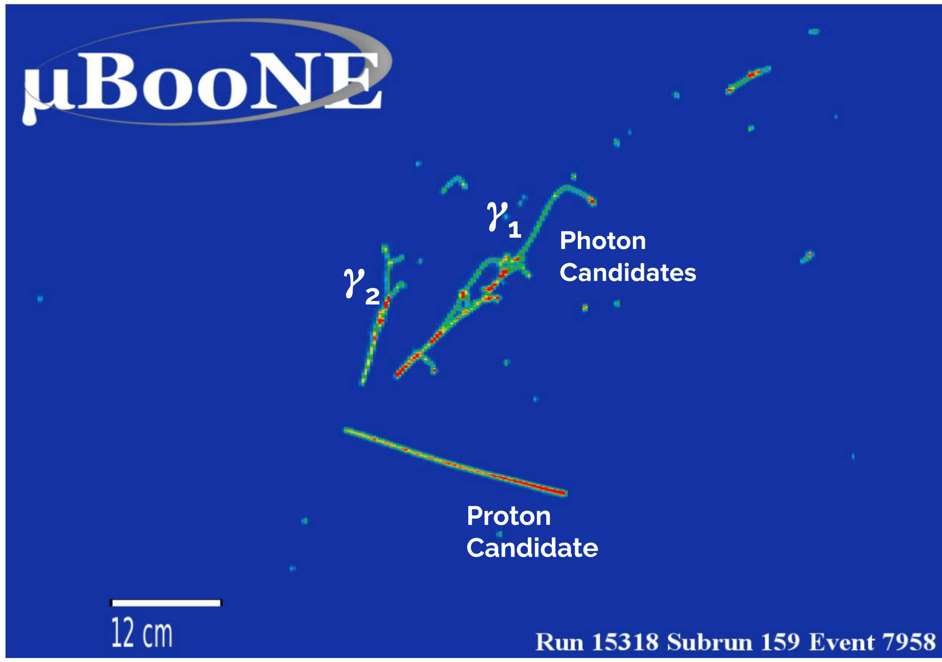
DANSS on a lifting platform

PROSPECT [Roca Catala @ NOW 2022]

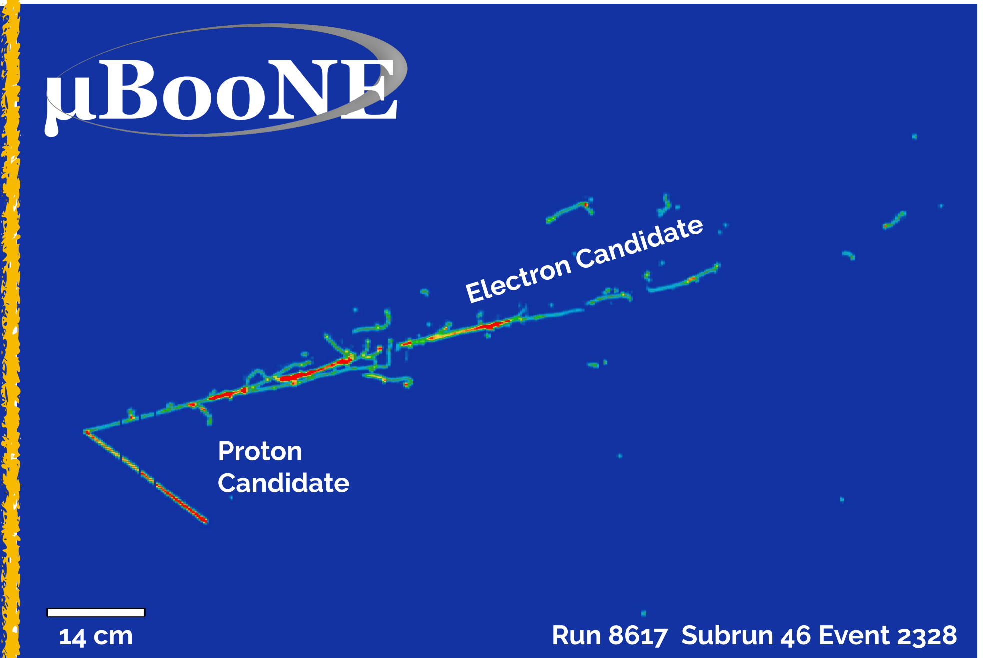


STEREO [del Amo Sanchez @ NOW 2022]





ν_μ NC π^0 candidate data event

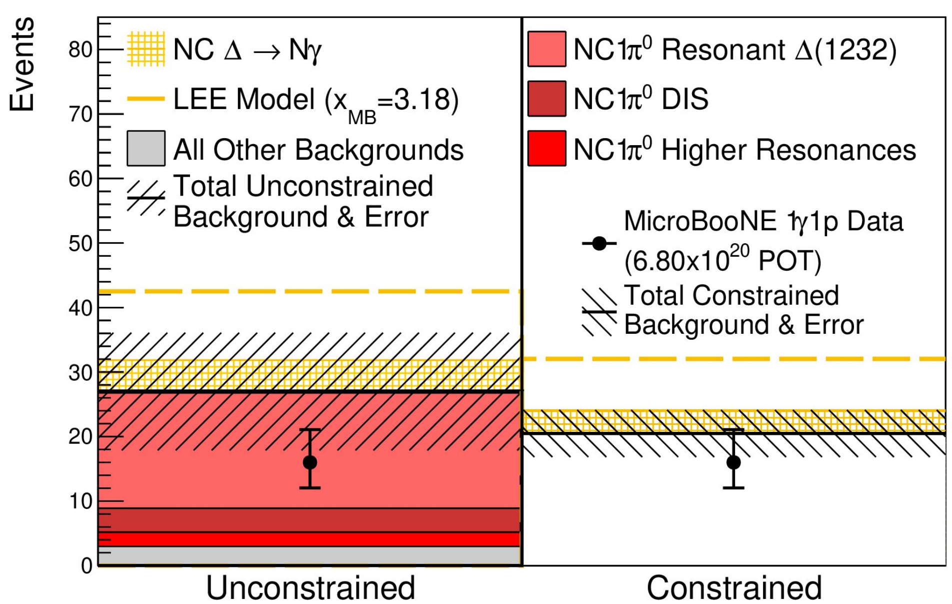


ν_e CC candidate data event

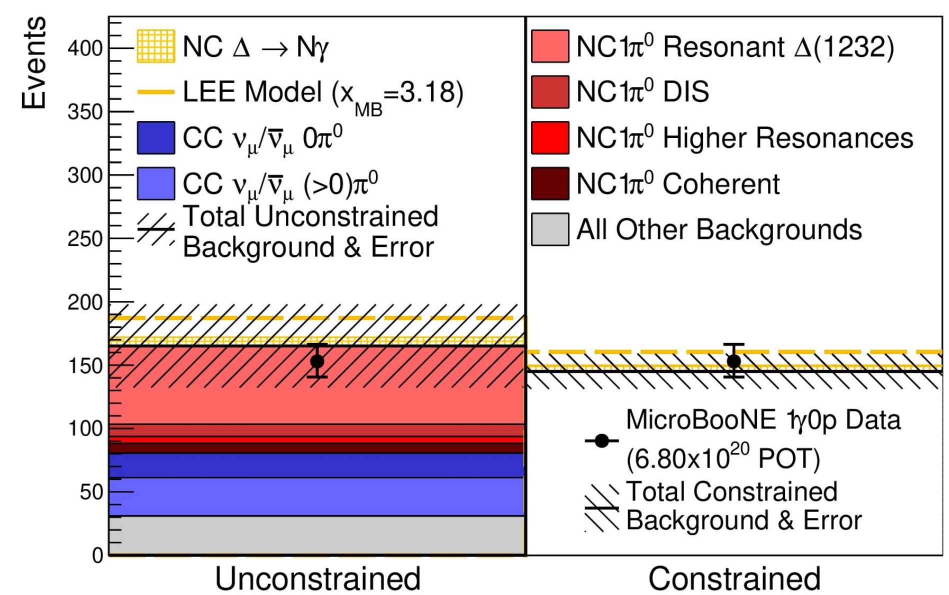
MicroBooNE photon search results!

MicroBooNE Collab, Phys. Rev. Lett. 128, 111801 (2022)

1γ1p



1γ0p



1γ1p

Unconstr. bkgd.	27.0 ± 8.1
Constr. bkgd.	20.5 ± 3.6
NC $\Delta \to N\gamma$	+ 4.88
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 15.5

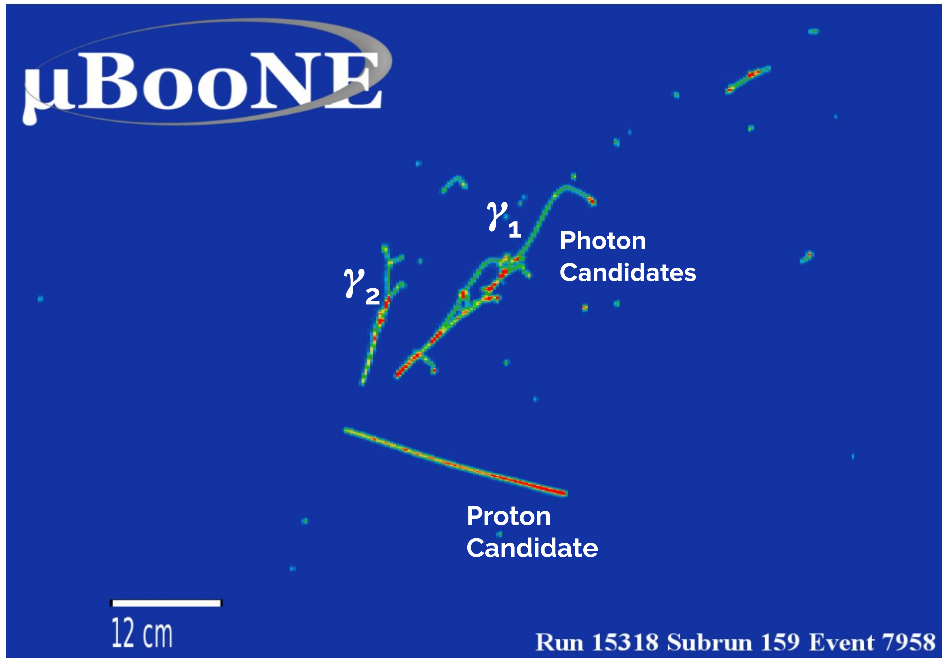
16
Data Events Observed

1γ0p

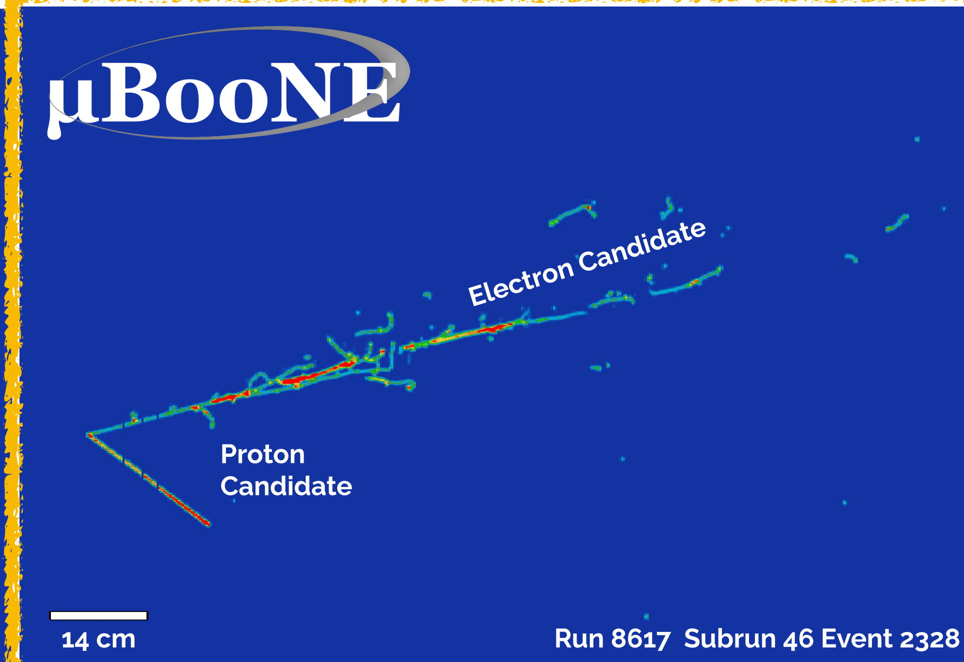
Unconstr. bkgd.	165.4 ± 31.7
Constr. bkgd.	145.1 ± 13.8
NC $\Delta \to N\gamma$	+ 6.55
LEE ($x_{\mathrm{MB}} = 3.18$)	+ 20.1

153
Data Events Observed

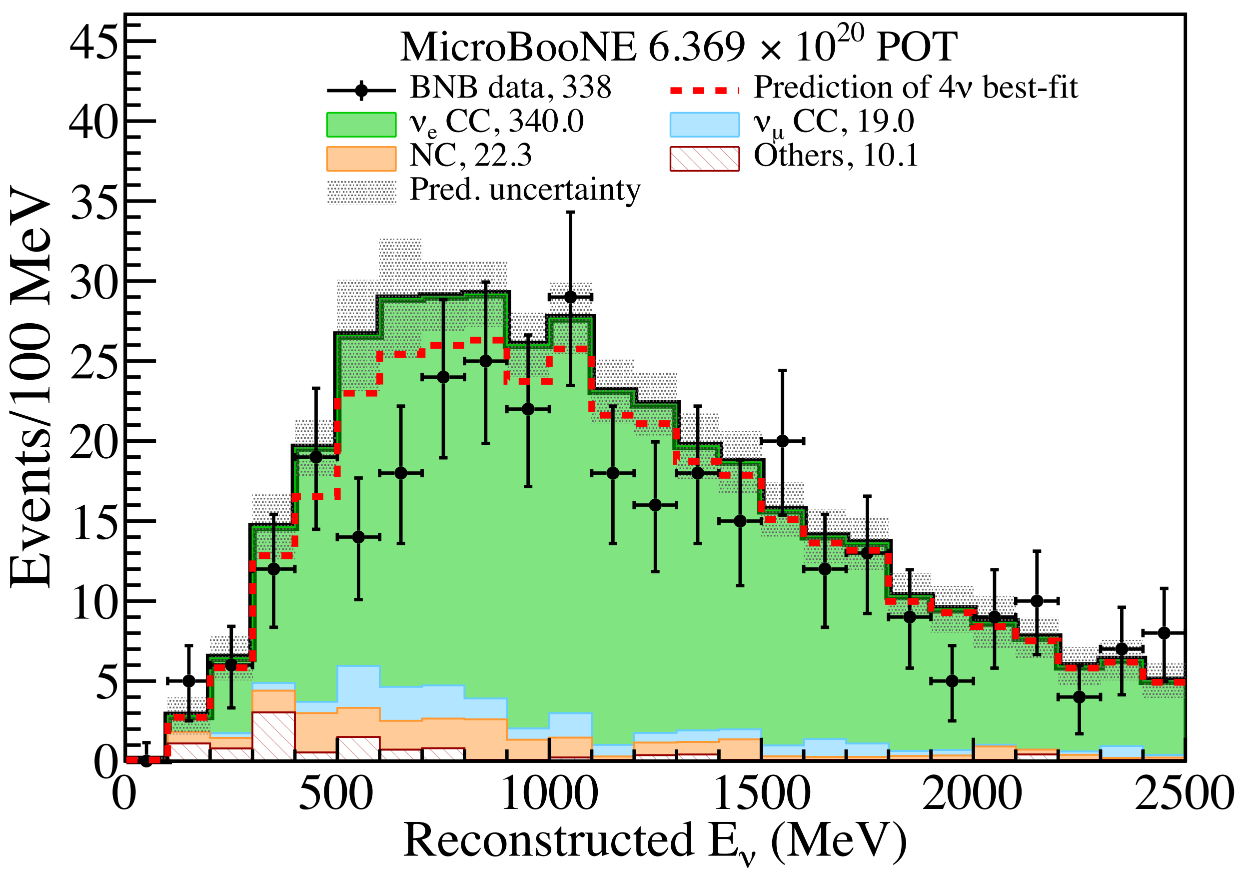
ALFRED P. SLOAN FOUNDATION

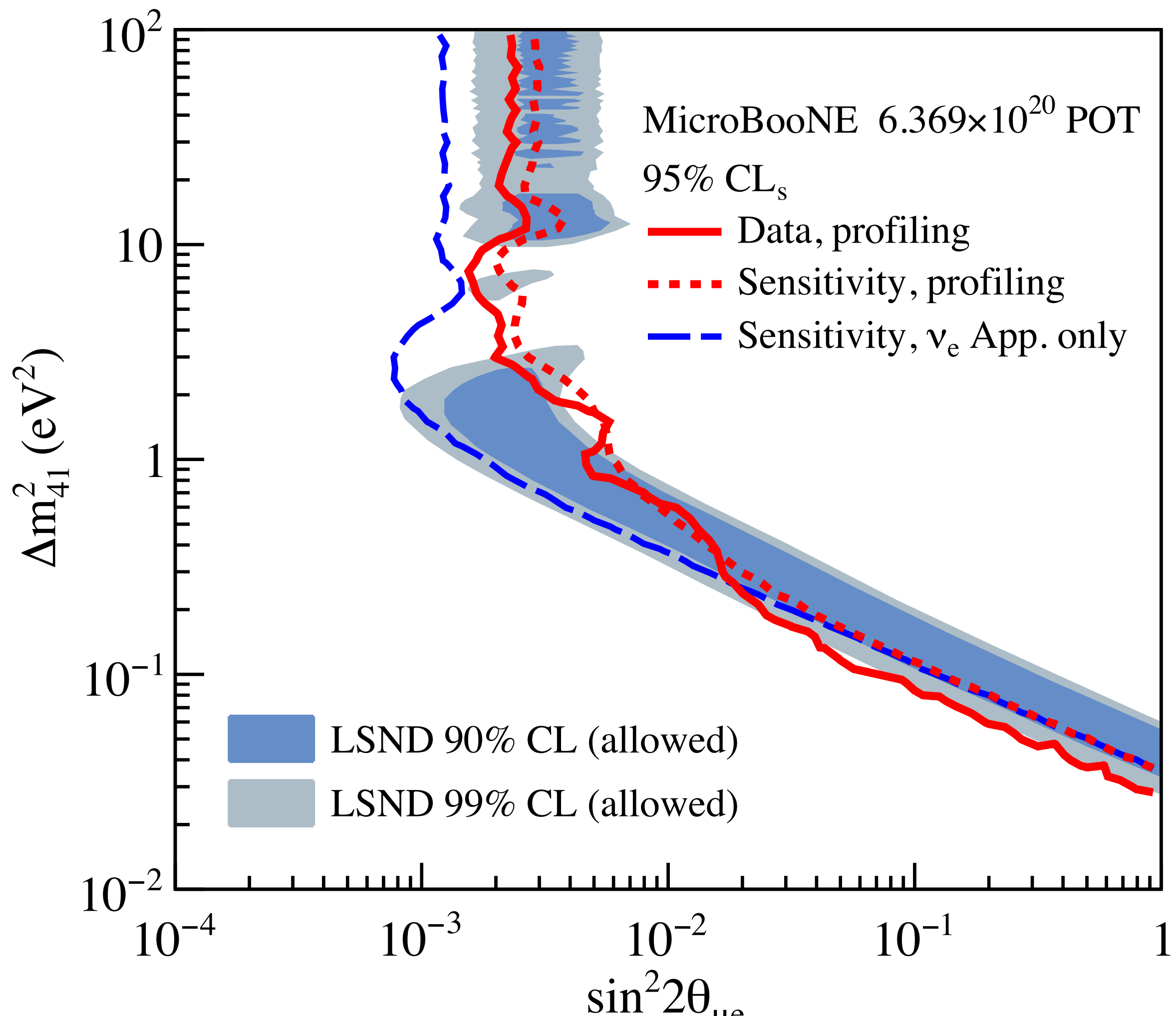


ν_μ NC π^0 candidate data event



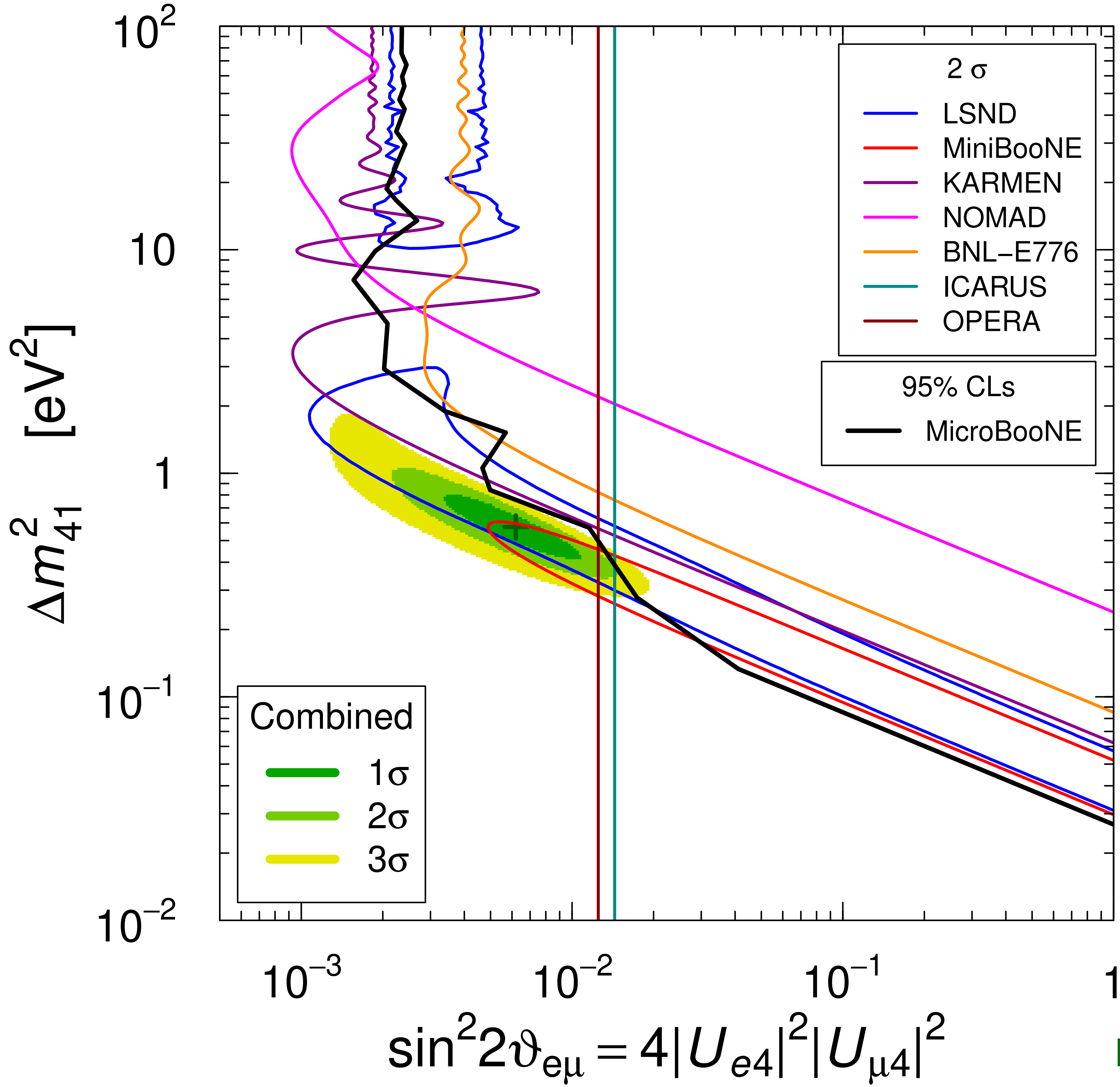
ν_e CC candidate data event





FERMILAB-PUB-22-750-ND (2022-11-01)

$\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ Appearance



μBooNEは前のページの結果の少し前

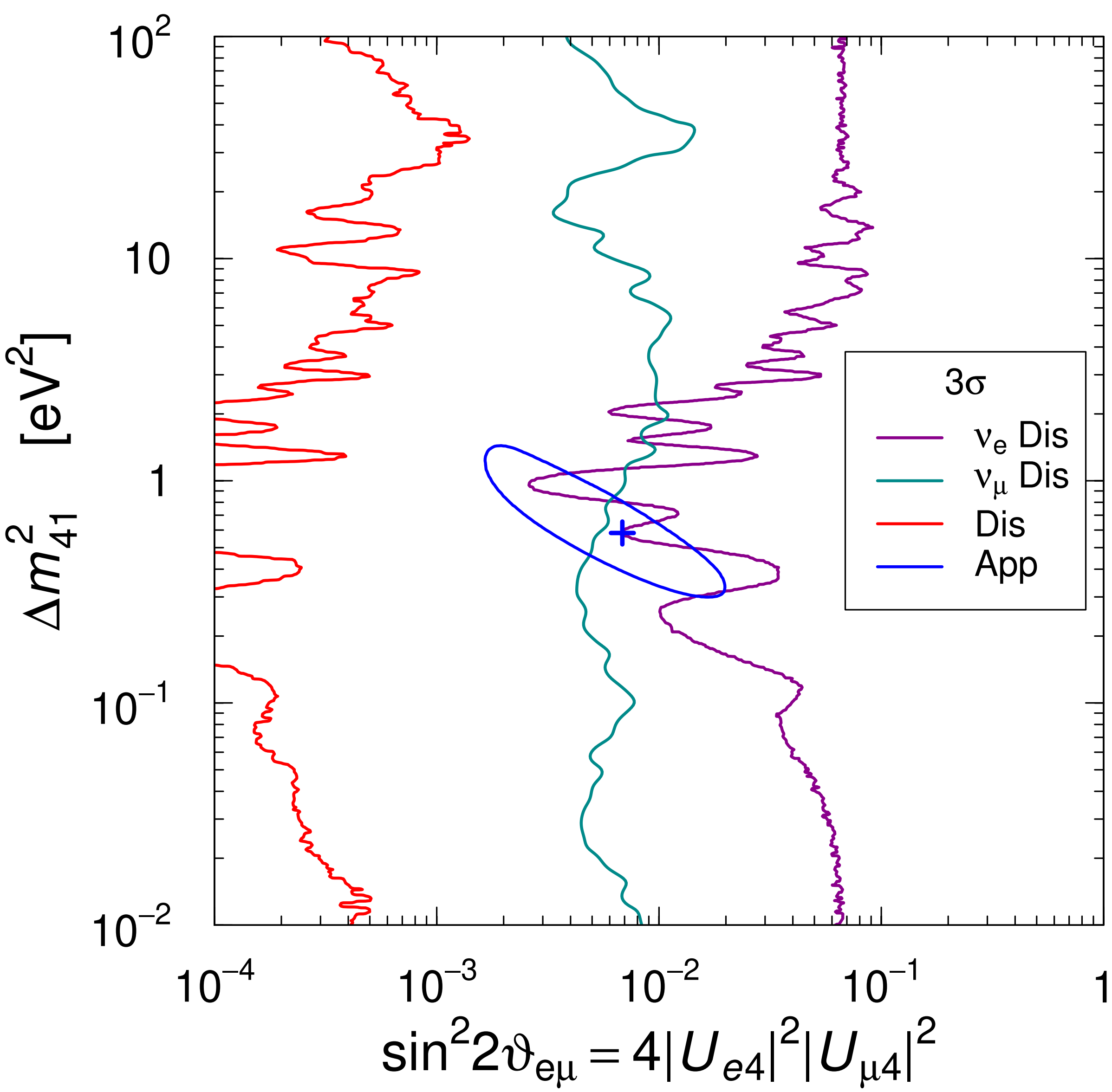
[MicroBooNE: Karagiorgi @ NOW 2022]

Global Appearance-Disappearance Tension

ν_e DIS
$\sin^2 2\vartheta_{ee} \simeq 4|U_{e4}|^2$

ν_μ DIS
$\sin^2 2\vartheta_{\mu\mu} \simeq 4|U_{\mu4}|^2$

$\nu_\mu \to \nu_e$ APP
$\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2|U_{\mu4}|^2 \simeq \frac{1}{4}\sin^2 2\vartheta_{ee}\sin^2 2\vartheta_{\mu\mu}$



- $\nu_\mu \to \nu_e$ is quadratically suppressed!
- 2019 Global Fit:

  $\chi^2/\mathrm{NDF} = 843.6/794$

  $\mathrm{GoF} = 11\%$

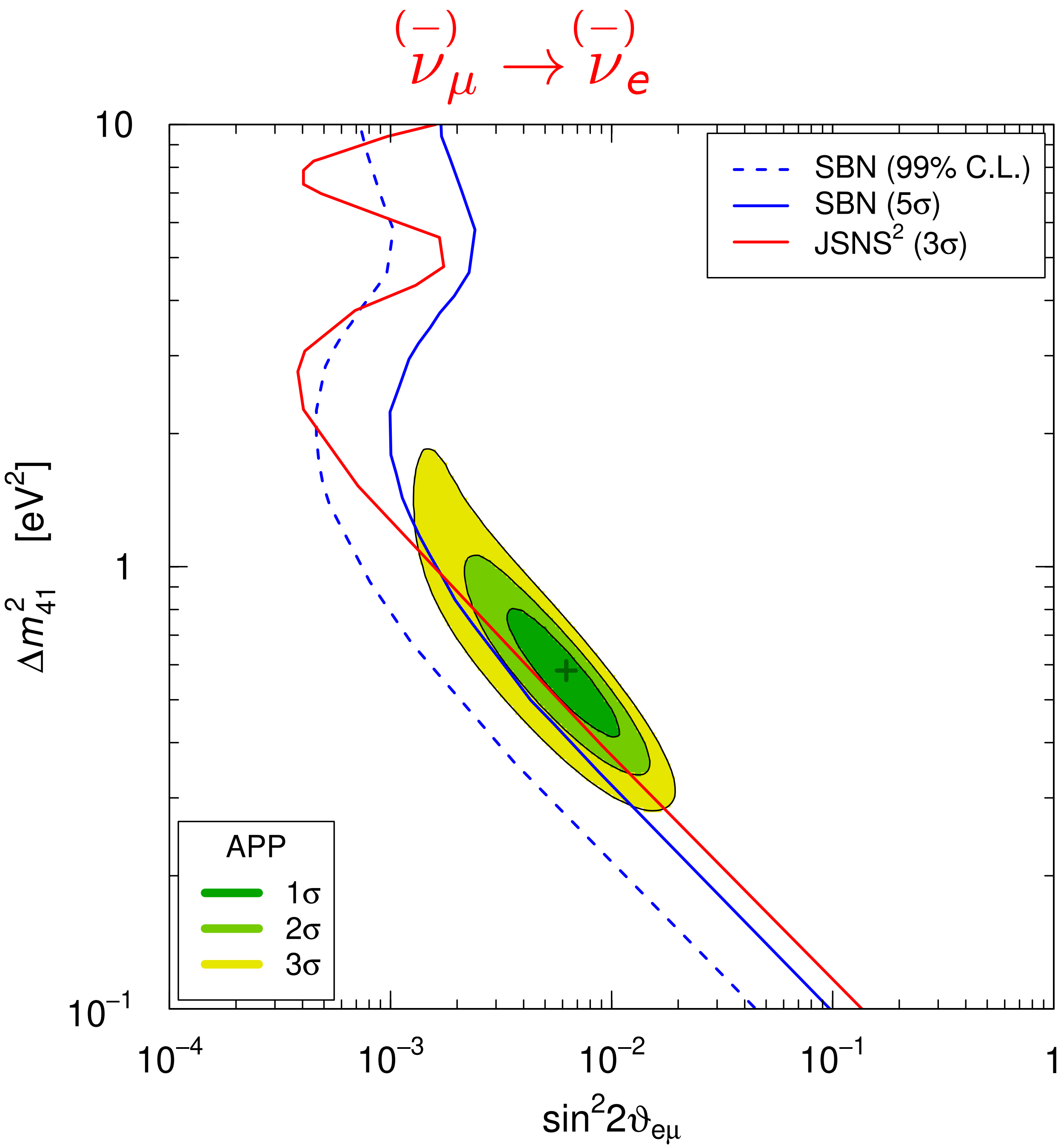
  $\chi^2_{\mathrm{PG}}/\mathrm{NDF}_{\mathrm{PG}} = 46.7/2$

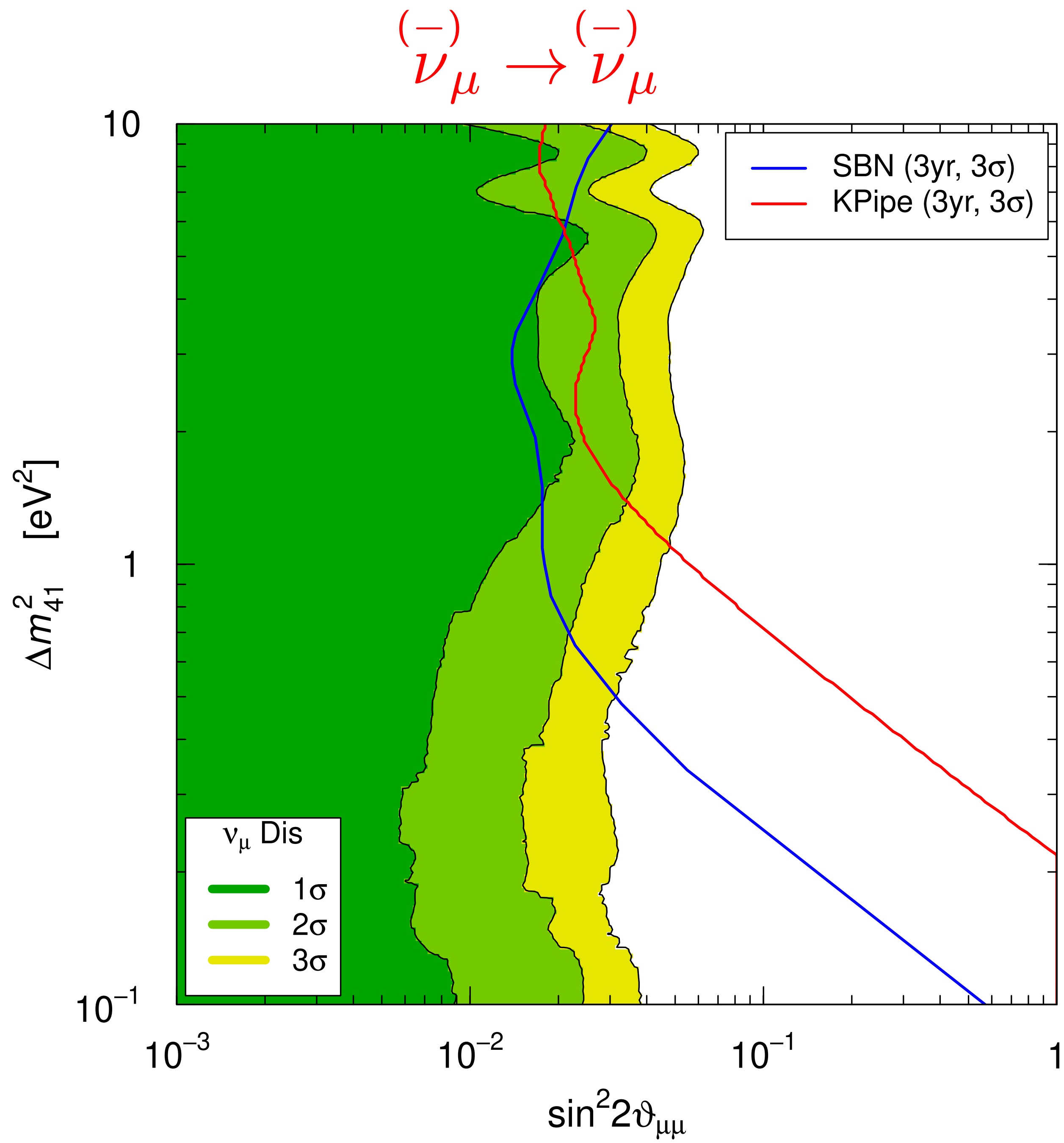
  $\mathrm{GoF}_{\mathrm{PG}} = 7 \times 10^{-11}$ $\leftarrow$ ☹
- Similar tension in

  $3+2, \quad 3+3, \quad \ldots, \quad 3+N_s$

[CG, Zavanin, arXiv:1508.03172]

New Dedicated Experiments

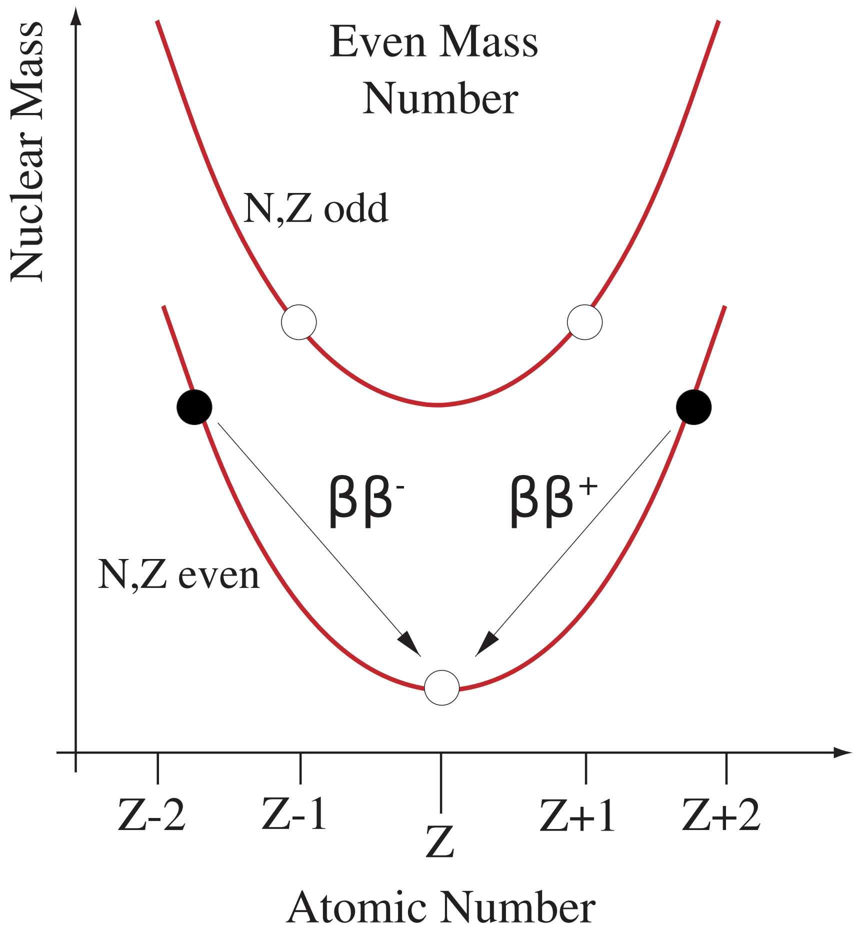




- SBN: Stanco @ NOW 2022 and Karagiorgi @ NOW 2022.
- JSNS^2 : August 2022 Long-Baseline Neutrino News: They are working on the blind analysis of the 1.45×10^{22} POT data taken until June 2021.

Non-oscillation neutrino physics

$\beta\beta$ decay

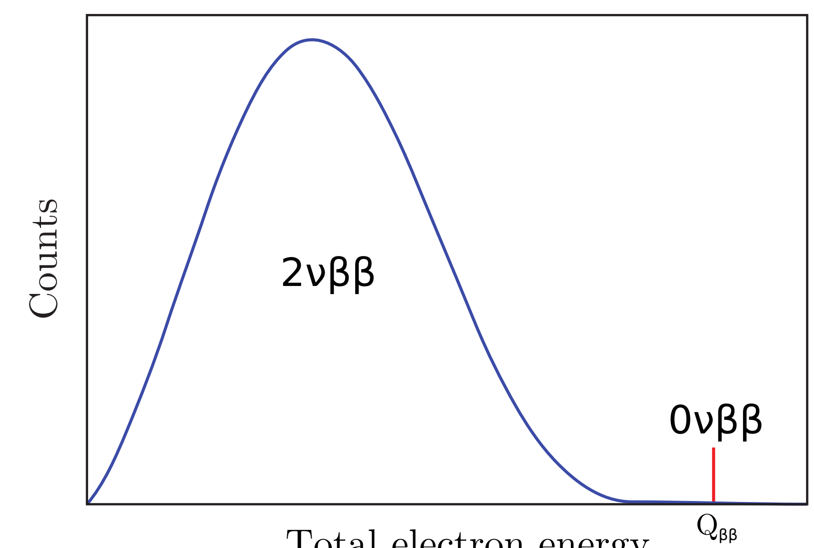


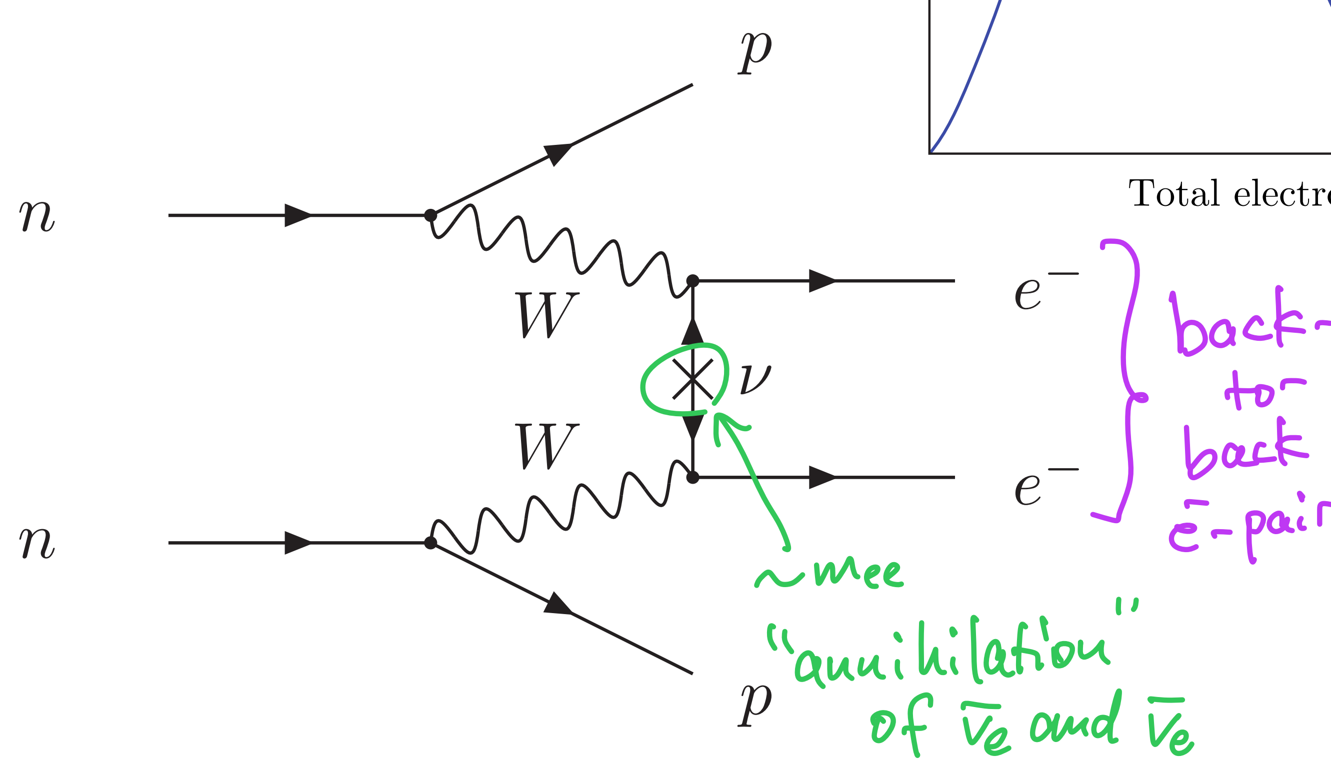
doi 10.1155/2016/2162659

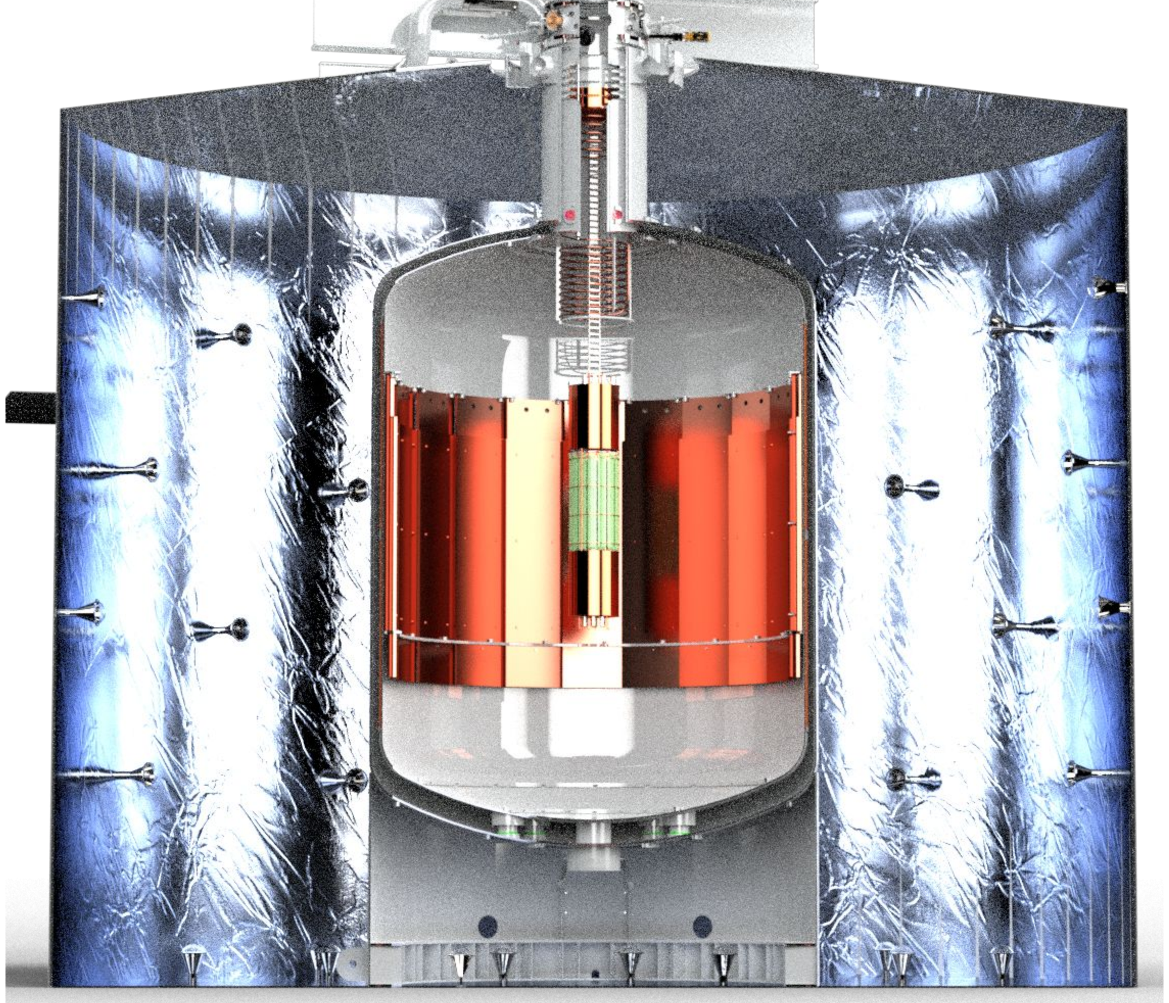
$2n \rightarrow 2p + 2e^- + 2\bar{\nu}$

Se, Xe, Ge, Te, Pd, …

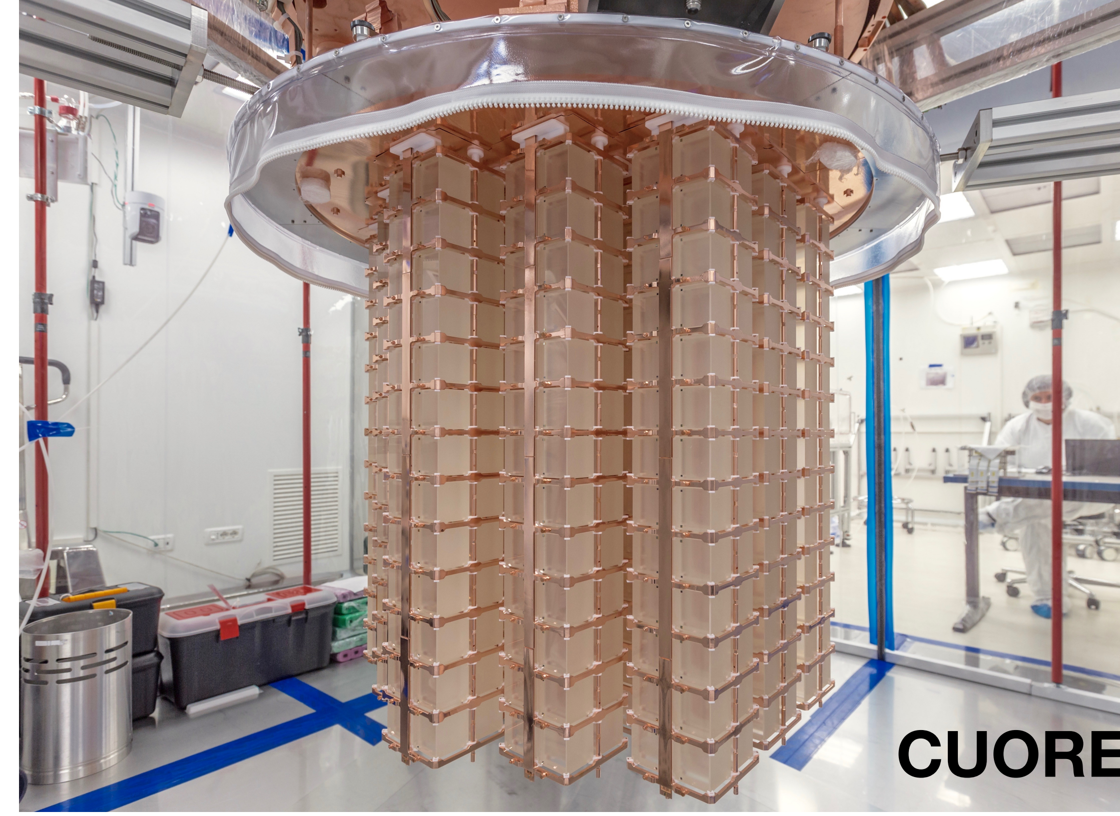
Neutrinoless-double beta $0\nu\beta\beta$



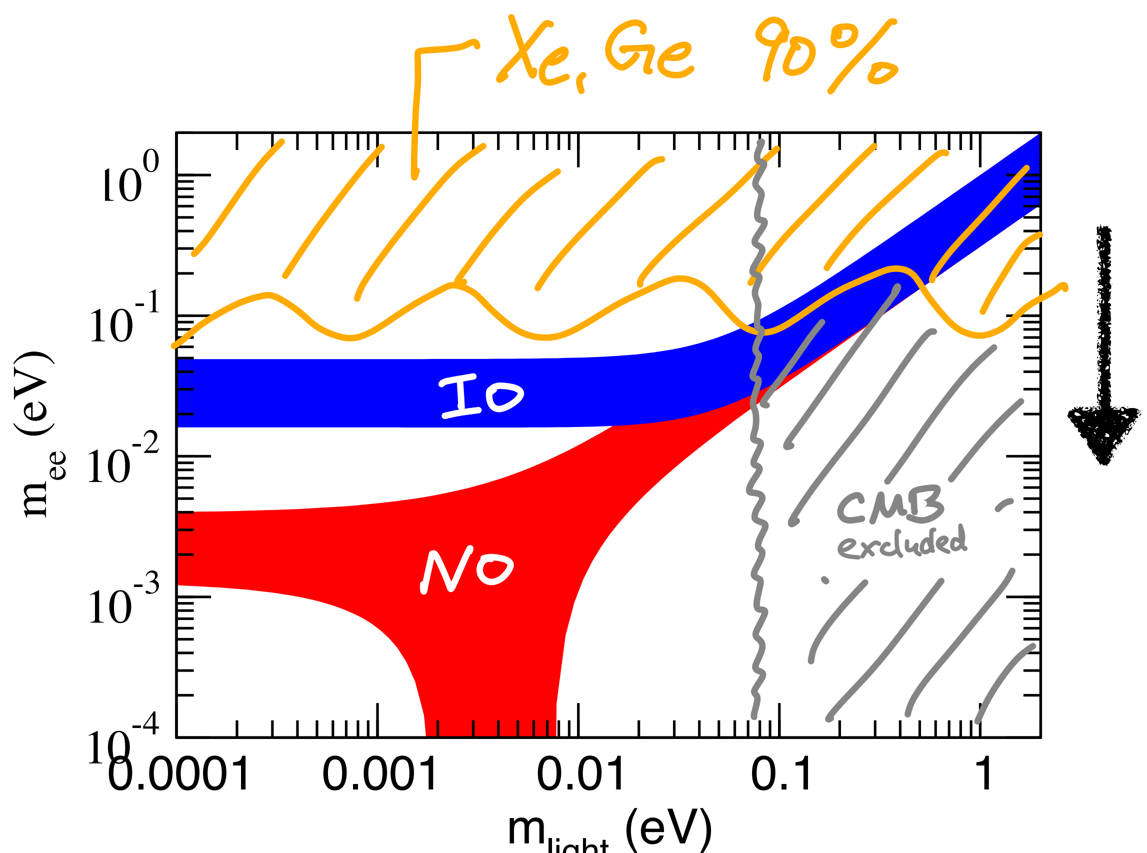




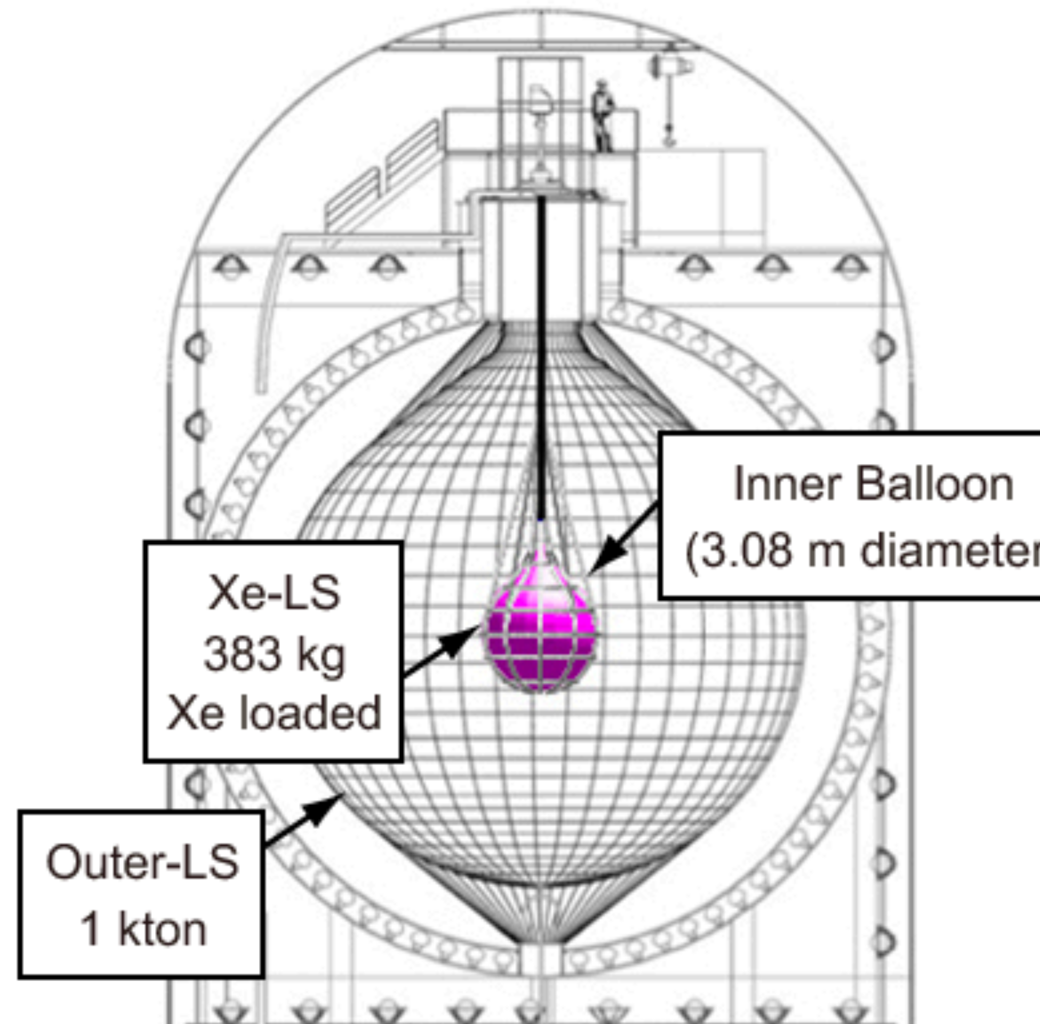
GERDA

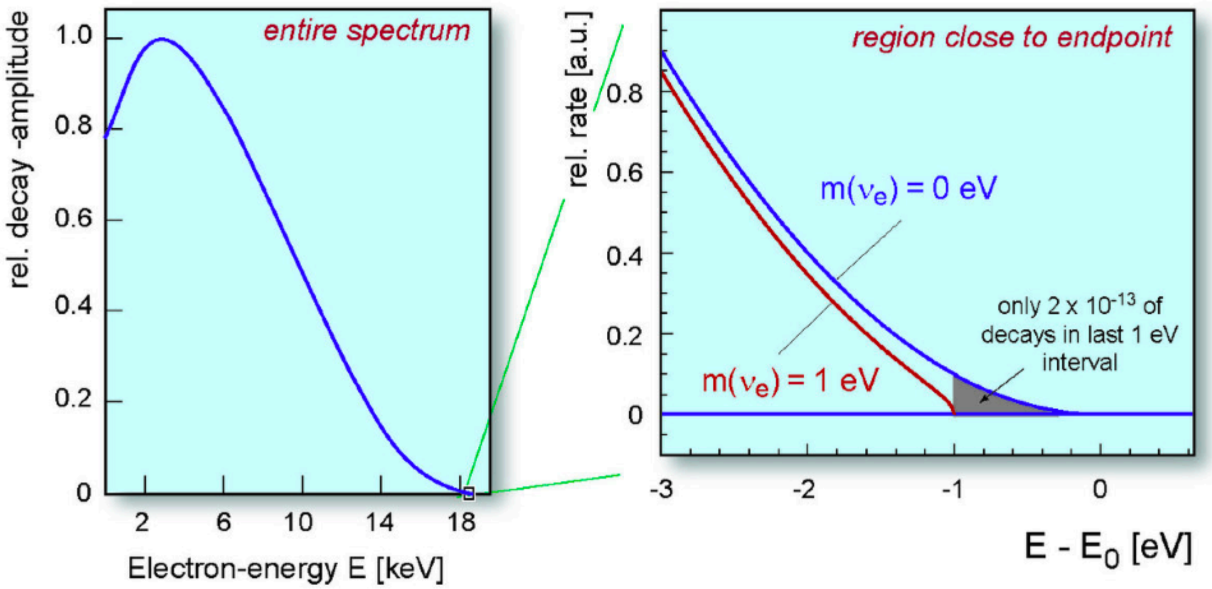


KAMLAND-Zen



Upcoming ton-scale experiments aim to reach below 10 meV



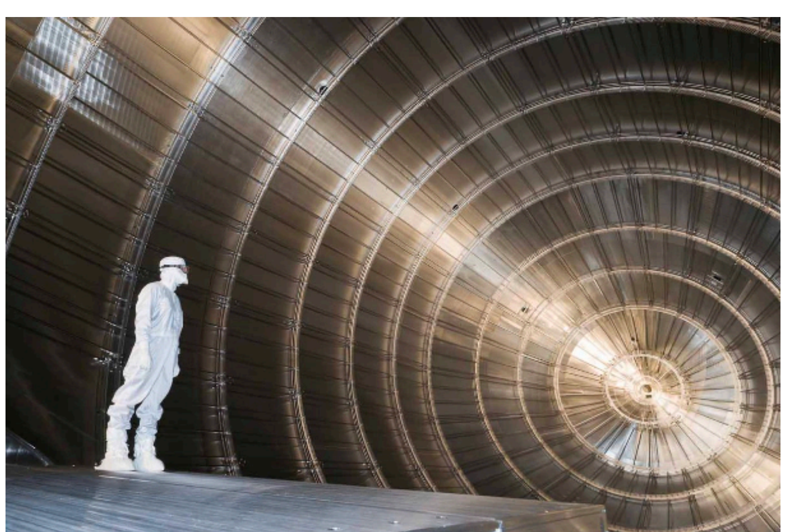


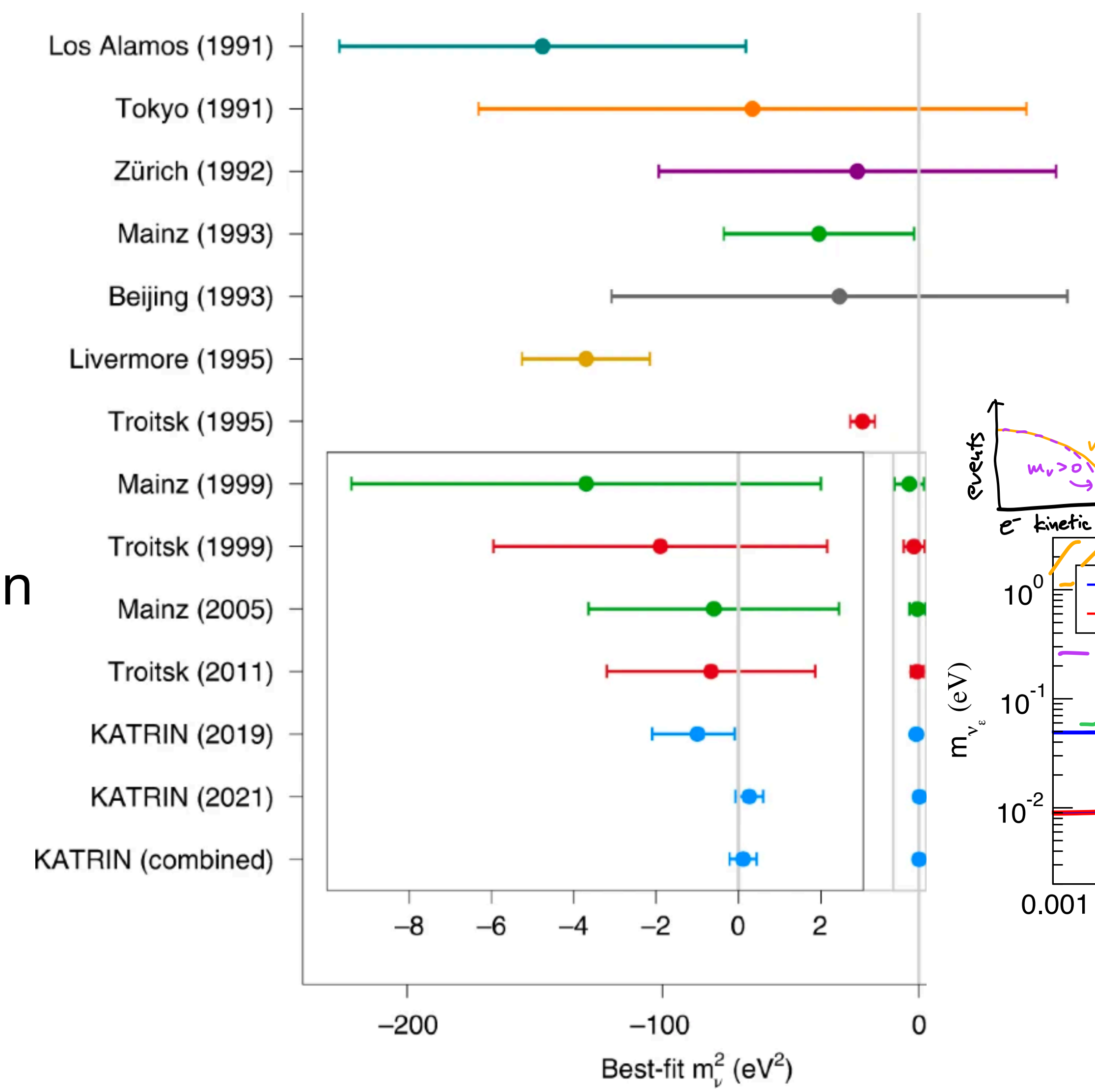
From KATRIN website

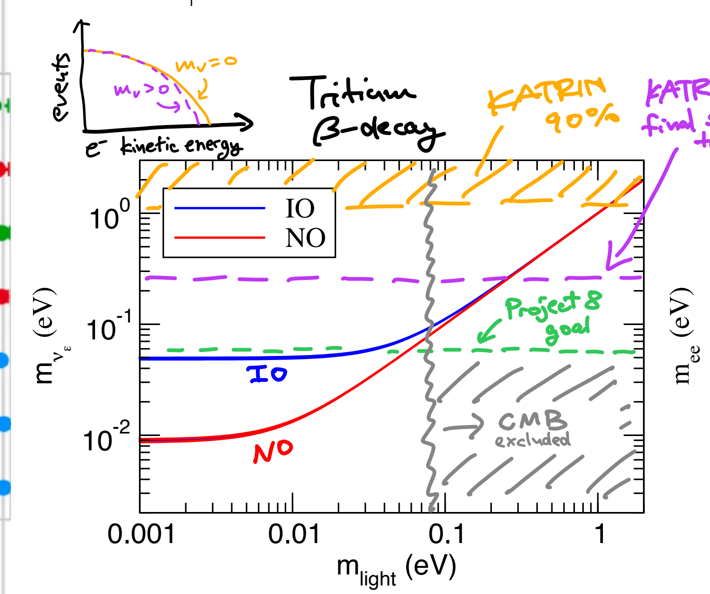
- Measure endpoint of Tr beta decay spectrum to constrain mass of electron neutrino (KATRIN). First results published in 2022.

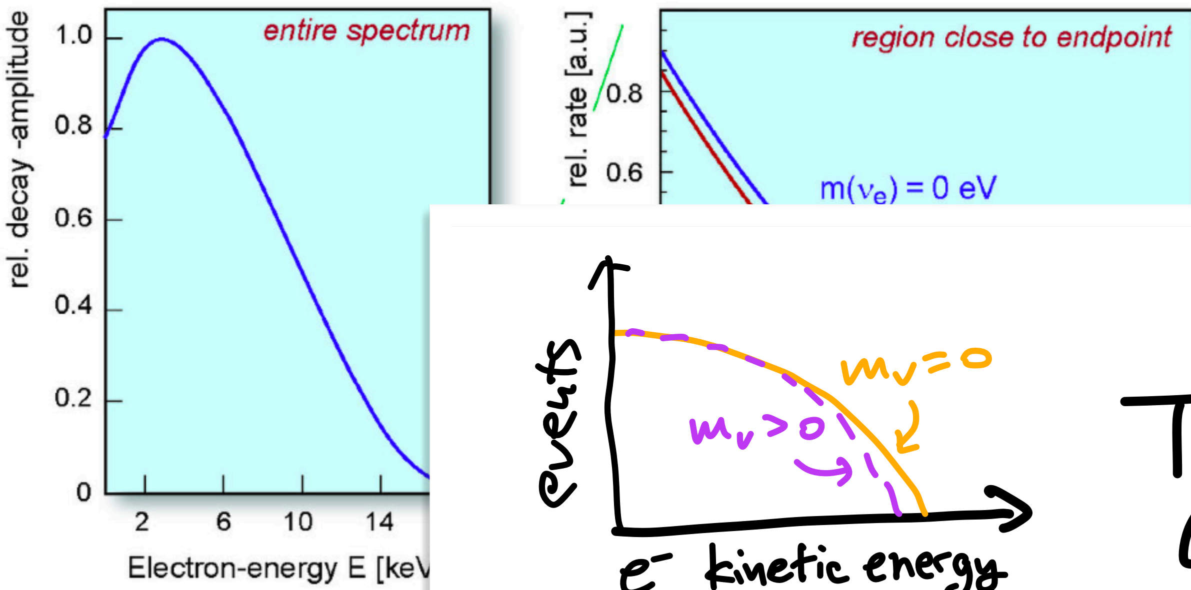
  Nat. Phys. **18,** 160–166 (2022). https://doi.org/10.1038/s41567-021-01463-1

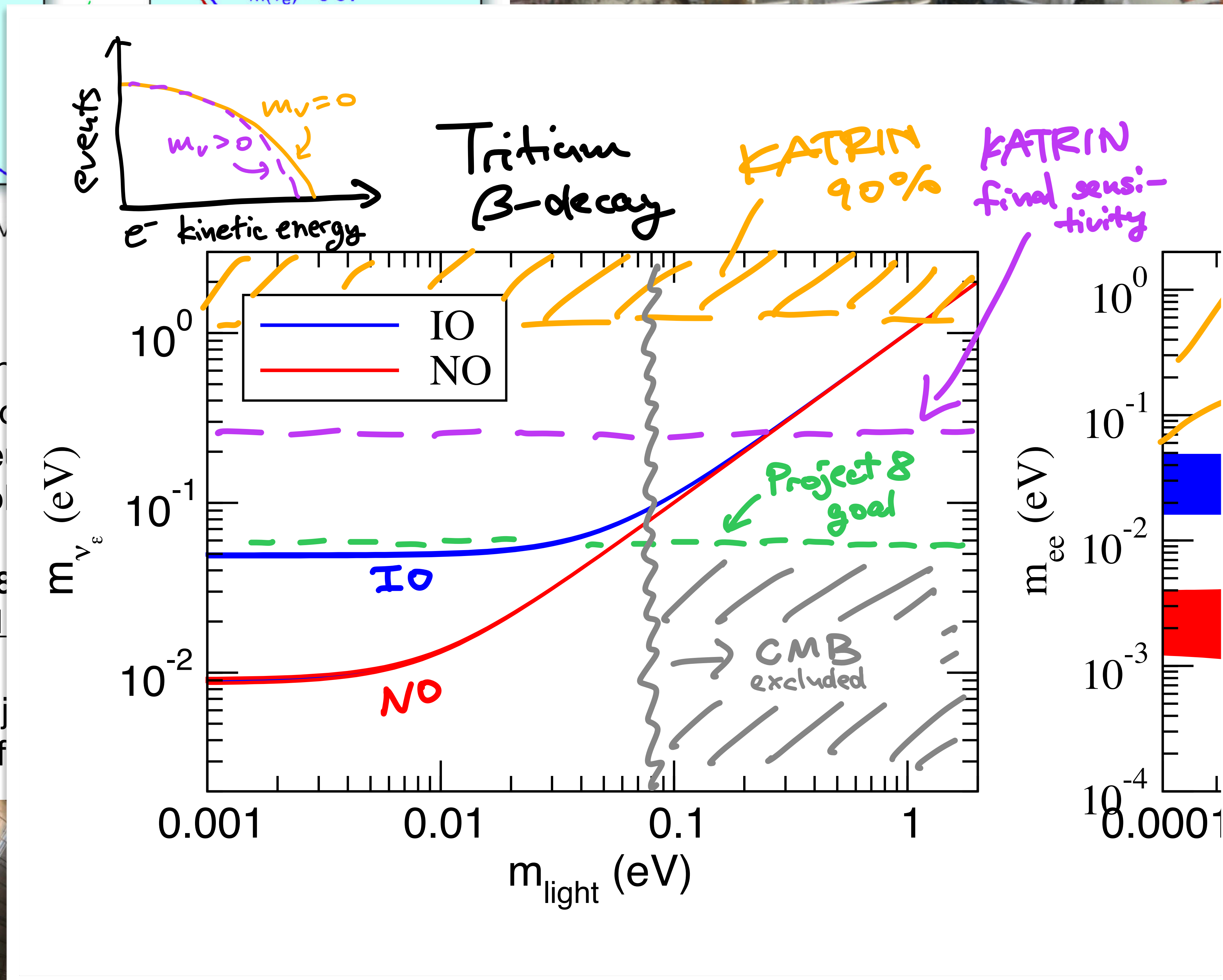
- Future: project 8 (measure precession of atoms after beta-decay)











- Measure er
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Nat. Phys. **18**
doi.org/10.1

- Future: proj
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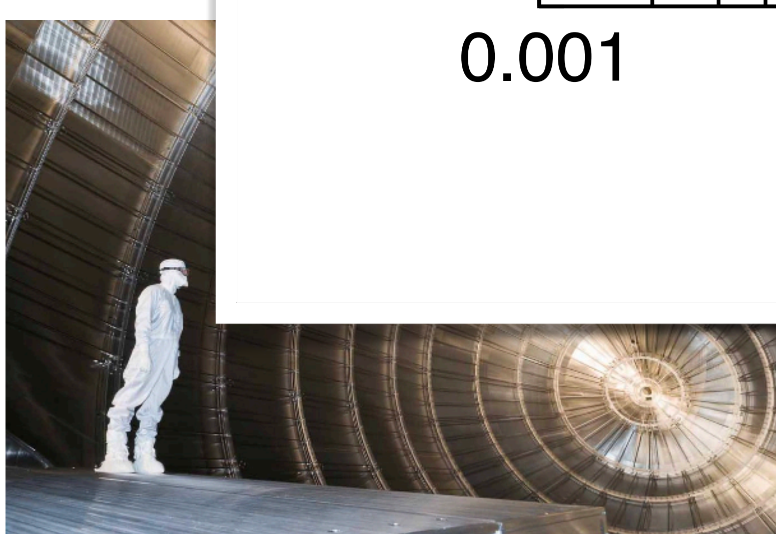

Best-fit m_ν^2 (eV^2)

Summary

- Neutrinos hopefully help us understand the universe better!
- 3-flavor oscillations moving toward completion and precision
  $\rightarrow$ consistency check of PMNS by measuring in different ways
- Today's talk was mostly oscillation, there are also important non-oscillation physics
  - Neutrino mass
  - Neutrino-less double beta (search for Majorana mass)
  - Coherent scattering
  - Supernova, Astrophysical, Cosmogenic neutrinos
  - Impact on cosmology
  - Magnetic moments

backup

Magnetic moments

- Same-flavor magnetic moments only for Dirac
  For Majorana exactly zero
- Flavor-changing magnetic moments allowed
- Best-limits from Borexino
- SM too small to measure, but SUSY etc. predict larger values (similar to eEDM)