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New physics and new technologies

in next-generation neutrino experiments

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Fermion mixing

The fields in $\mathrm{SU}(2)_L$ doublets and singlets are not mass eigenstates

Diagonalise mass matrix first, in order to define fermion masses.
Need of biunitary transformations:

$$\hat{\boldsymbol{\ell}}_L = V_L^{\ell\dagger}\,\boldsymbol{\ell}_L \quad , \quad \hat{\boldsymbol{\ell}}_R = V_R^{\ell\dagger}\,\boldsymbol{\ell}_R$$

$$\hat{\boldsymbol{q}}_L^D = V_L^{D\dagger}\,\boldsymbol{q}_L^D \quad , \quad \hat{\boldsymbol{q}}_R^D = V_R^{D\dagger}\,\boldsymbol{q}_R^D$$

$$\hat{\boldsymbol{q}}_L^U = V_L^{U\dagger}\,\boldsymbol{q}_L^U \quad , \quad \hat{\boldsymbol{q}}_R^U = V_R^{U\dagger}\,\boldsymbol{q}_R^U$$

$\mathrm{SU}(2)_L$ doublets

$$\boldsymbol{\nu}_L = (\nu_{eL}, \nu_{\mu L}, \nu_{\tau L}) \;,\; \boldsymbol{\ell}_L = (e_L, \mu_L, \tau_L)$$
$$\boldsymbol{q}_L^D = (d_L, s_L, b_L) \;,\; \boldsymbol{q}_L^U = (u_L, c_L, t_L)$$

$\mathrm{SU}(2)_L$ singlets

$$\boldsymbol{\ell}_R = (e_R, \mu_R, \tau_R) \;,$$
$$\boldsymbol{q}_R^D = (d_R, s_R, b_R) \;,\; \boldsymbol{q}_R^U = (u_R, c_R, t_R)$$

No transformation for neutrinos since there are no Dirac mass terms

Applying this to the fermionic currents

CC : for quarks, matrix $V = V_L^{U\dagger} V_L^D$ appears (CKM matrix);

for leptons, no transformation for $\boldsymbol{\nu}$, choose arbitrarily $\hat{\boldsymbol{\nu}}_L = V_L^{\ell\dagger}\,\boldsymbol{\nu}_L$ and current does not change

NC : GIM mechanism leaves currents the same as before the transformation

Neutrino mixing

Nothing forbids to **extend** the SM and introduce **right-handed** neutrino fields

$$\boldsymbol{\nu}_R = (\nu_{eR}, \nu_{\mu R}, \nu_{\tau R})$$

Now Dirac mass terms are allowed and transformations can be defined

$$\hat{\boldsymbol{\nu}}_L = V_L^{\nu\dagger}\, \boldsymbol{\nu}_L \quad , \quad \hat{\boldsymbol{\nu}}_R = V_R^{\nu\dagger}\, \boldsymbol{\nu}_R$$

In CC lepton current the matrix $U = V_L^{\nu\dagger} V_L^{\ell}$ appears (PMNS matrix).
The flavour of charged lepton is uniquely **defined by their masses**; re-define the left-handed flavour neutrino fields as

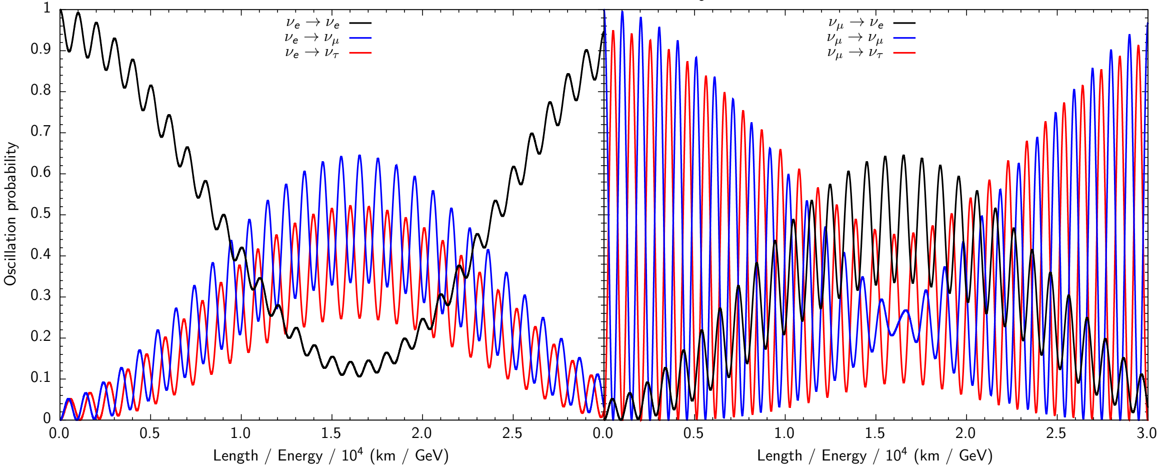
$$\boldsymbol{\nu}_L = U\, \hat{\boldsymbol{\nu}}_L \ , \quad \text{with} \quad \boldsymbol{\nu} = (\nu_e, \nu_\mu, \nu_\tau) \ , \ \hat{\boldsymbol{\nu}} = (\nu_1, \nu_2, \nu_3)$$

and CC Lagrangian is written in terms of "flavour" neutrinos.
If neutrino masses are taken into account, **mixing** of the fields occurs:

$$\nu_\alpha = \sum_i U_{\alpha i}^* \nu_i$$

Neutrino oscillation

After a few easy steps...
$$P(\nu_\alpha \to \nu_\beta) \equiv |\langle \nu_\alpha | \nu_\beta(t) \rangle|^2 = \sum_{ij} U^*_{i\alpha} U_{\beta i} U_{\alpha j} U^*_{j\beta} \exp\left(-i \frac{\Delta m^2_{ij} L}{2E}\right)$$



How to measure the mixing angles

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad \text{where} \quad \begin{matrix} c_{ij} \equiv \cos\theta_{ij} \\ s_{ij} \equiv \sin\theta_{ij} \end{matrix}$$

Neutrino oscillation experiments are simply **counting experiments**.

Ingredients:

- detector to "convert" neutrinos into charged leptons
- source that produces *a lot of* neutrinos
- patience to taste

Method:

- Count neutrinos at the source
- Count neutrinos at the detector

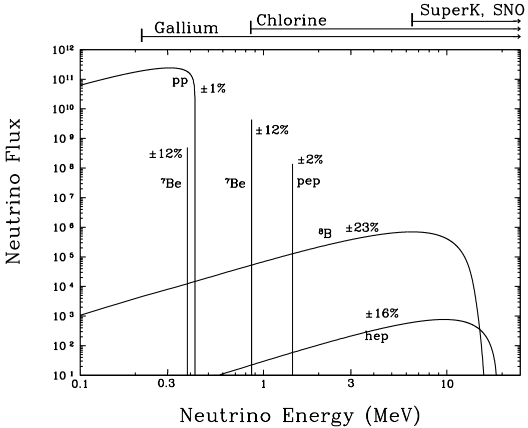
$$\boxed{N_{\mathrm{det}} = P(\nu_\alpha \to \nu_\beta) \otimes \Phi \otimes \sigma \otimes \varepsilon}$$

...and don't forget about **energy dependencies** of source, cross-section, detection efficiency and oscillation probability!

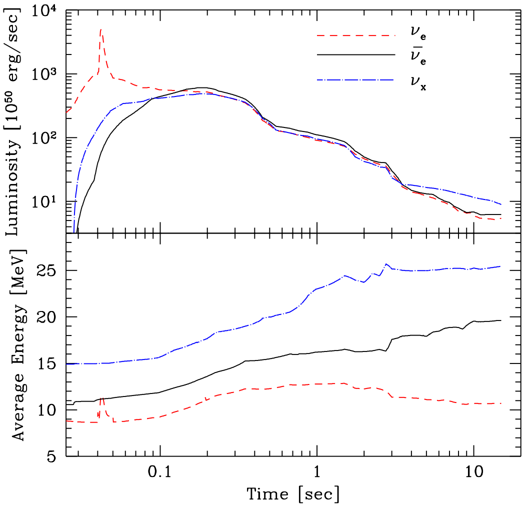
Input N in your favourite **Poissonian** likelihood to get **significance** of measurement.

Astrophysical neutrinos

Solar neutrinos

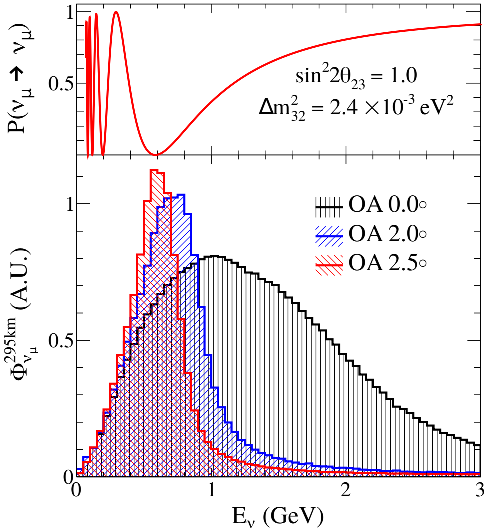


Supernova neutrinos

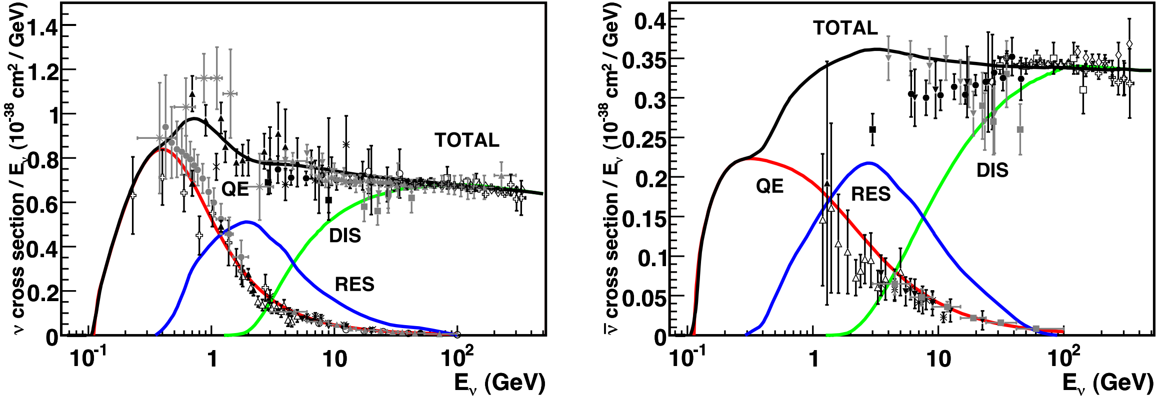


Accelerator neutrinos

- Two-body decays of pseudo-scalar meson (**helicity suppression**) $P^+ \to \mu^+ + \nu_\mu$ and muon decays $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$
- **Secondary particles** from proton beam impinging on fixed target (typically graphite).
- Energy profile of proton is known!
- Focusing system surrounds target pulsed toroidal **horns**, to improve quality of the beam.
- By changing the current direction of the horns, it is possible to **select and focus** particles of desired charge.
- Forward Horn Current (FHC) and Reverse Horn Current (RHC) result in a beam made of respectively **neutrinos** (ν-mode) and **anti-neutrinos** ($\overline{\nu}$-mode).



Neutrino cross-section



CEνNS, CCQE, NCE, IBD, COH, DIS etc...

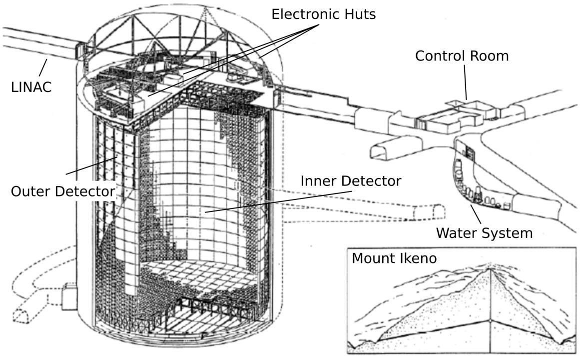
Apart from low-energies where CEνNS dominates, QE, COH, and DIS **cross-sections overlaps** in region of interest: difficult to pin-point best model.

In this talk...

R&D and phenomenological studies in the context of long-baseline oscillation experiments.

- **Super-Kamiokande**
  - Gadolinium-doping of water Cherenkov detectors
  - Neutron calibration
  - Gd-concentration monitoring
- **Hyper-Kamiokande**
  - Unprecedented statistics!
  - Sensitivity to mixing parameters, especially δ_{CP}.
  - Understand how much systematic uncertainties affect sensitivity.
- **DUNE Near Detector**
  - Perfect to study BSM physics, thanks to powerful beam and state-of-the-art near detector
  - Extensions to SM can explain neutrino masses and mixings
  - Low-scale implementations predict signatures accessible to the experiment

Super-Kamiokande



- 50 kt water Cherenkov detector in a steel cylinder 41.4 m $\times$ 39.3 m.
- **Fiducial volume** of 22.5 kt.
- Outer detector (OD) optically separated by inner detector (ID).
- **Ring-imaging Cherenkov** to detect electrons, muons, pions, and protons.
- Since SK-IV, **radon-purification system** lowers background below 3 mBq/m^3.

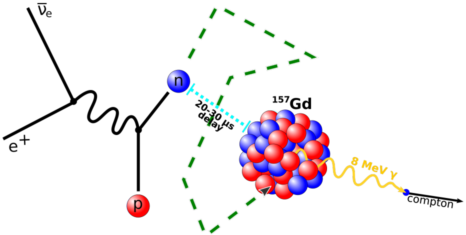
	SK-I	SK-II	SK-III	SK-IV	SK-V
Period	1996–2001	2002–2005	2005–2008	2008–2018	2019–
ID PMTs	11146 (40%)	5182 (19%)	11129 (40%)	11129 (40%)	11129 (40%)
ID DAQ	ATM	ATM	ATM	QBEE	QBEE

Neutrons in Super-Kamiokande

Neutrons are produced by **Inverse beta decay** (IBD), natural decay, or spallation.

Neutron capture process:

- At high energies (above keV) neutrons slow down via **elastic scattering**: *thermalisation*
- At **thermal energies** (0.025 eV) capture cross section dominates
- Neutron is absorbed by nucleus forming an unstable compound
- Compound nucleus decays hopefully giving visible signature.
- Mean capture time in water (hydrogen) is $(204.8 \pm 0.4)\,\mu s$.



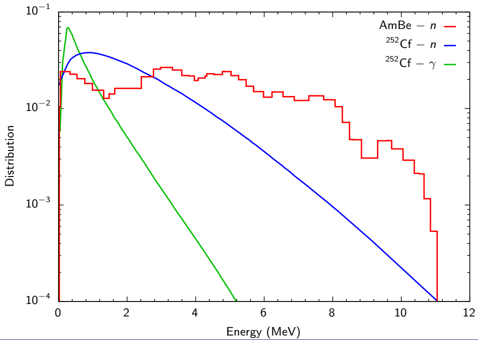
IBD + **neutron capture** can help distinguish between ν and $\overline{\nu}$.

Neutron tagging is crucial for: **Diffuse Supernova Neutrino Background** and Supernova explosions; accelerator, atmospheric, and reactor neutrinos; proton decay.

Measuring tagging efficiency

Am-Be ($t_{1/2} = 432.6$)

- ^{214}Am decays into ^{237}Np via α emission.
- α is captured by ^{9}Be nuclei to become ^{12}C* with emission of a neutron.
- ^{12}C* de-excites to ground state with sometimes emission of a 4.43 MeV γ.



^{252}Cf ($t_{1/2} = 2.645$ y)

- californium-252 undergoes α decay (96.91%) or SF (3.09%).
- SF emits 3.75 neutrons and 10.3 photons (8.2 MeV) on average per fission event.
- After trigger, multiple neutron captures are expected, separated by a few milliseconds each.
- **Multiplicity and time intervals** between captures can be used to determine neutron tagging efficiency, neutron mean life, and source activity.

◇ Photon(s) are detected by placing the source in a **scintillating material**

◇ Light **triggers** a search for neutron capture.

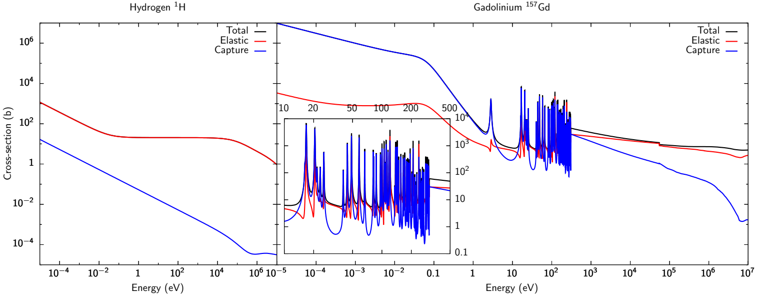
◇ Assumption: neutron does not travel far from source

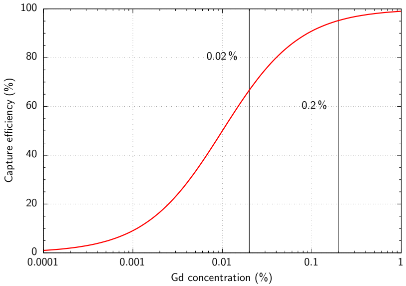
◇ Measured efficiency of SK-IV: 20 %.

Neutron tagging with Gd

Gadolinium-157 (abundance 15.65 %) has **highest thermal neutron capture cross-section** among stable nuclides: estimated around 2.537×10^5 b.

SK-Gd concept: dissolve 100 t of a gadolinium salt in water [J. Beacom, M. Vagins, '04].





Gadolinium sulphate is only viable salt; main challenge is **filtration system**.

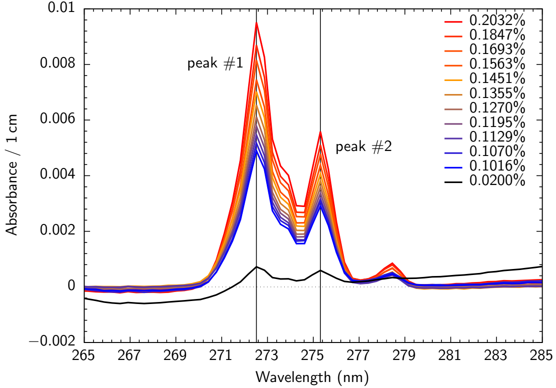
EGADS proved the concept successfully: with a 0.2% solution of $Gd_2(SO_4)_3$ tagging efficiency is 90% and mean capture time ∼30μs.

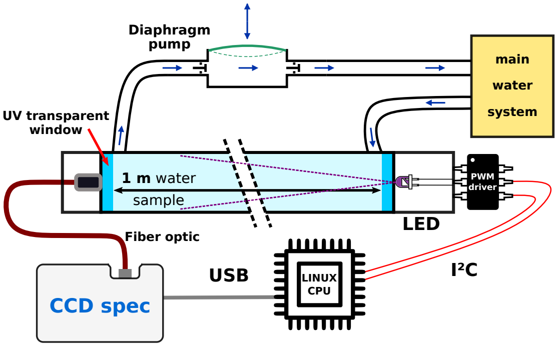
Concentration of Gd affects capture efficiency: important to measure it frequently!

EGADS technique uses Zeeman spectroscopy, slow process (once every month) and accuracy of 3%.

New method (almost continuous and higher accuracy) that exploits **UV spectroscopy**

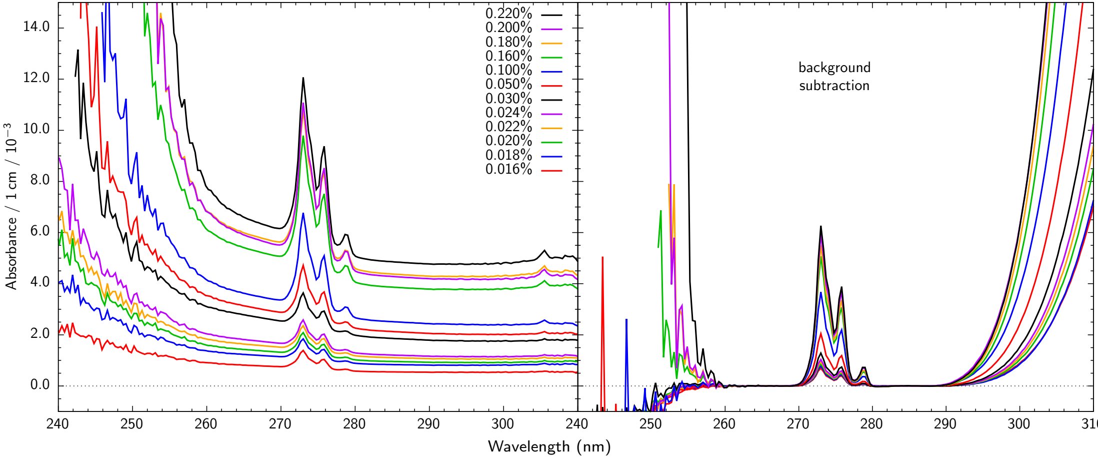
$$\Delta\mathcal{A} = a + b\,\rho_{\mathrm{Gd}}$$





Background subtraction

Alignment of optics, contamination of water, **micro-bubbles**, and LED stability all affect measurement. **Background subtraction** with 5-th grade polynomial is found to be effective.

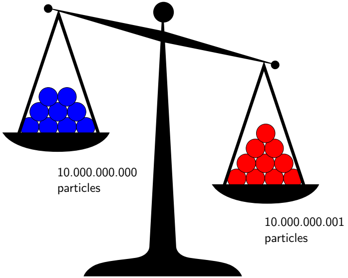


CP violation is necessary...

...to describe our universe as it is. Sakharov conditions are needed to obtain an **asymmetry** between matter and antimatter

1. Baryon number violation
2. C and CP violation
3. Out of thermal equilibrium interactions

$$\Longleftrightarrow \qquad \eta = \frac{n_B - n_{\overline{B}}}{n_\gamma} \simeq 10^{-10}$$



CP violation in the **quark sector** alone is not enough to describe current asymmetry in the SM.

If there were CP violation in **leptonic sector**, baryogenesis could be achieved with **leptogenesis**: adding **right handed neutrinos** allows for lepton number violation, which is converted into **baryon asymmetry** via **sphaleronic processes**. [Fukugita, Yanagida, '86].

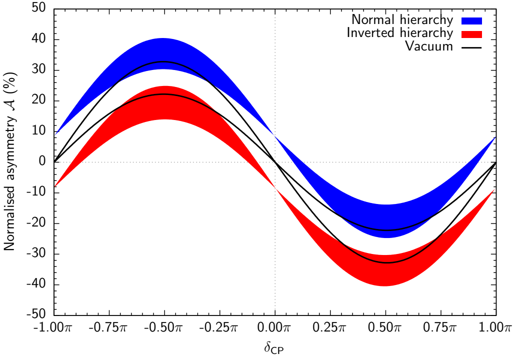
Successful leptogenesis requires $|\sin\theta_{13}\sin\delta_{\rm CP}| \gtrsim 0.09$, if no Majorana phase [S. Pascoli *et al.*, '06].

CPV in neutrino oscillation

- Neutrino oscillation **best probe** to look for CPV in lepton sector.
- PMNS matrix describes how **mass states** are mixed into **flavour states**, as $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$.
- CP violation is quantified as **difference** between neutrino and antineutrino probabilities; the term is proportional to the *Jarlskog invariant*

$$\mathcal{A}^{\text{CP}}_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)$$

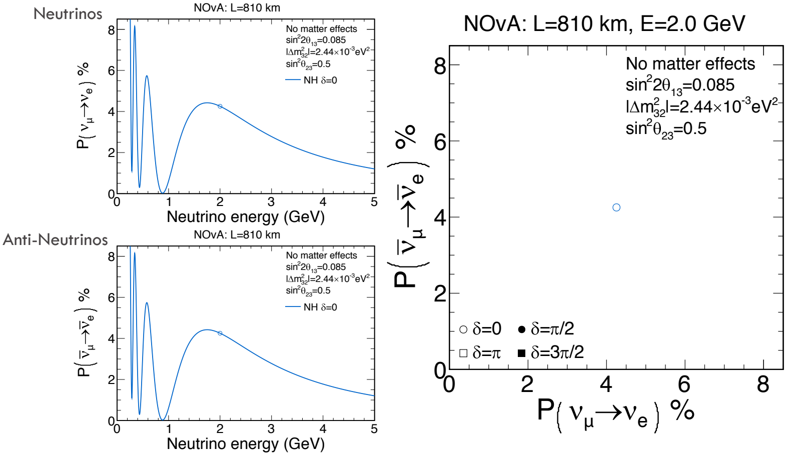
$$= 4 \sum_{i>j} \Im\left[U^*_{i\alpha} U_{\beta i} U_{\alpha j} U^*_{j\beta}\right] \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$



In LBL experiments, typically $|\Delta m^2_{31}|$ dominates $\to$ **two-flavour limit**
Effective angle θ_{eff} is invariant under CP and so $\mathcal{A}^{\text{eff}}_{\alpha\beta} = 0$.

Oscillation probabilities of ν and $\overline{\nu}$ in matter differ, because **medium is not CP–invariant**.

Measuring ν_e and $\bar{\nu}_e$ appearance



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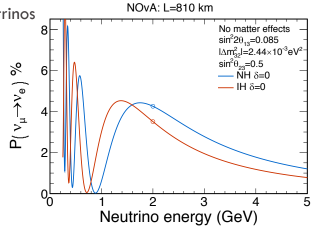
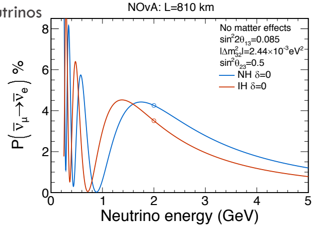
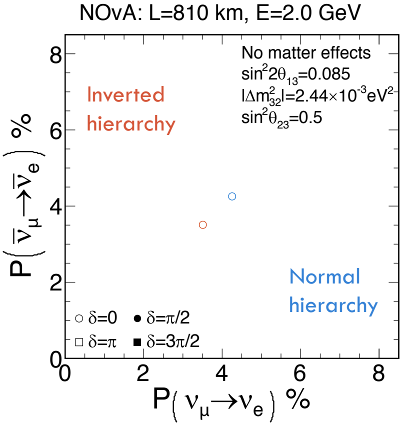
Measuring ν_e and $\bar{\nu}_e$ appearance

Neutrinos



Anti-Neutrinos





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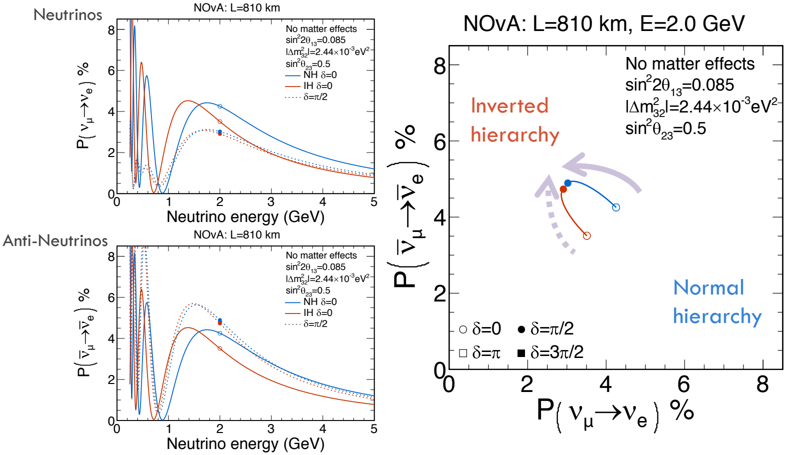

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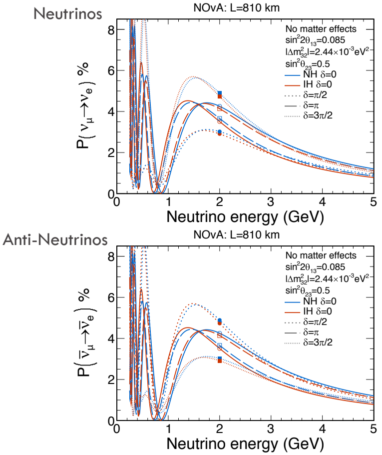
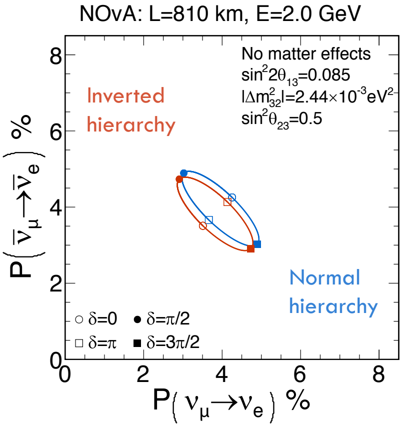
Measuring ν_e and $\bar{\nu}_e$ appearance





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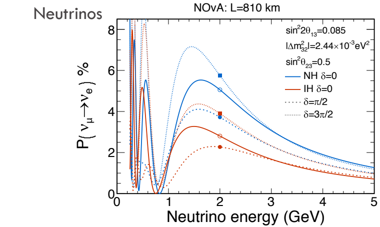
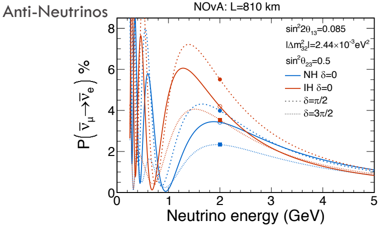
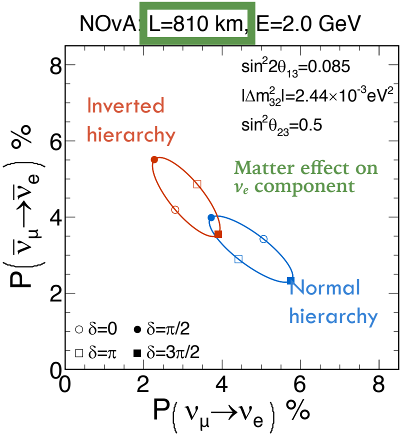
Measuring ν_e and $\bar{\nu}_e$ appearance







Larger matter effect at longer baselines like DUNE!

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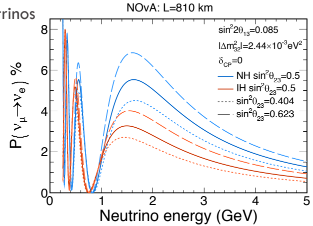
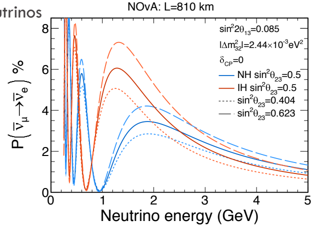
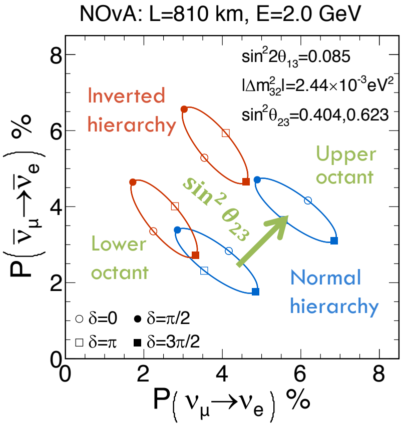
Measuring ν_e and $\bar{\nu}_e$ appearance

Neutrinos



Anti-Neutrinos





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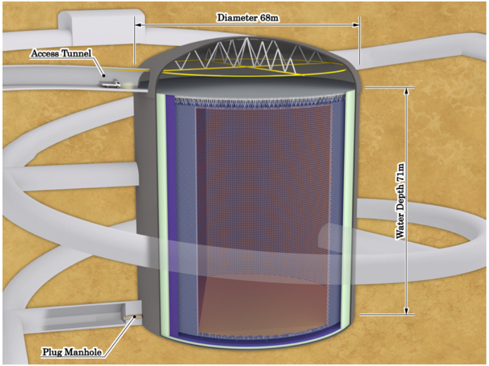
Hyper-Kamiokande

HK will be the **next-generation** water Cherenkov detector, start taking data in $\geq$2027.

- Cylindrical tank with a 68 m diameter and 72 m high.
- **Fiducial volume** of 188.4 kton, which is 8.4 times SK.
- Outer detector of 1 m to veto background.
- Same **photo-coverage** of SK, 40% ($\simeq 4 \times 10^4$ PMTs).
- New PMTs with twice QE, improved charge and timing resolution
- Possibility of a second tank in Korea.



Vast physics programme! Beam, solar, atmospheric, SNe, proton decay.

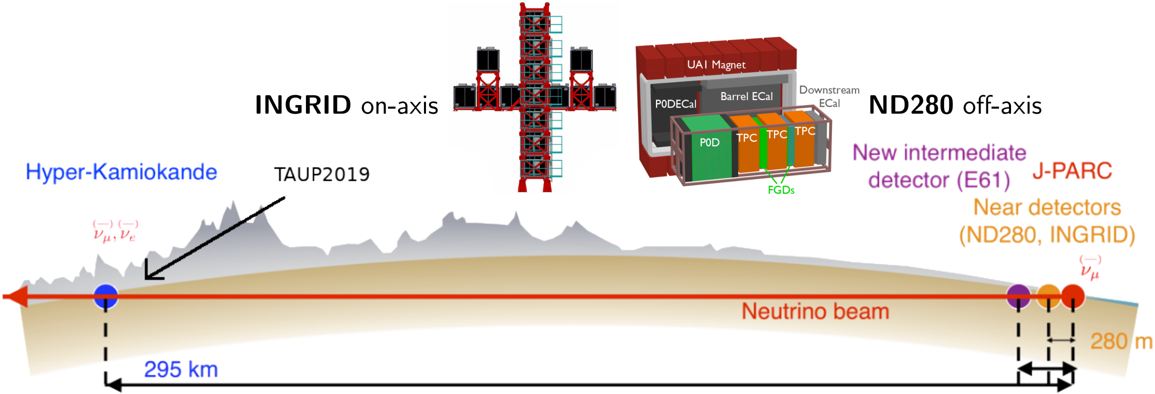
Main goal is to measure δ_{CP}, θ_{23}.

T2K beam

HK will be located **295 km** away from the target and **2.5° off-axis** with respect to beamline.

Planned upgrade of near detectors **ND280** and **INGRID**, and construction of new **Intermediate Water Cherenkov Detector** (IWCD), possibly loaded with Gd.

The 30 GeV proton beam accelerator **J-PARC** beam will upgrade to 1.3 MW.
Neutrino beam still peaks at 600 MeV.



Combined fitting framework

Combined fitting of **beam** and **atmospheric** oscillation data:

atmo: SK atmospheric MC scaled to HK statistics. Events **binned** in 19×2D histograms $\log p$ vs. $\cos\theta$ with various binnings: total of **2224 bins**.

beam: **Flux prediction** at far detector is tuned with ND constraints and 2D matrices are applied to transform E_{true} spectra (98 bins) into E_{reco} spectra (87 bins).

Total of 4×1D histograms are used in E_{reco} with **87 bins** for the four observables: 1 ring e-like and 1 ring μ-like events in ν and $\overline{\nu}$-mode.

Event distributions are "oscillated" for each combination of **oscillation parameters**, using E_{true}, and are tested against a "true" point to study χ^2 vs. oscillation parameters.

Sensitivity to δ_{CP} is quantified by testing every value of δ_{CP} as a true point and estimating:

$$\sigma = \sqrt{\min_{\delta_{\text{CP}}=0,\pm\pi} \chi^2 - \chi^2_{\text{true}}}$$

Test statistics

Following SK atmospheric analysis, start from **Poissonian binned-likelihood**

$$\mathfrak{L}(E_n, O_n) = \prod_n \frac{e^{-E_n} E_n^{O_n}}{O_n!} \ ,$$

where O_n and E_n are respectively observed (*true*) and expected events in n-th bin.
Linear response assumed in systematics: varying j-th systematic as $\beta_j \to \beta_j + \varepsilon_j \sigma_j$ expected events changes accordingly

$$\beta_j \overset{\text{MC}}{\longmapsto} E_n \qquad \Longrightarrow \qquad \beta_j + \varepsilon_j \sigma_j \overset{\text{MC}}{\longmapsto} E_n(1 + \varepsilon_j f_n^j) \ .$$

χ^2 is log-likelihood ratio **plus penalty term** for variances and covariances of systematic parameters.
Parameters ε_j (in units of σ) are introduced to account for systematic uncertainties

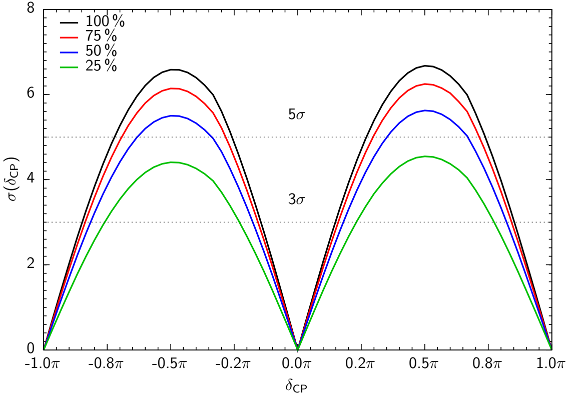
$$E_n \ \longrightarrow \ E_n \left(1 + \textstyle\sum_j f_j^n \varepsilon_j\right)$$

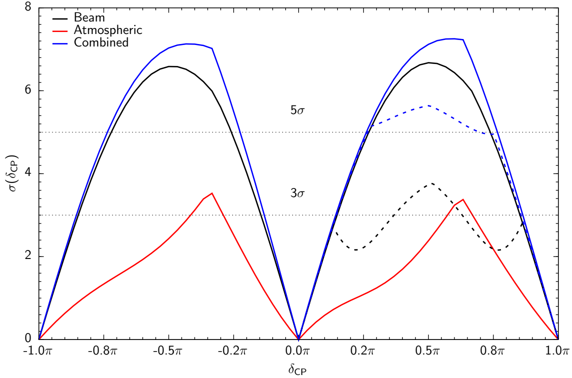
Full χ^2 is **minimised** with respect to systematics and scanned over **each point** of oscillation space

$$\chi^2 = \ 2 \sum_n \left[E_n(1 + \textstyle\sum_j f_j^n \varepsilon_j) - O_n - O_n \log\left(\frac{E_n(1 + \sum_j f_j^n \varepsilon_j)}{O_n} \right) \right] + \sum_{ij} \varepsilon_i \, \rho_{ij}^{-1} \, \varepsilon_j \ ,$$

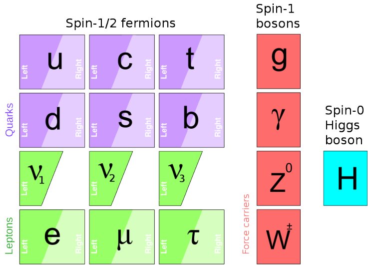
Sensitivity to CPV

Sensitivity to CPV from **beam sample only**, considering full statistics as 10 years of data (2.5 y in ν-mode and 7.5 y in $\overline{\nu}$-mode) for 2.7×10^{22} POT. Mass hierarchy (MH) is assumed to be **normal**.





If MH is not known, sensitivity is degraded. Atmospheric sample can help **restore** sensitivity when MH is unknown.



$\Longleftrightarrow$

- Plank survey [2018]

$$\sum_i m_{\nu_i} < 0.12\,\text{eV at } 90\%\text{C.L.}$$

- ν-fit 4.0 [2018]

$$\Delta m^2_{21} = 7.39^{+0.21}_{-0.20} \times 10^{-5}\,\text{eV}^2$$
$$|\Delta m^2_{31}| = 2.522^{+0.033}_{-0.031} \times 10^{-3}\,\text{eV}^2$$

- Troitsk [2011] with ^{3}H β-decay

$$\sum_i |U_{ei}|^2 m_{\nu_i} < 2.05\,\text{eV}$$

Problems:

- No ν_R in SM, so no Yukawa ($d \leq 4$).
- $m_\nu \ll m_e$, six orders of magnitude!
- ν can be a Majorana particle.

Solutions:

theory: many models and also minimal.

e.g. add heavy neutrinos to SM + seesaw.

phenomenology: not so nice.

e.g. Type I seesaw requires GUT scale particles.

experiment: need something appealing...

Inverse seesaw

"Recipe" for a minimal inverse seesaw [A. Abada, M. Lucente, '14]

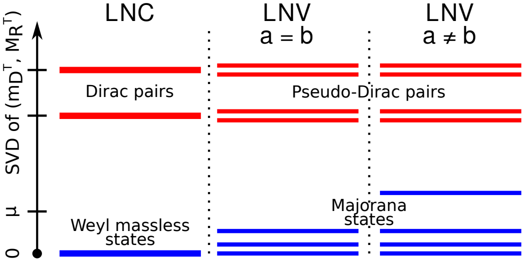
- Extend the SM by adding singlet fermions $N_{i=1..a}$ with LN $= +q_L$ and $S_{j=1..b}$ with LN $= -q_L$

  $\Rightarrow$ **symmetry-protection** lower the physics scale!
- Majorana mass terms, with "natural" LNV parameters and cancellations among high scale contributions.
- Light neutrinos described ✓, but also new heavier particles: **Heavy Neutral Leptons** (HNL).
- Forbidden mixing angles and masses accessible by current and future experiment

$$\mathcal{L} = \frac{1}{2}\left(\overline{\nu},\, \overline{N},\, \overline{S^C}\right)\begin{pmatrix} 0 & m_D^T & 0 \\ m_D & \mu_R & M_R^T \\ 0 & M_R & \mu_S \end{pmatrix}\begin{pmatrix} \nu^C \\ N^C \\ S \end{pmatrix}$$

HNL can be either Majorana or (pseudo-)Dirac

$$N_P = U_{si}\,\nu_i + i\,U_{sj}\,\nu_j \quad , \quad \overline{N}_P = U^*_{si}\,\nu_i + i\,U^*_{sj}\,\nu_j$$



Testable signatures

Sterile neutrinos **mix** with light neutrinos into flavour neutrinos: HNL take part in any neutrino process thanks to **mixing-suppressed couplings**.

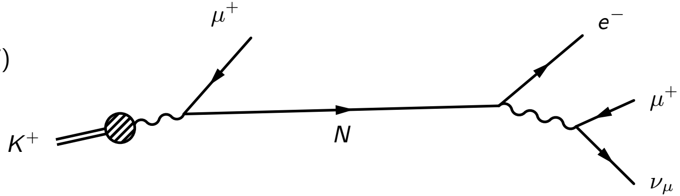
- kink in Curie plots of β decay (keV$\sim$MeV)
- $0\nu\beta\beta$ decay (keV$\sim$TeV)
- searches of HNL decays in beam dump experiments (MeV$\sim$GeV)
- peak searches in pion and kaon decays (MeV$\sim$GeV)
- searches of LNV or cLFV events (MeV$\sim$GeV)
- collider searches of displaced vertices (TeV)

$\Rightarrow$

Signature HNL produced in a **neutrino beam** and then **decay-in-flight** inside the detector.

Production two- and three-body decays from pseudo-scalar meson ($\pi^\pm, K^\pm, K^0, D_S^\pm$), muon and tau decay.

Decay semi-leptonic two-body decays into charged and neutral **pseudo-scalar mesons** or vector mesons, leptonic three-body decay, radiative decay etc.



Majorana vs Dirac and role of helicity

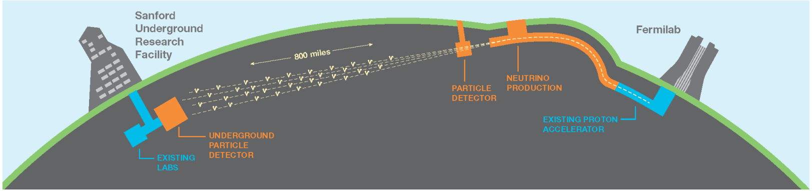
Practical Dirac-Majorana confusion theorem [Kayser, Shrock, 82] :

factor of two enhancement is absent for (almost) massless neutrinos,
due to polarisation which suppresses $\Delta L = 2$ contributions.

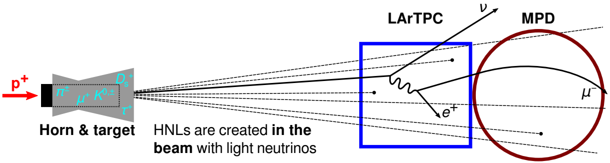
- If HNL mass is not negligible, Dirac and Majorana neutrinos have **distinct** total NC decay rates.
- Neglecting charges of final states in CC processes gives same result as NC channels.
- Otherwise, if pure ν beam w/o contamination, then a Dirac HNL decays only to $\Delta L = 0$ channels: **no events in LNV channel**
- If HNL is Majorana, both $\Delta L = 0$ and $\Delta L = 2$ decays expected with equal probability.
- Due to arbitrariness of polarisation, total decay not affected by helicity, but **angular distribution** is!
$$\frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega} \approx A \quad \text{for Majorana} \quad \text{nd} \quad \frac{\mathrm{d}\Gamma_\pm}{\mathrm{d}\Omega} \approx A \mp B\cos\theta \quad \text{for Dirac}$$
- Production channels for HNL are not affected by **helicity suppression**.
- HNL beam is not polarised and apparent **enhancement** of light-flavour channels.

DUNE Near Detector

Powerful proton beam equivalent to 80 GeV proton beam and 2.65×10^{22} POT for 6 y of ν–mode and 6 y in $\overline{\nu}$–mode.



Near Detector is required to **normalise flux** and remove **cross-section systematics**.
Placed at 574 m from target $\Rightarrow$ intense ν flux, 5×10^6 higher than at FD (1300 km), up to $E_\nu = 20$ GeV.



- **LArTPC** with fiducial volume 24 m^3 and mass 35 t.
- **Multi Purpose Detector** (MPD), gaseous TPC, fiducial volume 100 m^3 and mass 1 t.
- LArTPC and MPD are movable (DUNE-PRISM).
- 3D Scintillation Tracker, on-axis, for flux monitoring and neutron contamination.

Number of events

Number of events $\mathcal{N}_d$ to be compared with **background** $\mathcal{N}_b$ (SM neutrino–nucleon interactions)

$$\mathcal{N}_d = \int \mathrm{d}E \, e^{-\frac{\Gamma_{\mathrm{tot}} L}{\gamma\beta}} \left(1 - e^{-\frac{\Gamma_{\mathrm{tot}} \lambda}{\gamma\beta}}\right) \frac{\Gamma_d}{\Gamma_{\mathrm{tot}}} \frac{\mathrm{d}\phi_N}{\mathrm{d}E} W_d(E)$$

L = baseline
λ = length of detector

Parentage components of light neutrino beams are scaled by

$$\mathcal{K}^{\pm}_{X,\alpha}(m_N) \equiv \frac{\Gamma^{\pm}(X \to NY)}{\Gamma(X \to \nu_\alpha Y)} \,,$$

to fix phase space and helicity.
$\mathrm{d}\phi_N/\mathrm{d}E$ is the expected HNL beam at the ND site,

$$\frac{\mathrm{d}\phi_{N^\pm}}{\mathrm{d}E}(E_N) \approx \sum_{X,\alpha} \mathcal{K}^{\pm}_{X,\alpha}(m_N) \frac{\mathrm{d}\phi_{X\to\nu_\alpha}}{\mathrm{d}E}(E_N - m_N)$$

$W_d(E)$ is the **binned ratio** of E_{true} spectrum after and before the **background reduction**. Particle ID reduces background up to a 10^4 factor; to further reduce background:

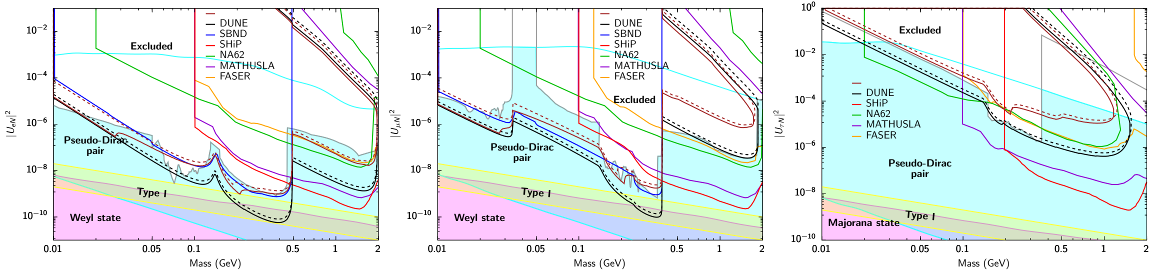
- GENIE simulation of neutrino events in Ar
- Custom MC simulation of HNL decays

are input to fast MC of DUNE ND reconstruction and **kinematic distributions** are compared

Sensitivity to discovery

Combining regions of channels with **“good” detection sensitivity** (high branching ratio, controlled background):

$$N \to \nu e^+ e^-,\ \nu\mu^+\mu^-,\ \nu e^\mp \mu^\pm,\ e^\mp\pi^\pm(|U_{eN}|^2),\ \mu^\mp\pi^\pm(|U_{\mu N}|^2),\ \nu\pi^0.$$



- Backgroundless lines ($\mathcal{N}_d > 2.44$).
- Sensitivity above m_{K^0} thanks to production from D_s meson.
- Charge-ID washed out $\Rightarrow$ sensitivity to Majorana HNL is $2\times$ better than to Dirac.
- Sensitivities to other channels (also with background analysis) and to $|U^*_{\alpha N} U_{\beta N}|$

solid : Majorana HNL
dashed : Dirac HNL

Conclusions

- **Super-Kamiokande** will improve neutron tagging thanks to Gd
  - ✓ Preliminary studies for a new **calibrating source** with ^{252}Cf
  - ✓ Developing a device to constantly **monitor Gd concentration** with UV spectroscopy
- **Hyper-Kamiokande** will determine δ_{CP} with high precision
  - ✓ On-going estimation of **sensitivity** to CP violation
  - ✓ Detailed study of the **systematic model** and how it impacts the sensitivity
- **DUNE Near Detector** is a great candidate for searches of novel physics.
  - ✓ Calculation of **polarised** production and decay rates for HNL
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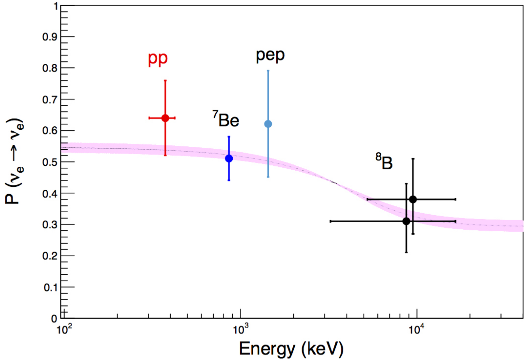
Thank you.

Extra.

Solar neutrinos

- Neutrinos produced by thermonuclear reactions in the core of the Sun: Proton–proton chain (*pp*) and by carbon–nitrogen–oxygen cycle (CNO), both cases with $4\,p \;+\; 2\,e^- \longrightarrow {}^4\mathrm{He} \;+\; 2\,\nu_e$ and 26.731 MeV.
- Standard solar model (SSM) [Bahcall et al. '63] agrees with helioseismology.
- Homestake, GALLEX/GNO, SAGE were in strong disagreement with the SSM.
- The **solar neutrino problem** was solved by SNO (flavour transition)
- BOREXINO measured neutrino across the energy spectrum in agreement with MSW effect.



Supernova neutrinos – core-collapse

- SN are classified by spectral lines at maximal luminosity: only type Ib, Ic, and II undergo **core-collapse** and emit neutrinos.
- Old stars with $M \gtrsim 8\,M_\odot$ and $M \lesssim 40\,M_\odot$ stratify as onions (H, He, C, Ne, Mg, Si, ...) with outer shells burning into inner shells, up to Fe at the core.
- Gravitational pressure is sustained by thermonuclear energy in outer shells.
- Core (Fe) is sustained by degenerate relativistic electrons, which is reduced by (PD) $\gamma + {}^{56}\mathrm{Fe} \to 13\,\alpha + 4\,n - 124.4\,\mathrm{MeV}$ and electron capture $e^- + p \to n + \nu_e$.
- It collapses when Fermi pressure is no longer sufficient, speeding up PD and EC.
- Density increases and neutrinos are trapped inside the core (adiabatic process).
- Free-falling core is stopped by the pressure of degenerate nucleons: shock wave is generated and slows down the imploding mantle.
- ν_e pile up behind the opaque wave until the shock reaches lower density
- ν_e are released in a few millisecond in a *neutronisation burst*, carrying away around 10^{50} erg.
- In most scenarios, the shock wave stalls and bounce mechanism is not enough to cause explosion.

Atmospheric neutrinos

- Generated by **cosmic rays** interacting with atmosphere.
- Interactions produces pseudo-scalar mesons, which decay into charged leptons and neutrinos.
- Two-body decays of $\pi^\pm$ and $K^\pm$ favour muon channel (**helicity suppression**)

$$\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu \ , \qquad K^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu \ ,$$

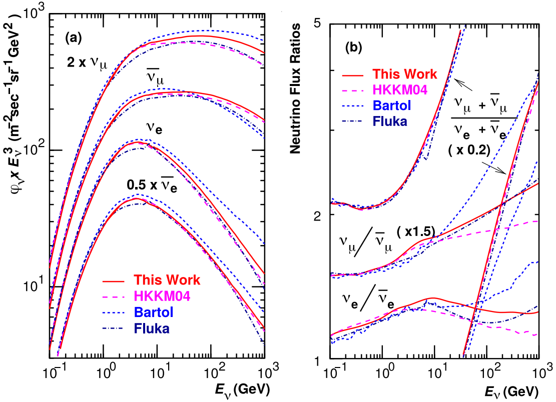
and muon decays

$$\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu \ , \qquad \mu^- \to e^- + \overline{\nu}_e + \nu_\mu \ .$$

- At $E \lesssim 1\,\text{GeV}$ proportions between flavours

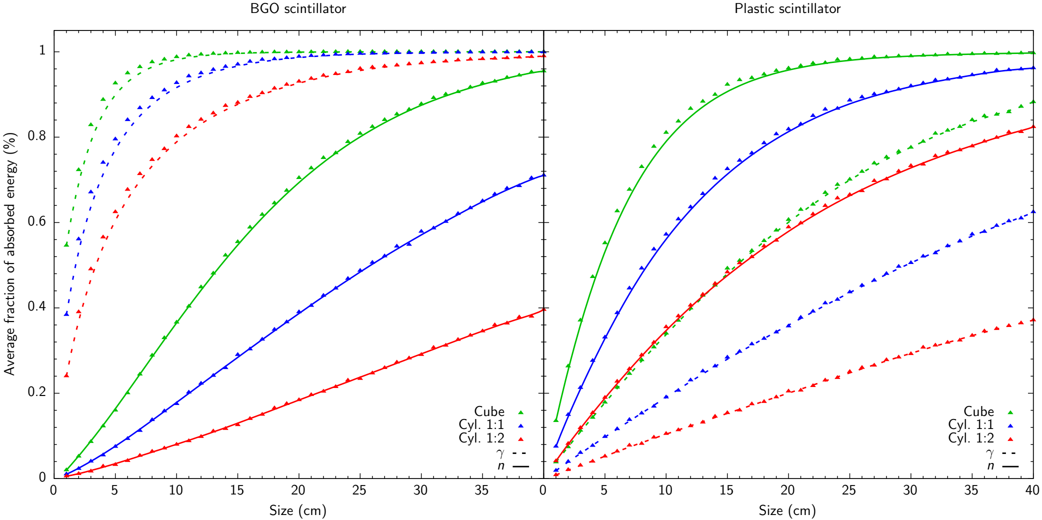
$$\phi_{\nu_e} : \phi_{\nu_\mu} = 1 : 2 \,, \qquad \phi_{\nu_\mu} : \phi_{\overline{\nu}_\mu} = 1 : 1 \,, \qquad \phi_{\nu_e} : \phi_{\overline{\nu}_e} = \phi_{\mu^+} : \phi_{\mu^-} \ .$$

Honda model



Simulating ^{252}Cf calibration device

Ideal calibrating device does not stop neutrons and absorbs all gammas.



Fundamental symmetries

Dirac lagrangian $\mathcal{L} = \overline{\psi}(x)(i\overset{\leftrightarrow}{\partial\!\!\!/} - m)\psi(x)$ is invariant under C, P, and T transformations.

- **charge conjugation** C

$$\psi(x) \longmapsto \psi^{\mathrm{C}}(x) = \xi_{\mathrm{C}}\,\mathcal{C}\,\overline{\psi}^{T}(x)$$
$$\overline{\psi}(x) \longmapsto \overline{\psi^{\mathrm{C}}}(x) = -\xi^*_{\mathrm{C}}\,\psi^{T}(x)\,\mathcal{C}^\dagger$$

- space inversion, or **parity**, P

$$\psi(x) \longmapsto \psi^{\mathrm{P}}(x) = \xi_{\mathrm{P}}\,\gamma^0\psi(x)$$
$$\overline{\psi}(x) \longmapsto \overline{\psi}^{\mathrm{P}}(x) = \xi^*_{\mathrm{P}}\,\overline{\psi}(x)\,\gamma^0$$

- **time inversion** T

$$\psi(x) \longmapsto \psi^{\mathrm{T}}(x) = \xi_{\mathrm{T}}\,\gamma^0\gamma^5\mathcal{C}\,\psi^*(x)$$
$$\overline{\psi}(x) \longmapsto \overline{\psi}^{\mathrm{T}}(x) = \xi^*_{\mathrm{T}}\,\psi^{T}(x)\,\mathcal{C}^\dagger\gamma^0\gamma^5$$

Strong and EM preserve C, P, and T.
Weak interactions do not!

- C is violated as ν_R and $\overline{\nu}_L$ have never been observed! Not if Majorana...
- P violation proposed [Lee, Yang, '56] and observed in ^{60}Co β decay [Wu, '57].
- T violation directly observed in $B^0 - \overline{B^0}$ oscillation [BaBar, '12].

Symmetries can be restored by combining two or more broken ones, e.g. **CP symmetry**.
However this happens to be violated, too!
Observed in K_0 decays [Cronin, Fitch, '64], in B decays [BaBar, '01] [Belle, '01] [LHCb, '13], and in D decays [LHCb, '19].

CPT symmetry is still conserved.

CP violation phase

Parameters of a **mixing matrix** V from mass matrix diagonalisation (e.g. CKM, PMNS) are

$$\left.\begin{array}{ll} \frac{N(N-1)}{2} & \text{mixing angles} \\ \frac{N(N+1)}{2} & \text{phases} \end{array}\right\} 2N^2 \quad \text{free parameters}$$

Not all the phases are observables: the only physical effect of the mixing matrix occurs in the weak charged current.
$2N-1$ phases can be **reabsorbed**, leaving

$$\frac{N(N+1)(N-2)}{2} \qquad \text{physical phases}$$

For three generations, there are **3 angles** and **1 phase**.

CP invariance is valid if $Y^{D\dagger}Y^{U}$ is vanishing or **real**, to give $V = V*$, and so the conditions for CP violation $\Longrightarrow$

- **no degeneracies** in the up-quark and down-quark mass matrices.
- no mixing angles equal to 0 or $\pi/2$
- physical phase is not 0 or π
- So the parameters are defined in
  - $0 < \theta < \pi/2$,
  - $-\pi < \delta < \pi$ and $\delta \neq 0$.

The CP violation is quantified by the *Jarlskog invariant*

$$\Im[V^*_{\alpha i} V_{\beta i} V_{\alpha j} V^*_{\beta j}] = s_{\alpha\beta;ij}\, J$$

Neutrino oscillation in matter

Neutrinos in matter are subject to forward coherent scattering, described by effective Hamiltonian

$$\mathcal{H}_{\mathrm{CC}} = \frac{G_F}{\sqrt{2}}\left[\overline{\nu}_e\gamma^\mu(1-\gamma^5)\nu_e\right]\left[\overline{e}\,\gamma_\mu(1-\gamma^5)e\right] \ ,$$

$$\mathcal{H}_{\mathrm{NC}} = \frac{G_F}{\sqrt{2}}\sum_{\alpha=e,\mu,\tau}\left[\overline{\nu}_\alpha\gamma^\mu(1-\gamma^5)\nu_\alpha\right]\sum_{\mathfrak{f}=e,p,n}\left[\overline{\mathfrak{f}}\,\gamma_\mu(g_V^F-g_A^F\gamma^5)\mathfrak{f}\right] \ ,$$

and $\mathcal{H}_{\mathrm{m}}\left|\nu_\alpha\right\rangle = V_\alpha\left|\nu_\alpha\right\rangle$.
Total potential is

$$V_\alpha = V_{\mathrm{CC}}\delta_{\alpha e} + V_{\mathrm{NC}} = \sqrt{2}\,G_F\left(n_e\delta_{\alpha e} - \frac{1}{2}n_n\right) \ .$$

Electron density gives contribution to CC potential, neutron density to NC potential.
In terms of neutrino oscillation, NC potential can be factorised out, leaving just on contribution

$$A_{\mathrm{CC}} \equiv 2\sqrt{2}E\,G_F\,n_e \ .$$

and effective mixing angle in 2-flavour approximation is

$$\tan 2\theta_M = \frac{\tan 2\theta}{1-\dfrac{A_{\mathrm{CC}}}{\Delta m^2\cos 2\theta}}$$

Systematic error model

The default **T2K 2018 error model** is applied: 119 systematic parameters, 74 from beam and ND280 flux measurements and 45 from SK detector efficiencies and Final State Interactions.

Near Detector Constraints

50 systematics for flux uncertainties of the four **beam components** ν_e, ν_μ, $\overline{\nu}_e$, and $\overline{\nu}_\mu$ (25 for ν mode, 25 for $\overline{\nu}$ mode). The other 24 are uncertainties on **cross section parameters**, among which

- ν and $\overline{\nu}$ $2p2h$ normalisation and shape for ^{16}O
- CCQE axial-mass scaling factor
- CC and NC interaction normalisations
- RPA coefficients
- Binding energy on oxygen

SK & FSI Model

36 systematics for the four **final state interaction types**:

- 12 ν-mode 1 ring e-like
- 6 ν-mode 1 ring μ-like
- 12 $\overline{\nu}$-mode 1 ring e-like
- 6 $\overline{\nu}$-mode 1 ring μ-like

and one for the **energy scale**.

Oscillation parameter space

Parameter space: $13 \times 13 \times 19 \times 61$ points in

$$(\Delta m^2_{23}, \sin^2 2\theta_{13}, \sin^2\theta_{23}, \delta_{\mathrm{CP}})$$

Parameter	Nominal	Range	Points
$\Delta m^2_{12}/10^{-5}\,\mathrm{eV}^2$	7.53	–	fixed
$\sin^2 2\theta_{12}$	0.8463	–	fixed
$\Delta m^2_{23}/10^{-3}\,\mathrm{eV}^2$	2.509	[2.464:2.554]	13
$\sin^2 2\theta_{13}$	0.085	[0.070:0.100]	13
$\sin^2\theta_{23}$	0.528	[0.426:0.579]	19
δ_{CP}	$-\pi/2$	$[-\pi:\pi]$	61

Creating χ^2 profiles for T2K reference point "Asimov A" ($\delta_{\mathrm{CP}} = -1.601 \simeq -\pi/2$).

Gaussian penalty term is added to the likelihood using future reactor constraints of θ_{13}, with $\sin^2 2\theta_{13} = 0.085 \pm 0.005$

Sensitivity to δ_{CP}: comparing null hypothesis (CP conservation) with all possible values of δ_{CP}.

$$\sigma = \sqrt{\min_{\delta_{\mathrm{CP}}=0,\pm\pi} \chi^2 - \chi^2_{\mathrm{true}}}$$

Correct χ^2

Original χ^2 as in SK atmospheric analysis applies systematics in an **additive** manner.
T2K beam analysis applies systematics in a **mulitplicative** way

$$E_n \longrightarrow E_n \prod_j \left(1 + f_j^n \varepsilon_j\right) .$$

Energy scale shift can be written as an analytic function

$$E'_n = \sum_m^{n_\text{bins}} \frac{E_m \prod_j \left(1 + f_j^m \varepsilon_j\right)}{4\left(1 + \hat{\varepsilon}\sigma\right) \Delta b_m} \zeta_{n,m}(1 + \hat{\varepsilon}\sigma)$$

Function $\zeta_{n,m}(x) \geq 0$ is “mask“ function, proportional to bin overlap between old binning and scaled binning, and is zero when there is no bin overlap

$$\begin{aligned} \zeta_{n,m}(x) &= (1 + s_\zeta)(\Delta b_n + x\,\Delta b_m - |b_n - x\,b_m| - |b_{n+1} - x\,b_{m+1}|) \\ s_\zeta &= \text{sign}(\Delta b_n + x\,\Delta b_m - |b_n - x\,b_m| - |b_{n+1} - x\,b_{m+1}|) \end{aligned}$$

The **correct** χ^2 is therefore $$\chi^2_\text{tot} = 2\sum_n \left[E'_n - O_n - O_n \log \frac{E'_n}{O_n}\right] + \sum_{kj} \varepsilon_k \rho^{-1}_{kj} \varepsilon_j$$

Gauss-Newton algorithm

Fitting and Newton's method... sounds a lot like **least squares**!

In least square problems we want to minimise the cost function with respect to the parameters $\vec{\varepsilon}$.

$$\chi^2 = \sum_n \left[O_n - E_n(\vec{\varepsilon}))^2\right] = \sum_n r_n^2 \qquad \text{(using same notation)}$$

Computing $\partial\chi^2/\partial\vec{\varepsilon} = 0$ with Taylor expansion, we get Gauss-Newton's method (**GNA**) and the **normal equations** for linear square fitting:

$$J^T J \left(\varepsilon_{n+1} - \varepsilon_n\right) = -J^T r_n \ ,$$

where $J = \partial r_n/\partial\varepsilon_k$ is the Jacobian and $J^T J$ approximates the hessian.

BONUS!

There is no need to solve a constrained system to find the uncertainty on one parameter.
Having the Hessian (or $J^T J$), we can estimate a covariance matrix for fitted parameters

$$\sigma = \frac{\chi^2}{\text{d.o.f.}} (J^T J)^{-1} \ ,$$

Levenberg-Marquardt algorithm

With GNA, the convergence is very fast (quadratic), but the algorithm can be unstable: large steps could be taken and the minimum is overshot.
A good improvement is the Levenberg-Marquardt algorithm (**LMA**), which considers

$$(J^T J + \lambda D)\,(\varepsilon_{n+1} - \varepsilon_n) = -J^T r_n \ ,$$

where D is a diagonal matrix and λ is chosen dynamically:

- $\lambda \to 0$, GNA limit and faster convergence, but unstable;
- $\lambda \to +\infty$, gradient descent limit, smaller steps $\sim \lambda^{-1}$, and stable convergence.

If the cost function χ^2 decreases then λ is reduced, otherwise it is increased and the step re-computed.

When the number of parameters is large, many issues may arise with LMA: parameter evaporation, canyons, cycles, etc.. There are various techniques to make LMA even more robust.

However, <u>LBL fitting is not least squares</u>, the cost function is very different.

Implementing a new fitter

Modification of osc3++ framework to implement LMA and covariance matrix for fitted systematics not very straightforward, also high risk of bugs difficult to catch.

Already have many tools for validation of systematic sets $\rightarrow$ put them together and wrote code from scratch that builds observables, implements LMA (with "delayed-gratification scheme" for λ) by solving

$$\left[\frac{\partial^2\chi^2(\vec{\varepsilon}_n)}{\partial\varepsilon_k\partial\varepsilon_j} + \lambda \max\left(\mathrm{diag}\frac{\partial^2\chi^2(\vec{\varepsilon}_n)}{\partial\varepsilon_k\partial\varepsilon_j}\right)\mathbb{1}\right](\vec{\varepsilon}_{n+1} - \vec{\varepsilon}_n)_j = -\frac{\partial\chi^2(\vec{\varepsilon}_n)}{\partial\varepsilon_k} \ ,$$

and returns the error on ε_k is given by

$$\sigma^2 = \frac{\chi^2(\vec{\varepsilon}_{\mathrm{best}})}{\mathrm{d.o.f.}}\left(\frac{\partial^2\chi^2(\vec{\varepsilon}_{\mathrm{best}})}{\partial\varepsilon_k\partial\varepsilon_j}\right)^{-1} \ .$$

Degrees of freedom are num of bins $-$ num of systematics $= 348 - 119 = 229$.

Error on ε

$$\chi^2_{\text{tot}} = 2\sum_n \left[E_n(1+\textstyle\sum_i f_n^i\varepsilon_i) - O_n - O_n \log\left(\dfrac{E_n(1+\sum_i f_n^i\varepsilon_i)}{O_n}\right)\right] + \sum_{kj} \varepsilon_i \rho_{kj}^{-1} \varepsilon_j$$

is minimised with respect to ε using Levenberg-Marquardt algorithm, by solving

$$\left[\frac{\partial^2\chi^2(\vec{\varepsilon}_n)}{\partial\varepsilon_k\partial\varepsilon_j} + \lambda \max\left(\text{diag}\frac{\partial^2\chi^2(\vec{\varepsilon}_n)}{\partial\varepsilon_k\partial\varepsilon_j}\right)\mathbb{1}\right](\vec{\varepsilon}_{n+1} - \vec{\varepsilon}_n)_j = -\frac{\partial\chi^2(\vec{\varepsilon}_n)}{\partial\varepsilon_k} \ ,$$

and returns the error on fitted ε_k is given by

$$\sigma^2 = \left(\frac{\partial^2\chi^2(\vec{\varepsilon}_{\text{best}})}{\partial\varepsilon_k\partial\varepsilon_j}\right)^{-1} \quad \text{width} \quad \frac{\partial^2\chi^2}{\partial\varepsilon_k\partial\varepsilon_j} = \sum_n \frac{O_n f_n^k f_n^j}{(1+\sum_i f_n^i\varepsilon_j)^2} + \rho_{kj}^{-1}$$

At best fit $\varepsilon_j = 0$, and since $f_n^i = \mathcal{O}(0)$ we have $\sigma^2 \simeq \rho$
Reminder: ε_j are units of sigma