T2K Exotics:

Sterile neutrinos and Lorentz violation searches

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On behalf of the T2Kcollaboration

Kongōrikishi outside Muramatsu Kokuzo Temple (near J-PARC)

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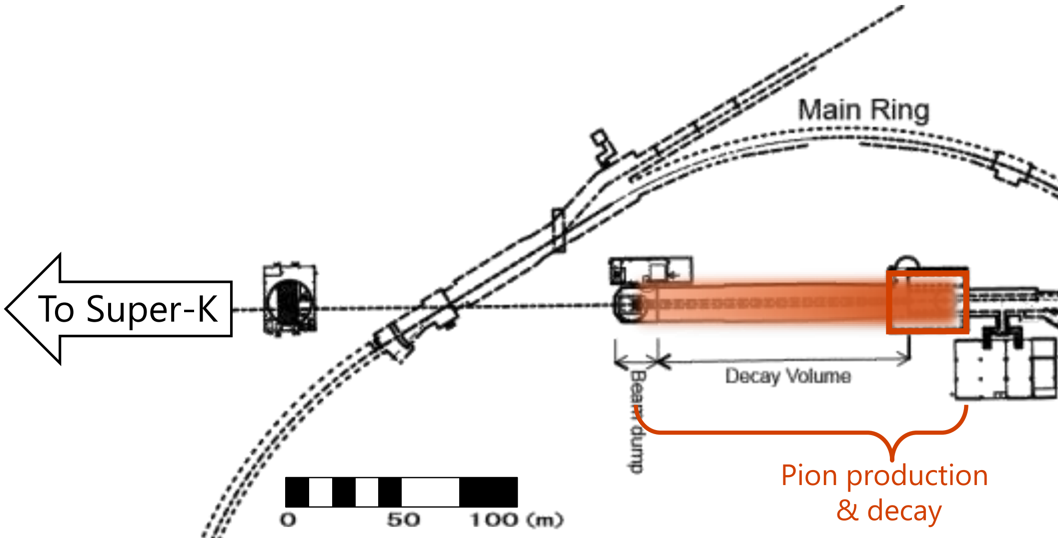
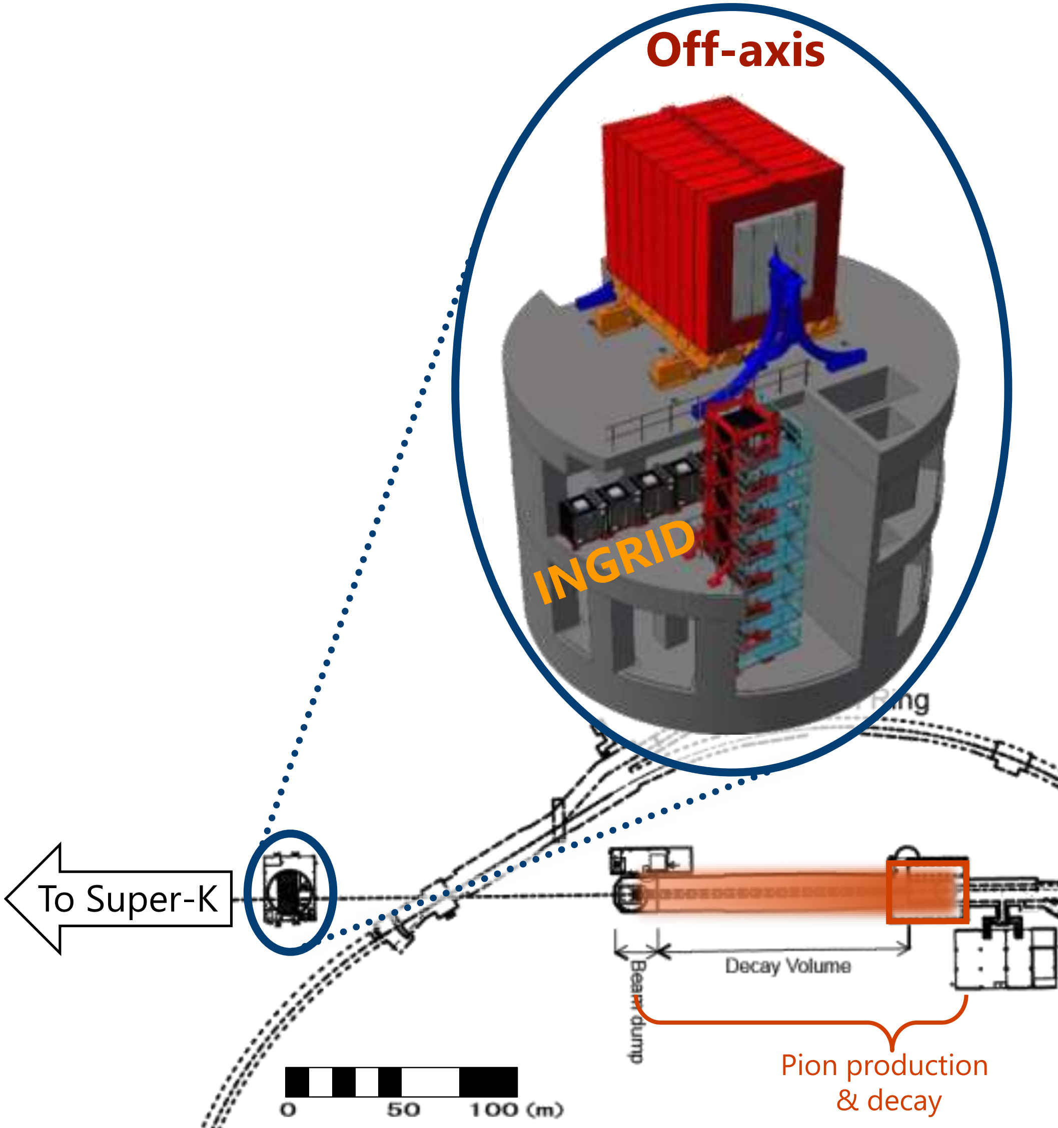
T2K ND280 during construction

The T2K experiment



The T2K experiment ND280



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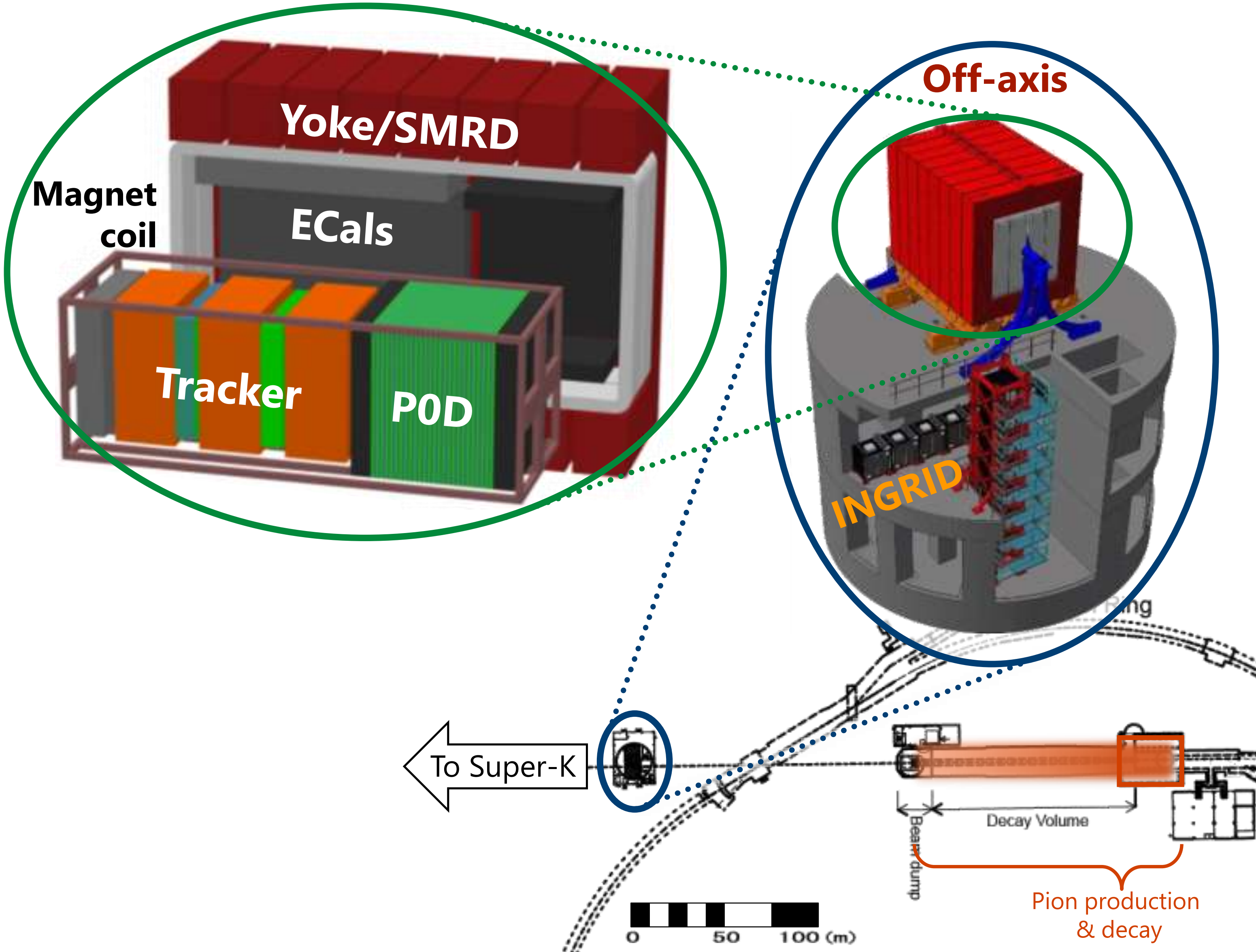

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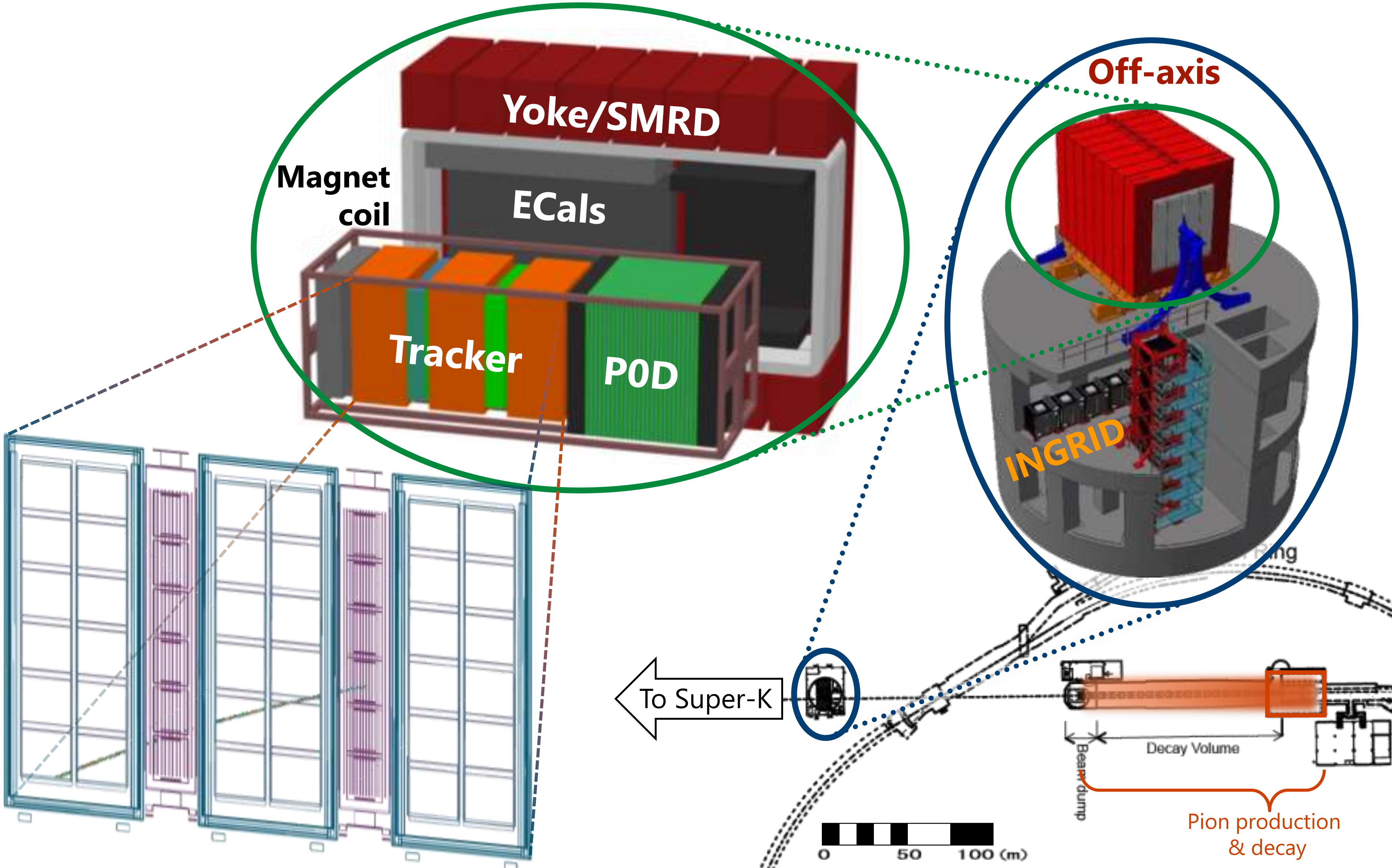

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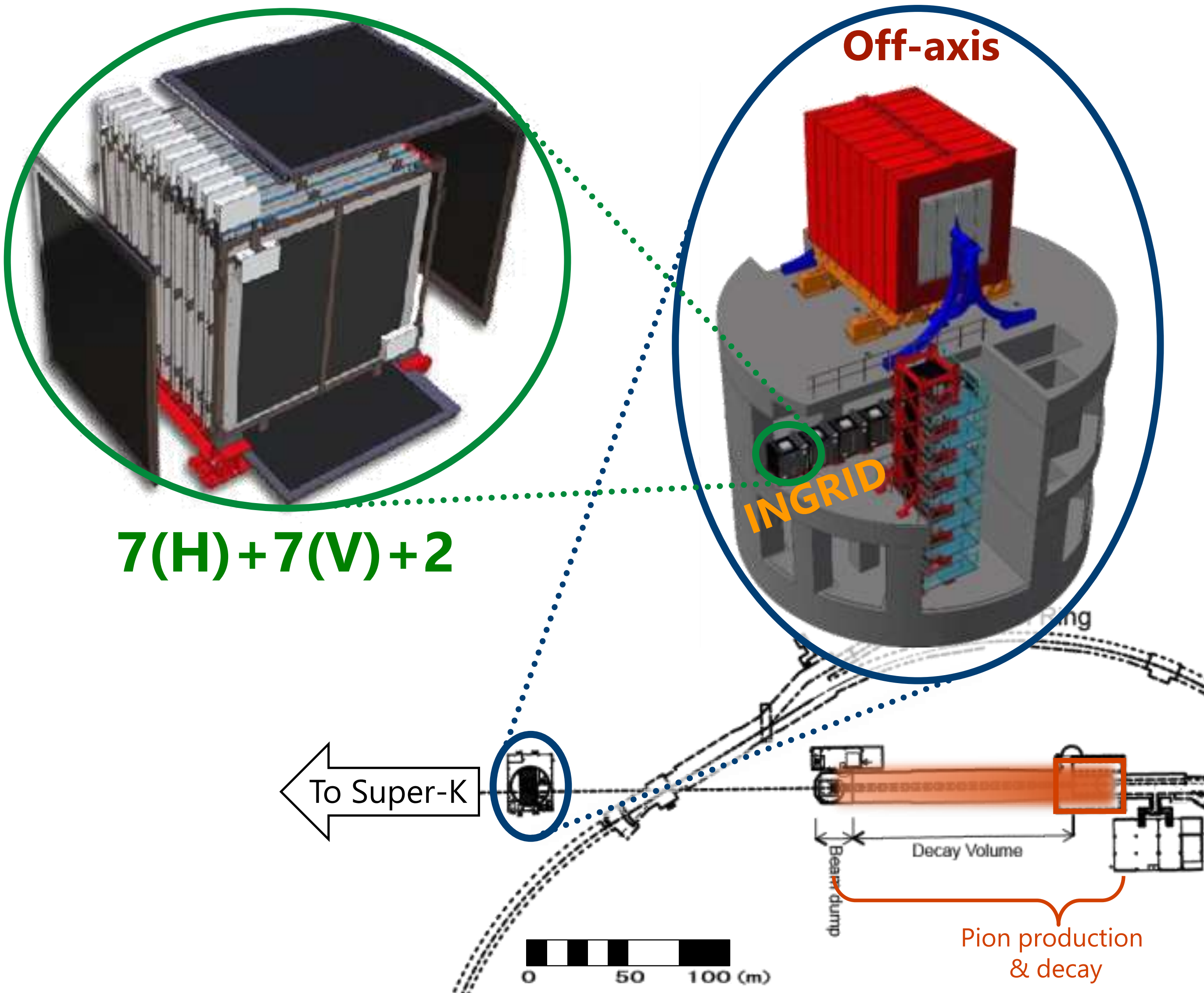

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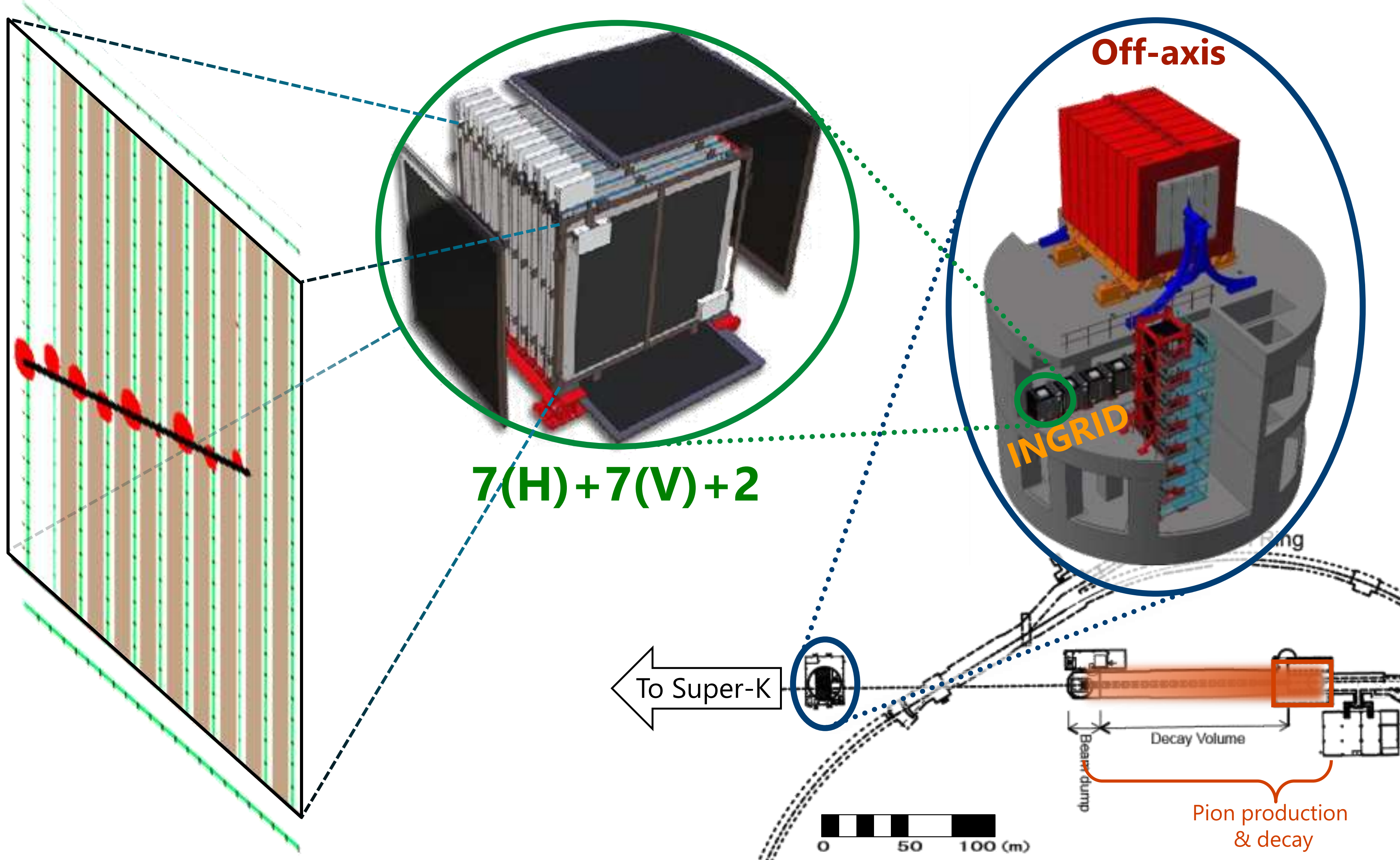

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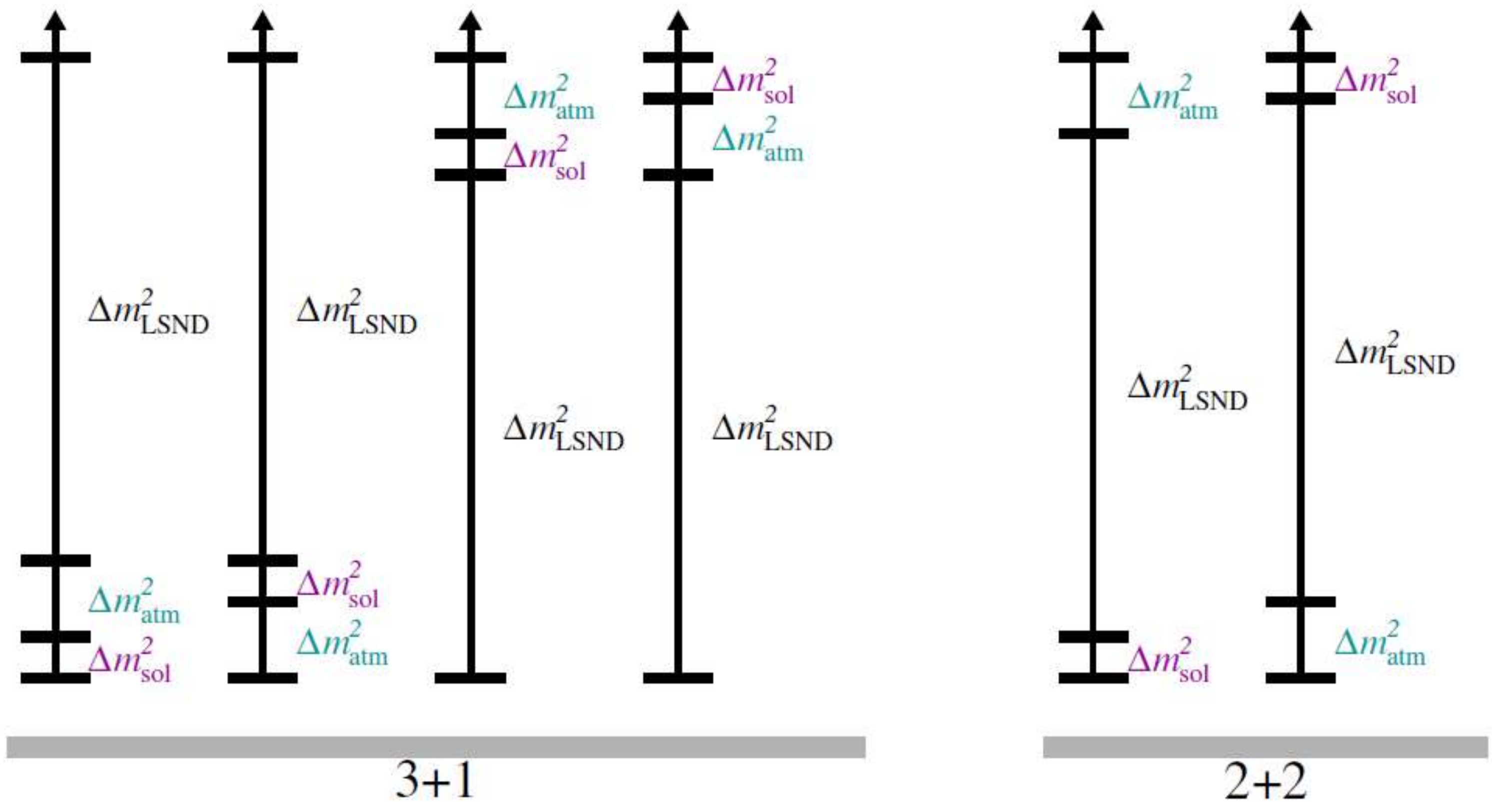
Sterile neutrinos

Could explain LSND/MB signal(s) plus other anomalies.

- $|\Delta m^2_{\mathrm{LSND}}| \gg |\Delta m^2_{31}| (\gg \Delta m^2_{21})$, therefore impossible with 3ν

Historically, large active/sterile mixing considered (e.g. 2+2)



Sterile neutrinos

Could explain LSND/MB signal(s) plus other anomalies.

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But now 'know' that $\sum_i |\langle \nu_\alpha | \nu_i \rangle|^2 \simeq 1$ for $\alpha = \mu, e$; $i = 1,2,3$

- Extra ν must be largely decoupled*
- Usually only consider $|\Delta m^2_{4i}| \gg |\Delta m^2_{31}|$
- Usually search for ν_4 (large Δm^2) not ν_s (NC depletion)

Normally analyse 3+*N* models with small active/sterile coupling → can use 2ν formalism for setting limits.

[*In *theory*; not always the case when setting limits]

Sterile formalism

Possible

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \hdashline \nu_s \\ \vdots \end{pmatrix} = \left(\begin{array}{ccc:cc} & & & U_{e4} & \\ & \boldsymbol{U_3} & & U_{\mu 4} & \cdots \\ & & & U_{\tau 4} & \\ \hdashline U_{s1} & U_{s2} & U_{s3} & U_{s4} & \\ & \vdots & & & \ddots \end{array}\right) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \hdashline \nu_4 \\ \vdots \end{pmatrix}$$

Pretty much impossible

- Upper matrix $\boldsymbol{U_3}$ similar to 3ν PMNS matrix (but be careful!)
- New active components $U_{\alpha 4}$ (etc) are relatively small
- Sterile-sterile mixing unobservable: lower rows from unitarity
  - In practice ν_τ row is also very difficult

Overall: Lots of parameters and not many constraints

Sterile '2ν' approximation

$$\bar{U}_{\alpha 4} = \sqrt{1 - |U_{\alpha 4}|^2}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \hdashline \nu_s \\ \vdots \end{pmatrix} = \left(\begin{array}{c:c} \bar{U}_{e4} & U_{e4} \\ \bar{U}_{\mu 4} & U_{\mu 4} \\ \bar{U}_{\tau 4} & U_{\tau 4} \\ \hdashline \bar{U}_{s4} & U_{s4} \end{array}\right) \begin{pmatrix} \nu_1 \\ \hdashline \nu_4 \end{pmatrix}$$

- Take $|\Delta m^2_{31}| \to 0$;
- Assume ν_5 (etc) are decoupled.

} Leaves only one mass scale in the oscillation

- Then $P(\nu_\alpha \nrightarrow \nu_\alpha) = \underbrace{4(1 - |U_{\alpha 4}|^2)|U_{\alpha 4}|^2}_{\sin^2 2\theta_{\alpha\alpha}} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$
- Also note: $P(\nu_\alpha \to \nu_\beta) = 4 \sin^2\theta_{\alpha\alpha} \sin^2\theta_{\beta\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right)$

T2K sterile neutrino searches

ν_4 searches performed at off-axis near detector (ND280)

- "SBL" L/E suitable for $\mathbf{1 \lesssim |\Delta m^2|/eV^2 \lesssim 100}$
  - Smoothing of energy dependence from decay volume length
  - Larger Δm^2 possible (rapid oscillation) but less sensitive.
  - Can in principle do $\nu_\mu \to \nu_e$ and ν_μ, ν_e disappearance channels, but only two are truly independent.

Searches for ν_s (i.e. NC depletion at SK) are generally much harder, not being pursued so actively.

Will show:

- Latest results from SBL $\nu_e \nrightarrow \nu_e$ search [arXiv: 1410.8811]
- Work towards a SBL $\nu_\mu \nrightarrow \nu_\mu$ search

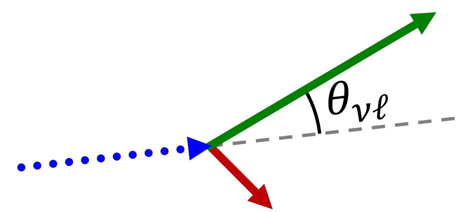
Generic features of SBL disappearance searches

Analyses use "Tracker" subsystem of ND280: Fine-grained scintillator target + TPCs for momentum and PID.

- Excellent discrimination at the track level.

Neutrino energy reconstructed assuming quasi-elastic kinematics*:

$$E_\nu \simeq \frac{m_p E_\ell - \frac{1}{2} m_\ell}{\left(m_p - E_\ell + p_\ell \cos\theta_{\nu\ell}\right)}$$



Main difficulty is lack of an oscillation-free 'Near' detector to provide expected event rates (= flux × cross-section)

- For T2K, flux is relatively well understood thanks to beam monitoring and auxiliary measurements (NA61/Shine)
- Control of uncertainties from cross-sections achieved using multiple samples.

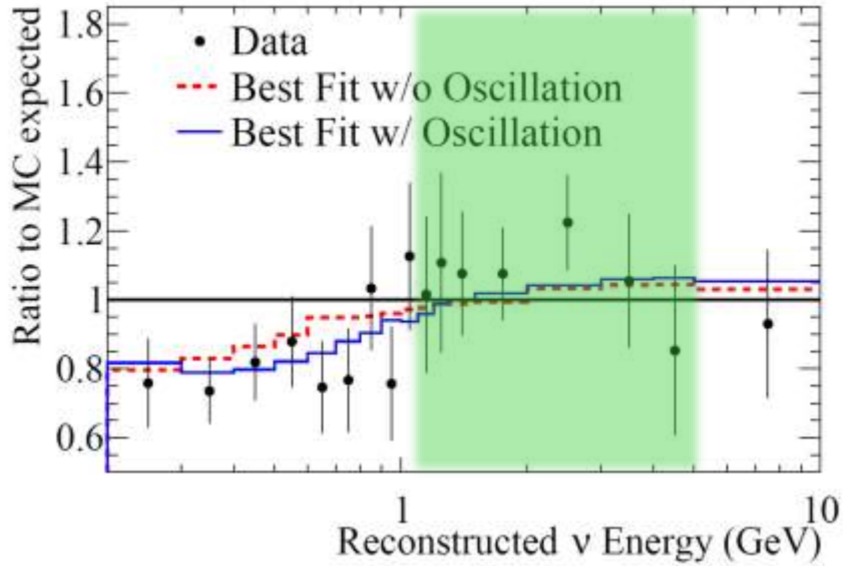
[* Approximate formula; see backups]

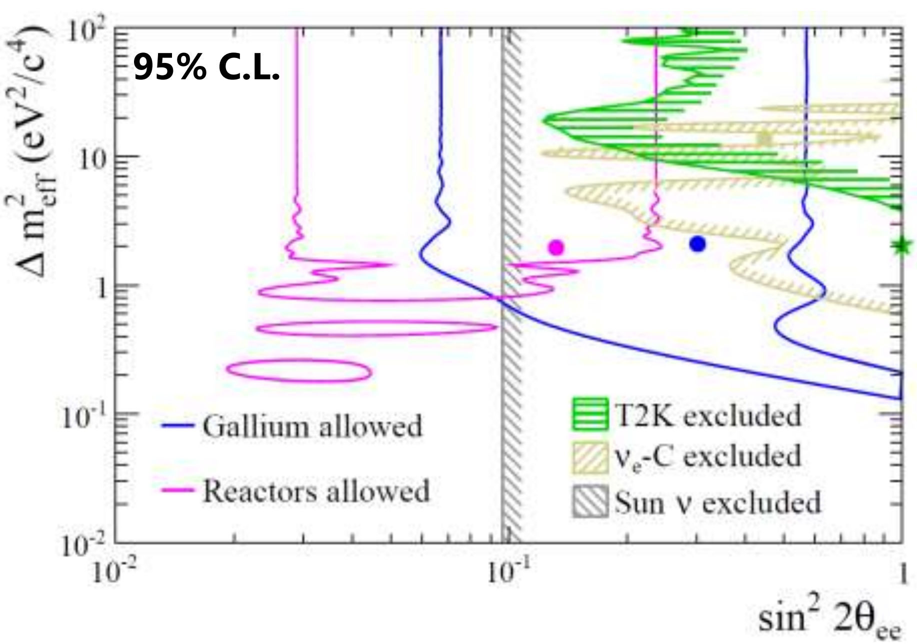
Results of ν_e disappearance

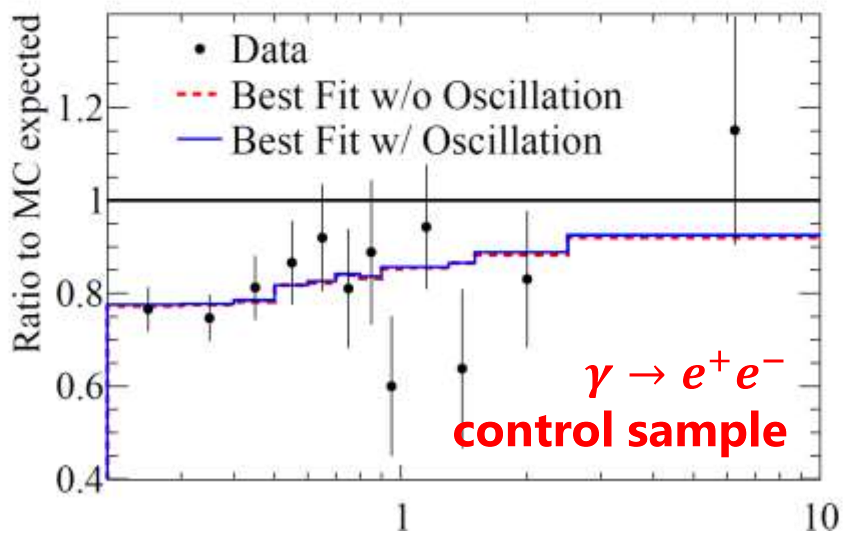
arXiv: 1410.8811 5.9×10^{20} POT

- ν_e expectation constrained by ν_μ rates
  - Therefore won't be independent from ν_μ measurements

No-oscillations: *p*-value = 0.085





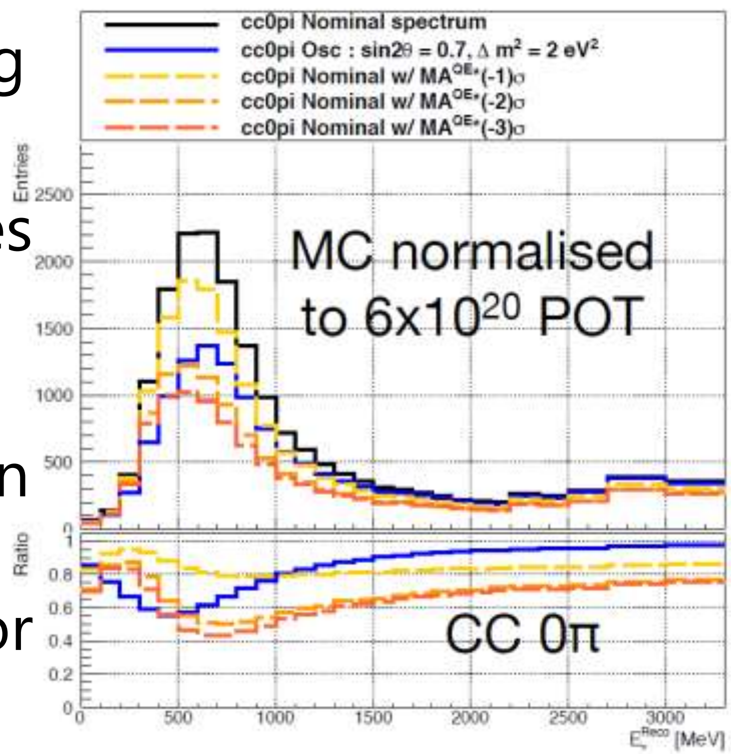


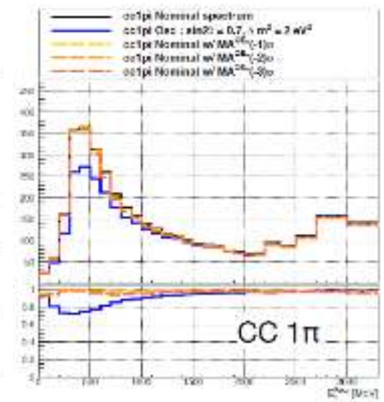
ν_μ disappearance search

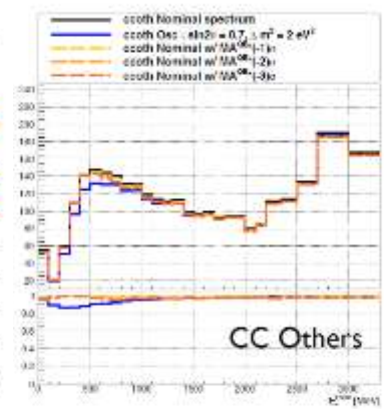
In contrast to e^-, can be confident that observed muons are from ν_μ vertices.

However, in this case there is ***no independent sample*** to constrain flux and cross sections.

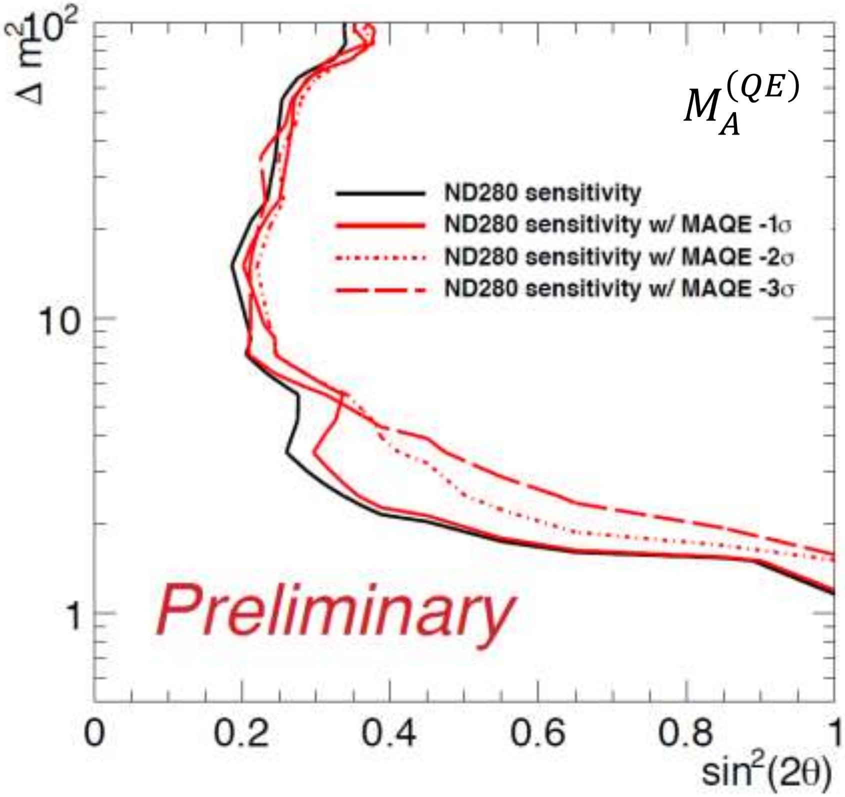
- Divide events according to hadronic activity
- Systematic uncertainties affect each sample differently
- Can untangle oscillation effect, but requires higher statistics than for ν_e analysis.

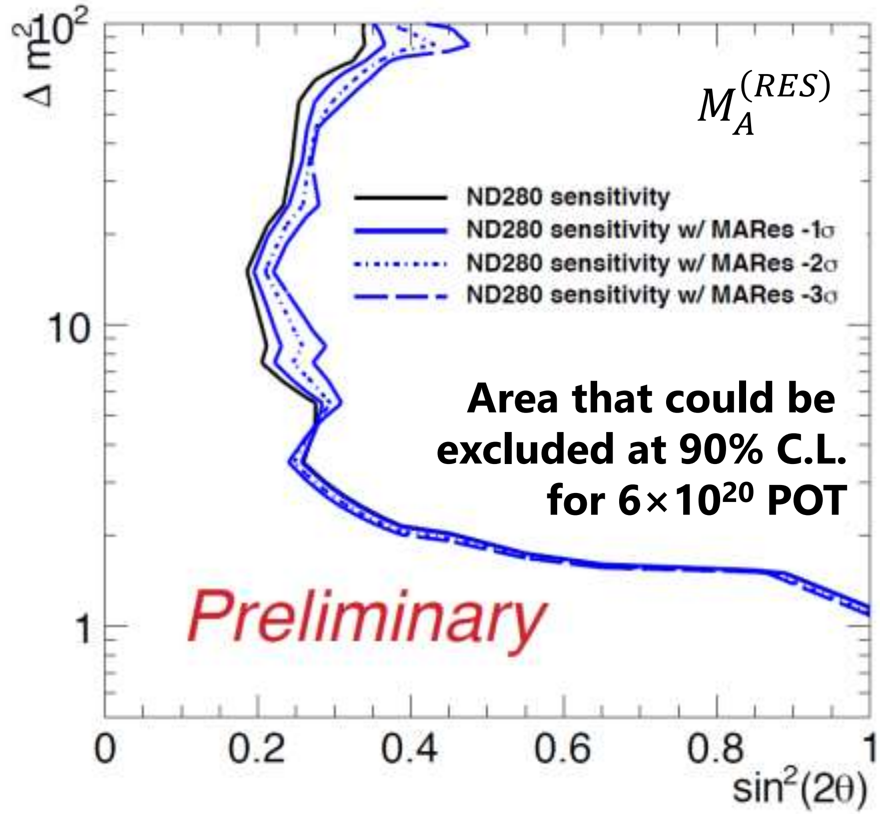






Analysis status





- Systematic uncertainties currently under study
- Hope to unblind later this year
- Sensitivity down to $\sin^2 2\theta \sim 0.2$

[M_A describes iso-axial charge (~pion field) distribution of nucleon]

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Lorentz violation Hamiltonian

$$H = k + \underbrace{\frac{1}{2E}\begin{pmatrix} \Delta m^2_{ab} & \\ & \Delta m^2_{\bar{a}\bar{b}} \end{pmatrix}}_{\text{Standard neutrino oscillations}} + \begin{pmatrix} \delta h_{ab} & \delta h_{a\bar{b}} \\ \delta h_{\bar{a}b} & \delta h_{\bar{a}\bar{b}} \end{pmatrix}$$

Where $\Delta m^2 = U^\dagger_{\text{PMNS}} \text{diag}(m_i - m_1) U_{\text{PMNS}}$

- Diagonal blocks induce mixing between (anti-)neutrinos:

$$\delta h_{ab} = \frac{1}{E}\left[a_L^\varepsilon p_\varepsilon - c_L^{\varepsilon\delta} p_\varepsilon p_\delta\right]_{ab}$$

- Off-diagonal blocks induce neutrino-to-antineutrino transitions at higher orders (ϵ_ε^+ is a ‘helicity vector’):

$$\delta h_{a\bar{b}} = -\mathrm{i}\sqrt{2}\epsilon_\varepsilon^+\left[\tilde{g}^{\varepsilon\delta} p_\delta - \widetilde{H}^\varepsilon\right]_{a\bar{b}}$$

Possible signatures

Effect of the Lorentz violating term can be evaluated with perturbation theory. Using $S_{ab} = e^{-\mathrm{i}H_{ab}t}$:

$$P(\nu_a \to \nu_b) \sim \left|S_{ab}^{(0)} + S_{ab}^{(1)} + S_{ab}^{(2)} + \cdots\right|^2$$

$$\sim \left|S_{ab}^{(0)}\right|^2 + 2\Re\left[\left(S_{ab}^{(0)}\right)^* S_{ab}^{(1)}\right] + 2\Re\left[\left(S_{ab}^{(0)}\right)^* S_{ab}^{(2)}\right] + \left|S_{ab}^{(1)}\right|^2 + \cdots$$

- 0^{th} order → regular PMNS oscillations
- 1^{st} order → LV-enhanced PMNS oscillations
- 2^{nd} order → LV-PMNS + **pure LV mixing**

1^{st} order terms modify existing oscillations → search at SK

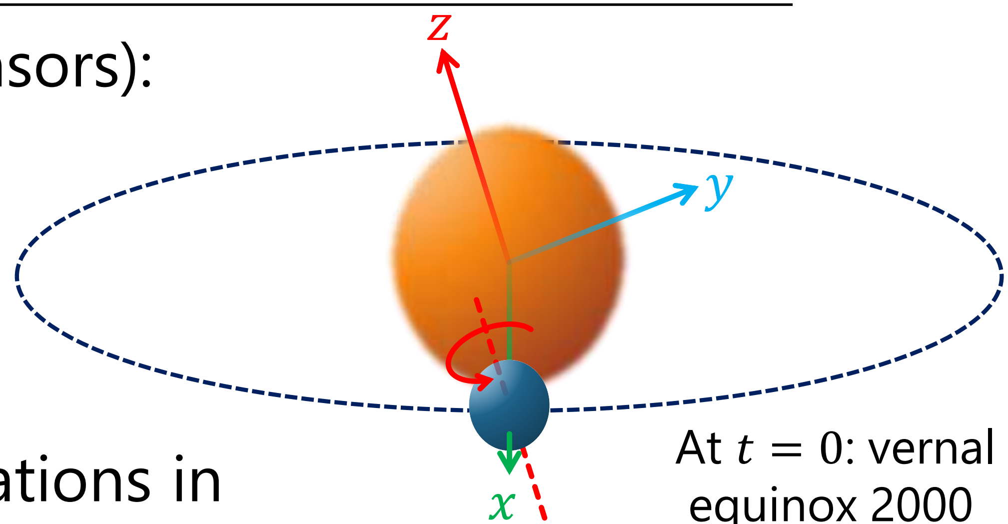
But pure LV term does not require PMNS evolution

∴ Can search for effects at Near Detector → INGRID

Co-ordinates for LV

LV terms are 4-vectors (or tensors):

- Propagation influenced by alignment of beam to LV preferred direction(s)
- Therefore *sidereal rotation* of earth will produce oscillations in time with base period $\boldsymbol{T_\oplus = 23^h 56^m 4.1^s}$



At $t = 0$: vernal equinox 2000

- Co-ordinate system: z axis parallel to earth rotation → x, y components of neutrino beam direction vary in this period. Thus, for a single neutrino beamline:
  - Coefficients in z, t *only* give rise to *non-varying* mixing terms
  - *Single* x, y coeff. (e.g. a_L^y, c_L^{xt}) produce period $T_\oplus$ terms
  - Double x, y tensor coefficients produce period $T_\oplus/2$ terms

Empirical LV (short propagation)

Thus quite generically the SME coefficients introduce a *sidereal* oscillation to the survival probability:

$$P^{\mathrm{SBL}}(\nu_a \to \nu_b) = \left| \begin{array}{l} \mathcal{C}_{ab} + \mathcal{A}_{ab} \sin \omega_\oplus t + \mathcal{A}'_{ab} \cos \omega_\oplus t \\ \quad + \mathcal{B}_{ab} \sin 2\omega_\oplus t + \mathcal{B}'_{ab} \cos 2\omega_\oplus t \end{array} \right|^2$$

These coefficients are experiment-specific

- SME coefficients are contracted with $p_\varepsilon = E(1, -\hat{\boldsymbol{n}})$ so in general have both constant and linear E dependence:

$\boldsymbol{a_L^\varepsilon p_\varepsilon}$:

$a_L^t, a_L^z \to \mathcal{C}$

$a_L^x, a_L^y \to \mathcal{A}, \mathcal{A}'$

$\boldsymbol{c_L^{\varepsilon\delta} p_\varepsilon p_\delta}$:

$E[c_L^{tt}, c_L^{tz}, c_L^{zz}] \to \mathcal{C}$

$E[c_L^{tx}, c_L^{ty}, c_L^{zx}, c_L^{zy}] \to \mathcal{A}, \mathcal{A}'$

$E[c_L^{xx}, c_L^{xy}, c_L^{yy}] \to \mathcal{B}, \mathcal{B}'$

INGRID selection

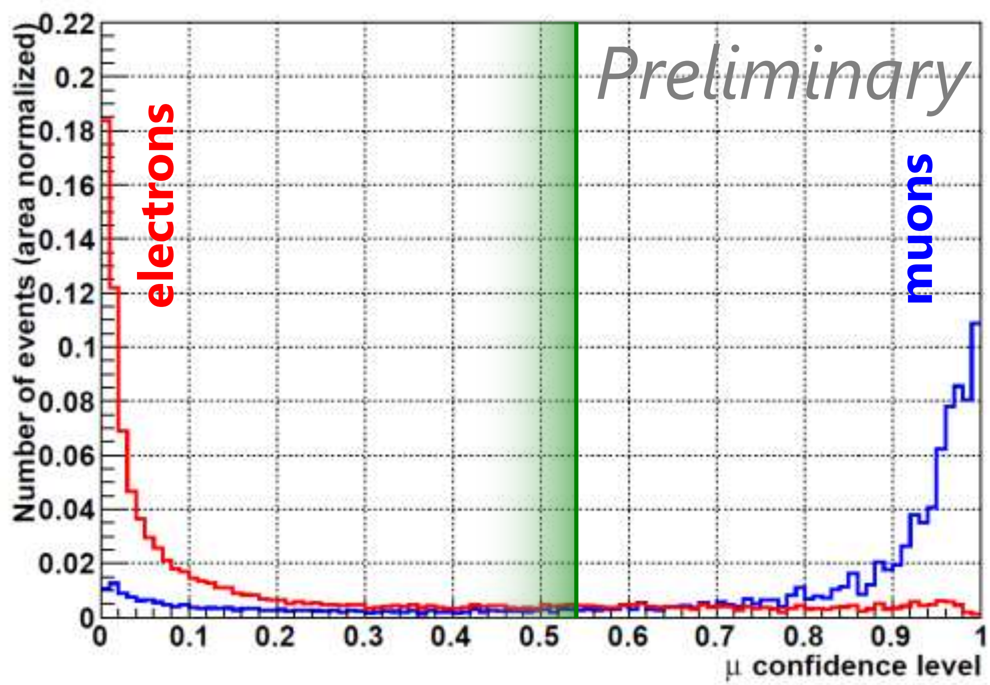
Must be sure to remove ν_e events in this analysis:

- LV signal is expected to be small
- No prediction of what flavour the ν_μ become

Events selected with a likelihood ratio:

- Track length
- Track width
- Activity (# hits) near vertex
- RMS of hit charge

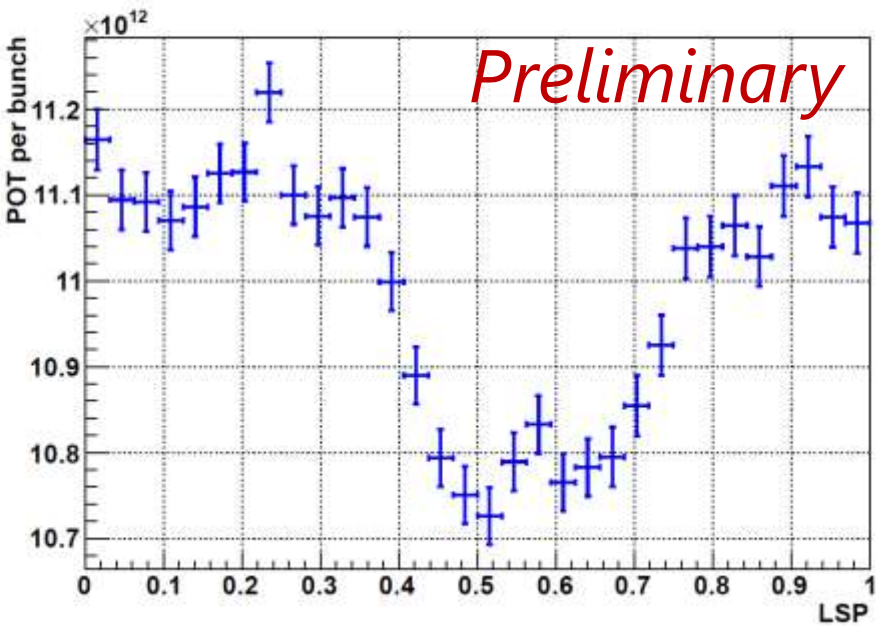
$$L_\mu = \frac{\prod_i P_i(x_i|\mu)}{\prod_i P_i(x_i|\mu) + \prod_i P_i(x_i|e)}$$



Average energy of selected events: $\langle E \rangle = 2.7\ \mathrm{GeV}$

Event rates and Local Sidereal Phase (LSP)

LV effect is periodic over $T_\oplus$, so present data with respect to the sidereal day. Specifically, **LSP is the fractional part of** $(\boldsymbol{t} - \boldsymbol{t_0})/\boldsymbol{T_\oplus}$



It is expected that many features are not uniform as a function of LSP:

- LSP advances slowly w.r.t. local time over a year
- Interventions typically happen during working hours
- The experiment does not run uniformly throughout the year (electricity costs)

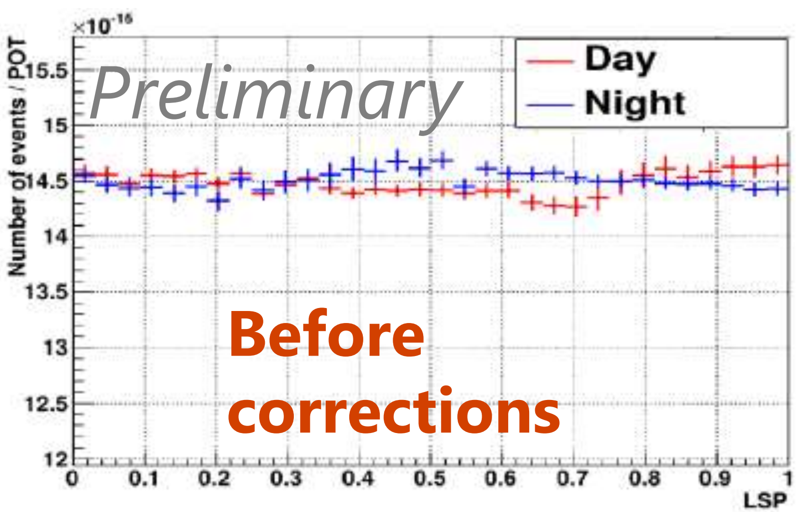
◄ e.g. Beam intensity (protons per bunch) vs LSP

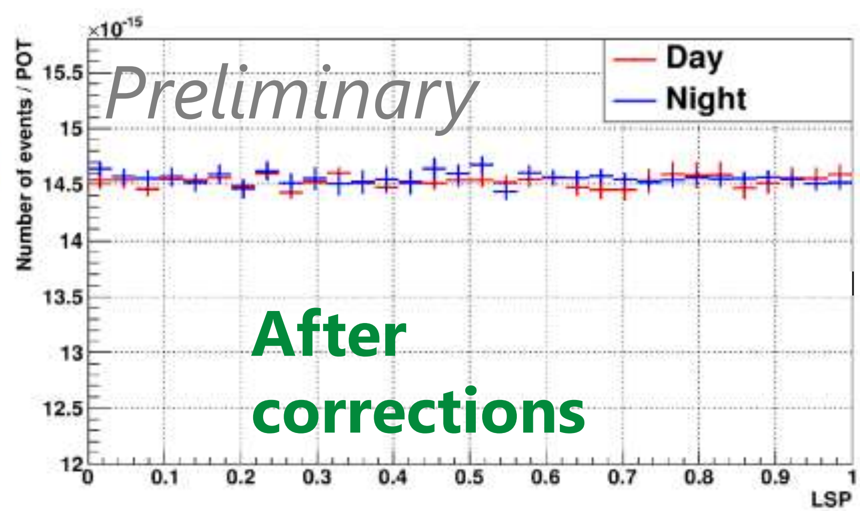
Systematic effects

The effects of various systematics are estimated.

- First-order effects (e.g. for pile-up) are corrected for
- Residual errors are estimated to be smaller than statistical variation.

Source	Effect size (% on bin)
Pile-up	0.01
Photo-sensor variation	0.06
Beam position	0.03
Long term variation	0.05
Total systematic	0.08
Statistical	**0.3**



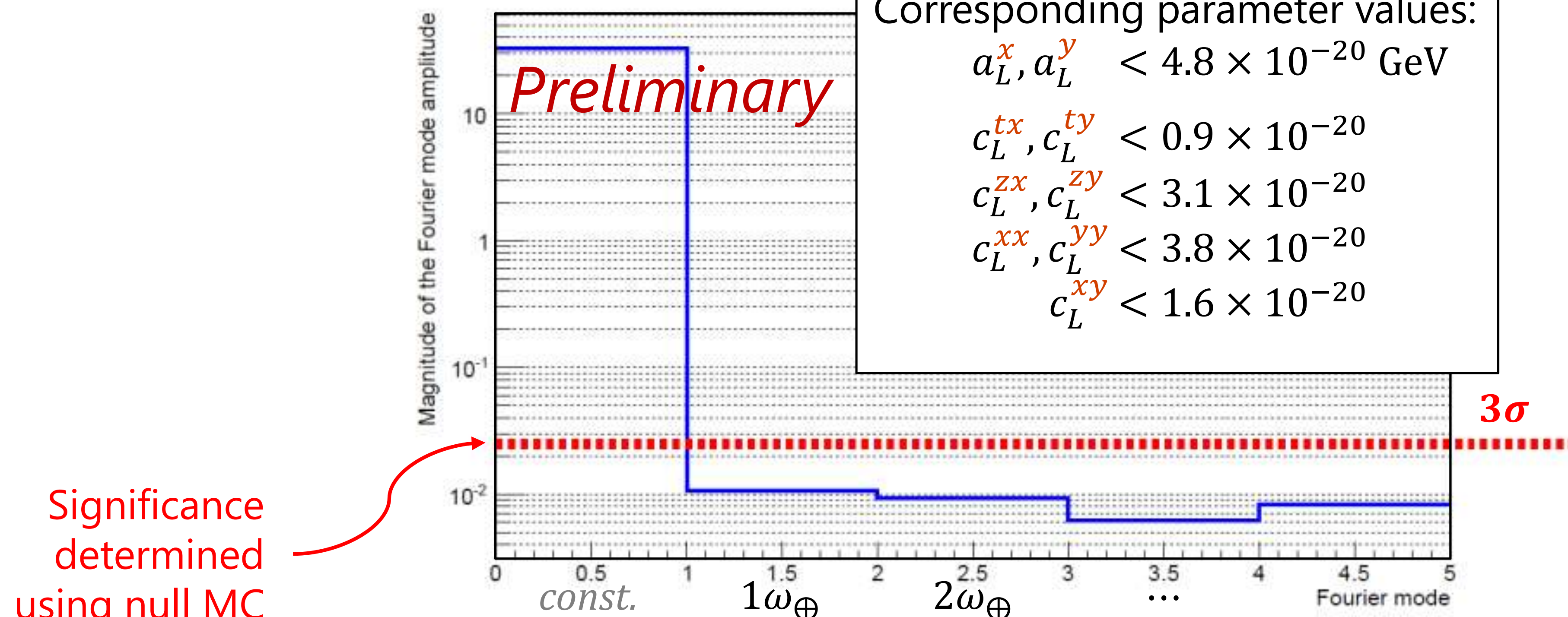


Parameter extraction

Parameters can be extracted using FFT

$$P^{\mathrm{SBL}}(\nu_a \to \nu_b) = \left| \mathcal{C}_{ab} + \mathcal{A}_{ab} \sin \omega_\oplus t + \mathcal{A}'_{ab} \cos \omega_\oplus t + \mathcal{B}_{ab} \sin 2\omega_\oplus t + \mathcal{B}'_{ab} \cos 2\omega_\oplus t \right|^2$$

∴ Fourier modes at $[1, 2, 3, 4] \times \boldsymbol{\omega}_\oplus$



Corresponding parameter values:

$a_L^x, a_L^y < 4.8 \times 10^{-20}$ GeV

$c_L^{tx}, c_L^{ty} < 0.9 \times 10^{-20}$

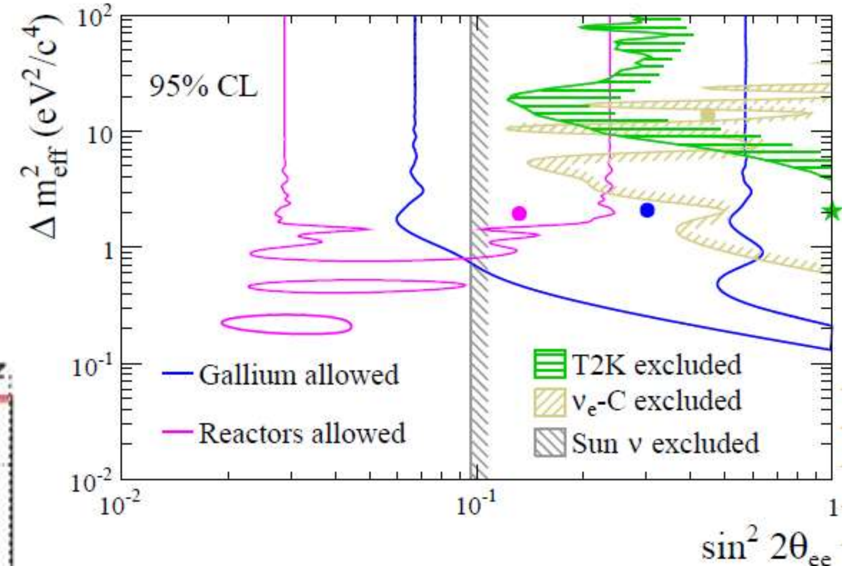
$c_L^{zx}, c_L^{zy} < 3.1 \times 10^{-20}$

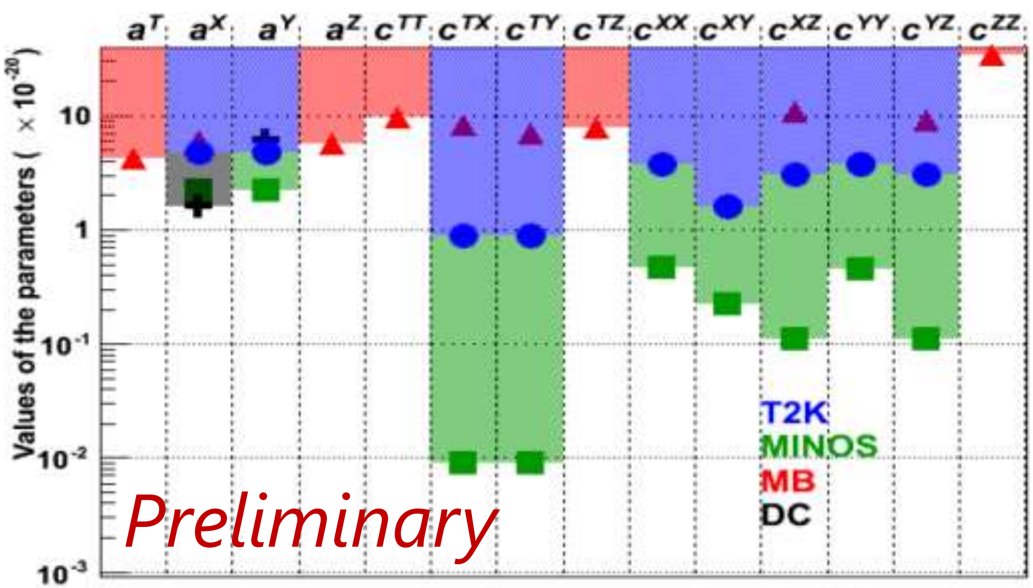
$c_L^{xx}, c_L^{yy} < 3.8 \times 10^{-20}$

$c_L^{xy} < 1.6 \times 10^{-20}$

Summary

- SBL ν_μ, ν_e searches: eliminate some regions favoured by anomalous results
  - Future: More data & ν_μ analysis





- LV searches: Competitive limits set for neutrino sector

Others: Heavy Neutral Leptons; Dark matter

Exotics WG—always interested in new ideas