IPMU colloquium

Towards precision neutrino physics

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KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Outline

History 1/3

State-of-the-art 1/3

T2K & HK 1/3

History

Historical note I

Theoretical proposal

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$$events = \sigma \times N \times \Phi \times t$$

- 1 year $3 \cdot 10^7$s
- 100 kg of water, N $\approx 5 \cdot 10^{26}$
- The flux at the detector needs to be >10^{10} ν/ (s·cm^2).

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It get's even worse:

- 1936: Muon is discovered.
- 1938: Muon is shown to decay.
- 1949: The outgoing electron in μ decay is not monochromatic! And therefore $\mu \to e + \nu + \nu$

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  - Discovers how enhance neutron cross-section by using moderators (Nobel Prize 1938).
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  - However... the detected rate is significantly lower than predictions from Bahcall.

Historical note III

The early days of the SM

- 1956 Lee &Yang propose weak interactions violate parity. Demonstrated in 1957 by Wu. (Nobel Prize 1957)
- 1957 Feynman & Gell-Mann cast weak interactions in its modern V-A shape.
- 1962 Lederman, Schwartz and Steinberger discover that $\nu_e \neq \nu_\mu$ (Nobel Prize 1988).
- 1961 Glashow unifies electromagnetic & weak interactions. Salam + Weinberg add SSB (Nobel Prize 1979).

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The SM grows up

- 1973 Kobayashi & Maskawa extend the number of quarks from 4 to 6 to explain observed CP violation.
- 1974 τ lepton is discovered at SLAC → people immediately assumes ν_τ exists.
- 1977 discovery of bottom quark, 1995 discovery of top quark.
- 2000 discovery of ν_τ by DONUT collaboration.
- 1990s-2000s Aleph collaboration shows number of neutrinos with mass below W boson mass is 3.
- 2012 ATLAS + CMS discover the Higgs boson.

Historical note IV

Neutrino oscillations & astrophysics

Theory

- 1950-60s Maki, Nakagawa, Sakata & 1967 Pontecorvo proposed neutrino flavor oscillations.
- 1978 Wolfenstein + 1985 Mikheyev & Smirnov describe ‘matter effects’, modern MSW effect.

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- 1987 Kamiokande (12 events) & IMB (5 events) detect SN1987A. (Koshiba, Nobel Prize 2002).
- 1990 Kamiokande demonstrates flux of neutrinos comes from the Sun (Koshiba+Davis, Nobel Prize 2002).
- 1990s Kamiokande finds a deficit in solar neutrinos **AND** in atmospheric neutrinos.
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Discovery of oscillations

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- 2002 SNO **demonstrates solar neutrino deficit is due to MSW effect**. (McDonald, Nobel Prize, 2015)

Contemporary history

The discovery of neutrino oscillations ignites a revolution

- Neutrinos have mass... (3 d.o.f)... but it is difficult to accommodate in SM. (Dirac - Majorana)
- Neutrinos mix (4 d.o.f.) $\rightarrow$ effectively violate lepton number conservation.
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Proliferation of data quantity, quality & diversity over years

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Start of precision neutrino physics

State-of-the-art

Modern ν physics phenomenology

Neutrinos interact as weak states $(\nu_e, \nu_\mu, \nu_\tau)$ **, but propagate as mass states** (ν_1, ν_2, ν_3)**.**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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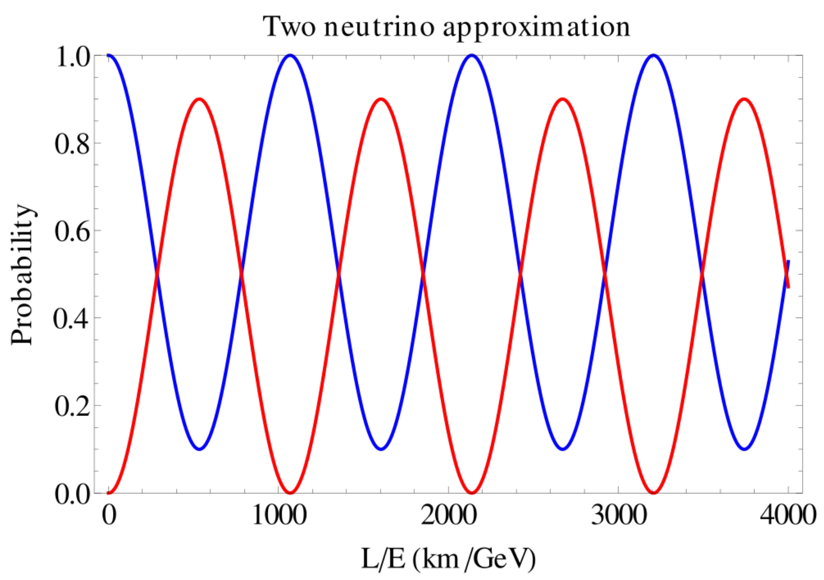
Flavor eigenstates evolve in time cyclically, with a frequency that depends on E.

$$P(\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta) = \delta_{\alpha\beta} - \underbrace{4\sum \mathscr{A}_{ij}\sin^2\frac{\Delta m^2_{ij}L}{4E_\nu}}_{\text{CP conserving}} \pm \underbrace{2\sum \mathscr{B}_{ij}\sin\frac{\Delta m^2_{ij}L}{2E_\nu}}_{\text{CP violating}}$$

$\pm$: ν or $\bar{\nu}$

$\Delta m^2_{ij} = m^2_i - m^2_j$



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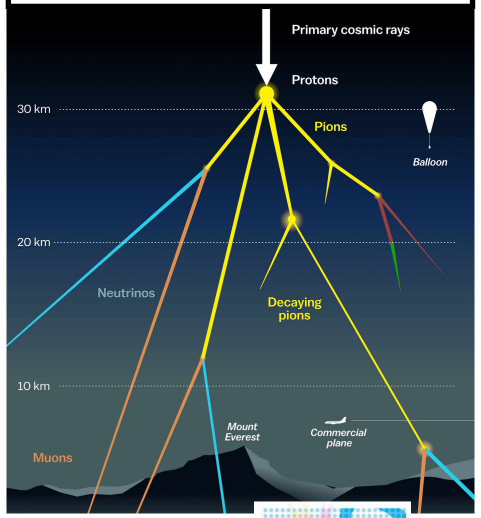
Δm^2_{23}

Δm^2_{12}

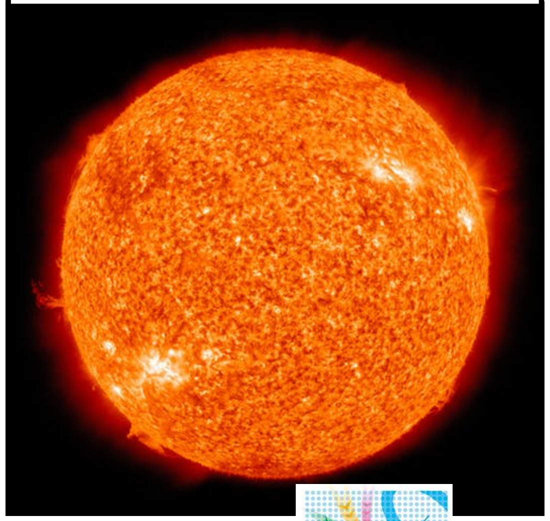
Atmospheric



Accelerator

Reactor

Solar



Different experiments have different typical L/E, allowing to explore different sets of parameters

Modern ν mass experiments

Neutrino oscillations inform us about the relative mass differences: $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$, but not about absolute value. **We need one extra constrain.**

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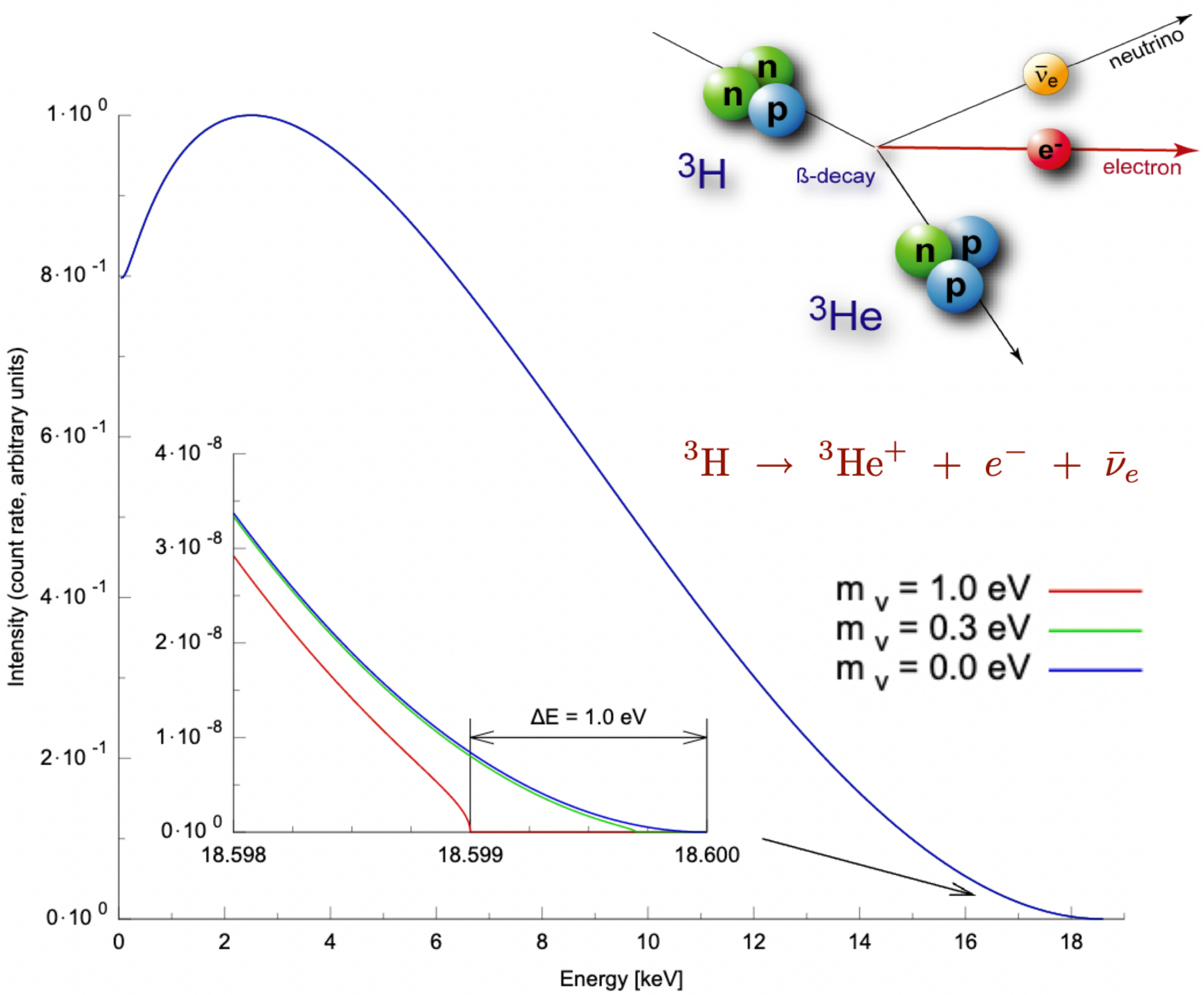
Direct mass searches (KATRIN)



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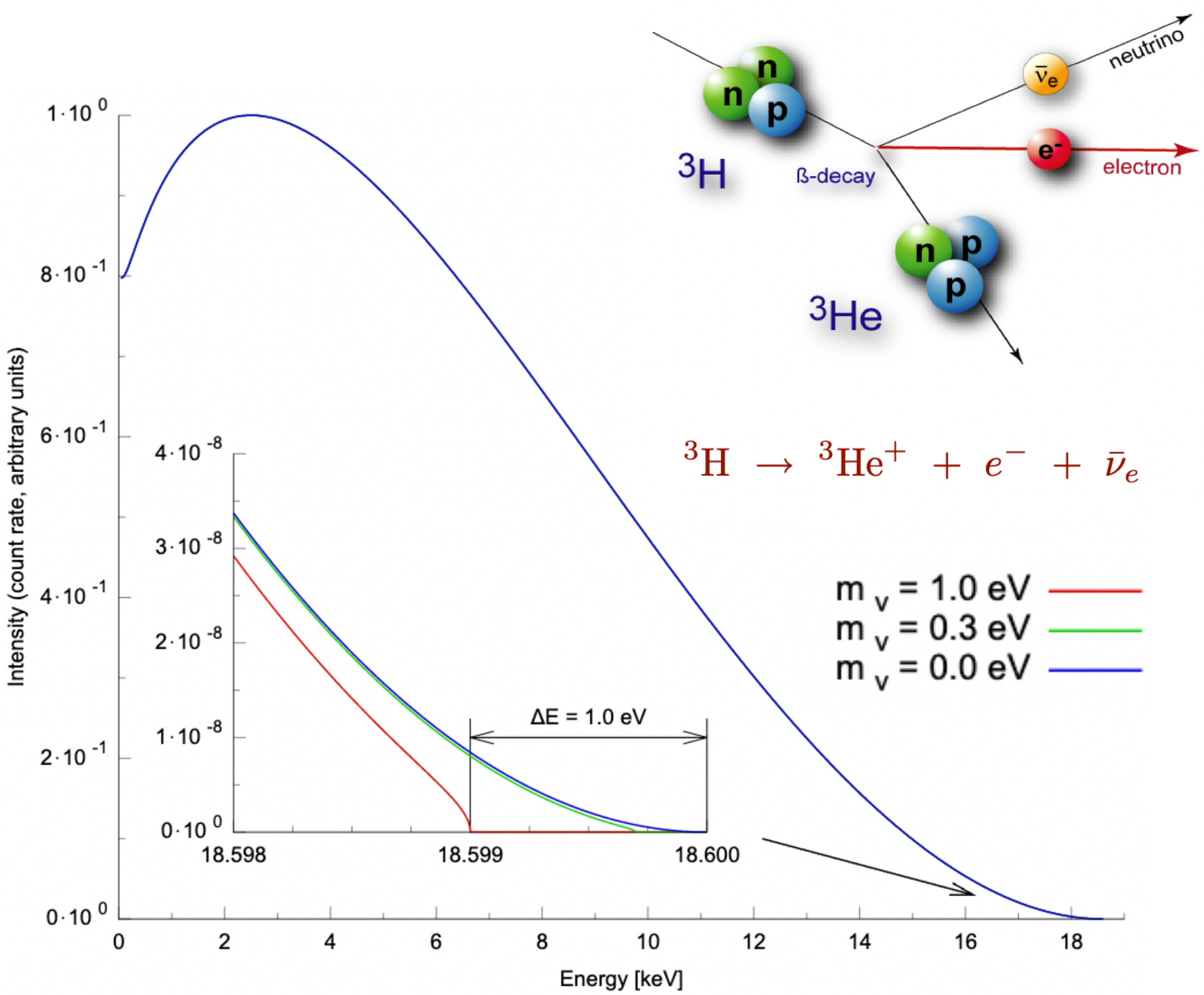
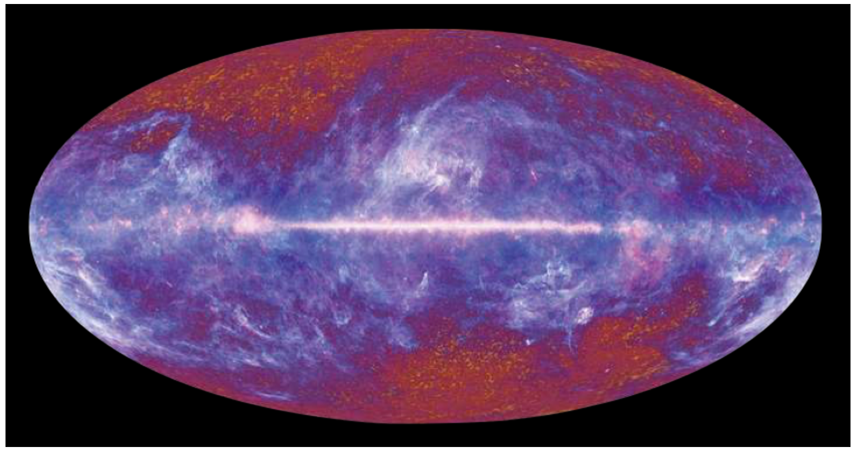


$$ ^3\mathrm{H} \rightarrow {}^3\mathrm{He}^+ + e^- + \bar{\nu}_e $$

Cosmological Probes



Neutrino energy density affects history of the Universe, leaving numerous imprints:

- CMB
- distribution of galaxy clusters
- Lyman-alpha forest.

Modern ν Knowledge

Mass scale

Direct mass search

$$\sum_i |U_{ei}|^2 m_i^2 < 0.8 \text{ eV (90\%C.L)}$$

Cosmology

$\sum m_\nu < 0.111$ eV (90%C.L) Would imply $m_{least} < 0.05\text{eV}.$

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Mixing

Oscillations

$$\theta_{12} : 4.6\% \, [14\%], \quad \theta_{13} : 2.9\% \, [9.0\%], \quad \theta_{23} : 5.1\% \, [27\%],$$
$$\Delta m^2_{21} : 5.5\% \, [16\%], \quad |\Delta m^2_{3\ell}| : 2.2\% \, [6.7\%], \quad \delta_{CP} : 39\% [100\%] \, .$$

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What we don't know?

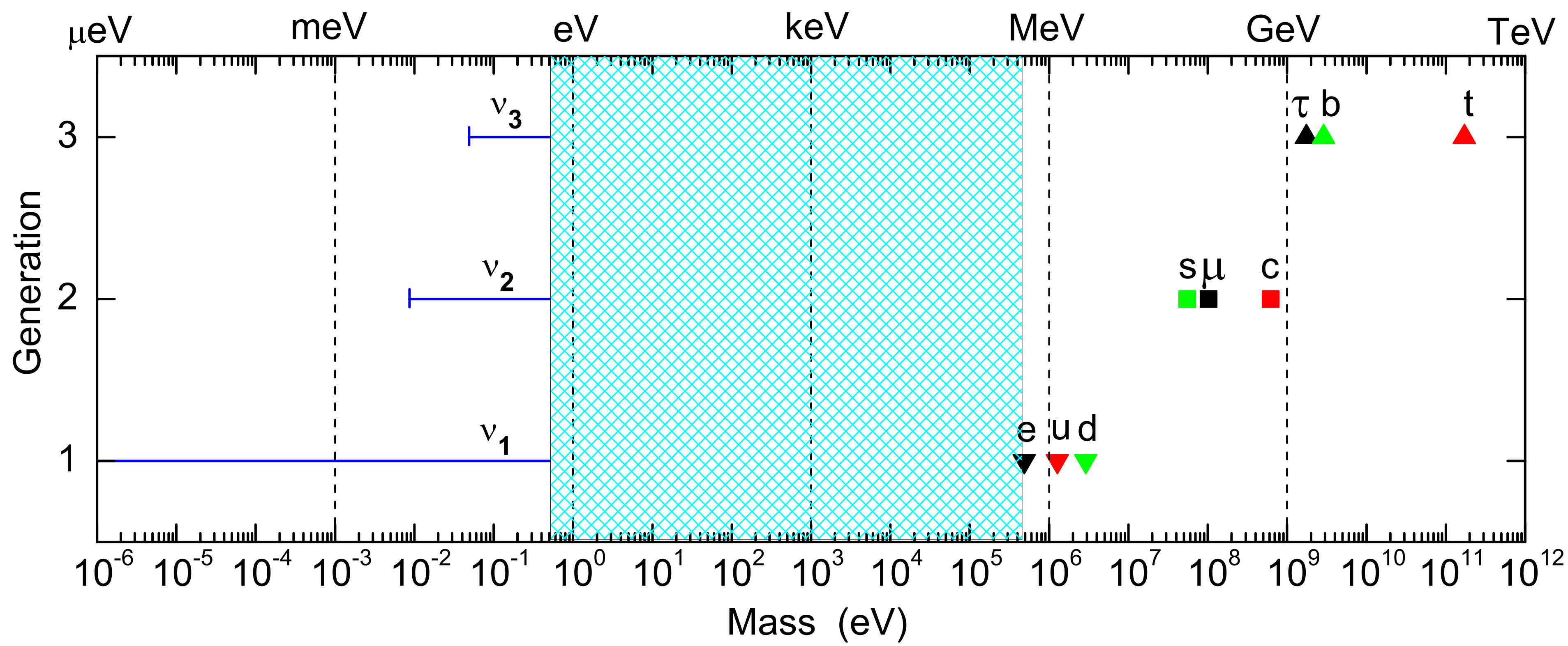
- Neutrino mass scale.
- Neutrino mass ordering.
- θ_{23} octant.
- CP violation.

7 d.o.f, still 4 unknowns.

Why do we care, I

The origin of neutrino masses

- Why are masses so small?



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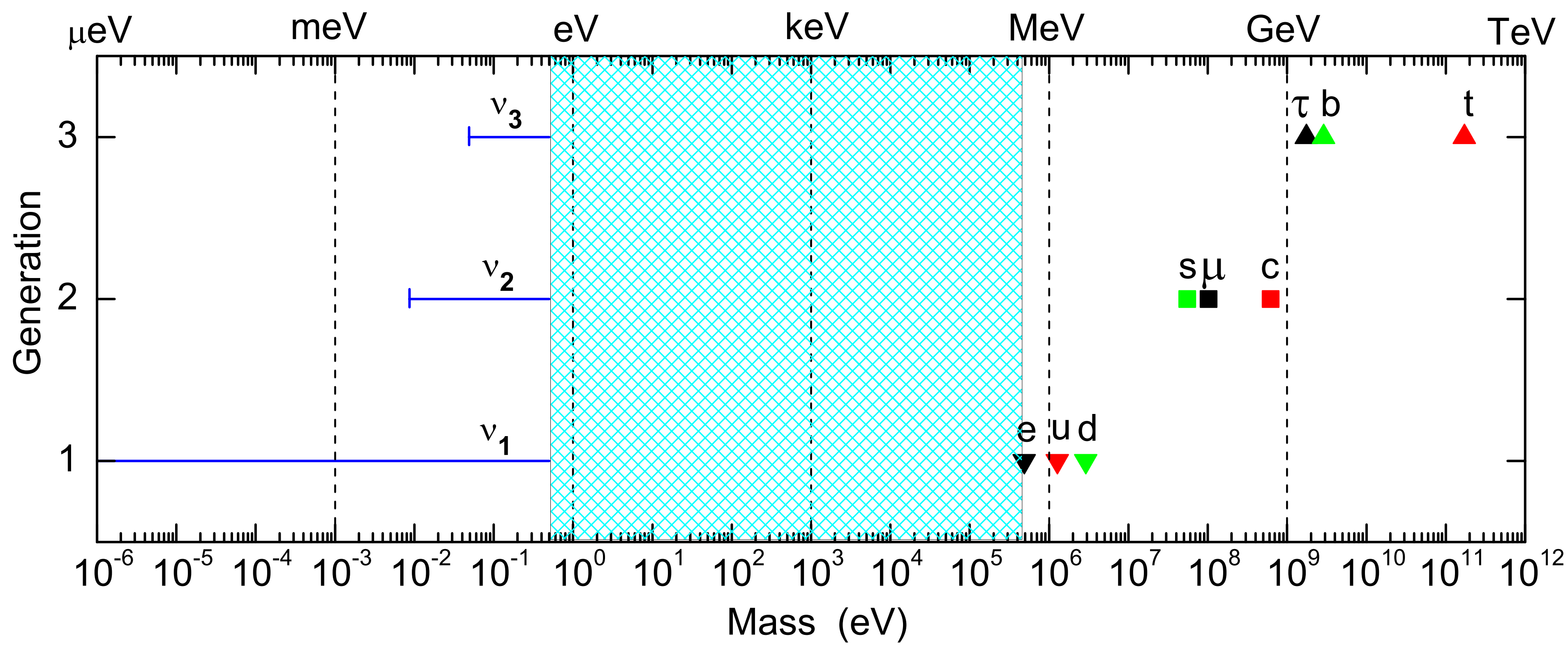

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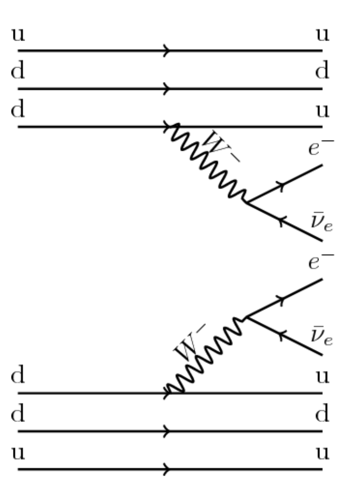
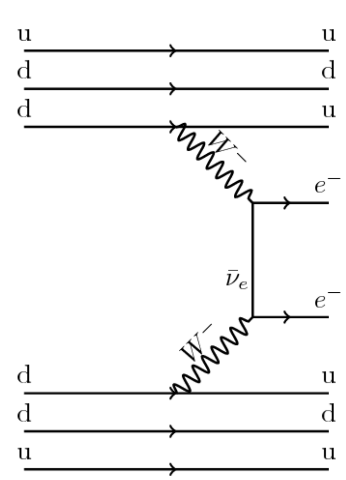
- Are neutrinos Majorana particles?





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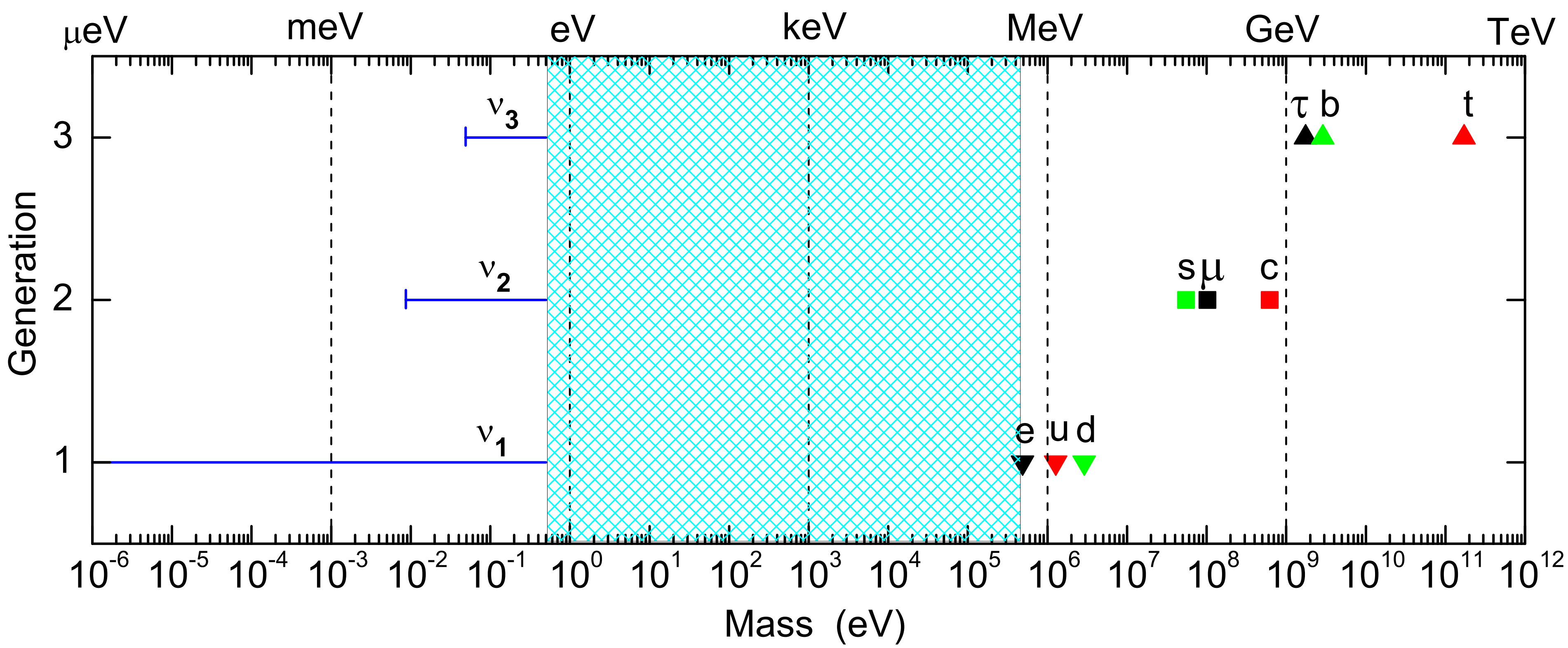

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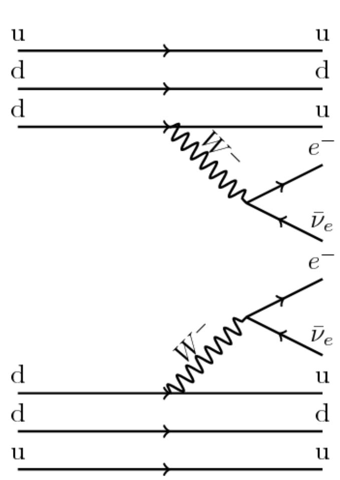
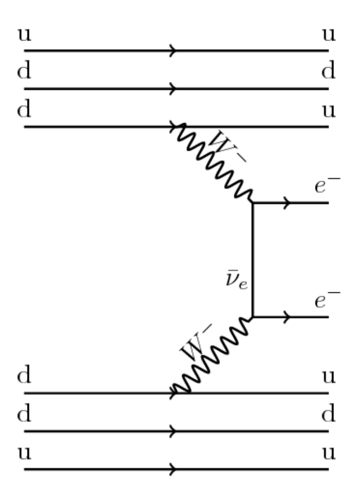
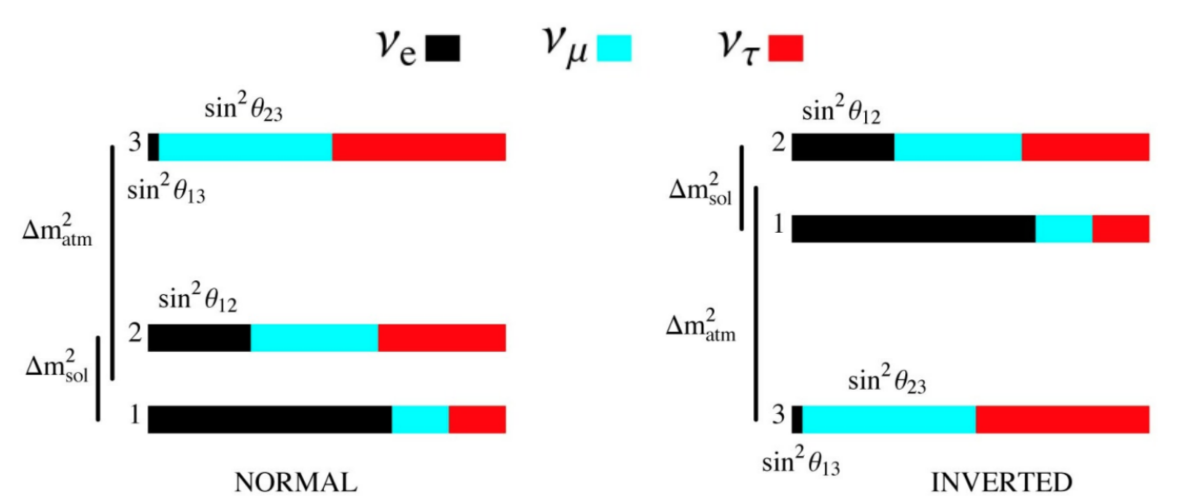




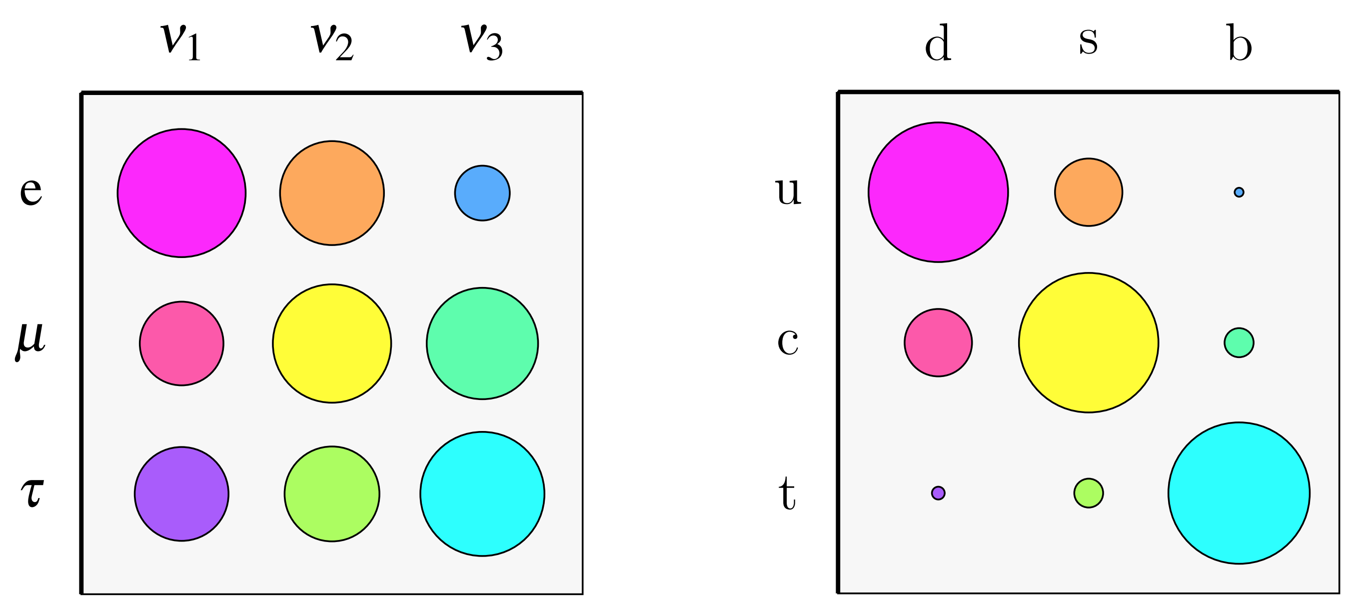
- What is the mass ordering?
- If IO: why???



Flavor patterns

GUTs: 3 generations... pairs of quarks, pairs of leptons... leptoquarks?

➤ Wait, what is this???



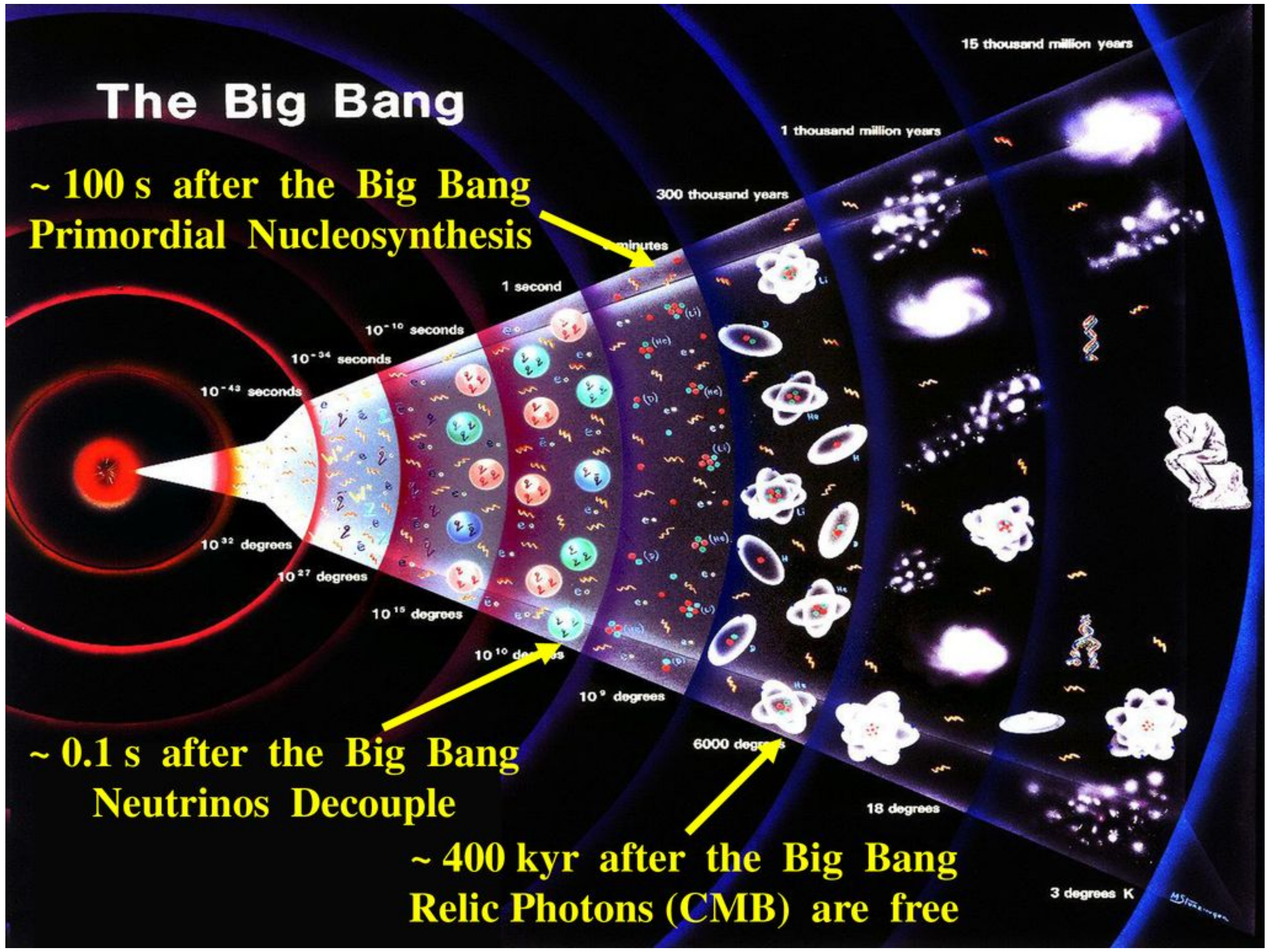
The 'democratic' PMNS pattern contrasts with the 'hierarchical' structure of the CKM matrix.

The value of θ_{23} is very close to 45deg. Important for model building.

By determining PMNS with precision, we can uncover BSM physics: similar to modern LHC searches.

Why do we care, III

Cosmology



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- Leptogenesis? → requires $\delta_{CP} \neq \{0, \pi\}$
- Measuring ν masses from HEP & cosmology would bring major insight.

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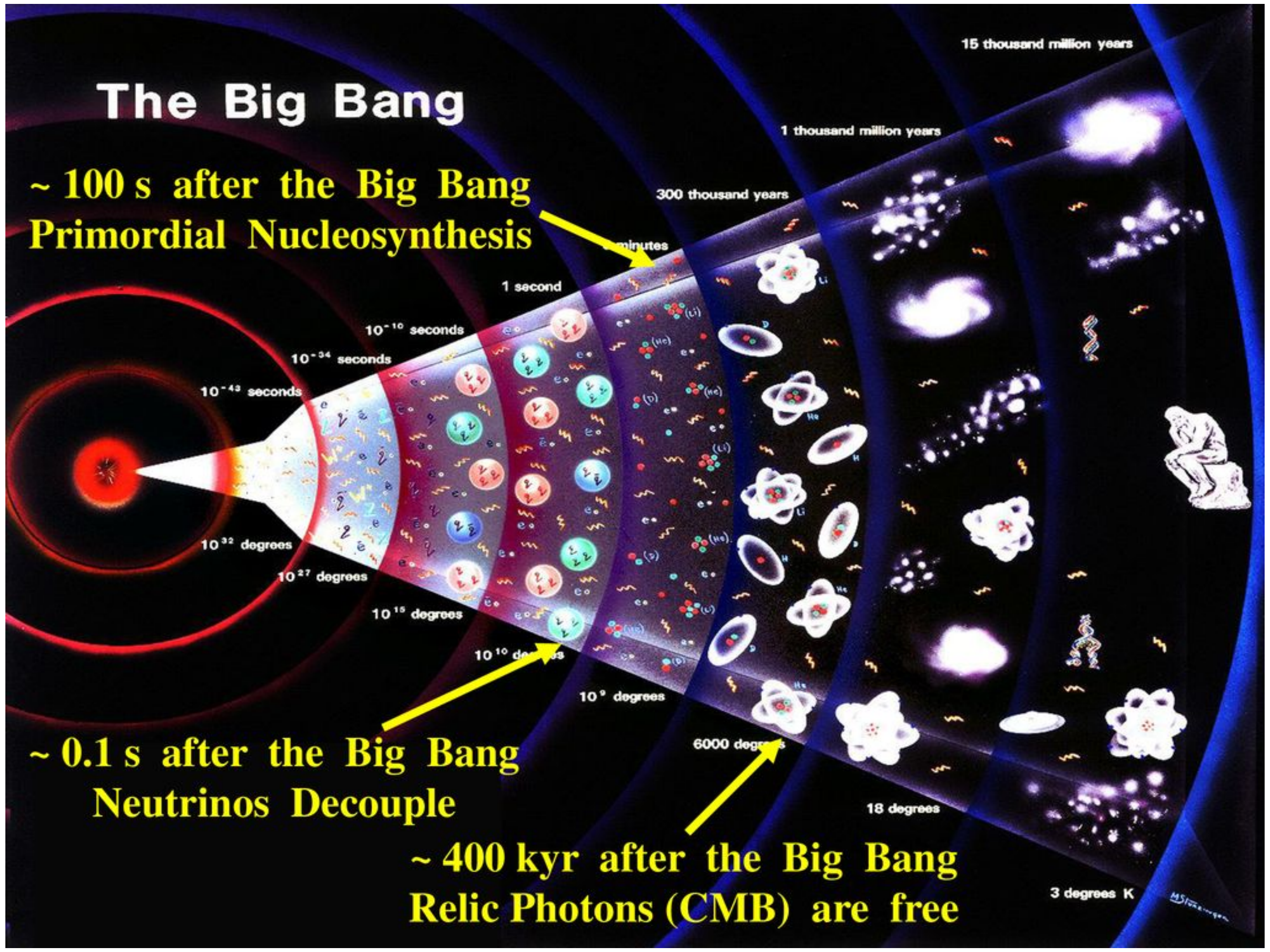

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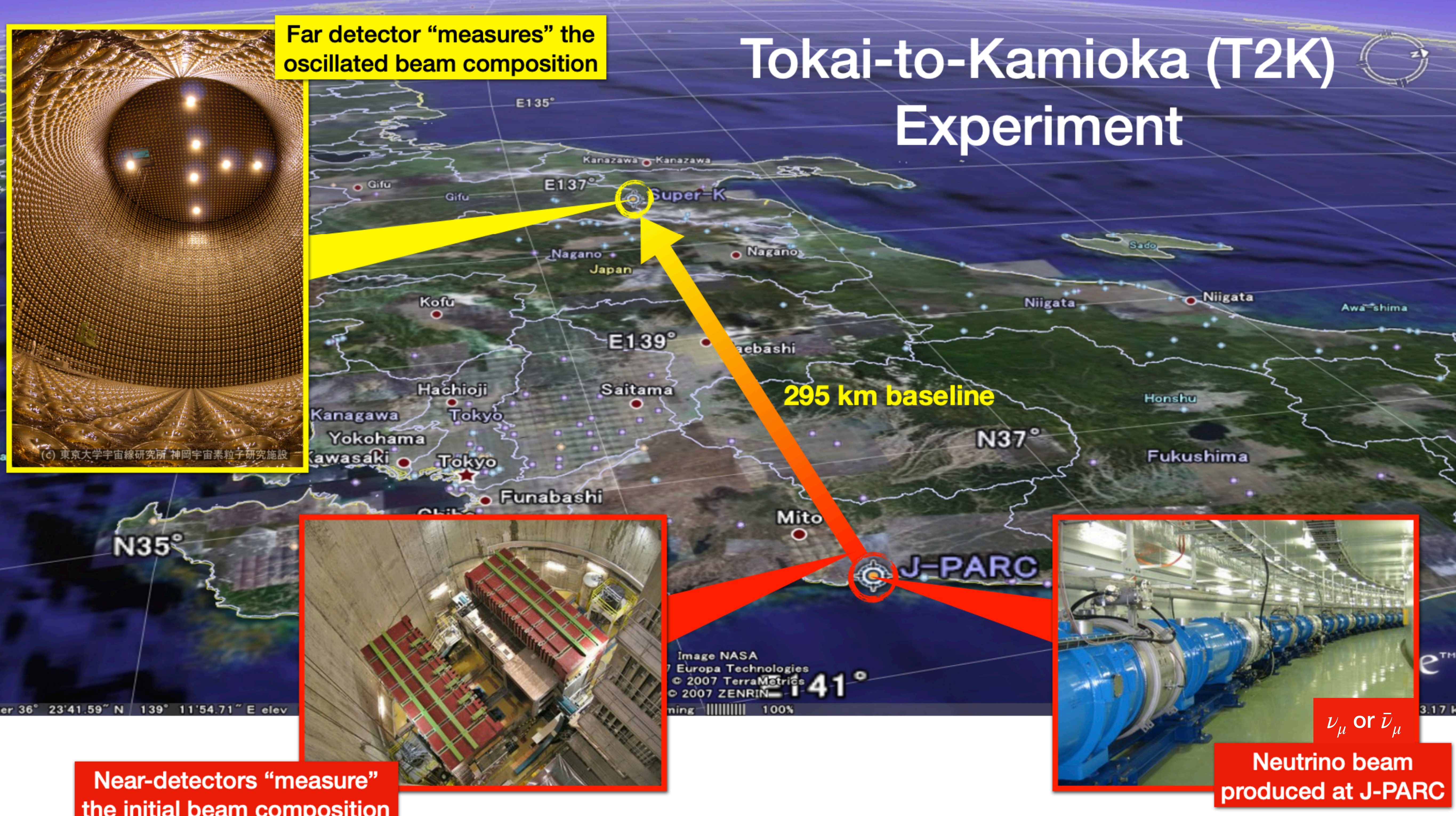
BONUS: CνB would allow us to look directly into the very early Universe

Let's do directly detect them!!!

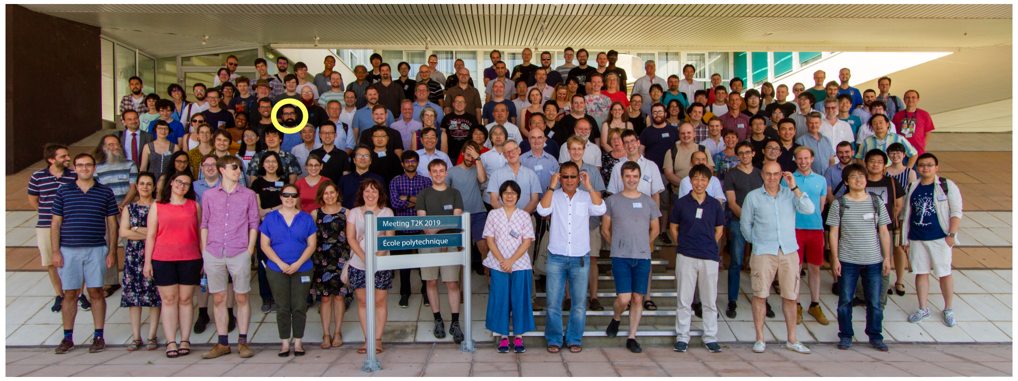
Wait... $E_\nu \sim 100$ μeV...
Nothing exists that is remotely similar to what is needed to attempt this.

Let’s do some measurement

Tokai-to-Kamioka (T2K) Experiment



- Discovery of $\theta_{13} > 0$.
- First hints of $\delta_{CP} \neq \{0,\pi\}$
- Leading sensitivity to $\Delta m^2_{23}, \theta_{23}, \delta_{CP}$.



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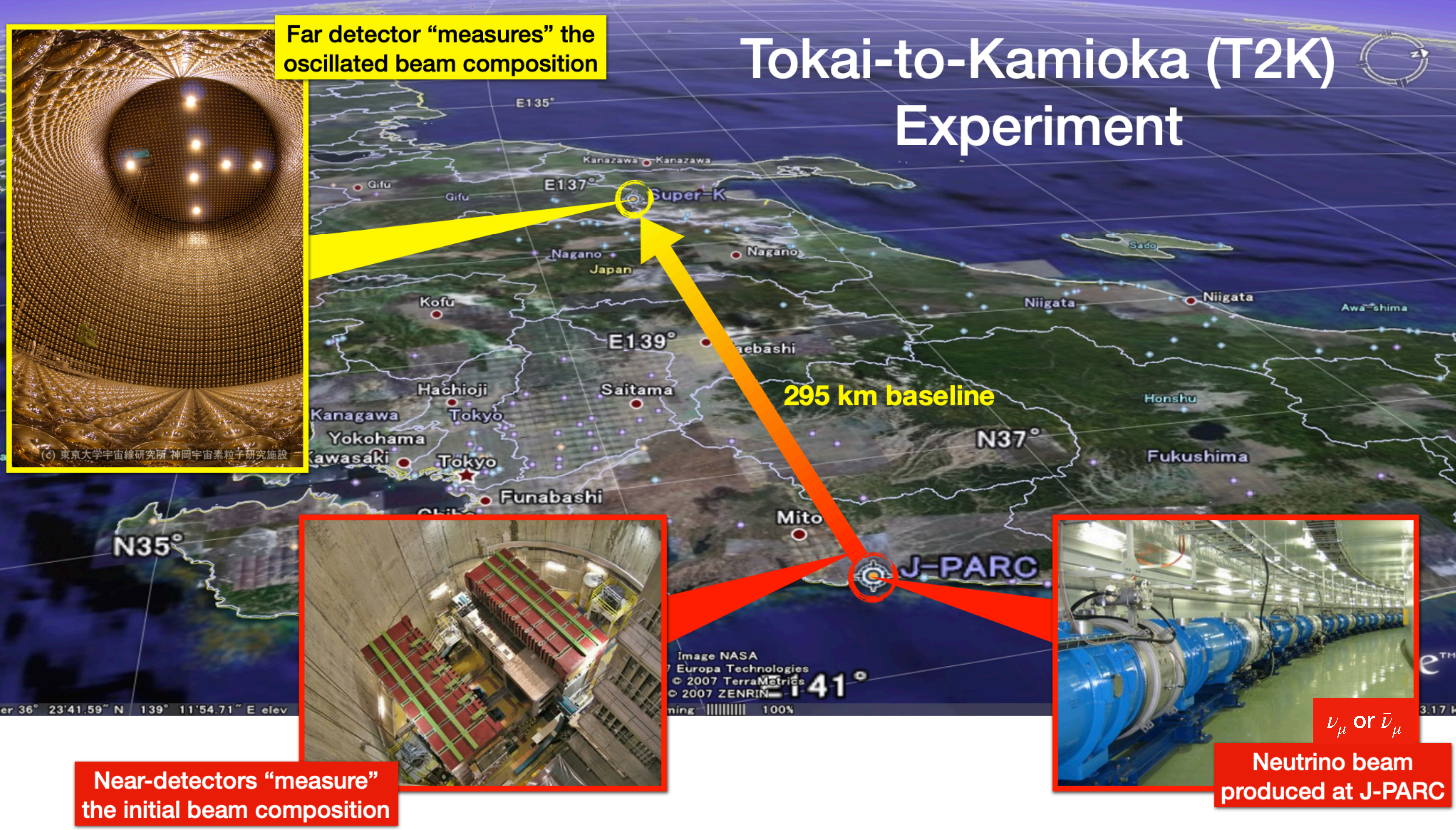
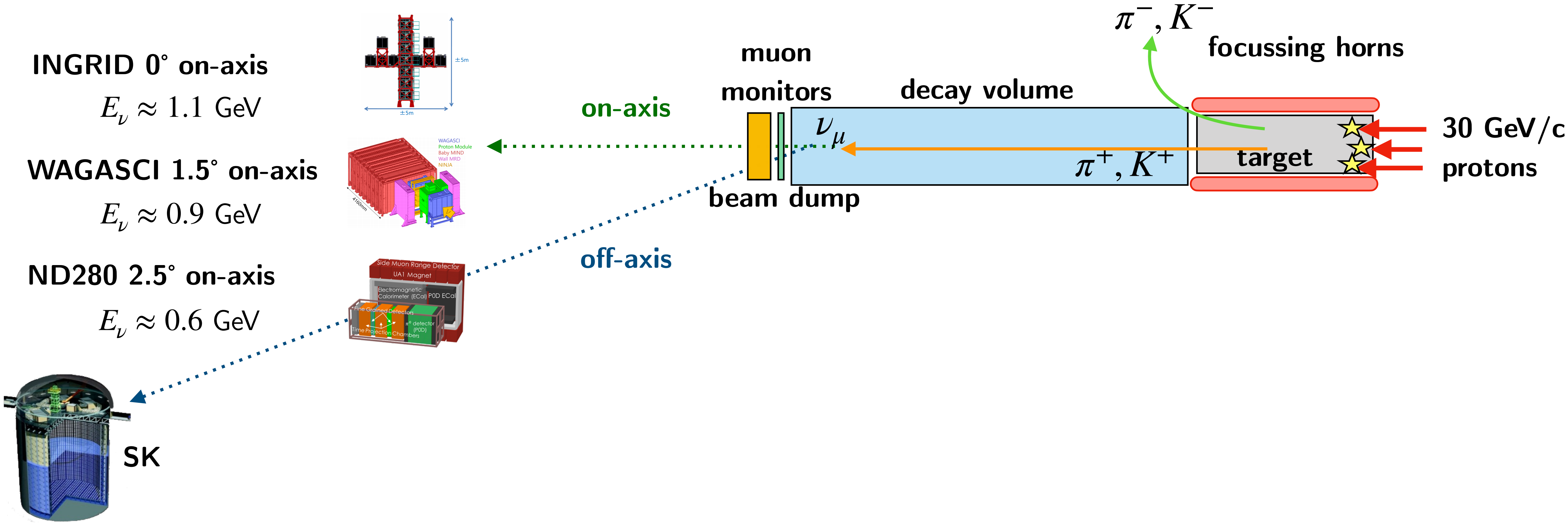
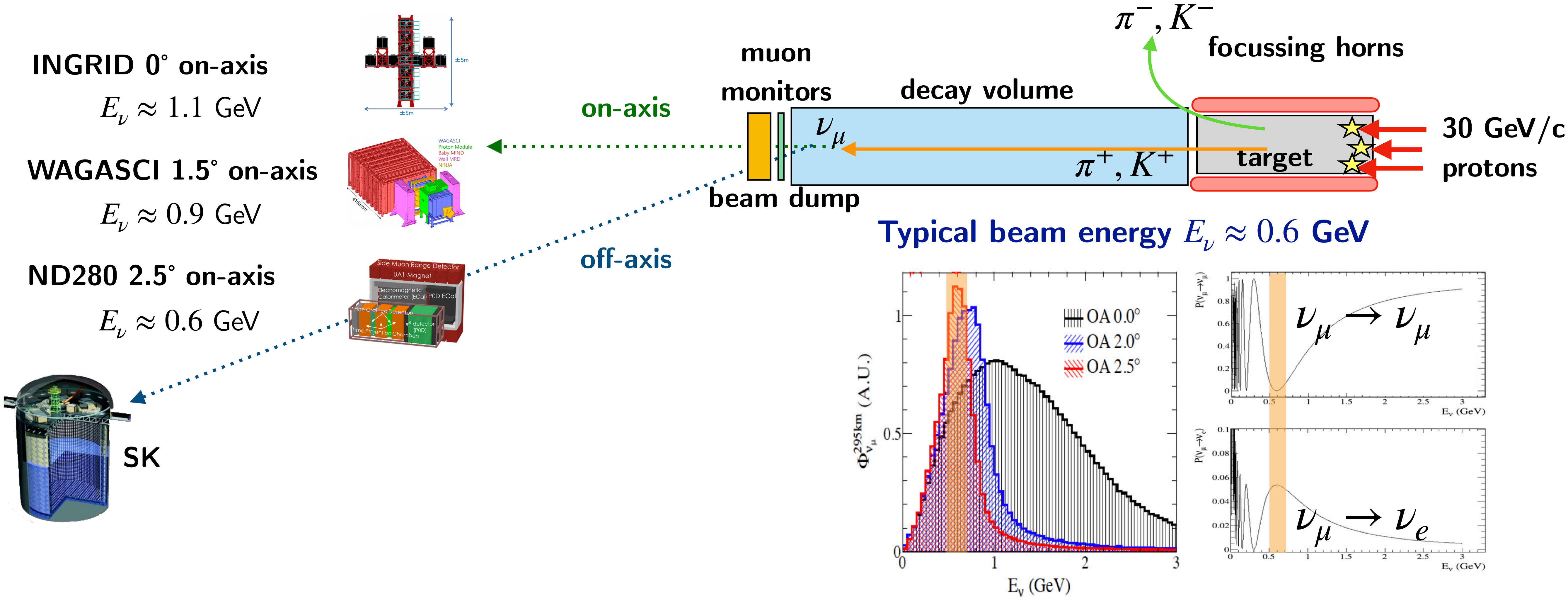


$$\underset{\text{Expected event rate}}{N_i^{exp}(E_\nu)} = \underset{\text{Oscillation probability}}{P(\nu_\alpha \to \nu_\beta)} \times \underset{\text{Interaction cross-section}}{\sigma_i(E_\nu)} \times \underset{\text{Neutrino flux}}{\Phi_\nu(E_\nu)} \times \underset{\text{Detector efficiency}}{\epsilon_i(E_\nu)}$$

T2K


INGRID 0° on-axis
$E_\nu \approx 1.1$ GeV
WAGASCI 1.5° on-axis
$E_\nu \approx 0.9$ GeV
ND280 2.5° on-axis
$E_\nu \approx 0.6$ GeV
SK
on-axis
off-axis
muon
monitors
beam dump
decay volume
ν_μ
π^+, K^+
π^-, K^-
focussing horns
target
30 GeV/c
protons

T2K



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π^+, K^+
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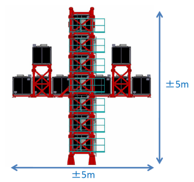
target
30 GeV/c protons
Typical beam energy $E_\nu \approx 0.6$ GeV
OA 0.0°
OA 2.0°
OA 2.5°
E_ν (GeV)
$\nu_\mu \rightarrow \nu_\mu$
$\nu_\mu \rightarrow \nu_e$

T2K

INGRID 0° on-axis

$E_\nu \approx 1.1$ GeV



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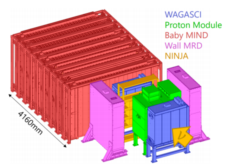

ND280 2.5° on-axis

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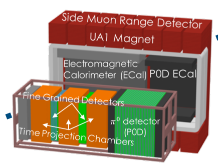
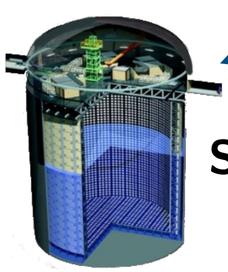
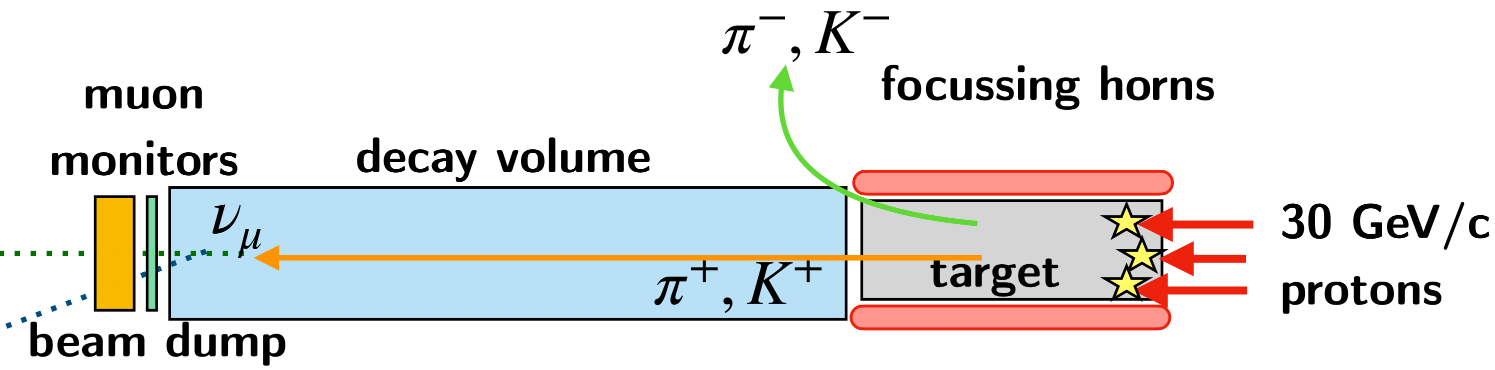


on-axis

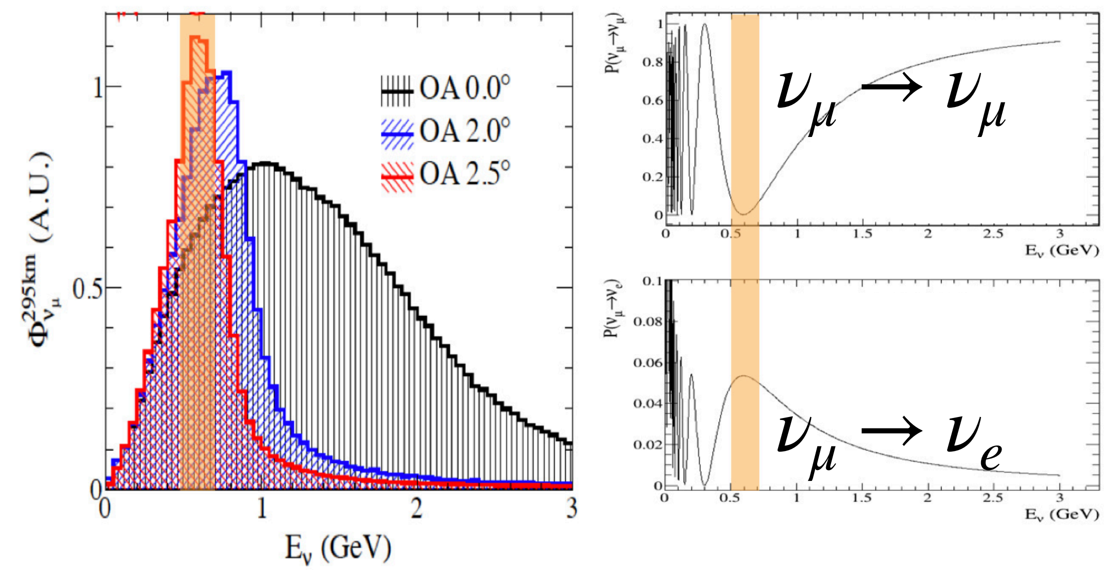
off-axis

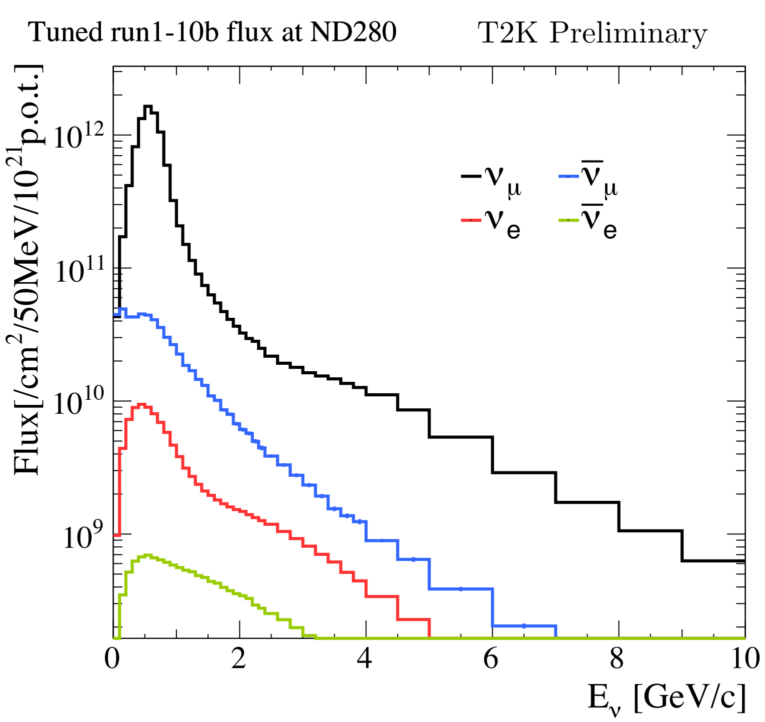


SK



Typical beam energy $E_\nu \approx 0.6$ GeV





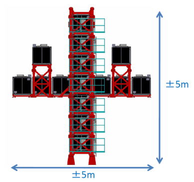
Highly pure

ν_μ or $\bar{\nu}_\mu$ beam

T2K

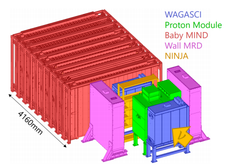
INGRID 0° on-axis

$E_\nu \approx 1.1$ GeV



WAGASCI 1.5° on-axis

$E_\nu \approx 0.9$ GeV



ND280 2.5° on-axis

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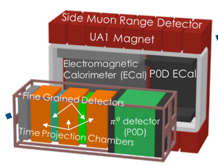
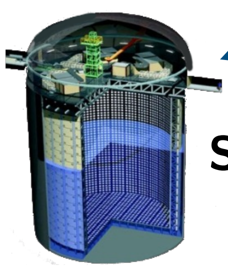
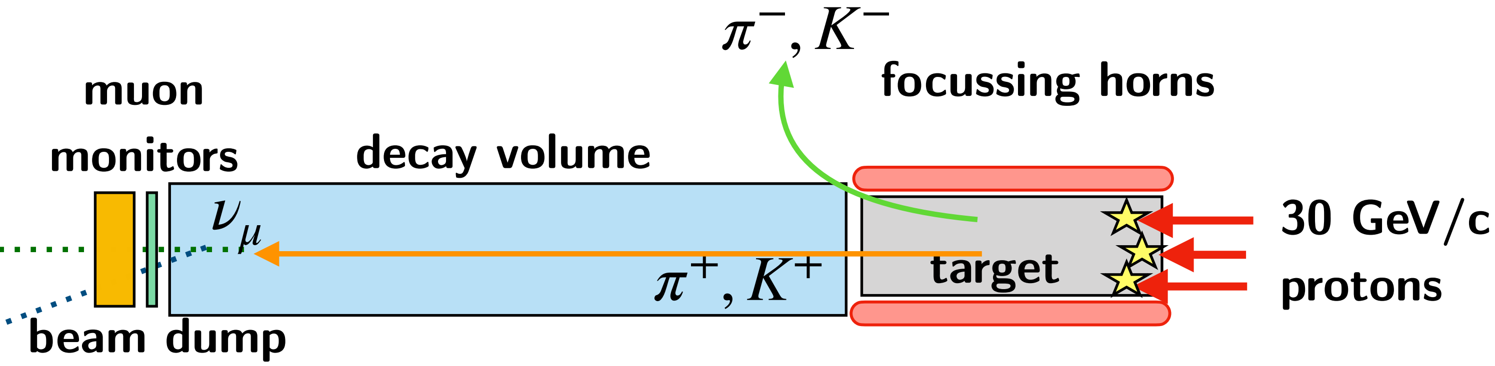




SK

on-axis

off-axis



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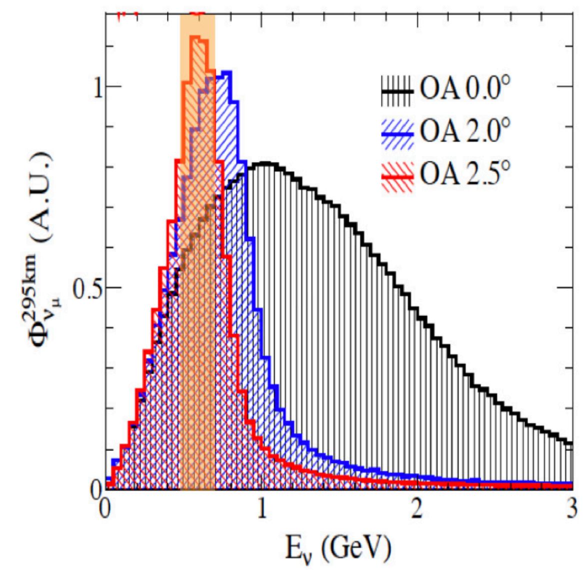
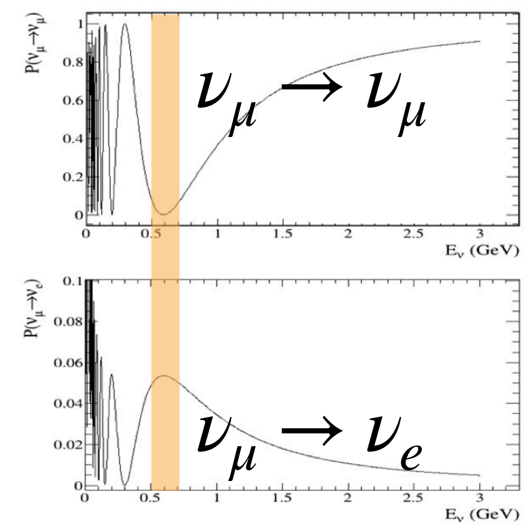
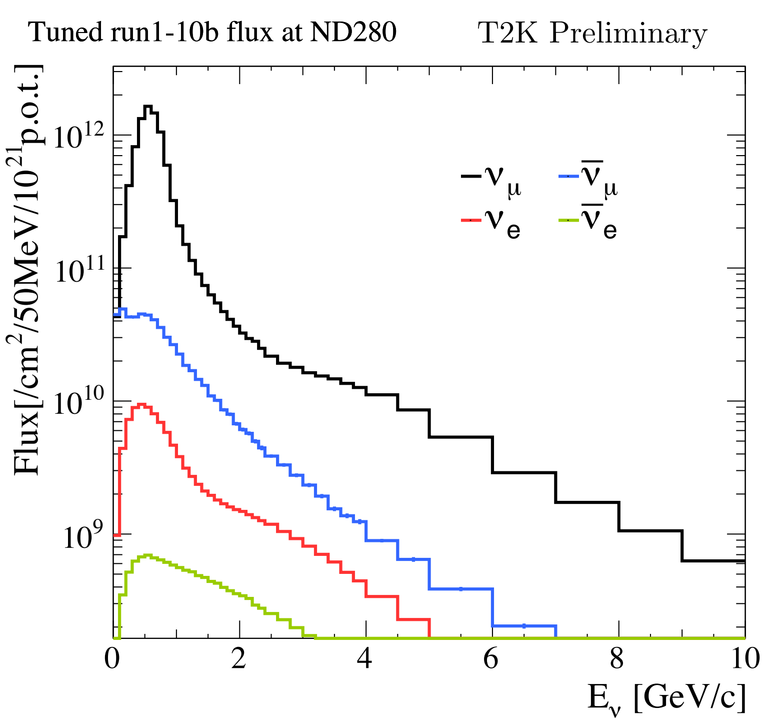
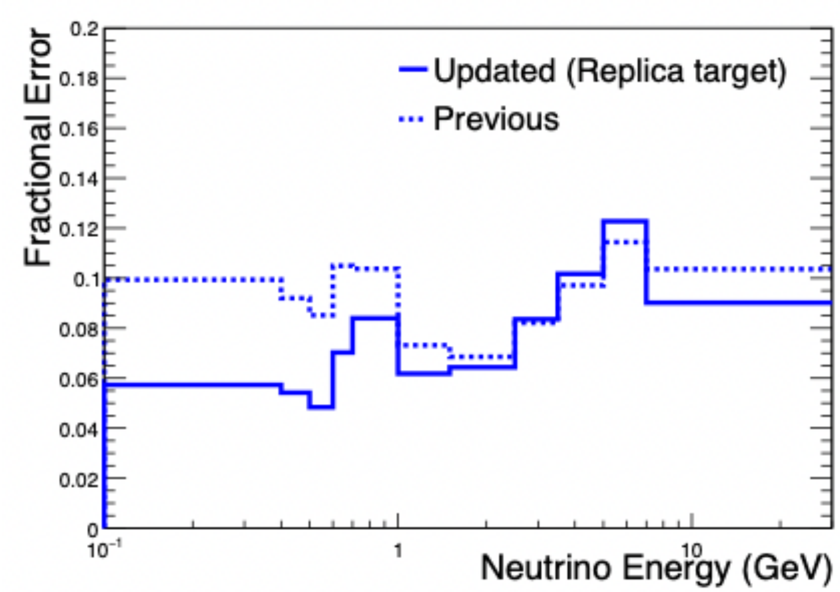




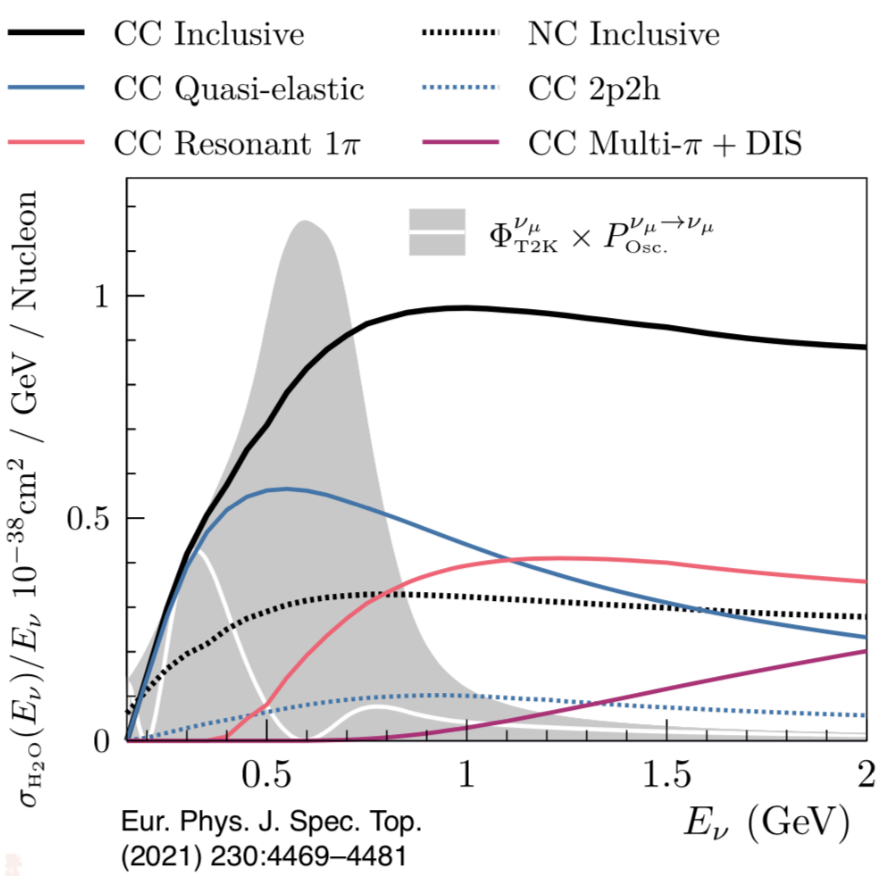


Highly pure ν_μ or $\bar{\nu}_\mu$ beam

Constrained flux using NA61 experiment @CERN

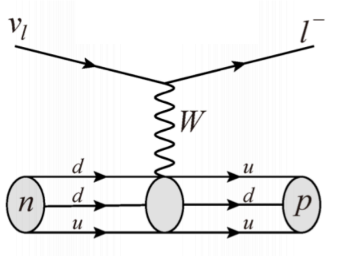


Cross-sections $E_\nu \approx 1$ GeV

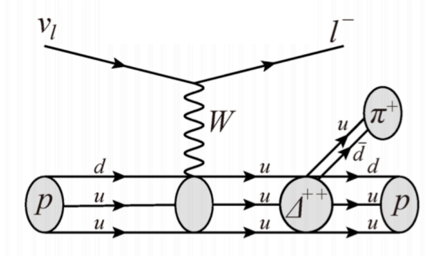


Interactions with a single nucleon

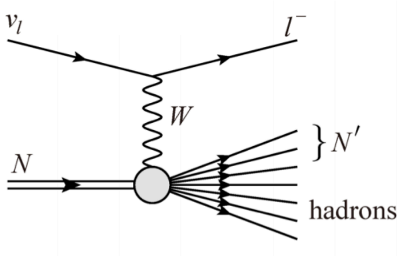
CC-QE

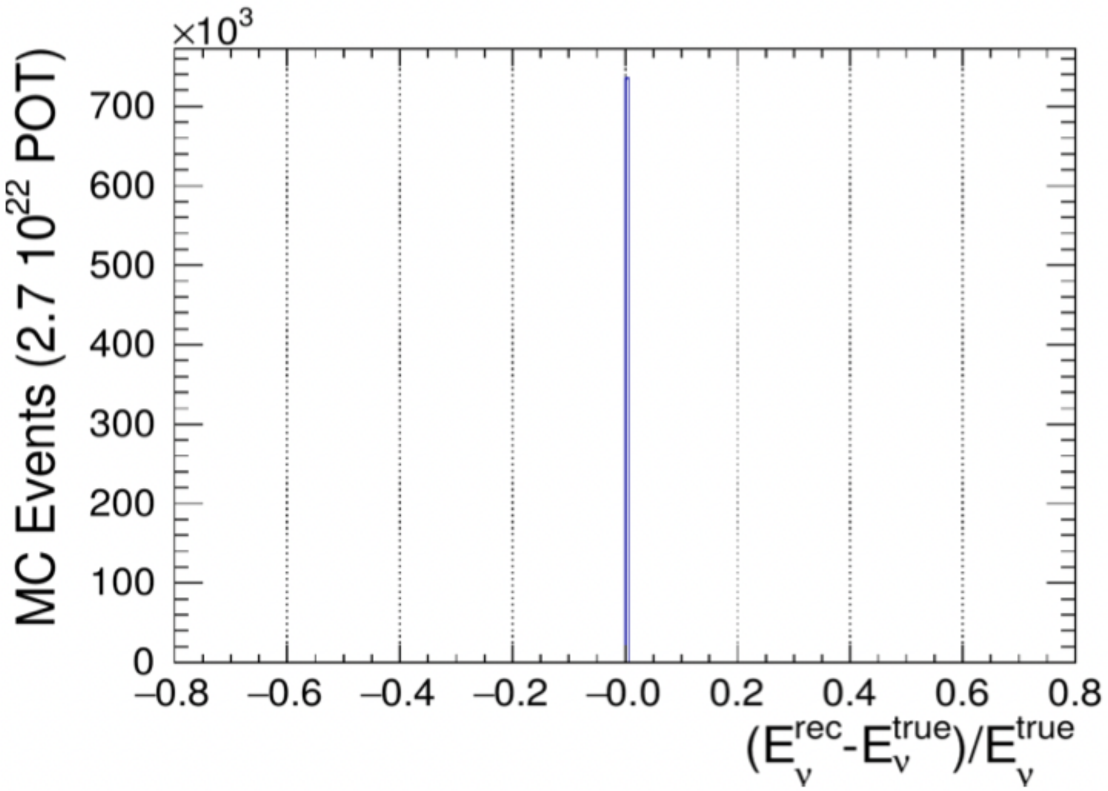


CC-RES



CC-DIS





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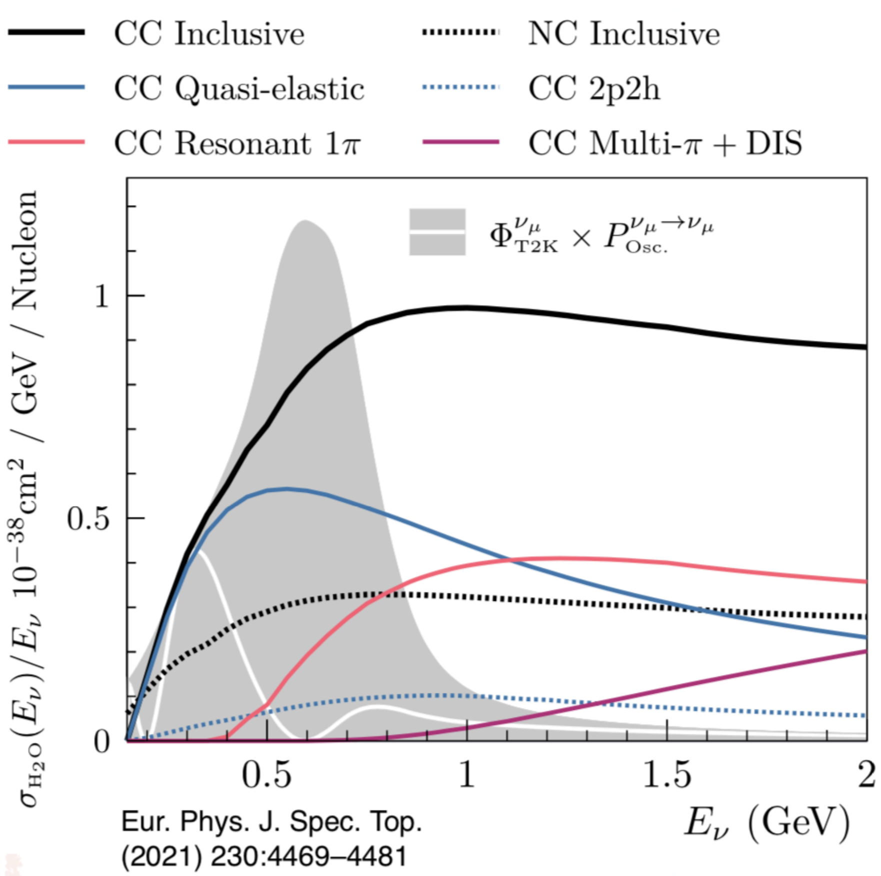

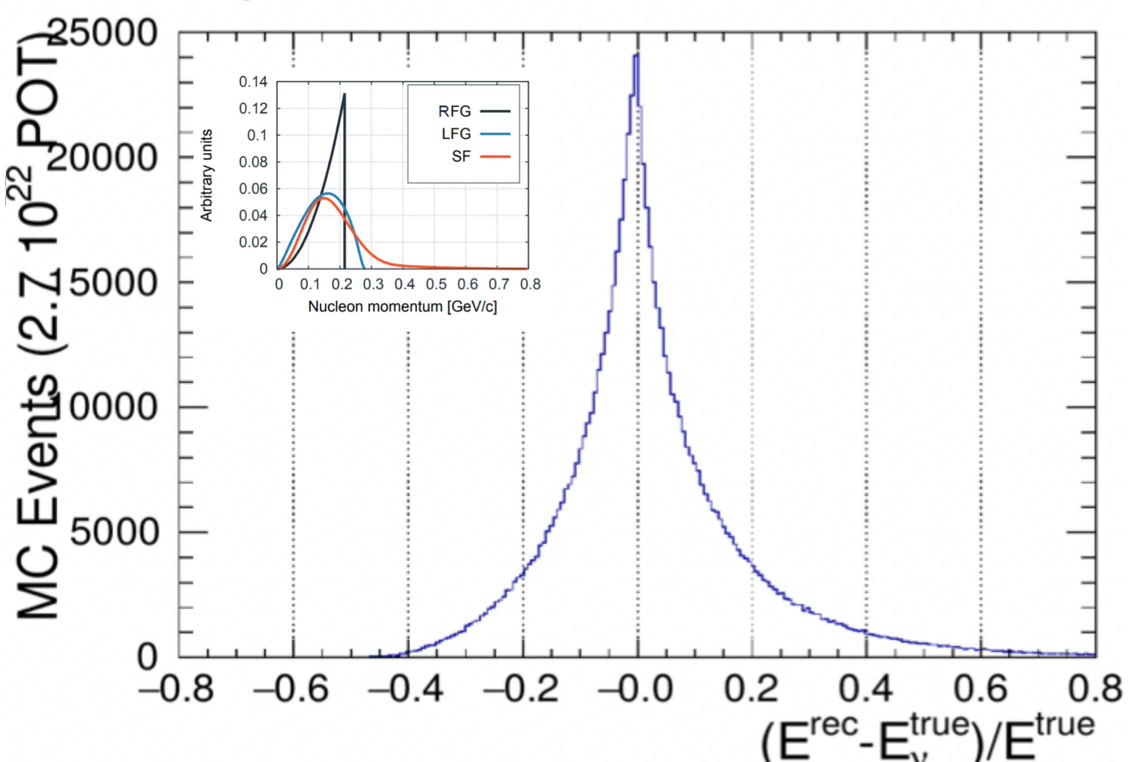

Interactions with a single nucleon

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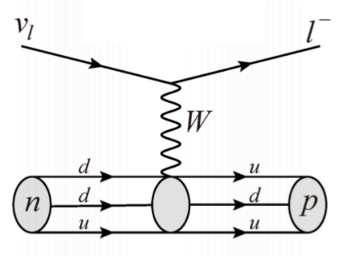

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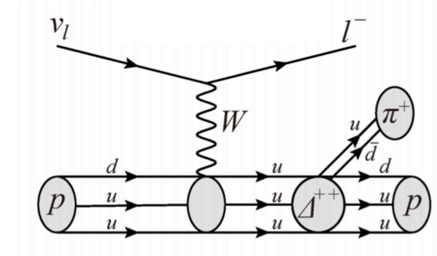
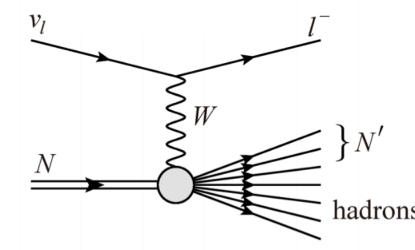
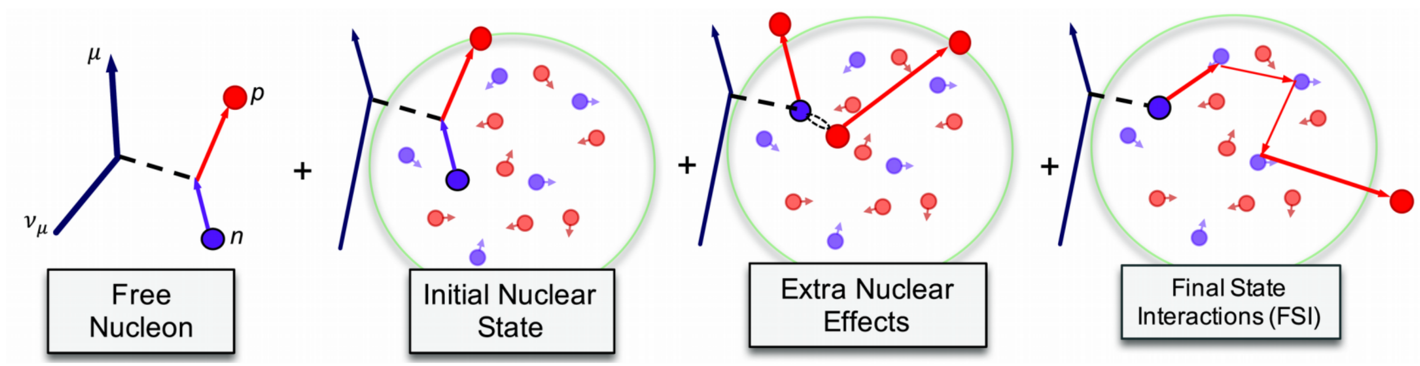


CC-DIS



Multi-nucleon effects



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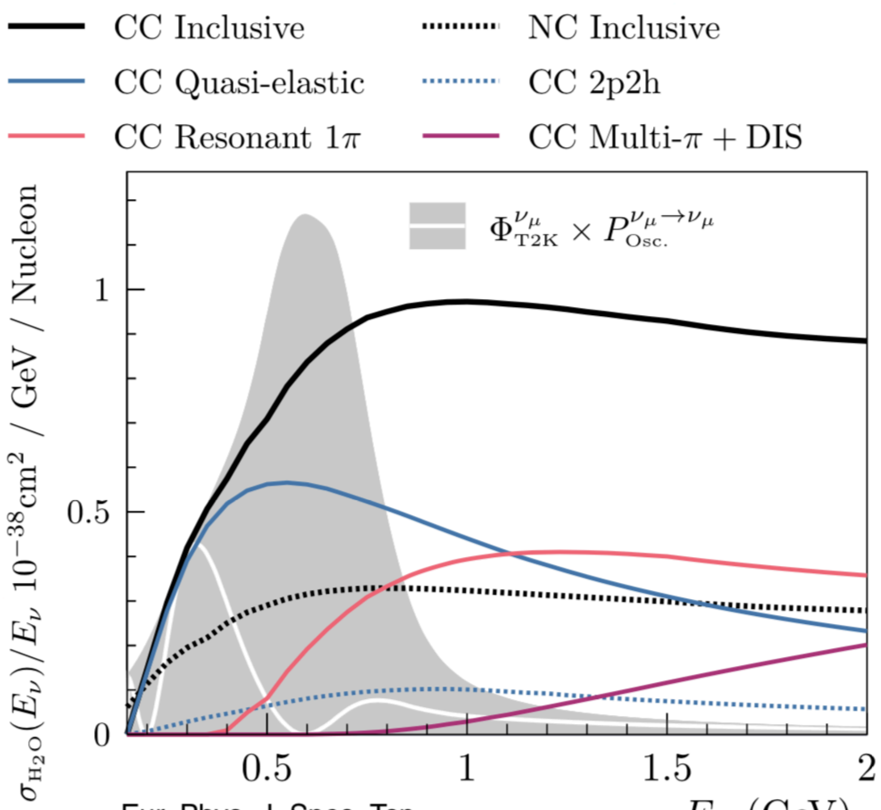
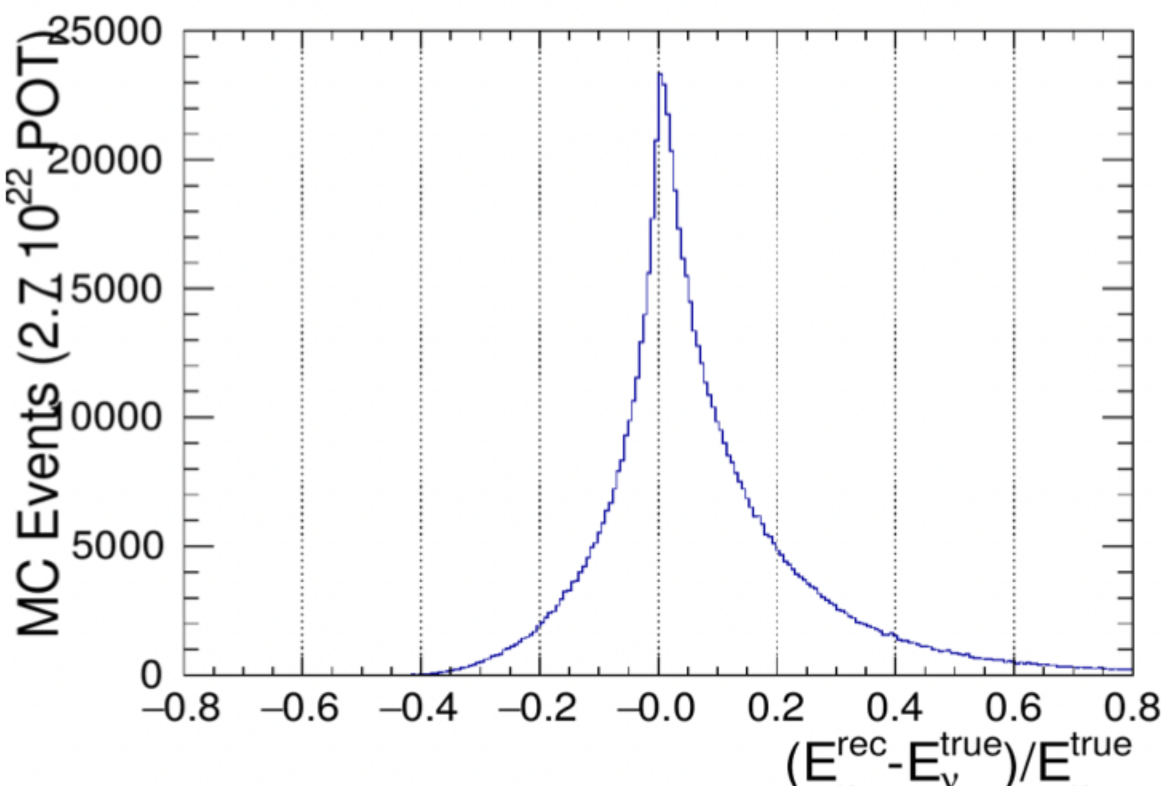
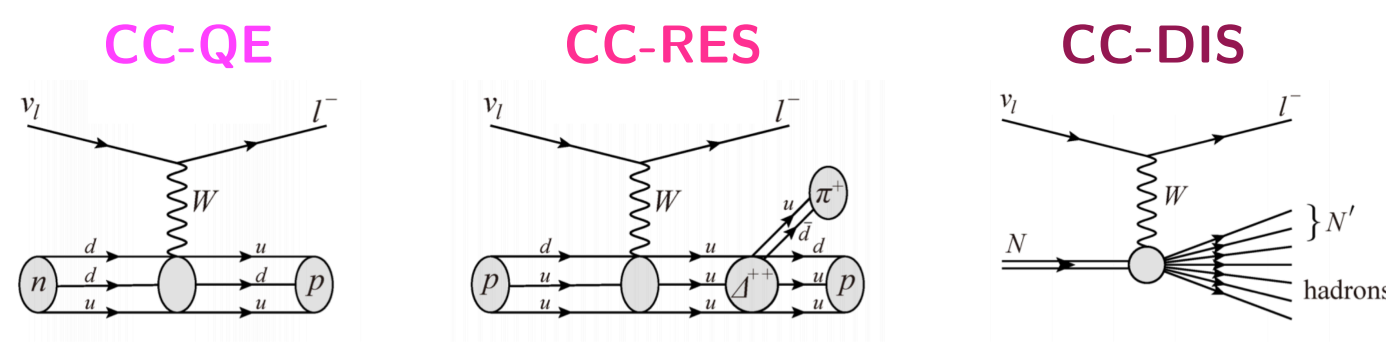


Eur. Phys. J. Spec. Top. (2021) 230:4469–4481



Interactions with a single nucleon



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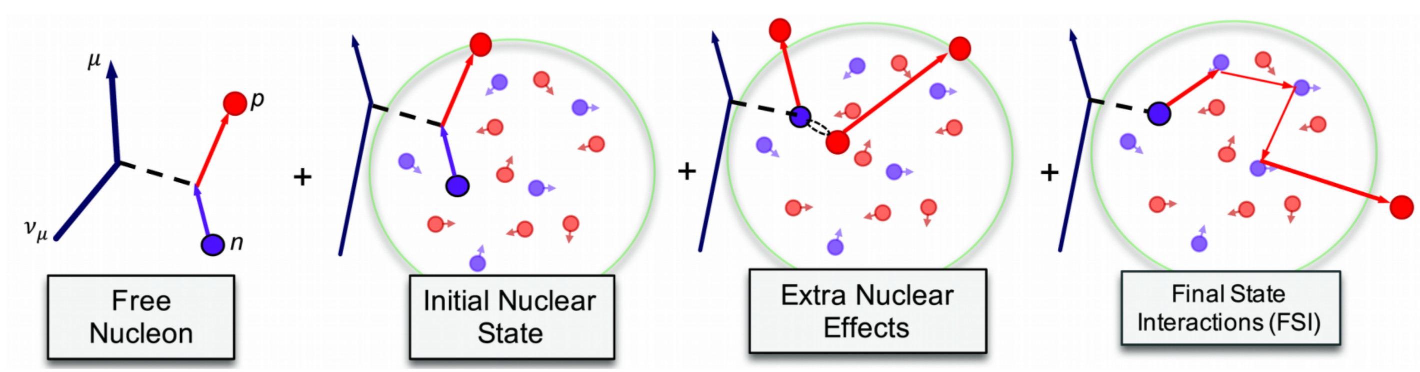

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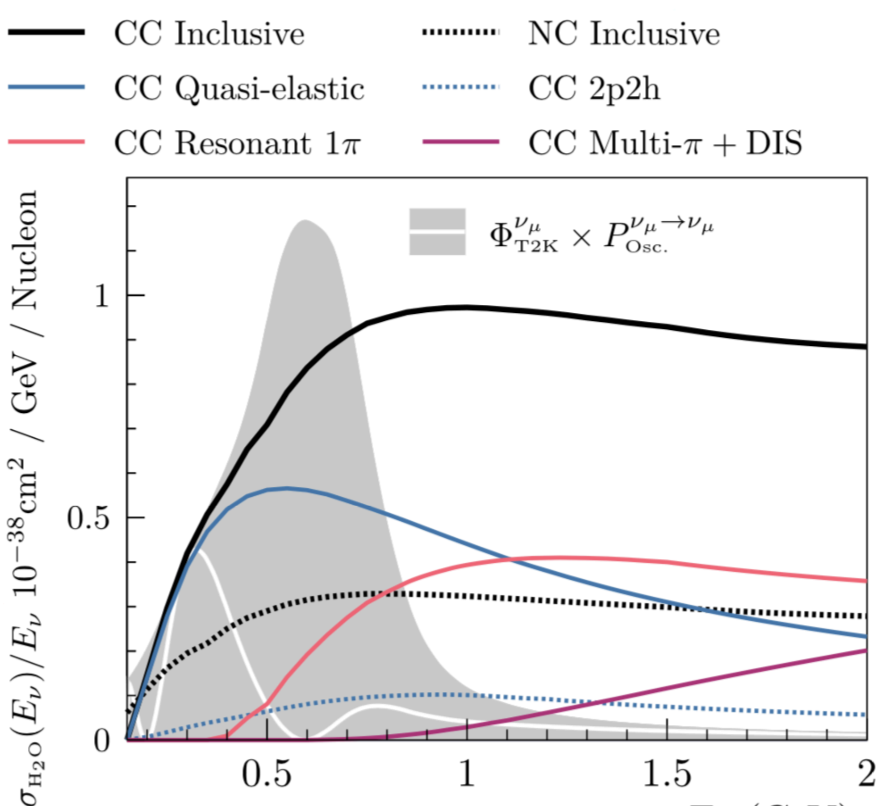

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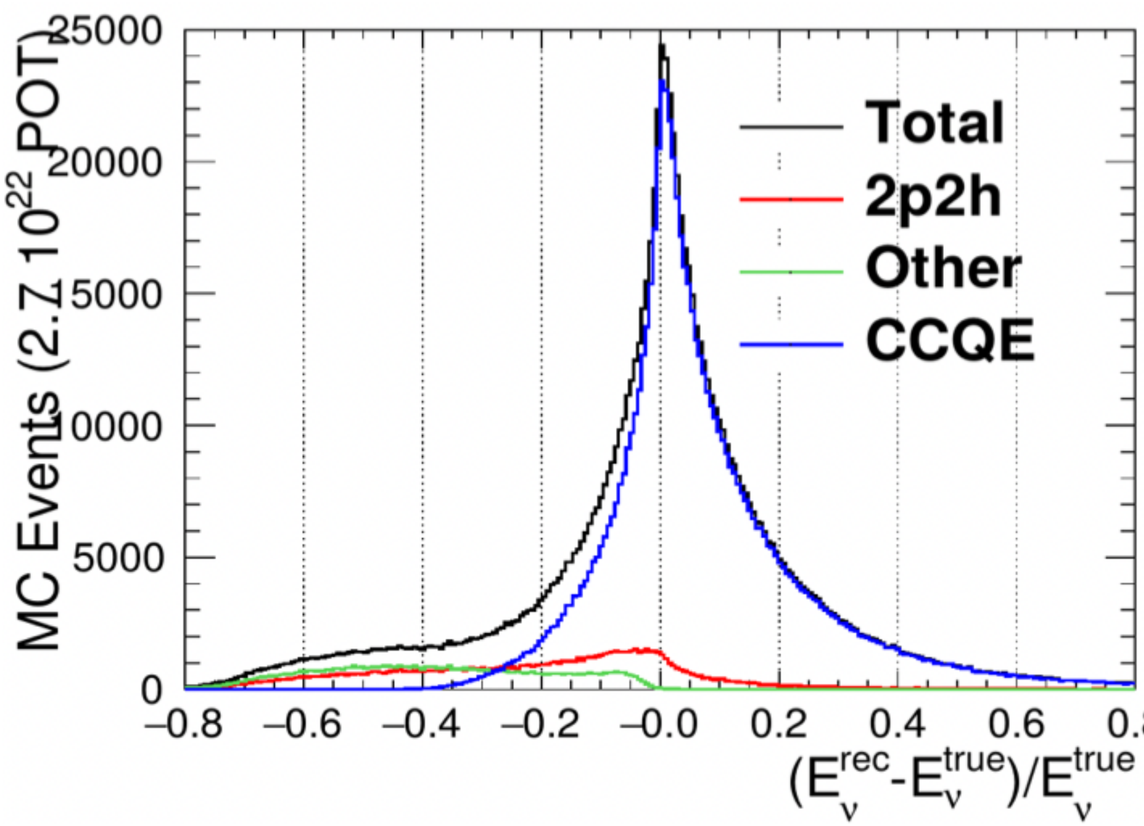
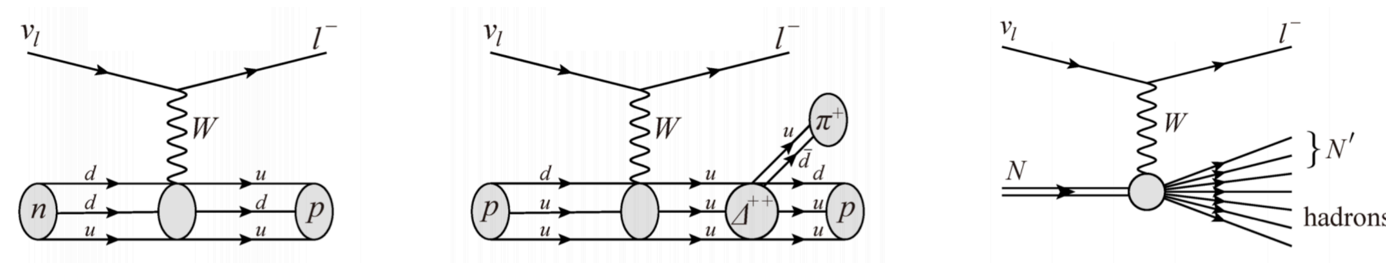
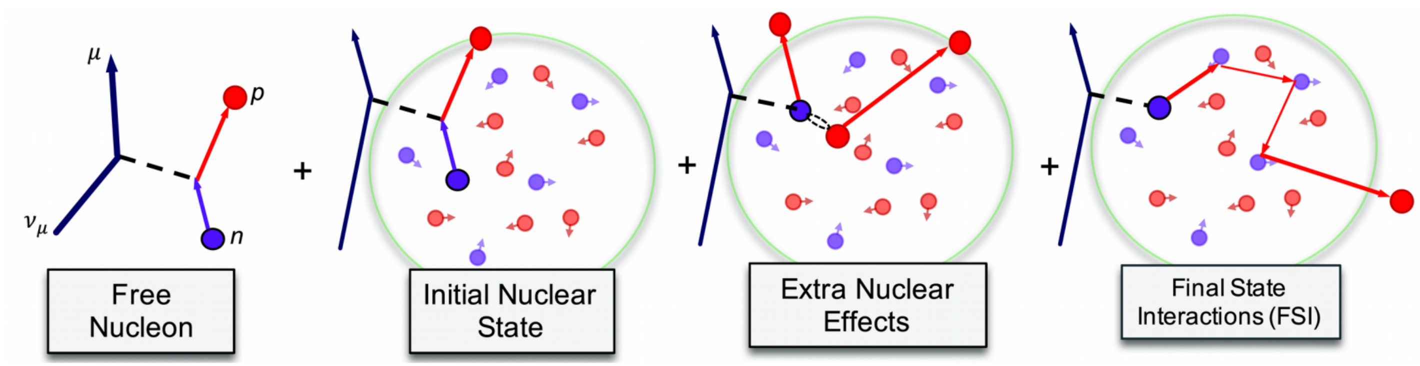


Interactions with a single nucleon

CC-QE CC-RES CC-DIS



Multi-nucleon effects



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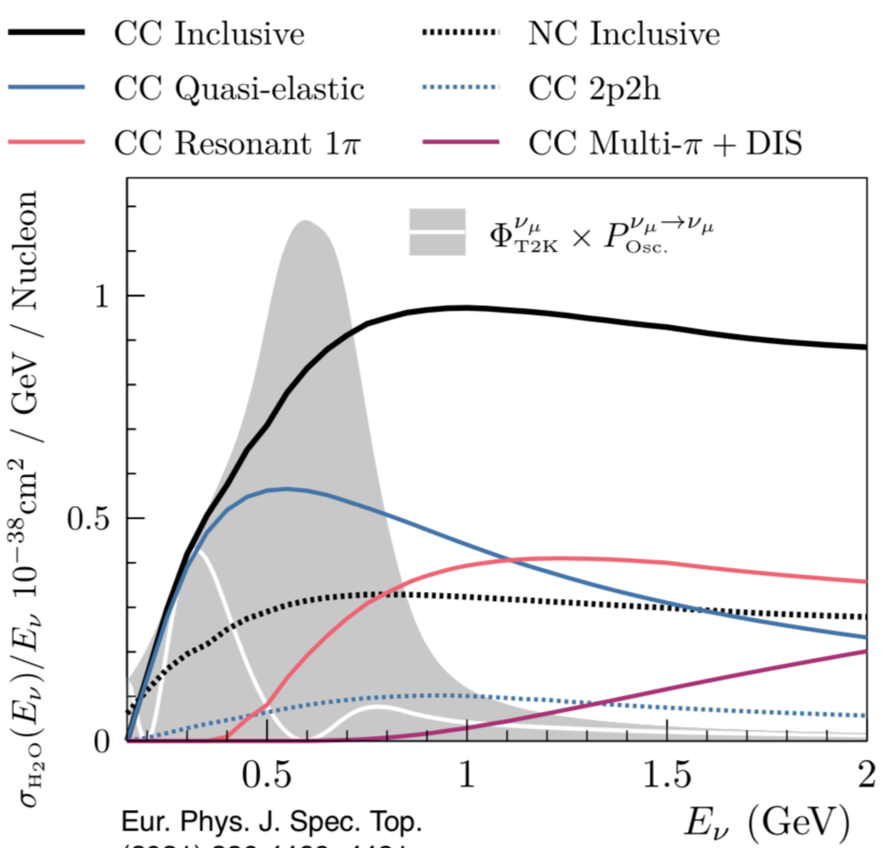

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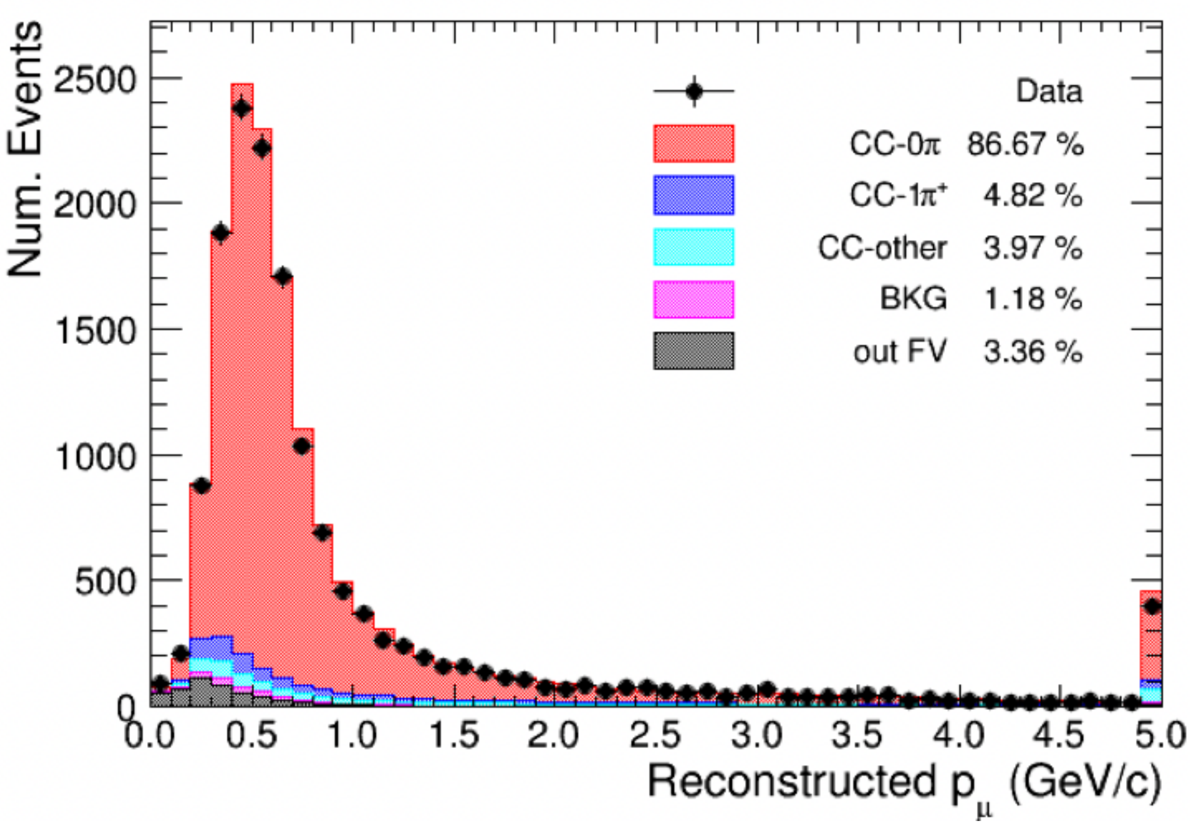

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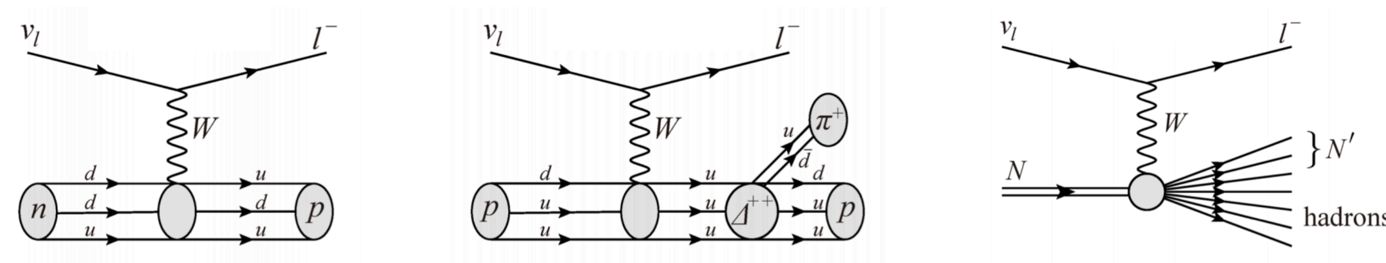

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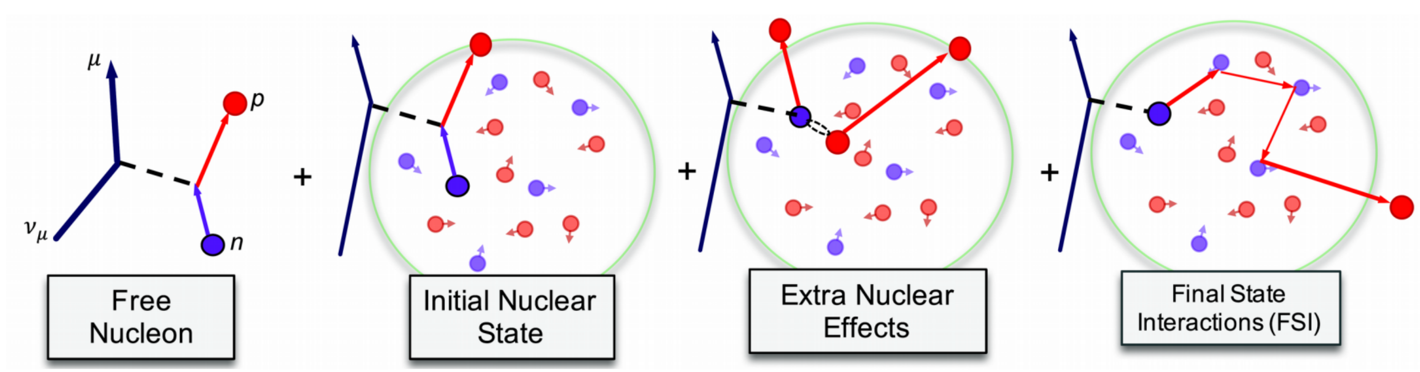
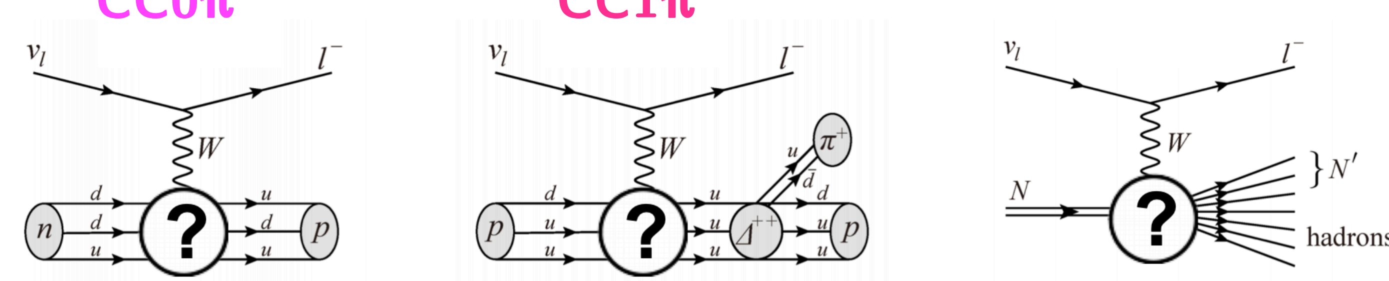


Interaction Topologies

CC0π CC1π CC-Other



Massive effort in T2K

KAVLI IPMU

T2K cross-section publications (>20 articles in ≈ 10 years)

6 ν_μ or $\bar{\nu}_\mu$ CC inclusive

- PRD arXiv: 1302.4908
- PRD arXiv: 1801.05148
- PTEP arXiv: 1904.09611
- PRD arXiv: 1407.4256
- PRD arXiv: 1509.06940
- PRD arXiv: 1706.04257

3 ν_e or $\bar{\nu}_e$ CC inclusive

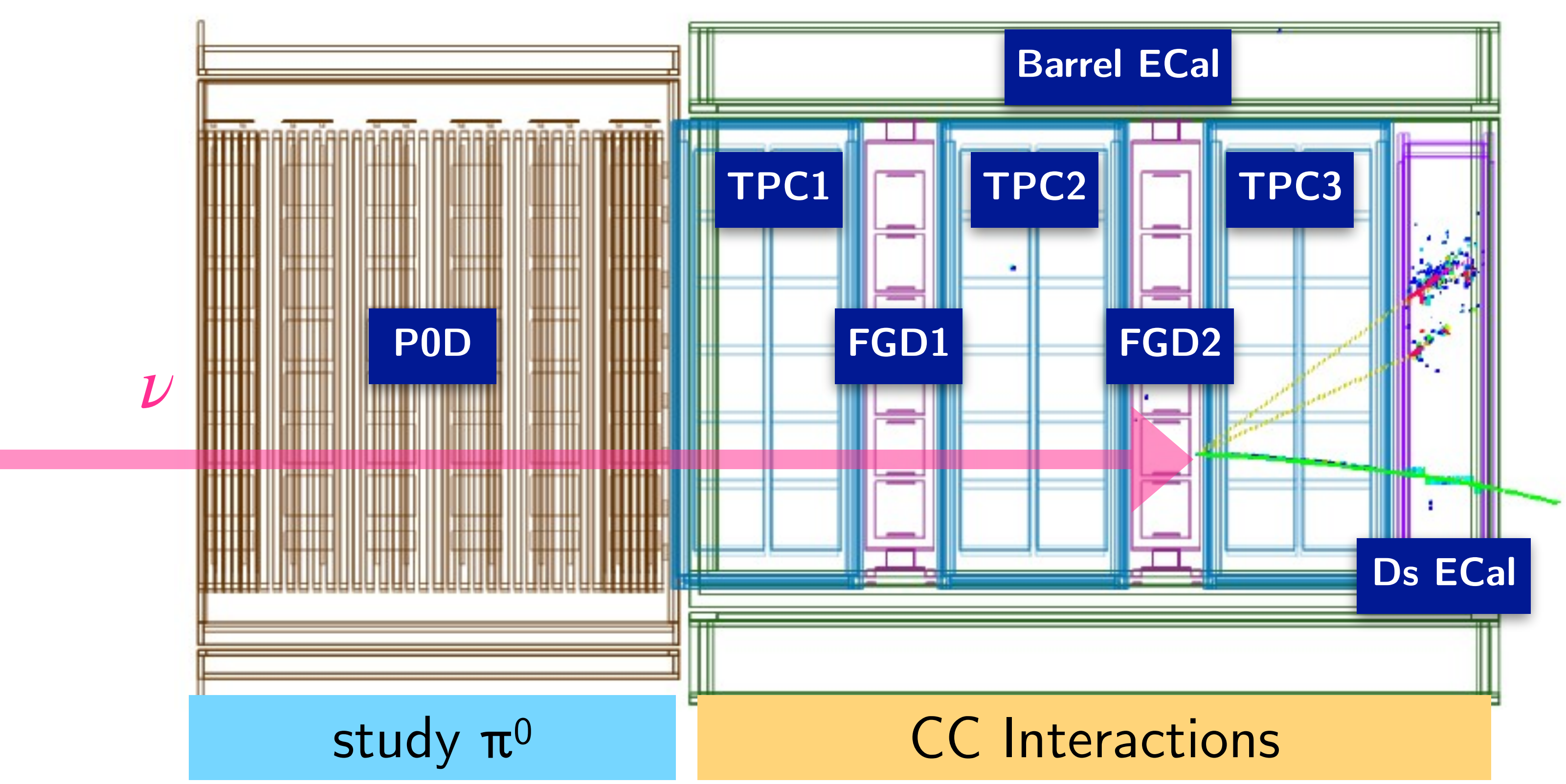
- PRL arXiv: 1407.7389
- PRD arXiv: 1503 .08815
- JHEP arXiv: 2002.11986

12 ν_μ or $\bar{\nu}_\mu$ CC0π

- PRD arXiv: 1602.03652
- PRD arXiv: 1708 . 06771
- PRD arXiv: 1908.10249
- PRD arXiv: 2002.09323
- PRD arXiv: 2004.05434
- PRD arXiv: 1503.07452
- PRD arXiv: 1411.6264
- PRD arXiv: 1403.3140
- PRD arXiv: 1910.09439
- PRD arXiv: 1802.05078
- PRD arXiv: 2102.03346
- PTEP arXiv: 2004.13989

4 ν_μ or $\bar{\nu}_\mu$ CC1π

- PRD arXiv: 1605.07964
- PRL arXiv: 1604.04406
- PRD arXiv: 1909.03936
- PRD arXiv: 1704.07467



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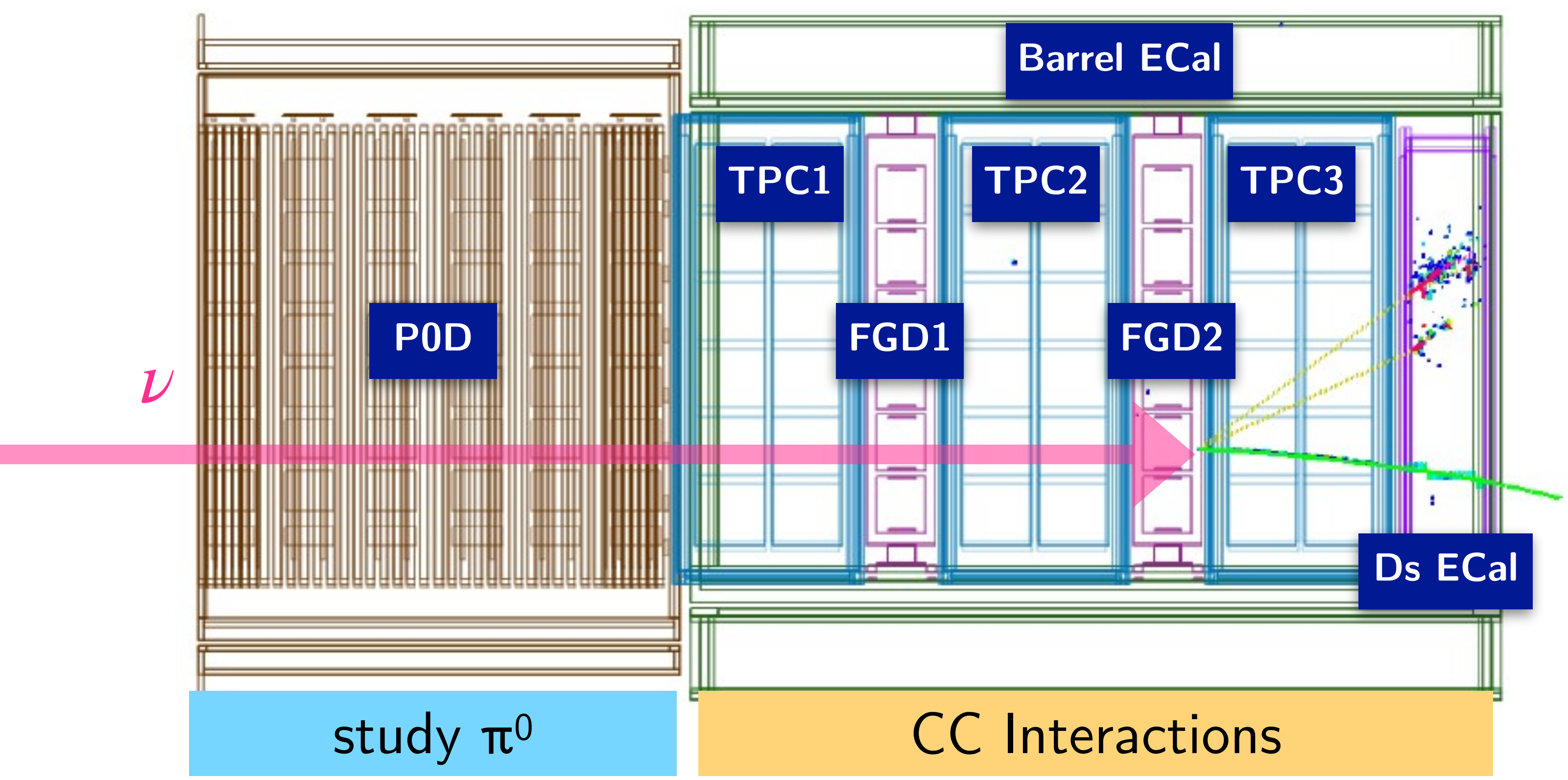


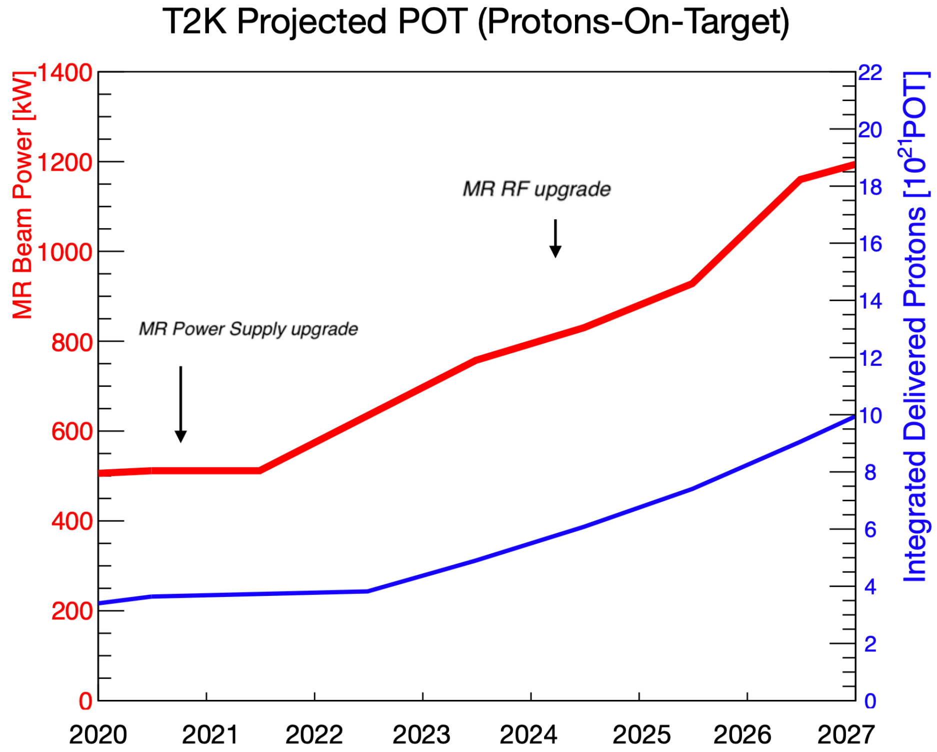
My work:

1 ν_μ **NC1π$^+$, first cross-section measurement in history.**

In preparation.

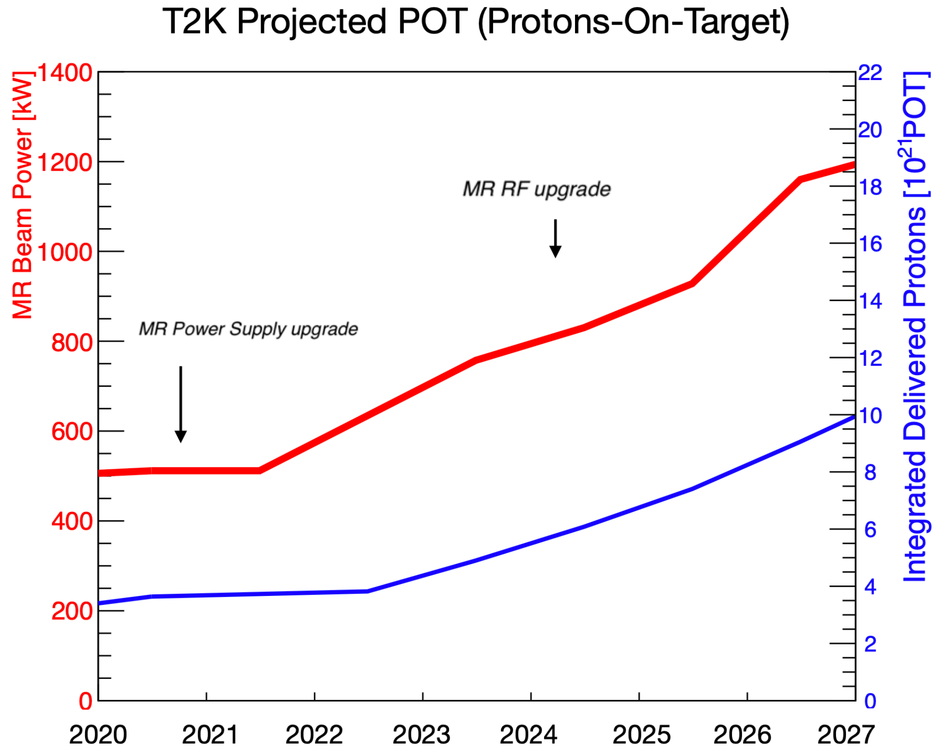
The future of T2K

Beam upgrade: TDR (2019): e-Print: 1908.05141

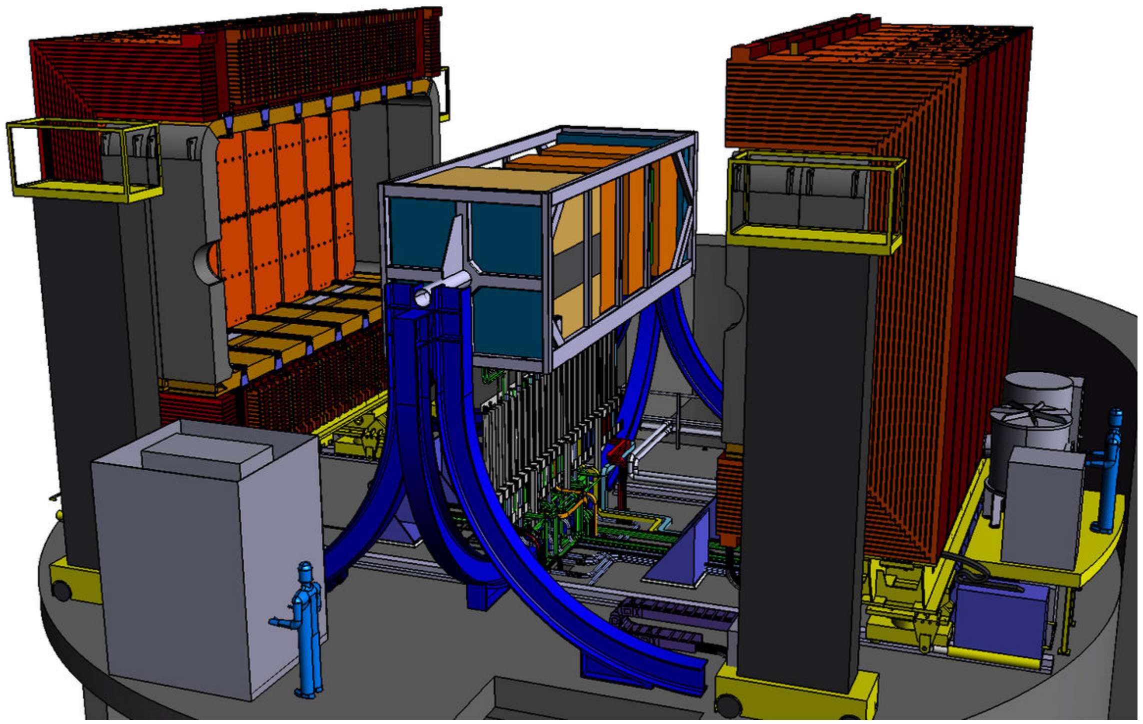


The future of T2K

Beam upgrade: TDR (2019): e-Print: 1908.05141

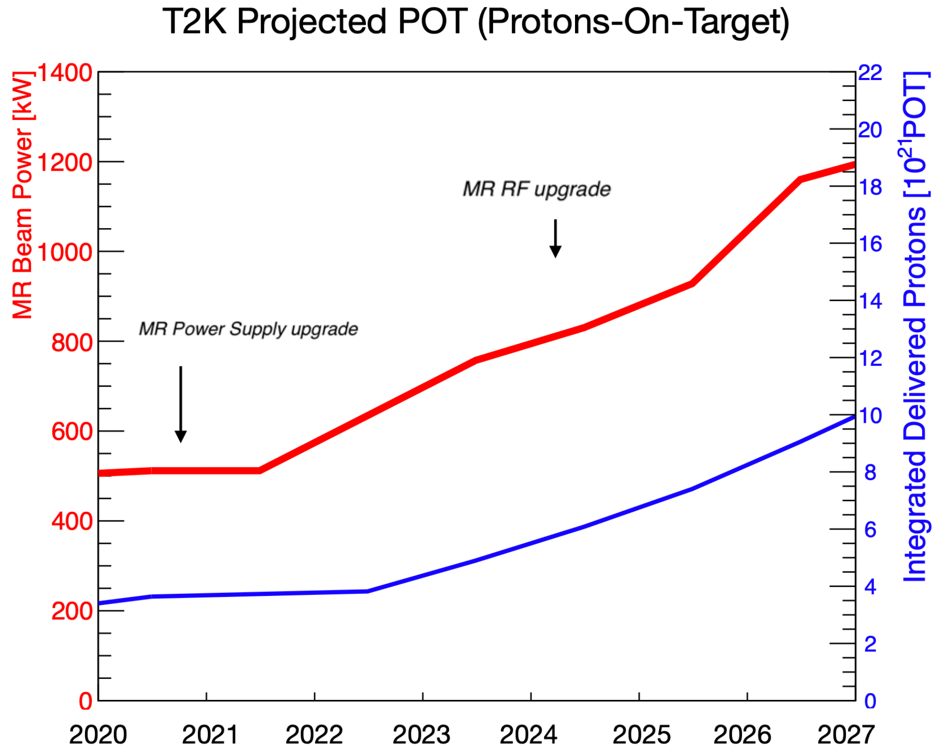


ND280 upgrade: TDR (2019): e-Print: 1901.03750



The future of T2K

Beam upgrade: TDR (2019): e-Print: 1908.05141



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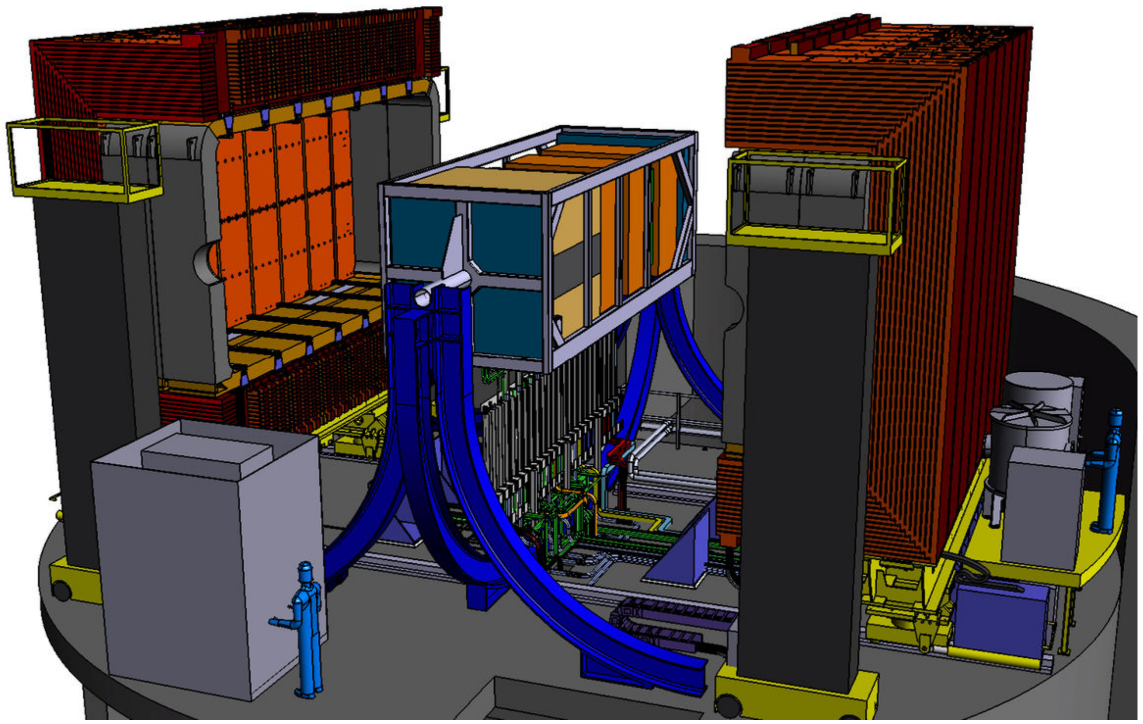


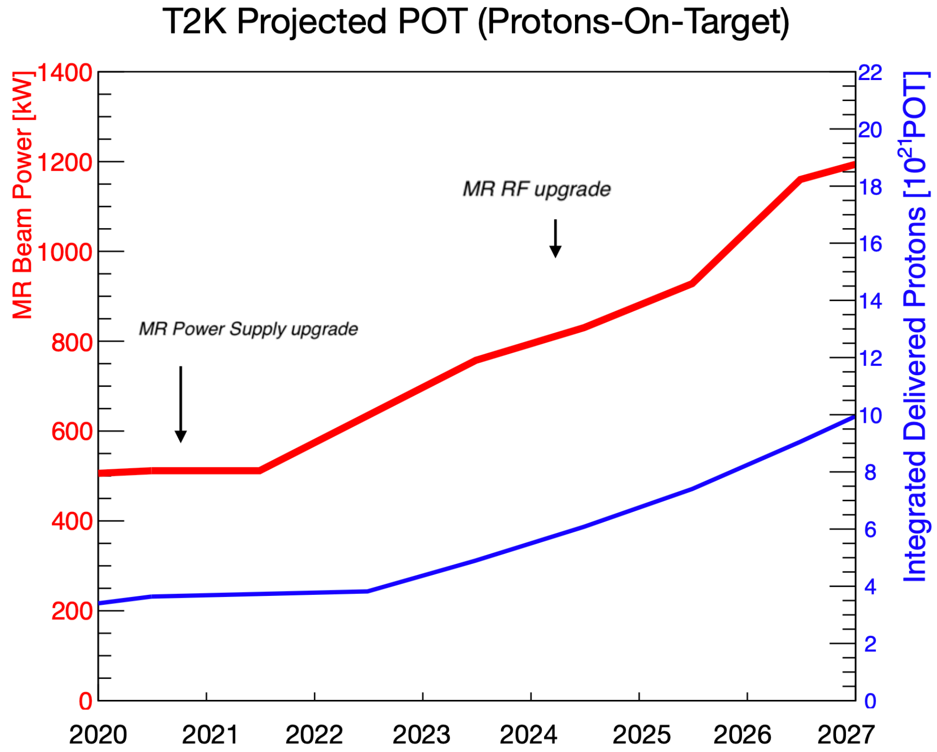
My work:

- ➤ Develop software & hardware to make possible this upgrade.
- ➤ Large project with >100 collaborators.
- ➤ First data taking in 2023.

The future of T2K

Beam upgrade: TDR (2019):

e-Print: 1908.05141



ND280 upgrade: TDR (2019):

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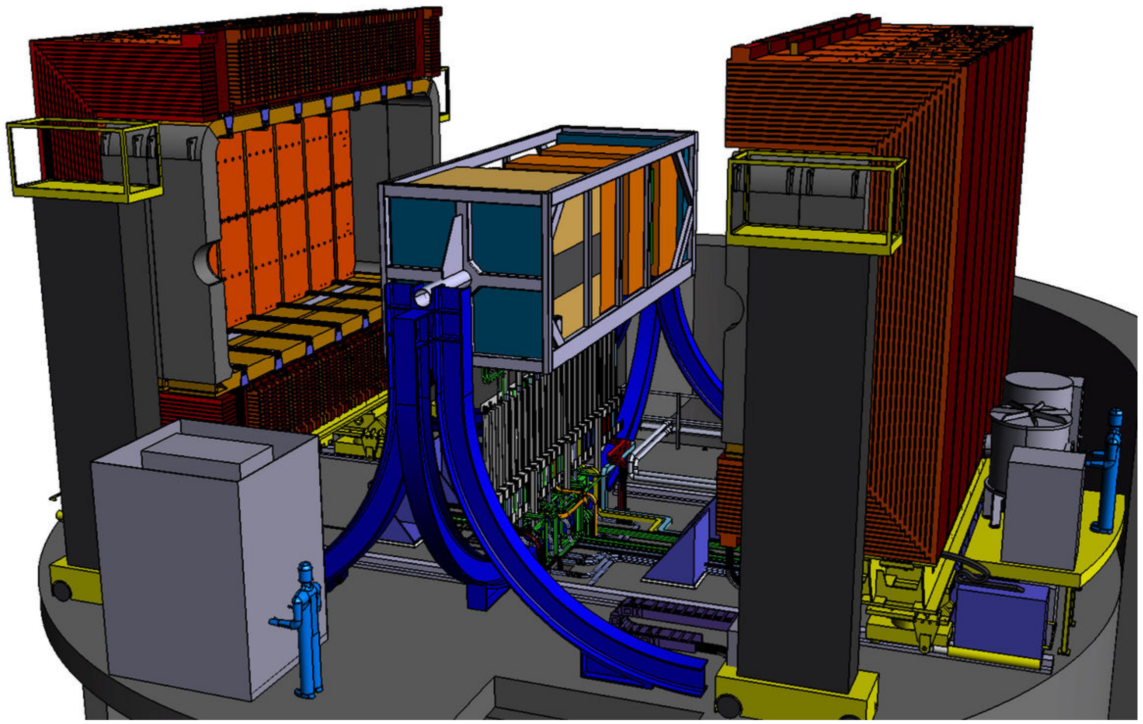
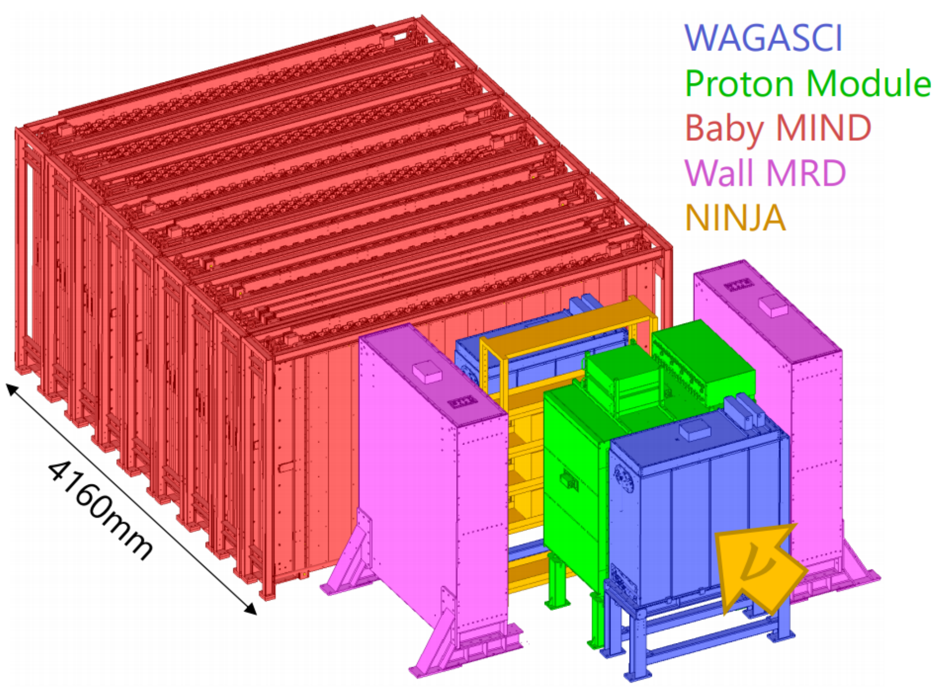


New 1.5° off-axis: First Physics Run 2019



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The future of T2K

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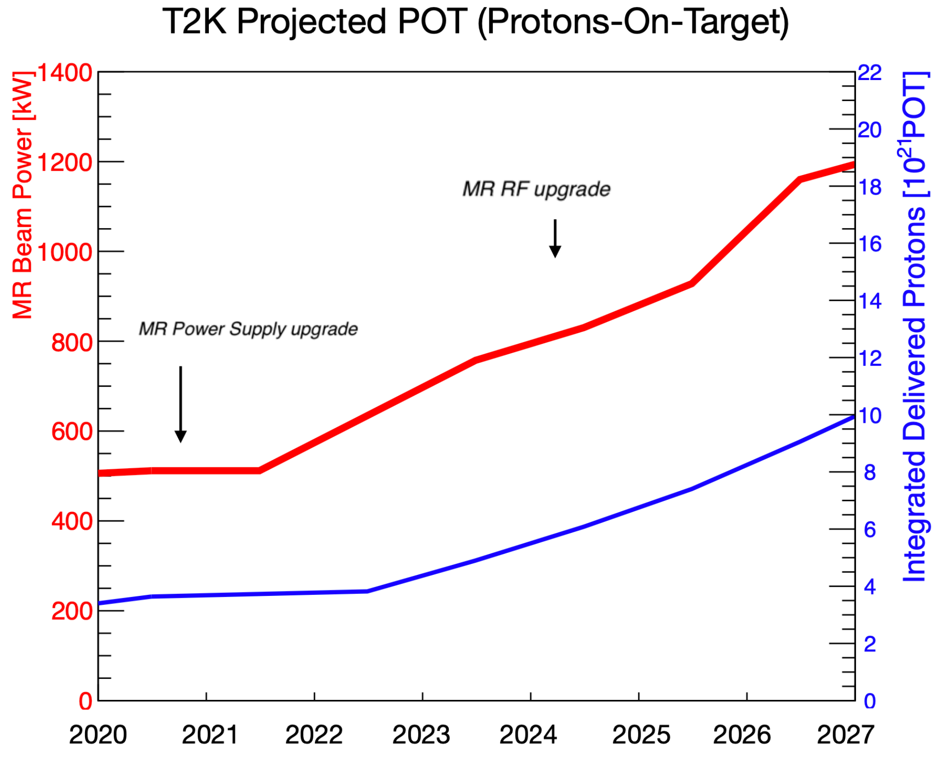
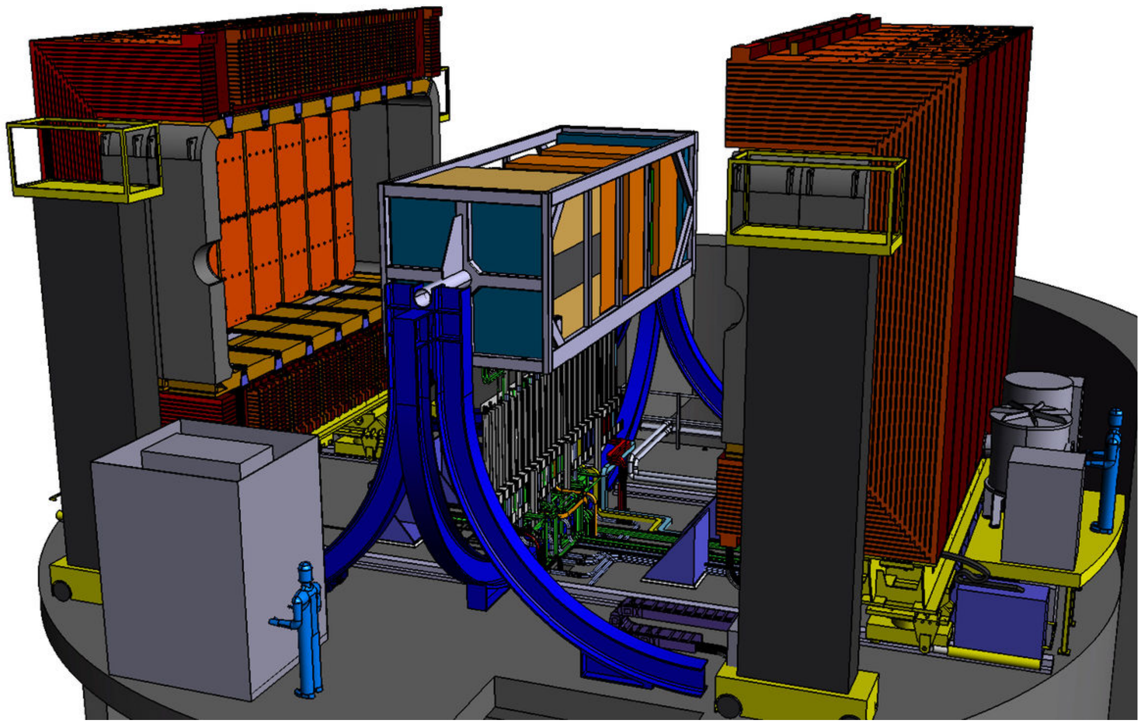


ND280 upgrade: TDR (2019): e-Print: 1901.03750



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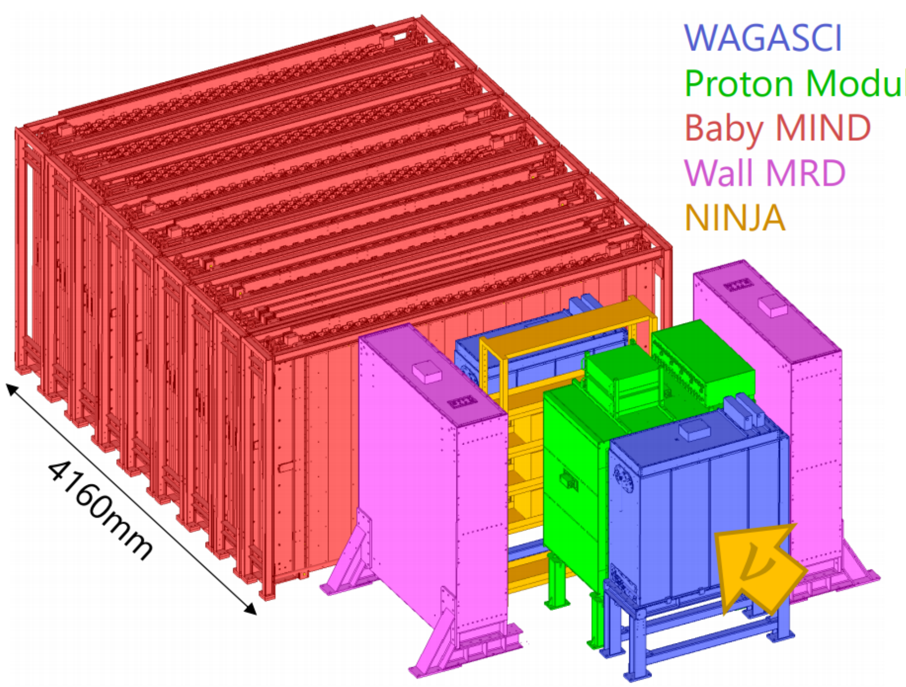
- First data taking in 2023.

New 1.5° off-axis: First Physics Run 2019

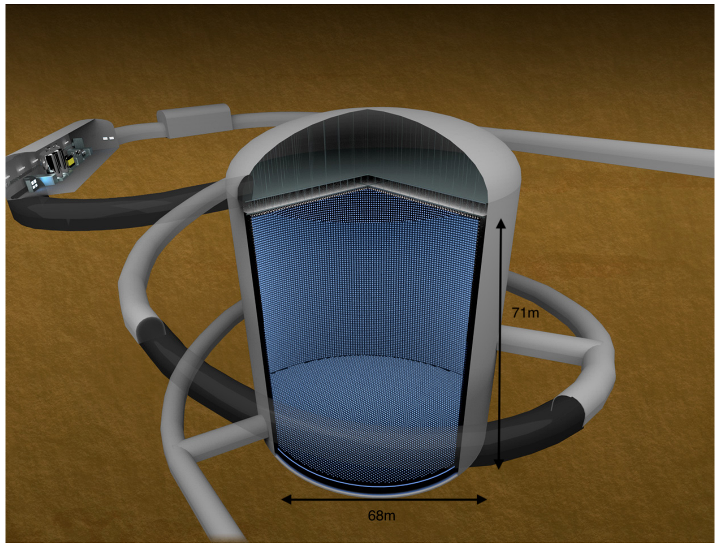


My work:

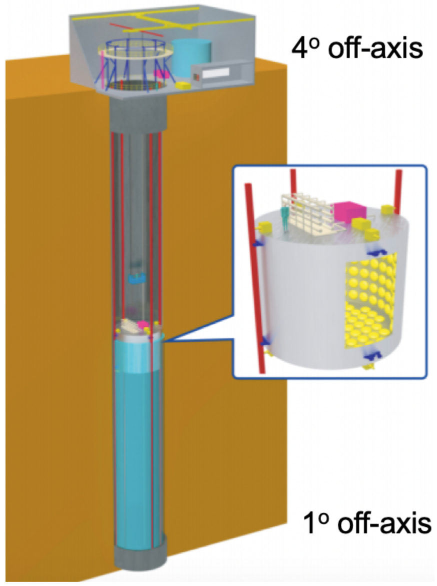
- Integration of W-BM detector in multi ND T2K oscillation analysis.
- Understanding what is needed for HK NDs.

Hyper Kamiokande (accelerator program)

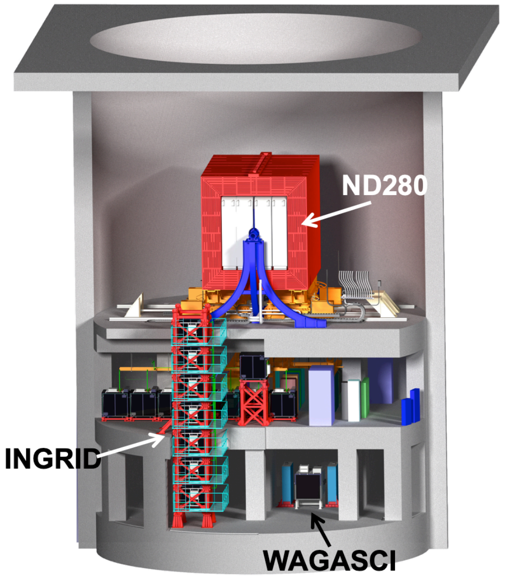
Hyper-Kamiokande 295km
SK $\times 9$



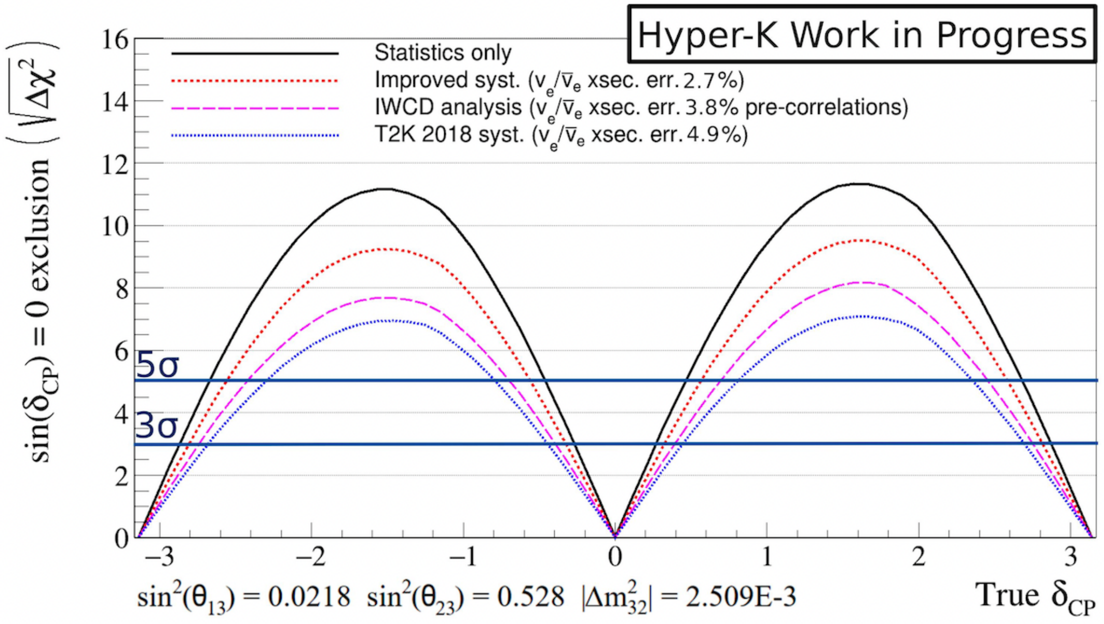
IWCD $\sim$1 km



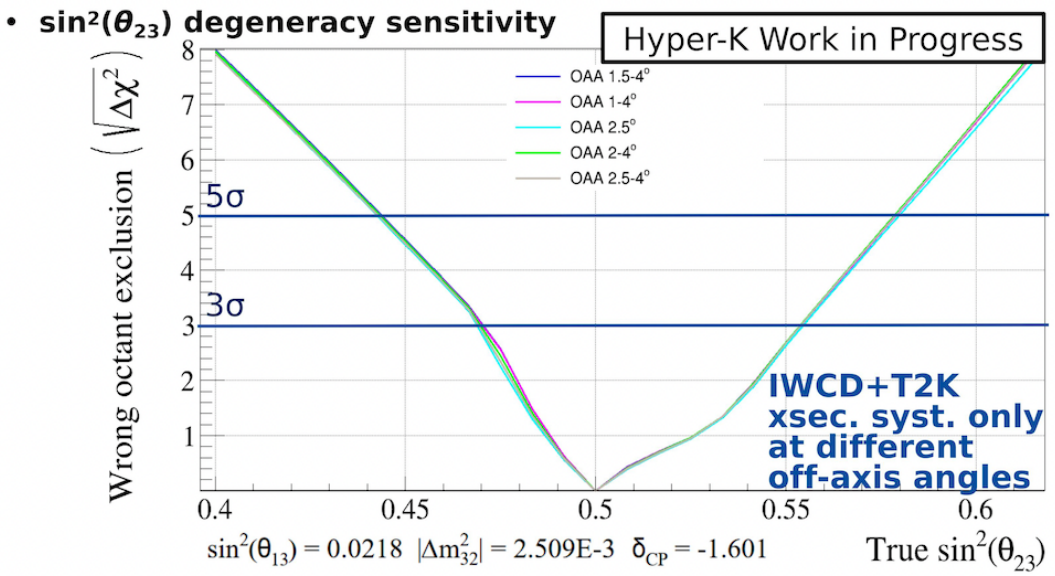
NDs @280



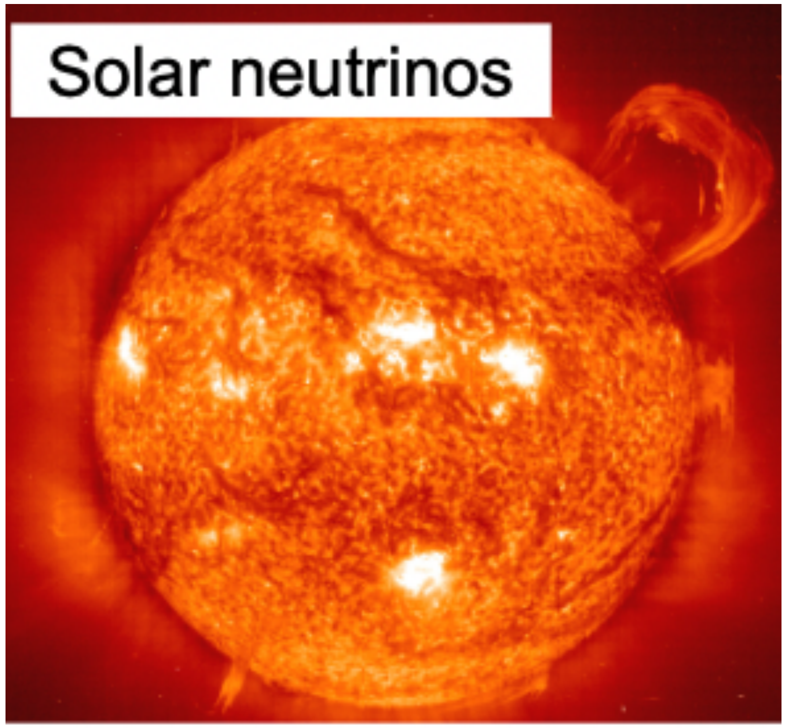
Chasing δ_{CP}



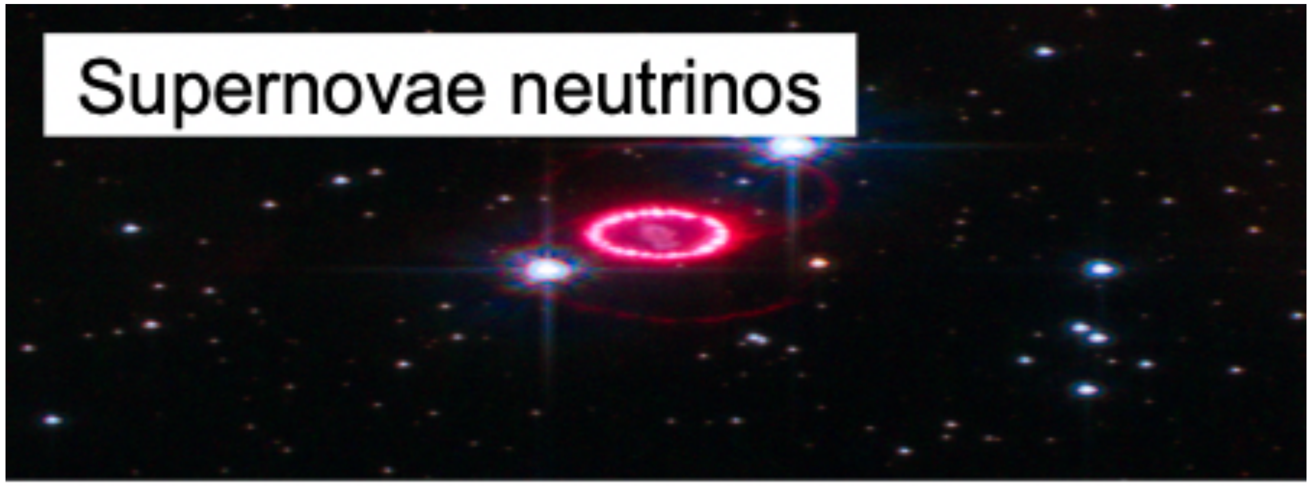
Chasing θ_{23}



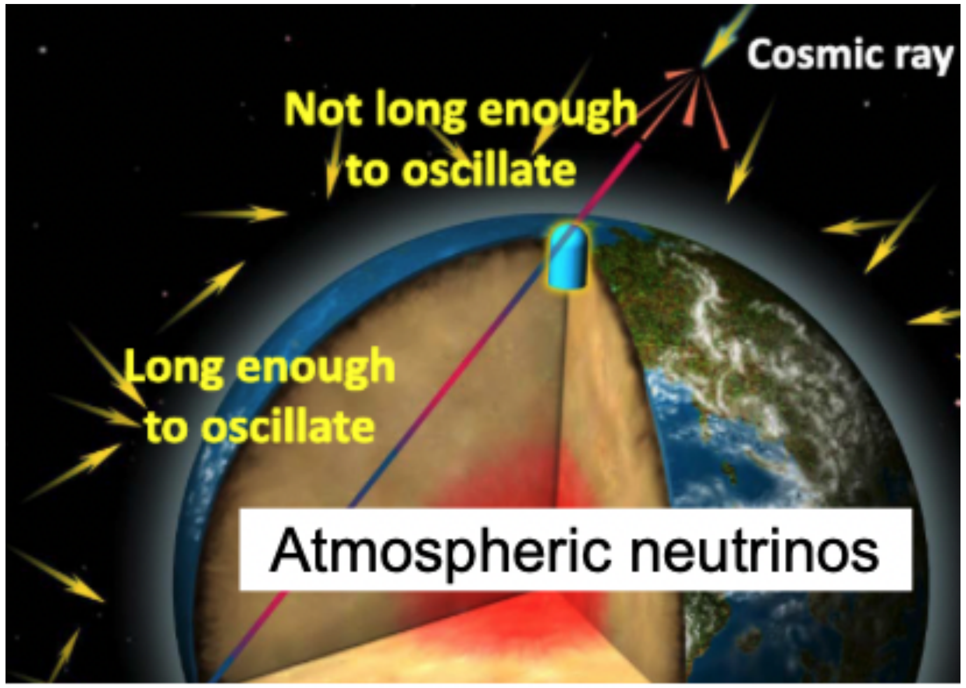
Hyper Kamiokande (much more!)



Survival probability up-turn
Solar/reactor tension
hep neutrinos

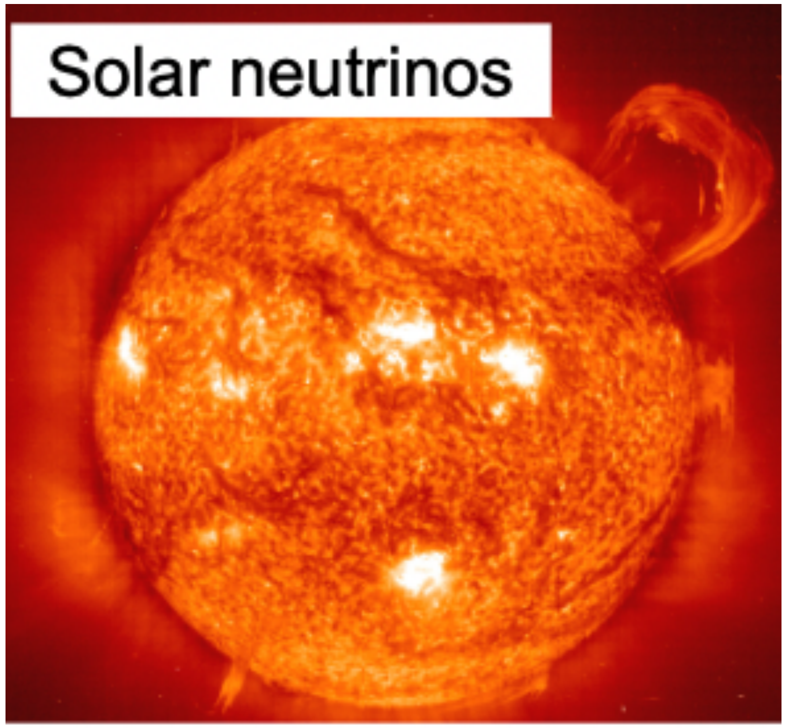


Core-collapse SNv: constrain SN profile models
Diffuse SuperNova v background



Oscillation affected by matter effects
Sensitive to MO

Hyper Kamiokande (much more!)



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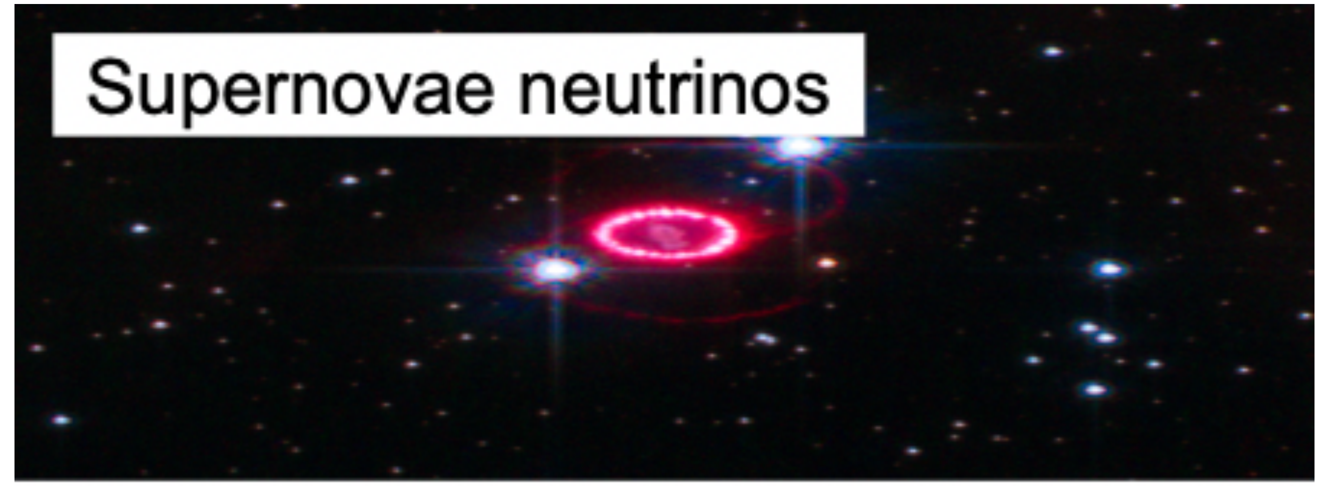
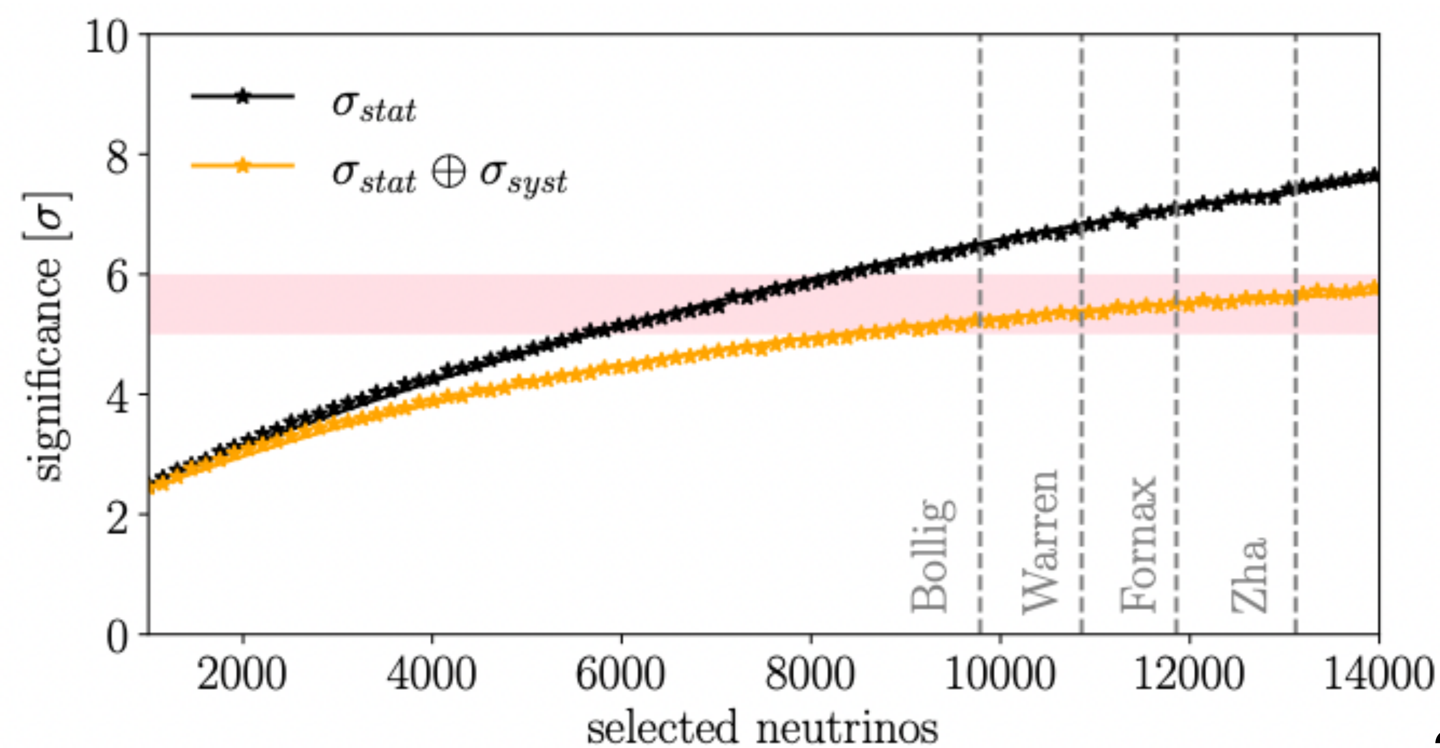
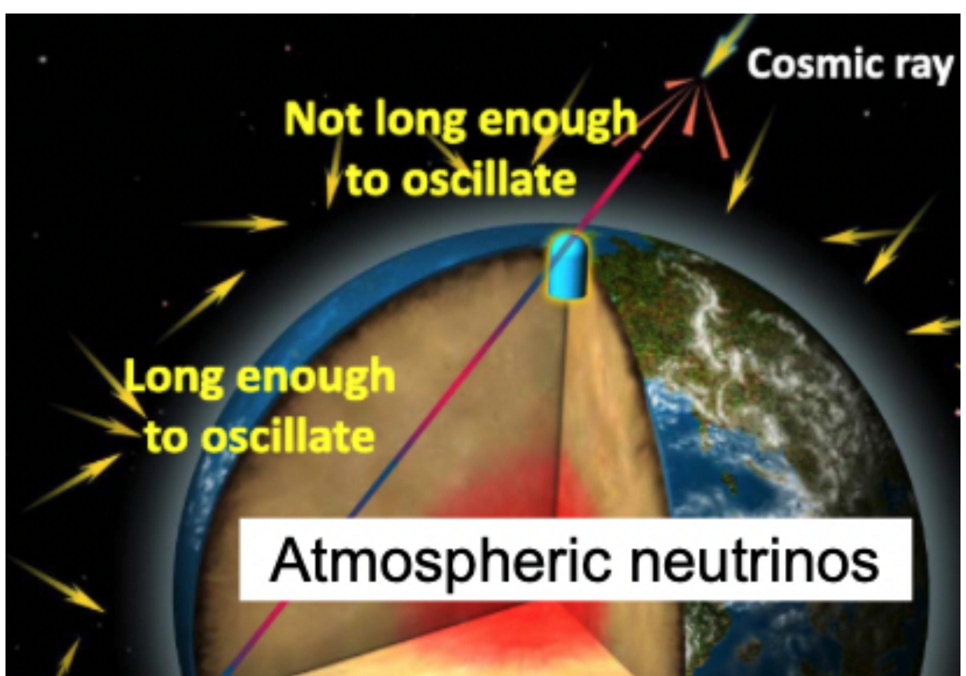


Core-collapse SNv: constrain SN profile models
Diffuse SuperNova v background

My work:

➤ Recently suggested that CCSN could be used to uncover νMO





Oscillation affected by matter effects
Sensitive to MO

Conclusions

- Over 90 years of study of neutrinos: much has been learnt, much still to be discovered.

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Start of precision neutrino physics

↓

The unknown, awaiting for us to uncover it!