Introduction to Experimental Neutrino Physics with Accelerators

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ELFT Particle Physics Summer School @ Mátrafüred Hotel Akadémia

Caveat

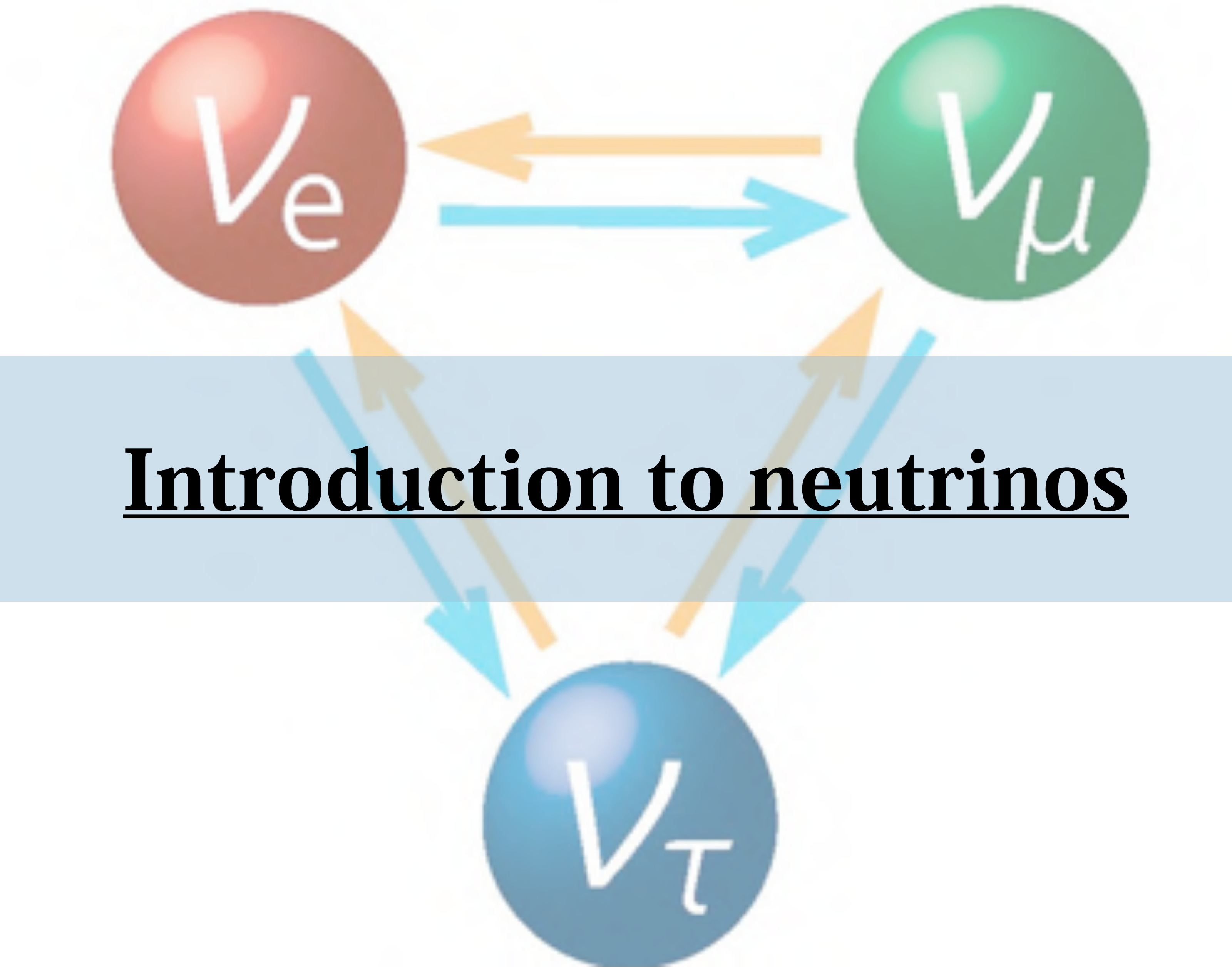
This lecture aims to deliver an "Introductory" review of experimental neutrino physics with accelerators

- I try to cover broad relevant topics comprehensively
  - We do not have much time to dive into the details of each topic, but I try to insert supplemental reference information on slides
- The selection of topics is biased leaning toward my expertise
  - e.g. more on beam and near detectors, less on far detectors

CONTENTS

- Introduction to neutrinos
- Accelerator-based neutrino experiments
- Producing and understanding neutrino beams
- Detecting neutrinos
- Activities of the experimental neutrino physics group in Hungary
- Wrap-up

Introduction to neutrinos



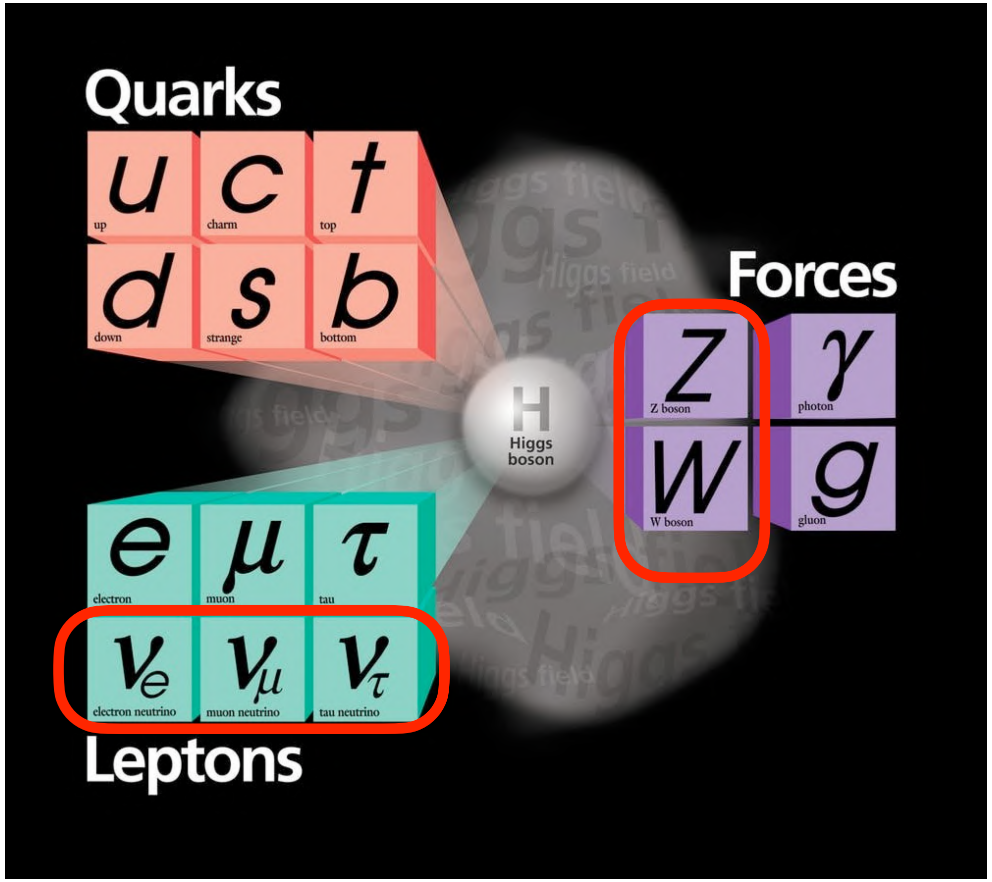
Neutrinos

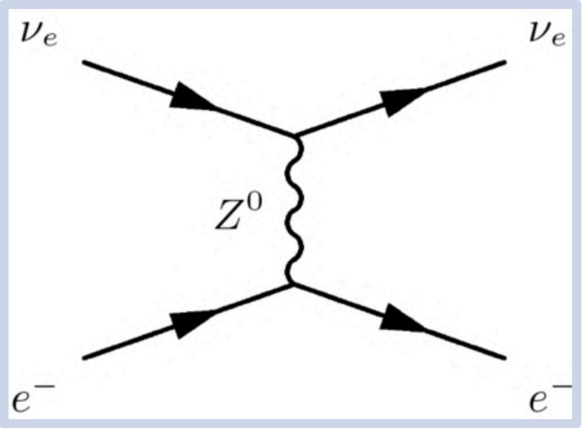
Neutrinos in the Standard Model of particle physics

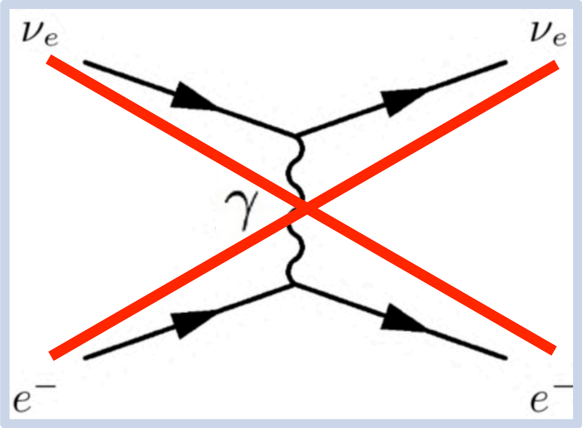
- Neutral cousins of charged leptons
  - Only weak interactions

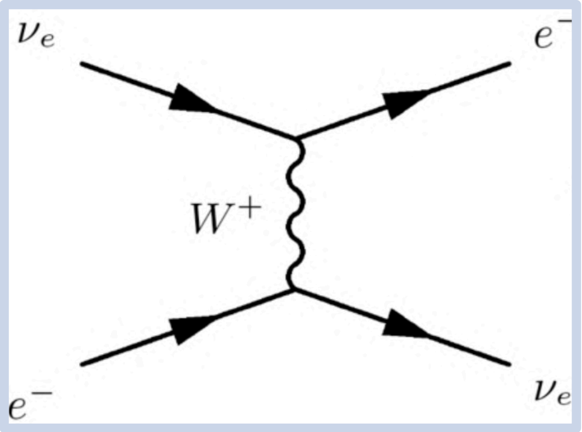
The fact

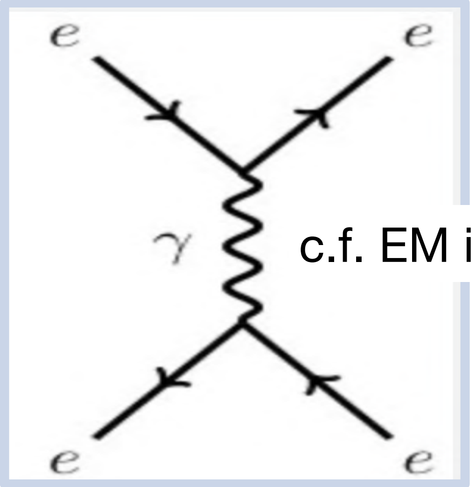
- Three types of neutrinos
  - Very elusive











c.f. EM interaction

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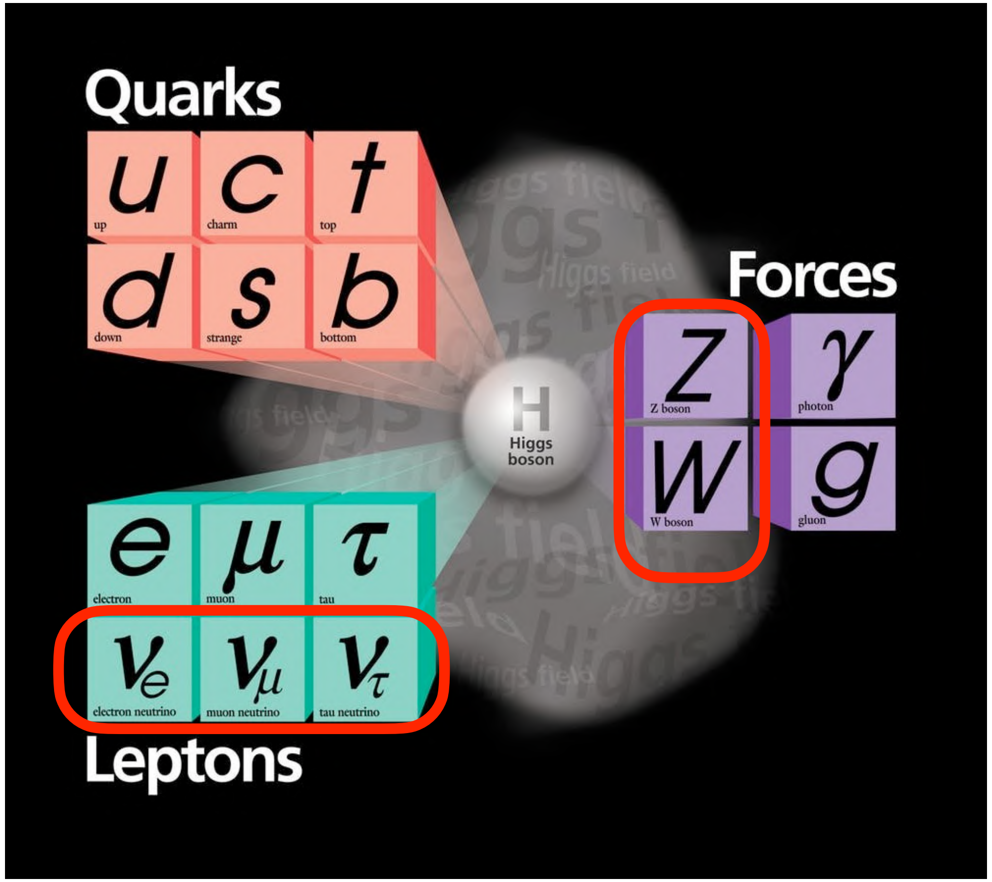
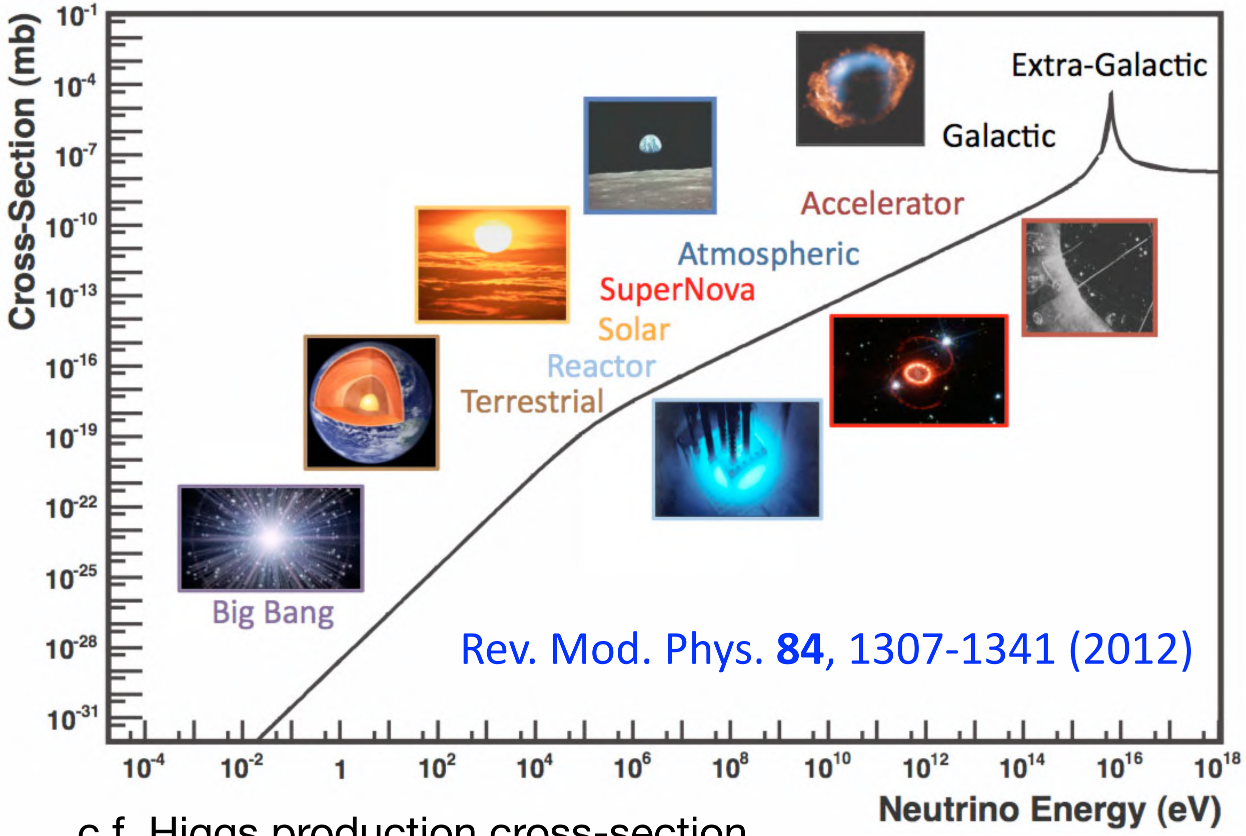


(mb = 10^{-27} cm²)



Rev. Mod. Phys. **84**, 1307-1341 (2012)

c.f. Higgs production cross-section
at 13 TeV LHC: ~50 pb (5×10^{-8} mb)

Neutrinos

Neutrinos in the Standard Model of particle physics

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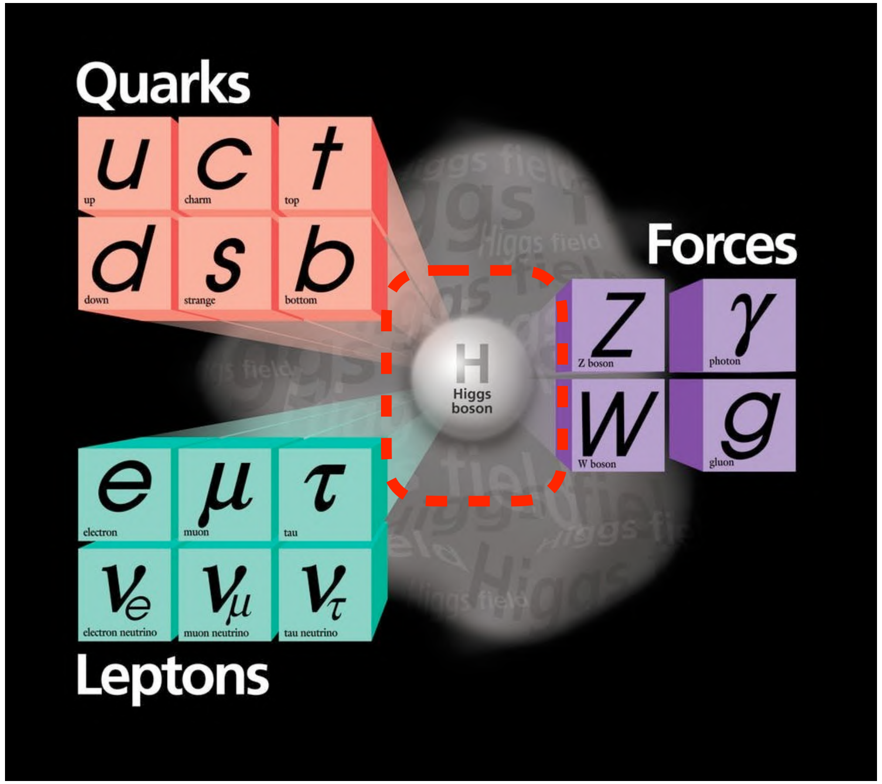
  - Only weak interactions
- Mass is strictly zero $m_\nu \equiv 0$

The fact

- Three types of neutrinos
  - Very elusive
- Non-zero mass



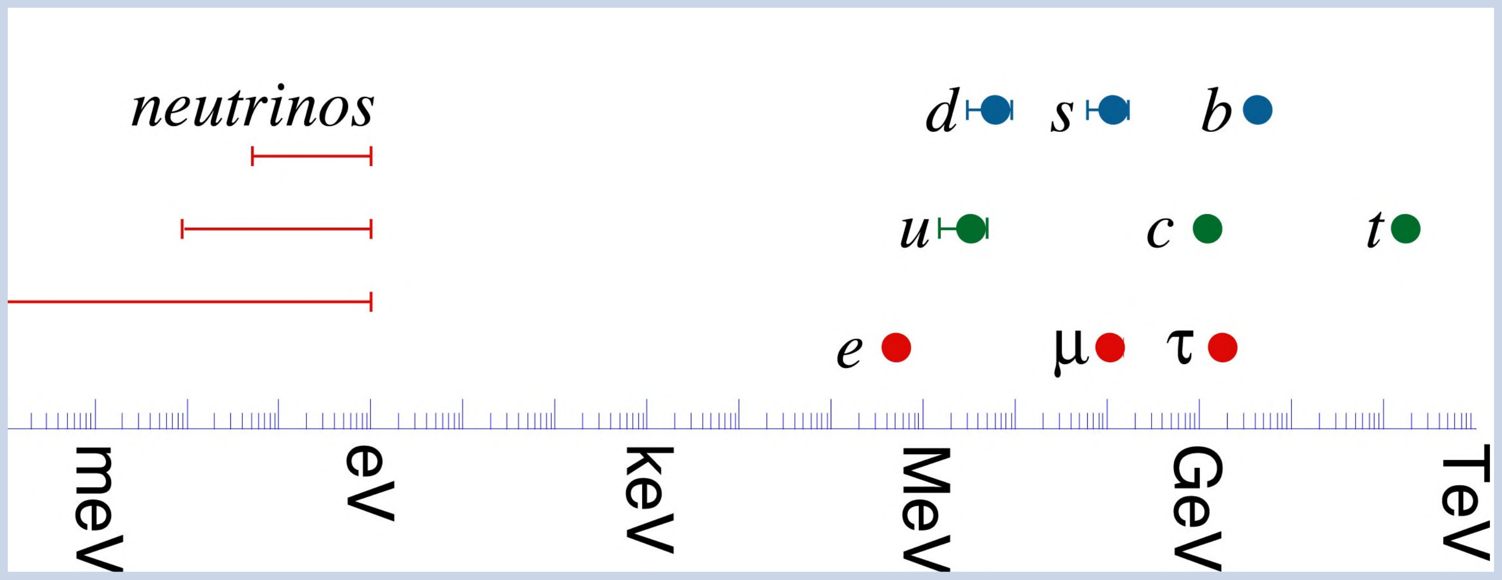


Image credit: Hitoshi Murayama of http://hitoshi.berkeley.edu/

Neutrinos

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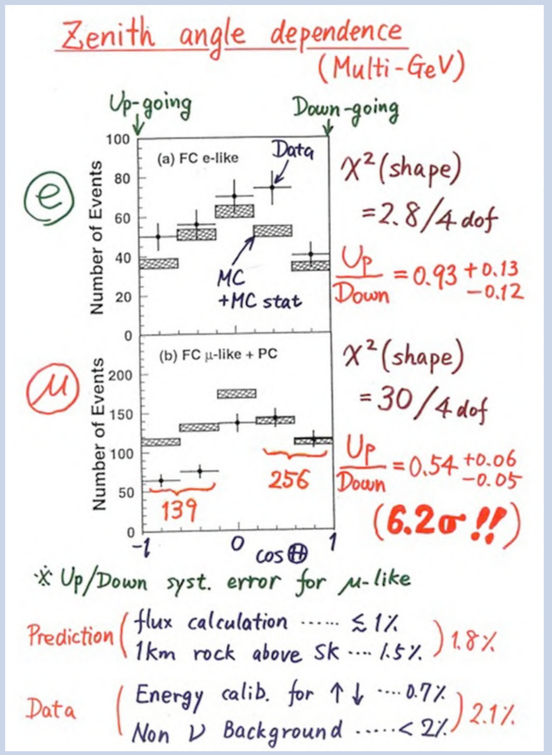
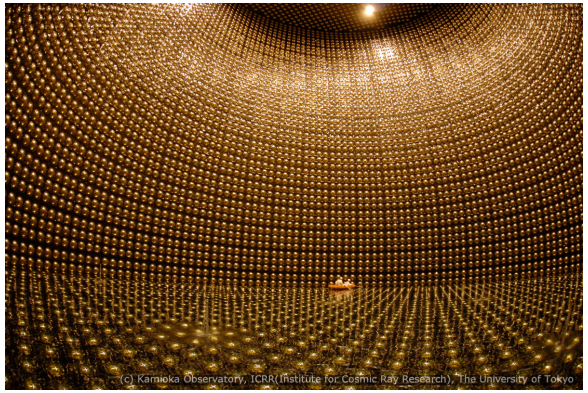
  - Very elusive
- Non-zero mass
  - Discovery of neutrino oscillation

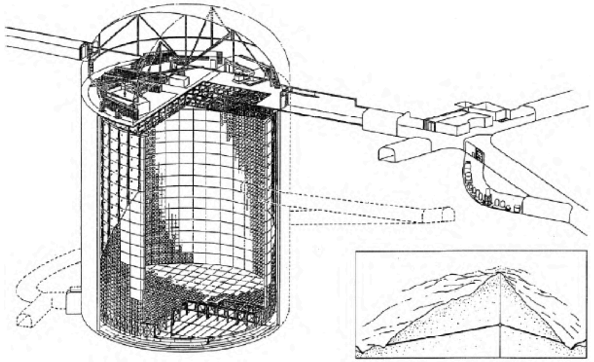


※ Up/Down syst. error for μ-like

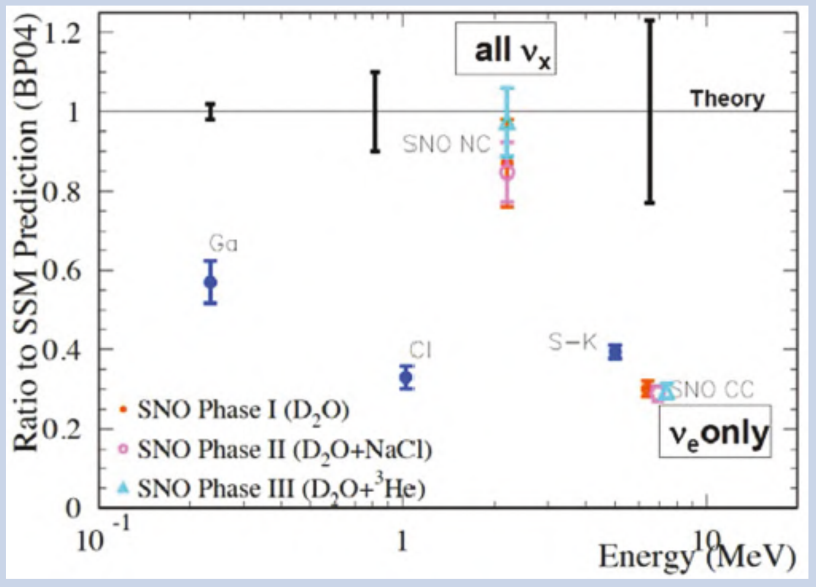
Prediction (flux calculation …… ≲1% / 1km rock above SK …. 1.5%) 1.8%

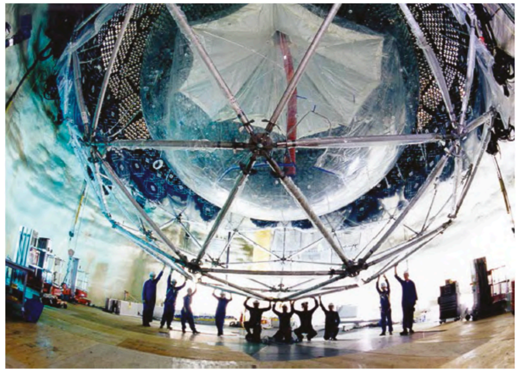
Data (Energy calib. for ↑↓ …. 0.7% / Non ν Background …..< 2%) 2.1%

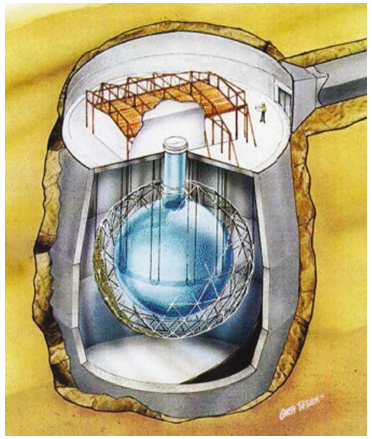

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



Super-Kamiokande (1998)



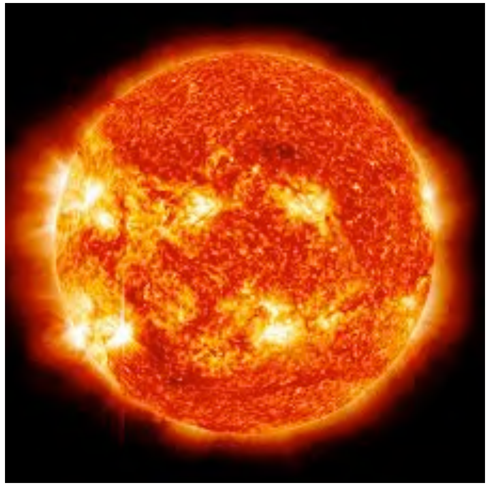




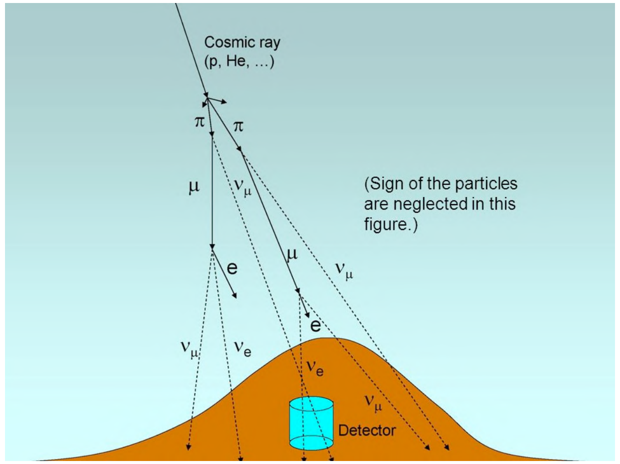
Sudbury Neutrino Observatory (2001)

Where are neutrinos?

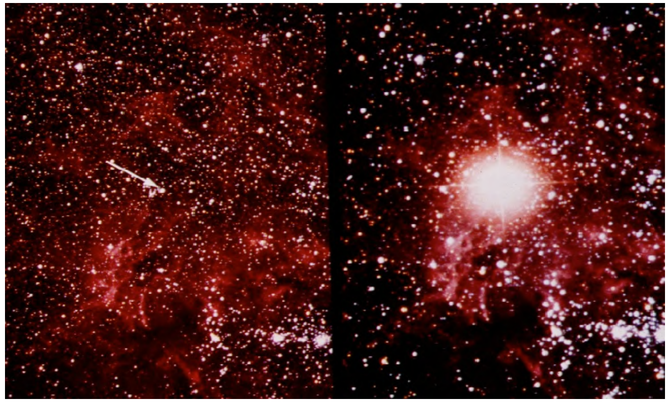
Natural sources



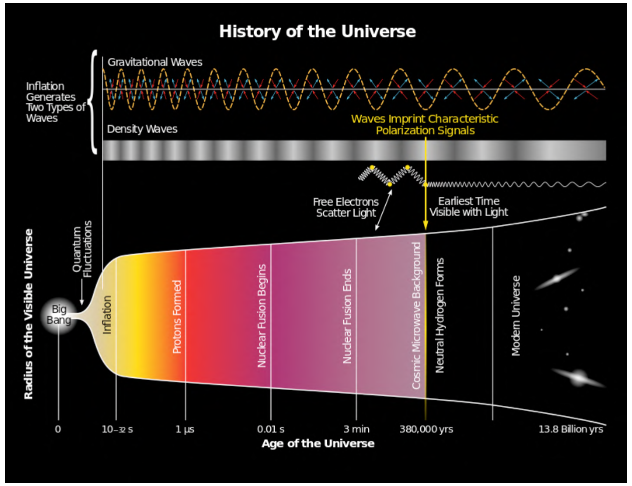
Solar neutrinos



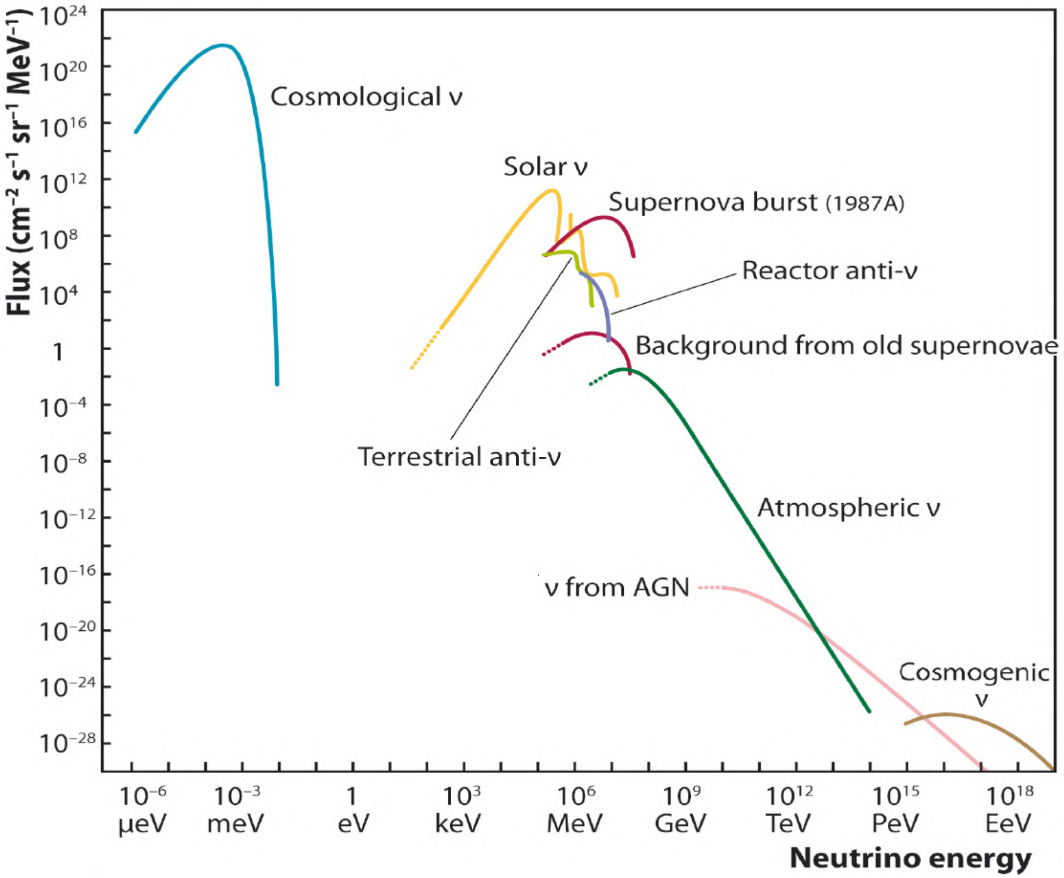
Atmospheric neutrinos



Supernova neutrinos



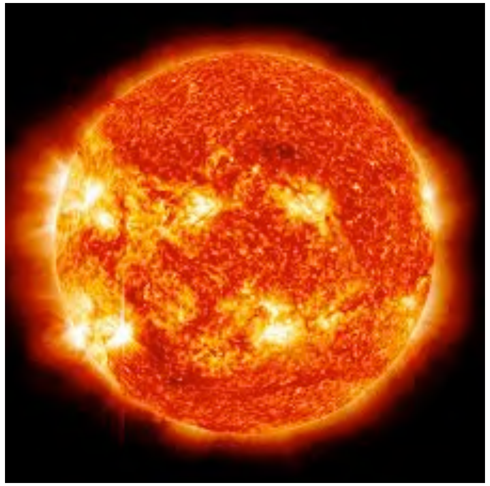
Cosmic neutrino background
(unconfirmed)



Everywhere !!

Where are neutrinos?

Natural sources



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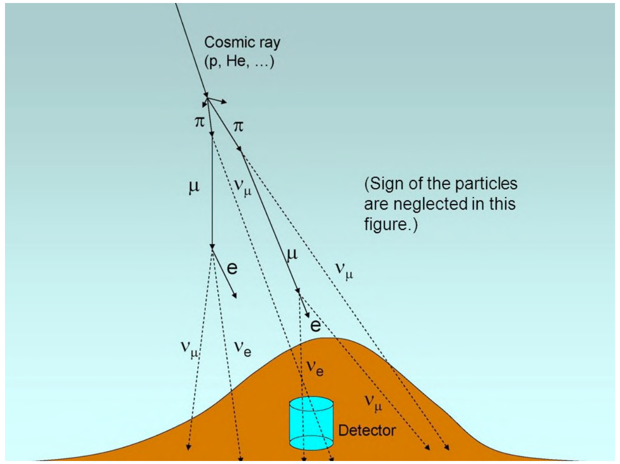

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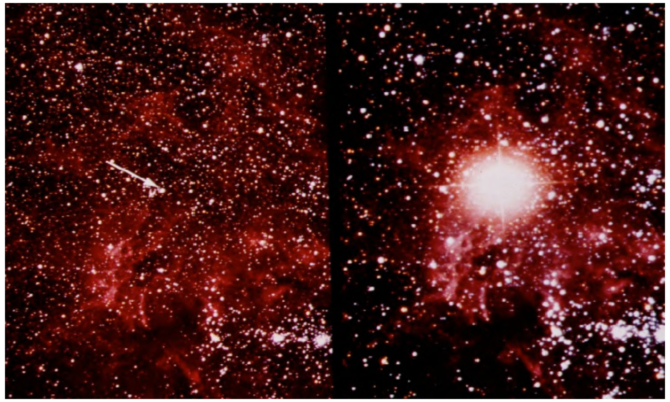

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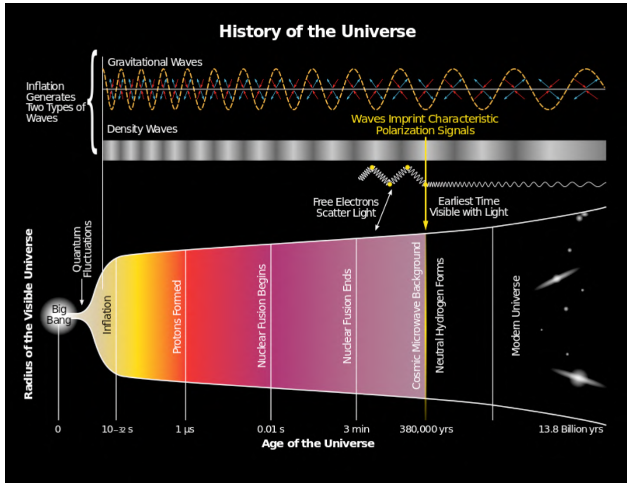

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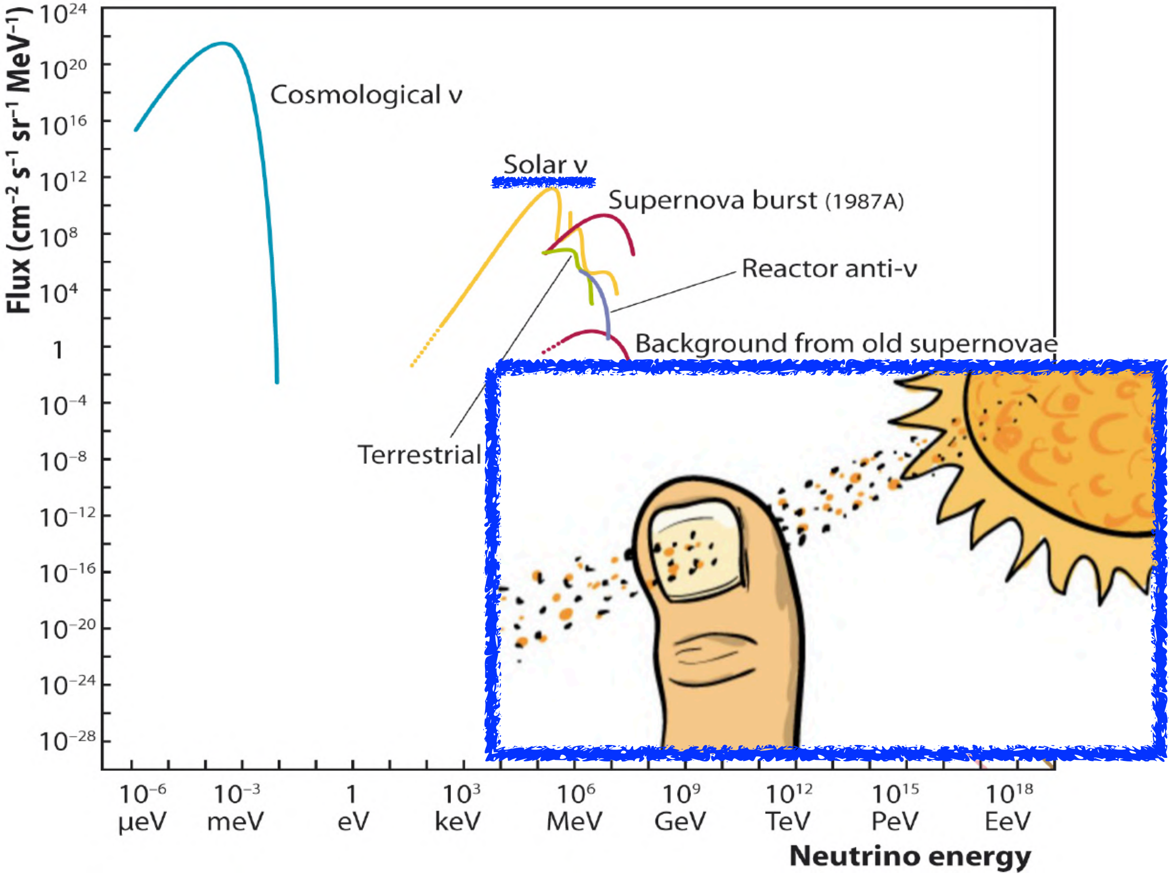
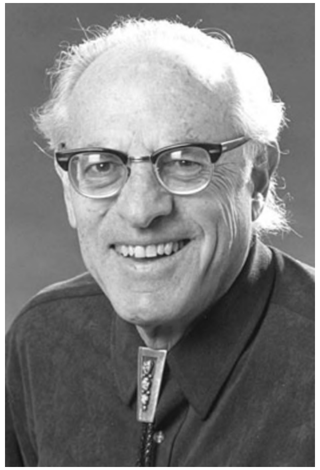


65 billion (65x10^9) neutrinos pass through your thumbnail every second !!

Example: A few milestones in the past

A long history of research, including several milestones awarded the Nobel Prize in Physics



Frederick Reines

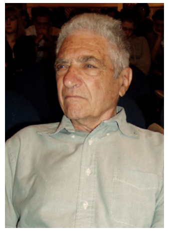
"**for the detection of the neutrino**" and "for pioneering experimental contributions to lepton physics"

Experiment (1956)

Nobel Prize (1995)

Leon Lederman

Melvin Schwartz



Jack Steinberger

"**for the neutrino beam method** and the demonstration of **the doublet structure of the leptons through the discovery of the muon neutrino**"

Experiment (1962)

Nobel Prize (1988)

Raymond Davis

Masatoshi Koshiba

"**for pioneering contributions to astrophysics**, in particular for the **detection of cosmic neutrinos**"

Experiment (Davis: 1967)
Koshiba: 1987)

Nobel Prize (2002)

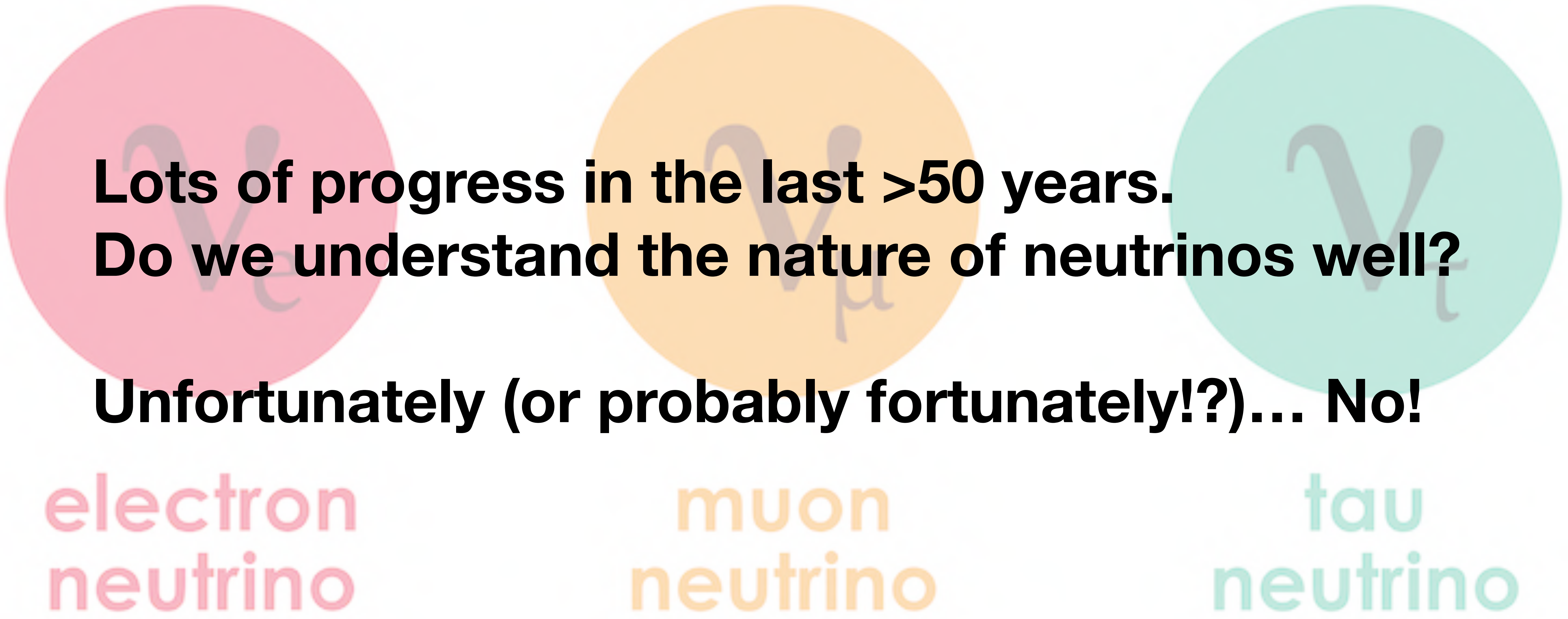
Takaaki Kajita

Arthur McDonald

"**for the discovery of neutrino oscillations**, which shows that **neutrinos have mass**"

Experiment (Kajita: 1998)
McDonald: 2001)

Nobel Prize (2015)



Lots of progress in the last >50 years.
Do we understand the nature of neutrinos well?

Unfortunately (or probably fortunately!?)… No!

Open Questions in Neutrino Physics

- Is a neutrino its own antiparticle?
- Are there any additional neutrinos?
- What is the absolute neutrino mass?
- Does the neutrino have a magnetic moment?
- Are they stable?
- Is there a CP violation in the neutrino sector?
- Is mass ordering normal or inverted?

Open Questions in Neutrino Physics

- Is a neutrino its own antiparticle? → 0ν double β decay (KamLAND-Zen, etc)
- Are there any additional neutrinos? → Short baseline neutrino oscillations (SBN at FNAL, JSNS^2 at J-PARC, etc)
- What is the absolute neutrino mass? → Beta decay kinematics (KATRIN, Project 8, HOLMES)
- Does the neutrino have a magnetic moment? → Neutrino decay search? (COBAND)
- Are they stable? → Neutrino decay search? (COBAND)
- Is there a CP violation in the neutrino sector?
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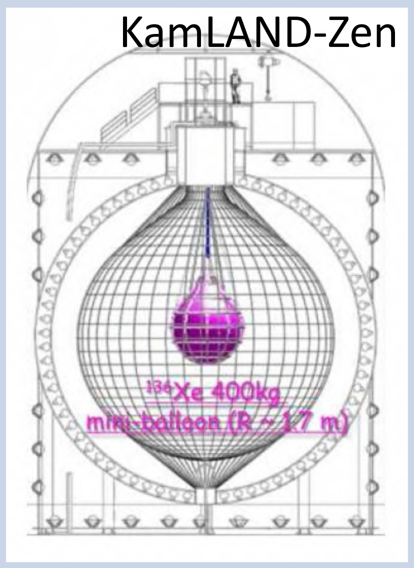
Example experiments

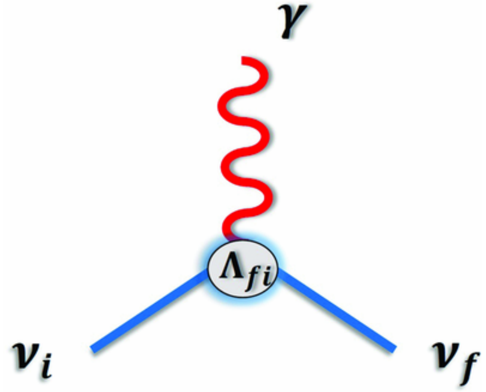
0ν double β decay (KamLAND-Zen, etc)

Short baseline neutrino oscillations
(SBN at FNAL, JSNS^2 at J-PARC, etc)

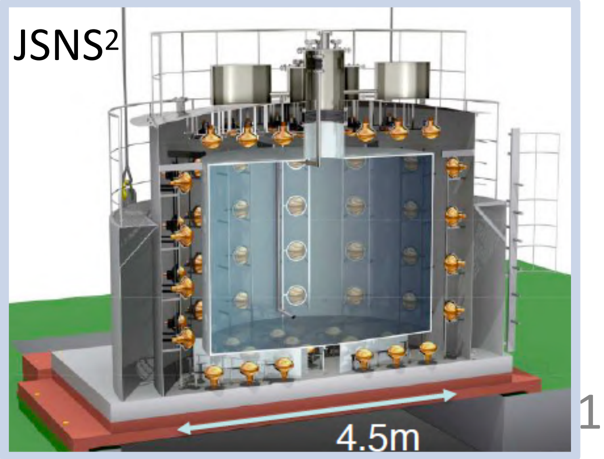
Beta decay kinematics
(KATRIN, Project 8, HOLMES)

Neutrino decay search?
(COBAND)
New ideas to win
the Nobel Prize?





$$\nu_3 \rightarrow \nu_{1,2} + \gamma$$



Open Questions in Neutrino Physics

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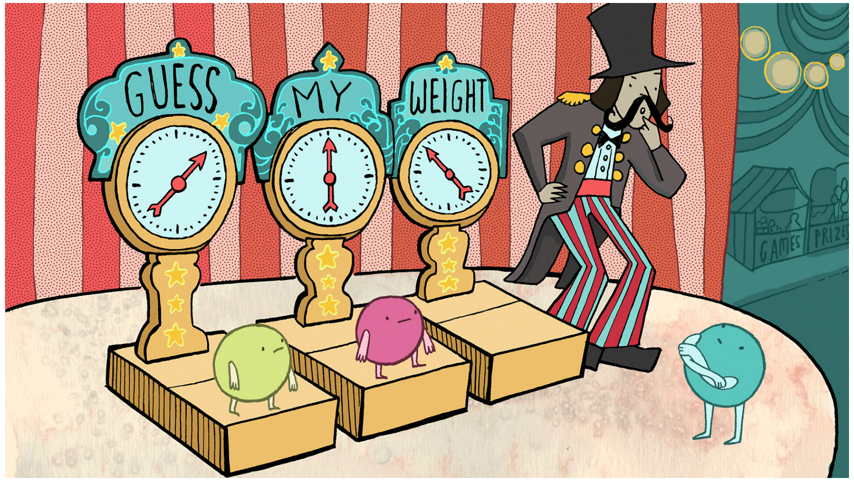


Apologize… No time to address each item in detail.

Let’s focus on two topics that can be addressed by a long-baseline experiment.

We search for these signals in neutrino oscillations.

Neutrino Oscillation in a Nutshell

- Neutrino flavor eigenstates are not the same as neutrino mass eigenstates

Flavor eigenstates

$$(\nu_e, \nu_\mu, \nu_\tau)$$

neutrino states on their interactions

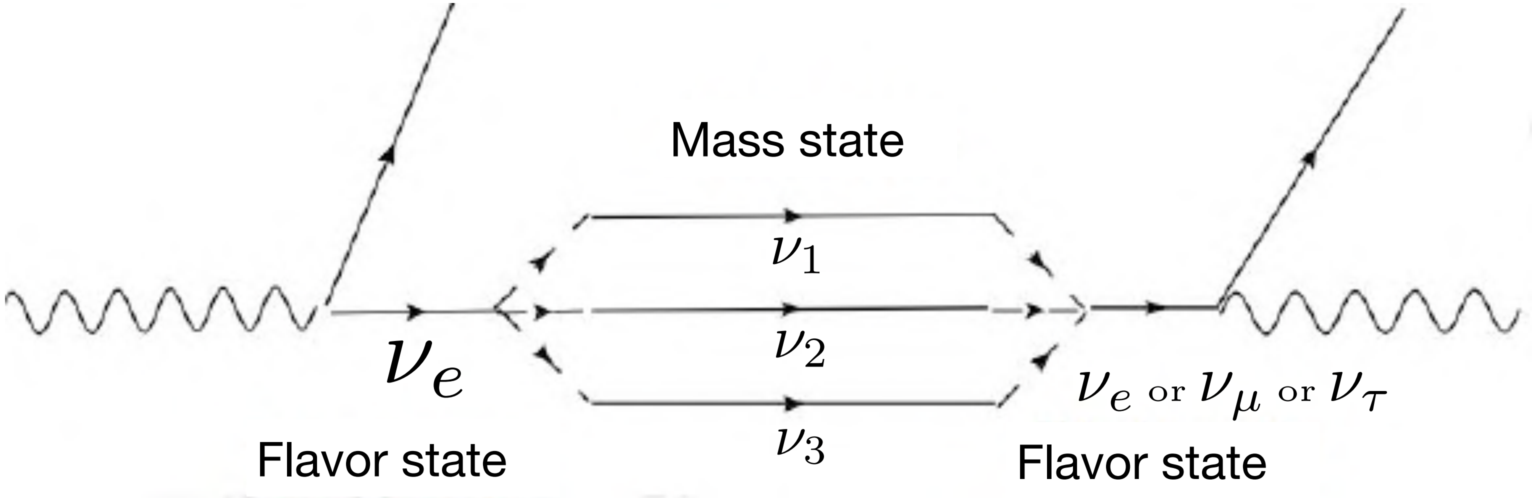
$$\nparallel$$

Mass eigenstates

$$(\nu_1, \nu_2, \nu_3)$$

neutrino states on their propagation

- Produced as a flavor neutrino (e.g. ν_e) but propagate in space as a superposition of mass eigenstate



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Neutrino Oscillation in a Nutshell

- Describe neutrino oscillation phenomena with
  - **3 mixing angles**
  - **2 independent mass splittings**
  - **1 *CP* phase**

Flavor eigenstates

$(\nu_e, \nu_\mu, \nu_\tau)$

neutrino states on their interactions

$\nparallel$

Mass eigenstates

(ν_1, ν_2, ν_3)

neutrino states on their propagation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{PMNS}\\ \text{matrix}\\ \text{(3x3)}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}\boxed{\updownarrow\ \Delta m^2_{21}}\ \boxed{\updownarrow\ \begin{matrix}\Delta m^2_{31}\\ \text{or}\\ \Delta m^2_{32}\end{matrix}}$$

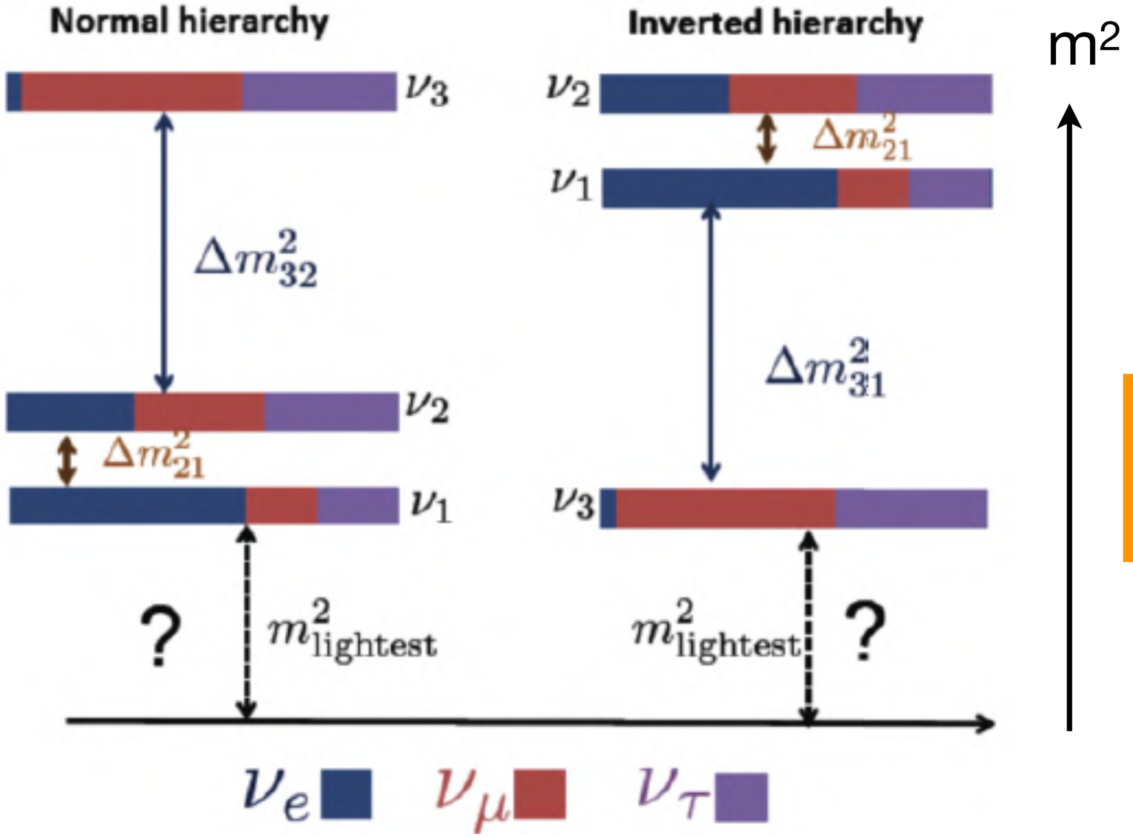
Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

$$U_{PMNS} = \underline{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}\underline{\begin{pmatrix}c_{13} & 0 & s_{13}e^{\boxed{-i\delta}}\\ 0 & 1 & 0\\ -s_{13}e^{\boxed{i\delta}} & 0 & c_{13}\end{pmatrix}}\underline{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}$$

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

Neutrino Oscillation in a Nutshell

- Describe neutrino oscillation phenomena with
  - **3 mixing angles**
  - **2 independent mass splittings**
  - **1 *CP* phase**

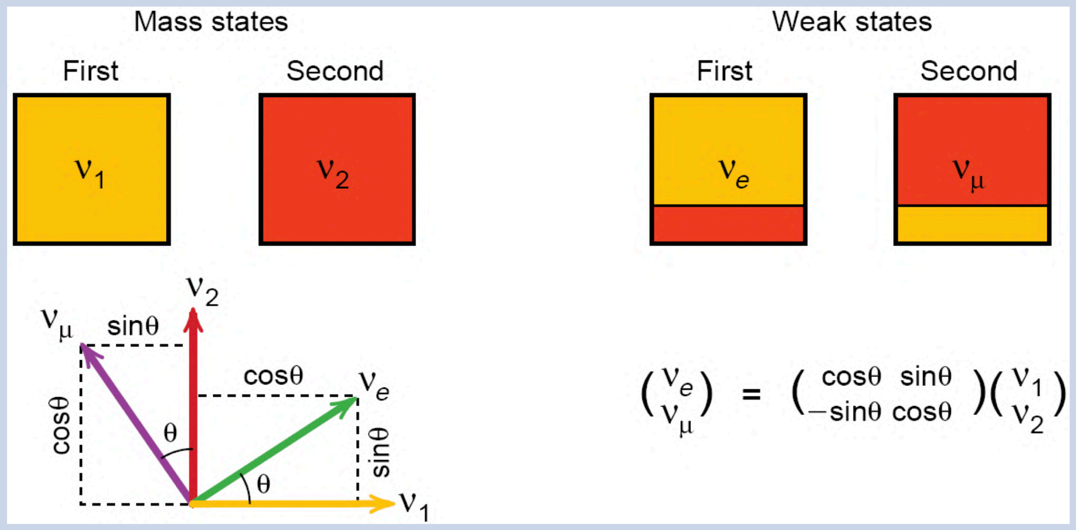


Δm^2_{31}
or
Δm^2_{32}

An open question
—> Which mass ordering?

Neutrino Oscillation in a Nutshell

Two-neutrino mixing (a good approximation to study atmospheric neutrino oscillation)



$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

Approximation: a plane wave with a common momentum for two mass states (ν_1, ν_2)

$$\begin{aligned}\Delta E &\equiv E_2 - E_1 = \sqrt{p^2+m_2^2} - \sqrt{p^2+m_1^2}\\ &\approx \left(p+\frac{m_2^2}{2p}\right) - \left(p+\frac{m_1^2}{2p}\right) \approx \frac{\Delta m^2}{2E}\end{aligned}$$

$$\boxed{\Delta m^2 \equiv m_2^2 - m_1^2\,, \quad E \approx p \gg m_{1,2}\,(\text{relativistic neutrino beam})}$$

with $\boxed{\hbar = c = 1\ (\text{natural units})}$

$$\begin{aligned}|\nu_\mu(0)\rangle &= |\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle\\ |\nu_\mu(t)\rangle &= -\sin\theta e^{-iE_1t}|\nu_1\rangle + \cos\theta e^{-iE_2t}|\nu_2\rangle\\ &= e^{-iE_1t}\left(-\sin\theta|\nu_1\rangle + \cos\theta e^{-i\Delta Et}|\nu_2\rangle\right)\end{aligned}$$

$$\boxed{P\left(\nu_\mu \to \nu_e\right)} = \left|\langle\nu_e|\nu_\mu(t)\rangle\right|^2 = \left|\left(\cos\theta\langle\nu_1| + \sin\theta\langle\nu_2|\right)\left(-\sin\theta|\nu_1\rangle + \cos\theta e^{-i\Delta Et}|\nu_2\rangle\right)\right|^2$$

$$= \left|\sin\theta\cos\theta\left(1-e^{-i\Delta Et}\right)\right|^2 = 2\left(\sin\theta\cos\theta\right)^2\left(1-\cos\frac{\Delta m^2 t}{2E}\right) \boxed{= \sin^2 2\theta\sin^2\frac{\Delta m^2 L}{4E}}$$

$$\boxed{P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta\sin^2\frac{\Delta m^2 L}{4E}}$$

Neutrino Oscillation in a Nutshell

Two-neutrino mixing (a good approximation to study atmospheric neutrino oscillation)

with realistic units Δm^2 in unit of eV^2 , L in unit of km , E in unit of GeV

$$P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

$$P\left(\nu_\mu \to \nu_\mu\right) = 1 - \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E}$$

Why does the factor "1.27" appear?

—> A good exercise if you are not familiar with the natural unit

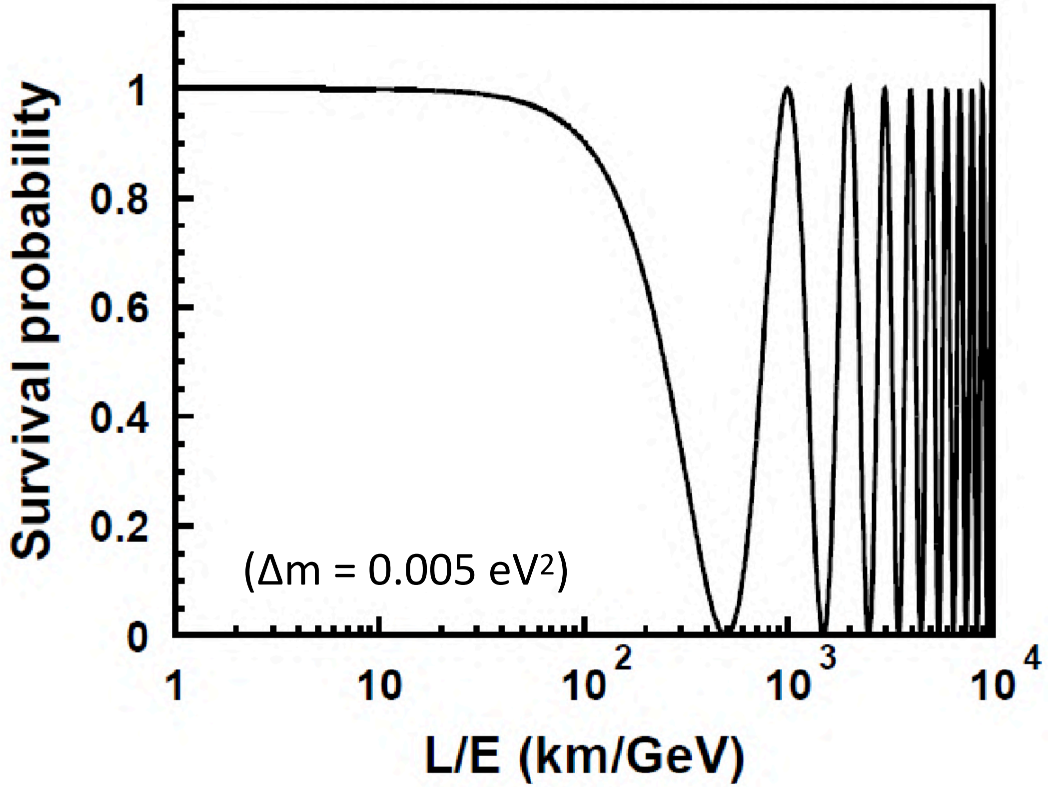
(Answer in the backup slide)

Neutrino Oscillation in a Nutshell

Two-neutrino mixing (a good approximation to study atmospheric neutrino oscillation)

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2(1.27\,\Delta m^2(\text{eV}^2)\boxed{\frac{L(\text{km})}{E(\text{GeV})}})$$

- Oscillations expected as a function of L/E



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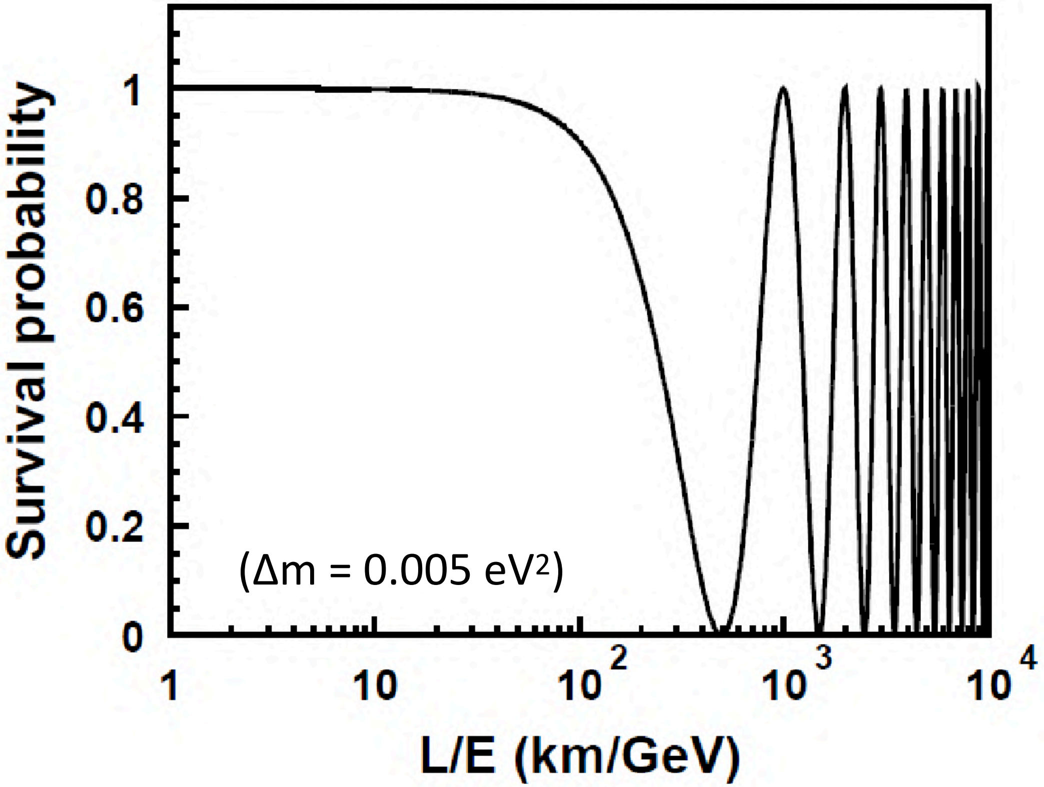
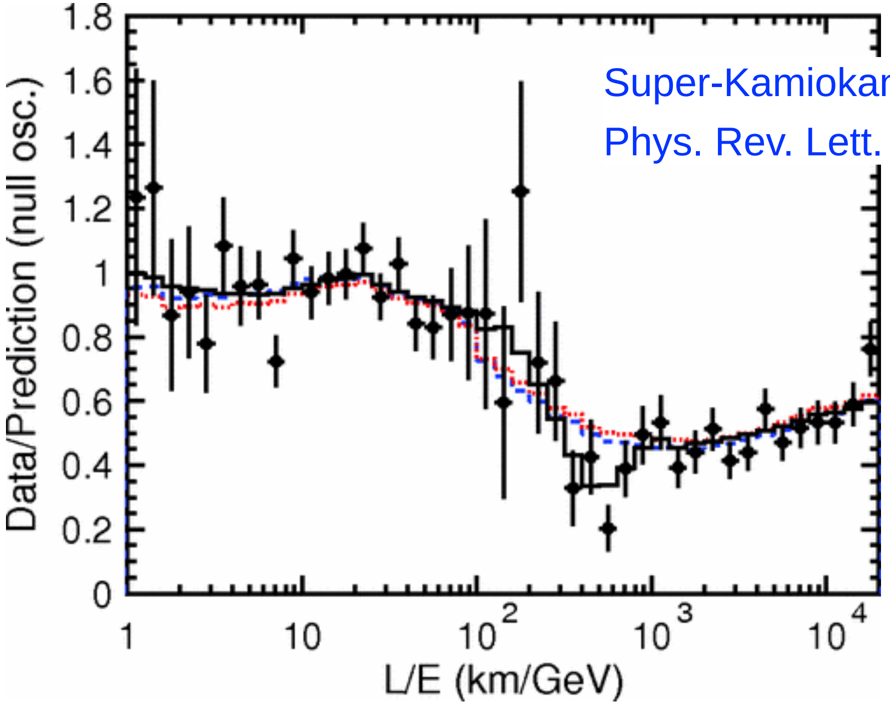
- Oscillations expected as a function of L/E -> Confirmed by experiments





Super-Kamiokande:
Phys. Rev. Lett. **93**, 101801 (2004)

(reconstructed kinematics)

Neutrino Oscillation in a Nutshell

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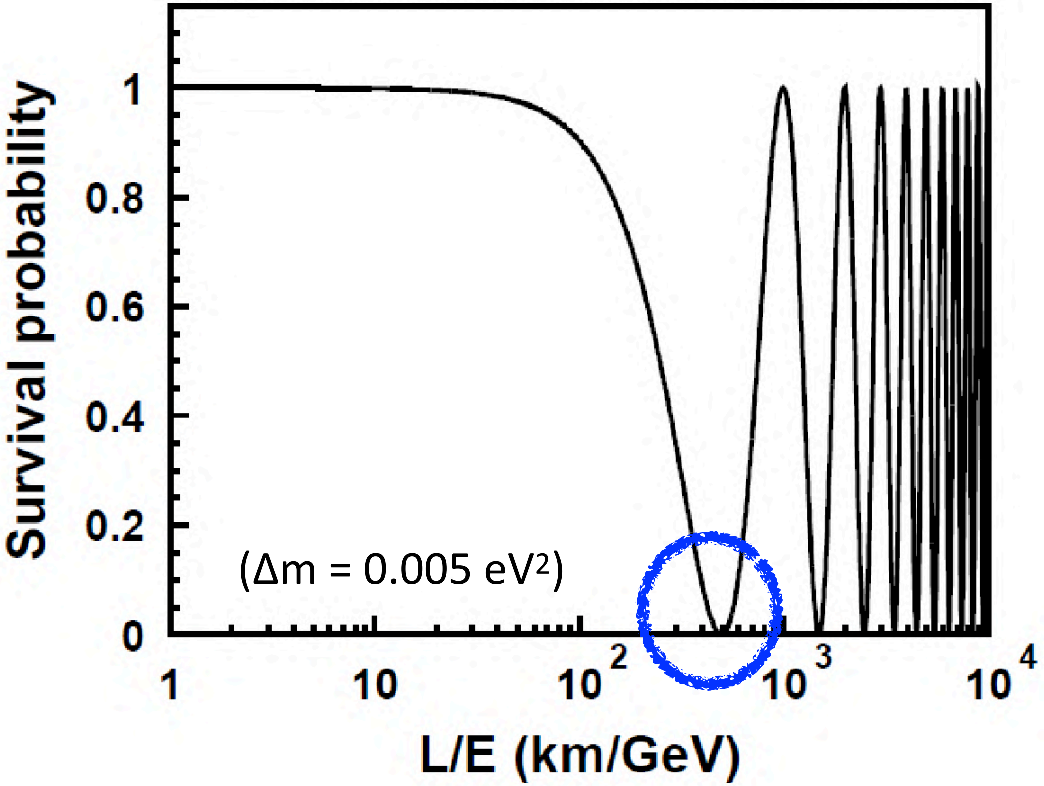


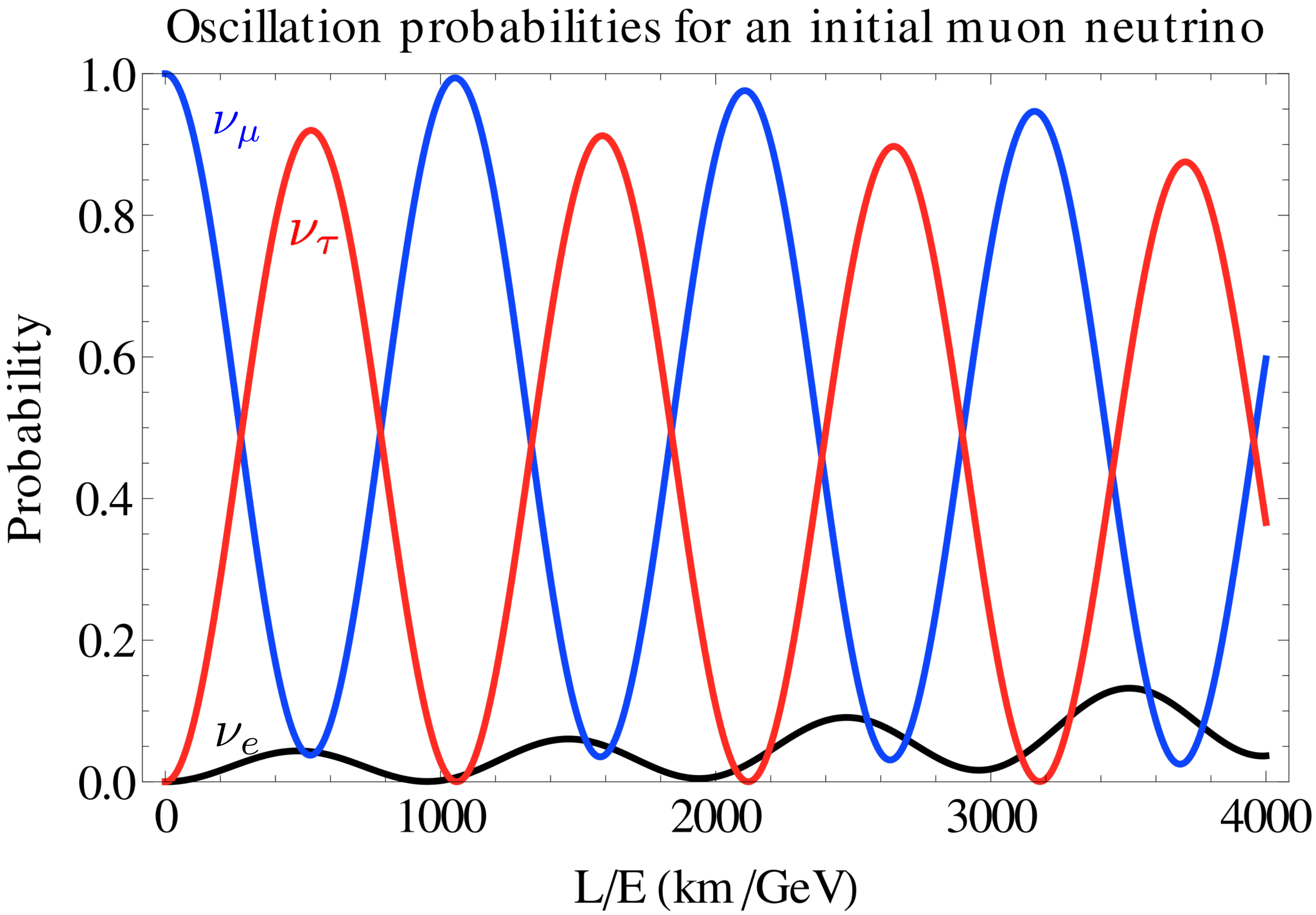
To study neutrino oscillations in detail, design experiments to maximize oscillation probability

=

Proper choice of L/E is a key factor

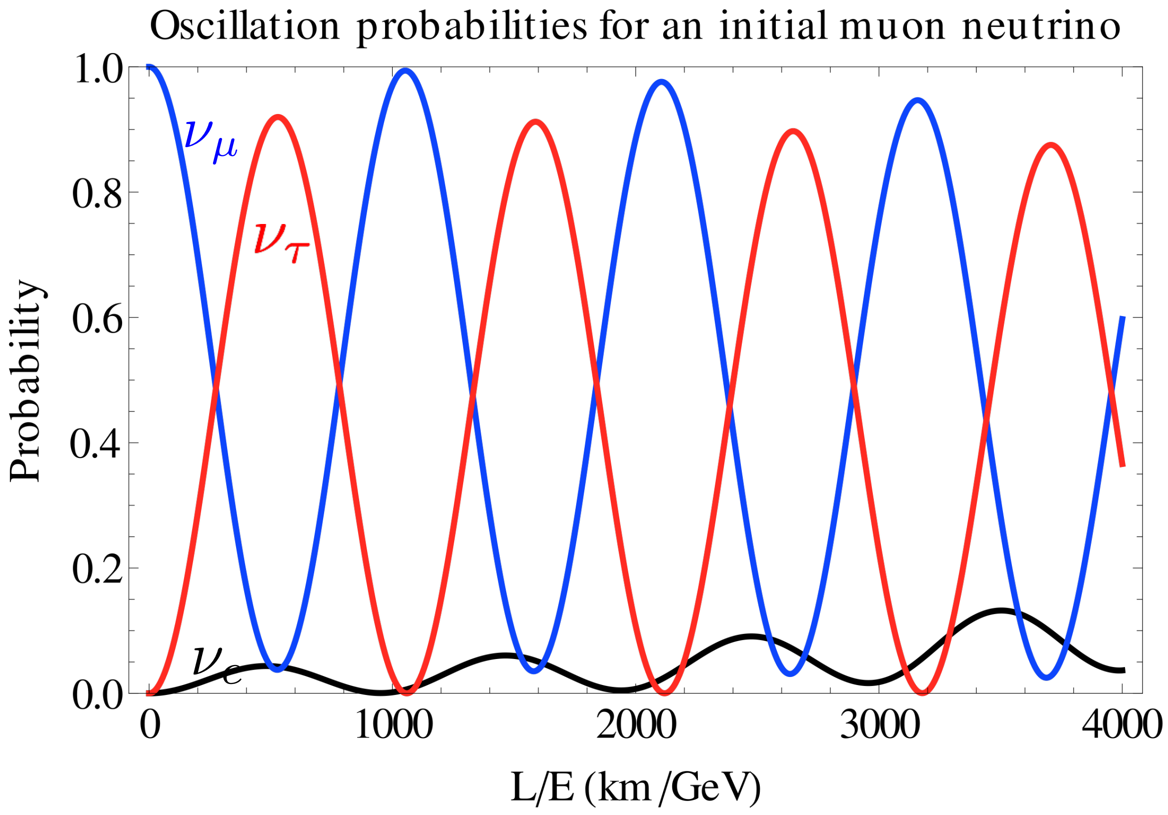
Neutrino Oscillation in a Nutshell

Three-neutrino oscillation probabilities



Neutrino Oscillation in a Nutshell

Three-neutrino oscillation probabilities



(ν_μ disappearance in vacuum)

$$P(\nu_\mu \to \nu_\mu) \approx 1 - 4\cos^2\theta_{13}\sin^2\theta_{23} \times (1-\cos^2\theta_{13}\sin^2\theta_{23})\sin^2\underline{\left(\frac{1.27\Delta m^2_{32}L}{E}\right)}$$

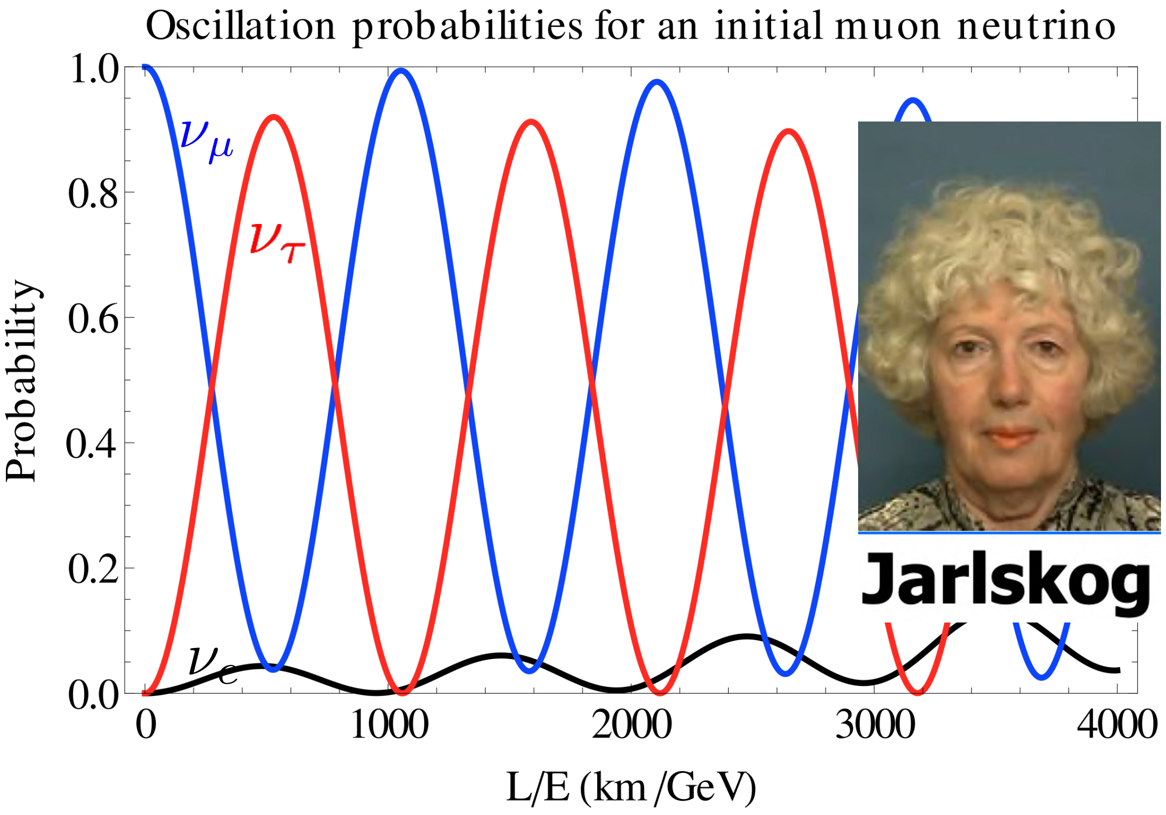
(ν_e appearance in vacuum)

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\underline{\left(\frac{1.27\Delta m^2_{32}L}{E}\right)} \mp \frac{1.27\Delta m^2_{21}L}{E} 8J_{CP}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

- Oscillations expected as a function of L/E

Neutrino Oscillation in a Nutshell

Three-neutrino oscillation probabilities



Jarlskog

(ν_e appearance in vacuum)

$$P(\nu_\mu \to \nu_e) \approx \sin^2(2\theta_{13})\sin^2\theta_{23}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

sign changes b/w ν and $\bar{\nu}$

$$\boxed{\mp}\frac{1.27\Delta m^2_{21}L}{E}\,8\boxed{J_{CP}}\sin^2\left(\frac{1.27\Delta m^2_{32}L}{E}\right)$$

Jarlskog invariant

$$\boxed{J_{CP} = \frac{1}{8}\cos\theta_{13}\sin(2\theta_{12})\sin(2\theta_{23})\sin(2\theta_{13})\sin\delta_{CP}}$$

(if $\delta_{CP} = 0$ or π, *CP* symmetry is conserved)

- ν_e appearance probability can be different between ν and $\bar{\nu}$

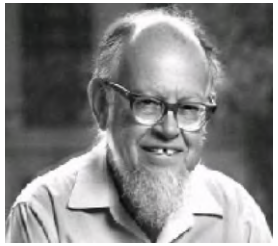
An open question —> Is CP symmetry broken?

(bonus: Can leptonic CP violation explain matter-dominated universe?)

so-called **Leptogenesis scenario**

Neutrino Oscillation in a Nutshell

Neutrino traveling through matter



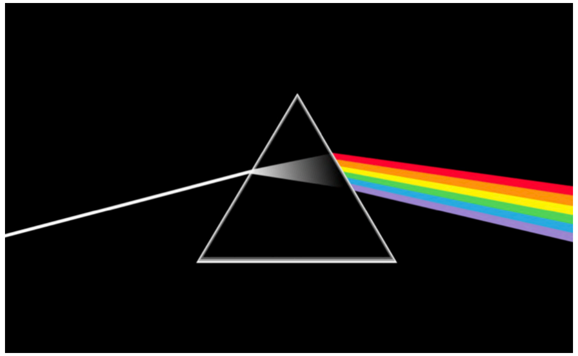
In addition, neutrinos interact with matter when traveling through a medium —> **Matter effects (MSW effect)**

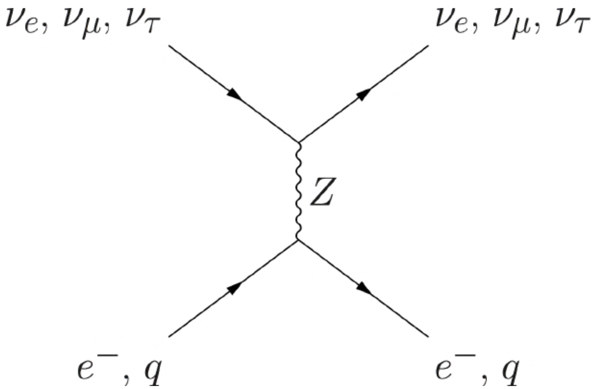
L. Wolfenstein : First suggestion on the CC-induced phase changing the neutrino oscillation behavior *Phys. Rev. D 17, 2369-2374 (1978)*

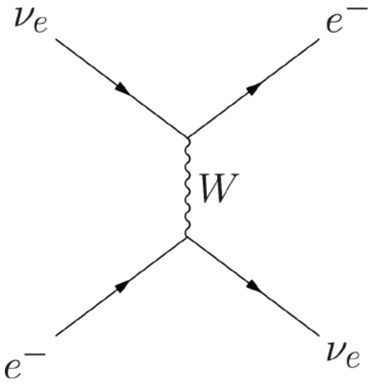
S.P. Mikheyev and A.Yu. Smirnov: Matter effect inside the Sun *Sov.J.Nucl.Phys. 42, 913-917 (1985)*

The phenomenon is analogous to light traveling through a medium.
Light sees a **refractive index** due to coherent forward scattering on the medium.

A similar phenomenon applies to neutrino flavor states as they travel through matter.
- All flavors (ν_e, ν_μ, ν_τ) see a common refractive index via **NC forward scattering** in matter.
- Only electron (anti)neutrinos see an extra refractive index via **CC forward scattering** in matter.







Neutrino Oscillation in a Nutshell

Matter effects (just outcomes without any serious calculations)

electron neutrinos experience an additional potential energy: $U_e \propto G_F N_e$

Mixing angle in matter θ_m compared to θ in vacuum: $\sin^2 2\theta_m = \dfrac{\sin^2 2\theta}{(\cos 2\theta - A)^2 + \sin^2 2\theta}$, $A = \pm 2\sqrt{2} G_F E_\nu N_e / \Delta m^2$

Key points

1. Oscillation probability for neutrinos and antineutrinos can be different because of the ± sign in front of "***A***"

   => Even if neutrino does not violate *CP* symmetry (fake *CP* effect)

2. Maximal mixing occurs when $A = \cos 2\theta$

   => the resonance condition that significantly enhances neutrino oscillation probability

   (This is always happening for the solar neutrinos above 1 MeV energy with $\theta_{sol} \sim 30^\circ$ and $\Delta m^2_{sol} \sim 8 \times 10^{-5}\,\mathrm{eV}^2$)

3. Resonance condition can occur if "***A***" is positive, which depends on the sign of Δm^2

   => This is the reason why (enough) long-baseline experiments are sensitive to resolving mass hierarchy if $\Delta m^2 \sim \Delta m^2_{23}$. Typically, *O*(1000 km) with *O*(GeV) is required.

Skip the extraction of modified probability today

—> A good exercise why it becomes this conclusion (Example calculations in the backup slide)

Neutrino Oscillation in a Nutshell

Three-neutrino oscillation complexity in reality

(ν_e appearance in matter)

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \approx{}& \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} \\
&+\alpha\boxed{\tilde{J}}\cos(\Delta\boxed{\pm}\delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)} \\
&+\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}
\end{aligned}
$$

Jarlskog invariant

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$

$$\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$

$$\Delta = \Delta m^2_{31}L_\nu/4E_\nu$$

$$A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{13}$$

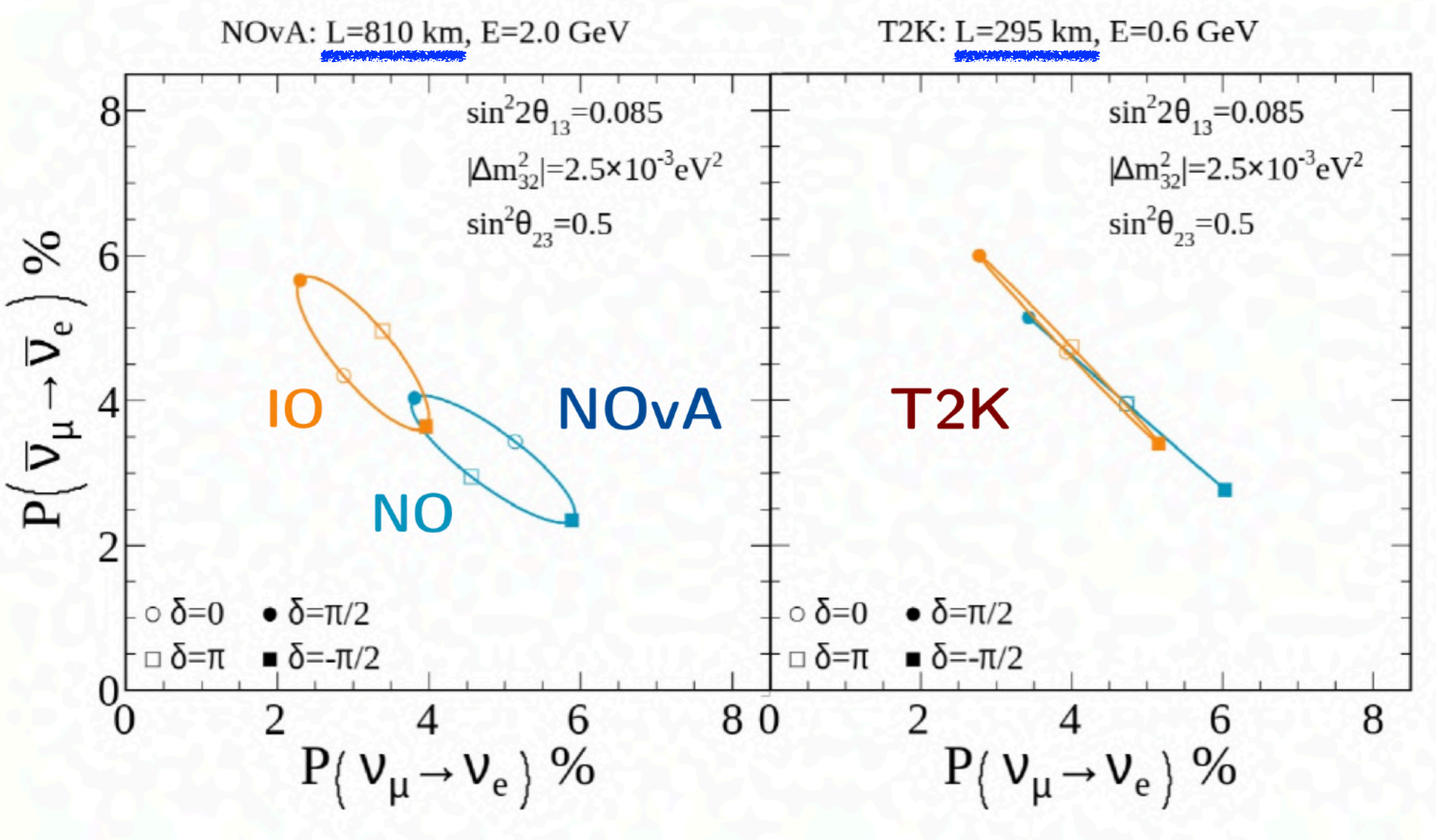
Matter and *CP* effects appear in an entangled way.

-> Very complicated effect!!

Even if *CP* is conserved, matter effects make ν_e and anti-ν_e appearance probabilities different.

-> Mimic the *CP* effect

Disentangling CP and Matter Effects



	T2K	NOvA
L (baseline)	295 km	810 km
Energy (beam peak)	0.6 GeV	2 GeV
Matter effect*	~ ±9%	~ ±19%
CP effect*	~ ±30%	~ ±25%

*calculated at beam peak energy

This implies no single experiment may distinguish CP and Matter effects!

example: What if the truth CP is -π/2 with Inverted Order?

=> Combine different baseline experiments (complementarity)

T2K-NOvA combination (See seminar: https://indico.fnal.gov/event/62062 , paper under preparation)

T2K-SuperK combination (See seminar: https://kds.kek.jp/event/49194 , arXiv:2405.12488)

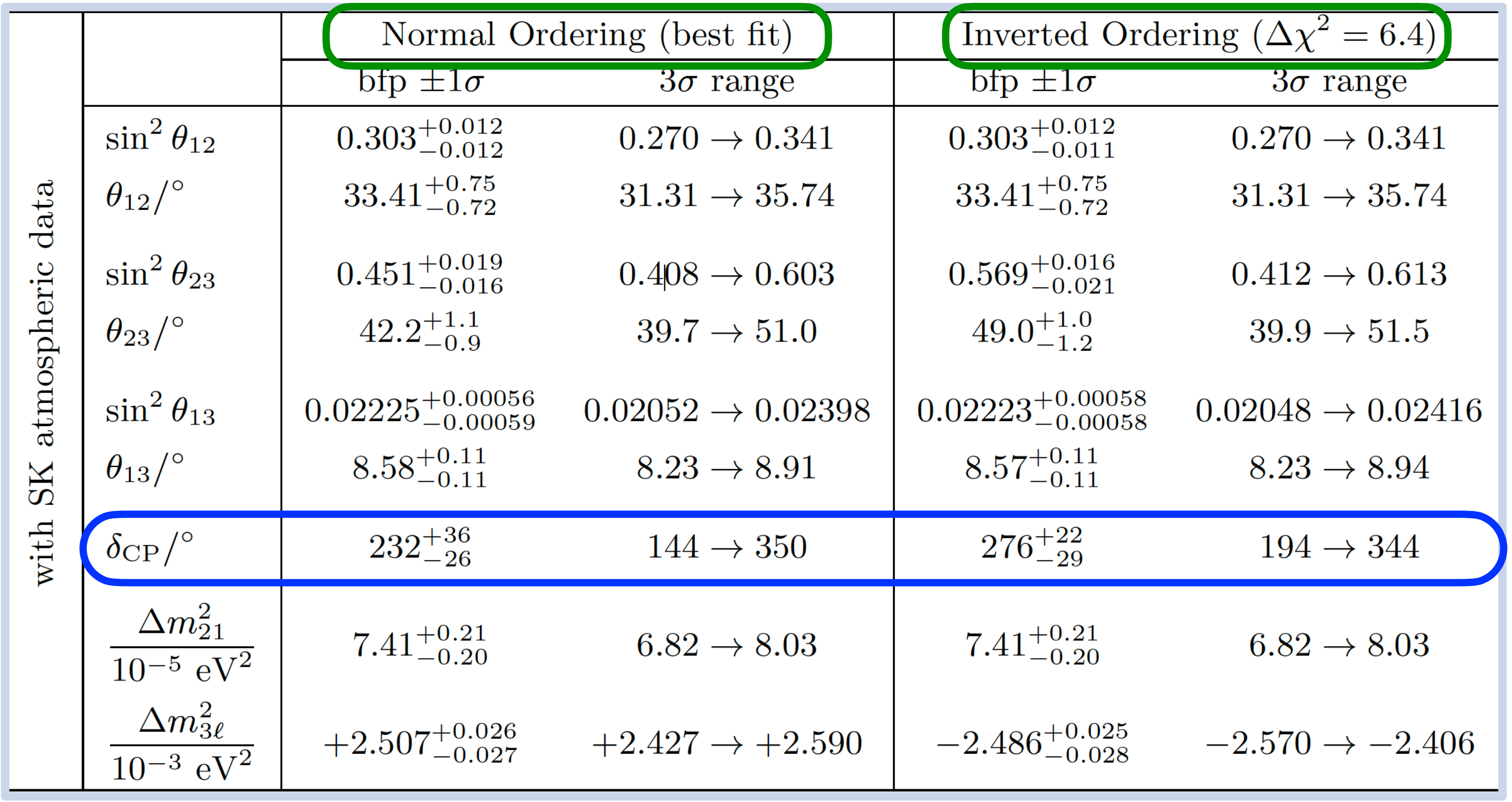
Oscillation Parameters (Current Knowledge)

$$\underbrace{\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}}_{\text{flavor}} = \begin{pmatrix}\text{PMNS}\\ \text{matrix}\end{pmatrix} \underbrace{\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}}_{\text{mass}} \quad \boxed{\Delta m^2_{21}} \quad \boxed{\begin{matrix}\Delta m^2_{31}\\ \text{or}\\ \Delta m^2_{32}\end{matrix}}$$

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & \boxed{s_{13}e^{-i\delta}}\\ 0 & 1 & 0\\ \boxed{-s_{13}e^{i\delta}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

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

JHEP 09 (2020) 178 [arXiv:2007.14792], NuFIT 5.2 (2022), www.nu-fit.org



with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{\rm CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

Two open questions

Mass-ordering

Best fit with Normal ordering (Inverted ordering disfavored with ~2σ level)

CP phase ($\delta_{\rm CP}$)

A hint on $\delta_{\rm CP} \neq 0$?

No definitive conclusion yet

Oscillation Parameters (Current Knowledge)

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}\text{PMNS}\\ \text{matrix}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

flavor

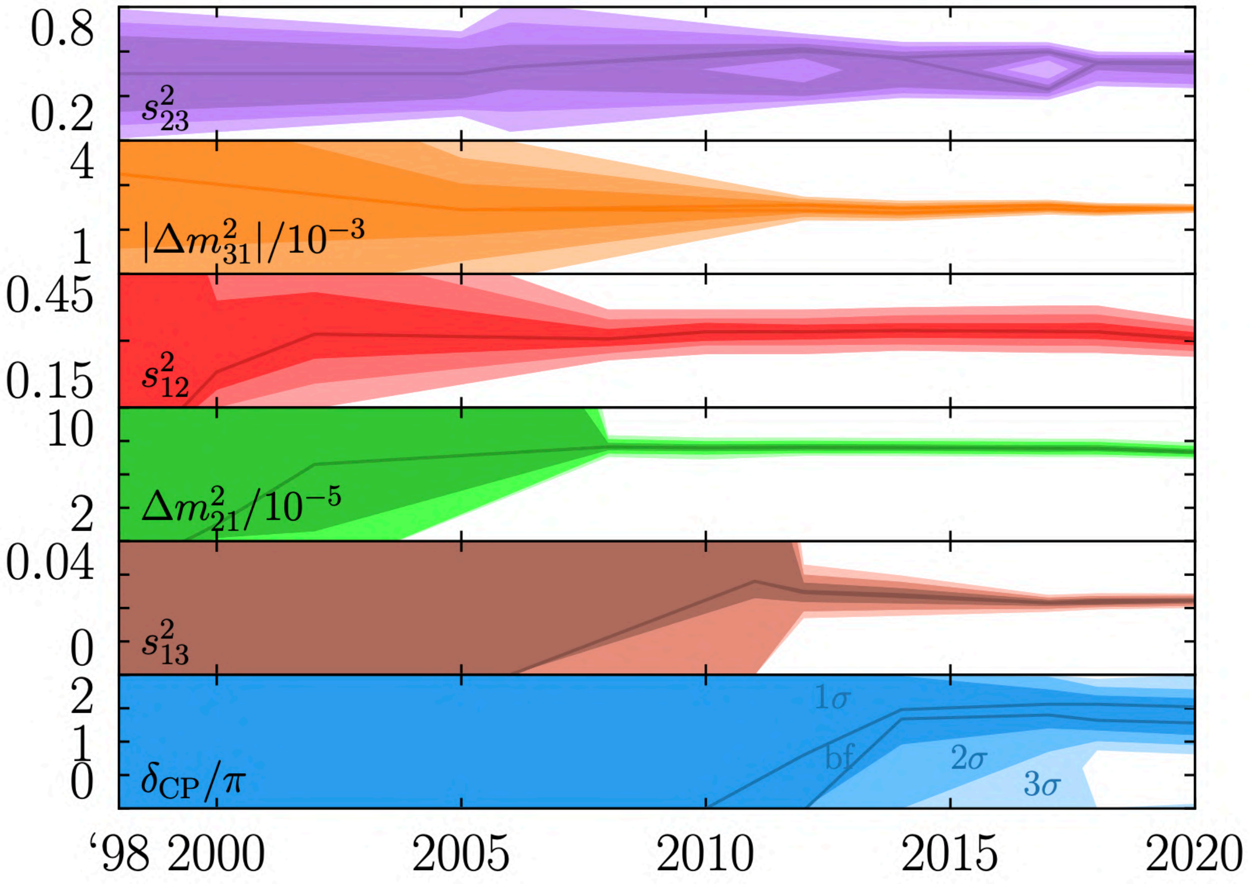
mass

Δm^2_{21}

Δm^2_{31} or Δm^2_{32}

$$U_{PMNS} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

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

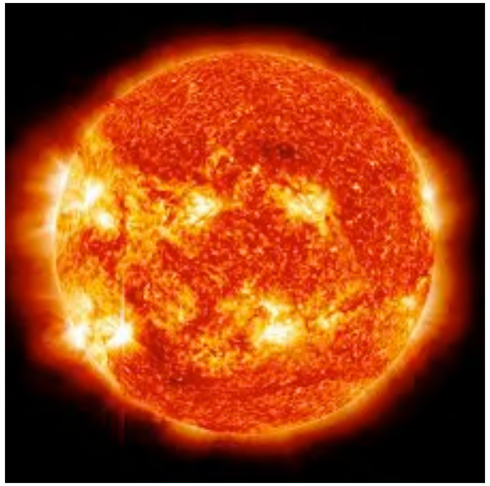


Snowmass Neutrino Frontier:
NF01 Topical Group Report on
Three-Flavor Neutrino Oscillations
https://doi.org/10.48550/arXiv.2212.00809

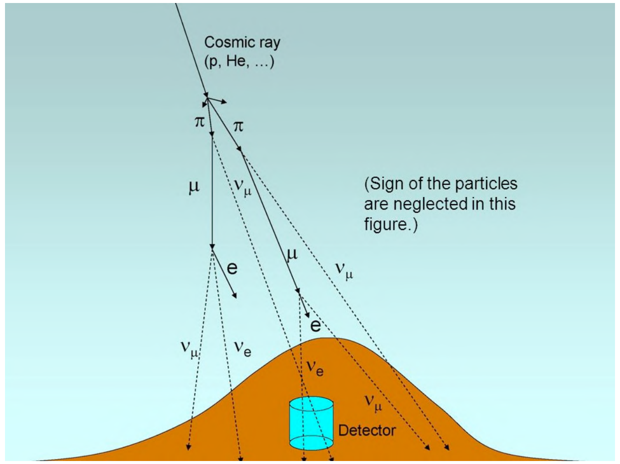
Entering the precision era on neutrino oscillation studies!!

What neutrino sources can we use?

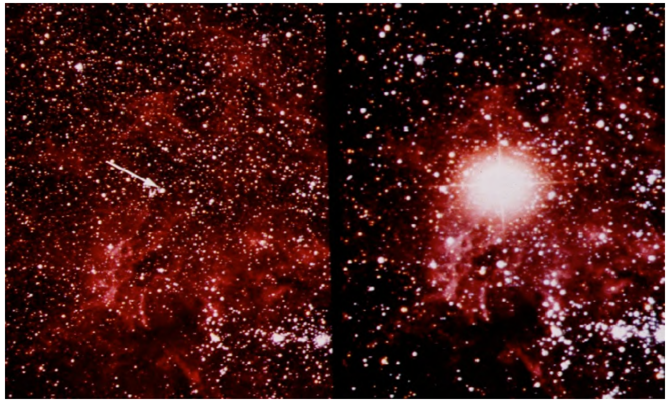
Natural sources



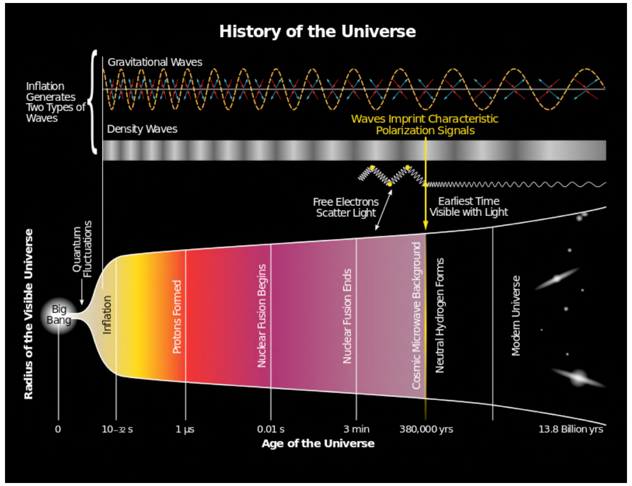
Solar neutrinos



Atmospheric neutrinos



Supernova neutrinos



Cosmic neutrino background
(unconfirmed)

Pros:
- Source is free

Lots of past milestones achieved with natural sources

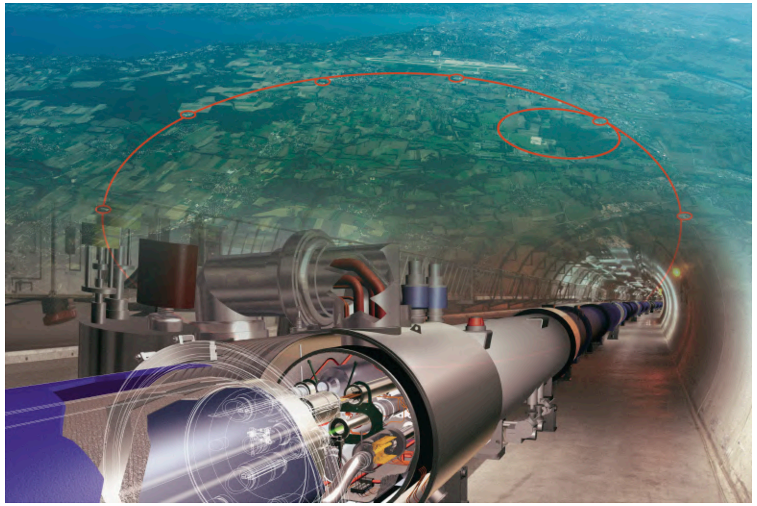
Cons:
- Cannot control exp. parameters
 (e.g. L/E for oscillation studies)
- Not enough intensity

What neutrino sources can we use?

Artificial sources

Accelerator neutrinos
(MeV~GeV)

Reactor neutrinos
(MeV)



Collider neutrinos
(GeV~TeV)

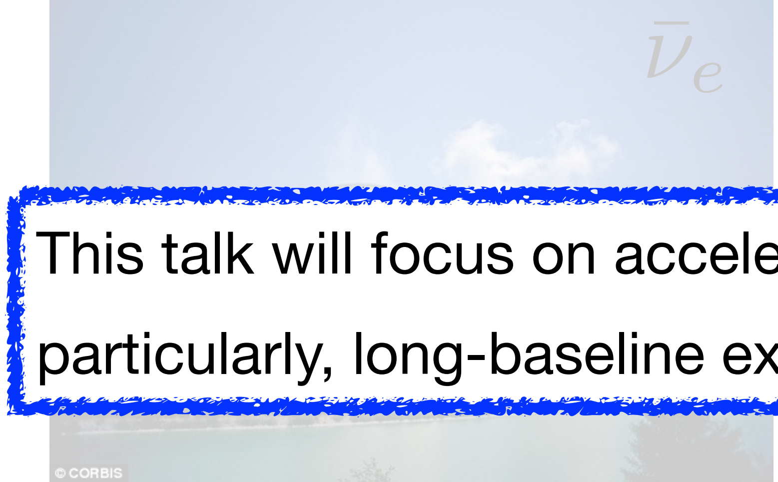
Use artificial neutrino sources for precision oscillation measurements

- High intensity achievable (high statistics data)
- Well-understood *ν* beam spectrum (E is either known or controllable)
- Flexible choice of detector positions (L is controllable)

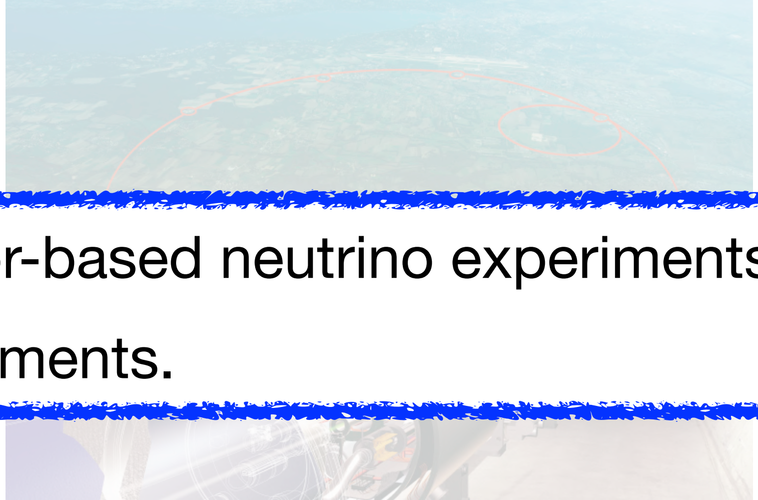
What neutrino sources can we use?

Artificial sources

Accelerator neutrinos
(MeV~GeV)



Reactor neutrinos
(MeV)



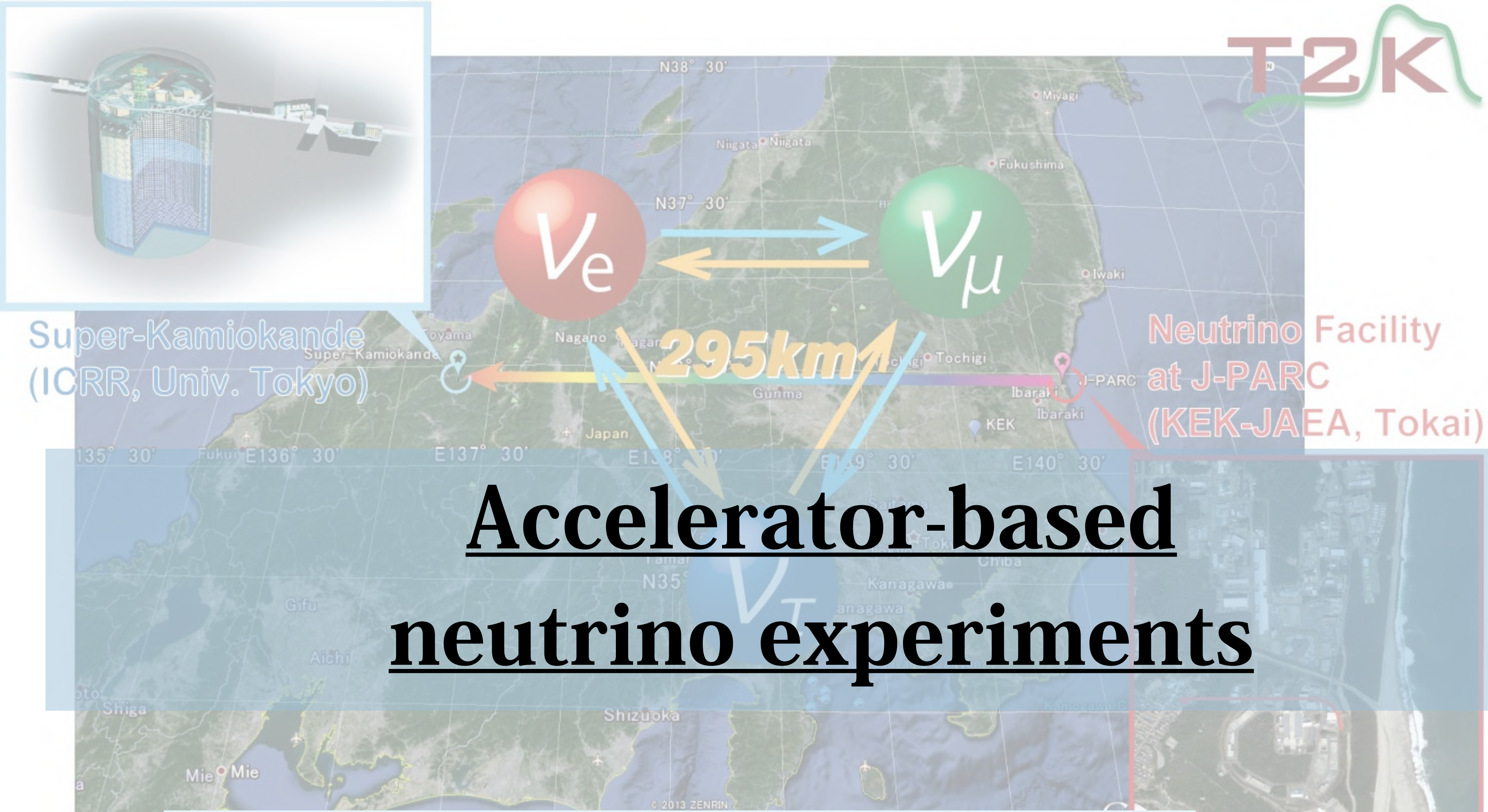
Collider neutrinos
(GeV~TeV)

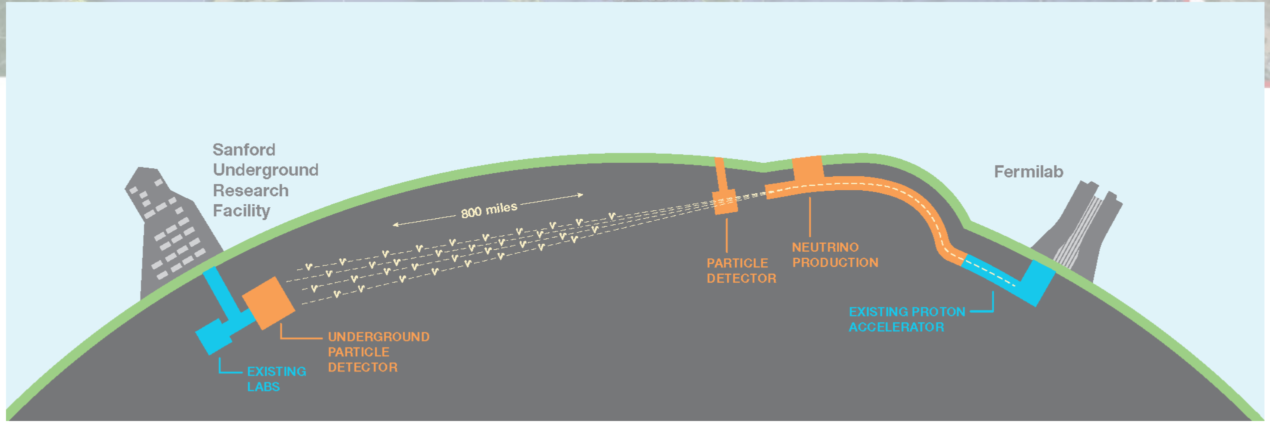
This talk will focus on accelerator-based neutrino experiments, particularly, long-baseline experiments.

Use artificial neutrino sources for precision oscillation measurements

- High intensity achievable (high statistics data)
- Well-understood *ν* beam spectrum (E is either known or controllable)
- Flexible choice of detector positions (L is controllable)

Accelerator-based neutrino experiments

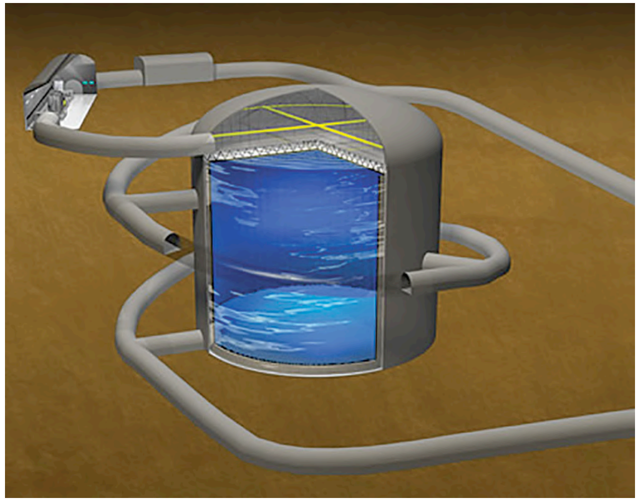


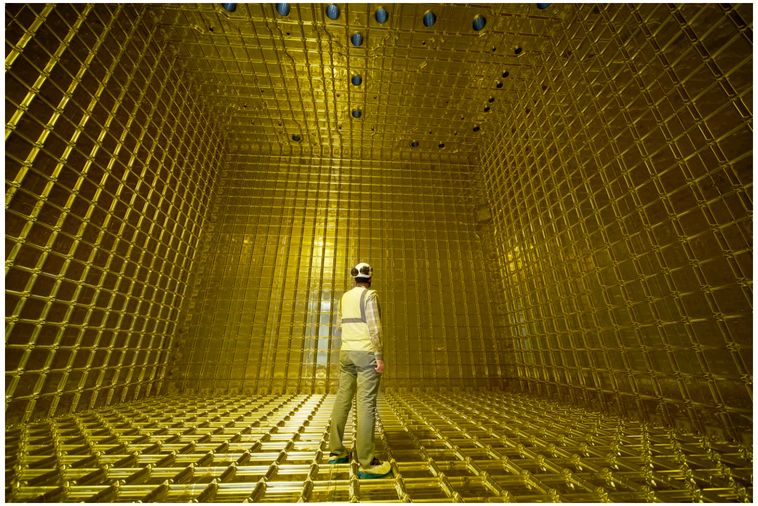


We learned that neutrinos are elusive.
How can we overcome the difficulty?
The basic strategy of neutrino physics is simple.

1. More neutrinos!
   - Large neutrino fluxes
     -> a solution: High intensity beams with accelerators

2. More neutrino targets!
   - A tremendous amount of target nuclei
     -> solution 1: Scale-up detector size
     e.g. Kamiokande-> Super-K -> Hyper-K
     -> solution 2: Denser material
     e.g. liquid Ar as the neutrino target





Modern Neutrino Beam Experiments

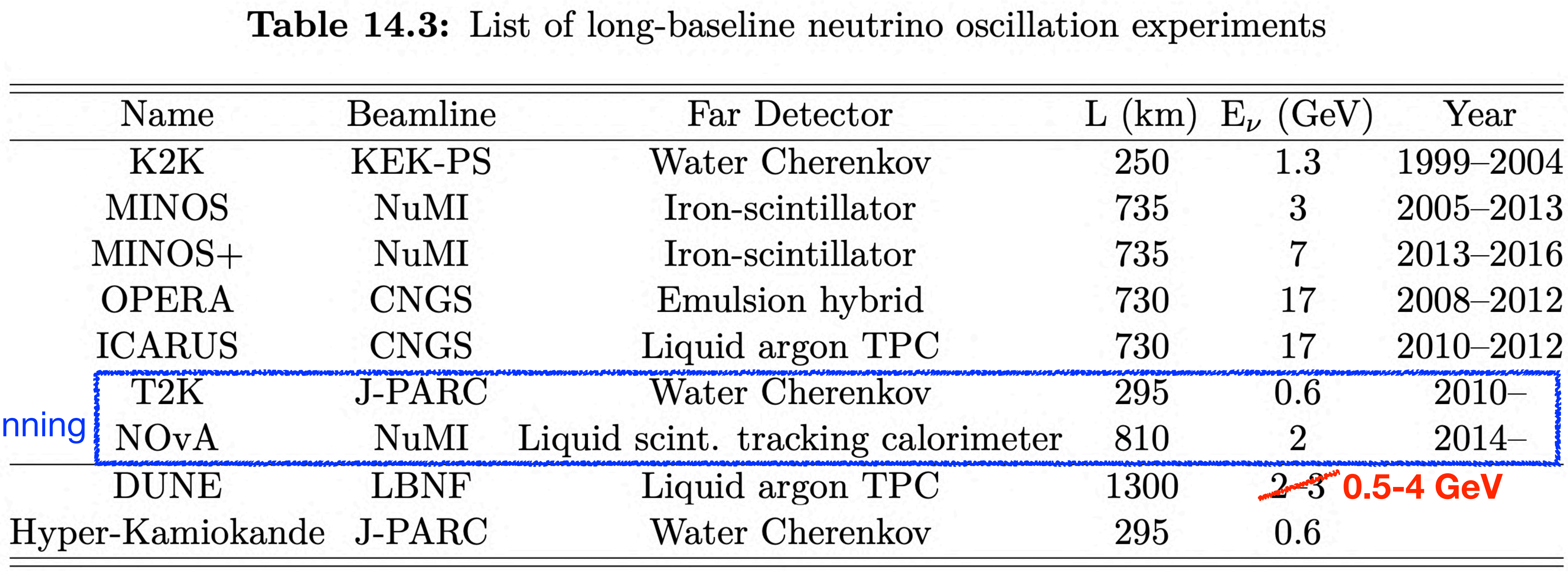


Table 14.3: List of long-baseline neutrino oscillation experiments

Name	Beamline	Far Detector	L (km)	E_ν (GeV)	Year
K2K	KEK-PS	Water Cherenkov	250	1.3	1999–2004
MINOS	NuMI	Iron-scintillator	735	3	2005–2013
MINOS+	NuMI	Iron-scintillator	735	7	2013–2016
OPERA	CNGS	Emulsion hybrid	730	17	2008–2012
ICARUS	CNGS	Liquid argon TPC	730	17	2010–2012
T2K	J-PARC	Water Cherenkov	295	0.6	2010–
NOvA	NuMI	Liquid scint. tracking calorimeter	810	2	2014–
DUNE	LBNF	Liquid argon TPC	1300	~~2–3~~ **0.5-4 GeV**	
Hyper-Kamiokande	J-PARC	Water Cherenkov	295	0.6	

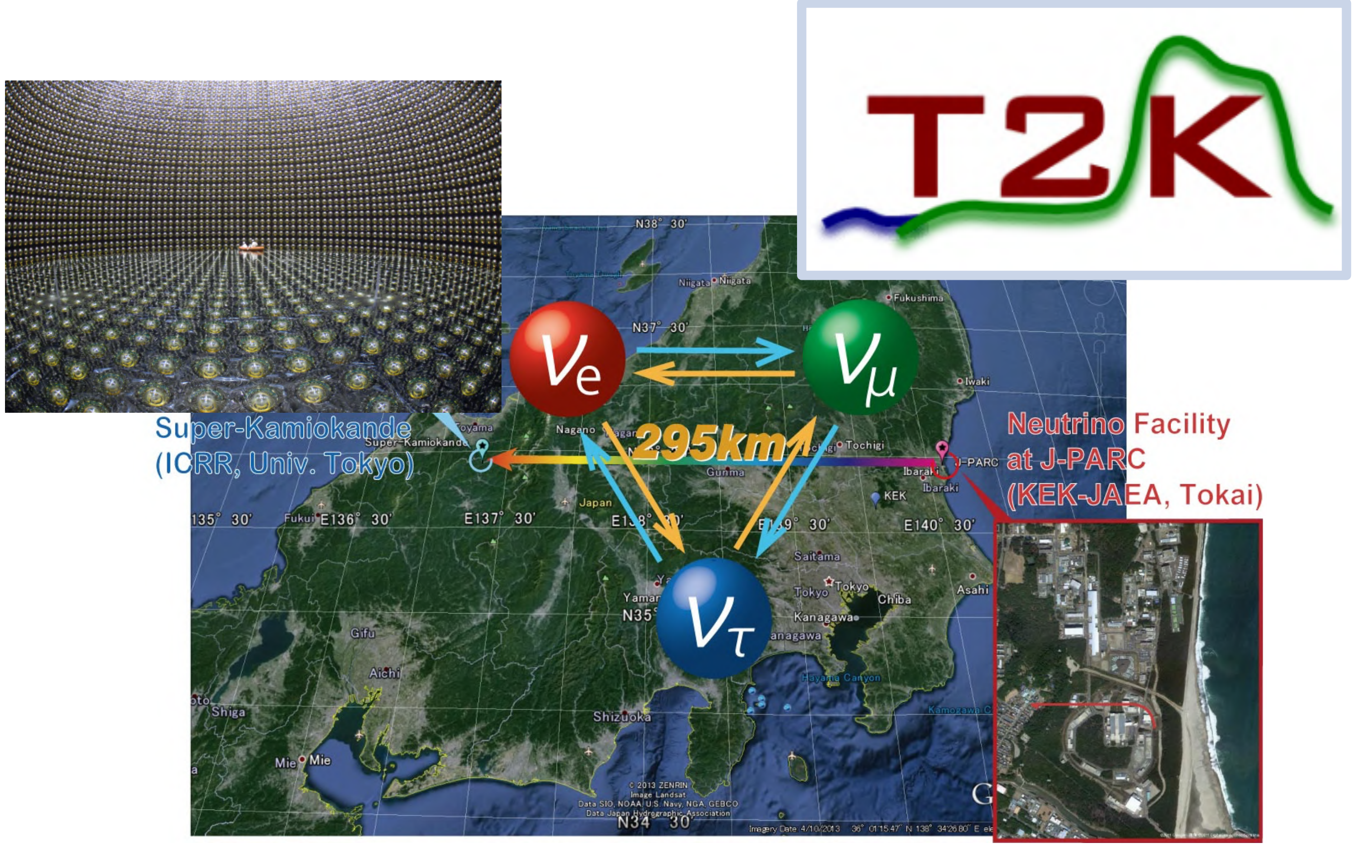
running

PDG: Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

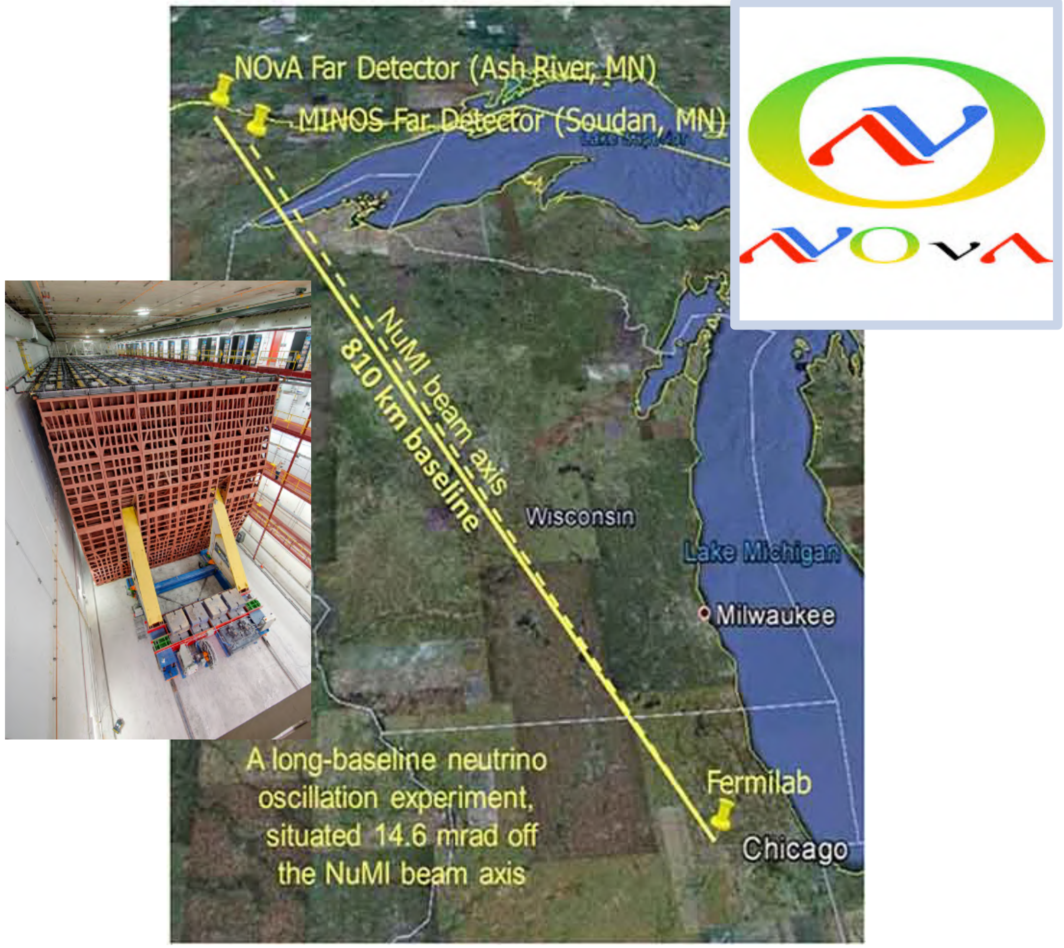
There are also short-baseline accelerator-based experiments, e.g., at Fermilab
-> Will not discuss in this lecture, but try googling **"Short Baseline Neutrino"** or **"SBN experiments"**

Long-Baseline Neutrino Experiments (Present)

- Running experiments using intense ν_μ and $\bar{\nu}_\mu$ beams



J-PARC beamline (30 GeV proton beam)
running experiment: T2K



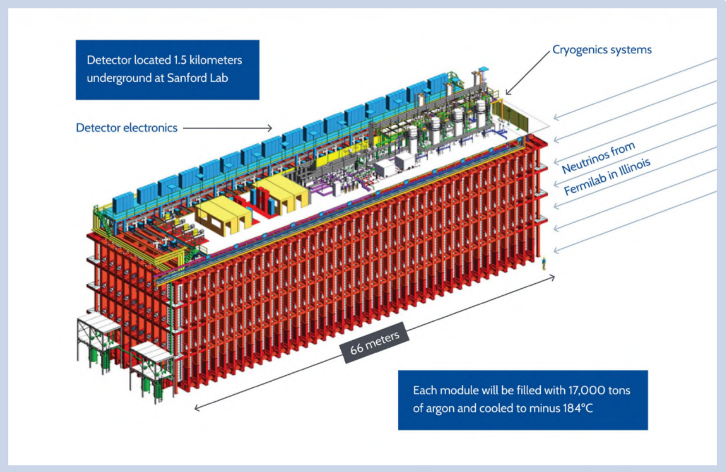
NuMI beamline (120 GeV proton beam)
running experiments: NOvA

Long-Baseline Neutrino Experiments (Future)

- Future experiments using intense ν_μ and $\bar{\nu}_\mu$ beams (after 2028)

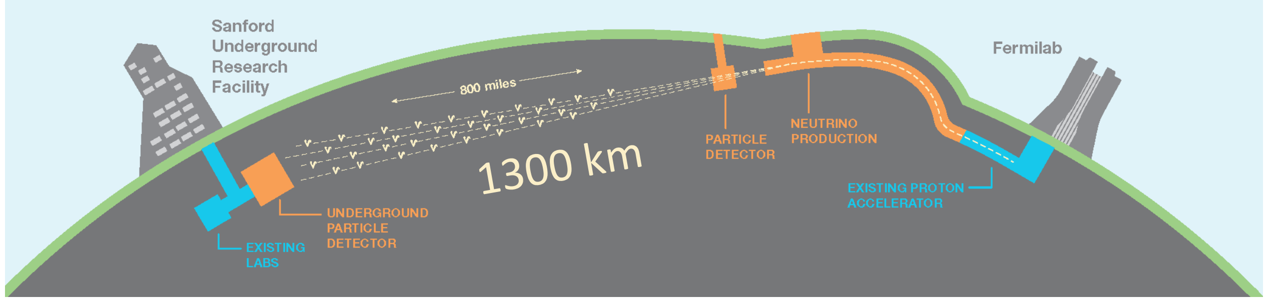
Hyper-Kamiokande

J-PARC beamline (30 GeV proton beam)
future experiment: T2HK


Detector located 1.5 kilometers underground at Sanford Lab

Each module will be filled with 17,000 tons of argon and cooled to minus 184°C

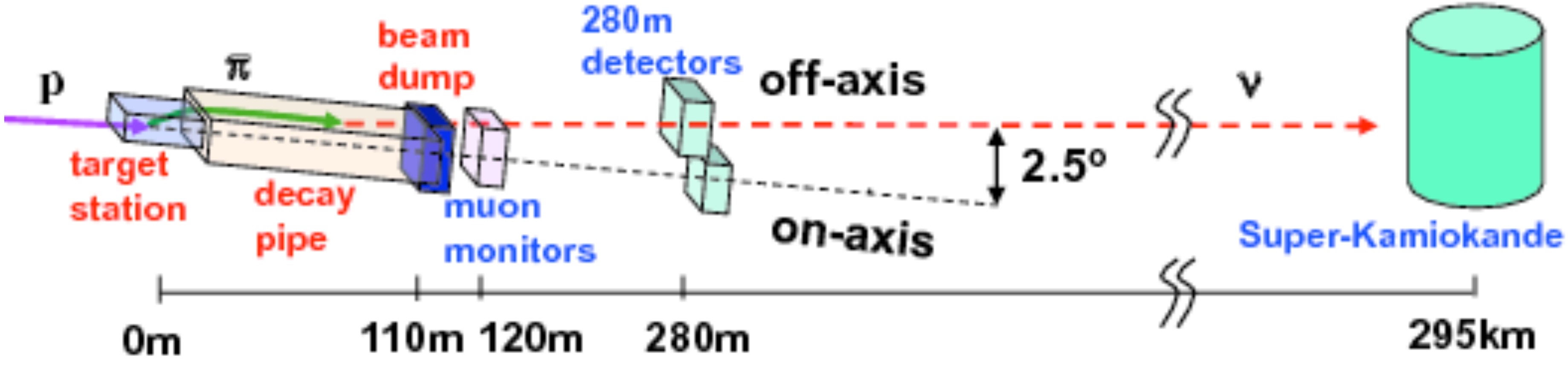
DEEP UNDERGROUND NEUTRINO EXPERIMENT



LBNF beamline (likely 120 GeV proton beam)
future experiment: DUNE

Long-Baseline Neutrino Experiments

example: T2K experiment
(Running: 2011- present)

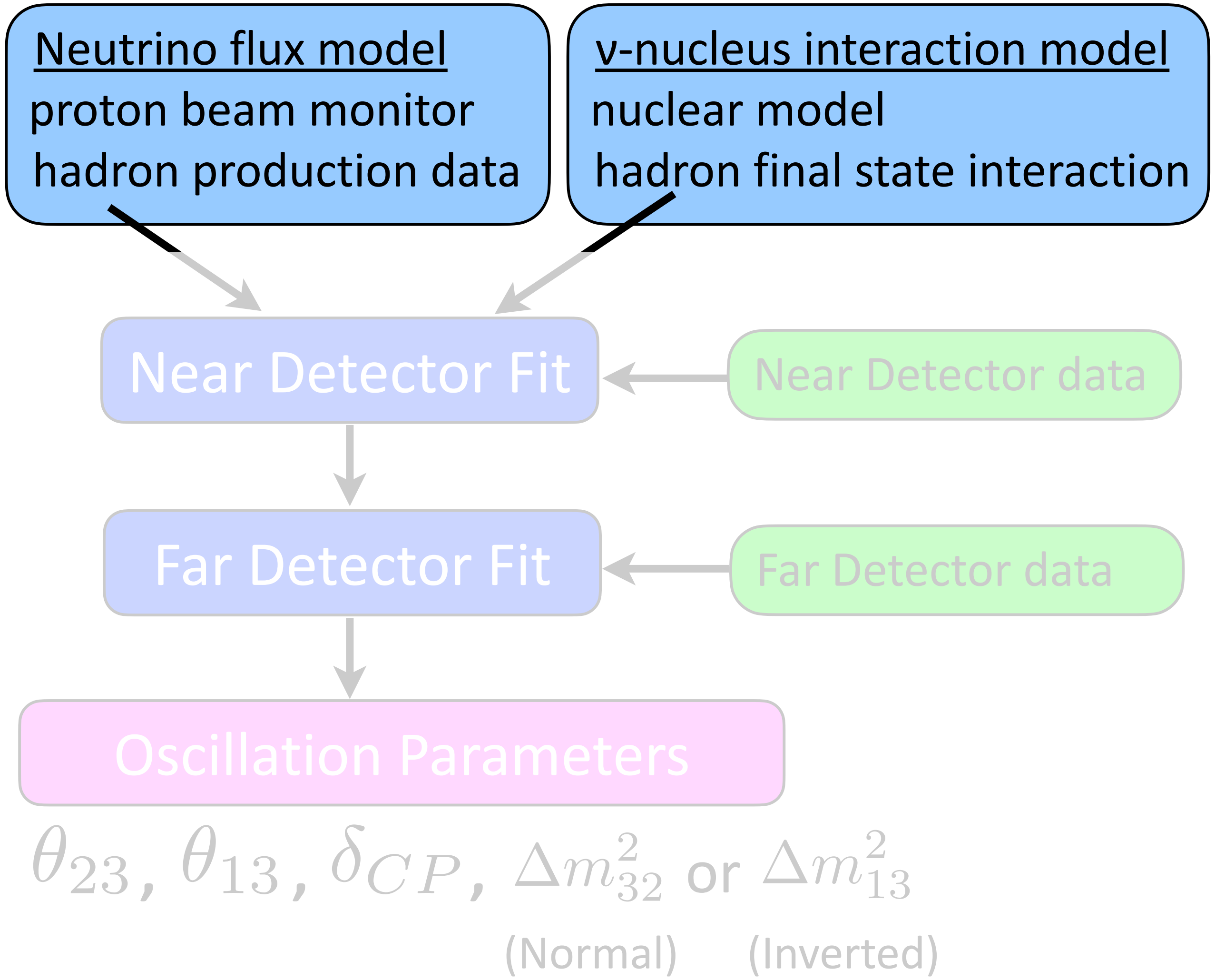


- Beamline
  - Create intense (anti-)neutrino beams Φ_{initial}
- Near detector
  - Constrain flux and cross-section for far detector prediction
  - Measure neutrino-nucleus cross-section in detail $N_{ND} \propto \int \Phi_{ND} \cdot \sigma \, dE_\nu$
- Far detector
  - Extract neutrino oscillation parameters by counting oscillated neutrino events

$$N_{FD} \propto \int \Phi_{FD} \cdot \sigma \cdot P_{osc} \, dE_\nu$$

Neutrino Oscillation Analysis

- Neutrino oscillation



Neutrino flux model
proton beam monitor
hadron production data

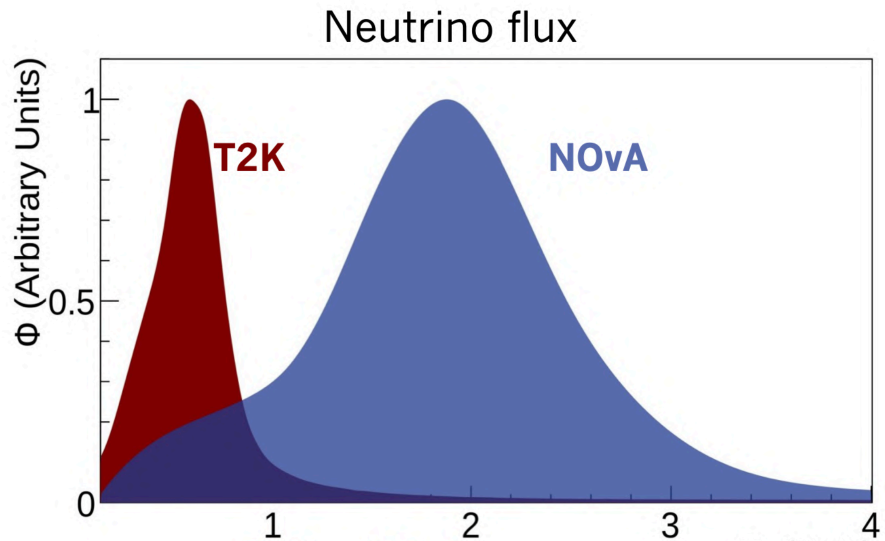
ν-nucleus interaction model
nuclear model
hadron final state interaction

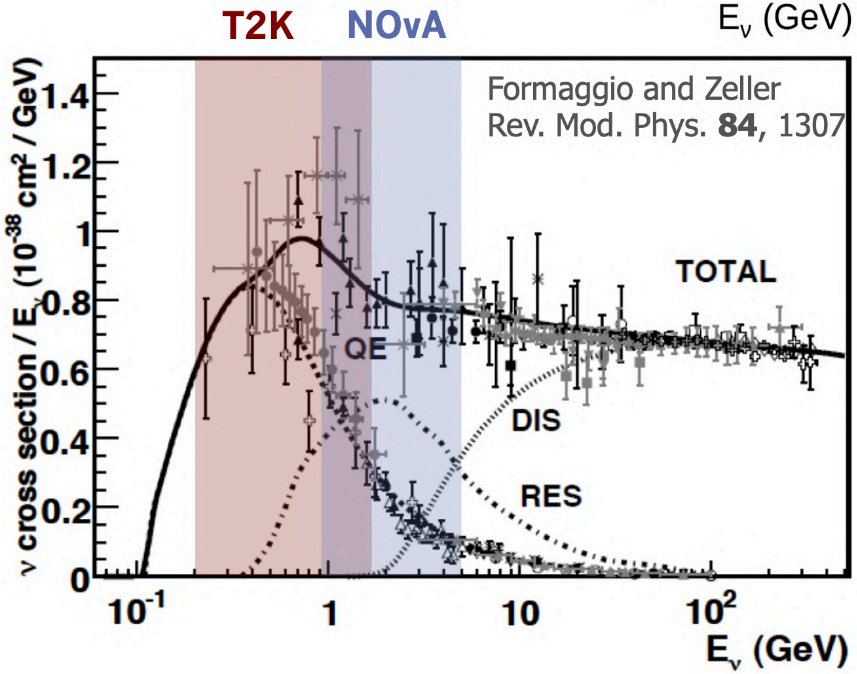
Near Detector Fit ← Near Detector data

Far Detector Fit ← Far Detector data

Oscillation Parameters

$\theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{32}$ or Δm^2_{13}
(Normal) (Inverted)

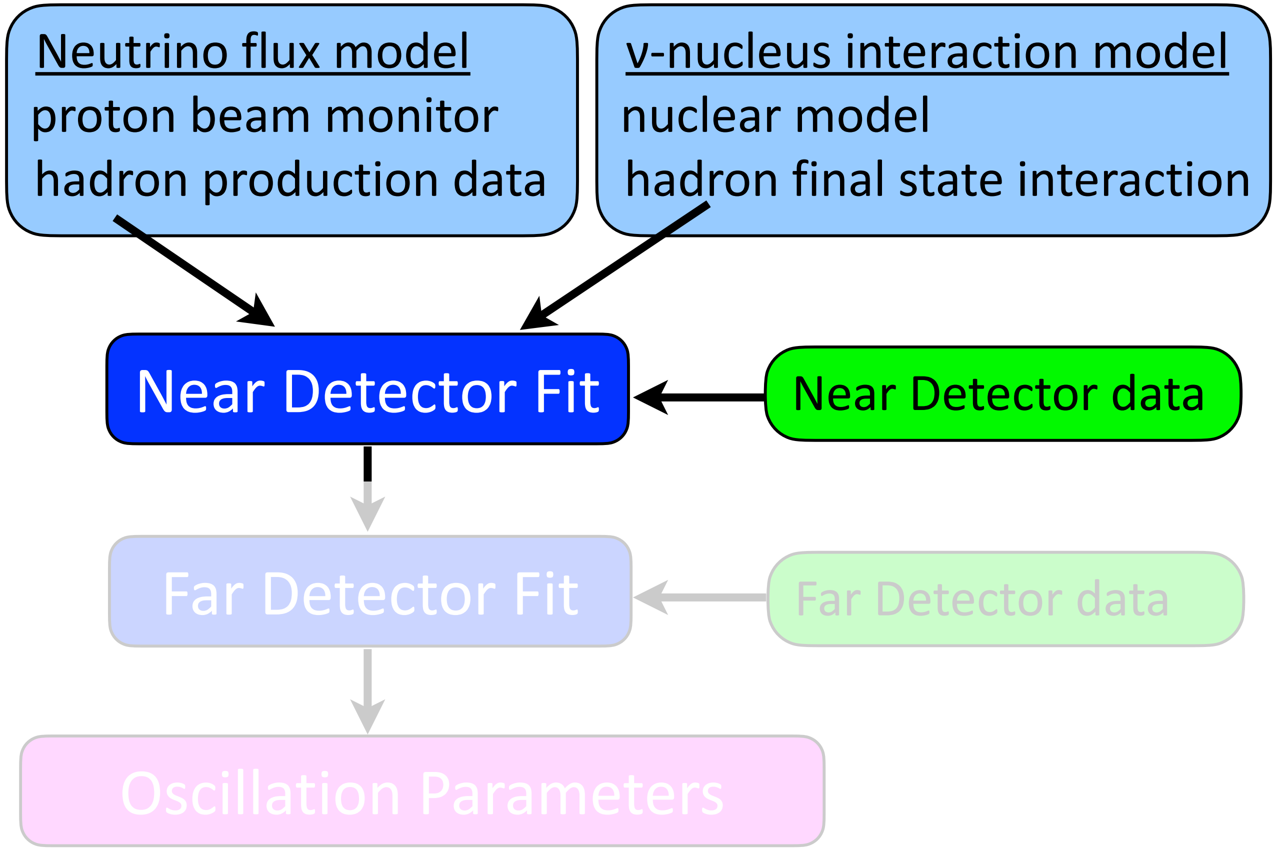




Formaggio and Zeller
Rev. Mod. Phys. **84**, 1307

Neutrino Oscillation Analysis

- Neutrino oscillation



<u>Neutrino flux model</u>
proton beam monitor
hadron production data

<u>ν-nucleus interaction model</u>
nuclear model
hadron final state interaction

Near Detector Fit

Near Detector data

Far Detector Fit

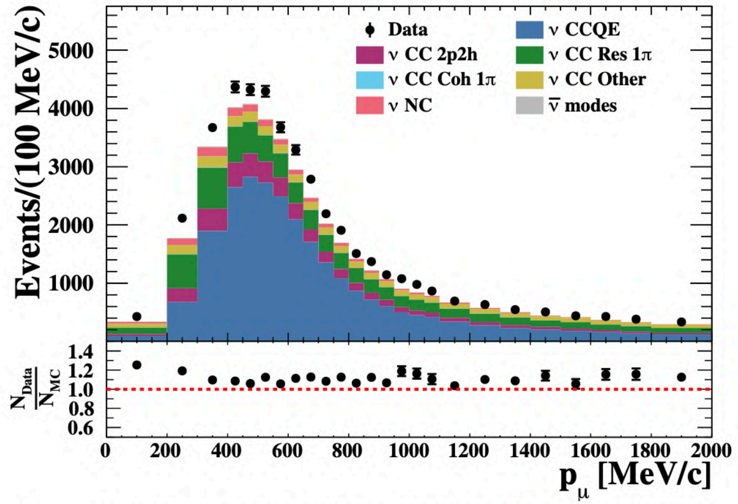
Far Detector data

Oscillation Parameters

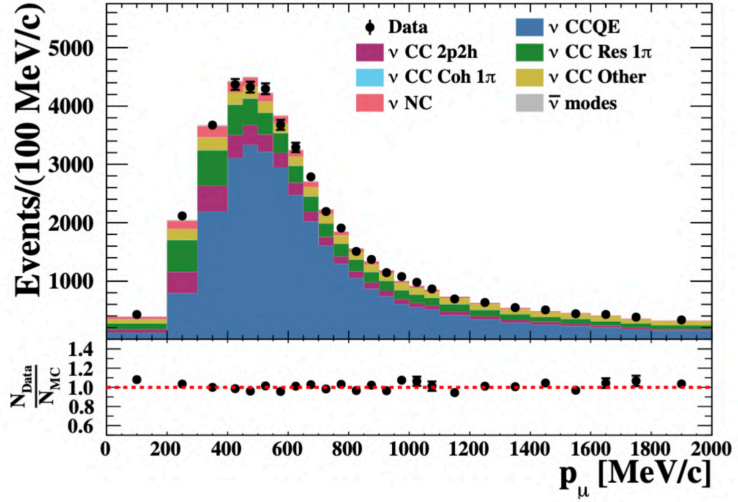
$\theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{32}$ or Δm^2_{13}

(Normal) (Inverted)

<u>ν_μ events at near detector</u>



(before fit)

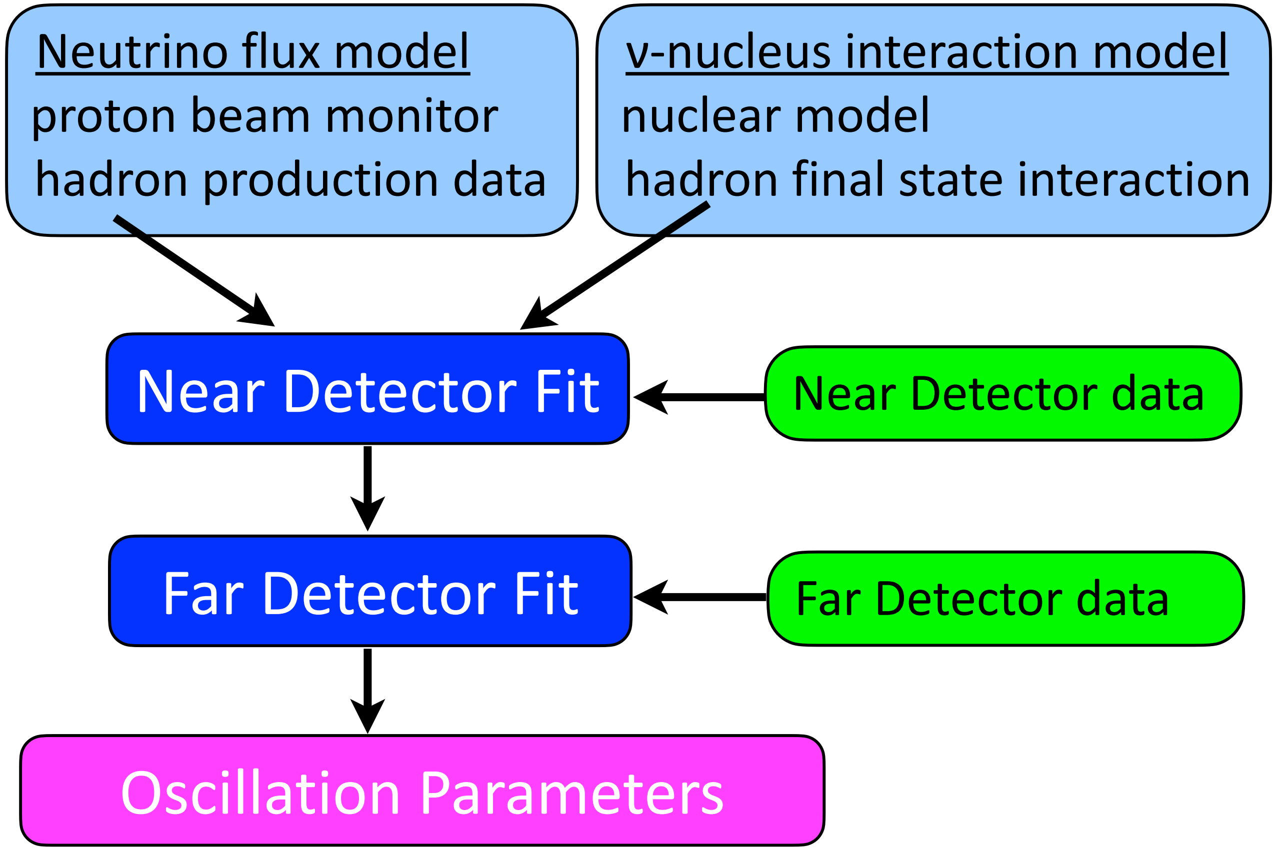


(after fit)

T2K: *Eur.Phys.J.C* 83 (2023) 9, 782

Neutrino Oscillation Analysis

- Neutrino oscillation



Neutrino flux model
proton beam monitor
hadron production data

ν-nucleus interaction model
nuclear model
hadron final state interaction

Near Detector Fit

Near Detector data

Far Detector Fit

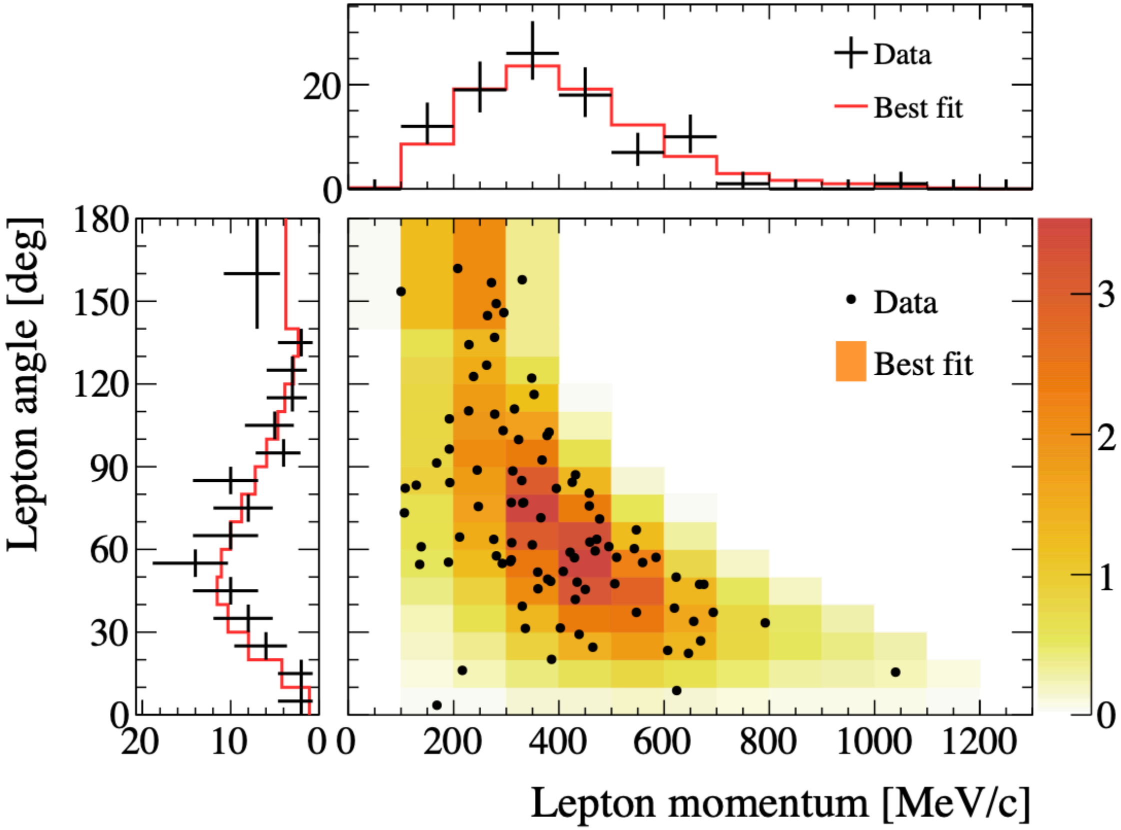
Far Detector data

Oscillation Parameters

θ_{23}, θ_{13}, δ_{CP}, Δm^2_{32} or Δm^2_{13}

(Normal) (Inverted)

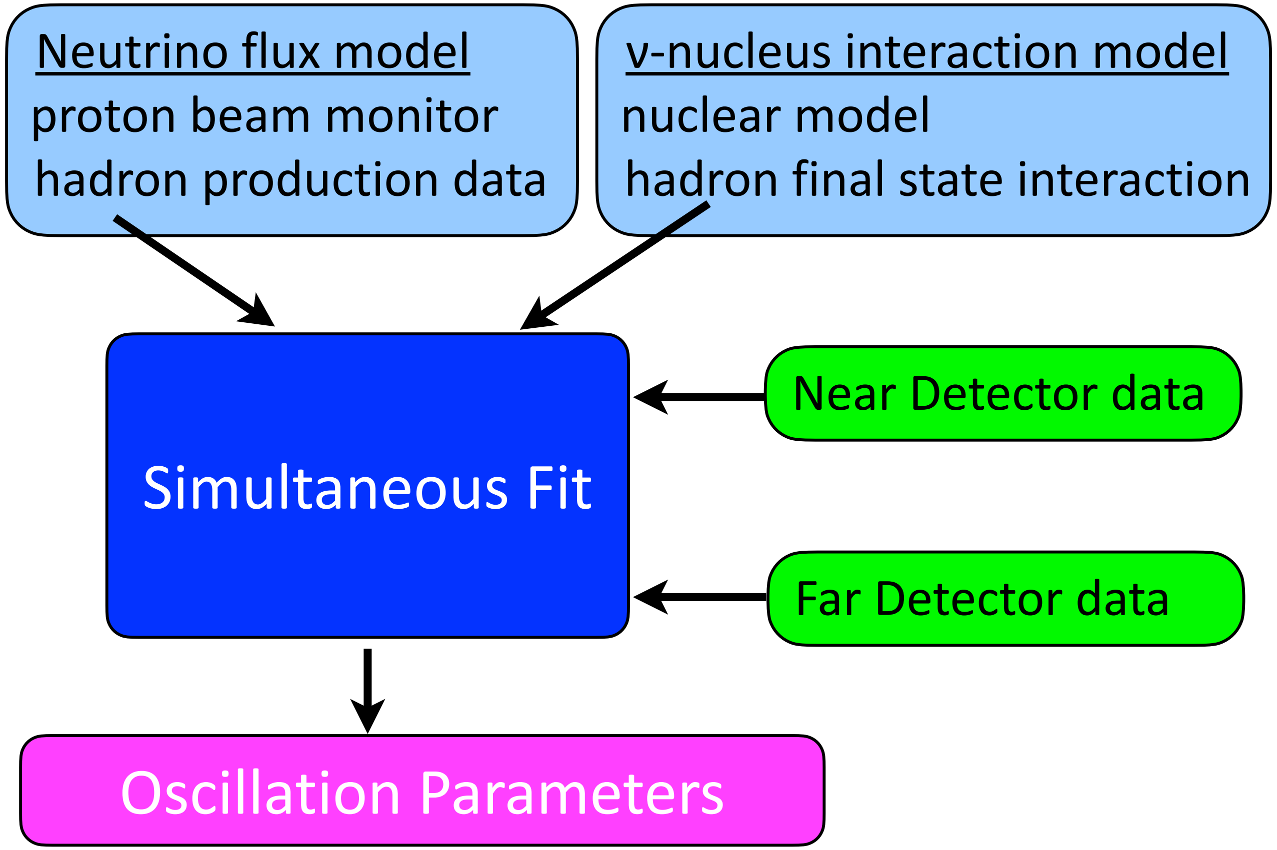
ν_e events (appearance) at far detector



T2K: *Eur.Phys.J.C* 83 (2023) 9, 782

Neutrino Oscillation Analysis

- Neutrino oscillation



Neutrino flux model
proton beam monitor
hadron production data

ν-nucleus interaction model
nuclear model
hadron final state interaction

Simultaneous Fit

Near Detector data

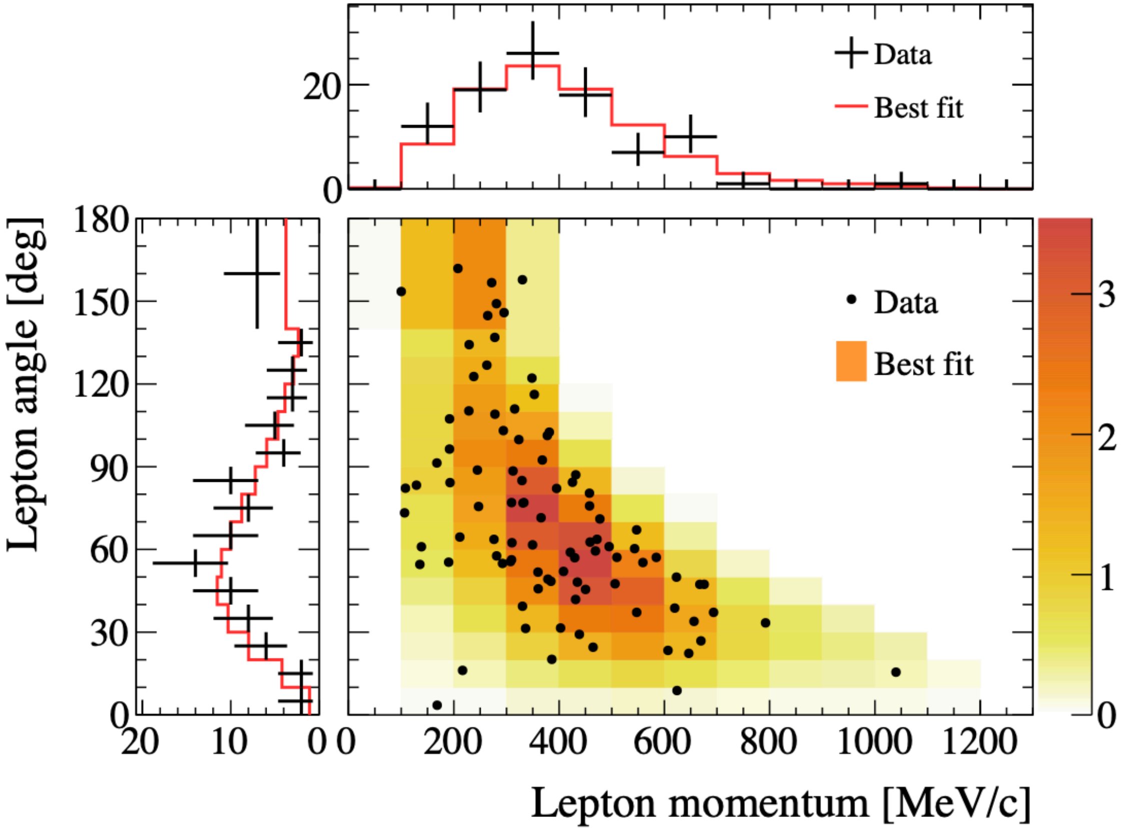
Far Detector data

Oscillation Parameters

θ_{23}, θ_{13}, δ_{CP}, Δm^2_{32} or Δm^2_{13}

(Normal) (Inverted)

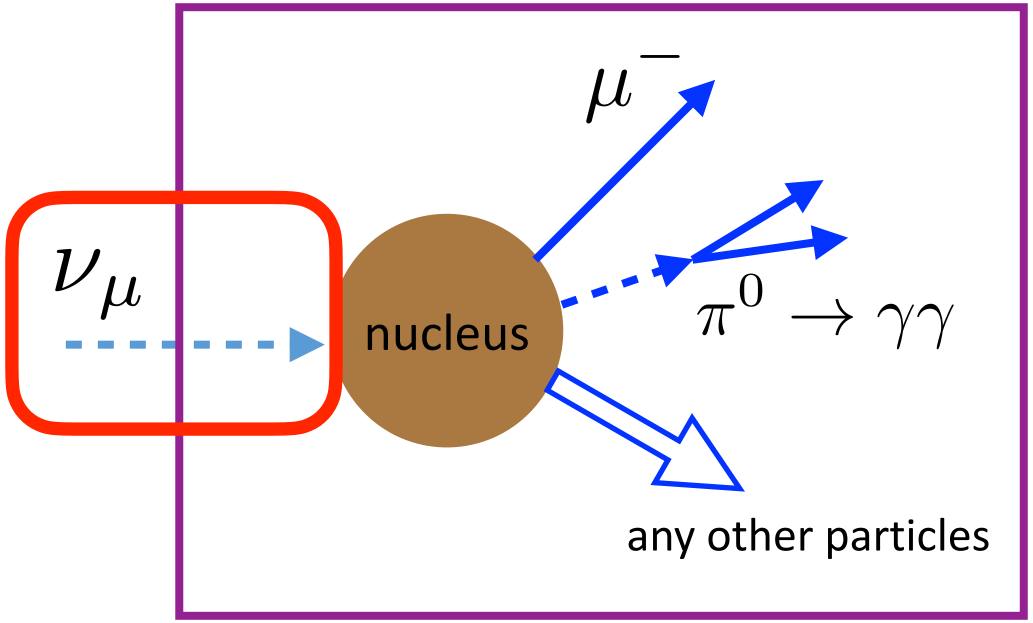
ν_e events (appearance) at far detector



T2K: *Eur.Phys.J.C* 83 (2023) 9, 782

Other Physics Programs

- Neutrino interactions studies



Near Detector

- BSM

Search for

- Dark photon production on neutrino target
- Lorentz violation
- CPT violation
- Non-Standard interactions (NSI)
- Sterile neutrinos, heavy neutrinos

…

Rich physics topics.

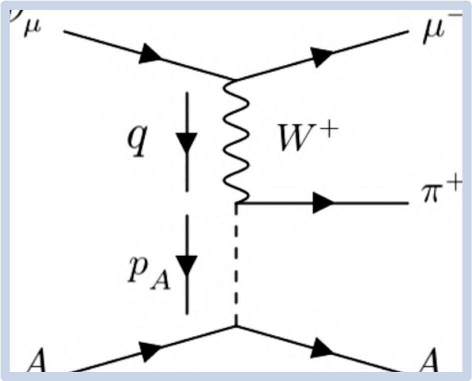
Add your shopping list here!!

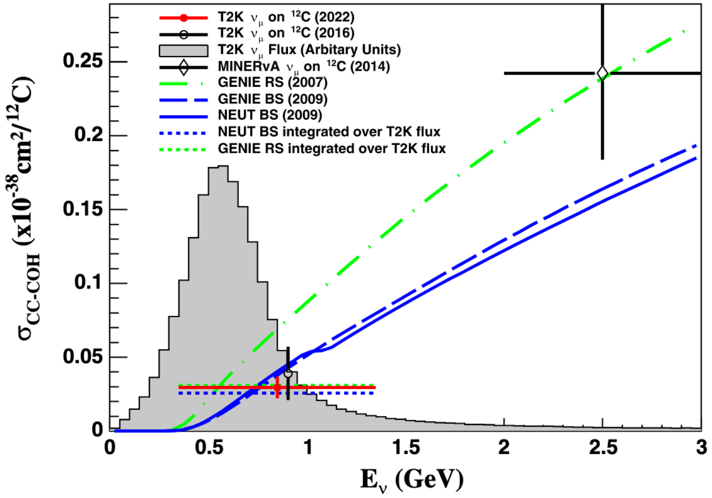
Other Physics Programs

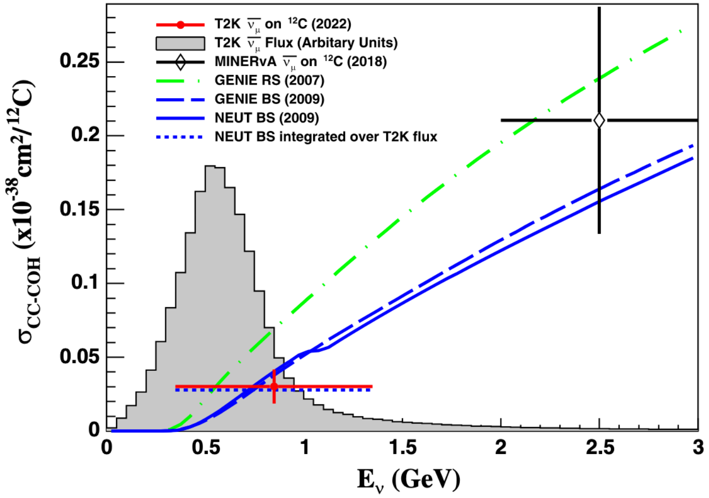
- Neutrino interactions studies

e.g. Measurement of coherent pion production on ^{12}C

T2K: Phys.Rev.D 108 (2023), 092009



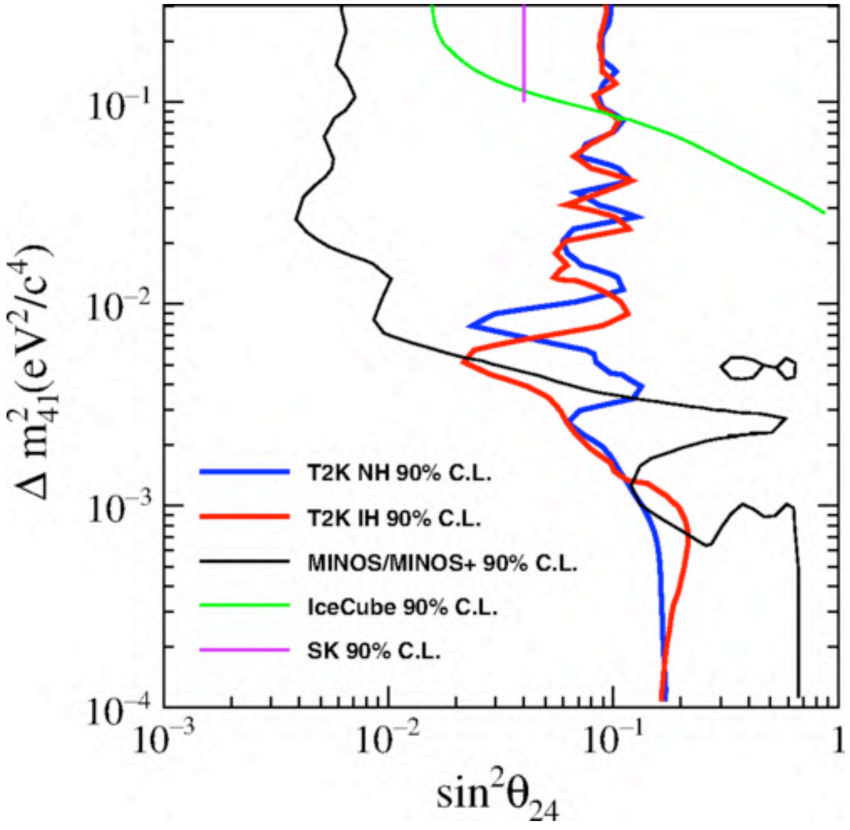


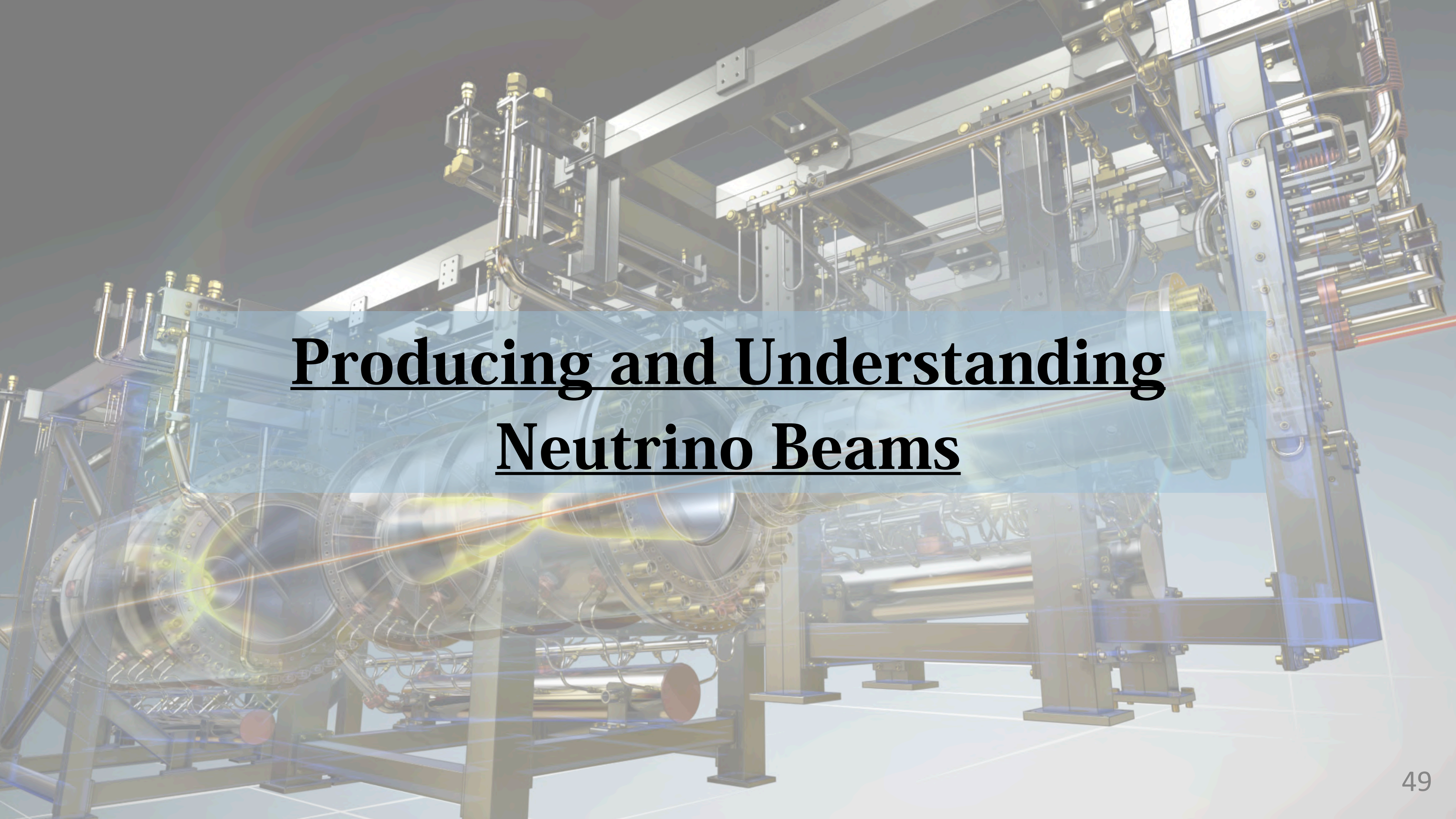


- BSM

e.g. Search for light sterile neutrinos

T2K: Phys.Rev.D 99 (2019) 7, 071103



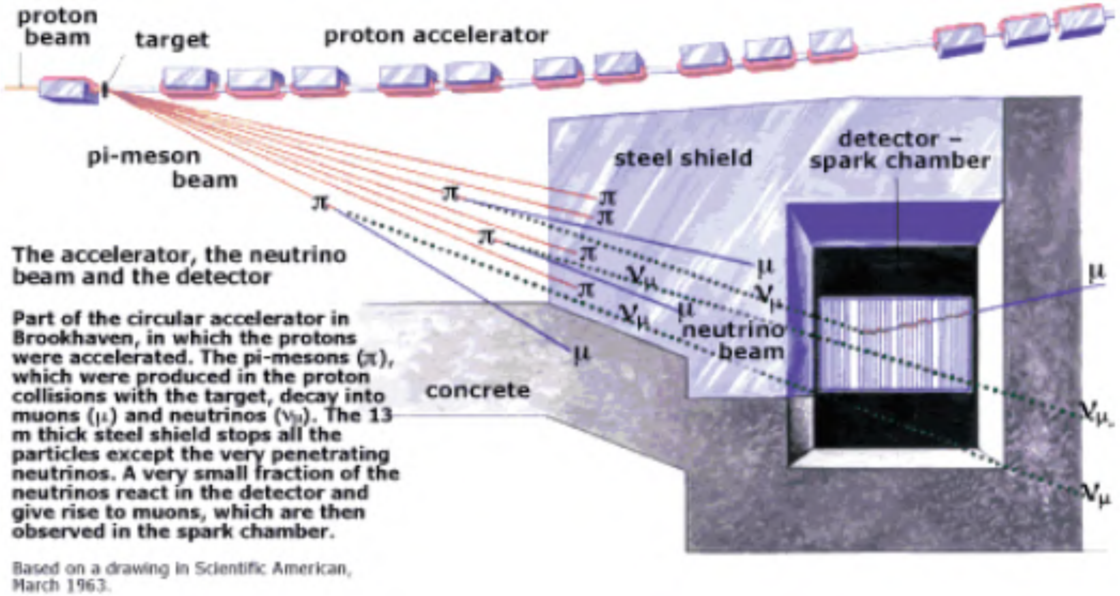


Producing and Understanding Neutrino Beams

Neutrino Beams

Not a recent idea, more than 60 years of history!

1962: The first accelerator neutrino beam and the discovery of the muon neutrino



The accelerator, the neutrino beam and the detector

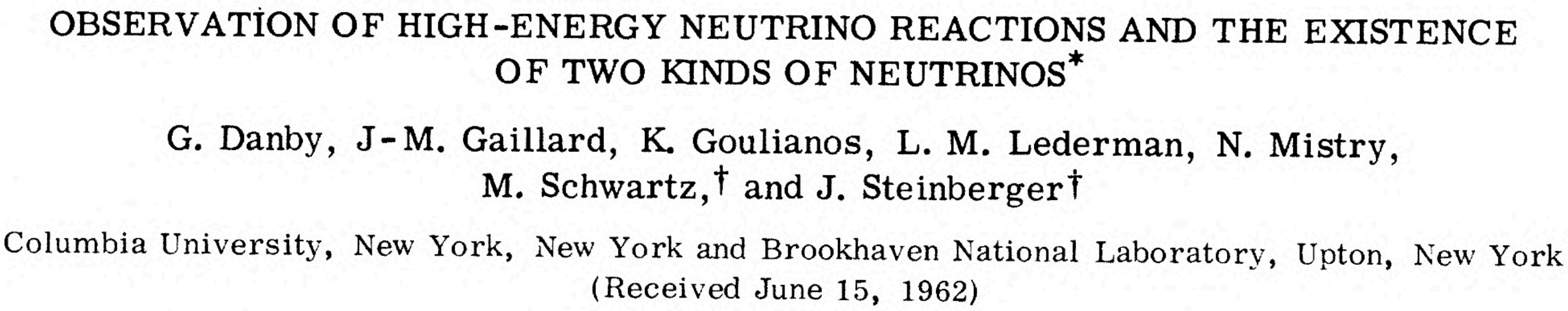
Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons (π), which were produced in the proton collisions with the target, decay into muons (μ) and neutrinos (ν_μ). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.


Leon Lederman


Melvin Schwartz


Jack Steinberger


OBSERVATION OF HIGH-ENERGY NEUTRINO REACTIONS AND THE EXISTENCE OF TWO KINDS OF NEUTRINOS*

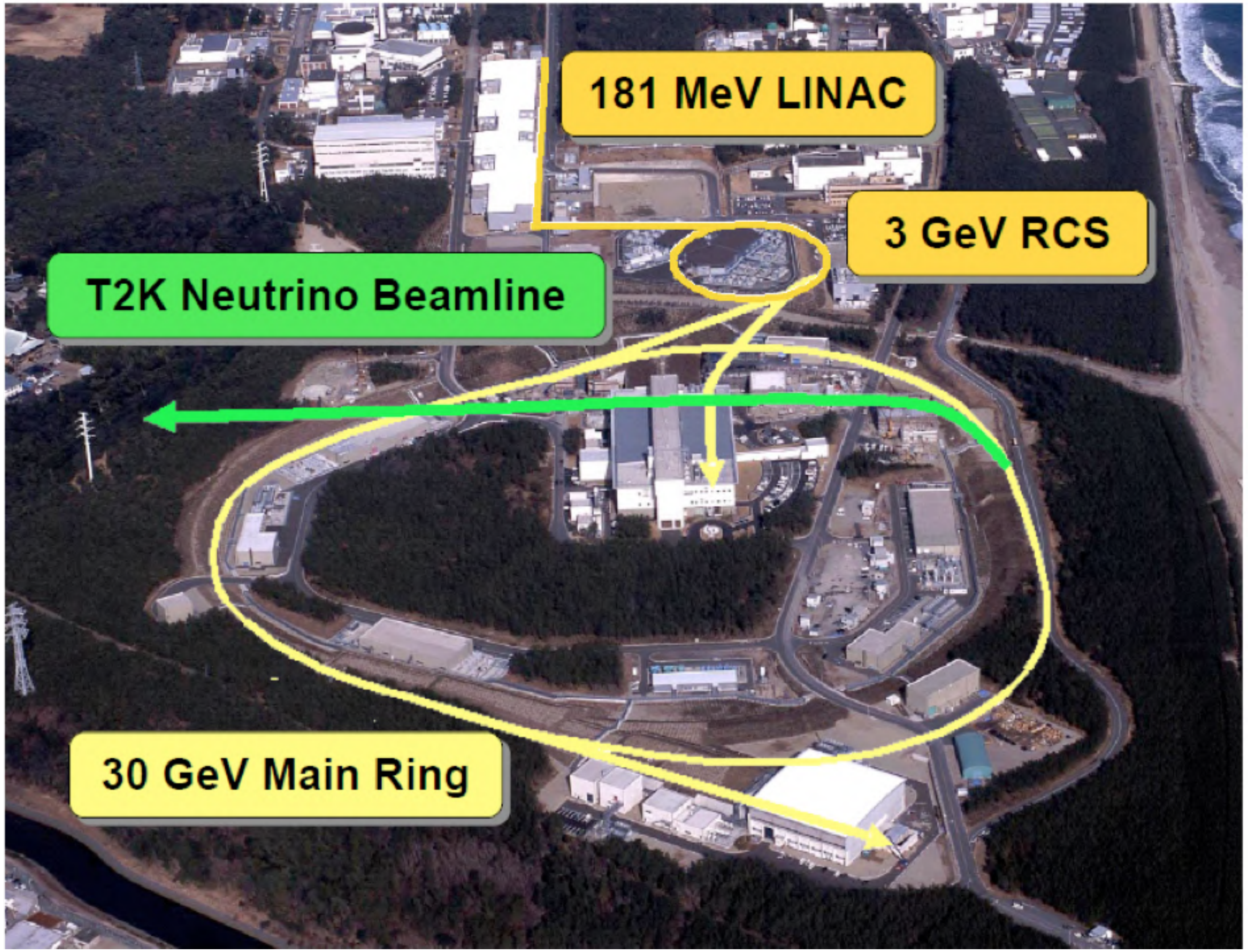
G. Danby, J-M. Gaillard, K. Goulianos, L. M. Lederman, N. Mistry, M. Schwartz,† and J. Steinberger†

Columbia University, New York, New York and Brookhaven National Laboratory, Upton, New York
(Received June 15, 1962)

The Nobel Prize in Physics 1988

Neutrino Beams with Accelerators

An example: J-PARC accelerator complex



Key parameters for the neutrino beamline

- protons per bunch: 3.13×10^{13}

  —> To be upgraded to 4.0×10^{13}

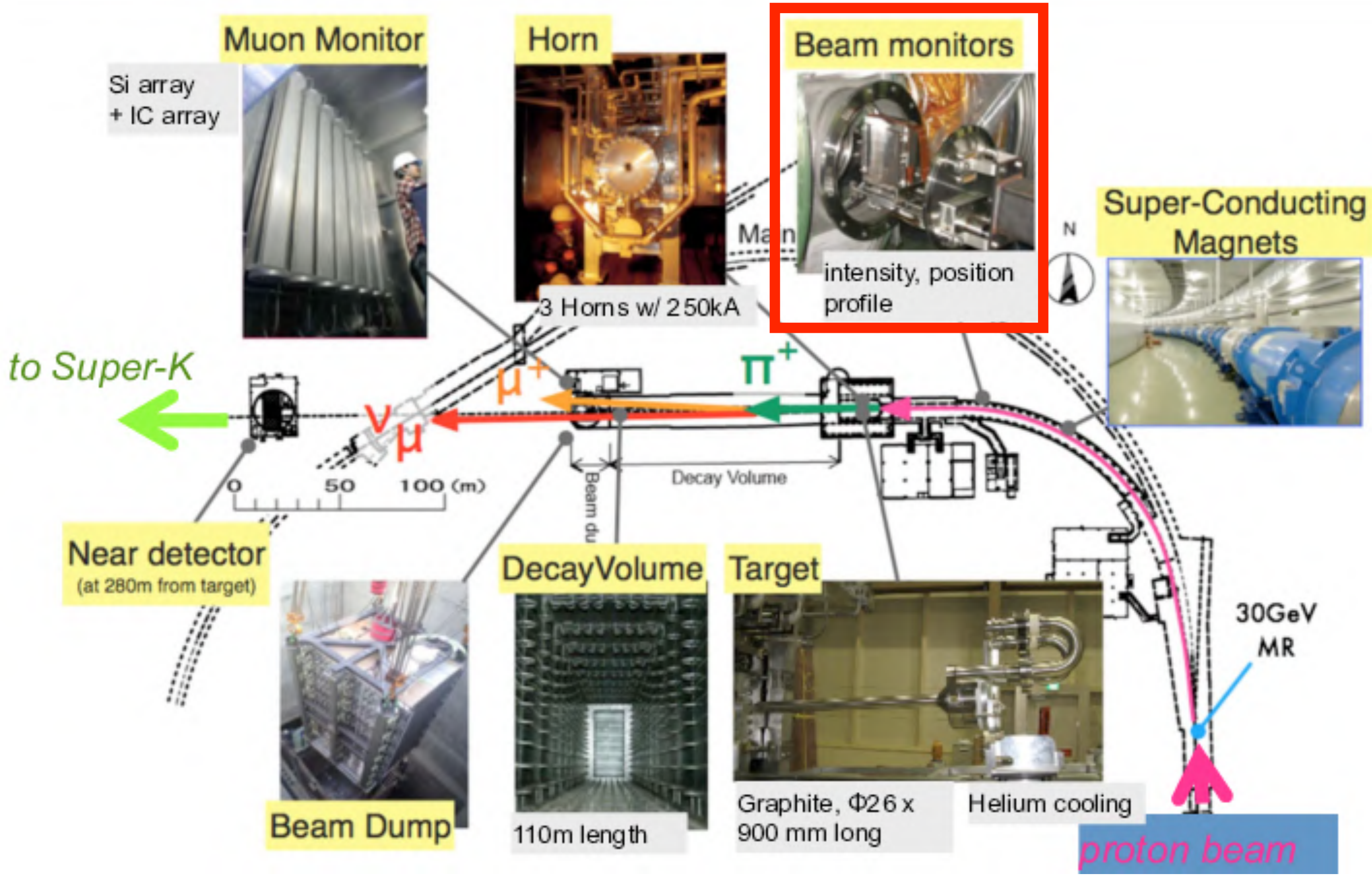
  (c.f. LHC Run3: ~10^{11} protons per bunch)
- repetition rate: 1.36 s

  —> To be upgraded to 1.16 s

=> ~750 kW (Achieved), 1.3 MW by 2027

Beam power (W) = Beam current (A) x Beam energy (eV)
Beam current (A) = # of protons/sec.
Beam energy (eV) = 30 GeV (for T2K)
-> More protons with a shorter repetition rate makes higher beam power

Neutrino Beamline at J-PARC



Beam monitors

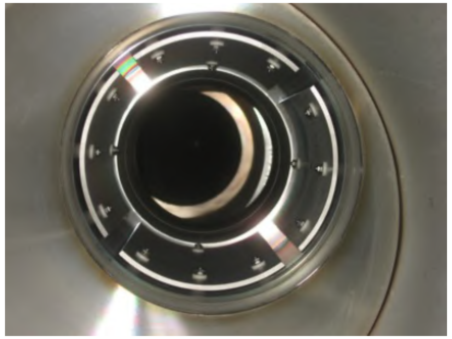
- Essential to protect beamline from high-power proton beam (now 750 kW —> 1.3 MW)
- Essential for understanding and predicting the ν flux

Beam intensity

- Current transformer
- < 2.7% precision

Beam Position

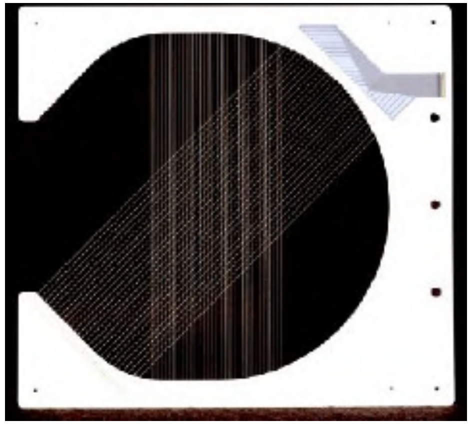
- Electro-static monitor
- 450 μm precision



Beam position & profile

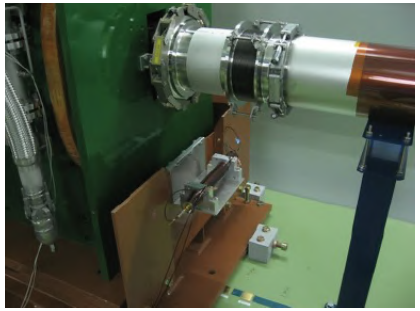
- various technology
- ~100 μm resolution

wire secondary emission monitor

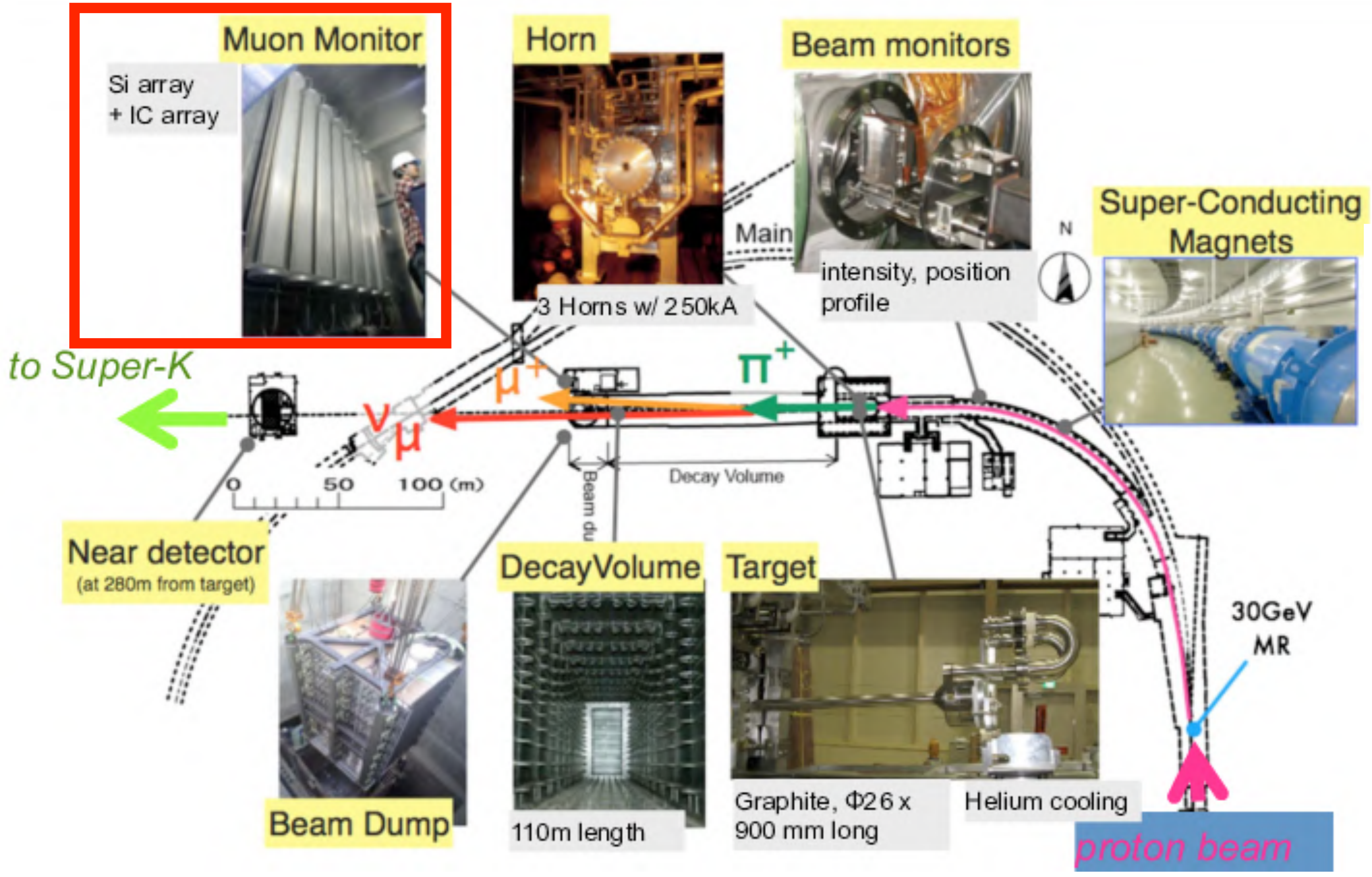


Beam loss

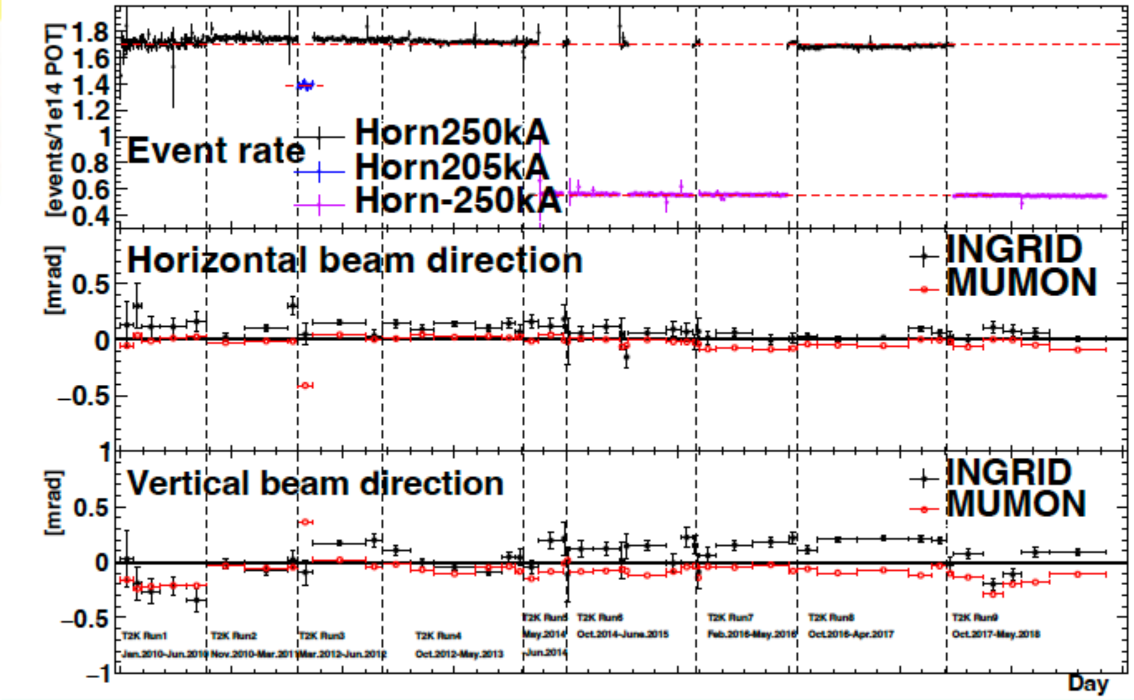
- Sensitive down to 16 mW



Neutrino Beamline at J-PARC



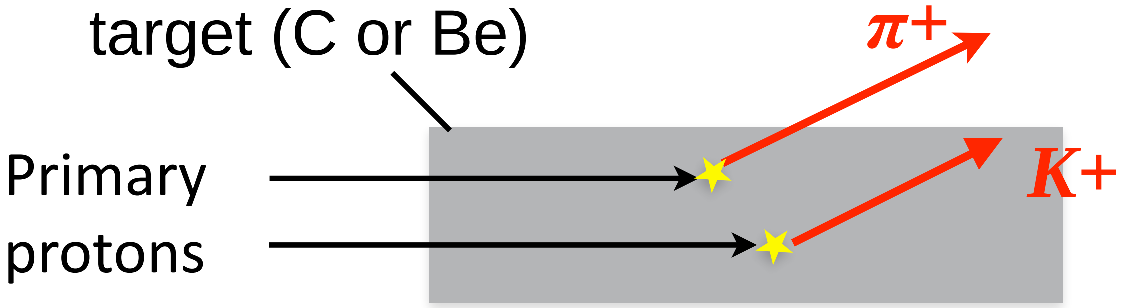
One example: beam direction

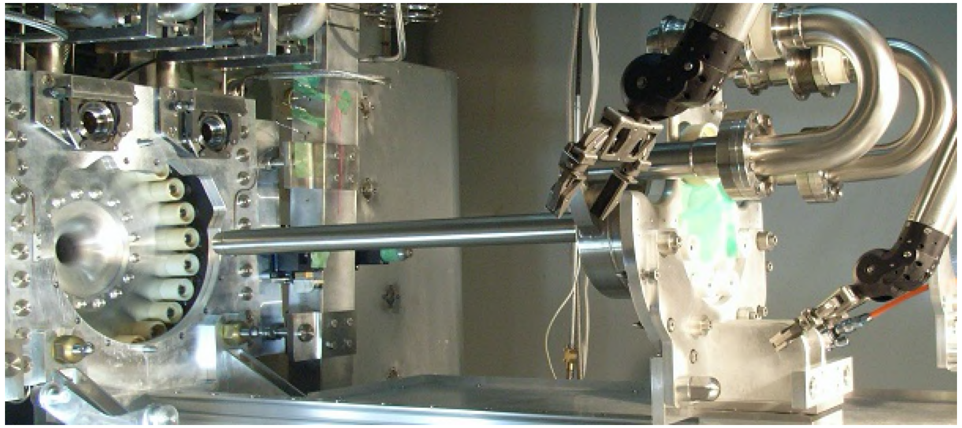


<u>Muon monitor</u>

- Monitor neutrino direction using muons

Accelerator Neutrino Production





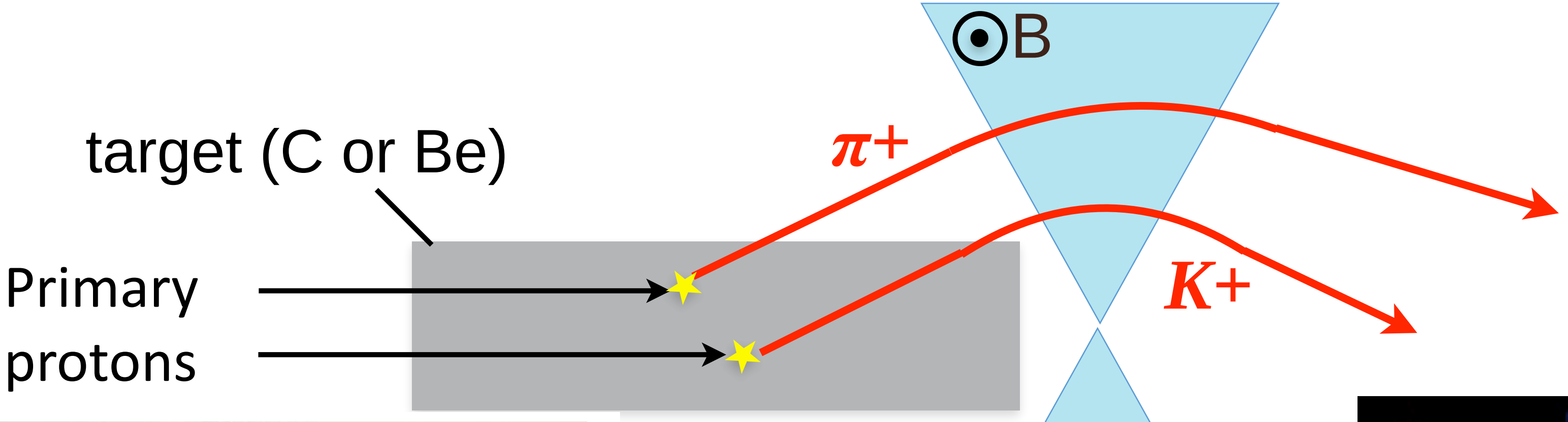
T2K target at J-PARC (Japan)

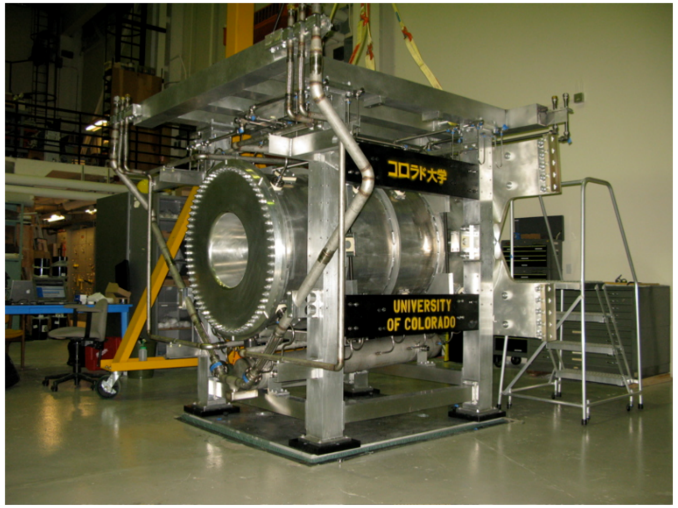
length: 90 cm

Hadron productions of $\pi^{\pm}$ and $K^{\pm}$ through primary interactions in the target (p + C, p + Be)

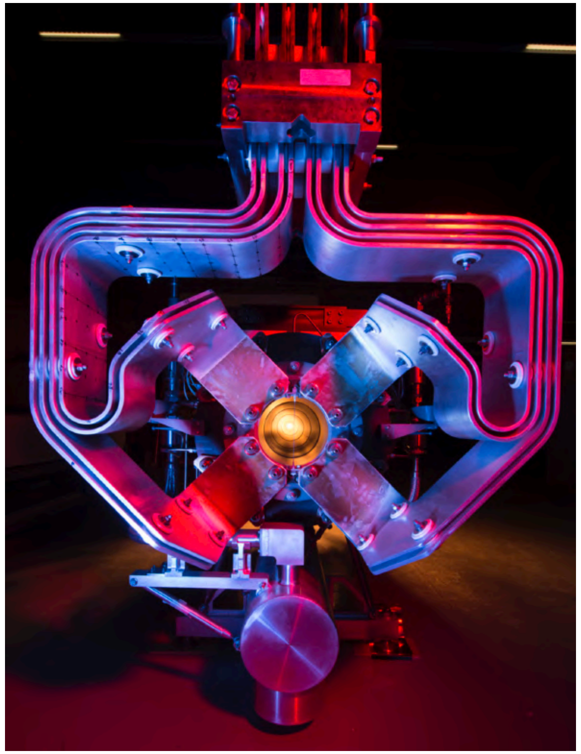
NuMI target at Fermilab (USA)
length: 120 cm

Accelerator Neutrino Production





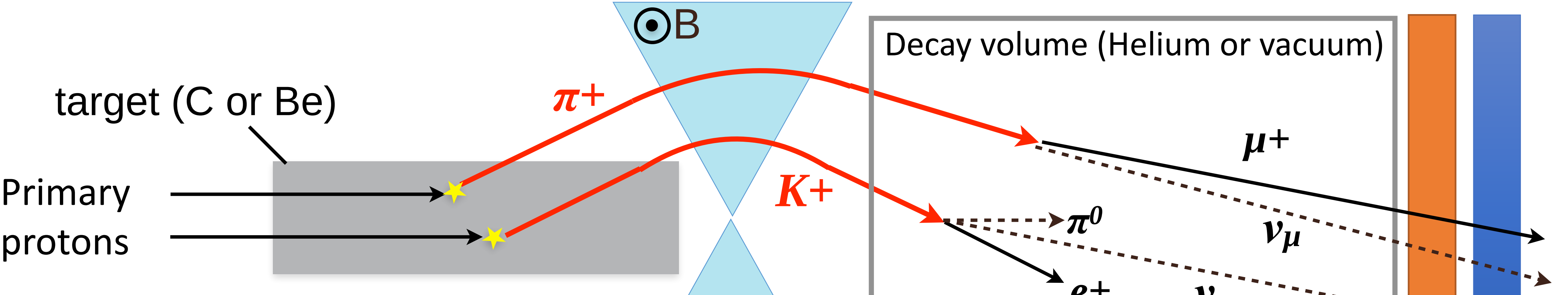
T2K magnetic horn



NuMI magnetic horn

Charged hadrons (pions and kaons) are focused by a toroidal field (magnetic horns) to produce (anti)neutrino-enhanced beams

Accelerator Neutrino Production

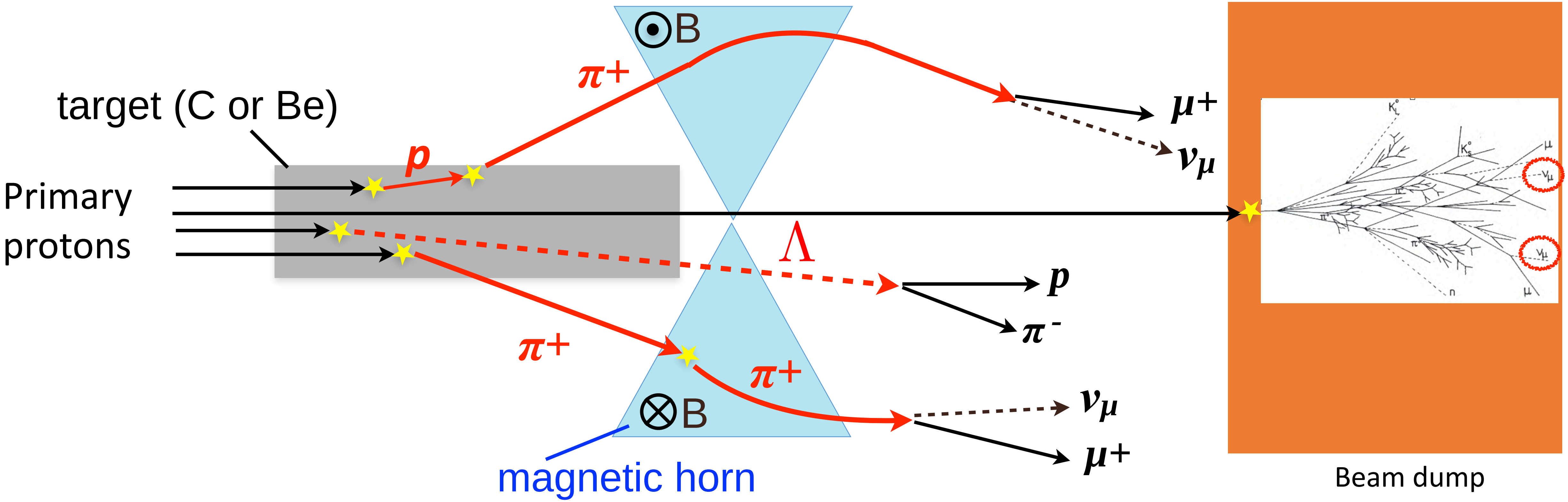


T2K decay volume
(Helium filled, length: 110m)

NuMI decay pipe
(~1 Torr vacuum,
length: 675 m)

Charged hadrons (pions and kaons) decays to neutrinos in decay volume
—> Primary contribution to the neutrino flux

Accelerator Neutrino Production



Hadron production process can be more complex:

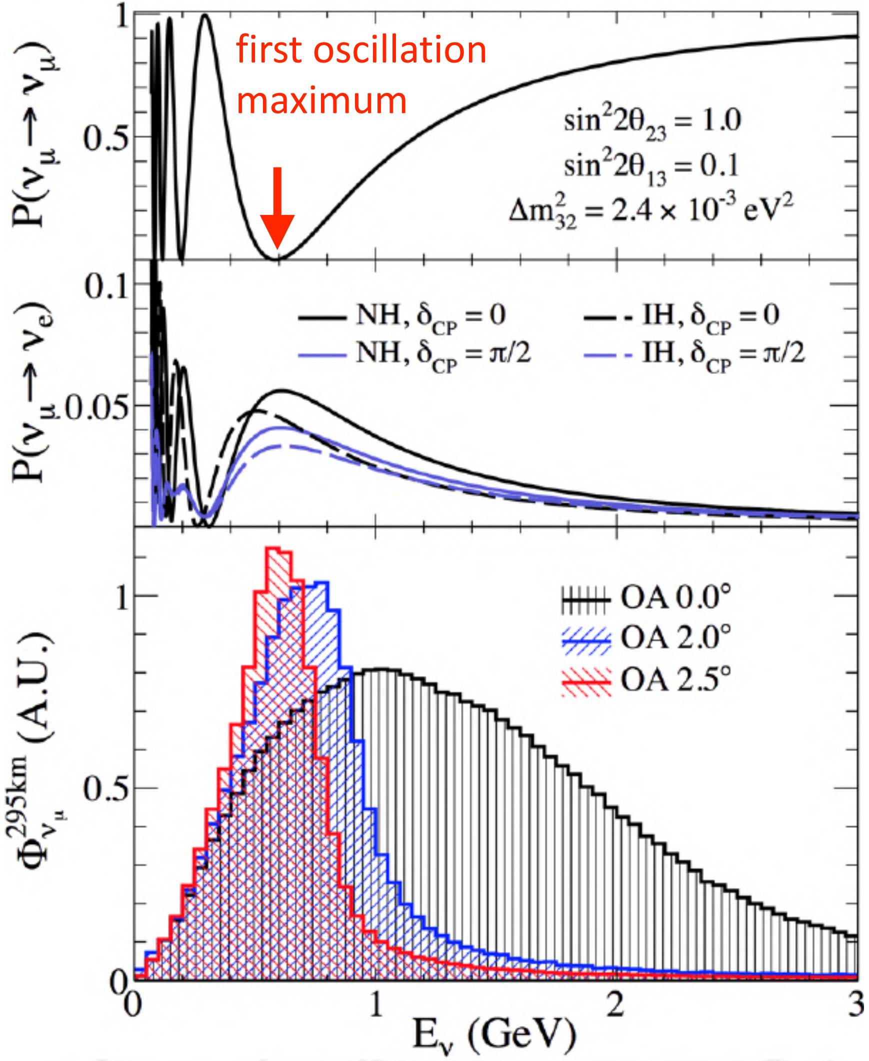
- Secondary interactions with beamline materials
  - X = C, Be, Al, Ti, Fe, H_2O, etc..
- Neutral hadron decay (*p* + C / Be —> V^0 + X)
- Non-interacted primarily protons reach at beam dump

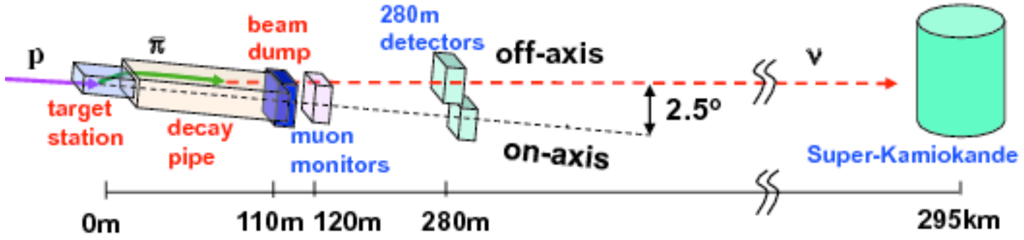
=> Non-negligible contribution to the neutrino flux

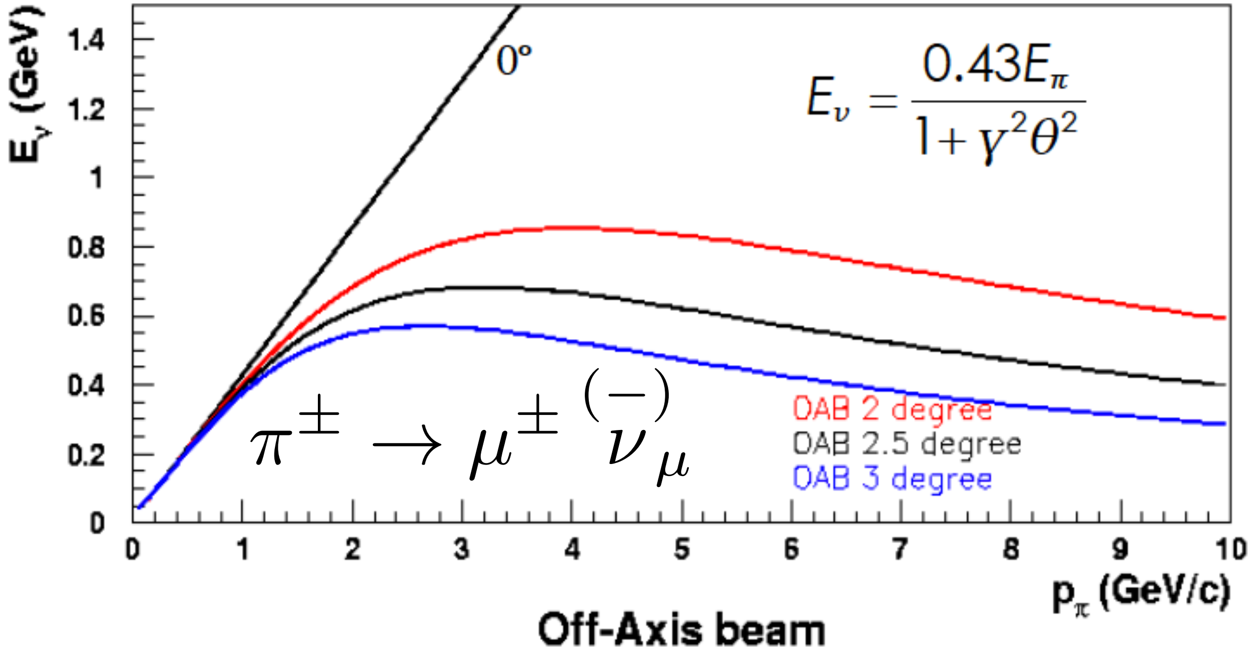
Off-axis Beam

- Why do T2K and NOvA use off-axis beams?

—> Optimize the flux at the first oscillation maximum


first oscillation maximum



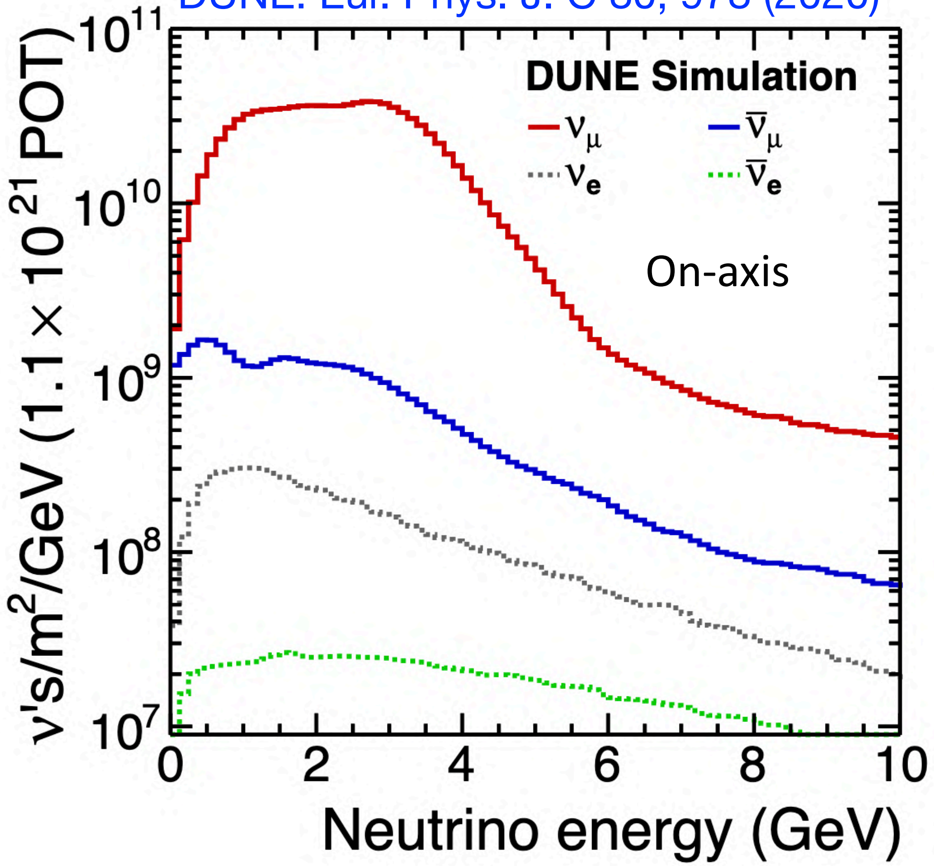


Reminder: Oscillations are seen as a function of L/E

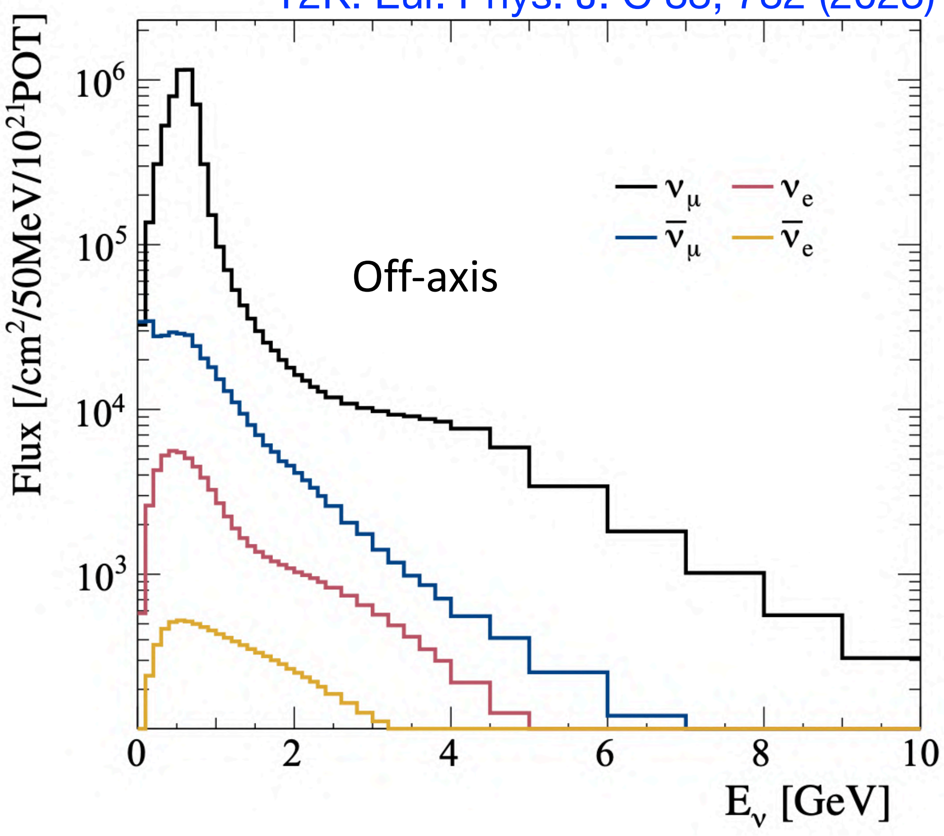
—> Detectors cannot move (fixed L value), we need a monochromatic beam to maximize oscillation probability

On-axis vs Off-axis Neutrino Beams

DUNE: Eur. Phys. J. C 80, 978 (2020)



T2K: Eur. Phys. J. C 83, 782 (2023)

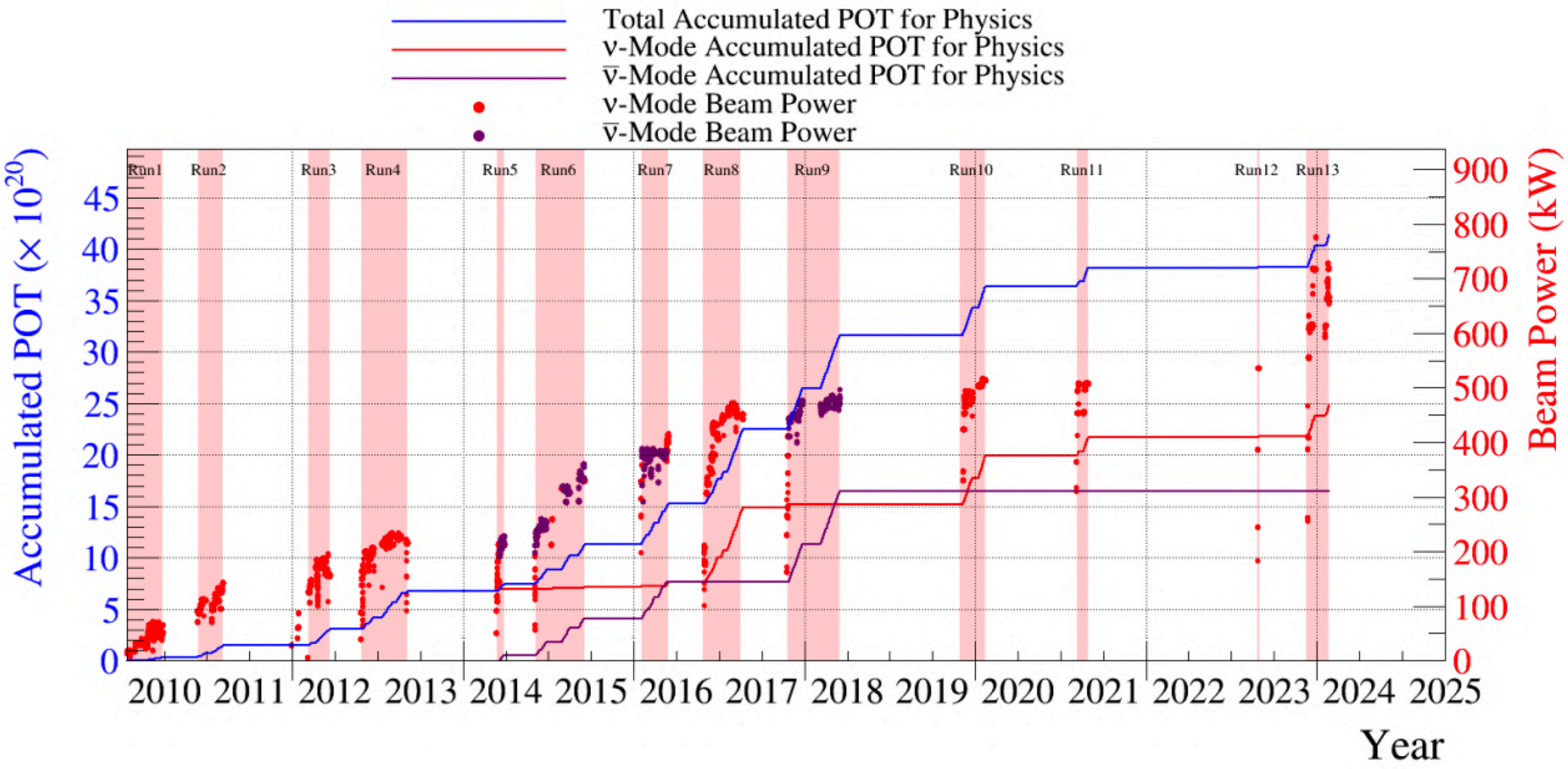


pros	- Maximum neutrino flux - Can study broader phase-space (1st and 2nd osc. maxima)	- A priori knowledge of neutrino energy - Can be tuned to a preferable L/E (osc. maxima)
cons	- Neutrino reconstruction is tough	- Lower neutrino flux

Representing Data Statistics

Protons On Target (**POT**) to express data statistics

- A typical measure for representing statistics in fixed target experiments (Collider experiments typically use integrated Luminosity, *L* [cm$^{-2}\cdot$s^{-1}])



<u>Example: T2K</u>

Run period:
Jan 2010 - Feb 2024

Power max:
780.631 kW (design: 750 kW)

POT total:
4.14047 x 10^{21}

(ν-mode) 2.49x10^{21} (~60%)

(ν̄-mode) 1.65x10^{21} (~40%)

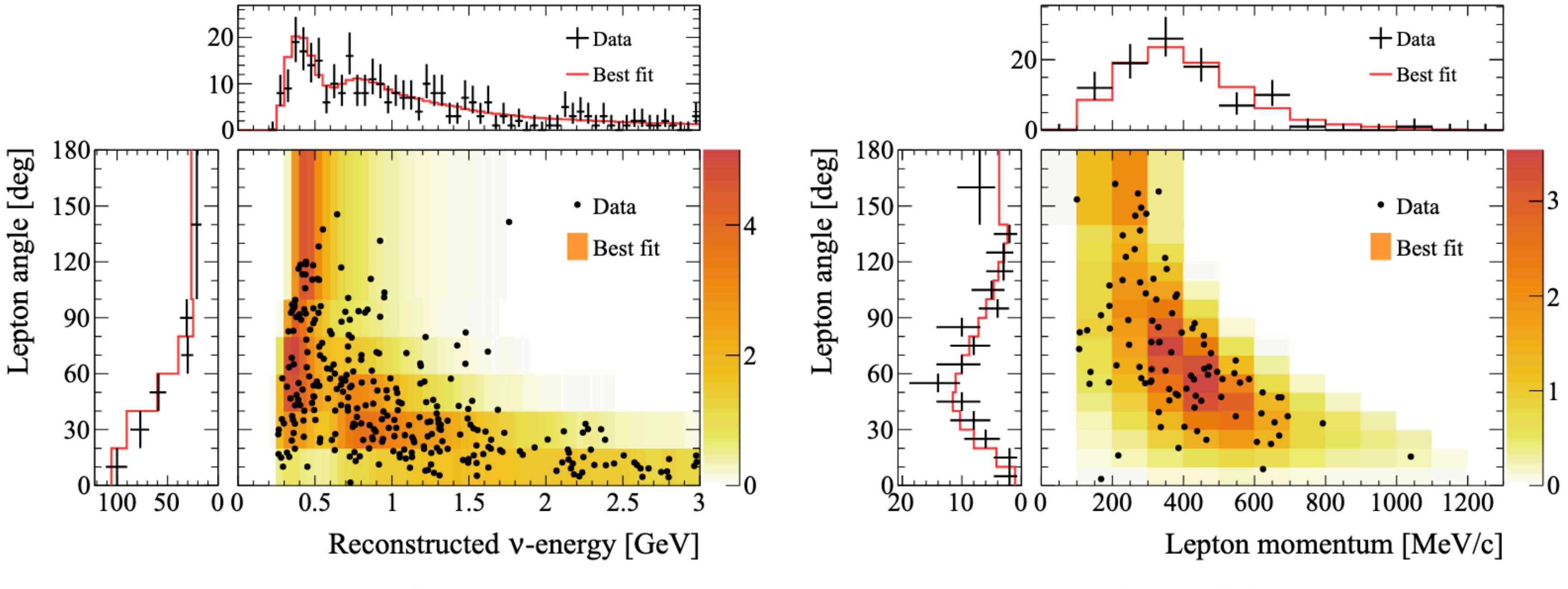
Representing Data Statistics

The goal for the current generation experiments (T2K and NOvA): **POT ~O(10^{22})**

—> To give you some idea, it is roughly

$\overset{(-)}{\nu}_{\mu}$ -> $\overset{(-)}{\nu}_{e}$ appearance channel: **~100 ν_e or $\bar{\nu}_e$ events** at the far detector

$\overset{(-)}{\nu}_{\mu}$ -> $\overset{(-)}{\nu}_{\mu}$ disappearance channel: **~1000 ν_μ or $\bar{\nu}_\mu$ events** at the far detector



(a) ν-mode 1Rμ (b) ν-mode 1Re

T2K

Eur.Phys.J.C 83 (2023) 9, 782

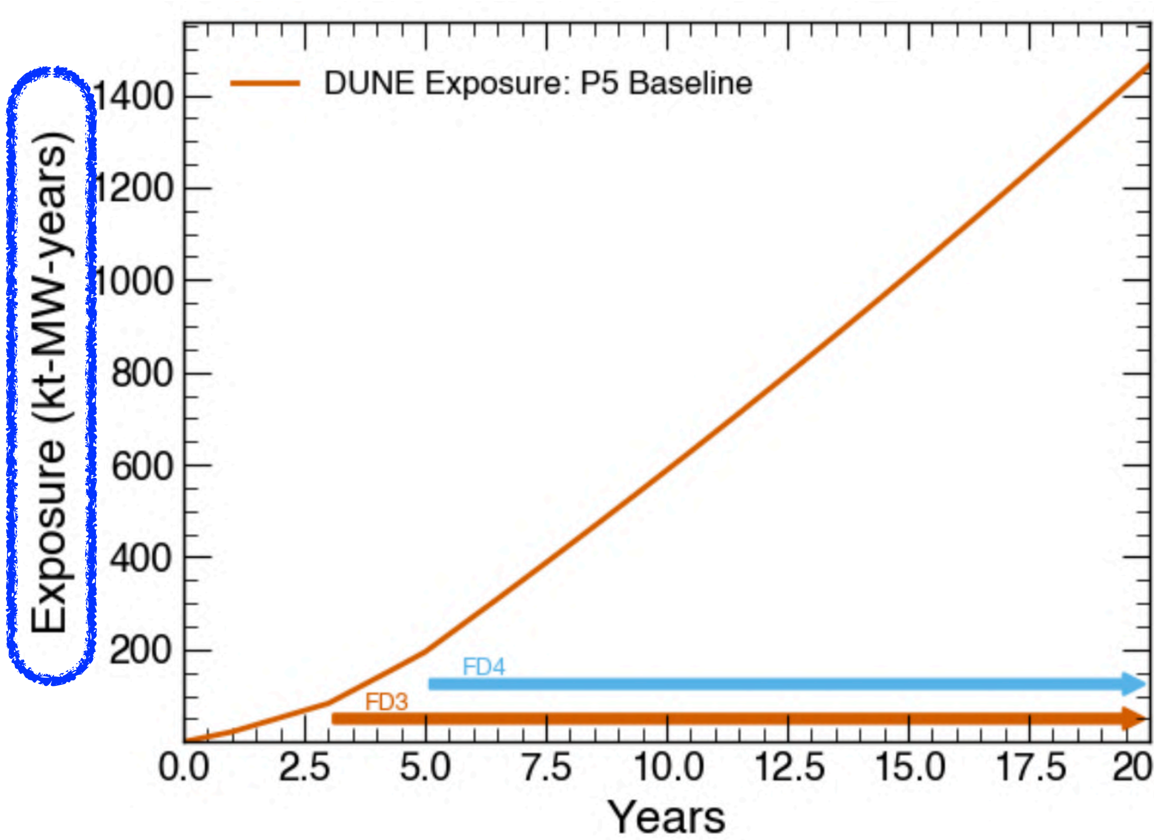
1.97x10^{21} POT

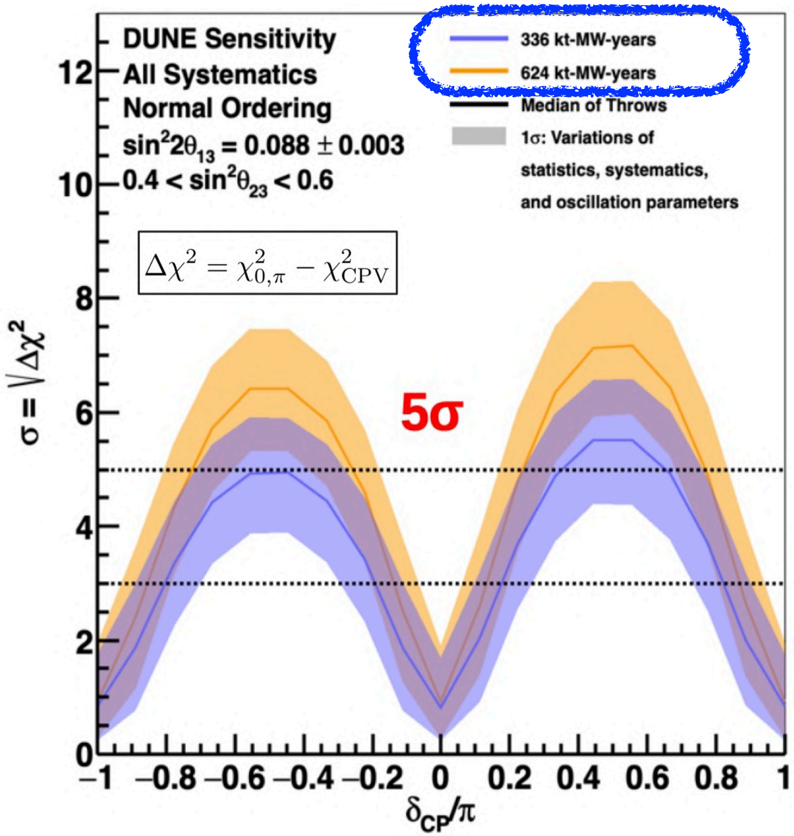
Representing Data Statistics

The goal for the next generation experiments (Hyper-K and DUNE): **POT > O(10^{22})**

Note: POT does not indicate the size of the detector (= number of target nuclei)

—> We also use a different measure to represent data statistics: **kt-MW-years**





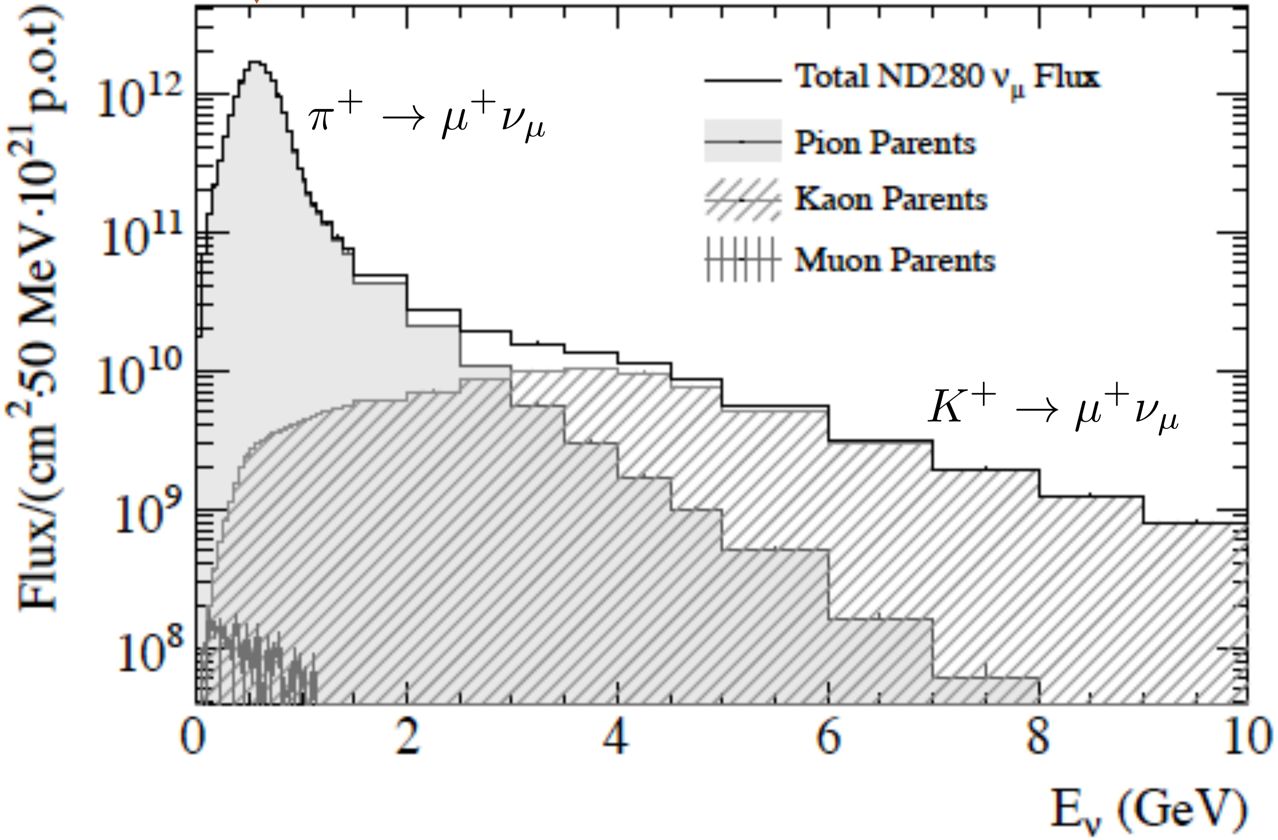
EPJC 80 (2020) 978

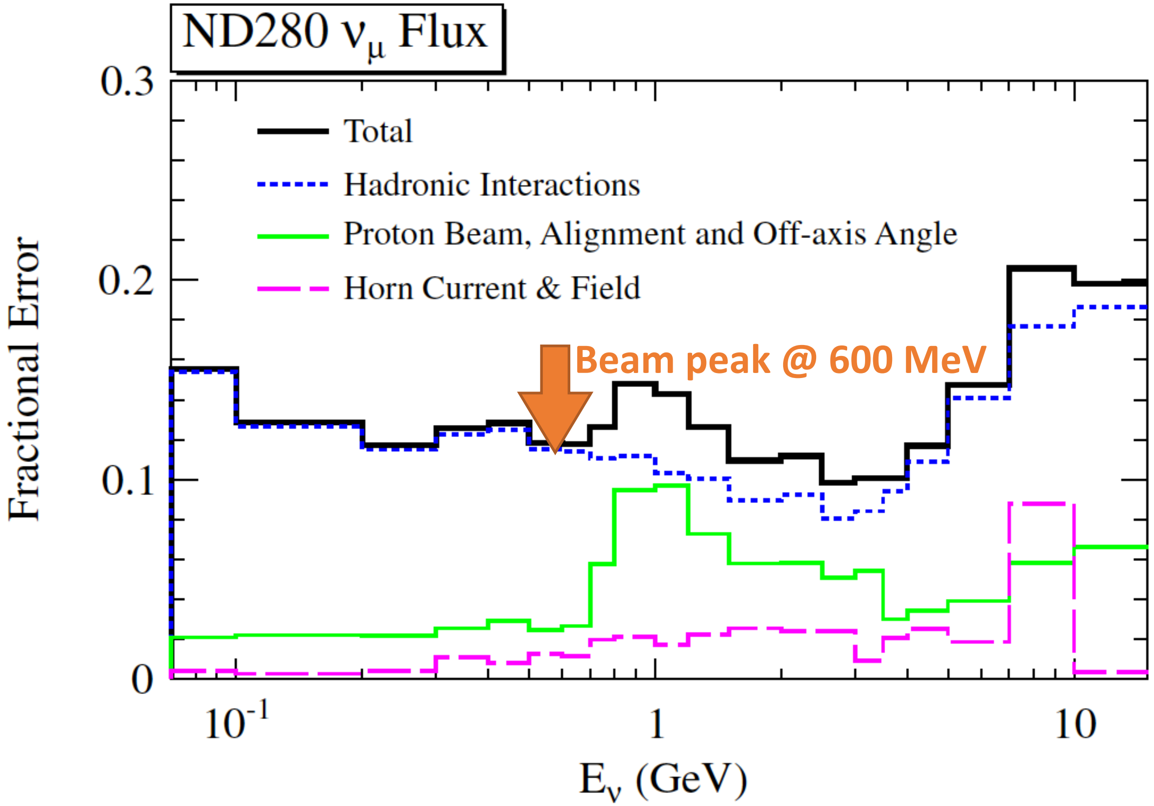
Understanding Neutrino Beams

Beam peak @ 600 MeV

J-PARC beamline (T2K flux)

T2K: Phys. Rev. D87, 012001 (2013)





Two major uncertainty sources: **Beamline hardware** and **Hadron production**

A leading source of systematic uncertainty on flux prediction -> Hadron Production

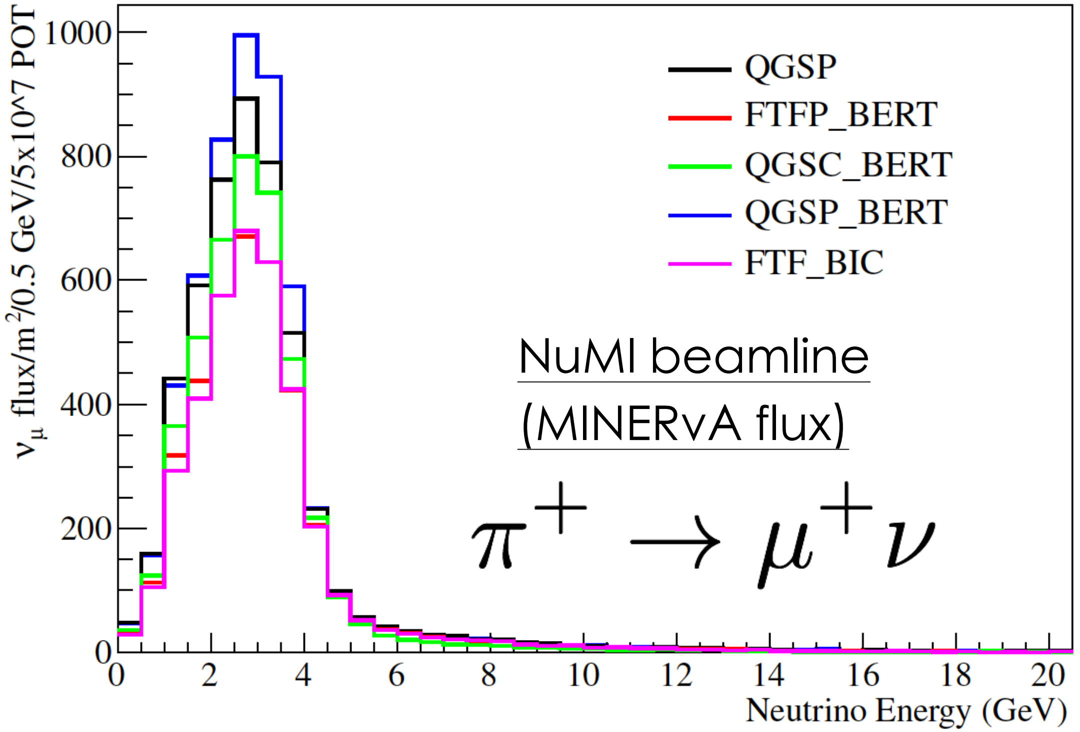
Requirement for future experiments: **below 2-3% uncertainty on flux prediction!!**

Flux Prediction

We rely on hadronic interaction models to calculate the neutrino flux

- FLUKA (J-PARC/T2K)
- Geant 4 FTFP_BERT (Fermilab experiments at NuMI, LBNF, and Booster beamlines)

However, prediction of hadron production is difficult…



NuMI beamline

(MINERνA flux)

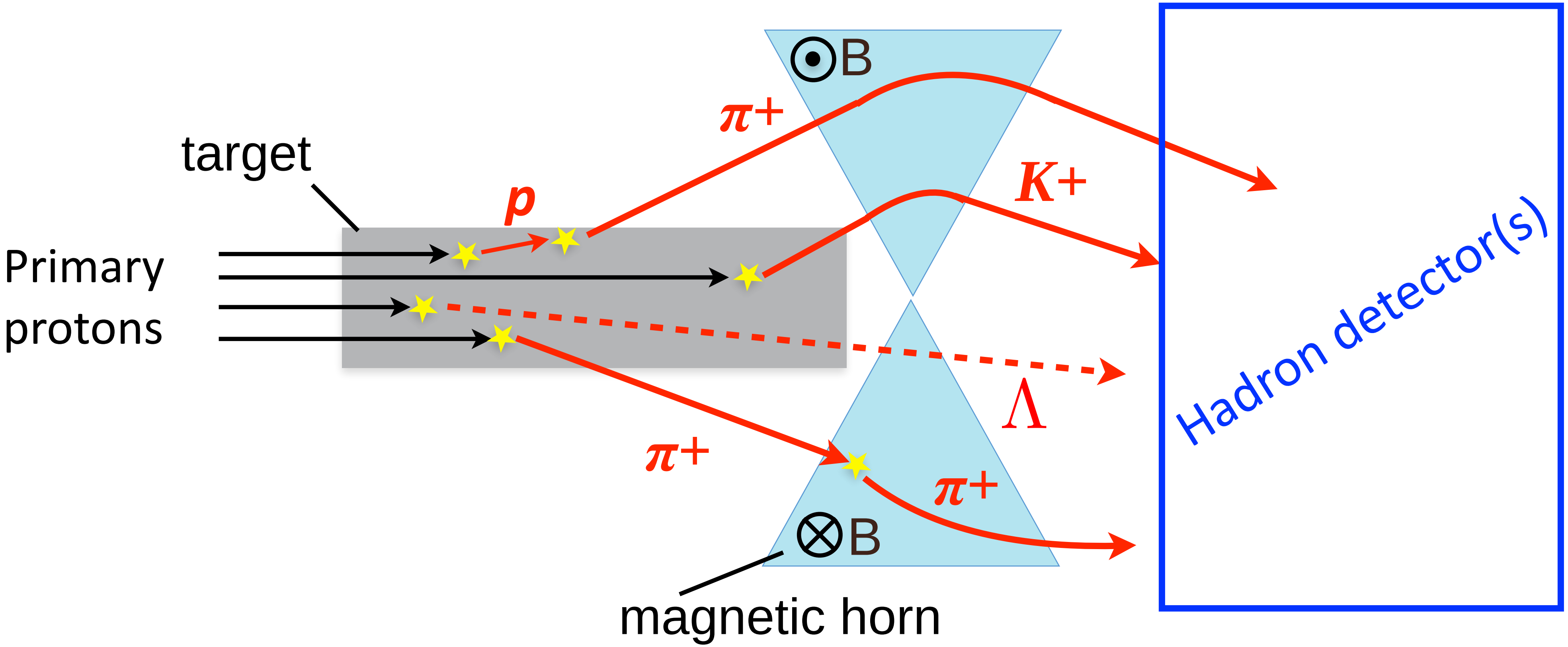
$$\pi^+ \rightarrow \mu^+ \nu$$

Leonidas Aliaga (Ph.D Thesis, 2016)

Need to constrain flux uncertainty coming from hadron production

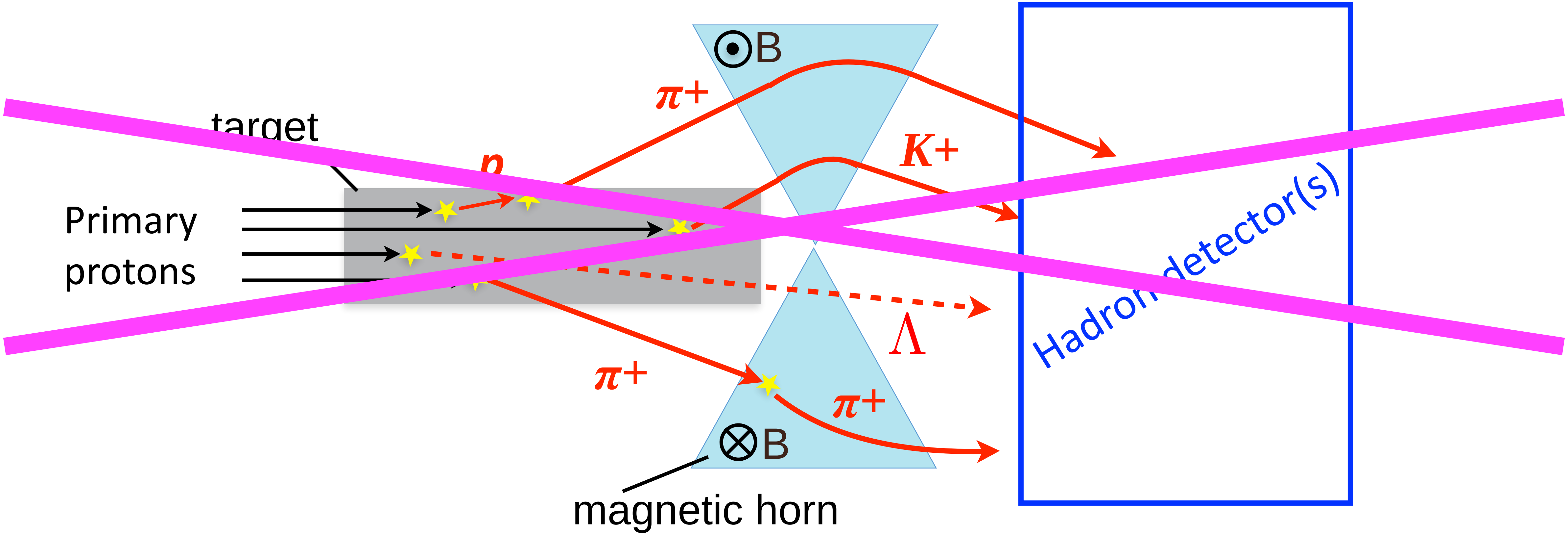
Hadron Production Measurement

- You may think of “in situ” hadron production measurement at the neutrino beamline



Hadron Production Measurement

- You may think of “in situ” hadron production measurement at the neutrino beamline



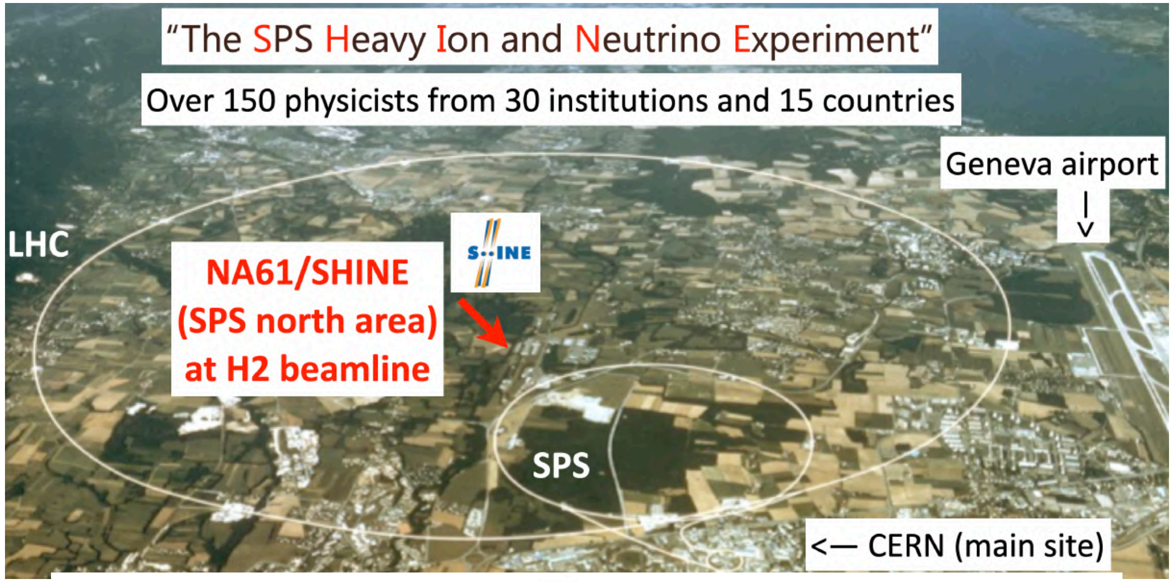
Not practically possible because…

- proton beam intensity is too high!
  - **protons per bunch ~10^{13}** (c.f LHC Run 3: protons per bunch -> ~10^{11})

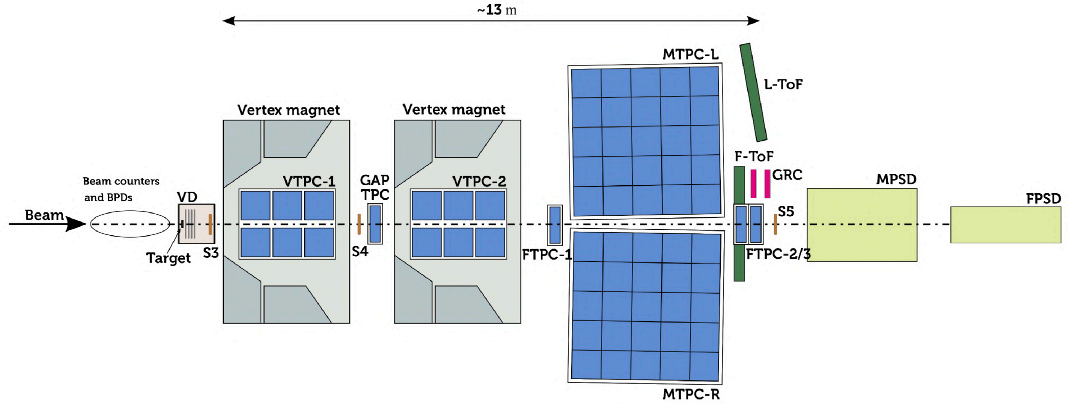
External Hadron Production Measurement

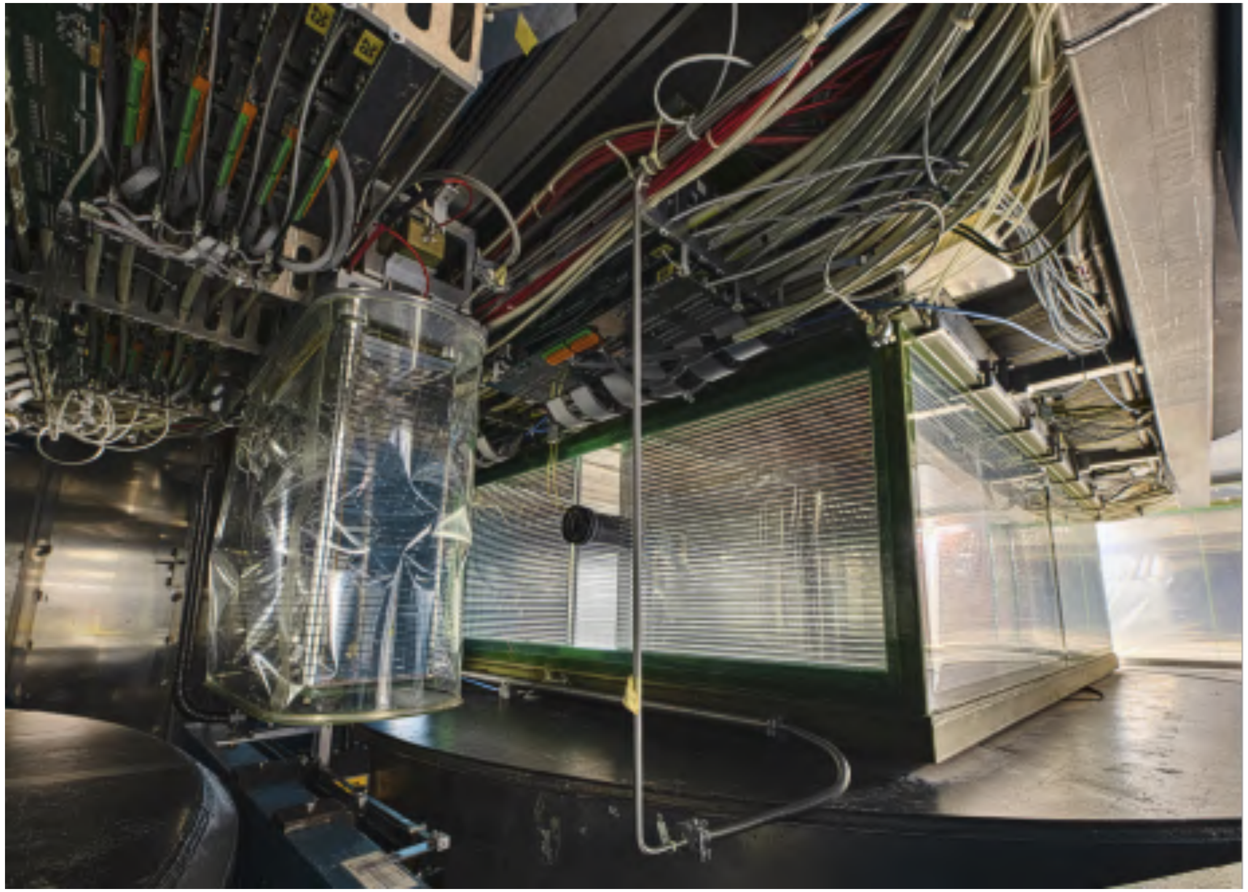
- Instead, we rely on “external” measurements to understand hadron production

One such experiment is NA61/SHINE at CERN SPS

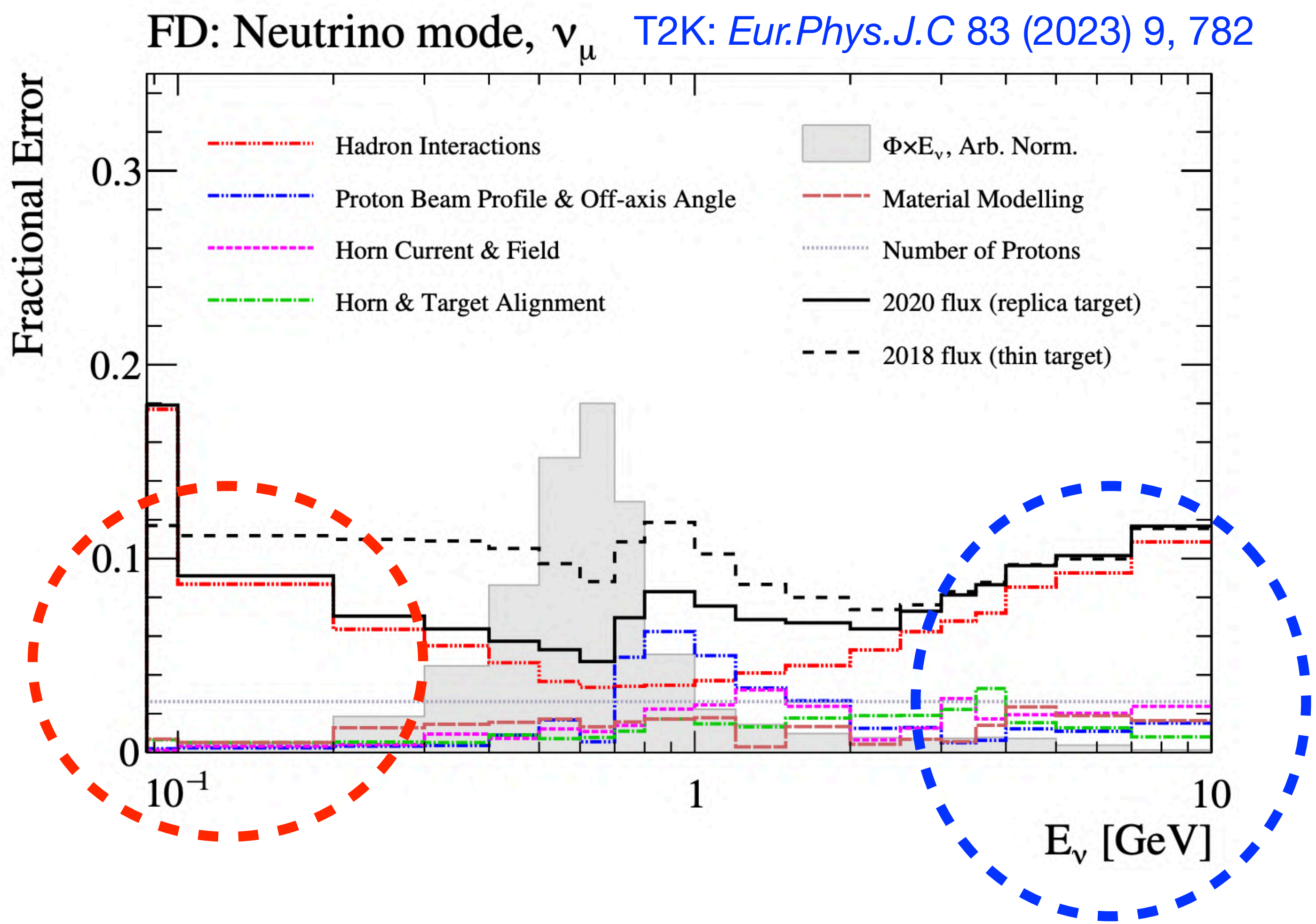

“The SPS Heavy Ion and Neutrino Experiment”

Over 150 physicists from 30 institutions and 15 countries





T2K Flux Uncertainty with NA61/SHINE Data



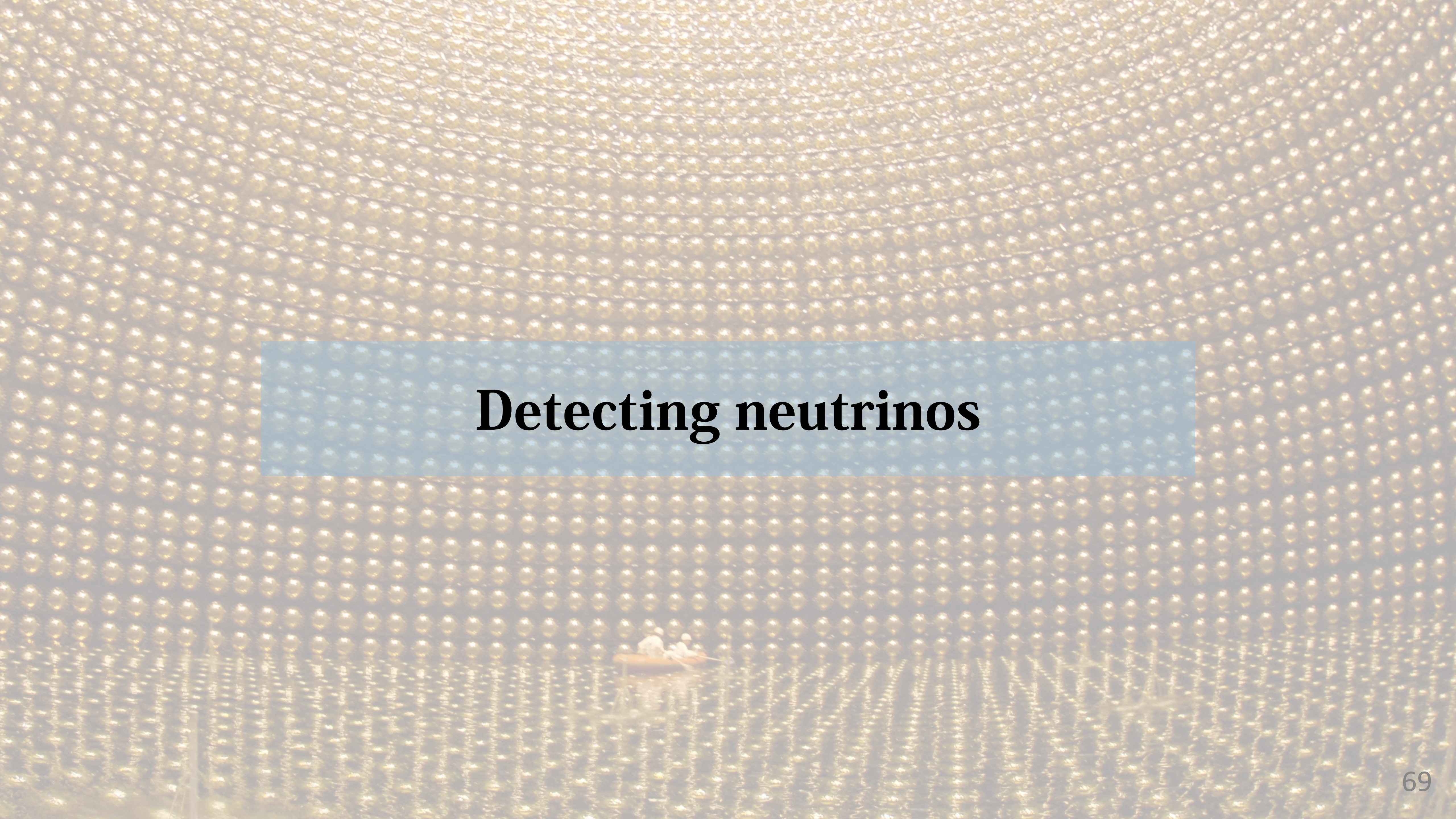
T2K: *Eur.Phys.J.C* 83 (2023) 9, 782

Achieved

- Flux uncertainty < 5% at the flux peak

Next step

- Flux outside of the peak needs to be further reduced
  - Low energy side: low-momentum hadron rescattering
  - High energy side: kaon production
- Flux of intrinsic beam background
  - anti-ν and electron-ν



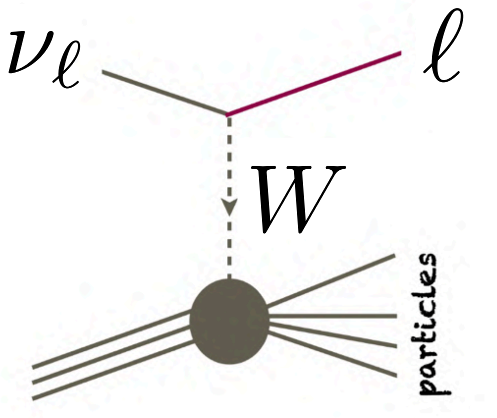
Detecting neutrinos

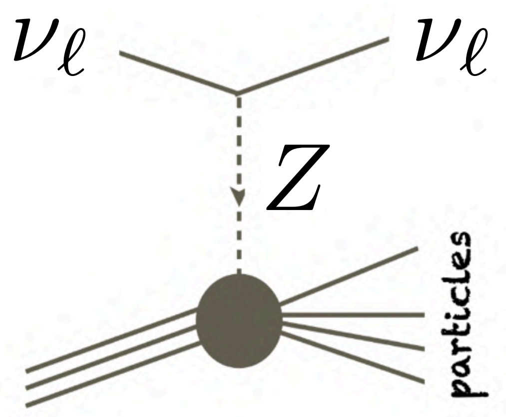
Neutrino Interactions

- Charged current (CC) interactions
  - Exchange a W boson
  - Produce a charged lepton of the same flavor

- Neutral current (NC) interactions
  - Exchange a Z boson
  - No charged leptons produced

- Other particles also get produced
  - Protons
  - Neutrons
  - Hadrons (e.g. pions, kaons)





Neutrino Detection Goals

This depends largely on the experiment, but typically for long-baseline experiments:

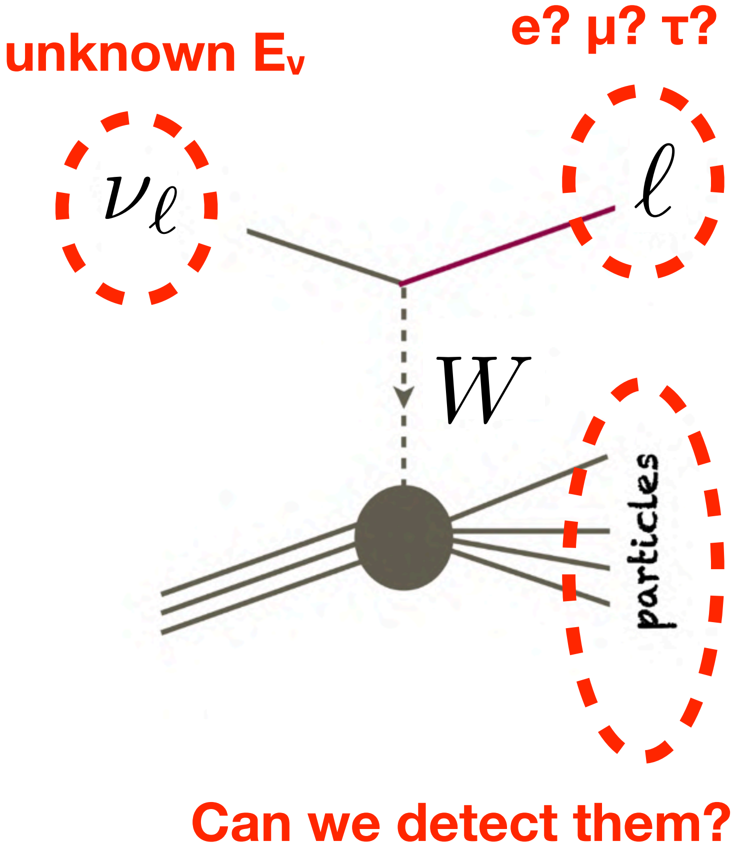
- Identify the flavor of the neutrinos
  - Only via produced particles in neutrino interactions
    - Use CC interactions!!

- Reconstruct neutrino energy
  - Only via produced particles in neutrino interactions
    - outgoing leptons
    - other particles (if detectable!)

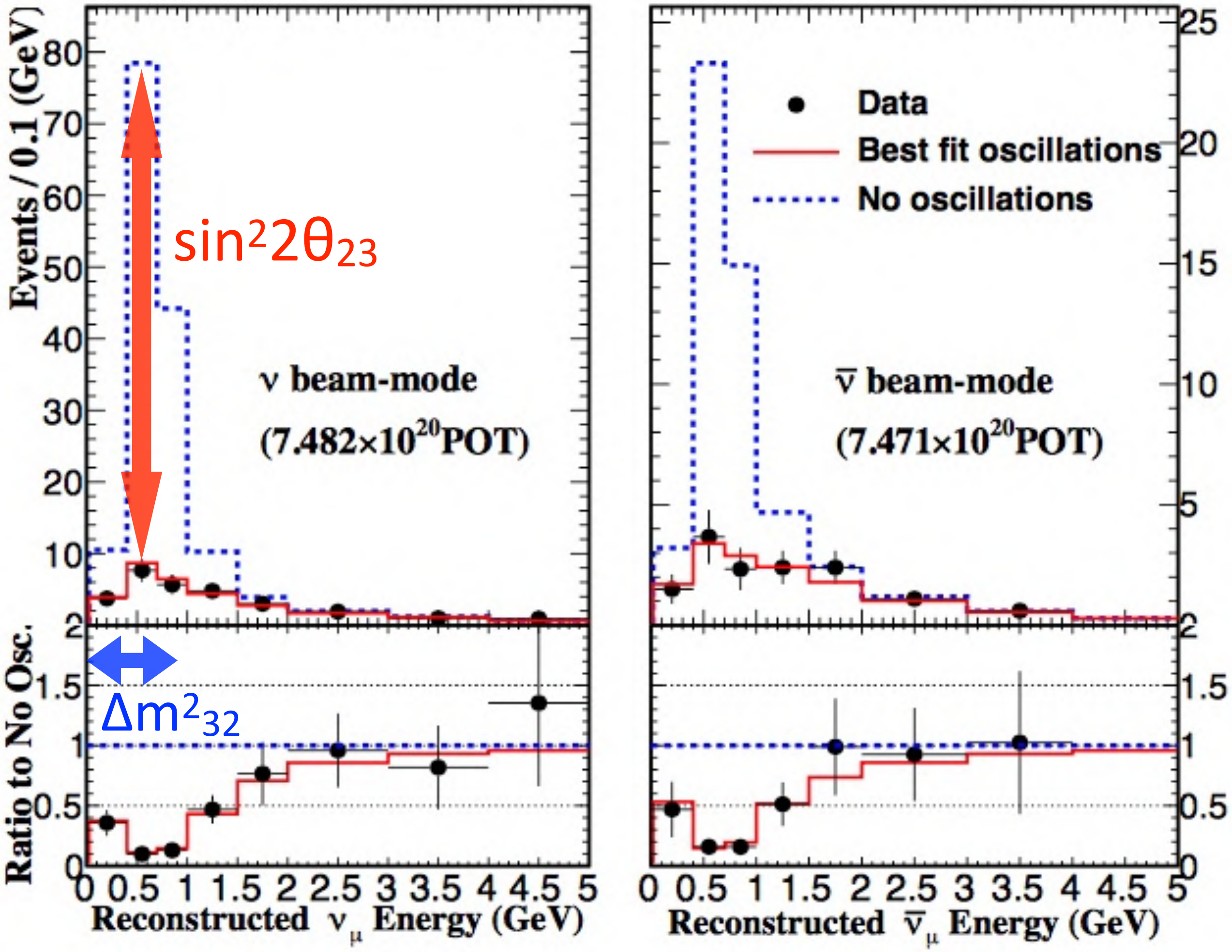
  -> a motivation to use an off-axis beam to ease this business

- Determine neutrinos or antineutrinos
  - Key information for searching for *CP* violation

  -> a motivation to use (anti)neutrino-enhanced beams to ease this business



Neutrino Energy Reconstruction

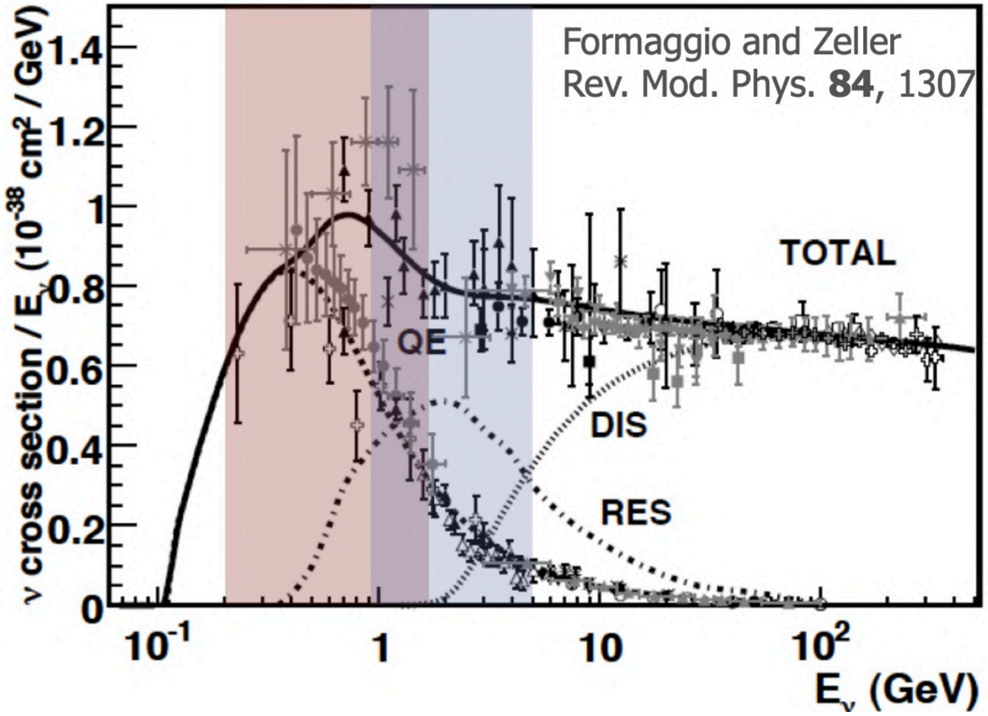


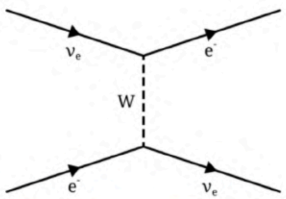
T2K: Phys.Rev.D 96 (2017) 1, 011102

Neutrino experiments use reconstructed neutrino energy spectrum for each flavor to extract neutrino oscillation parameters

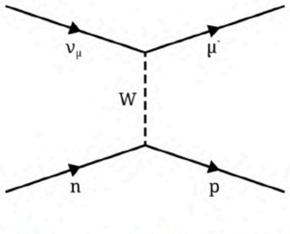
Neutrino interactions and reconstruction are one of the biggest challenges we face!!

Neutrino Interactions

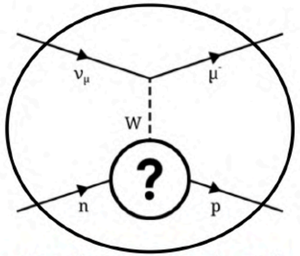




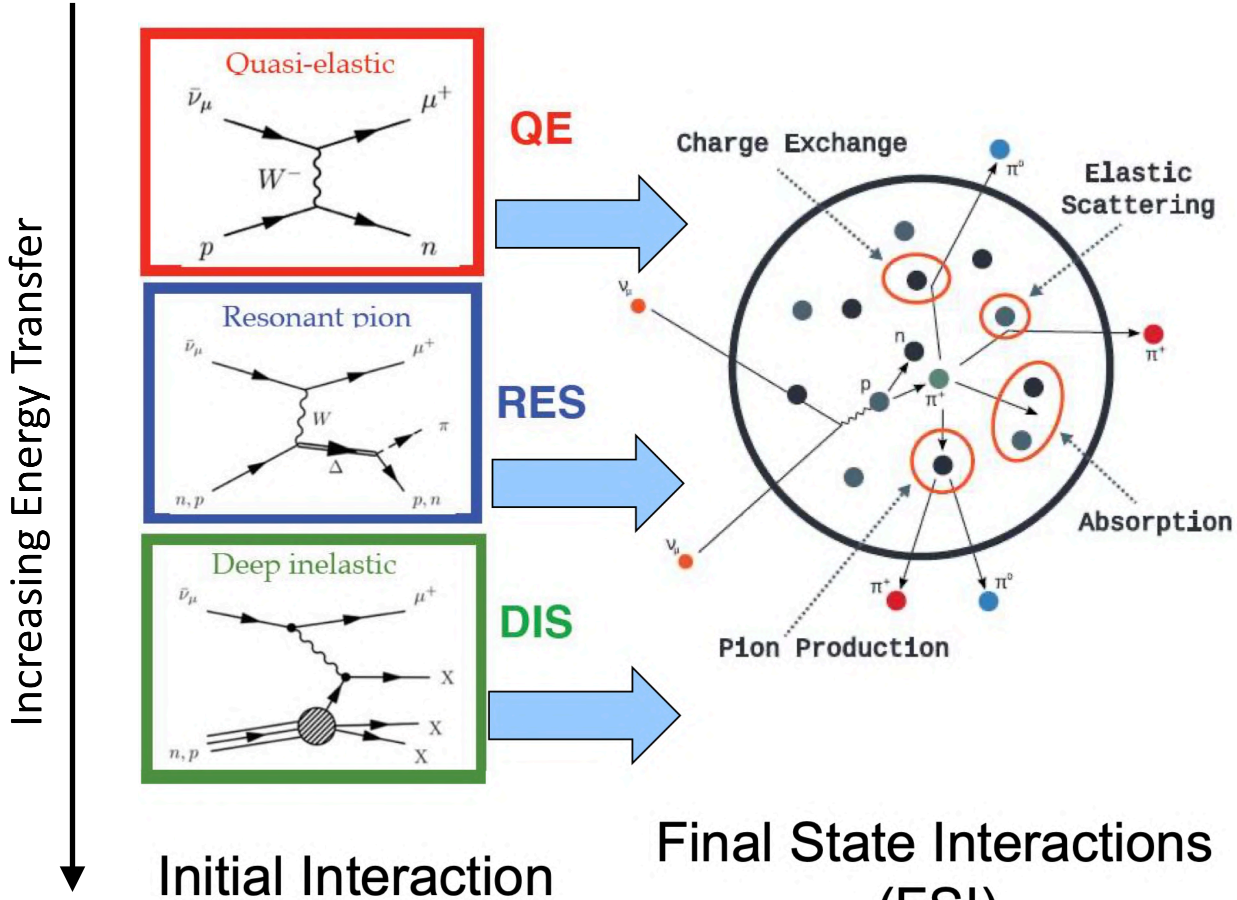
Point-like: Masters homework problem



Nucleon: mostly harmless



Nucleus: very hard



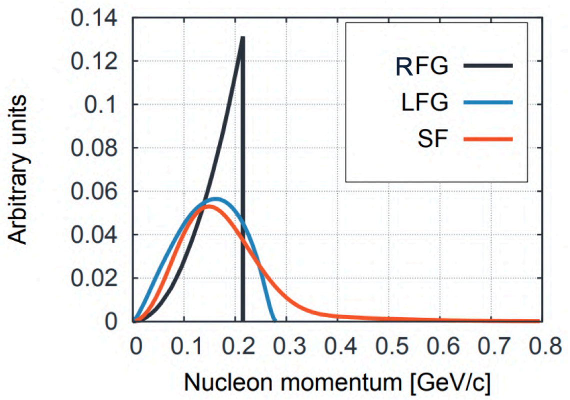
Initial Interaction

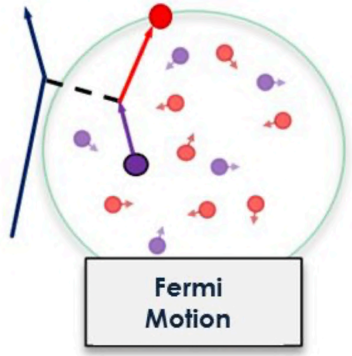
Final State Interactions (FSI)

- Nuclear effects join the business
  - Getting tougher!

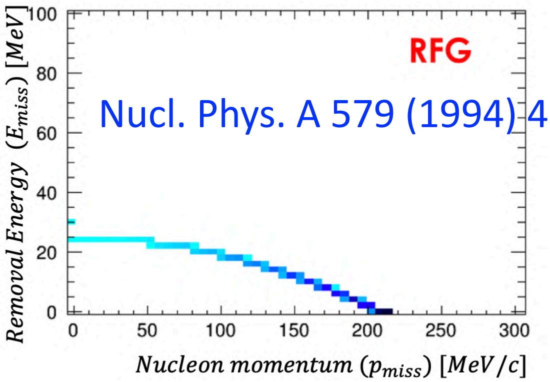
Nuclear Effects Modeling (Very Briefly)

- <u>Fermi Motion</u>
  - Nucleons are moving targets
  - Their momenta isn't so different than neutrino energy



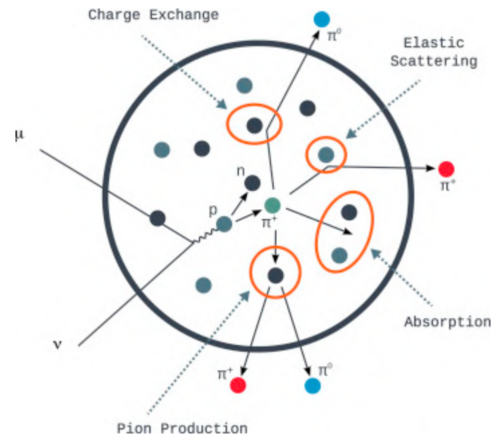


- <u>Nuclear Removal Energy</u>
  - Nucleons are bound inside the nucleus
  - Most models predict that removal energy and Fermi motion should be correlated



Nucl. Phys. A 579 (1994) 493-517

- <u>Final State Interaction (FSI)</u>
  - Hadrons can re-interact inside the nucleus
  - Distorts kinematics and changes the final state topology

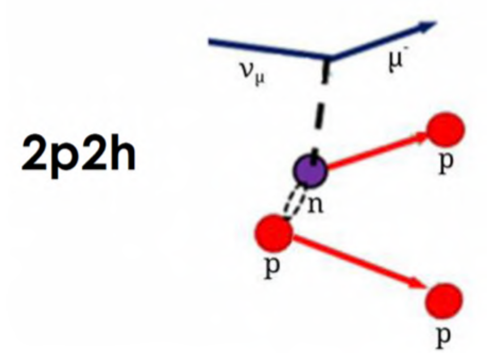


A very rich field where nuclear physics meets neutrino physics!!

For more detail, check lecture by S. Doran:
https://indico.cern.ch/event/1011452/contributions/4448410

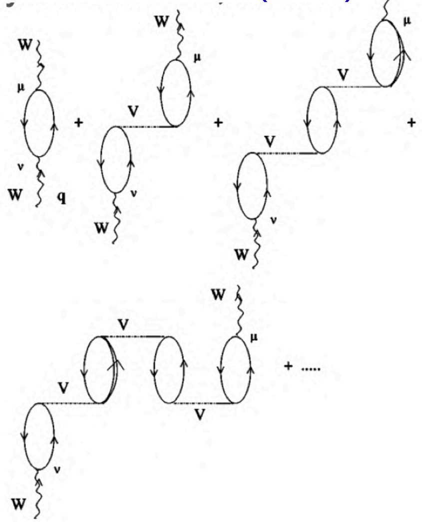
Nuclear Effects Modeling (Very Briefly)

- Multi-nucleon Interactions
  - Nucleons are interacting with each other inside the nucleus
  - Some interactions are with nucleons bound together somehow **"2p2h"**

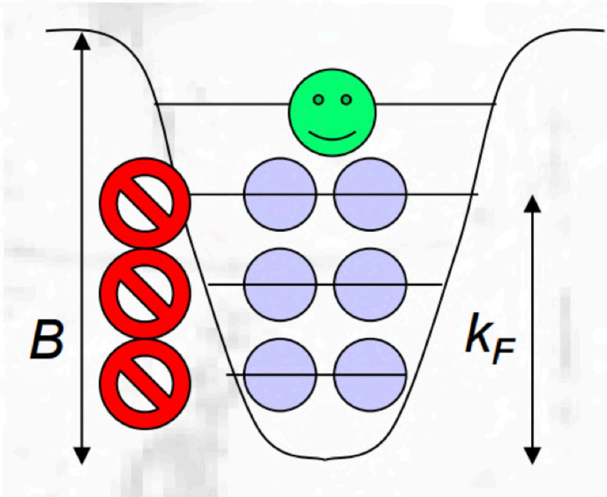


- Additional Correlations
  - "Long-range" interactions between nucleons can act to shield target
  - Difficult, usually parameterized and treated via Random Phase Approximation (RPA)

Phys. Rev. C 70, 055503 (2004)



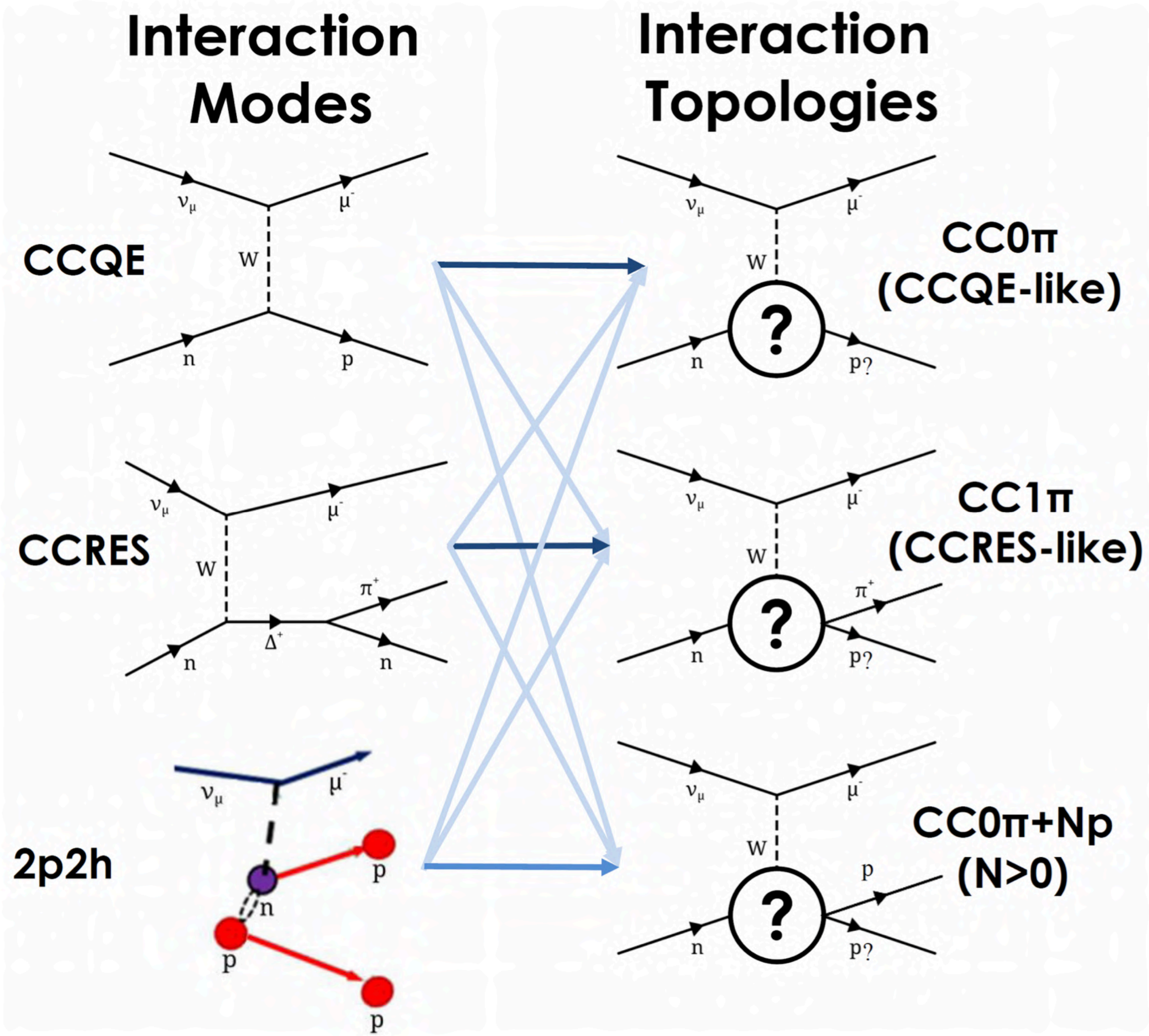
- Pauli Blocking
  - Nucleons cannot be excited into nuclear states that are already filled
  - Reduction of cross-section at low-E transfer



A very rich field where nuclear physics meets neutrino physics!!

For more detail, check lecture by S. Doran:
https://indico.cern.ch/event/1011452/contributions/4448410

What do we actually measure?



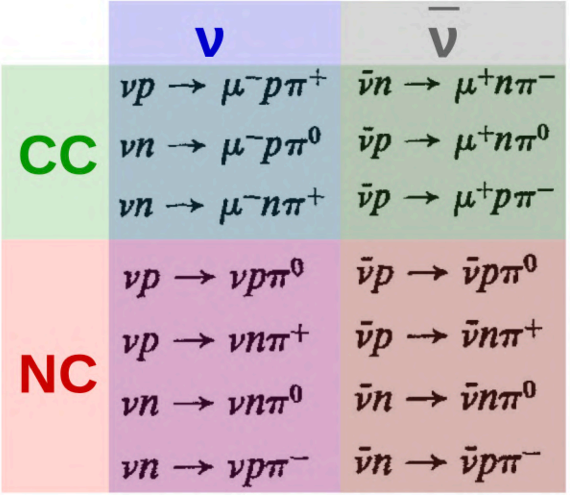
<u>T2K/Hyper-K main channel</u>

CC0π = 1p1h + 2p2h + 1π(+abs) + ...

<u>NOvA/DUNE main channel</u>

CC resonance

Rein-Sehgal model (1981) -> ~18 nucleon resonances

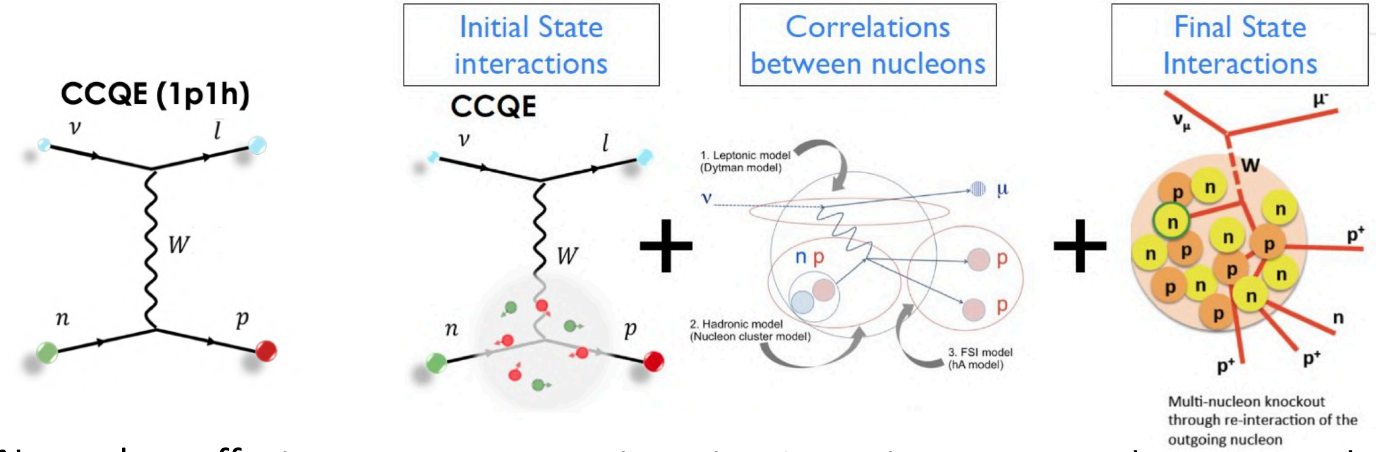


	ν	$\bar{\nu}$
CC	$\nu p \rightarrow \mu^- p \pi^+$	$\bar{\nu} n \rightarrow \mu^+ n \pi^-$
	$\nu n \rightarrow \mu^- p \pi^0$	$\bar{\nu} p \rightarrow \mu^+ n \pi^0$
	$\nu n \rightarrow \mu^- n \pi^+$	$\bar{\nu} p \rightarrow \mu^+ p \pi^-$
NC	$\nu p \rightarrow \nu p \pi^0$	$\bar{\nu} p \rightarrow \bar{\nu} p \pi^0$
	$\nu p \rightarrow \nu n \pi^+$	$\bar{\nu} p \rightarrow \bar{\nu} n \pi^+$
	$\nu n \rightarrow \nu n \pi^0$	$\bar{\nu} n \rightarrow \bar{\nu} n \pi^0$
	$\nu n \rightarrow \nu p \pi^-$	$\bar{\nu} n \rightarrow \bar{\nu} p \pi^-$

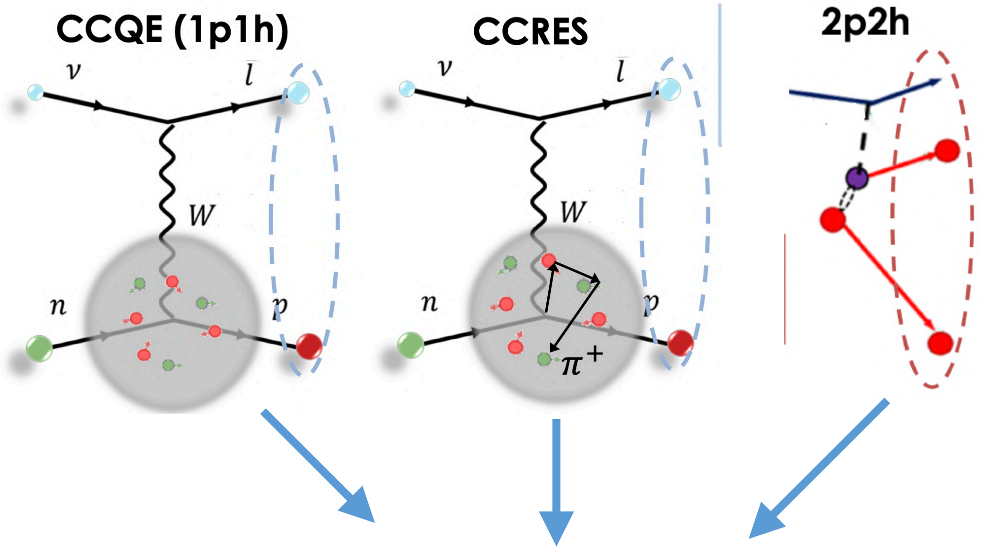
Why do we care?

Example: T2K CCQE reconstruction based on lepton kinematics

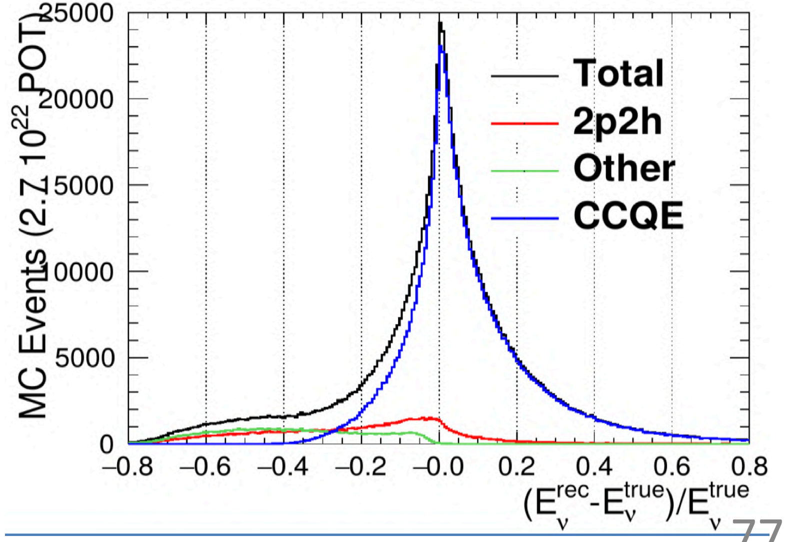
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos\theta_\mu)}$$



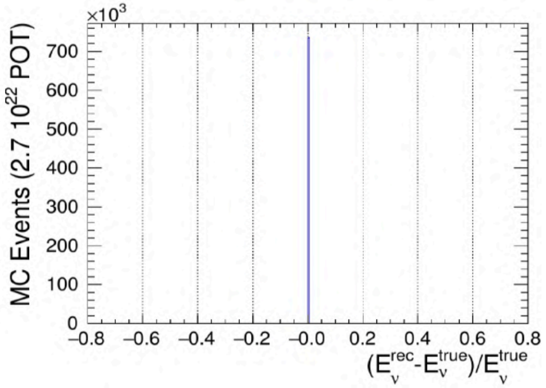
Multi-nucleon knockout through re-interaction of the outgoing nucleon



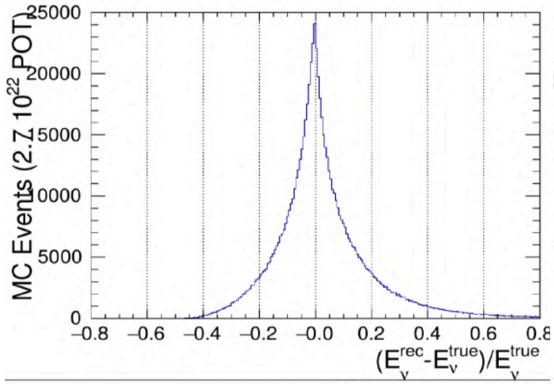
Topological Contamination



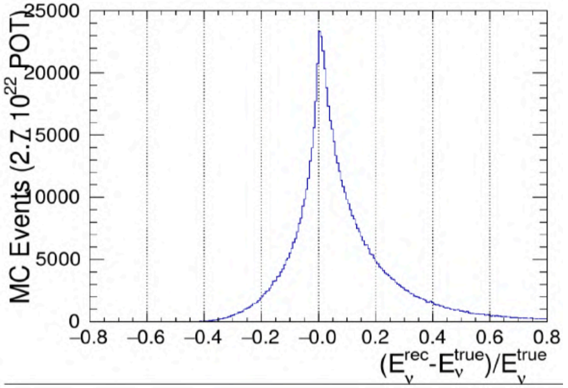
No nuclear effect



Fermi Motion Smearing



Nuclear Removal Energy Loss



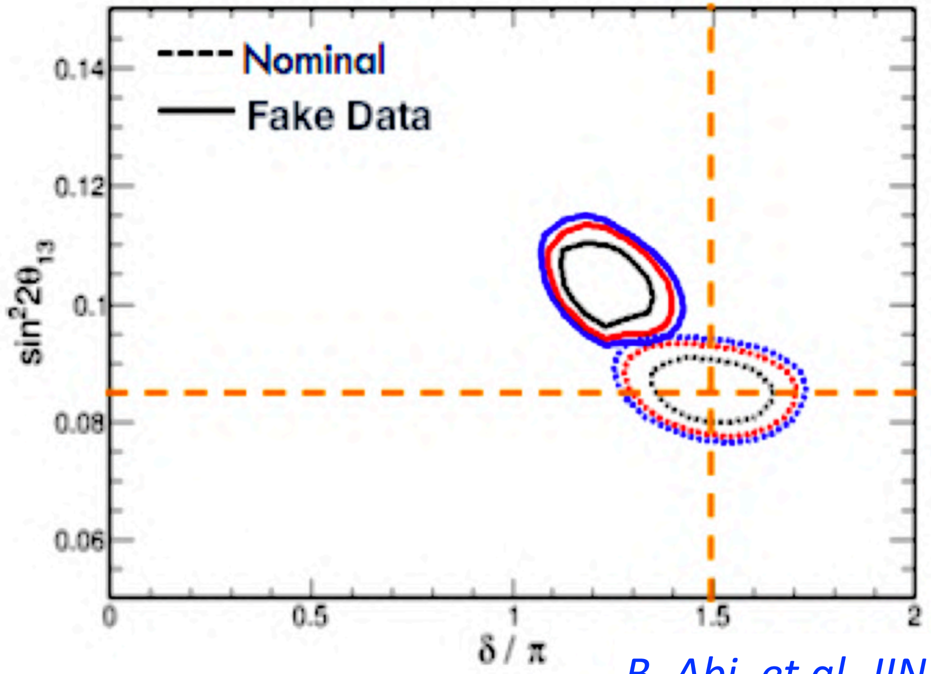
Impact on Oscillation Parameters

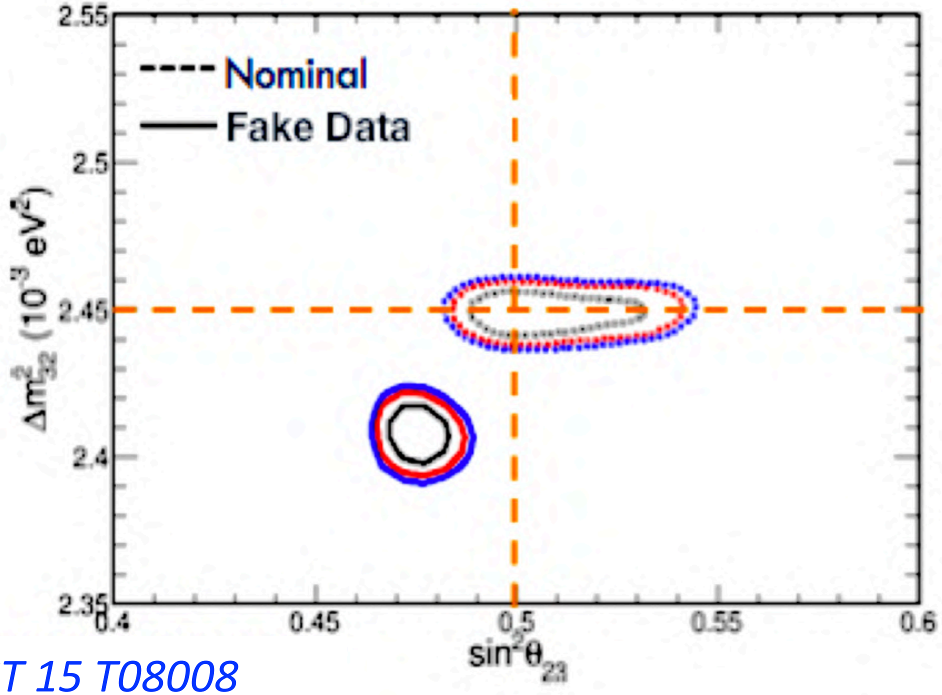
- Neutrino energy is **incorrectly** estimated if particles emerging from a neutrino interaction are **unaccounted for**
- A simple case study:
    - Getting “only” 20% of the proton energy wrong can have significant impacts on the measurements of the oscillation parameters

assume:

Calometric energy estimation method

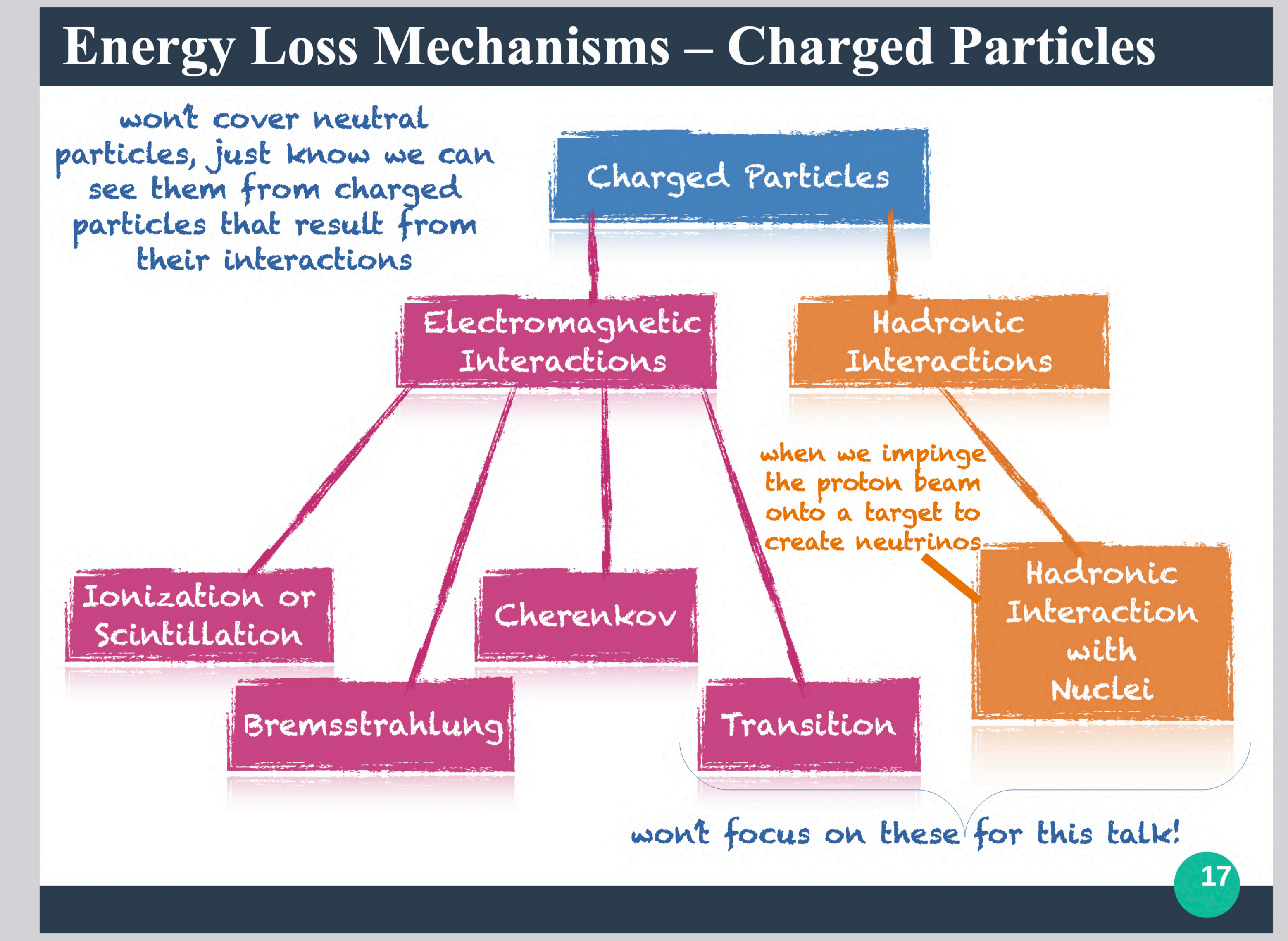
$E_\nu = E_\mu + E_{had}$





B. Abi, et al. JINST 15 T08008

Detector Technology Choice



Energy Loss Mechanisms – Charged Particles

won't cover neutral particles, just know we can see them from charged particles that result from their interactions

Charged Particles

Electromagnetic Interactions

Hadronic Interactions

Ionization or Scintillation

Bremsstrahlung

Cherenkov

Transition

Hadronic Interaction with Nuclei

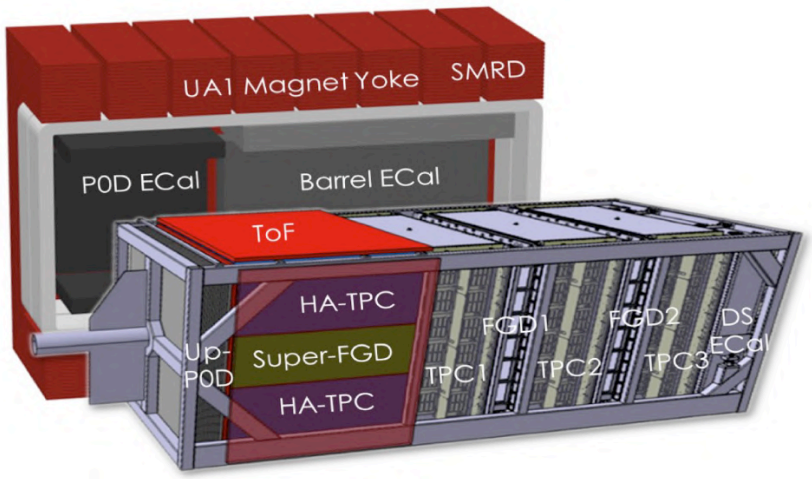
when we impinge the proton beam onto a target to create neutrinos

won't focus on these for this talk!

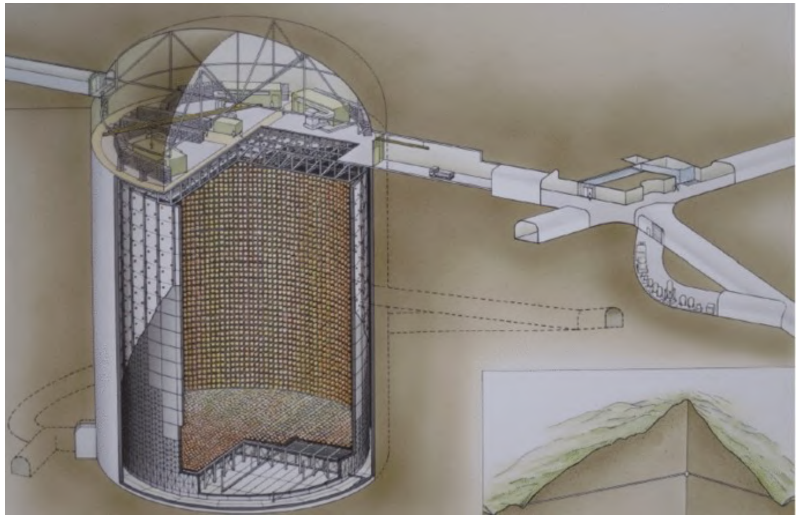
Slides by Tanaz Mohayai
shown at "Neutrino University" 2023
https://npc.fnal.gov/neutrino-university

Designing a Neutrino Detector

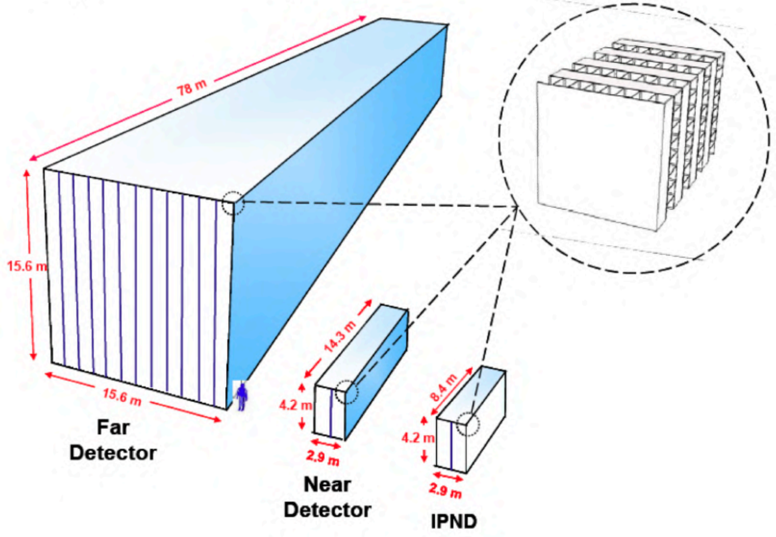
T2K Near Detector   Multi-purpose detector



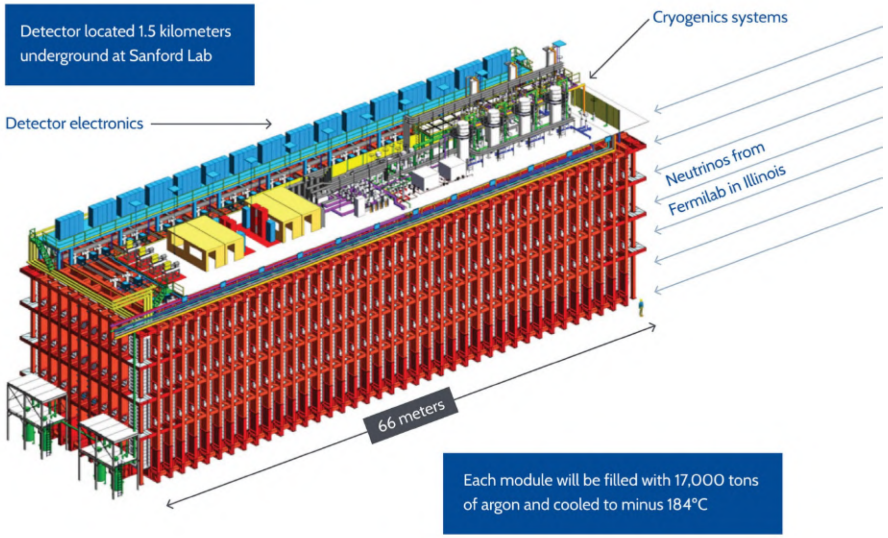
T2K Far Detector   Water Cherenkov



NOvA   Liquid scintillator tracker



(proto)DUNE   Liquid Ar TPC   (ionization)



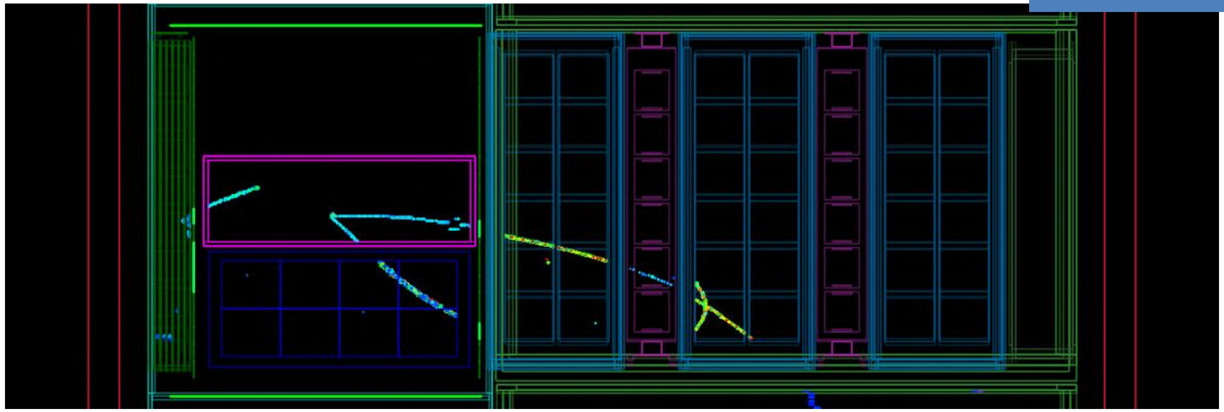
Detector located 1.5 kilometers underground at Sanford Lab

Each module will be filled with 17,000 tons of argon and cooled to minus 184°C

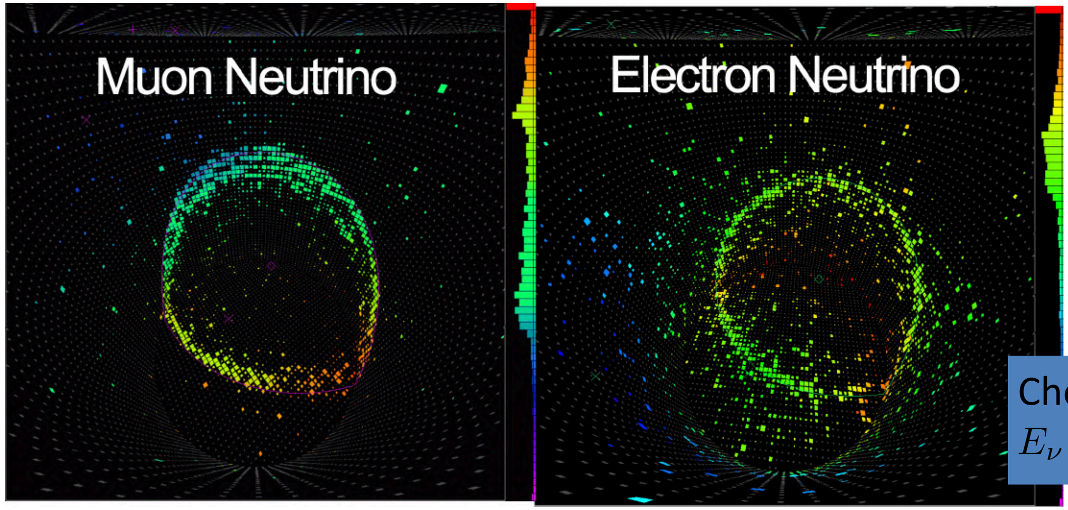
Designing a Neutrino Detector

T2K Near Detector   Multi-purpose detector

Tracking-based
+ (EM cal)
+ (ToF)



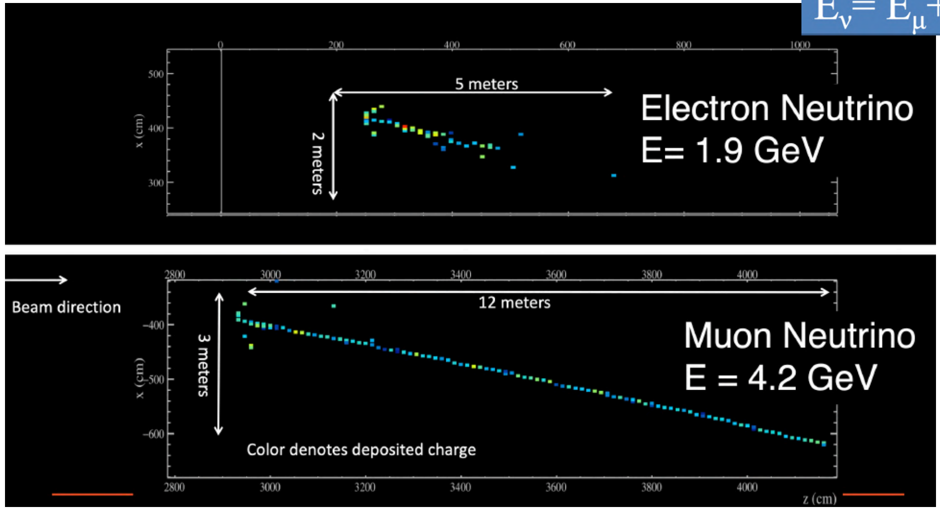
T2K Far Detector   Water Cherenkov



Cherenkov-based:
$E_\nu \propto \#$ of photons

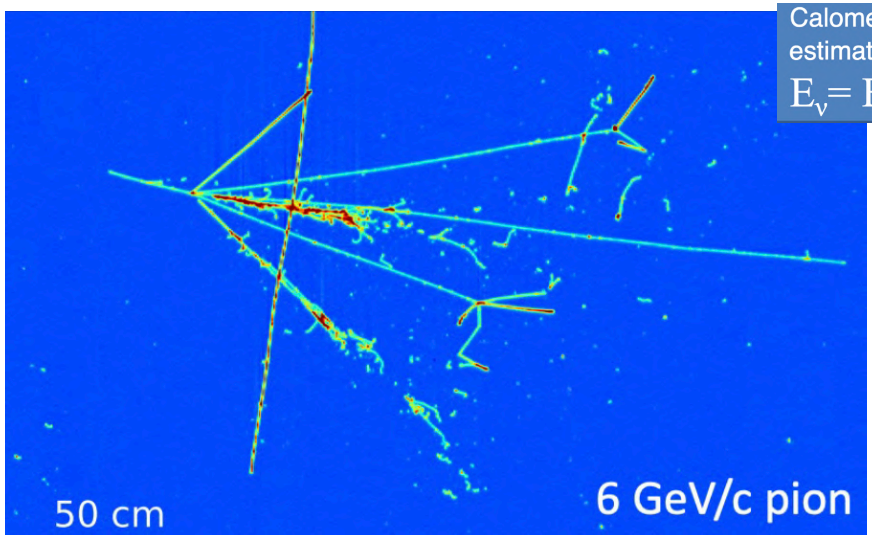
NOvA   Liquid scintillator tracker

Calometric energy estimation method
$E_\nu = E_\mu + E_{had}$



(proto)DUNE   Liquid Ar TPC   (ionization)

Calometric energy estimation method
$E_\nu = E_\mu + E_{had}$



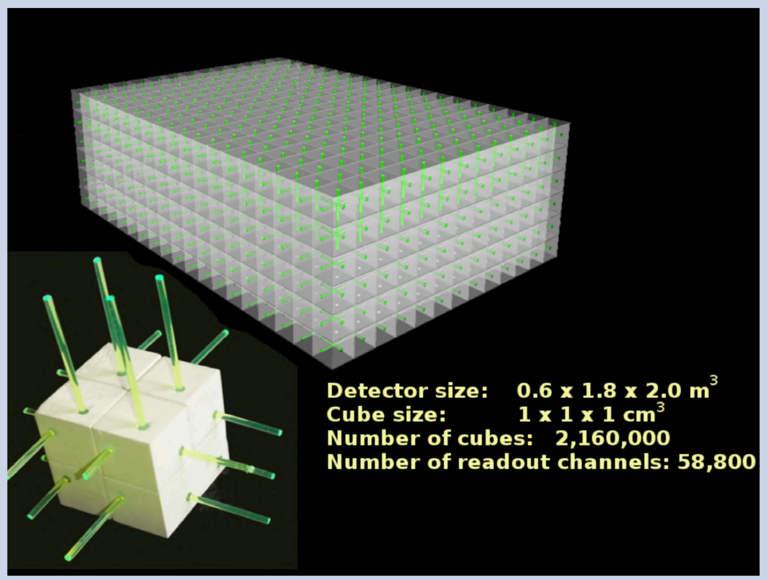
Detector Upgrade towards Lower Threshold

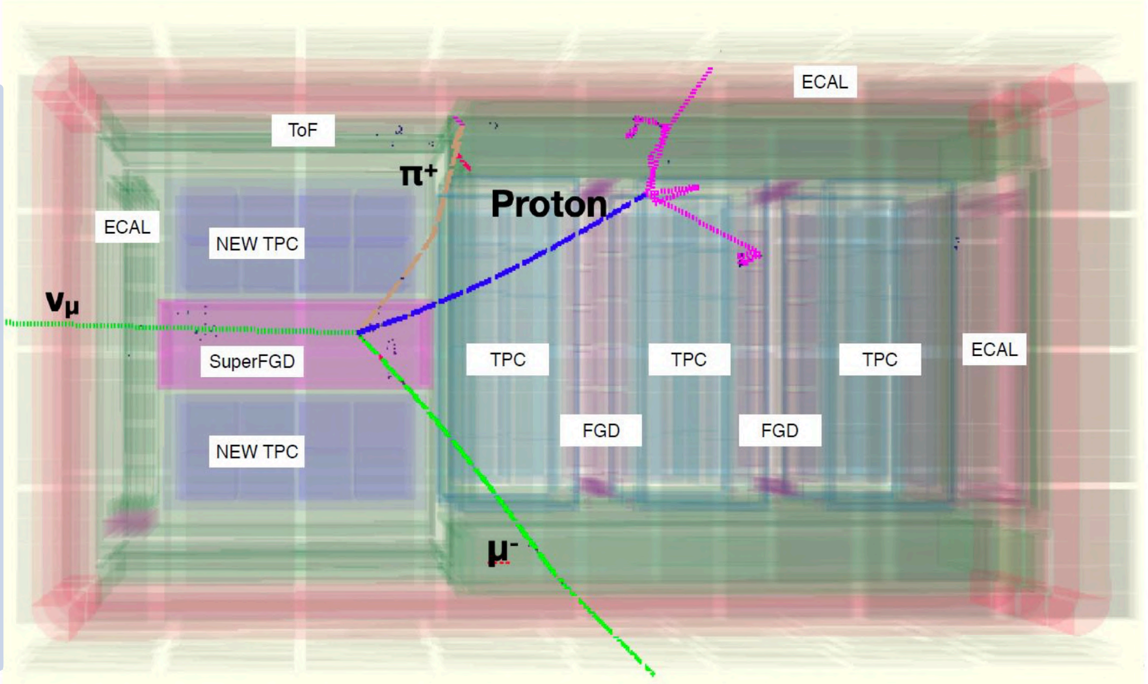
As we learned, the detector's capability to reconstruct low-momentum particles is a key.

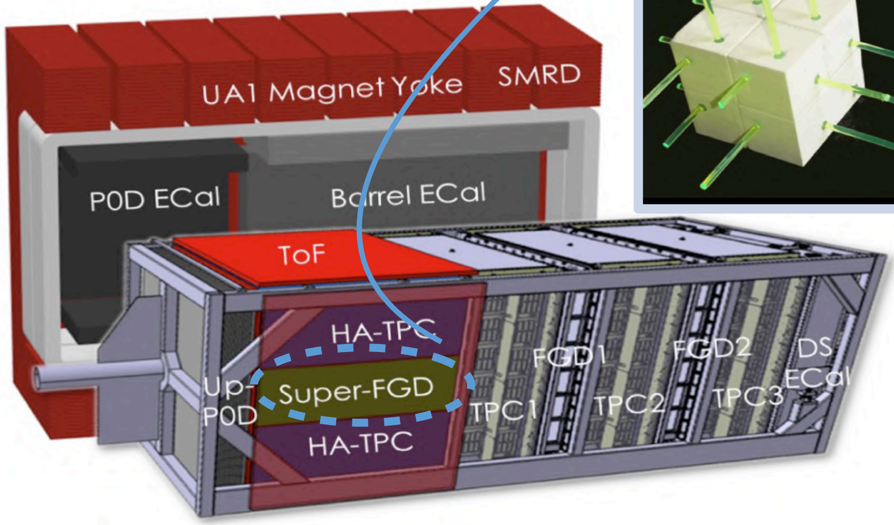
- T2K
  - Fine-Grained Detector (FGD) -> Super-FGD (2024!!)

Threshold: **400 MeV -> 250 MeV** (for protons)

FGD: *Nucl.Instrum.Meth.A* 696 (2012) 1-31
Super-FGD: *arXiv:1901.03750*


Detector size: 0.6 x 1.8 x 2.0 m^3
Cube size: 1 x 1 x 1 cm^3
Number of cubes: 2,160,000
Number of readout channels: 58,800





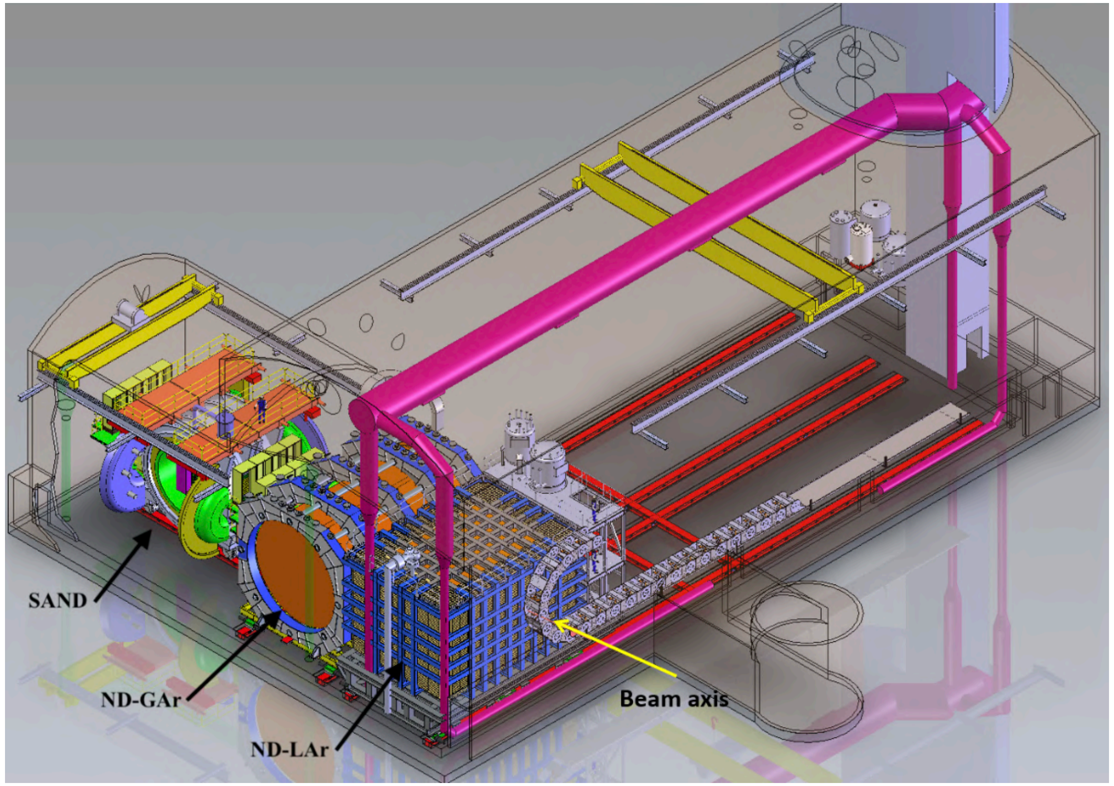
We made a press release:

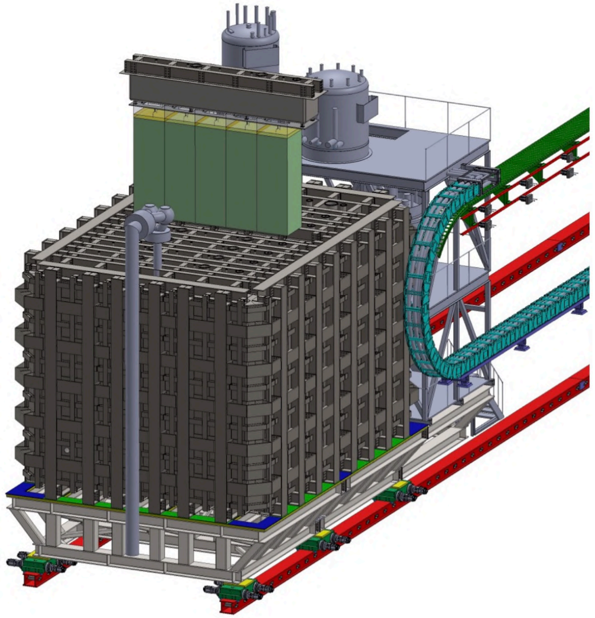
NEUTRINO RESEARCH HAS ENTERED A NEW PHASE

(English) https://www.elte.hu/en/content/neutrino-research-has-entered-a-new-phase.t.3016
(Hungarian) https://www.elte.hu/content/uj-szakaszba-lepett-a-neutrinokutatas.t.29847

Detector Upgrade towards Lower Threshold

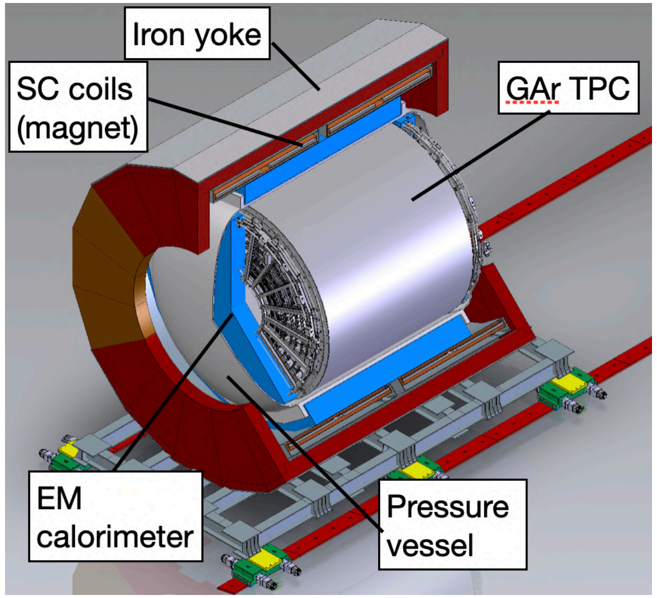
- DUNE
  - Liquid Argon TPC (Phase-I)
    Threshold: **40 MeV** (for protons)
  - High-pressure gas Argon TPC (Phase-II)
    Threshold: **4 MeV** (for protons)





Liquid Ar TPC
(ND-LAr)

5x7 = 35 TPC modules
(module: 1m x 1m x 3 m)



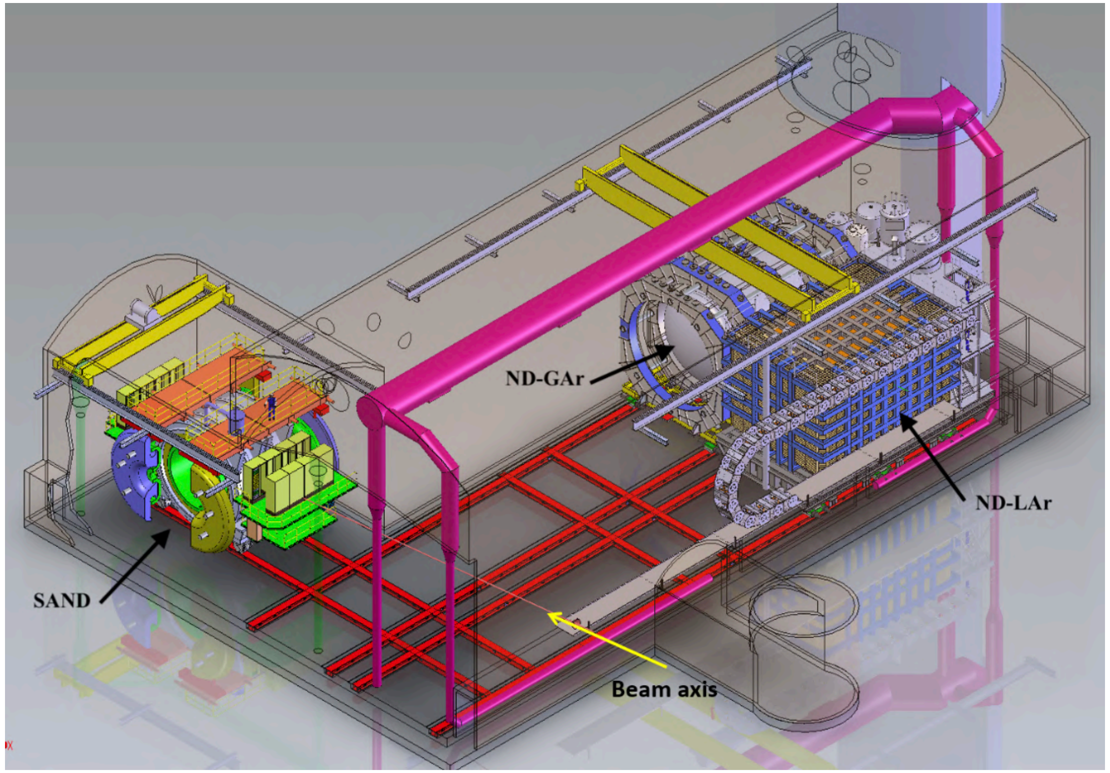
High-pressure gas Ar TPC
(ND-GAr)

Repurposed ALICE TPC
(5.2 m drift length)
(5.2 m diameter)

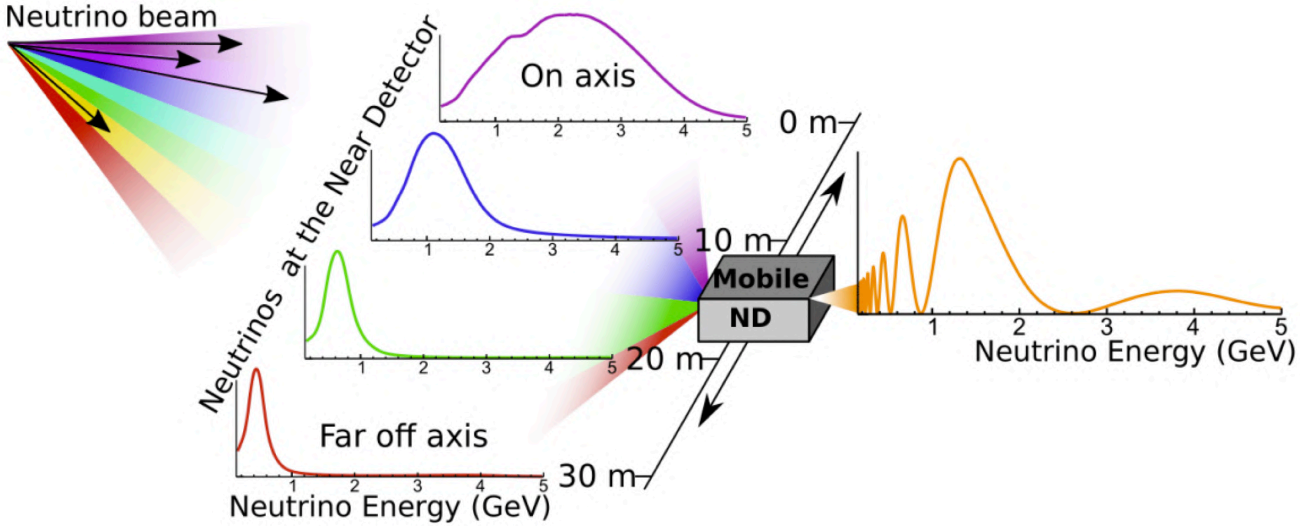
DUNE Near Detector Conceptual Design Report: *Instruments 5 (2021) 4, 31*

Detector Upgrade towards Lower Threshold

- DUNE
  - Liquid Argon TPC (Phase-I)
    Threshold: **40 MeV** (for protons)
  - High-pressure gas Argon TPC (Phase-II)
    Threshold: **4 MeV** (for protons)



DUNE PRISM



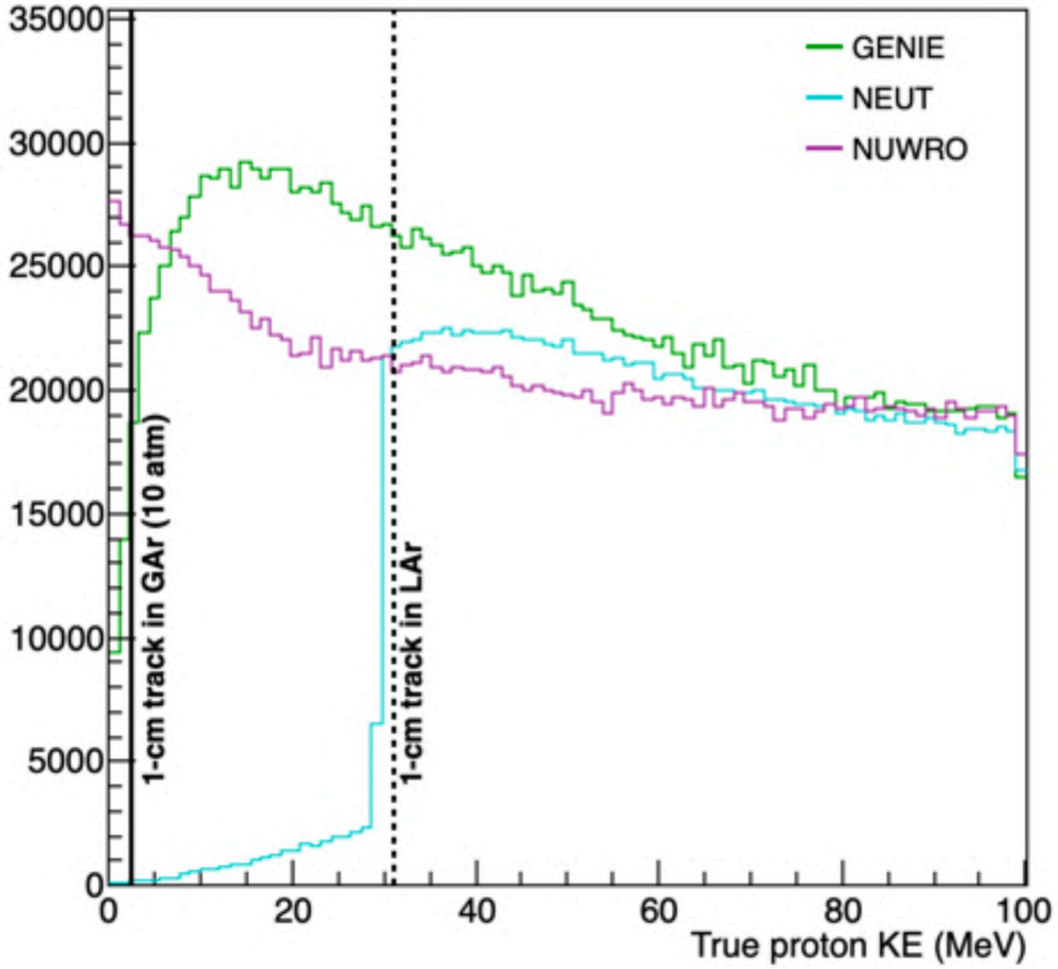
Form "oscillated flux" at the near detector with linear combinations of multiple off-axis data

-> An approach to make the far detector spectra **"largely" interaction model independent**

DUNE Near Detector Conceptual Design Report: *Instruments 5 (2021) 4, 31*

Power of the Low Threshold Detector

protons produced through neutrino-Ar interaction (DUNE)



Low-energy protons produced via neutrino interactions

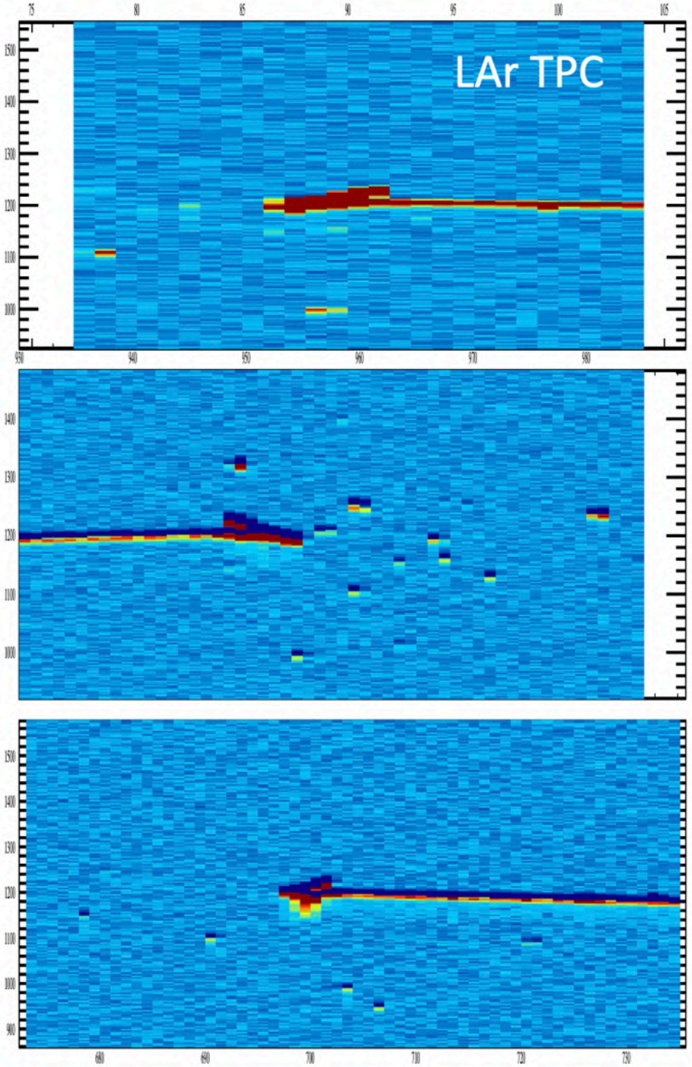
-> **Very model-dependent**

(Because we do not have any past data to constrain the model prediction)

Next generation experiments must have the capability to constrain these model uncertainties.

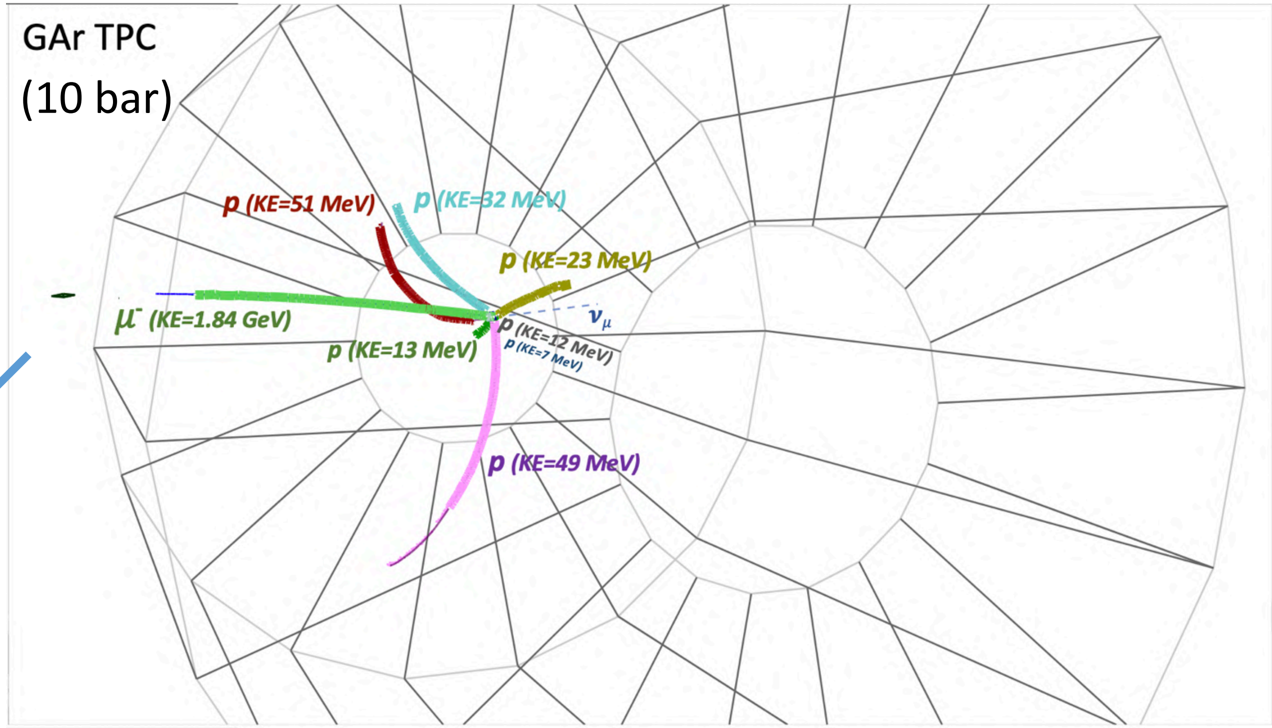
Power of the Low Threshold Detector

Assume a neutrino CC interaction produce 1 muon, 7 low energy protons, and 9 neutrons

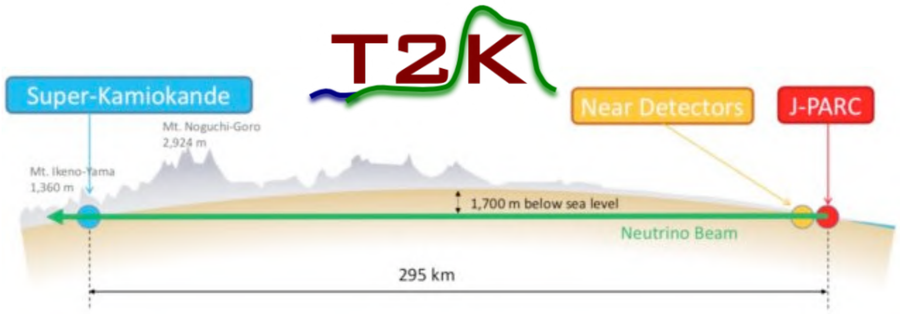


with LAr TPC
CC 1p -like

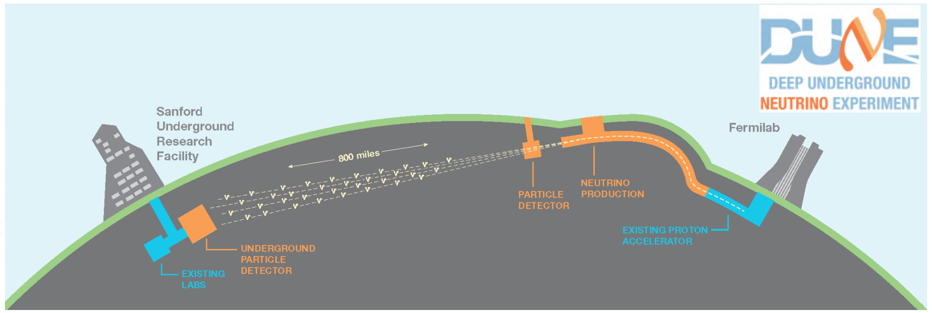
with GAr TPC
CC multi-p like



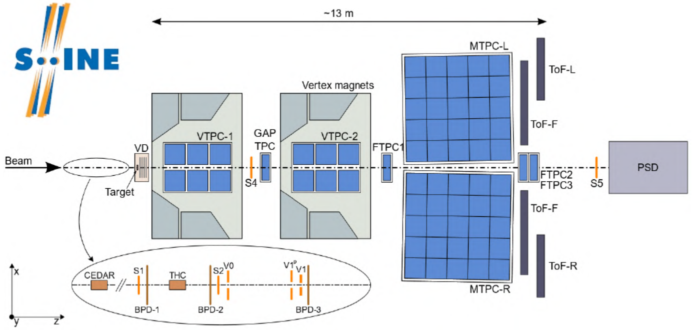
Note: the same neutrino event simulated in ND-LAr and ND-GAr
Lower density gaseous argon allows low energy particles to travel further
—> Easier to detect and reconstruct their tracks
—> Even neutrons can be detected in combination with ECAL (not shown)



(Japan)



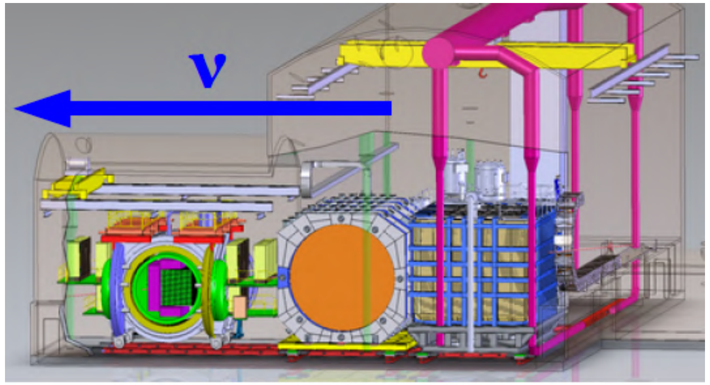
(USA)



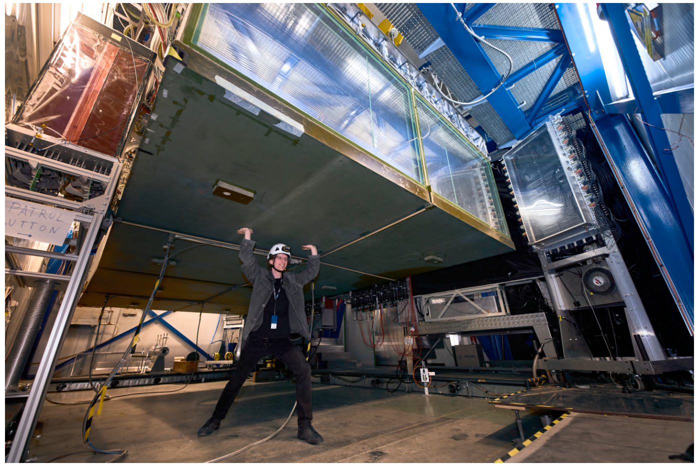
(CERN)

Advertisement:

Activities of the experimental neutrino physics group in Hungary



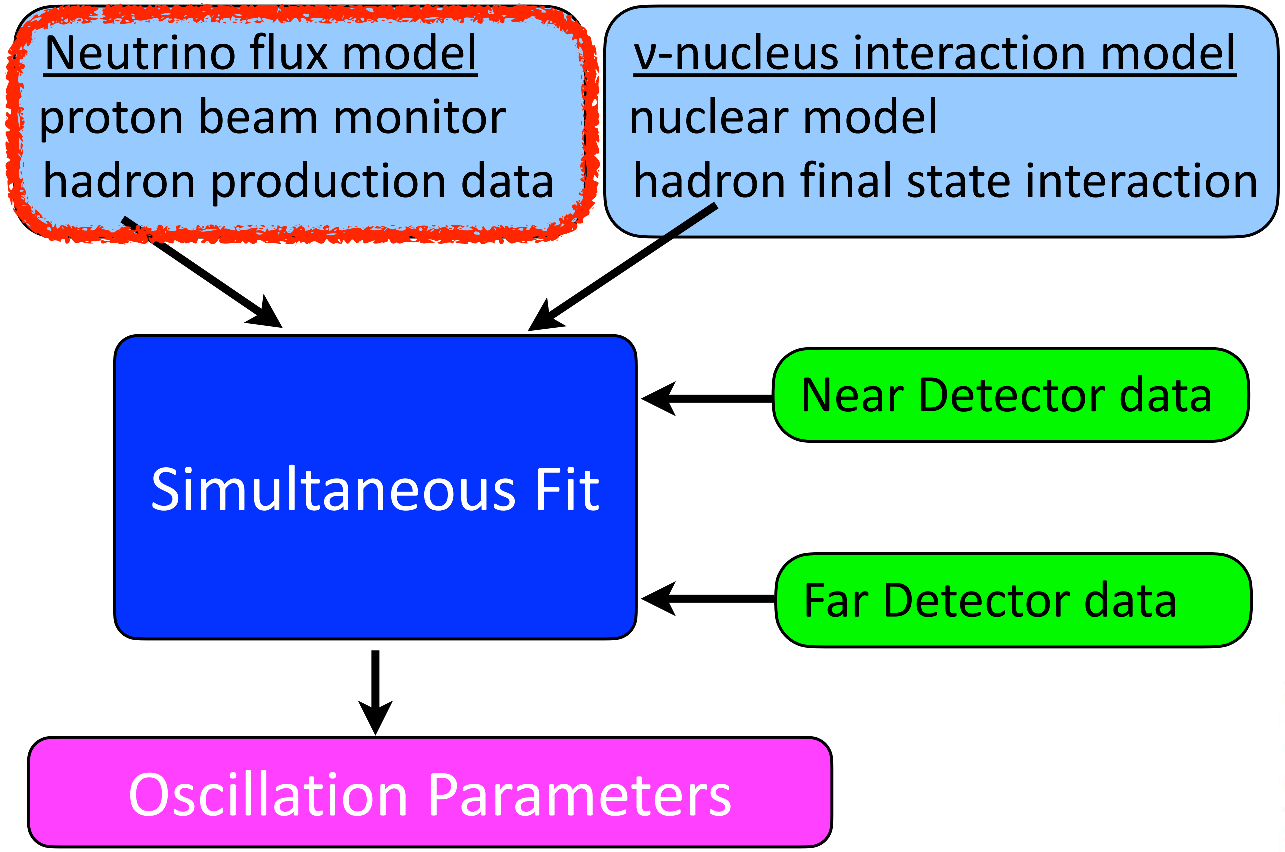
SAND ND-GAr ND-LAr



We are a member institute of three international experimental collaborations!!

Our Activities in Hungary

- Neutrino oscillation



Neutrino flux model
proton beam monitor
hadron production data

ν-nucleus interaction model
nuclear model
hadron final state interaction

Simultaneous Fit

Near Detector data

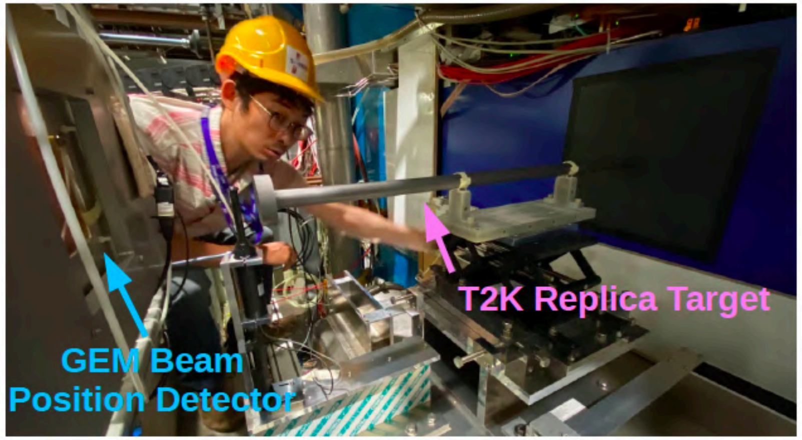
Far Detector data

Oscillation Parameters

θ_{23}, θ_{13}, δ_{CP}, Δm^2_{32} or Δm^2_{13}

(Normal) (Inverted)

NA61/SHINE: Hadron production measurements for T2K and DUNE



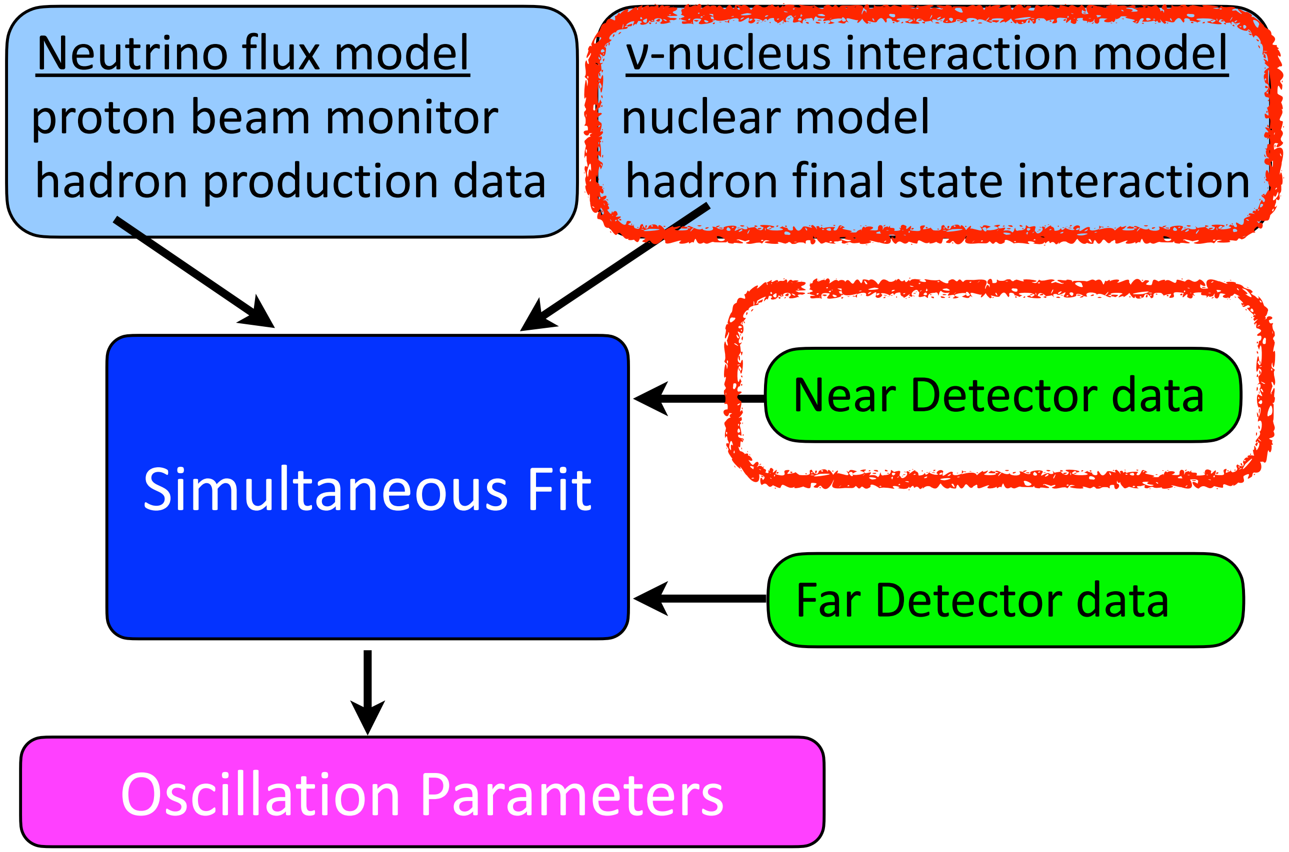
T2K: Beam group leadership

760 kW continuous operation

Photo from P. Dasgupta

Our Activities in Hungary

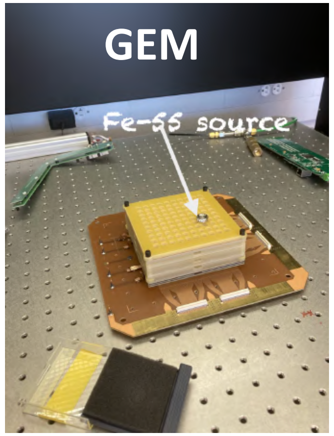
- Neutrino oscillation

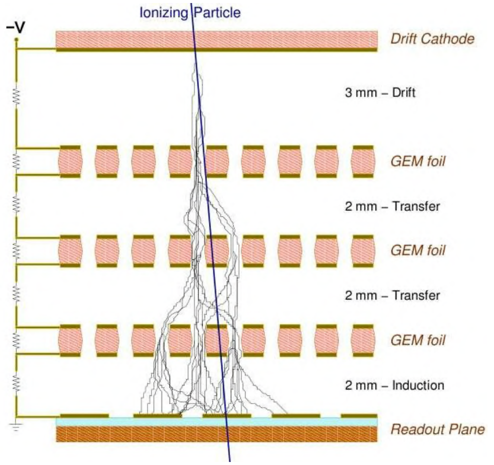


$\theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{32}$ or Δm^2_{13}

(Normal) (Inverted)

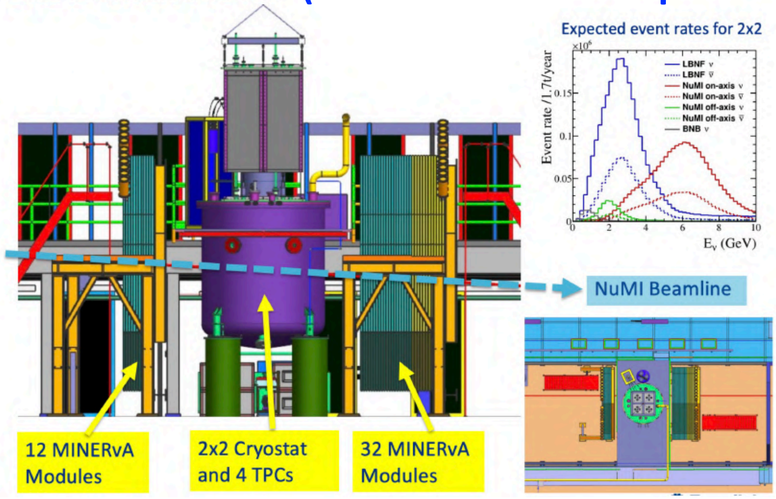
DUNE: Novel detector R&D





DUNE: neutrino-Ar interaction studies at NuMI

2x2 Demonstrator **(Small-scale ND-LAr prototype)**



Wrap-up

- Apologies for only staying today because of a private reason.
  - I stay till 18:30 today (will catch the last bus to Budapest)
  - Feel free to catch me during lunch, coffee, or the discussion session

- Also, feel free to contact me after this summer school!!
  - I'm happy to have follow-up communications

- Want to dive into the world of neutrino physics?
  - I'm happy to discuss with you
  - We have various research topics :-)

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Thank you for your attention!!

Acknowledgement

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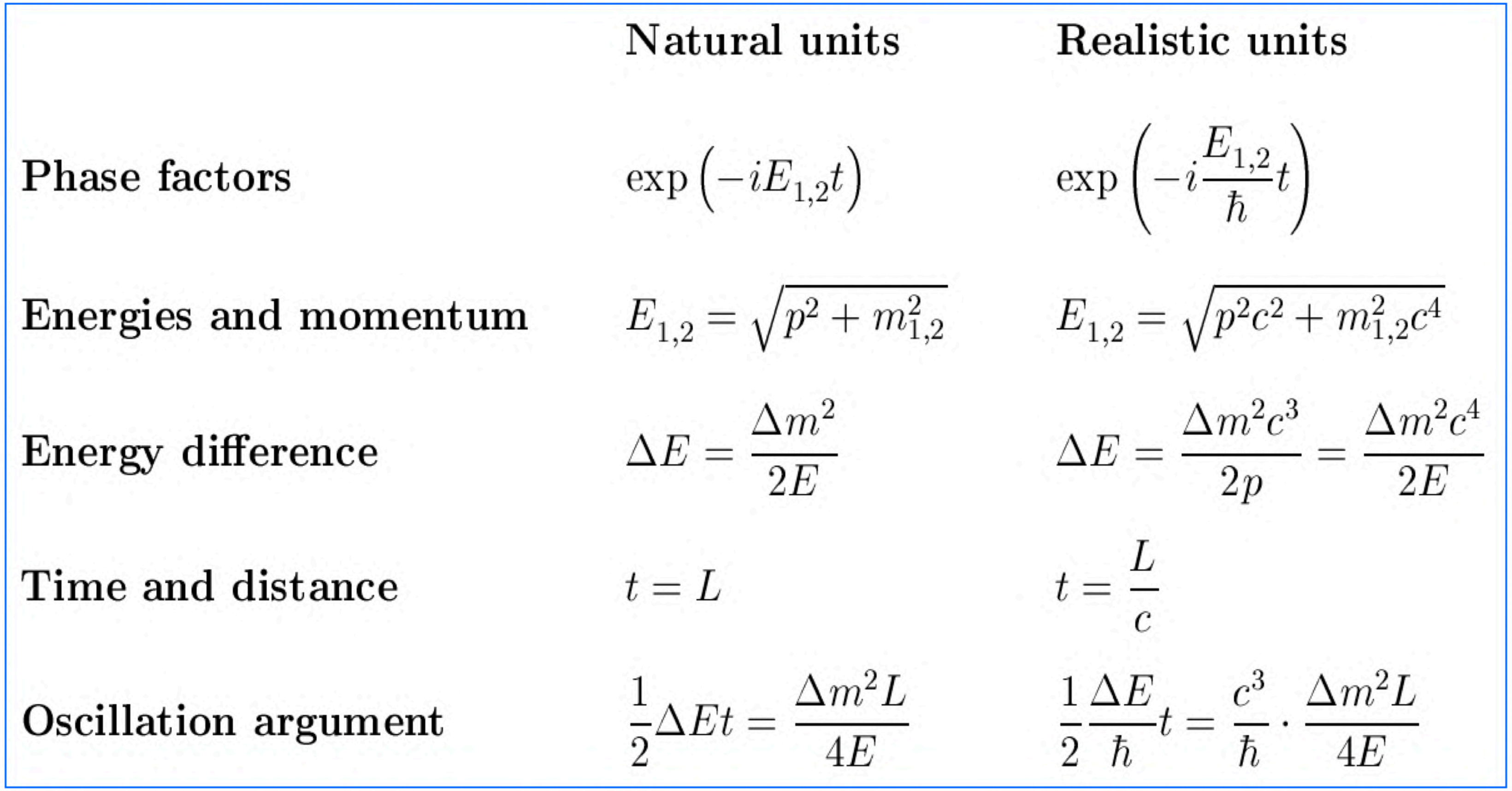
- TKP2021-NKTA-64

Backup

Exercise: Why 1.27?



	Natural units	Realistic units
Phase factors	$\exp\left(-iE_{1,2}t\right)$	$\exp\left(-i\frac{E_{1,2}}{\hbar}t\right)$
Energies and momentum	$E_{1,2}=\sqrt{p^2+m_{1,2}^2}$	$E_{1,2}=\sqrt{p^2c^2+m_{1,2}^2c^4}$
Energy difference	$\Delta E=\frac{\Delta m^2}{2E}$	$\Delta E=\frac{\Delta m^2c^3}{2p}=\frac{\Delta m^2c^4}{2E}$
Time and distance	$t=L$	$t=\frac{L}{c}$
Oscillation argument	$\frac{1}{2}\Delta Et=\frac{\Delta m^2L}{4E}$	$\frac{1}{2}\frac{\Delta E}{\hbar}t=\frac{c^3}{\hbar}\cdot\frac{\Delta m^2L}{4E}$

$$c = 2.998\times10^{5}\ \mathrm{km\,s^{-1}}$$

$$\hbar = 6.582\times10^{-25}\ \mathrm{GeV\,s}$$

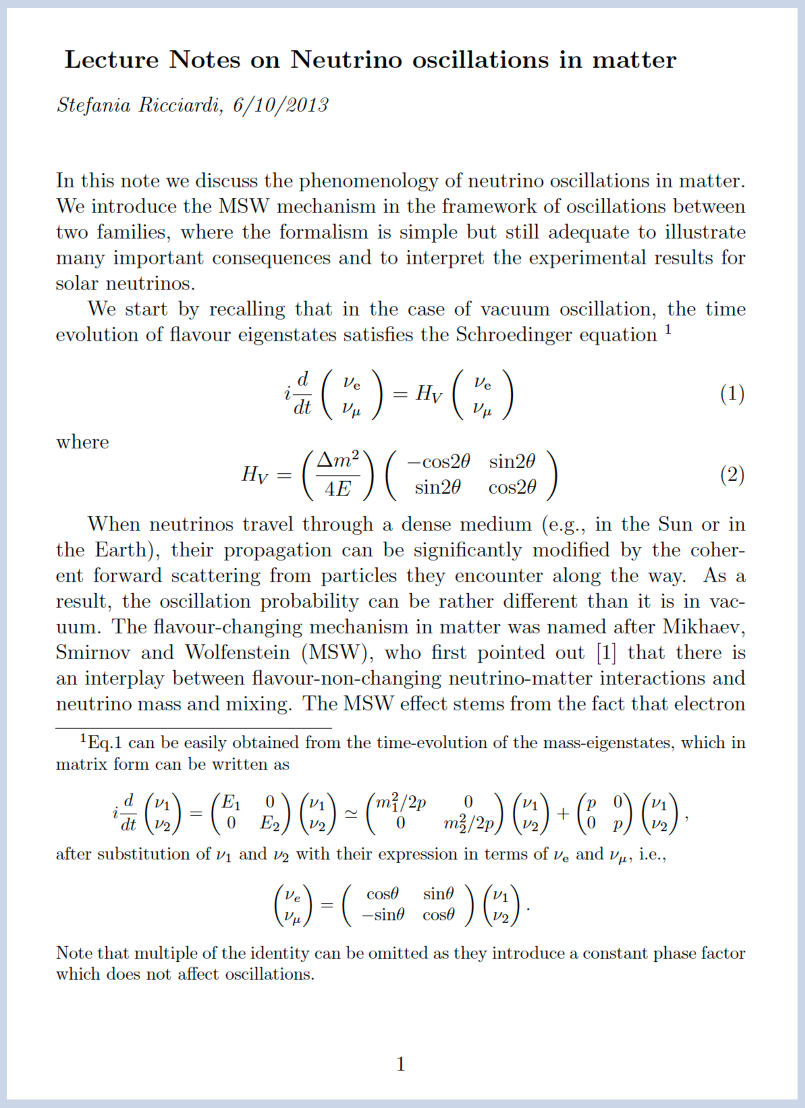
$$\frac{c^3}{4\hbar} \Rightarrow \frac{1}{4\times0.1973} = 1.267 \approx 1.27$$

$$c = 1 \quad \Rightarrow \quad \hbar = 6.582\times10^{-25}\ \mathrm{GeV}\times2.998\times10^{5}\ \mathrm{km}$$

$$= 1.973\times10^{-19}\ \mathrm{GeV\,km} = 0.1973\,\mathrm{eV^2\,GeV^{-1}\,km}$$

Matter Effects

Matter effects (Borrowed Lecture Notes by Stefania Ricciardi)



Lecture Notes on Neutrino oscillations in matter

Stefania Ricciardi, 6/10/2013

In this note we discuss the phenomenology of neutrino oscillations in matter. We introduce the MSW mechanism in the framework of oscillations between two families, where the formalism is simple but still adequate to illustrate many important consequences and to interpret the experimental results for solar neutrinos.

We start by recalling that in the case of vacuum oscillation, the time evolution of flavour eigenstates satisfies the Schroedinger equation [1]

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = H_V\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} \qquad (1)$$

where

$$H_V = \left(\frac{\Delta m^2}{4E}\right)\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix} \qquad (2)$$

When neutrinos travel through a dense medium (e.g., in the Sun or in the Earth), their propagation can be significantly modified by the coherent forward scattering from particles they encounter along the way. As a result, the oscillation probability can be rather different than it is in vacuum. The flavour-changing mechanism in matter was named after Mikhaev, Smirnov and Wolfenstein (MSW), who first pointed out [1] that there is an interplay between flavour-non-changing neutrino-matter interactions and neutrino mass and mixing. The MSW effect stems from the fact that electron

---

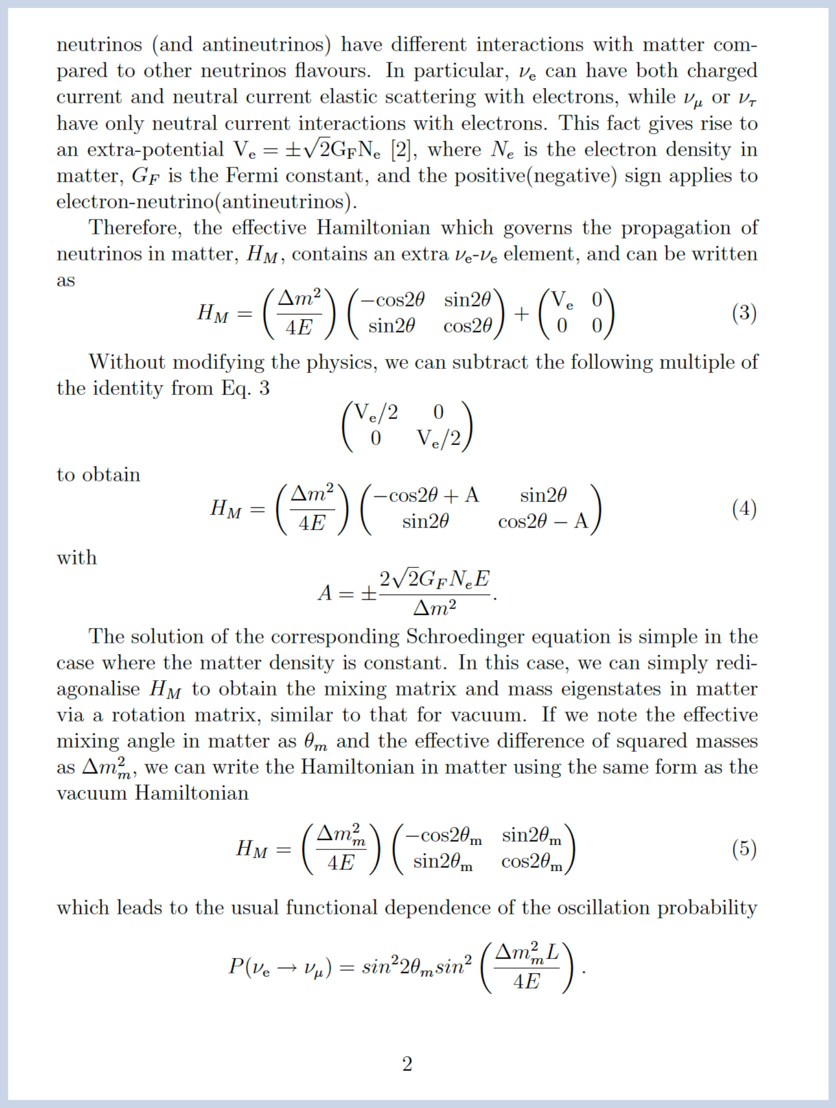
[1] Eq.1 can be easily obtained from the time-evolution of the mass-eigenstates, which in matrix form can be written as

$$i\frac{d}{dt}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} = \begin{pmatrix}E_1 & 0\\ 0 & E_2\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} \simeq \begin{pmatrix}m_1^2/2p & 0\\ 0 & m_2^2/2p\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix} + \begin{pmatrix}p & 0\\ 0 & p\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix},$$

after substitution of ν_1 and ν_2 with their expression in terms of ν_e and ν_μ, i.e.,

$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}.$$

Note that multiple of the identity can be omitted as they introduce a constant phase factor which does not affect oscillations.



neutrinos (and antineutrinos) have different interactions with matter compared to other neutrinos flavours. In particular, ν_e can have both charged current and neutral current elastic scattering with electrons, while ν_μ or ν_τ have only neutral current interactions with electrons. This fact gives rise to an extra-potential $V_e = \pm\sqrt{2}G_F N_e$ [2], where N_e is the electron density in matter, G_F is the Fermi constant, and the positive(negative) sign applies to electron-neutrino(antineutrinos).

Therefore, the effective Hamiltonian which governs the propagation of neutrinos in matter, H_M, contains an extra ν_e-ν_e element, and can be written as

$$H_M = \left(\frac{\Delta m^2}{4E}\right)\begin{pmatrix}-\cos 2\theta & \sin 2\theta\\ \sin 2\theta & \cos 2\theta\end{pmatrix} + \begin{pmatrix}V_e & 0\\ 0 & 0\end{pmatrix} \qquad (3)$$

Without modifying the physics, we can subtract the following multiple of the identity from Eq. 3

$$\begin{pmatrix}V_e/2 & 0\\ 0 & V_e/2\end{pmatrix}$$

to obtain

$$H_M = \left(\frac{\Delta m^2}{4E}\right)\begin{pmatrix}-\cos 2\theta + A & \sin 2\theta\\ \sin 2\theta & \cos 2\theta - A\end{pmatrix} \qquad (4)$$

with

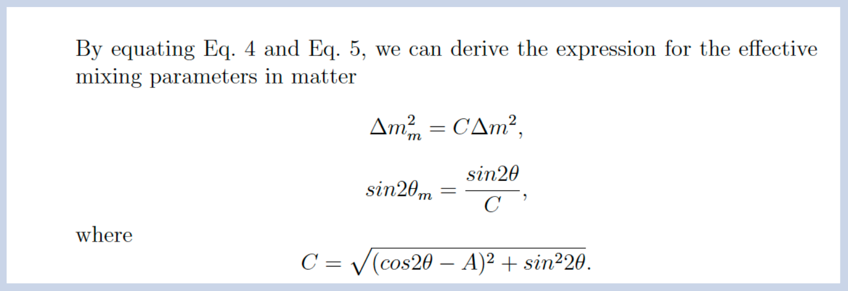
$$A = \pm\frac{2\sqrt{2}G_F N_e E}{\Delta m^2}.$$

The solution of the corresponding Schroedinger equation is simple in the case where the matter density is constant. In this case, we can simply redi-agonalise H_M to obtain the mixing matrix and mass eigenstates in matter via a rotation matrix, similar to that for vacuum. If we note the effective mixing angle in matter as θ_m and the effective difference of squared masses as Δm_m^2, we can write the Hamiltonian in matter using the same form as the vacuum Hamiltonian

$$H_M = \left(\frac{\Delta m_m^2}{4E}\right)\begin{pmatrix}-\cos 2\theta_m & \sin 2\theta_m\\ \sin 2\theta_m & \cos 2\theta_m\end{pmatrix} \qquad (5)$$

which leads to the usual functional dependence of the oscillation probability

$$P(\nu_e \rightarrow \nu_\mu) = sin^2 2\theta_m sin^2\left(\frac{\Delta m_m^2 L}{4E}\right).$$



By equating Eq. 4 and Eq. 5, we can derive the expression for the effective mixing parameters in matter

$$\Delta m_m^2 = C\Delta m^2,$$

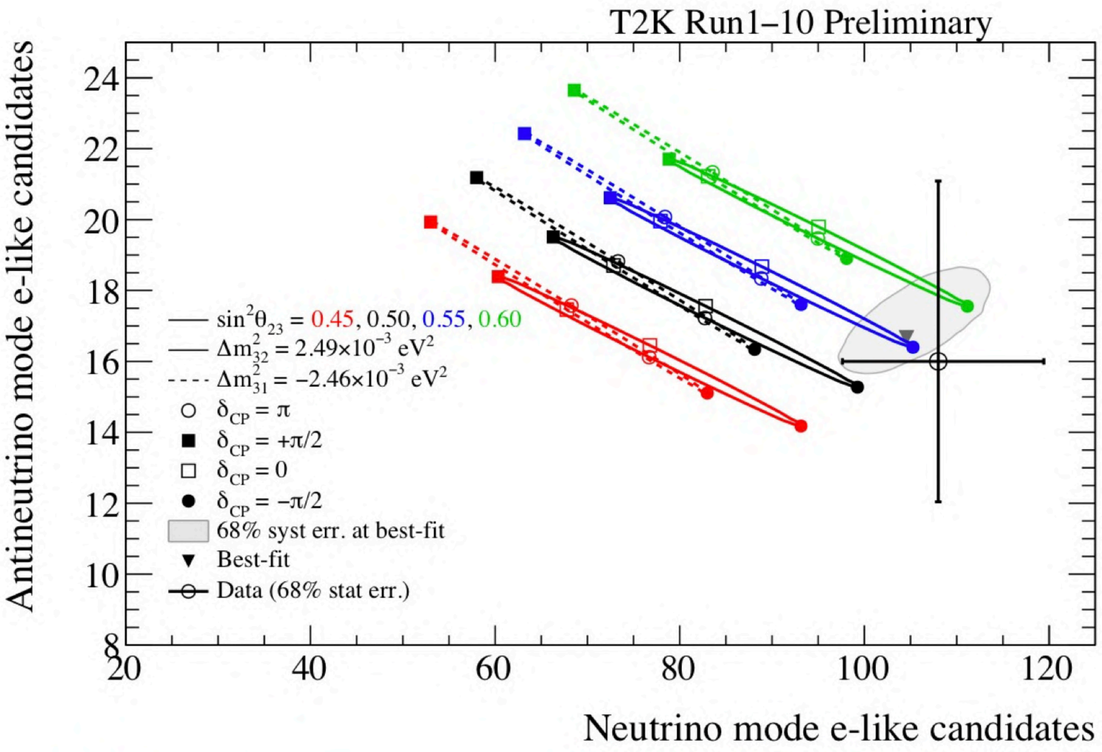
$$sin 2\theta_m = \frac{sin 2\theta}{C},$$

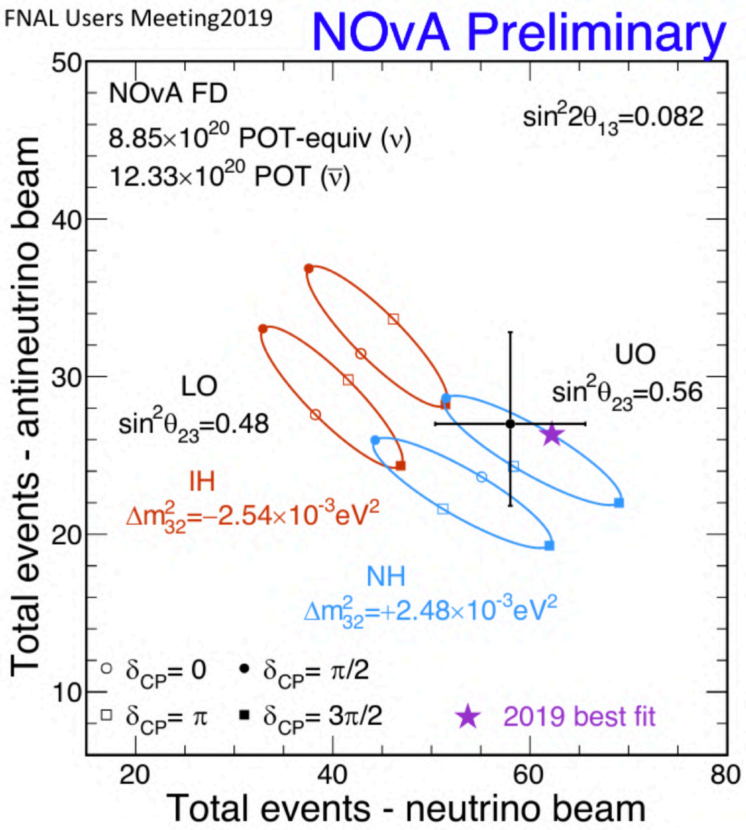
where

$$C = \sqrt{(cos 2\theta - A)^2 + sin^2 2\theta}.$$

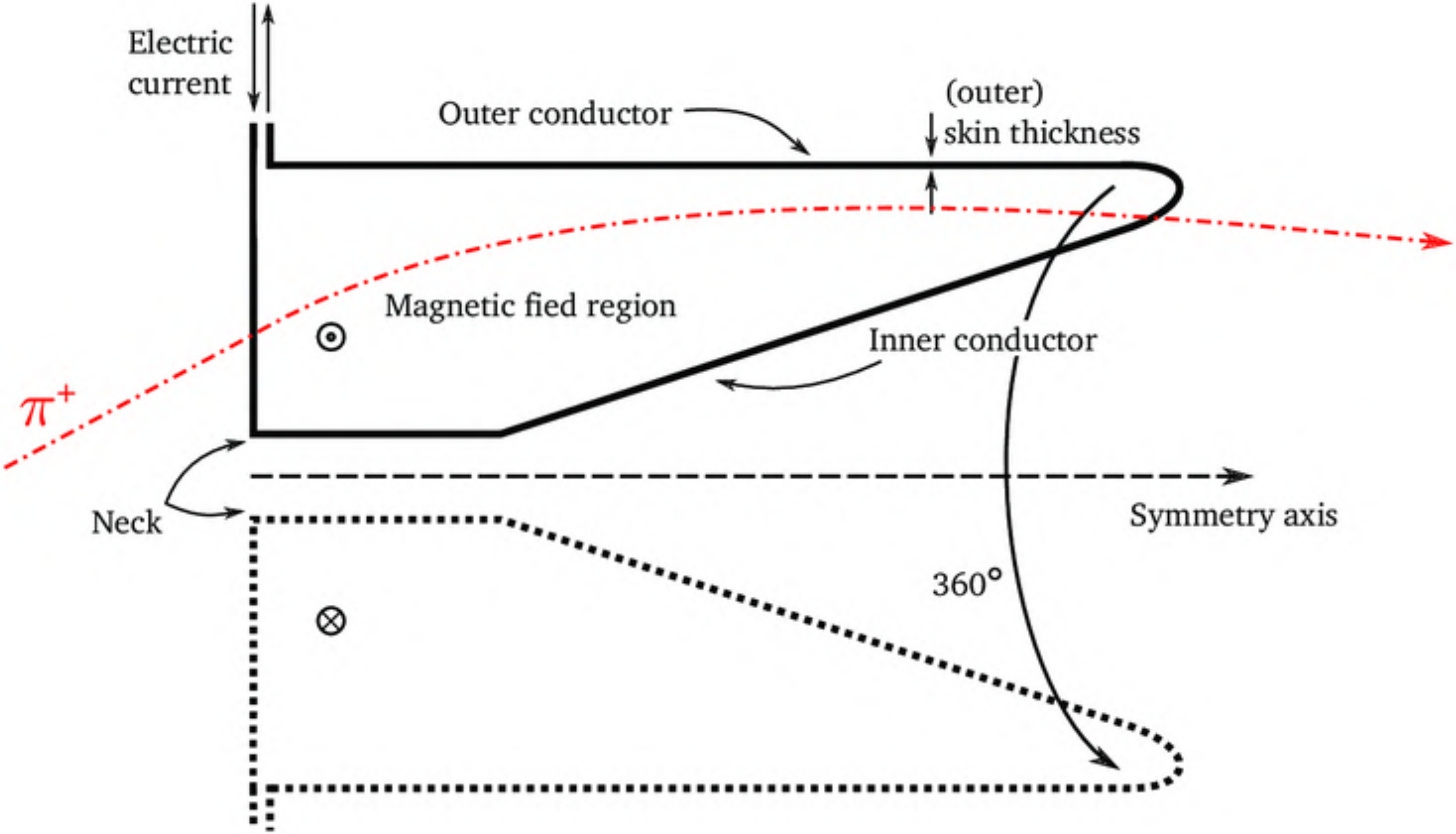
Bi-Event T2K and NOvA

- T2K and NOvA have different baselines and energies so have different sensitivities to oscillation parameters
- Joint-fit between the two experiments should lift some degeneracies in oscillation parameters and give more precise measurements





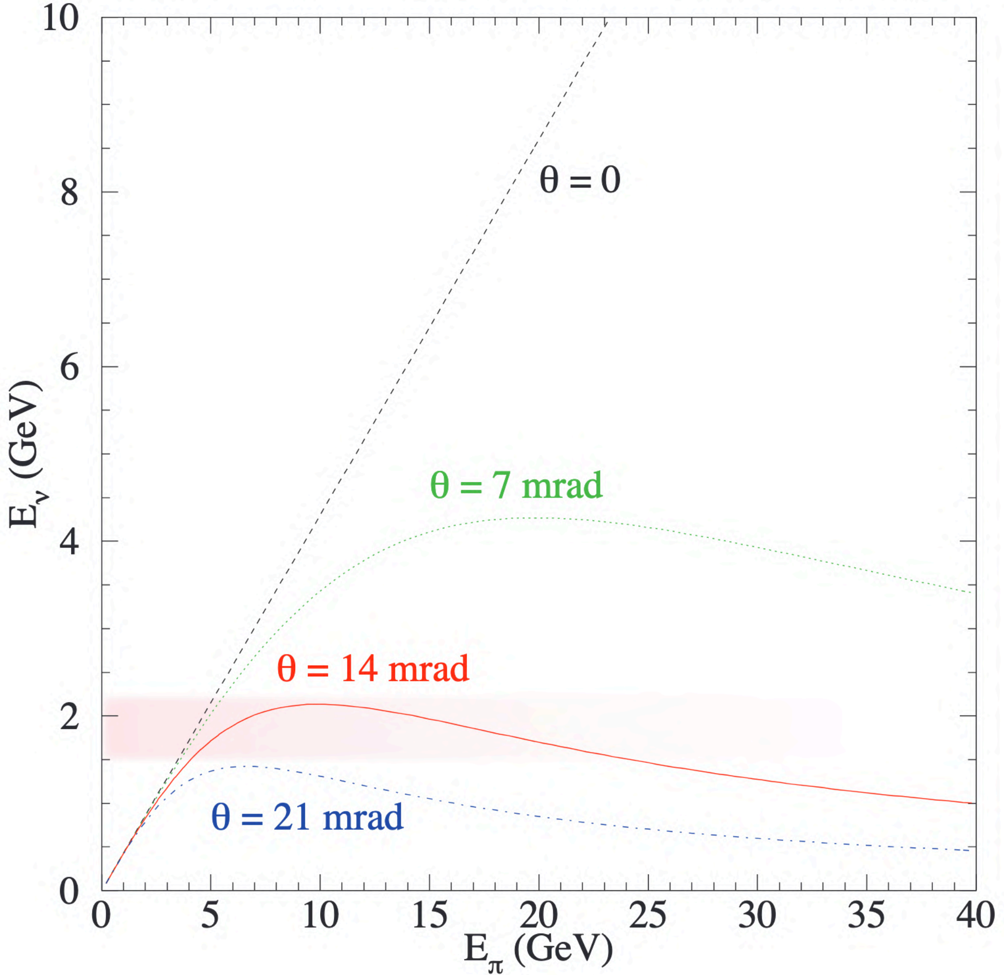
Magnetic Horn Focusing



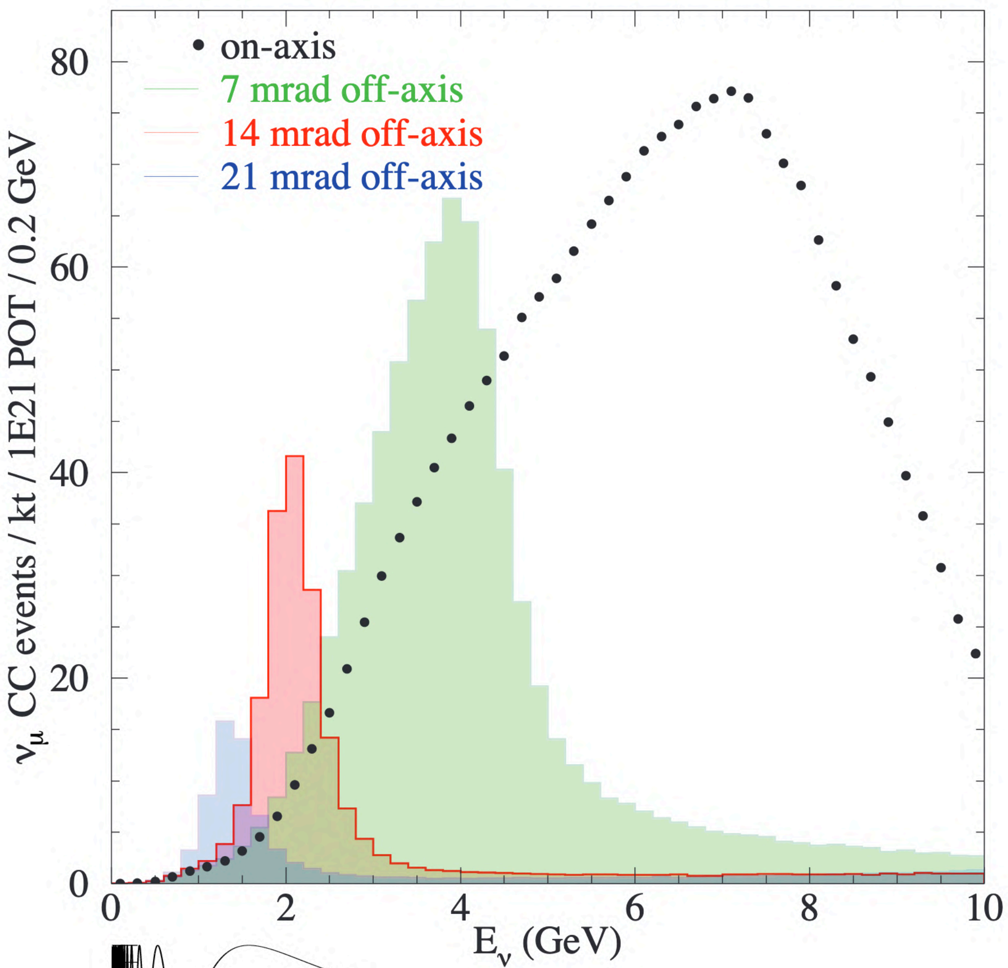
Off-axis Beam

- Downside: loss of flux

$$E_\nu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2} \frac{E_\pi}{1 + \gamma^2 \theta_{\mathrm{Lab}}^2}$$

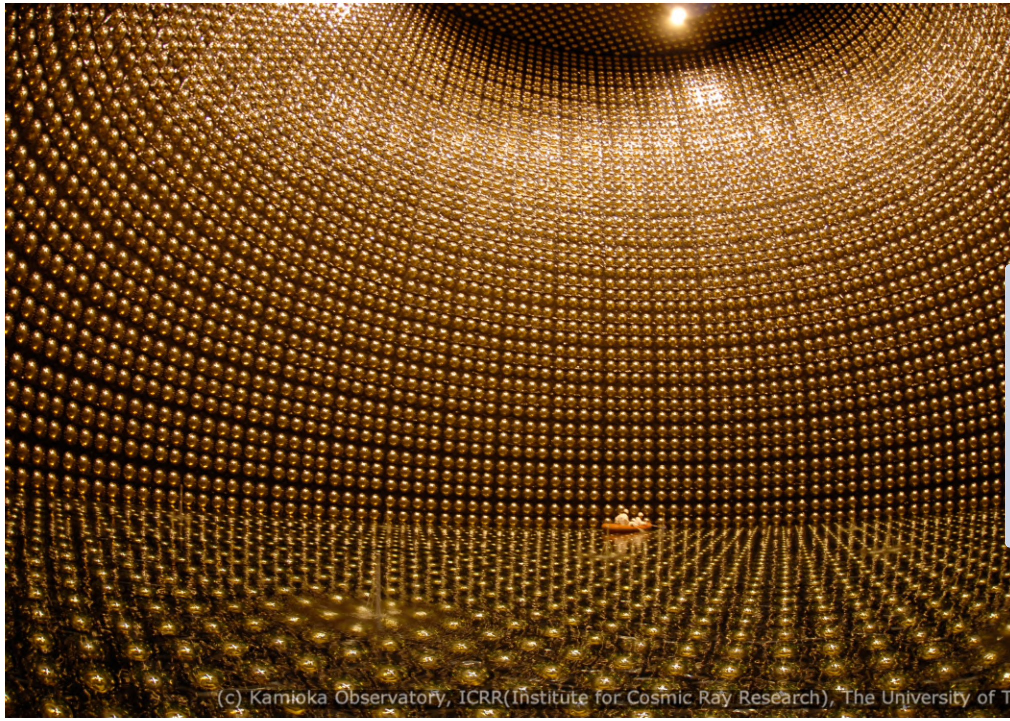


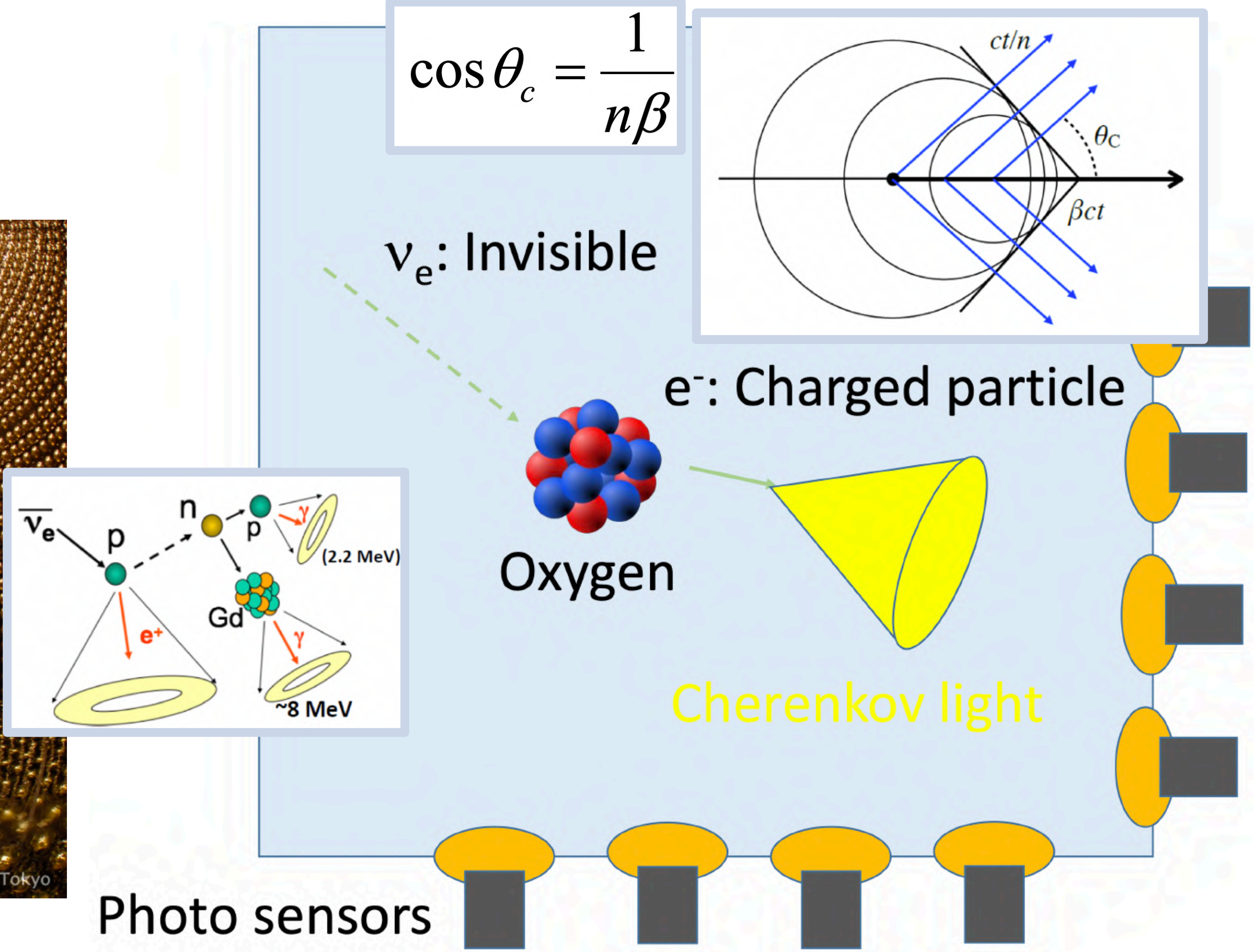
Medium Energy Tune



Water Cherenkov Far Detector

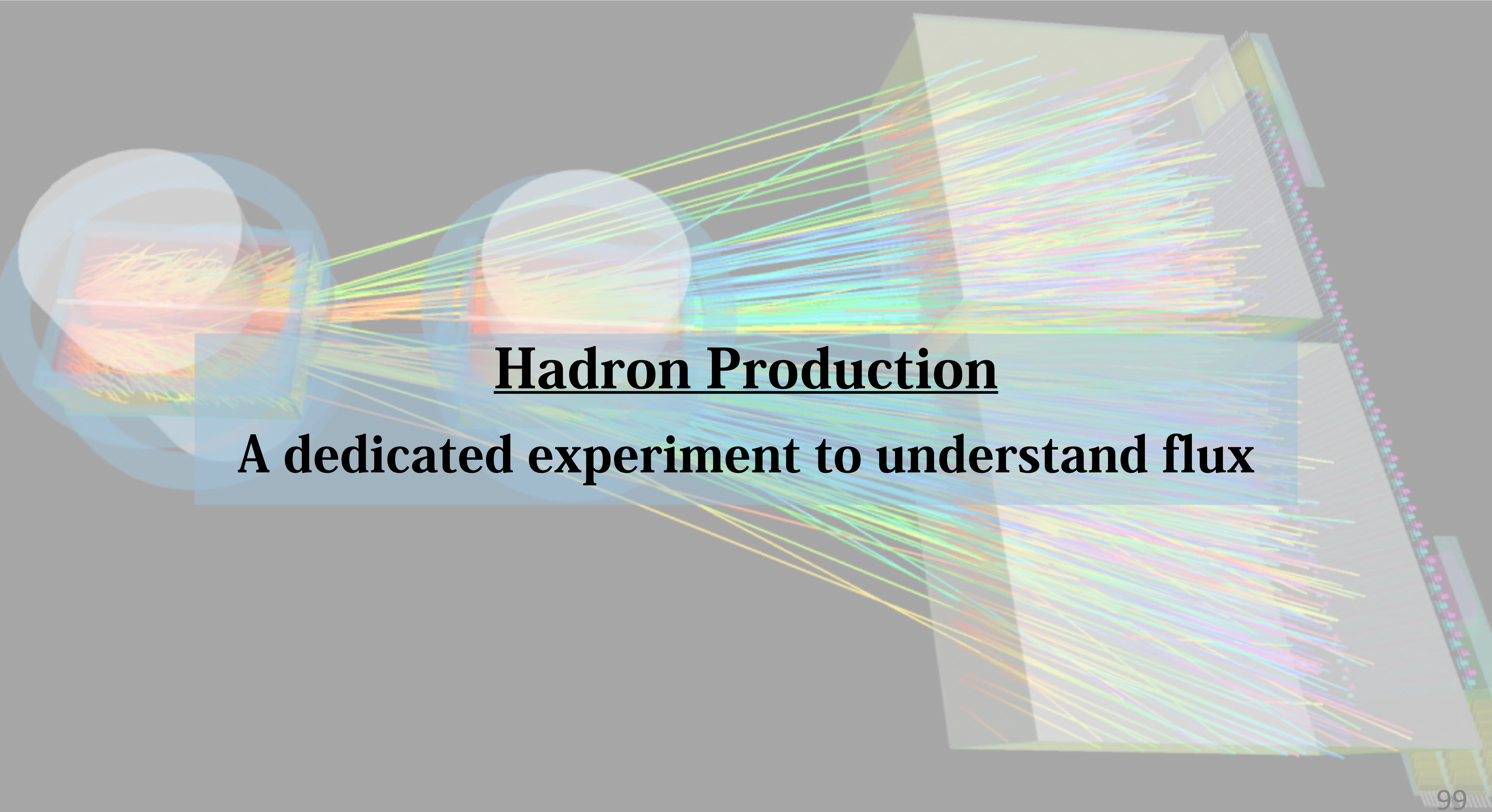
Example: Super-K
Until 2018 -> pure water
Now -> water + Gd (enhancing neutron capture)


(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo



$$\cos\theta_c = \frac{1}{n\beta}$$

The Cherenkov threshold is 0.569 MeV/c for electrons, 115.7 MeV/c for muons and 1.04 GeV/c for protons.
Detector threshold is ~3 MeV
Note: neutrino energy reconstruction is proportional to number of photons detected



Hadron Production

A dedicated experiment to understand flux

The NA61/SHINE Experiment

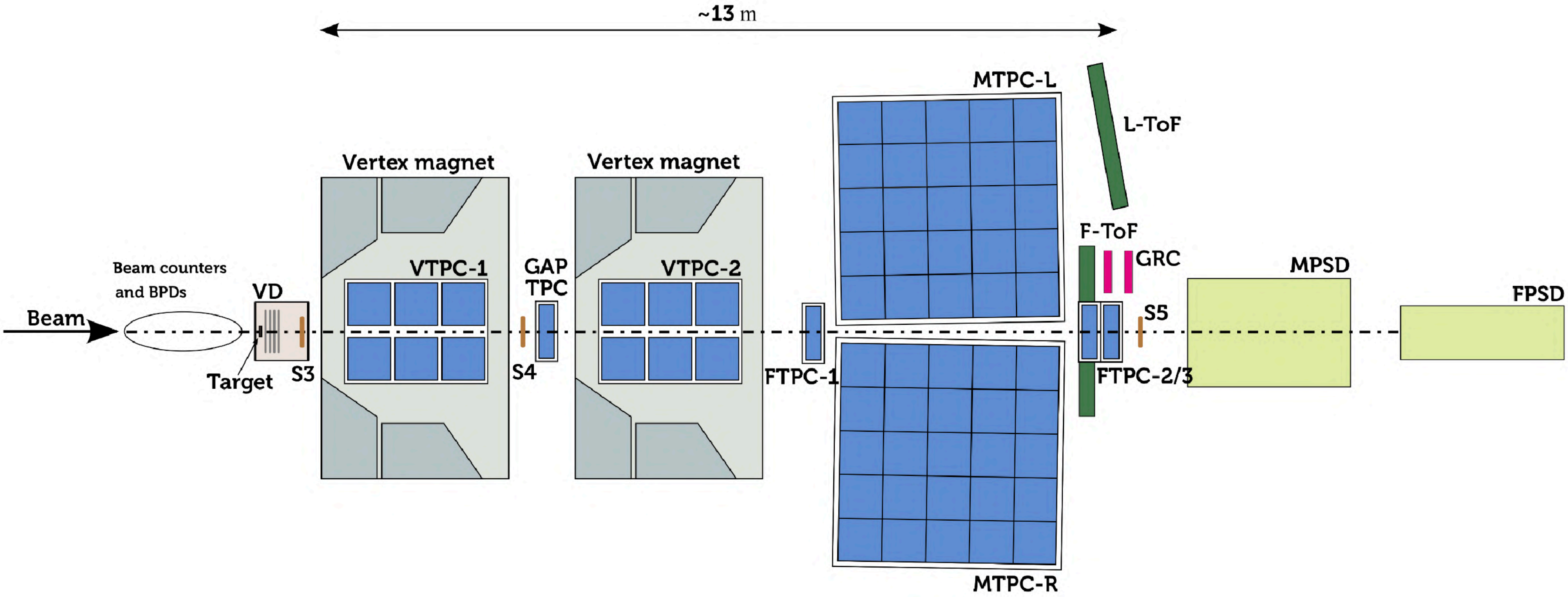
"The SPS Heavy Ion and Neutrino Experiment"

Over 150 physicists from 30 institutions and 15 countries

The NA61/SHINE Experiment

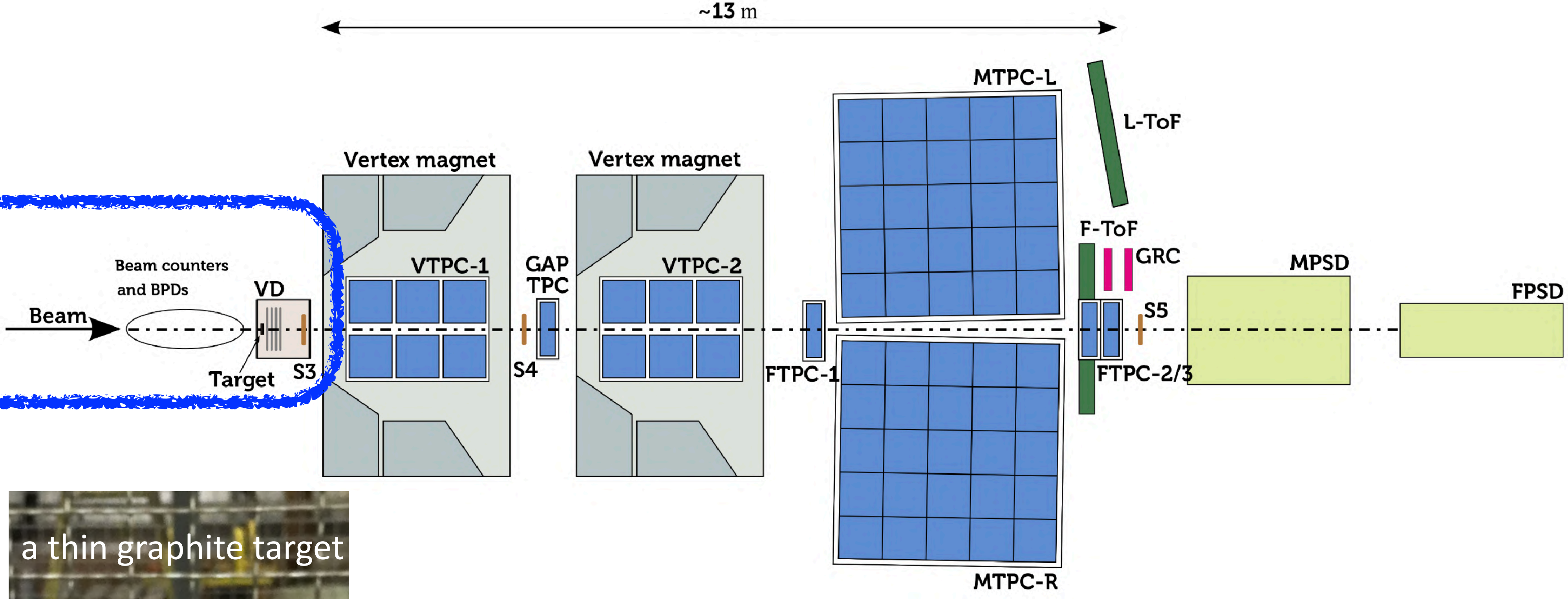
a fixed target experiment at CERN SPS

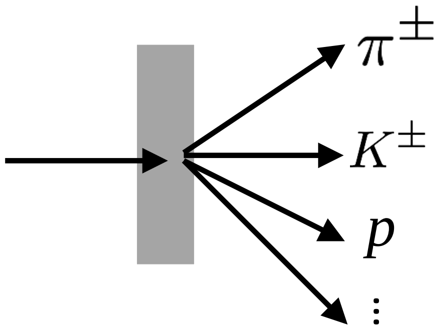
top-view

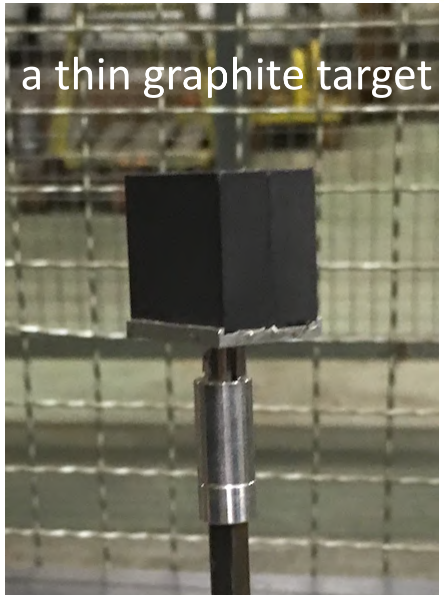


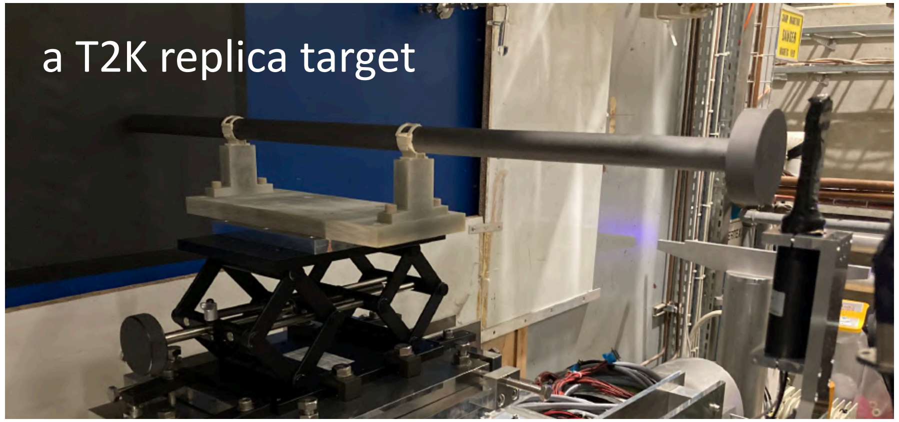
The NA61/SHINE Experiment

hadron beams
(p, π+/-, K+/-)
between 30-350 GeV

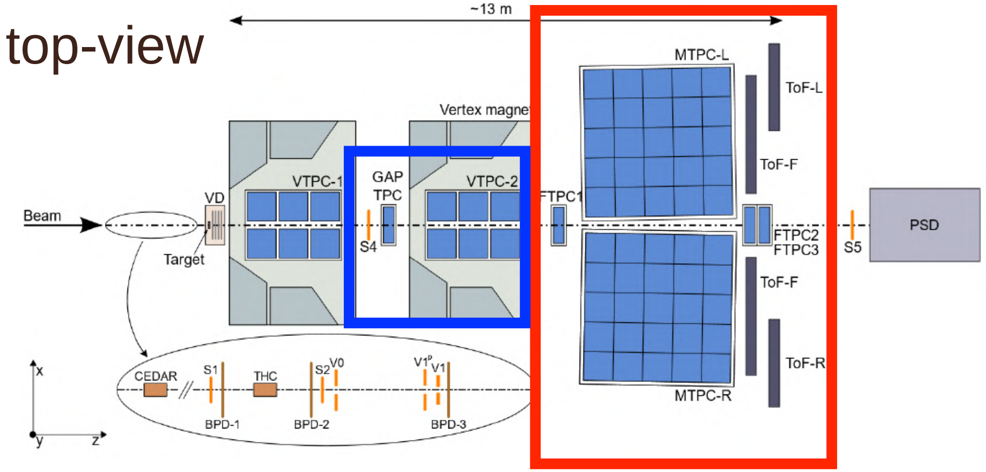




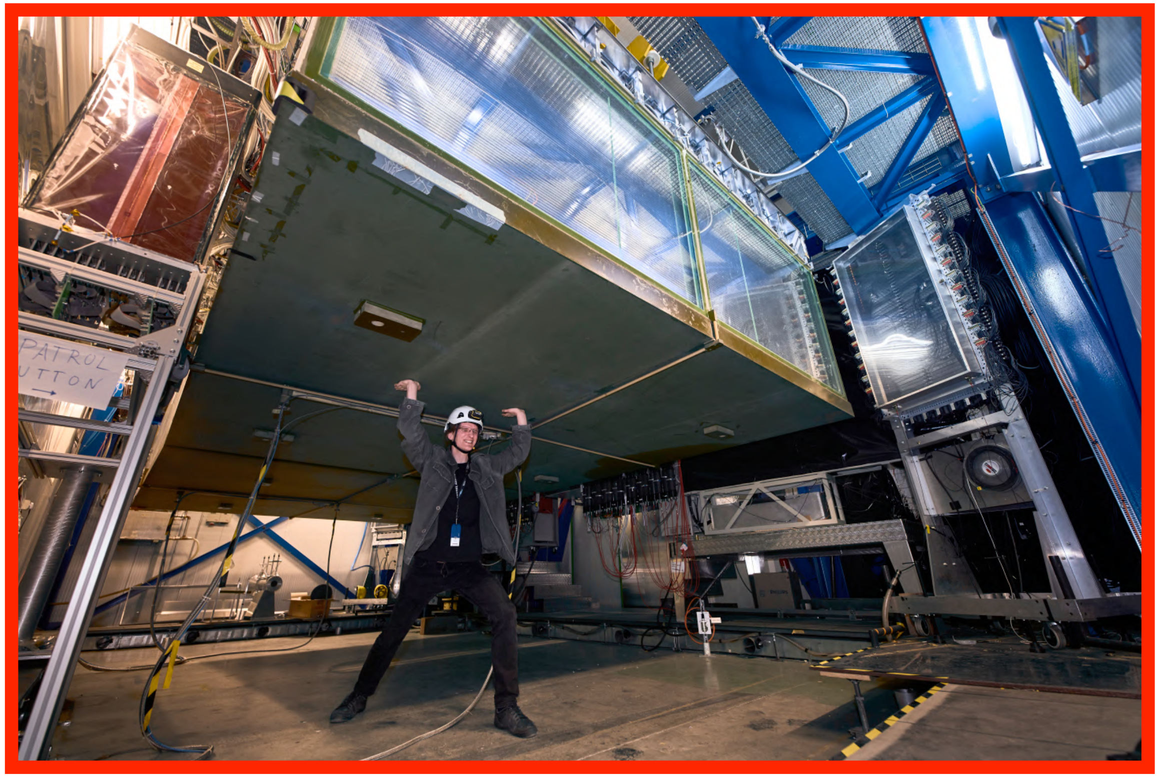

a thin graphite target


a T2K replica target

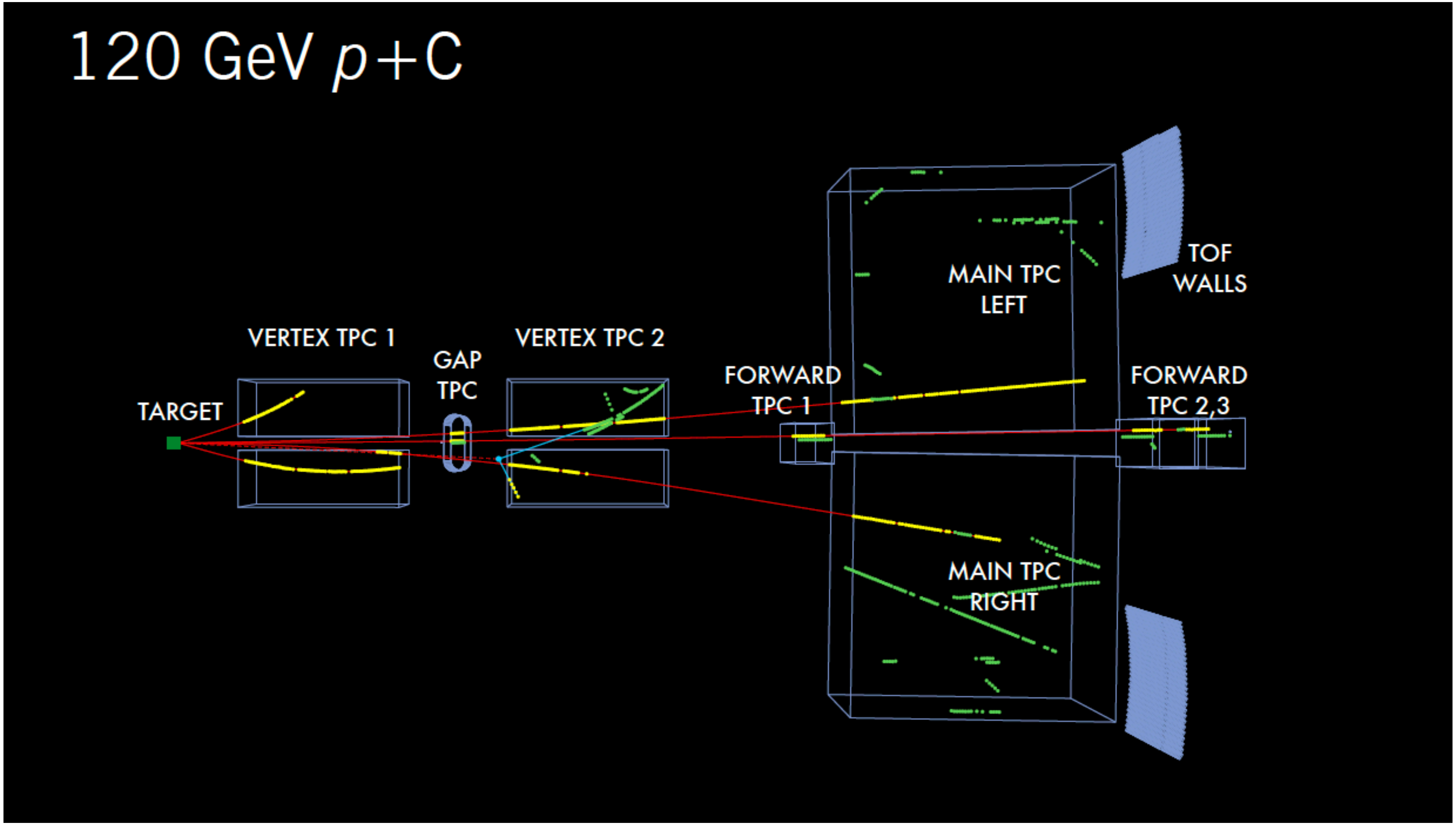
The NA61/SHINE Experiment



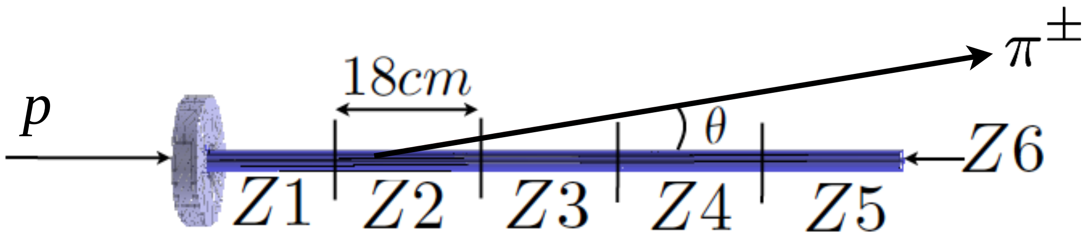
Tracking with Time Projection Chambers
- Good position resolution and particle identification
- Good momentum resolution with two magnets



Event Display



Example: a dedicated measurement for T2K



$p + \text{T2K replica} @ 30 \text{ GeV}$

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