# Understanding Neutrino Beams

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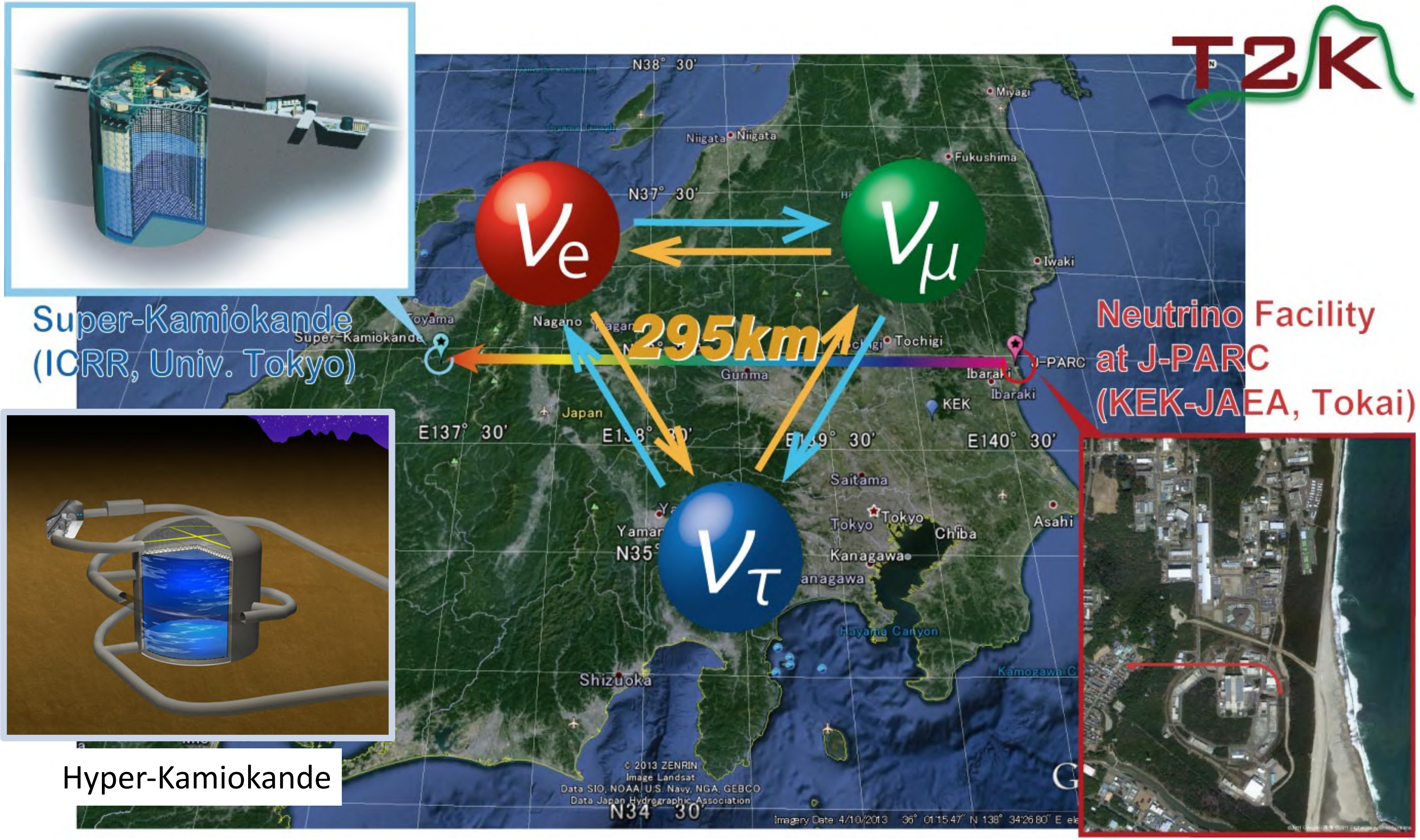
# Contents


# Introduction

# Main Focus: Accelerator-Based Neutrino Experiment

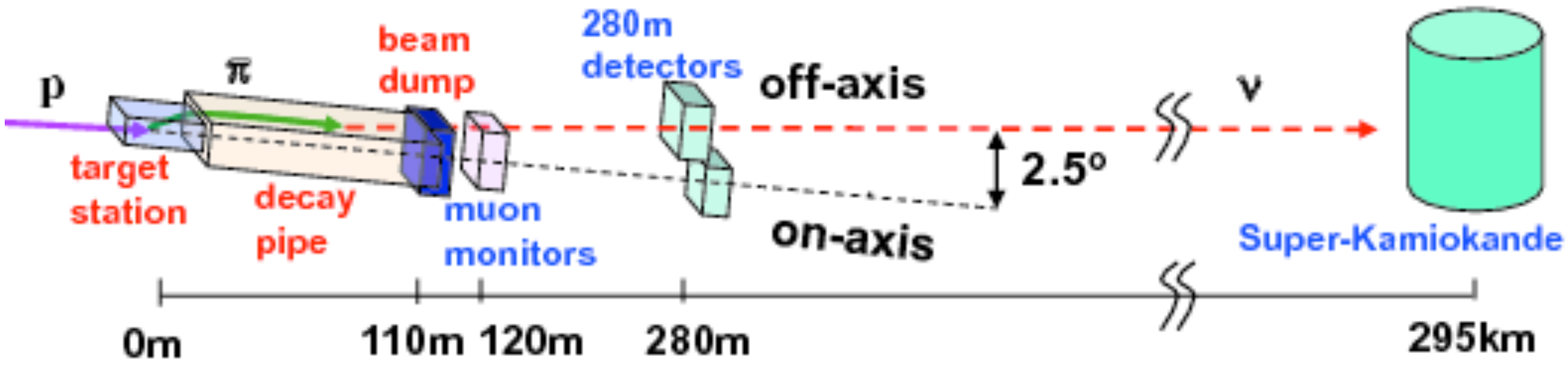



J-PARC beamline (30 GeV proton beam)
experiments: T2K (running), T2HK (2027~)

A long-baseline neutrino experiment
to primarily study neutrino oscillation.

# Long-baseline Neutrino Experiments

example:
T2K experiment




<u>Beamline</u>

- Create intense $\nu_\mu$ and $\bar{\nu}_\mu$ beams by shooting proton beams on target, focusing hadrons, and letting them decay to neutrinos

$$\Phi_{\text{initial}}$$

<u>Near detector</u>

- Flux and cross section constraint for far detector prediction
- Near detector physics measurements

—> neutrino-nucleus cross sections, search for new physics, etc

$$N_{ND} \propto \int \Phi_{ND} \cdot \sigma \; dE_\nu$$

<u>Far detector</u>

- Count $\nu_e$ and $\bar{\nu}_e$ appearance signals (measure the size of CP violation)
- Measure $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance

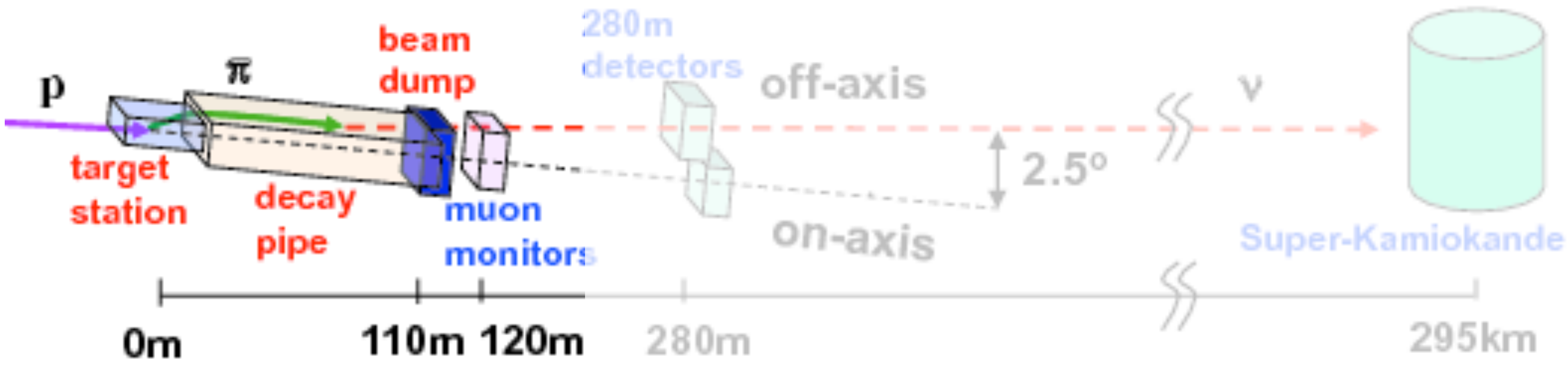
—> neutrino oscillations

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

$$\propto \int R_{\frac{FD}{ND}} \cdot \Phi_{ND} \cdot \sigma \cdot P_{osc} \; dE_\nu$$

# Long-baseline Neutrino Experiments

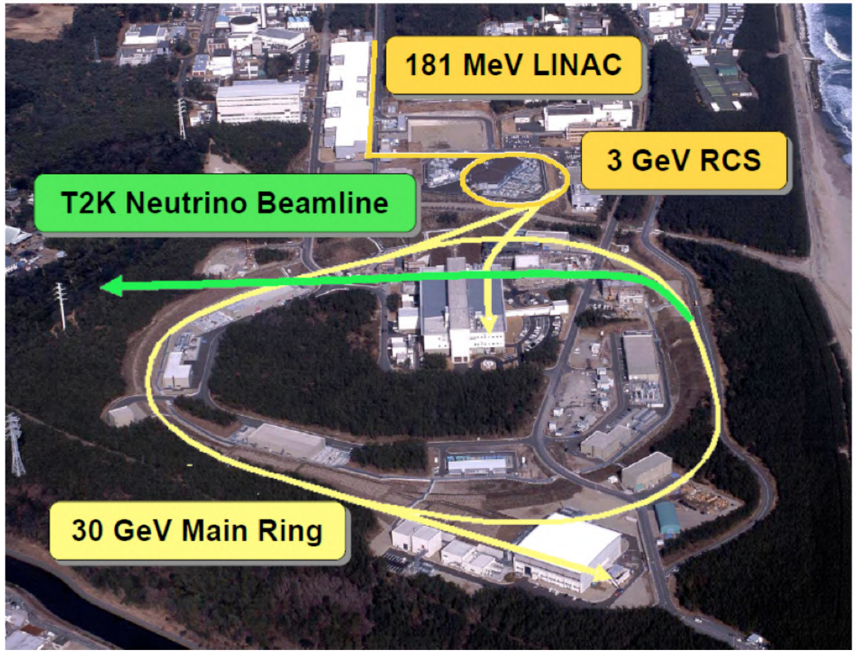
example:
T2K experiment




**Beamline**

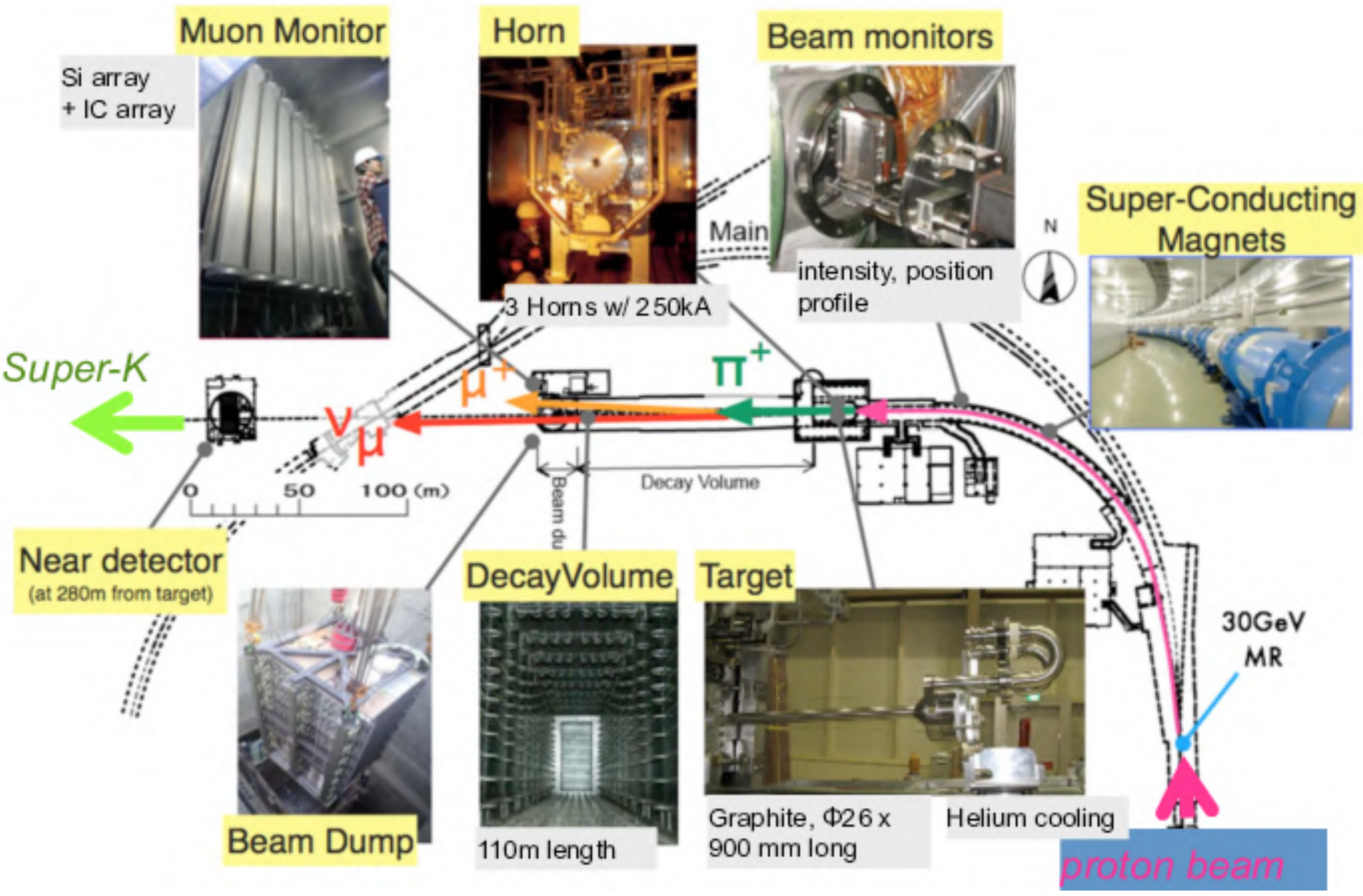
- Create intense $\nu_\mu$ and $\bar{\nu}_\mu$ beams by shooting proton beams on target, focusing hadrons, and letting them decay to neutrinos

$\Phi_{\text{initial}}$




Main question of this talk:
How many neutrinos does the accelerator produce and shoot towards the detector?

# Neutrino Beamline at J-PARC




To understand neutrino beams…

- How many primary protons?
- Proton beam profile on the target?
- Secondary hadron production?
- Magnetic field of horns?
- Muon profile after decay of secondary hadrons
- etc …

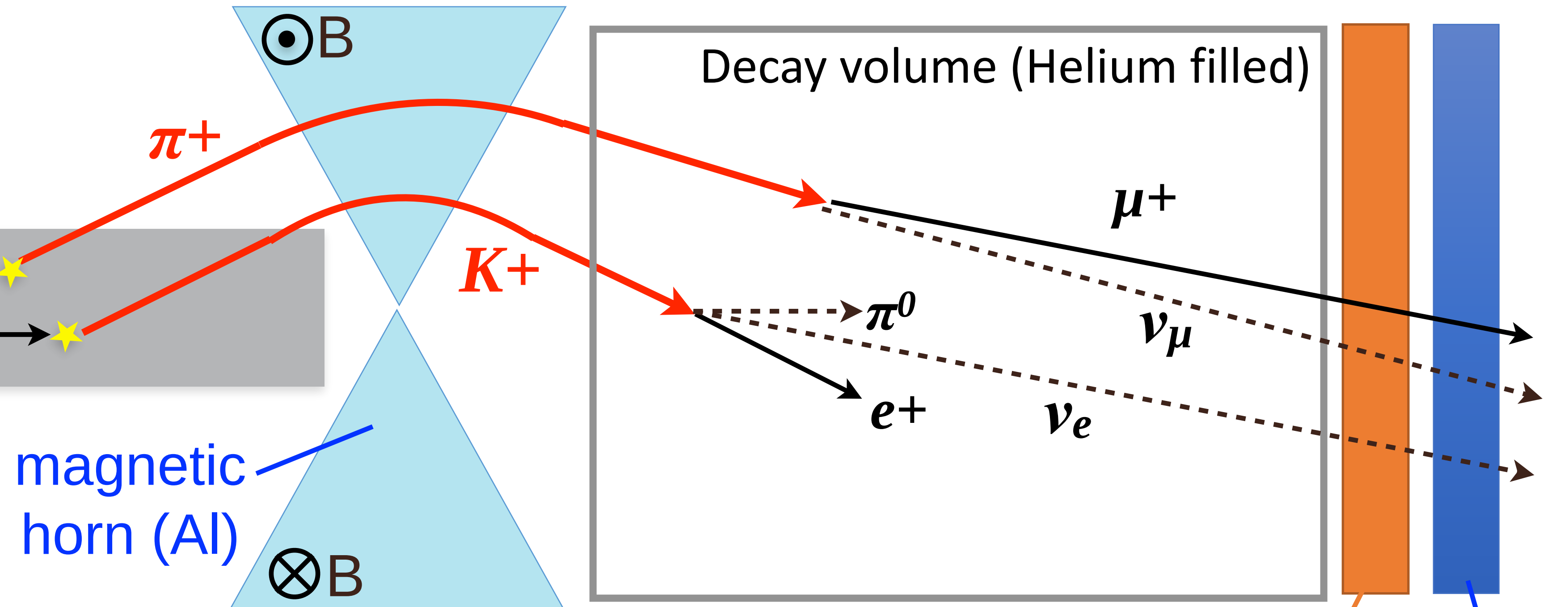
We need to know these parameters very precisely.

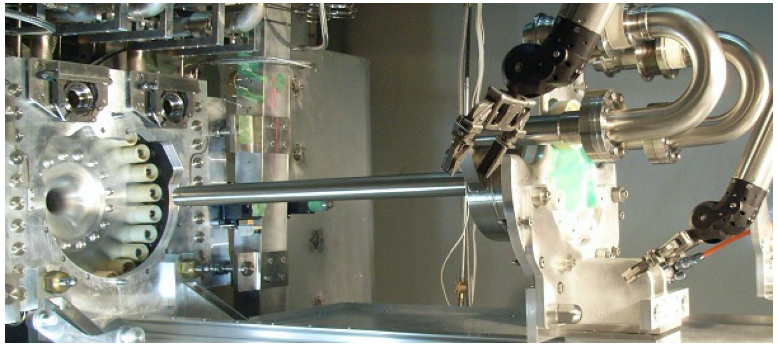
This talk focuses on production of hadrons which are ancestor of neutrinos

(neutrino) $\pi^+ \rightarrow \mu^+ \nu_\mu$

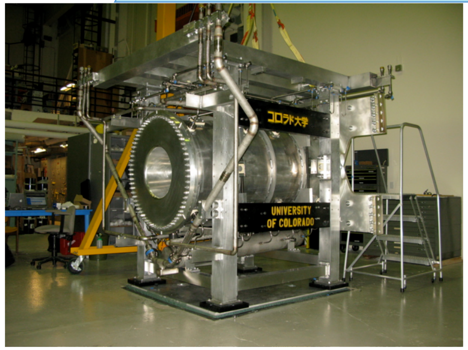
(antineutrino) $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$

# How to Make a Neutrino Beam



T2K target (90 cm, 1.9 λ)



T2K decay volume (110 m)

Hadron productions of $\pi^{\pm}$ and $K^{\pm}$ through primary interactions in the target

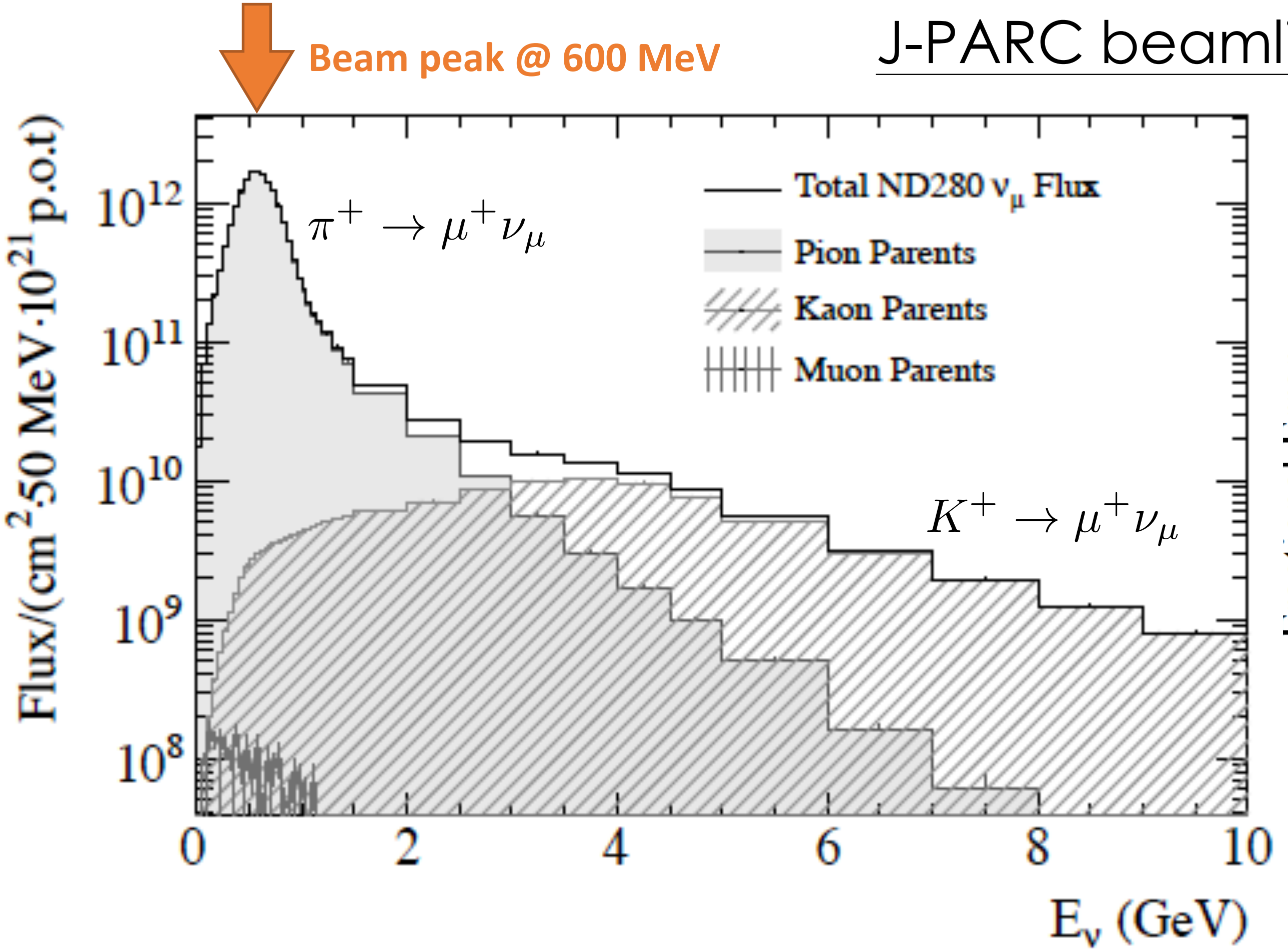
—> Primary contribution to the neutrino flux

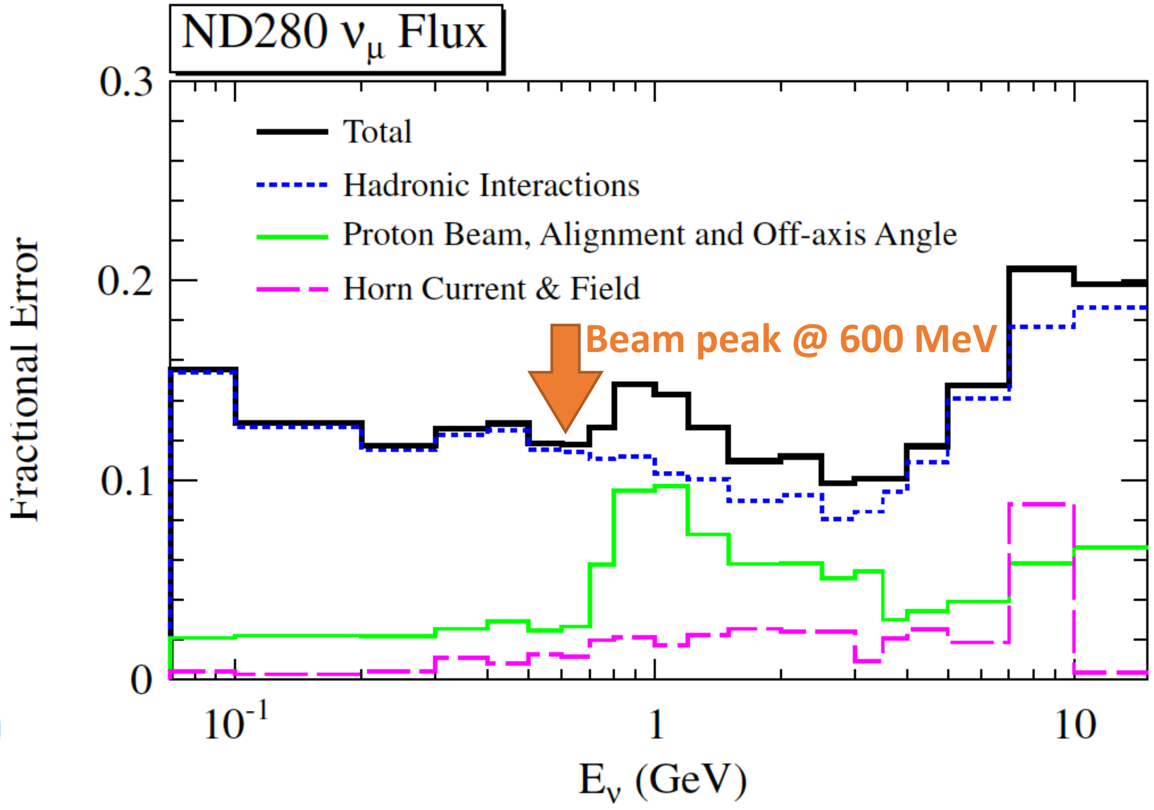
# Uncertainty on Flux Prediction

How well do we understand neutrino flux?

J-PARC beamline (T2K flux)

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




A leading source of the systematic uncertainty !!

Goal: below 5% (next few year), below 3% (for next generation experiments)

# Constraining Hadron Production Uncertainty

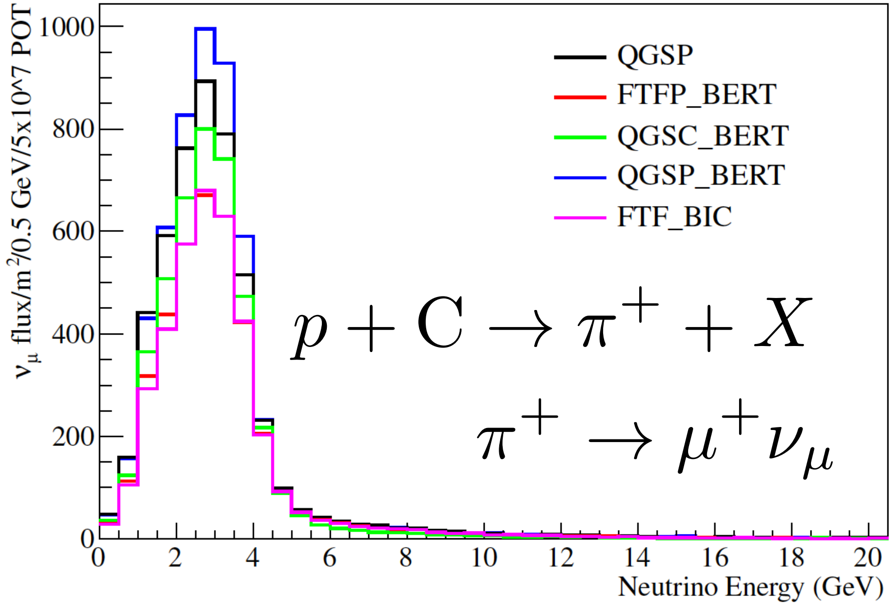
- Neutrino flux predictions rely on model predictions
  - FLUKA (J-PARC/T2K) to simulate p+C —> hadrons
  - Geant3 to simulate the rest of interactions

However, hadron production prediction is difficult…

External data is necessary to constrain uncertainty on model predictions

External hadron production measurements are essential!

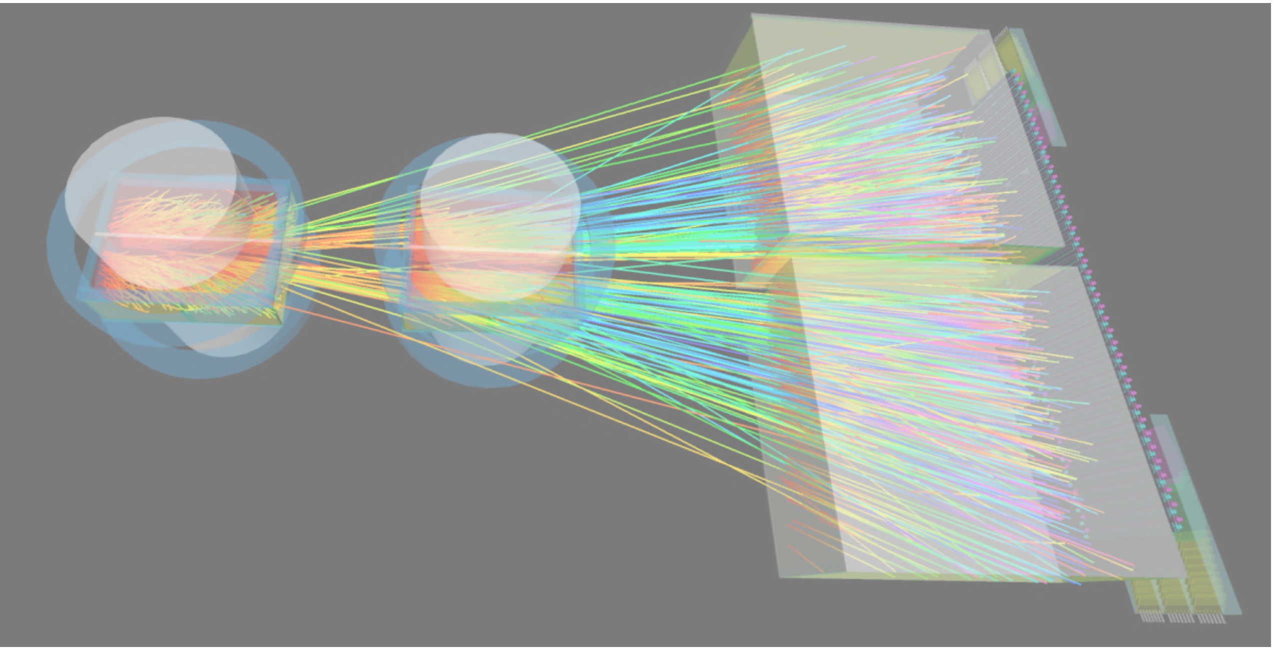
NuMI beamline at FNAL (MINERvA flux)




Leonidas Aliaga (Ph.D Thesis, 2016)

- Allaby et al Tech. Rep. 70-12, CERN (1970)
- Eichten et al Nucl. Phys. B44, 333 (1972)
- BNL E910 Phys. Rev. C77, 015209 (2008)
- HARP Nucl. Phys. B732, 1 (2006), EPJ C52, 29 (2007), Astr. Phys. 29, 257 (2008)
- NA61/SHINE (running, see following slides)
- EMPHATIC (running, arXiv:2106.15723)

Only some key data sets relevant to the T2K beam energy (30 GeV)

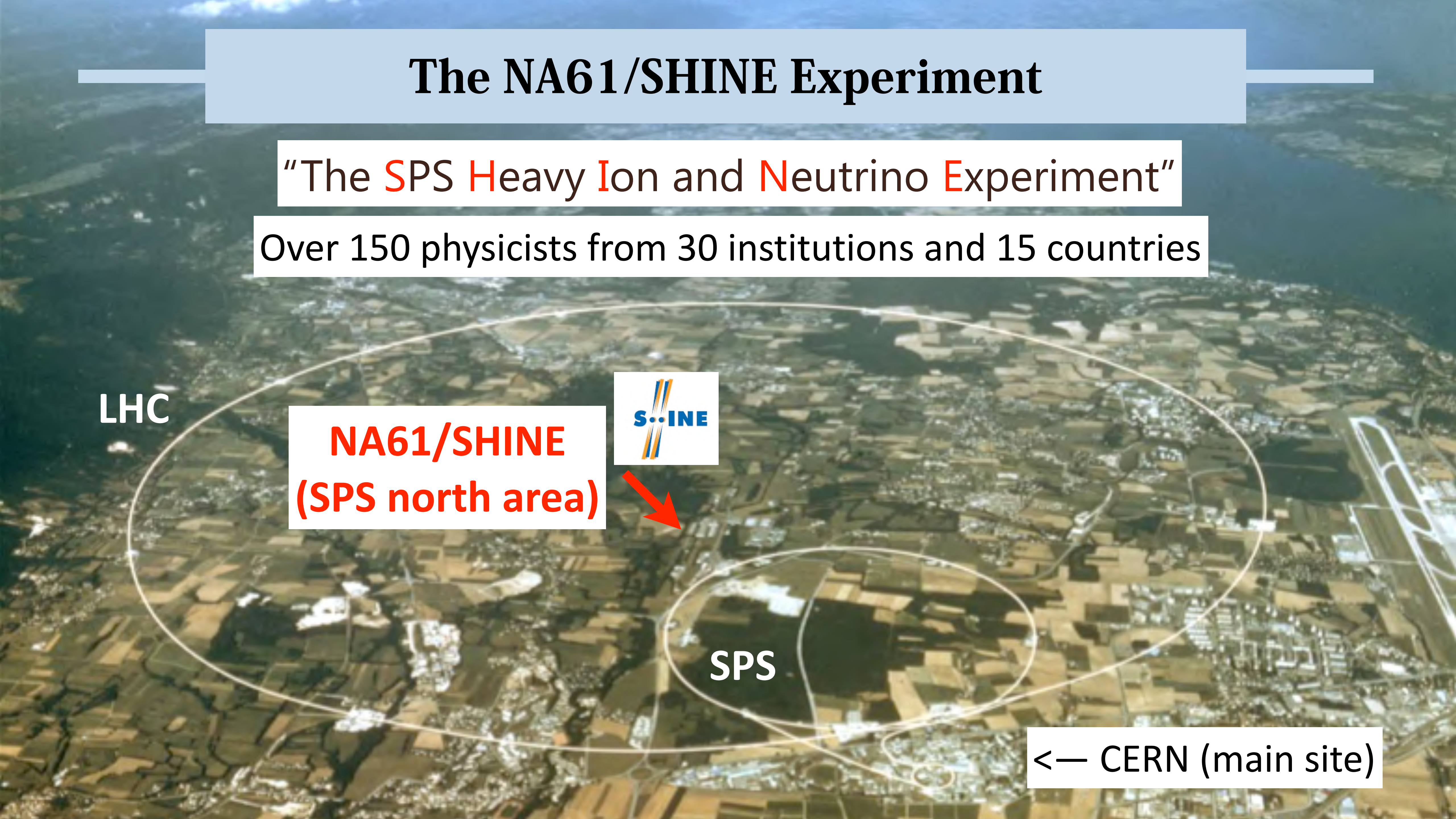



# NA61/SHINE Measurements for T2K

# The NA61/SHINE Experiment

"The SPS Heavy Ion and Neutrino Experiment"

Over 150 physicists from 30 institutions and 15 countries

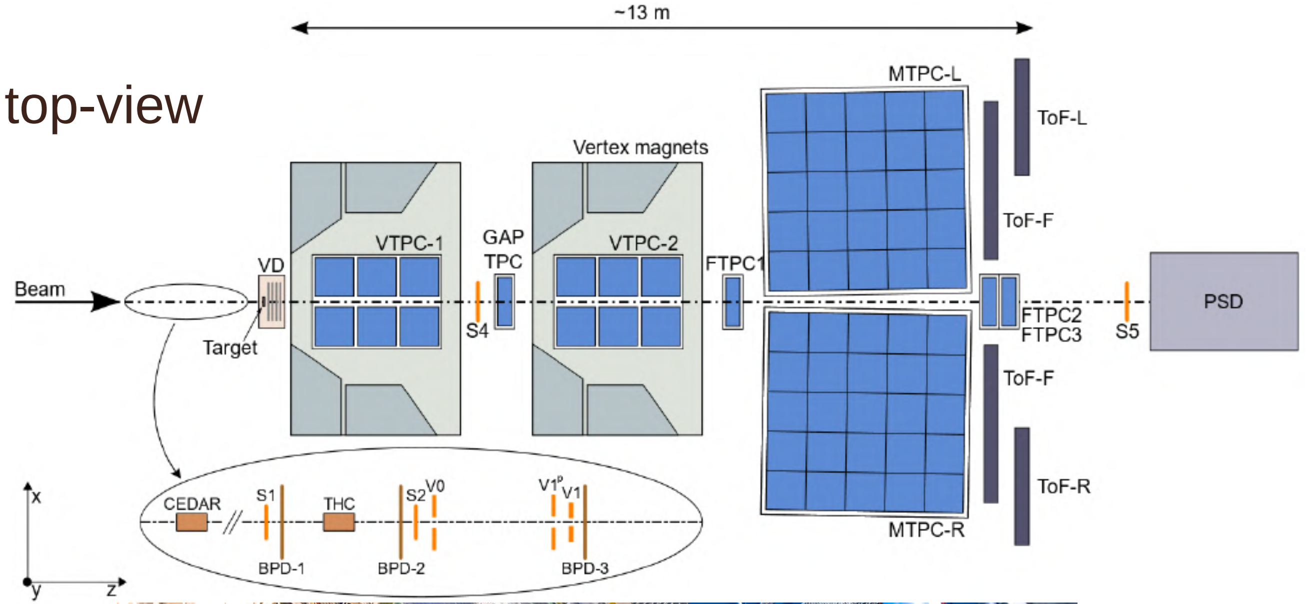


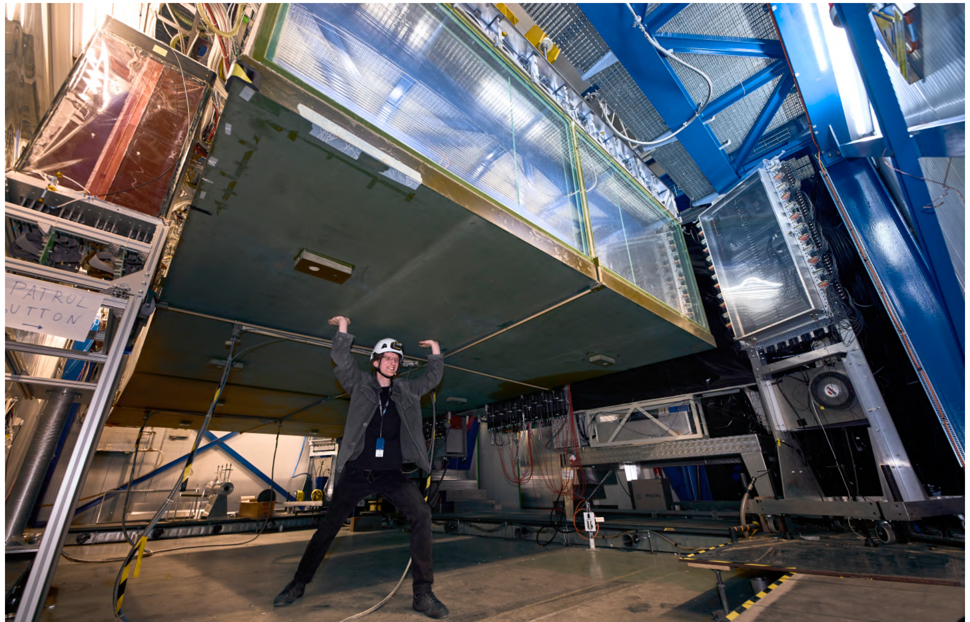
# NA61/SHINE Experimental Facility

A fixed target experiment at SPS with
- Good beam particle selection ($p$, $\pi$, $K$) using beamline Cherenkov detectors
- Large acceptance spectrometer for charged particles
  - Time Projection Chambers (TPCs) for tracking and dE/dx
  - 2 dipole magnets with 1.5 T field
  - Time-of-flight detectors placed downstream

Precise tracking with:
- Particle identification
- Momentum measurement

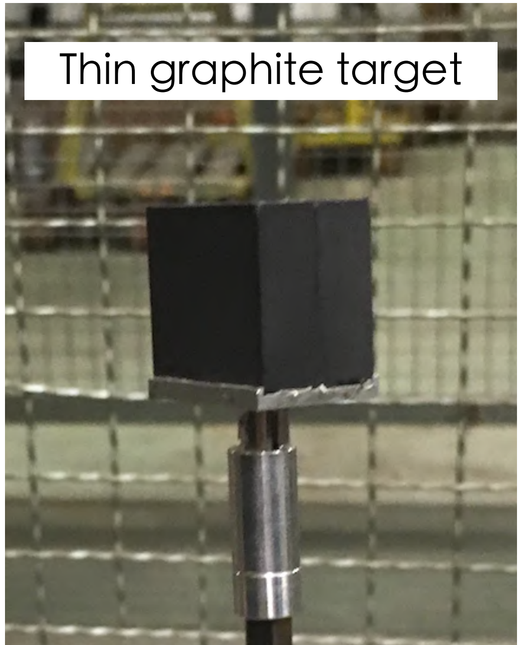
top-view

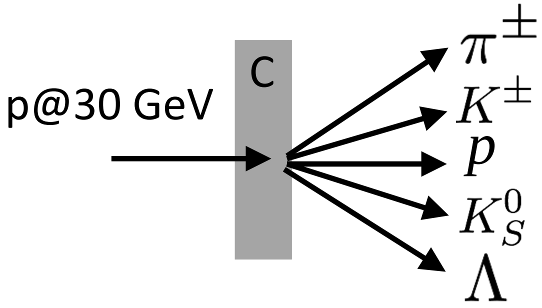


# NA61/SHINE Measurements for T2K

- Thin target: *p*@30 GeVon 2cm graphite target
  - total cross-section and $\pi^{+/-}$ spectra measurements (Phys. Rev. C84 034604 (2011) )
  - $K^+$ spectra measurement (Phys. Rev. C85 035210 (2012) )
  - $K^0_S$ and $\Lambda$ spectra measurements (Phys. Rev. C89 (2014) 025205 )
  - total cross-section and $\pi^{+/-}$,$K^{+/-}$ $p$, $K^0_S$, and $\Lambda$ spectra measurements (Eur. Phys. J. C76 84 (2016) )




- Total cross section (hadron production cross-section)
- Differential cross section or multiplicity of each particle species

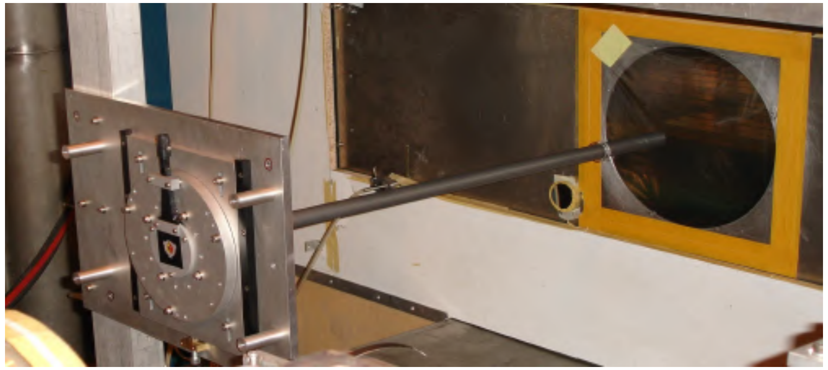
$$\left( \frac{d^2\sigma}{dp d\theta} = \sigma_{\text{prod}} \frac{d^2 n}{dp d\theta} \right)$$

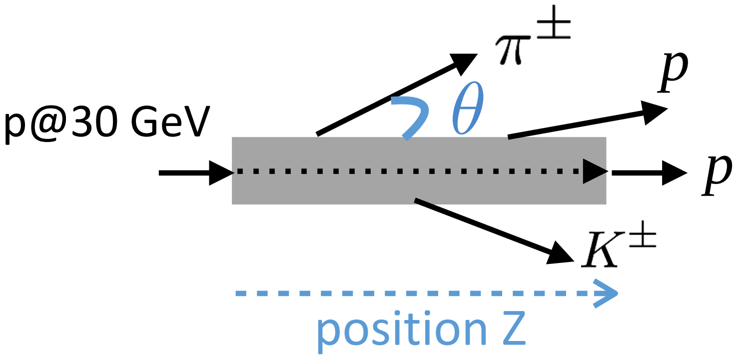
# NA61/SHINE Measurements for T2K

- Replica target: $p$@30 GeV on 90cm replica graphite target
  - methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 99-114 (2013) )
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 617 (2016) )
  - $\pi^{+/-}$, $p$, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79, no.2 100 (2019) )
  - proton beam survival probability measurement (Phys. Rev. D 103, 012006 (2021))

Show results briefly

T2K replica graphite target
(90 cm, 1.9 λ)

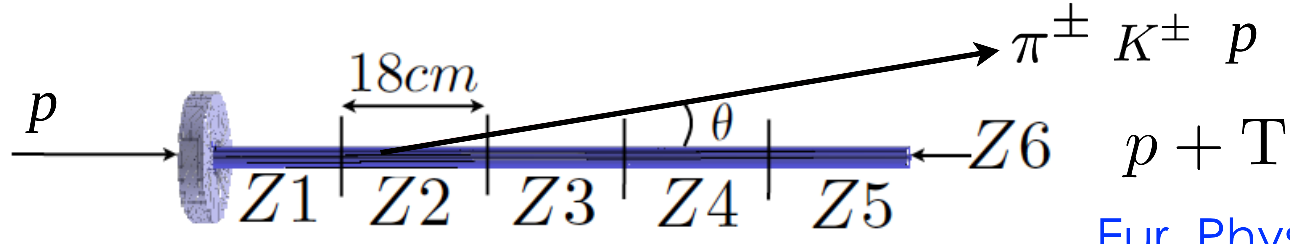





- Differential hadron yields or multiplicity ( $\frac{d^3n}{dpd\theta dz}$ )
- Hadron production cross-section via beam attenuation

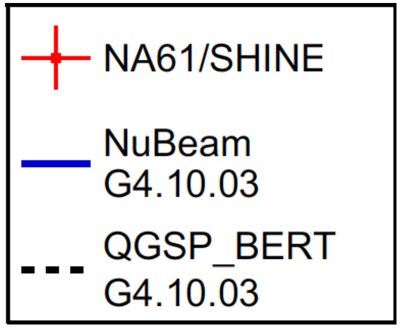
$$( P_{\mathrm{survival}} = e^{-Ln\sigma_{\mathrm{prod}}} )$$

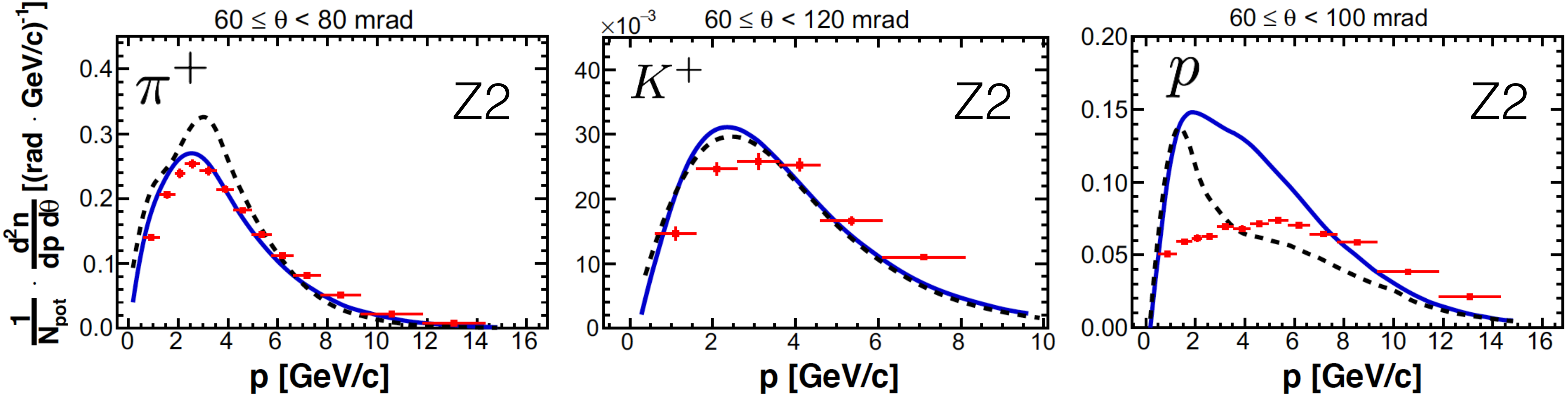
# T2K Replica Target Results




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

Eur. Phys. J. C79, no.2 100 (2019)




( 15 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
10 θ-bins for 0 < θ < 300 mrad (Z6) )

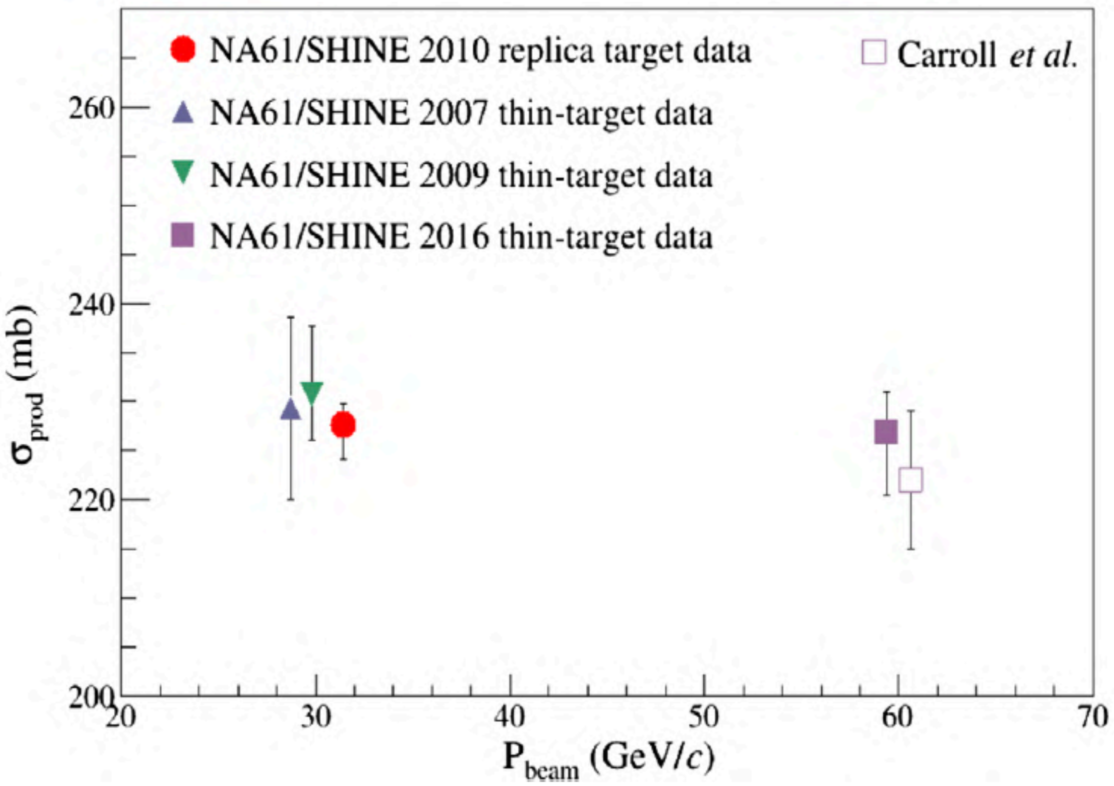
( 4 θ-bins for 0 < θ < 280 mrad (Z1-Z5)
2 θ-bins for 0 < θ < 120 mrad (Z6) )

( 10 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
8 θ-bins for 0 < θ < 260 mrad (Z6) )

Negative pions and kaons have been measured as well.

# T2K Replica Target Results


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




$$P_{\text{survival}} = e^{-Ln\sigma_{\text{prod}}}$$

Phys. Rev. D 103, 012006 (2021)

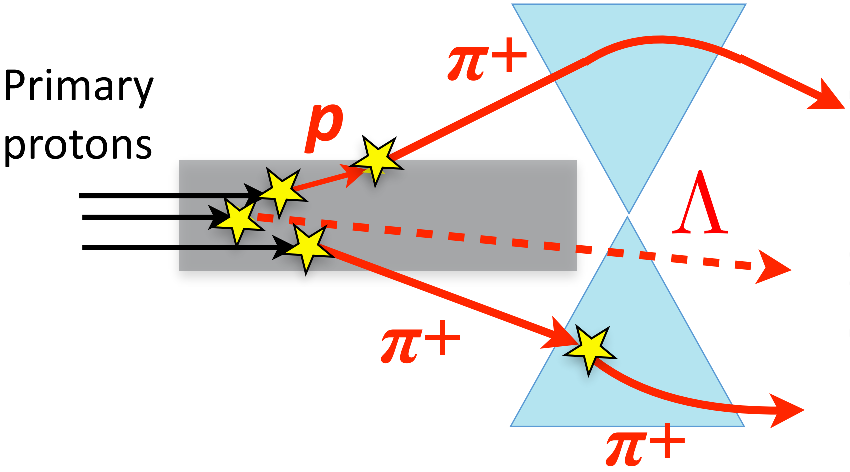
A production cross section measurement using the attenuation of beam particles

—> Achieved 2% total uncertainty in good agreement with past measurements

# How to Improve Flux Model with External Data

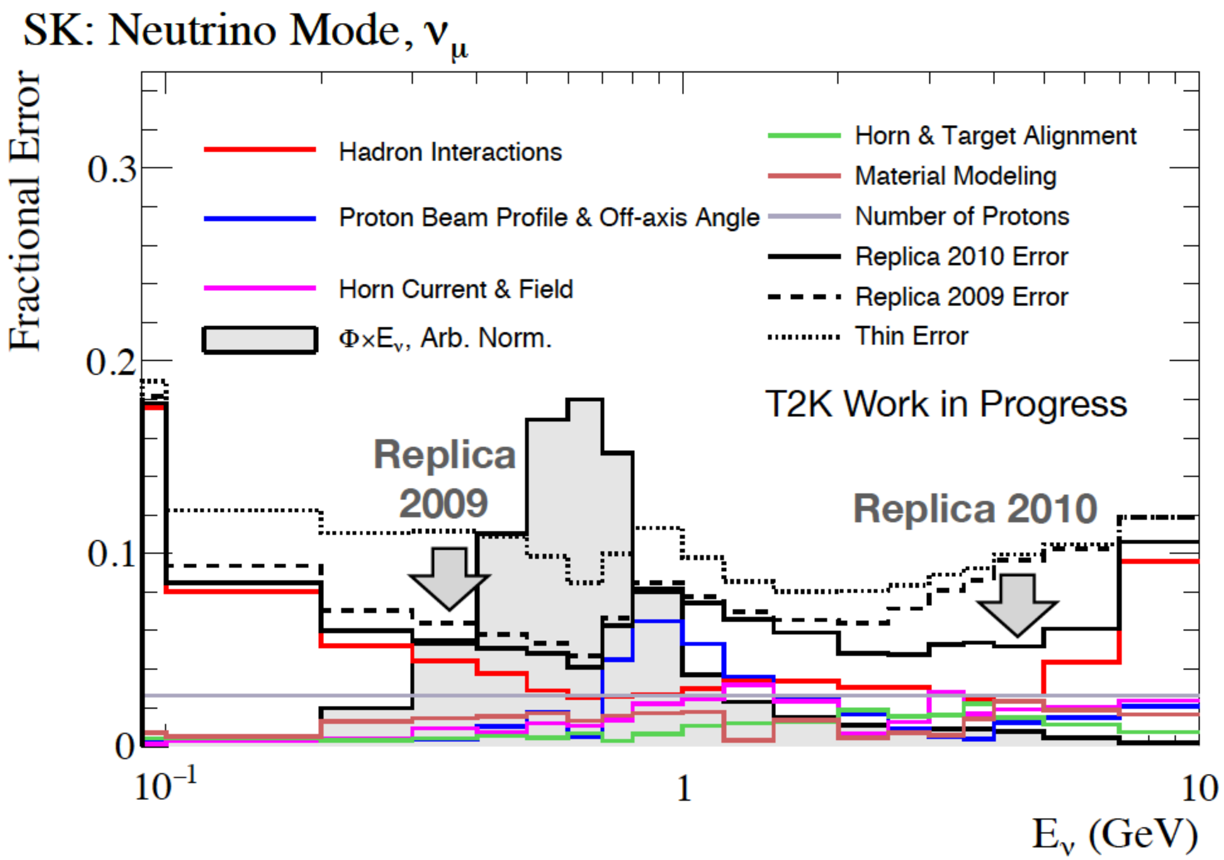
Two corrections to constrain model ambiguity

- Interaction length: Tune production cross-section to external measurement
- Multiplicity: Tune differential hadron multiplicity (differential cross-section) to external measurement




| | **Interaction length**<br>tune $\sigma_{prod}$(p+C) to NA61 measurement | **Multiplicity**<br>Mostly 30 GeV p+C data by NA61 |
| --- | --- | --- |
| **At interaction** | "Vertex" weight<br>$\sigma_{\mathrm{DATA}}/\sigma_{\mathrm{MC}}$ | $\left(\frac{\mathrm{d}^2 n}{\mathrm{d}p\,\mathrm{d}\theta}\right)_{\mathrm{DATA}} \Big/ \left(\frac{\mathrm{d}^2 n}{\mathrm{d}p\,\mathrm{d}\theta}\right)_{\mathrm{MC}}$<br>$p, \theta$: outgoing particle kinematics |
| **For distance L traversed in matter** | "Attenuation" weight<br>$e^{-(\sigma_{\mathrm{DATA}}-\sigma_{\mathrm{MC}})\,\rho L}$ | N.A. |

# Flux Uncertainty with NA61/SHINE Data



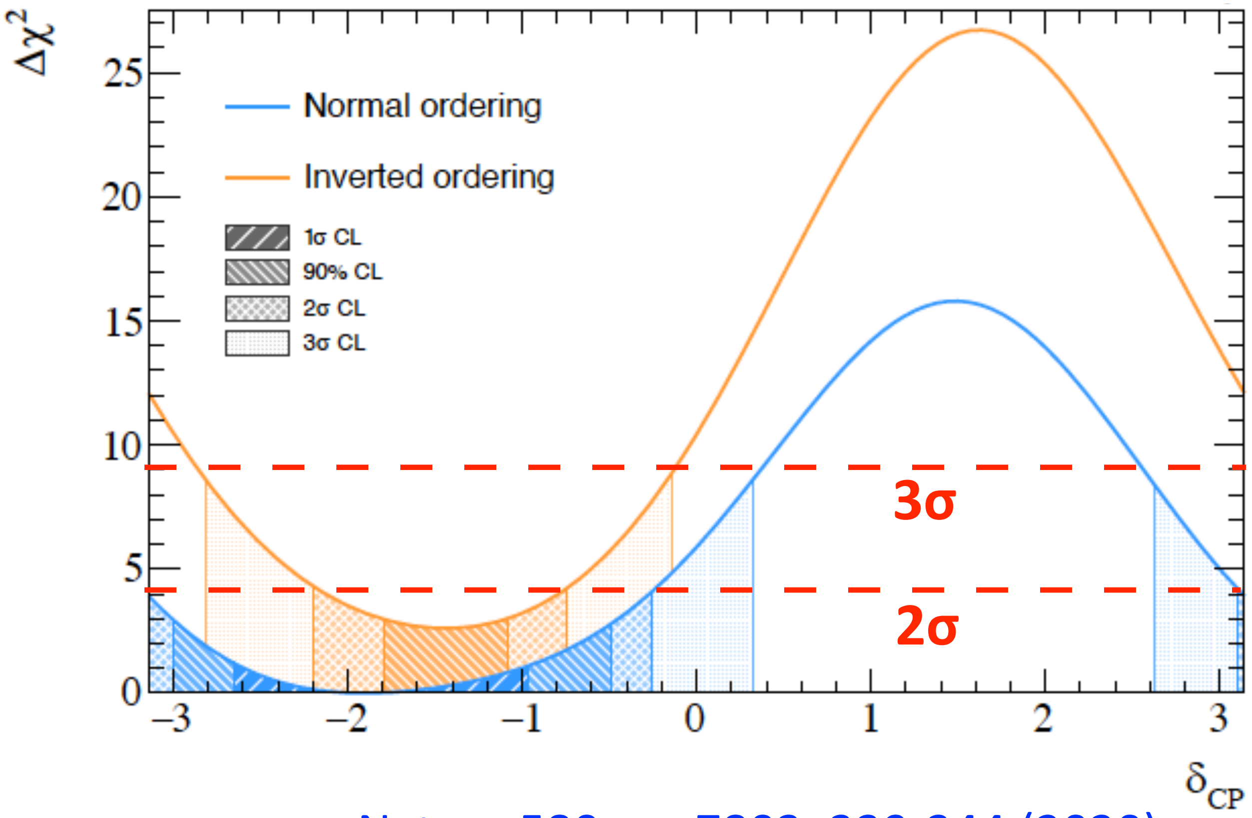

Lukas Berns (NBI 2019)

- Replica target measurements will improve uncertainty down to 5%

  —> Huge improvement has been achieved

  —> Nevertheless, precision is not enough. T2K/Hyper-K goal is 2-3% !!

# T2K: Constraint on $\delta_{CP}$ Phase

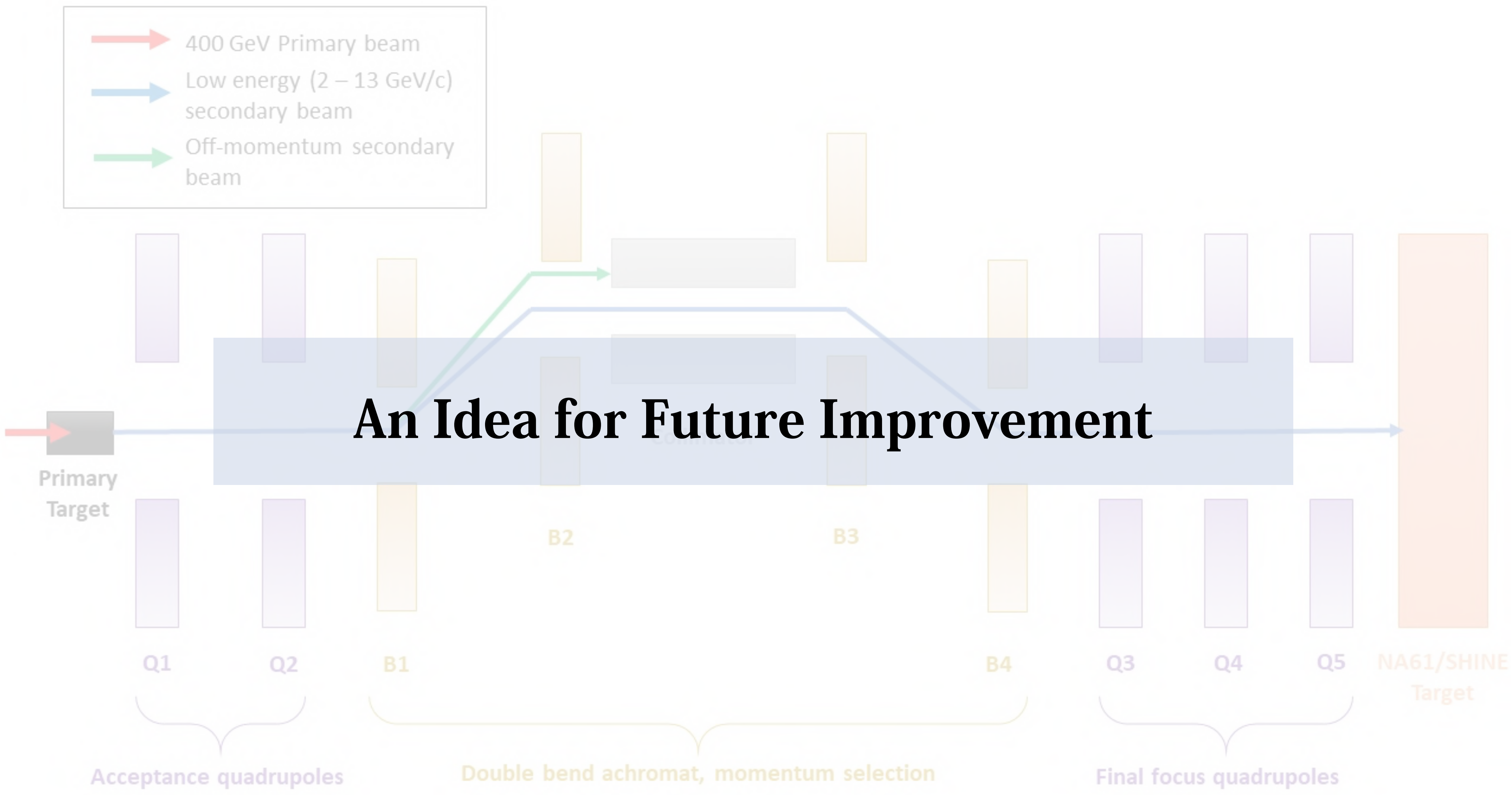

Nature 580, no.7803, 339-344 (2020)

T2K set the most stringent constraint on the *CP*-phase in neutrino oscillations.

**—> NA61/SHINE data have largely contributed to achieve this milestone!**

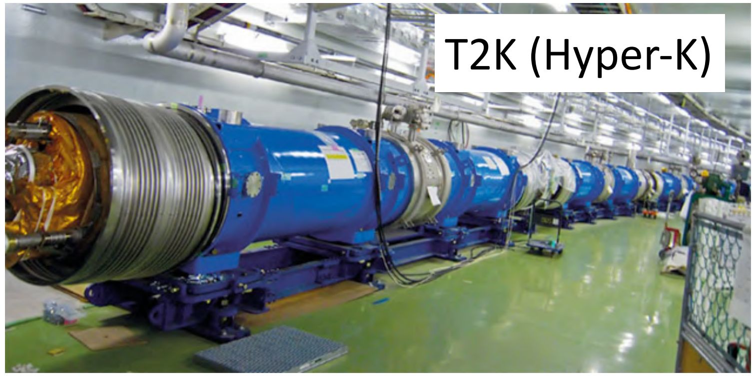
(note: T2K Nature result used only NA61 thin target data —> result will further improve)

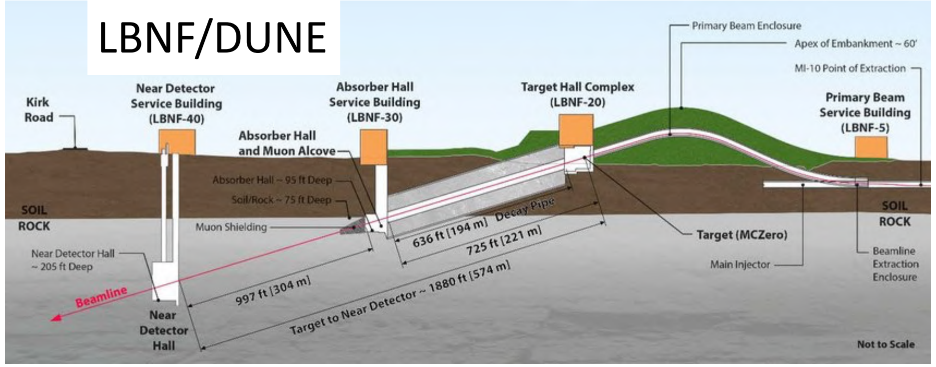
# An Idea for Future Improvement



# Understanding Various Neutrino Sources

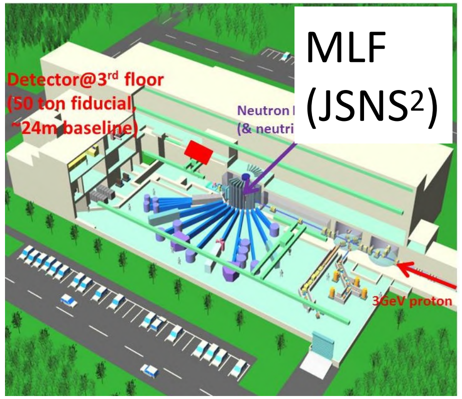
- As we discussed, precise flux knowledge is a key input for neutrino experiments



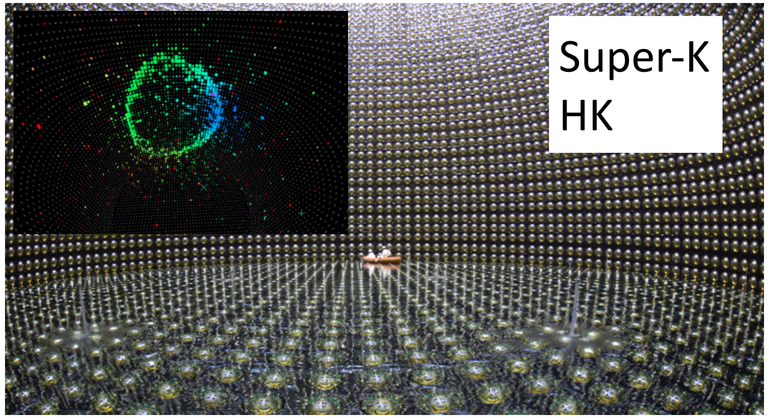




Accelerator neutrinos (T2K, HK, DUNE, SBN, etc…)

(I have spoken about T2K)


Neutrinos from spallation neutron source

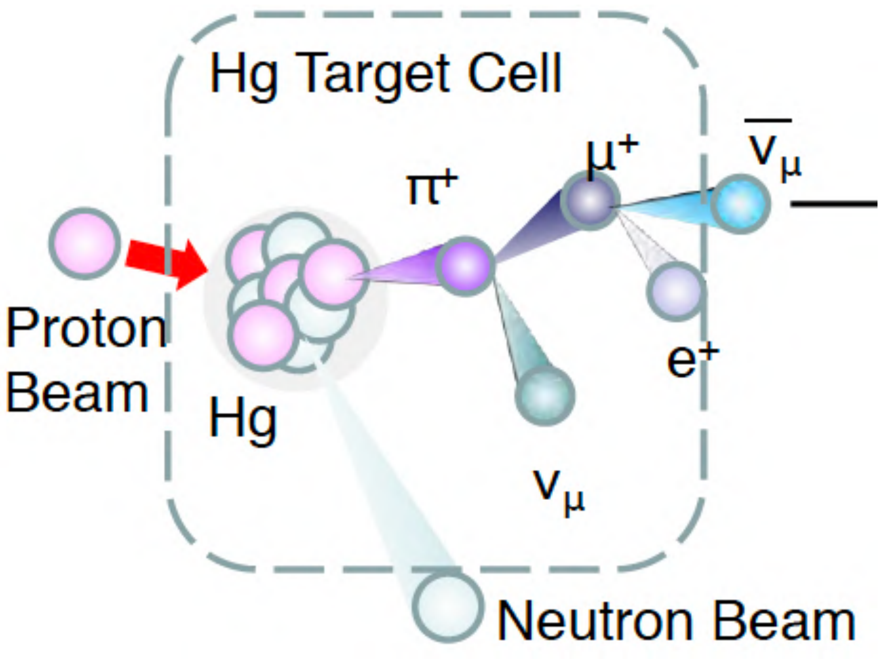



Atmospheric neutrinos

- A common bottleneck on flux prediction: Hadron production (not much data available for low-energy region 1-10 GeV)

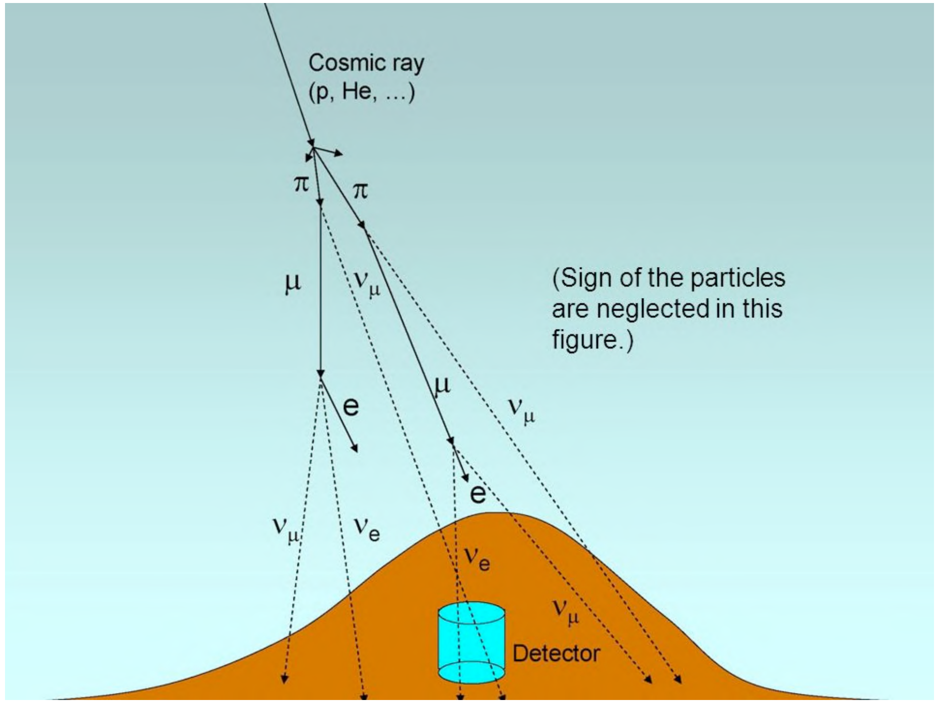
# Hadron Production & Flux Prediction

Neutrinos from spallation neutron source




neutrinos from pion decay-at-rest source
(3 GeV proton beam at MLF)

Atmospheric neutrinos

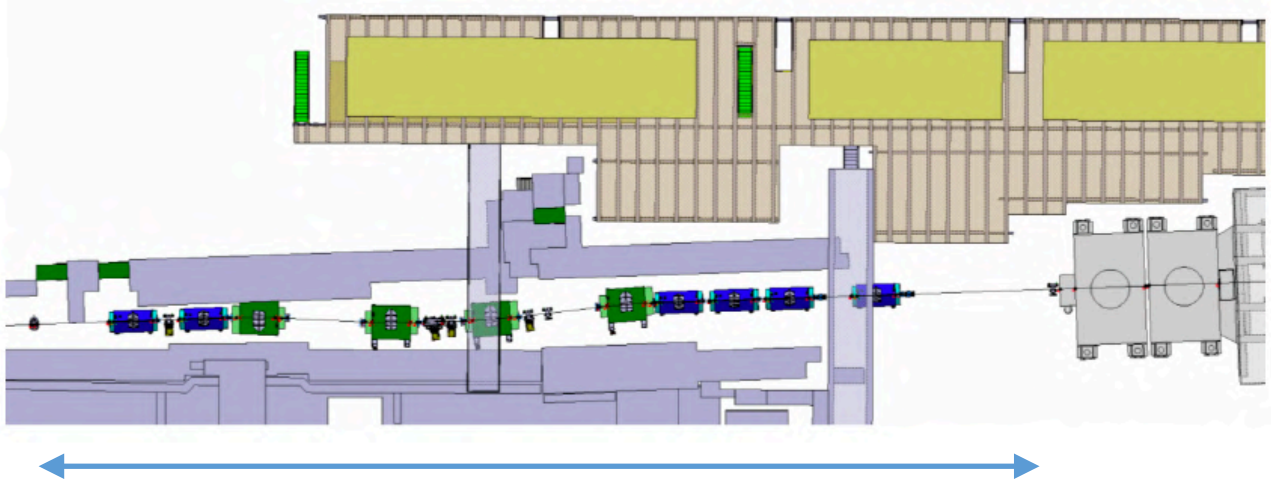



neutrinos from secondary hadrons
(1-10 GeV proton data are crucial)

- A common bottleneck on flux prediction: Hadron production (1-10 GeV)

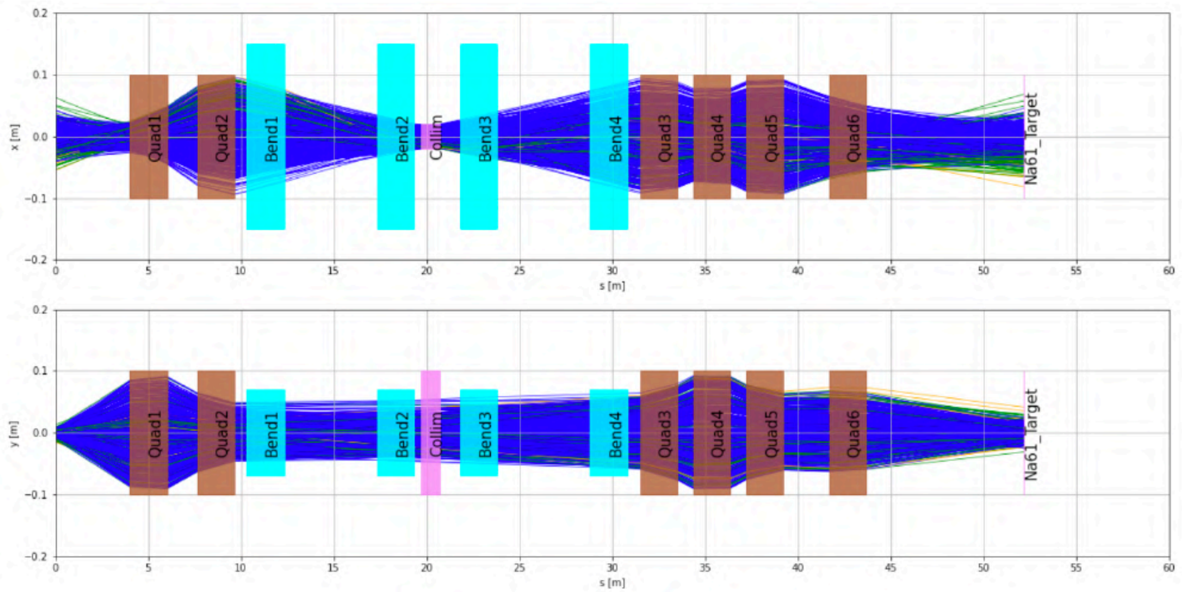
# Low-Energy Beamline at the CERN H2 beamline

- We are finalizing the design of new tertiary low-E beamline at CERN SPS H2-bemeline
  - Low-Energy = 2-13 GeV —> the lowest energy NA61 achieved was 13 GeV
  - proton, pion and kaon beams with good beam particle ID
- We have submitted a document to express our intention to build a new beamline at CERN SPS —> we seek official project approval in next year
  - Construction: 2022 - early 2024
  - First beam, second half of 2024



~45m

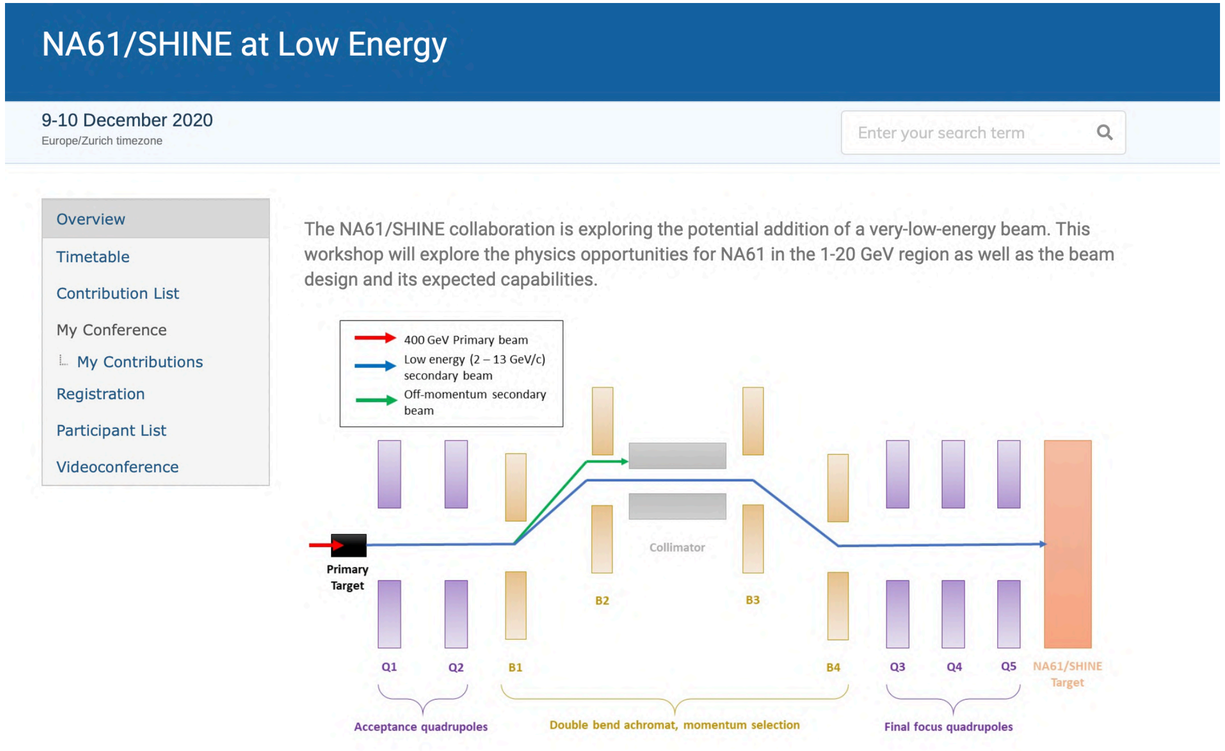
CAD rendering of beam area




beam particle tracking in low-E beamline

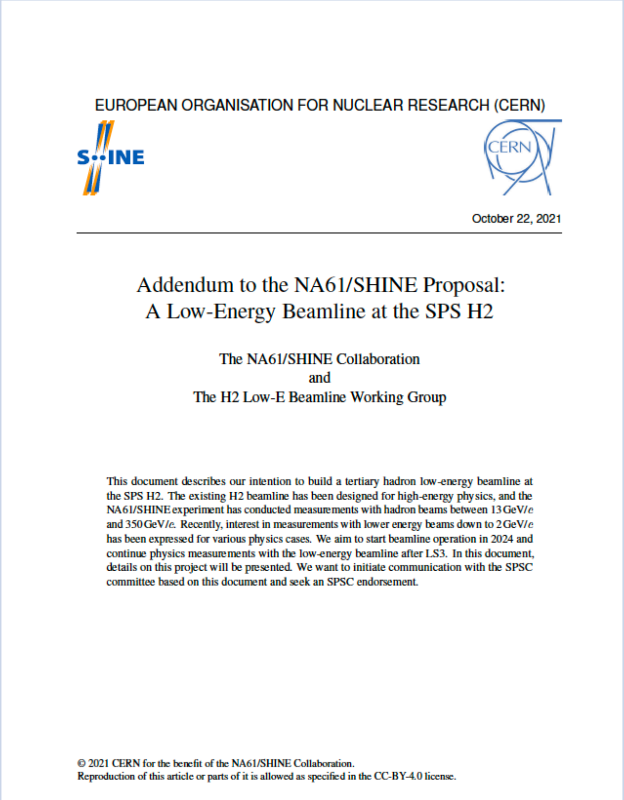
# Low-E beamline: Project Detail

Dedicated workshop last year




https://indico.cern.ch/event/973899

Submitted project document in October



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

October 22, 2021

Addendum to the NA61/SHINE Proposal:
A Low-Energy Beamline at the SPS H2

The NA61/SHINE Collaboration
and
The H2 Low-E Beamline Working Group

This document describes our intention to build a tertiary hadron low-energy beamline at the SPS H2. The existing H2 beamline has been designed for high-energy physics, and the NA61/SHINE experiment has conducted measurements with hadron beams between 13 GeV/$c$ and 350 GeV/$c$. Recently, interest in measurements with lower energy beams down to 2 GeV/$c$ has been expressed for various physics cases. We aim to start beamline operation in 2024 and continue physics measurements with the low-energy beamline after LS3. In this document, details on this project will be presented. We want to initiate communication with the SPSC committee based on this document and seek an SPSC endorsement.



http://cds.cern.ch/record/2783037

- Open to everyone! If you are interested in, please subscribe to the dedicated e-group "na61-lowe-beamline" from here: https://e-groups.cern.ch (or contact me if you cannot)

# Summary

- Precise flux knowledge is crucial for accelerator-based neutrino experiments
  - Hadron production is the leading source of flux uncertainty

- External hadron production measurements are essential to reduce the leading systematic uncertainty on neutrino flux prediction
  - NA61/SHINE measurements largely improved T2K flux prediction

- A new idea to further improve flux knowledge: building a new low-E bamline
  - It is not only for conventional neutrino beams but also for other neutrino sources
  - The low-E beamline can start operation after 2024 at the earliest (if approved!)

# Backup

# Neutrino Oscillation in a Nutshell

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

—> the mixing of flavor and mass eigenstates leads to oscillations

Flavor eigenstates

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

neutrino states on their interactions

$\not\parallel$

Mass eigenstates

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

neutrino states on their propagation

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

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

$\Delta m^2_{21}$ $\quad$ $\Delta m^2_{31}$ or $\Delta m^2_{32}$

Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix

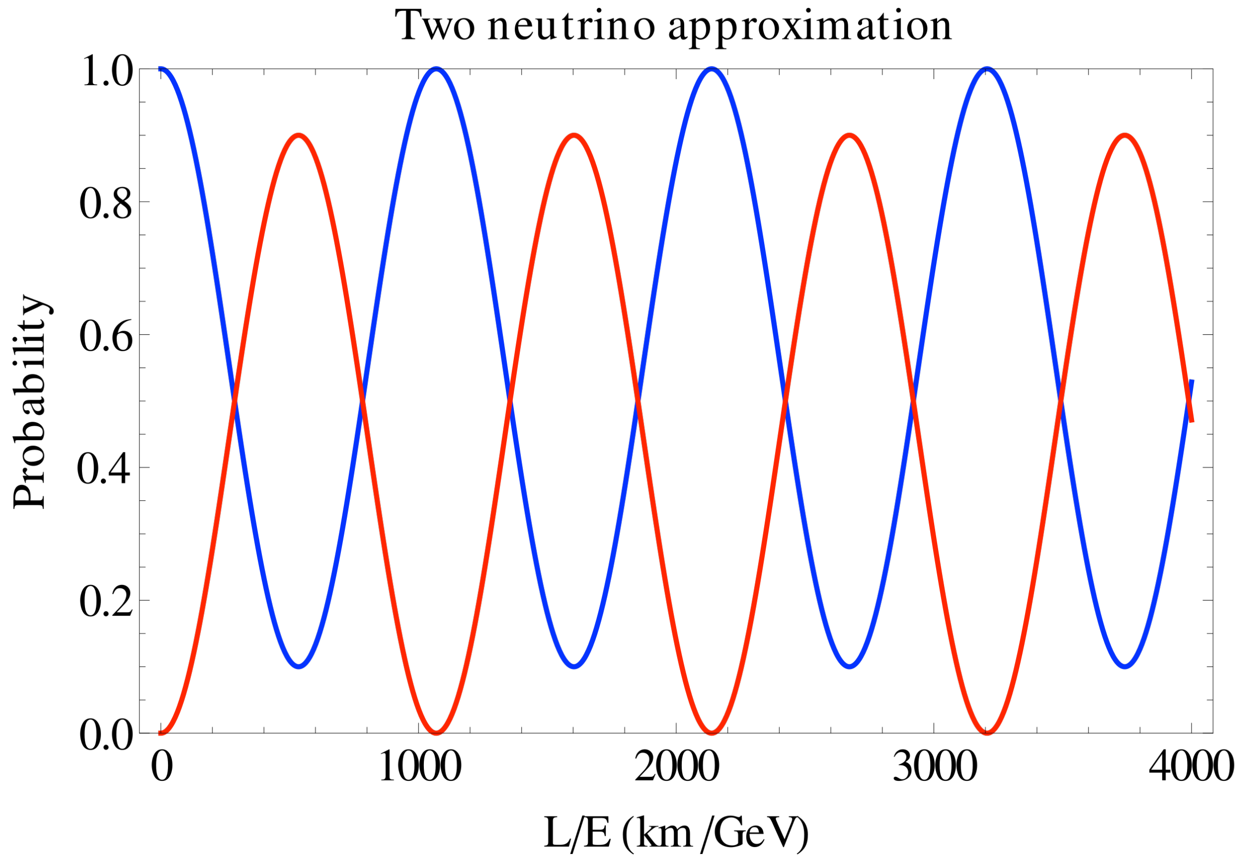
$$U_{PMNS} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

# Neutrino Oscillation in a Nutshell

Two-neutrino mixing approximation (for simplicity)

$$P(\nu_i \to \nu_j) = |<\nu_i|\nu_j;t>|^2 = \sin^2 2\theta \sin^2(\Delta m^2(\text{eV}^2)\frac{L(\text{km})}{E(\text{GeV})})$$




- Oscillations are seen as a function of L/E

—> Design experiments to maximize oscillation probability based on this parameter

# Neutrino Oscillation in a Nutshell

## Three-neutrino oscillation probabilities

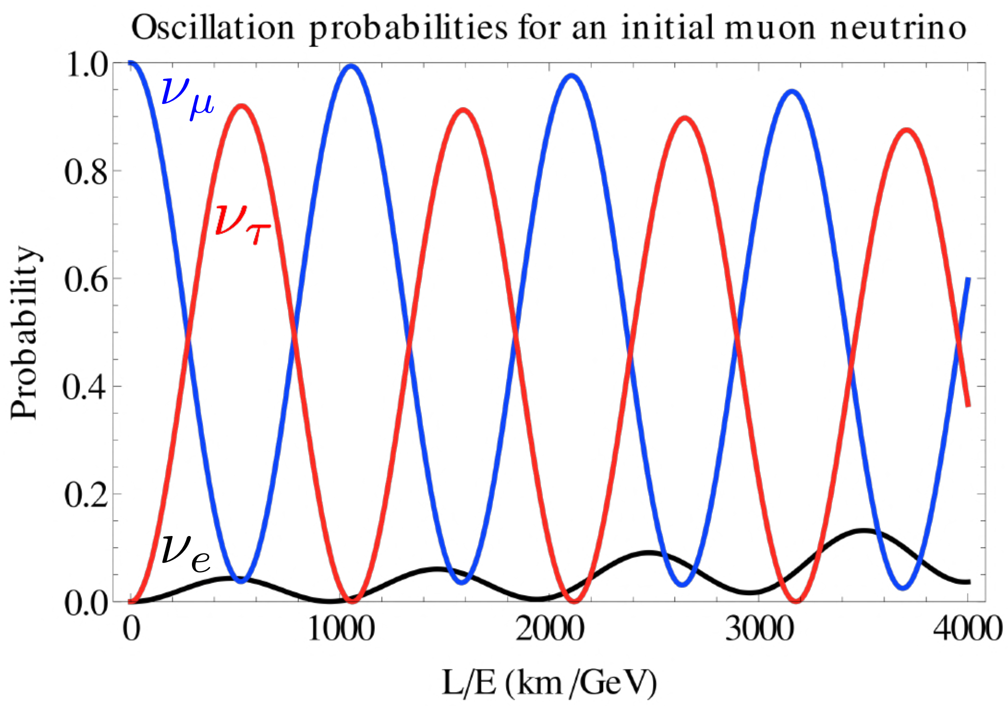
($\nu_\mu$ disappearance)

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

($\nu_e$ appearance)

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

sign changes b/w $\nu$ and $\bar{\nu}$ →




- The size of *CP* symmetry-violating effect depends on the Jarlskog invariant:

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

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

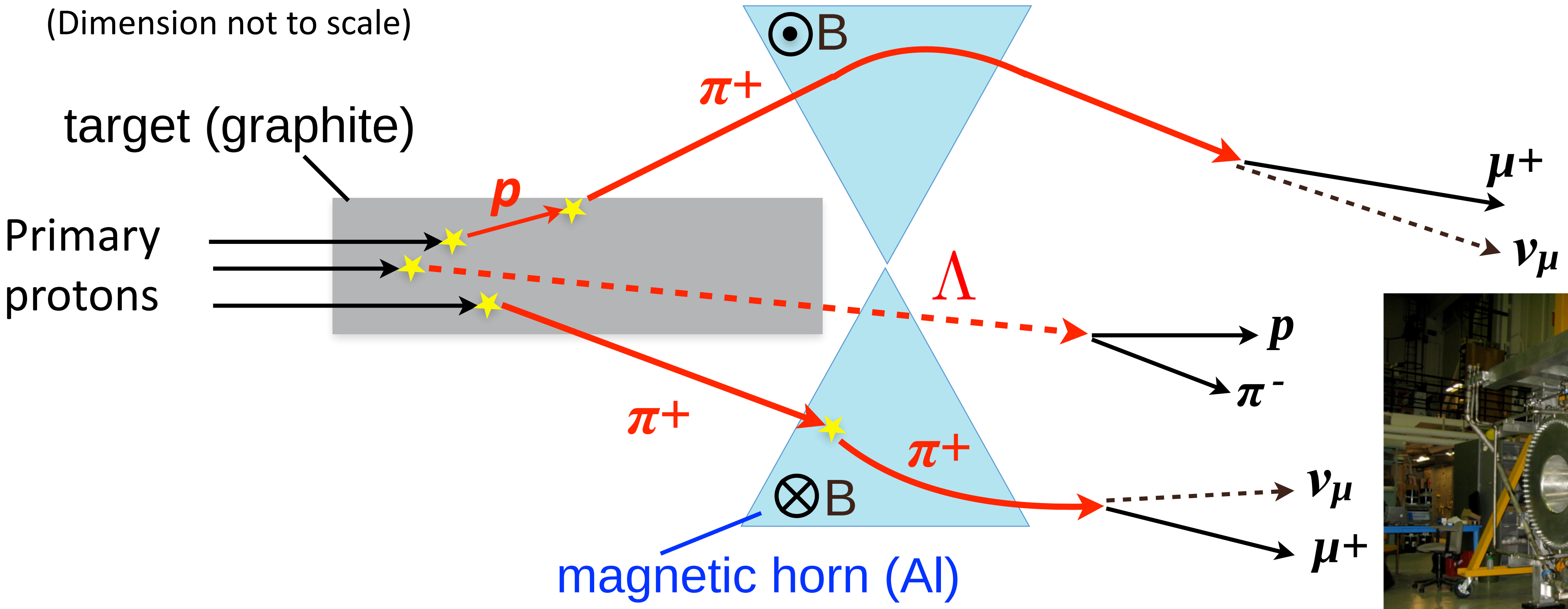
- $\nu_\mu$ disappearance —> sensitive to $\boldsymbol{\theta_{23}}$ and $\boldsymbol{\Delta m^2_{32}}$
- $\nu_e$ appearance —> sensitive to $\boldsymbol{\theta_{13}}$, $\boldsymbol{\theta_{23}}$, and $\boldsymbol{\delta_{CP}}$

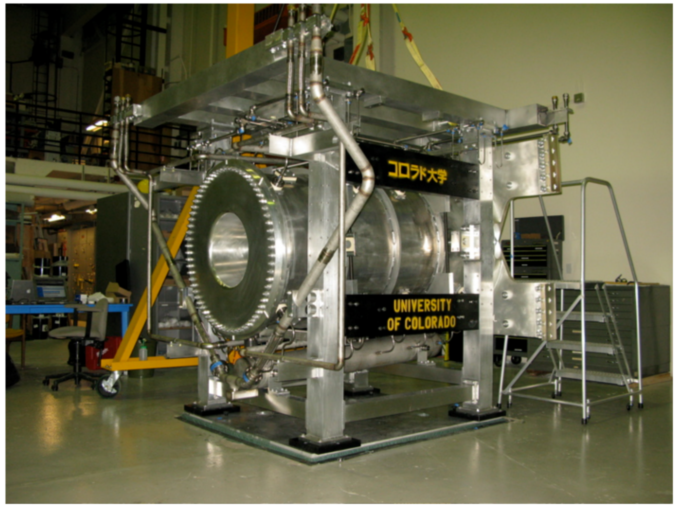
# NA61/SHINE Physics Program

- Hadron beams
  - primary protons at 400 GeV/c
  - secondary hadrons ($p$, $\pi$, $K$) at 13 - 350 GeV/c
- Ion beams
  - primary (Ar, Xe, Pb) at 13-150 AGeV/c
  - secondary Be at 13 - 150 AGeV/c (from Pb fragmentation)
- Broad physics program
  - Neutrino
    - Hadron production measurements to improve neutrino beam flux predictions
  - Strong interaction / Heavy ion
    - Search for the critical point
    - Study the onset of QCD deconfinement
    - Study open-charm production mechanism
  - Cosmic ray
    - Hadron production measurements to improve air-shower model predictions
    - Study (anti-)deuteron production mechanism for the AMS and GAPS experiments
    - Nuclear fragmentation cross sections to understand cosmic-ray flux

# How to Make a Neutrino Beam

(Dimension not to scale)



T2K magnetic horn

Hadron production process can be more complex:

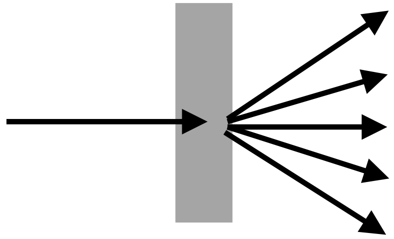
- Secondary interactions in the target (hadrons + C/Be)
- Secondary interactions with horn or beamline materials (hadrons + X)
- Neutral hadron decay ($p$ + C / Be —> $V^0$ + X)

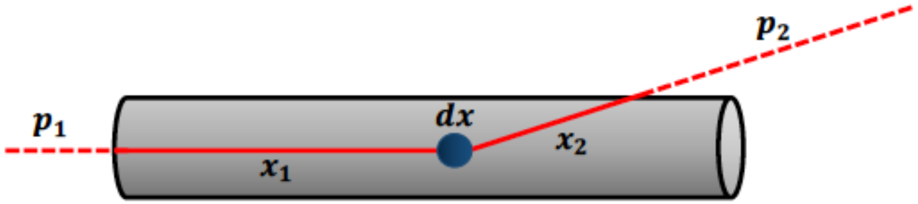
—>Non-negligible contribution to the neutrino flux

# Thin Target Measurement

- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Total cross sections (inelastic and production cross sections)

$$\sigma_{\rm inel} = \sigma_{\rm total} - \sigma_{\rm el}\,, \quad \sigma_{\rm prod} = \sigma_{\rm inel} - \sigma_{\rm qe}$$






—> Results are used to correct hadron interaction length (probability of interaction)

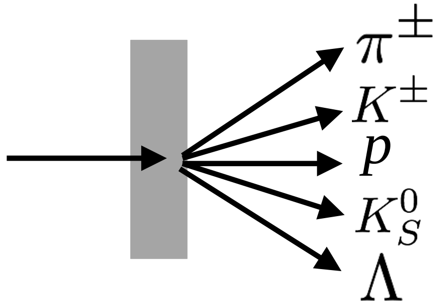
$$\mathrm{W}(p_1, p_2, x_1, x_2) = \frac{[P_{\rm interaction} \cdot P_{\rm escape}]_{\rm data}}{[P_{\rm interaction} \cdot P_{\rm escape}]_{\rm MC}}$$

$$= \frac{\sigma_{\rm data}(p_1)}{\sigma_{\rm MC}(p_1)} \cdot e^{-x_1[\sigma_{\rm data}(p_1) - \sigma_{\rm MC}(p_1)]\rho} \cdot e^{-x_2[\sigma_{\rm data}(p_2) - \sigma_{\rm MC}(p_2)]\rho}$$

—> Results are also important to obtain proper normalization for the differential cross section yields

# Thin Target Measurement

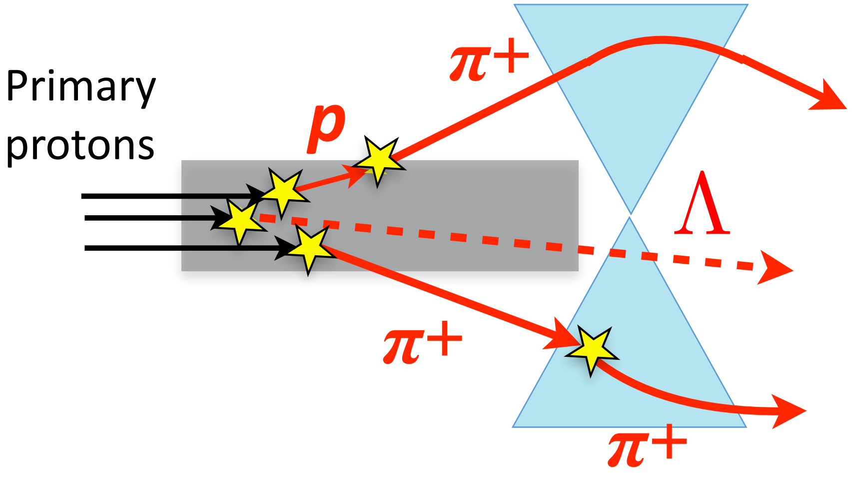
- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Measurement of differential cross sections ( $\frac{d^2\sigma}{dpd\theta}$ )




We measure differential production yields ( $\frac{d^2n}{dpd\theta} = N(p,\theta)$ )

(yield of particles per interaction, momentum, radian)

then, relate to differential cross section via $\sigma_{\text{prod}}$ : $\frac{d^2\sigma}{dpd\theta} = \sigma_{\text{prod}} \frac{d^2n}{dpd\theta}$

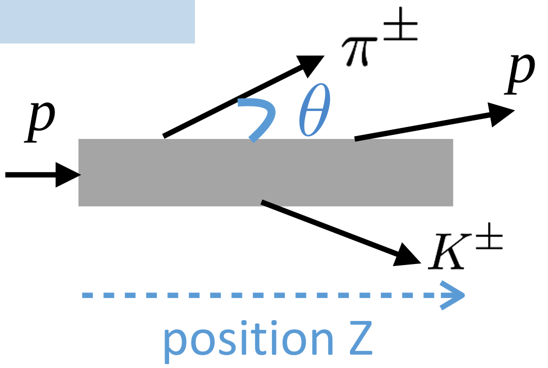



—> Results are used to calculate weights for each interactions (☆) to correct neutrino flux predictions

$$W(p,\theta) = \frac{N(p,\theta)_{\text{Data}}}{N(p,\theta)_{\text{MC}}}$$

# Replica Target Measurements

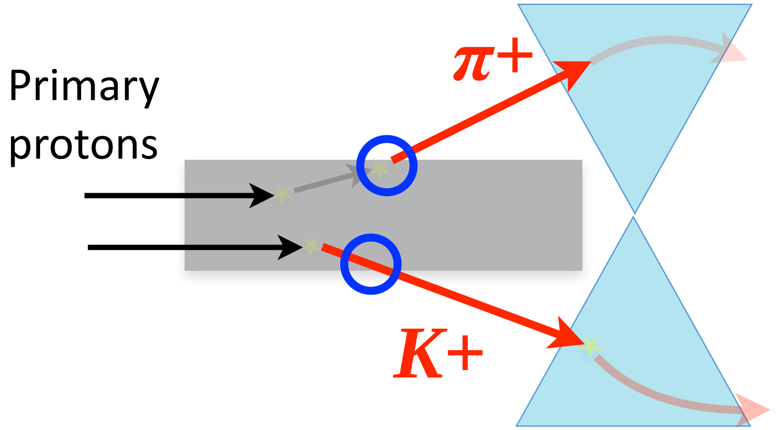
- Replica target: T2K (90 cm graphite), NuMI (120 cm graphite)




  - Measurement of differential production yields ( $\frac{d^3n}{dpd\theta dz} = N(p,\theta,z)$ )

    (yield of particles per interaction, momentum, radian, z)

    —> maybe also $\varphi$ if target cross-section is not circular, like NuMI target

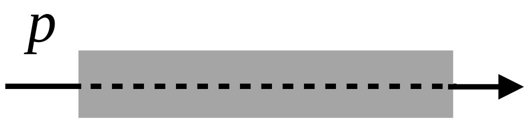



Weights for each exiting point (○) to apply correction to neutrino flux prediction

$$W(p,\theta,z) = \frac{N(p,\theta,z)_{\mathrm{Data}}}{N(p,\theta,z)_{\mathrm{MC}}}$$

  - Measurement of beam survival probability ( $P_{\mathrm{survival}} = e^{-Ln\sigma_{\mathrm{prod}}}$ )

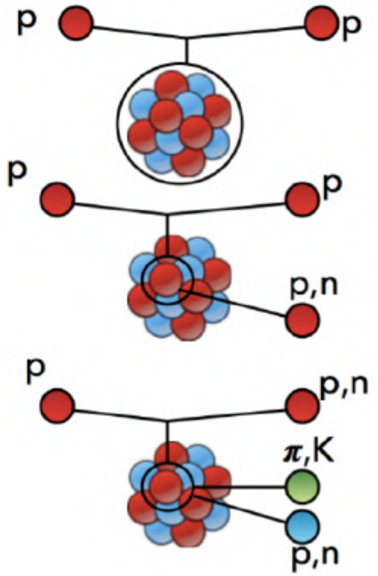
    ($L$: length of target, $n$: number of atoms per unit volume)




—> Results are useful to understand beam attenuation inside the target via $\sigma_{\mathrm{prod}}$ measurement

# Note: Notation of Production Cross Section

- Not all experiments use the same definition for the production cross section




Coherent elastic process:
interaction on the nucleus —> $\sigma_{\rm el}$

Quasi-elastic process:
interaction on bound nucleons —> $\sigma_{\rm qe}$

Production process:
interaction with new hadron production
—> $\sigma_{\rm prod}$

—> $\sigma_{\rm inel}$

$$\sigma_{\rm inel} = \sigma_{\rm total} - \sigma_{\rm el}$$
$$\sigma_{\rm prod} = \sigma_{\rm inel} - \sigma_{\rm qe}$$

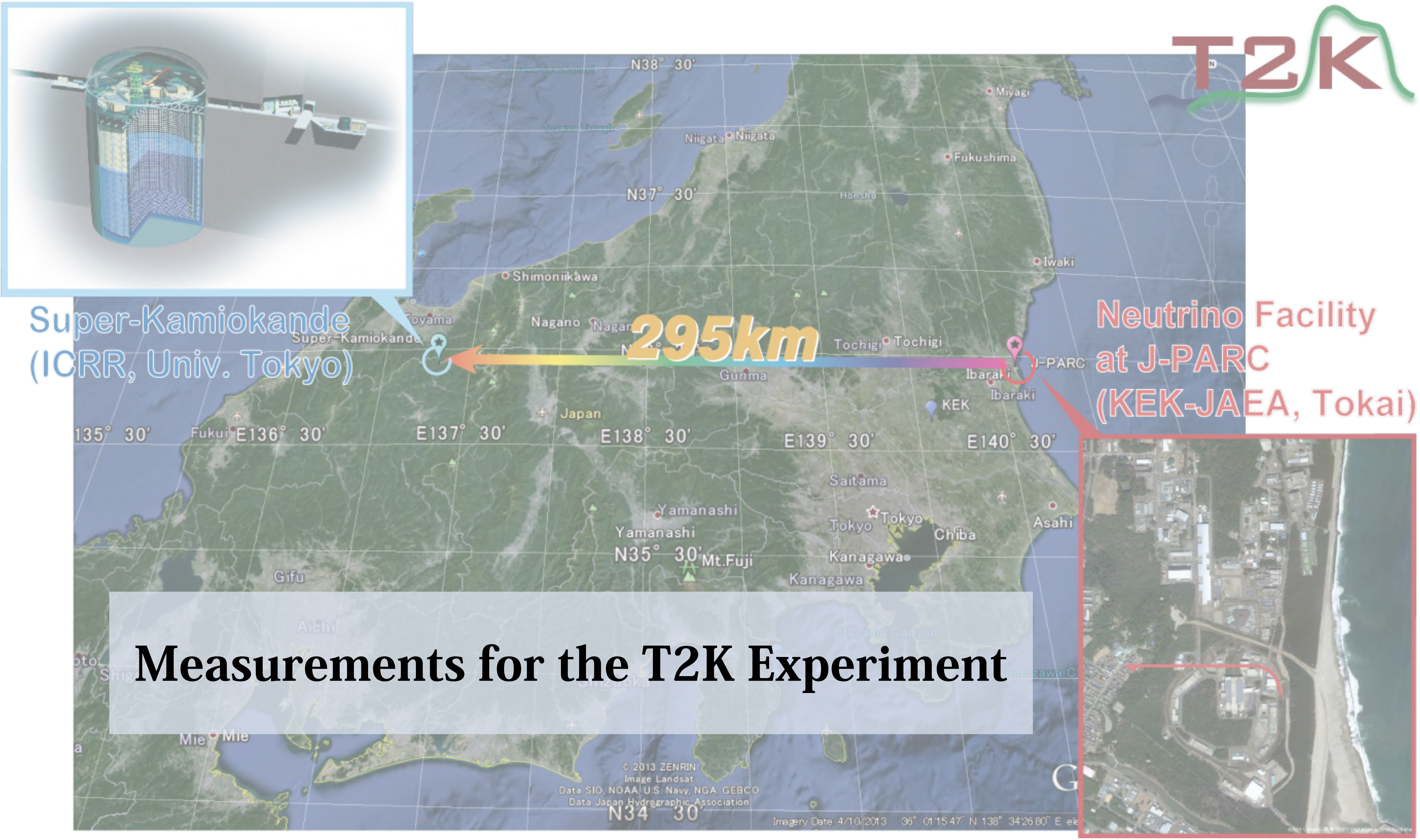
Use this definition through the talk
(T2K uses this definition)

- NuMI flux tuning definition: $\sigma_{\rm inel} = \sigma_{\rm total} - \sigma_{\rm el} - \sigma_{\rm qe}$ —> $\sigma_{\rm prod}$ in our definition
  $\sigma_{\rm absorption} = \sigma_{\rm total} - \sigma_{\rm el}$ —> $\sigma_{\rm inel}$ in our definition

- Earlier experiments: mixed up inelastic and production cross sections

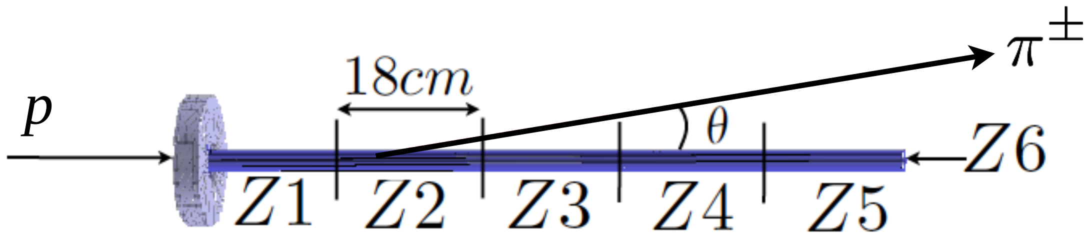
  e.g. Denisov, et. al (1973): $\sigma_{\rm absorption} = \sigma_{\rm total} - \sigma_{\rm el}$ —> $\sigma_{\rm inel}$ in our definition

  e.g. Carroll, et. al (1979): $\sigma_{\rm absorption} = \sigma_{\rm total} - \sigma_{\rm el} - \sigma_{\rm qe}$ —> $\sigma_{\rm prod}$ in our definition



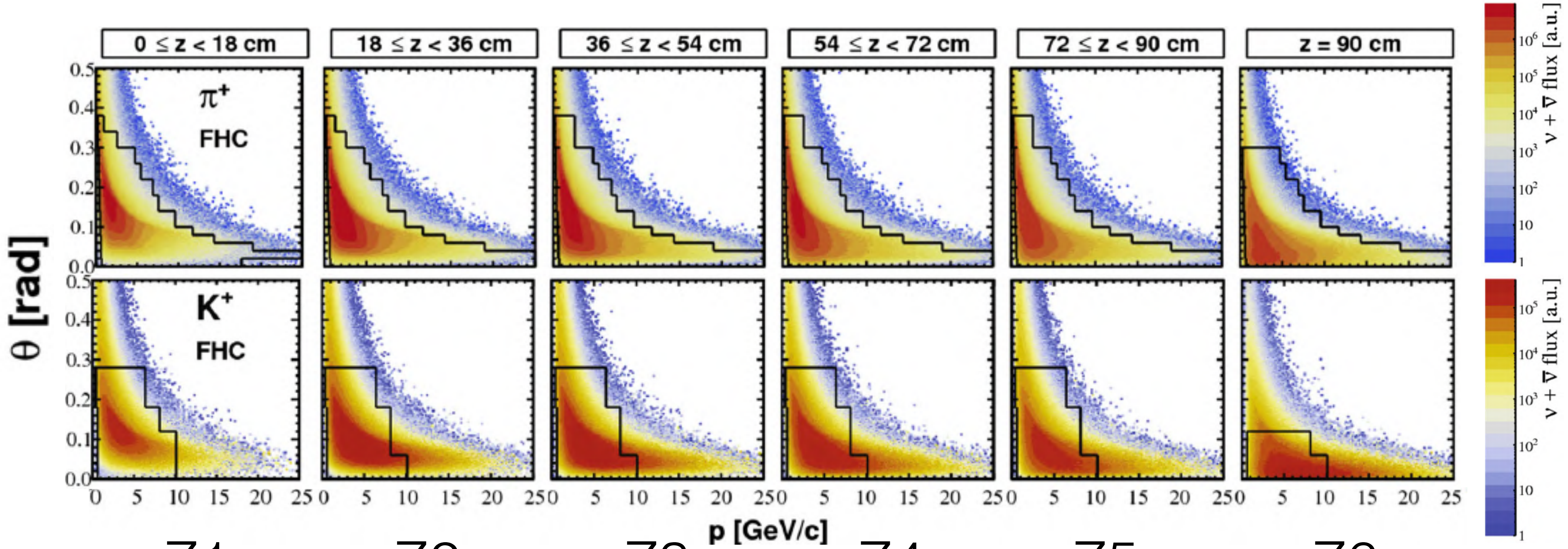

# Measurements for the T2K Experiment

# T2K Replica Target Results




$p$ + T2K replica @ 30 GeV

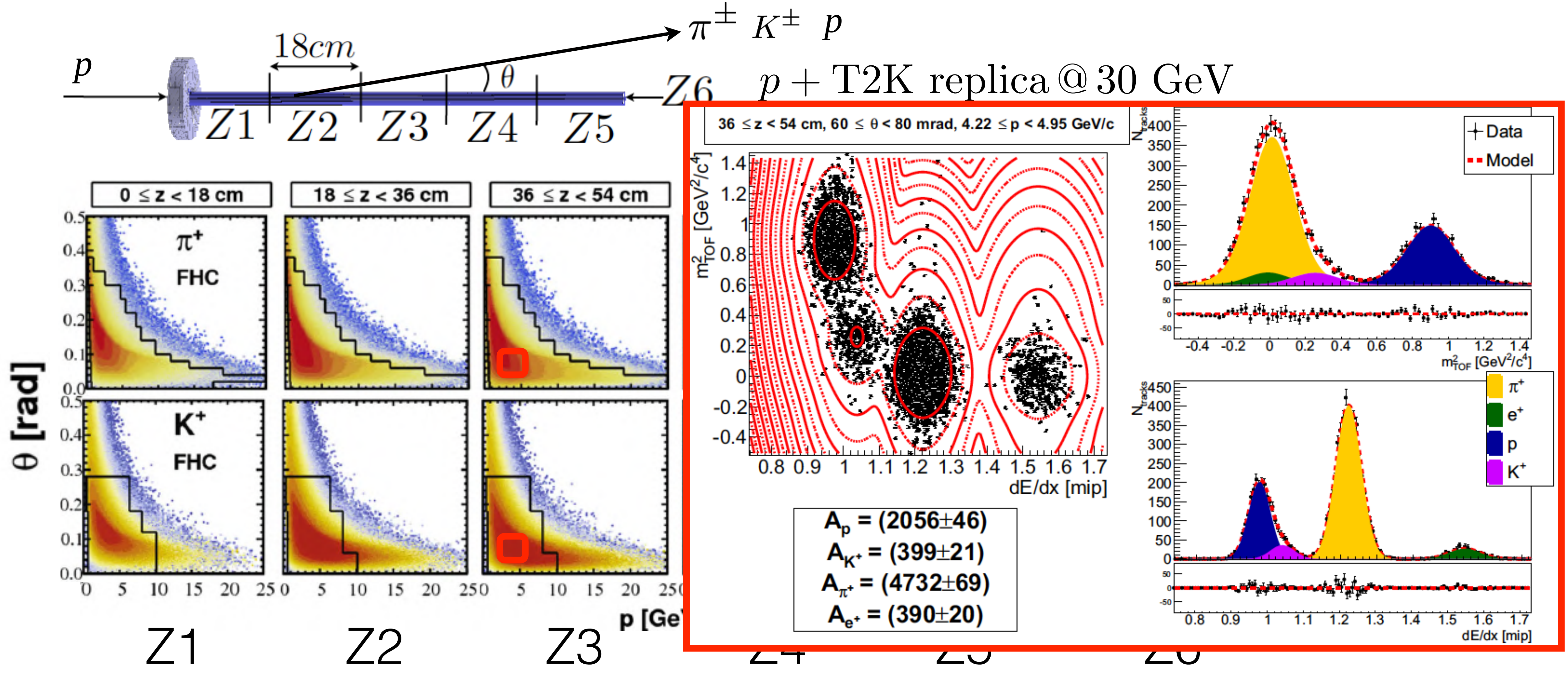
Eur. Phys. J. C79, no.2 100 (2019)




Z1 Z2 Z3 Z4 Z5 Z6

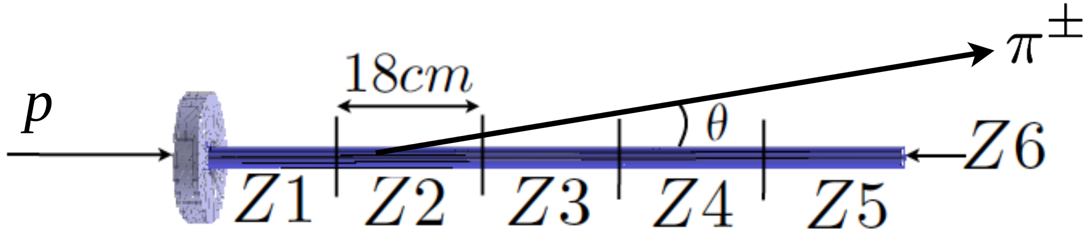
(This shows hadron distribution contributing to the T2K flux, not NA61 data)

# T2K Replica Target Results



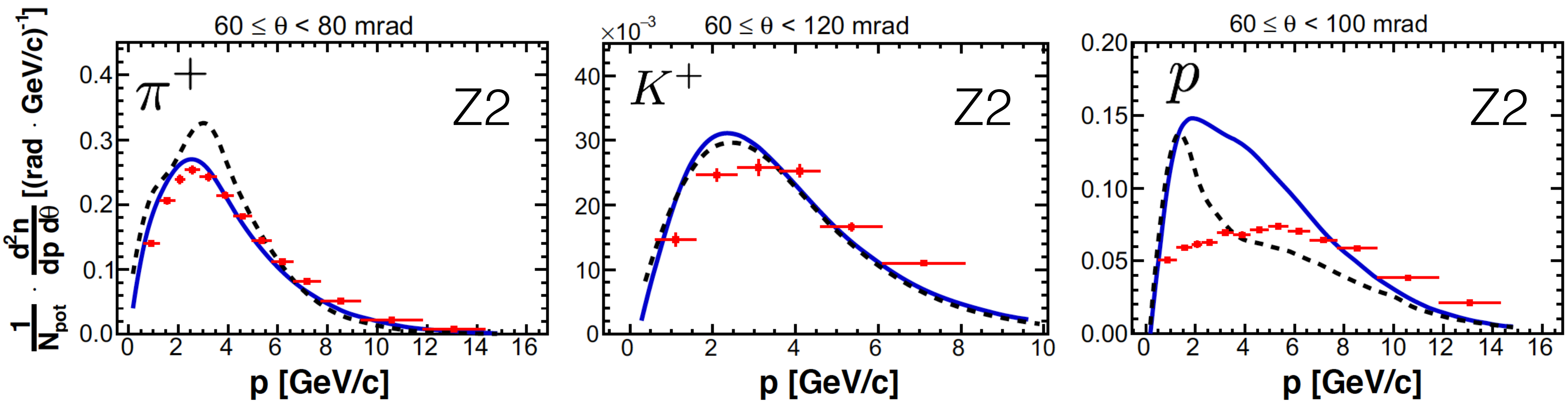

(This shows hadron distribution contributing to the T2K flux, not NA61 data)

# T2K Replica Target Results




$p +$ T2K replica @ 30 GeV

Eur. Phys. J. C79, no.2 100 (2019)




(15 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
10 θ-bins for 0 < θ < 300 mrad (Z6))

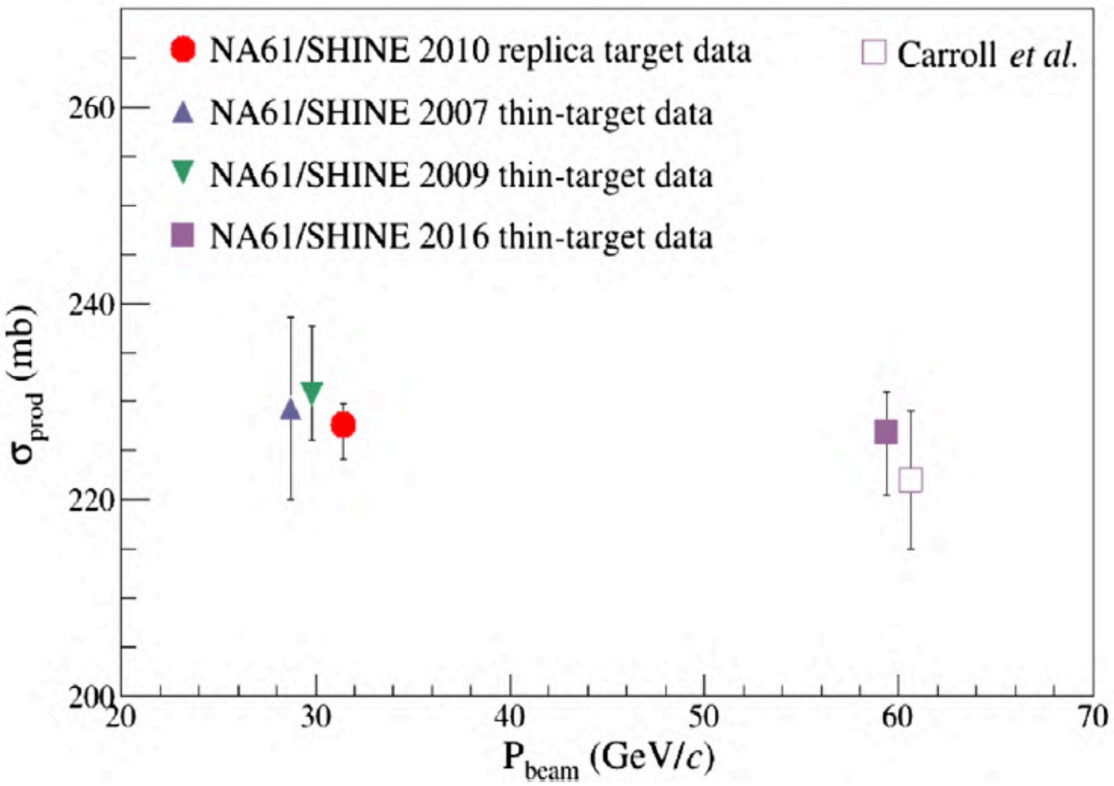
(4 θ-bins for 0 < θ < 280 mrad (Z1-Z5)
2 θ-bins for 0 < θ < 120 mrad (Z6))

(10 θ-bins for 0 < θ < 380 mrad (Z1-Z5)
8 θ-bins for 0 < θ < 260 mrad (Z6))

Negative pions and kaons have been measured as well.

# T2K Replica Target Results


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



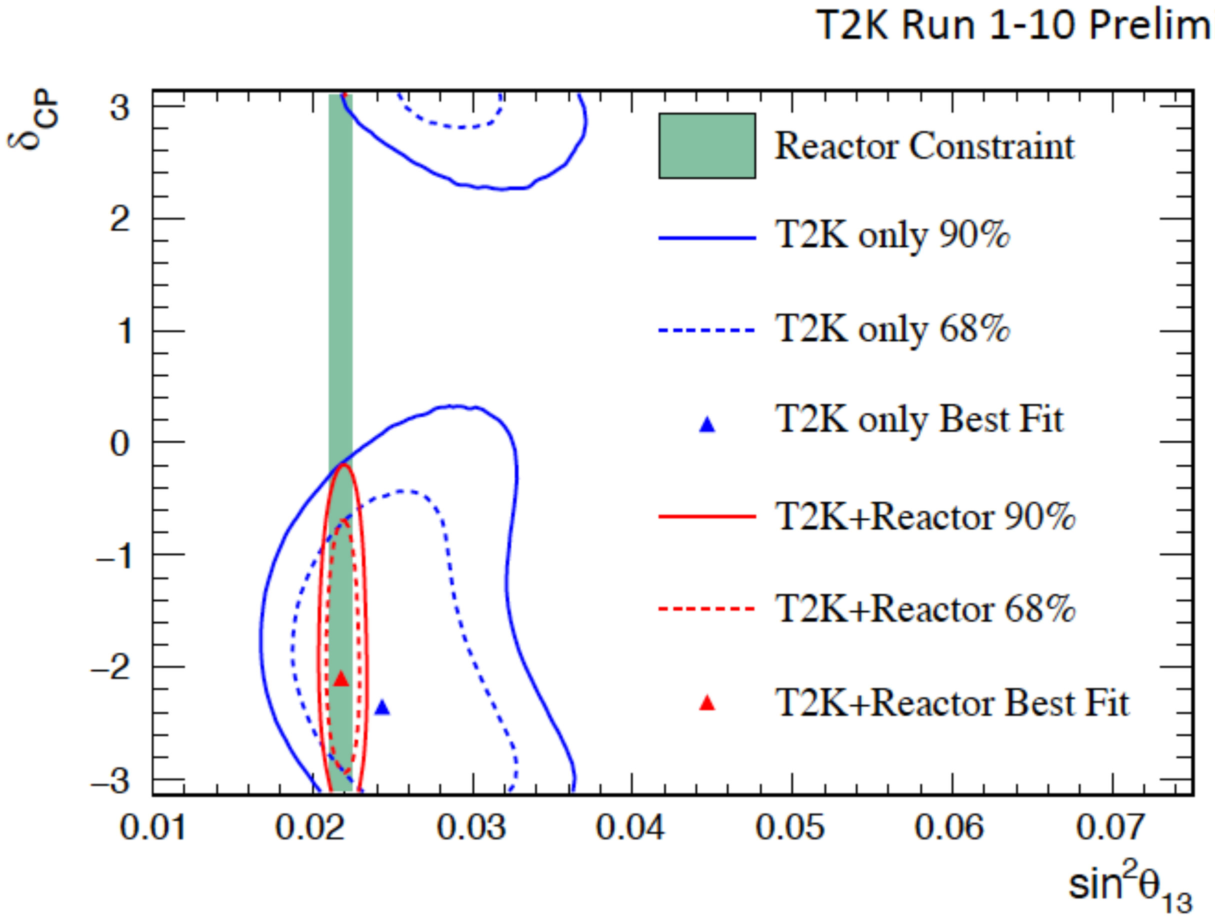

$$P_{\text{survival}} = e^{-Ln\sigma_{\text{prod}}}$$

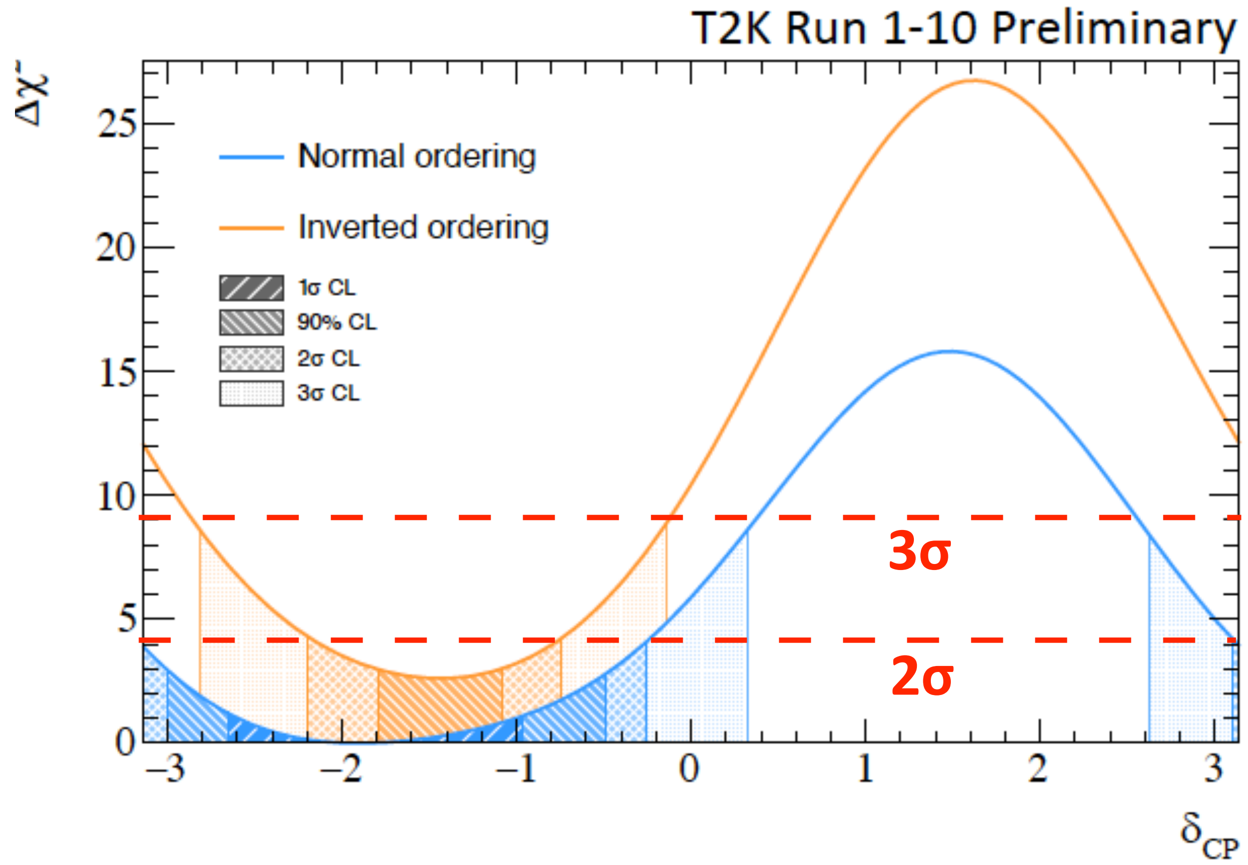
Phys. Rev. D 103, 012006 (2021)

A production cross section measurement using the attenuation of beam particles

—> Achieved 2% total uncertainty in good agreement with past measurements

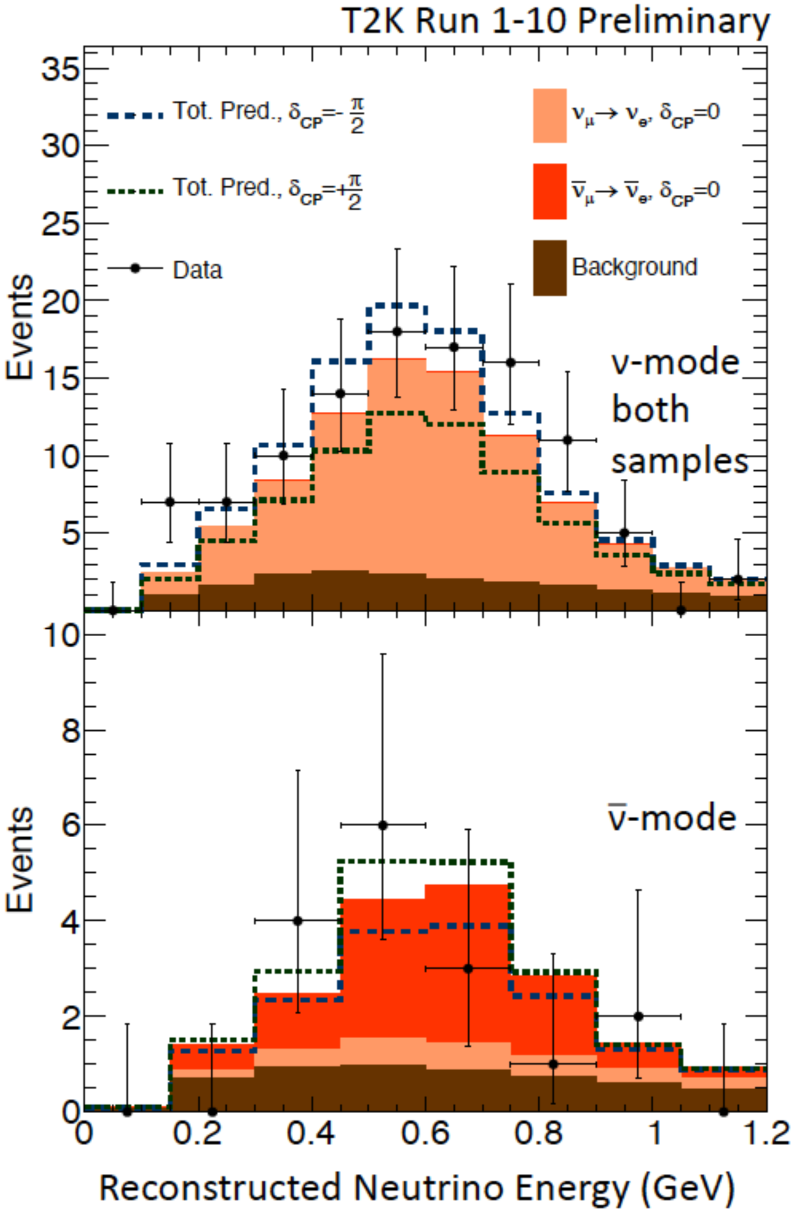
# Constraint on $\delta_{CP}$ Phase

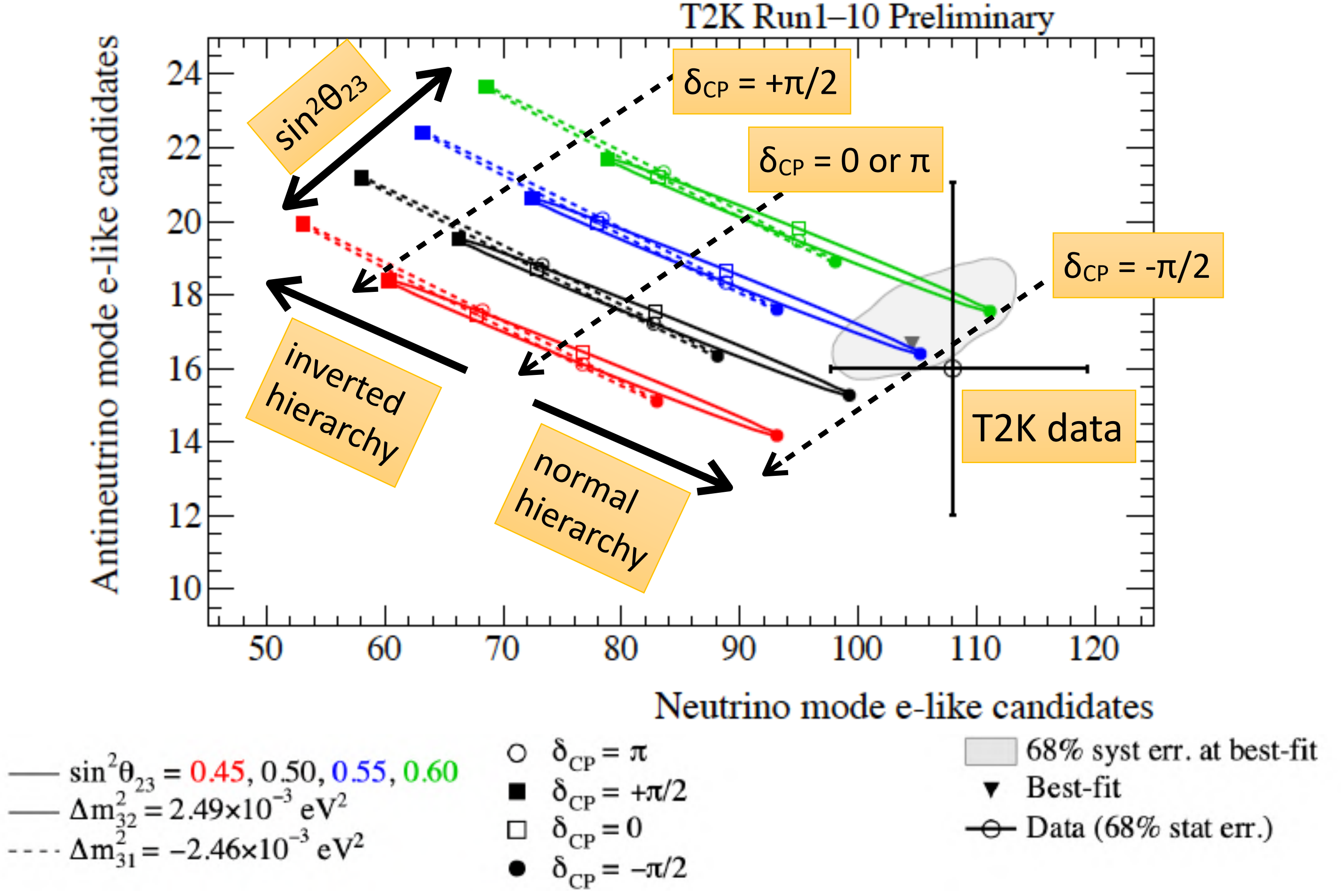



**The most stringent constraint on the *CP*-violating phase in neutrino oscillations !!**

# Extracting Oscillation Parameters




- T2K data prefers $\delta_{CP}$ = -π/2 hypothesis
- T2K data weakly prefers non-maximal $\sin^2\theta_{23}$
- T2K data weakly prefers normal hierarchy