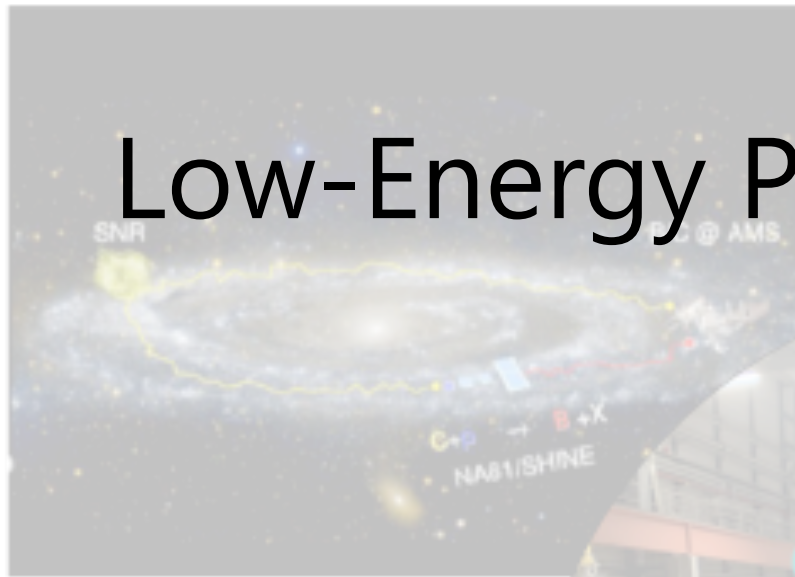
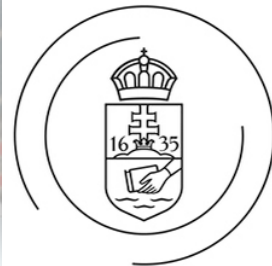


# Low-Energy Physics Opportunities



Yoshikazu Nagai

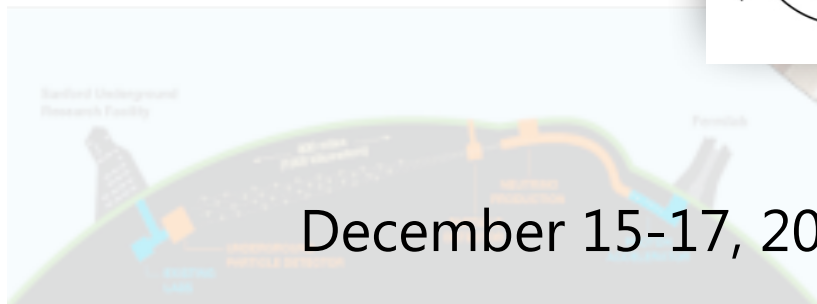


**ELTE**

Eötvös Loránd  
University

Physics opp

ons to pions



December 15-17, 2022, NA61++/SHINE Workshop@CERN

# CONTENTS

- Introduction to the Low-Energy Beamline at H2
- Physics Opportunities with the Low-Energy Beamline
  - Accelerator-based neutrino experiments
  - Atmospheric neutrino experiments
  - Spallation source experiments
  - Muon experiments
- Summary

A 3D schematic diagram of a low-energy beamline. The beamline is a long, narrow tunnel containing several green and blue components, likely magnets and diagnostics, arranged in a sequence. A red line represents the particle beam path, which is slightly curved. The beamline is surrounded by various support structures, including a large yellow structure at the top and several grey structures along the sides. The entire scene is rendered in a clean, technical style with a light blue background.

# Introduction to the Low-Energy Beamline

# Why do we need the new beamline?

## Accelerator-based neutrino experiments

- To achieve the necessary precision on flux calculation of ongoing and next-generation neutrino experiments (T2K, Hyper-K)

example: T2K/Hyper-K

$\Delta m^2$ : few % 'energy scale' of the flux  $\rightarrow$  0.5% for future (S. Bolognesi)

$\sin^2\theta_{23}$ : few % on normalization of the flux  $\rightarrow$  1% for future

$\theta_{23}$  octant:  $\sim$ 1% on  $\nu_e$  normalization of the flux

CPV and MH (for future):  $<$ 2% on  $\nu_e/\bar{\nu}_e$  anticorrelated uncertainties

$\delta_{CP}$  precision: similar needs as  $\Delta m^2$

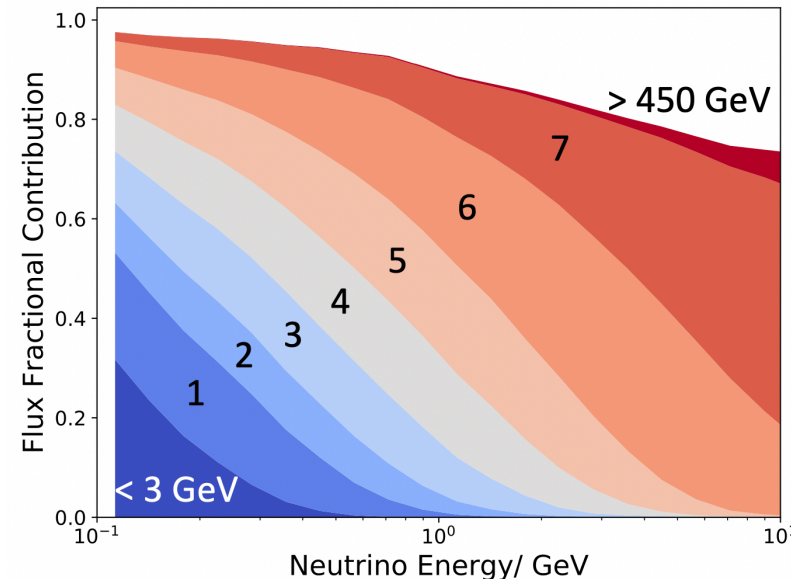
ACCURATE

## Atmospheric neutrino experiments

- To become sensitive to CP-phase (sub-GeV region) and mass ordering (multi-GeV region)
- > Super-Kamiokande
- > Hyper-Kamiokande
- > DUNE

example:  
sub-GeV and multi-GeV  
atmospheric neutrino flux

Uncertainty on the flux needs to be **below 2-3%** for the entire region



(G. Barr)  
1: 3 GeV  
2: 6 GeV  
3: 8 GeV  
4: 13 GeV

Uncertainty on the flux needs to be **below 4%** (for CP-phase measurement)

(green: current unconstrained interaction error, pink: with low-E beam data)

# Project Overview

## Physics Cases

The main focus of this talk.

I will review potential physics opportunities.

(Each experiment's status and demand are further discussed in dedicated presentations.)

## Beamline

The design of the beamline has been finalized. (See Carlo's talk for detail)

## Instrumentation

The baseline strategy for the beam instrumentation has been determined.

(See Carlo's talk for detail)

# Low-E hadron beams at H2: A little bit of History

- 2017: Initial idea based on the experience of proto-DUNE beamline (NA61 Beyond 2020 Workshop)

CERN ENGINEERING DEPARTMENT

## Possibilities for (Very) Low Energy beams at CERN North Area

N. Charitonidis (CERN, EN-EA)

**EHN1 Extension - H2 VLE Beam Schematic Layout**

Legend:

- Incoming beam: 80 GeV/c; high intensity ( $\sim 10^{11}-10^{12}$  pps)
- Attenuated incoming beam
- Low energy beam (0.4 - 12 GeV/c)

Legend:

- BENDS: MBPL, gap 140mm
- QUADS: QPL + QPS large aperture (200 mm)

NA61 BEYOND 2020  
Future Physics Opportunities with the NA61/SHINE Spectrometer  
July 26-28, 2017  
UNIVERSITÉ DE GENÈVE  
FACULTÉ DES SCIENCES  
SHINE NA61  
<https://indico.cern.ch/event/629968/>

## H2-VLE (2003)

**Four-bends layout**

- Available magnets: MBPL 120mrad for 1-9 GeV beams

Legend:

- Incoming beam: 40-80 GeV/c; high intensity (low UV)
- Attenuated incoming beam
- Low energy beam

Legend:

- BENDS: MBPL, gap 140mm
- QUADS: QPL + QPS large aperture (200 mm)

27/7/2017

Courtesy: I. Efthymiopoulos

## H2-VLE (2017)

**Layout of existing secondary H2 and tertiary H2-VLE beam lines of EHN1**

Vertical plane

400 GeV/c primary protons extracted from SPS

2x300 mm Be Primary Target 'TZ'

underground

80 GeV/c mixed hadron beam

Surface

Low energy beam 0.5 - 12 GeV

Secondary Target

ProtoDUNE-OP Liquid Argon Cryostat 11 x 11 m

H2 secondary beam line 631 m

H2-VLE beam line 40 m

→ Using large angles and off-axis placement of the detector wrt the secondary beam reduces the muon background

N. Charitonidis - Very Low Energy Beams in EHN1

9

<https://indico.cern.ch/event/629968>

Note: the idea of a low-energy beamline at the SPS north area is not new

# Low-E hadron beams at H2: A little bit of History

- 2017: Initial idea based on the experience of proto-DUNE beamline (NA61 Beyond 2020 Workshop)
- 2020 February: Launched the Low-E beamline working group
  - Identification of physics motivations, beamline requirement
- 2020 December: A dedicated workshop (NA61/SHINE at Low Energy)
  - Discussion on the physics case and technical feasibility

## The idea

➤ Can we make a special beam line branch, that can provide (very) low energy particles in front of the NA61 detector ?

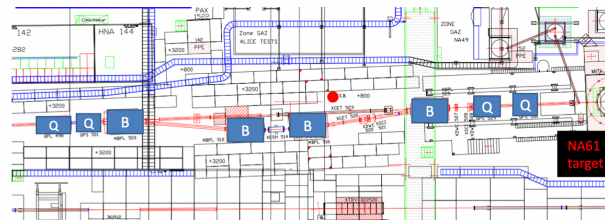
• **Low energy beam in front of PPE152 existed in the past. It had different specifications, for different experiment. But the idea is not new.**

Hi Nikos,  
Happy new year!  
Yes, please check followings, sorry for my late communication.  
-----  
+ As a starting point, I quote proto-Dune numbers from arXiv:1607.07612

+ Desired beam types:  
pions: 2-6 GeV, and below 2 GeV  
protons: 3-12 GeV (also > 13 GeV)  
kaons: < 5 GeV (if possible, but maybe difficult??)  
-> For NA61 analysis side, beam particle ID is a main challenge since it can be a leading systematic source of measurement

+ Desired beam size: proto-DUNE size ( $r \sim 40$  mm) may be too big for us.  
-> Our Beam Position Detector size is 48mm x 48mm, and relatively broader beam can miss our beam position counters.  
-> Our typical target size is 25mm wide.  
-> We can put larger (huge) veto scintillator counter with a small hole in center in our trigger logic, and wider target.  
-> But still narrower beam is preferable (e.g.  $r < 10$  mm)

+ Beam composition  
-> We took 60 GeV kaon beam data in 2015 with 3% composition.  
-> This may be the absolute minimum in terms of composition to keep reasonably high rate.  
-> After shutdown, we need various type of interactions (e.g. 2-3 data sets per week) to be recorded compared to past measurement (typically 1 data sets per week).  
-> Obviously, higher composition will be better. In that sense, proton enhancement is very attractive for low-E proton beams. (This may attract atmospheric neutrino committee as well)



04/02/2020

N. Charitonidis - H2 Beyond

2

## NA61/SHINE at Low Energy

9-10 December 2020  
Europe/Zurich timezone

Enter your search term

Overview

Timetable

Contribution List

My Conference

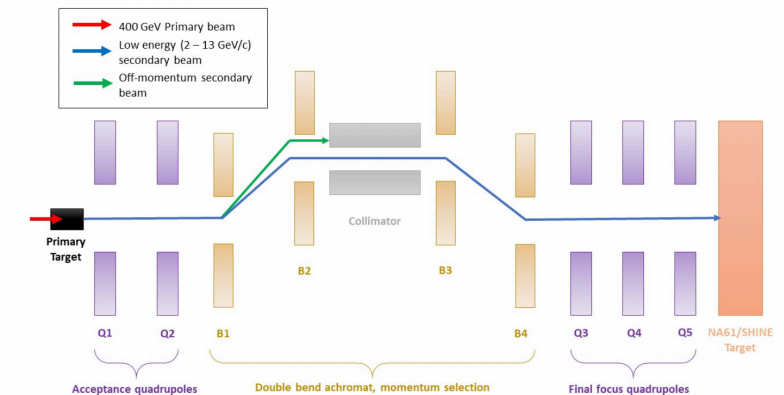
My Contributions

Registration

Participant List

Videoconference

The NA61/SHINE collaboration is exploring the potential addition of a very-low-energy beam. This workshop will explore the physics opportunities for NA61 in the 1-20 GeV region as well as the beam design and its expected capabilities.



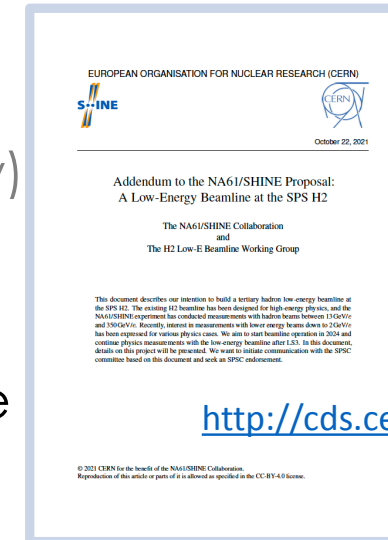
<https://indico.cern.ch/event/973899>

# Low-E hadron beams at H2: A little bit of History

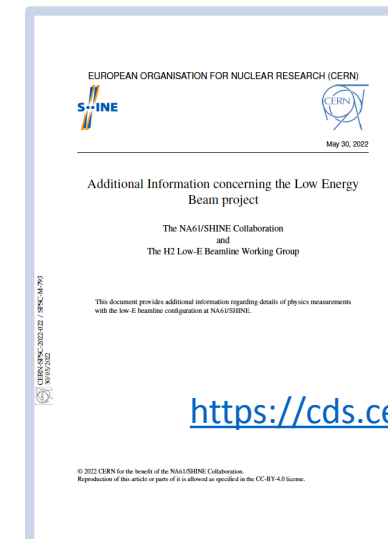
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  - Discussion on the physics case and technical feasibility
- 2021 October: Addendum for SPSC evaluation (SPSC-P-330-ADD-12)
  - First document to express our interest on building Low-E beamline
- 2022 May: Memorandum to SPSC (SPSC-M-793)
  - Additional documents to address SPSC referee's questions

Positively evaluated by the SPSC committee

The SPSC **recognizes the scientific value** of the improvements that the low energy beam line could bring to the knowledge of the neutrino cross sections and **recommends that the corresponding technical feasibility be studied in detail.**



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



<https://cds.cern.ch/record/2810696>



# Low-E hadron beams at H2: A little bit of History

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- 2022 May: Memorandum to SPSC (SPSC-M-793)
  - Additional documents to address SPSC referee's questions
- 2022 November-December: Engineering Change Request (ECR) for the experimental area
  - Finalized beamline design
  - Beamline implementation plan
  - Cost estimation

## ENGINEERING CHANGE REQUEST

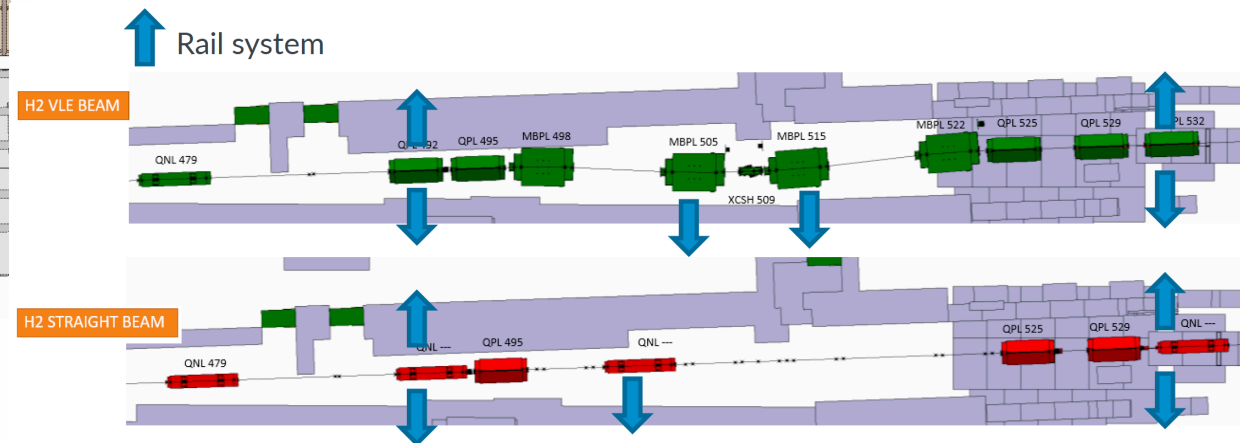
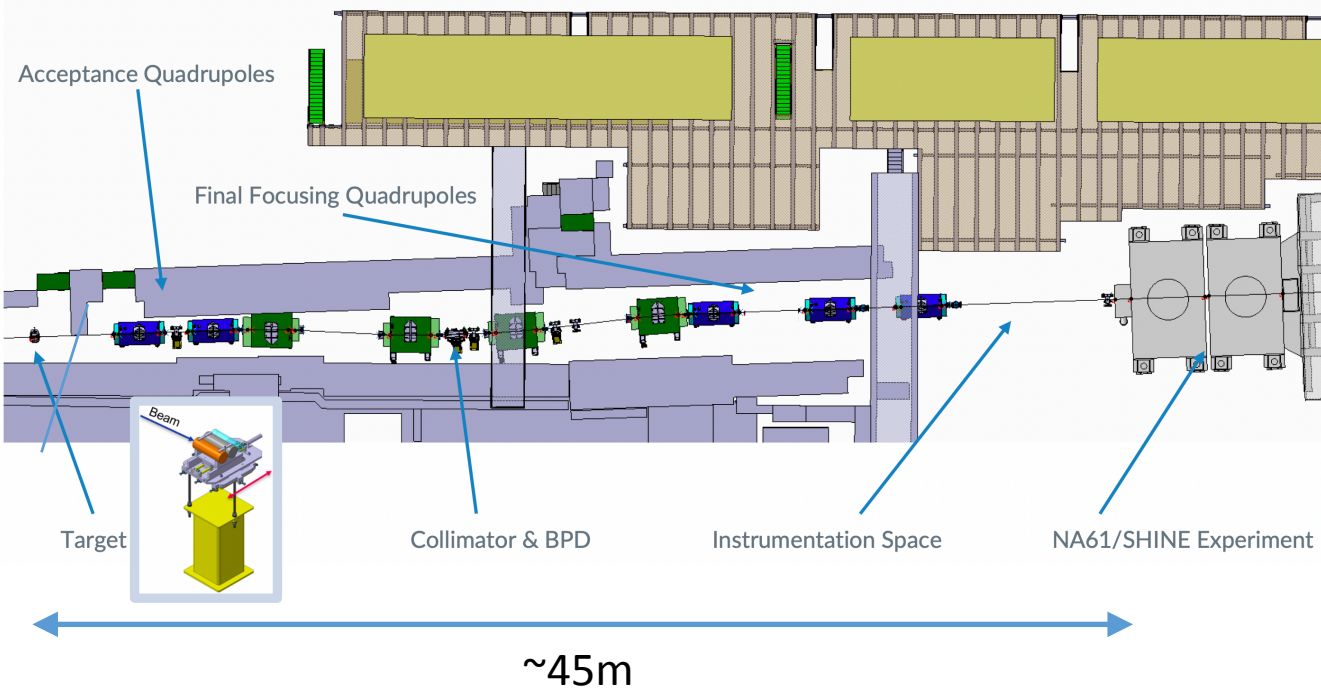
### **A new tertiary branch of H2 beam line for low energy particle beams (H2-LE)**

#### BRIEF DESCRIPTION OF THE PROPOSED CHANGE(S):

This document describes the necessary changes to install a new tertiary branch of the H2 line, to be located in PPE132-142-152 zones in EHN1, in front of the NA61/SHINE TPC hut. New magnets and the existing power supplies powering the H2-VLE line of the neutrino platform need to be installed. Extra shielding needs to be installed, as well as rail systems that will allow the transition between the existing H2 line and this low-energy configuration. In this ECR, the new configuration is described, as well as its necessary cost breakdown.

# Low-Energy Beamline Overview

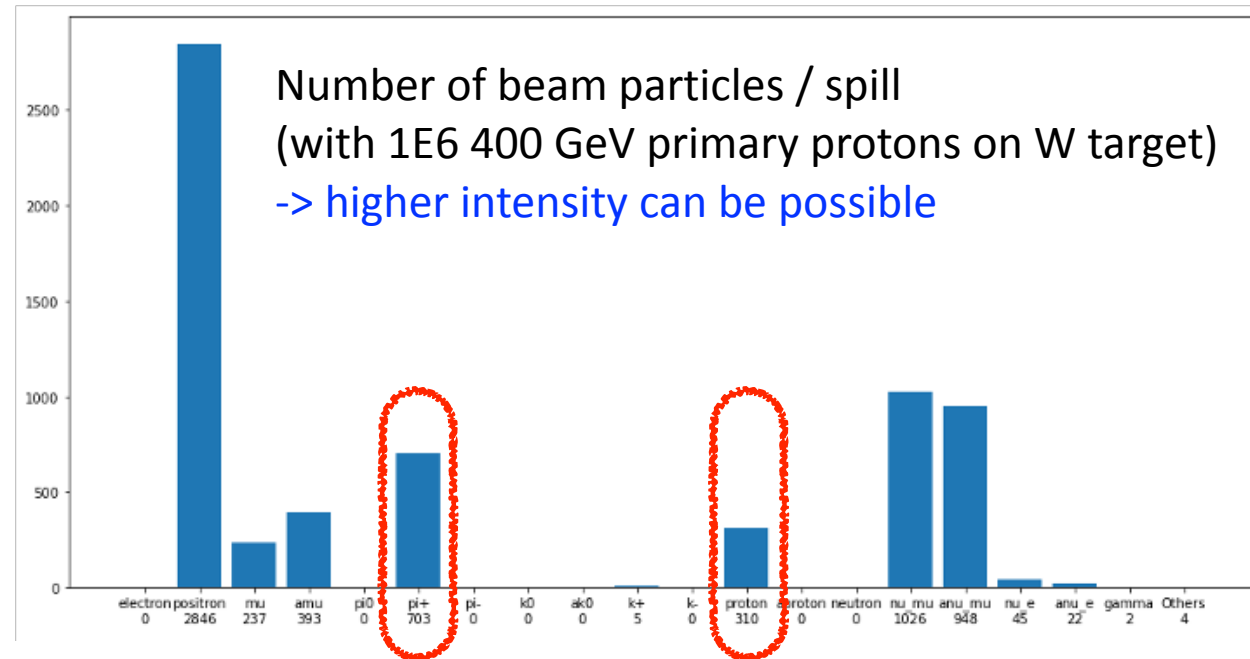
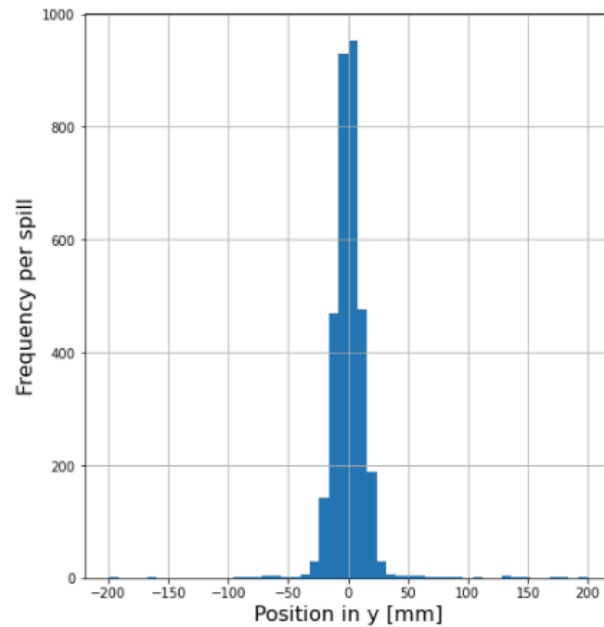
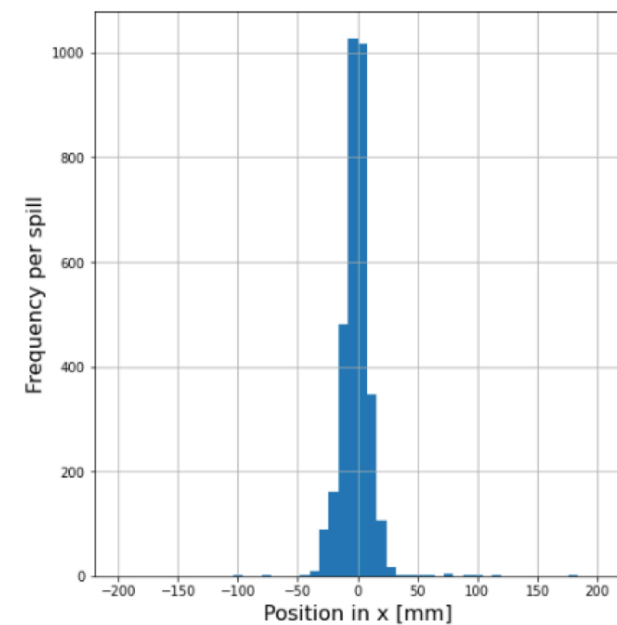
- A new tertiary low-E hadron beamline at CERN SPS H2 (where NA61/SHINE is located)
  - Low-Energy = 1-13 GeV (2-13 GeV/c) (the lowest momentum NA61 achieved was 13 GeV/c)
  - Design with readily available equipment (magnets, power supplies, etc)
  - Push-and-pull design to quickly switch beamline configurations



# Low-Energy Beamline Overview

- A new tertiary low-E hadron beamline at CERN SPS H2 (where NA61/SHINE is located)
  - Hadron beams with good quality (well-focused below  $\sigma_x, \sigma_y < 20$  mm)
  - Enhanced proton fraction (For above 5 GeV, kaons as well)

Example: 2 GeV/c beam (@ NA61 target)



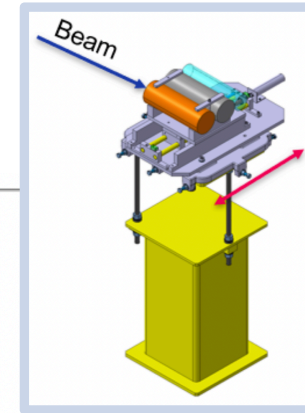
Standard deviation in x = 12.03  
Standard deviation in y = 16.18

proton / pion ratio > 1/3

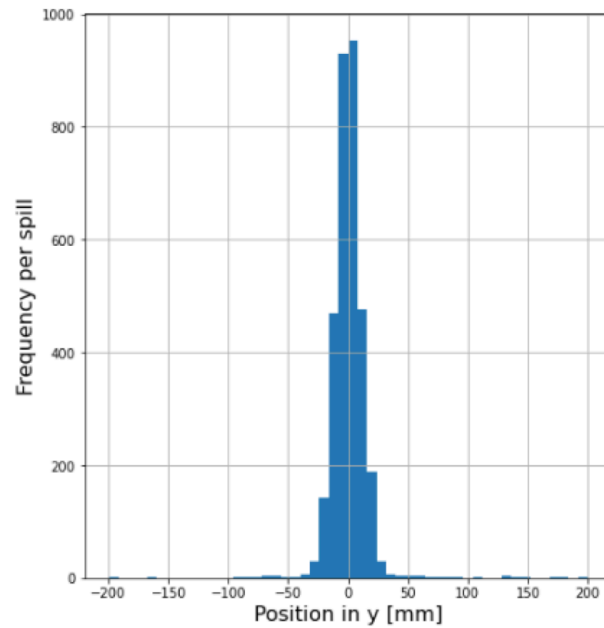
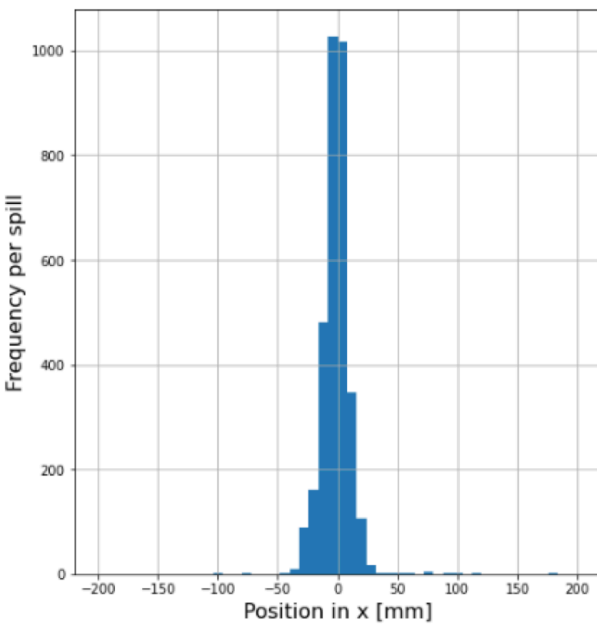
# Low-Energy Beamline Overview

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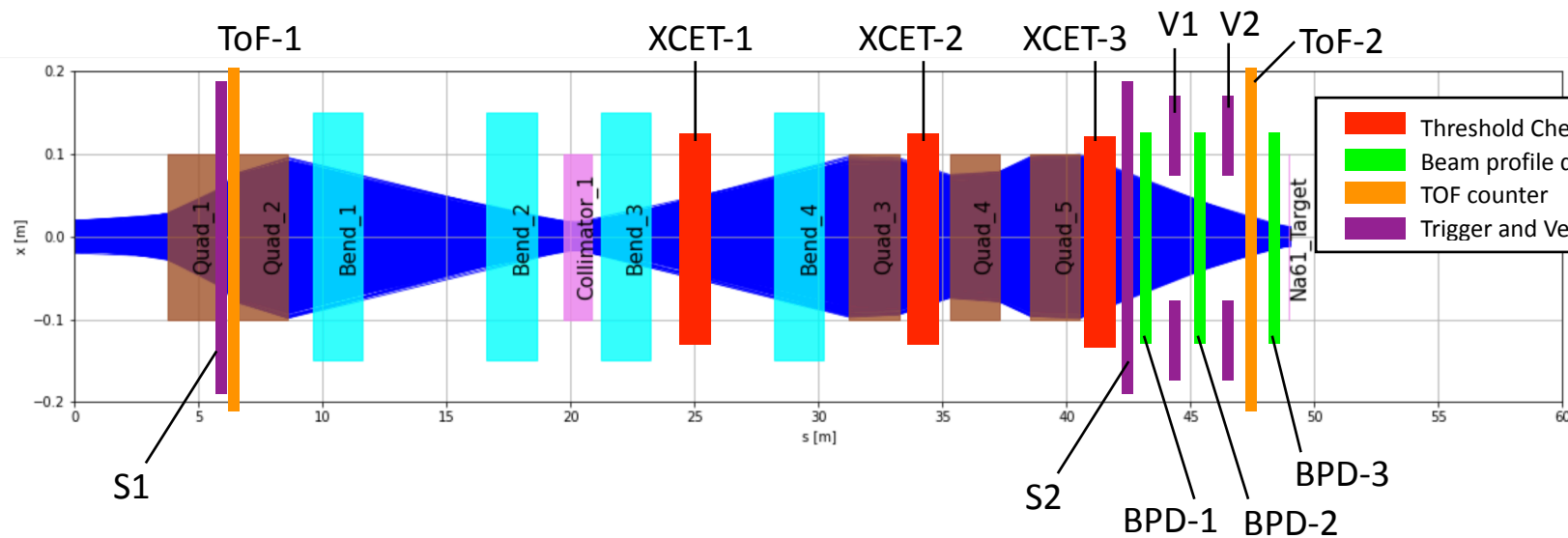
Further optimization of low-E hadron beam target is possible!!



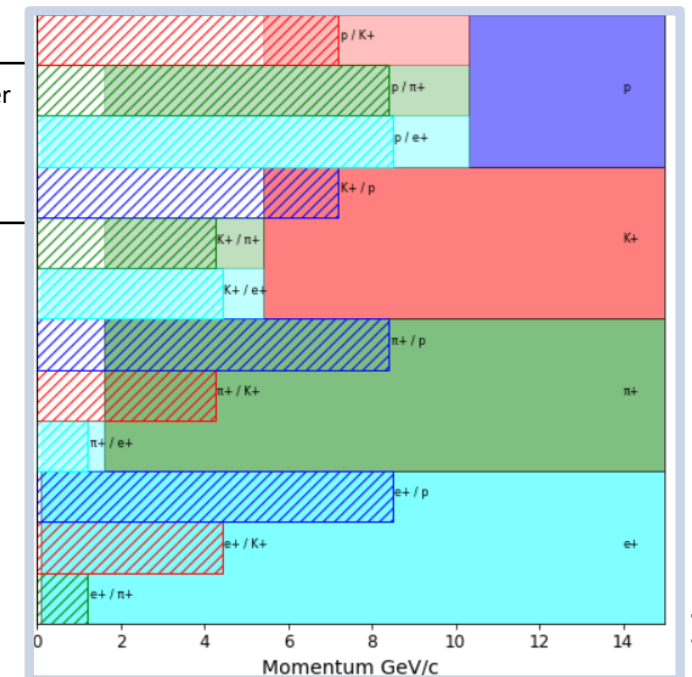
Standard deviation in x = 12.03  
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# Low-Energy Beamline Overview

- A new tertiary low-E hadron beamline at CERN SPS H2 (where NA61/SHINE is located)
  - Hadron beams with good quality (well-focused below  $\sigma_x, \sigma_y < 20$  mm)
  - Beamline instrumentation for position monitoring and beam PID
    - Beam profile detector (silicon), Time-Of-Flight (scintillator), threshold Cherenkov



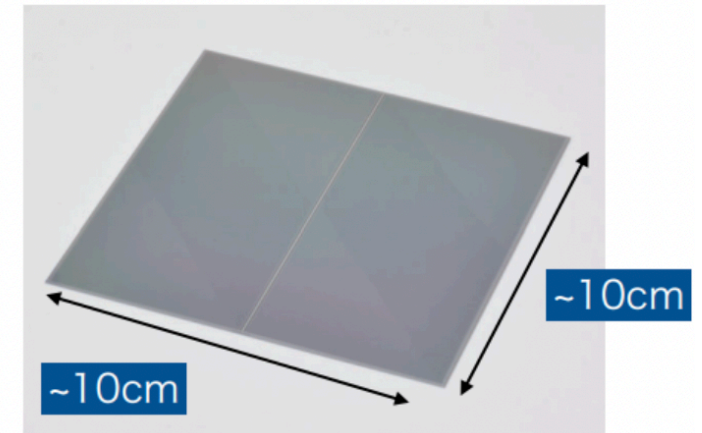
PID with 3 XCETs (filled color area)  
+ 200 ps ToF (hash area)



# Status and Prospect

- Beamline cost is estimated (~1 MCHF)
  - Seeking external funding sources
    - Requested a European grant
    - Other contributions under consideration
    - **Support from CERN is under discussion**
- Beam instrumentation is under development (Okayama, KEK)
  - Silicon-based beam profile detector
  - Investigating thin Time-of-Flight detector options
- First beam in 2024 at the earliest (depending on the funding)
  - Installation during Year-End-Technical-Stop (YETS) -> December 2023 - March 2024
- Beamtime expectation
  - We included an initial beamtime request in the annual SPSC report

Si strip detector(Hamamatsu S13804)



0.19mm pitch x 512ch x 2

## **Physics with very-low-energy hadrons:**

- **2024:** one week pilot run to characterize beam
- **2025:** several weeks physics data – studies ongoing to refine beam request

<https://indico.cern.ch/event/1214949>

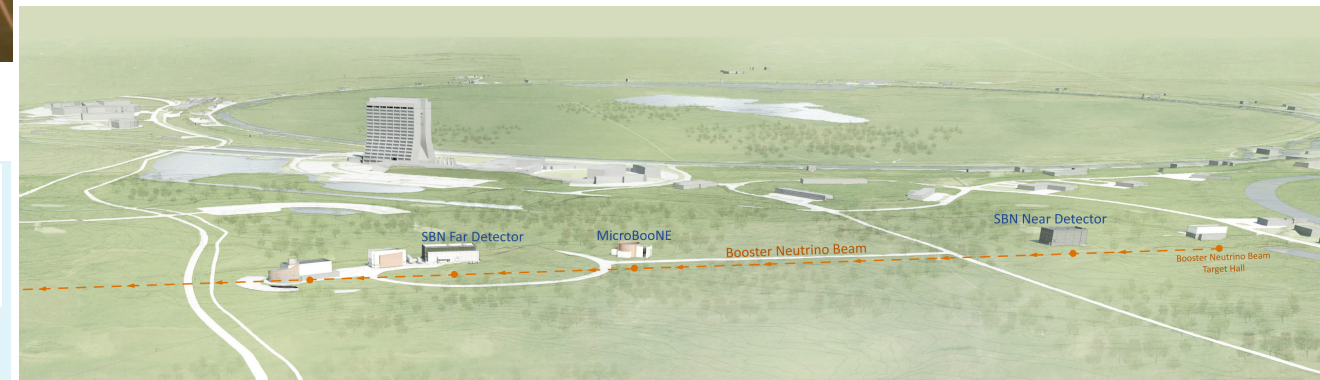
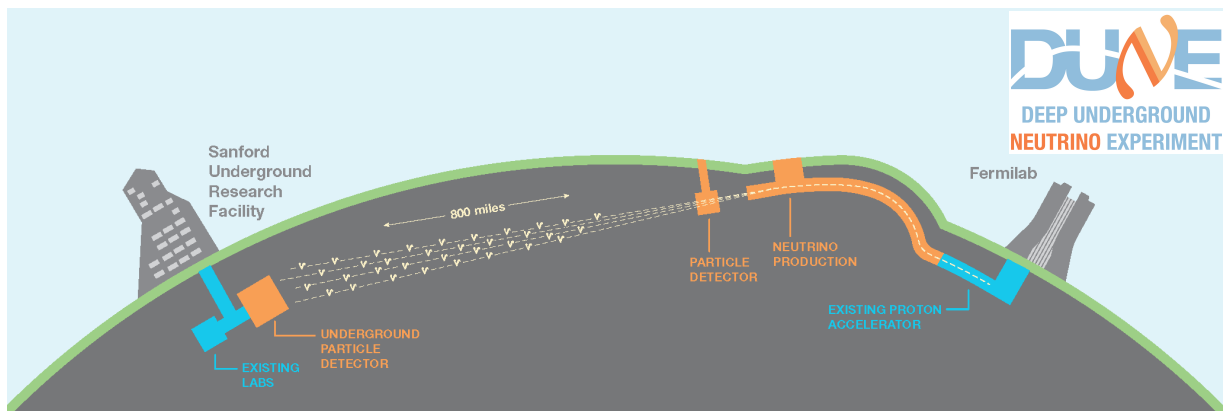
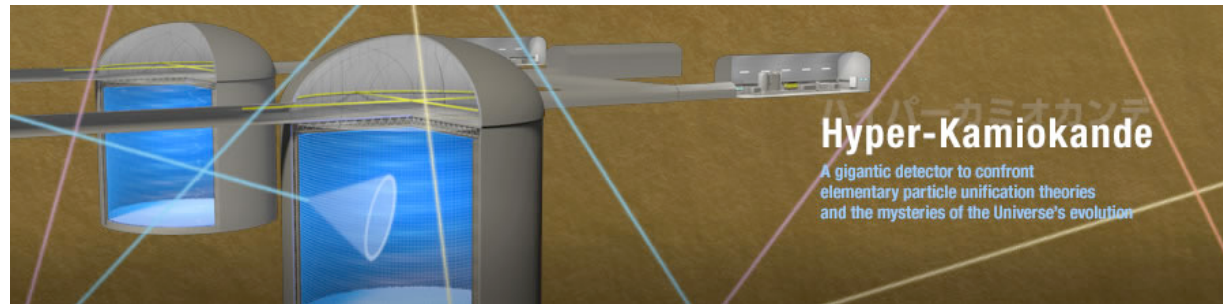
A vibrant, cartoonish illustration of a crowd of neutrino characters. The characters are depicted as colorful spheres (yellow, green, purple, blue, orange) with simple facial expressions, some wearing sunglasses or holding small signs. Two prominent characters in the foreground hold large white banners with the word 'NEUTRINO' written on them, accompanied by a stylized neutrino symbol. The background is a light, textured grey with faint lines suggesting a crowd or a large gathering.

# Physics Opportunities with the Low-E Beamline

# Physics Cases

Accelerator-based neutrino experiments (to study secondary hadron scatterings not covered by current data)

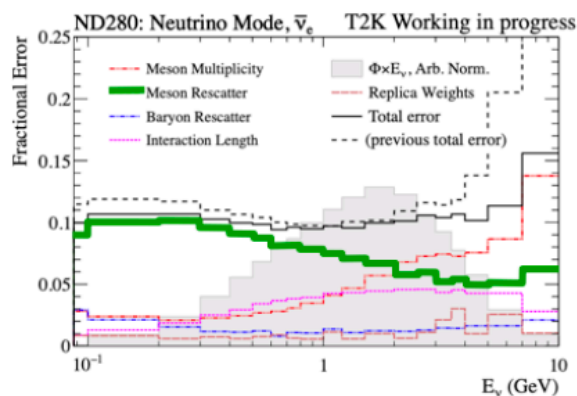
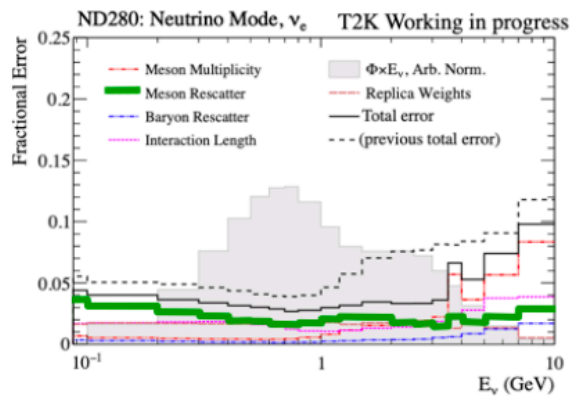
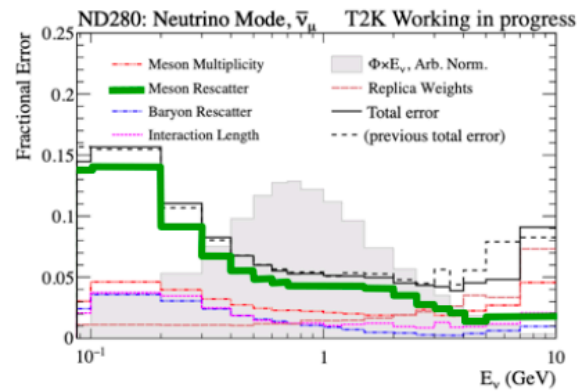
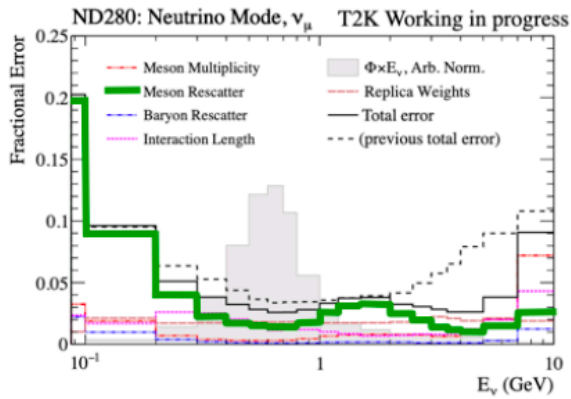
- Long-baseline: T2K / Hyper-K at J-PARC (← **detailed study in SPSC document**), LBNF/DUNE at FNAL
- Short-baseline: Booster Neutrinos (SBND, MicroBooNE, ICARUS) at FNAL





# Current Neutrino Flux (example: T2K)

NA61/SHINE Run1 data (2007-2010) helped to achieve 5% flux uncertainty at the flux peak (black solid line)  
NA61/SHINE Run3 data (2022 summer) will help to reduce uncertainty for high-energy neutrinos



But these are **NOT enough** for the precision era of accelerator-based neutrino experiments (T2K/Hyper-K, DUNE)  
-> The goal on the flux uncertainty is below 3%

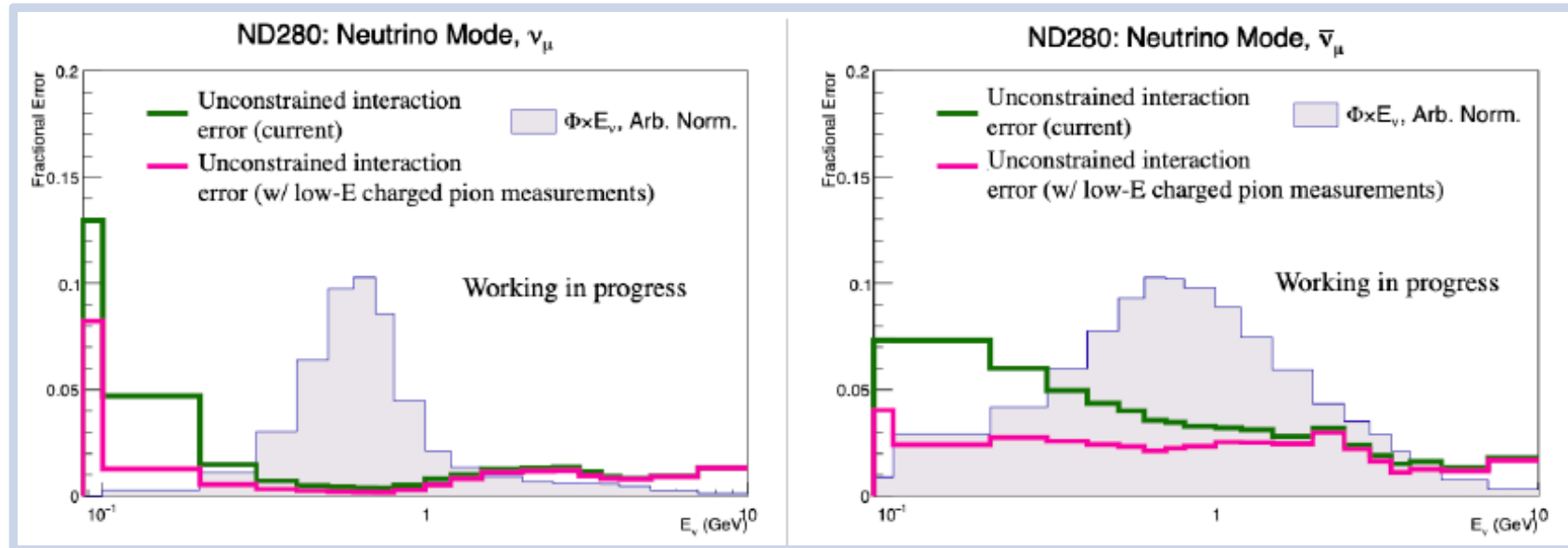
We need:

- pion beam: 2-6 GeV
- proton beam: above 4 GeV
- kaon beam: above 5 GeV

# If we have low-E data.. (example: T2K/HK)

After all available data...

Example from T2K/Hyper-K:



SPSC-M-793

For the next generation experiments (DUNE, Hyper-K), flux uncertainty needs to be constrained within 2-3%

There are still unconstrained interactions that limit physics sensitivity. Improvement is possible if we have additional hadron production data not yet measured by past/present experiments. (e.g. low energy pion scattering)

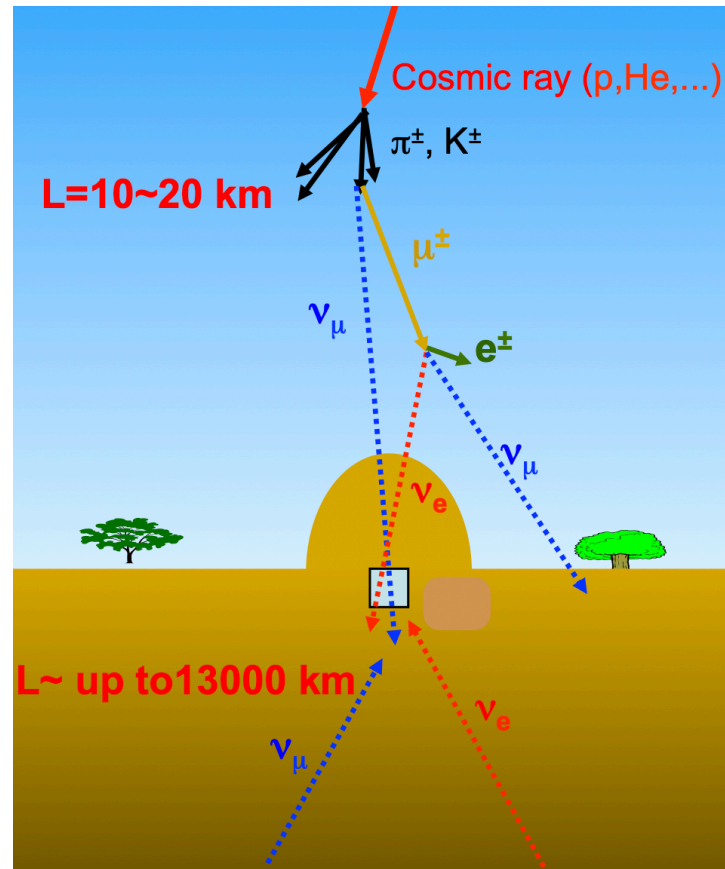
# Physics Cases

Accelerator-based neutrino experiments (to study secondary hadron scatterings not covered by current data)

- Long-baseline: T2K / Hyper-K at J-PARC, LBNF/DUNE at FNAL
- Short-baseline: Booster Neutrinos (SBND, MicroBooNE, ICARUS) at FNAL

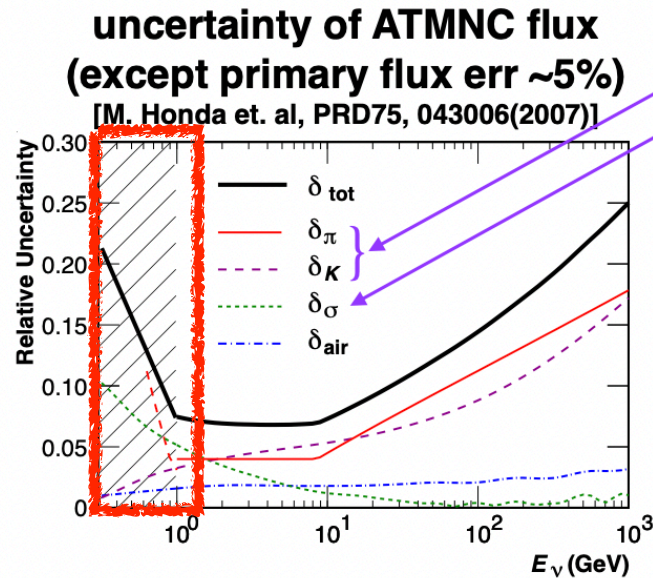
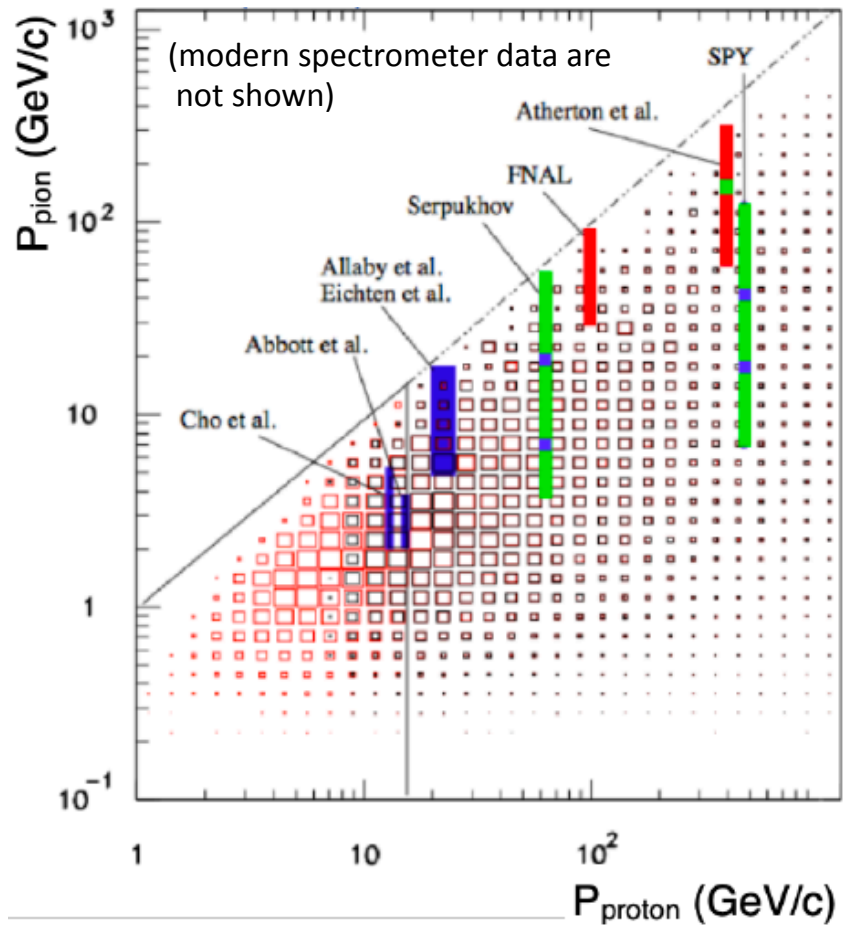
Atmospheric neutrino experiments (to study cosmic ray proton scatterings)

- Sub-GeV and Multi-GeV neutrinos: Super-K, Hyper-K, DUNE ← **detailed study in SPSC document**



# Current Flux Uncertainties (Atmospheric $\nu$ )

- Hadron production data is sparse
  - Hadron Production is the leading uncertainty source of flux predictions



hadron production  
hadronic cross-section

• *hadronic interactions in air shower*  
→ **dominant!**

- Hadronic Model
  - JAM (E<31GeV)
  - dpmJet3 (otherwise)

K. Sato, talk at the “NA61/SHINE at Low Energy workshop” (2020)

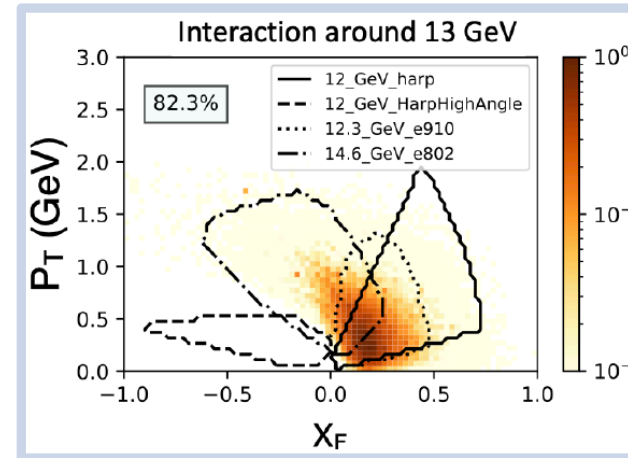
➡ More hadron production data are necessary

# Old Hadron Production Data Issues

- List of concerns:
  - No detail on error report
  - No covariance matrix
  - Inconsistency between experiments

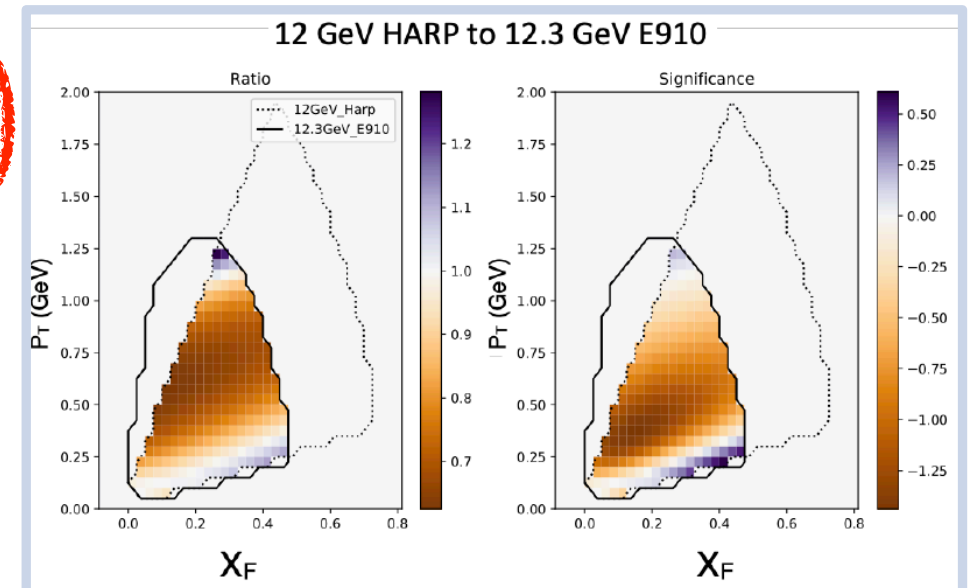
example: Hadron production data for  
< 15 GeV atmospheric neutrino fluxes

phase-space coverage of 3 experiments



SPSC-M-793  
(Plots by L. Cook)

(In)consistency b/w HARP and E910



Energy [GeV]	Process	Error report	Covariance Matrix	Experiment (year)
3, 5, 8, 12	$p+C \rightarrow \pi^\pm, K^\pm$	stat. and syst. separately	No	HARP (2009)
6.4, 12.3, 17.5	$p+Be \rightarrow \pi^\pm$	only total error	No	E910 (2008)
14.6	$p+Al \rightarrow \pi^\pm, K^\pm$	only stat.	No	E802 (1991)

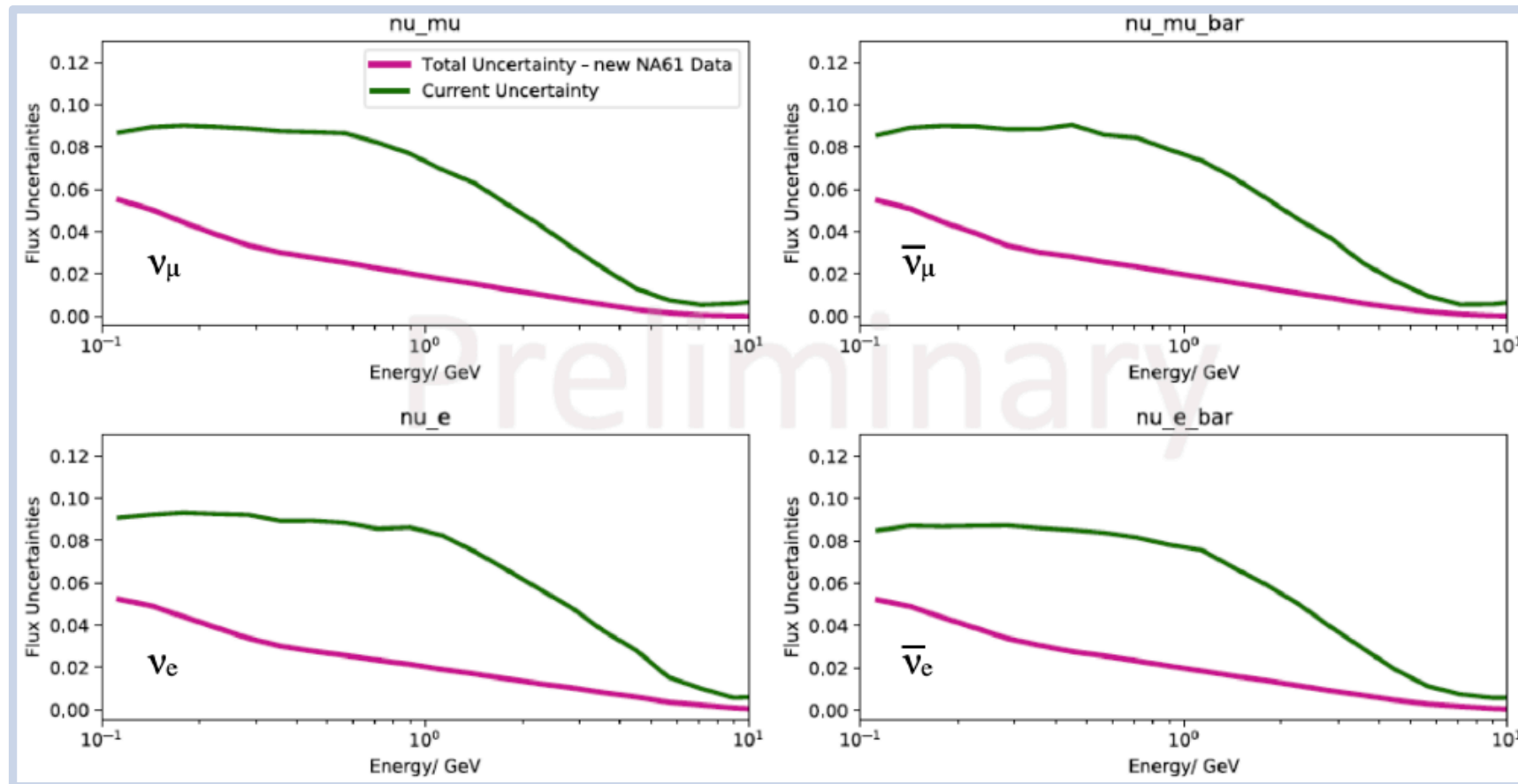
Table 1: Past hadron production datasets relevant to the momentum range of the low-E beamline project.

SPSC-M-793

These issues remain as of now -> We want to improve this!!

# If we have low-E data.. (example: atmospheric $\nu$ )

Drastic improvement in the atmospheric neutrino flux is possible  
if we have data for lower energy  $p + N \rightarrow \pi^\pm + X$  interactions (down to a few GeV)



SPSC-M-793  
(Plots by L. Cook)

# Physics Cases

Accelerator-based neutrino experiments (to study secondary hadron scatterings not covered by current data)

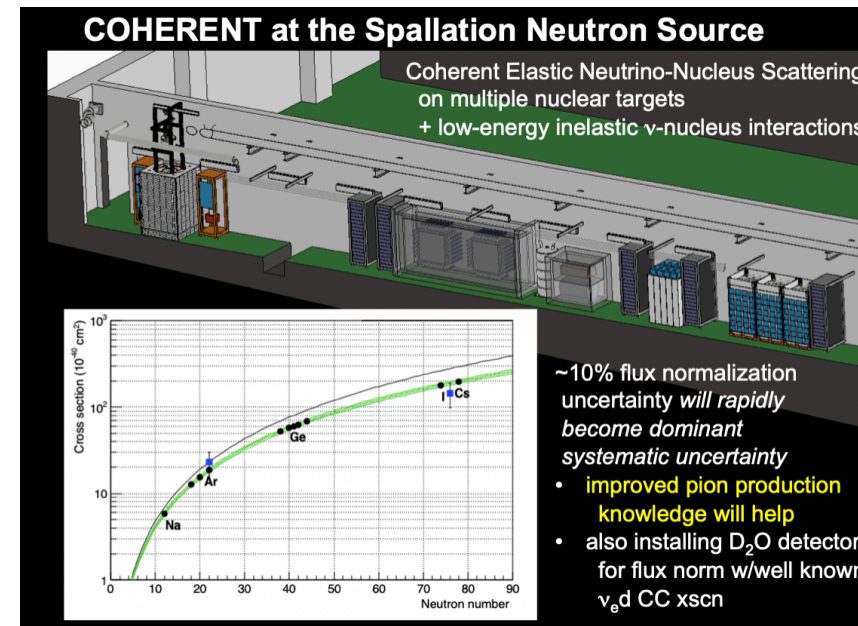
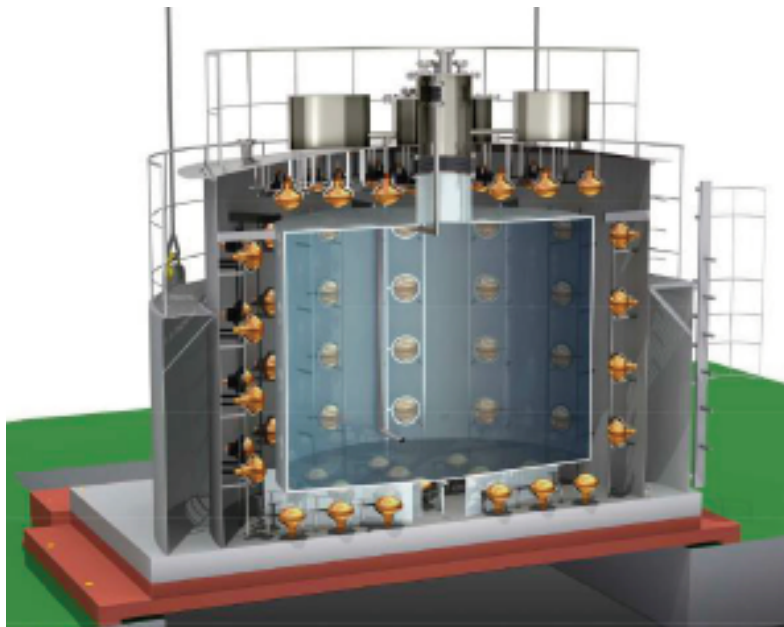
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- Sub-GeV and Multi-GeV neutrinos: Super-K, Hyper-K, DUNE

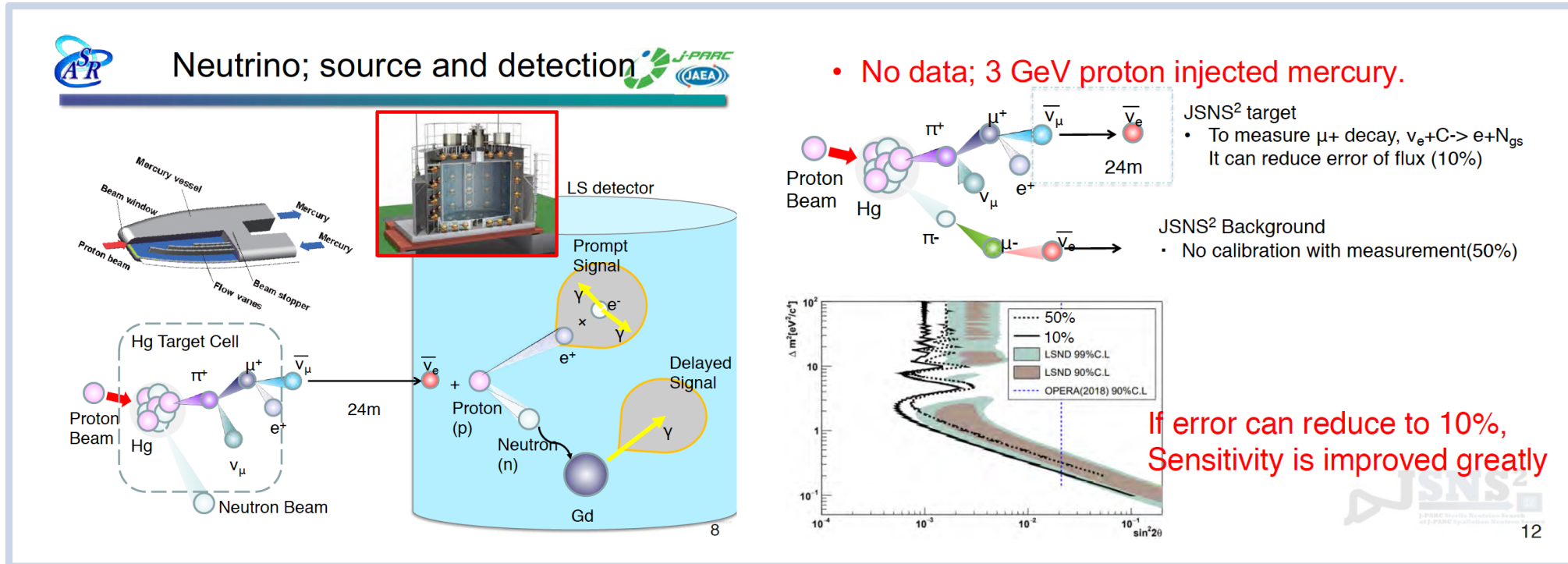
Spallation neutron source neutrino experiments

- JSNS<sup>2</sup> at J-PARC MLF (sterile neutrino search): hadron production on p+Hg at 3 GeV (3.82 GeV/c)
- COHERENT at ORNL (coherent elastic neutrino scattering): hadron production on p+Hg around 2 GeV/c



# Sensitivity (example: JSNS<sup>2</sup>)

Hadron production limits sensitivity of the experiment  
 Basically, no data exists for p+Hg reactions



S. Hasegawa  
 (9th July, 2020 at low-E working group meeting)



# Physics Cases

Accelerator-based neutrino experiments (to study secondary hadron scatterings not covered by current data)

- Long-baseline: T2K / Hyper-K at J-PARC, LBNF/DUNE at FNAL
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Atmospheric neutrino experiments (to study cosmic ray proton scatterings)

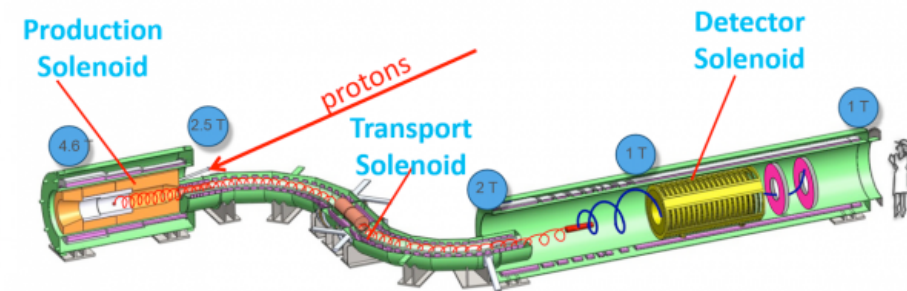
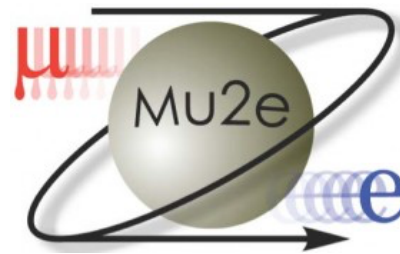
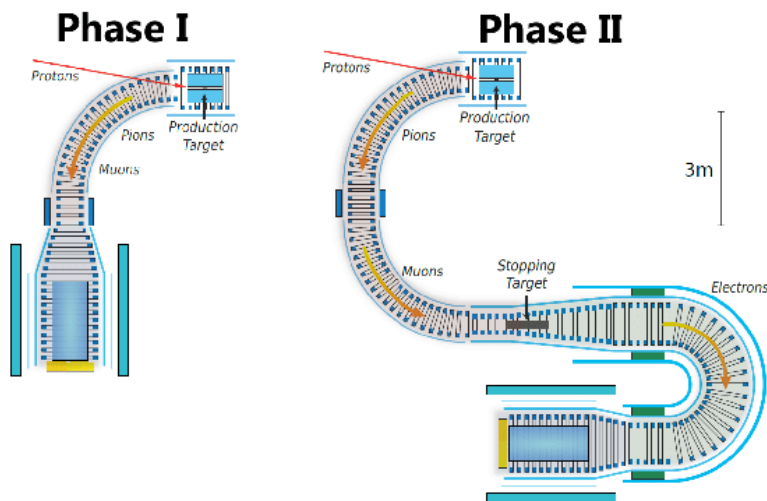
- Sub-GeV and Multi-GeV neutrinos: Super-K, Hyper-K, DUNE

Spallation neutron source neutrino experiments

- JSNS<sup>2</sup> at J-PARC MLF (sterile neutrino search): hadron production on p+Hg at 3 GeV (3.82 GeV/c)
- COHERENT at ORNL (coherent elastic neutrino scattering): hadron production on p+Hg around 2 GeV/c

Muon experiments

- COMET at J-PARC (muon to electron): hadron production on p+X at 8 GeV (X = C, W, or heavy material)
- (potentially) Mu2e at FNAL: hadron production on p+W at 8 GeV



# Summary

- Precision hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction
  - Recent data helps a lot to improve flux knowledge of T2K, and near future for DUNE
  - Nevertheless, we need further improvement, including low-E hadron interactions below the currently available beam energy at SPS H2
- Low-E beamline project is moving forward quickly
  - Positively evaluated by SPSC
  - ECR to obtain green light for experimental area modification
  - Aiming at the first beam before LS3 (current NA61/SHINE era)
    - And continue beyond LS3 (NA61++ era)
- We identified various physics cases
  - Primarily for neutrino physics community (LBL, SBL, atmospheric, spallation source)
  - Also relating field (muon physics, understand nuclear target for spallation source)

We welcome new idea, new collaborators!!

Stay Tuned!

# Backup

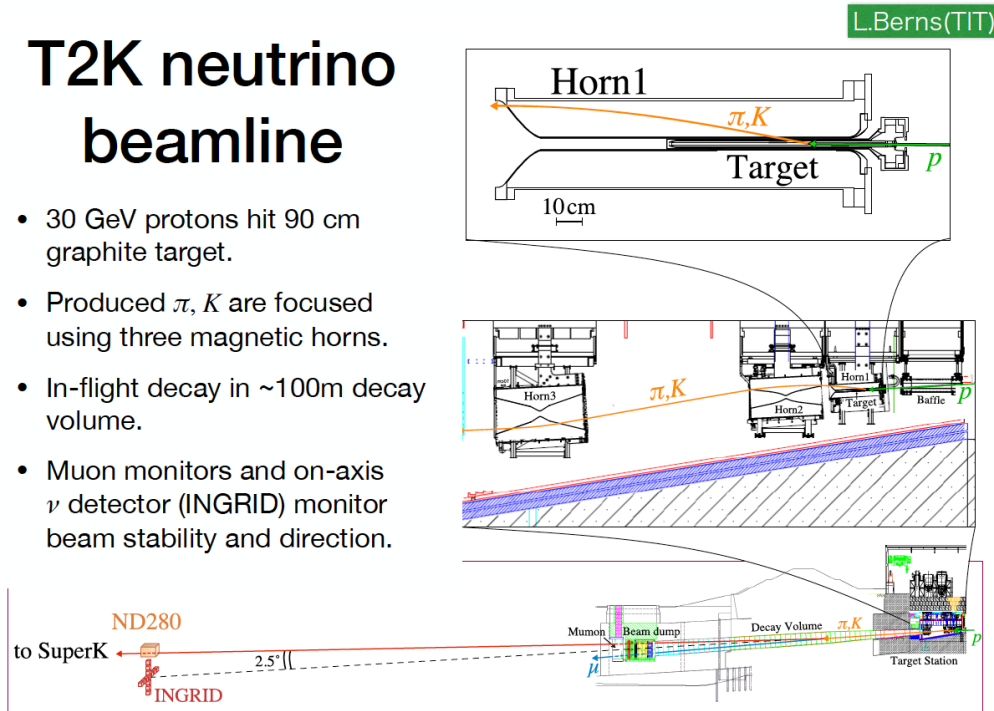
# T2K / Hyper-K

## Beam species and energy

- pion beam: < 2 GeV, 2-6 GeV
- proton beam: 4-12 GeV, > 12 GeV
- kaon beam: < 5 GeV, above 5 GeV

## T2K neutrino beamline

- 30 GeV protons hit 90 cm graphite target.
- Produced  $\pi, K$  are focused using three magnetic horns.
- In-flight decay in  $\sim 100\text{m}$  decay volume.
- Muon monitors and on-axis  $\nu$  detector (INGRID) monitor beam stability and direction.

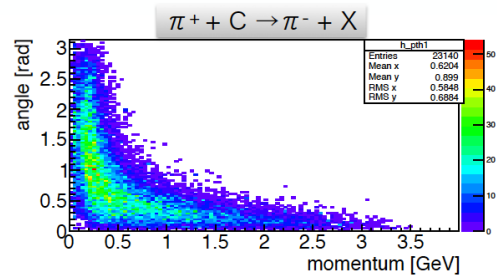
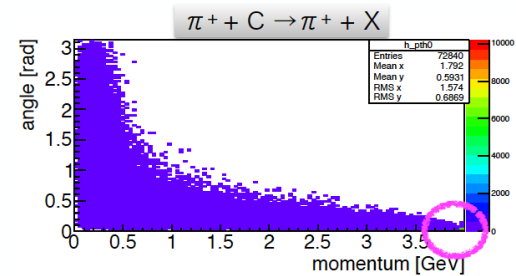


## Fraction of tuned hadronic interaction

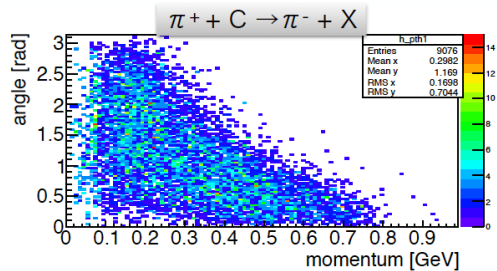
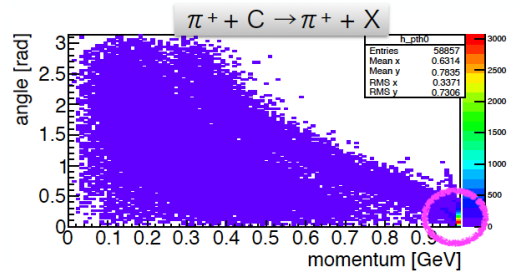
Dataset	Tuned Hadronic Interactions in Neutrino Ancestry							
	SK $\nu$ -mode				SK $\bar{\nu}$ -mode			
	$\nu_\mu$	$\bar{\nu}_\mu$	$\nu_e$	$\bar{\nu}_e$	$\nu_\mu$	$\bar{\nu}_\mu$	$\nu_e$	$\bar{\nu}_e$
NA61 2009 Thin	85.8%	80.0%	83.8%	76.9%	80.9%	85.3%	77.6%	83.2%
+ NA61 2009 Replica	94.0%	83.6%	89.2%	77.3%	84.4%	93.6%	77.9%	89.5%
+ HARP	96.5%	87.6%	90.5%	77.8%	87.8%	96.2%	78.3%	91.1%

still  $\sim 10\%$  of hadronic interaction are untuned

4GeV  $\pi^+ + C$

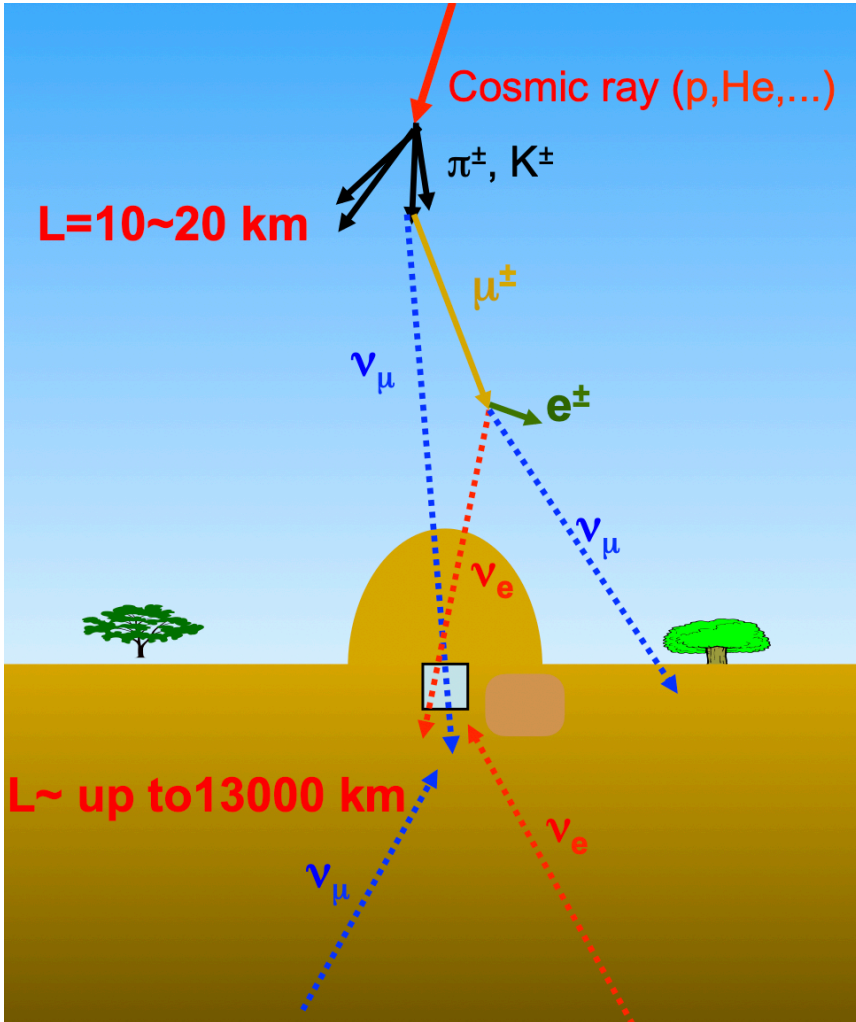


1GeV  $\pi^+ + C$



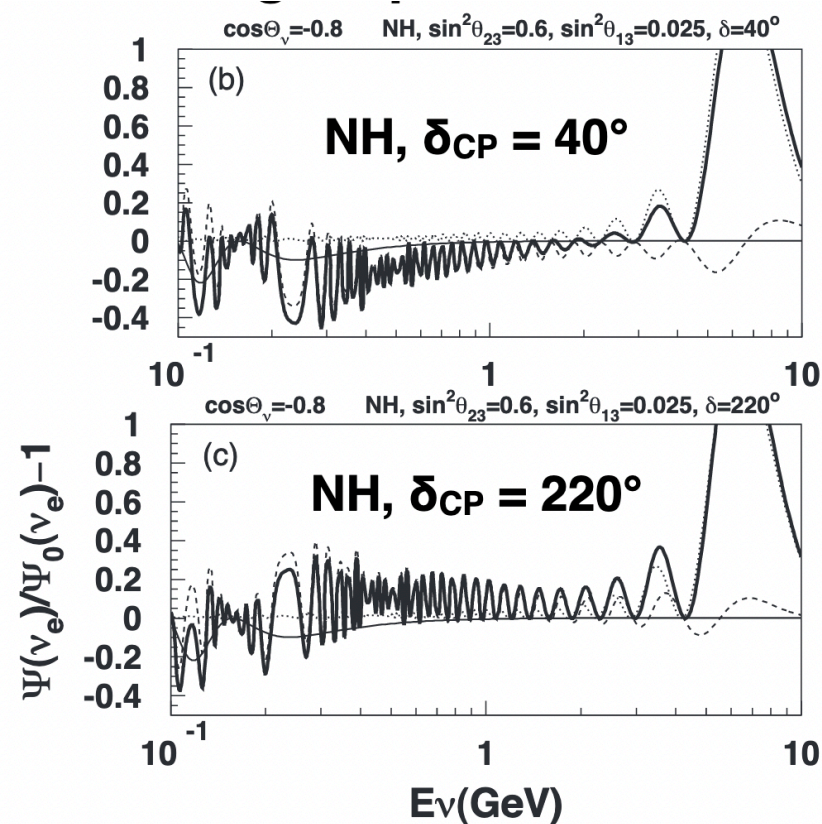
Most of scattering particles go to the forward direction while charge exchanged particles have a large angle

# Atmospheric Neutrino Production



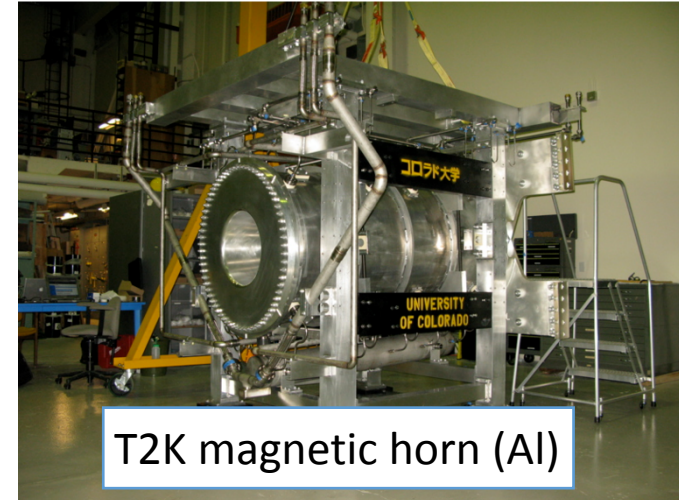
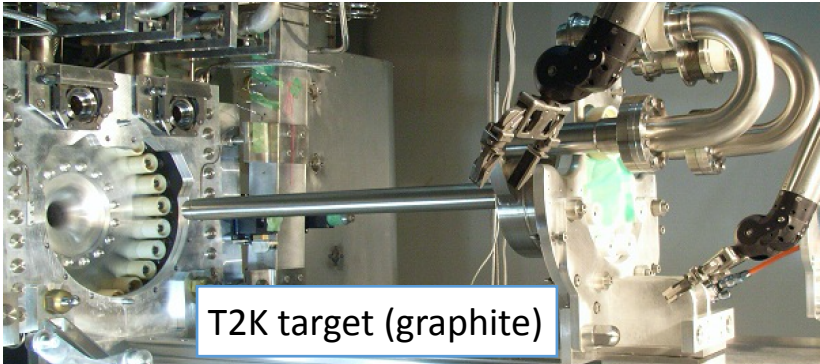
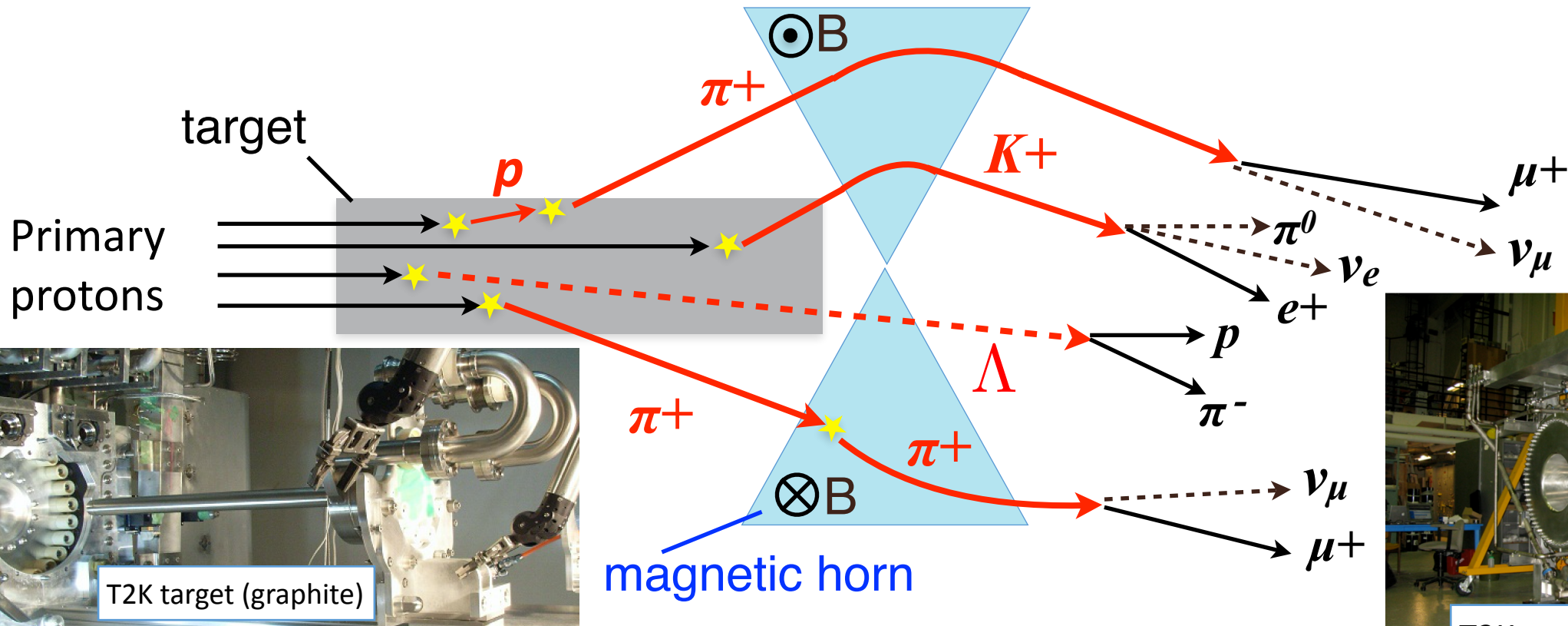
- Primary interactions in atmosphere ( $p + N \rightarrow \pi$ )
- Neutrino flux ranges below 100 MeV to above 10 TeV
  - 0.1-1.0 GeV (sub-GeV): sensitive to CP phase
  - 1.0-10 GeV (multi-GeV): sensitive to mass hierarchy

$\nu_e$  flux ratio  
 (oscillation / non-oscillation)



HK design report

# Accelerator Neutrino Production



Hadron production process is complex:

- Primary interactions in the target ( $p + C \rightarrow \pi^\pm$  and  $K^\pm$ ) -> Primary contribution to the neutrino flux
- Secondary interactions with beamline materials (hadrons + C/Be/Al/Ti/Fe/H<sub>2</sub>O/etc..)
- Neutral hadron decay ( $p + C \rightarrow V^0 + X$ ) ↪ Non-negligible contribution to the neutrino flux