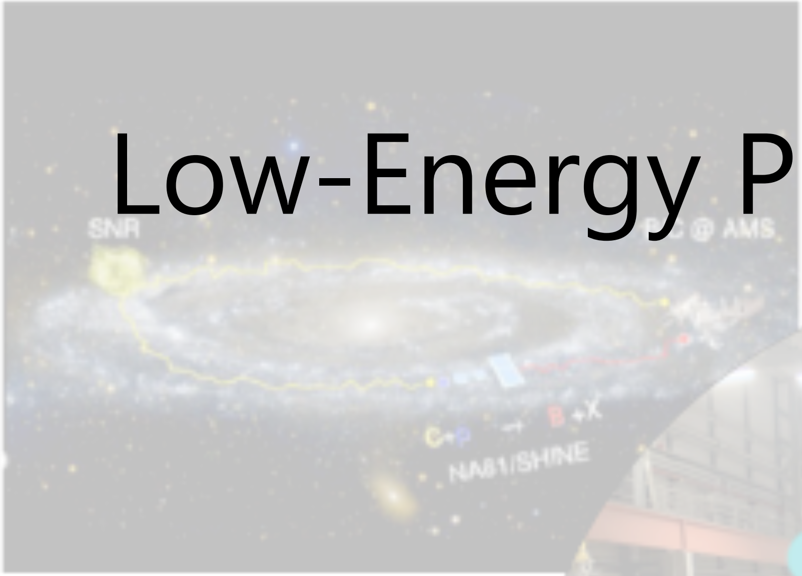


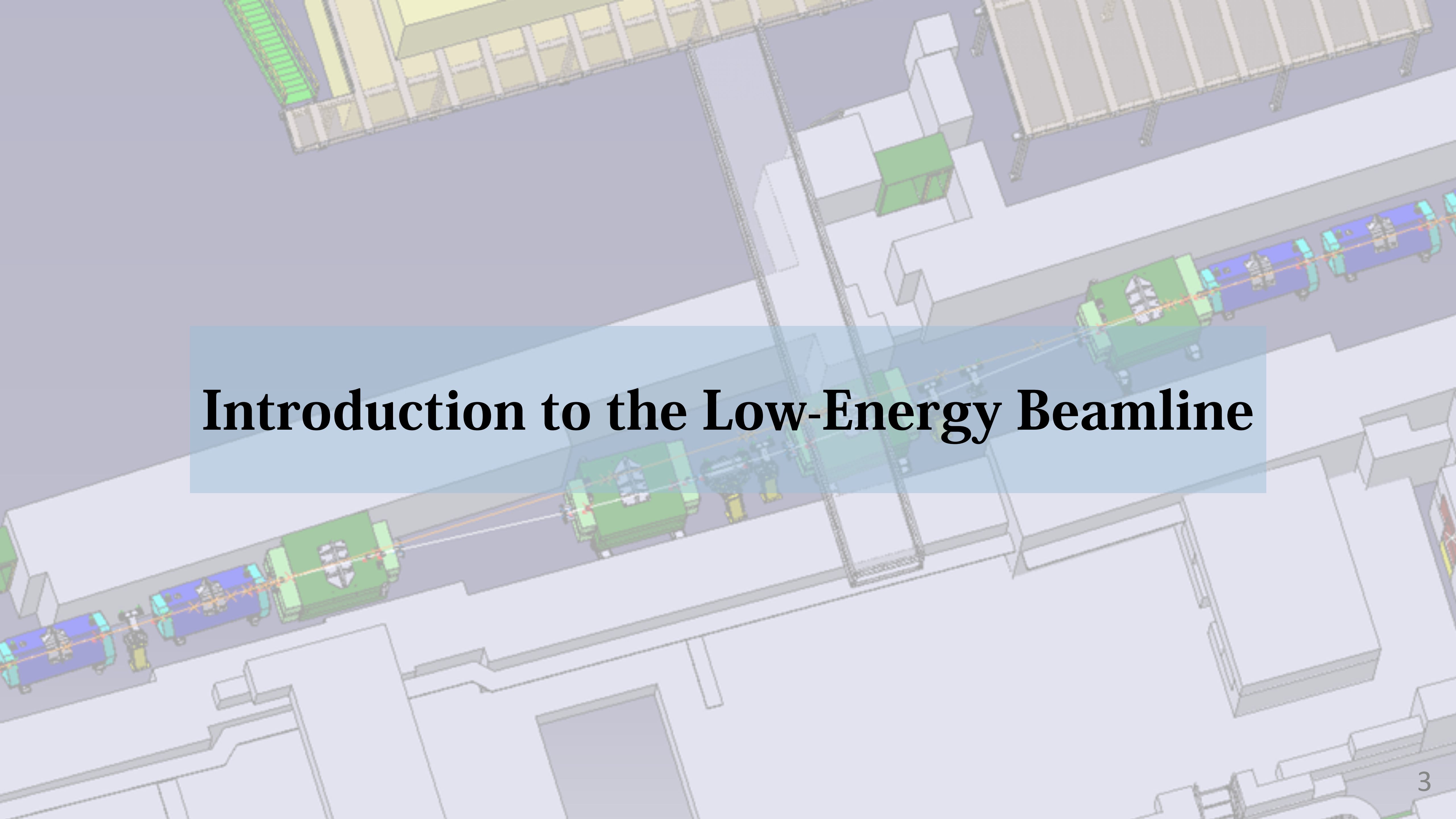
Low-Energy Physics Opportunities

Yoshikazu Nagai

ELTE Eötvös Loránd University

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

Contents



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

Δm^2: few % 'energy scale' of the flux → 0.5% for future (S. Bolognesi)

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

θ_{23} octant: ~1% on ν_e normalization of the flux

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

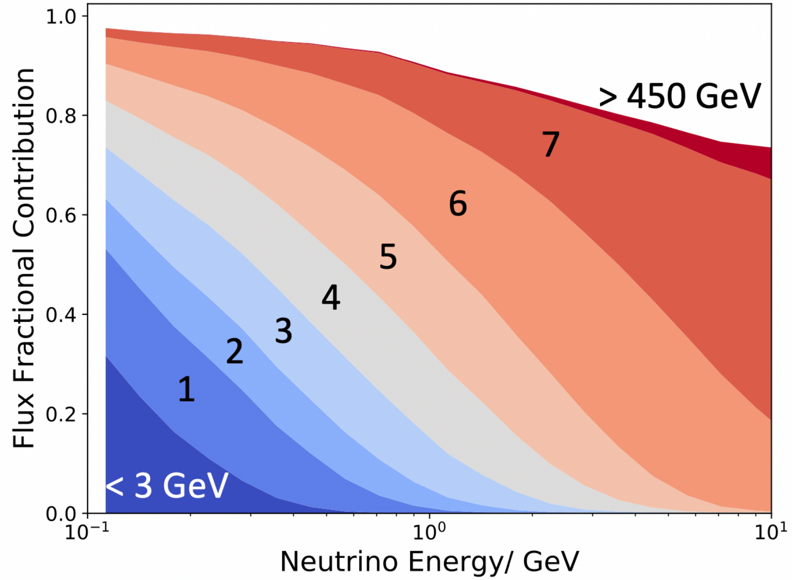
δ_{CP} precision: similar needs as Δm^2

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

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



(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

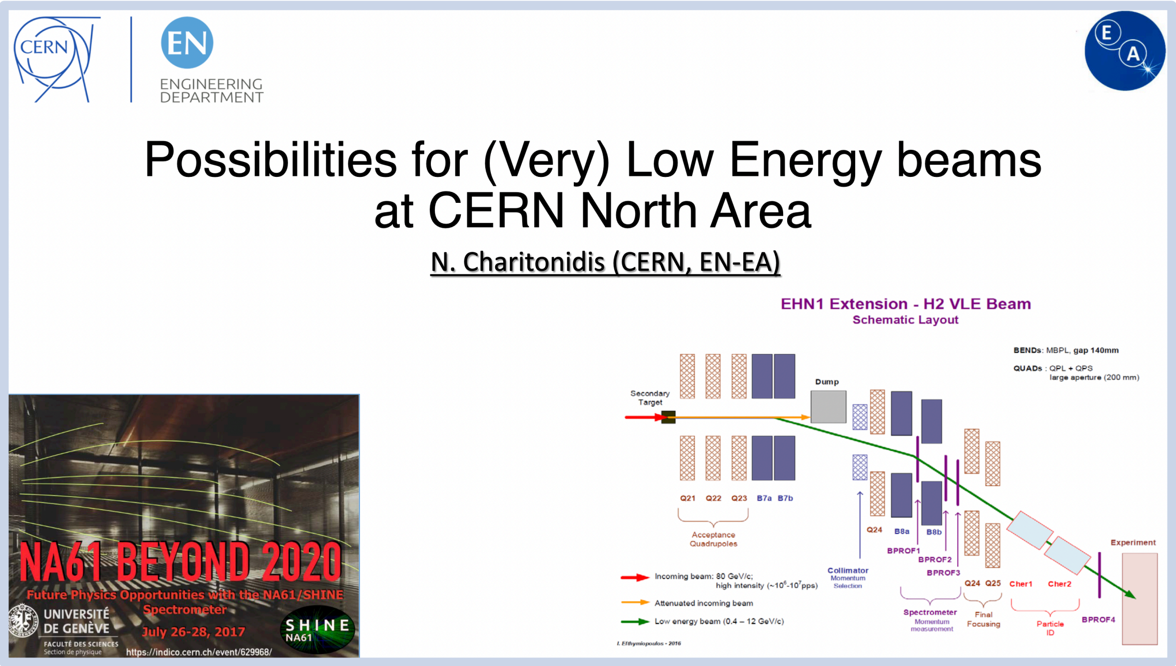
The design of the beamline has been finalized. (See Carlo's talk for detail)

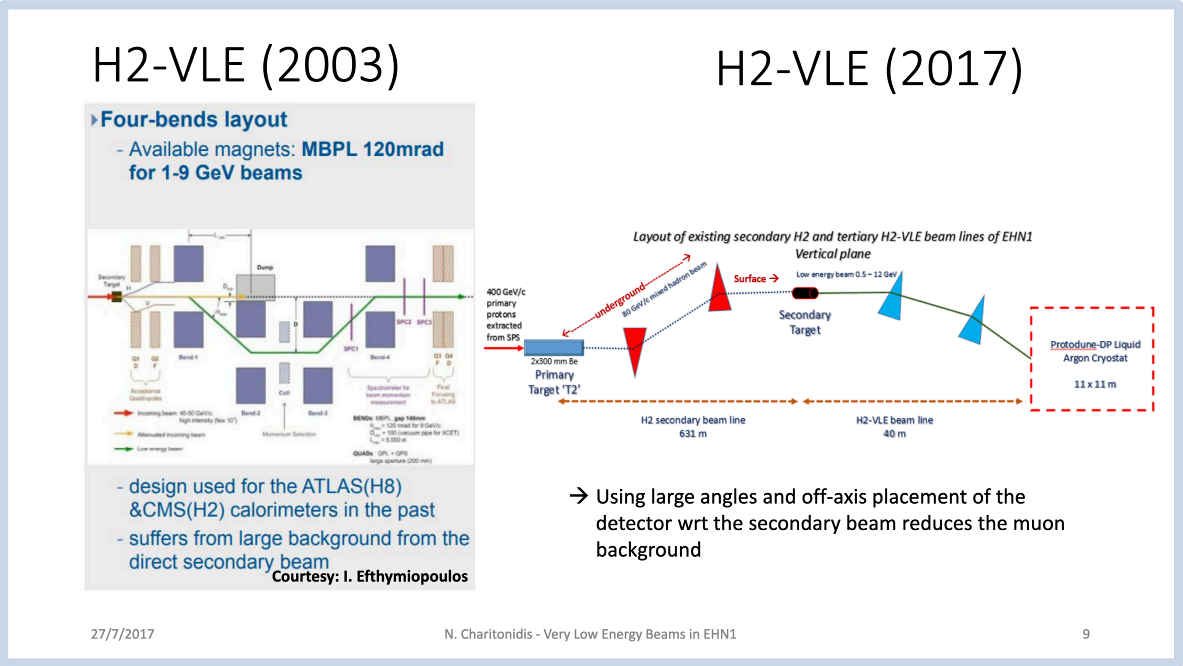
Instrumentation

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)





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

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  - Identification of physics motivations, beamline requirement
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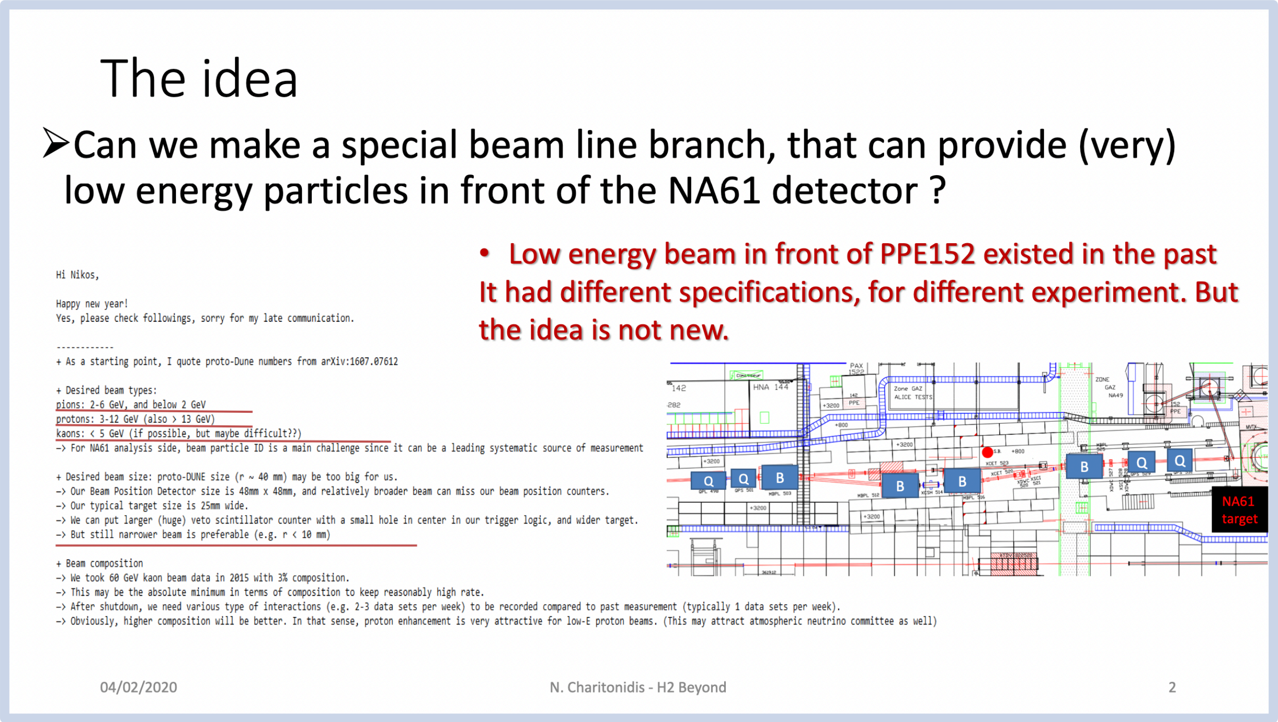
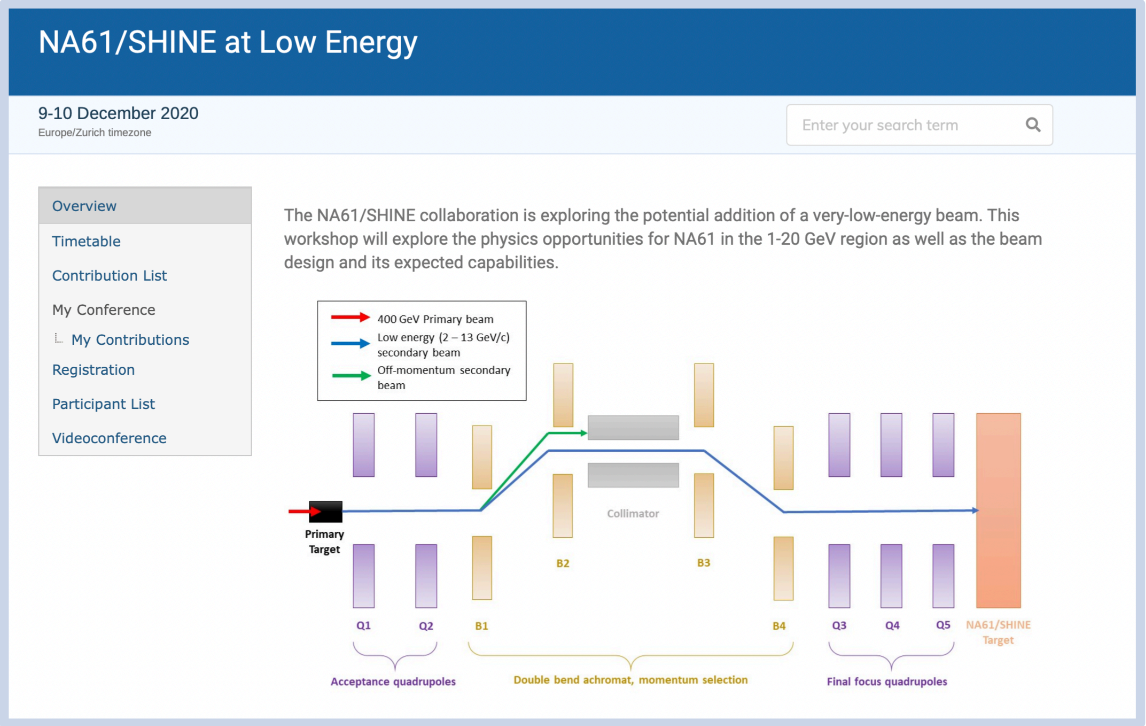
  - Discussion on the physics case and technical feasibility





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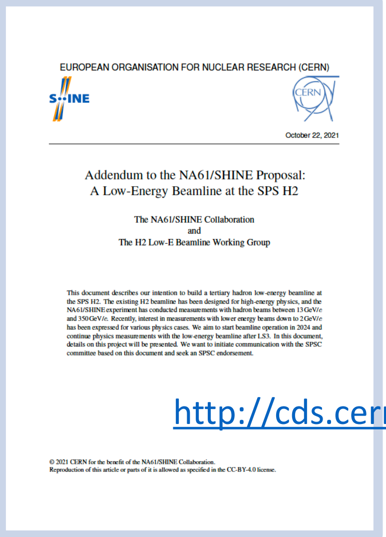
- 2021 October: Addendum for SPSC evaluation (SPSC-P-330-ADD-12)
  - First document to express our interest on building Low-E beamline
- 2022 May: Memorandum to SPSC (SPSC-M-793)
  - Additional documents to address SPSC referee's questions



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

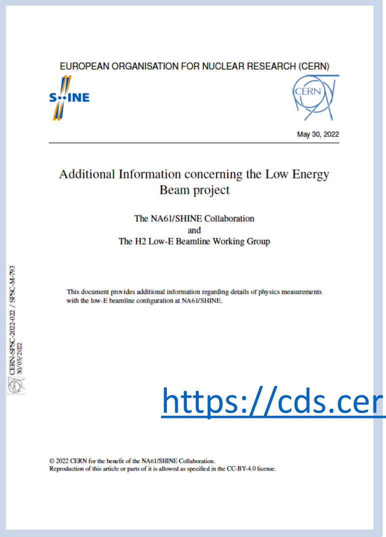
October 22, 2021

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



EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

May 30, 2022

CERN-SPSC-2022-022 / SPSC-M-793
30/05/2022

Additional Information concerning the Low Energy Beam project

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

This document provides additional information regarding details of physics measurements with the low-E beamline configuration at NA61/SHINE.

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

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.

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

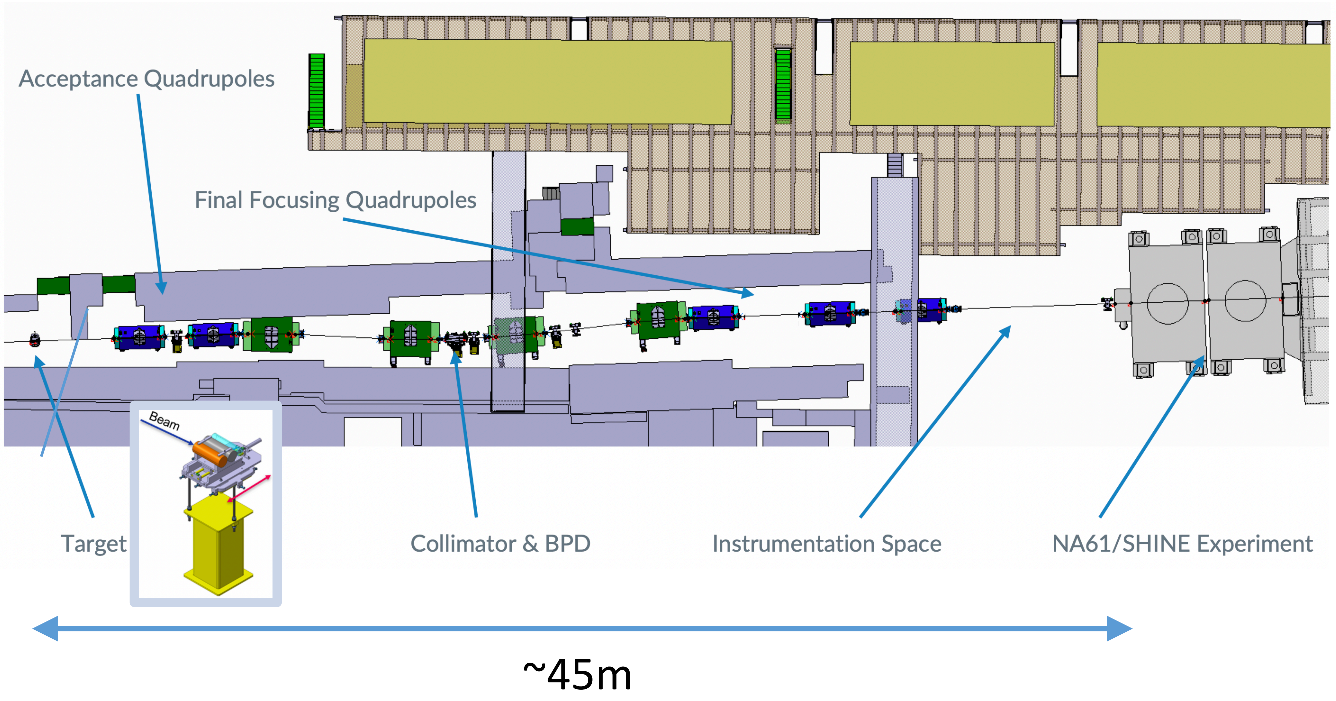
A new tertiary branch of H2 beam line for low energy particle beams (H2-LE)

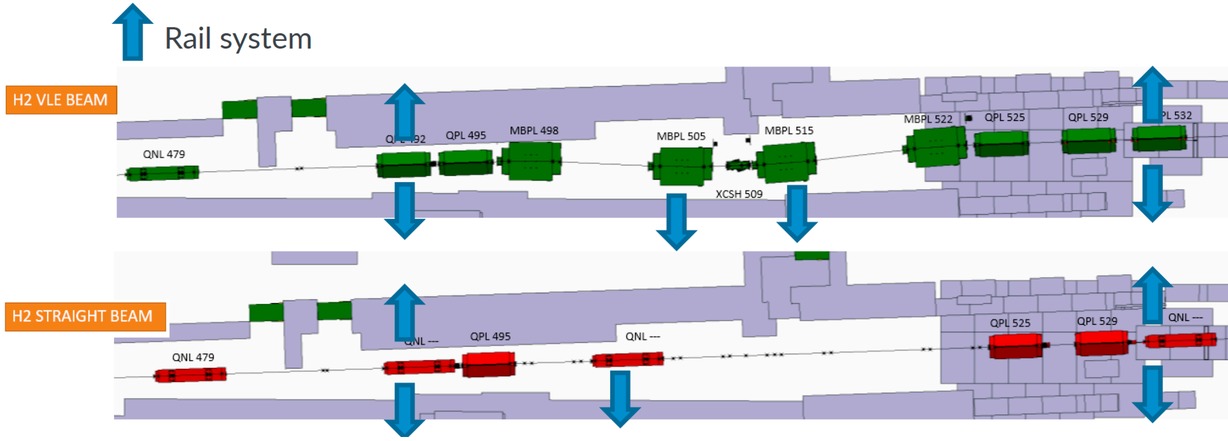
BRIEF DESCRIPTION OF THE PROPOSED CHANGE(S):

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

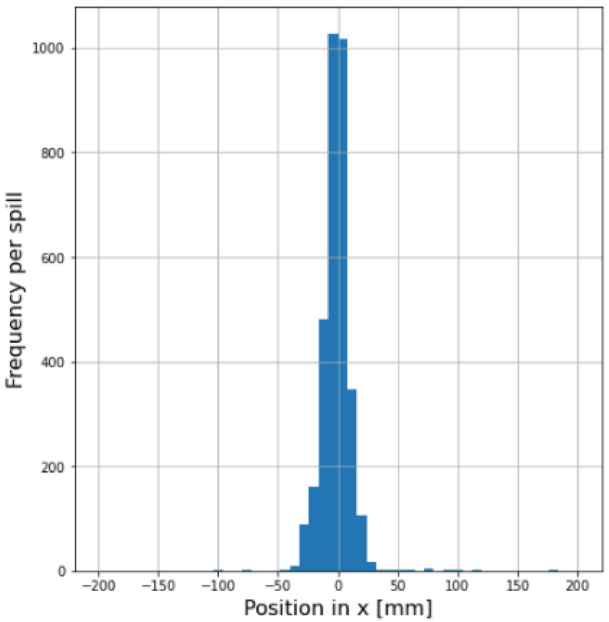


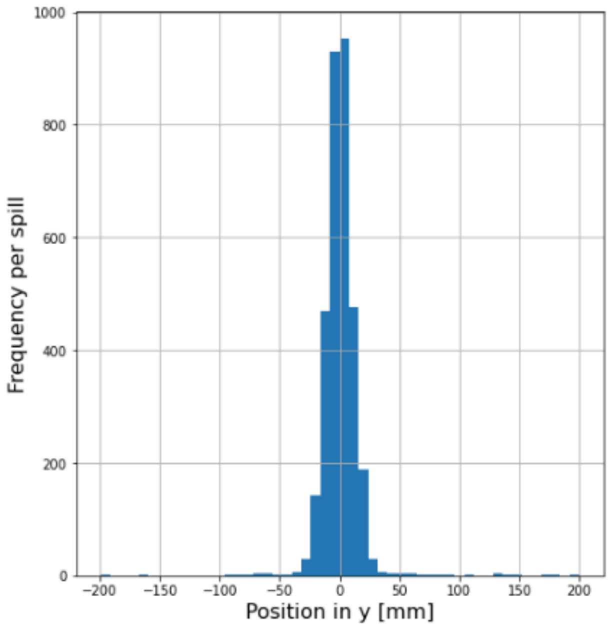


Low-Energy Beamline Overview

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

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



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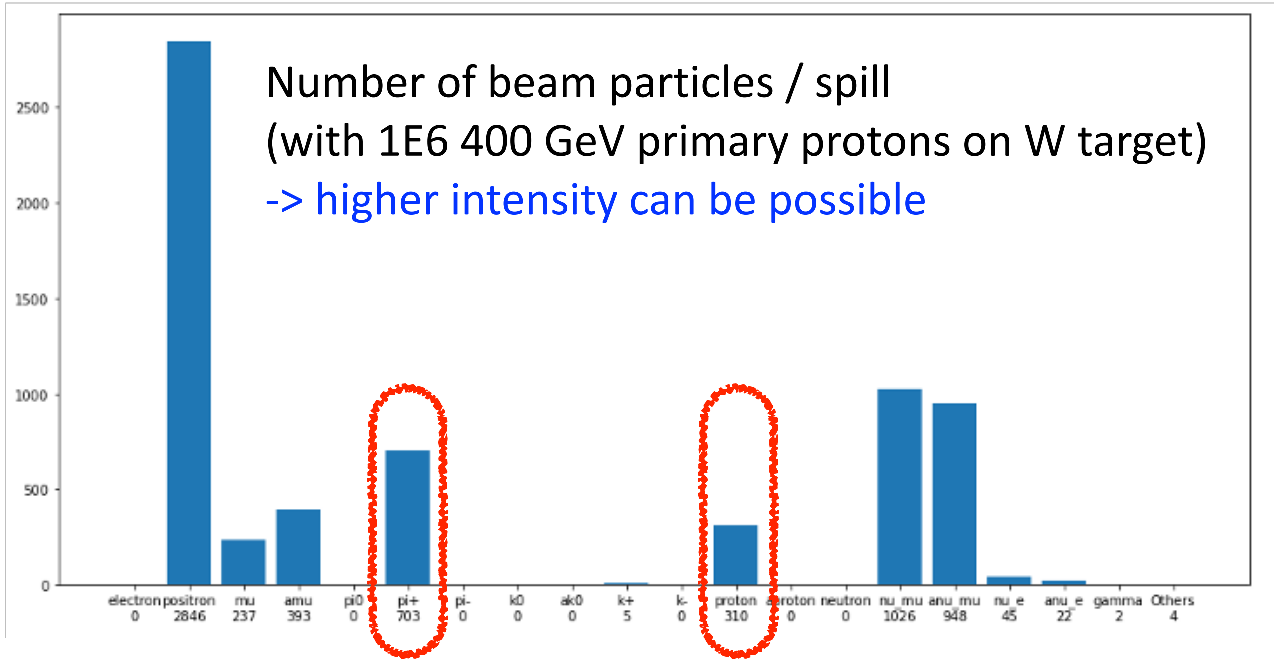
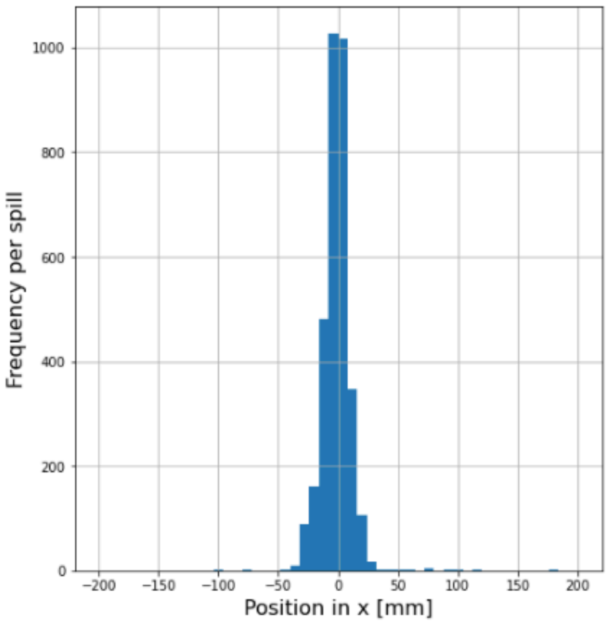


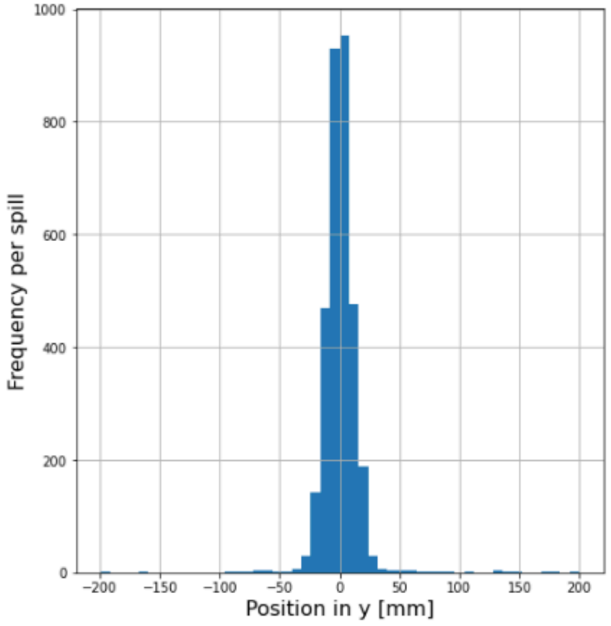
proton / pion ratio > 1/3

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 σx, σy < 20 mm)
  - Enhanced proton fraction (For above 5 GeV, kaons as well)

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





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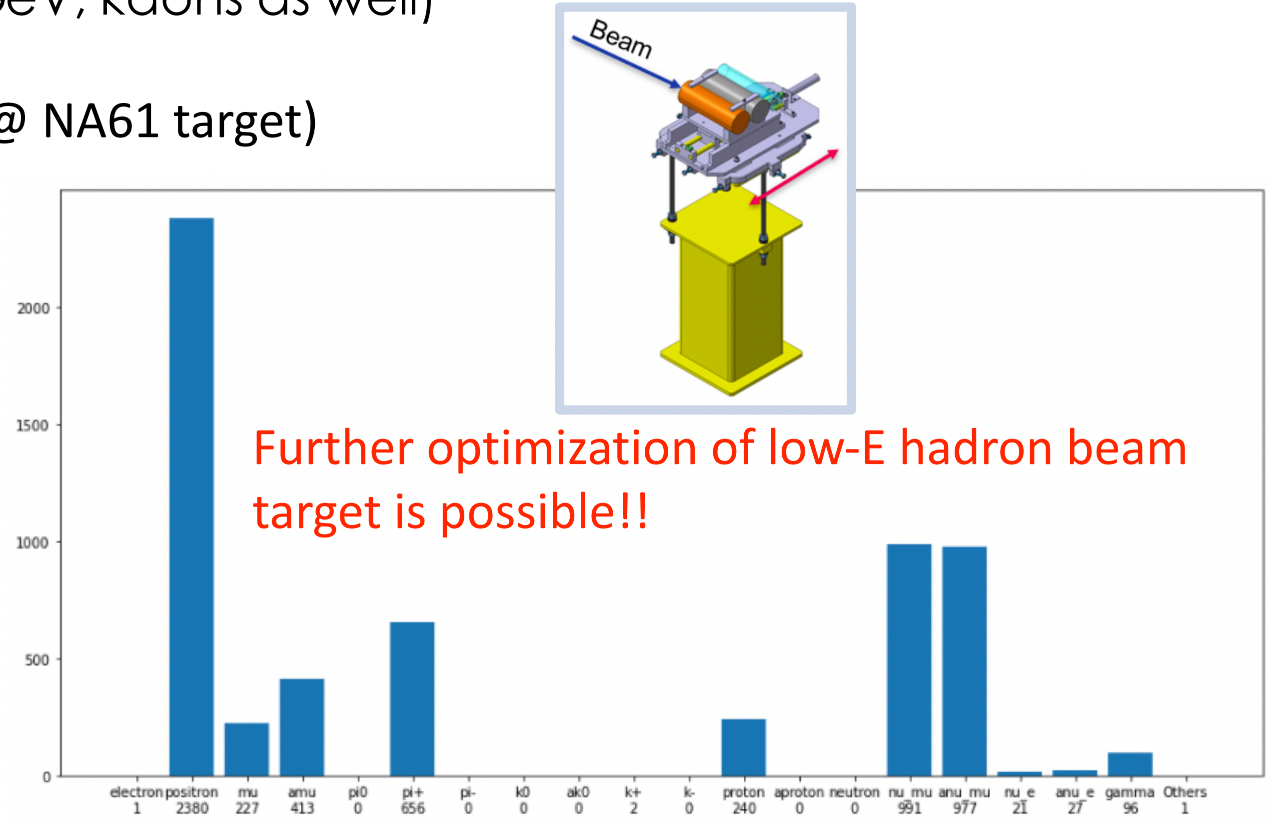
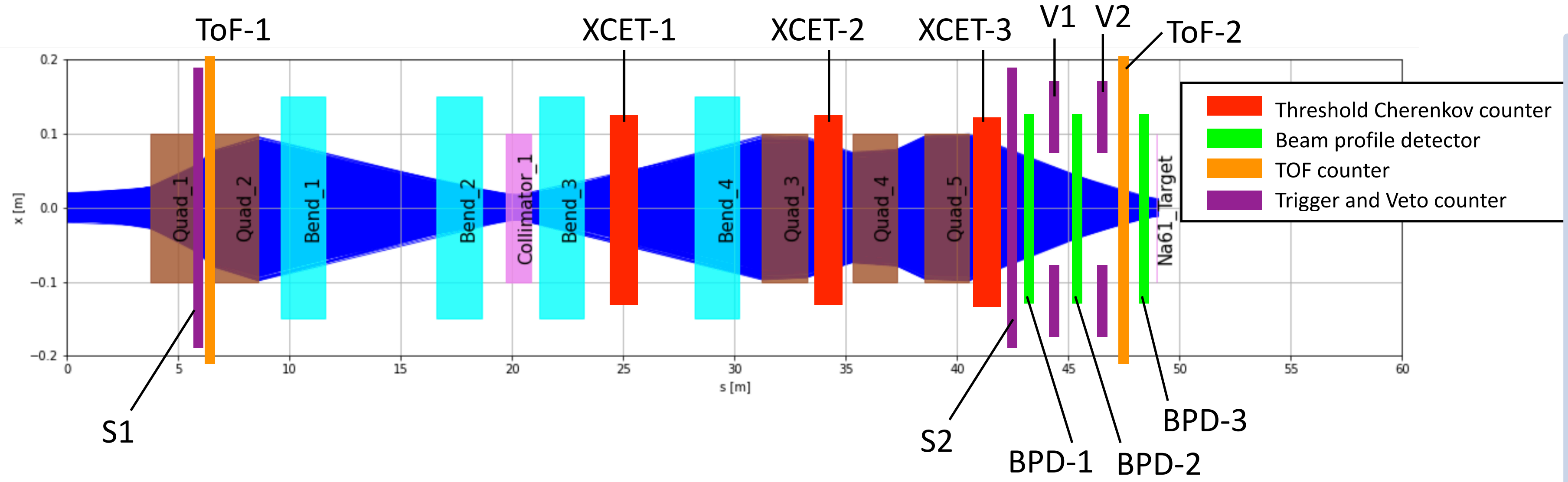


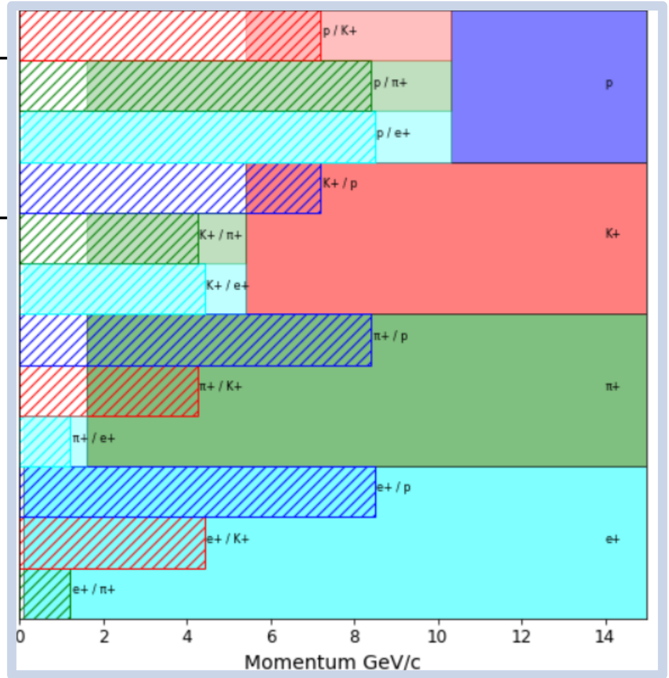
Further optimization of low-E hadron beam target is possible!!

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 σx, σy < 20 mm)
    - Beamline instrumentation for position monitoring and beam PID
      - Beam profile detector (silicon), Time-Of-Flight (scintillator), threshold Cherenkov



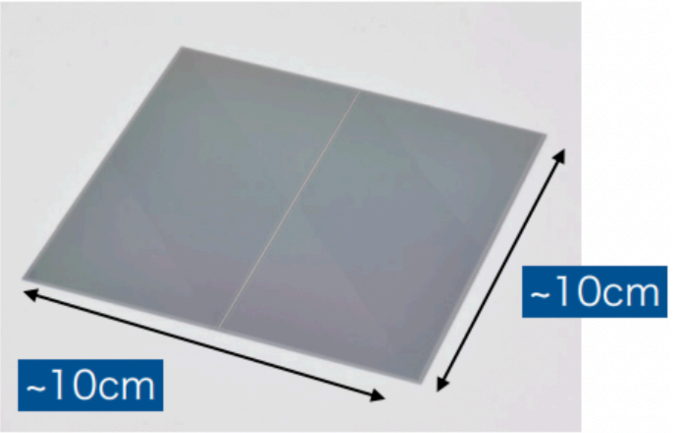
PID with 3 XCETs (filled color area)
+ 200 ps ToF (hash area)



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

Si strip detector(Hamamatsu S13804)



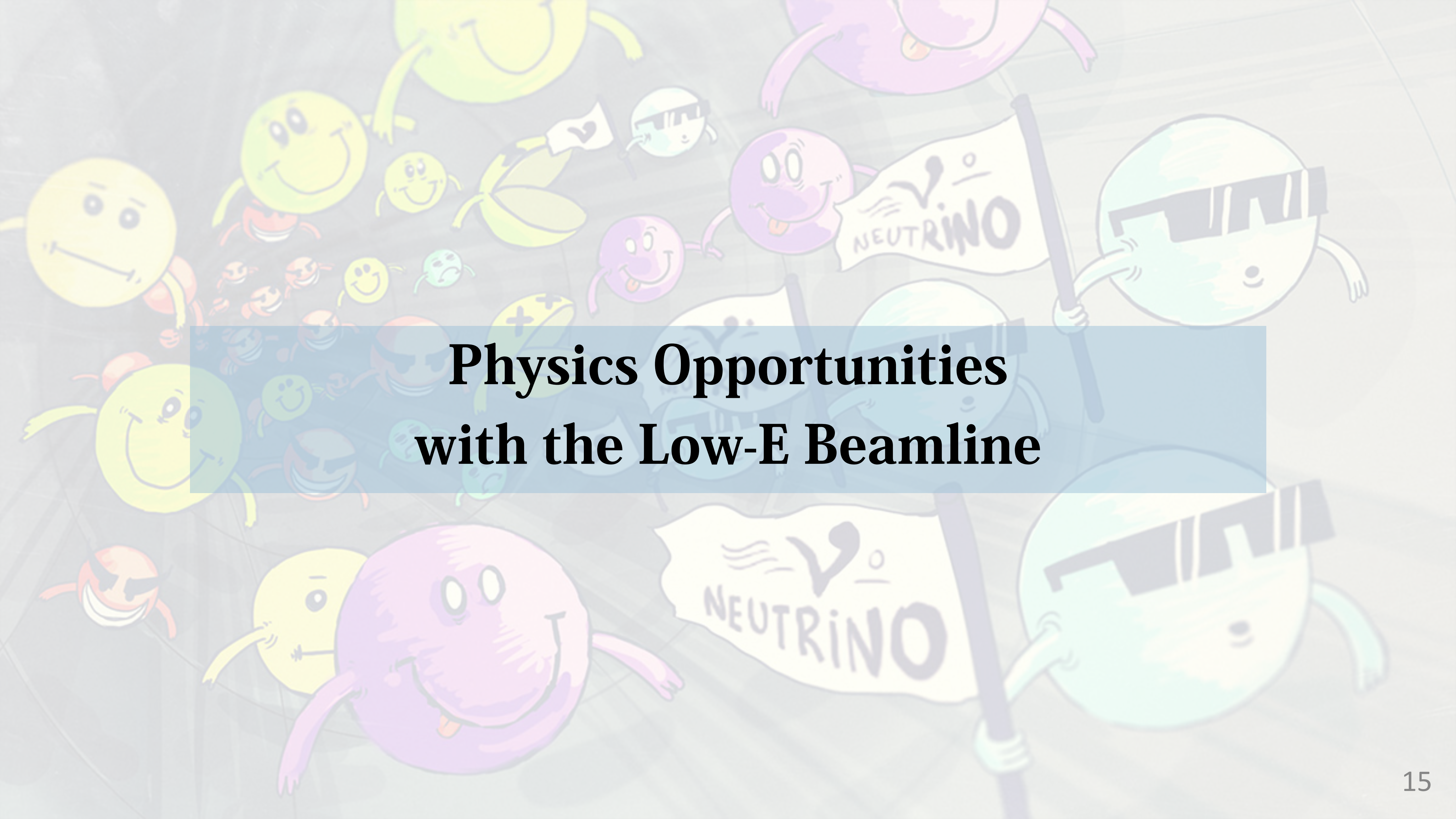
0.19mm pitch x 512ch x 2

- 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

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

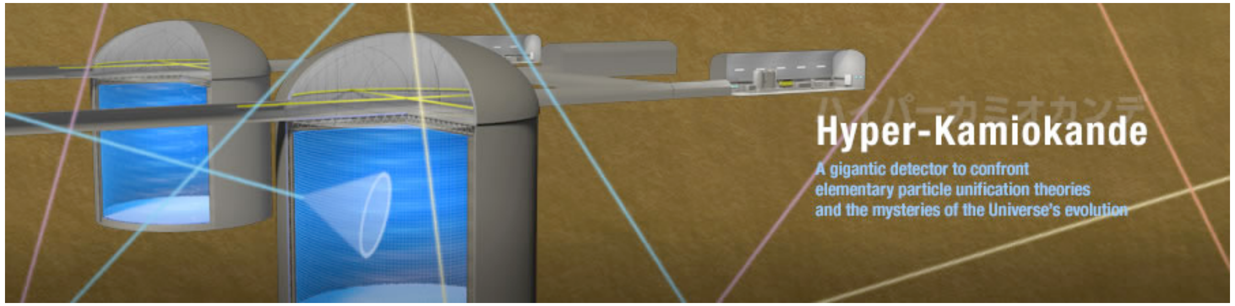


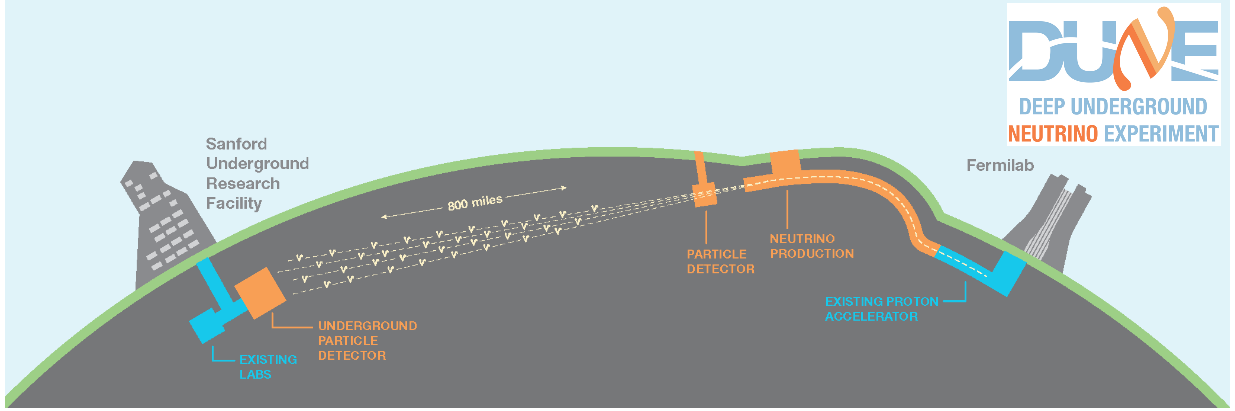
Physics Opportunities with the Low-E Beamline

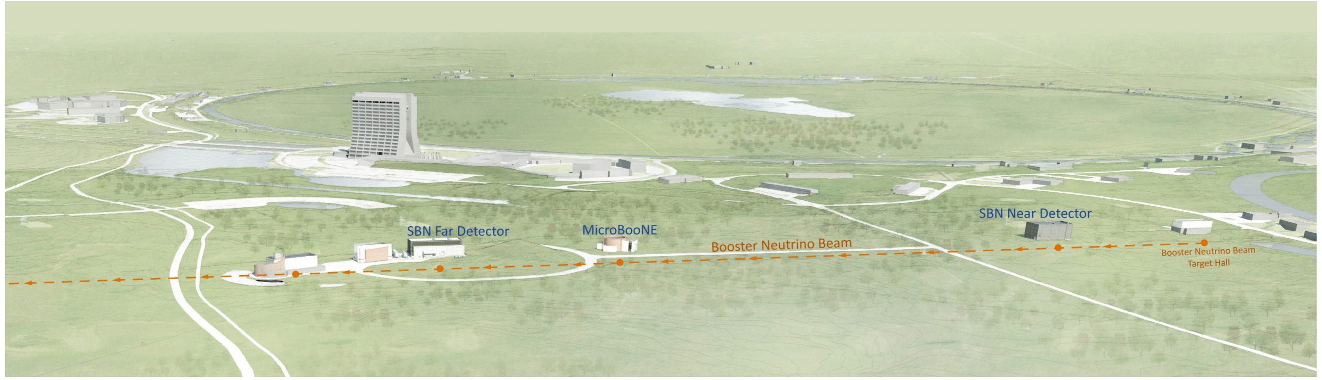
Physics Cases

<u>Accelerator-based neutrino experiments</u> (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

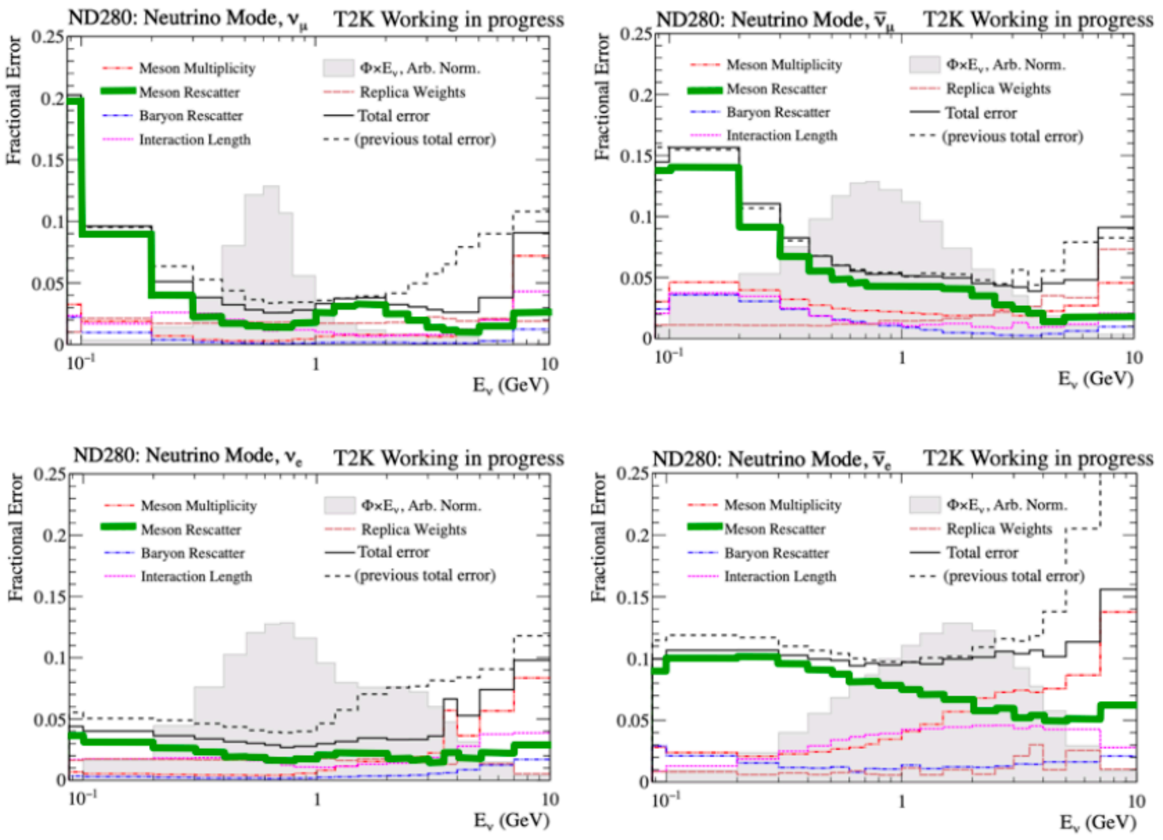






Current Neutrino Flux (example: T2K)

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:

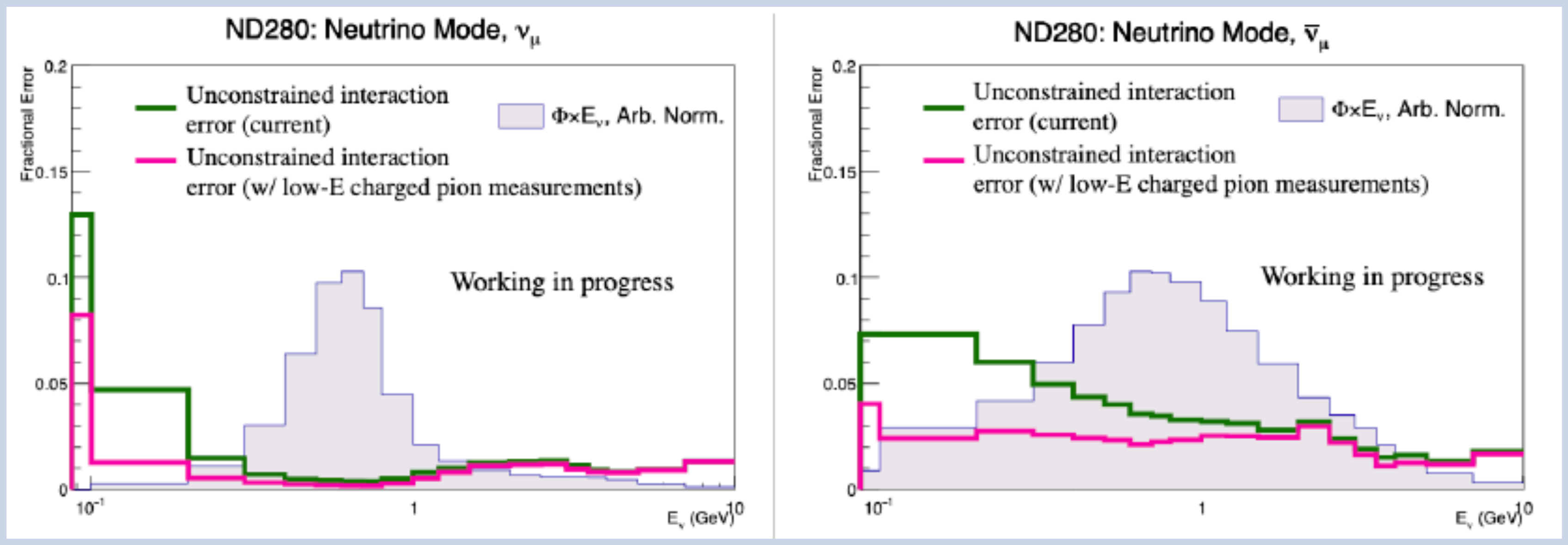
- pion beam: 2-6 GeV
- proton beam: above 4 GeV
- kaon beam: above 5 GeV

SPSC-M-793 https://cds.cern.ch/record/2810696

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)

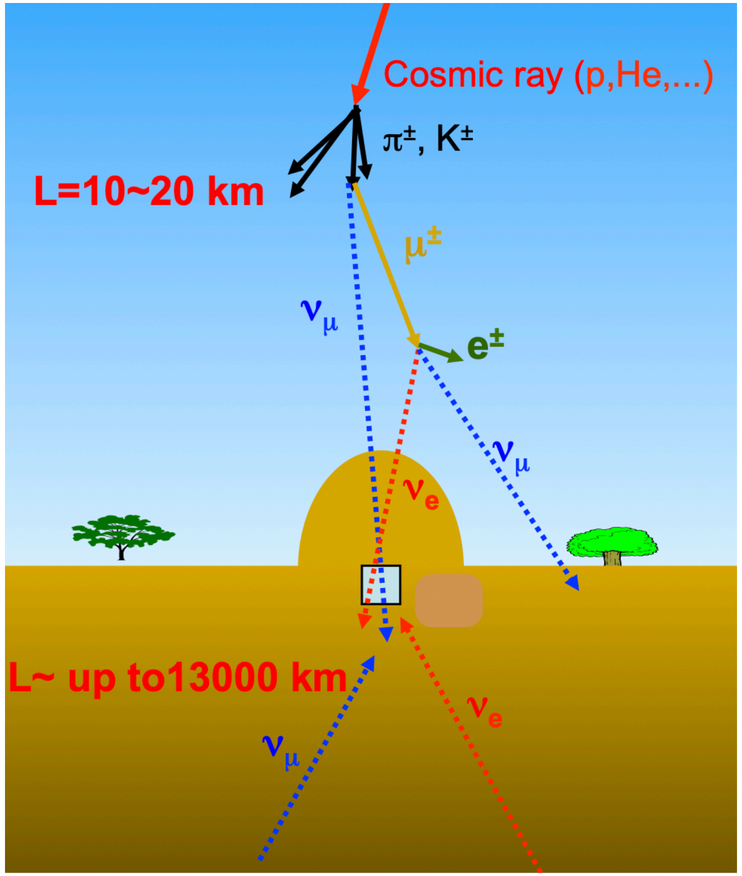
Physics Cases

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

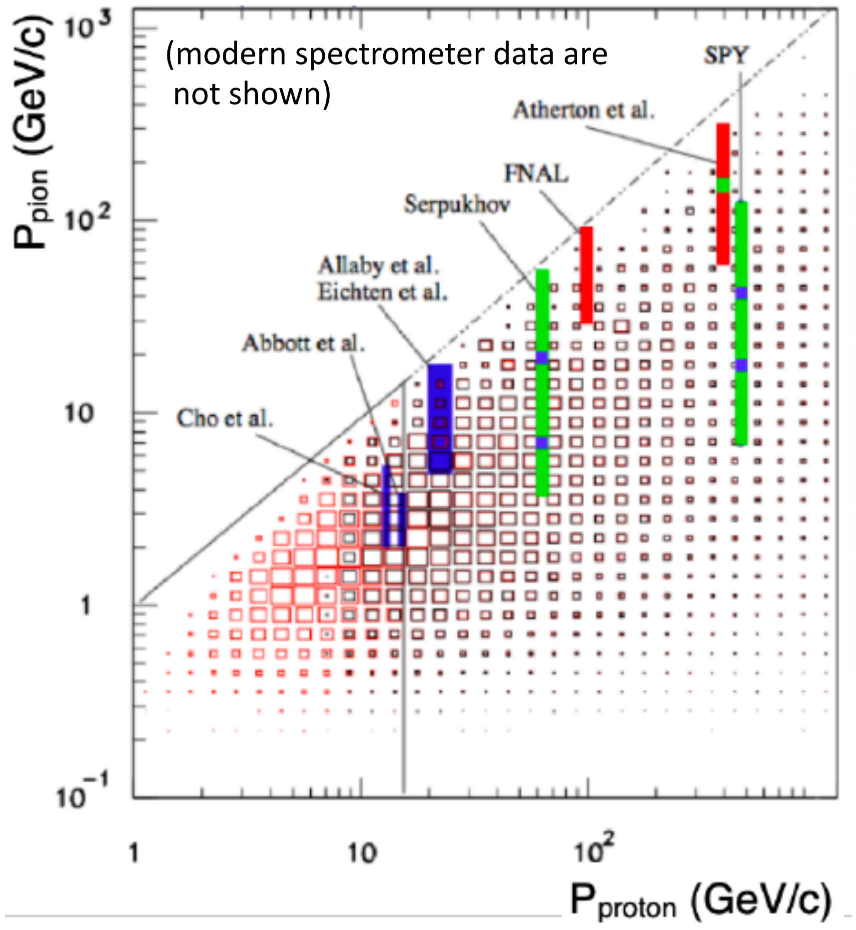
Atmospheric neutrino experiments (to study cosmic ray proton scatterings)

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

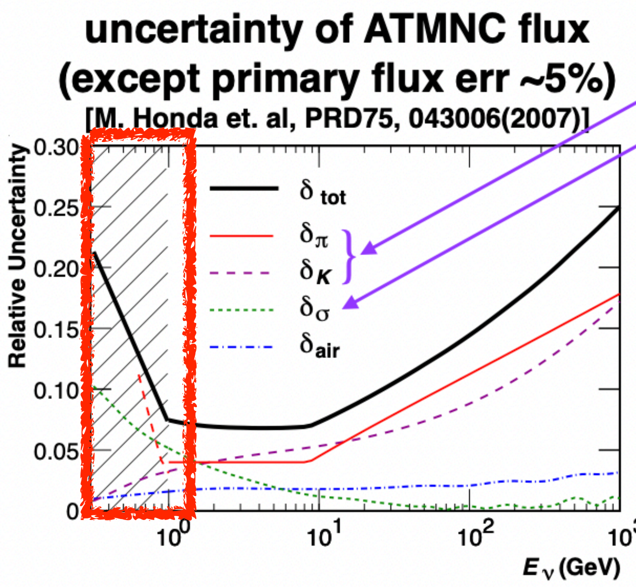


Current Flux Uncertainties (Atmospheric ν)

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



Phys. Rev. D74, 094009 (2006)



- 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

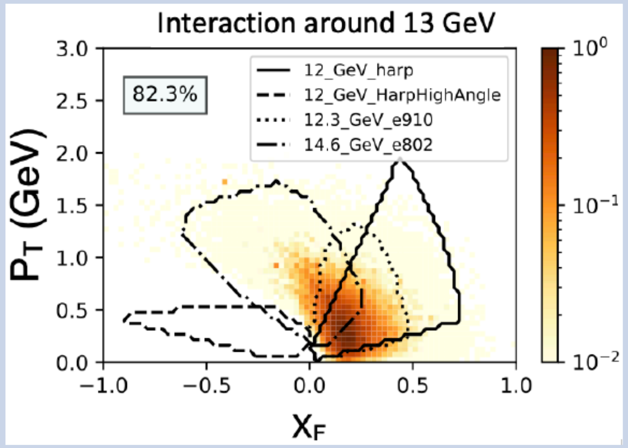
example: Hadron production data for
< 15 GeV atmospheric neutrino fluxes

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.

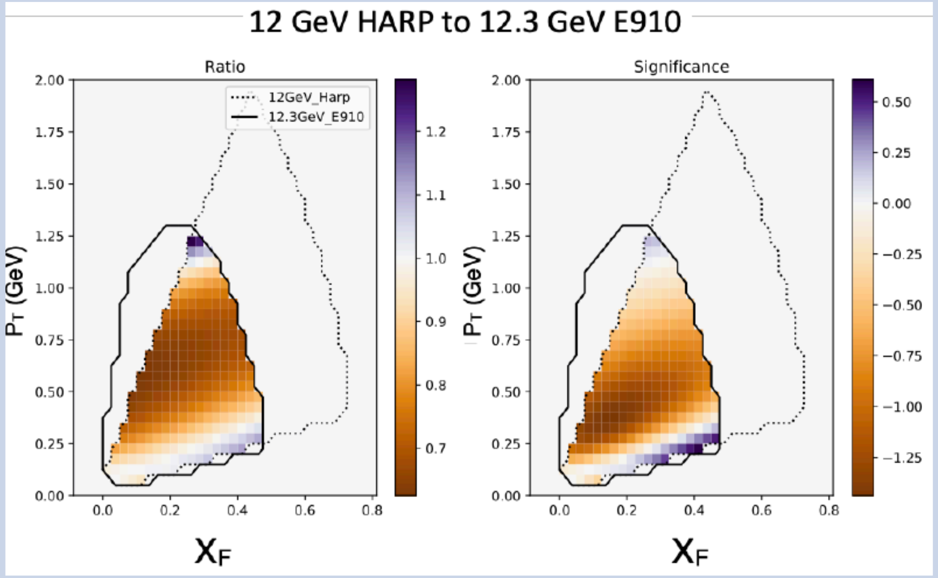
SPSC-M-793

phase-space coverage of 3 experiments



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

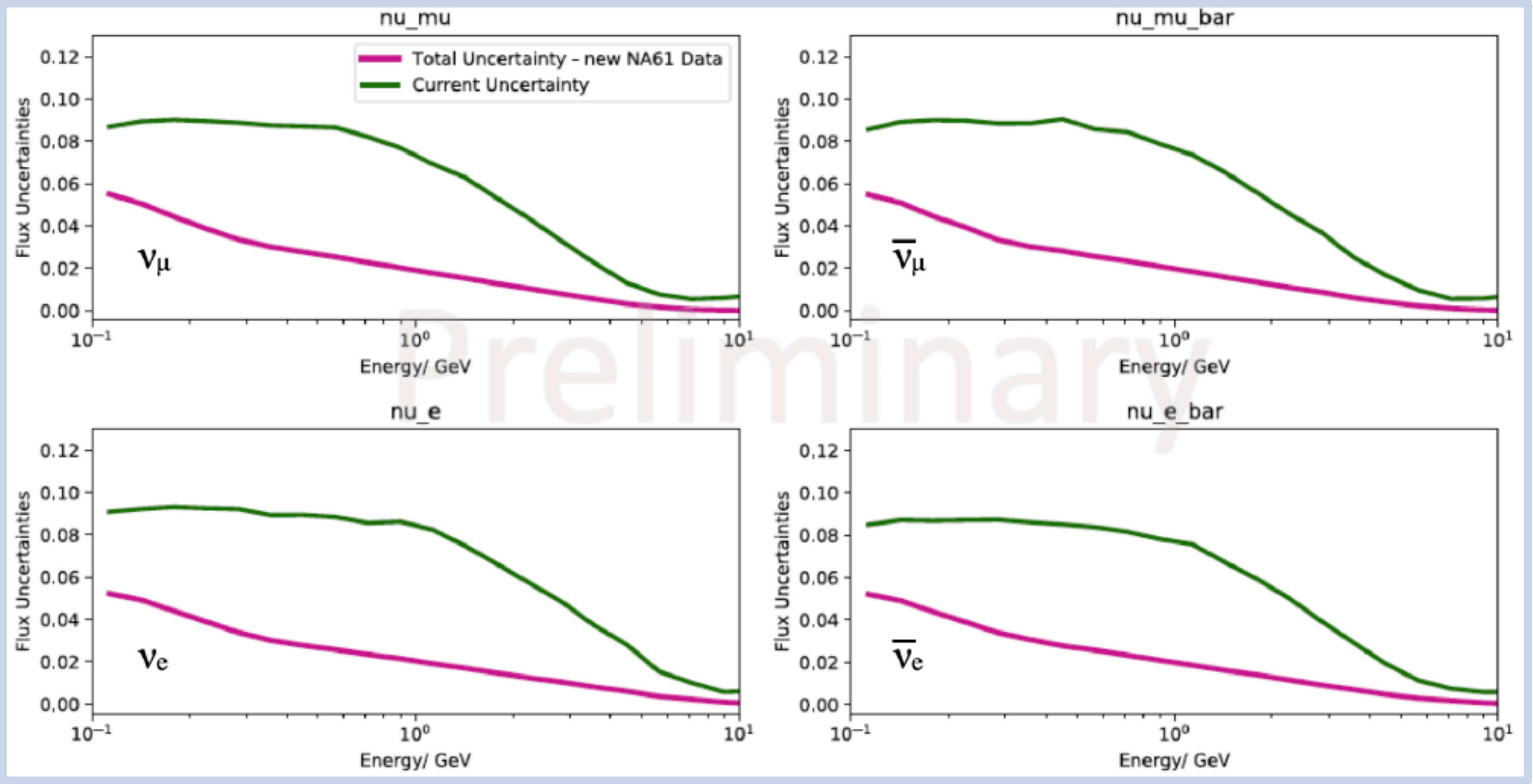
(In)consistency b/w HARP and E910



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

If we have low-E data.. (example: atmospheric ν)

Drastic improvement in the atmospheric neutrino flux is possible
if we have data for lower energy $\mathrm{p} + \mathrm{N} \rightarrow \pi^{\pm} + X$ 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)
- Long-baseline: T2K / Hyper-K at J-PARC, LBNF/DUNE at FNAL
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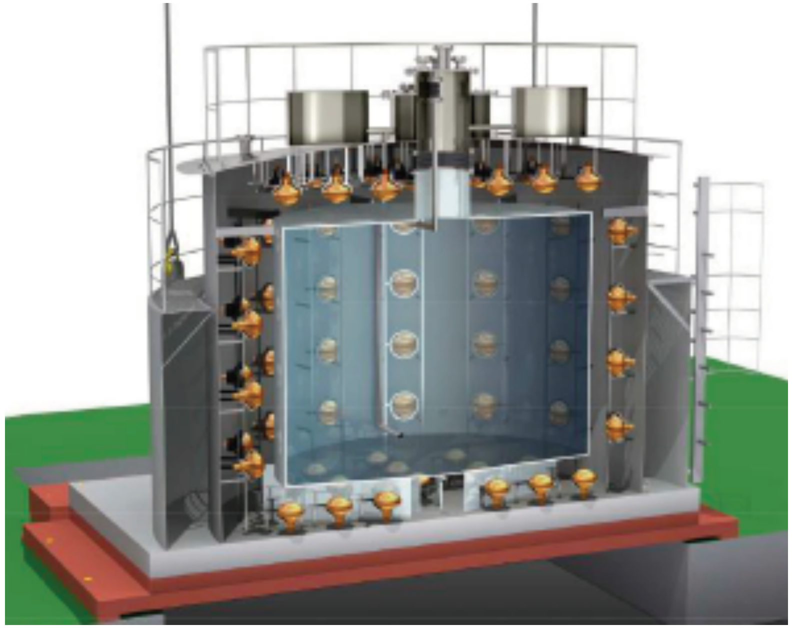
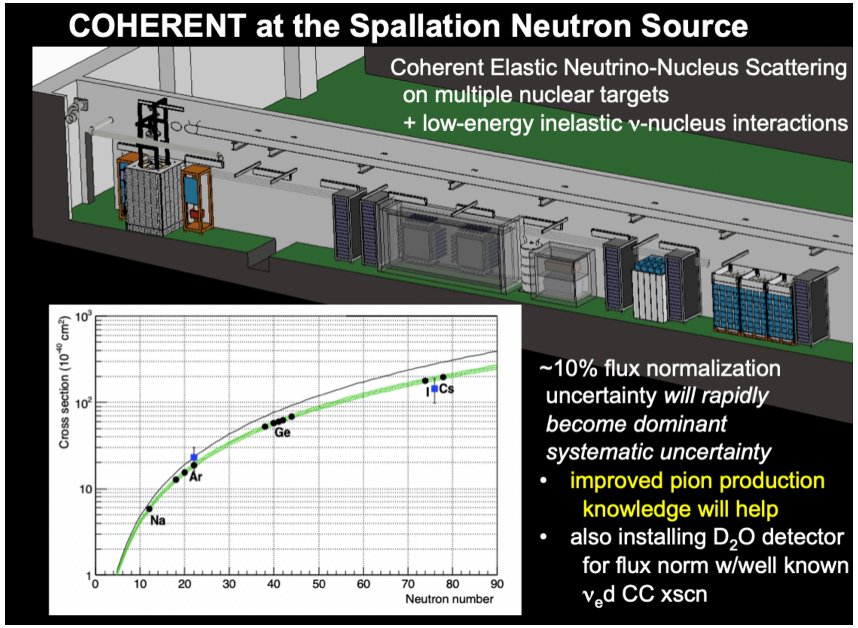
Atmospheric neutrino experiments (to study cosmic ray proton scatterings)
- Sub-GeV and Multi-GeV neutrinos: Super-K, Hyper-K, DUNE

Spallation neutron source neutrino experiments
- JSNS^2 at J-PARC MLF (sterile neutrino search): hadron production on p+Hg at 3 GeV (3.82 GeV/c)
- COHERENT at ORNL (coherent drastic neutrino scattering): hadron production on p+Hg around 2 GeV/c

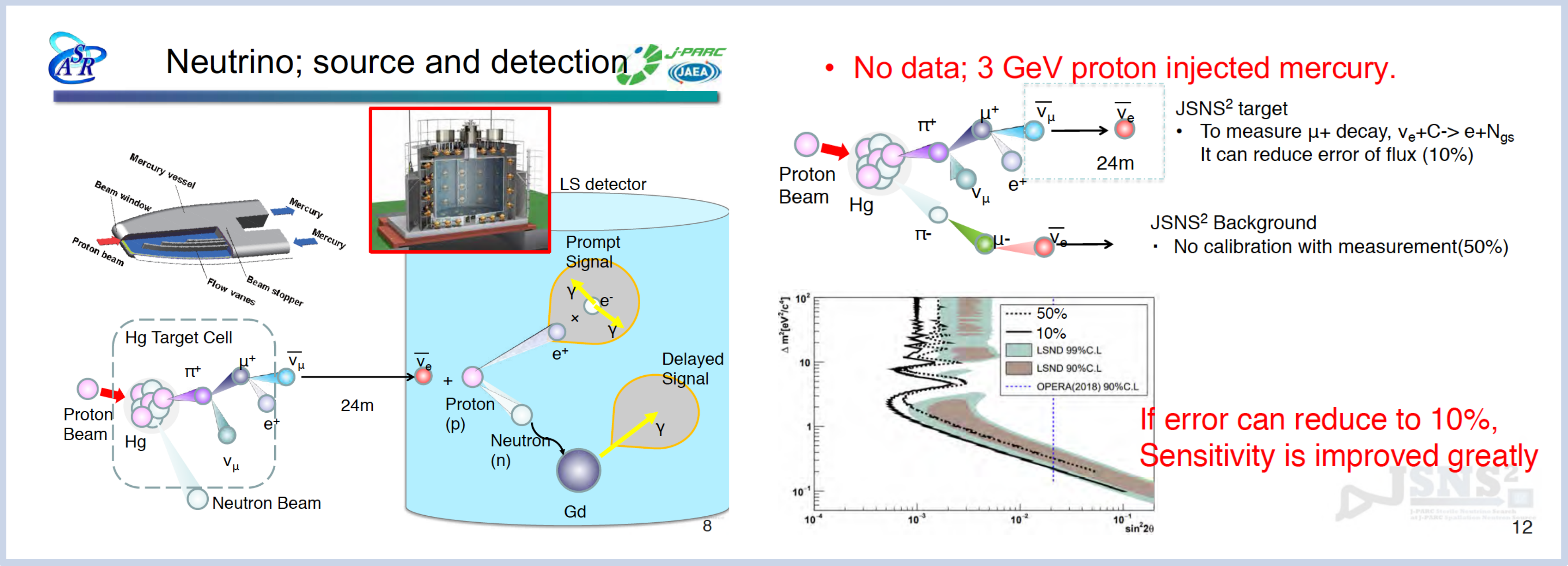




Sensitivity (example: JSNS^2)

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)

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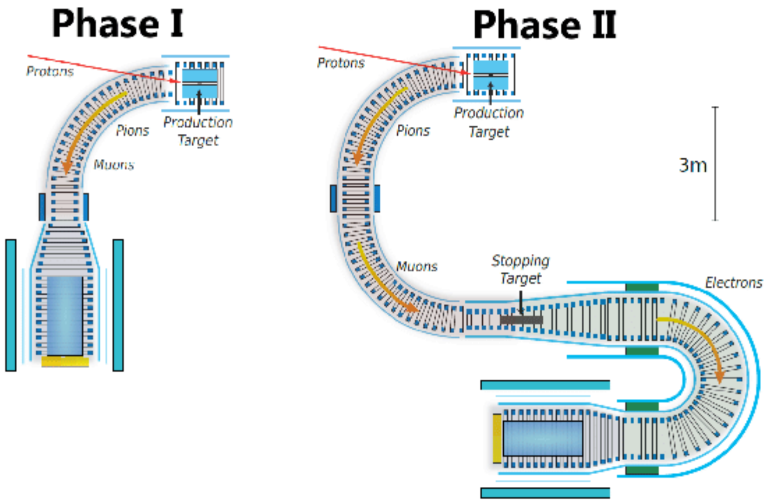
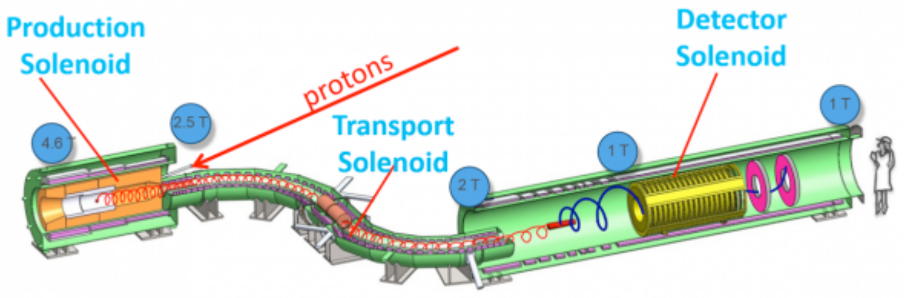
Muon experiments

- 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

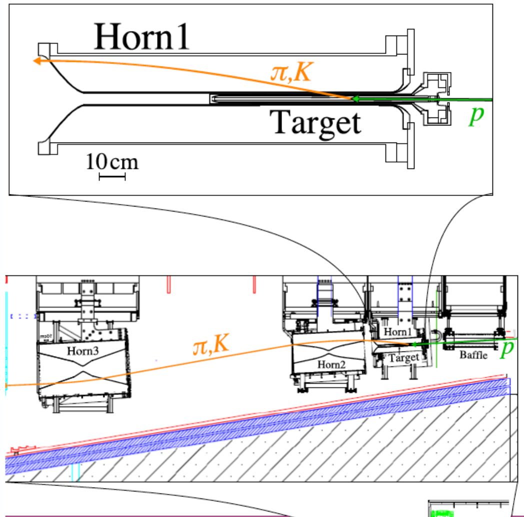
Beam species and energy

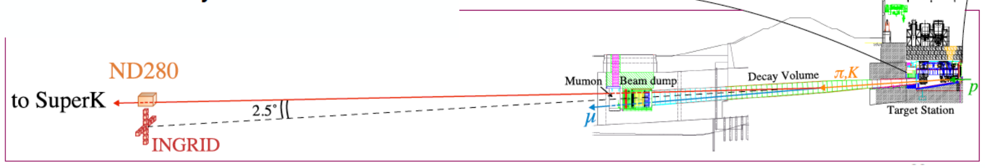
- pion beam: < 2 GeV, 2-6 GeV
- proton beam: 4-12 GeV, > 12 GeV
- kaon beam: < 5 GeV, above 5 GeV

L.Berns(TIT)

T2K neutrino beamline

- 30 GeV protons hit 90 cm graphite target.
- Produced π, K are focused using three magnetic horns.
- In-flight decay in ~100m decay volume.
- Muon monitors and on-axis ν detector (INGRID) monitor beam stability and direction.

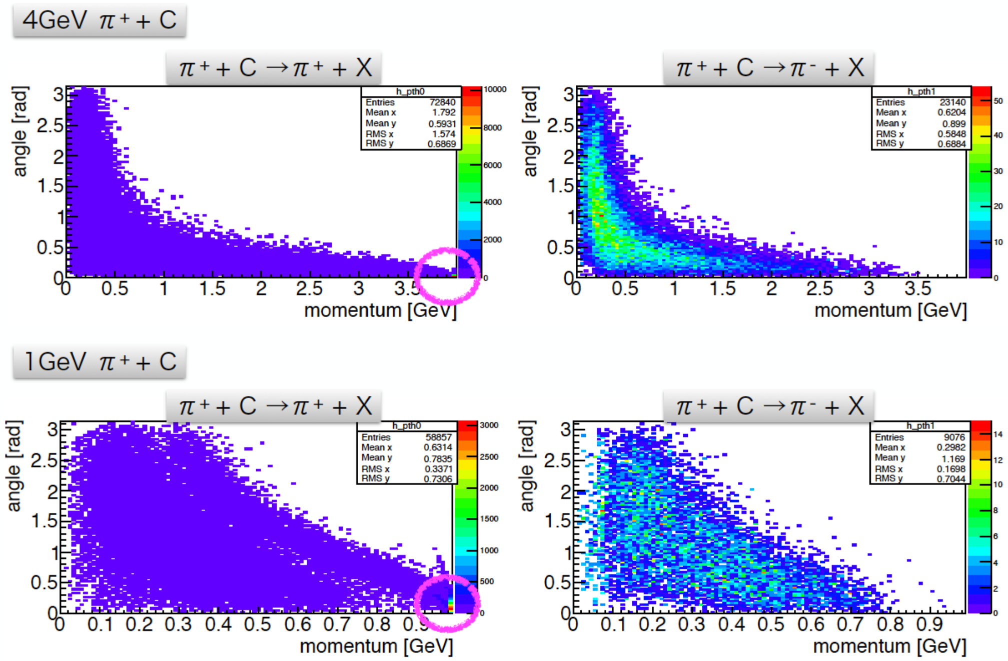




Fraction of tuned hadronic interaction

Dataset	Tuned Hadronic Interactions in Neutrino Ancestry							
	SK ν-mode				SK $\bar{\nu}$-mode			
	ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$	ν_μ	$\bar{\nu}_\mu$	ν_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 ~10% of hadronic interaction are untuned

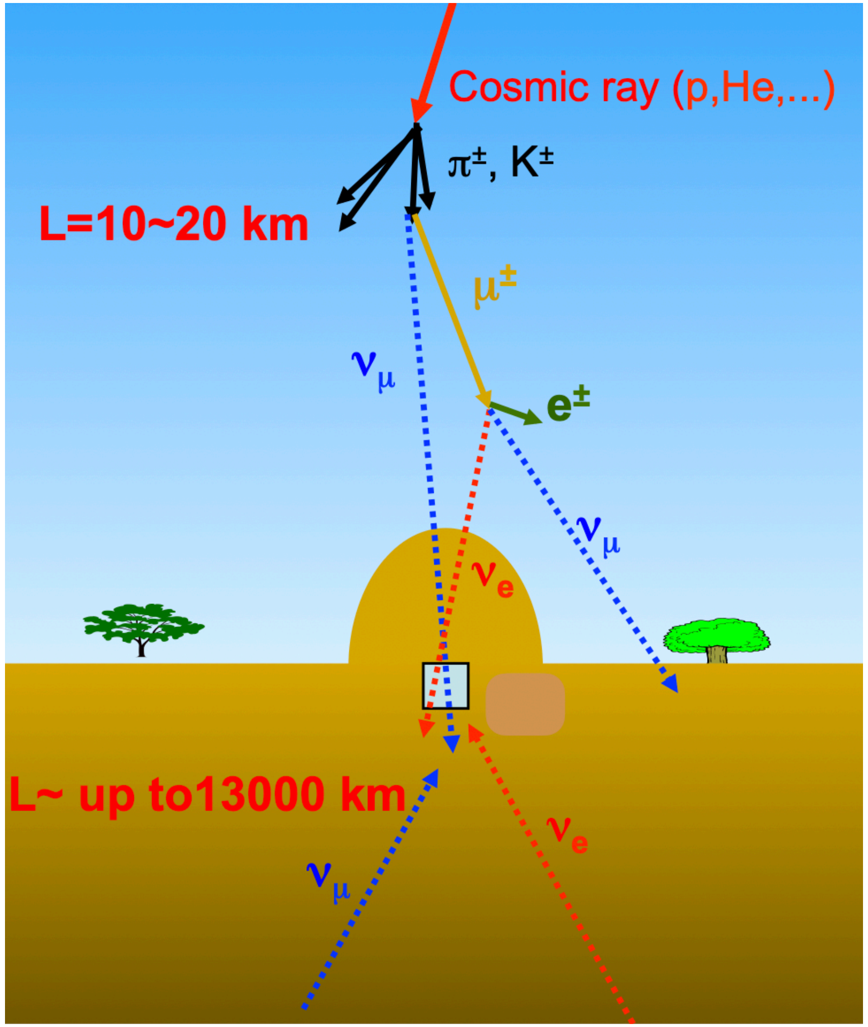


Most of scattering particles go to the forward direction while charge exchanged particles have a large angle

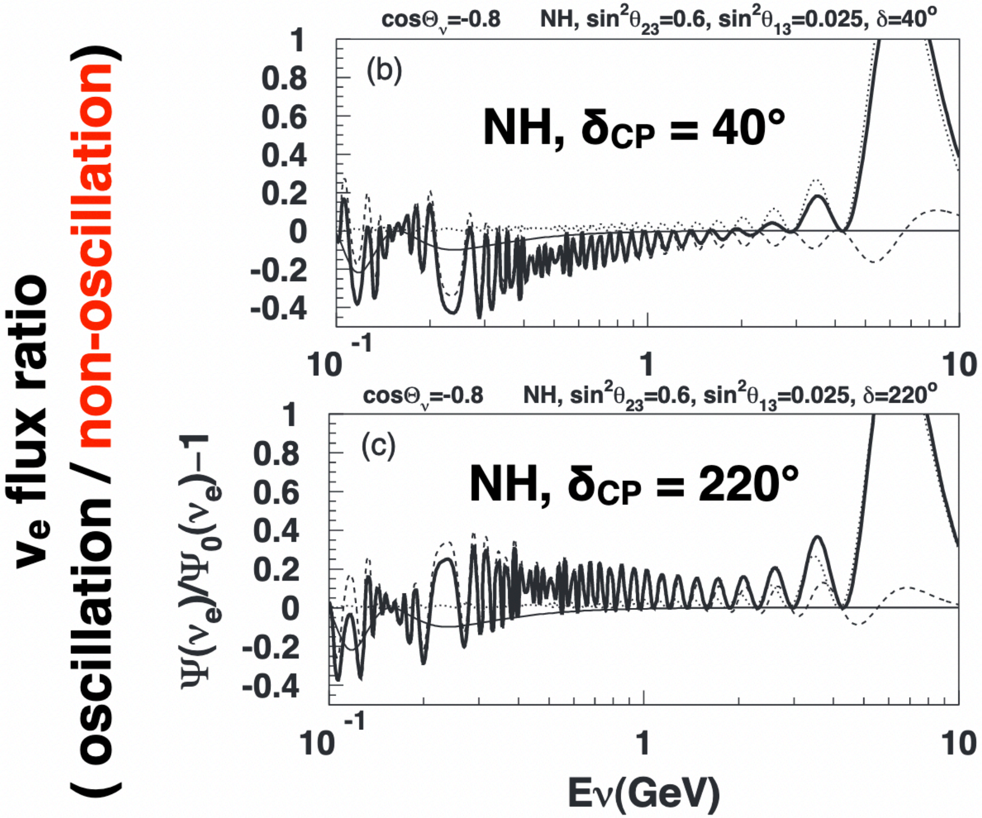
More study necessary: NA61 acceptance, π^+/K^+ + C/Al/Fe

K. Sakashita, 6th May, 2020

Atmospheric Neutrino Production

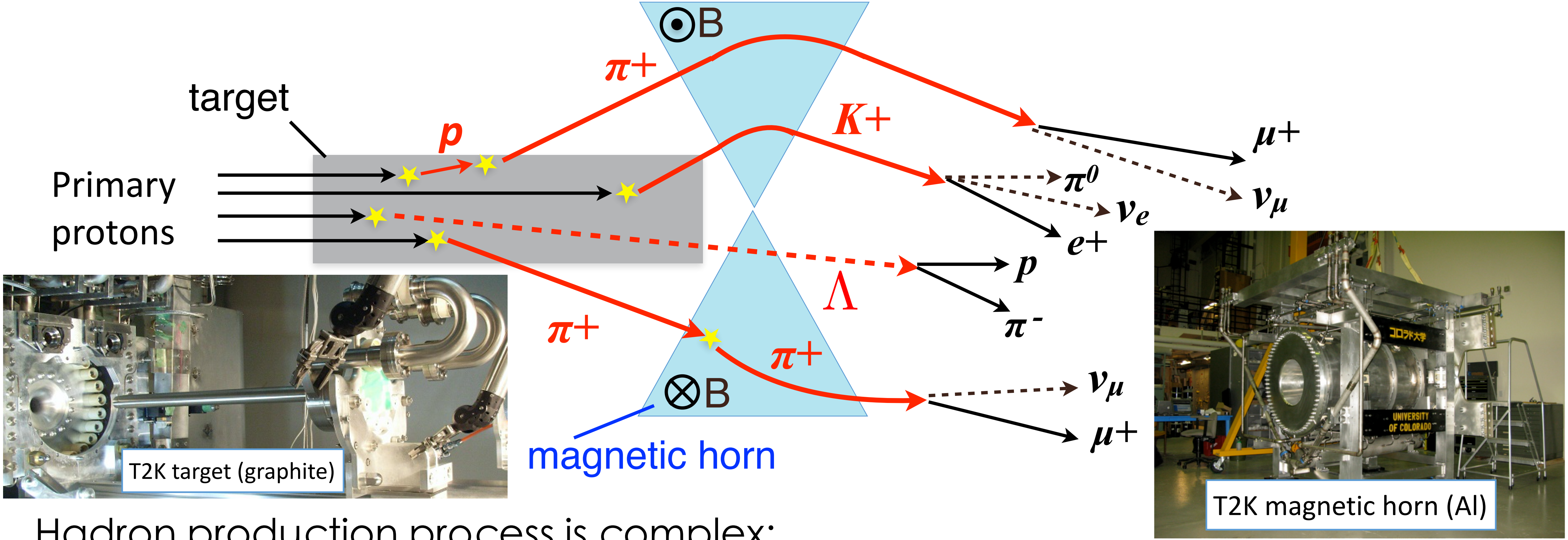


- Primary interactions in atmosphere (p + N -> π)
- Neutrino flux ranges below 100 MeV to above 10 TeV
  - 0.1-1.0 GeV (sub-GeV): sensitive to CP phase
  - 1.0-10 GeV (multi-GeV): sensitive to mass hierarchy



HK design report

Accelerator Neutrino Production



T2K target (graphite)

T2K magnetic horn (Al)

Hadron production process is complex:

- Primary interactions in the target (p + C -> $\pi^{\pm}$ and $K^{\pm}$) -> Primary contribution to the neutrino flux
- Secondary interactions with beamline materials (hadrons + C/Be/Al/Ti/Fe/H_2O/etc..)
- Neutral hadron decay (p + C —> V^0 + X)

Non-negligible contribution to the neutrino flux