NA61/SHINE Experiment

- Status & Plans -

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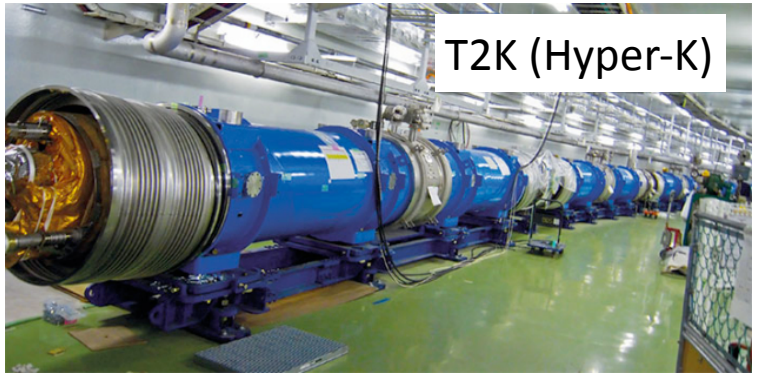
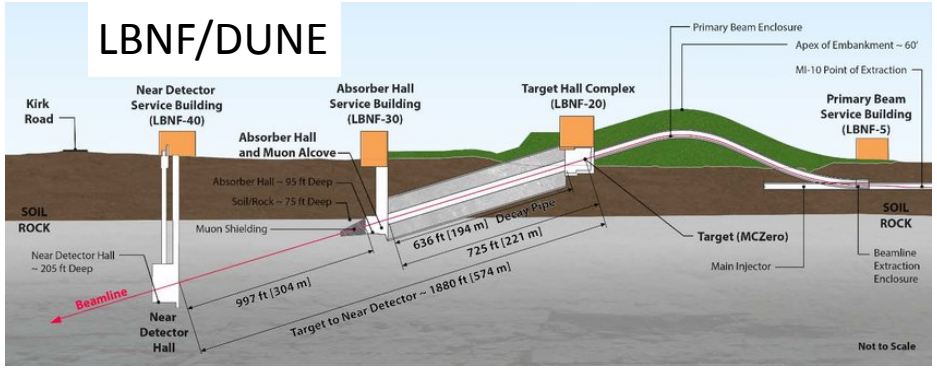
- (Backup Slides)

Introduction

Artificial Neutrino Sources

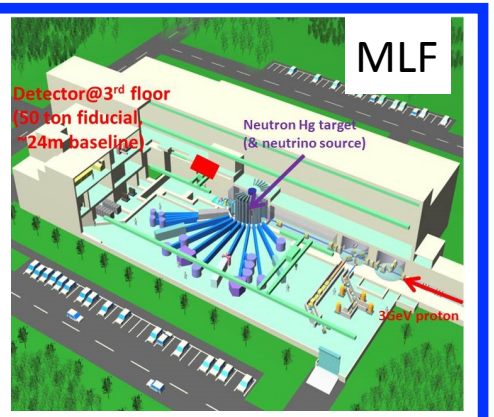
- Precise flux knowledge is a key input for neutrino experiments



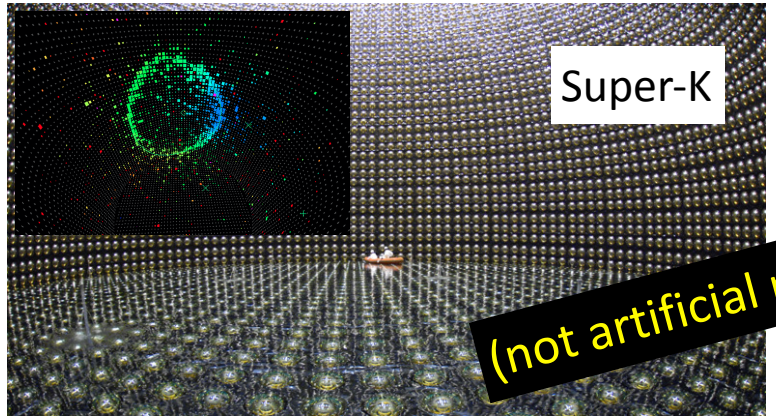


Accelerator neutrinos

(main focus of this talk)



Neutrinos from spallation neutron source

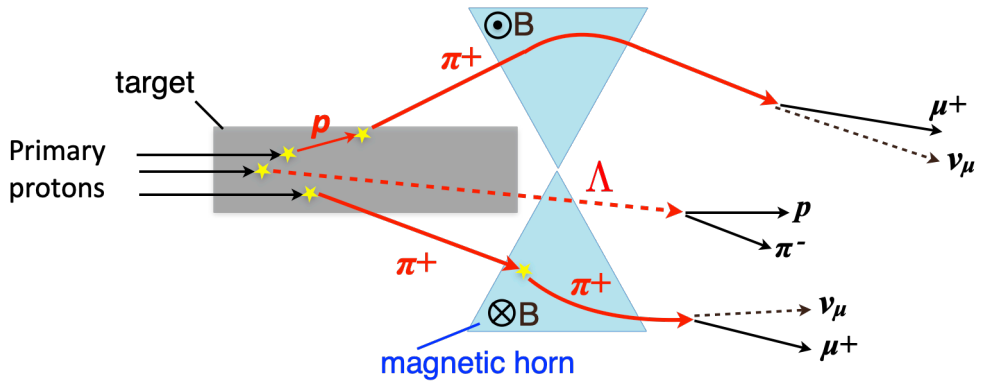


(not artificial neutrino source)

Atmospheric neutrinos

Artificial Neutrino Sources

- Precise flux knowledge is a key input for neutrino experiments



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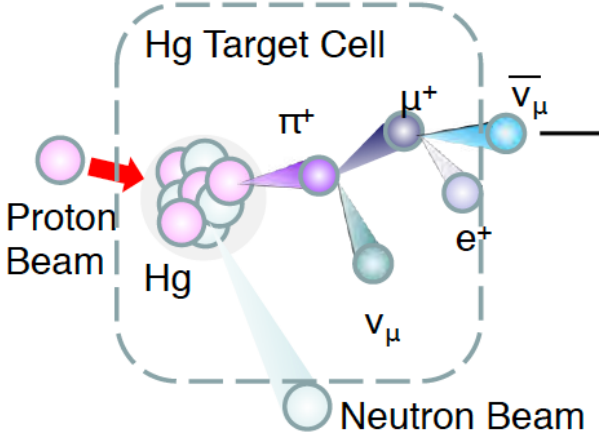
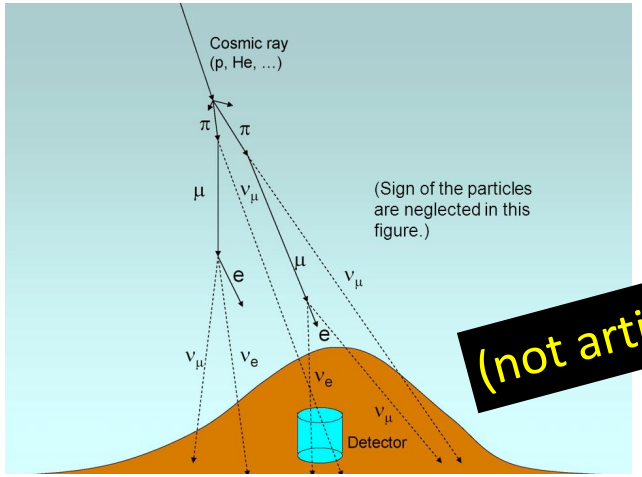


Neutrinos from spallation neutron source



(not artificial neutrino source)

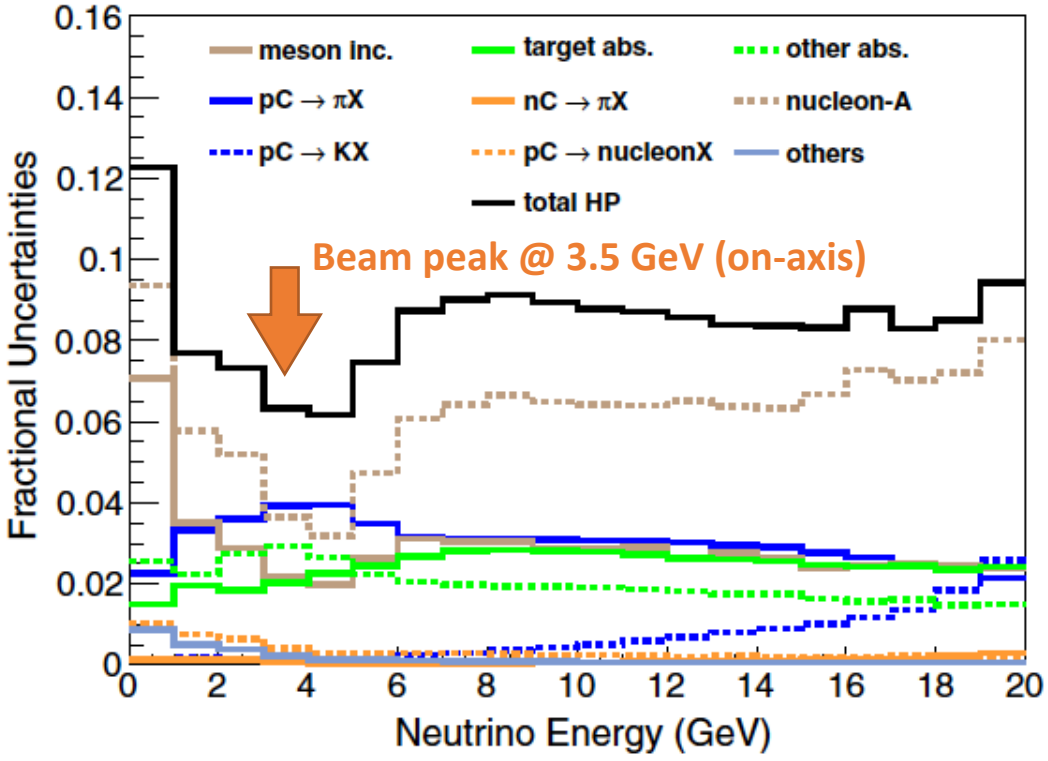
Atmospheric neutrinos

- A common bottleneck on flux prediction: Hadron production

Hadron Production Uncertainty (accelerator- ν)

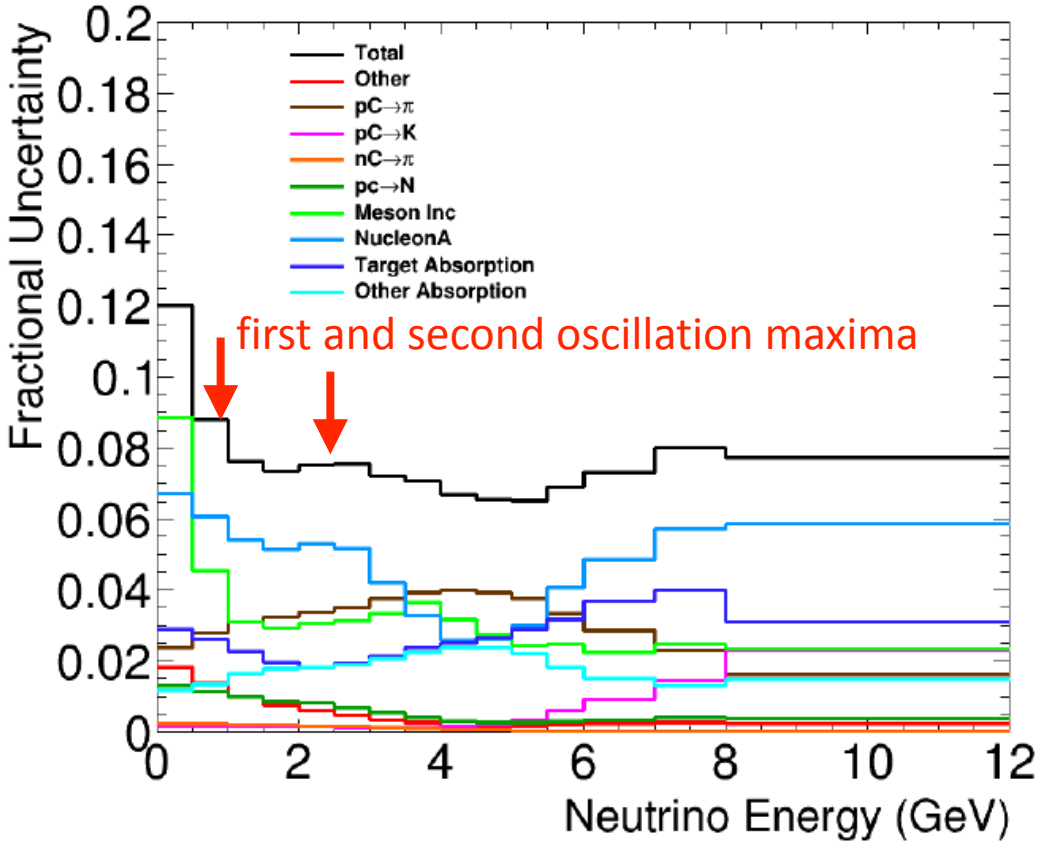
Hadron Production is the leading uncertainty source of flux predictions

NuMI beamline (MINERvA flux)



MINERvA: Phys. Rev. D94, 092005 (2016)
(only hadron production-relating errors)

LBNF beamline (DUNE flux)



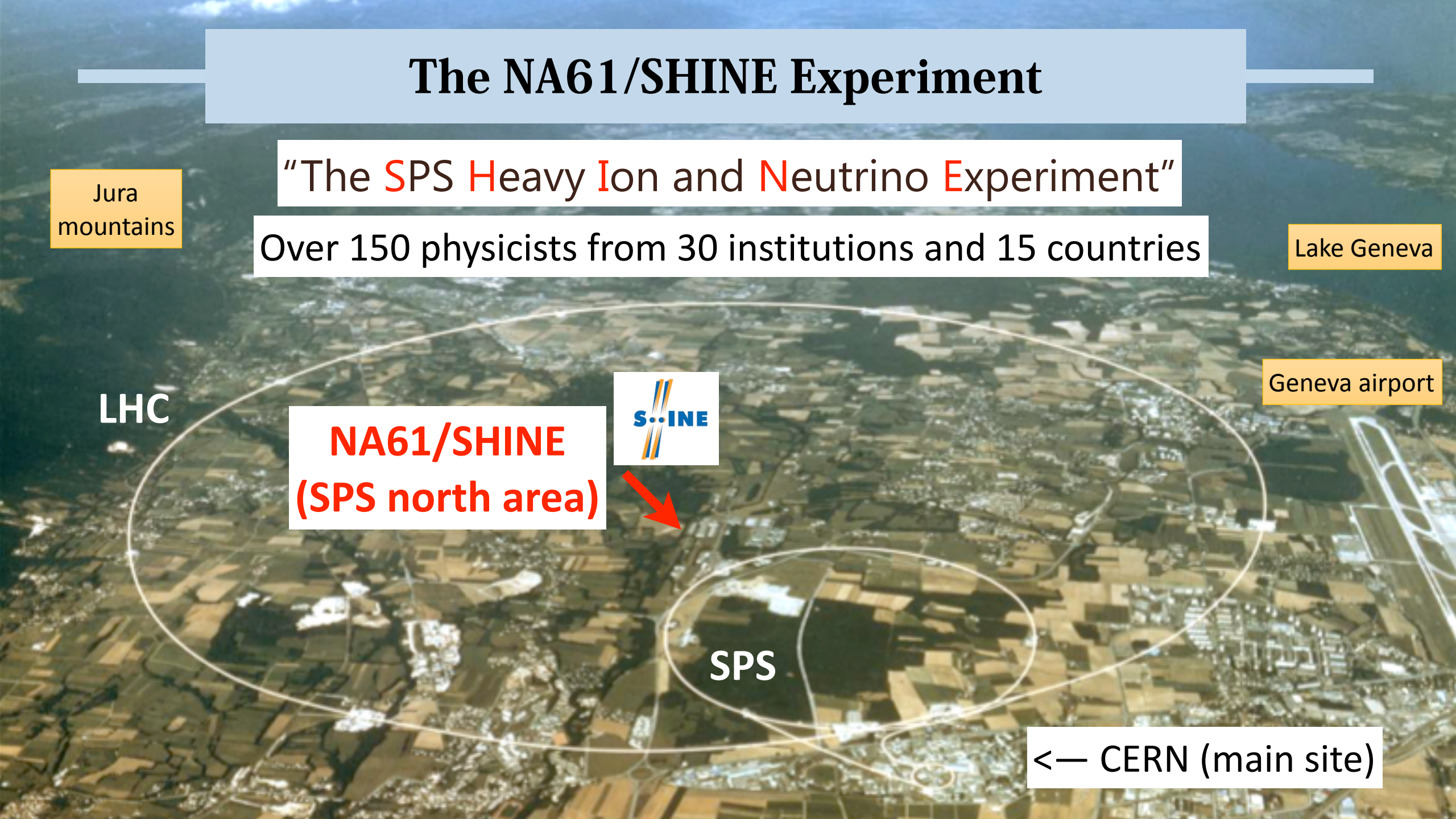
L. Fields (NA61 beyond 2020 workshop)
(only hadron production-relating errors)

NA61/SHINE Experiment

The NA61/SHINE Experiment

"The SPS Heavy Ion and Neutrino Experiment"

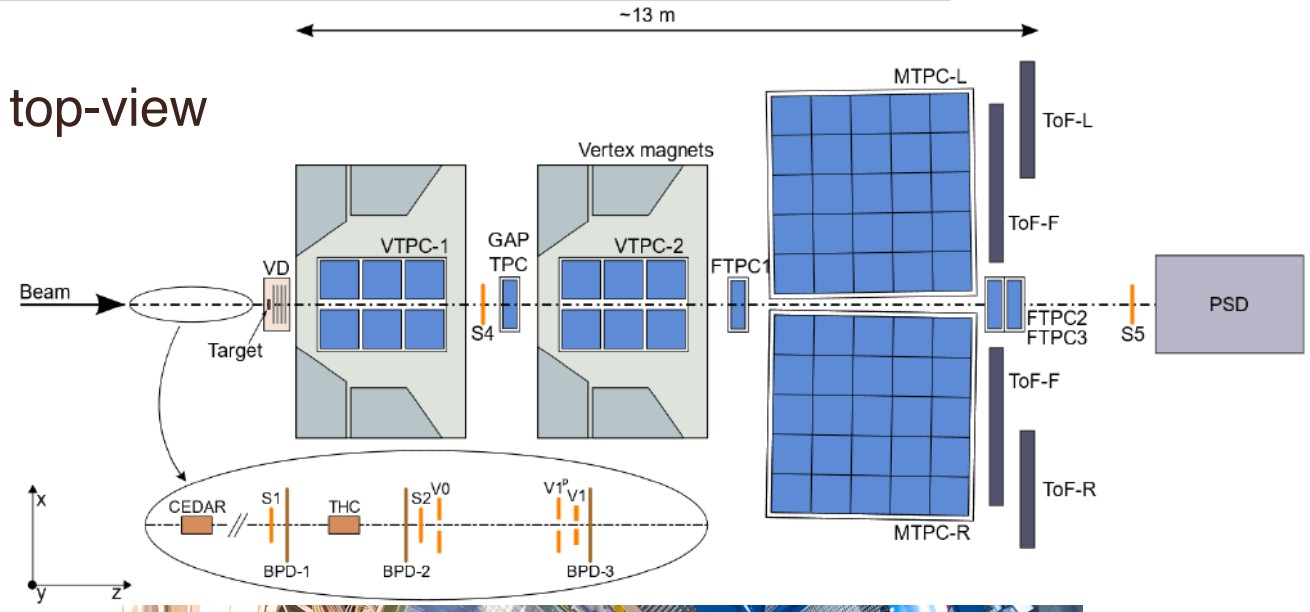
Over 150 physicists from 30 institutions and 15 countries

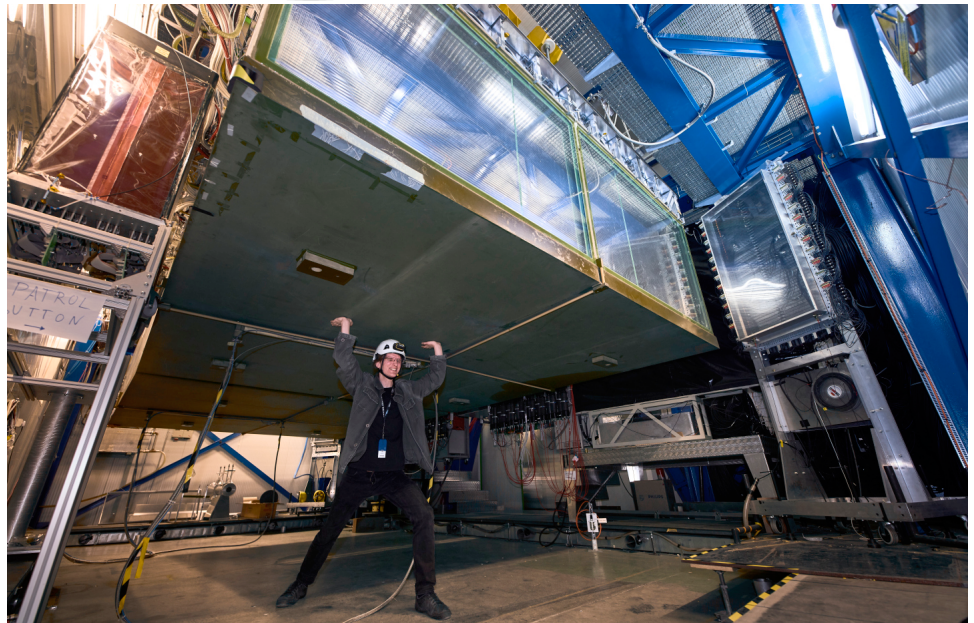


NA61/SHINE Experimental Facility

- A fixed target experiment at SPS
- 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





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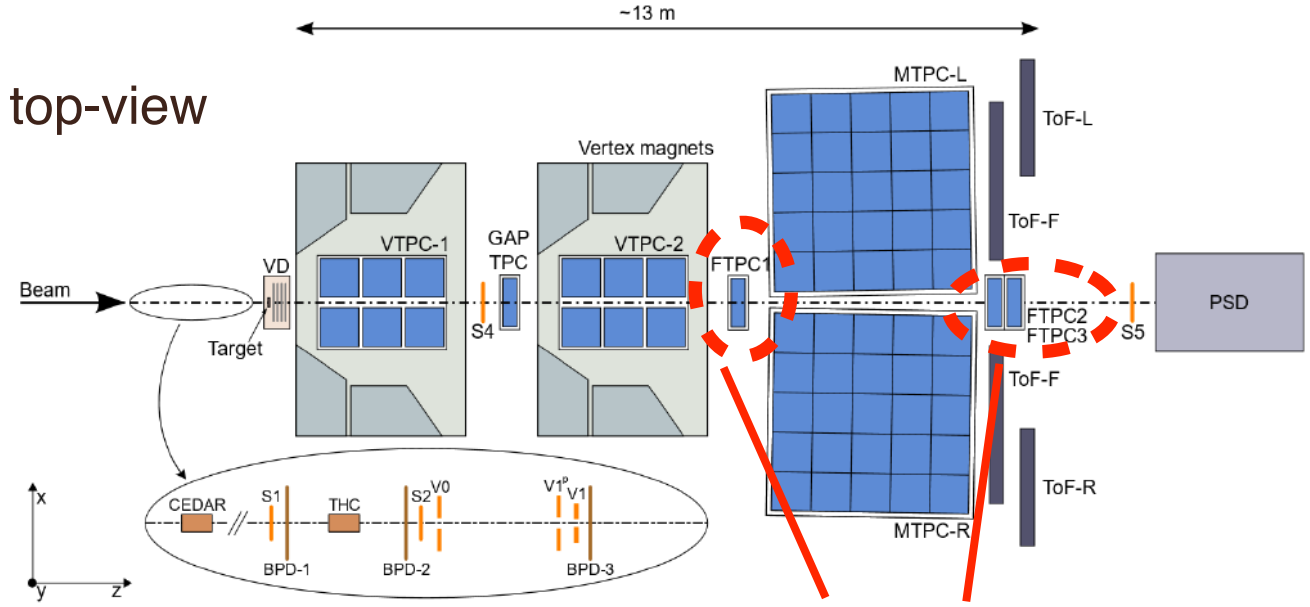


3 TPCs (FTPCs) built in 2015-2017

Precise tracking with:
- Particle identification
- Momentum measurement

Further facility upgrade is ongoing (discuss later)

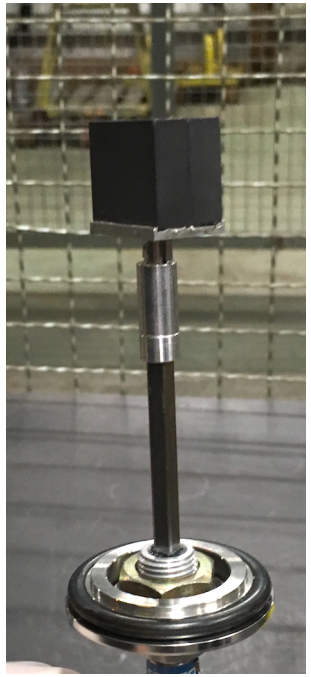
The NA61/SHINE Experiment

- Hadron beams
  - primary protons at 400 GeV/c
  - secondary hadrons (p, π, 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 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

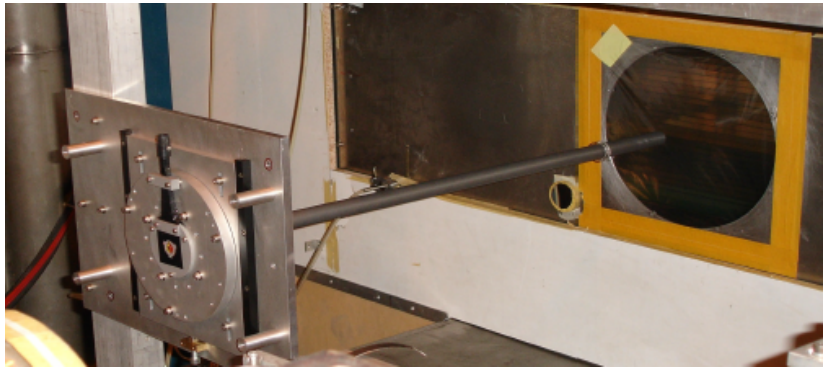
Strategy of Measurements in NA61/SHINE

- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Total cross sections (inelastic and production cross sections)
  - Differential cross sections ($\frac{d^2\sigma}{dpd\theta}$)
- Replica (thick) target: same geometry and material as real neutrino beamline
  - Differential production yields ($\frac{d^3n}{dpd\theta dz} = N(p,\theta,z)$)
  - Beam survival probability (extract production cross section)

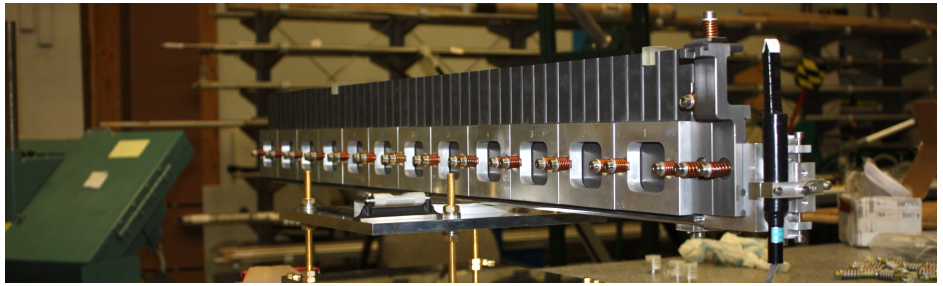
Thin graphite target (1.5 cm, 3.1% of λ)



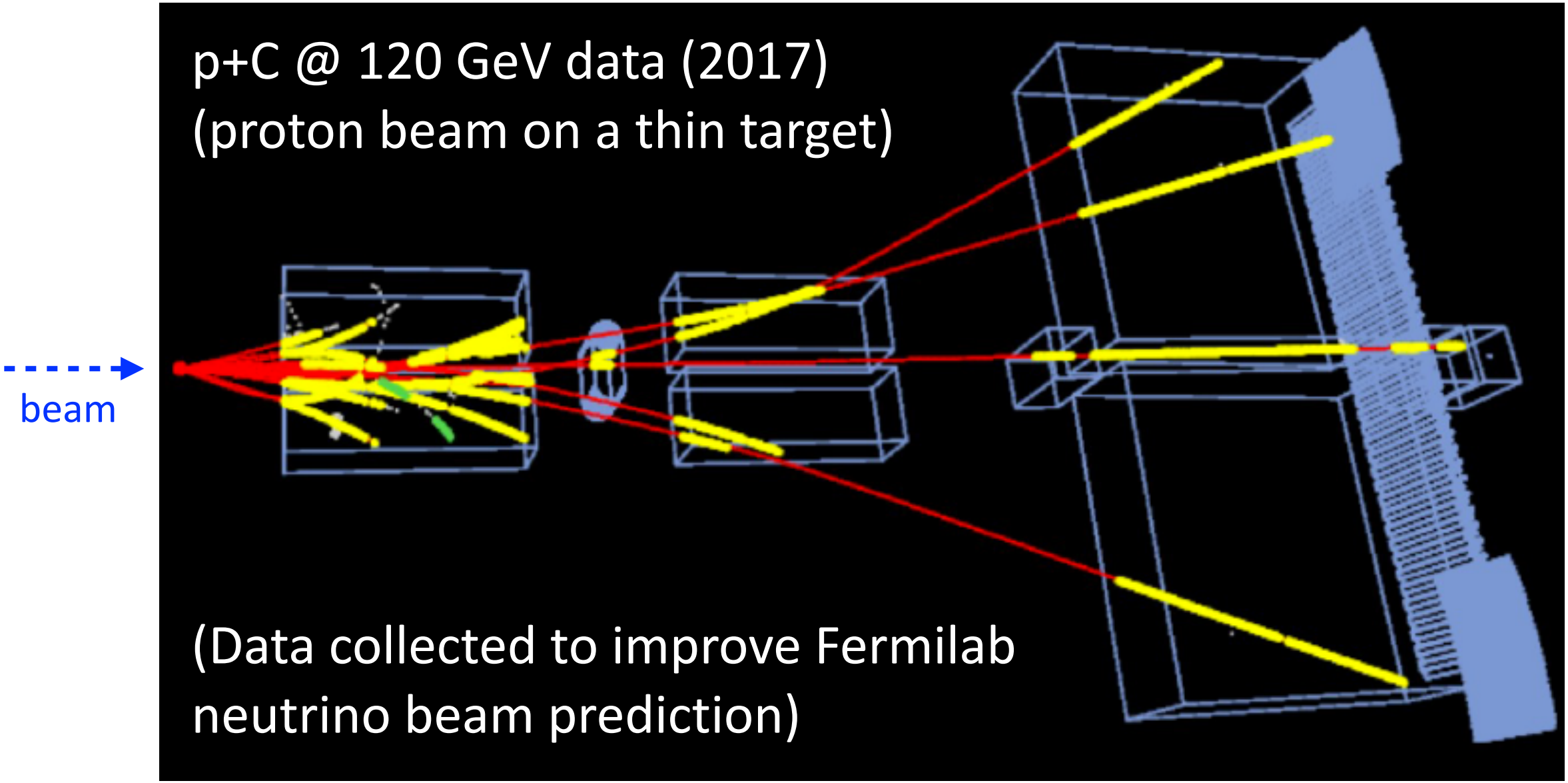
T2K replica graphite target (90 cm, 1.9 λ)



NuMI replica graphite target (120 cm, 2.5 λ)



An Example Event



Series of Data Taking for Neutrino Program

- Measurements for T2K (2007-2010): with proton beam at 30 GeV
  - Thin graphite target measurements to study primary interactions
  - T2K replica graphite target measurements (90 cm long, graphite rod)

  —> Almost complete data analysis (list of papers in backup slide)

  —> Additional data taking after 2021 is planned

- Measurements for Fermilab (2015-2018): with various beam types and energies
  - Thin target (C, Be, Al) measurements to study primary and secondary interactions
  - NOvA replica graphite target measurements (120 cm long, graphite fins)

  —> Complete first data taking between 2015 and 2018

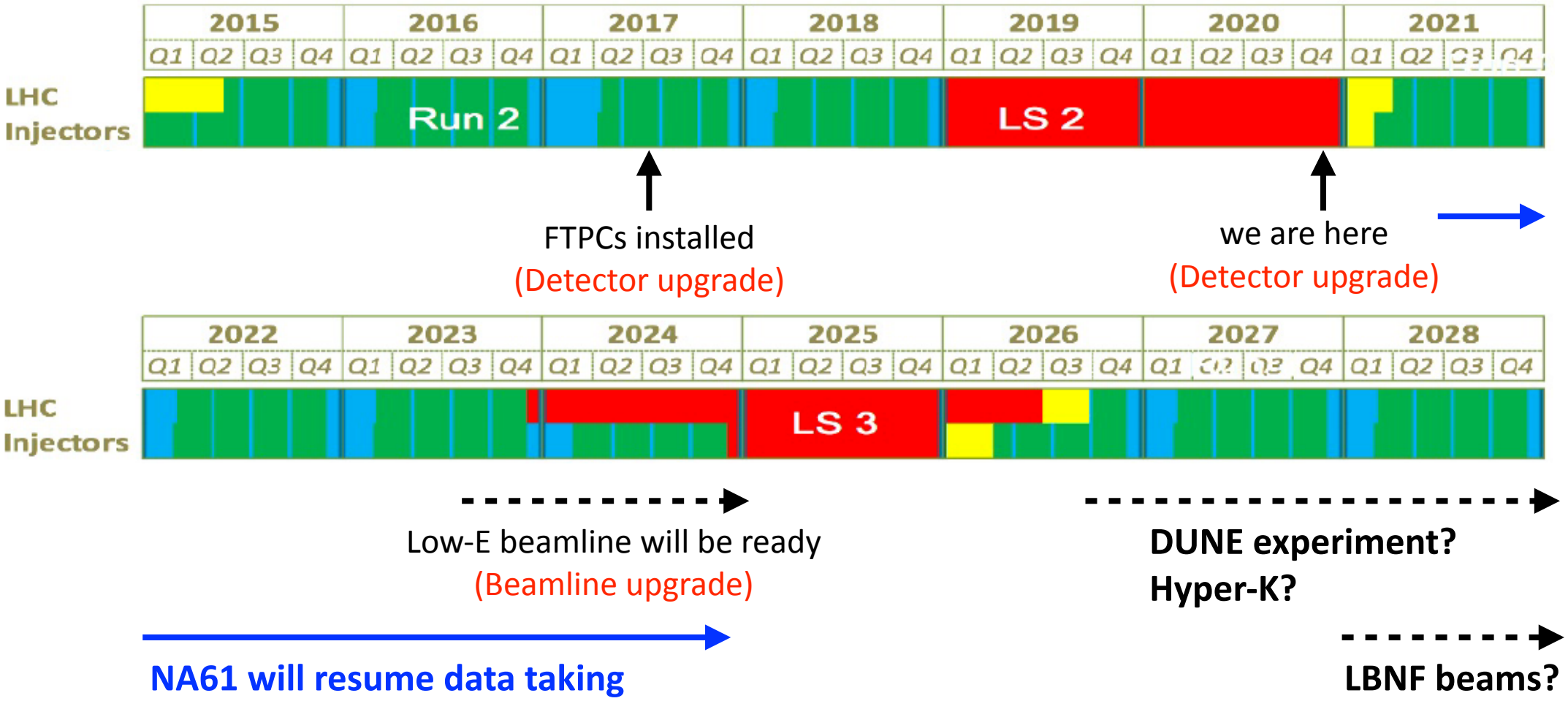
  —> Analysis ongoing (publication and analysis status in backup slide)

  —> Further data taking after 2021 is under discussion

Plans after Long Shutdown 2 (2021-2024)

Future Measurement with NA61/SHINE

- NA61/SHINE will resume data taking after LS 2 (2021-2024)



Future Hadron Production Measurements

- What do we need to measure further?

Thin Target

- Unmeasured materials (Al, Fe, Ti, Water, etc…)
- Phase-space extension (Uncovered / limited coverage)

—> T2K/Hyper-K: low momentum (1-5 GeV/c) hadron interactions

—> DUNE: $\pi^{\pm}$ and $K^{\pm}$ re-interactions (30-60 GeV/c)

—> SBN at FNAL: p+Be at 8 GeV/c

—> Spallation neutrinos: p+Hg data at 1-3 GeV/c

—> atm-ν: p+air (p+N, p+C) data for various energy (1-400 GeV/c)

Replica Target

- Improved precision

—> More statistics for T2K and NuMI replica target data

—> Target tracking detector will be necessary for longer target

- New replica target

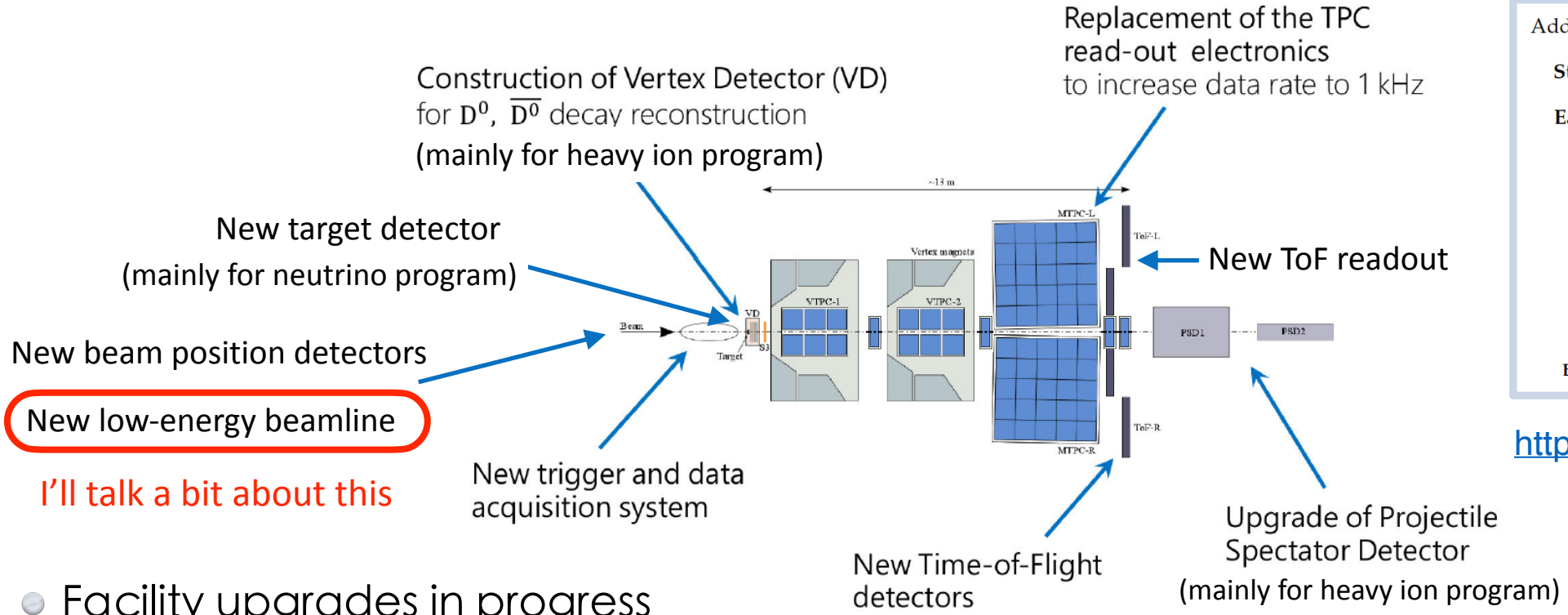
—> Hyper-K and DUNE targets are under development

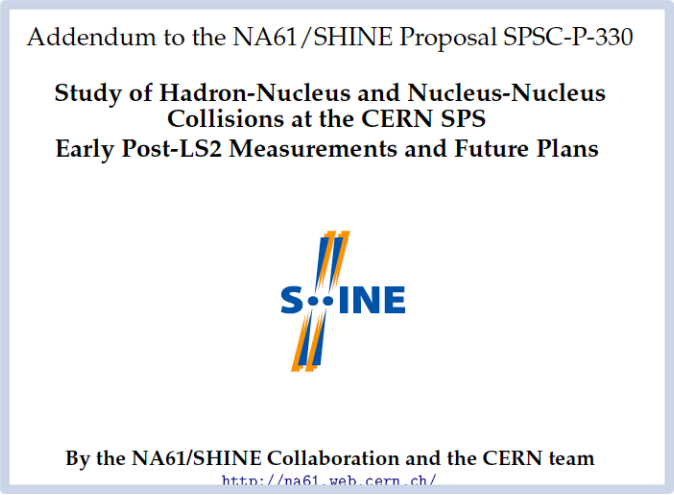
all measurements are possible with NA61/SHINE after upgrade

Plans with NA61/SHINE

- Measurement planned or under discussion
  - Additional T2K replica target data taking (late 2021 or 2022) —> Requested already to SPSC
  - LBNF/DUNE replica target (at least 1.5 m long) data taking when available (likely after 2023)
  - Kaon scattering with thin targets
  - Improved statistics for various measurements
  - Measurements for uncovered phase-space (e.g. low-E beams, see next pages) and materials

NA61/SHINE Upgrade Detector




Addendum to the NA61/SHINE Proposal SPSC-P-330

Study of Hadron-Nucleus and Nucleus-Nucleus Collisions at the CERN SPS
Early Post-LS2 Measurements and Future Plans

By the NA61/SHINE Collaboration and the CERN team

https://cds.cern.ch/record/2309890

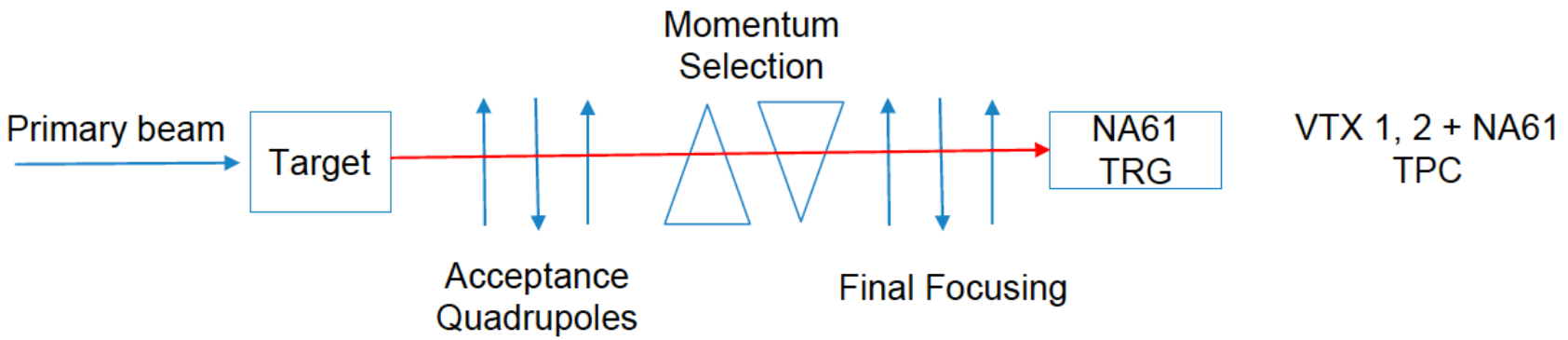
- Facility upgrades in progress
  - DAQ upgrade: ~1kHz TPC (~100 Hz now)
  - New ToF walls with mRPC (improved resolution)
  - New beam position detectors
- Various ideas under consideration
  - Construction of low-energy beamline
  - New target tracking detector

- So far no major delays
  - covid-19 pandemic may affect upgrade schedule, but we still expect upgrade to be completed by mid-2021

Low-Energy Beamline at NA61/SHINE

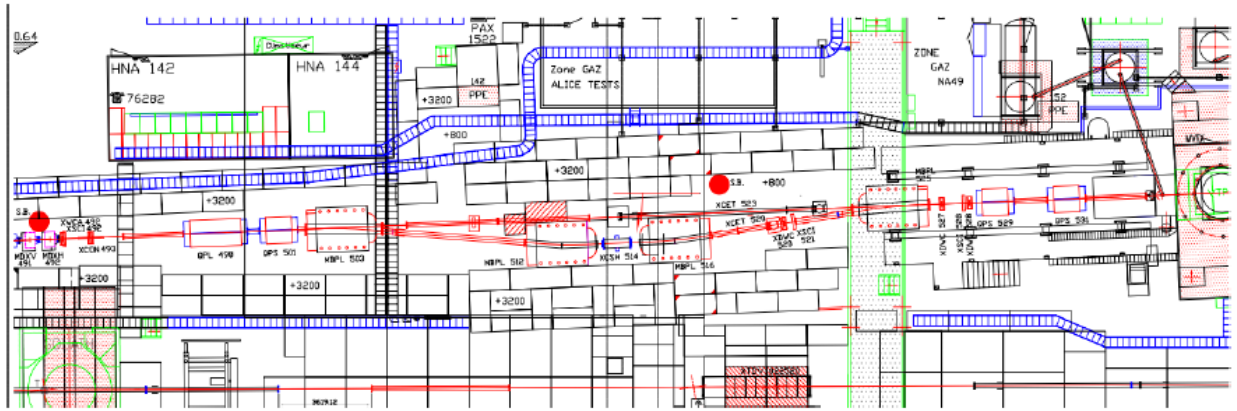
- We have started design works for new low-E beamline at CERN SPS H2-bemeline
  - Low-Energy = 1-20 GeV —> Open new physics opportunities

Principle of a Low Energy Beam for SHINE



Data taking can occur 2023-2024 at the earliest case

(Plan can be find in NA61 status report) https://cds.cern.ch/record/2739340



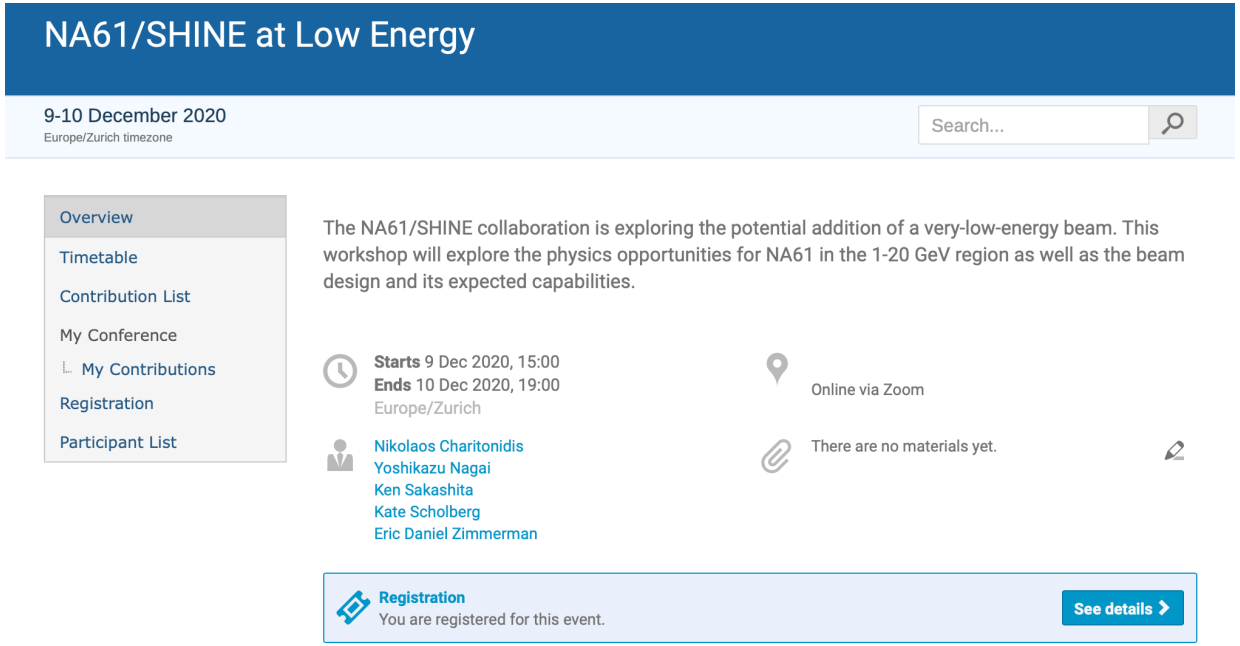
A low energy beam was there in ~2000 (NA49 times) serving CMS downstream.

Low-Energy Beamline Workshop (Next week!!)

- A dedicated workshop next week (Dec. 9-10, 15:00-19:00 CET)
  - Physics cases
    - Neutrinos from spallation source (J-PARC, SNS)
    - Accelerator neutrinos (J-PARC, Fermilab)
    - Atmospheric neutrinos (sub-GeV neutrino flux)
  - Accelerator R&D
    - Project outline
    - Status of design effort
    - Beamline instrumentation

Registration is open, please join discussion if you are interested in low-E beams!!

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



Summary

- Precision hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction
  - NA61/SHINE has provided critical data to improve neutrino flux predictions
- Significant facility upgrade is ongoing
  - Further measurement will resume post LS2 (2021-2024)
  - Low-E beamline will open further physics opportunities

  —> Dedicated workshop next week! https://indico.cern.ch/event/973899

There are many opportunities in NA61/SHINE.
We welcome new collaborators !!

Thank you for your attention!

NA61/SHINE Collaboration

- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- Hungary
  - Wigner RCP, Budapest
- Japan
  - KEK Tsukuba, Tsukuba
- Norway
  - University of Bergen, Bergen
- Poland
  - UJK, Kielce
  - NCBJ, Warsaw
  - University of Warsaw, Warsaw
  - WUT, Warsaw
  - Jagiellonian University, Kraków
  - IFJ PAN, Kraków
  - AGH, Kraków
  - University of Silesia, Katowice
  - University of Wrocław, Wrocław
- Russia
  - INR Moscow, Moscov
  - JINR Dubna, Dubna
  - SPBU, St.Petersburg
  - MEPhI, Moscow
- Serbia
  - University of Belgrade, Belgrade
- Switzerland
  - ETH Zürich, Zürich
  - University of Bern, Bern
  - University of Geneva, Geneva
- USA
  - University of Colorado Boulder, Boulder
  - LANL, Los Alamos
  - University of Pittsburgh, Pittsburgh
  - FNAL, Batavia
  - University of Hawaii, Manoa

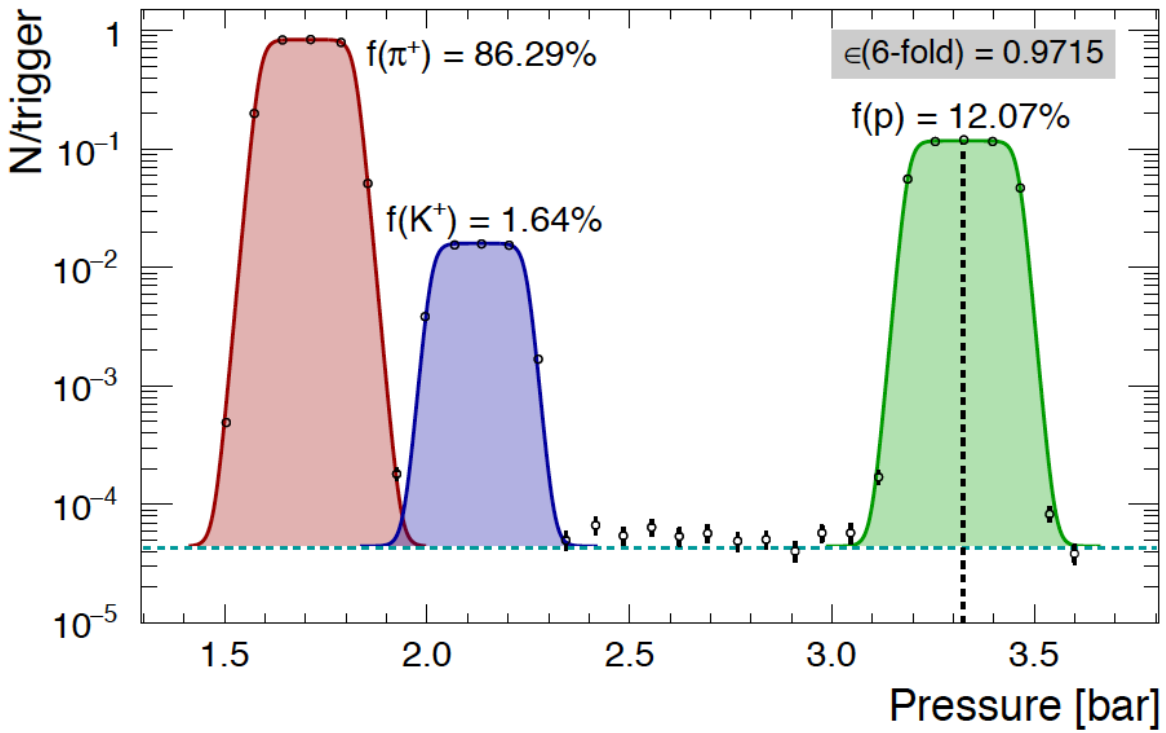
~150 physicists from ~30 institutes

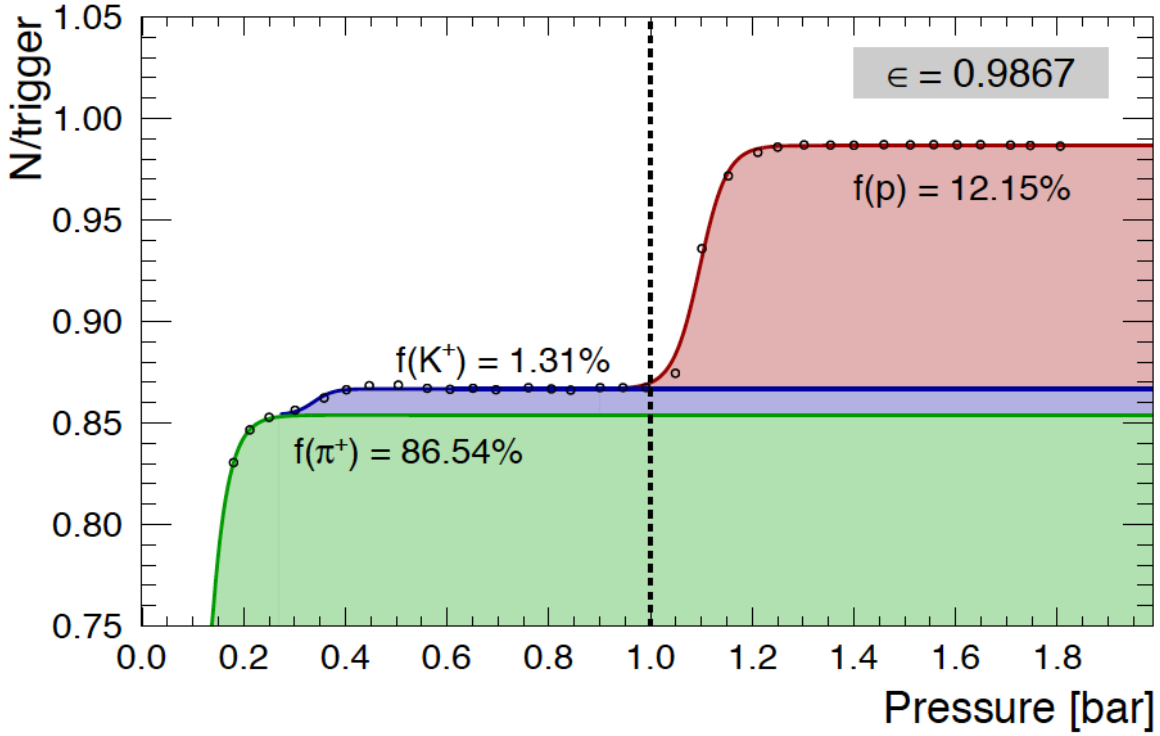
http://shine.web.cern.ch

We welcome new collaborators !!

Backup

Beam Particle Selection





NA61/SHINE Detector Performance

typical momentum resolution

$$\frac{\sigma(p)}{p^2} \approx 10^{-4}\ (\mathrm{GeV}/c)^{-1}$$

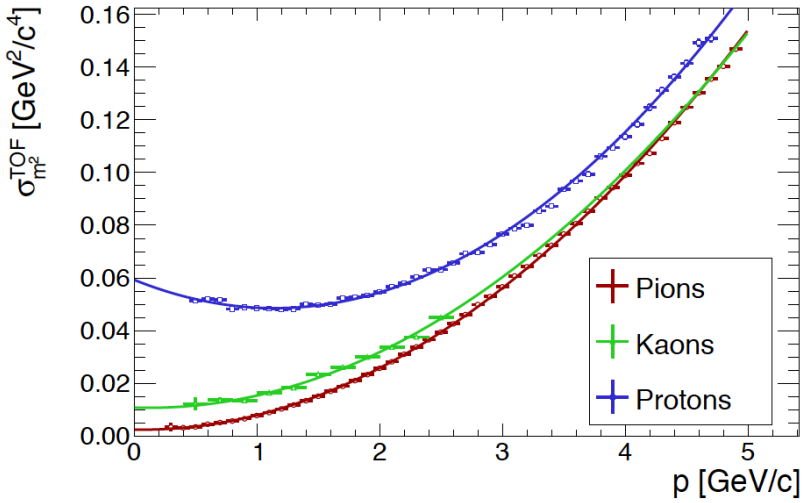
typical dE/dx resolution

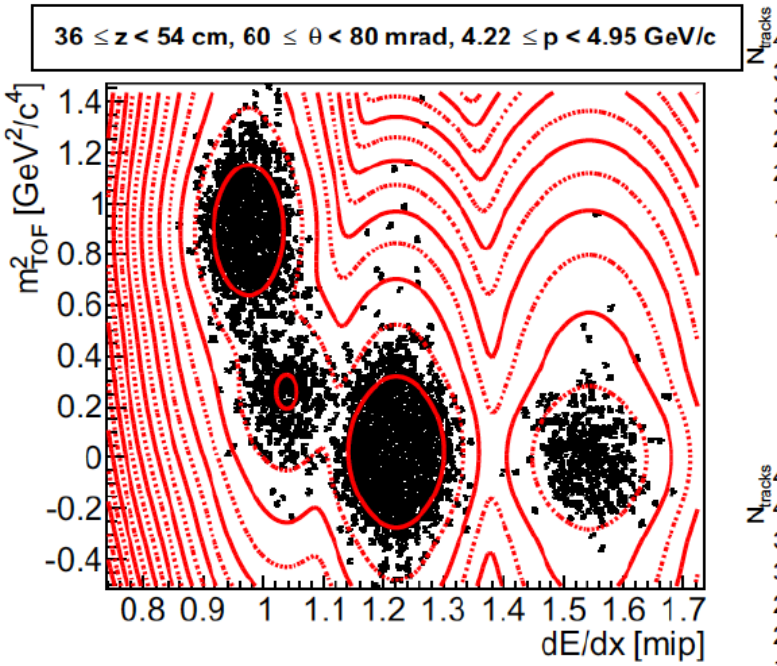
$$\frac{\sigma(dE/dx)}{dE/dx} \approx 0.04$$

ToF resolution

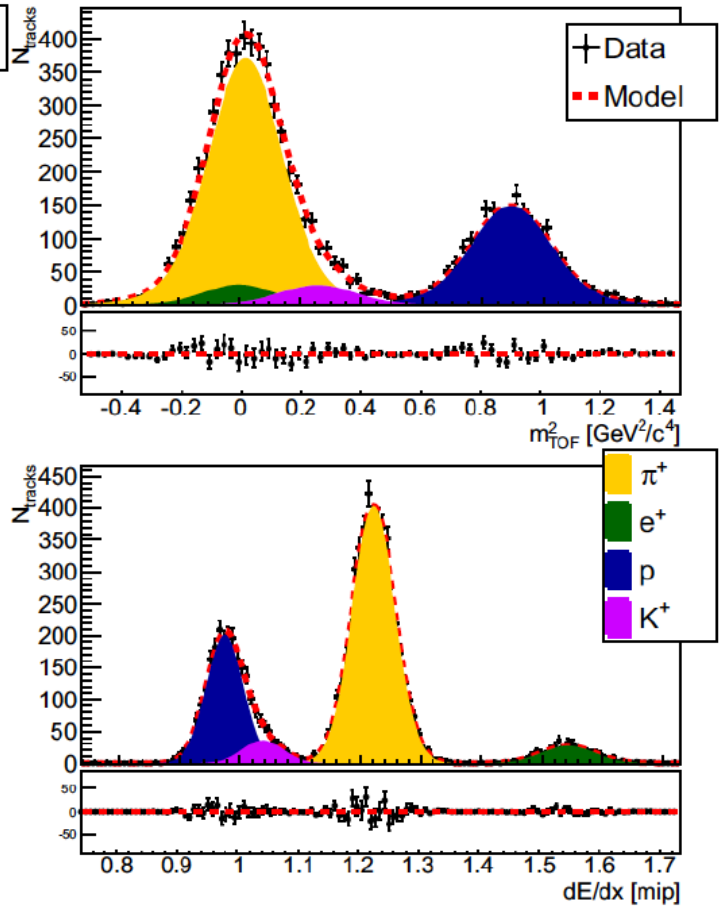
$$\sigma(\text{ToF-L/R}) < 90\ \text{ps}$$

$$\sigma(\text{ToF-F}) \approx 120\ \text{ps}$$

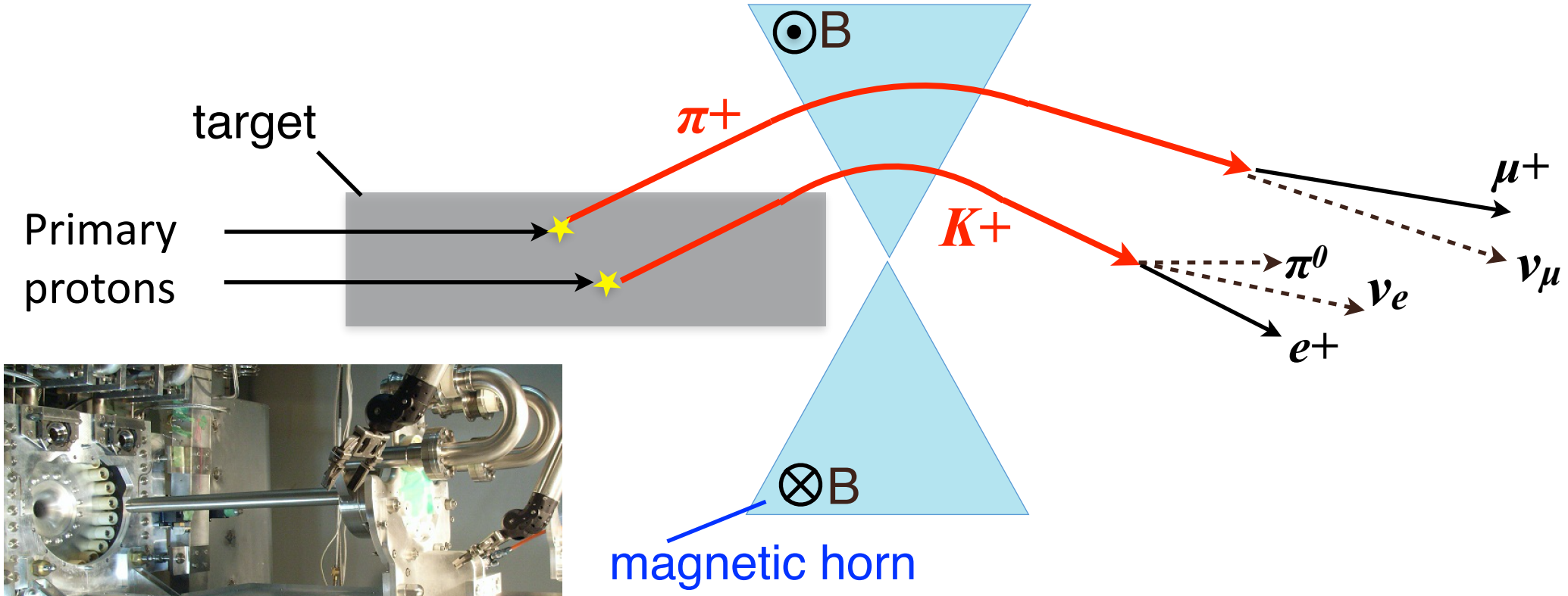


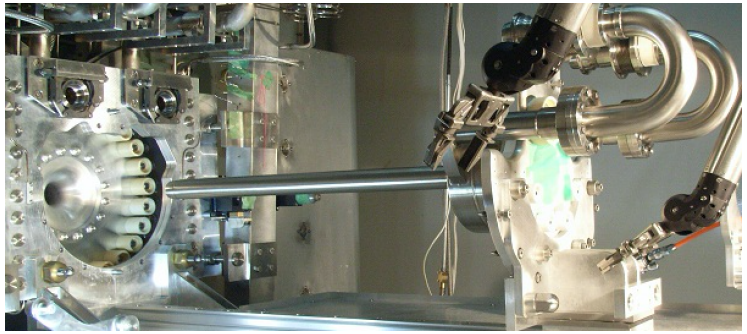


$A_p = (2056 \pm 46)$
$A_{K^+} = (399 \pm 21)$
$A_{\pi^+} = (4732 \pm 69)$
$A_{e^+} = (390 \pm 20)$



How to Make a Neutrino Beam



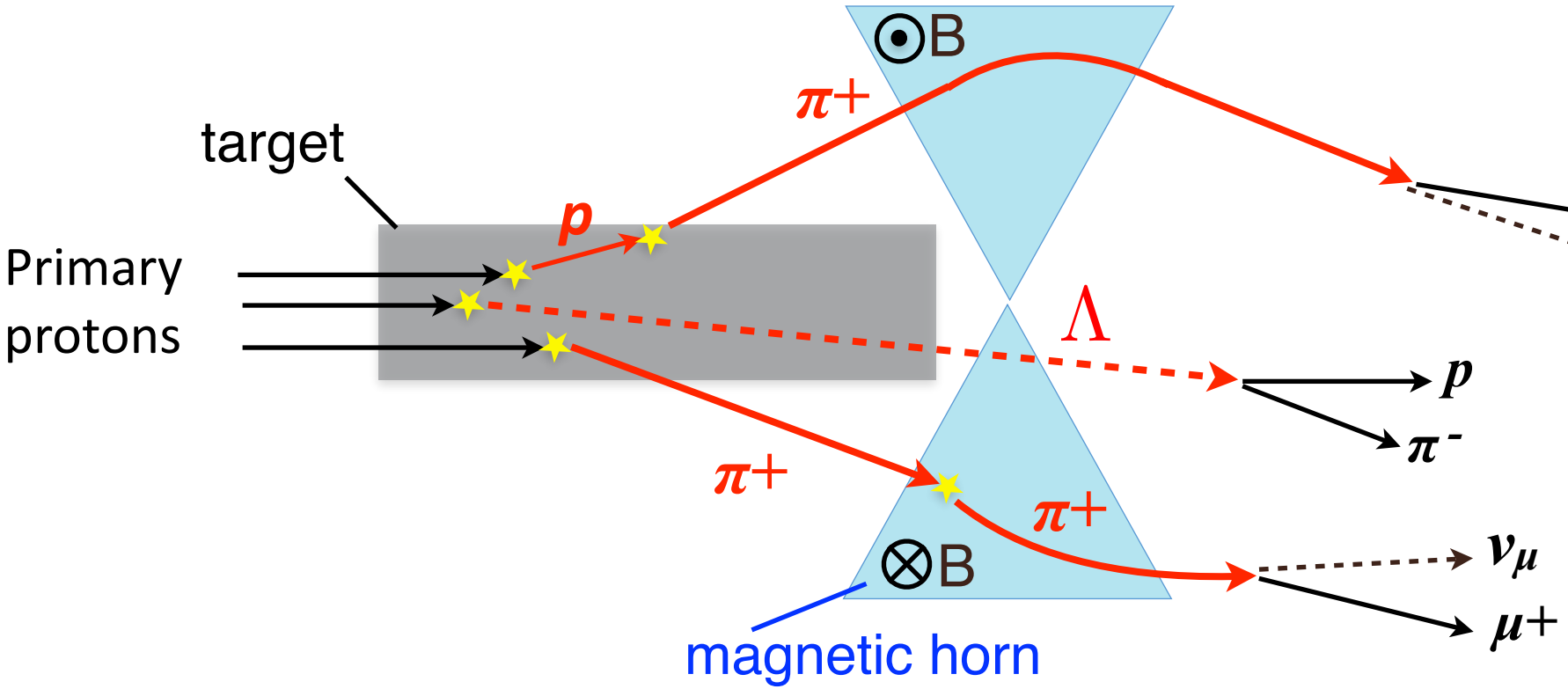


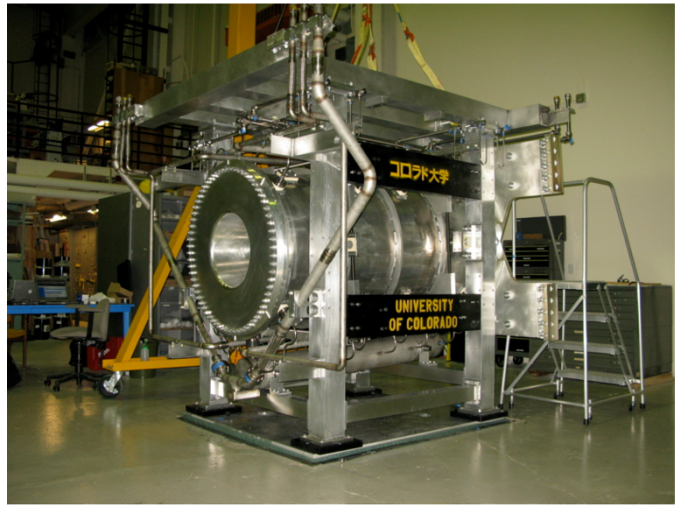
T2K target

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

—> Primary contribution to the neutrino flux

How to Make a Neutrino Beam





T2K magnetic horn

Hadron production process can be more complex:

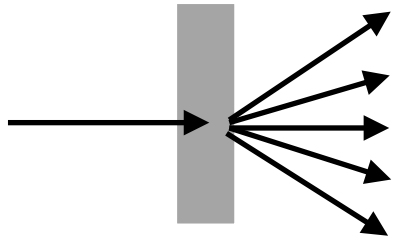
- Secondary interactions in the target (hadrons + C/Be)
- Secondary interactions with horn or beamline materials (hadrons + X)
- Neutral hadron decay (p + C / Be —> V^0 + X)

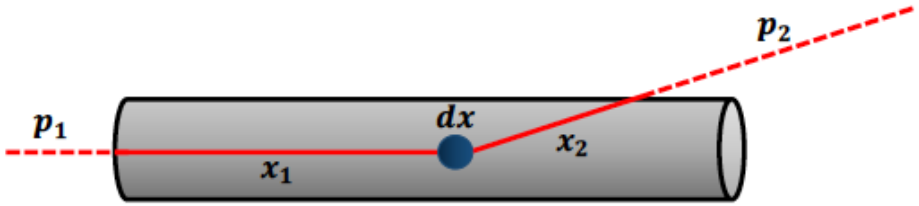
—>Non-negligible contribution to the neutrino flux

Thin Target Measurement

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

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





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

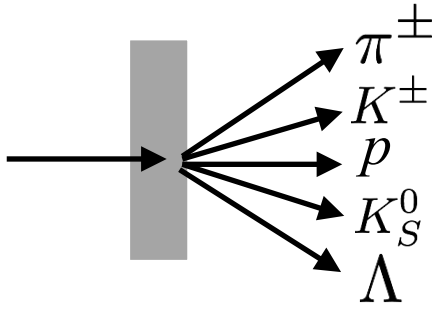
$$\mathrm{W}(p_1, p_2, x_1, x_2) = \frac{[P_{\text{interaction}} \cdot P_{\text{escape}}]_{\text{data}}}{[P_{\text{interaction}} \cdot P_{\text{escape}}]_{\text{MC}}}$$

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

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

Thin Target Measurement

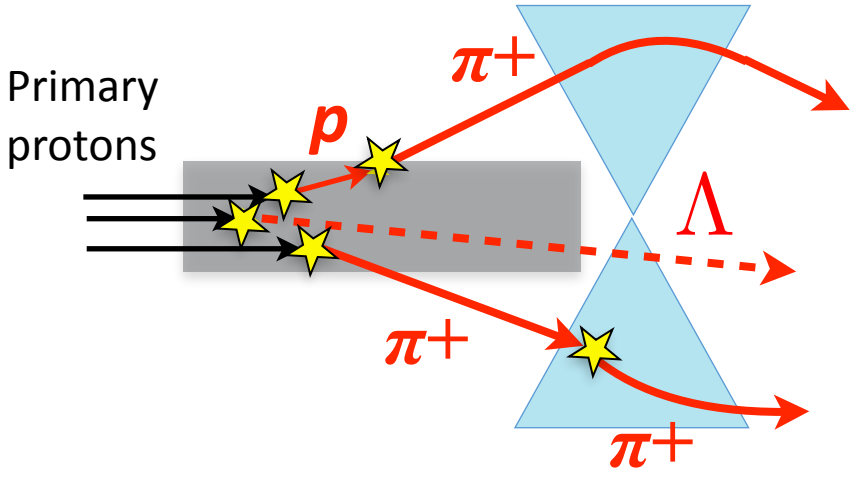
- Thin target: a few % of nuclear interaction length (λ) to study single interactions
  - Measurement of differential cross sections ($\frac{d^2\sigma}{dpd\theta}$)



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 σ_{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

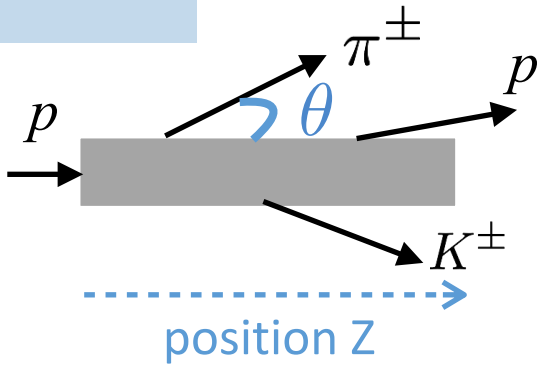
$$W(p,\theta) = \frac{N(p,\theta)_{\text{Data}}}{N(p,\theta)_{\text{MC}}}$$

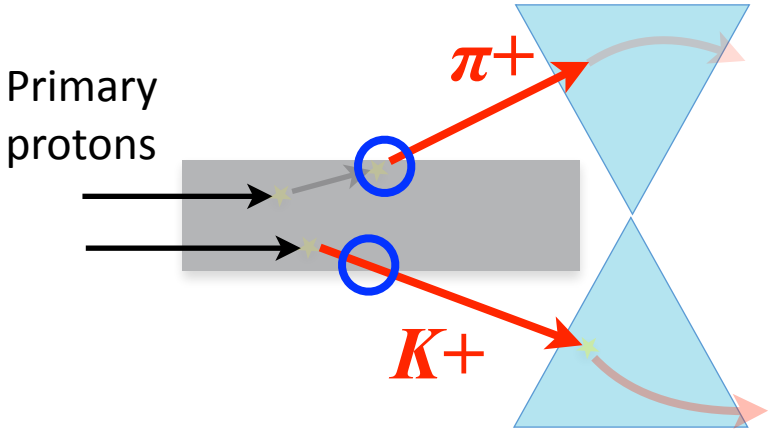
Replica Target Measurements

- Replica (thick) 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 φ if target cross-section is not circular, like NuMI target



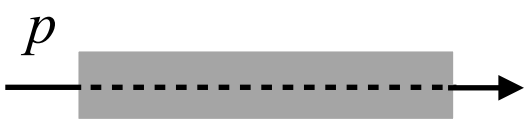


Weights for each exiting point (○) to apply correction to neutrino flux prediction

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

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

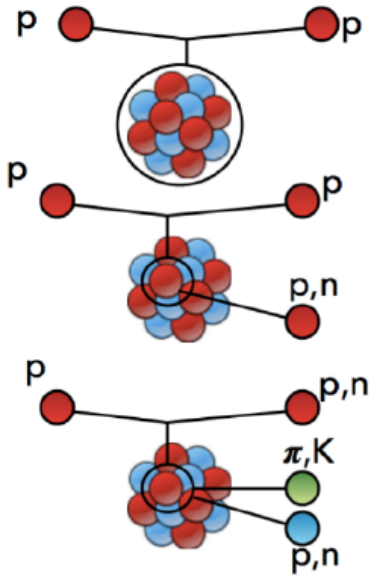
    (L: length of target, n: number of atoms per unit volume)



—> Results are useful to understand beam attenuation inside the target via σ_{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 —> σ_{el}

Quasi-elastic process:
interaction on bound nucleons —> σ_{qe}

Production process:
interaction with new hadron production
—> σ_{prod}

—> σ_{inel}

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

<u>Use this definition through the talk</u>
(T2K uses this definition)

- NuMI flux tuning definition:

$$\sigma_{\mathrm{inel}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$$ —> σ_{prod} in our definition

$$\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}}$$ —> σ_{inel} in our definition

- Earlier experiments: mixed up inelastic and production cross sections

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

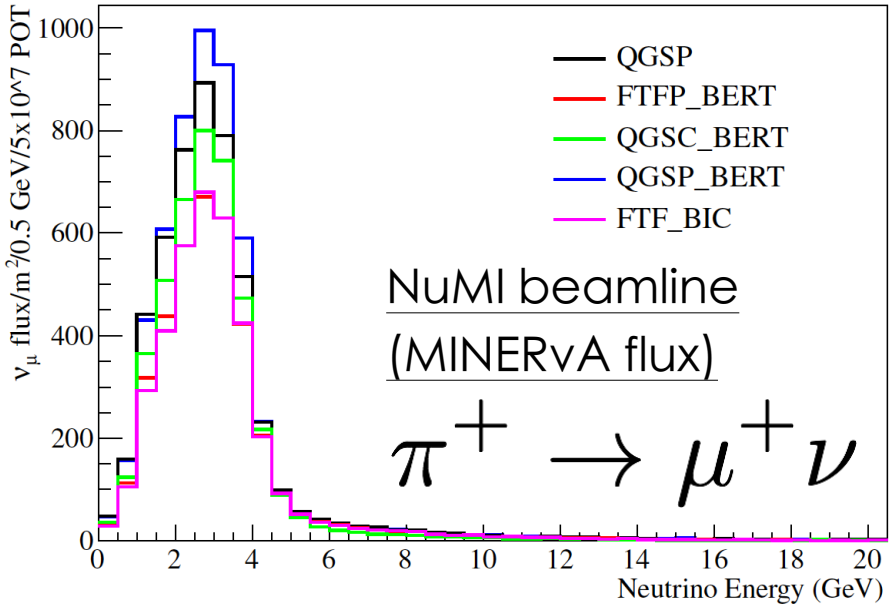
e.g. Carroll, et. al (1979): $\sigma_{\mathrm{absorption}} = \sigma_{\mathrm{total}} - \sigma_{\mathrm{el}} - \sigma_{\mathrm{qe}}$ —> σ_{prod} in our definition

Why Hadron Production Measurements?

- We rely on hadronic interaction models for the neutrino flux predictions
  - FLUKA (J-PARC/T2K), Geant4 FTFP_BERT (NuMI experiments)

However, hadron production prediction is difficult…

e.g. Five interaction models in Geant 4
—> variations neutrino flux prediction
~40% at the focusing peak



Leonidas Aliaga (Ph.D Thesis, 2016)

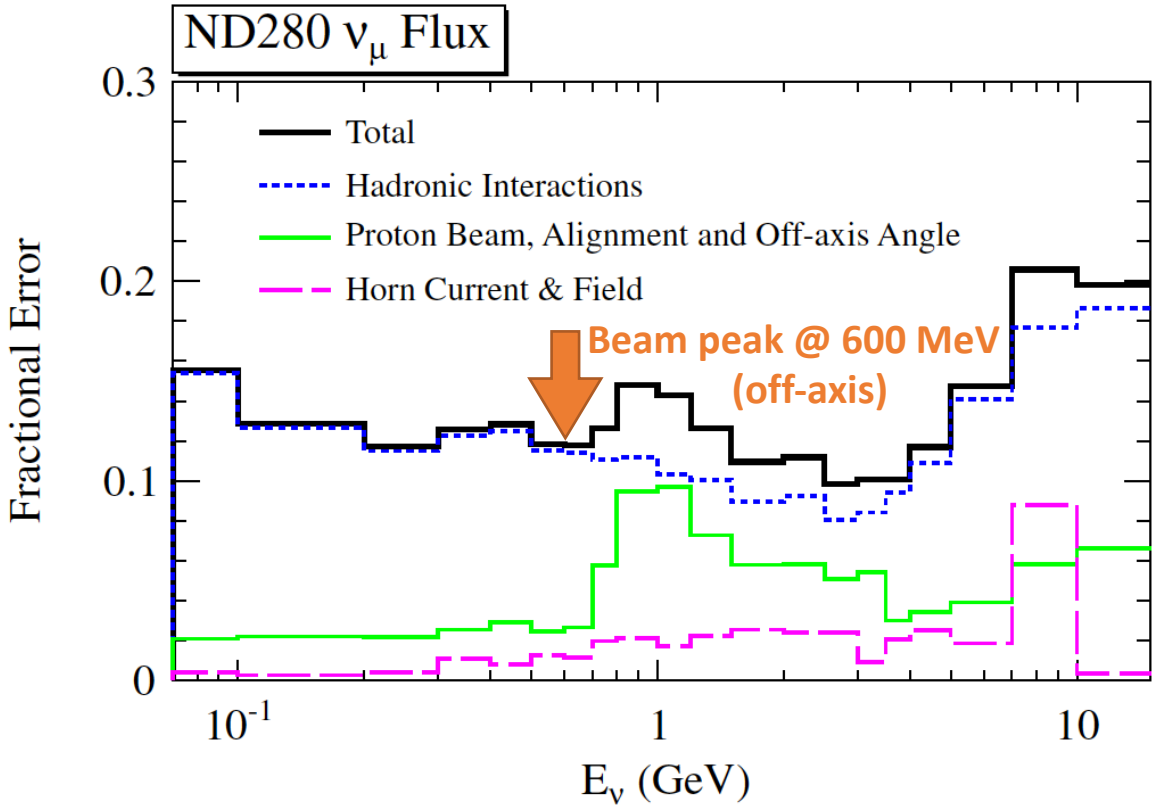
Need to constrain neutrino flux uncertainty coming from hadron production

⇨ Hadron production measurements with NA61/SHINE

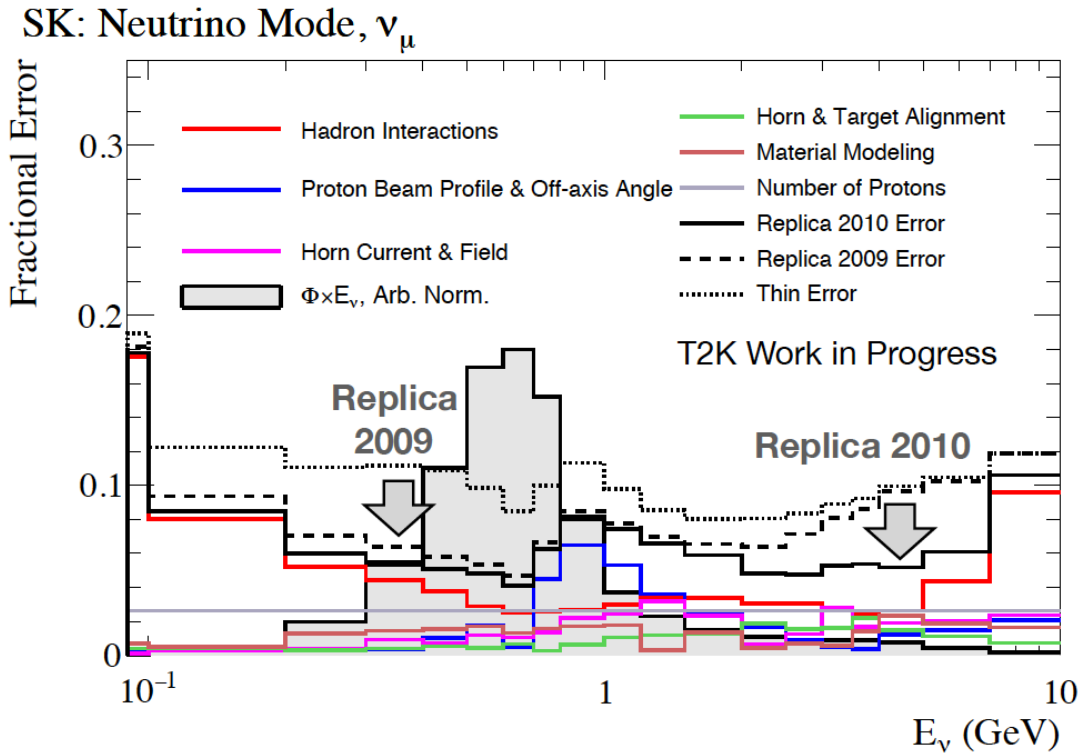
Hadron Production Uncertainty (accelerator- ν)

Hadron Production is the leading uncertainty source of flux predictions

J-PARC beamline (T2K flux)



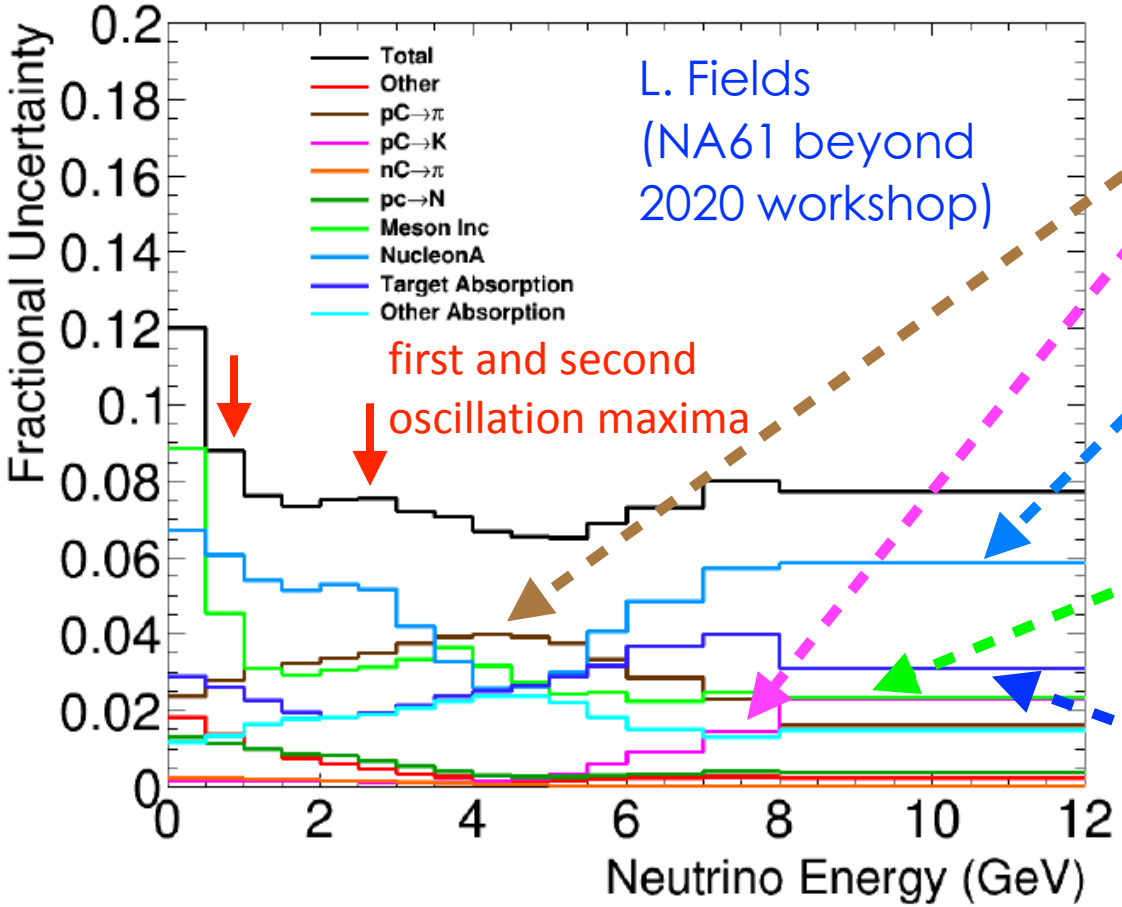
T2K: Phys. Rev. D87, 012001 (2013)
(with only thin target data)



Lukas Berns (NBI 2019)
(with replica and thin target data)

Importance of Hadron Production Measurements

- Requirements for the DUNE experiment
  - "Total" systematic uncertainty: below 5% for neutrino oscillation measurements
    —> goal for flux: 2-3% on flux uncertainty for broad range of energies!!



Source of uncertainty

Errors on existing pion and kaon productions on *p*+C data

Nucleon interactions not covered by existing data

Pion and Kaon re-interactions

Total probability of interaction in target

What we need !!

Measurements with larger statistics

New measurements with sufficient large acceptance

Measurements with π and K beams

Measurements with DUNE replica target

NA61 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 Λ spectra measurements (Phys. Rev. C89 (2014) 025205)
  - total cross-section and $\pi^{+/-}$,$K^{+/-}$ p, K^{0}_{S}, and Λ spectra measurements (Eur. Phys. J. C76 84 (2016))
- 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 (arXiv: 2010.11819, submitted to PRD)

Measurements for Fermilab Neutrino Program

- Thin target: various interactions in 2015 - 2017

Data sets		
no magnetic field (2015)	with magnetic field (2016)	with magnetic field (2017)
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c) **(with FTPCs)**
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c) **(with FTPCs)**
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C (31 GeV/c) **(no FTPCs)**
K^++Al/C (60 GeV/c)		π^++Al (60 GeV/c) **(no FTPCs)**
(no FTPCs)	**(no FTPCs)**	π^-+C (60 GeV/c) **(with FTPCs)**

- Total cross-section
  - 2015 π^+ and K^+ beams (Phys. Rev. D98, 052001 (2018))
  - 2016 proton beams (Phys. Rev. D100, 112001 (2019))
  - 2016 π^+ beams (Phys. Rev. D100, 112004 (2019)) (with differential multiplicity analysis)

Measurements for Fermilab Neutrino Program

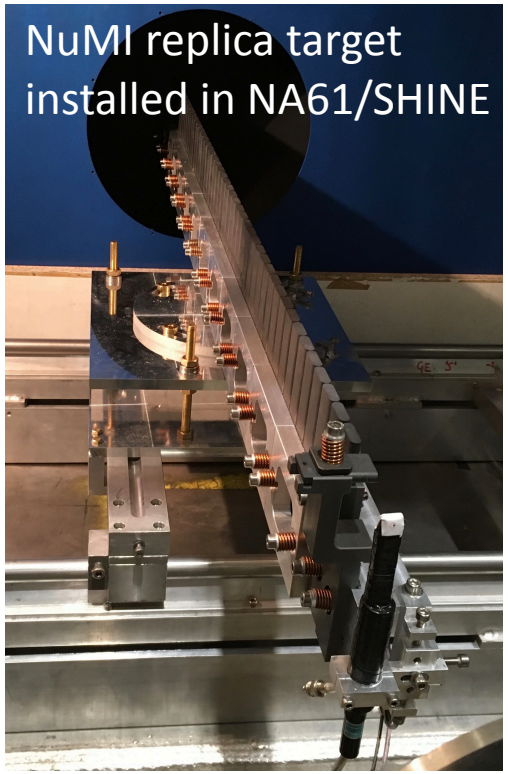
- Thin target: various interactions in 2015 - 2017

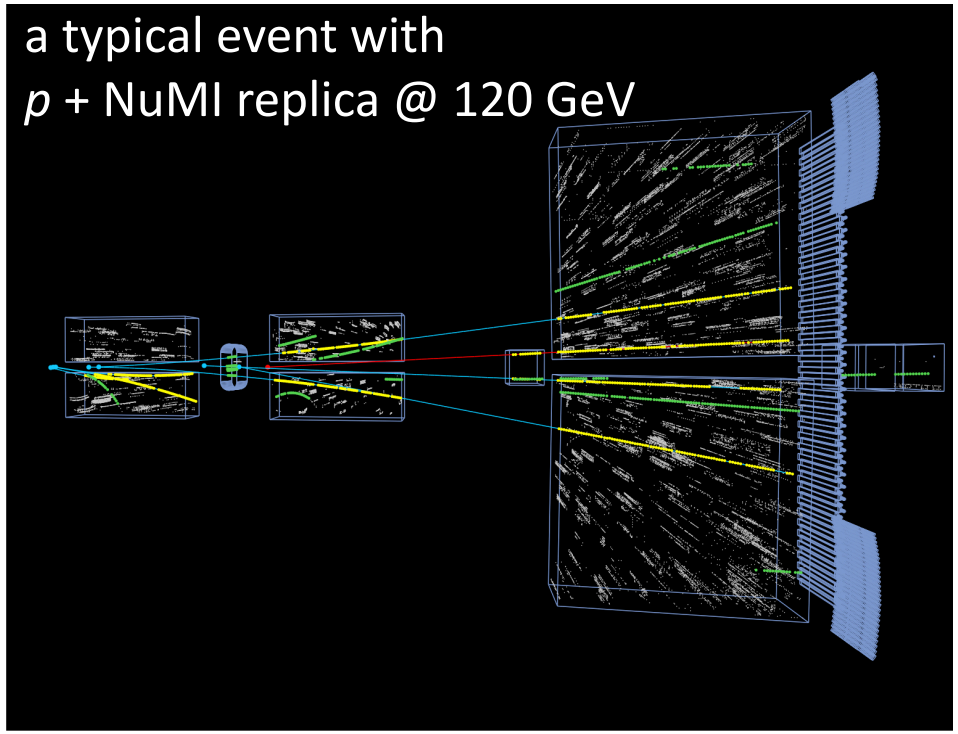
Data sets		
no magnetic field (2015)	with magnetic field (2016)	with magnetic field (2017)
p+C (31 GeV/c)	p+Al/Be/C (60 GeV/c)	p+C (90 GeV/c) **(with FTPCs)**
π^++Al/C (31 GeV/c)	p+Be/C (120 GeV/c)	p+Be/C (120 GeV/c) **(with FTPCs)**
π^++Al/C (60 GeV/c)	π^++Be/C (60 GeV/c)	π^++C (31 GeV/c) **(no FTPCs)**
K^++Al/C (60 GeV/c)		π^++Al (60 GeV/c) **(no FTPCs)**
(no FTPCs)	**(no FTPCs)**	π^-+C (60 GeV/c) **(with FTPCs)**

- Differential production multiplicity
  - 2016 π^+ beams (Phys. Rev. D100, 112004 (2019)) (with total cross-section analysis)
  - 2016 proton beams (preliminary results)
  - 2017 proton beams (analysis ongoing)

Measurements for Fermilab Neutrino Program

- Replica target: proton beam @ 120 GeV/c in 2018 on NOvA replica target
  - Large statistics (~18M events) for measurement of differential hadron yields





- Measurement of differential hadron production yields
  - Measurement will be conducted in similar way as T2K replica target measurement

—> Possibly additional binning because of asymmetric geometry in ϕ

Facility Upgrade for Fermilab Measurements

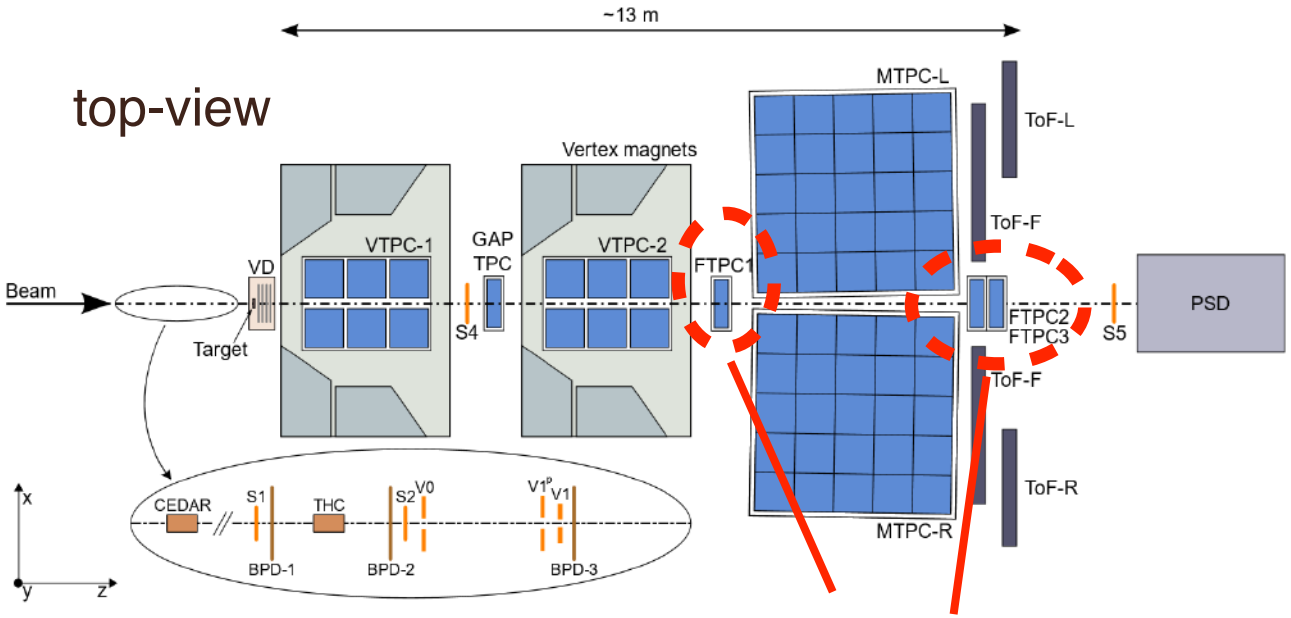
- Fermilab long-baseline neutrino experiments have proton beam energy:
  - NuMI: 120 GeV, LBNF: 60 - 120 GeV

—> Large chance to have forward hadron production with higher momentum

—> Need to improve NA61/SHINE detector acceptance for the forward region

- Requirements
  - Low mass to minimize multiple scattering and beam interactions
  - Beam off-time background rejection "Tandem-TPC" concept
  - Momentum resolution (< 10% @ 100 GeV)
  - Proton / Pion particle identification

—> Our Solution: gaseous ($Ar+CO_2$) TPCs



3 TPCs (FTPCs) built in 2015-2017

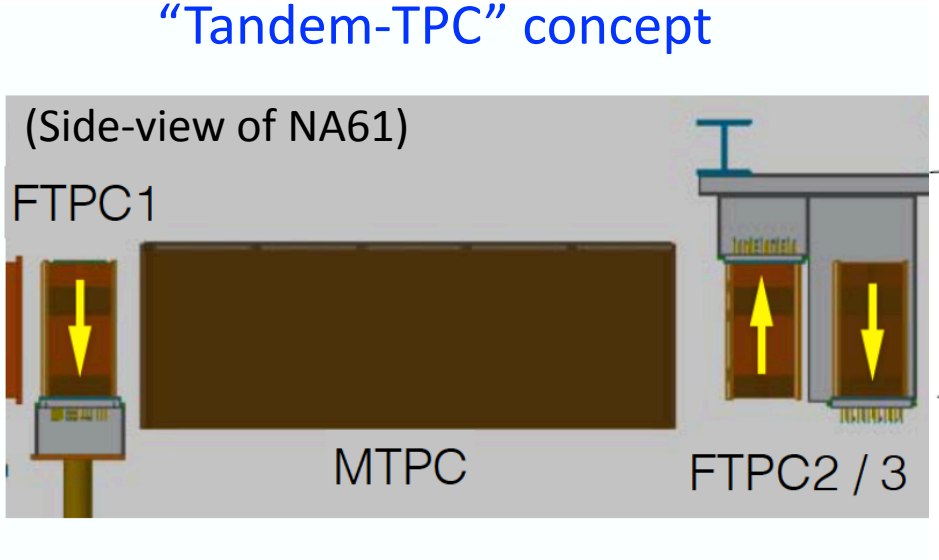
Forward Time Projection Chambers (FTPCs)

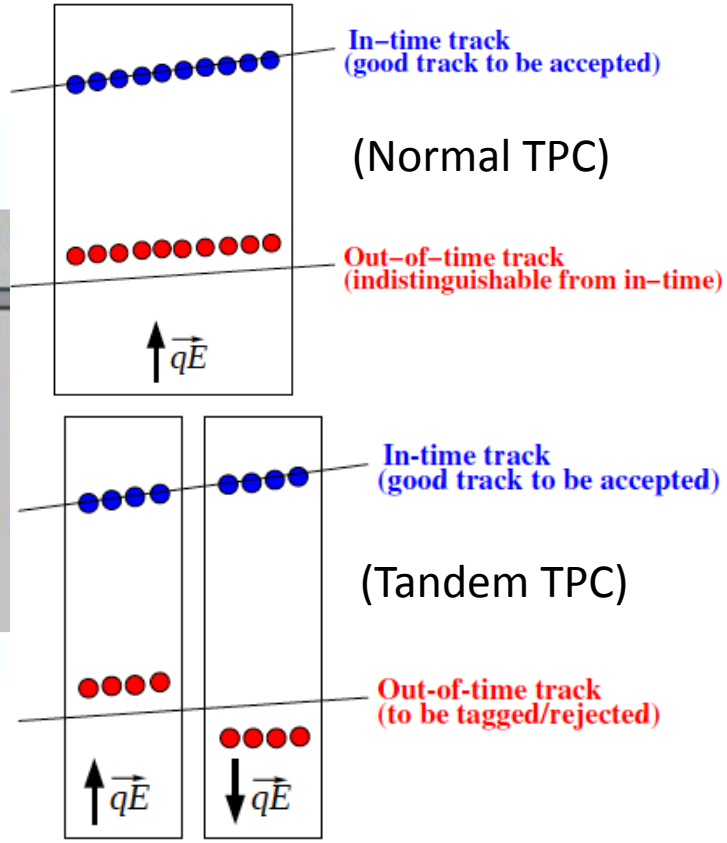
- Construction complete by 2017 and included in data taking since 2017
  - A major contribution from the US-NA61 group

Low mass TPC design

- light plastic frame
- thin copper-etched kapton film field cage

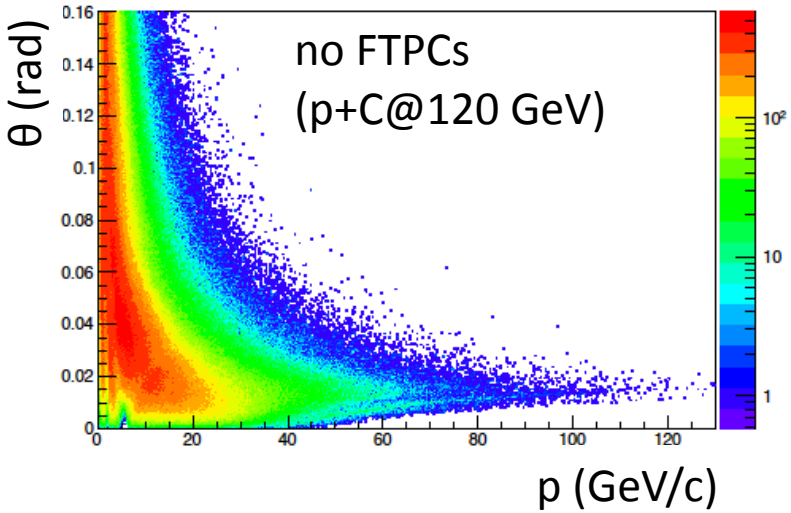
Beam off-time background rejection

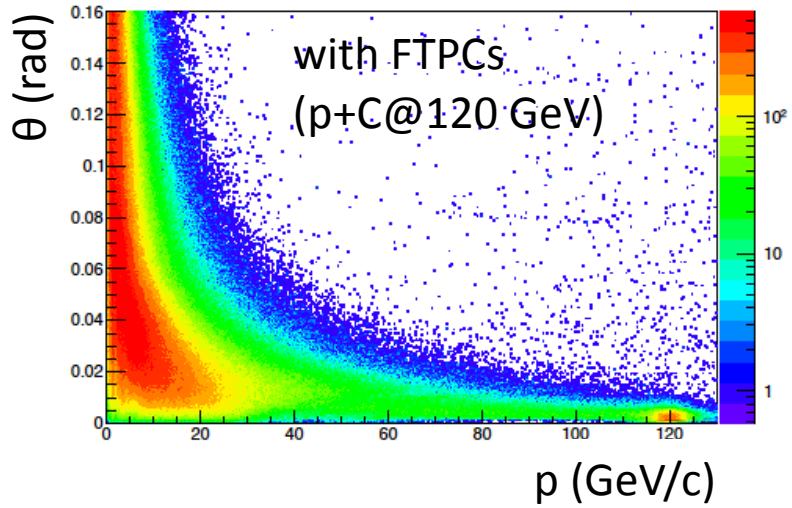




FTPC Performance

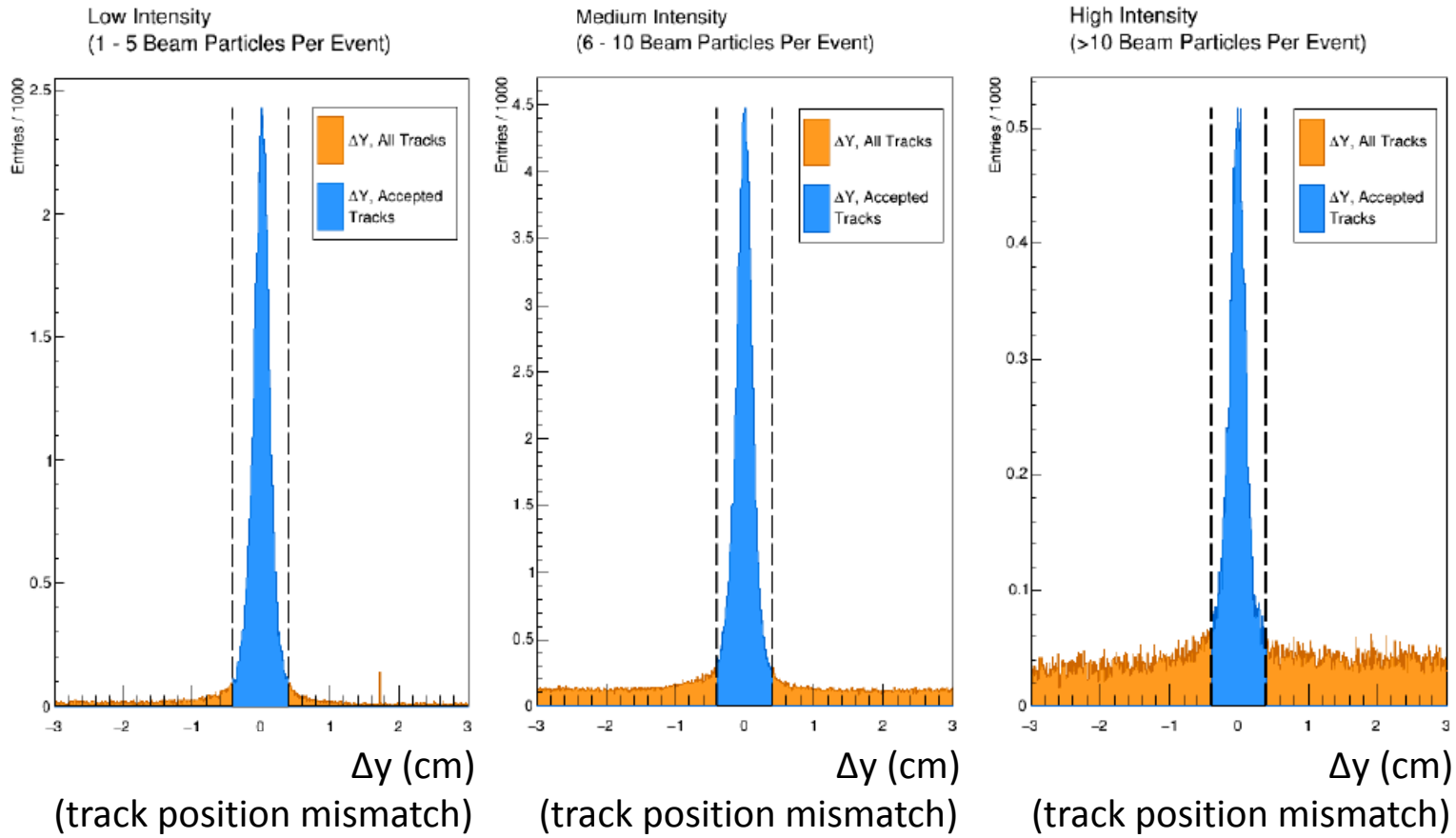
- Particle acceptance





Greatly improves the forward acceptance

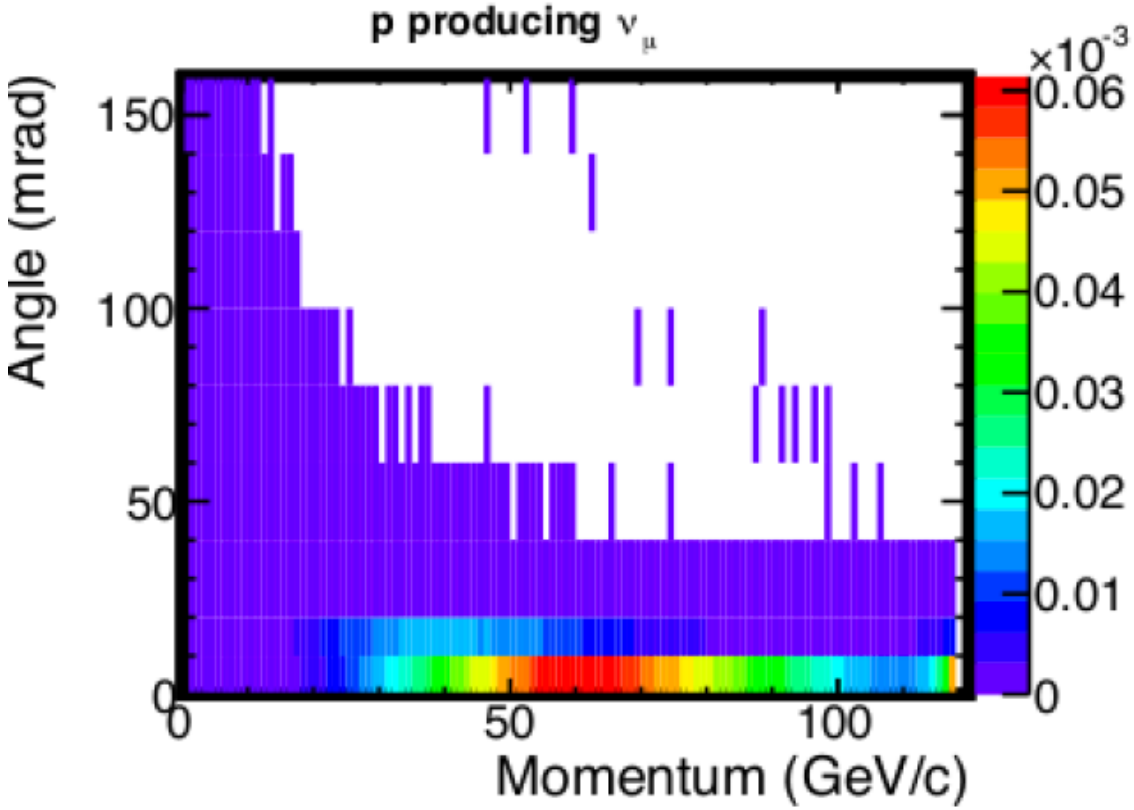
- Beam off-time background rejection



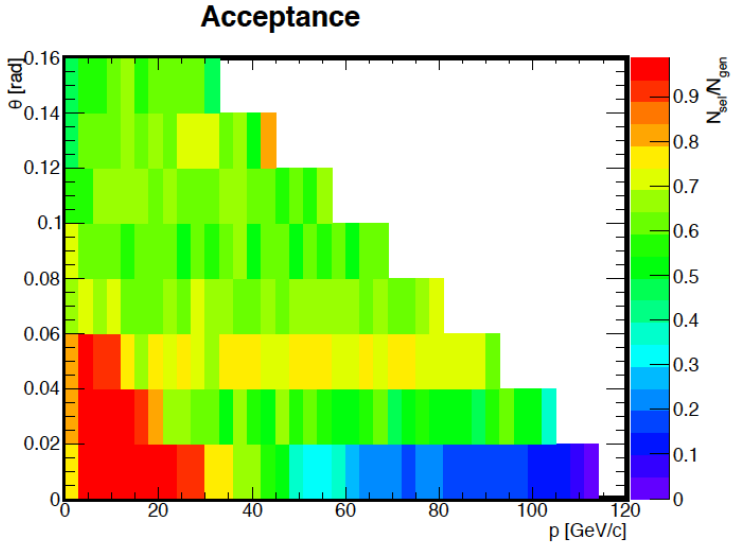
Can select particles that arrive in-time (= trigger timing)

FTPC performance paper has been submitted to *JINST*
(Preprint —> arXiv:2004.11358)

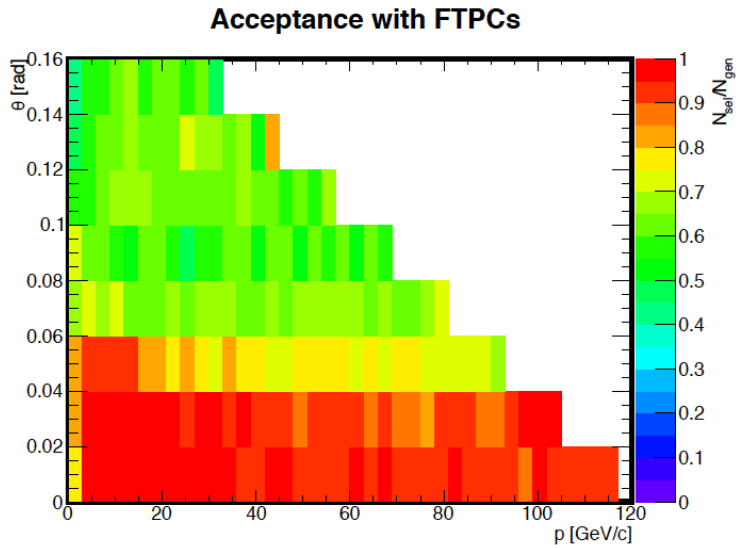
Hardware: Forward TPCs



DUNE with 120 GeV beam
(proton contribution to the neutrino flux)



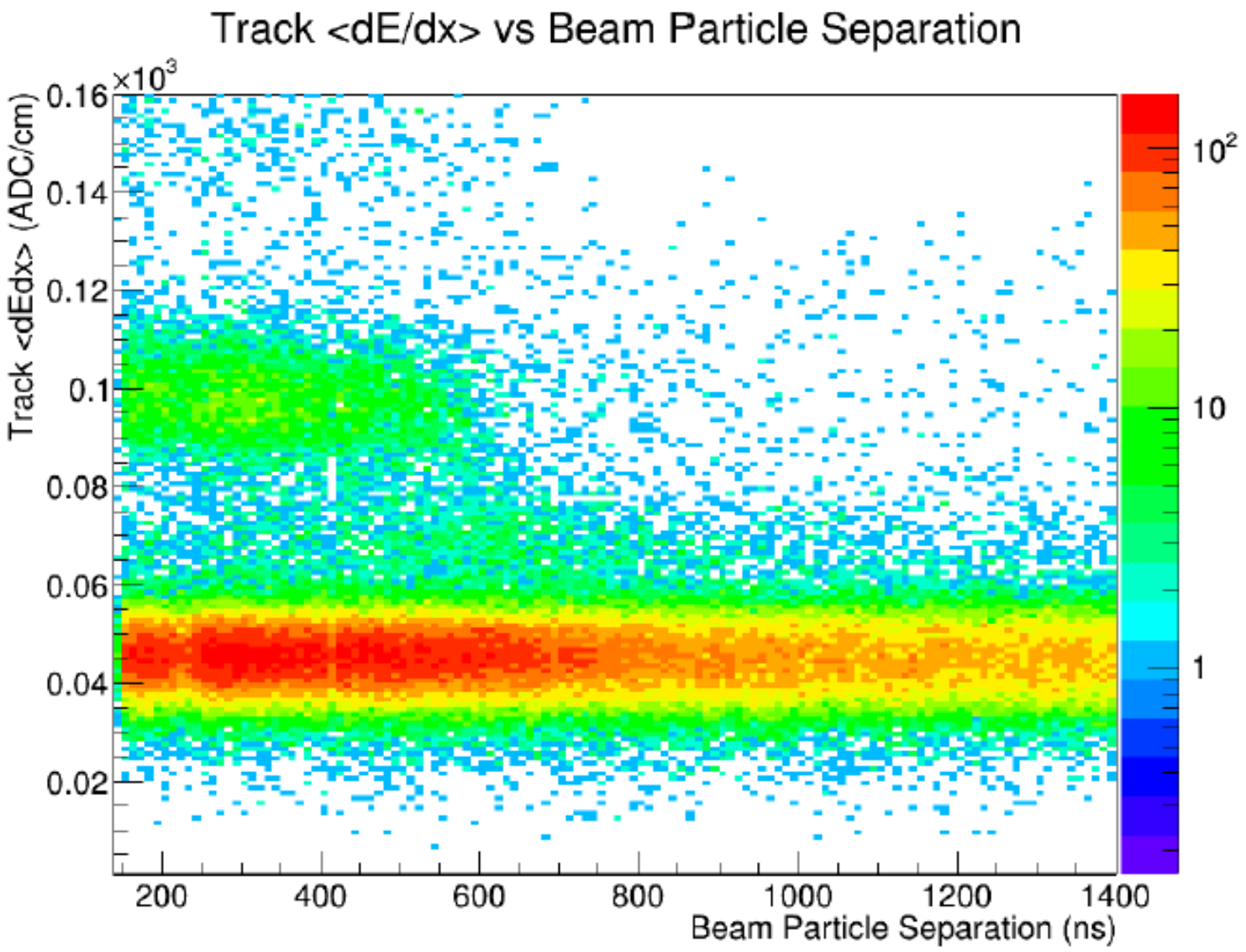
NA61/SHINE acceptance (original)



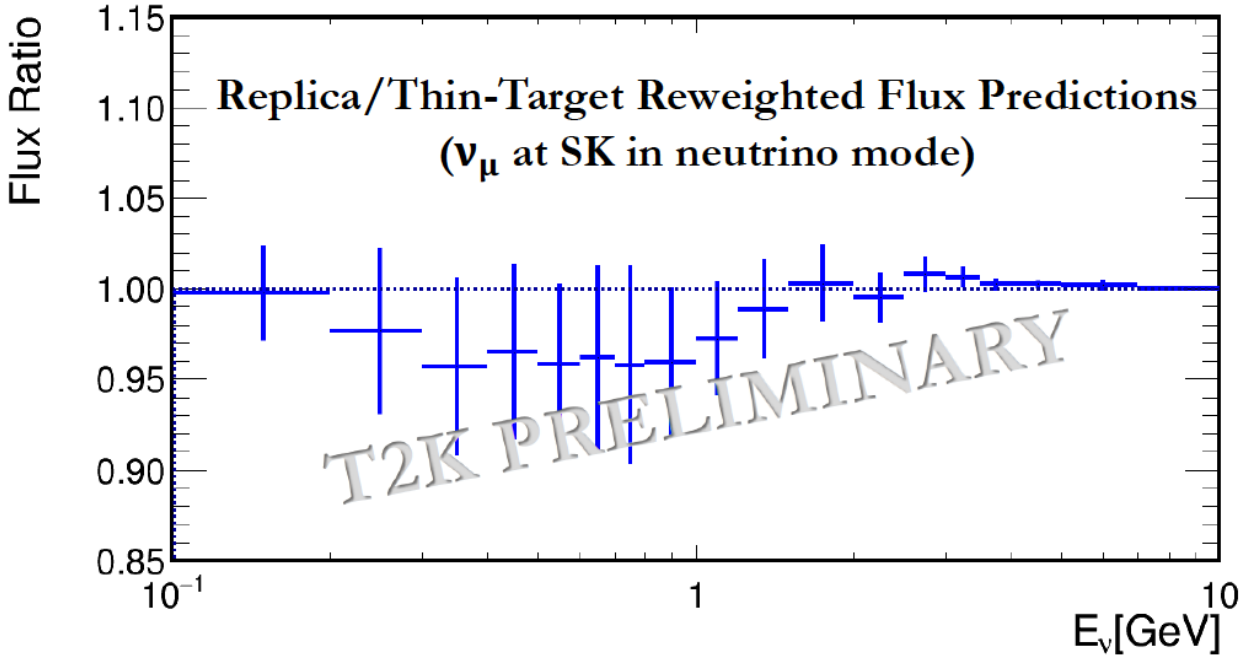
(with FTPCs)

- Fully cover important phase-space for the LBNF beamline

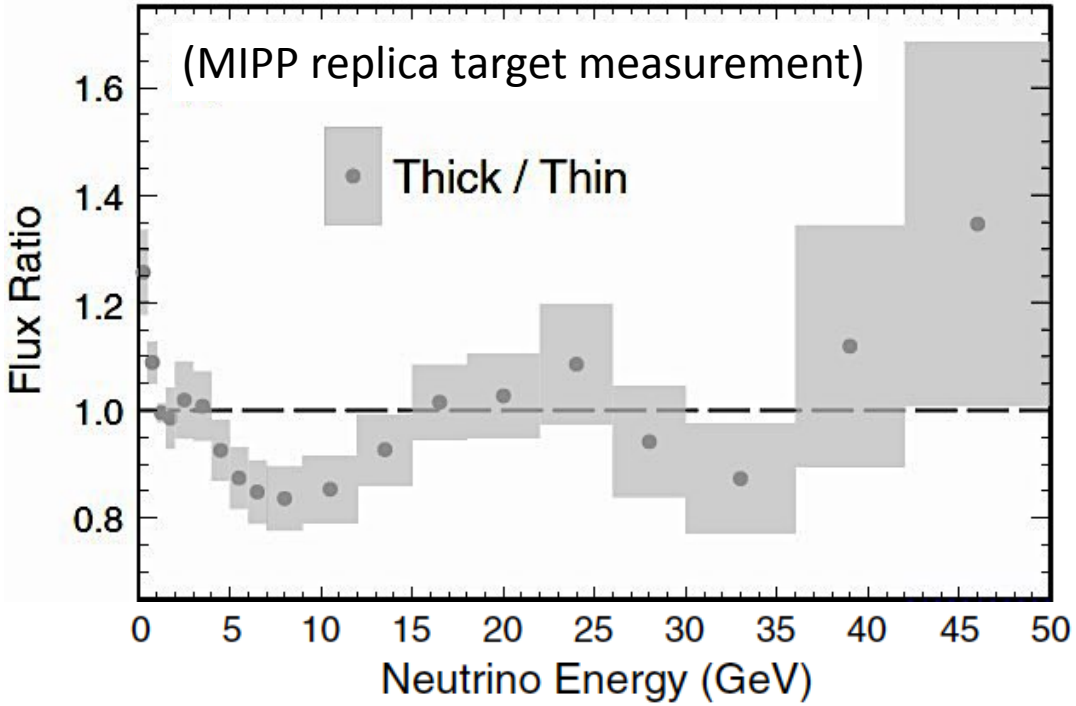
Hardware: Forward TPCs



Thin vs Replica Data Flux Tuning



T2K (T. Vladisavljevic): arXiv:1804.00272



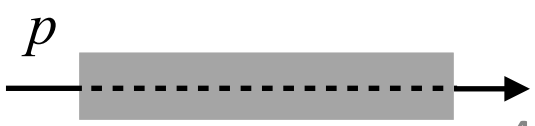
MINERvA: Phys. Rev. D94, 092005 (2016)

- Difference observed for both T2K and NuMI beamlines —> Due to beam interaction rate?
- This issue needs to be understood

  —> Measurements of beam attenuation, further precision total cross section

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

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



Low-Energy Beamline at NA61/SHINE

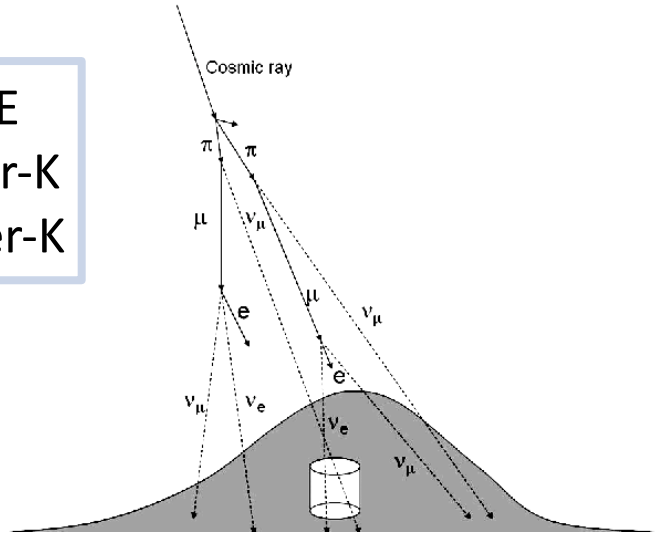
T2K / Hyper-K

- Measurements of unconstrained interactions
  - pion beam: 1-6 GeV
  - proton beam: > 4 GeV
  - kaon beam: 1-10 GeV

Atmospheric neutrinos

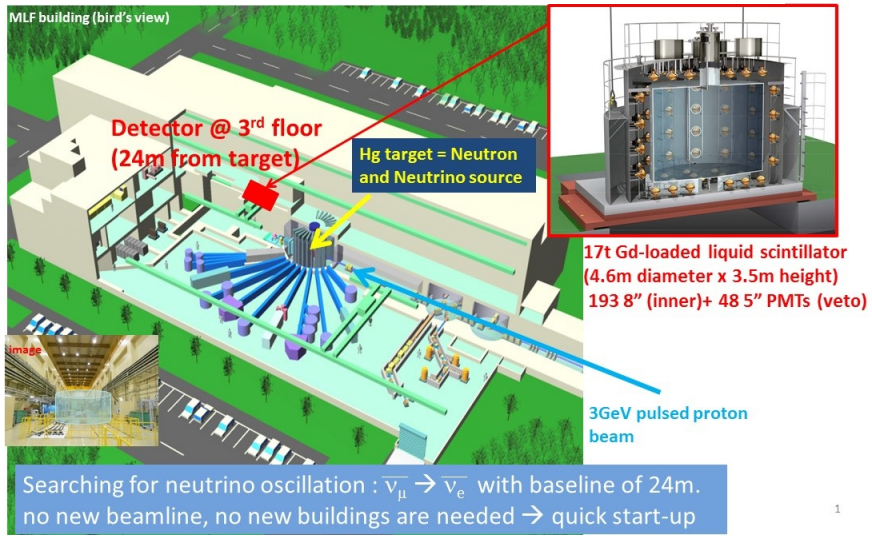
- Measurements to improve flux predictions

- DUNE
- Super-K
- Hyper-K



JSNS2 (J-PARC E56) experiment (sterile neutrino)

- proton (3 GeV) on mercury target
  - No data exist —> Hard to predict BG

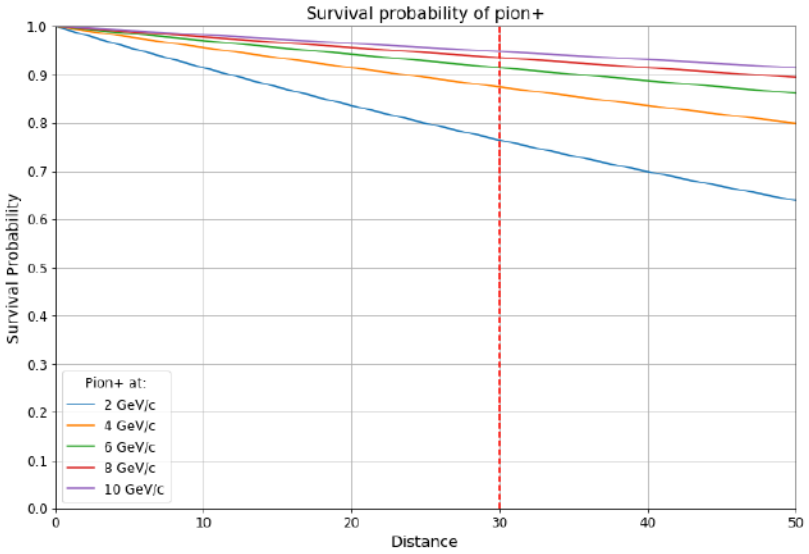


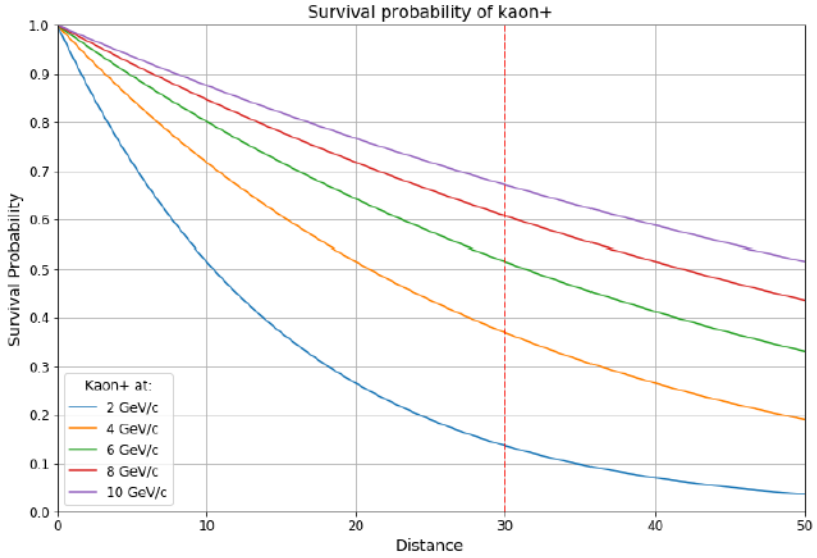
(At MLF building in J-PARC)

We welcome new ideas and collaborators !!

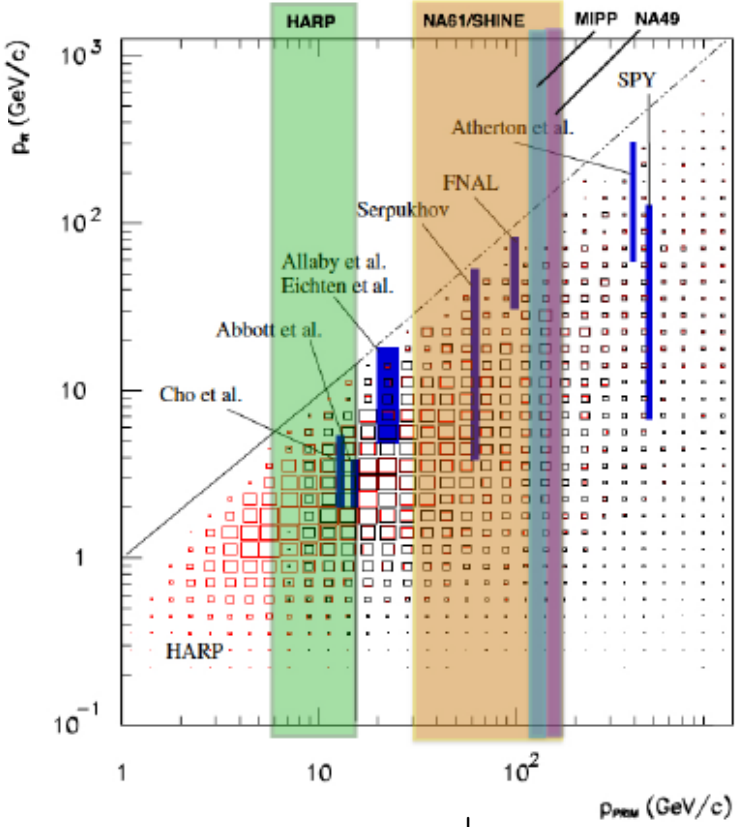
Low Momentum Beamline

- There is a possibility to have a low momentum (< 20 GeV/c) beamline around 2024
- This can be useful for:
  - Low momentum hadron data set which does not exist to constrain neutrino flux
  - Atmospheric neutrino flux studies





G. Barr
(NA61 beyond 2020 workshop)



$$p + \mathrm{N} \rightarrow \pi^{\pm} + X$$