Hadron Production Measurements for Long-Baseline Neutrino Experiments with NA61/SHINE

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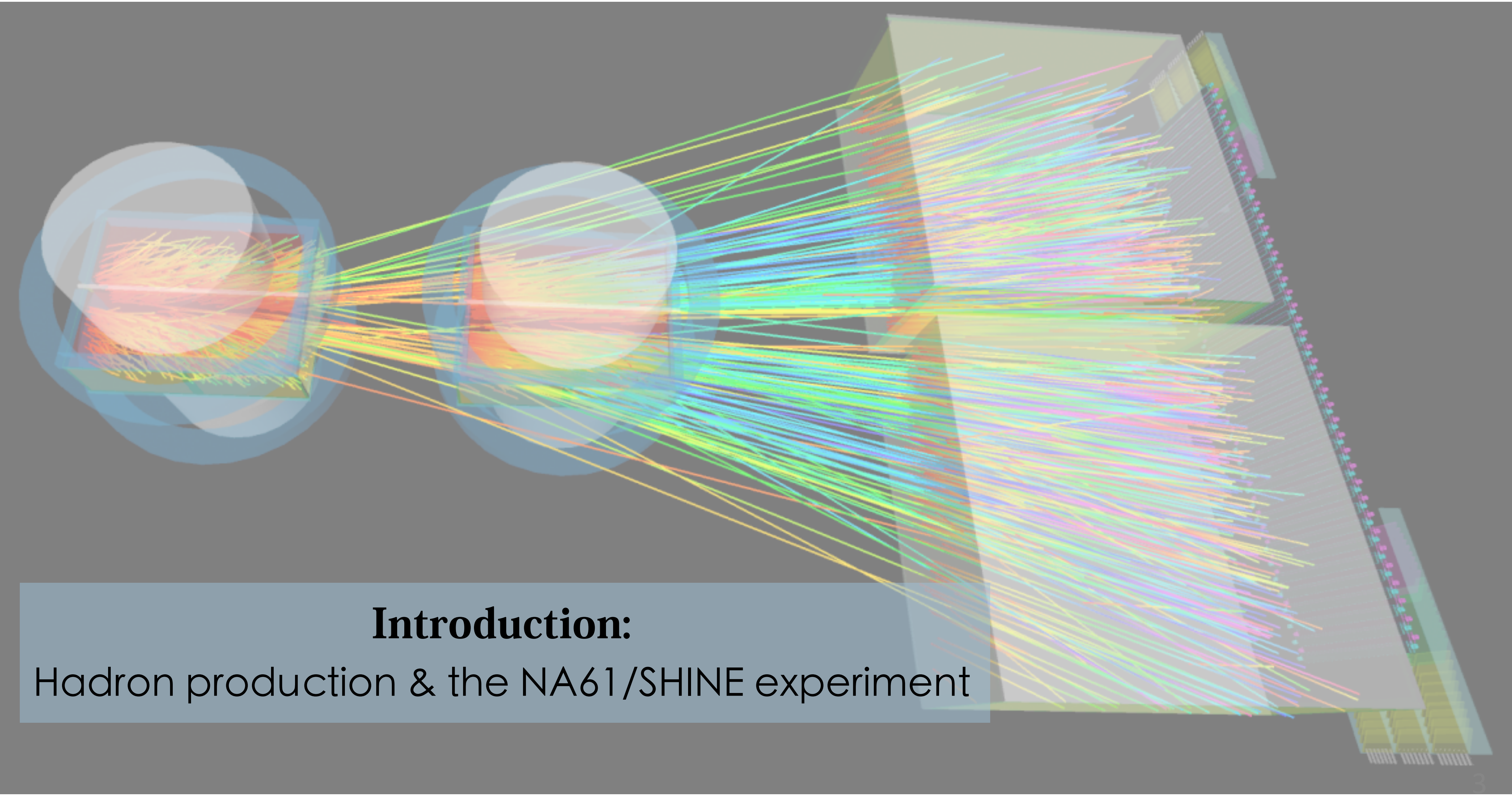
Contents

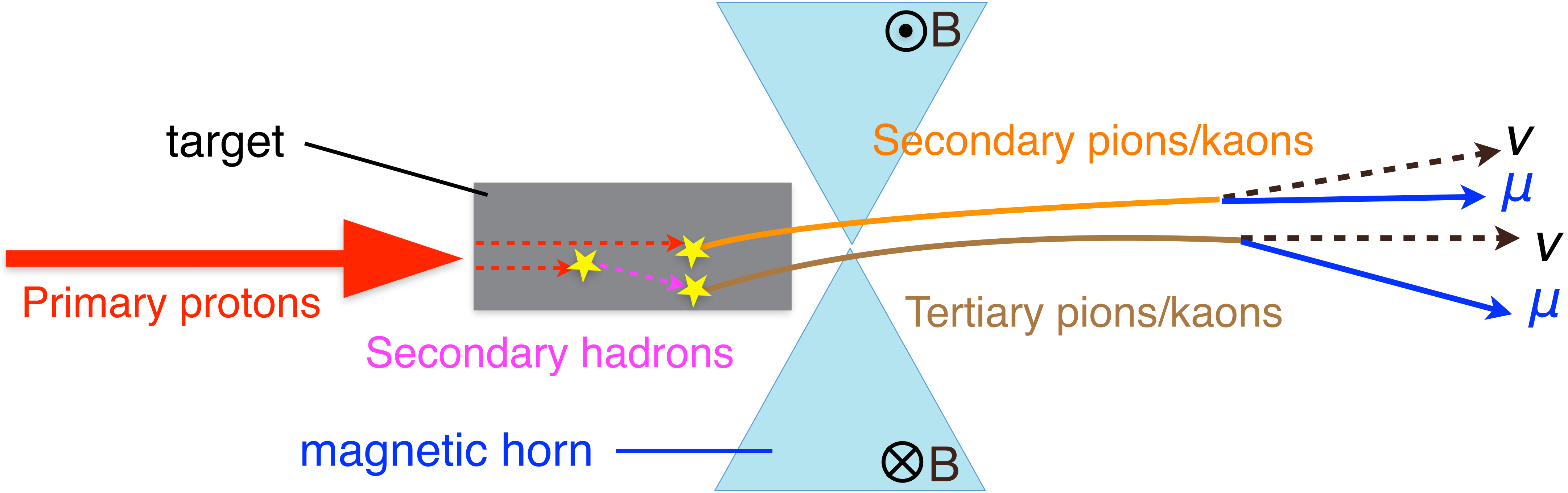
- Introduction: Hadron production & the NA61/SHINE experiment
- Results and Plans: Measurements for the T2K flux prediction
- Results and Plans: Measurements for the Fermilab neutrino program
- Prospect: NA61 beyond 2020
- Summary



Introduction:

Hadron production & the NA61/SHINE experiment

Hadron production



Pions, Kaons, protons, and other hadrons are produced in:

- Primary interactions in the target (p + C, p + Be)
- Secondary interactions in the target (hadrons + C/Be)
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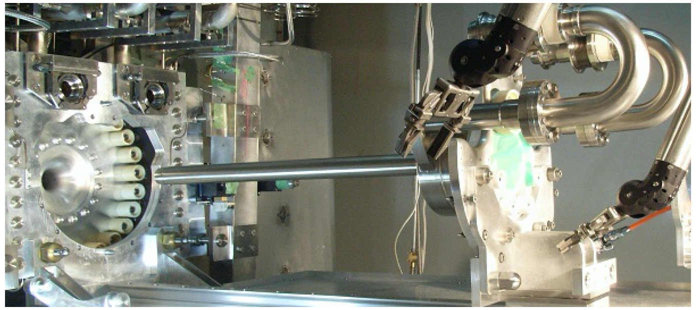
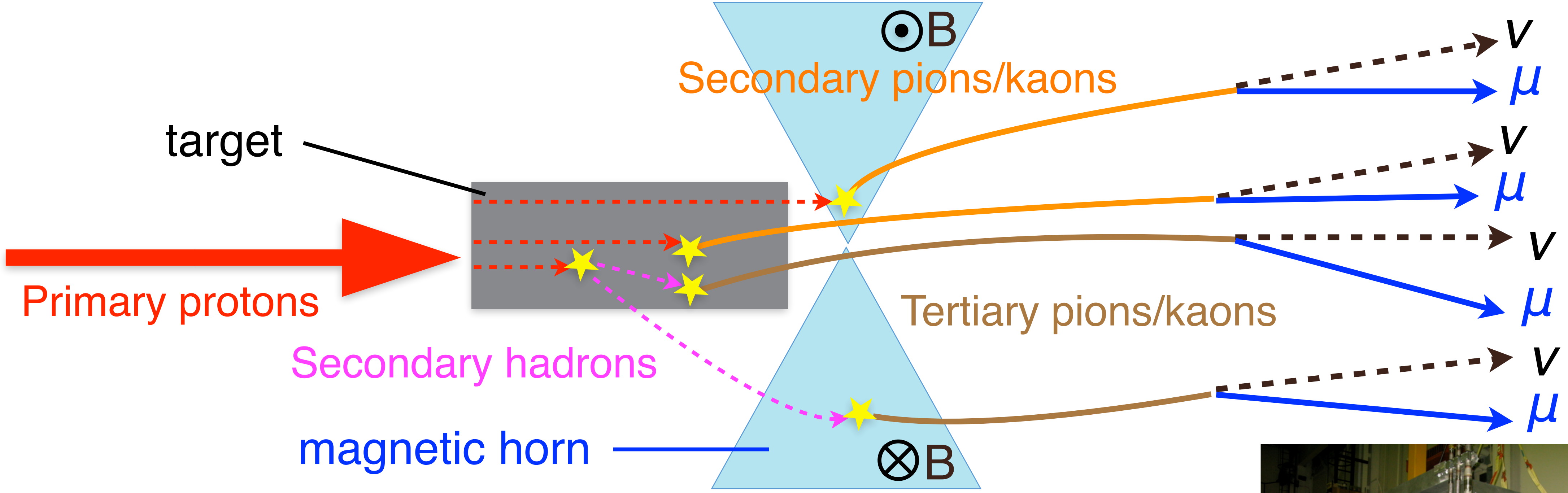
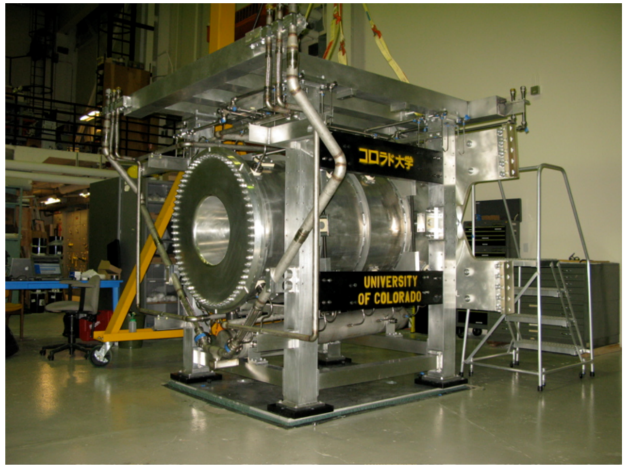


T2K target

Hadron production





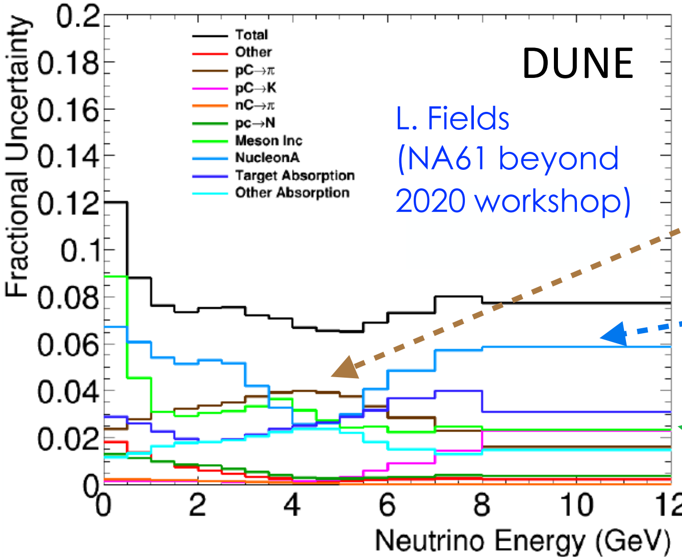
T2K horn

Pions, Kaons, protons, and other hadrons are produced in:

- Primary interactions in the target (p + C, p + Be)
- Secondary interactions in the target (hadrons + C/Be)
- Primary interactions with horn or beamline materials (p + X)
- Secondary interactions with horn or beamline materials (hadrons + X)

Importance of hadron production measurements

- Hadron production is the leading source of uncertainty on the neutrino flux prediction
  - Near-detectors can not fully constrain the flux at the far site (near-to-far flux ratio)
  - Neutrino cross-section measurements and near-detector physics rely on precise neutrino flux prediction (absolute flux)
- Requirements for the future long-baseline neutrino experiments (Hyper-K, DUNE)
  - Total systematic uncertainty: below 4% for oscillation measurements
  - Current T2K (ν_e CCQE): ~6% total uncertainty, including ~3% uncertainty on "Φ x σ"
  - Similar situation will be expected for the Hyper-K and DUNE experiments



The largest sources (e.g. DUNE)

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

Nucleon interactions not covered by existing data

Pion and Kaon re-interactions

Precise measurements with larger statistics

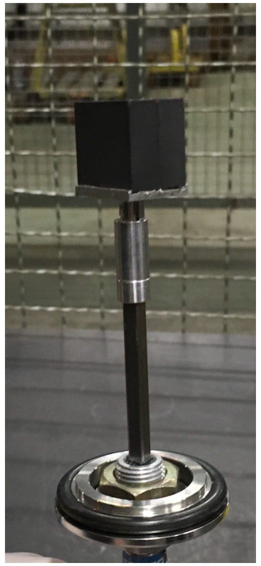
New measurements with sufficient large acceptance

Dedicated measurements with π and K beams

What kind of measurements to constrain flux?

- Thin target: a few % of nuclear interaction length(λ)
  - Measure total inelastic and production cross-sections
  - Measure differential cross-sections ($\frac{d^2\sigma}{dp\,d\theta}$) of produced hadrons

p, $\pi^{+/-}$, $K^{+/-}$ beams on nuclear targets (C, Be, Al, etc..) to study primary and secondary interactions

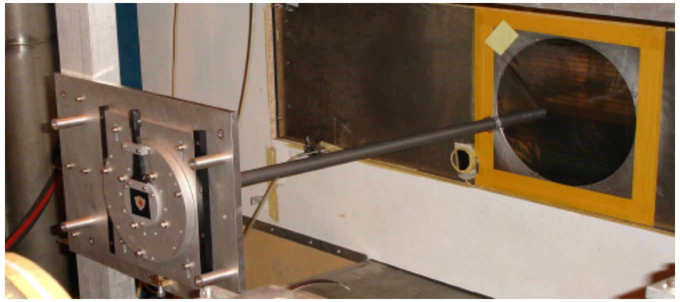


Thin graphite target

- Replica target (thick target):
  - Measure hadron production yields exiting target
  - Measure beam survival probability to estimate production cross-section

$$P_{\mathrm{survival}} = e^{-Ln\sigma_{\mathrm{prod}}}$$ (*L*: length of target, *n*: number of carbon atoms per unit volume)

proton beams on replica targets



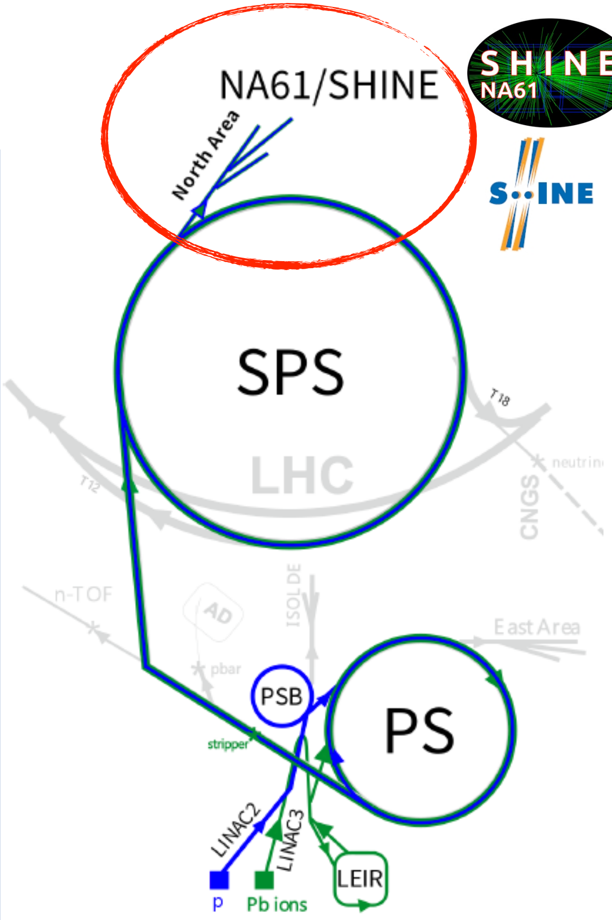
T2K replica graphite target (1.9 λ)

NA61/SHINE can satisfy hadron production needs for long-baseline neutrino experiments !

The NA61/SHINE Experiment

"The SPS Heavy Ion and Neutrino Experiment"

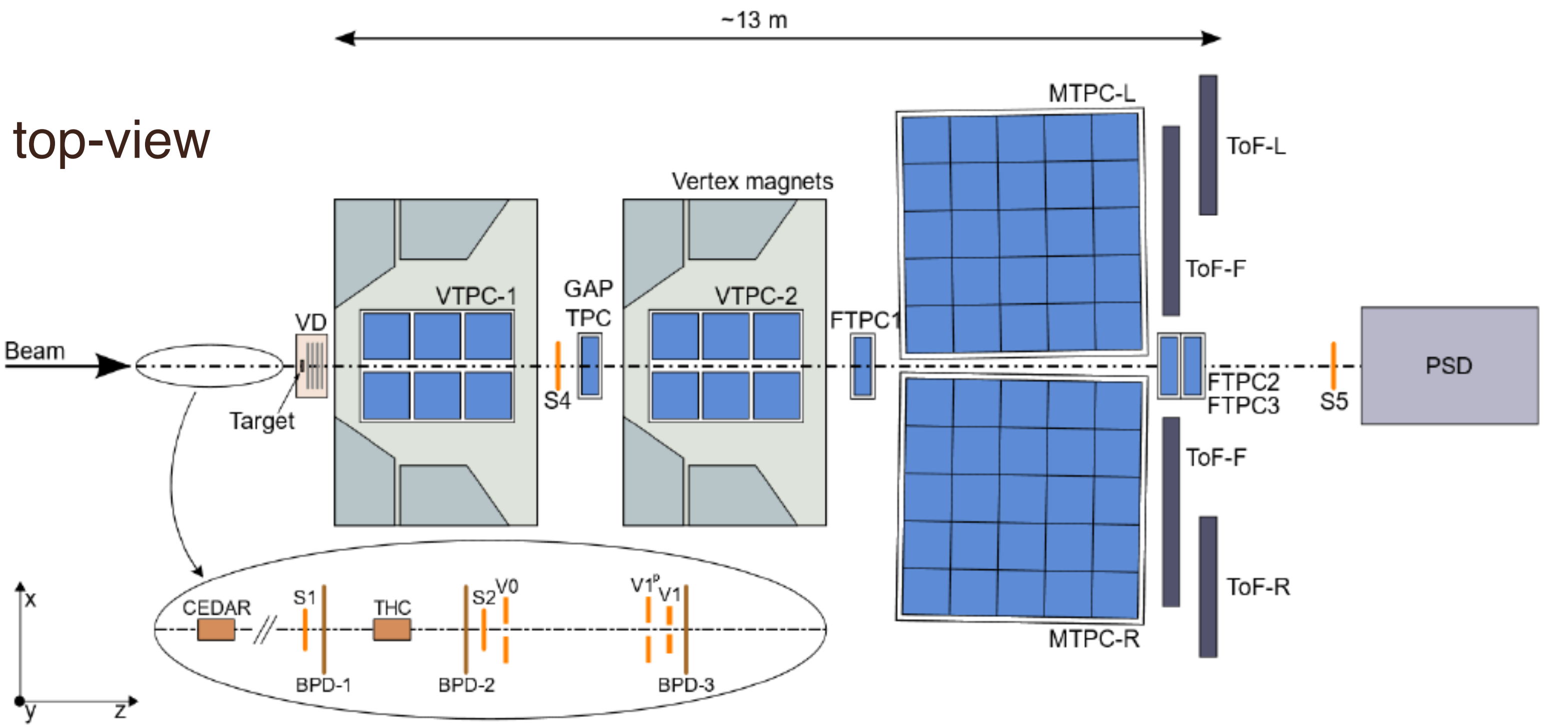
- hadron beams
  - primary protons at 400 GeV/c
  - secondary hadrons (*p*, *π*, *K*) at 13 - 350 GeV/c
- Ion beams
  - primary (Ar, Xe, Pb) at 13 - 150 AGeV/c
  - secondary Be at 13 - 150 AGeV/c (from Pb fragmentation)

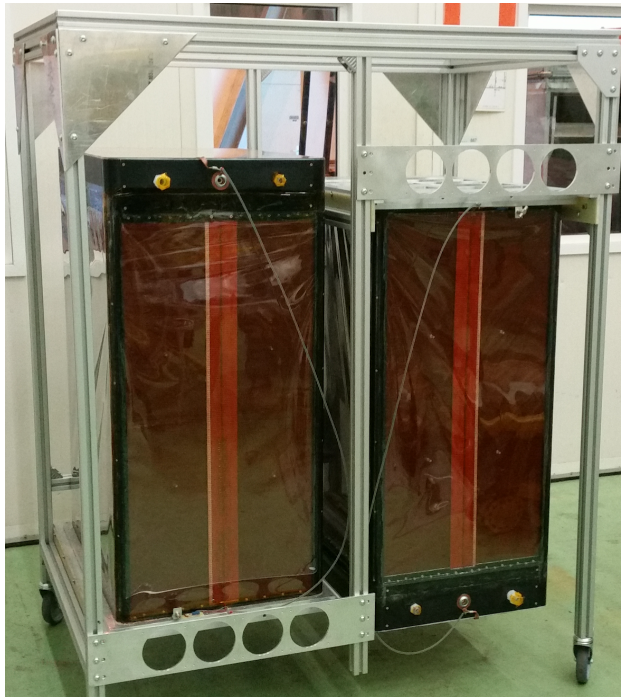


- Broad physics program
  - Heavy ion
    - Search for the critical point
    - Study the onset of QCD deconfinement
  - Cosmic ray
    - Hadron production measurements to improve air-shower model predictions
    - Study (anti-)deuteron production mechanism for the AMS and GAPS experiments
  - Neutrino
    - Hadron production measurements to improve neutrino beam flux predictions

NA61/SHINE experimental facility

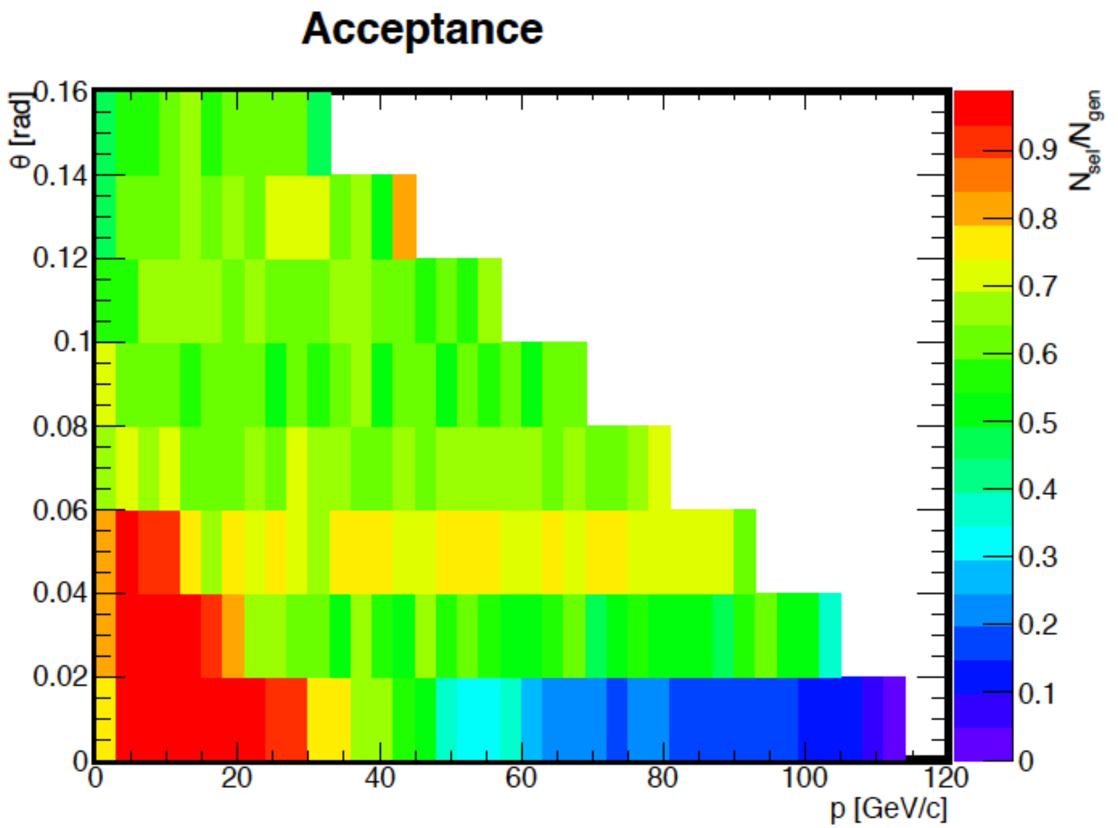
top-view

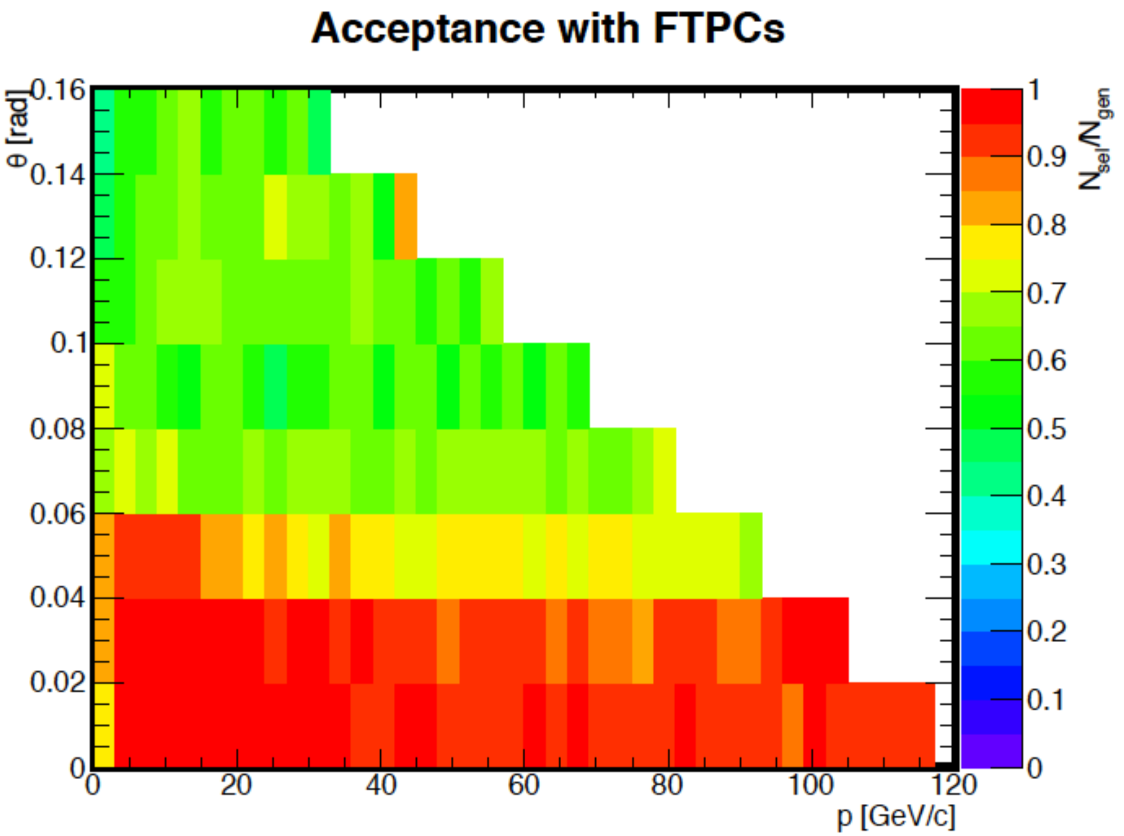




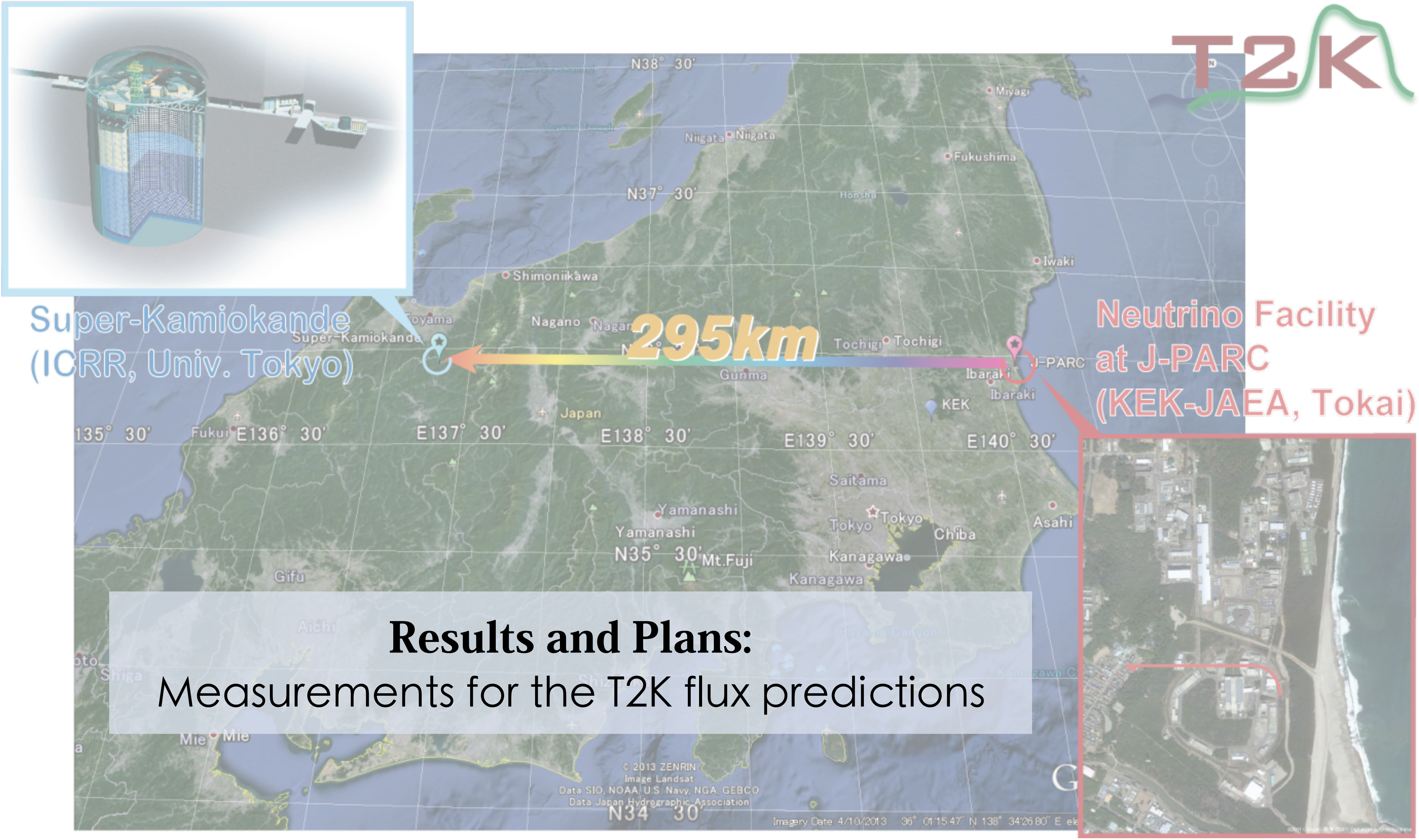
- Large acceptance spectrometer for charged particles
  - TPCs as main tracking detector, time-of-flight detectors placed downstream
  - 2 dipole magnets with 1.5 T maximum field (9 Tm bending power)
- Recent facility upgrades
  - Forward TPCs to fill the forward acceptance gap
  - New DAQ readout with DRS4 chips replacing FASTBUS, CAMAC, and custom electronics

NA61/SHINE acceptance after facility upgrade





- Huge improvement on the forward acceptance
  - Particularly important to understand forward proton and pion productions for NuMI and LBNF beamlines



Results and Plans:

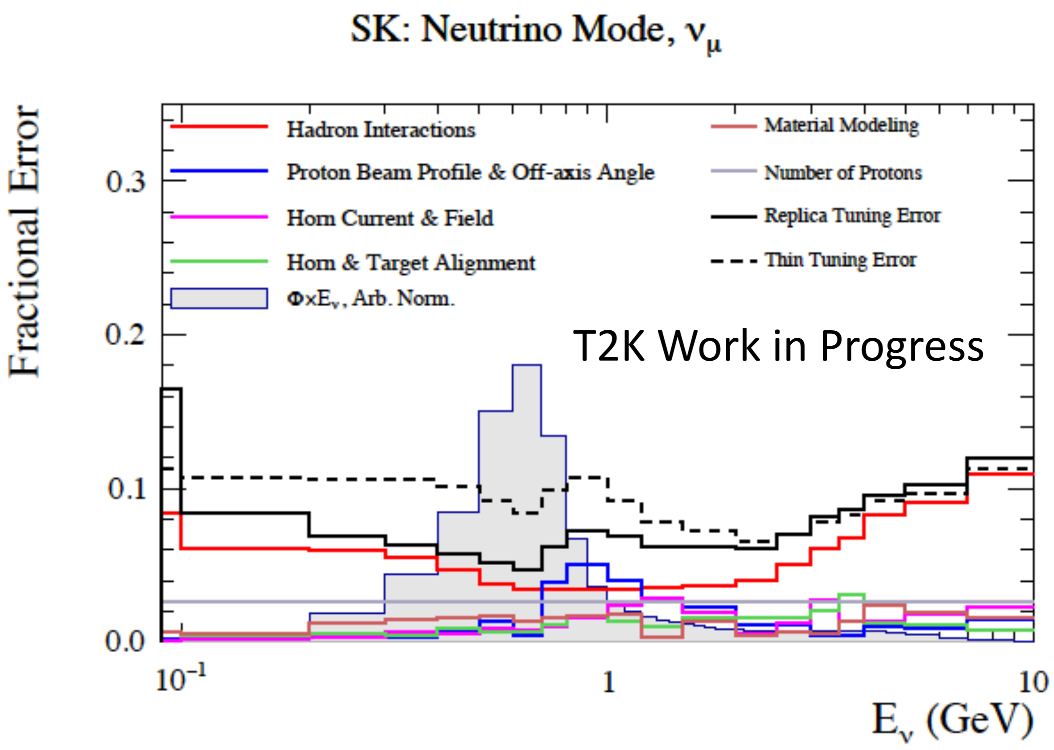
Measurements for the T2K flux predictions

Previous and ongoing measurements for T2K

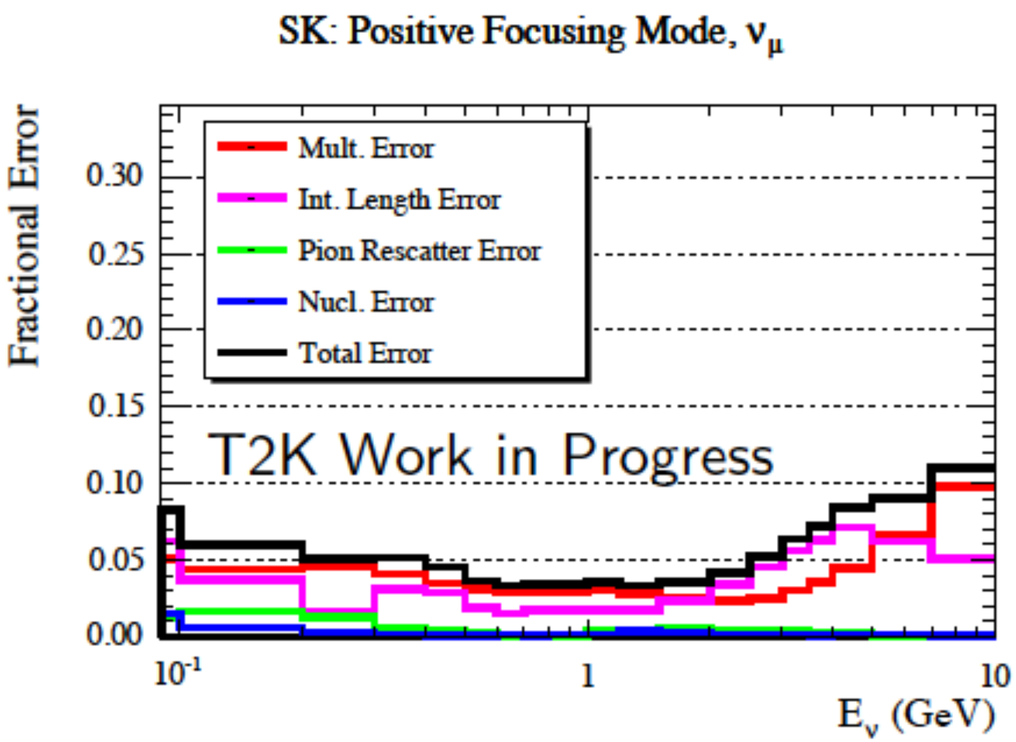
- Thin target: p@ 31 GeV/c on 2cm graphite target
  - 2007: 0.7M triggered events
    - total cross-section and $\pi^{+/-}$ spectra measurements (Phys.Rev. C84 (2011) 034604)
    - K^{+} spectra measurement (Phys.Rev. C85 (2012) 035210)
    - K^{0}_{S} and Λ^{0} spectra measurements (Phys.Rev. C89 (2014) 025205)
  - 2009: 5.2M triggered events.
    - total cross-section and $\pi^{+/-}$, p, K^{0}_{S}, and Λ^{0} spectra measurements (Eur.Phys.J. C76 (2016) 84)
- Replica target: p@ 31 GeV/c on 90cm replica graphite target
  - 2007: 0.2M triggered events (pilot run)
    - methodology, $\pi^{+/-}$ yield measurement (Nucl.Instrum.Meth. A701 (2013) 99-114)
  - 2009: 4.0M triggered events
    - $\pi^{+/-}$ yield measurement (Eur.Phys.J. C76 (2016) 617)
  - 2010: 10.0M triggered events
    - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Paper under preparation, preliminary results: https://edms.cern.ch/document/1828979/1)
  - 2010: 1.2M triggered events (high magnetic field)
    - p beam survival probability measurement (Analysis ongoing)

T2K flux uncertainty with NA61/SHINE measurements

With NA61 thin and 2009 replica target measurements



Breakdown of hadron production systematic uncertainty

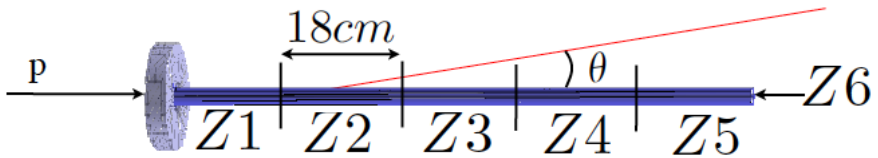


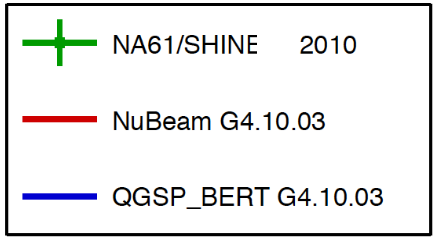
M. Friend (NA61/SHINE Beyond 2020 Workshop)

- Thin target measurements improved T2K flux uncertainty down to 10%
- 2009 replica target measurements will improve uncertainty down to < 5% (for ν from $\pi^{+/-}$)

—> Further improvement with 2010 replica target measurements !!

2010 replica target results

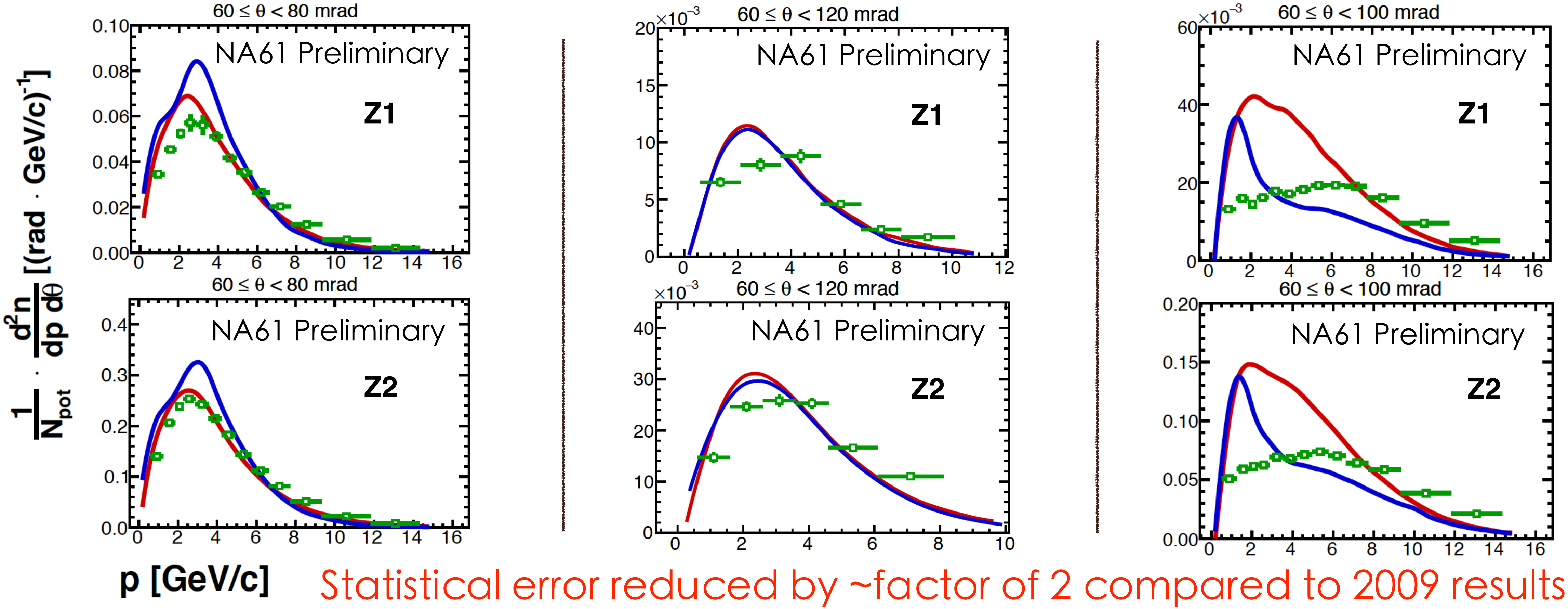




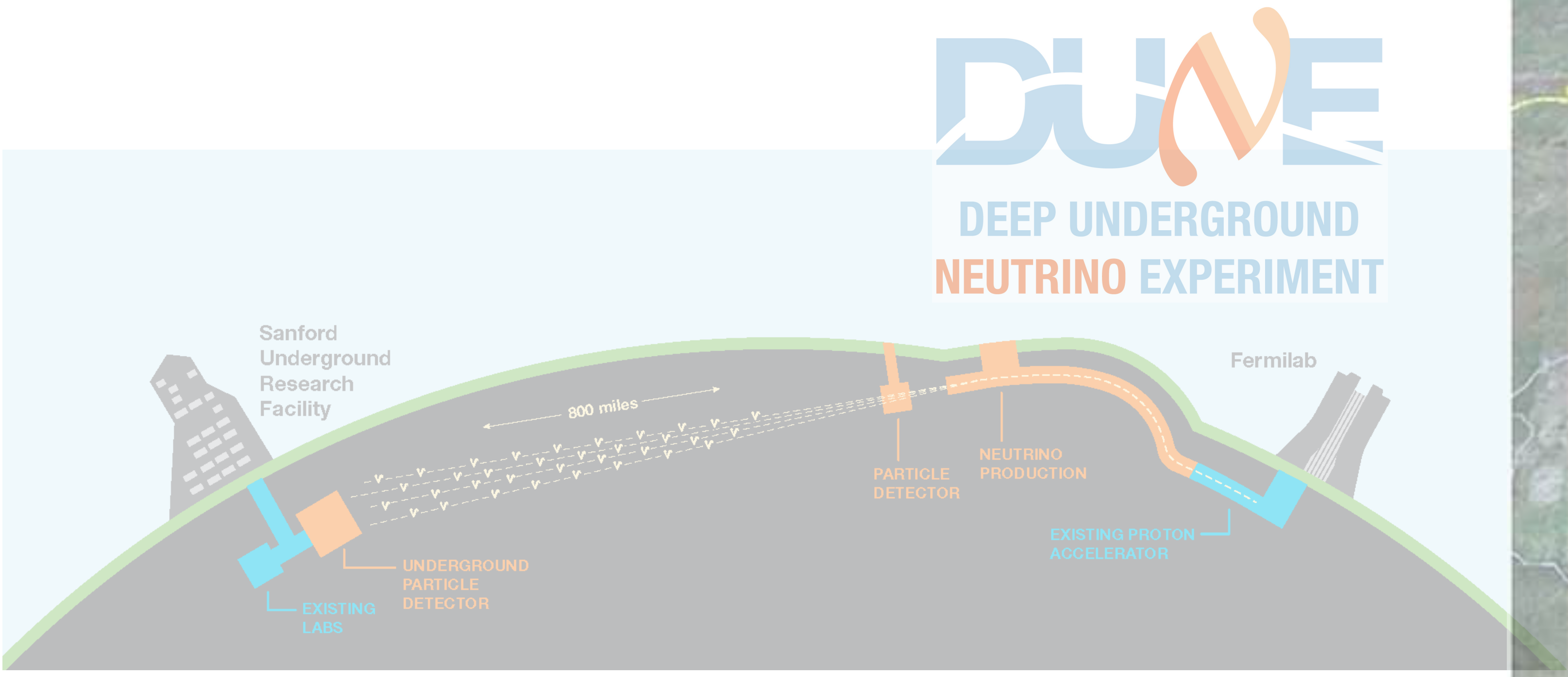
π^+ yields measurement

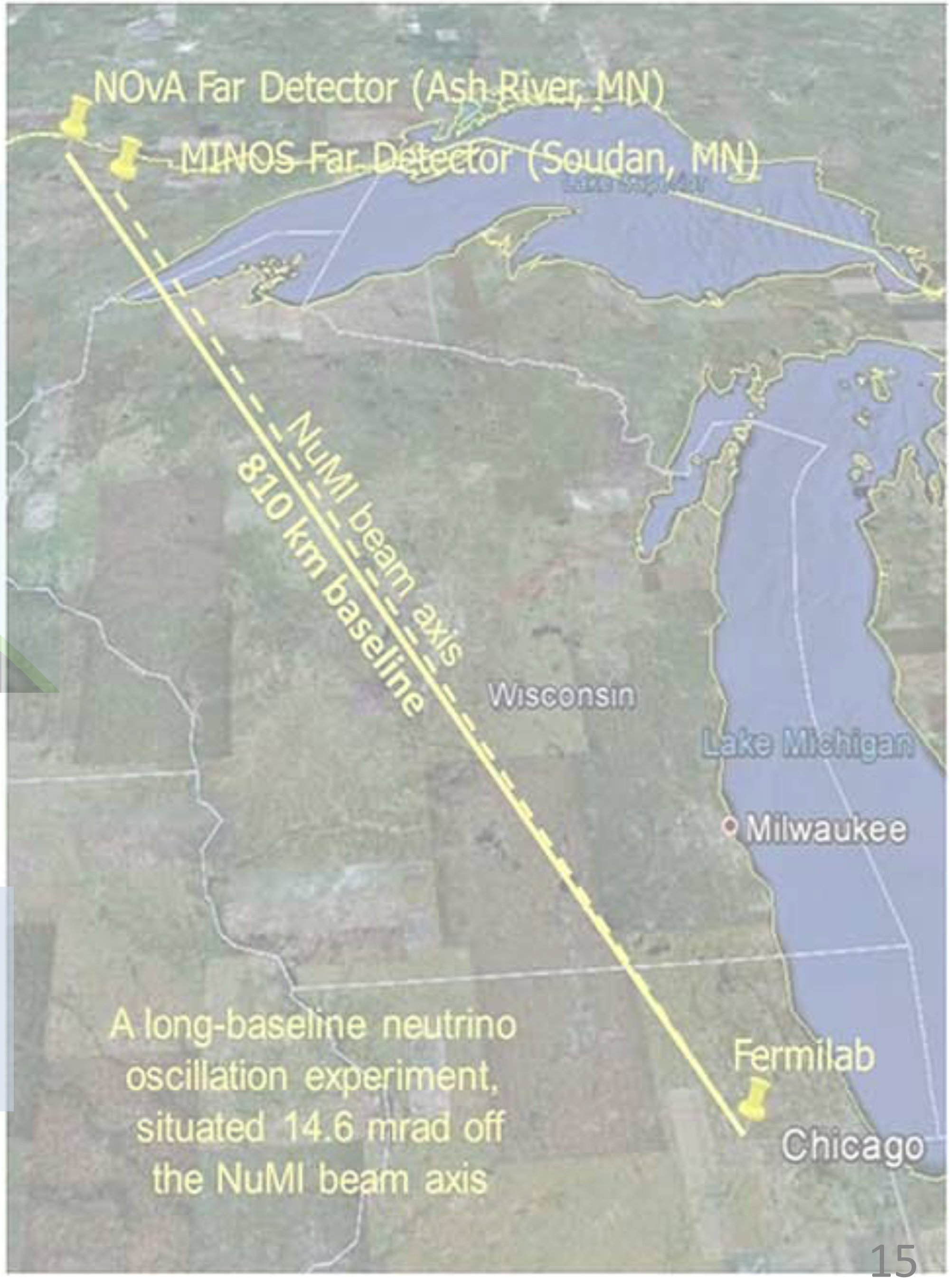
K^+ yields measurement

p yields measurement



Statistical error reduced by ~factor of 2 compared to 2009 results





Results (2015) and Plans:

Measurements for the Fermilab neutrino program

Ongoing measurements for Fermilab ν beams

- 2015 - 2017: $\pi^{+/-}$, p, K^+ beams on various thin nuclear targets (Be, C, Al)
  - 2015: total inelastic and production cross-section measurements (submitted to PRD, arXiv:1805.04546)
  - 2016: spectra measurements of $\pi^{+/-}$, $K^{+/-}$, p, K^0_S, and Λ^0 (analysis ongoing)
  - 2017: data taken last summer (calibration ongoing)

2015

dataset	events
p+C 31 GeV/c	0.4M *
π^++C 31 GeV/c	1.2M *
π^++Al 31 GeV/c	0.8M *
π^++C 60 GeV/c	0.8M *
π^++Al 60 GeV/c	0.7M *
K^++C 60 GeV/c	0.7M *
K^++Al 60 GeV/c	0.5M *

2016

dataset	events
p+C 60 GeV/c	3.1M
p+Be 60 GeV/c	2.2M
p+Al 60 GeV/c	3.5M
π^++C 60 GeV/c	3.0M
π^++Be 60 GeV/c	2.7M
p+C 120 GeV/c	4.6M
p+Be 120 GeV/c	2.5M

2017

dataset	events
π^++C 30 GeV/c	2.2M
π^++Al 60 GeV/c	3.3M
π^-+C 60 GeV/c	3.6M **
p+C 90 GeV/c	3.3M **
p+C 120 GeV/c	2.6M **
p+Be 120 GeV/c	4.0M **

very rich dataset is being analyzed

* no magnetic field

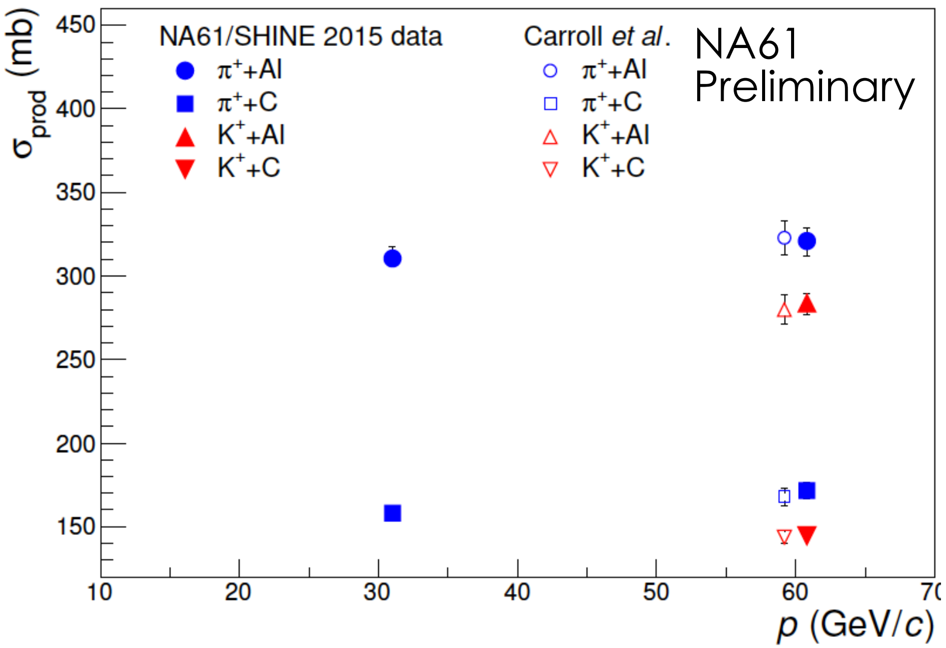
** with forward TPCs and forward ToFs

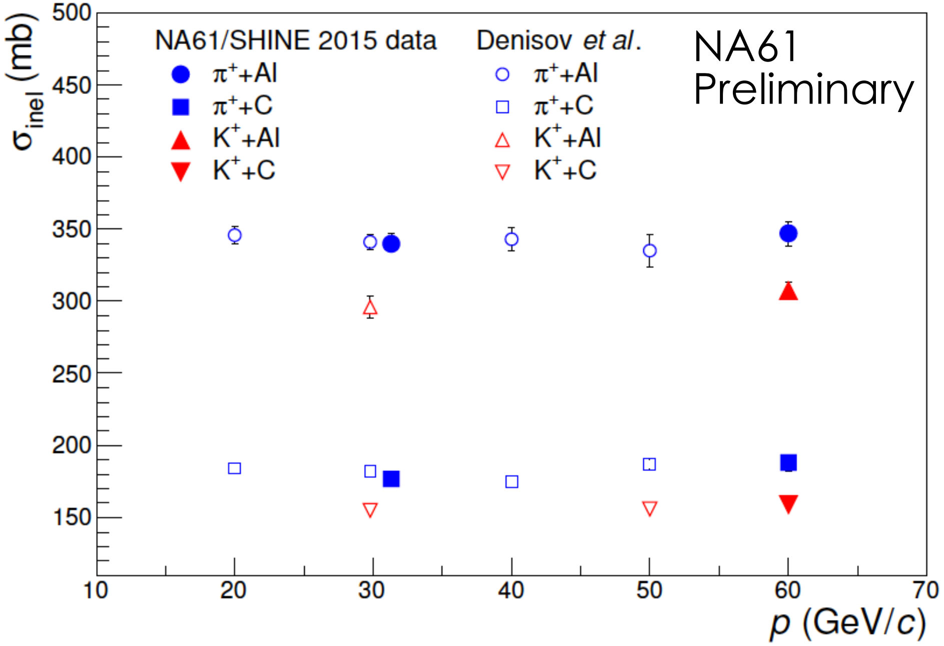
Total cross-section measurements (2015)

2015

dataset	events
p+C 31 GeV/c	0.4M *
π^++C 31 GeV/c	1.2M *
π^++Al 31 GeV/c	0.8M *
π^++C 60 GeV/c	0.8M *
π^++Al 60 GeV/c	0.7M *
K^++C 60 GeV/c	0.7M *
K^++Al 60 GeV/c	0.5M *

* no magnetic field





- Measurements for 6 different interactions
- Precision of measurements: 2~3%, while current NuMI beam for MINERvA assumes an uncertainty of 5% for pions and 10-30% for kaons
  - Greatly reduce the uncertainty, especially for kaon interactions

Preprint available: https://arxiv.org/abs/1805.04546

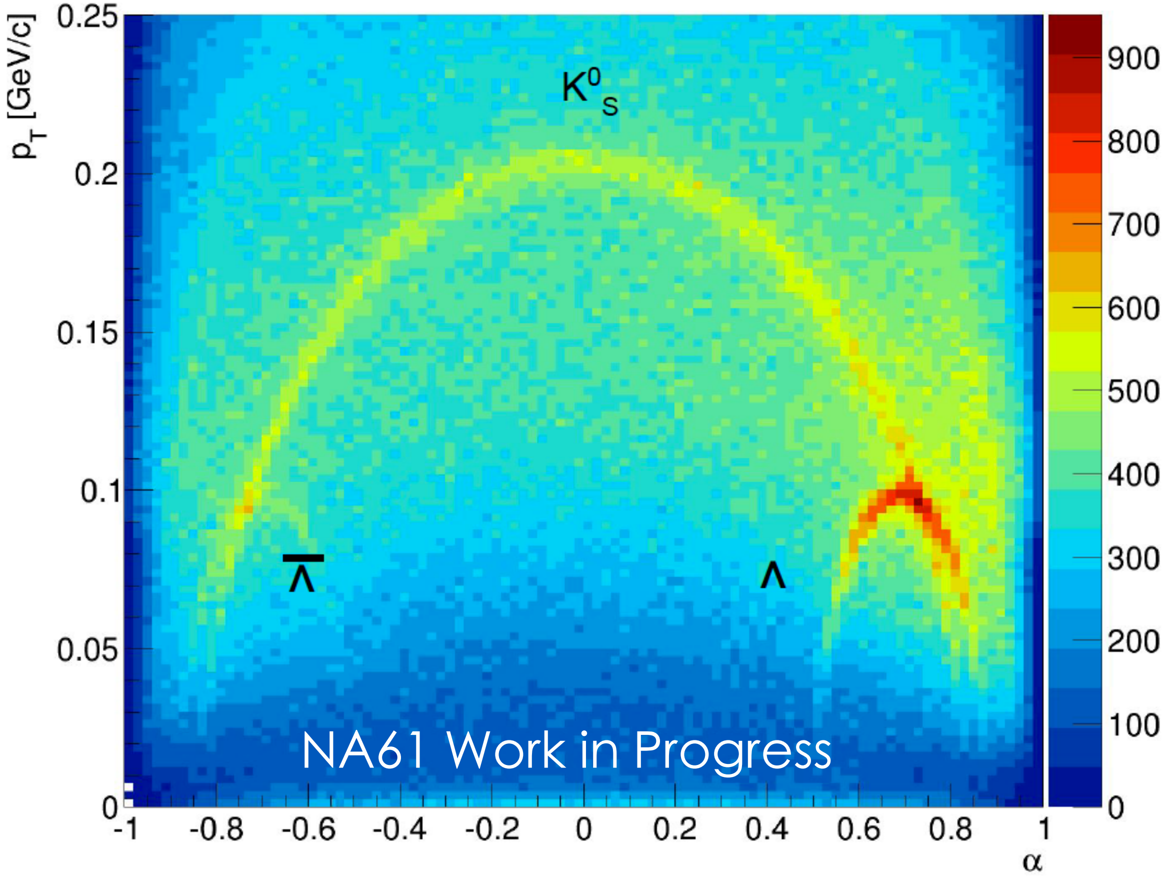
Submitted to Phys. Rev. D

Spectra measurements (2016)

2016

dataset	events
p+C 60 GeV/c	3.1M
p+Be 60 GeV/c	2.2M
p+Al 60 GeV/c	3.5M
π^++C 60 GeV/c	3.0M
π^++Be 60 GeV/c	2.7M
p+C 120 GeV/c	4.6M
p+Be 120 GeV/c	2.5M

V_0 candidates in Armenteros-Podolanski plot



p_T: transverse momentum of oppositely charged decay products with respect to the V_0

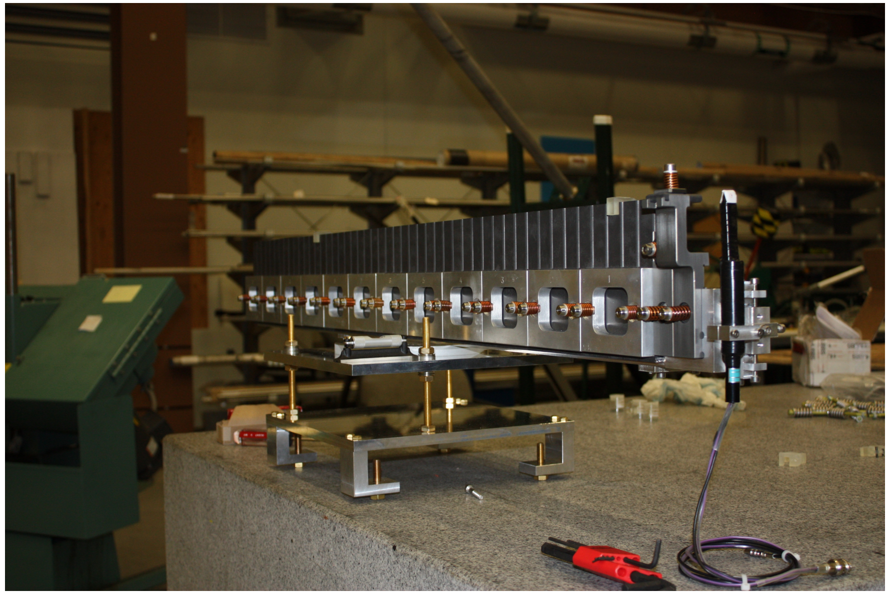
α: longitudinal momentum asymmetry

$$\alpha = \frac{p_l^+ - p_l^-}{p_l^+ + p_l^-}$$

- Spectra measurements for Fermilab neutrino beam tunings are ongoing

2018 data taking plans

- Replica target: *p*@ 120 GeV/c on 1.2m NuMI replica target (graphite fins)
  - 4 weeks in July 2018 (beam time allocated)
- Thin target: K^+ beam@ 60 GeV/c on thin nuclear targets
  - 1 week in fall 2018 (beam time allocated)



The last year of currently approved NA61/SHINE physics program

—> Program extension "Addendum to the NA61/SHINE proposal" has been submitted to the SPSC in March 2018

Prospect:

NA61 beyond 2020

NA61 beyond 2020

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
http://na61.web.cern.ch/

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

- Significant facility upgrades are planned
  - DAQ upgrade: ~1kHz TPC readout
  - new ToF walls with mRPC
  - SCIFI-based beam position detector
  - Large-acceptance silicon pixel detector (ALPIDE)
  - Construction of low momentum beamline (under discussion with CERN beam group)
- Potential neutrino measurements in 2021-2024
  - Hadron production below 18 GeV/c for accelerator-based and atmospheric neutrino experiments
  - Replica target of DUNE and HyperK (if prototypes are ready) with dedicated tracking detectors
  - new nuclear target measurements: target materials (e.g. Super-sialon ceramic) and support materials (Al, Fe, Ti, water, etc..)

Summary

- Precision hadron production measurements are essential to reduce the leading systematic uncertainty on the neutrino flux prediction
  - NA61/SHINE thin and replica target measurements have improved and will further improve the flux prediction in T2K
  - NA61/SHINE measurements for the Fermilab neutrino programs are ongoing
- NA61/SHINE is proposing program extension after LS2
  - Significant facility upgrades allow us to pursue important measurements
  - If you need dedicated hadron production data, this is a great opportunity to measure it !

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, Moscow
  - 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

NA61/SHINE detector performance

momentum resolution

- typical resolution:

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

timing resolution

- ToF-L/R:

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

- ToF-F:

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

dE/dx resolution

- typical resolution:

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

Particle ID