NUCLEUS – 2020: October 11-17, 2020

Hadron production measurements at NA61/SHINE for precise determination of accelerator neutrino fluxes

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for the NA61/SHINE collaboration

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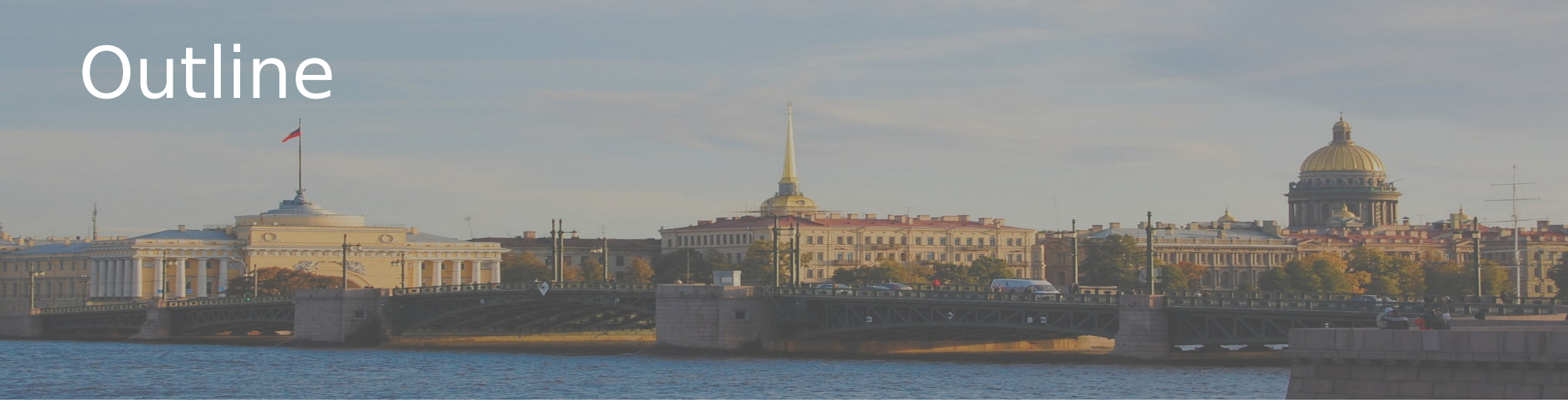
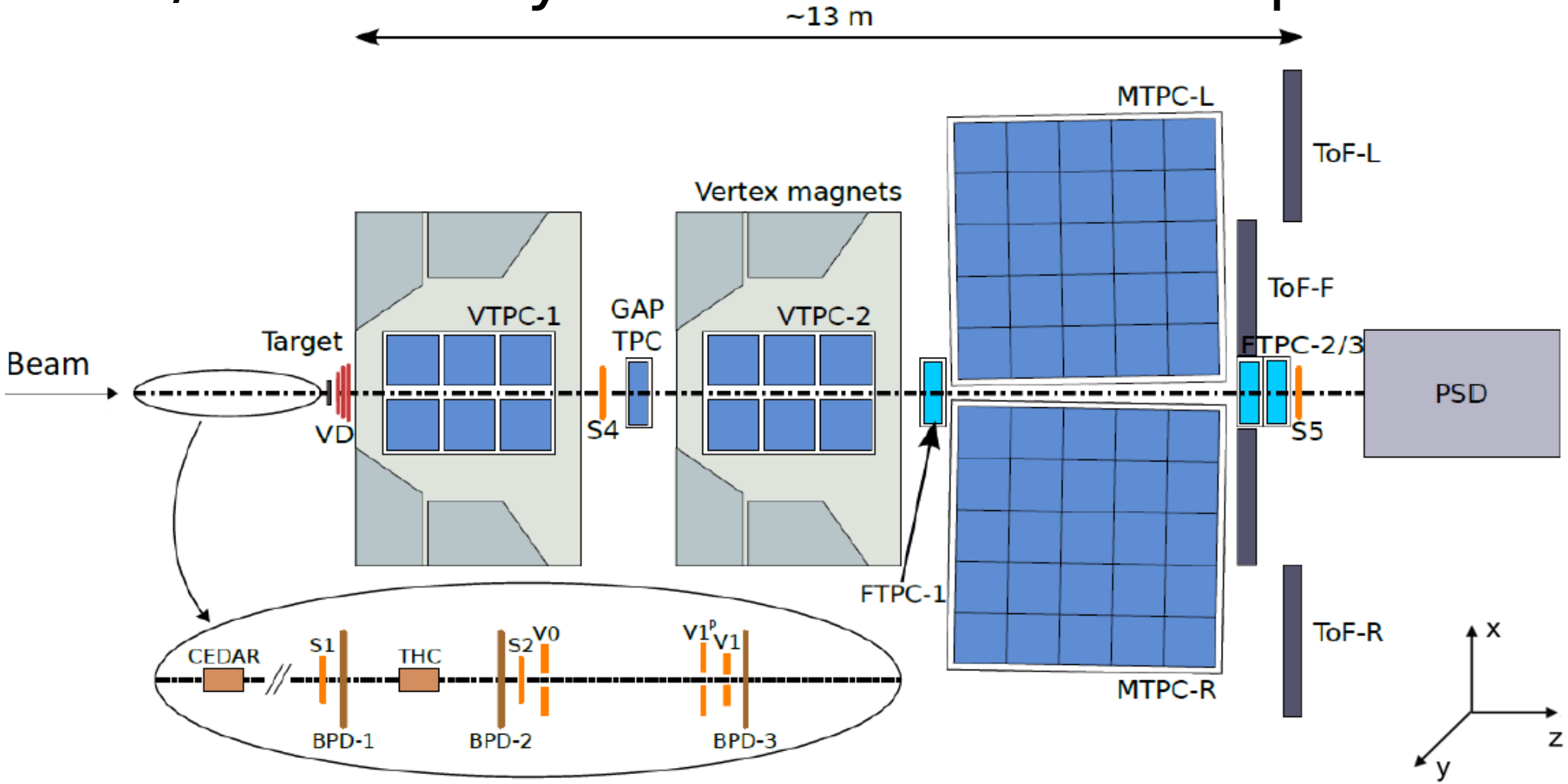
Outline



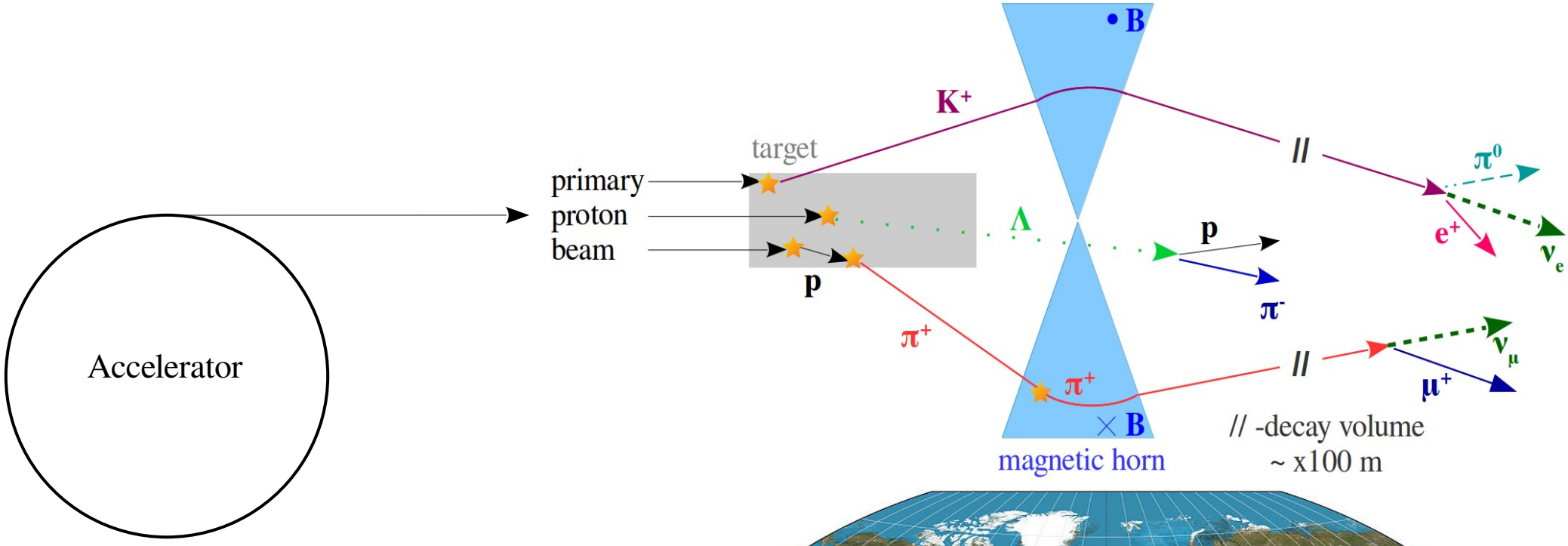
- The NA61/SHINE experiment
- Introduction to hadron production measurements for accelerator neutrino experiments
- Latest results
- Future plans

NA61/**S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

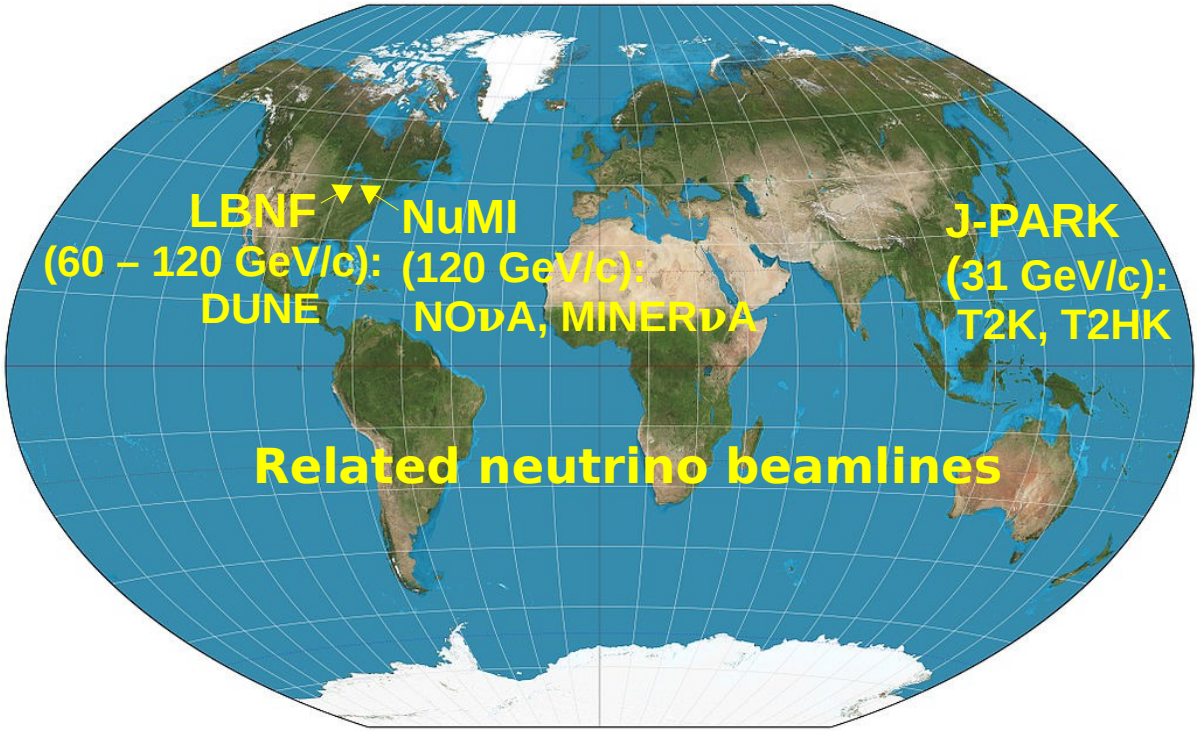


- fixed-target experiment at CERN's SPS
- operating with ion and hadron beams in range 13 - 400 GeV/c
- momentum, charge and dE/dx measurements provided by TPC tracking system
- particle ID with TPC and TOF detectors

Accelerator-generated neutrino beams

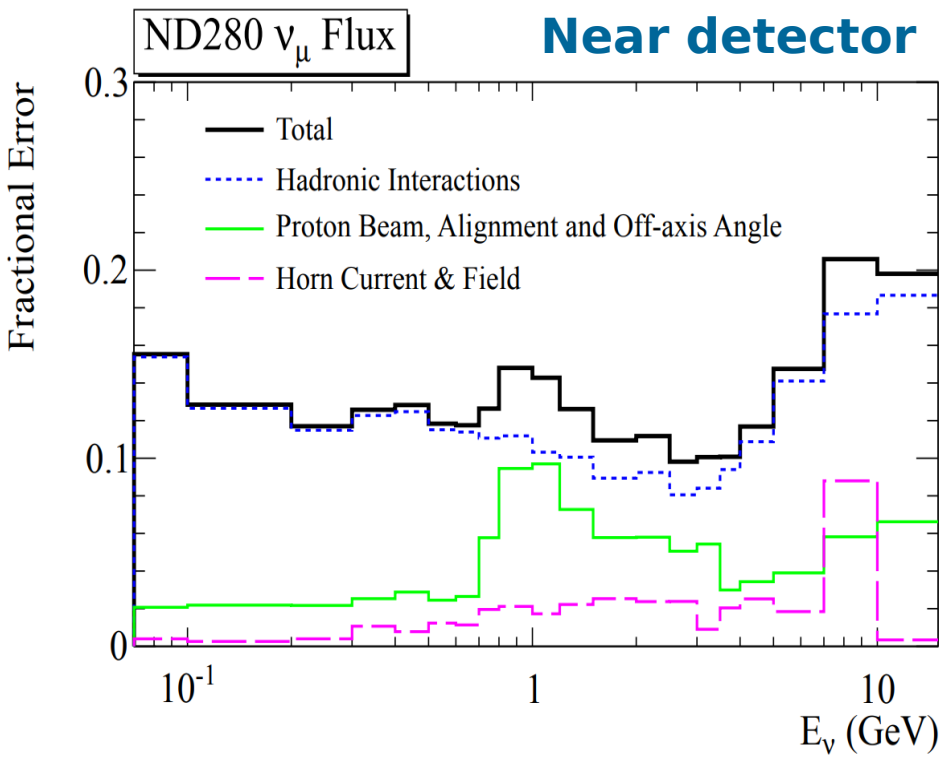


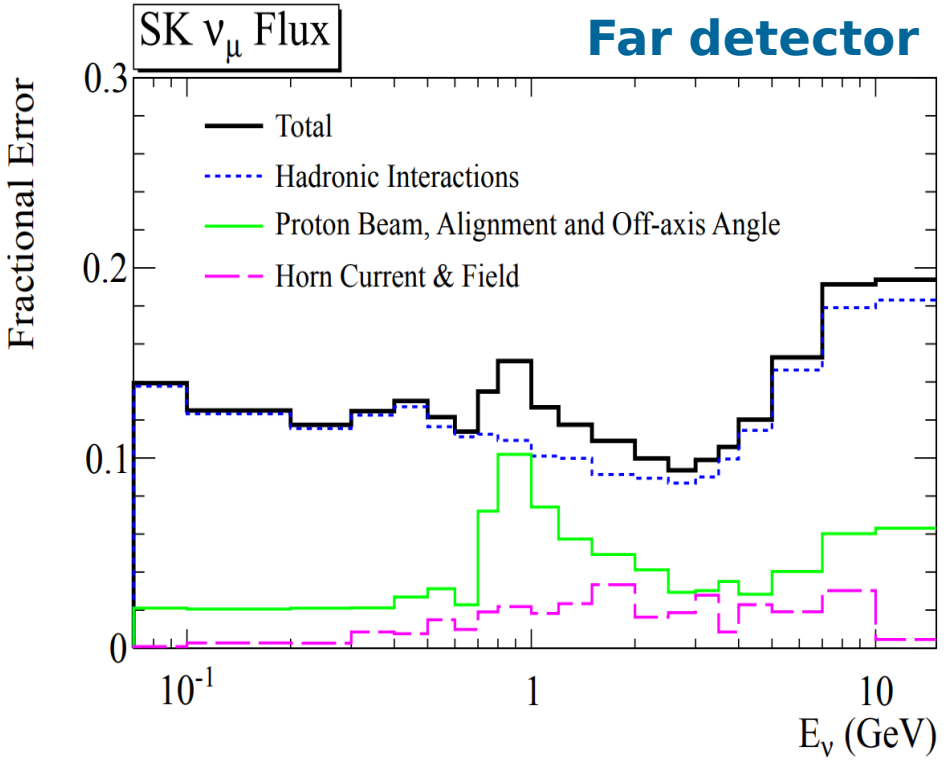
- Muon (anti)neutrino beams
- Initiated by proton beams
- Decays of hadrons produced in hadronic interactions in the target (e.g. C, Be) or beamline materials (e.g. Al)



Necessity for hadron production measurements

- Precise neutrino flux prediction is key for the precise prediction of neutrino interaction rates at the near and far detectors, aiding both **neutrino oscillation** and **neutrino cross-section** measurements
- Hadron production dominates the uncertainty of the neutrino flux prediction at both the near and the far detector sites



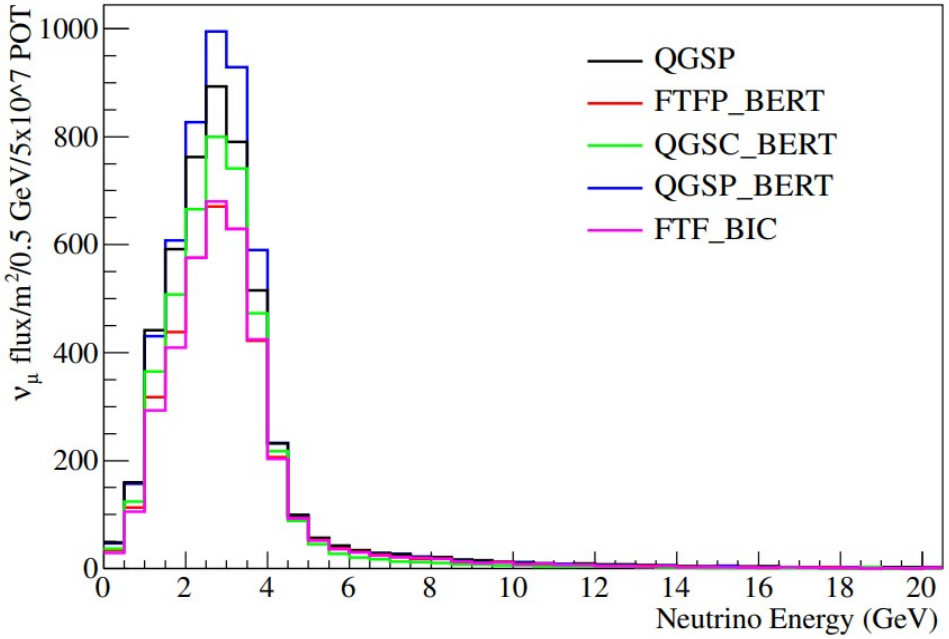


T2K: Phys.Rev. D87, 012001 (2013)

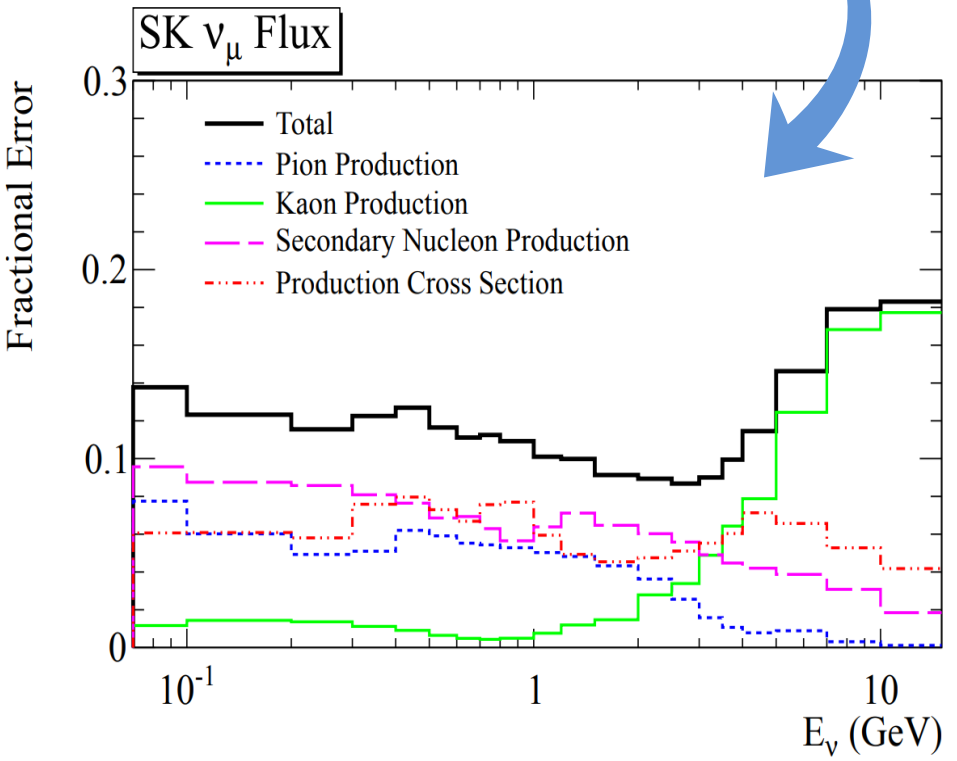
Necessity for **direct** hadron production measurements

- Monte Carlo hadronic interaction models give different predictions of the neutrino flux
- Need direct measurements of both particle yields and interaction cross sections

NuMI beamline (MINERνA): $\pi^+ \rightarrow \mu^+\nu$

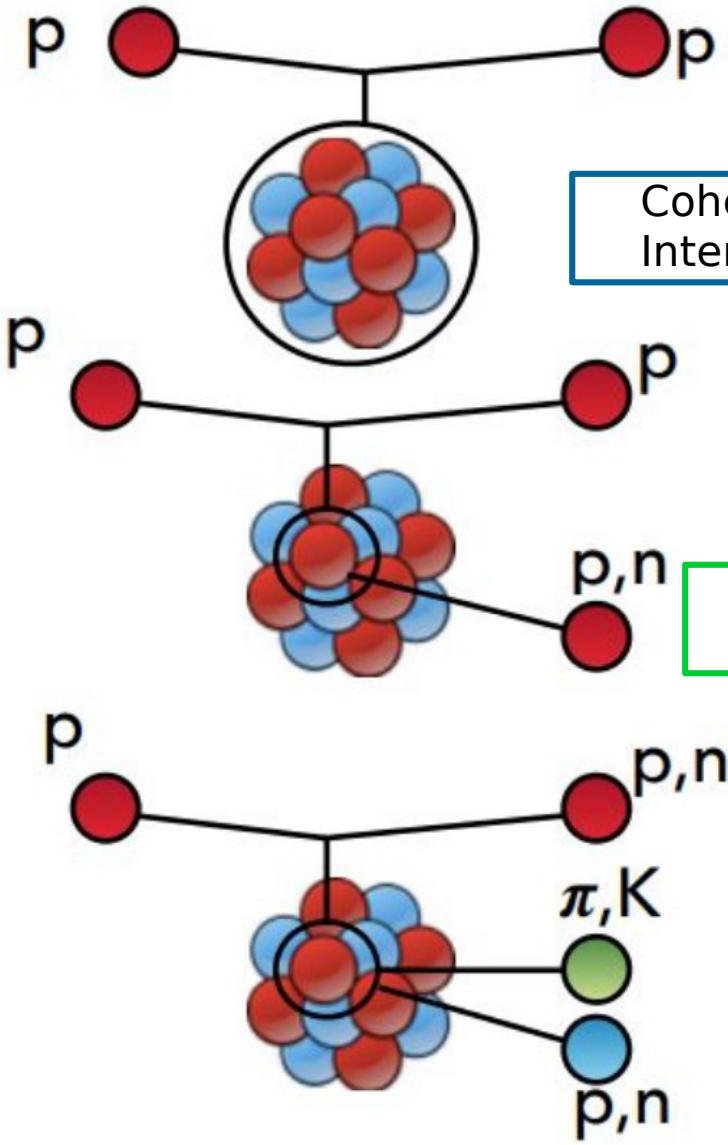


Leonidas Aliaga (Ph.D Thesis, 2016)



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

Employed classification of nuclear interactions



Coherent elastic scattering:
Interaction on the nucleus (σ_{el})

Quasi-elastic scattering:
Interaction on nucleons (σ_{qe})

Inelastic process:
(σ_{inel})

Production process:
Interaction with new hadron production (σ_{prod})

$$\sigma_{inel} = \sigma_{total} - \sigma_{el}$$

$$\sigma_{prod} = \sigma_{inel} - \sigma_{qe}$$

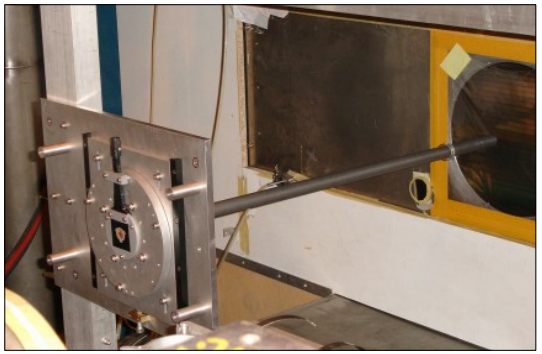
NA61/SHINE and T2K use this definition
NuMI definition is slightly different:

$\sigma_{prod} \rightarrow \sigma_{inel}$

$\sigma_{inel} \rightarrow \sigma_{absorption}$

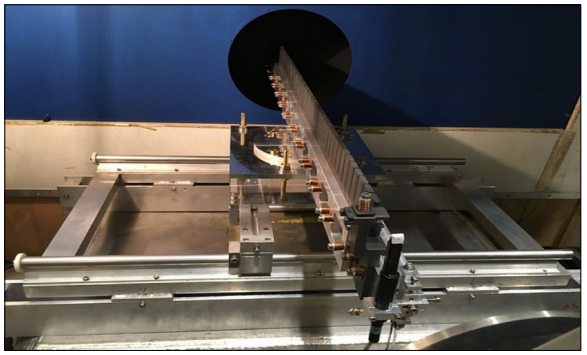
Hadron production measurements

2 cm graphite target



T2K replica target –
90 cm graphite rod

NuMI replica target -
120 cm long graphite fins



Thin target measurements

- Single interactions
- p , $\pi^{\pm}$, $K^{\pm}$ beams on C, Be, Al targets
- Inelastic and production cross sections
- Differential cross sections
- Differential particle yields

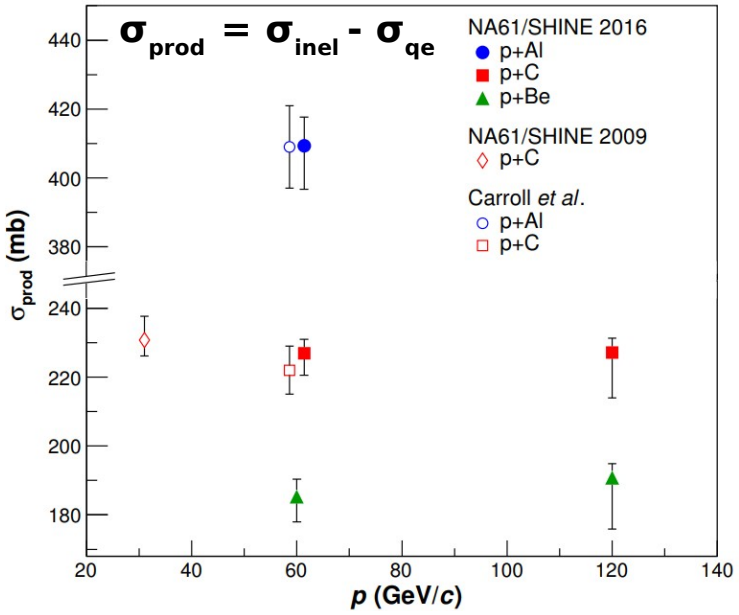
Thick target measurements

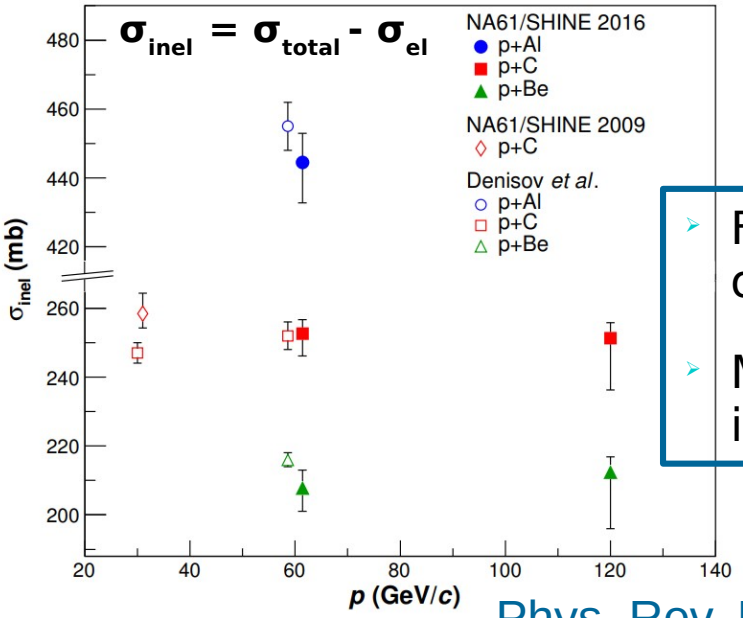
- Proton beams on replica targets
- Multiple interactions inside the target
- Differential hadron yields on target surface
- Beam survival probability and related production cross section

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

L target length; n number density of nuclei

Hadron production measurements in p interactions

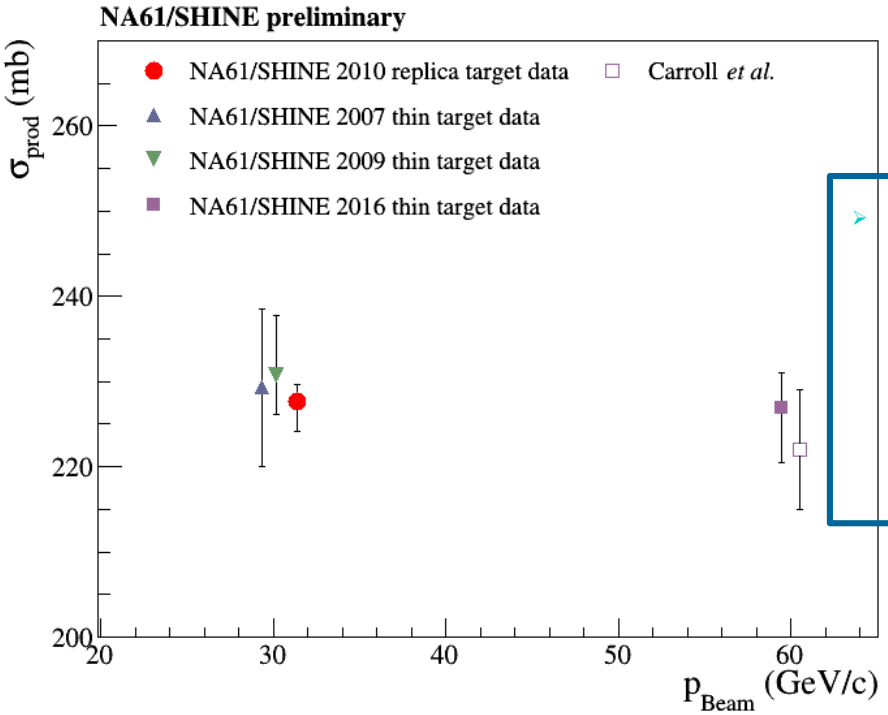




Main objective:
J-PARC and Fermilab beamlines

- First measurement of p@120GeV/c
- Model uncertainty is dominant (2-8%)

Phys. Rev. D 100, 112001 (2019)



- **Brand new** measurement of σ_{prod} *p+C* @31GeV/c with the T2K replica based on beam attenuation in target
  - Improved precision
  - Model uncertainty is <0.4%

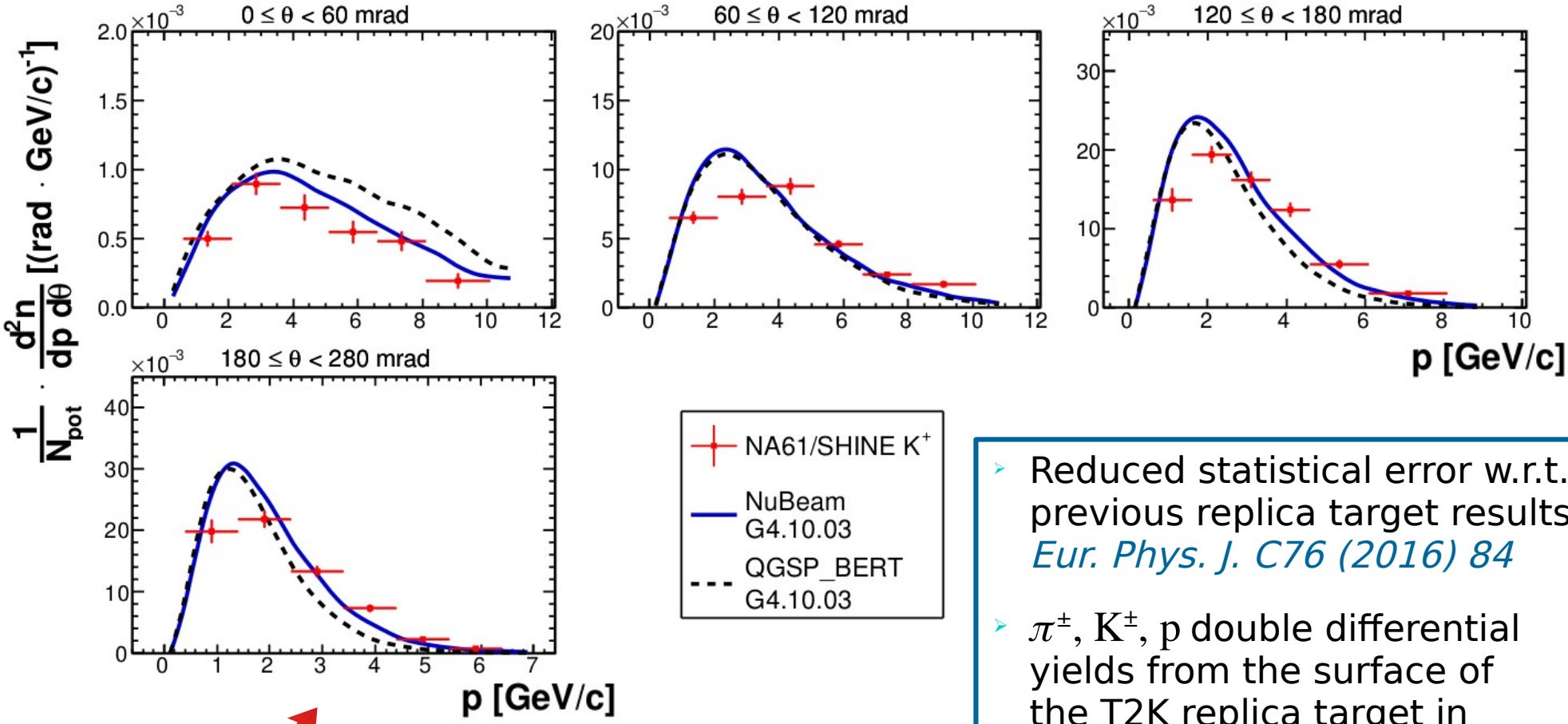
Paper status: *Collaboration review*

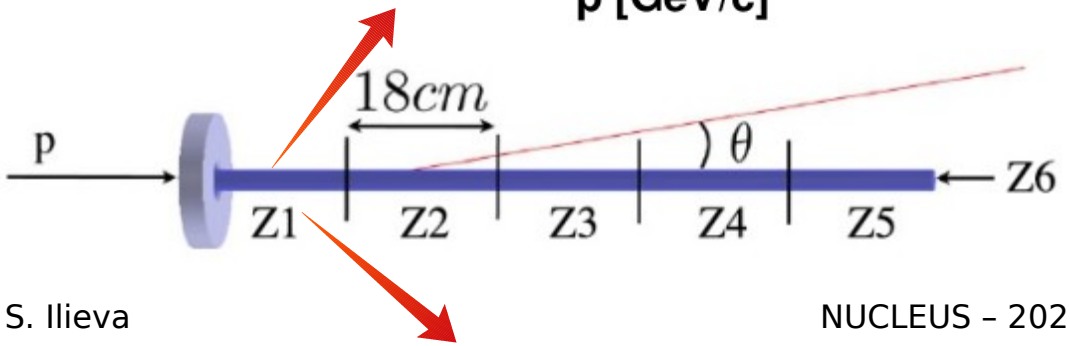
Hadron production measurements in p interactions

T2K replica target measurement

Main objective:
J-PARC beamline
T2K experiment

K^+ production in *p + C @ 31 GeV/c* and $0 \le z \le 18$ cm





- Reduced statistical error w.r.t. previous replica target results *Eur. Phys. J. C76 (2016) 84*
- $\pi^{\pm}$, $K^{\pm}$, p double differential yields from the surface of the T2K replica target in *p+C* @31GeV/c

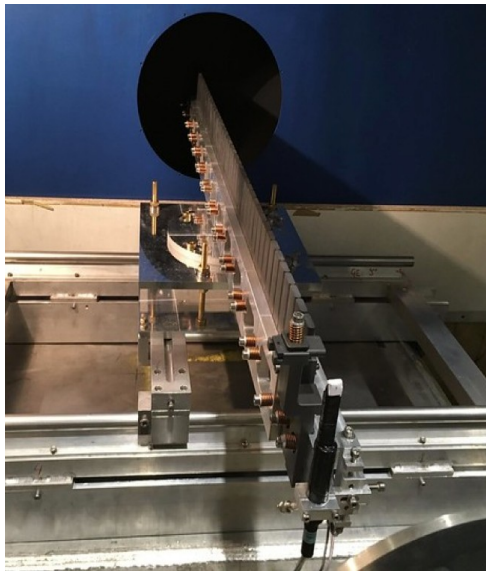
Eur.Phys.J.C 79 (2019) 2, 100

Hadron production measurements in p interactions

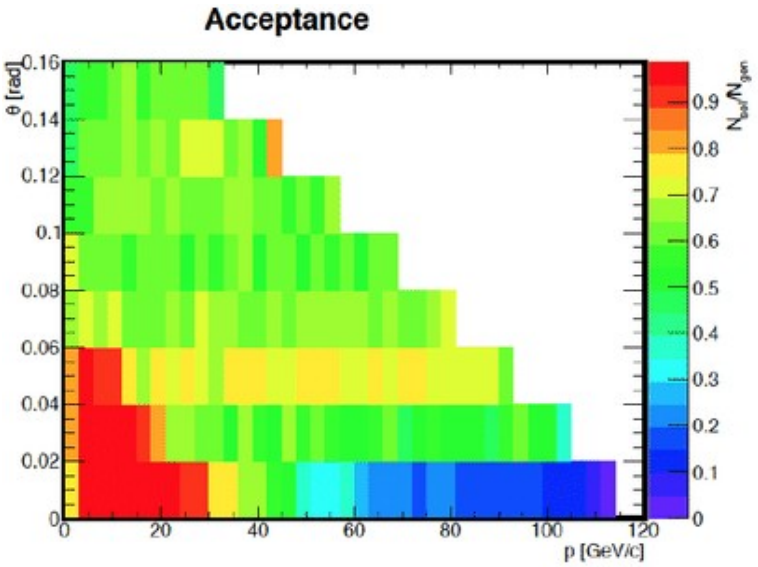
NuMI replica target measurement

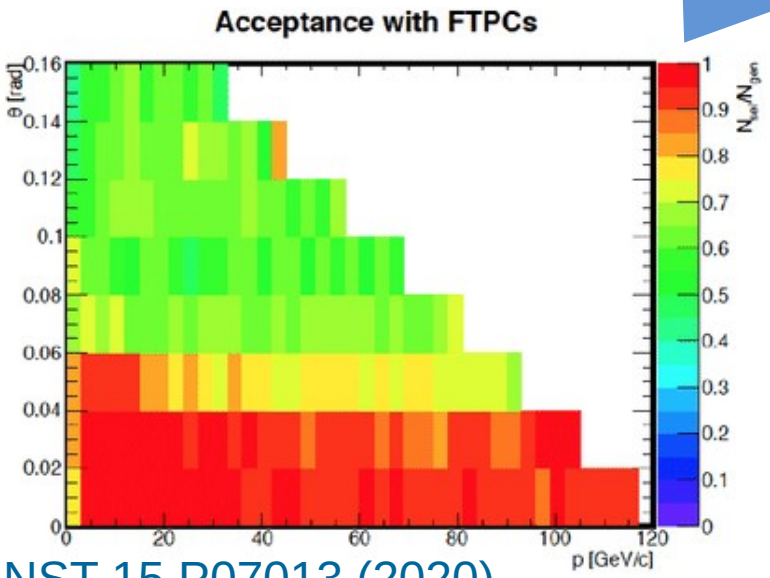
Main objective:
NuMI beamline
NOνA experiment

p + C @ 120 GeV/c



- Three Forward TPCs (FTPCs) installed in 2017
  - Improve forward acceptance
  - Allow separation of protons and pions @100GeV/c
- 5 weeks of data taking in 2018
- 15M recorded events
- Data Analysis Status: Calibration

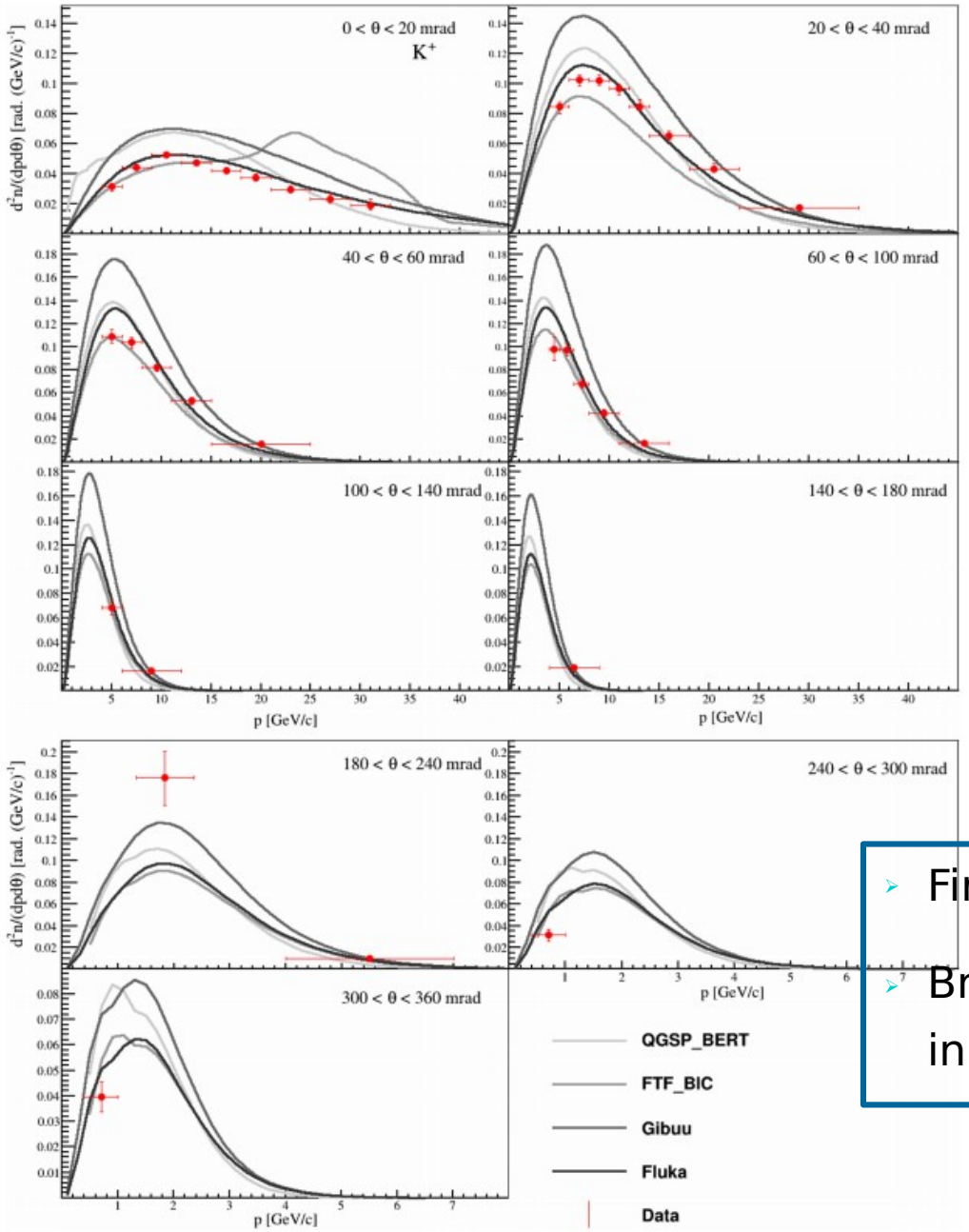




JINST 15 P07013 (2020)

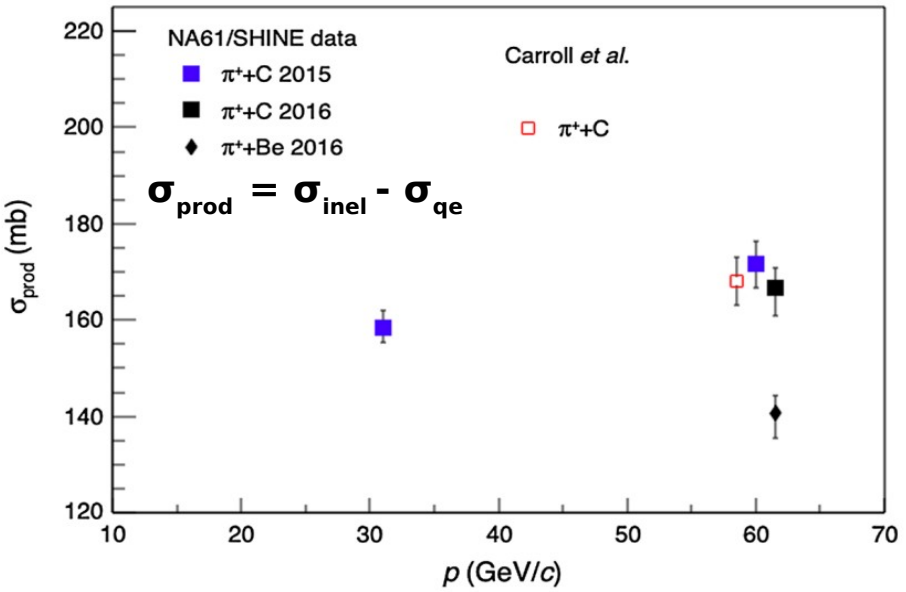
Hadron production measurements in π^+ interactions

K^+ production in *$\pi^+ + C$ @ 60 GeV/c*



Main objective:
NuMI and LBNF beamlines

$\pi^+ + C$ and $\pi^+ + Be$

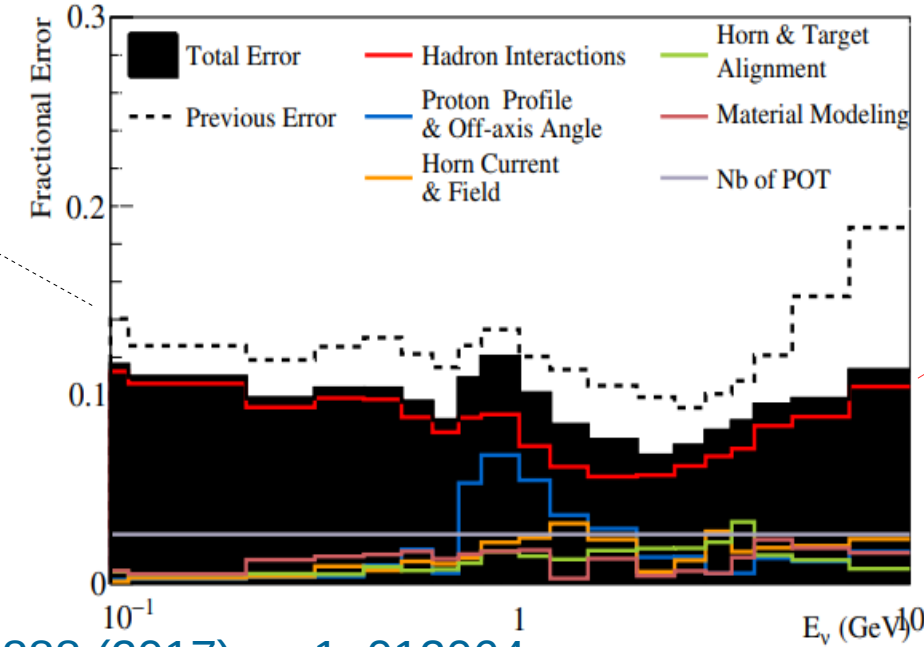


- First measurement of σ_{prod} in $\pi^+ + Be$ @60GeV/c
- Broad study of $\pi^{\pm}$, $K^{\pm}$, p, K^0_s, Λ production in $\pi^+ + C$ and $\pi^+ + Be$

Phys. Rev. D 100, 112004 (2019)

Impact on the T2K neutrino flux prediction

with 2007
NA61/SHINE
thin target data



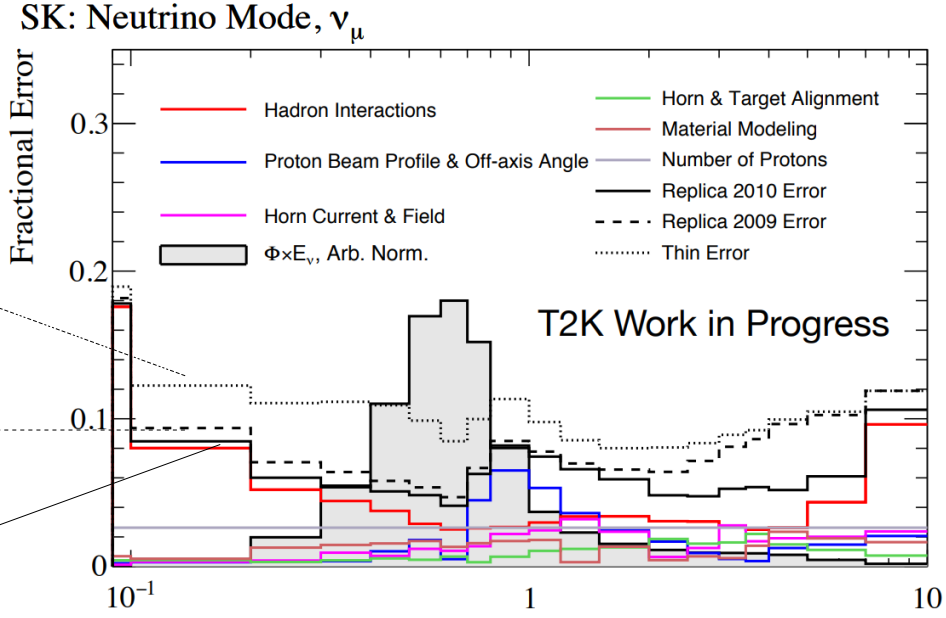
with 2009 NA61/SHINE
thin target data

J.Phys.Conf.Ser. 888 (2017) no.1, 012064

with 2009 NA61/SHINE
thin target data

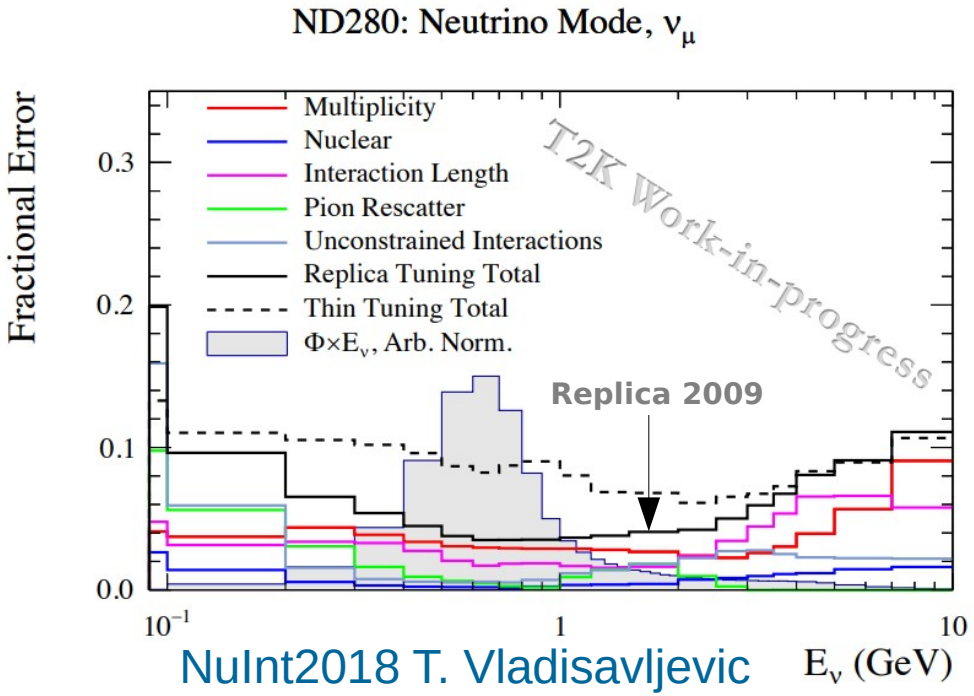
with 2009 NA61/SHINE
T2K **replica target data**
- $\pi^{\pm}$ diff. yields meas.

with 2010 NA61/SHINE
T2K **replica target data**:
- $\pi^{\pm}$, $K^{\pm}$, p diff. yields meas.



NA61/SHINE 2020 Status Report

Very Low Energy beamline for NA61/SHINE



NuInt2018 T. Vladisavljevic

Very Low Energy (VLE): 1 - 20 GeV/c beamline

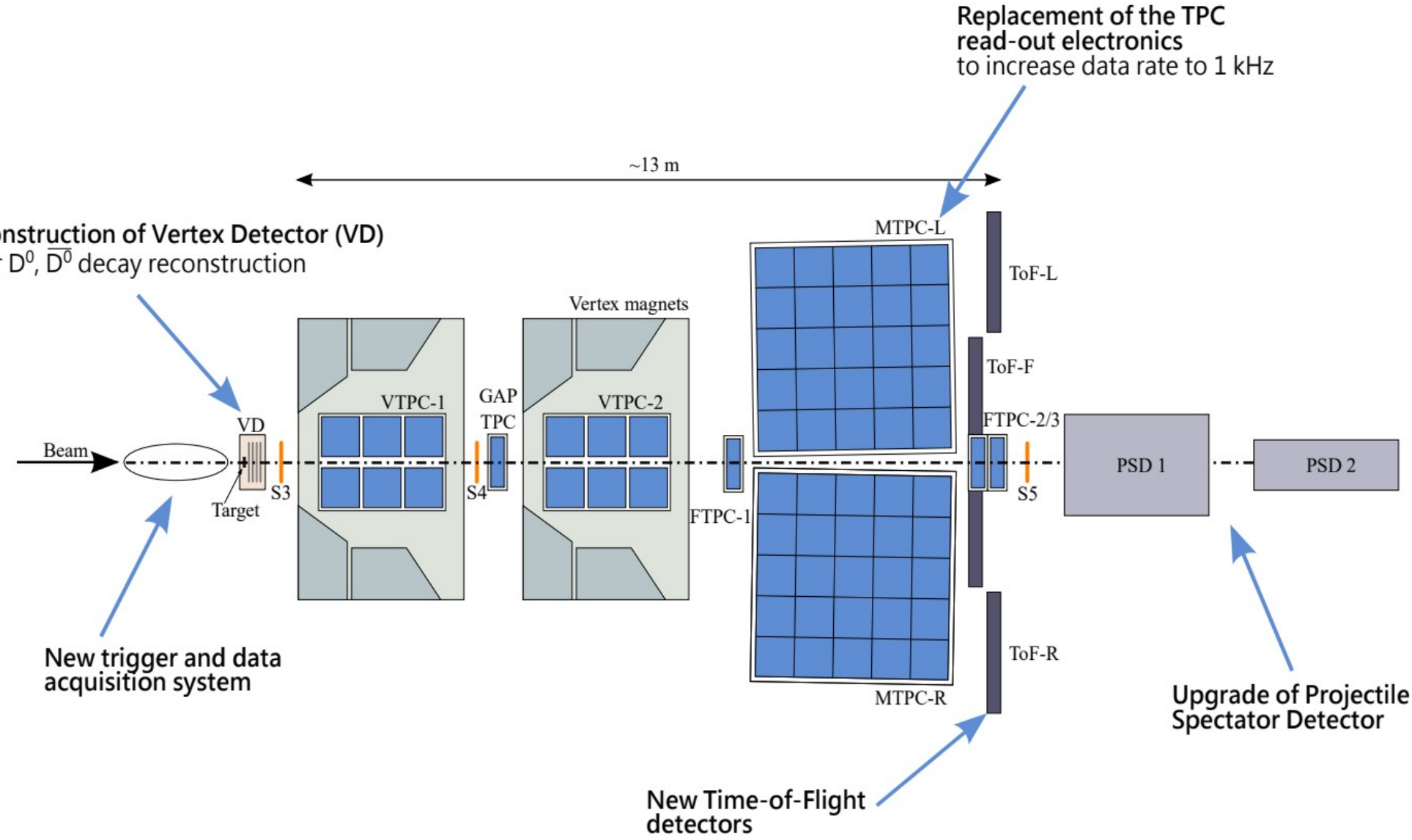
Beam particles and energies:

T2K-II and Hyper-K, DUNE

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

- Further reduction of the hadronic interaction uncertainty in the neutrino flux prediction is desirable: **unconstrained interactions**
  - The T2K-II and Hyper-K goal is 2-3% flux uncertainty for a wide range of neutrino energies
- Aim at realization before LS3
- VLE beamline is also relevant for
  - neutrinos from spallation neutron sources
  - atmospheric ν fluxes:
    - protons < 20 GeV
- Project proposal of Very Low Energy beamline included in NA61/SHINE Status Report 2020!

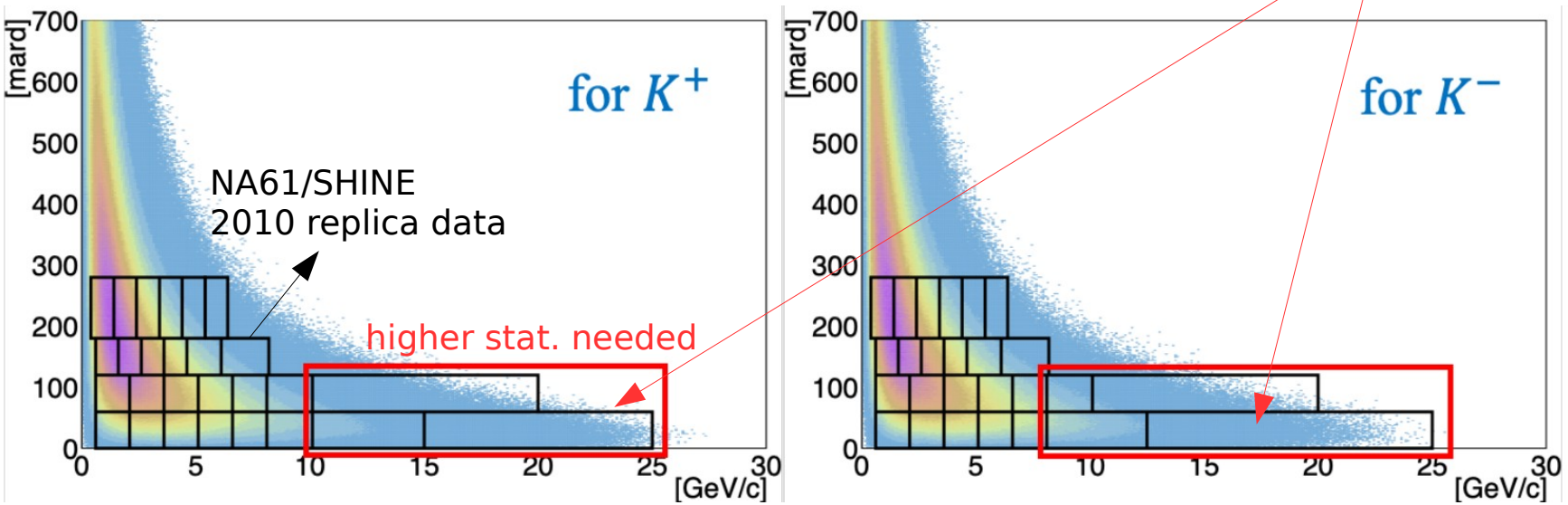
Upgrades of the NA61/SHINE spectrometer during LS2



Planned neutrino-related measurements

Measurements in 2021:

- Additional p @31 GeV/c on T2K replica target – constrain high-energy charged kaon production



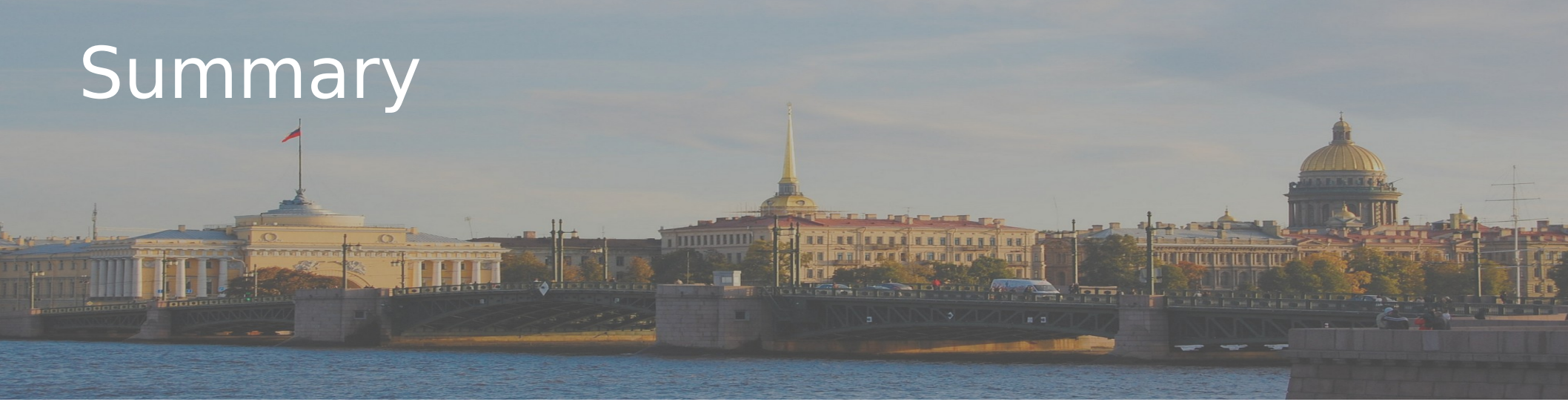
Request for measurements in 2022-2024:

- K^+ @60 GeV/c on thin graphite target – neutrinos from kaon parents dominate the high-energy tail of the DUNE neutrino flux
- p @120 GeV/c on thin titanium target (LBNF target containment vessel)
- p @120 GeV/c on LBNF/DUNE prototype target

Ideas for after LS3:

- Measurements with Hyper-K and LBNF replica targets

Summary



- Direct hadron production measurements have successfully aided reduction of hadronic interaction uncertainties in the T2K neutrino flux prediction
  - Thin target measurements by NA61/SHINE improved T2K flux uncertainty to ~ 10 %
  - Further reduction to ~ 5% is achieved using the NA61/SHINE replica target measurements
- Broad data-taking and analysis campaign for Fermilab ν experiments
- After LS2 NA61/SHINE plans for diverse hadron production measurements based on ν experiments needs
- Proposal for construction of Very Low Energy (1 - 20 GeV/c) beamline before LS3

Acknowledgements

https://shine.web.cern.ch

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