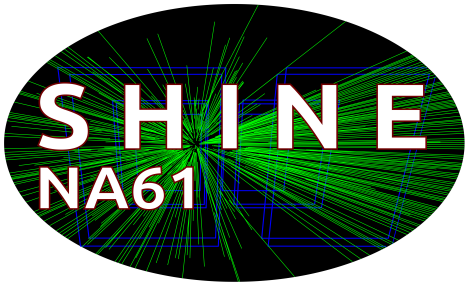
Status of NA61/SHINE Measurements for Neutrino Experiments

Athula Wickremasinghe, University of Pittsburgh
On behalf of the
NA61/SHINE Collaboration



NuFact 2018
Virginia Tech, Blacksburg
Aug 16, 2018

Outline

Importance of the hadron production data

NA61/SHINE experiment

Measurements for T2K targets

Data taken for Fermilab targets

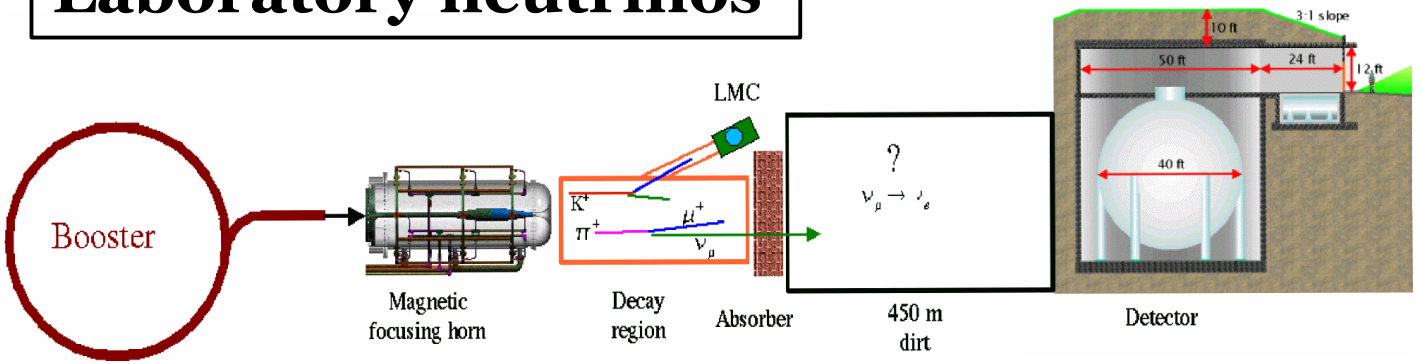
Hardware upgrades in 2017 & Data

NA61/SHINE Plans beyond 2020

Neutrinos from meson decays

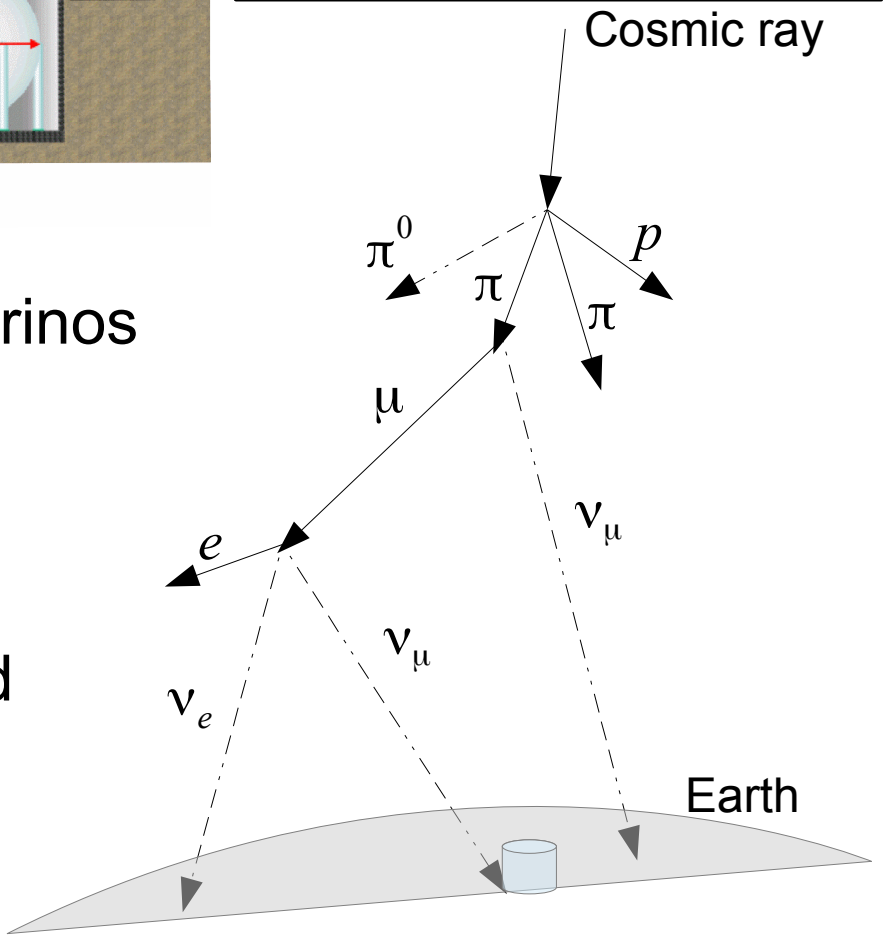
Laboratory neutrinos

Credit to MiniBooNE collaboration



- Decay of charged mesons produce neutrinos
- Have to model the hadron production to understand the neutrino flux
- Need to understand all uncertainties and particle generations in the MC model predictions

Cosmic air showers



Why we need hadron production data?

To answer following important questions:

- **How do you predict neutrino beam fluxes?**
  + *Using combined simulators: FLUKA, GEANT4 … etc*
  + *Using Data-driven model prediction*
  + *Using near detector measurements .. Maybe not sufficient*

- **Is it possible to reduce the flux systematics dominated by hadron productions?**
  + *Yes of course ….improve models with data, use more production data to cover full space, Use replica target data*

- **How do you validate thin to thick target extrapolation?**
  + *Use replica target hadron production measurements …*

!! Good to have hadron production data !!

Next

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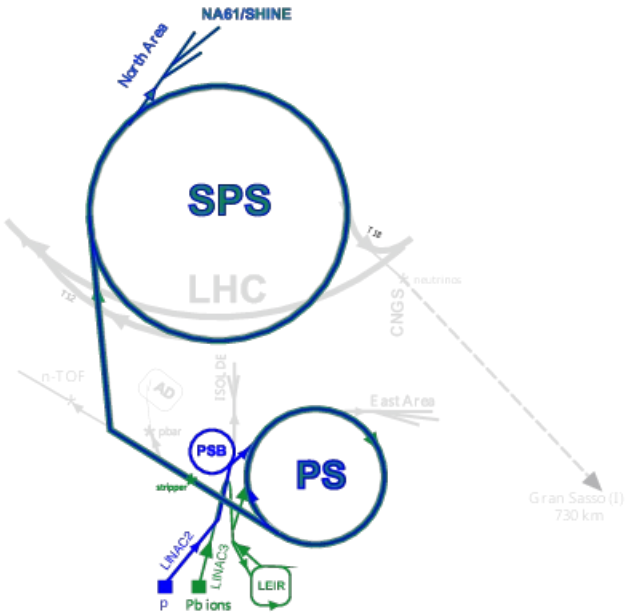
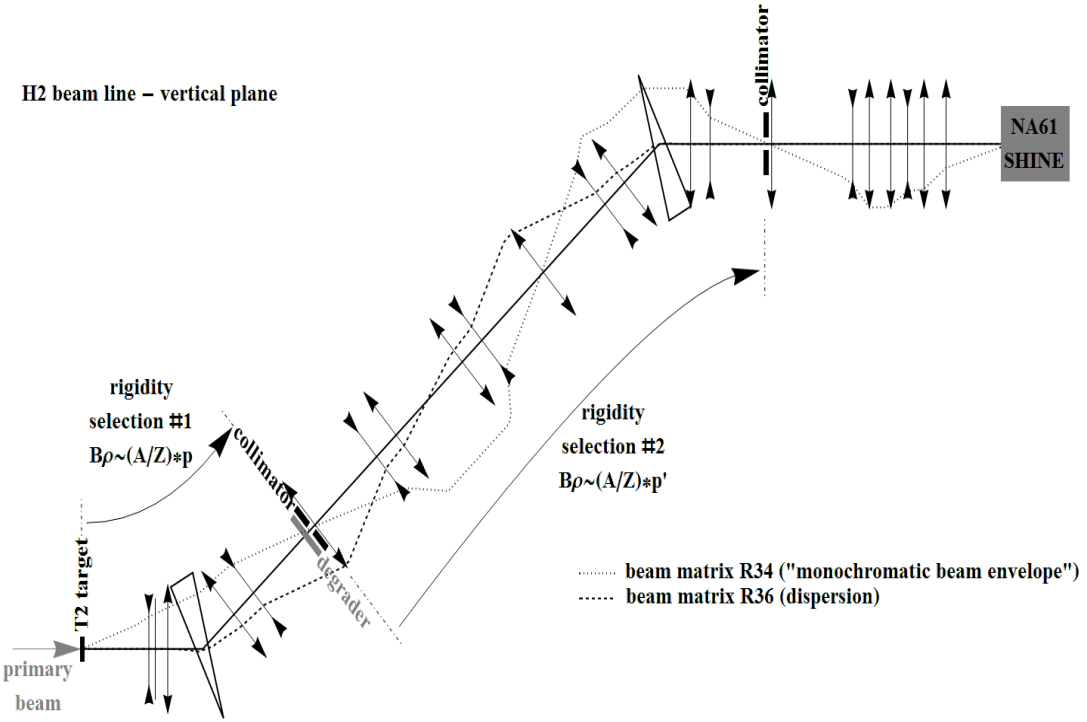
NA61/SHINE Experiment: Beam

NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a fixed target, large acceptance hadron production measurement experiment at the Super Proton Synchrotron (SPS) at CERN

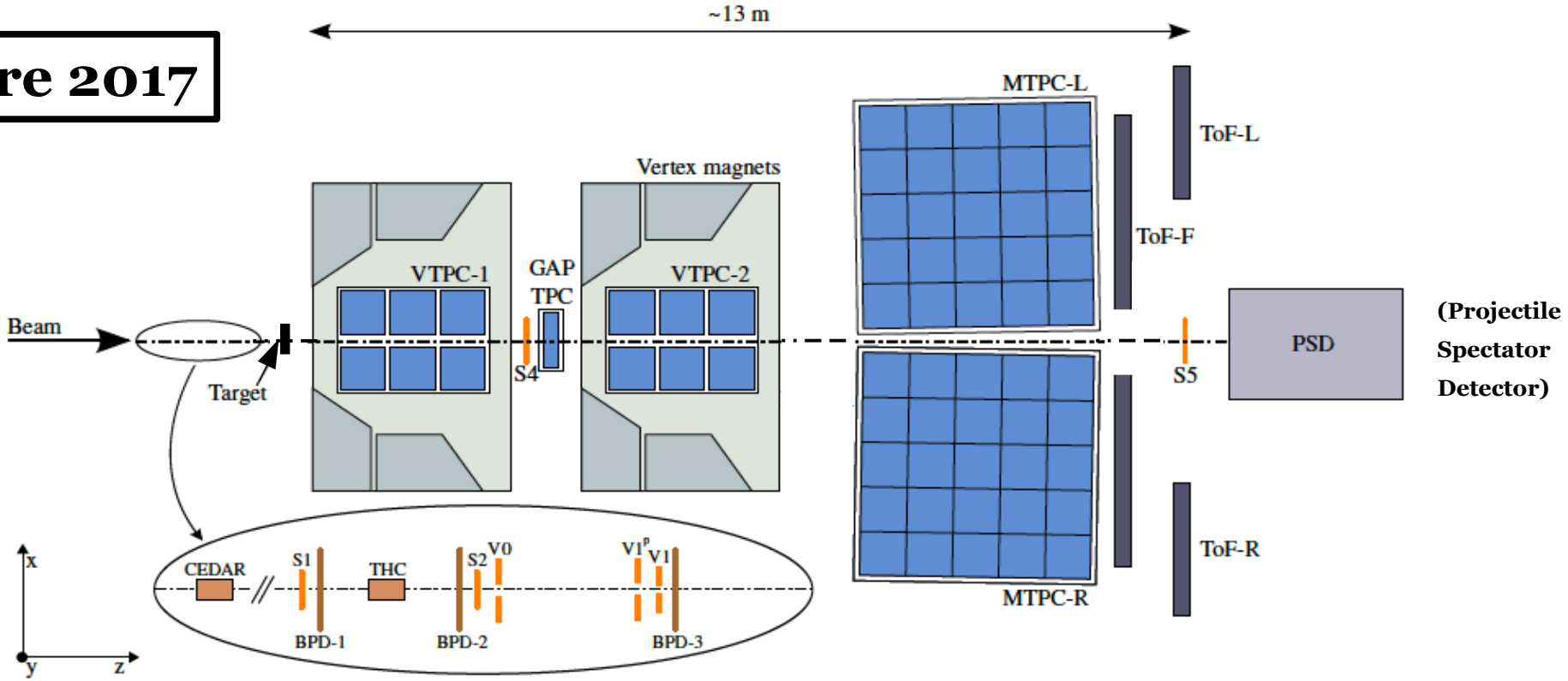




- 400 GeV/c SPS primary proton beam collides with T2 (Be) target
- The secondary beam for NA61/SHINE can be selected from 13 GeV/c to 350 GeV/c
- Heavy ion beams are generated through LINAC3 for ion-ion collision measurements

NA61/SHINE Experiment: Detector

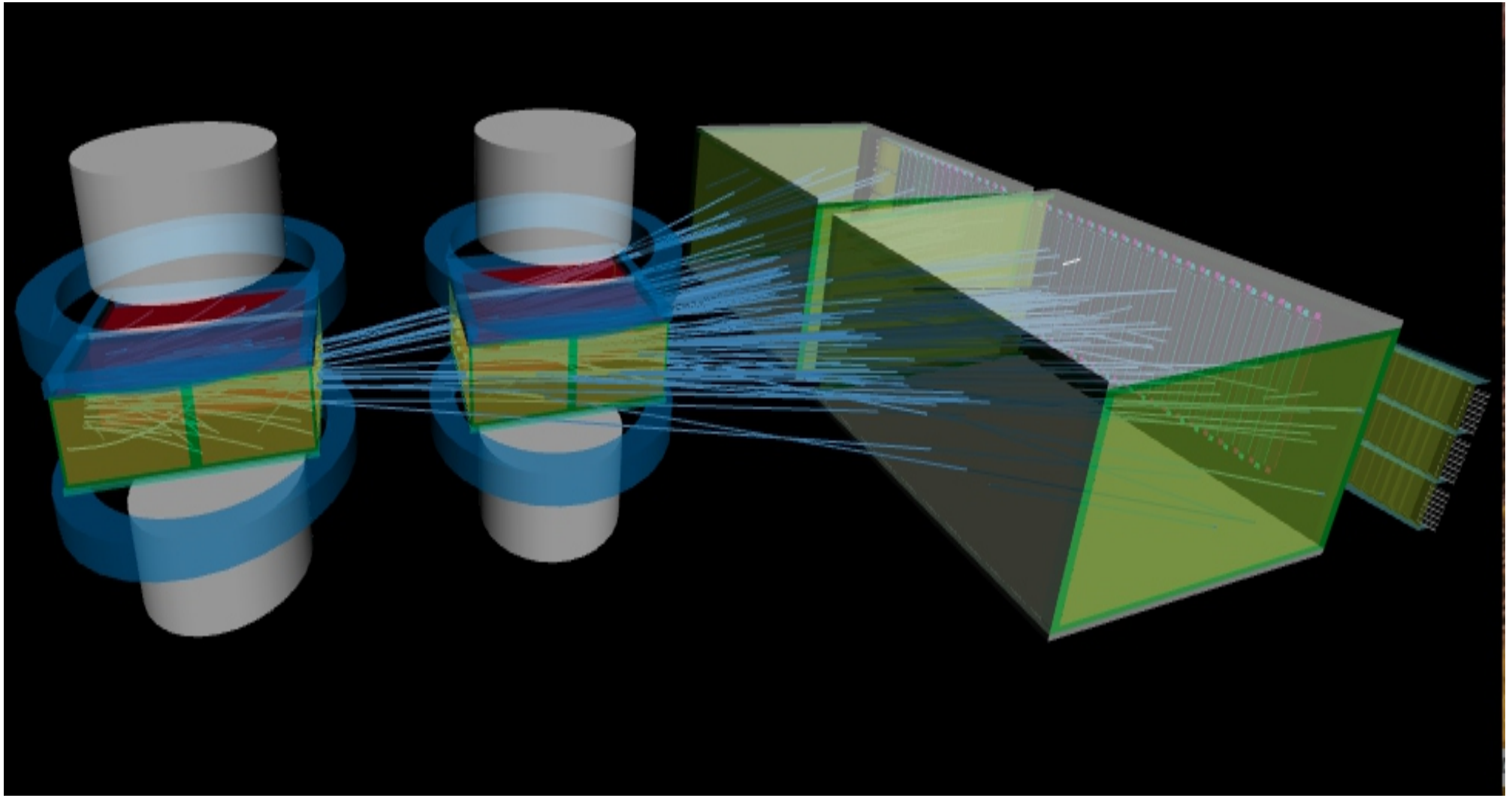
Before 2017



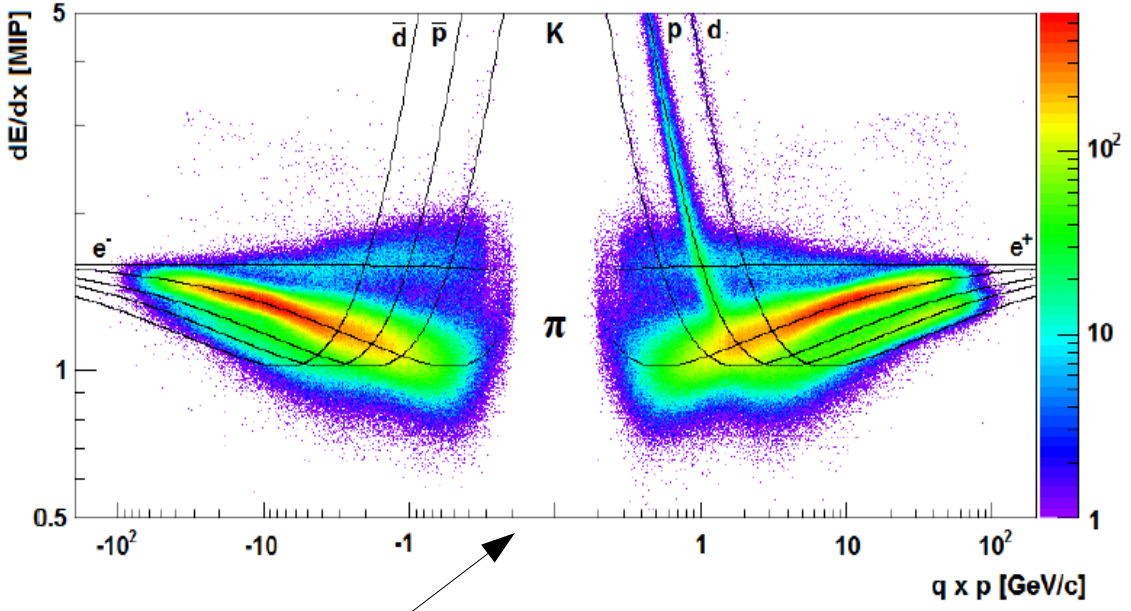
- **Beam profile is obtained by using CEDAR+THC and BPD information**
- **TPC system: Two vertex TPCs (VTPC1 & VTPC2) including 2 superconducting dipole magnets with the bending power of 9Tm + Gap-TPC + 2 Main-TPCs (MTPC-L & MTPC-R)**
- **TOF system: Left, right and forward Time-of-Flight detector arrays**

NA61/SHINE 3D Visualization

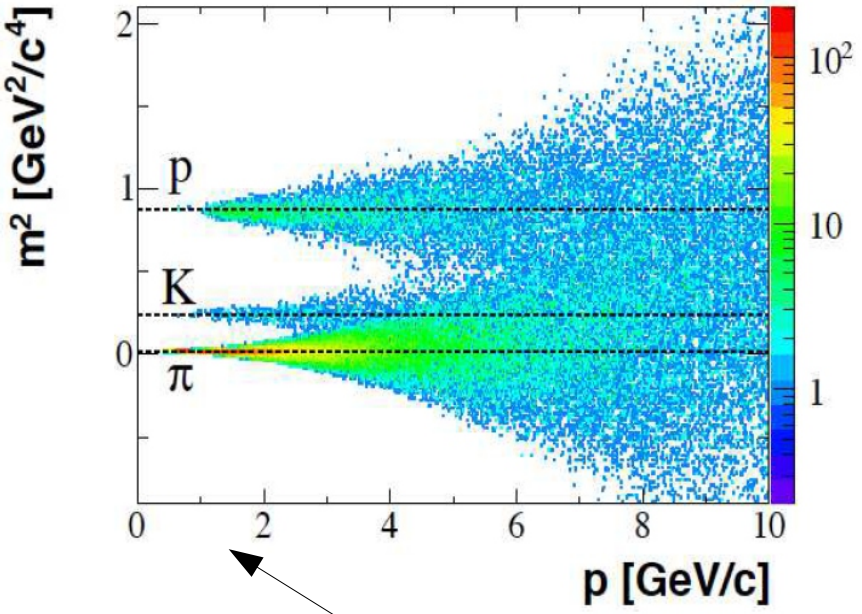
NA61/SHINE 3D Virtual reality: http://shine3d.web.cern.ch/shine3d/



NA61 Particle Identification

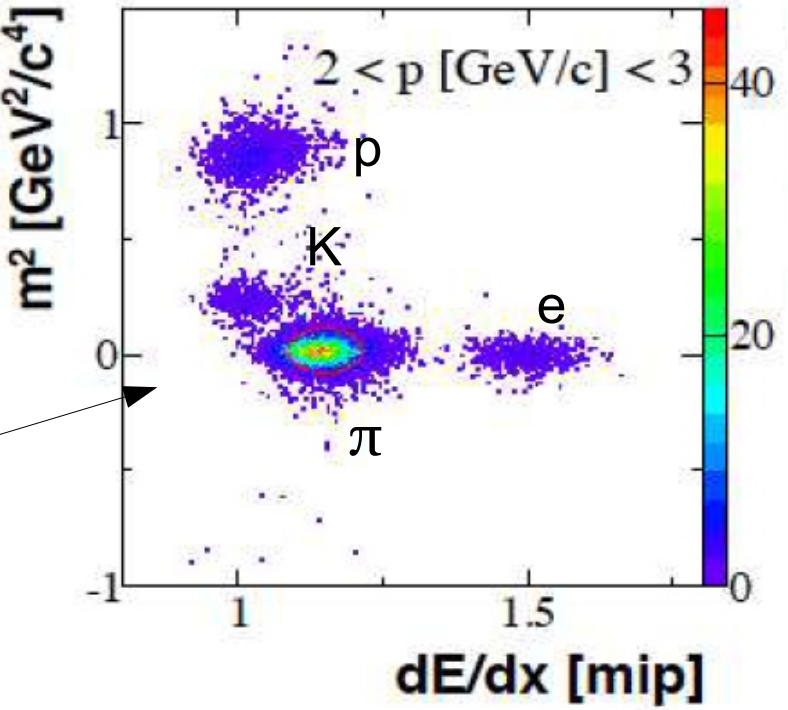


dE/dx analysis from the energy loss in TPCs
- Resolution : 3-4%



PID using ToF measurements
- Good for p < 6 GeV/c
- Resolution: 80-100 ps

dE/dx - ToF combined analysis
* Helpful to analyze the dE/dx crossing regions
* Important for Kaons PID



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Measurements for T2K

Data has been taken from 2007 to 2010 for T2K thin and replica targets

Thin Target

X x Y x Z = 2.5 cm x 2.5 cm x 2 cm

r = 1.3 cm and L = 90 cm

Measurements for T2K

Data has been taken from 2007 to 2010 for T2K thin and replica targets

Interaction	Target length	Production Measurements	Results / Publications
31GeV/c p+C	2 cm	π^+, π^-	• Phys. Rev. C84 (2011) 034604
		K^+	• Phys. Rev. C85 (2012) 035210
		K_S^0, Λ	• Phys. Rev. C89 (2014) 025205
		$\pi^+, \pi^-, K^+, K^-, K_S^0$, p, Λ	• Eur.Phys.J. C76 (2016) 84
31GeV/c p+C	90 cm replica target	π^+	• Nucl.Instrum.Meth. A701 (2013) 99-114
		π^+, π^-	• Eur.Phys.J. C76 (2016) no.11,617
		π^+, π^-, K^+, K^-	• Paper in preparation https://edms.cern.ch/ui/file/1828979/1/Results.pdf

Overview of Latest T2K Thin Target Results

Eur. Phys. J. C (2016) 76:84
DOI 10.1140/epjc/s10052-016-3898-y

THE EUROPEAN PHYSICAL JOURNAL C

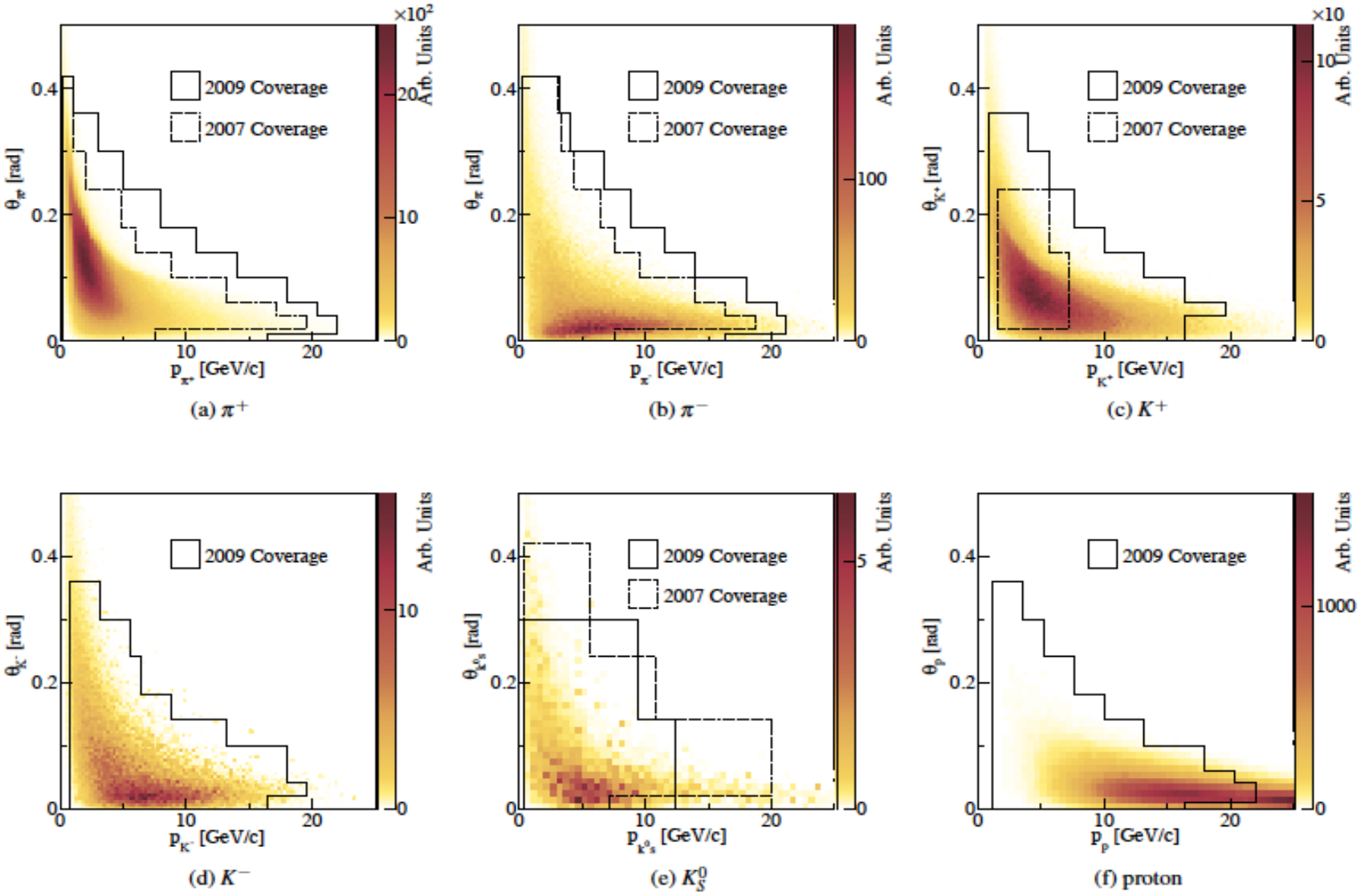
Regular Article - Experimental Physics

Measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS

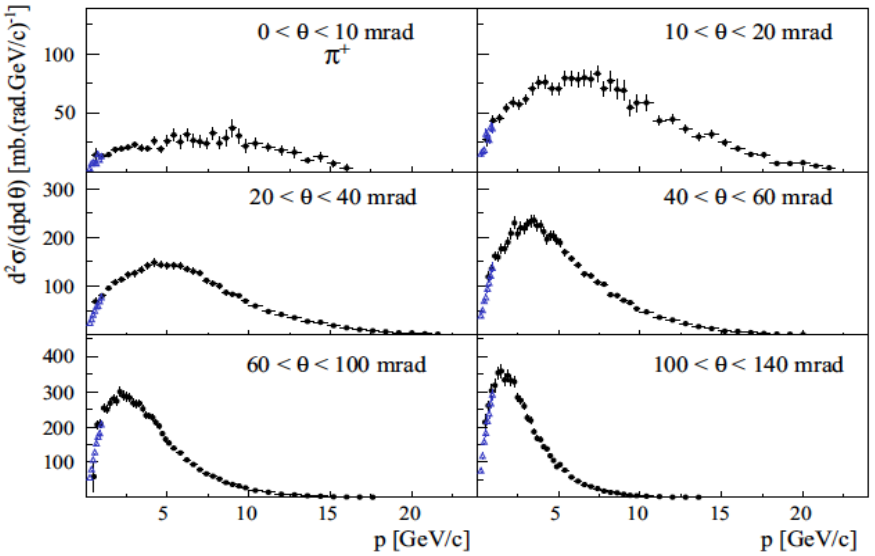
Abstract Measurements of hadron production in p + C interactions at 31 GeV/c are performed using the NA61/SHINE spectrometer at the CERN SPS. The analysis is based on the full set of data collected in 2009 using a graphite target with a thickness of 4 % of a nuclear interaction length. Inelastic and production cross sections as well as spectra of $\pi^{\pm}$, $K^{\pm}$, p, K^0_S and Λ are measured with high precision. These measurements are essential for improved calculations of the initial neutrino fluxes in the T2K long-baseline neutrino oscillation experiment in Japan. A comparison of the NA61/SHINE measurements with predictions of several hadroproduction models is presented.

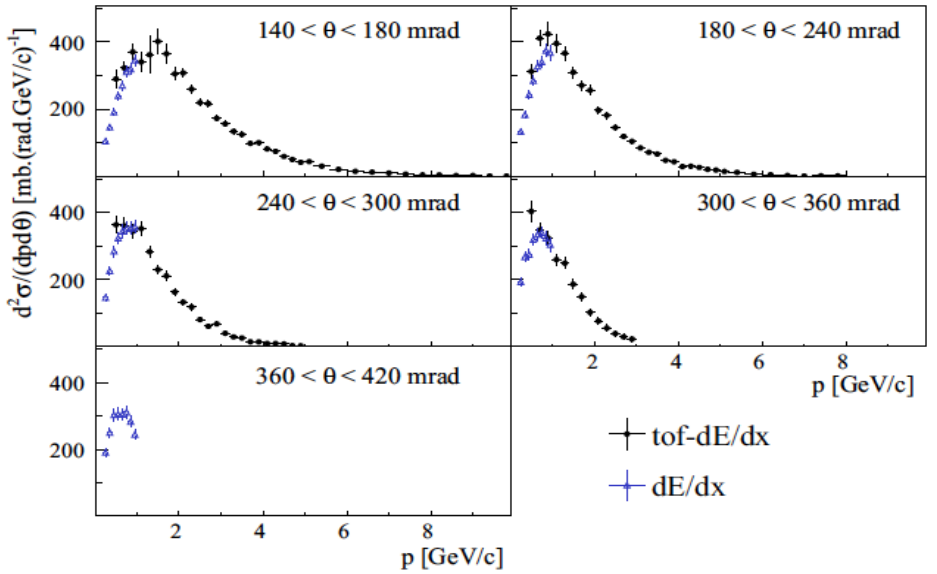
Overview of Latest T2K Thin Target Results

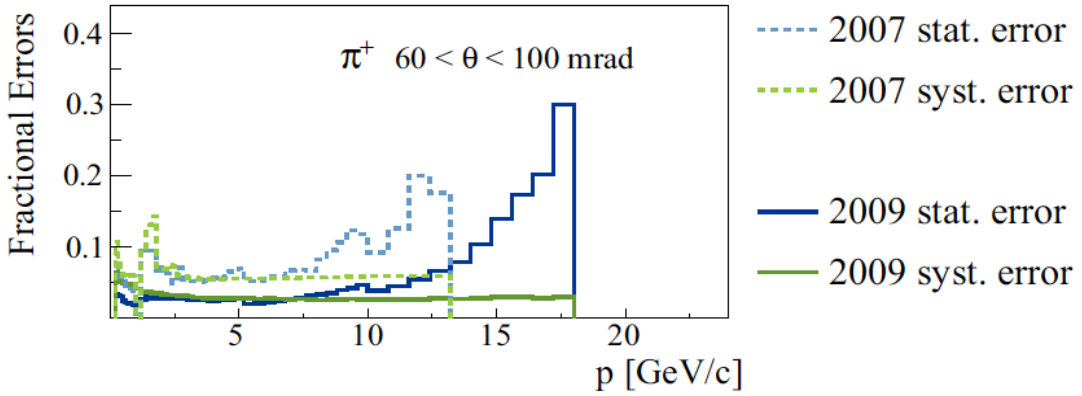
Hadrons Production data coverage in (p, θ) kinematical space to predict neutrino flux at Super-Kamiokande with "positive" focusing (neutrino mode)



Latest T2K Thin Target Results : π^+ Production







The paper has described the precise measurements of π^+, π^-, K^+, K^-, K_s^o, p and Λ production cross sections

Overview of T2K Replica Target Results

Eur. Phys. J. C (2016) 76:617
DOI 10.1140/epjc/s10052-016-4440-y

THE EUROPEAN PHYSICAL JOURNAL C

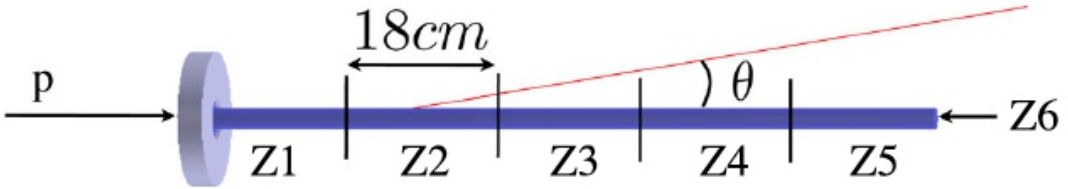
Regular Article - Experimental Physics

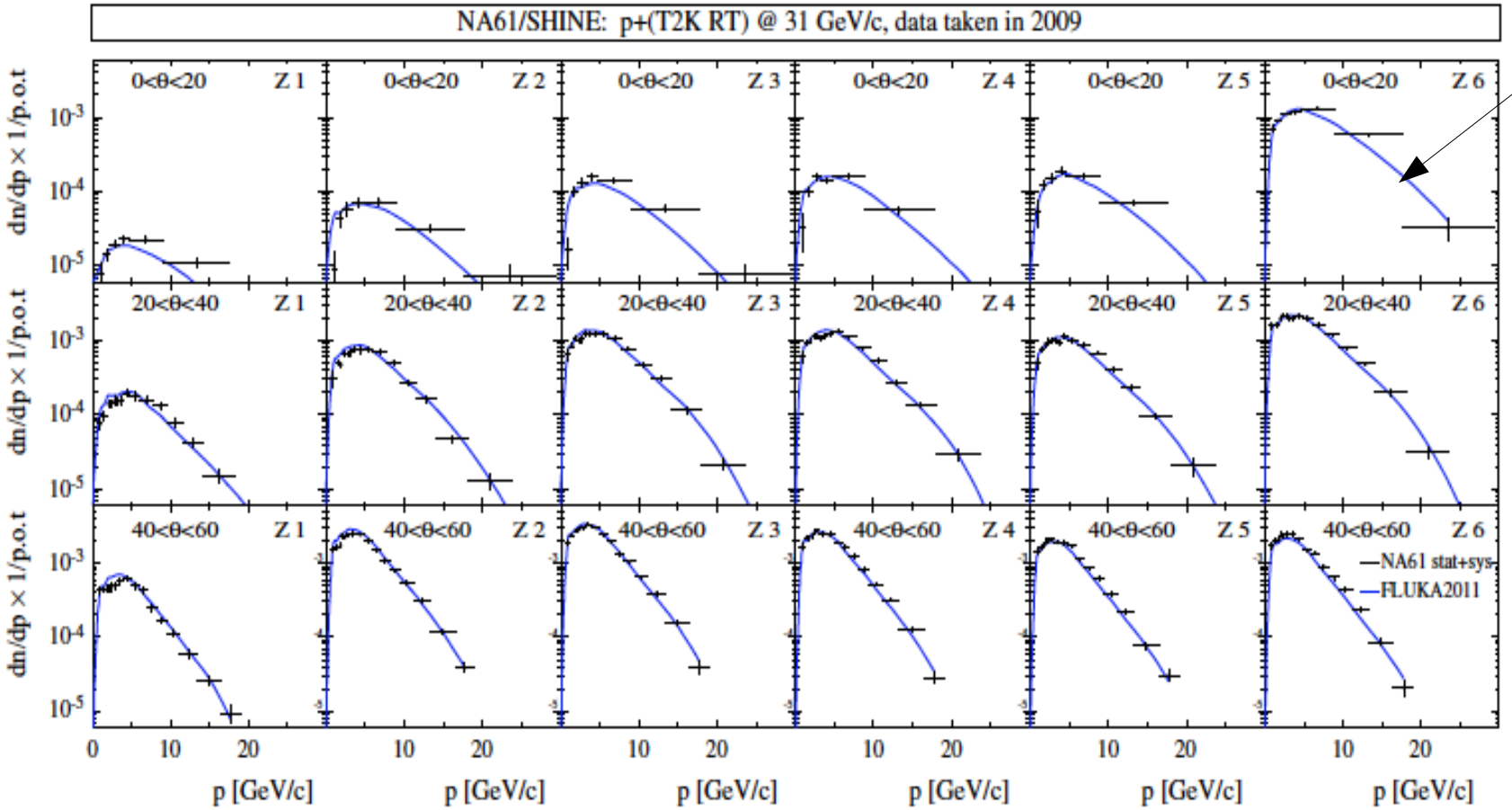
Measurements of $\pi^{\pm}$ differential yields from the surface of the T2K replica target for incoming 31 GeV/*c* protons with the NA61/SHINE spectrometer at the CERN SPS

Abstract Measurements of particle emission from a replica of the T2K 90 cm-long carbon target were performed in the NA61/SHINE experiment at CERN SPS, using data collected during a high-statistics run in 2009. An efficient use of the long-target measurements for neutrino flux predictions in T2K requires dedicated reconstruction and analysis techniques. Fully-corrected differential yields of $\pi^{\pm}$-mesons from the surface of the T2K replica target for incoming 31 GeV/*c* protons are presented. A possible strategy to implement these results into the T2K neutrino beam predictions is discussed and the propagation of the uncertainties of these results to the final neutrino flux is performed.

T2K Replica Target Results: π^+ Production

Binning along the replica target



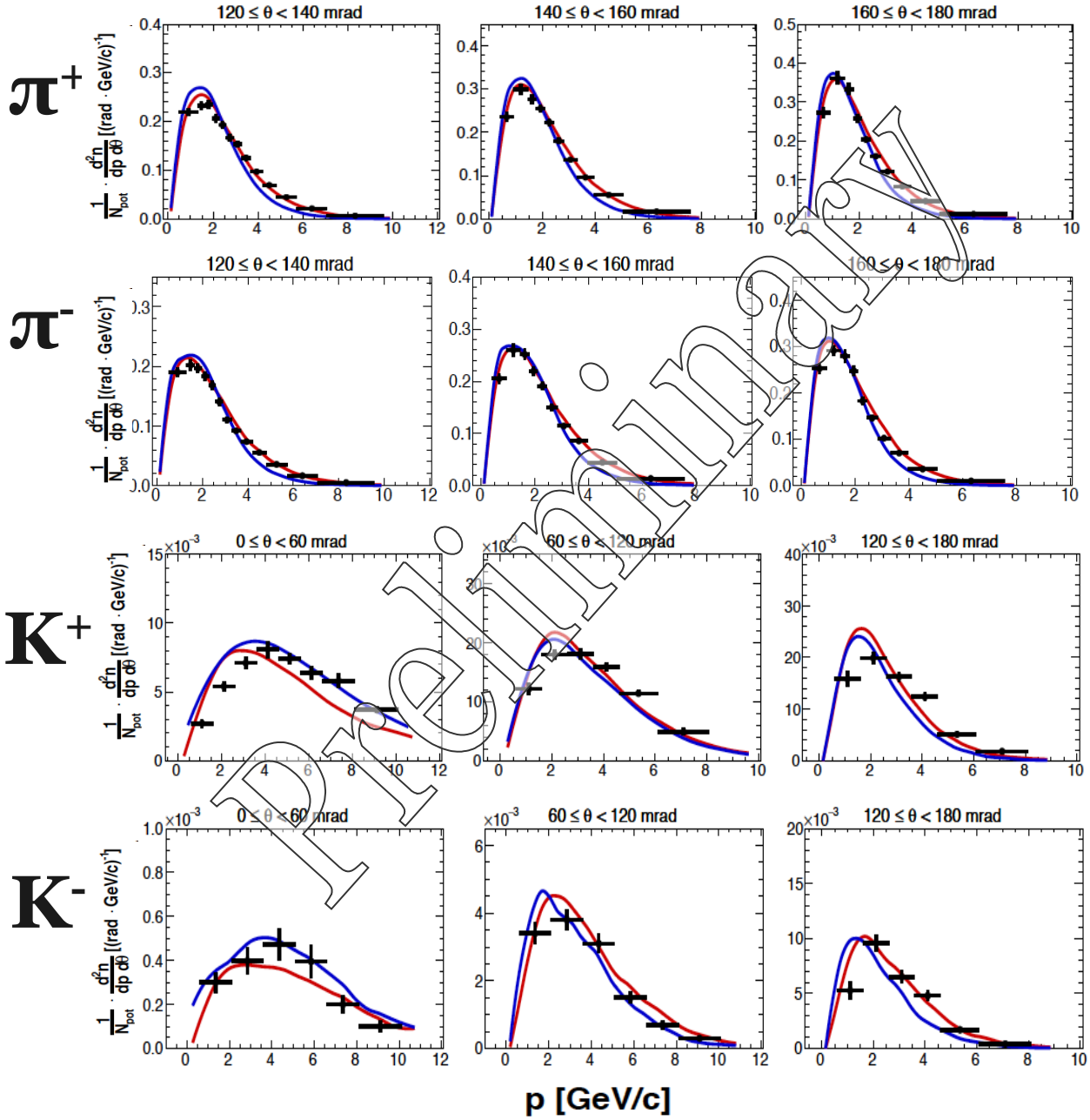


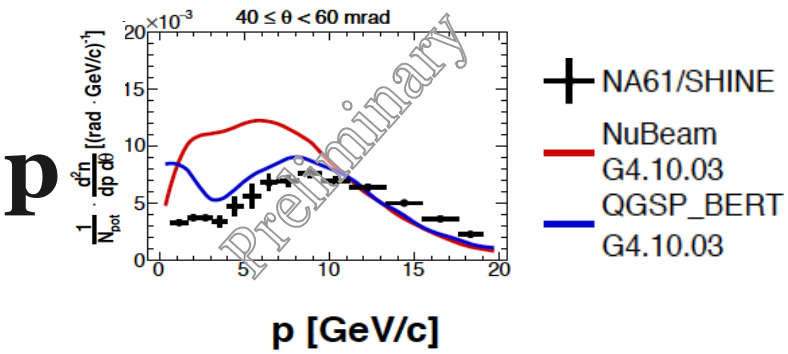
FLUKA2011

Results continue for $\theta < 340$ mrad

Visit: Eur.Phys.J. C76 (2016) no.11,617

T2K Replica Target 2010 data
Preliminary Results

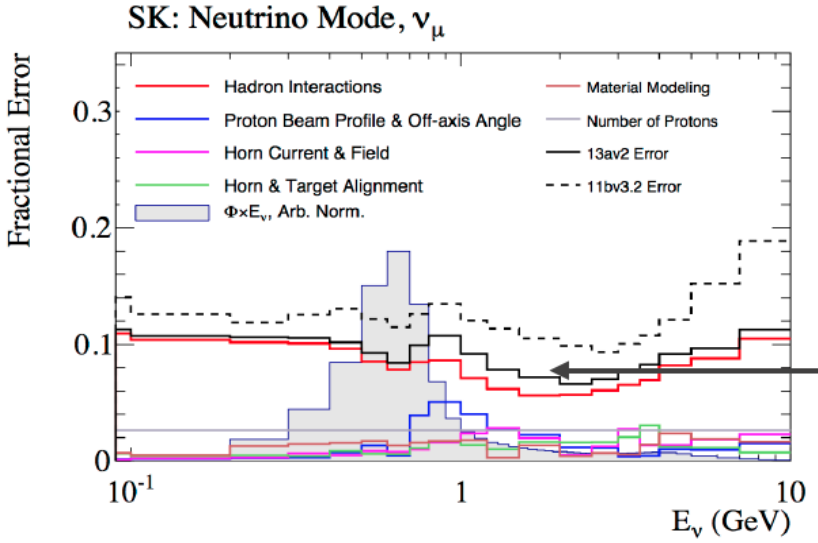




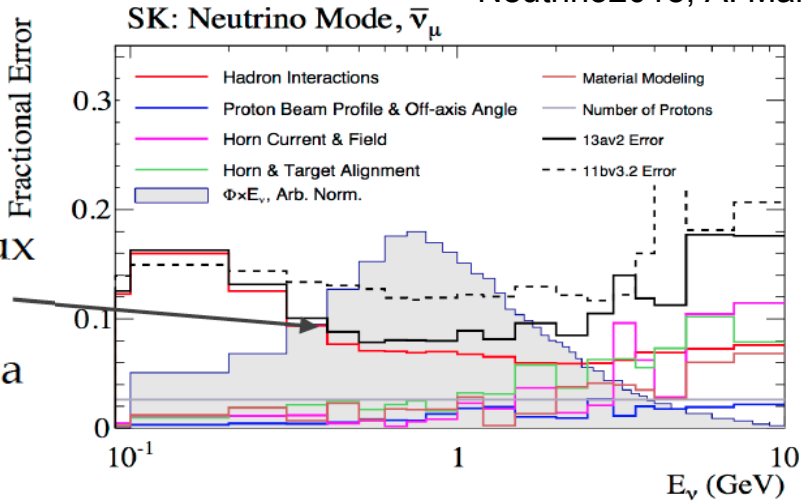
- **Double differential yields have been measured**
- **Draft paper is in preparation**
- **Plots for preliminary results: https://edms.cern.ch/ui/file/1828979/1/Results.pdf**

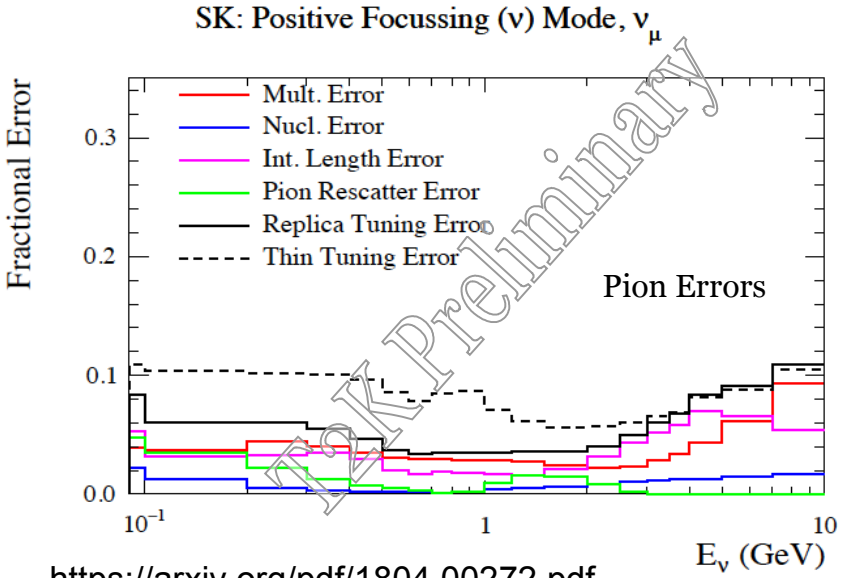
T2K Flux Uncertainty Updates

Neutrino2018, A. Marino



Current T2K flux uncert using thin target data





https://arxiv.org/pdf/1804.00272.pdf

- **The T2K flux uncertainty is reduced from 12% to ~9% due to the thin target measurement updates**
- **The uncertainty will be reduced down to ~ 5% after implementing the replica target measurements**

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Data Taken for Fermilab Experiments 2012 - 2016

Interaction	Year	Triggers	Magnet Config
p+C @ 120 GeV/c	2012	2.8M	B-field VTX1 Off
π^+ +C @ 31 GeV/c	2015	745k	B-field OFF
π^+ +Al @ 31 GeV/c	2015	565k	B-field OFF
p+C @ 31 GeV/c	2015	388k	B-field OFF
π^+ +C @ 60 GeV/c	2015	577k	B-field OFF
π^+ +Al @ 60 GeV/c	2015	535k	B-field OFF
K^+ +C @ 60 GeV/c	2015	506k	B-field OFF
K^+ +Al @ 60 GeV/c	2015	339k	B-field OFF
p+C @ 60 GeV/c	2016	2.9M	B-field ON
p+Al @ 60 GeV/c	2016	3.2M	B-field ON
π^+ +C @ 60 GeV/c	2016	4.2M	B-field ON
p +C @ 120 GeV/c	2016	4.3M	B-field ON
π^+ +Be @ 60 GeV/c	2016	2.6M	B-field ON
p +Be @ 120 GeV/c	2016	2.2M	B-field ON
p +Be @ 60 GeV/c	2016	2.1M	B-field ON

Analyzed and the paper has been accepted by Phys Rev D

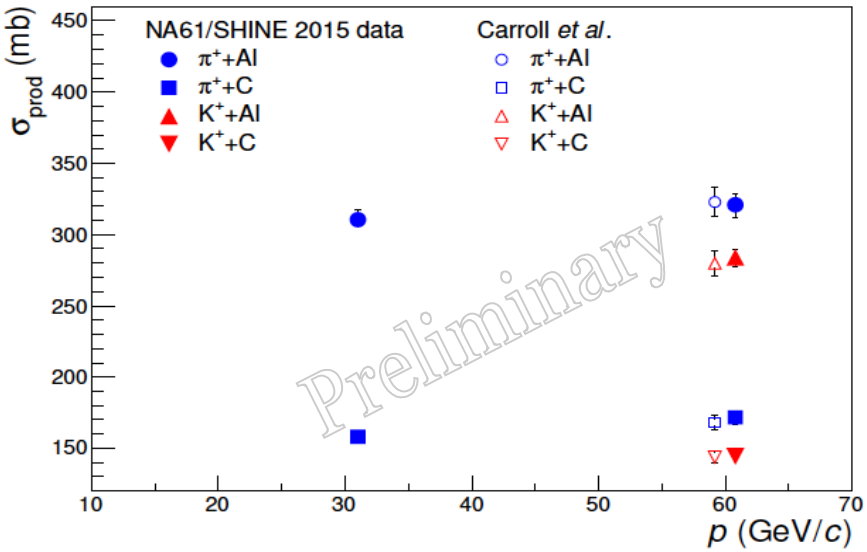
Analysis is in progress

Recent Production Cross Sections Results

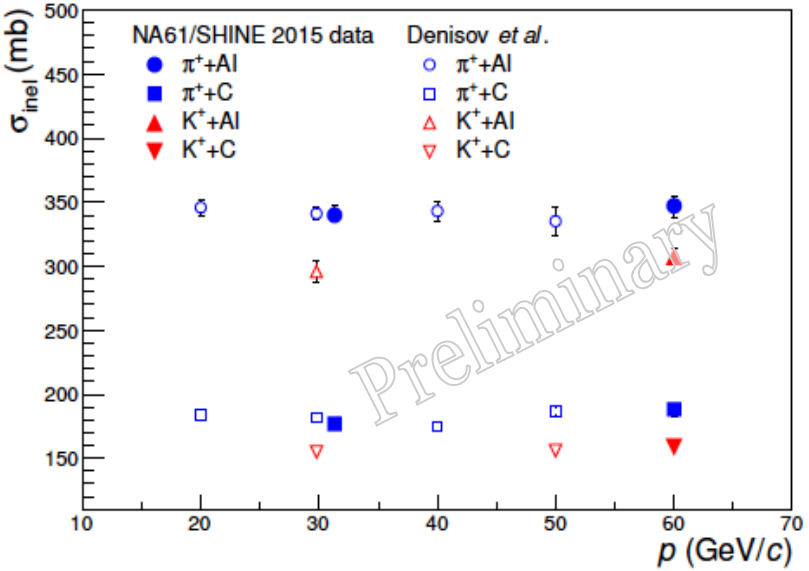
Measurements of total production cross sections for π^++C, π^++Al, K^++C, and K^++Al at 60 GeV/c and π^++C and π^++Al at 31 GeV/c

The data taken in 2015 on C and Al targets without magnetic fields have been analyzed to measure the total production cross sections and inelastic cross sections

Production Cross Sections



Inelastic Cross Sections



Preprint : https://arxiv.org/pdf/1805.04546.pdf

The paper has been accepted by Phys.Rev. D

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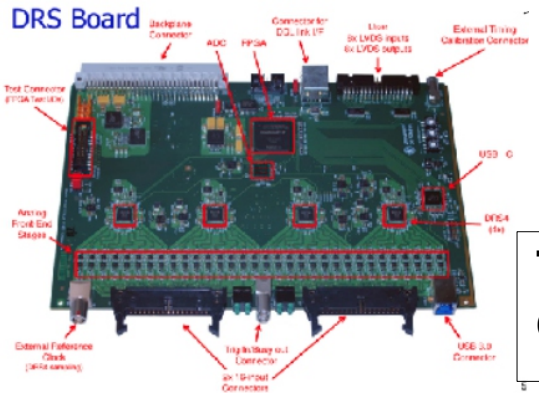
Hardware Upgrades in 2017

- **Installed 3 new Forward-TPCs to improve the forward acceptance**
- **Reinstalled the TOF-Forward detector system with DSR4 readout upgrades in 2017**
- **32 scintillator bars with 64 PMTs**

FTPC 1

FTPC 2/3

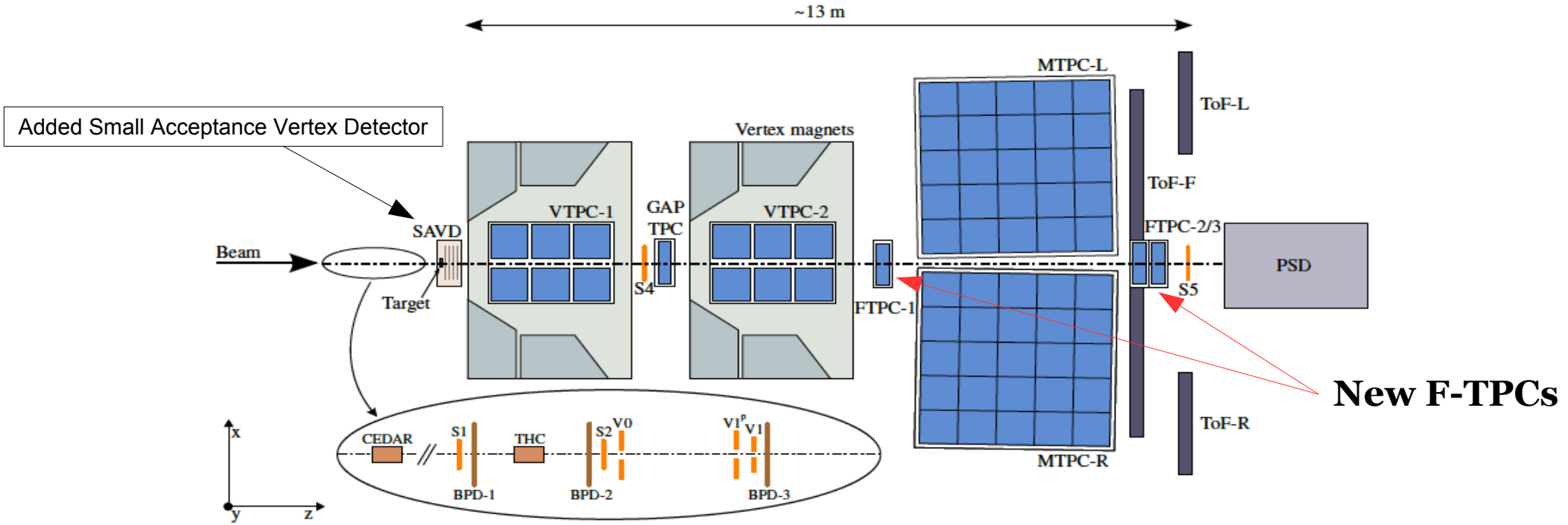


University of Geneva DRS4 board:
32 channels & 5GHz sampling rate

There is a future plan to upgrade all detector readouts with DRS4

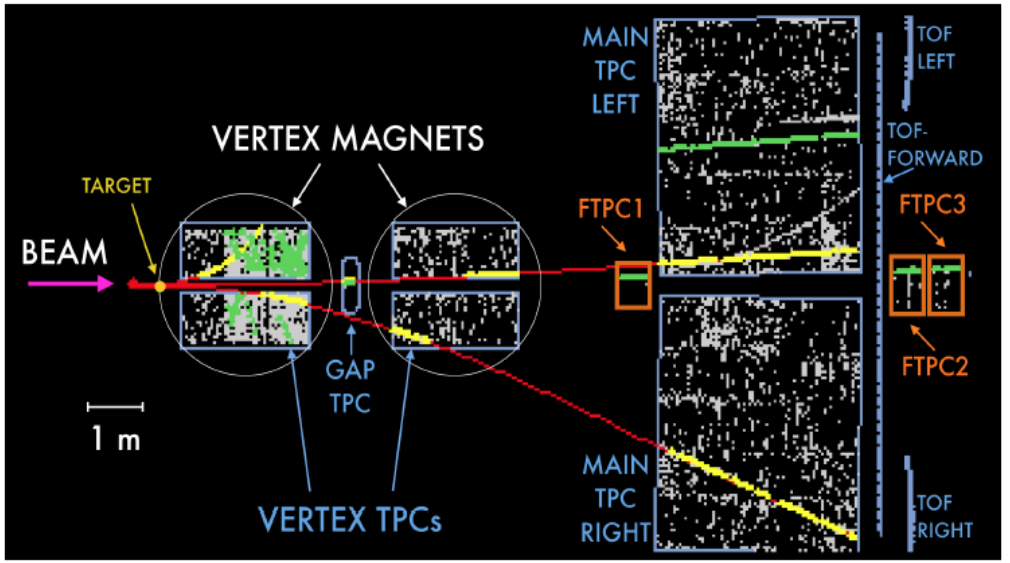
A FTOF module (out of 4 modules) with 8 scintillator bars before the installation

Current NA61/SHINE Detector



New F-TPCs

Event display with local tracks



NA61 neutrino program data in 2017

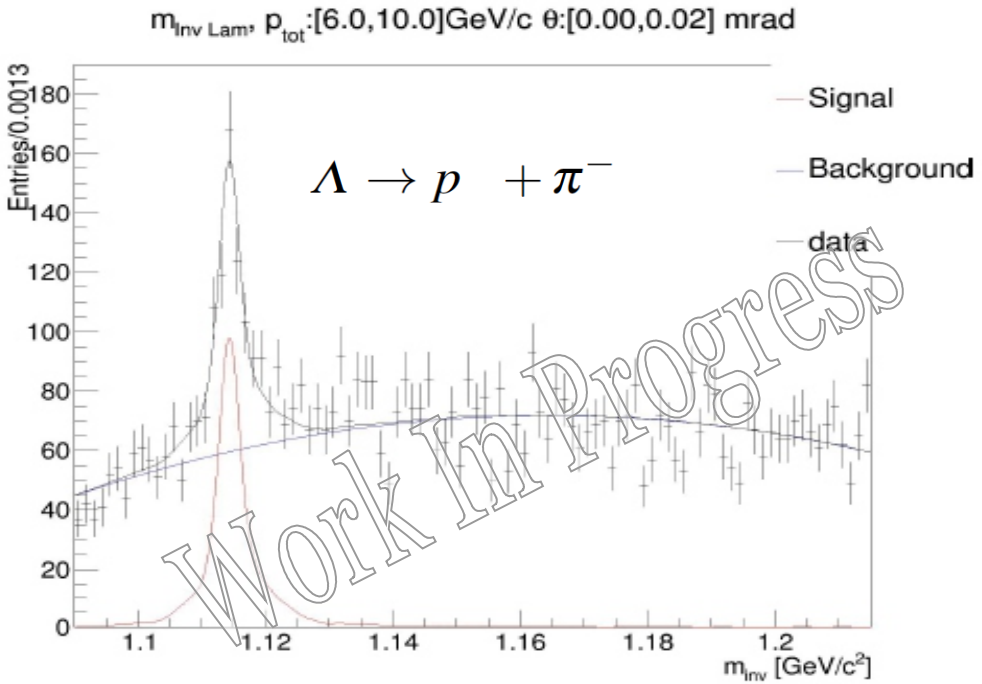
Interaction	Year	Triggers	Config: B-field ON
π^+ +C @ 31 GeV/c	2017	2.2M	No F-TOF & no FTPCs
π^+ +Al @ 60 GeV/c	2017	2.3M	No F-TOF & no FTPCs
π^- + C @ 60 GeV/c	2017	3.1M	With F-TOF & FTPCs
p+C @ 120 GeV/c	2017	2.5M	With F-TOF & FTPCs
p+Be @ 120 GeV/c	2017	2.6M	With F-TOF & FTPCs
p+C @ 90 GeV/c	2017	2.6M	With F-TOF & FTPCs

- **Analysis priority is given for:**
  π^+ + C @ 60 GeV/c (2016) and
  p + C @ 120 GeV/c (2016-2017)

Current Analysis Plan

- **Analysis of hadron production yields for π^+ + C @ 60 GeV/c and π^+ + Be @ 60 GeV/c**

$\pi^{\pm}, K^{\pm}, K^0_S, \Lambda$ **and proton**



- **Analysis of off axis K^0_S production yields for p + C @ 120 GeV/c**

$$K^0_S \rightarrow \pi^+\pi^-$$

Fermilab Targets for 2018 runs

- **NOvA replica target data taking is on going in this summer (July – August):**

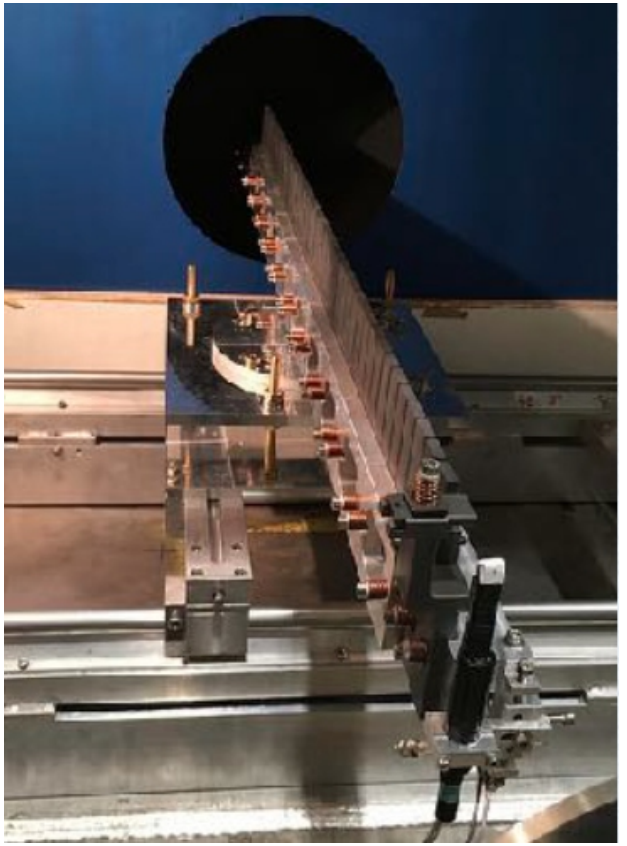
  p+C @ 120 GeV/c

  Target length = 120 cm

- **Possible thin target runs:**

  K+C @ 60 GeV/c

NOvA (NuMI) replica target



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NA61 neutrino program beyond 2020

*** Long Shutdown (LS2) from 2019 – 2020**

Hardware / Software Upgrade Plans:

- *New TPC read-out electronics used in ALICE*
- *New DAQ system capable of 1kHz readout*
- *New ToF walls with multi-gap Resistive Plate Chamber (mRPC) technology*
- *New BPD system based on scintillating fibers*

Run Plan for 2021 – 2025:

- *DUNE thin target measurements*
- *DUNE (LBNF) and Hyper-K/T2K II replica targets*
- *Thin target running on Titanium*
- *More kaon interaction data runs*

Summary

- *NA61 has provided precise hadron production measurements for the T2K experiment to improve the flux predictions and systematics*
- *NA61 detector system has been upgraded with FTPCs and FTOF systems in 2017 to cover the large kinematical space by improving the forward acceptance*
- *Results from 2015 data have been submitted to Phys Rev D and the analysis of 2016 – 2017 data is ongoing*
- *NA61 is recording NOvA replica target data in this summer*
- *Planing 2020+ detector upgrades to improve the trigger and detector systems*
- *Preparing to record DUNE and Hyper-K targets data after 2020*

The NA61/SHINE Collaboration

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Thank You

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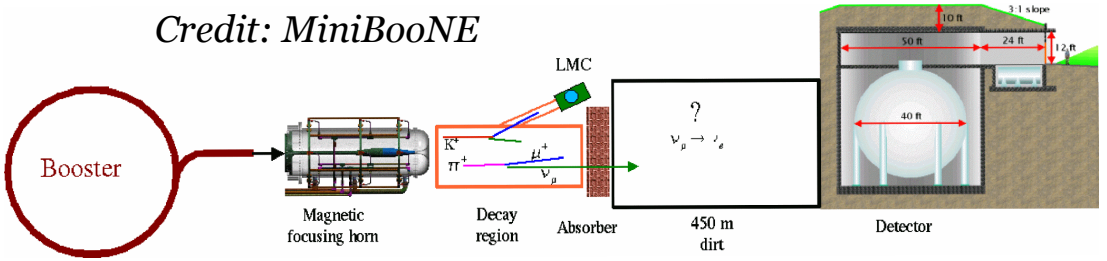
Backup Slides

Few Examples of Neutrino Beamlines

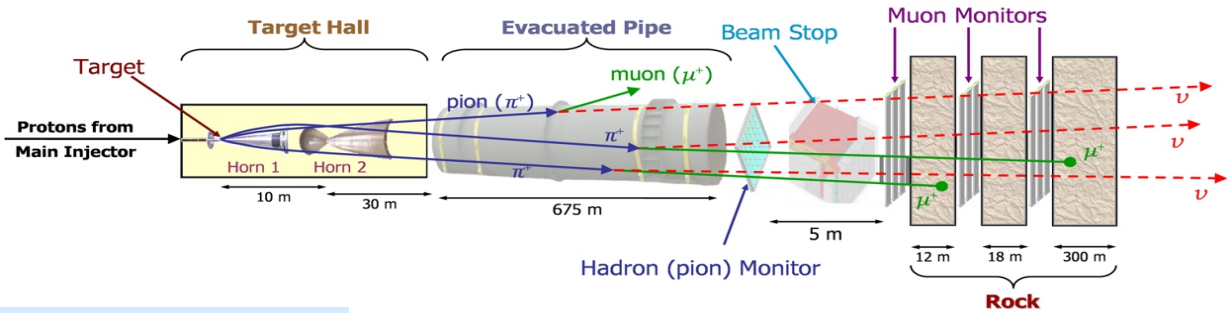
Credit: MiniBooNE



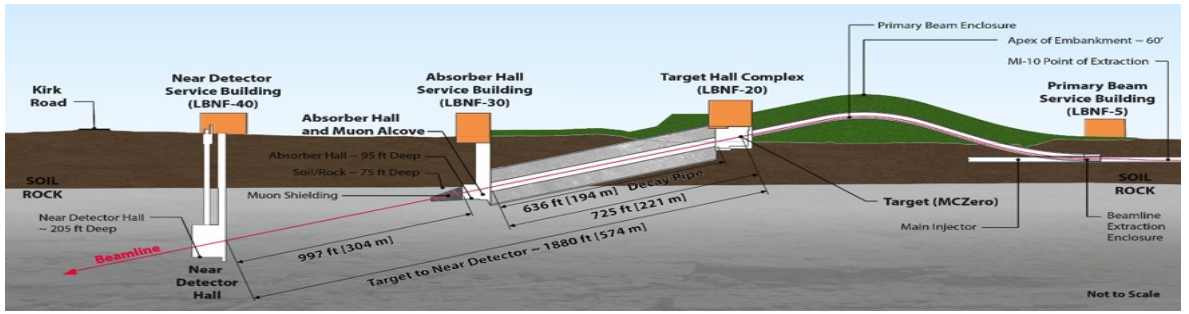
BNB at Fermilab: use data-driven flux models with including HARP measured p (8.9 GeV/c)+Be data

Credit: NOvA, MINOS, FNAL

NuMI beam at Fermilab: Use GEANT4, FLUKA models, and NA49, MIPP data .. etc to model the flux

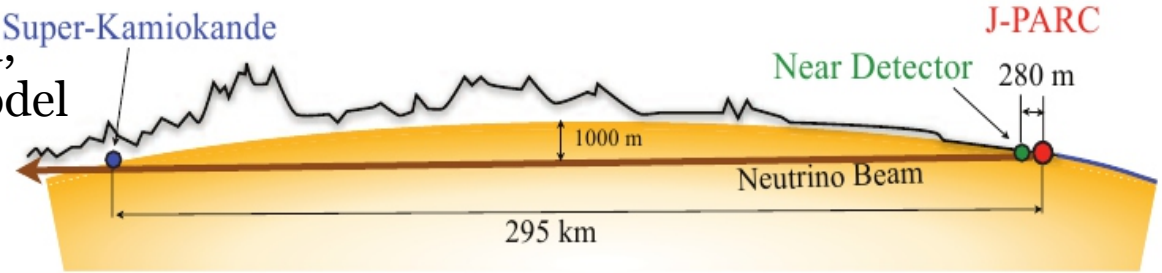


Credit: DUNE



LBNF beam at Fermilab: The primary proton beam will be 60-120 GeV on a Be or C target. Planing to have NA61 data and hopefully some models to predict the flux

T2K beam: Use 2 near detector data, FLUKA and NA61 + other data to model the flux predictions



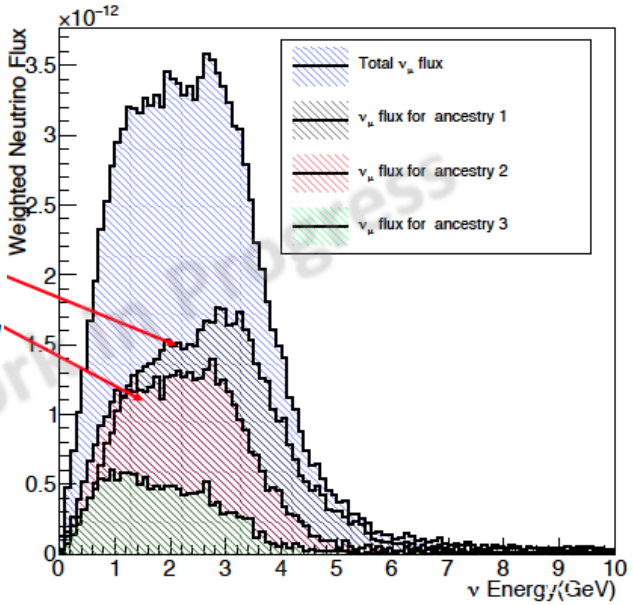
Credit: T2K

NuMI and LBNF flux predictions

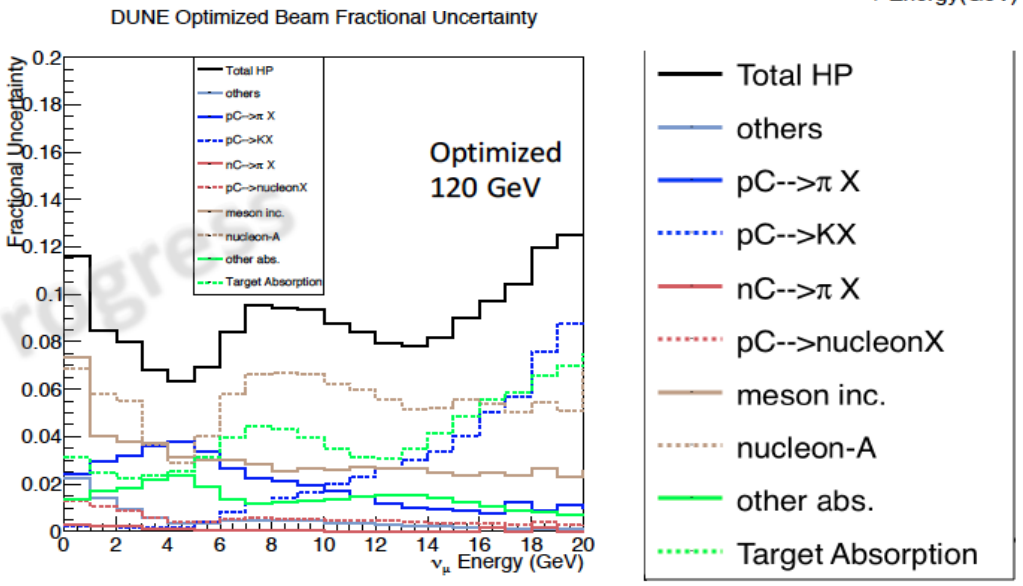
DUNE Flux

Ancestry 1: p→X→ν

Ancestry 2: p→X→Y→ ν



From Amit Bashyal

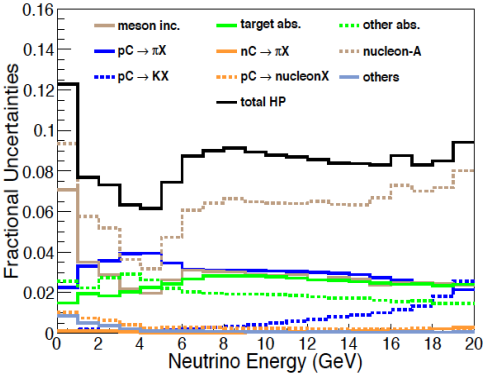


Ref: https://indico.fnal.gov/event/11999/session/9/contribution/262

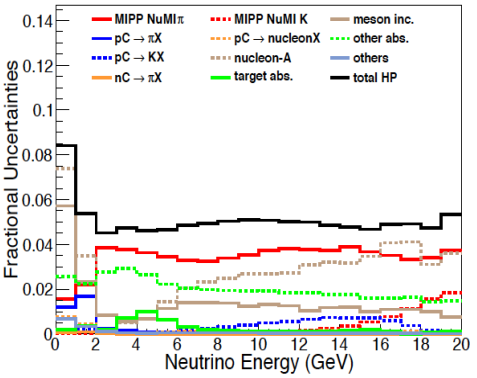
NuMI Flux for Minerva

Ref: Phys. Rev. D 94, 092005 (2016):

Low Energy thin target

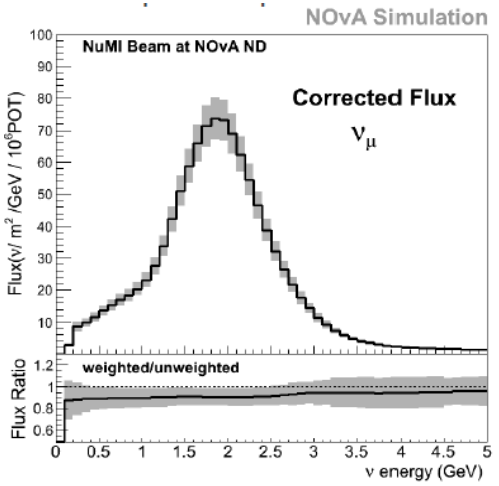


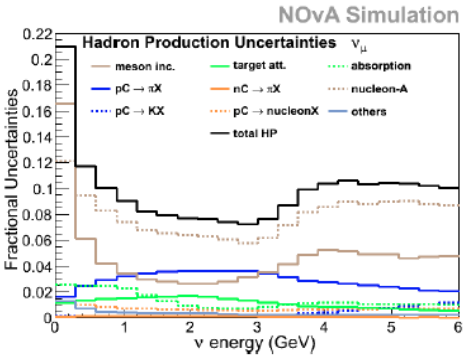
Low Energy thick target



NuMI Flux for NOvA ND

Ref: Leo Aliaga (NBI 2017)





TPC Parameters

	VTPC-1	VTPC-2	MTPC-L/R	GAP-TPC
size (L×W×H) [cm]	250 × 200 × 98	250 × 200 × 98	390 × 390 × 180	30 × 81.5 × 70
No. of pads/TPC	26 886	27 648	63 360	672
Pad size [mm]	3.5 × 28(16)	3.5 × 28	3.6 × 40, 5.5 × 40	4 × 28
Drift length [cm]	66.60	66.60	111.74	58.97
Drift velocity [cm/μs]	1.4	1.4	2.3	1.3
Drift field [V/cm]	195	195	170	173
Drift voltage [kV]	13	13	19	10.2
gas mixture	Ar/CO_2 (90/10)	Ar/CO_2 (90/10)	Ar/CO_2 (95/5)	Ar/CO_2 (90/10)
# of sectors	2 × 3	2 × 3	5 × 5	1
# of padrows	72	72	90	7
# of pads/padrow	192	192	192, 128	96