Hadron Production Measurements for Neutrino Experiments with NA61/SHINE

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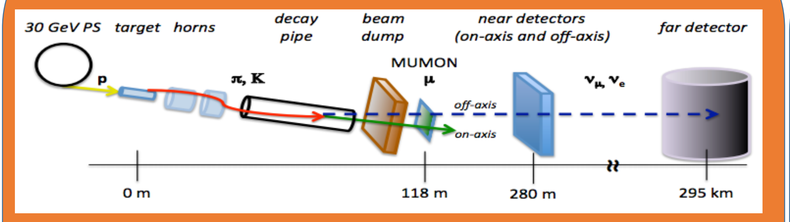
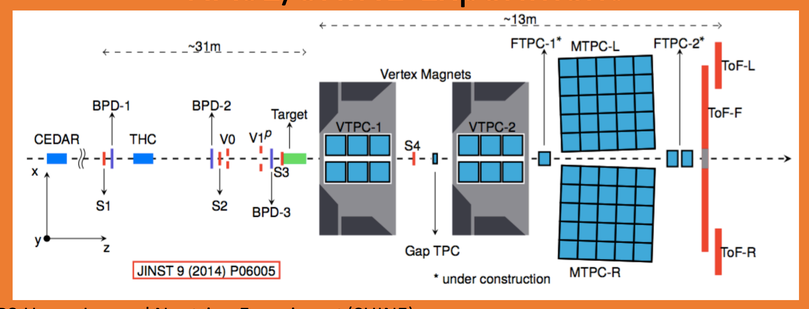
On behalf of the NA61/SHINE experiment

Why Hadron Production Measurements?



- Accelerator-based neutrino beams (T2K shown) focus charged pions that decay into neutrinos
- MC is used to predict the neutrino flux incident on the neutrino detectors
- Hadron production data allows us to replace the model-predicted hadron interaction rates with real measurements improving systematic uncertainties

NA61/SHINE Experiment



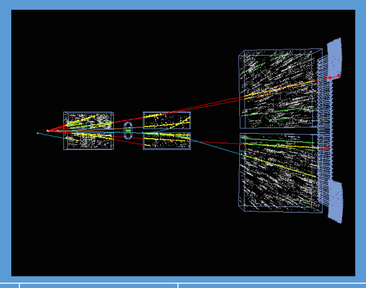
- SPS Heavy Ion and Neutrino Experiment (SHINE)
- 140 Physicists from 14 countries and 28 institutions
- Large acceptance hadron spectrometer
- Energies [13, 350] GeV/c²
- TPCs measure energy loss and track particles ($\sigma_{dE/dx}/\langle dE/dx\rangle \approx .04$) – two new forward TPCs (FTPC) are currently being constructed and implemented to expand detector acceptance in the forward region
- ToF measures m² (≈100 ps resolution)
- Two superconducting magnets enable momentum measurement (max field: 9 Tm)

Physics Programs:

- Heavy Ion
- **Neutrino**
- Cosmic Ray

Summary of Data Taken for T2K

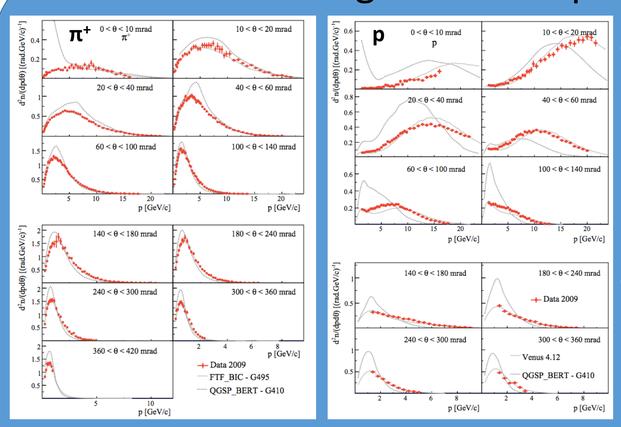
- 31 GeV/c protons on thin (2 cm) and T2K replica (90 cm) carbon targets
- Data taken in 2007, 2009 and 2010
- Spectra of pions, kaons, protons, lambdas obtained
- Small amount of π^+@31 GeV/c data was also recorded



Beam	Target	Year	Triggers ×10⁶	Measurements	Analysis Status
p@31 GeV/c	C 2 cm	2007	0.7	$\pi^\pm$, K^+, K^0_S, Λ_0	published [1,2]
p@31 GeV/c	C 2 cm	2009	5.4	$\pi^\pm$, $K^\pm$, p, K^0_S, Λ_0	published [3]
π^+@31 GeV/c	C 2 cm	2009	0.2	$\pi^\pm$	analysis ongoing
p@31 GeV/c	C 90 cm	2007	0.2	$\pi^\pm$	published [4]
p@31 GeV/c	C 90 cm	2009	4	$\pi^\pm$	published [5]
p@31 GeV/c	C 90 cm	2010	10	$\pi^\pm$, $K^\pm$	analysis ongoing

[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Eur. Phys. J. C (2016) 76: 84
[4] Nucl. Instrum. Meth. A701, 99 (2013).
[5] arXiv:1603.06774 (2016)

2009 Thin Target Results: pC@31 GeV/c

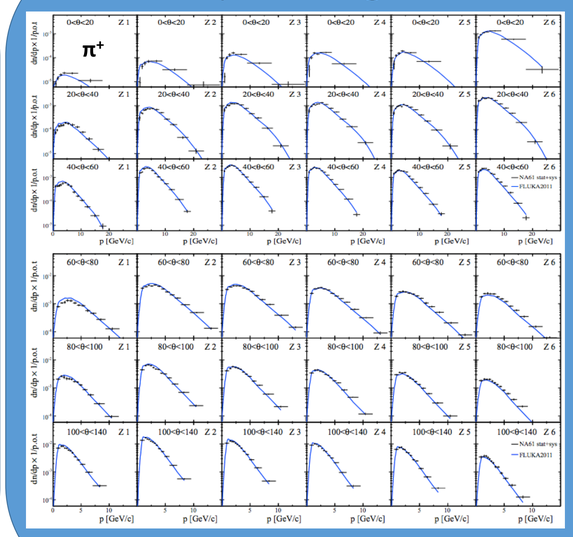


- Differential cross section measurements were obtained for 7 particle species (π^+, π^-, protons, K^+, K^-, K^0_S, and Λ)
- Measurements of the total inelastic and production cross section were also made

$$\sigma_{inel} = 258.4 \pm 2.8(\text{stat}) \pm 1.2(\text{det})^{+5.0}_{-2.9}(\text{mod})mb$$

$$\sigma_{prod} = 230.7 \pm 2.8(\text{stat}) \pm 1.2(\text{det})^{+6.3}_{-3.5}(\text{mod})mb$$

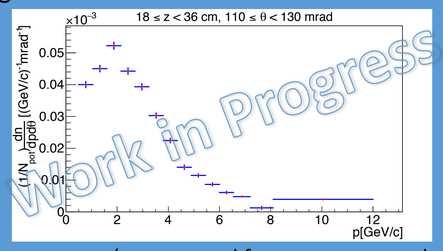
2009 Replica Target Results: pC@31 GeV/c



- A T2K replica target was used to study the effects of particles reinteracting inside the target volume
- Differential cross section measurements were obtained for π^+ and π^-
- Z bins include particles exiting the target face and 5 longitudinal bins
- Shown are the π^+ spectra obtained for the first 6 angular bins

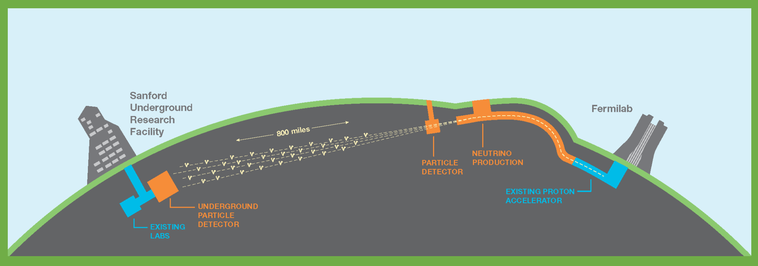
2010 Replica Target Analysis

- Analysis of the 2010 T2K Replica Target data is underway
  - Larger statistics and detector improvements compared to data from 2009
  - Part of the data is taken with a higher magnetic field to access higher acceptance in the forward region
- Instead of reweighting every interaction in beam MC simulations, just reweight particles exiting the target
- These measurements are needed to achieve T2K's goal of reducing the neutrino flux uncertainties to < 5%



Sample π^+ raw spectra (uncorrected for acceptance and other effects) – spectra of π^-, K^+ and K^- are also being analyzed

Data For Fermilab Neutrino Experiments



- Fermilab neutrino experiments (DUNE, MINERvA, MINOS+, NOvA) also need hadron production data to improve neutrino flux predictions
- Total cross section data was taken in 2012 and 2015 for a variety of interactions
- Ongoing and future spectra measurements in 2016 and 2017:
  - π^+ and protons at 31, 60 and 120 GeV/c incident on C, Be and Al targets
- Possibility to run with DUNE and NuMI replica targets

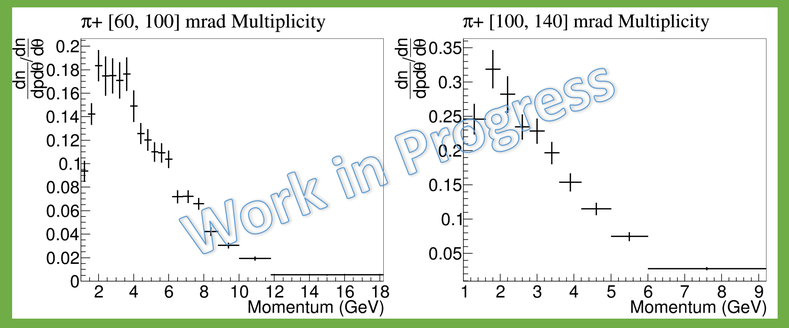
Cross Section Analyses

- We are currently analyzing data taken from 2012 and 2015
- This data contains a variety of interactions with the magnetic field turned off or at a partial field setting
- Total production and total inelastic cross sections are being measured

Year	Beam Particle	Beam Momentum	Target	Triggers ×10⁶
2012	p	120 GeV/c	C	2.8
2015	π^+	31 GeV/c	C	1.2
2015	π^+	31 GeV/c	Al	0.8
2015	π^+	60 GeV/c	C	0.8
2015	π^+	60 GeV/c	Al	0.7
2015	K^+	60 GeV/c	C	0.7
2015	K^+	60 GeV/c	Al	0.5
2015	p	31 GeV/c	C	0.6

- These cross section measurements can be used for tuning beam MC simulations in the NuMI and DUNE beamlines

Spectra Analyses for FNAL Experiments



- Analysis of 2009 π^+ C@31 GeV/c data is ongoing
- Shown are normalized momenta distributions of π^+ with only statistical uncertainties shown
- Analyses of 2016 and 2017 thin target data will be started as the data is taken and calibrated