Hadron Production Measurements for Neutrino Experiments with NA61/SHINE

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ICHEP 2018
July 6, 2018

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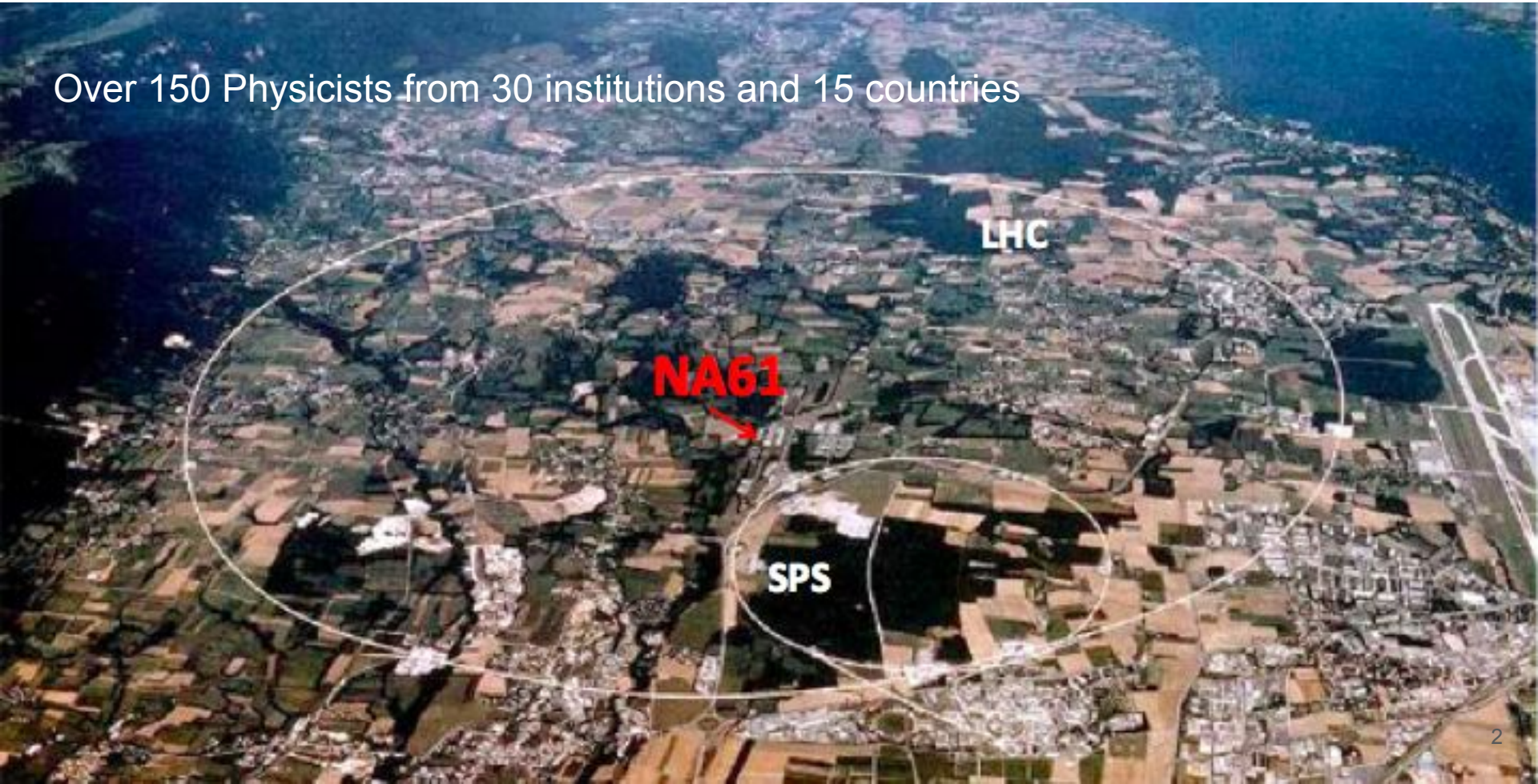
The NA61/SHINE Collaboration

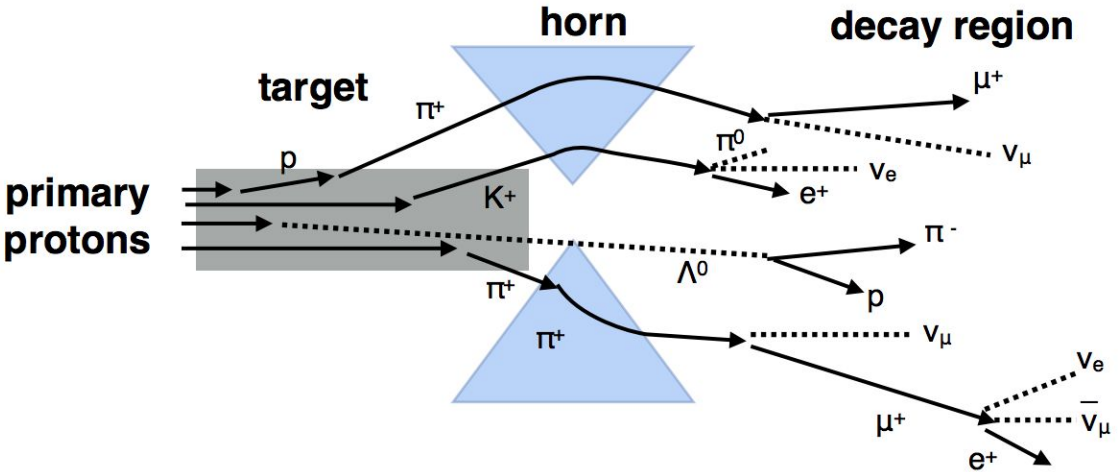


The NA61/SHINE Experiment

- SPS Heavy Ion and Neutrino Experiment
- Broad physics program
  - Heavy Ion
    - Study the onset of deconfinement
    - Critical point search
  - Cosmic Ray
    - Hadron production measurements to tune simulations of cosmic ray showers
  - **Neutrino**
    - **Hadron production measurements to improve precision of neutrino flux estimations**
- Capable of receiving **secondary beam of charged hadrons (pions, kaons and protons) [~13, 350] GeV/c**
- Light ions from Pb fragmentation [13A, 150A] GeV/c
- Primary Ar, Xe and Pb [13A,150A] GeV/c and primary protons [400] GeV/c
- Accepts many **solid thin targets**, liquid hydrogen and **replica targets** for neutrino experiments
- Capable of recording over 500,000 events per day

Necessity for Hadron Production Measurements

- Near detectors are insufficient for understanding neutrino flux at the far detector
  - Different angular acceptance and often different interaction material at near and far sites
- Neutrino cross section measurements depend on precise neutrino flux
- Which interactions do we need to understand?
  - Primary interactions of protons with target and beam material (eg. Al, Ti) at the beam energy
  - Secondary interactions of protons, pions and kaons with target and beam material at lower energies
- NA61 is capable of studying most of these interactions

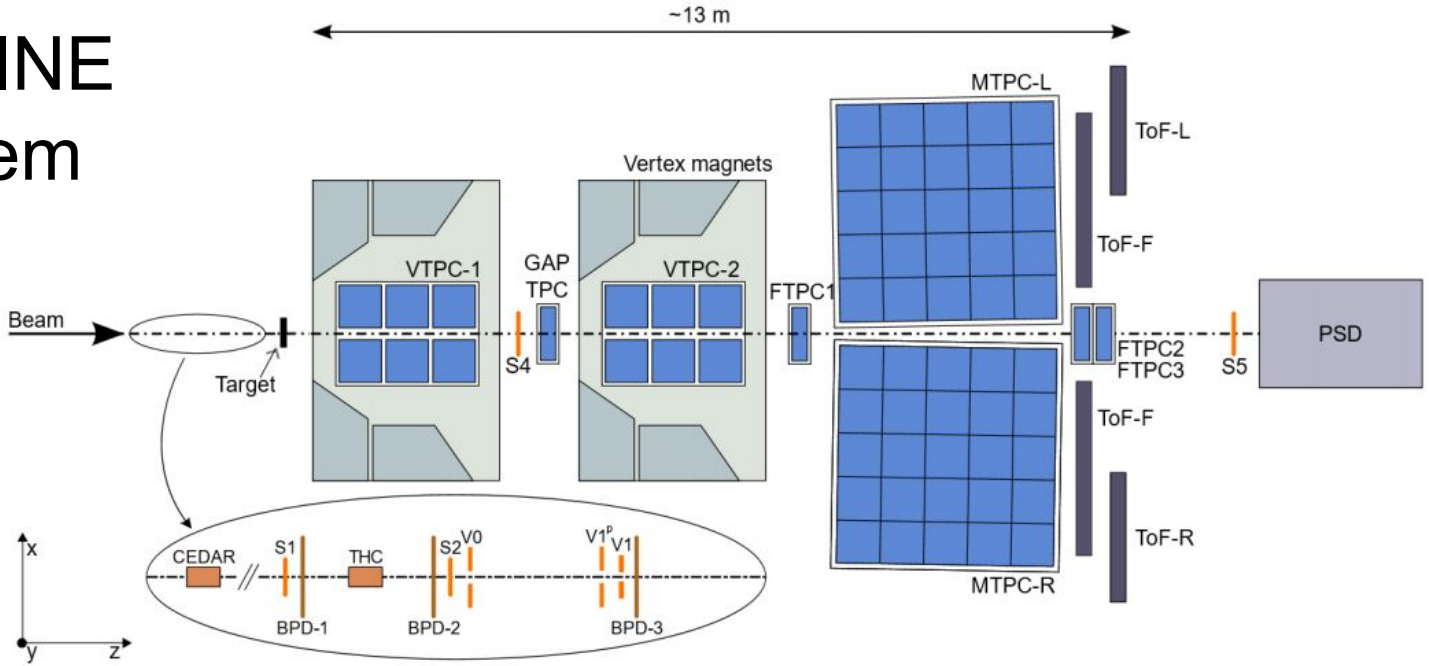


Neutrino Parents in T2K

Parent	Flux percentage of each (all) flavor(s) ν_μ	$\bar{\nu}_\mu$	ν_e	$\bar{\nu}_e$
Secondary				
$\pi^\pm$	60.0(55.6)%	41.8(2.5)%	31.9(0.4)%	2.8(0.0)%
$K^\pm$	4.0(3.7)%	4.3(0.3)%	26.9(0.3)%	11.3(0.0)%
K^0_L	0.1(0.1)%	0.9(0.1)%	7.6(0.1)%	49.0(0.1)%
Tertiary				
$\pi^\pm$	34.4(31.9)%	50.0(3.0)%	20.4(0.2)%	6.6(0.0)%
$K^\pm$	1.4(1.3)%	2.6(0.2)%	10.0(0.1)%	8.8(0.0)%
K^0_L	0.0(0.0)%	0.4(0.1)%	3.2(0.0)%	21.3(0.0)%

Phys Rev D **87** 012001 (2013)

The NA61/SHINE Detector System



- TPC system tracks charged particles and measures dE/dx ($\sigma_{dE/dx}/\langle dE/dx \rangle \approx .04$)
- Two Vertex TPCs are contained inside two superconducting vertex magnets (with 9 Tm of bending power)
- Two large Main TPCs
- Gap TPC and three new Forward-TPCs provide forward acceptance
- Time of Flight systems measure m^2 (~100 ps resolution)

Earlier Measurements for the T2K Experiment

- Thin target measurements from data recorded in 2007 and 2009
- T2K replica target measurements from 2007, 2009 and 2010

Beam	Target	Year	Measurements
p@31 GeV/c	C 2 cm	2007	$\pi^{\pm}$ [1], K^{+} [2], K^{0}_{S}, Λ^{0} [3]
p@31 GeV/c	C 2 cm	2009	$\pi^{\pm}$, $K^{\pm}$, p, K^{0}_{S}, Λ^{0} [4]
p@31 GeV/c	C 90 cm	2007	$\pi^{\pm}$ [5]
p@31 GeV/c	C 90 cm	2009	$\pi^{\pm}$ [6]
p@31 GeV/c	C 90 cm	2010	$\pi^{\pm}$, $K^{\pm}$, p, preliminary release [7], paper in progress
p@31 GeV/c High Field	C 90 cm	2010	Production cross section analysis in progress

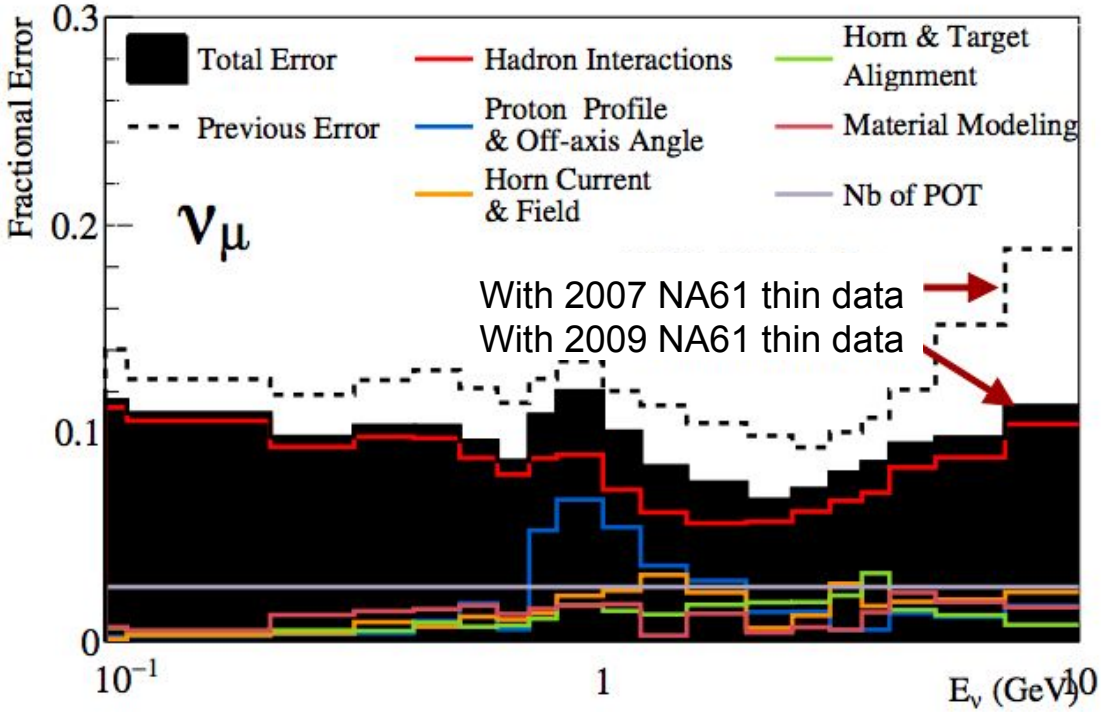
2 cm thin carbon target

90 cm T2K replica target

[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Phys. Rev C89, 025205 (2014).
[4] Eur. Phys. J. C (2016) 76: 84
[5] Nucl. Instrum. Meth. A701, 99 (2013)
[6] Eur.Phys.J. C76 (2016) no.11, 617
[7] https://edms.cern.ch/document/1828979/1

Effect on Neutrino Flux Prediction

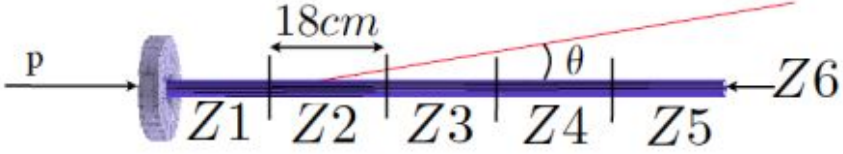
Phys.Rev. D87 (2013) no.1, 012001 and
J.Phys.Conf.Ser. 888 (2017) no.1, 012064

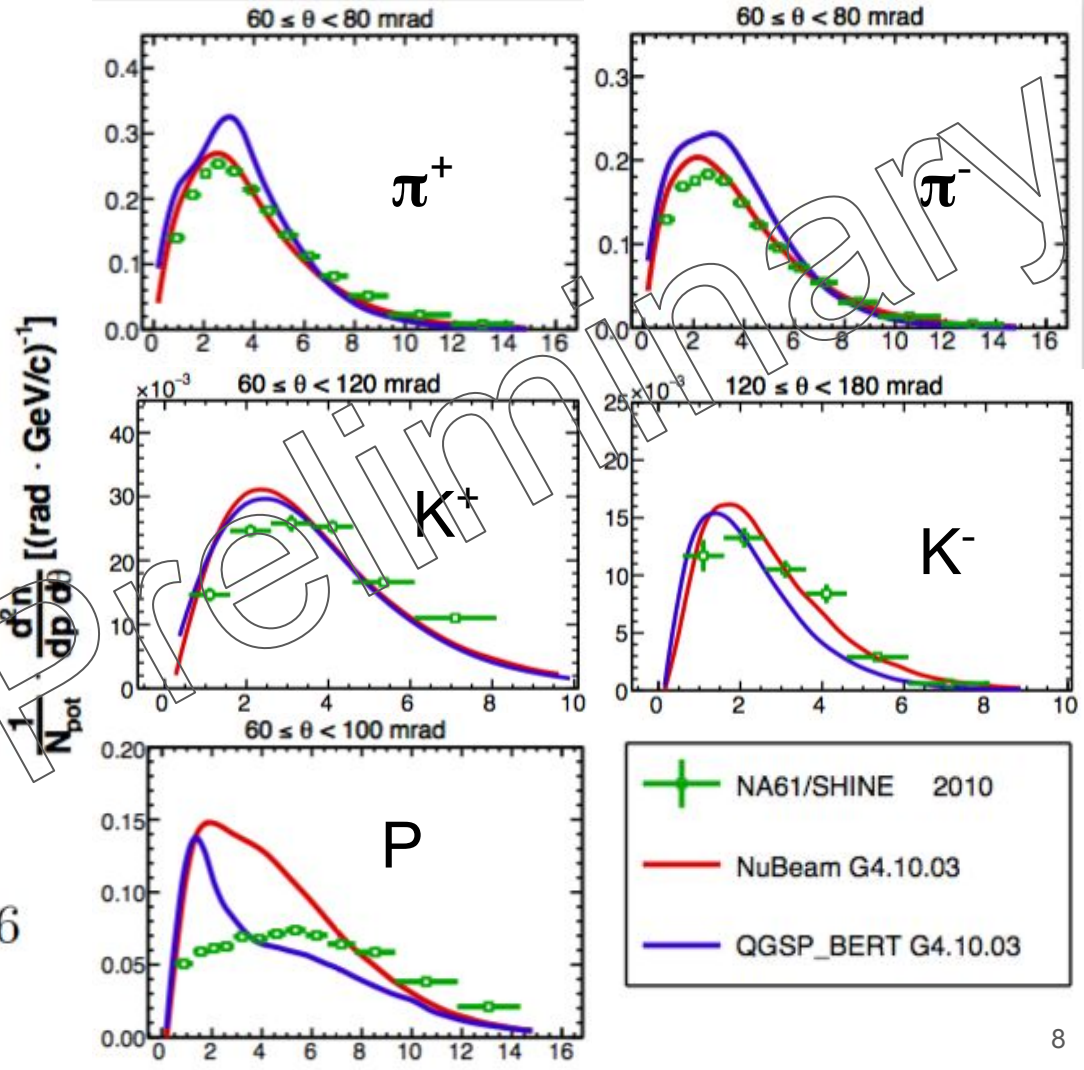


- Thin target beam MC reweighting with the 2007 and 2009 (higher stats) NA61 thin target datasets has already improved the T2K flux estimation
- A method has been developed to implement the replica target results into the flux estimation - it is expected to reduce uncertainties related to hadron production to < 5% everywhere

Select 2010 T2K Replica Target Results

- Plots are for the second longitudinal bin along the replica target
- Statistical errors reduced by factor of 2 compared to 2009 data
- Eg. for π^+: statistical typically < 4%, systematics typically < 3%
- Preliminary results released: https://edms.cern.ch/document/1828979/1

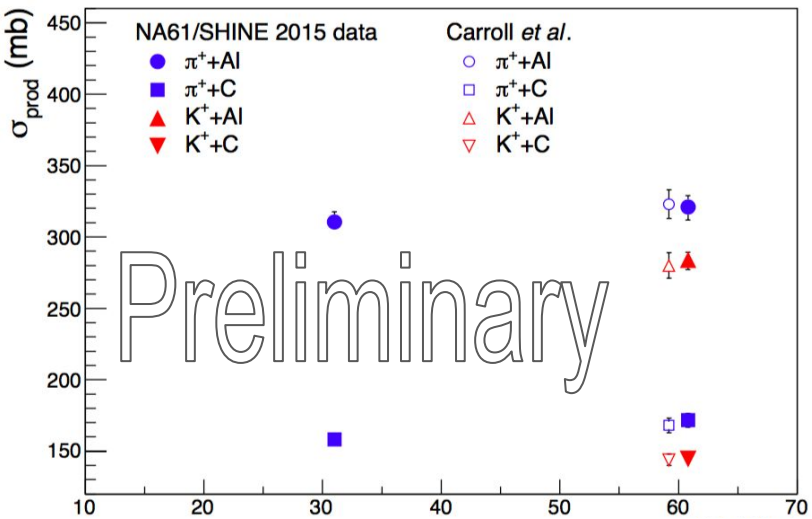


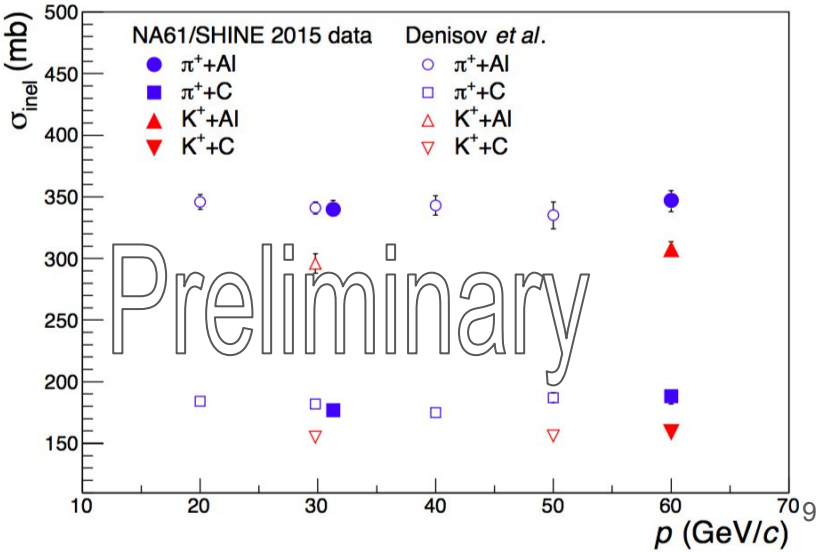


Total Cross Section Measurements from 2015 Data

- Magnets not operational in 2015, so spectra analysis was not possible
- Total inelastic and total production cross sections were measured for 6 different reactions
- Preprint: arXiv:1805.04546 (2018)
- Paper submitted to PRD

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





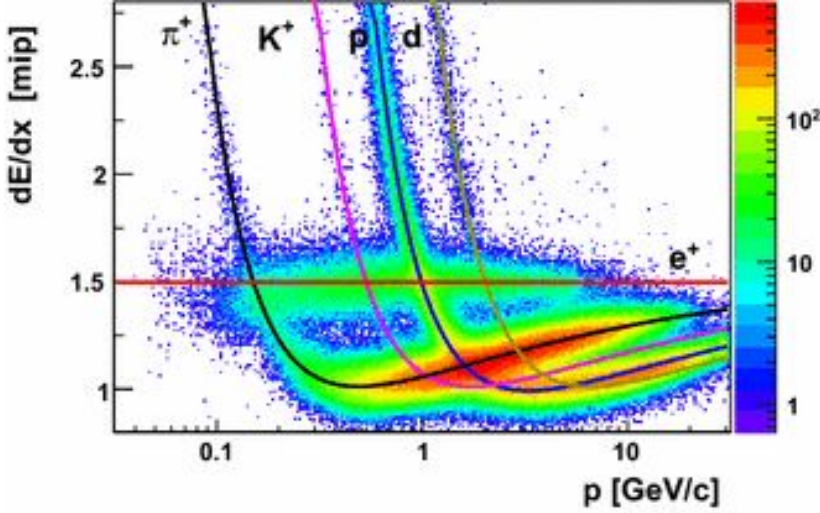
2016 Spectra Data for Neutrino Experiments

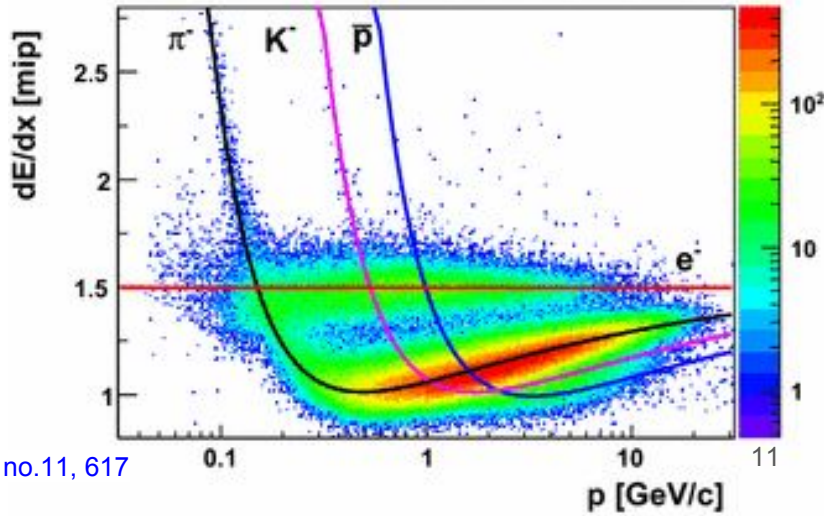
- Data for 7 different reactions were recorded - calibration ongoing
- π^++C@60GeV/c and π^++Be@60GeV/c are currently being analyzed
  - Total inelastic and total production cross sections
  - Differential cross sections of charged pions, kaons and protons
  - Differential cross sections of neutral K^0_S, Λ and $\overline{\Lambda}$

Beam Particle	Beam Momentum	Target
π^+	60 GeV/c	C
π^+	60 GeV/c	Be
p	60 GeV/c	C
p	60 GeV/c	Al
p	60 GeV/c	Be
p	120 GeV/c	C
p	120 GeV/c	Be

dE/dx Analysis

- Charged tracks are reconstructed to a main interaction vertex
- Reconstructed momenta are obtained from the vertex fits
- Energy loss is calculated from charge collected in the TPCs
- $e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, protons and deuterons fall along their Bethe-Bloch curves (dE/dx from p+C@31GeV/c interactions shown)
- Fits are performed in kinematic bins to discriminate particle species





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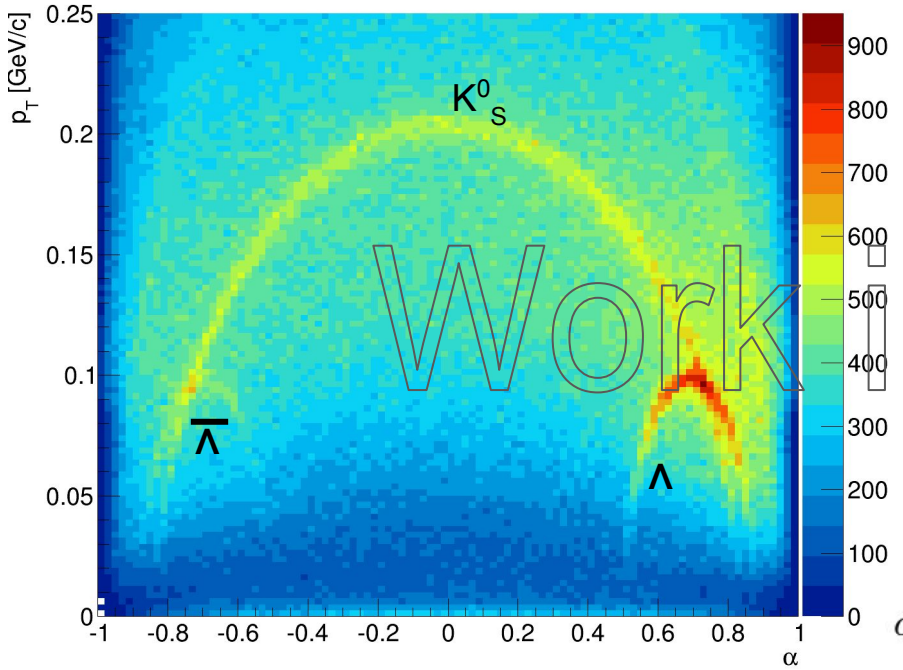
Analysis of Weakly Decaying Neutral Particles

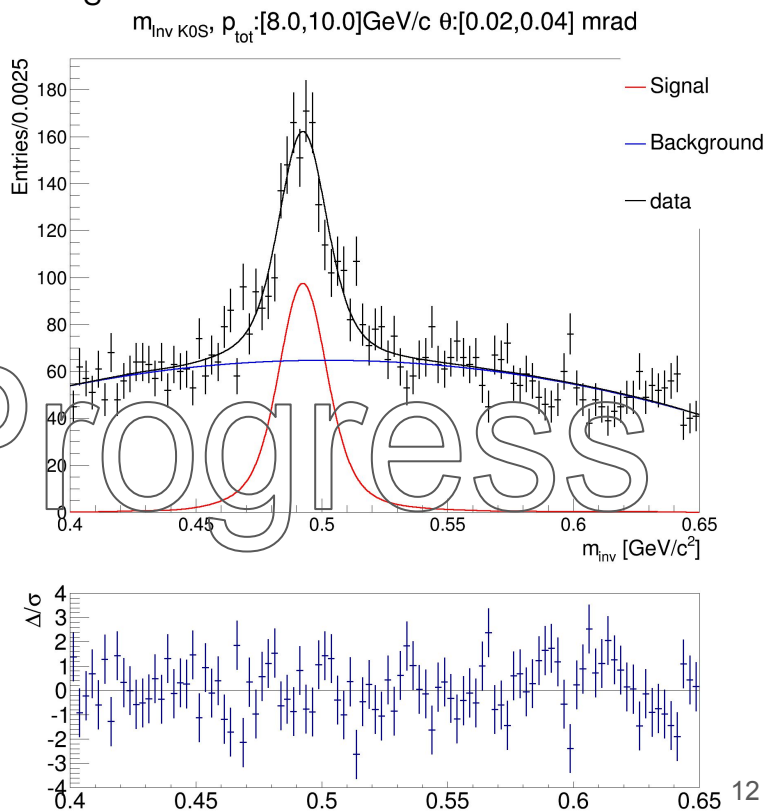
- A reconstruction algorithm identifies decay vertices of neutral particles by searching for secondary vertices with 1 positively charged track and 1 negatively charged track
- Fits are performed to the invariant mass distributions for K^0_S, Λ or $\overline{\Lambda}$ in each kinematic bin

Armenteros-Podolansky, π^++C@60GeV/c



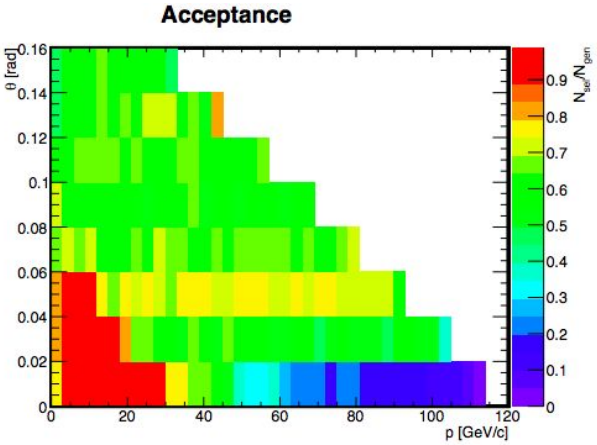
$$\alpha = \frac{p_l^+ - p_l^-}{p_l^+ + p_l^-}$$

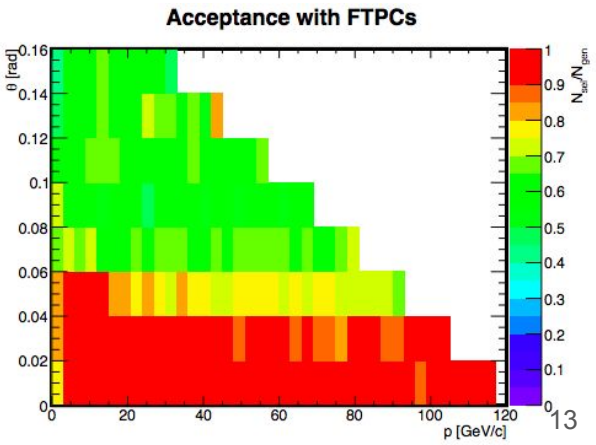
Fitted	
N_S	1098.17
N_{BG}	5871.83
f_s	0.1576



Recent Hardware Upgrades: FTPCs and Electronics

- Forward TPCs fill the void in the forward acceptance
- Particularly important for measuring forward scattering of protons and pions
- Began upgrading the readout to a more modern DRS4 system
  - Enabling easier maintenance and customization of detector components

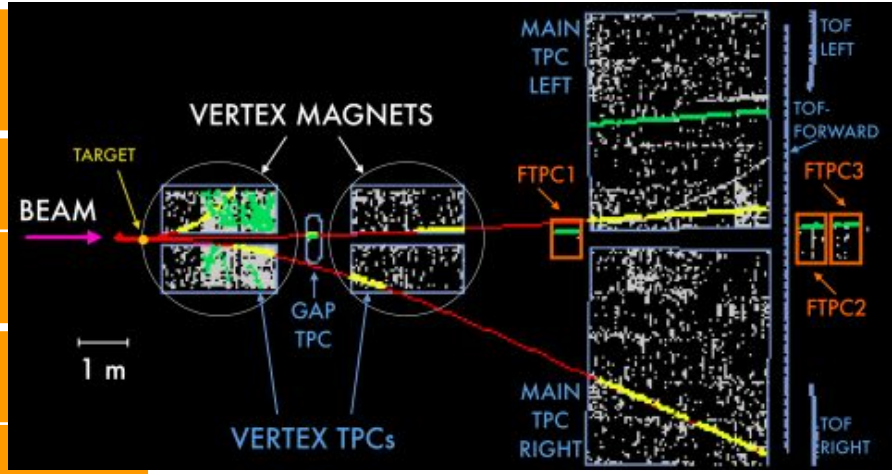




2017 Spectra Data for Neutrino Experiments

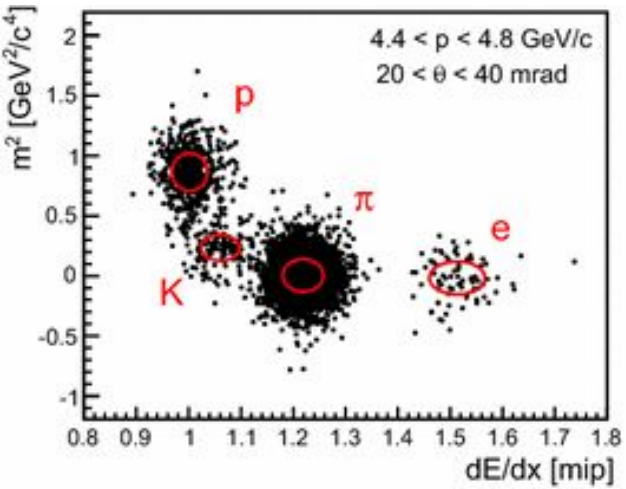
- Variety of interactions were studied
  - Including first data to be recorded with the FTPCs installed!
  - New reconstruction framework will be used to reconstruct these datasets
  - Have local tracking, but full reconstruction in progress

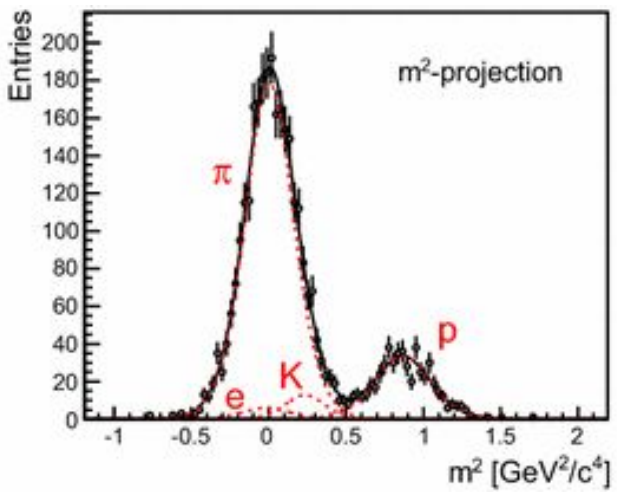
Beam Particle	Beam Momentum	Target	
π^+	60 GeV/c	Al	
π^+	30 GeV/c	C	
π^-	60 GeV/c	C	w/ FTPCs and F-ToF
p	120 GeV/c	C	w/ FTPCs and F-ToF
p	120 GeV/c	Be	w/ FTPCs and F-ToF
p	90 GeV/c	C	w/ FTPCs and F-ToF

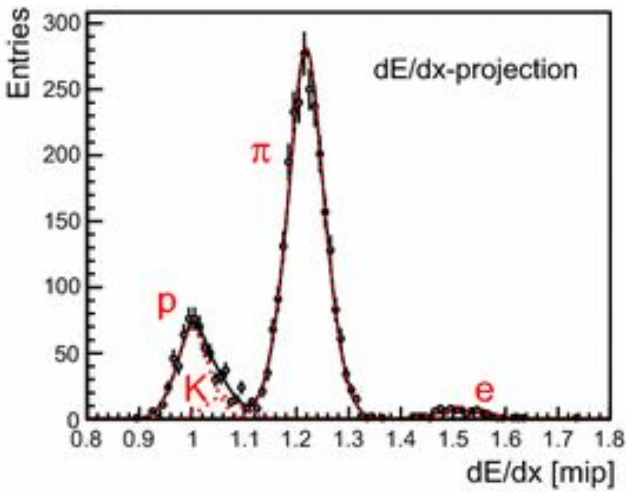


Combined dE/dx and ToF Analysis

- With the Forward Time-of-Flight system in place, we can perform a combined dE/dx and ToF analysis
- Improves particle identification for momenta less than 10 GeV/c especially in the Bethe-Bloch crossing regions







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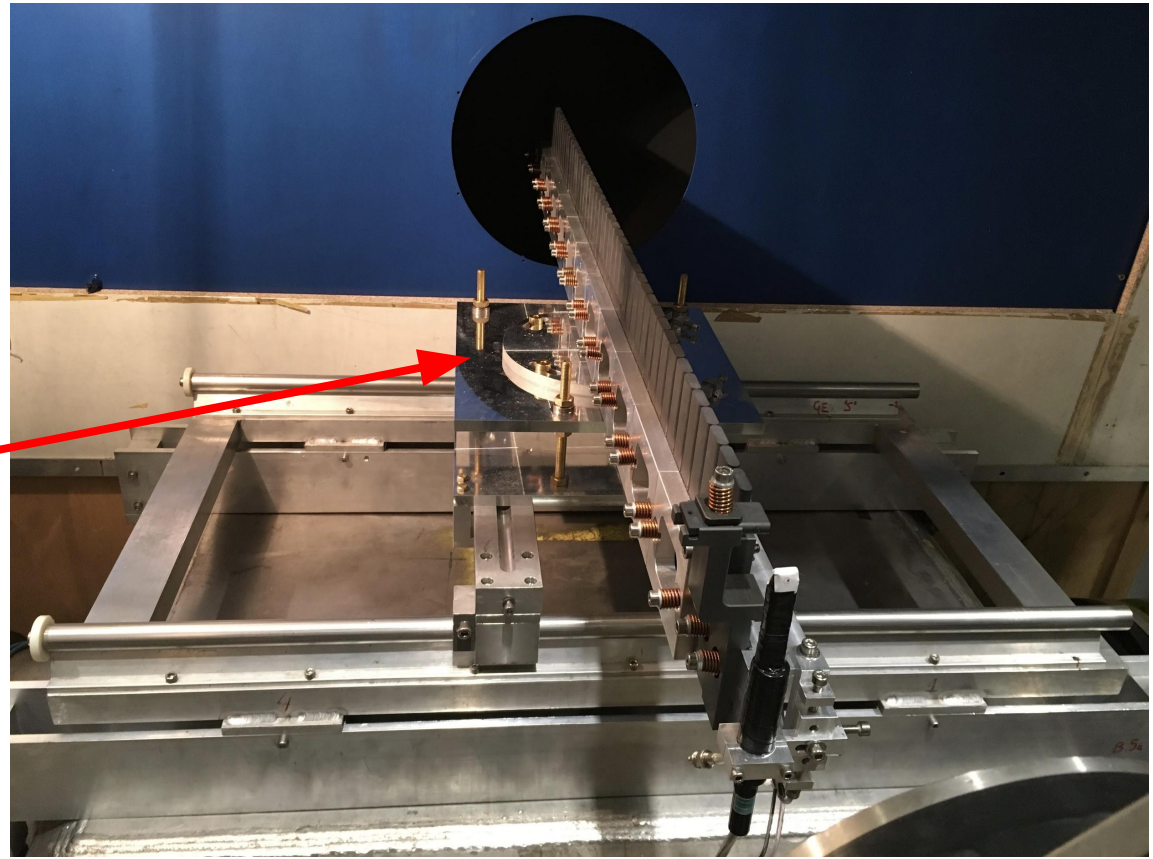
Data Taking Plans for 2018

- 120 GeV/c protons on NOνA replica target ~ 4 weeks in July 2018 - interactions being recorded now!
- 120 cm target composed of graphite fins
- Replica target installed in NA61 beam
- 1 week of 60 GeV/c K^+ on thin carbon target scheduled for Fall 2018



NA61 Beyond 2020

- Will resume the NA61 experiment after Long Shutdown 2
- Upgrades to the beamline are being considered
  - Possible tertiary beam allowing for lower energy hadron beams
- Upgrades to NA61 being considered - addendum to the SPSC report: https://cds.cern.ch/record/2309890
  - Upgrades to TPC readout and DAQ system allowing 1 kHz readout rate
  - New ToF walls based on mRPC
  - New Beam Positions Detectors based on scintillating fibers
  - Large Acceptance Vertex Detector based on ALPIDE sensors
- Potential measurements for the neutrino program 2021-2024
  - Hadron beams below 18 GeV/c if possible - many unstudied/understudied reactions for neutrino experiments could be studied
  - **Replica target measurements** and dedicated thin target measurements for **DUNE**
  - Interactions with T2K-II/Hyper-K target material and possibly replica target measurements
  - Low energy measurements for atmospheric neutrino flux estimations
  - Kaon interaction data if more is needed

Summary

- NA61 data has been used to improve T2K's flux prediction and increase precision on physics results!
  - Even better precision will be attained by implementing latest replica target results
- NA61 has been recording interactions relevant for Fermilab neutrino experiments from 2015-2018
  - **Paper on total cross section measurements** from 2015 dataset is on the arXiv and in the process of being published
  - Analysis of spectra data from 2016 is ongoing
  - Spectra data taken with **new FTPCs** implemented in 2017
  - NOνA replica target data-taking is ongoing, K^++C@60GeV/c in the fall
- NA61 upgrades will enable improved measurements after LS2
  - Most important measurement for DUNE will be **DUNE replica target measurements**
  - Many more thin target and potentially replica target measurements will be made as well - selected reactions will depend on what is most important for DUNE and other neutrino experiments

Thank you for your Attention!

- This work is supported in part by the U.S. Department of Energy
- Thanks to all of my collaborators at NA61/SHINE

- 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

S··INE

Questions?

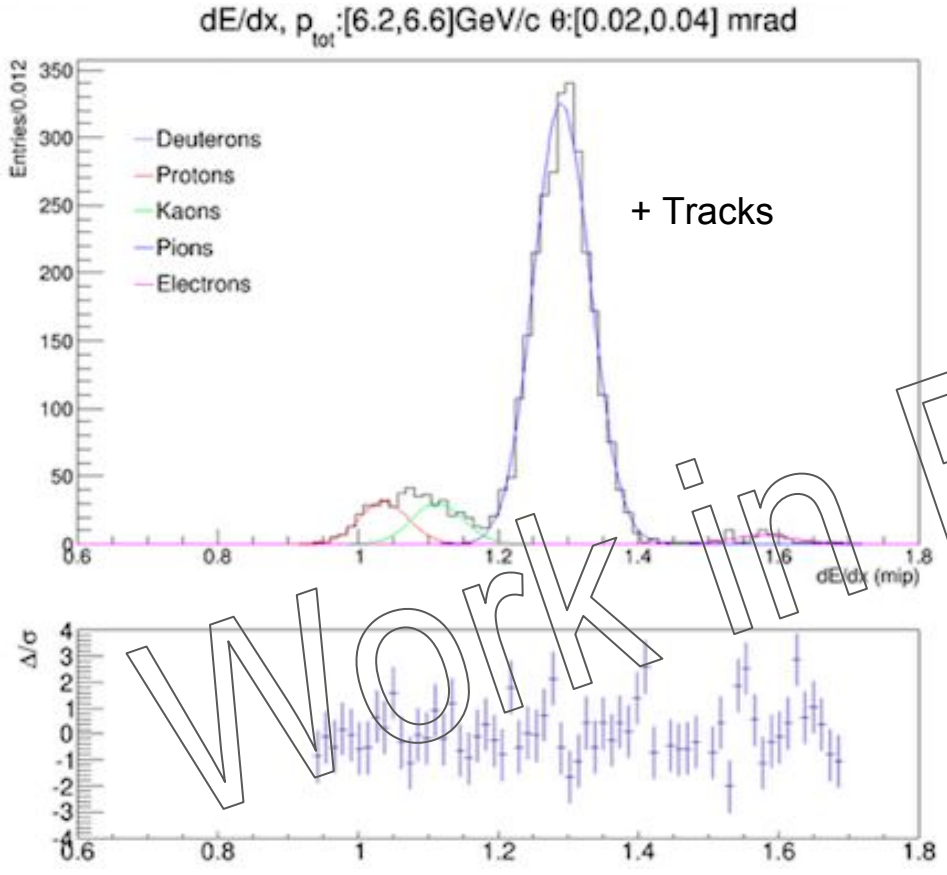
Back-Up

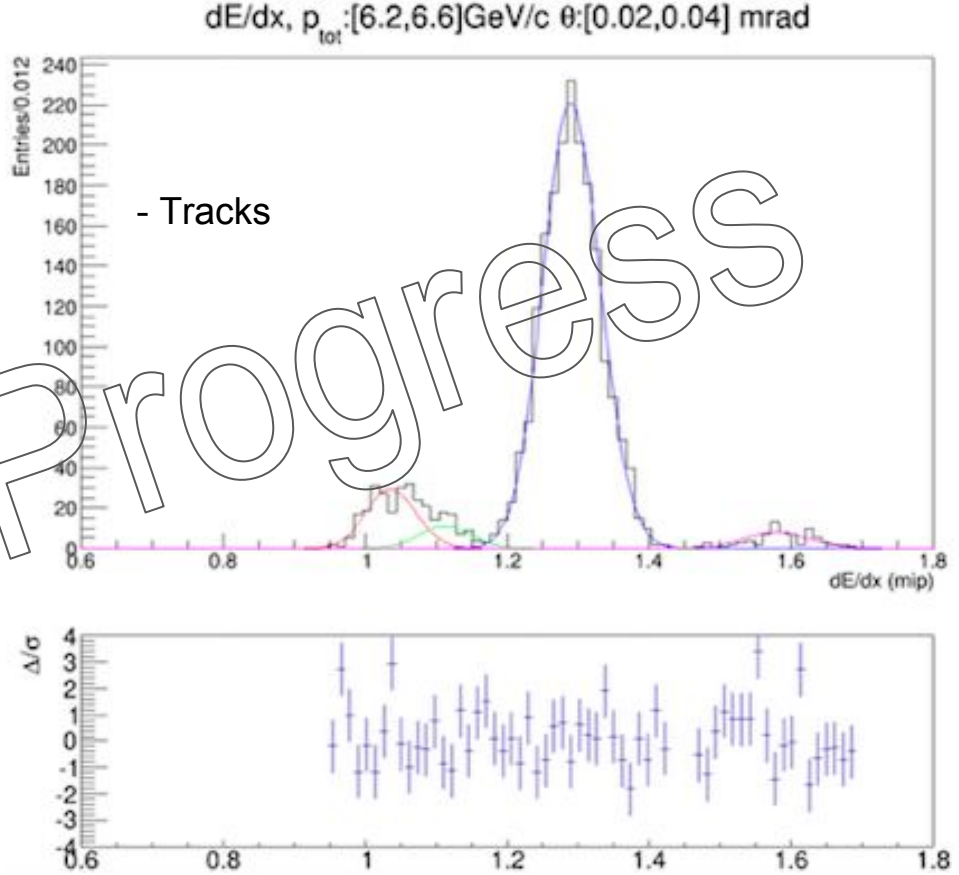
Total Cross Section Data Taken in 2015 - Statistics

- No magnets in 2015, but total cross section data was taken for a variety of interactions

Beam Particle	Beam Momentum	Target	Triggers $\times 10^6$
π^+	31 GeV/c	C	1.2
π^+	31 GeV/c	Al	0.8
π^+	60 GeV/c	C	0.8
π^+	60 GeV/c	Al	0.7
K^+	60 GeV/c	C	0.7
K^+	60 GeV/c	Al	0.5

dE/dx Analysis - Example Fit from π^++C@60GeV/c Interactions





V0 Analysis

- Invariant mass is calculated with a K^0_S, Λ or $\bar{\Lambda}$ hypothesis
- Fits are performed to the invariant mass distributions for each kinematic bin