Hadron Production Measurements for Neutrino Beam Experiments with NA61/SHINE

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NUFACT2019
August 27, 2019

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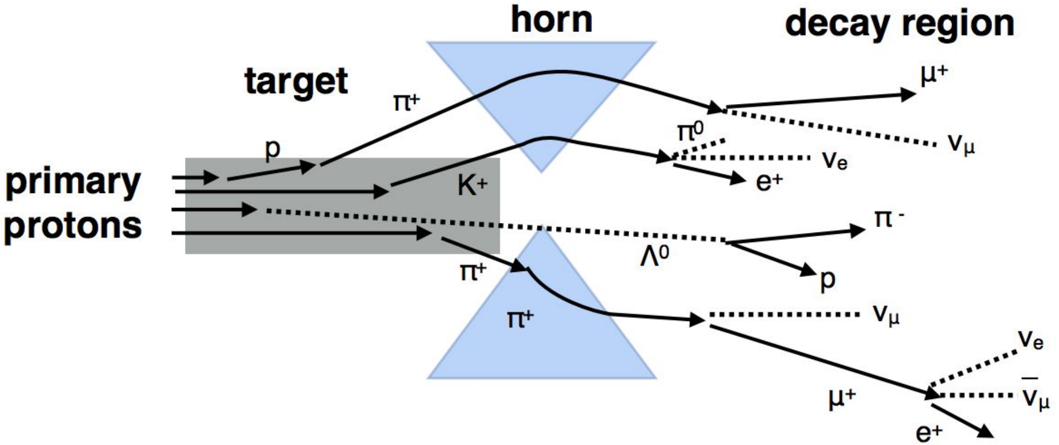
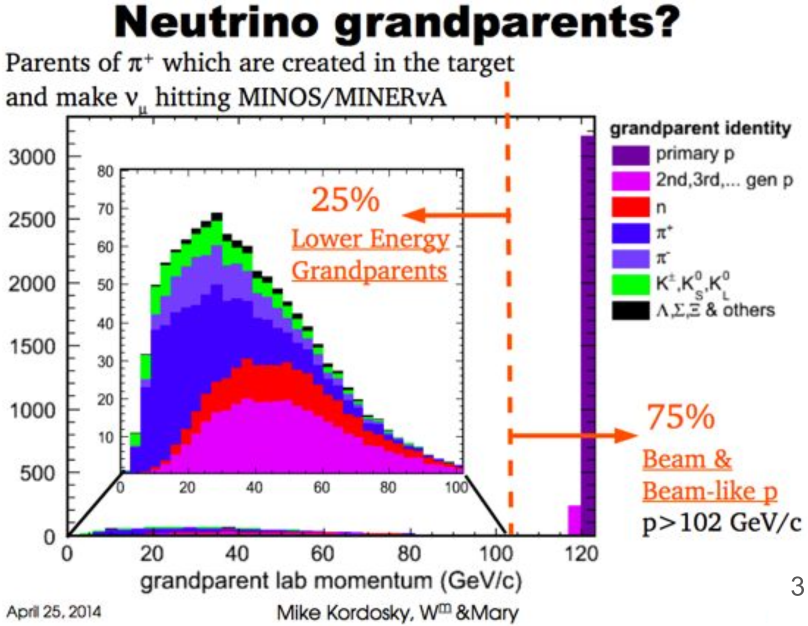
Outline

- Why are hadron production measurements needed for neutrino beam experiments?
- NA61/SHINE - detector and physics programs
- Summary of NA61's measurements for T2K and their effect on flux predictions
- NA61's physics program for FNAL neutrino experiments
- Recent total cross section measurements
- Differential cross section measurements of produced hadrons in π^++C@60GeV/c and π^++Be@60GeV/c interactions
- Future detector upgrades and physics objectives for the neutrino program

Hadron Interactions in Neutrino Beams

- Collisions of beam protons with targets produce many types of hadrons
- These secondary particles can reinteract in target or beam line material to generate even more hadrons
  - Hadrons and muons contribute to $\boldsymbol{\nu}_e$, $\boldsymbol{\nu}_\mu$, anti-$\boldsymbol{\nu}_e$, anti-$\boldsymbol{\nu}_\mu$
- Better knowledge of hadron production rates in more reactions → more precise neutrino flux predictions → more precise neutrino oscillation and xsec measurements

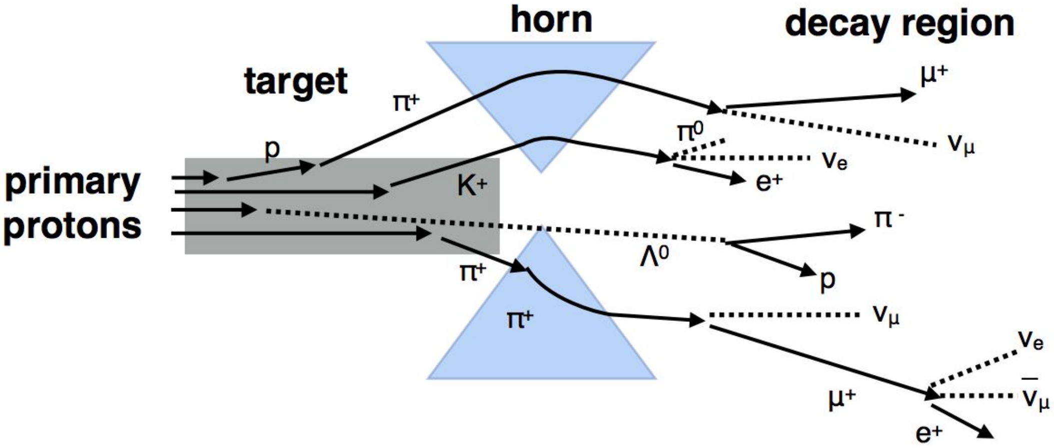




Neutrino Beam Simulations and Reweighting

- To predict neutrino flux, simulate neutrino beams with Monte Carlo
- The physics generators do not accurately predict hadron production rates
- Simulated neutrinos are reweighted based on their hadron ancestors to better constrain the neutrino flux
  - Measured hadron production rates from data are used to replace the MC-predicted hadron production rates
- Scaling schemes are used to cover incident momenta and interaction material not covered by data

$$x_F = \frac{p_L^{cm}}{p_{L(max)}^{cm}}$$



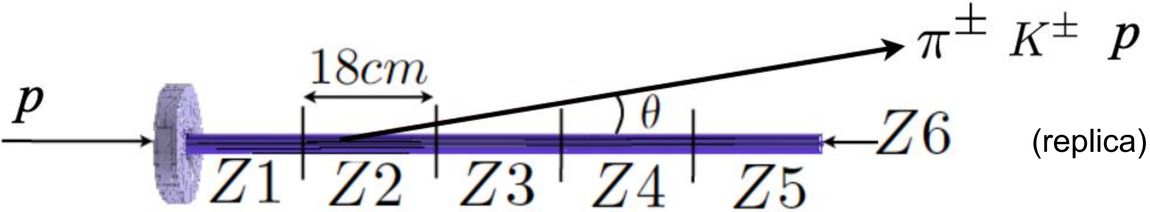
Reweighting Strategies

$$x_F = \frac{p_L^{cm}}{p_{L(max)}^{cm}}$$

m_s = multiplicity of a produced hadron species *s*

- Reweighting with thin target data
  - Depend on material and momentum scaling to access reactions not covered by data
- Reweighting with replica target data
  - Reweight neutrinos based on where their hadron ancestor exited the target

(thin) $$w_s = \frac{m_s(x_F, p_T)^{\mathrm{data}}}{m_s(x_F, p_T)^{\mathrm{MC}}}$$

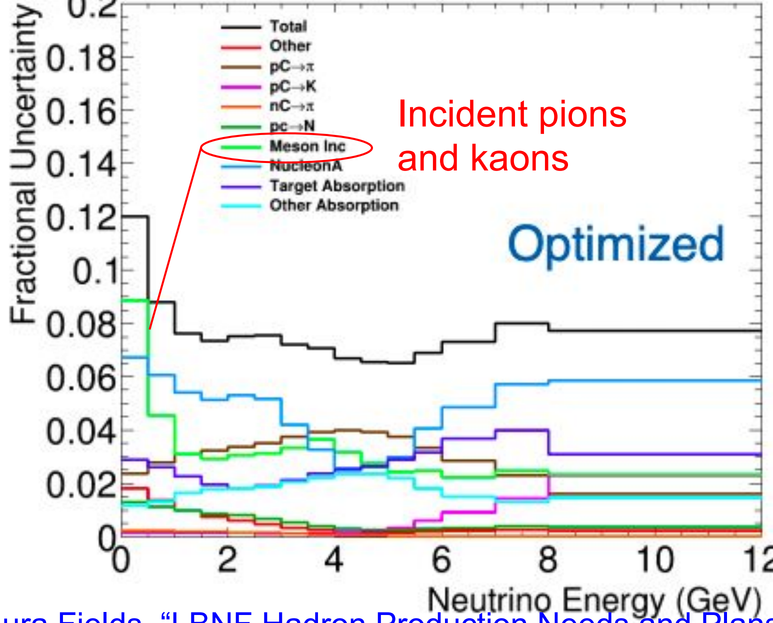


(replica) $$w_s = \frac{m_s(p, \theta, z)^{\mathrm{data}}}{m_s(p, \theta, z)^{\mathrm{MC}}}$$

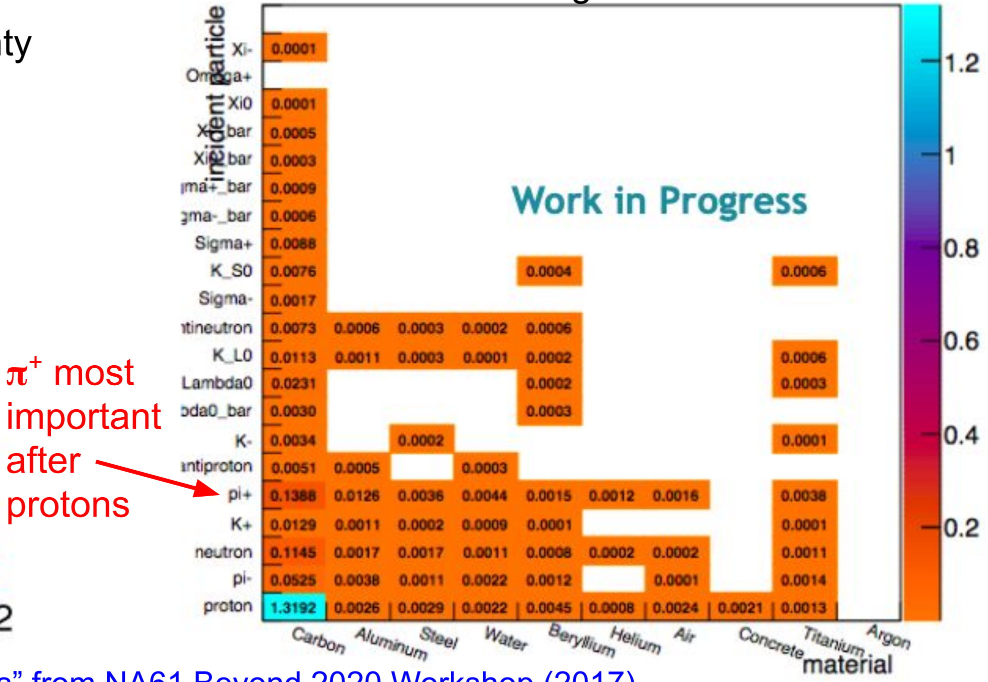
Importance of Various Interactions

- Neutrino experiments determine which hadron+nucleus reactions are the most important for understanding their neutrino beams
- p+C → hadrons becoming well-known
- Interactions of secondary mesons (especially pions) with target and beam line material are becoming more important

Contributions to LBNF flux uncertainty

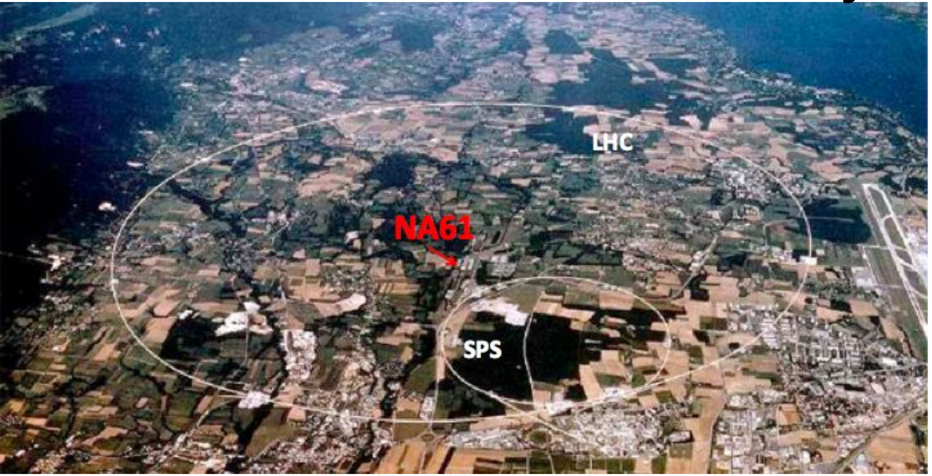


Interactions leading to neutrinos in LBNF



From: Laura Fields. “LBNF Hadron Production Needs and Plans” from NA61 Beyond 2020 Workshop (2017)

NA61/SHINE: SPS Heavy Ion and Neutrino Experiment



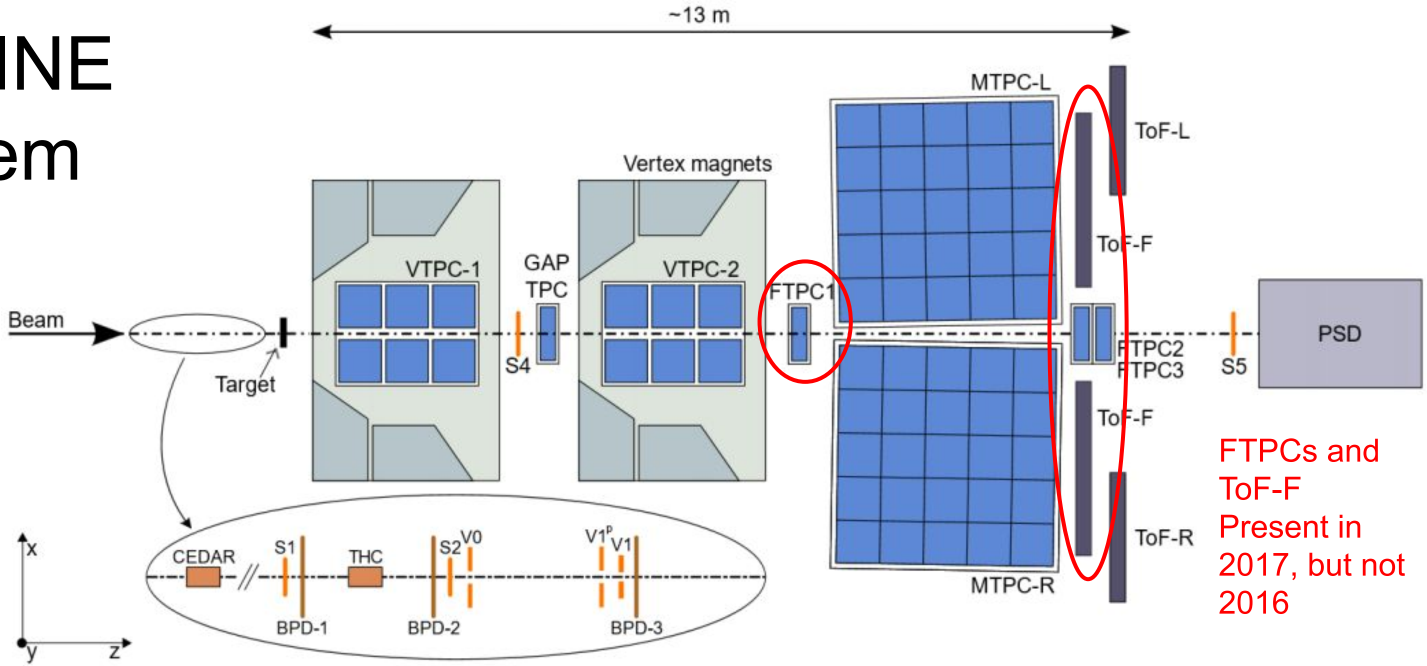
- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- 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

$\sim$150 physicists from $\sim$30 institutes

SHINE

- Fixed target experiment located at CERN’s SPS (Super Proton Synchrotron)
- NA61’s physics program covers three main topics:
  - Nuclear physics - Study the phase transition between hadron gas and QGP and search for a critical point
  - Cosmic ray physics - Hadron production measurements relevant to space and ground-based cosmic ray experiments
  - **Neutrino physics - Hadron production measurements used to constrain neutrino flux uncertainties for accelerator-based neutrino experiments**

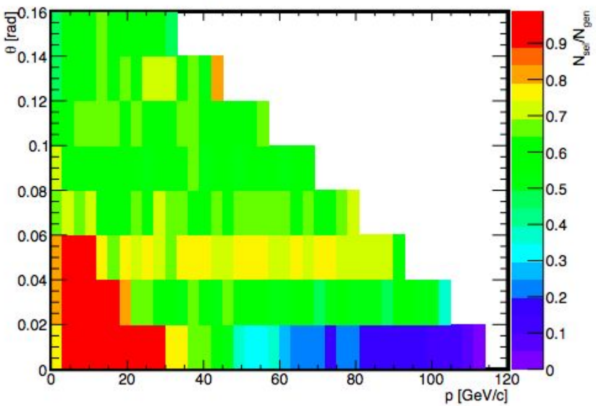
The NA61/SHINE Detector System

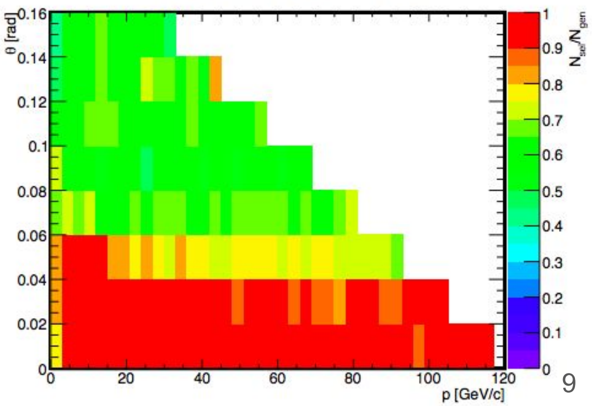


- TPC system tracks charged particles and measures dE/dx ($\sigma_{dE/dx}/\langle dE/dx \rangle \approx .04$)
- Two Vertex TPCs are contained inside superconducting vertex magnets (with 9 Tm of bending power)
- Two large Main TPCs
- Gap TPC and three new Forward-TPCs provide forward acceptance
- Time of Flight systems measure m^2 (~100 ps resolution)
- FTPCs and ToF-F were not present for the 2016 data discussed in this talk

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 - can be a large contribution to neutrino flux
- Began upgrading the readout to a more modern DRS4 system
  - Enabling easier maintenance and customization of detector components

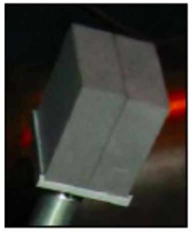




Measurements for the T2K Experiment (2007-2010)

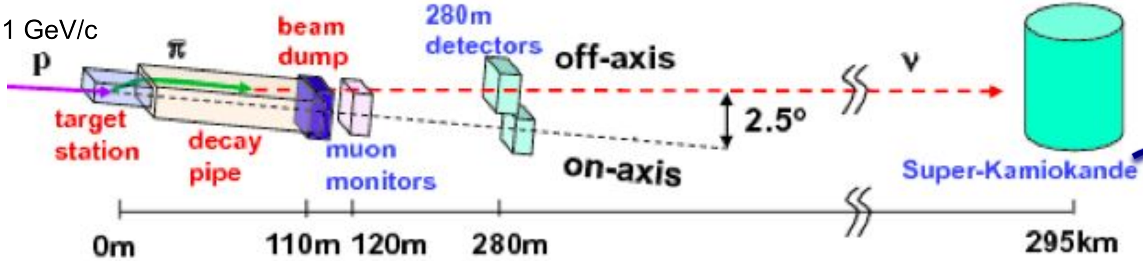
- Thin target measurements from data recorded in 2007 and 2009
- T2K replica target measurements from 2007, 2009 and 2010

2 cm thin carbon target



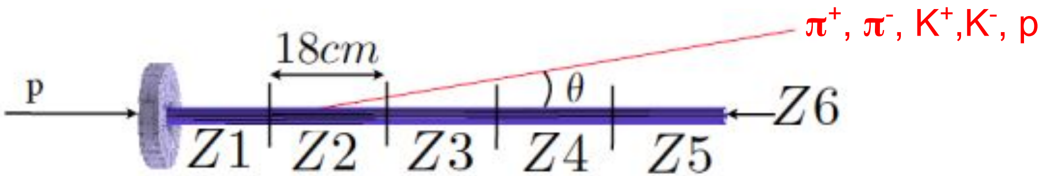
90 cm T2K replica target

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 [7]
p@31 GeV/c High Field	C 90 cm	2010	Production cross section analysis in progress



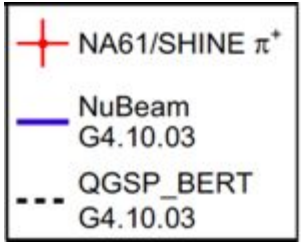
[1] Phys. Rev. C84, 034604 (2011).
[2] Phys. Rev. C85, 035210 (2012).
[3] Phys. Rev C89, 025205 (2014).
[4] Eur. Phys. J. C (2016) 76: 84
[5] Nucl. Instrum. Meth. A701, 99 (2013)
[6] Eur.Phys.J. C76 (2016) no.11, 617
[7] Eur. Phys. J. C79, no.2 100 (2019)

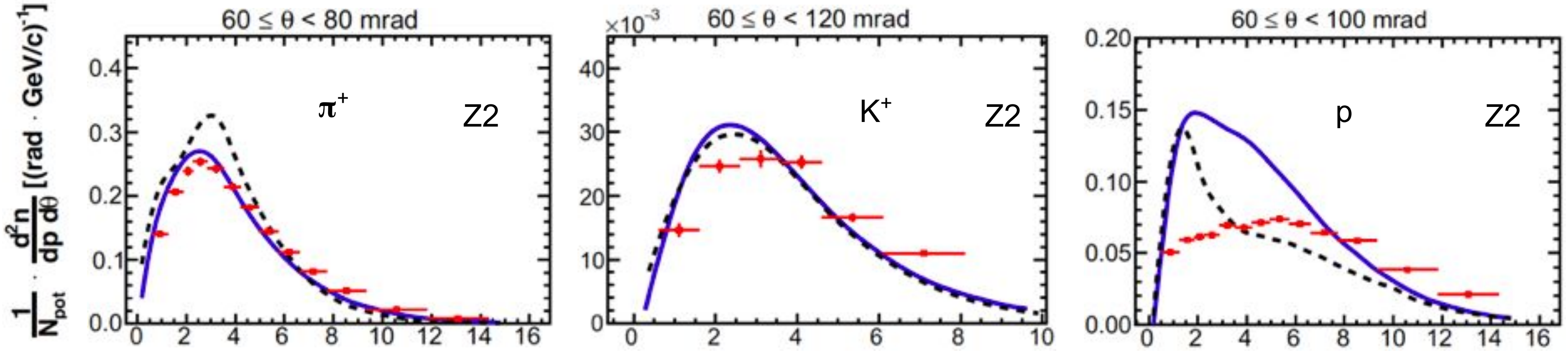
T2K Replica Target Results



- High statistics data set of 31 GeV/c protons interacting with a T2K replica target recorded in 2010
- Triple differential multiplicity measurements of charged pions, charged kaons and protons emanating from a T2K replica target

Eur. Phys. J. C79, no.2 100 (2019)

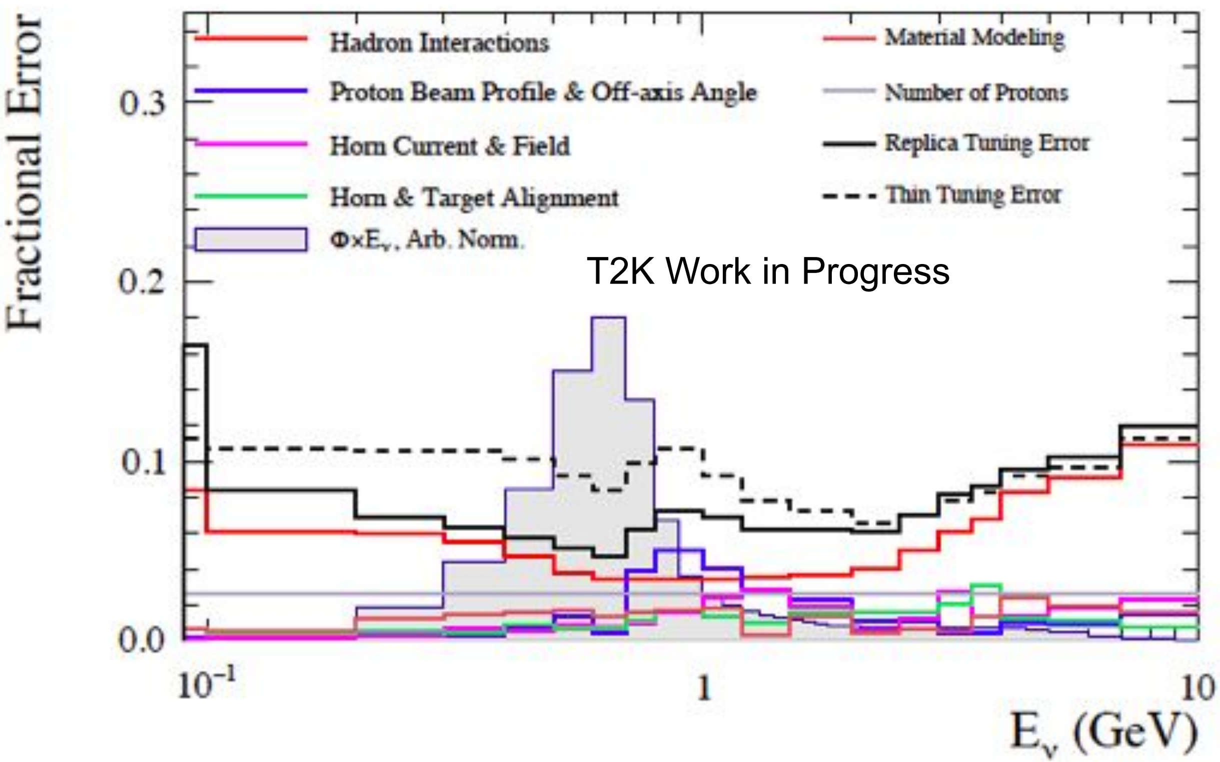




Another analysis is underway to more precisely measure the production cross section by measuring the survival rate of beam protons through the T2K replica target data

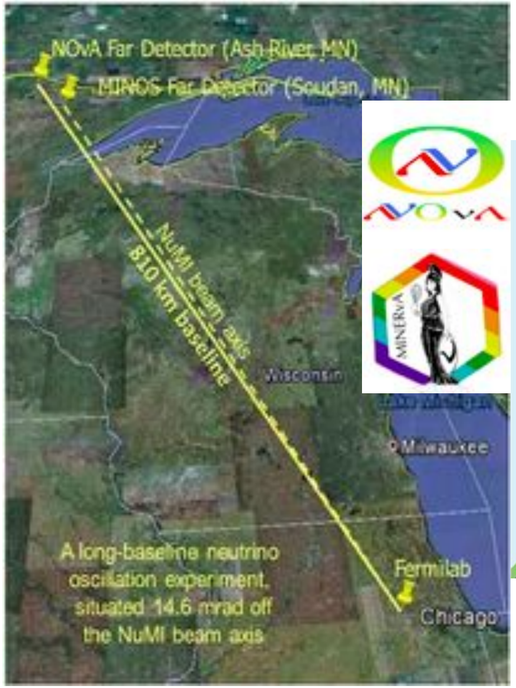
Effect of NA61 Results on T2K Flux Predictions

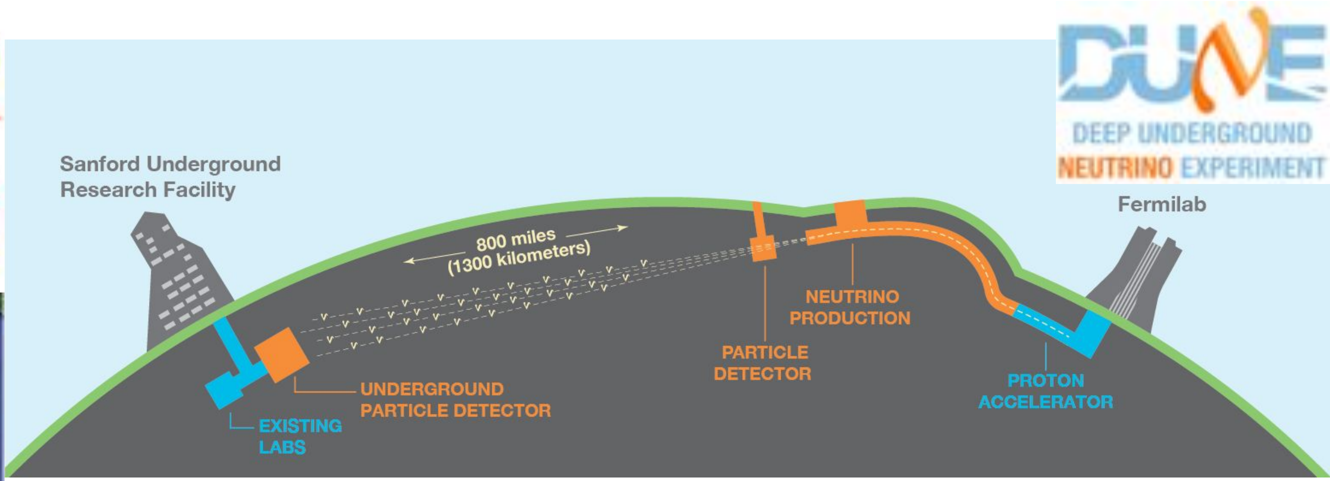
- Tuning only with thin target results led to uncertainties just below 10% at the oscillation maximum
- Replica tuning with 2009 replica target results improves uncertainties to ~5%
- Uncertainties shown in the figure (includes only pion tuning) will be reduced further when the full 2010 replica target results are implemented



NA61 Data Taking for the FNAL Neutrino Program

- Interactions were recorded in 2015-2018 by NA61 for the benefit of FNAL neutrino experiments
  - First set of analyses from these data are presented here
- Beam particles, beam momenta and target material were selected for their importance to experiments using the NuMI and LBNF beam lines





2015 Total Cross Section Data

- Data for 6 different reactions were recorded
- Total production and total inelastic cross sections were measured and published
- No differential measurements due to issues with magnets
- Important for DUNE and NOvA experiments for tuning interaction rates of secondary particles

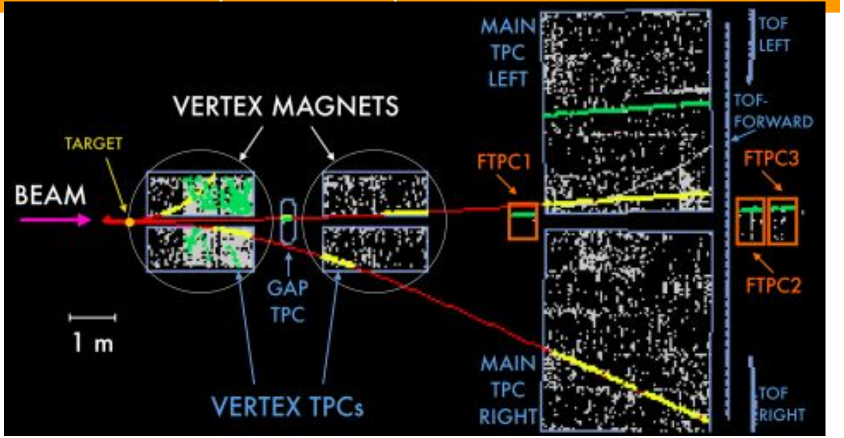
2015 data runs - magnetic fields OFF			
Beam Particle	Beam Momentum	Target	Triggers 10^6
π^+	31 GeV/c	C	1.2
π^+	31 GeV/c	Al	0.8
π^+	60 GeV/c	C	0.8
π^+	60 GeV/c	Al	0.7
K^+	60 GeV/c	C	0.5
K^+	60 GeV/c	Al	0.3

NA61/SHINE: Phys. Rev. D98, No.5 052001 (2018)

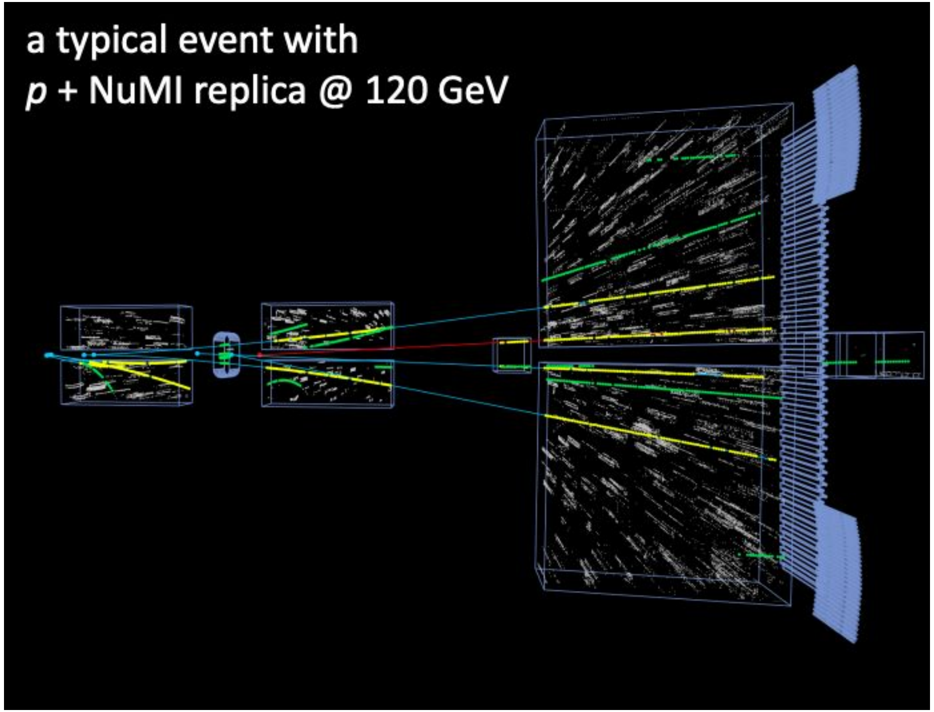
2016 Differential Cross Section Data 2017

Beam	Target	Analysis
60 GeV/c π^+	C	Differential and Total Cross Sections measured - publication in collab. review
60 GeV/c π^+	Be	
60 GeV/c p	C	Total cross sections measured - publication in collab review, spectra analyses in progress
60 GeV/c p	Al	
60 GeV/c p	Be	
120 GeV/c p	C	
120 GeV/c p	Be	

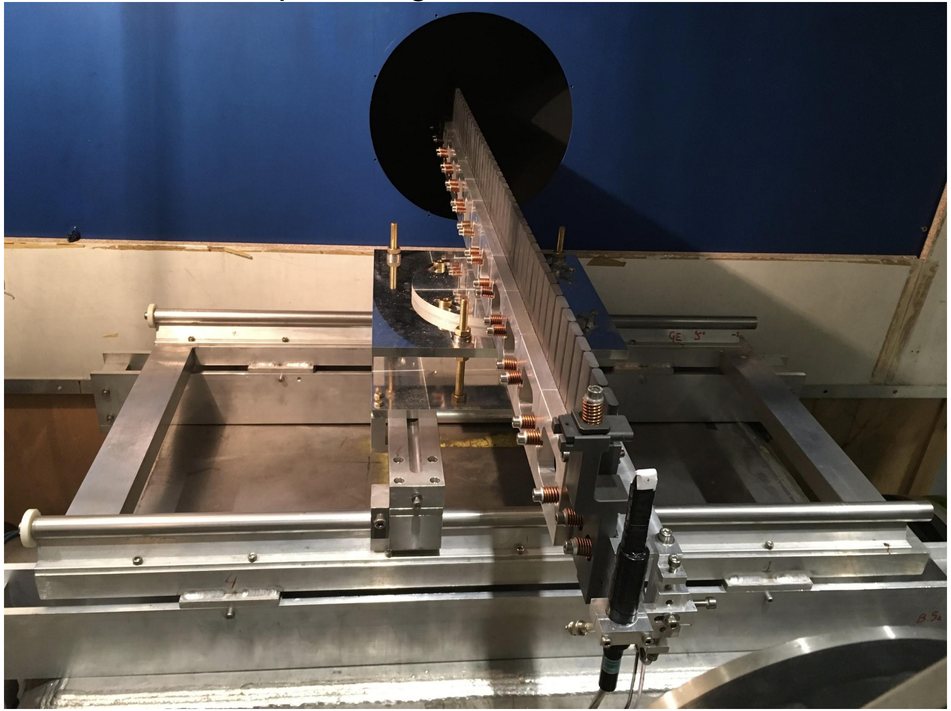
Beam Particle	Target	
60 GeV/c π^+	Al	
30 GeV/c π^+	C	
60 GeV/c π^-	C	w/ FTPCs and F-ToF
120 GeV/c p	C	w/ FTPCs and F-ToF
120 GeV/c p	Be	w/ FTPCs and F-ToF
90 GeV/c p	C	w/ FTPCs and F-ToF



2018 NOvA Replica Target Data



NOvA replica target in the NA61 beam line

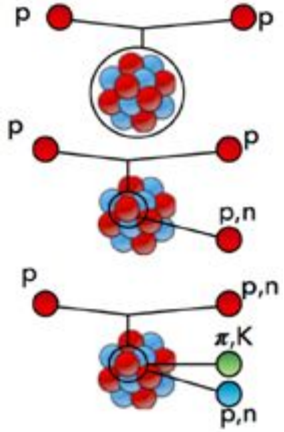


- Big effort underway to improve replica target reconstruction software to more precisely determine locations of particles exiting the target
- Calibration and analysis will begin soon

Total Cross Section Measurements

- We report total inelastic and total production cross sections
- Experiments are not consistent in their definitions and terminology of integrated cross sections

This is our definition:



Coherent **elastic** scattering of a hadron with the nucleus as a whole

Quasi-elastic scattering of a hadron with a proton or neutron, which can cause fragmentation of the nucleus but produces no new hadrons

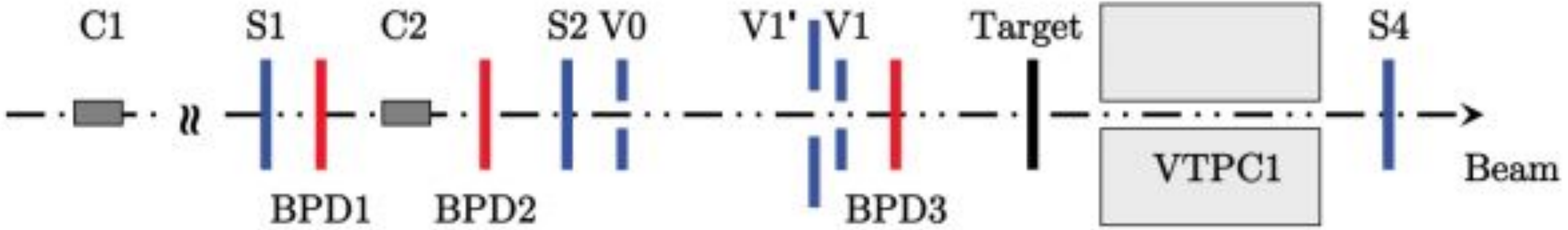
Production processes occur when new hadrons are formed

$$\sigma_{tot} = \sigma_{inel} + \sigma_{el}$$

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

Beam detectors most important for these measurements - dependent on models to determine scattering angles of the various processes - hope to improve these measurements with detector upgrades

These cross sections are necessary to normalize our spectra measurements and constrain neutrino flux predictions



Total Cross Section Analysis - Results for incident π^+ and K^+

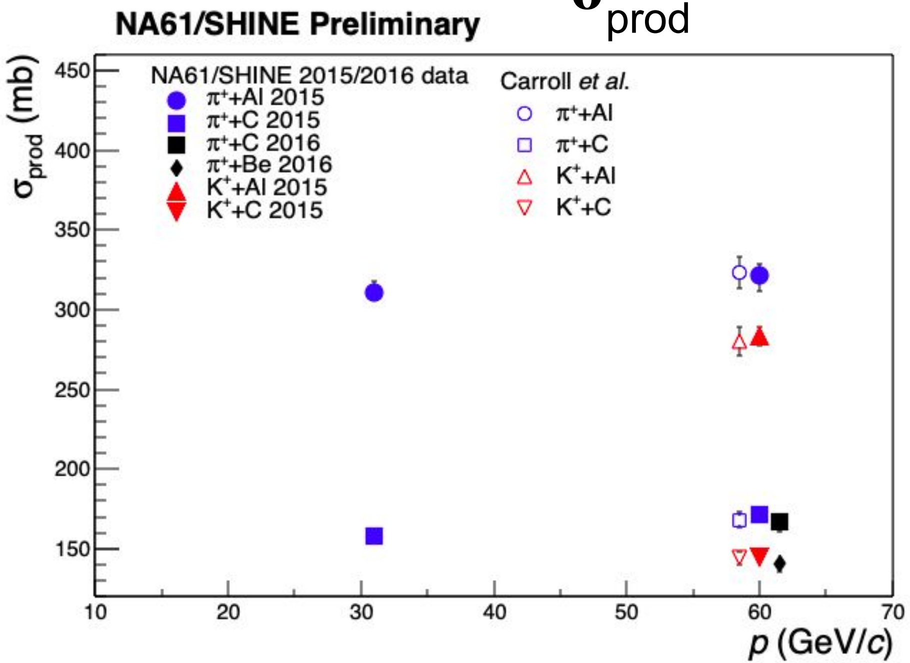
First measurements of σ_{prod} in π^++C@31GeV/c and π^++Al@31GeV/c and improved precision for the other measurements

Results from 2015 data were published:

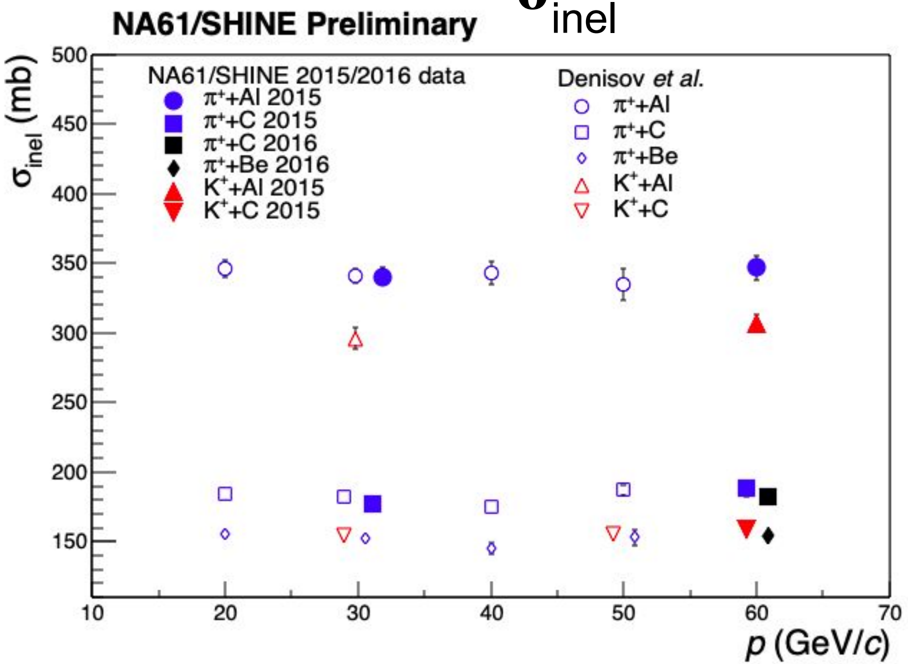
NA61/SHINE: Phys. Rev. D98, No.5 052001 (2018)

Results from 2016 data to be published with hadron spectra measurements (in collaboration review):

σ_{prod}



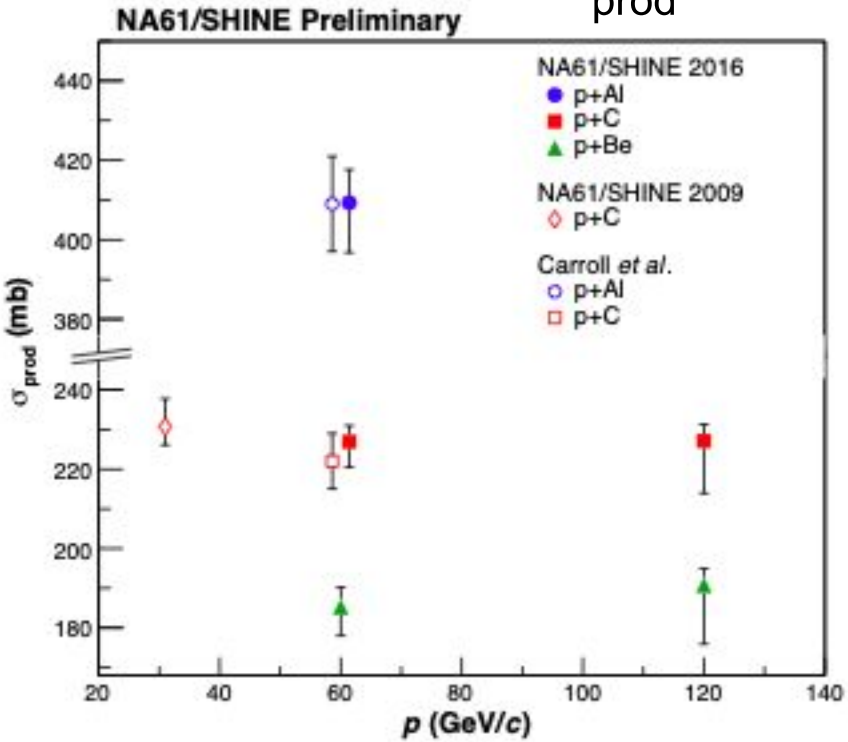
σ_{inel}



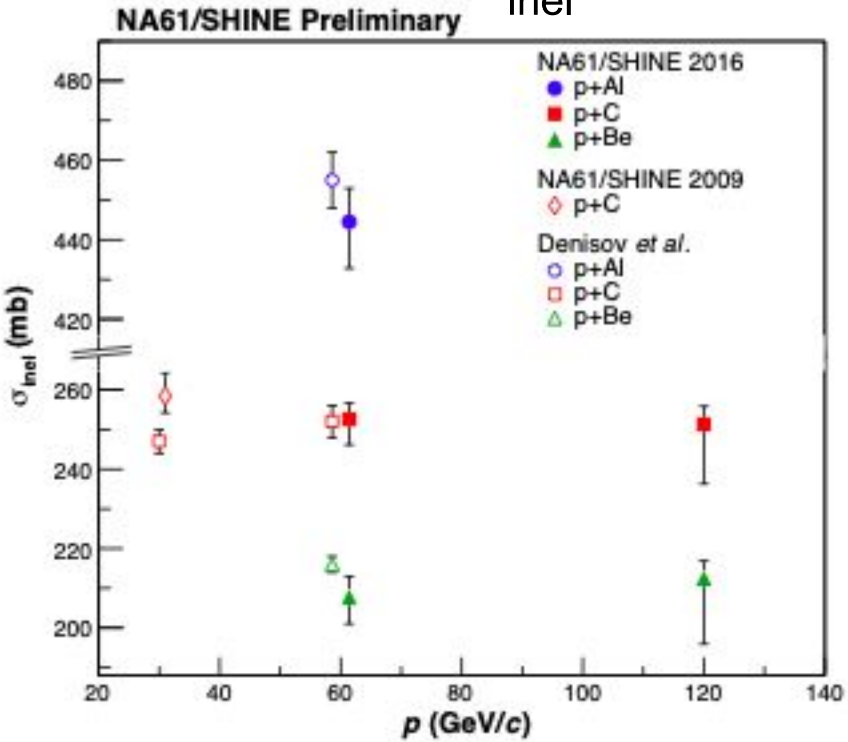
Total Cross Section Analysis - Results for incident protons

- p+C@120GeV/c, p+Be@120GeV/c and p+Be@60GeV/c (prod) are the first reported measurements
- Publication with these results is currently under collaboration review

σ_{prod}



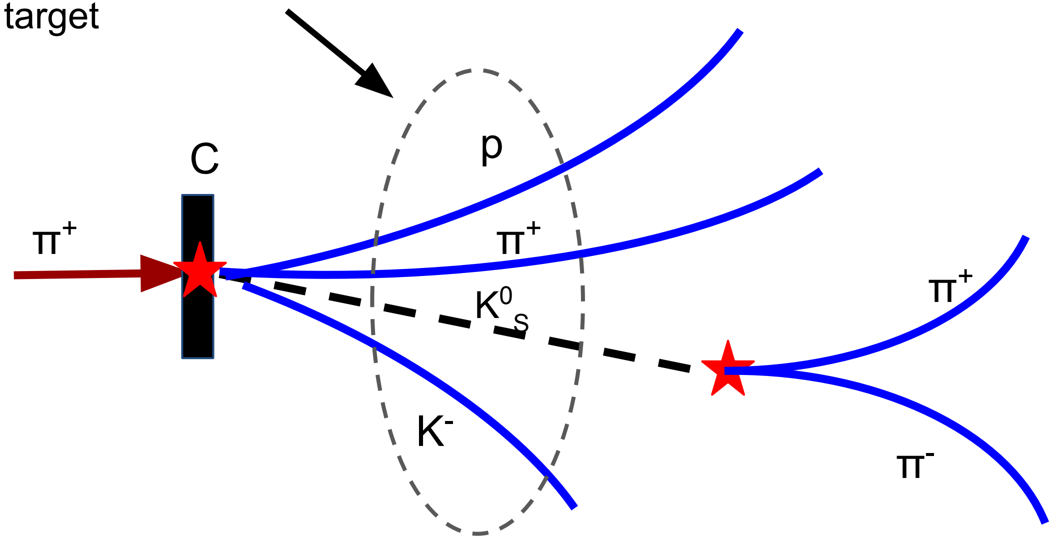
σ_{inel}



Differential Cross Section Measurements from interactions of 60 GeV/c π^+

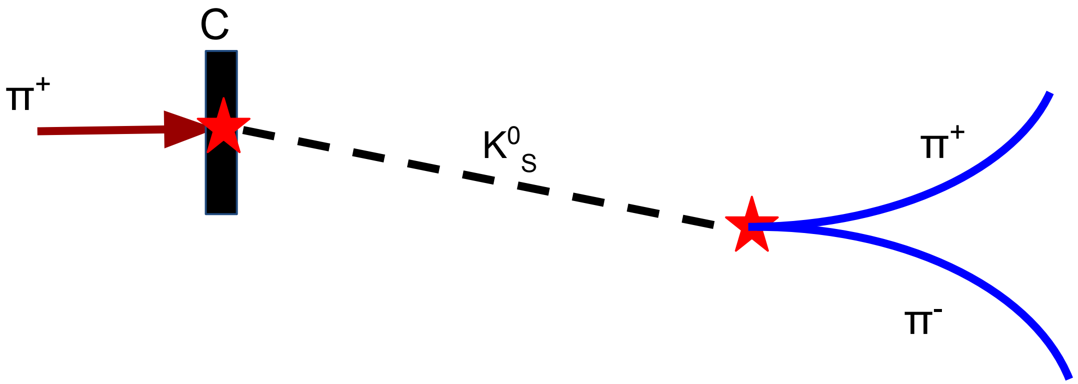
- π^++C@60GeV/c and π^++Be@60GeV/c: analysis complete and publication under collab. review
  - Total inelastic and total production cross sections
  - Double differential cross sections of charged pions, kaons and protons
  - Double differential cross sections of neutral K^0_S, Λ and $\overline{\Lambda}$

We identify the hadrons produced in strong interactions inside of the target



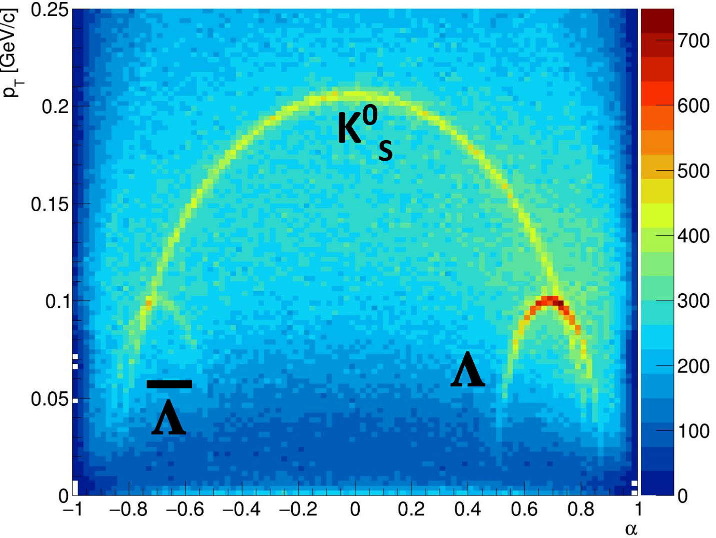
Beam Particle	Beam Momentum	Target
π^+	60 GeV/c	C
π^+	60 GeV/c	Be
p	60 GeV/c	C
p	60 GeV/c	Al
p	60 GeV/c	Be
p	120 GeV/c	C
p	120 GeV/c	Be

Neutral Hadron Spectra Analysis - Methodology

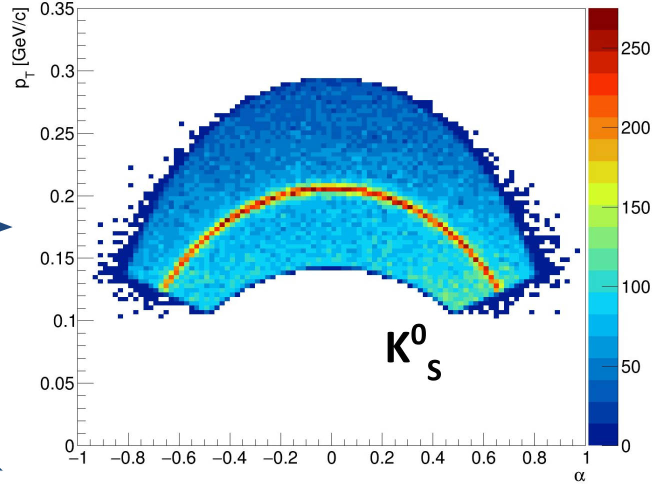


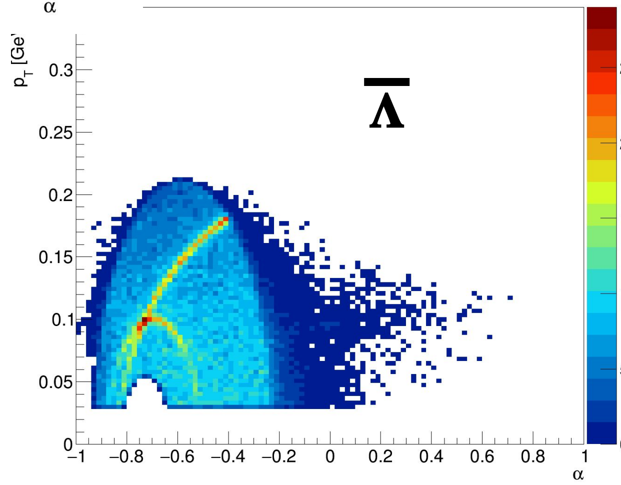
- A reconstruction algorithm identifies decay vertices of neutral particles by searching for secondary vertices with 1 positively charged track and 1 negatively charged track
- Fits are performed to the invariant mass distributions (assuming a decay hypothesis) in each kinematic bin
- Able to measure K^0_S, Λ and $\bar{\Lambda}$
- Decays of these hadrons can lead to neutrinos in neutrino beam experiments
- The results can be applied to the charged hadron analysis to correct for pions and protons coming from secondary decays of K^0_S, Λ and $\bar{\Lambda}$ and reduce the associated uncertainty

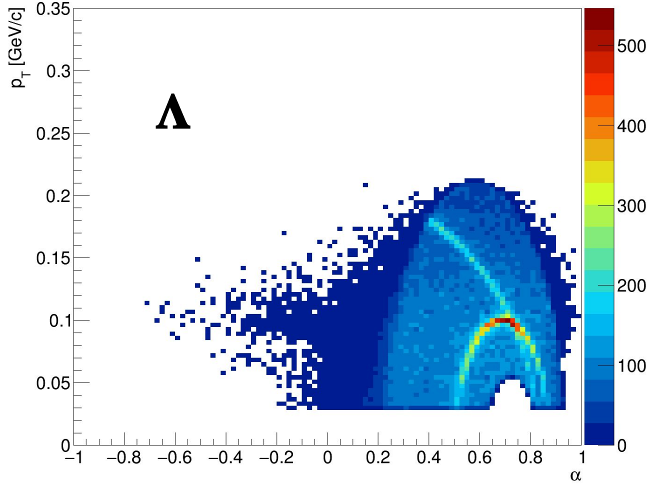
π^+C@60 GeV/c Podolansky-Armenteros



Species Specific Selections





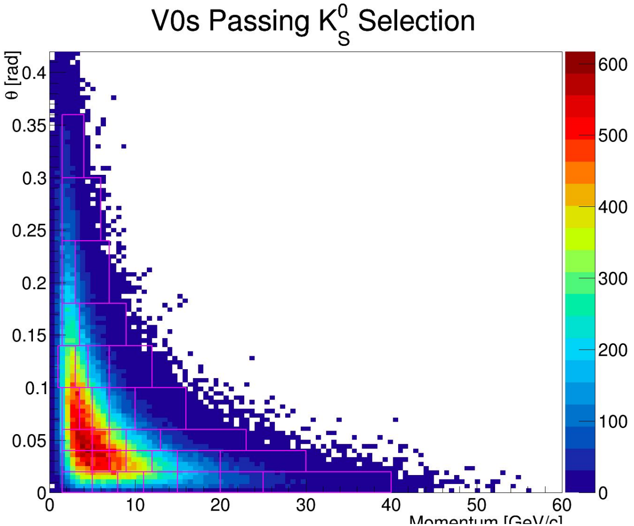


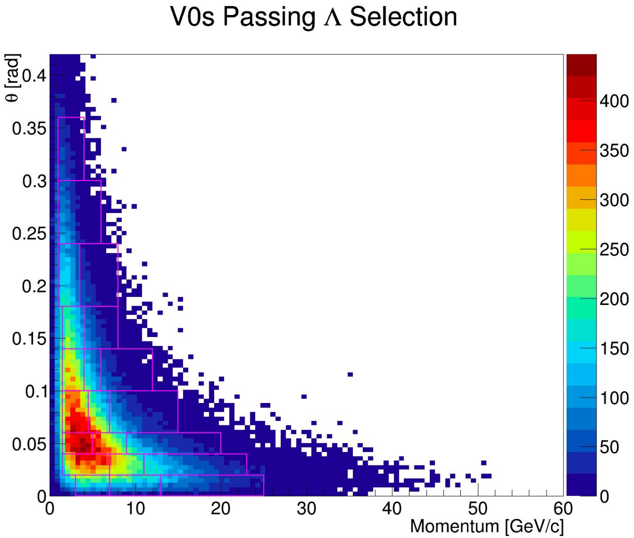
$$\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$$

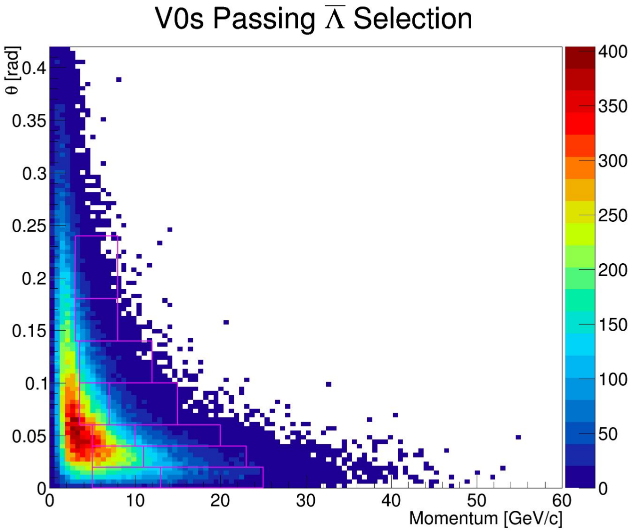
$$p_T = |p_T^+| + |p_T^-|$$

V0 Kinematics and Binning Schemes

- Momentum ranging from 1 to 40 GeV/c
- Scattering angle θ from 0 to 360 mrad

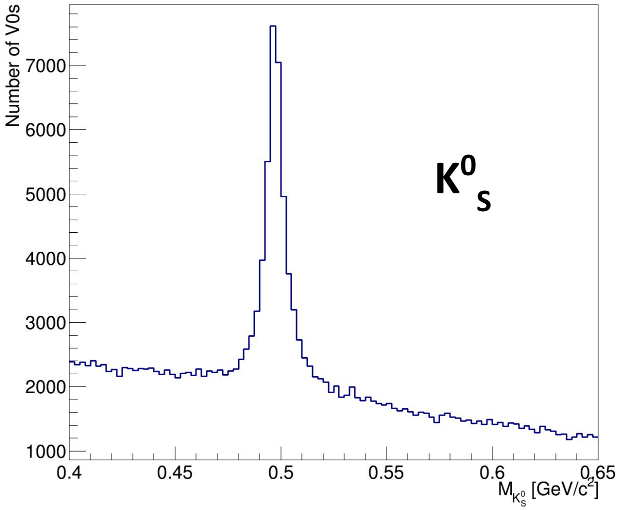




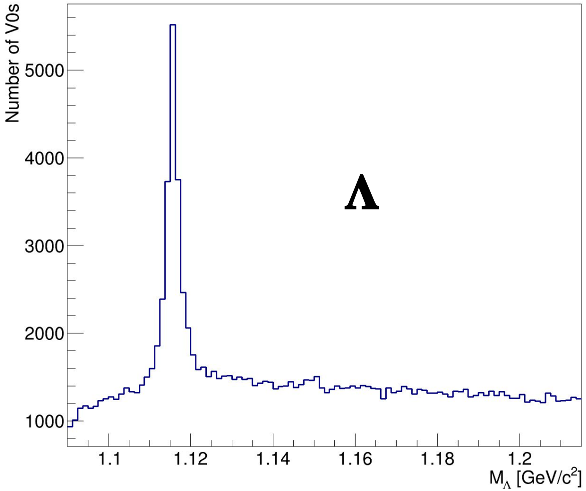


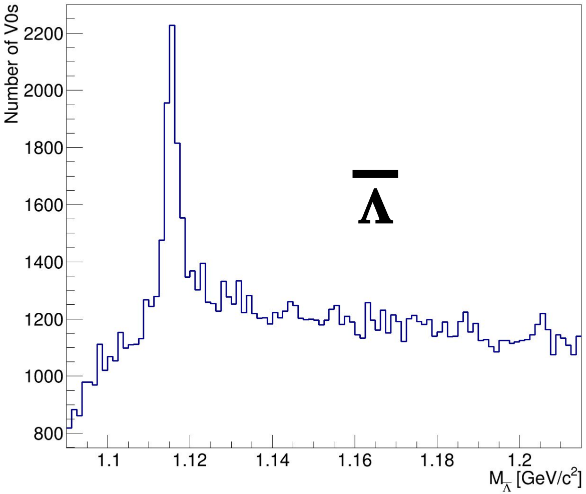
Invariant Mass Distributions

- Invariant mass is calculated with a K^0_S, Λ or $\overline{\Lambda}$ hypothesis
- Fits are performed to the invariant mass distributions for each kinematic bin (here, the full phase space is shown)



$K^0_S \longrightarrow \pi^+ + \pi^-$
$\Lambda \longrightarrow p + \pi^-$
$\overline{\Lambda} \longrightarrow \overline{p} + \pi^+$

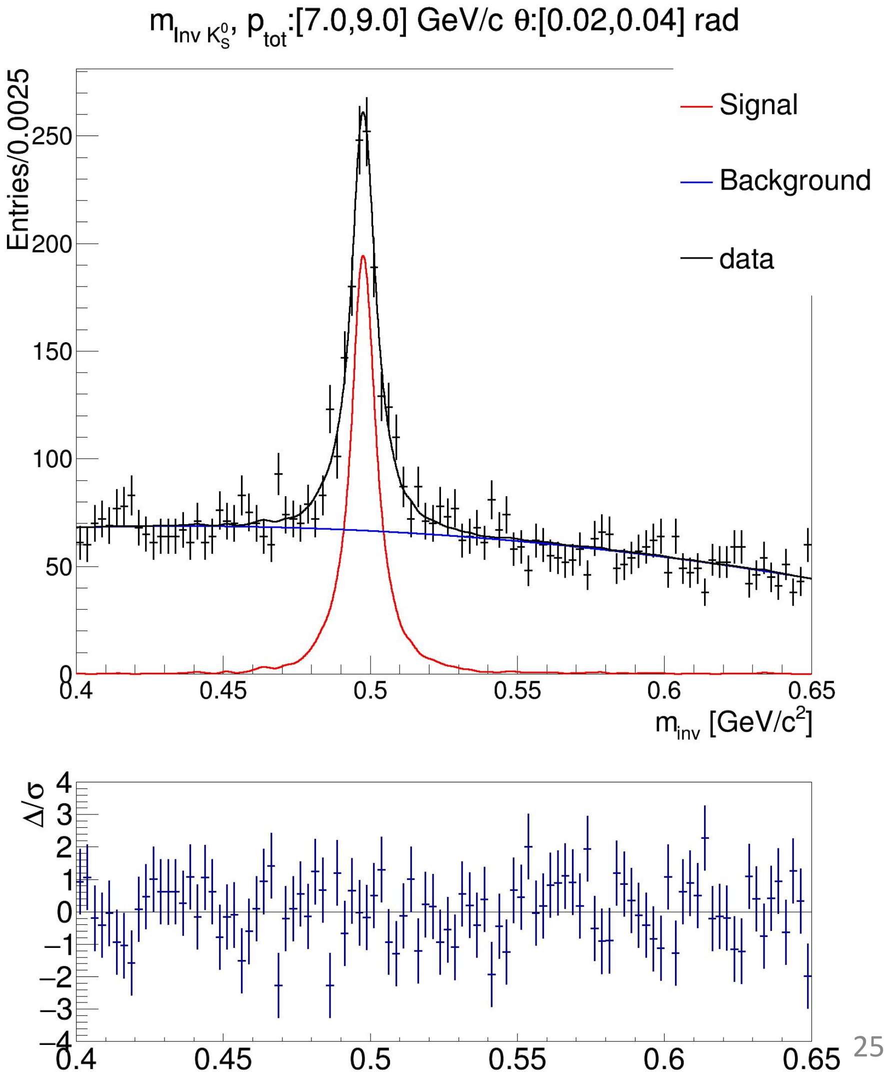




Example K^0_S Fit

	Fitted
N_S	1100.20
N_{BG}	6170.80
f_s	0.1513

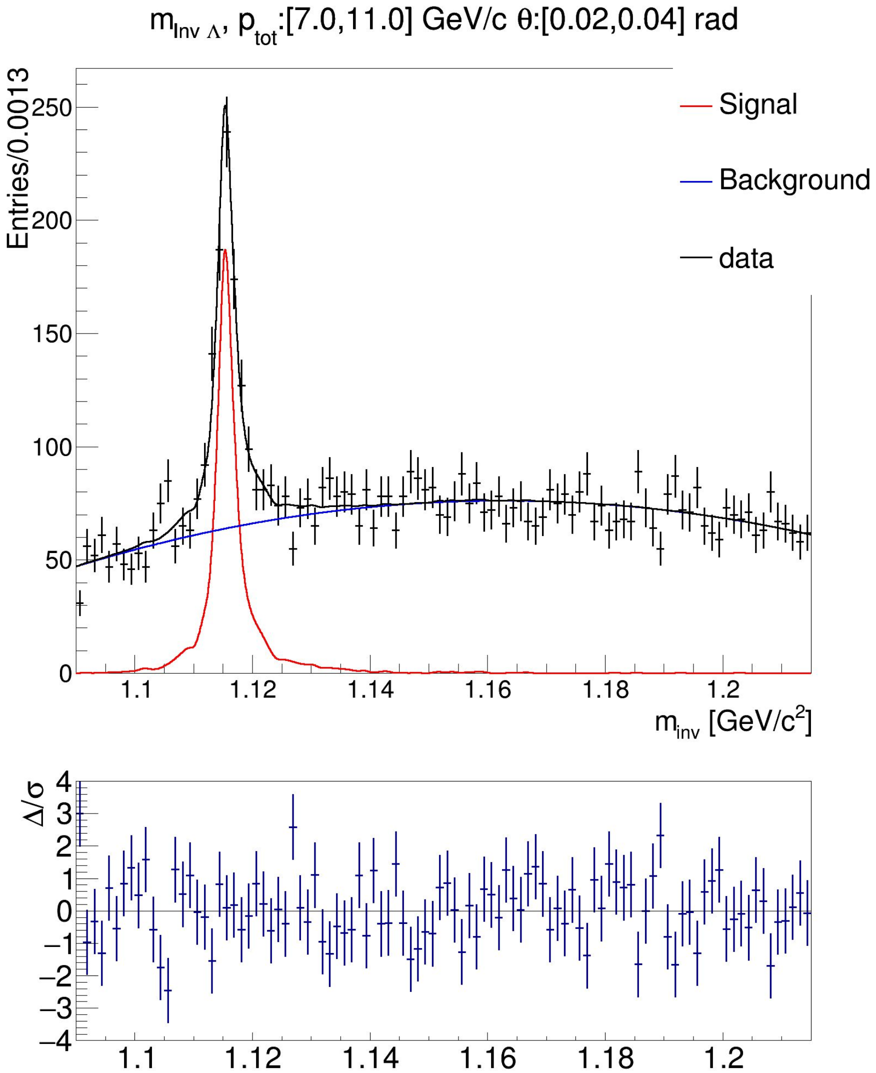
- The signal is fitted to a K^0_S template taken from a Monte Carlo simulation
- The background is fitted to a 2nd degree polynomial



Example Lambda Fit

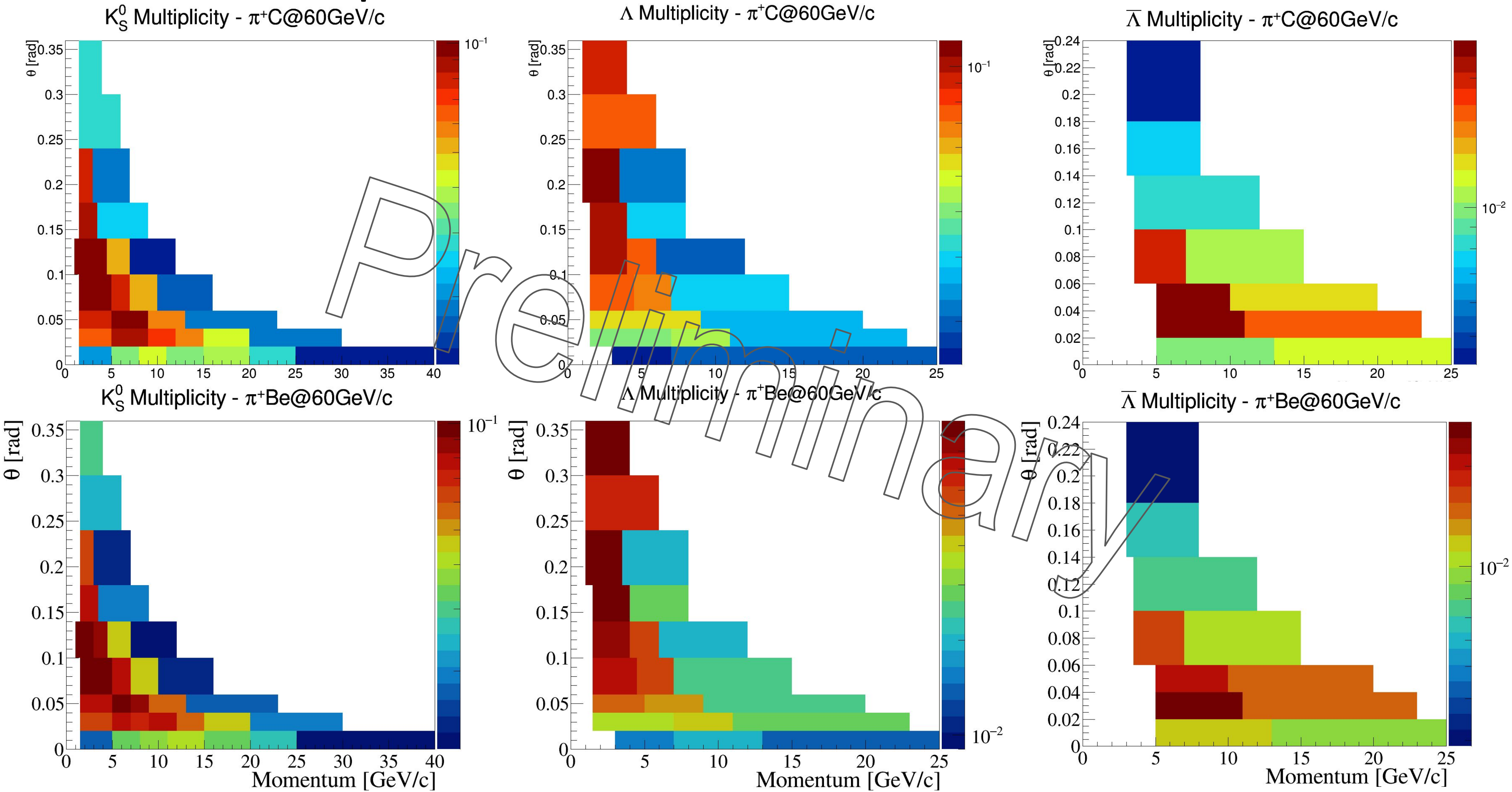
- The signal is fitted to a Λ template taken from a Monte Carlo simulation
- The background is fitted to a 2nd degree polynomial

	Fitted
N_S	752.00
N_{BG}	6843.00
f_s	0.0990



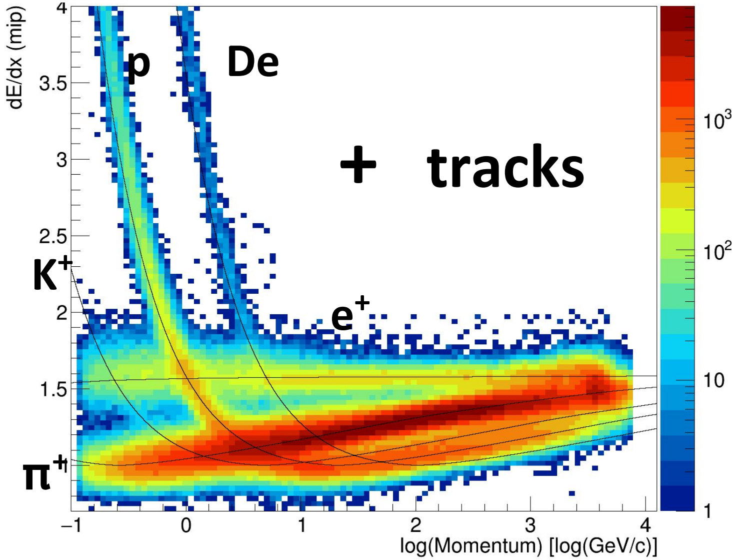
2D V0 Spectra

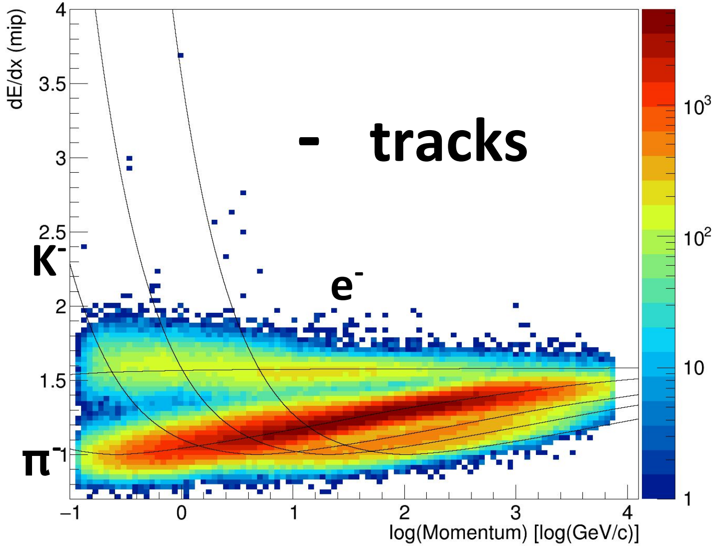
Multiplicity (particles produced per production interaction)



Charged Hadron Spectra Analysis - dE/dx Method

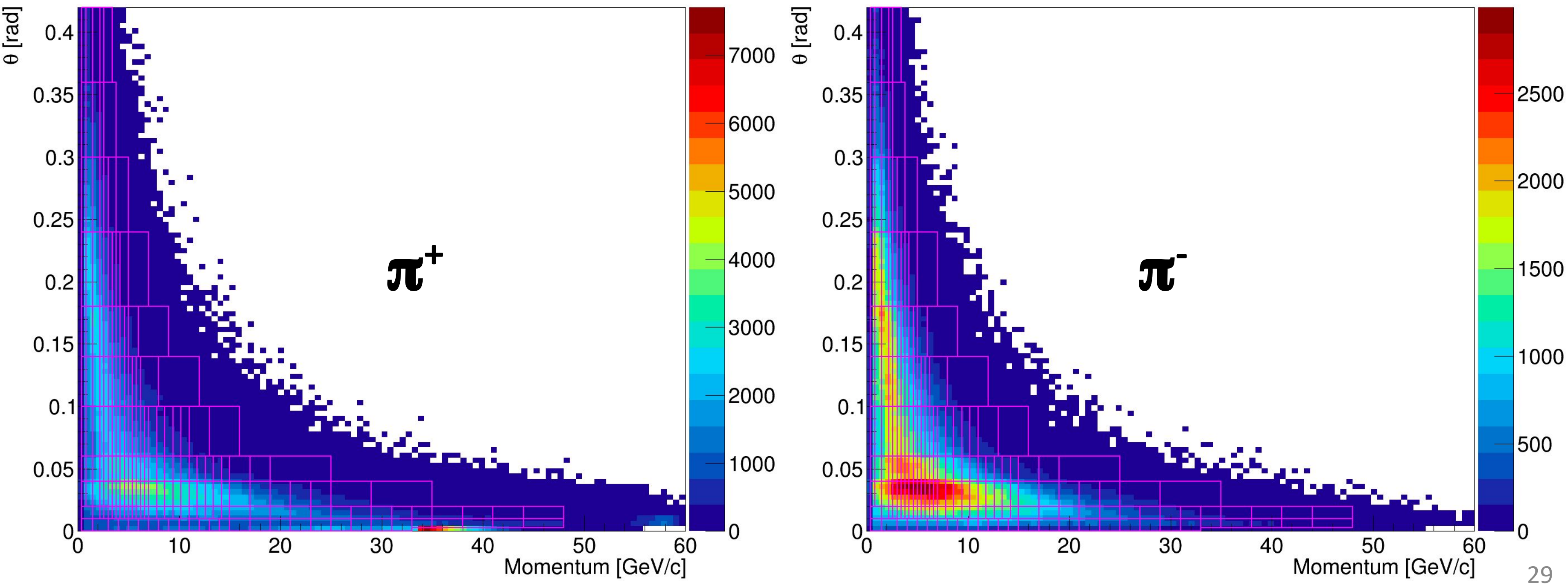
- Charged tracks are reconstructed to a main interaction vertex
- Reconstructed momenta are obtained from the vertex fits
- Energy loss is calculated from charge collected in the TPCs
- $e^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, protons and deuterons fall along their Bethe-Bloch curves (dE/dx from π^{+}+C@60GeV/c interactions shown)
- Fits are performed in kinematic bins to discriminate particle species



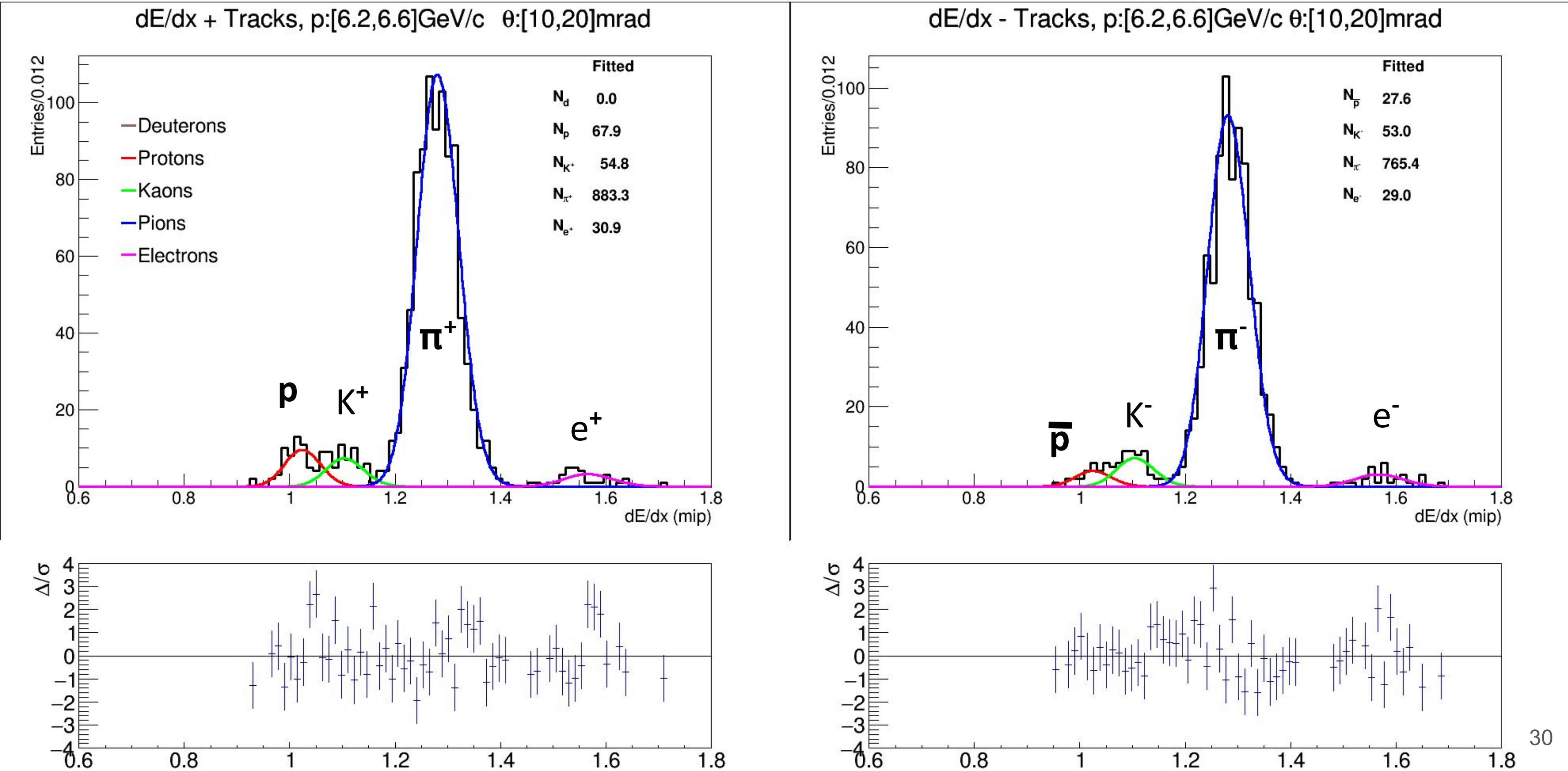


Kinematic Region and Binning Scheme

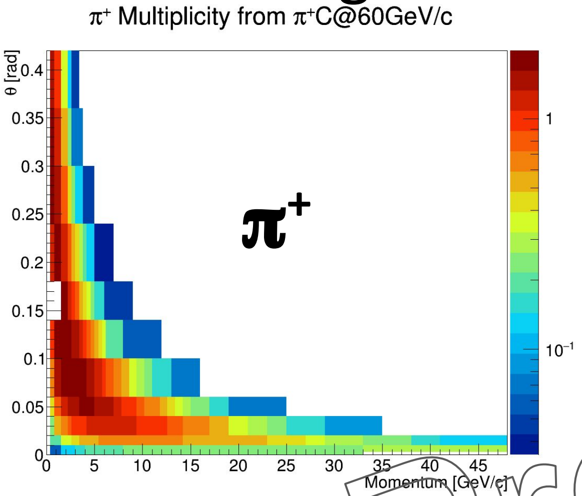
- Momentum ranging from 0.4 GeV/c to 48 GeV/c
- Scattering angle θ from 0 to 420 mrad
- Binning scheme for pions overlaid on p-θ distribution of tracks

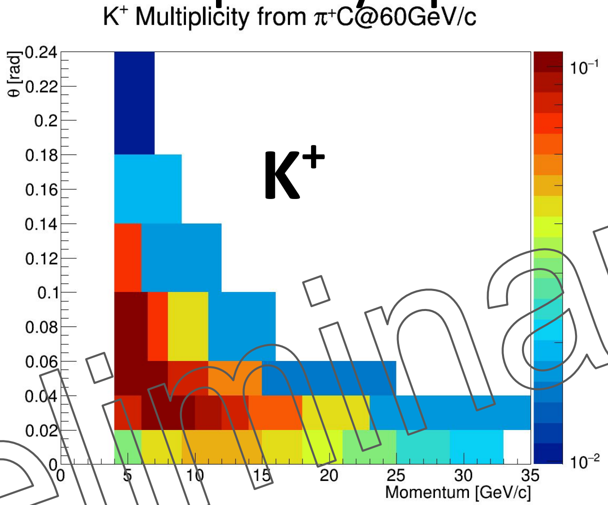


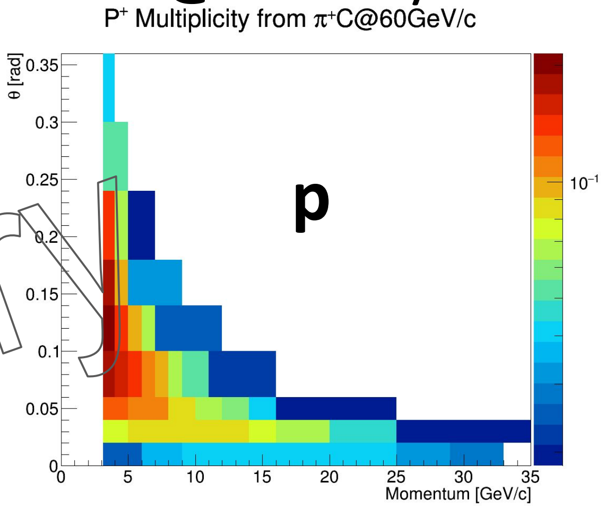
dE/dx Analysis - Example Fit from π^++Be@60GeV/c Interactions

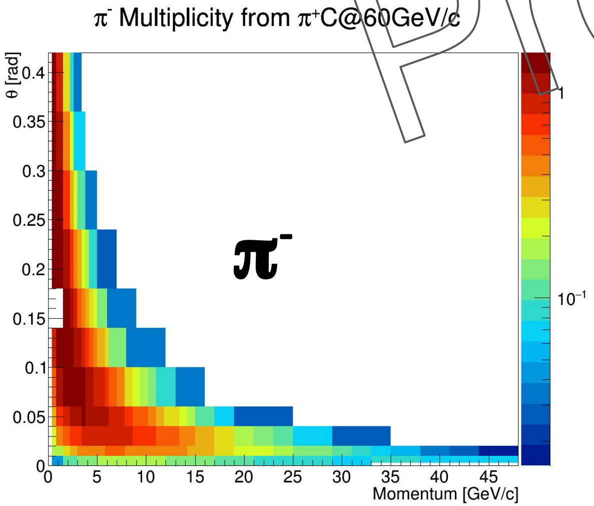


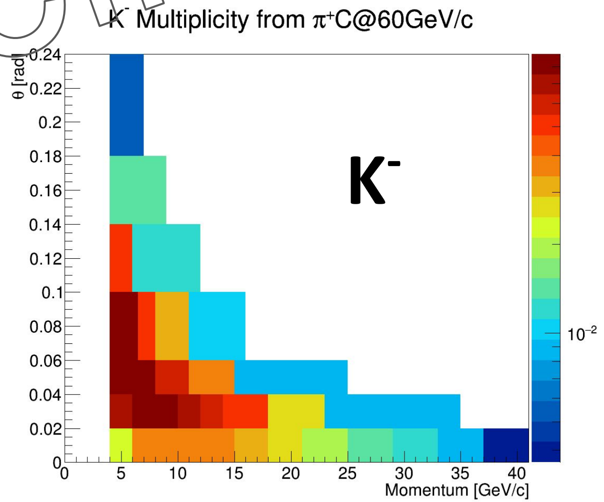
2D Charged Hadron Multiplicity Spectra - π^++C@60GeV/c





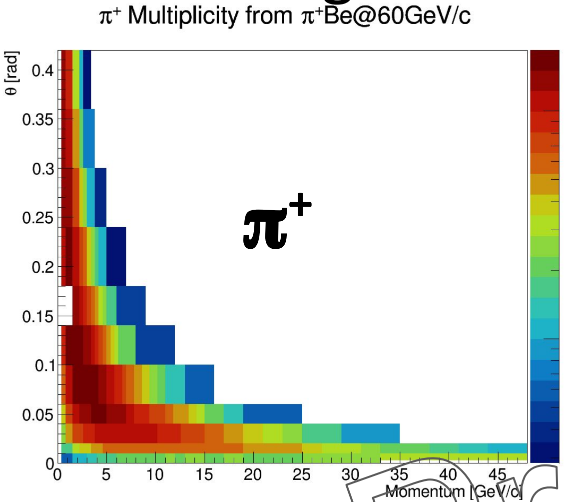


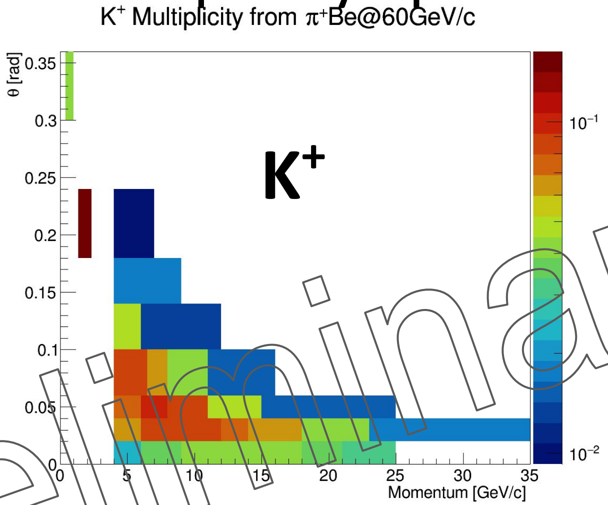


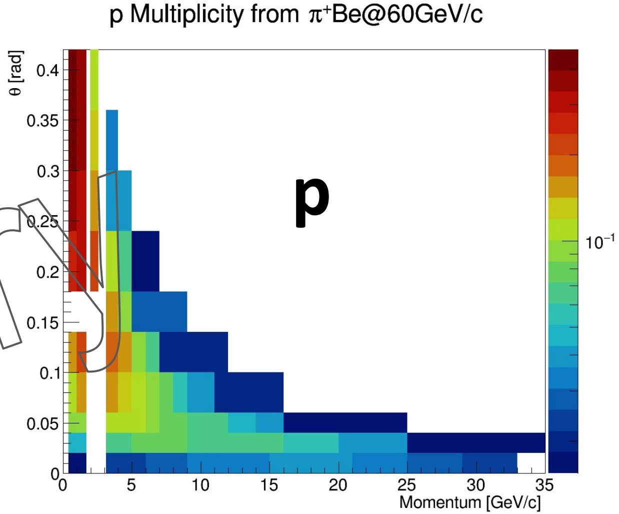


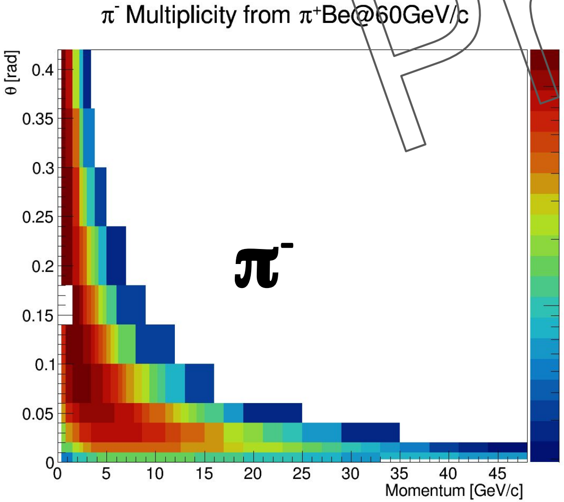
Multiplicity: number of particles produced per production interaction

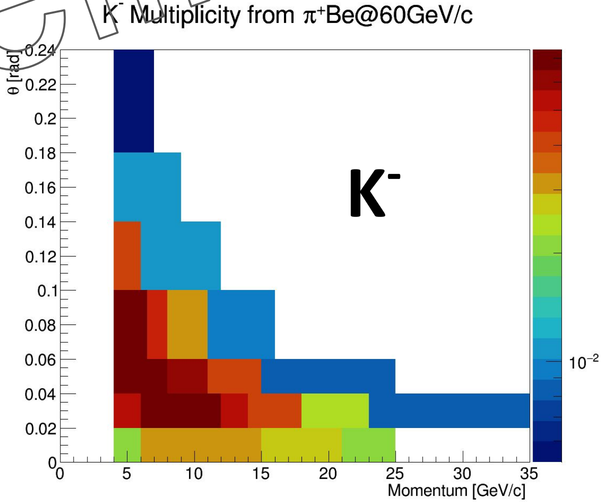
2D Charged Hadron Multiplicity Spectra - π^++Be@60GeV/c





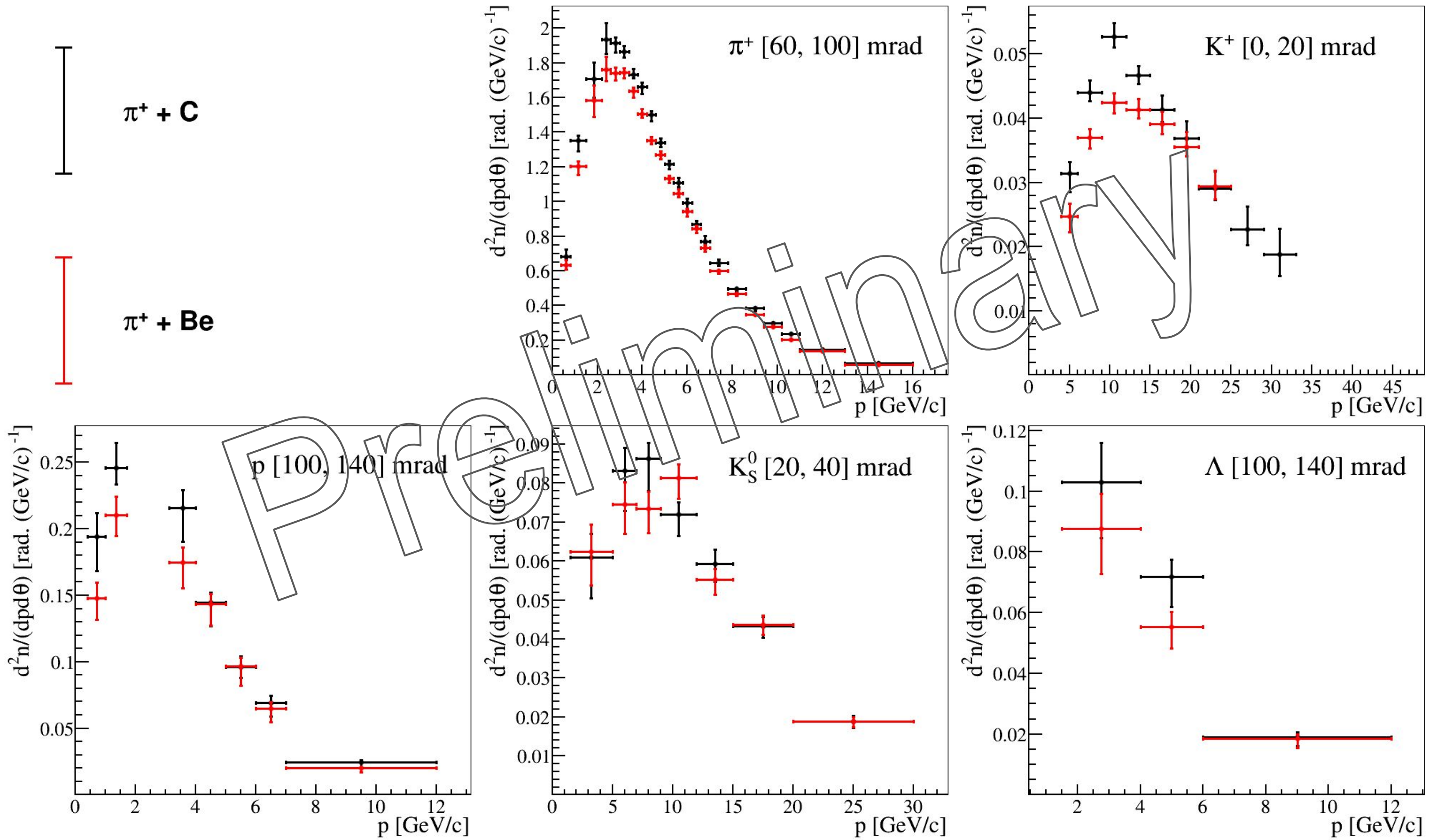






Multiplicity: number of particles produced per production interaction

1D Spectra of π^++C and π^++Be Measurements



- Largest differences are seen at low momenta and large scattering angle

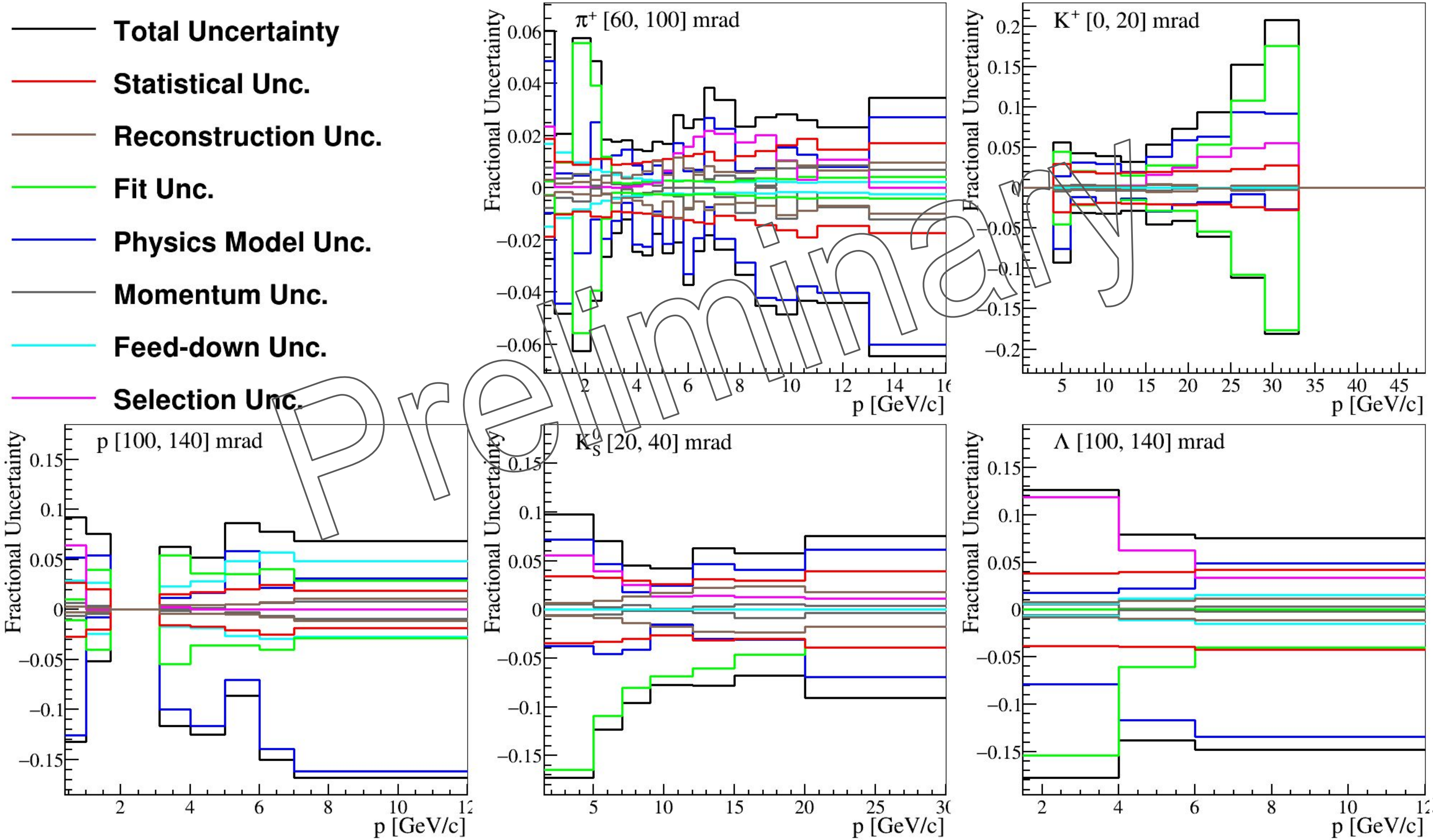
Uncertainties on the Differential Multiplicity Measurements

- Uncertainties were evaluated for a number of effects
  - **Statistical** uncertainties
  - Uncertainties associated with the **selection** efficiency
  - Uncertainties associated with the **physics** models
  - Uncertainties associated with production of weakly decaying neutral particles that decay into the hadron species studied (**feed-down**)
  - Uncertainties associated with the **reconstruction** efficiency
  - Uncertainties on the reconstructed **momentum**
  - Uncertainties associated with separating particle species (**fit** uncertainties)
  - **Normalization** uncertainty associated with the total cross section analysis
- Uncertainties very similar for π^++C and π^++Be

Can be improved with vertex detector upgrade

Can be improved with use of ToF-F

Uncertainties on the Differential Multiplicity Measurements (π^++C@60GeVc)



NA61 Beyond 2020 - Detector Upgrades

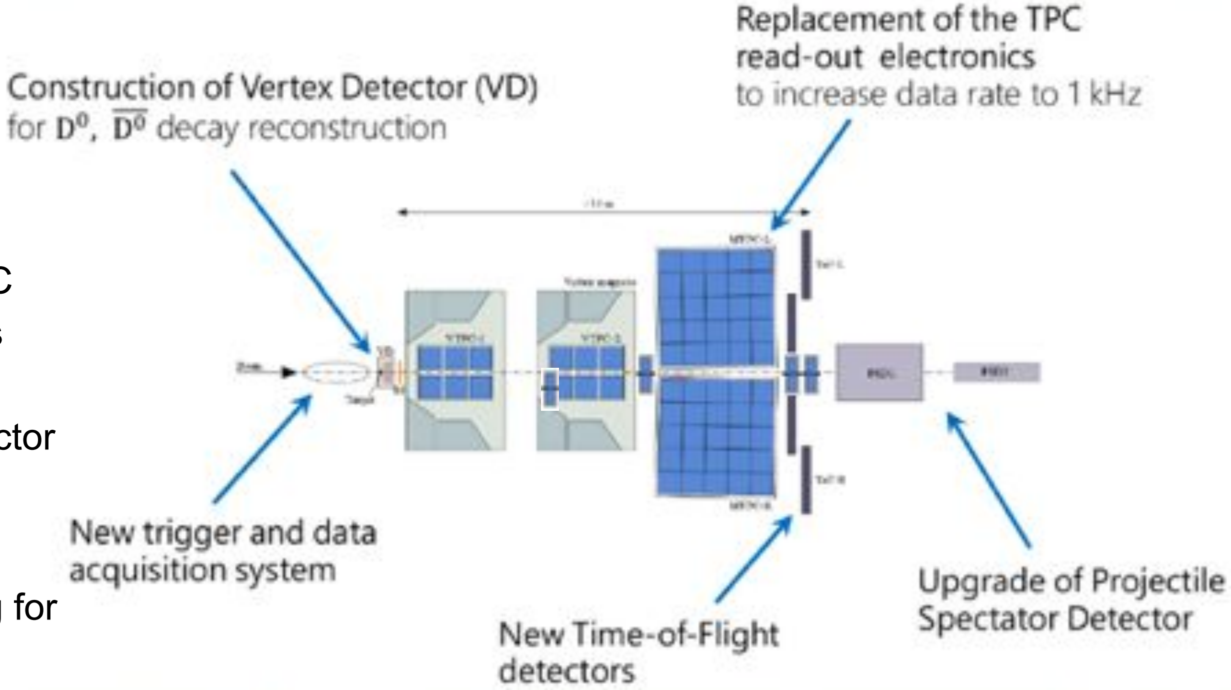
- Upgrades to NA61 in progress

  - 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

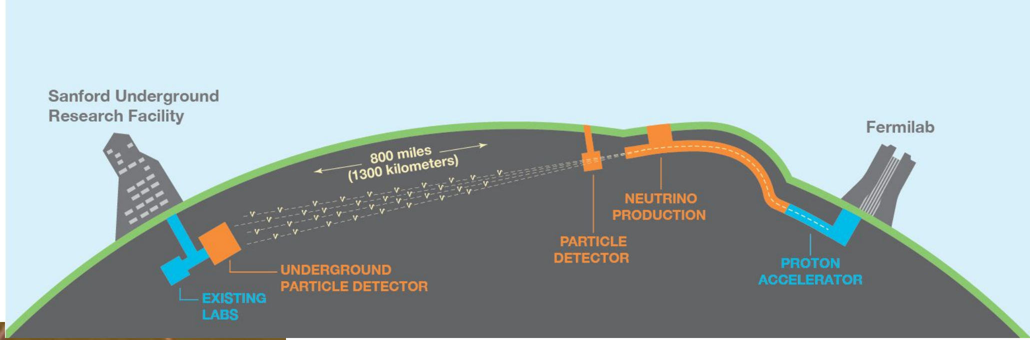
- Upgrades being considered

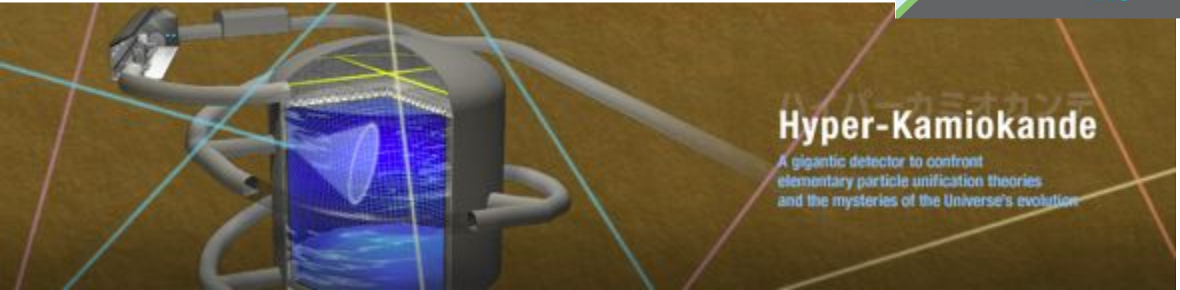
    - Possible tertiary beam allowing for lower energy hadron beams
    - Target tracking detector for replica target data taking



NA61 Beyond 2020 - Measurements for Neutrino Beams

- Will resume data taking with NA61 after Long Shutdown 2
- Potential measurements for the neutrino program 2021-2025
  - Hadron beams below 18 GeV/c if possible - many unstudied/understudied reactions for neutrino experiments could be studied
  - Low energy measurements for atmospheric neutrino flux estimations
  - **Replica target measurements** and dedicated thin target measurements for **DUNE**
  - Interactions with T2K-II/Hyper-K target material and possibly replica target measurements
  - Kaon interaction data if more is needed





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

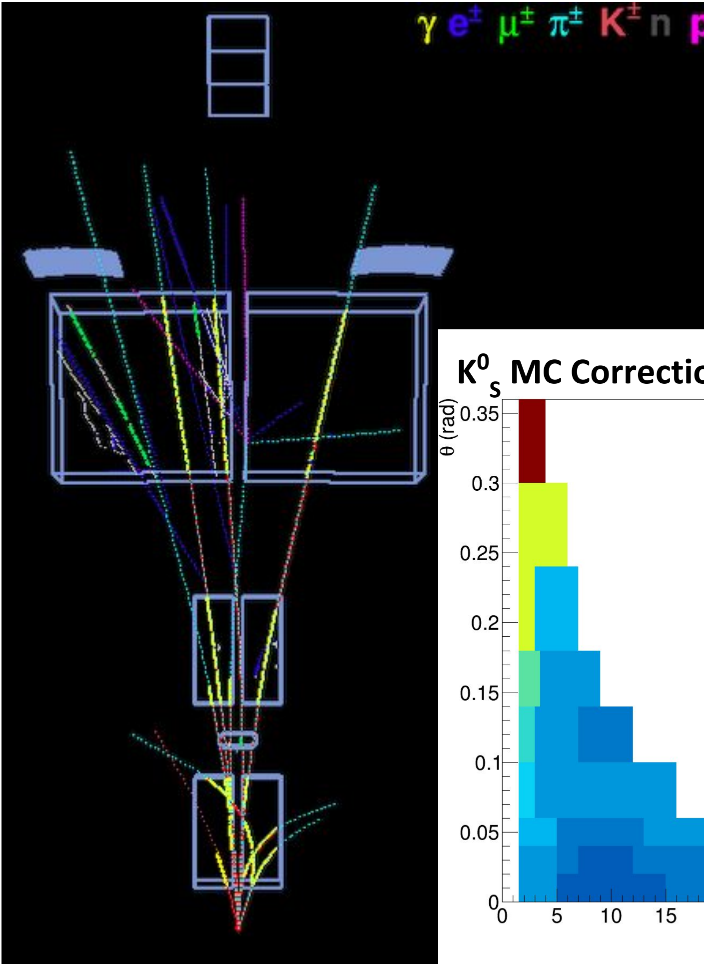
- Azerbaijan
  - National Nuclear Research Center, Baku
- Bulgaria
  - University of Sofia, Sofia
- Croatia
  - IRB, Zagreb
- France
  - LPNHE, Paris
- Germany
  - KIT, Karlsruhe
  - Fachhochschule Frankfurt, Frankfurt
  - University of Frankfurt, Frankfurt
- Greece
  - University of Athens, Athens
- 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, 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

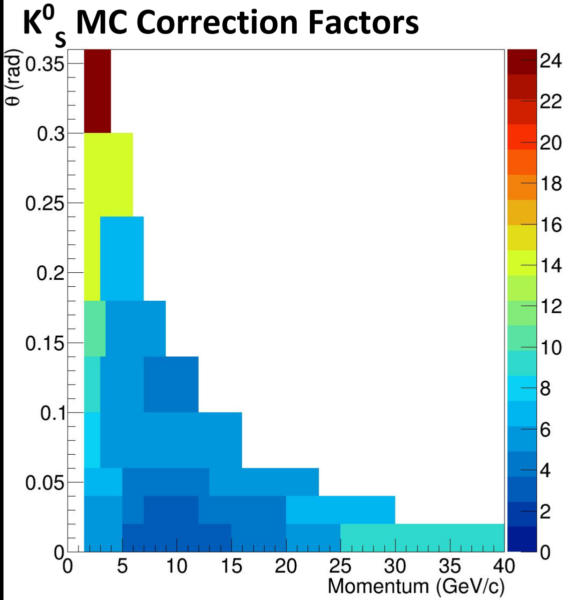
Questions?

Back-Up

V0 MC Corrections



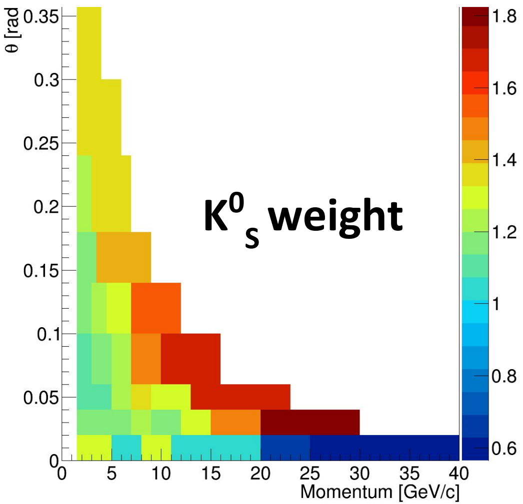
- Interactions are simulated using GEANT 4
- Simulated particles are run through a detector simulation
- The reconstruction is performed on the simulated data
- In short, the correction factors are determined from the ratio of reconstructed V0s to true simulated V0s



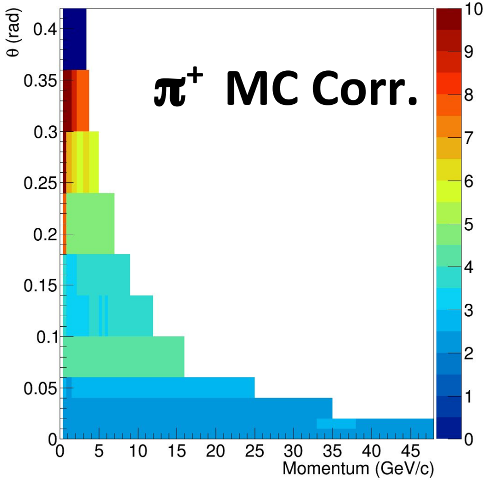
- MC Corrections account for:
  - V0 candidates coming from heavier weakly decaying particles
  - V0 candidates produced in secondary interactions
  - Geometrical acceptance of the detector
  - Efficiency of the selection criteria
  - Efficiency of the reconstruction

MC Corrections with V0 Reweighting

- Interactions are simulated using GEANT4
- Simulated particles are run through a detector simulation
- The reconstruction is performed on the simulated data
- **Reconstructed tracks coming from V0s are reweighted according to the results of the V0 analysis**
  - **Major reduction in uncertainties from this procedure**
- In short, the correction factors are determined from the ratio of reconstructed charged tracks to true simulated charged hadrons



- MC Corrections account for:
  - Hadrons coming from heavier weakly decaying particles
  - Hadrons produced in secondary interactions
  - Geometrical acceptance of the detector
  - Efficiency of the selection criteria
  - Efficiency of the reconstruction



Neutrino grandparents?