Hadron Production Measurements at NA61/SHINE for Accelerator-based Neutrino Experiments

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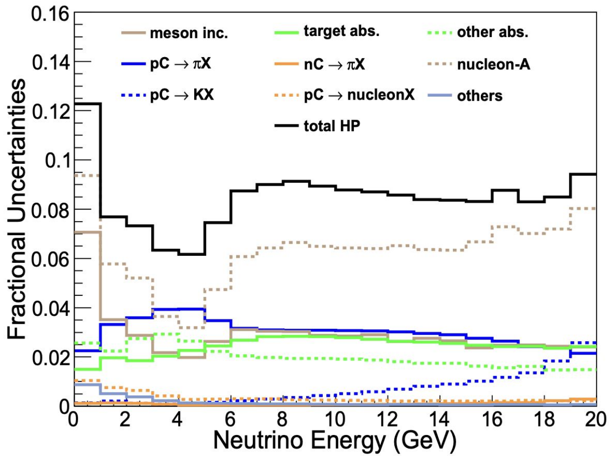
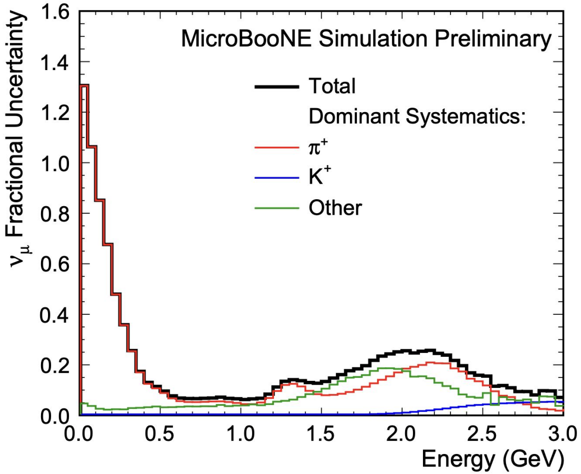
Neutrino Flux Uncertainty

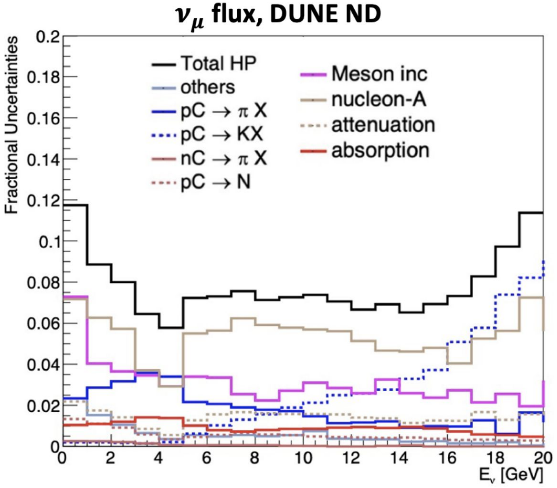
- Neutrino flux uncertainty limits the precision of measurements in all accelerator-based neutrino experiments
  - Dominated by hadron production uncertainty



MINERvA at NuMI beamline



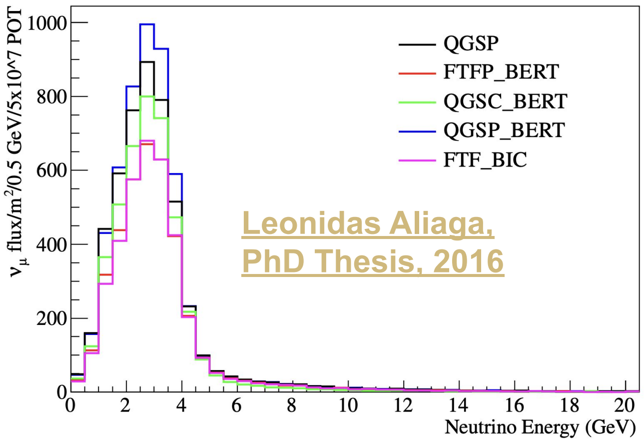
MicroBooNE at Booster Neutrino Beam

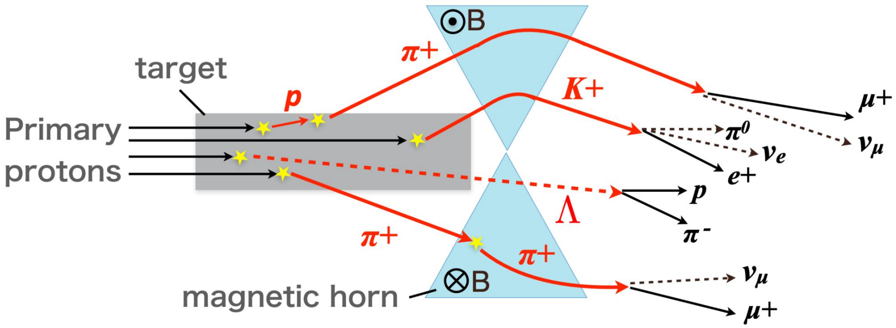


DUNE ND at LBNF

How to Model Neutrino Flux

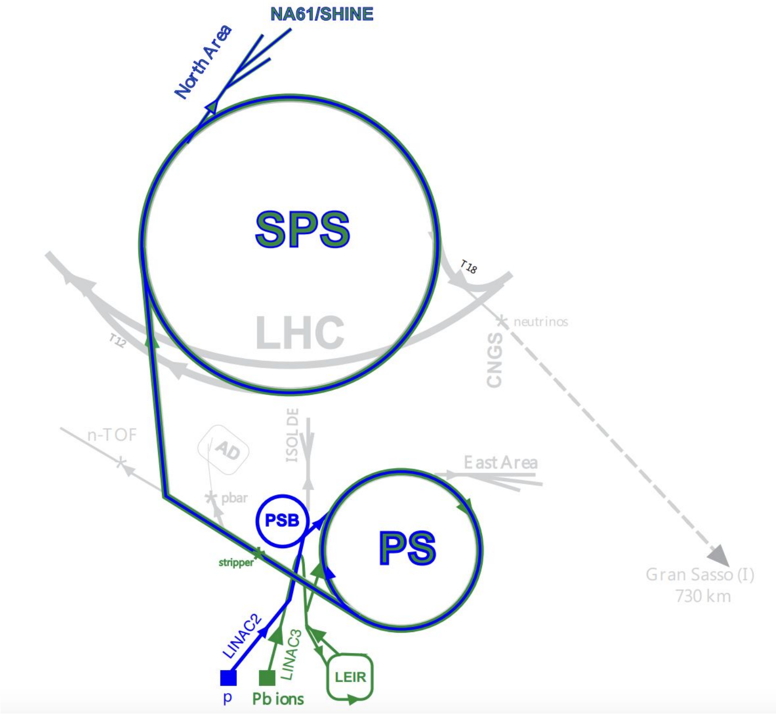
- Neutrino flux simulation relies on the hadronic interaction models used in MC event generators
  - i.e. FLUKA or GEANT4
  - Very large uncertainty (>20%)
- Important to have constraints on the hadronic processes
  - Primary proton-target interaction
  - Secondary interactions
    - Inside the target
    - Other materials





NA61/SHINE

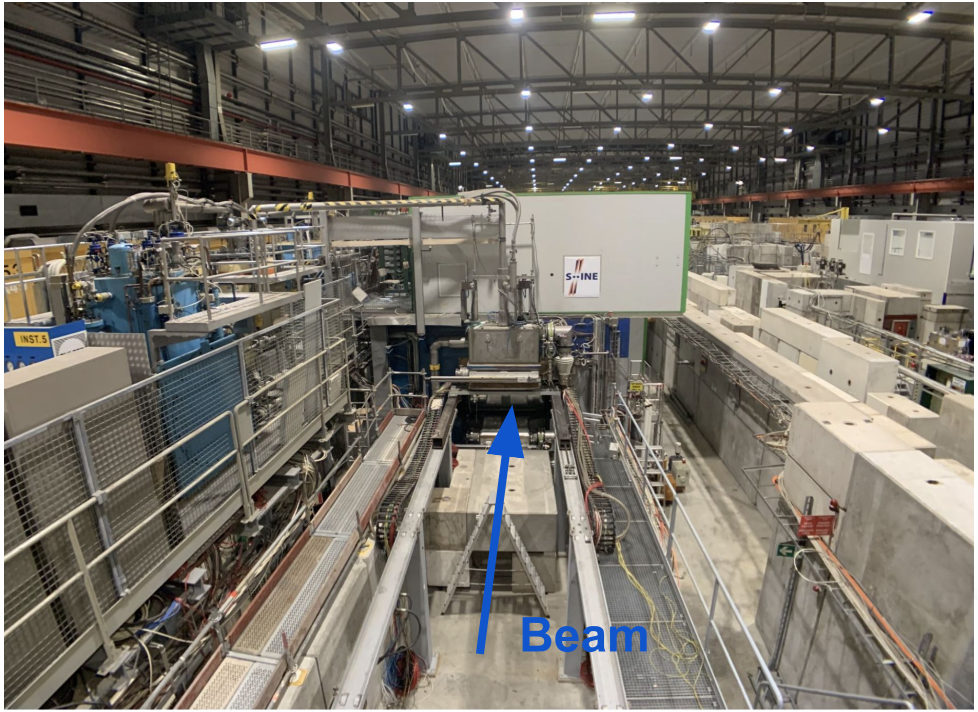
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment

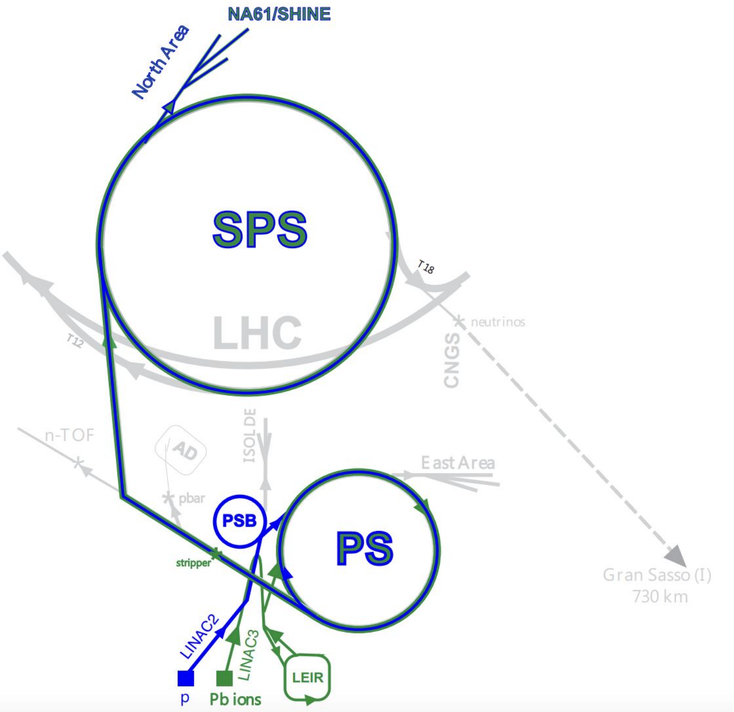


[*JINST* 9 (2014) P06005]

NA61/SHINE

- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Beam

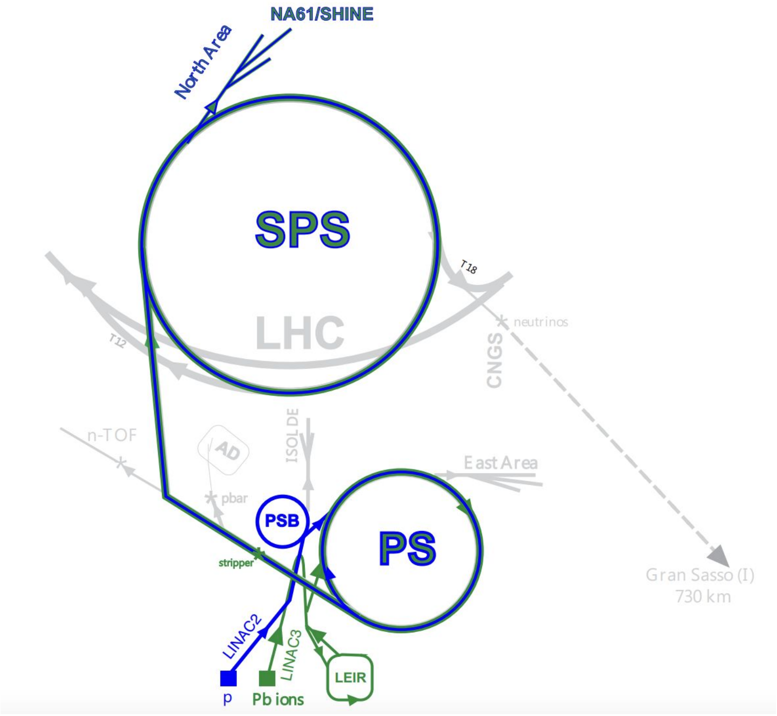




[*JINST* 9 (2014) P06005]

NA61/SHINE

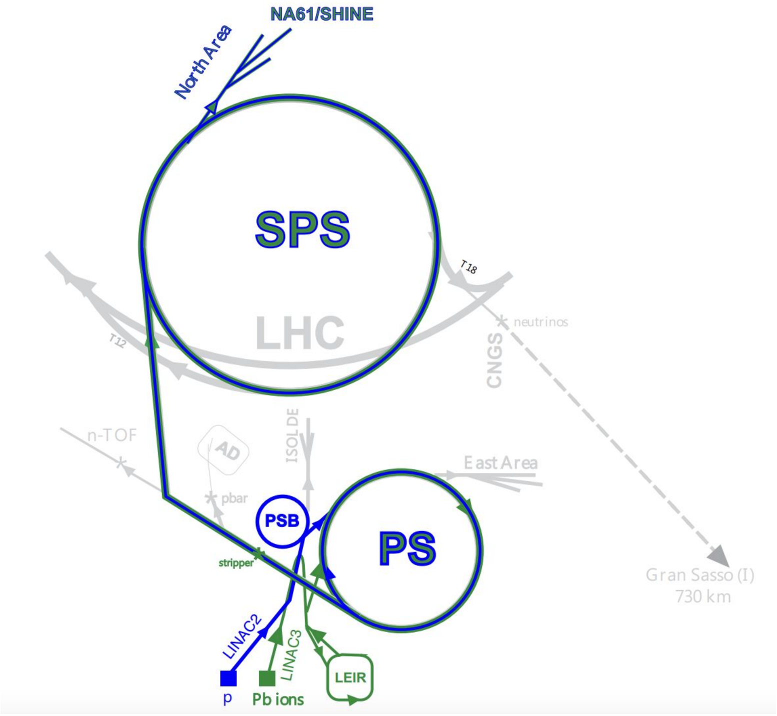
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Beam
  - Primary proton beam from CERN SPS
  - Secondary beam of proton, kaon, pion, etc.



[*JINST* 9 (2014) P06005]

NA61/SHINE

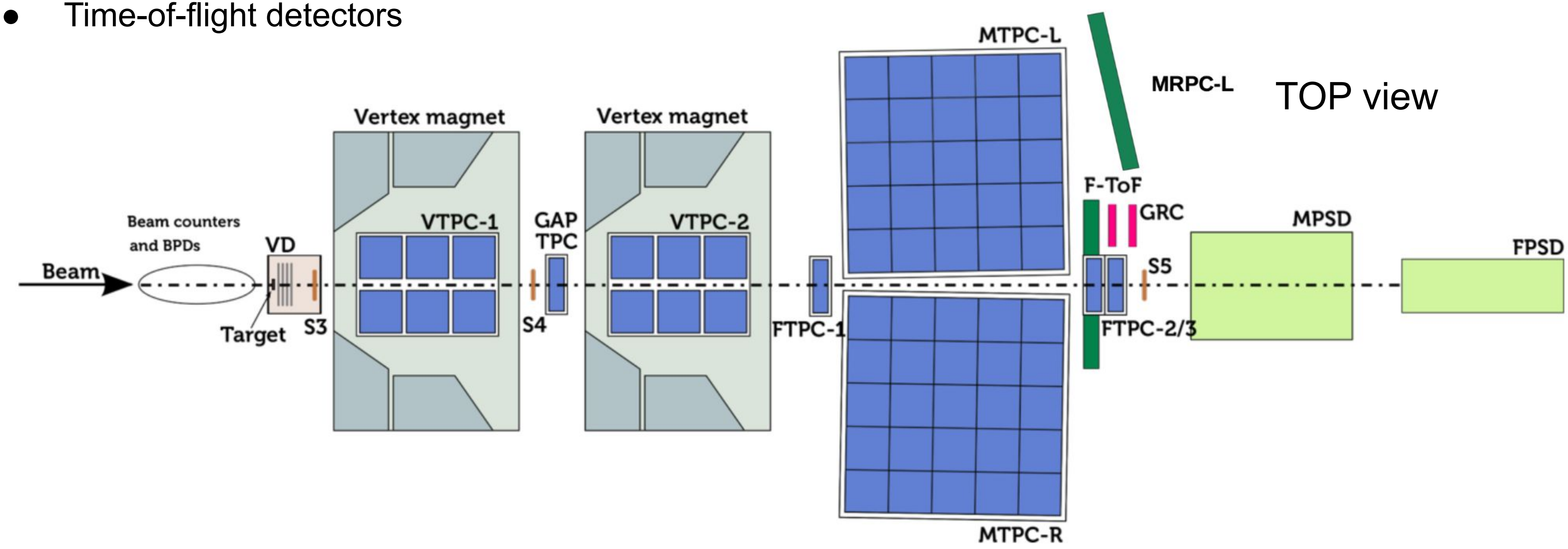
- **S**PS **H**eavy **I**on and **N**eutrino **E**xperiment
- Beam
  - Primary proton beam from CERN SPS
  - Secondary beam of proton, kaon, pion, etc.
- Physics program
  - Heavy ions / strong interaction
  - Cosmic-ray production
  - **Hadron production for neutrino beams**



JINST 9 (2014) P06005

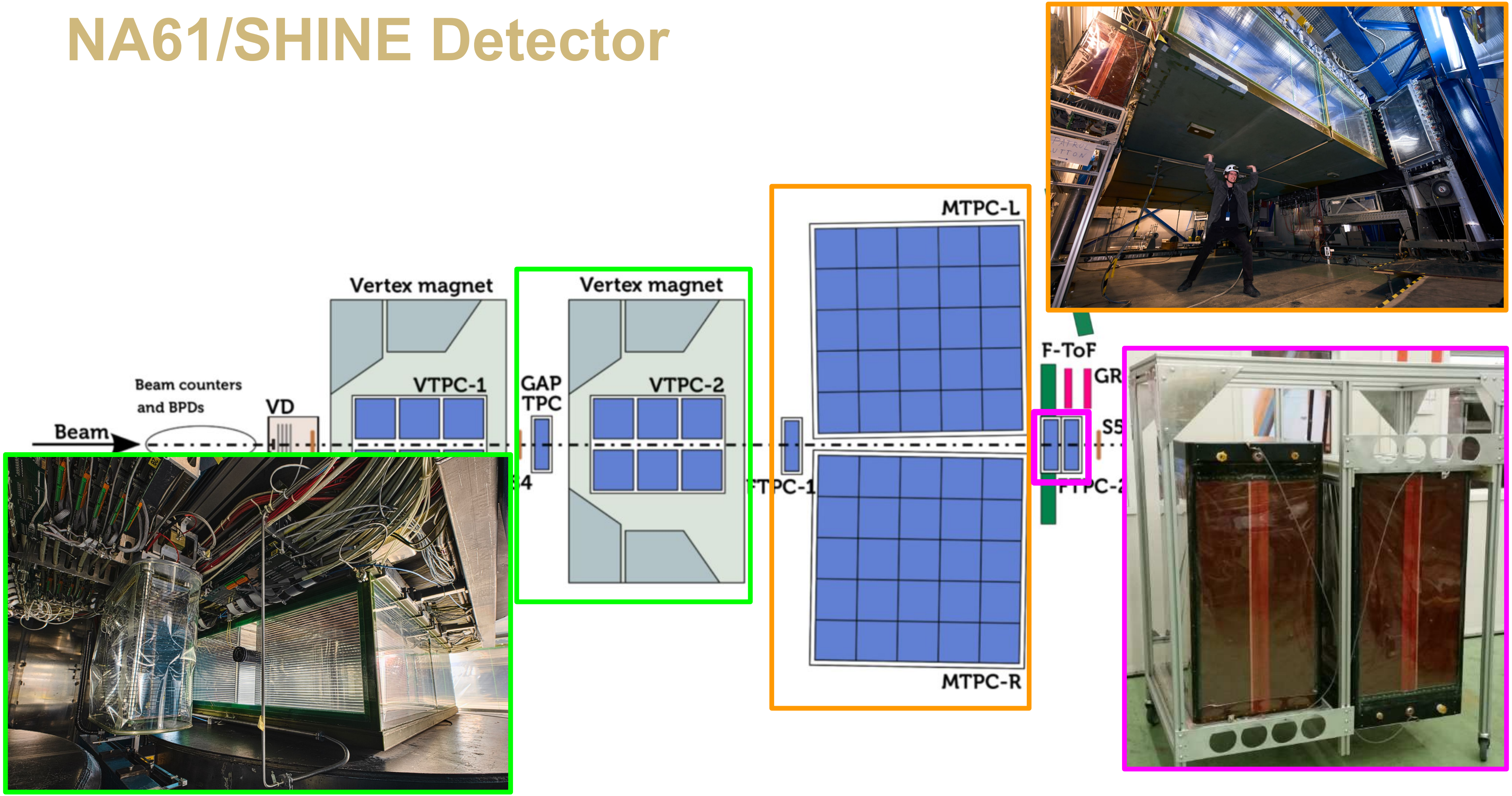
NA61/SHINE Detector

- Eight Time Projection Chambers (TPCs)
- Two superconducting magnets
- Time-of-flight detectors

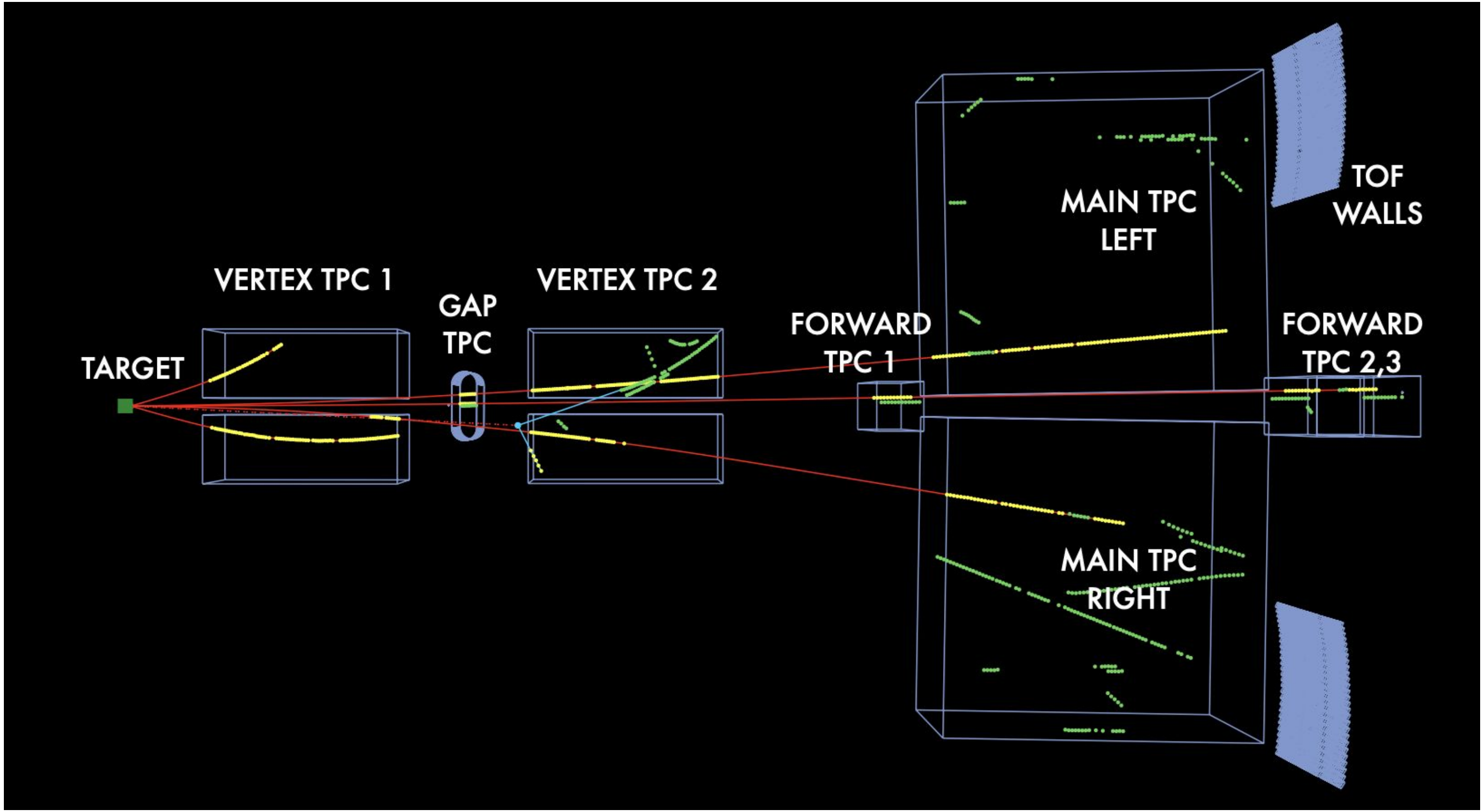


- Projectile Spectator Detectors (PSDs)
- Major detector upgrade finalized in 2022

NA61/SHINE Detector



Event Display of 120 GeV/c proton + Carbon



The Neutrino Program at NA61/SHINE

- Dedicated hadron production measurements for long-baseline neutrino oscillation experiments
  - T2K, Hyper-K, NOvA, DUNE, …
- Run periods

T2K
Proton at 31 GeV/c

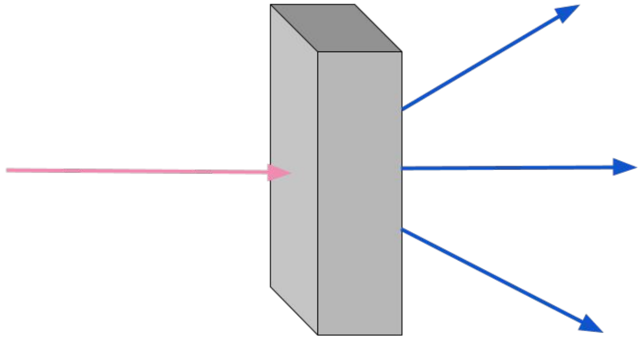
NuMI experiments
Proton at 120 GeV/c
Proton at 60 and 90 GeV/c
Pion at 60 GeV/c

T2K
Proton at 31 GeV/c

NuMI, LBNF/DUNE
Proton at 120 GeV/c
Kaon at 60 GeV/c

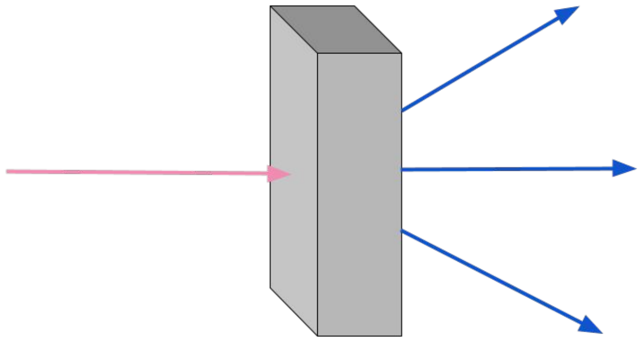
Hadron Production Measurements

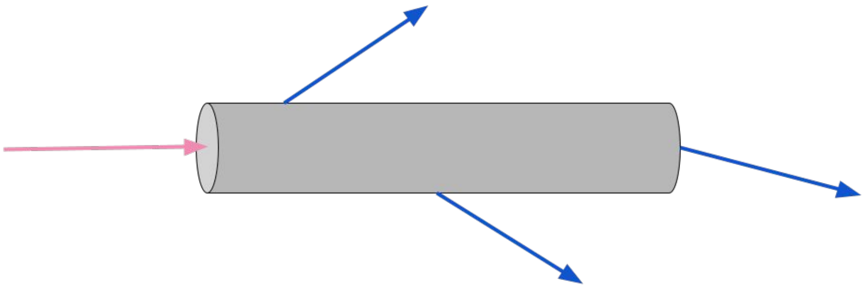
- Thin-target measurements
  - Total, inelastic and production cross sections
  - Charged and neutral hadron yields from primary interactions
  - Input to reweight flux simulations



Hadron Production Measurements

- Thin-target measurements
  - Total, inelastic and production cross sections
  - Charged and neutral hadron yields from primary and secondary interactions
  - Input to reweight flux simulations
- Replica-target measurements
  - Differential production yield measurements from the surface of the target
  - Beam survival probability
  - Input to reweight flux simulations
  - Input to understand beam attenuation

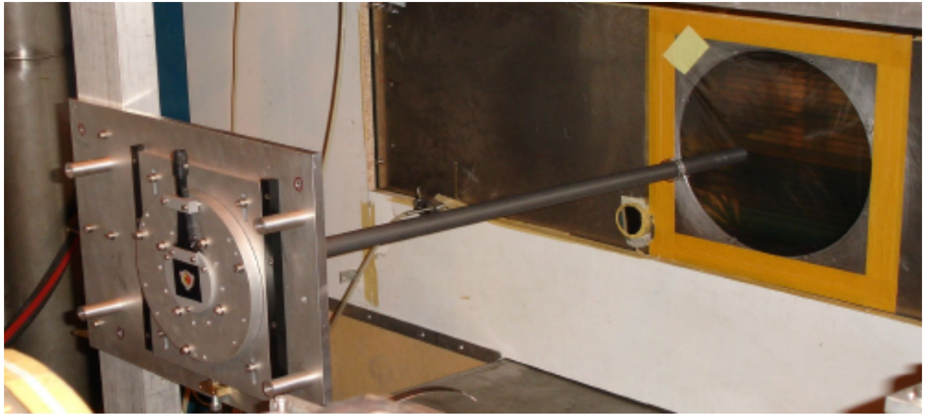


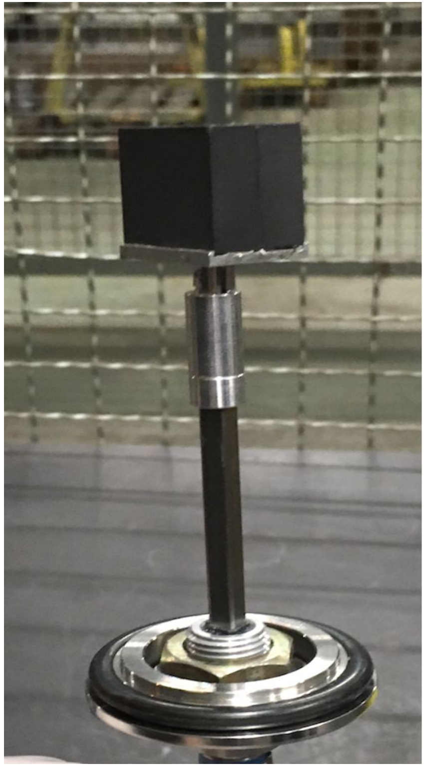



2007 - 2010
Long Shutdown (LS) 1
2015 - 2018
LS2
2022 - 2025
LS3
2027 - ?

Measurements for the T2K Experiment

- Proton at 31 GeV/c
- Targets
  - Thin: 2 cm graphite target
  - Thick: 90 cm replica graphite target



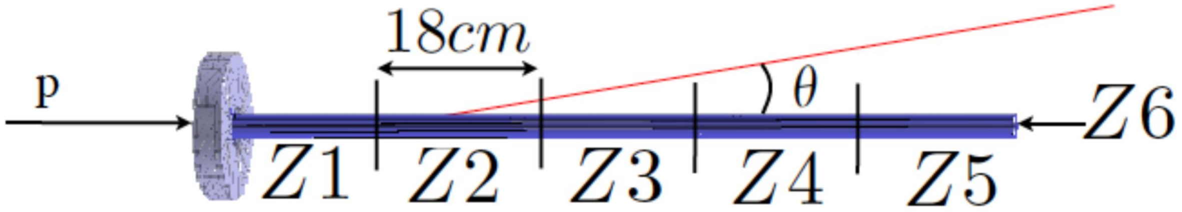


Measurements for T2K

- Thin target: 31 GeV/c proton on 2 cm graphite target
  - Total cross-section and $\pi^{+/-}$ spectra measurements (Phys. Rev. C84 (2011) 034604)
  - K^+ spectra measurement (Phys. Rev. C85 (2012) 035210)
  - K^0_S and Λ^0 spectra measurements (Phys. Rev. C89 (2014) 025205)
  - Total cross-section and $\pi^{+/-}$, $K^{+/-}$, p, K^0_S, and Λ^0 spectra measurements (Eur. Phys. J. C76 (2016) 84)
- Replica target: 31 GeV/c proton on 90 cm replica graphite target
  - Methodology, $\pi^{+/-}$ yield measurement (Nucl. Instrum. Meth. A701 (2013) 99-114)
  - $\pi^{+/-}$ yield measurement (Eur. Phys. J. C76 (2016) 617)
  - $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))
  - p beam survival probability measurement (Phys. Rev. D103 012006 (2021))

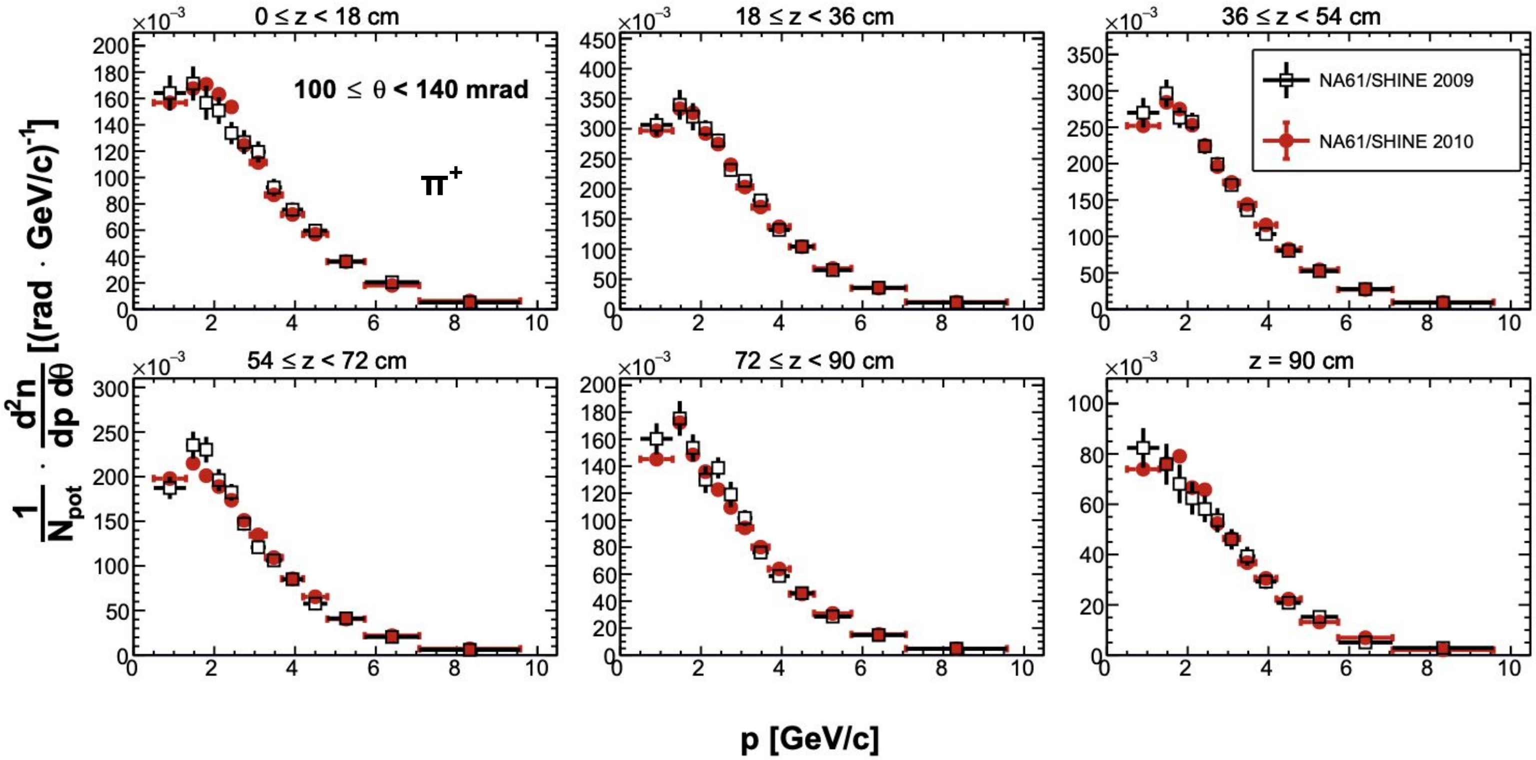
Thick Target Measurements for T2K

- Replica target: $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))



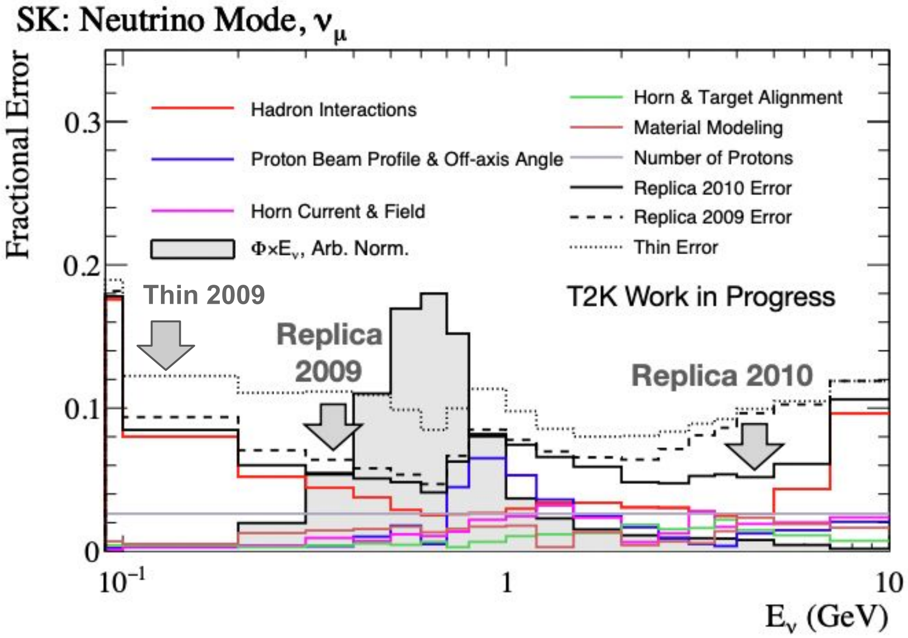
Thick Target Measurements for T2K

- Replica target: $\pi^{+/-}$, p, and $K^{+/-}$ yield measurements (Eur. Phys. J. C79 100 (2019))



Effect on T2K Flux Uncertainty

- Improved T2K flux uncertainty down to ~5%



Lukas Berns, NBI 2019

$\pi^{+/-}$ yield measurement

(Eur. Phys. J. C76 (2016) 617)

$\pi^{+/-}$, p, and $K^{+/-}$ yield measurements

(Eur. Phys. J. C79 100 (2019))


2007 - 2010
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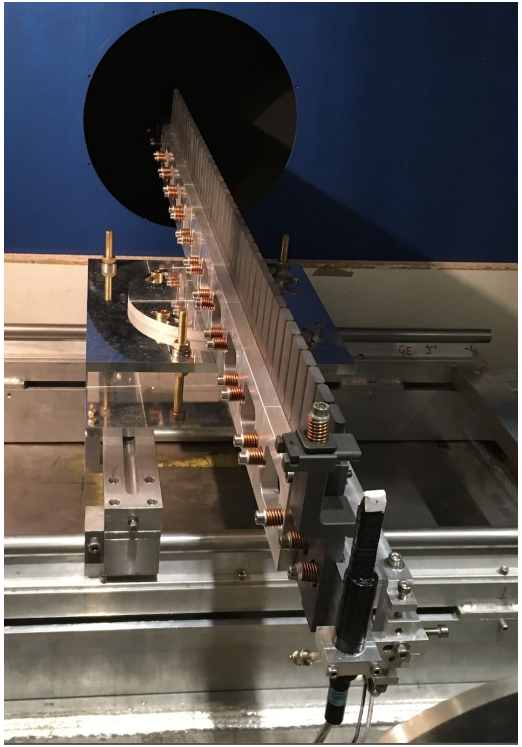
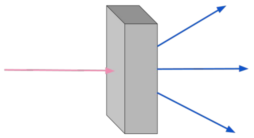
Measurements for Fermilab Experiments

- Beam
  - Proton at 120 GeV/c
  - Proton at 60, 90 GeV/c
  - Pion at 60 GeV/c
- Target
  - Thin (1.5 cm)
    - Carbon
    - Beryllium
    - Aluminum
  - Thick
    - NuMI replica

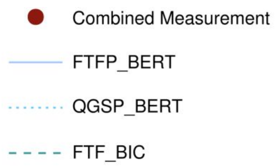


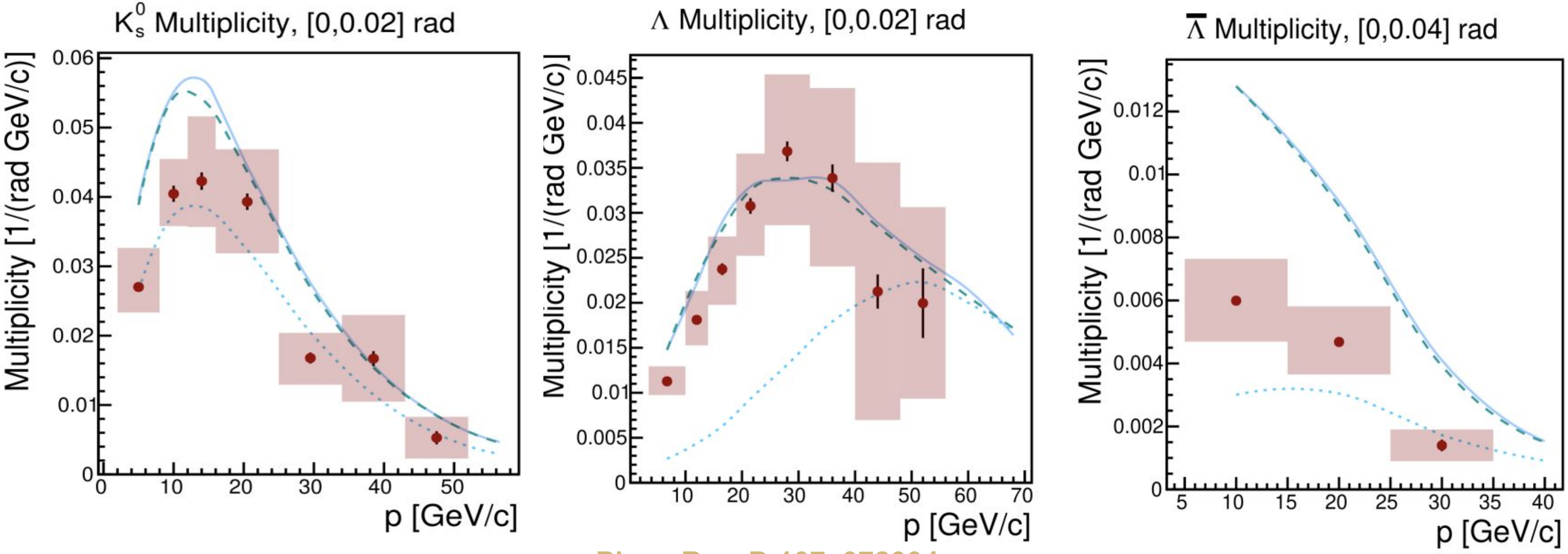
NuMI replica target
“target in” at NA61

Measurements of p + C at 120 GeV/c



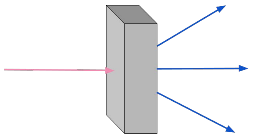
- 2016 and 2017 data combined
- 120 GeV/c p + C neutral hadron multiplicities



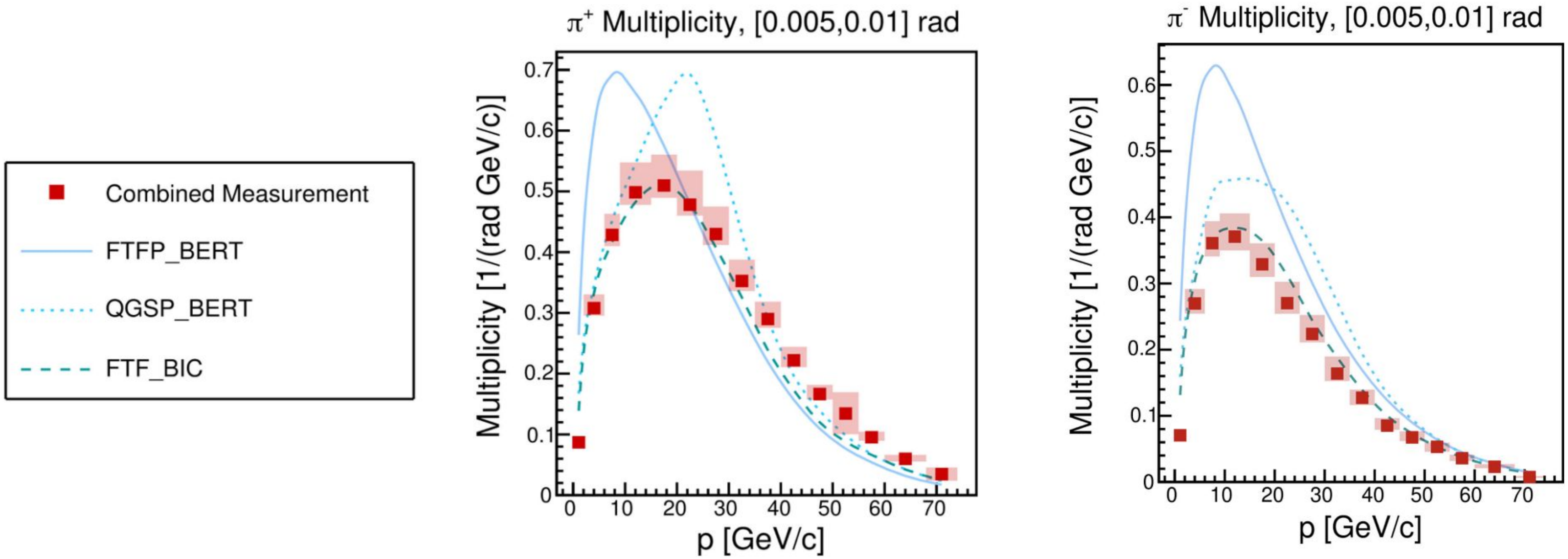


Phys. Rev. D 107, 072004

Measurements of p + C at 120 GeV/c

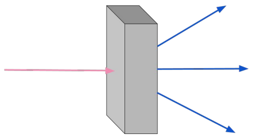


- 2016 and 2017 data combined
- 120 GeV/c p + C charged hadron multiplicities



Phys.Rev.D 108 (2023) 072013

Measurements of p + C at 120 GeV/c



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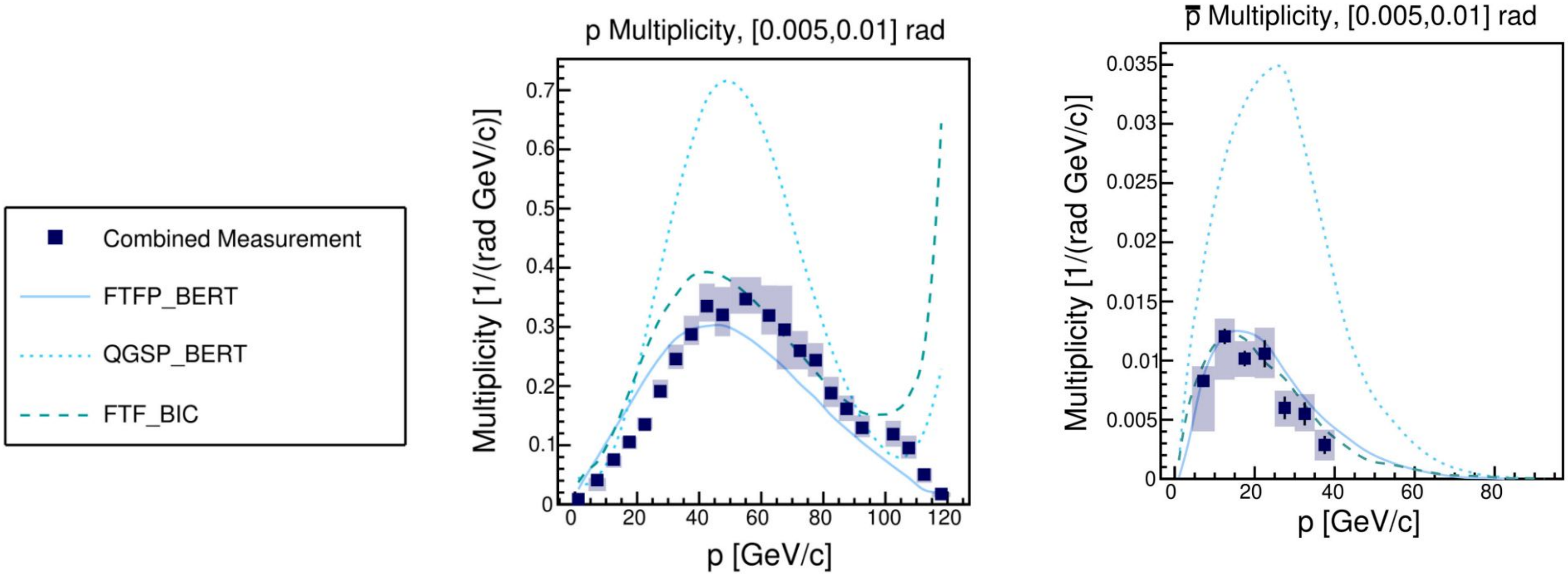
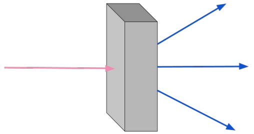


Phys.Rev.D 108 (2023) 072013

Measurements of p + C at 120 GeV/c



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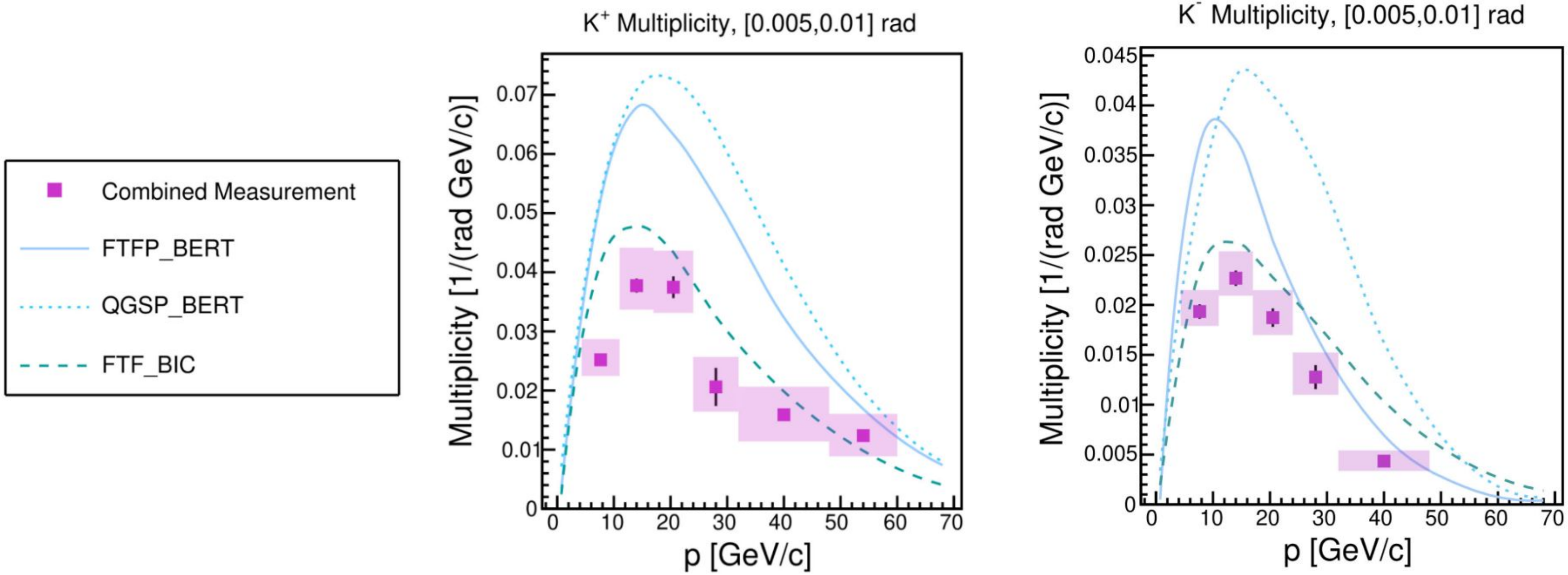
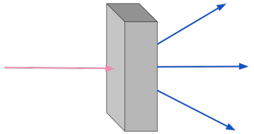
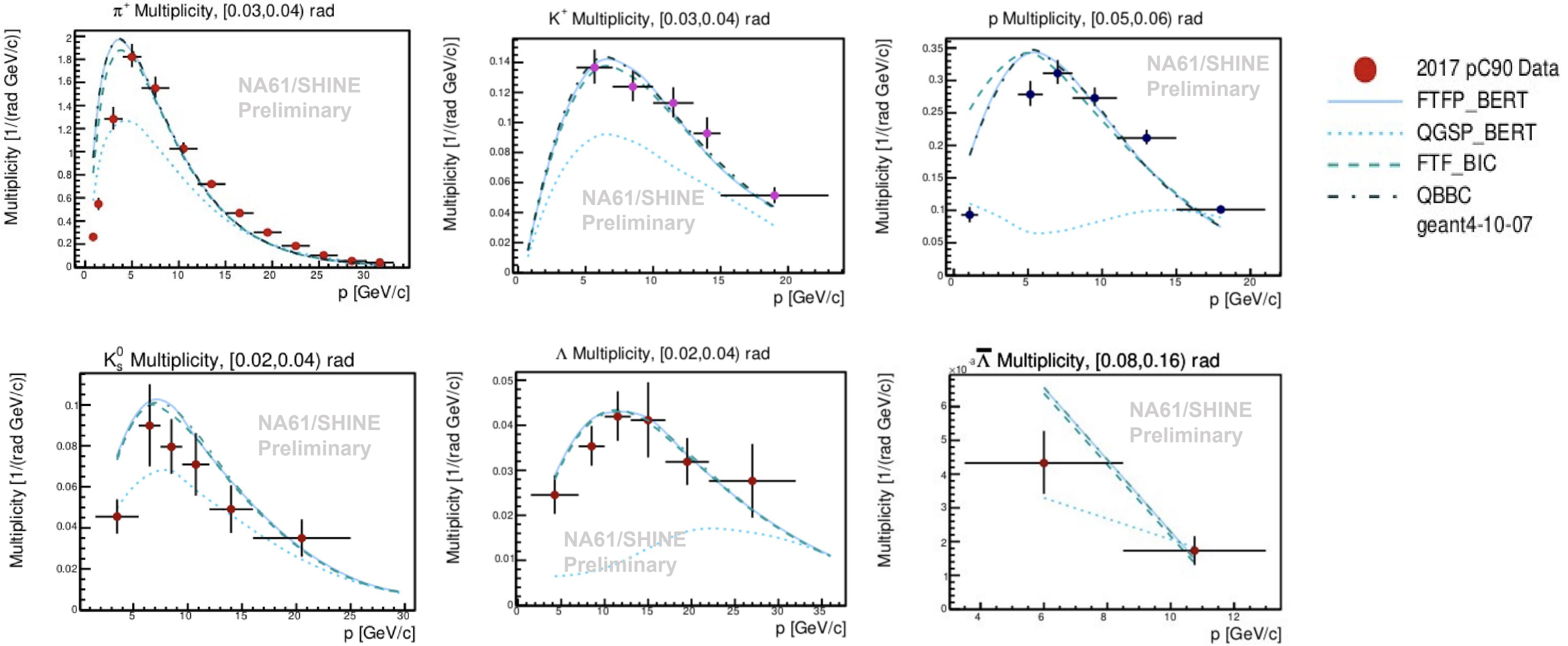


Phys.Rev.D 108 (2023) 072013

Measurements of p + C at 90 GeV/c

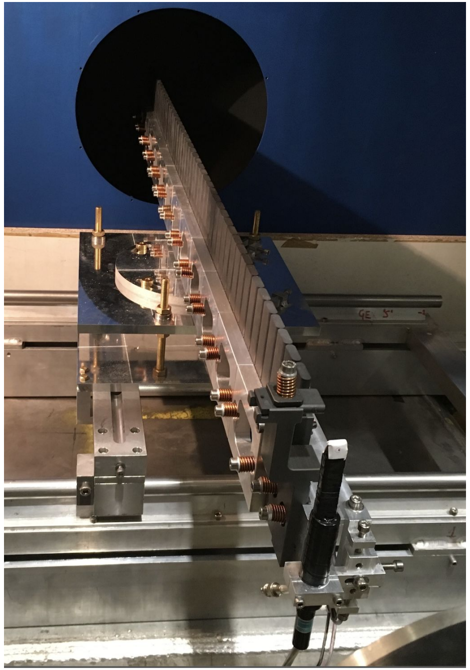




Paper in preparation

Other Ongoing Analyses

- 60 GeV/c p + C charged and neutral hadron multiplicities
- 120 GeV/c p + NuMI replica target data analysis
  - Calibration is underway
  - Measurement of differential hadron production yields
    - In similar way as T2K replica target measurement
- Implementing 120 GeV/c p + C results into PPFX*
  - Could be used by all NuMI experiments and DUNE



NuMI replica target "target in" at NA61

* *See Ian's talk for more about PPFX*


2007 - 2010
Long Shutdown (LS) 1
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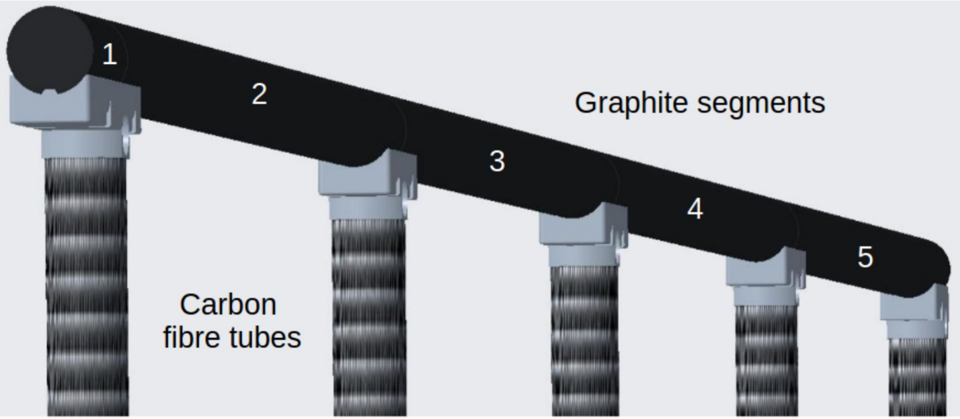
LS3
2027 - ?

2022 - 2023

- More T2K replica target data collected in 2022
  - Proton at 31 GeV/c
  - 18 times 2010 statistics
  - Being calibrated
  - Measure high-momentum kaon yields
- More thin target data collected for NuMI/DUNE in 2023
  - Proton at 120 GeV/c on Carbon
  - Proton at 120 GeV/c on Titanium
  - Kaon at 60 GeV/c on Carbon

Data-taking with LBNF/DUNE Prototype Target

- 120 GeV/c proton beam
- 1.5-m long LBNF/DUNE prototype target
- Data-taking planned in July 2024
- Partial target (fewer segments) data-taking in 2025
- Measurement of differential hadron production yields




2007 - 2010
Long
Shutdown
(LS) 1
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LS2
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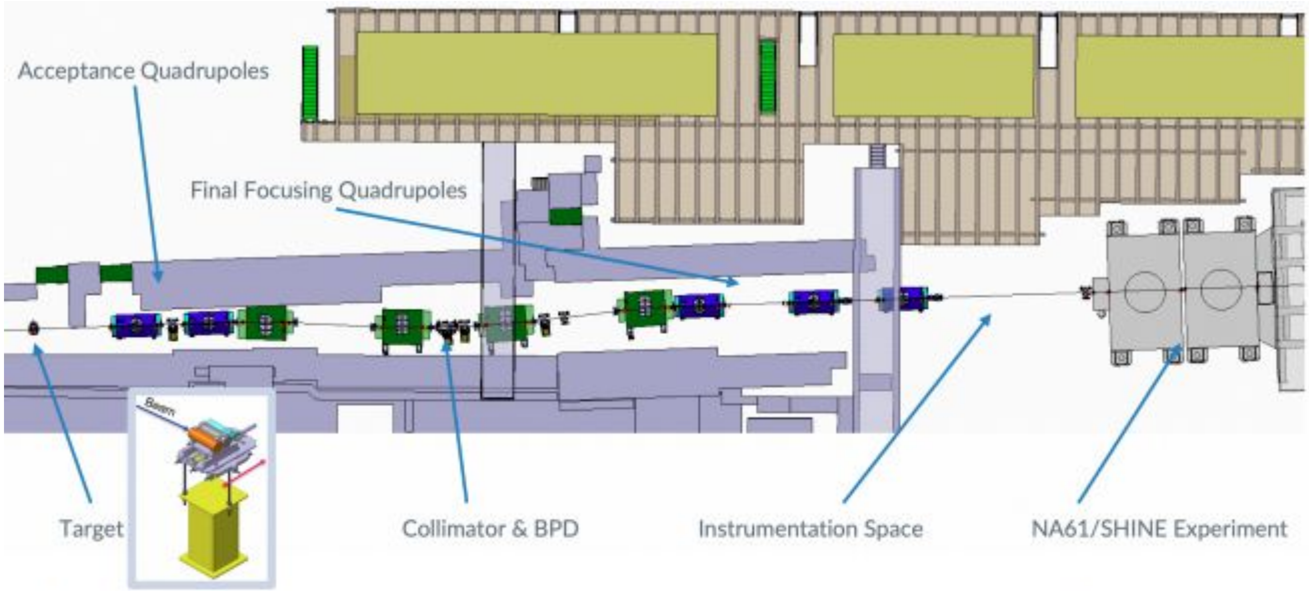
LS3
2027 - ?

Post-LS3 (2027-)

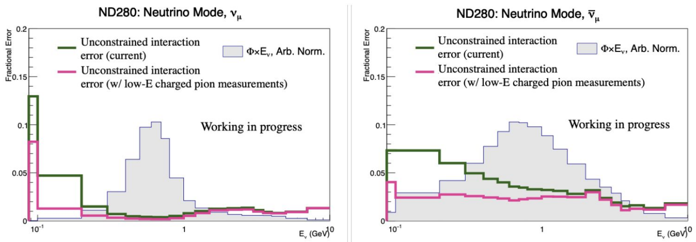
- A low-energy (2-13 GeV/c) beam designed by CERN beam group
- Beam may be available after CERN's Long Shutdown 3

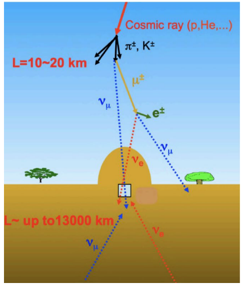


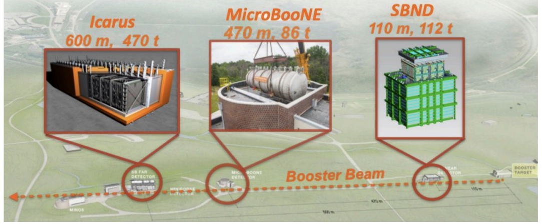
SPSC-M-793

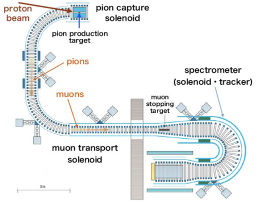
Physics Motivations of the Low-energy Beam

- Accelerator-based neutrino experiments
  - T2K, Hyper-K (pion at 2 GeV, 8 GeV)
  - LBNF/DUNE
  - Short-baseline Neutrino Program (proton at 8 GeV)
- Atmospheric neutrino experiments
  - sub-GeV neutrinos at Super-K, Hyper-K, DUNE
- Spallation neutron source neutrino experiments
  - JSNS^2 (proton at 3 GeV)
  - COHERENT (proton <2 GeV)
- Muon experiments
  - COMET (proton at 8 GeV)
- …

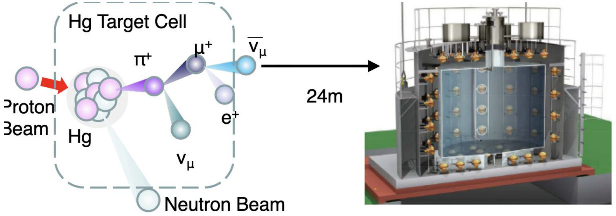


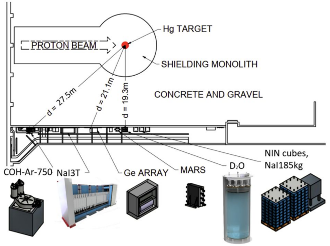






More details at [NA61++/SHINE open workshop]





Summary

- NA61/SHINE provides unique hadron production measurements to support the accelerator-based neutrino experiments
  - Greatly reduced T2K flux uncertainty
  - Recent results will benefit neutrino experiments at Fermilab
- DUNE prototype target data taking planned this year
- Many exciting opportunities after LS3 (2027-)
- **We welcome new collaborators!**

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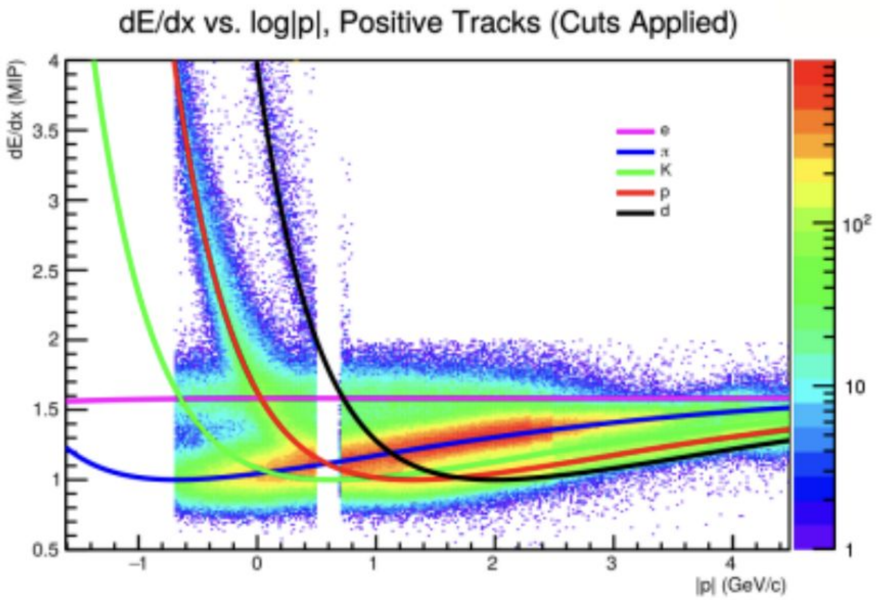
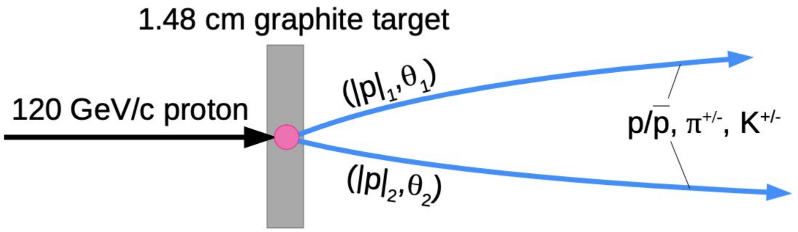
Thank you!

Backup

Charged Analysis

- In each kinematic bin, likelihood-based dE/dx fit performed to track dE/dx distribution
- Result: Fraction of e+/- , π+/- , K+/-, p/p, D+/- in each kinematic bin
  - Positive and negative tracks fit simultaneously in order to constrain calibration parameters
- Total number of each species used to calculate identified multiplicity in each bin





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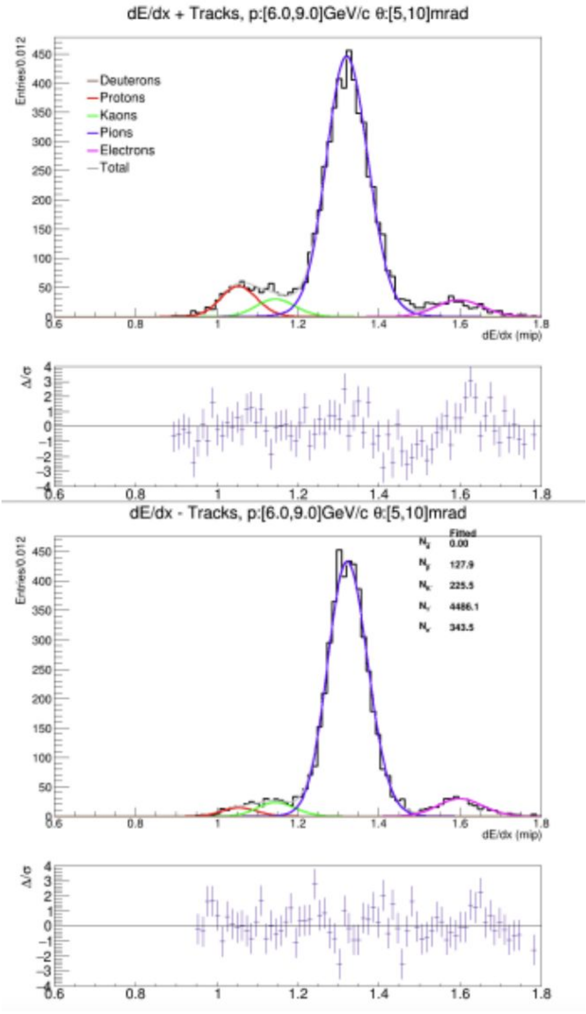
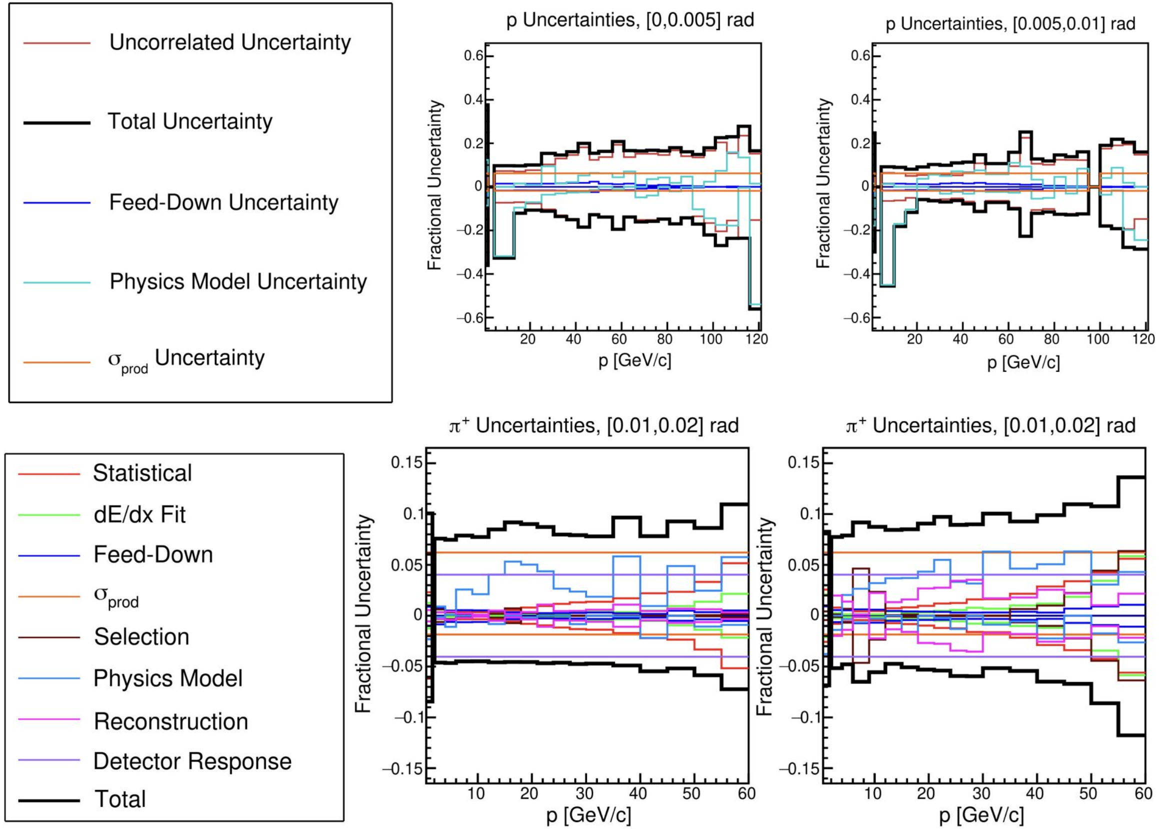
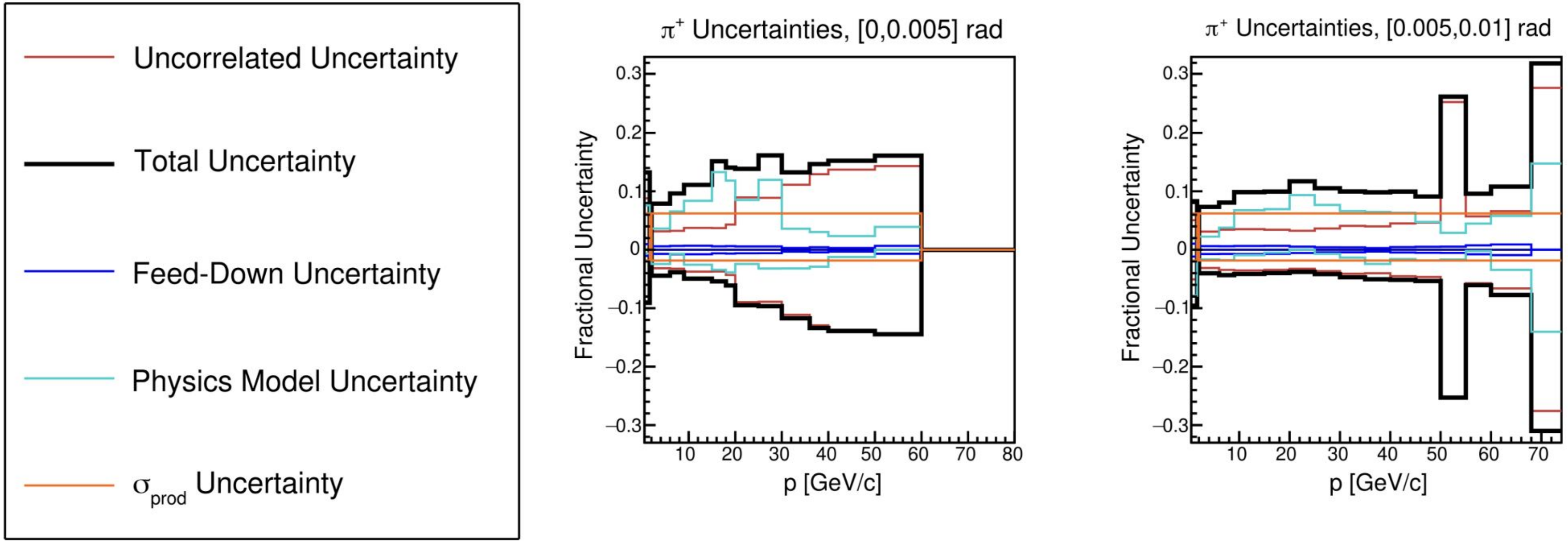


Uncertainty of pC120 Charged Analysis

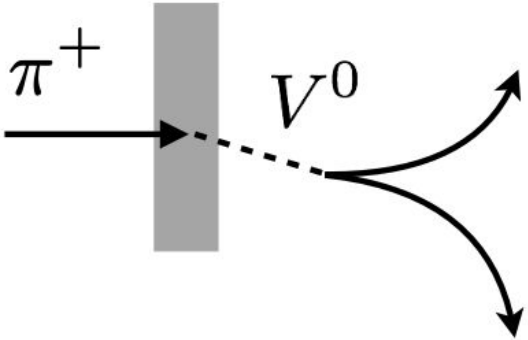


Uncertainty of pC120 Charged Analysis



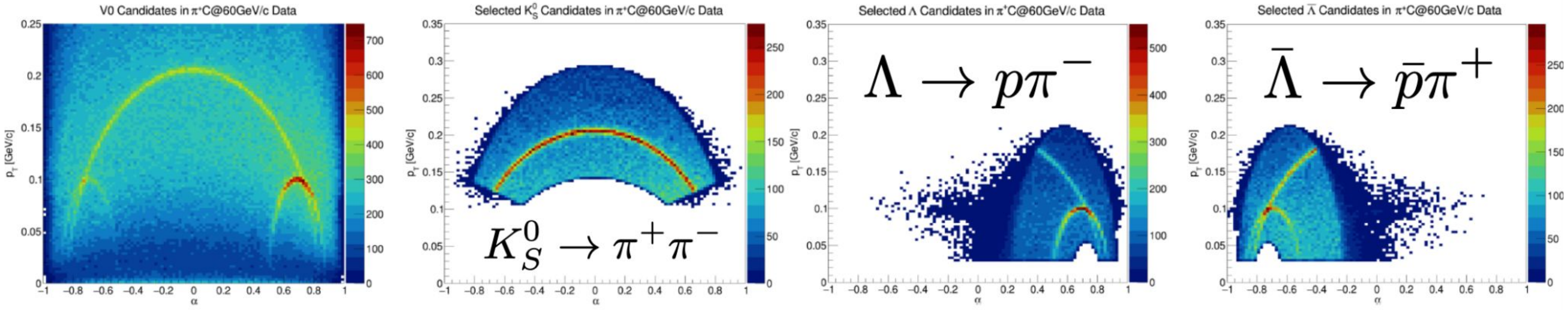
V0 analysis

- Reconstruct collection of V0 candidates using V0 finder & fitter algorithms
- Calculate neutral kinematics using decay product assumption
- Improve purity of V0 sample by applying selection cuts
- Fit invariant mass distributions for signal yield
- Calculate & apply bin-by-bin Monte Carlo corrections
- Calculate multiplicities



V0 analysis

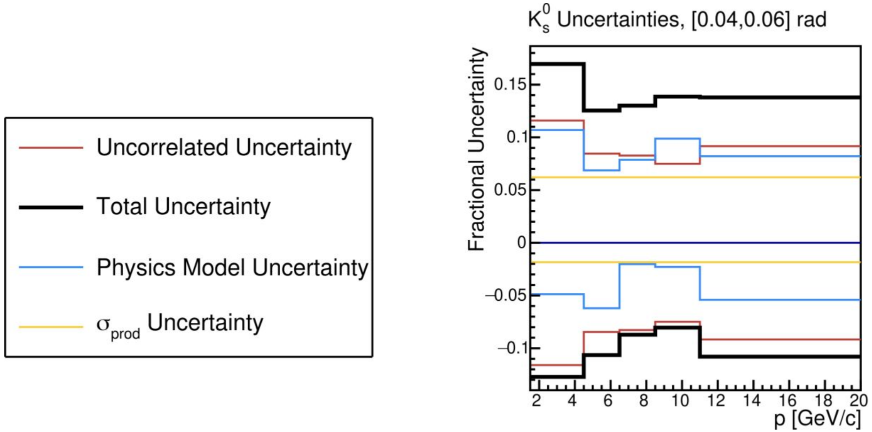
- The Armenteros-Podolansky distribution

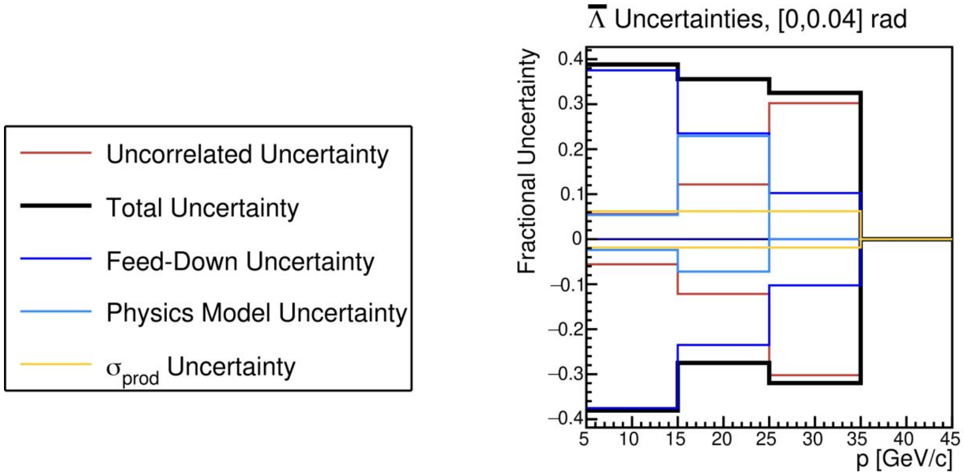


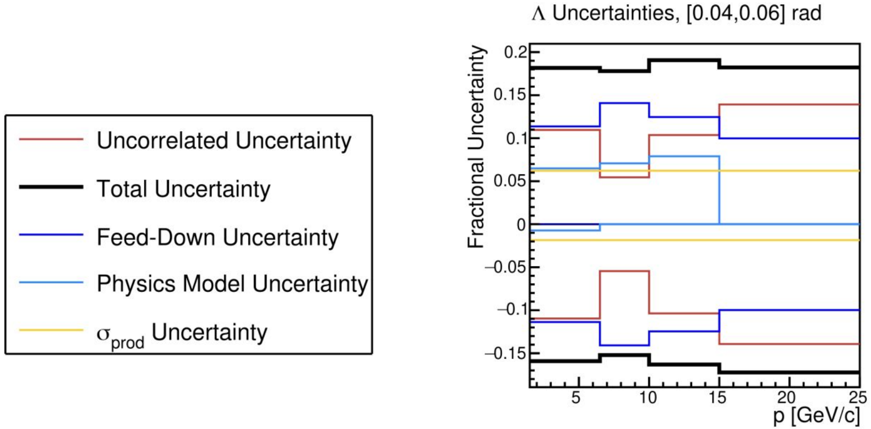
X-axis: $\alpha = \frac{p_L^+ - p_L^-}{p_L^+ + p_L^-}$ (Asymmetry in the longitudinal momenta of the child tracks with respect to the V^0 track)

Y-axis: p_T (Transverse momenta of V^0 track)

Uncertainty of pC120 Neutral Analysis



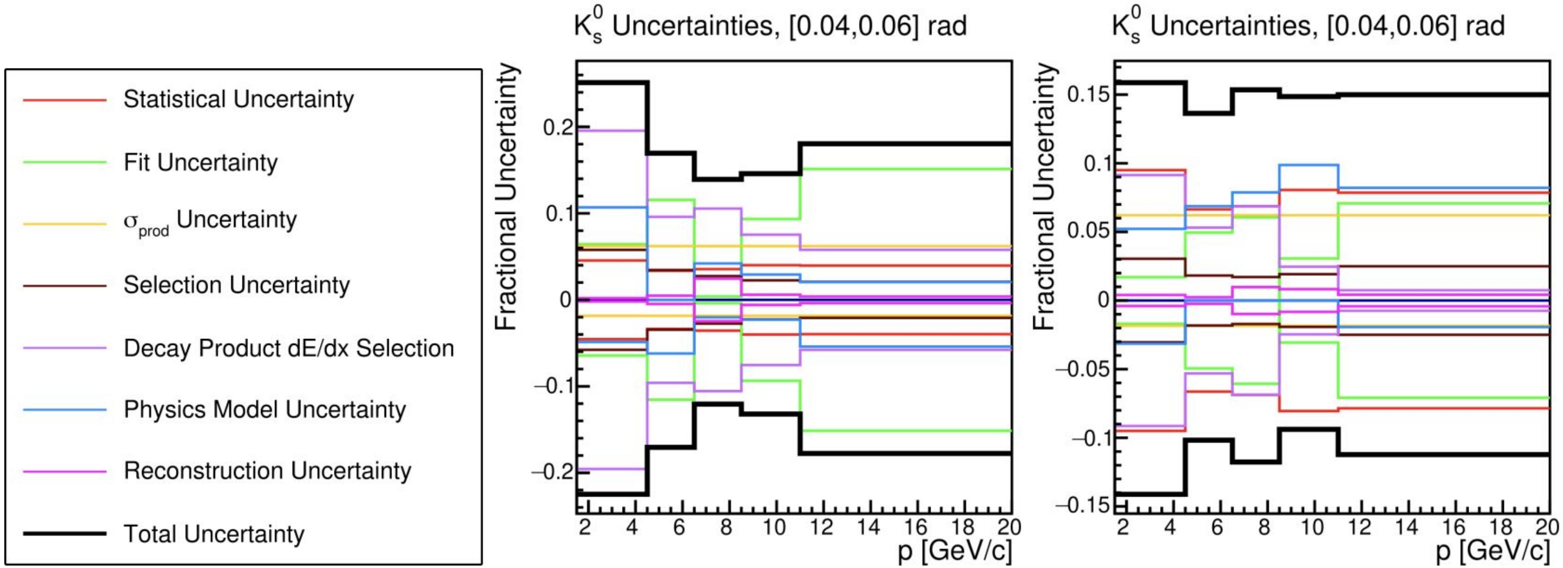




Uncorrelated:
statistical uncertainty, invariant mass fit uncertainty, decay product dE/dx selection uncertainty, reconstruction uncertainty, and V 0 selection uncertainty

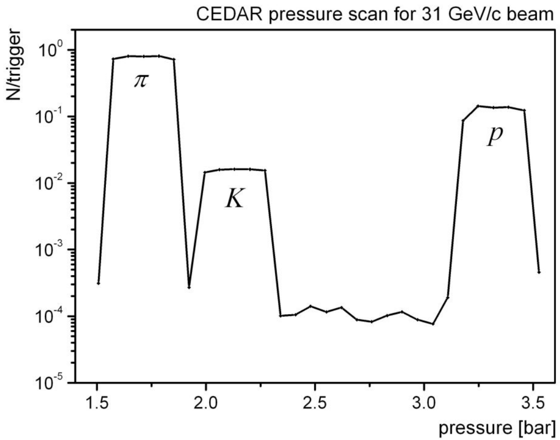
Uncertainty of pC120 Neutral Analysis

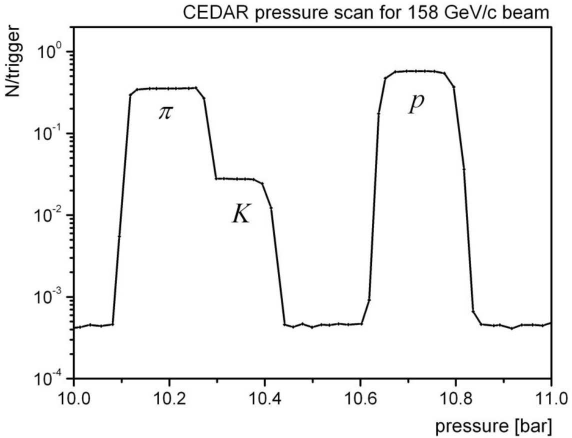
$$m_{\text{combined}} = \frac{\frac{m_1}{\sigma_1^2} + \frac{m_2}{\sigma_2^2}}{\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2}}$$



CEDAR

- Cherenkov Differential Counter with Achromatic Ring Focus (CEDAR) counter
  - Uses a gas as radiator, Helium for beam momenta higher than 60 GeV/c and Nitrogen for lower momenta
  - Sophisticated optical system that collects and focuses the Cherenkov photons onto the plane of a diaphragm whose opening can be tuned
  - For a given gas pressure, such as to allow only the photons from the wanted species to pass through and get detected by the 8 PMTs of the counter





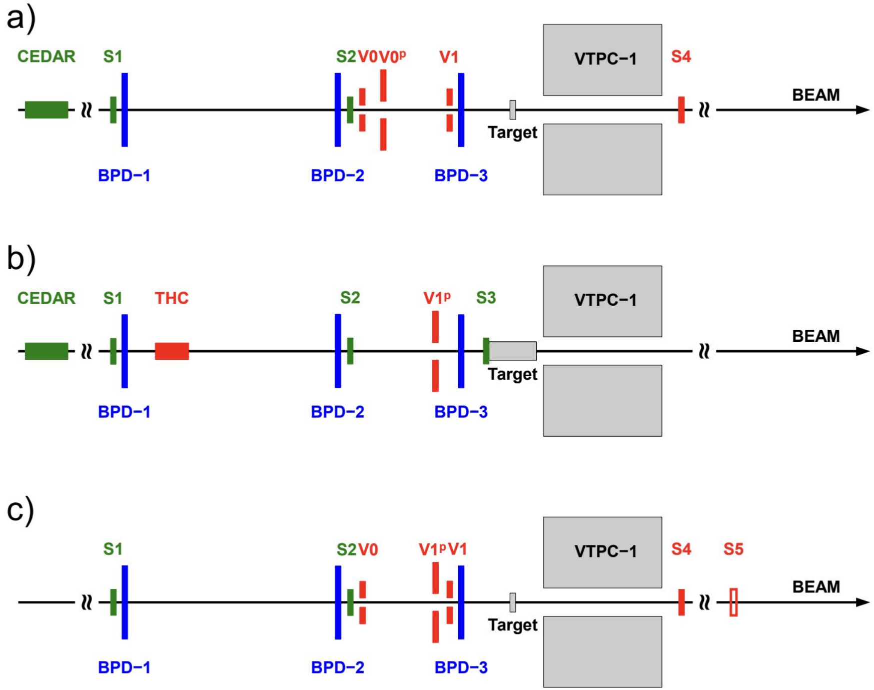
TPCs

	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

Beam Counters

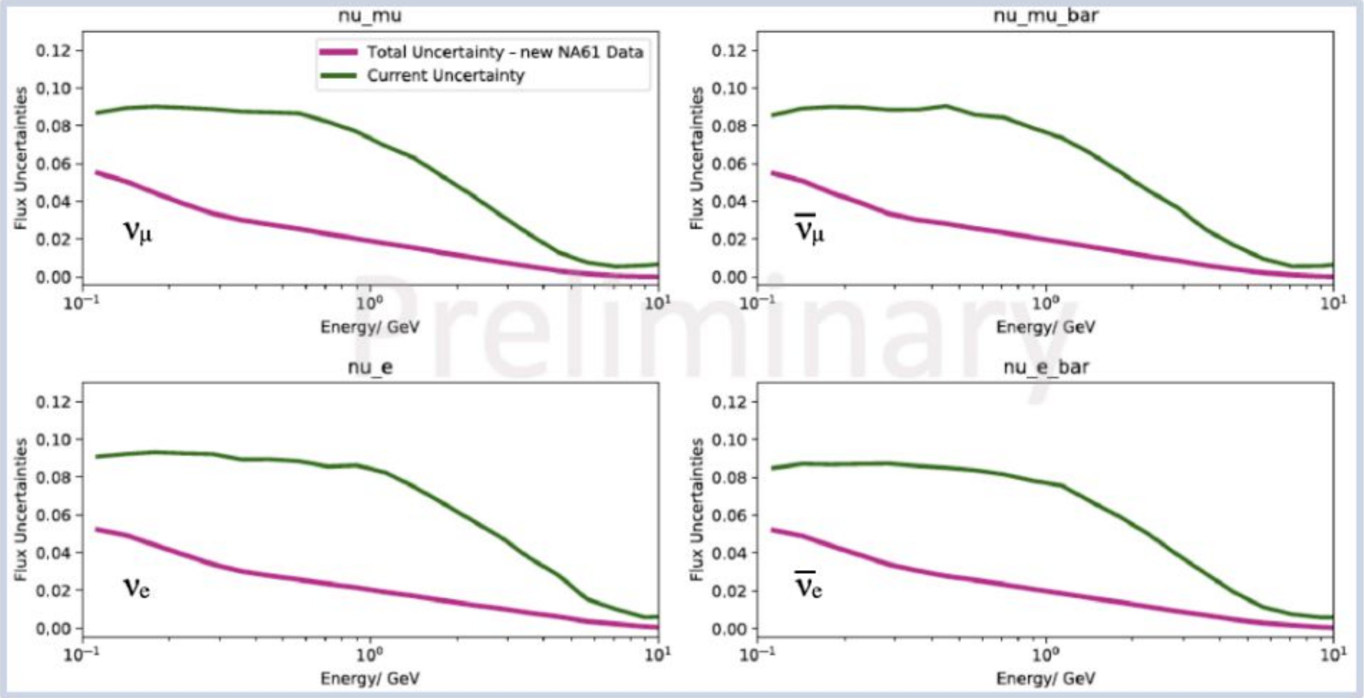
- T1 (identified beam): S1*S2*V1_bar*CED6
- T2 (beam interaction): T1*S4_bar
- T3 (unidentified beam): S1*S2*V1_bar
- T4 (unidentified interaction): T3*S4_bar

detector	dimensions [mm]	hole [mm]	position [m]	material budget $[\%\lambda_I]$	material budget $[\%X_0]$
S1	$60 \times 60 \times 5$		-36.42	0.635	1.175
S2	$\phi = 28 \times 2$		-14.42	0.254	0.470
S3	$\phi = 26 \times 5$		-6.58	0.635	1.175
S4	$\phi = 20 \times 5$		-2.11	0.635	1.175
S5	$\phi = 20 \times 5$		9.80	0.635	1.175
V0	$\phi = 80 \times 10$	$\phi = 10$	-14.16		
$V0^p$	$300 \times 300 \times 10$	$\phi = 20$	$\approx$ -14		
V1	$100 \times 100 \times 10$	$\phi = 8$	-6.72		
$V1^p$	$300 \times 300 \times 10$	$\phi = 20$	-6.74		
A	$150 \times 5 \times 15$		$\approx$ -146	1.904	3.526
Z	$160 \times 40 \times 2.5$		-13.81	0.562	2.034
BPD-1	$48 \times 48 \times 32.6$		-36.20	0.025	0.070
BPD-2	$48 \times 48 \times 32.6$		-14.90	0.025	0.070
BPD-3	$48 \times 48 \times 32.6$		-6.70	0.025	0.070
Typical thin target position			-5.81		



Atmospheric neutrino

if we have data for lower energy $\mathrm{p} + \mathrm{N} \rightarrow \pi^{\pm} + X$ interactions (down to a few GeV)



SPSC-M-793
(Plots by L. Cook)