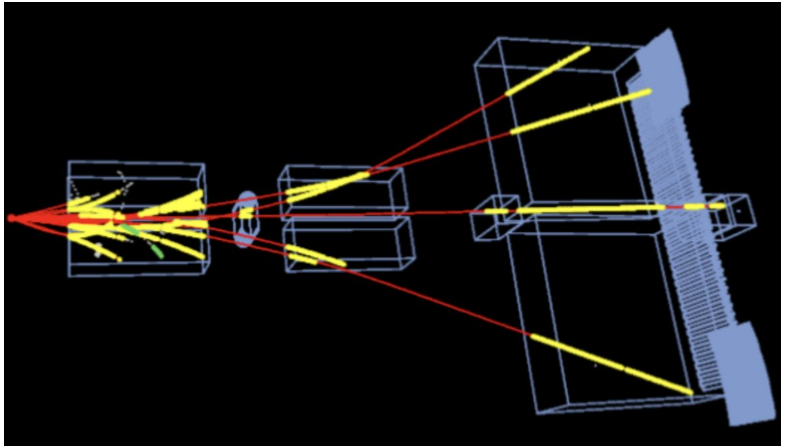
NA61/SHINE Hadron Production Measurements for Long-baseline Neutrino Beams



UNIVERSITY OF NOTRE DAME

Dominic Battaglia

New Perspectives 2023

FERMILAB-SLIDES-23-112-V

SHINE NA61

Overview

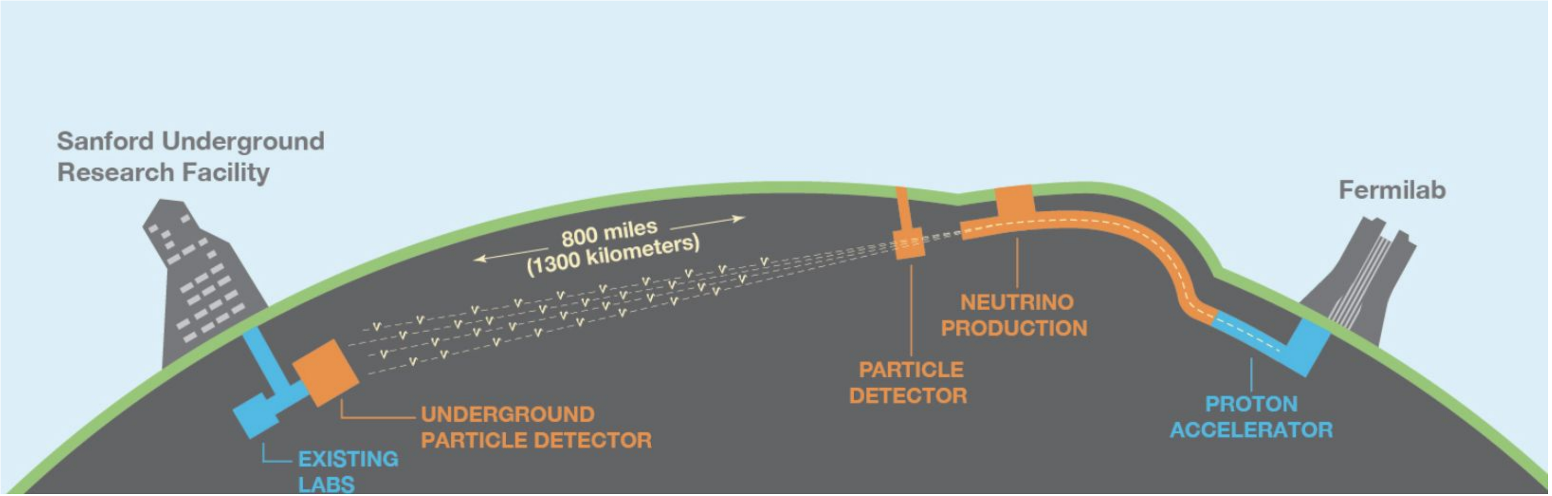
I. Long-baseline Neutrino Experiments

II. NA61/SHINE

III. Recent Thin Target Results

IV. Numi Target Analysis

Long-Baseline Neutrino Experiments



https://www.dunescience.org/

Neutrino beam created (in this instance at Fermilab)

Neutrino beam measured at near detector

Another detector placed large distance away to measure neutrino oscillations

Current & Future Experiments: NOvA, T2K, Hyper-K, DUNE

Neutrino Flux Measurement Uncertainty

Largest source of flux uncertainty results from Hadron Production (HP) uncertainty: Uncertainty of the number of hadrons that are produced from the Proton-Target interaction

Long-baseline neutrino oscillation physics potential of the DUNE experiment

DUNE Collaboration: B. Abi, R. Acciarri, M. A. Acero, G. Adamov, D. Adams, M. Adinolfi, Z. Ahmad, J. Ahmed, T. Alion, S. Alonso Monsalve, C. Alt, J. Anderson, C. Andreopoulos, M. P. Andrews, F. Andrianala, S. Andringa, A. Ankowski, M. Antonova, S. Antusch, A. Aranda-Fernandez, A. Ariga, L. O. Arnold, M. A. Arroyave, J. Asaadi, A. Aurisano, V. Aushev, D. Autiero, F. Azfar, H. Back, J. J. Back, C. Backhouse, P. Baesso, L. Bagby, R. Bajou, S. Balasubramanian, P. Baldi, B. Bambah, F. Barao, G. Barenboim, G. J. Barker, W. Barkhouse, C. Barnes, G. Barr, J. Barranco Monarca, N. Barros, J. L. Barrow, A. Bashyal, V. Basque, F. Bay, J. L. Bazo Alba, J. F. Beacom, E. Bechetoille, B. Behera, L. Bellantoni, G. Bellettini, V. Bellini, O. Beltramello, D. Belver, N. Benekos, F. Bento Neves, J. Berger, S. Berkman, P. Bernardini, R. M. Berner, H. Berns, S. Bertolucci, M. Betancourt, Y. Bezawada, M. Bhattacharjee, B. Bhuyan, S. Biagi, J. Bian, M. Biassoni, K. Biery, B. Bilki, M. Bishai, A. Bitadze, A. Blake, B. Blanco Siffert, F. D. M. Blaszczyk, G. C. Blazey, E. Blucher, J. Boissevain, S. Bolognesi, T. Bolton, M. Bonesini, M. Bongrand, F. Bonini, A. Booth, C. Booth, S. Bordoni, A. Borkum, T. Boschi, N. Bostan, P. Bour, S. B. Boyd, D. Boyden, J. Bracinik, D. Braga et al. (874 additional authors not shown)

ure 4. The largest principal component (component 0) matches the hadron production uncertainty on nucleon-nucleus interactions in a phase space region not covered

arXiv:2006.16043 **[hep-ex]**

The T2K Neutrino Flux Prediction

T2K Collaboration, K. Abe, N. Abgrall, H. Aihara, T. Akiri, J. B. Albert, C. Andreopoulos, S. Aoki, A. Ariga, T. Ariga, S. Assylbekov, D. Autiero, M. Barbi, G. J. Barker, G. Barr, M. Bass, M. Batkiewicz, F. Bay, S. W. Bentham, V. Berardi, B. E. Berger, S. Berkman, I. Bertram, D. Beznosko, S. Bhadra, F. d. M. Blaszczyk, A. Blondel, C. Bojechko, S. Boyd, A. Bravar, C. Bronner, D. G. Brook-Roberge, N. Buchanan, R. G. Calland, J. Caravaca Rodriguez, S. L. Cartwright, R. Castillo, M. G. Catanesi, A. Cervera, D. Cherdack, G. Christodoulou, A. Clifton, J. Coleman, S. J. Coleman, G. Collazuol, K. Connolly, A. Curioni, A. Dabrowska, I. Danko, R. Das, S. Davis, M. Day, J. P. A. M. de Andre, P. de Perio, G. De Rosa, T. Dealtry, C. Densham, F. Di Lodovico, S. Di Luise, J. Dobson, T. Duboyski, F. Dufour, J. Dumarchez, S. Dytman, M. Dziewiecki, M. Dziomba, S. Emery, A. Ereditato, L. Escudero, L. S. Esposito, A. J. Finch, E. Frank, M. Friend, Y. Fujii, Y. Fukuda, V. Galymov, A. Gaudin, S. Giffin, C. Giganti, K. Gilje, T. Golan, J. J. Gomez-Cadenas, M. Gonin, N. Grant, D. Gudin, P. Guzowski, D. R. Hadley, A. Haesler, M. D. Haigh, D. Hansen, T. Hara, M. Hartz, T. Hasegawa, N. C. Hastings, Y. Hayato, C. Hearty, R. L. Helmer, J. Hignight, A. Hillairet, A. Himmel et al. (252 additional authors not shown)

experiments [1–4]. However, it is difficult to simulate the flux precisely due to uncertainties in the underlying physical processes, particularly hadron production in proton-nucleus interactions. To reduce flux-related

arXiv:1211.0469 **[hep-ex]**

Measurement of Neutrino Flux from Neutrino-Electron Elastic Scattering

MINERvA Collaboration: J. Park, L. Aliaga, O. Altinok, L. Bellantoni, A. Bercellie, M. Betancourt, A. Bodek, A. Bravar, H. Budd, T. Cai, M.F. Carneiro, M.E. Christy, J. Chvojka, H. da Motta, S.A. Dytman, G.A. Diaz, B. Eberly, J. Felix, L. Fields, R. Fine, A.M. Gago, R.Galindo, A. Ghosh, T. Golan, R. Gran, D.A. Harris, A. Higuera, J. Kleykamp, M. Kordosky, T. Le, E. Maher, S. Manly, W.A. Mann, C.M. Marshall, D.A. Martinez Caicedo, K.S. McFarland, C.L. McGivern, A.M. McGowan, B. Messerly, J. Miller, A. Mislivec, J.G. Morfin, J. Mousseau, D. Naples, J.K. Nelson, A. Norrick, Nuruzzaman, J. Osta, V. Paolone, C.E. Patrick, G.N. Perdue, L. Rakotondravohitra, M.A. Ramirez, H. Ray, L. Ren, D. Rimal, P.A. Rodrigues, D. Ruterbories, H. Schellman, C.J. Solano Salinas, N. Tagg, B.G. Tice, E. Valencia, T. Walton, J. Wolcott, M.Wospakrik, G. Zavala, D. Zhang

is precisely known. Consequently a measurement of this process in an accelerator-based ν_μ beam can improve the knowledge of the absolute neutrino flux impinging upon the detector; typically this knowledge is limited to $\sim 10\%$ due to uncertainties in hadron production and focusing. We

arXiv:1512.07699 **[physics.ins-det]**

Neutrino Beam Flux Uncertainty

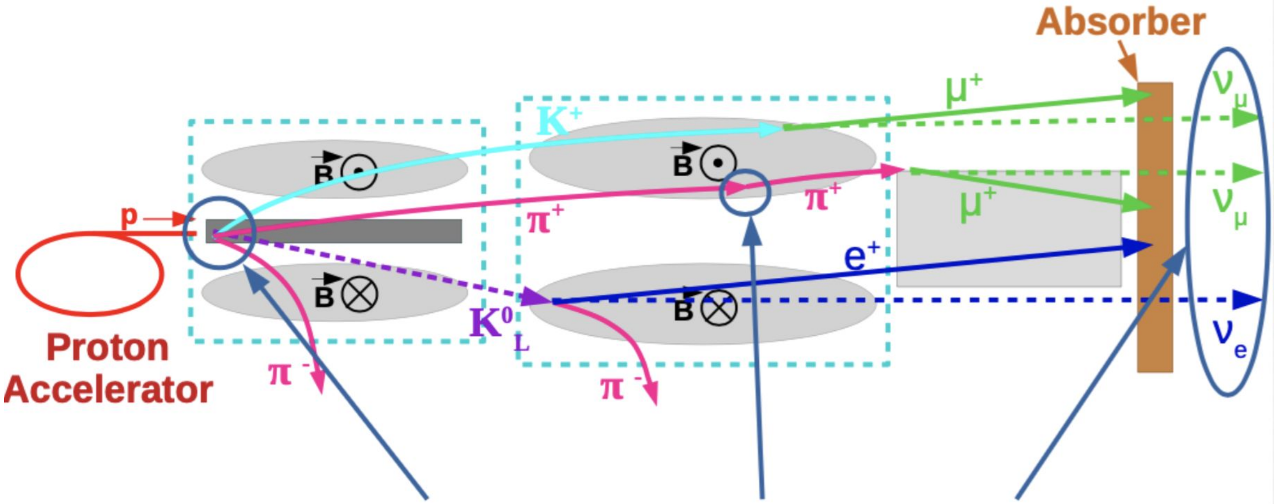


Image thanks to
Brant Rumberger

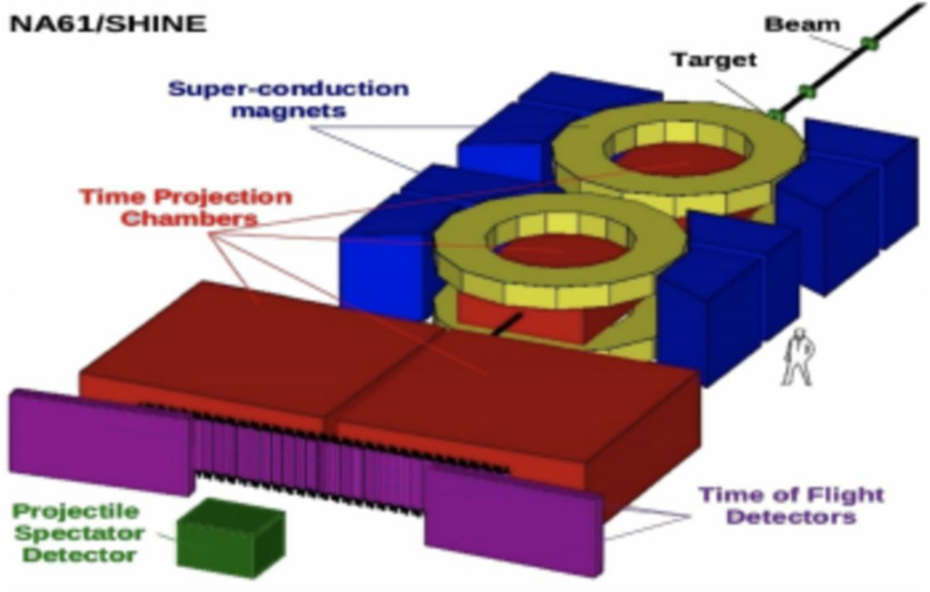
Neutrino beam depends on primary and secondary hadrons produced in the beamline!

Mesons produced through strong interactions which can't be predicted precisely

NA61/SHINE

Experiment located at the North Area of CERN

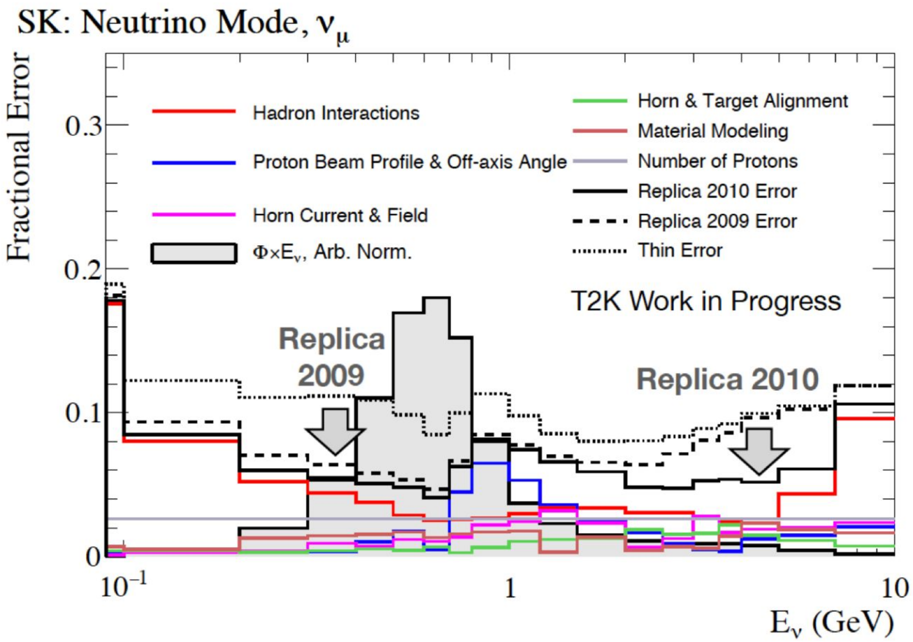
SHINE: SPS Heavy Ion and Neutrino Experiment



NA61/SHINE Replica Target Measurements for T2K

Provides external hadron production measurements for neutrino experiments

Example: T2K Replica target reduced its uncertainty via NA61



Lukas Berns (NBI 2019)

How does NA61 make these measurements?

1. Replicate hadron beam on target of interest

2. Trigger on events from correct interactions
   a. Ensure beam particle of correct type
   b. Identify that the particle interacted within target

3. Reconstruct particle tracks

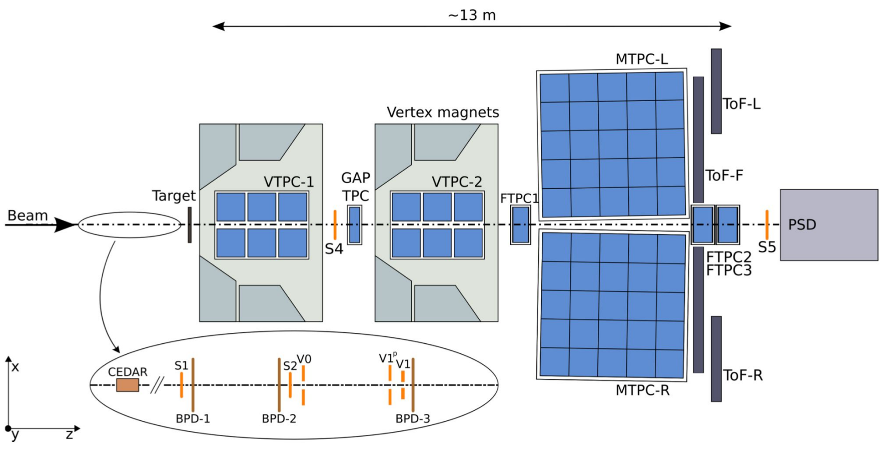
4. Identify hadrons in the reconstructed track

Reconstruct Particle Tracks

Time Projection Chambers (TPCs)

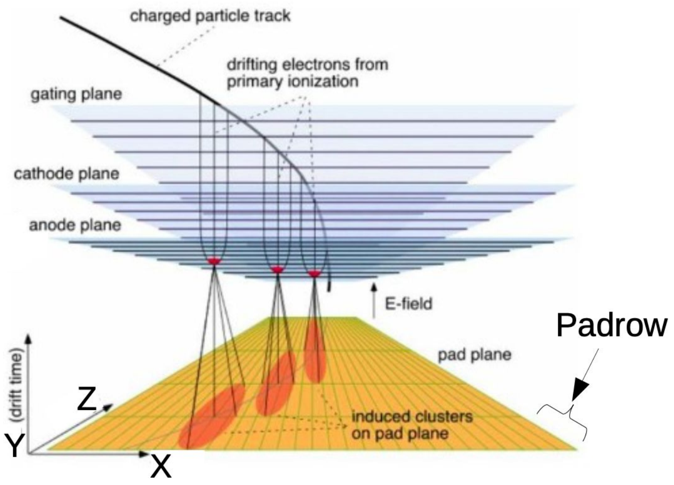
Incoming particles ionize gas volume→ electrons drift toward readout plane due to E-field where they induce charge on the pads

NA61 Detector Setup (Top View)



arXiv:2306.02961 **[hep-ex]**

Example of TPC track readout



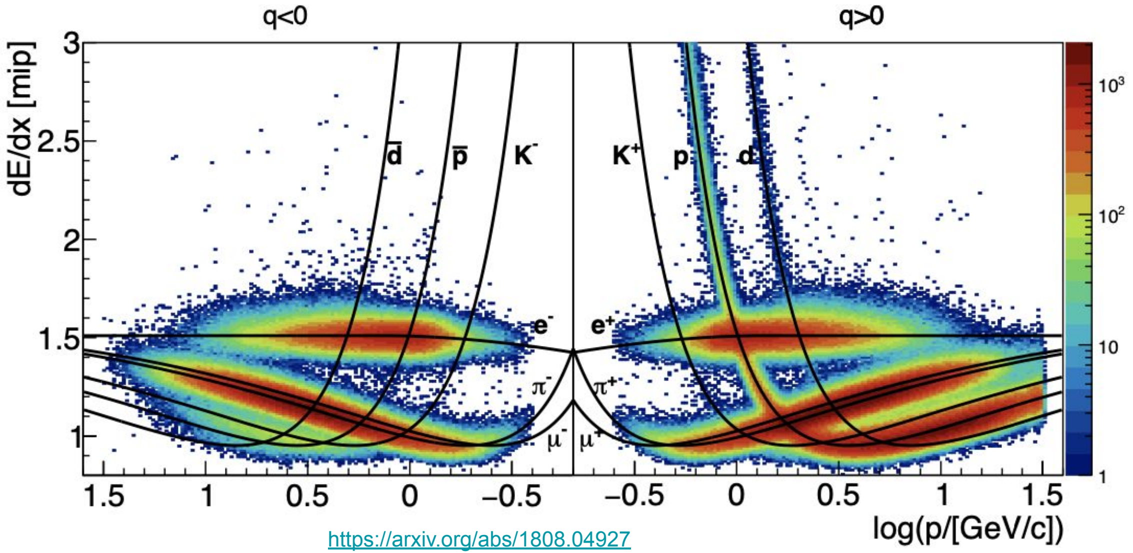
Particle Identification

VTPCs: Give particle charge

VTPCs + MTCPs: Give dE/dx & particle path

These give energy deposition vs momentum (Bethe-Bloch curve) →Particle ID

Bethe-Bloch Function overlaid on T2K Replica Target specific energy loss in the TPCs



https://arxiv.org/abs/1808.04927

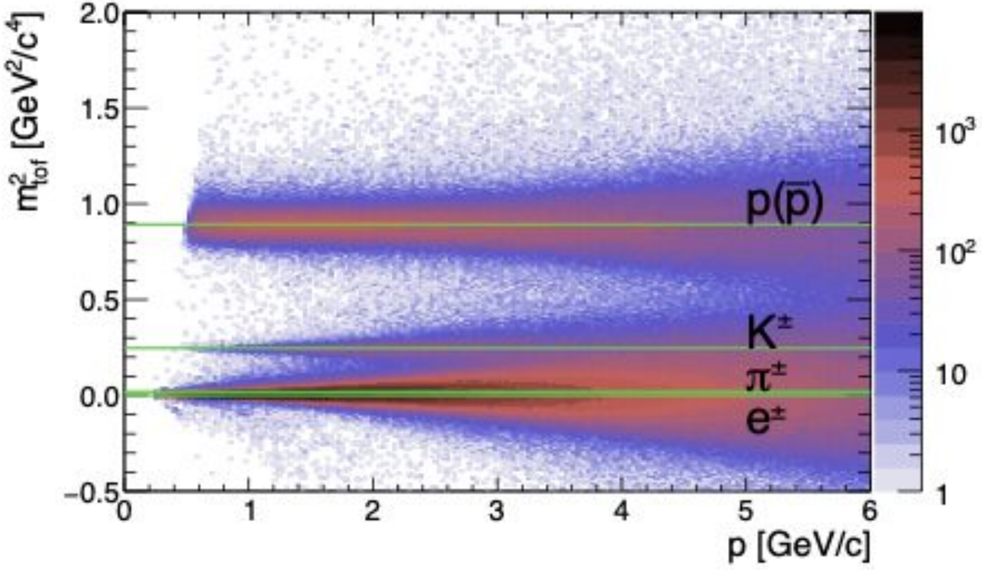
Time-of-Flight (ToF) Wall

Some particle species regions of Bethe-Bloch crossover→Use ToF

Scintillator, measures time

Using track info from MTPCs/VTPCs, we can identify particle type using ToF

$$m_{tof}^2 = \left(\frac{p}{c}\right)^2 \left[\frac{c^2 tof^2}{l^2} - 1\right]$$



Recent Thin Target Results

120 GeV/c protons on thin carbon target

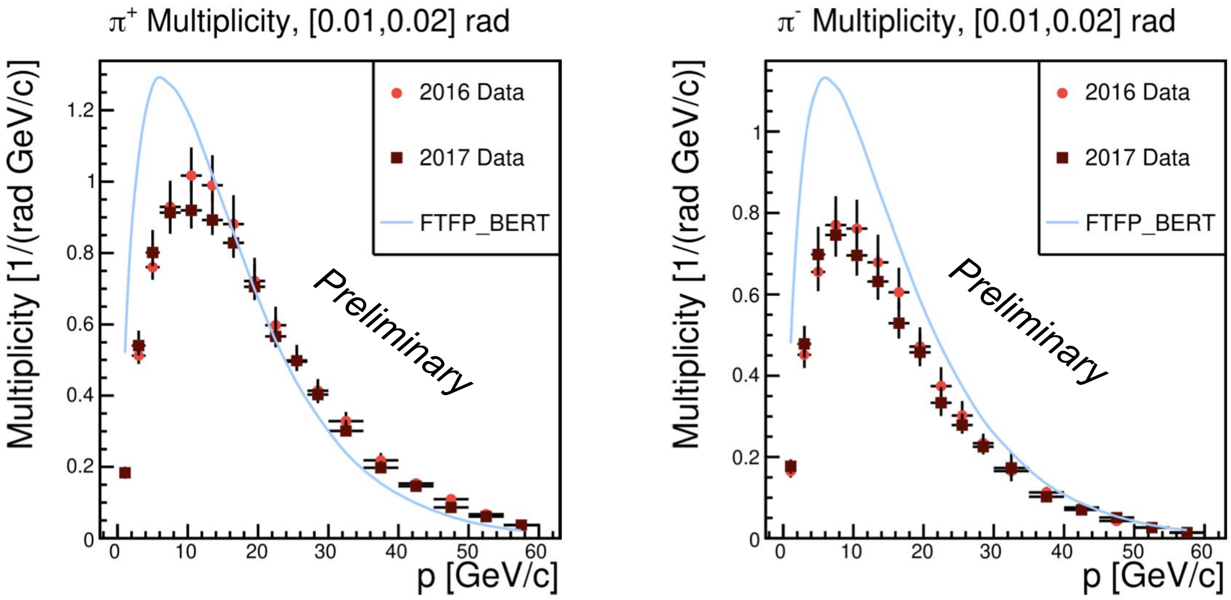
Double differential multiplicity of produced pions (comparing 2016 & 2017 runs)

$$\frac{d^2 n_i}{dp d\theta} = \frac{y_i}{N_{\mathrm{prod}} \Delta p \Delta \theta}$$

Extract production cross section to weight MC

Also have neutral hadron production analysis publication:

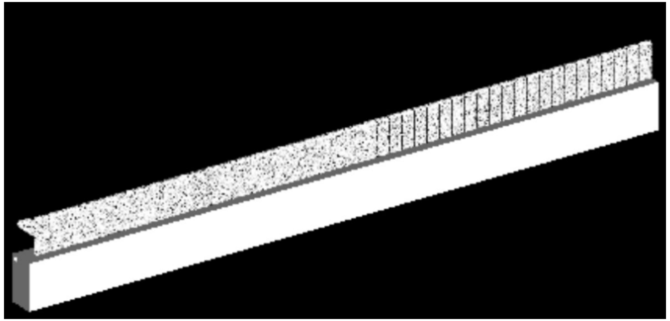
Phys. Rev. D **107**, 072004



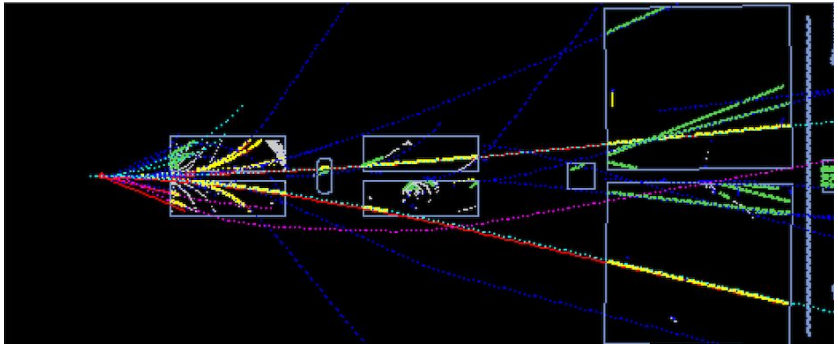
arXiv:2306.02961

Upcoming NuMI Replica Target Analysis & Future Measurements

2018 NuMI Replica Target Geometry imported into software framework



Streamline calibration and analysis process for long targets to be applied to LBNF Replica target data in 2024



Right: Reconstructed Monte Carlo event display using above replica target geometry

Summary

Hadron production uncertainty limits our neutrino flux measurement uncertainty

NA61/SHINE provides external hadron measurements

Recent proton-Carbon @ 120 GeV on thin target measurements were shown

Future Results: 2018 NuMI Replica target results (currently being analyzed) & LBNF Replica target data taking to come