NEUTRINO FLUX AND HADRON PRODUCTION

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Neutrino flux and hadron production

- Why is neutrino flux important?
- Strategies for constraining hadron production
- Experiments doing hadron production now
- Future prospects

Why is neutrino flux important?

- Neutrino flux is generally modeled poorly by Monte Carlo packages
- Neutrino oscillation measurements (even with near detectors) depend on understanding the neutrino source:
  - Only partial cancellation of flux errors in long-baseline near/far ratios
  - Neutrino oscillation measurements depend on precise understanding of neutrino interaction cross-sections
  - No near/far cancellation in neutrino cross-section measurements, which are essential for oscillation measurement precision

Hadron production measurement strategy

- *In situ* measurements
  - Measurements in the decay region
    - Hadron monitors in the decay region (hard)
    - Meson decay product detection in the decay region (very hard!)
  - Muon measurements downstream of hadron absorber (measurements are feasible, interpretation is difficult)
- *Ex situ* measurements
  - Thin-target measurements for precise measurement of production cross-sections
  - Replica targets for constraints on entire primary/secondary interaction chain

In-situ measurements

- Muon measurements
  - Mostly used for stability monitoring
  - Very limited ability to constrain neutrino flux
- Other measurements in beamline
  - Pion monitors in the decay region (hard)
  - Meson decay product detection in the decay region (very hard!)
    - ENUBET: proposed sign-selected neutrino beam with fully instrumented decay region.
    - See Andrea Longhin's talk tomorrow

Ex-situ measurements

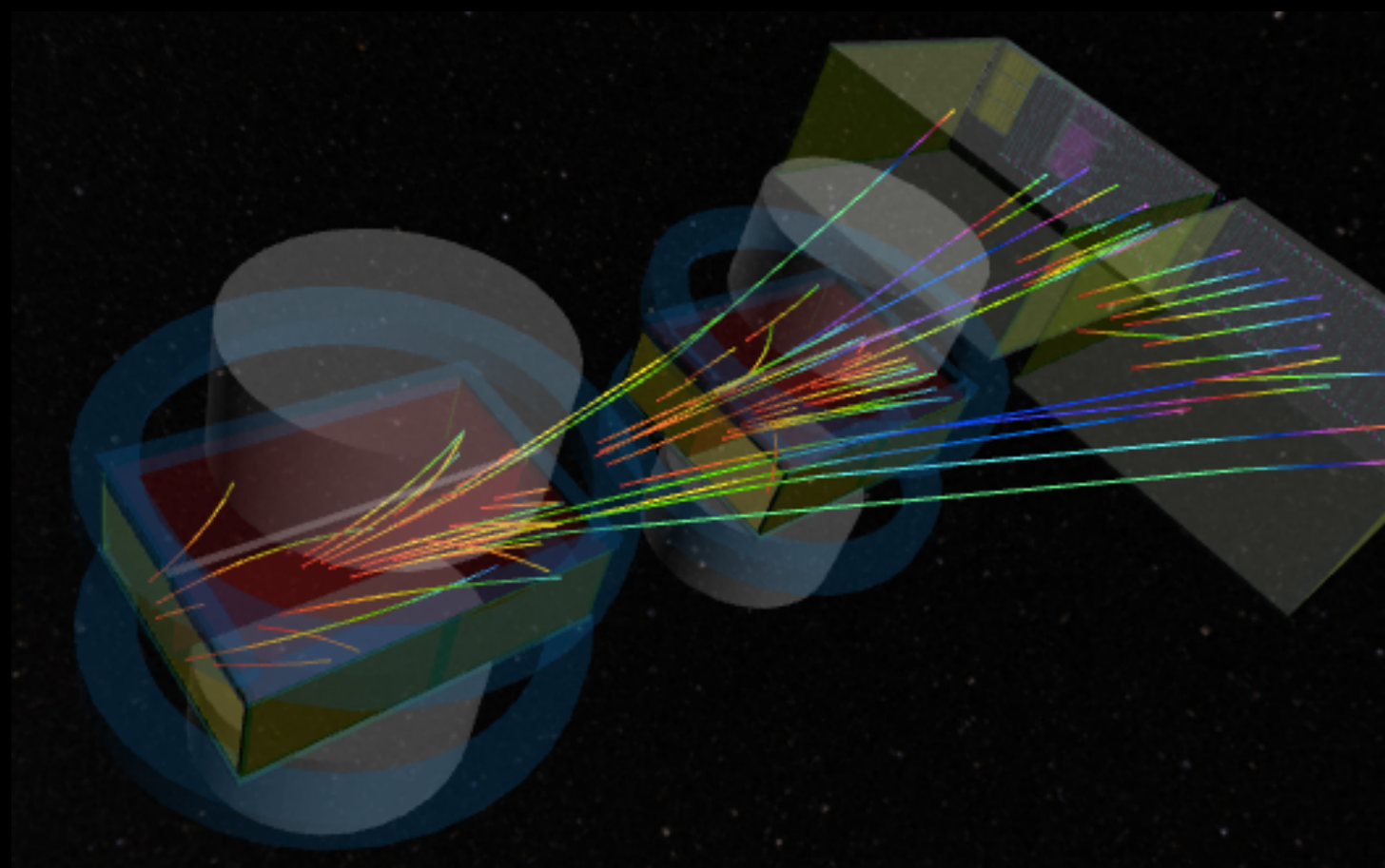
- Thin-target measurements for precise measurement of production cross-sections
- Replica targets for constraints on entire primary/secondary interaction chain
- Generally, these measurements need:
  - **Well-tagged beam with many particle types and wide momentum range available**
  - **Large-acceptance spectrometer with good particle ID**
  - **Ability to accommodate a variety of long and short targets**

Ex-situ measurements

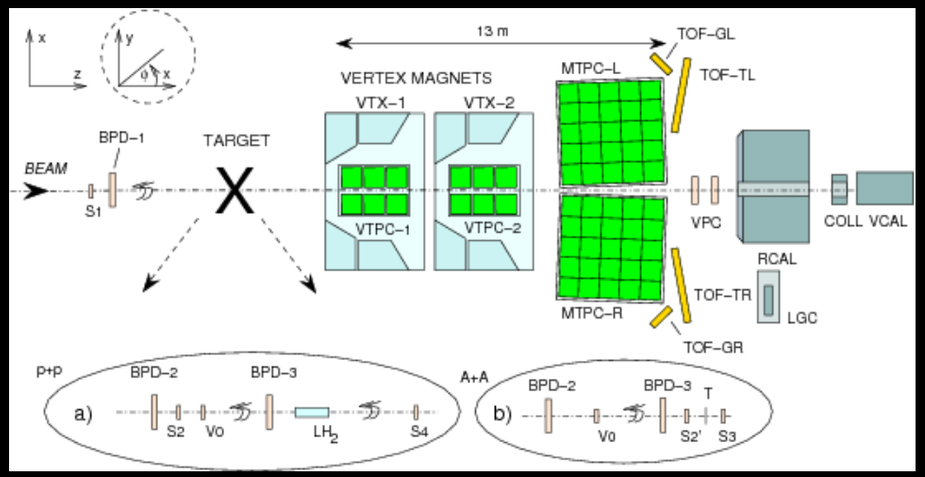
- History
  - CERN NA49: 158 GeV/*c* *p*+C measurements, used for NuMI with momentum scaling
  - E907/MIPP: some data for NuMI
  - HARP (CERN PS) and E910 (BNL): used for Booster Neutrino Beam, K2K
  - Single-arm spectrometers
    - Several measurements from 1970s/80s still useful for some low-momentum and secondary processes
- Present and future
  - NA61/SHINE
  - EMPHATIC

NA61: The SPS Heavy Ion and Neutrino Experiment

- Fixed-target experiment using H2 beam at CERN SPS
- ~150 collaborators. Spokespeople: Marek Gazdzicki, EDZ (deputy)
- Designed around the former NA49 heavy-ion spectrometer
- Primary proton beam from CERN SPS, Secondary beams ~25 to 350 GeV/*c*
- Diverse physics program includes
  - ✦heavy ion physics
  - ✦hadron production for neutrino beams
  - ✦cosmic ray production

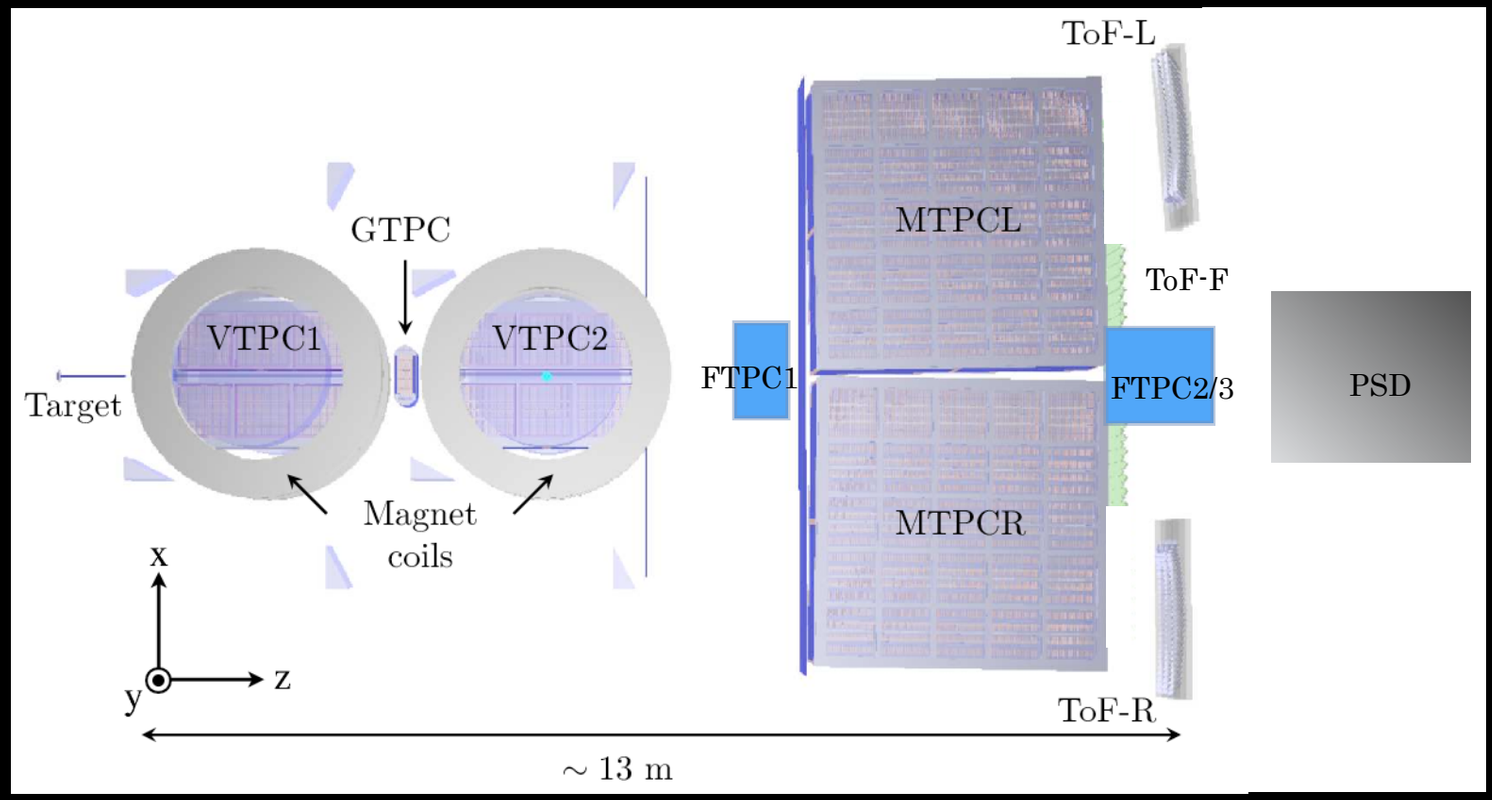


NA61 detector system



NA49

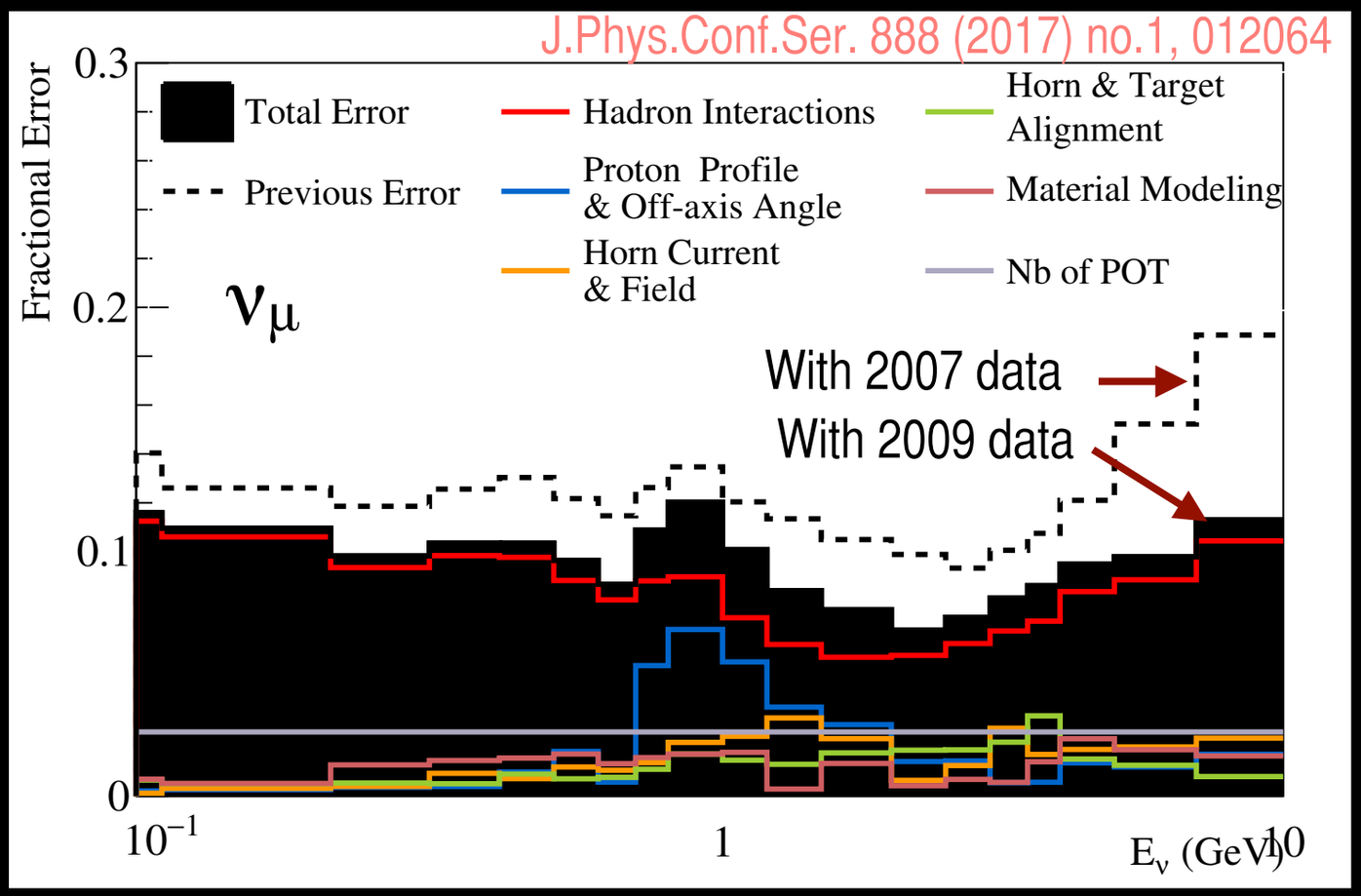
NA61



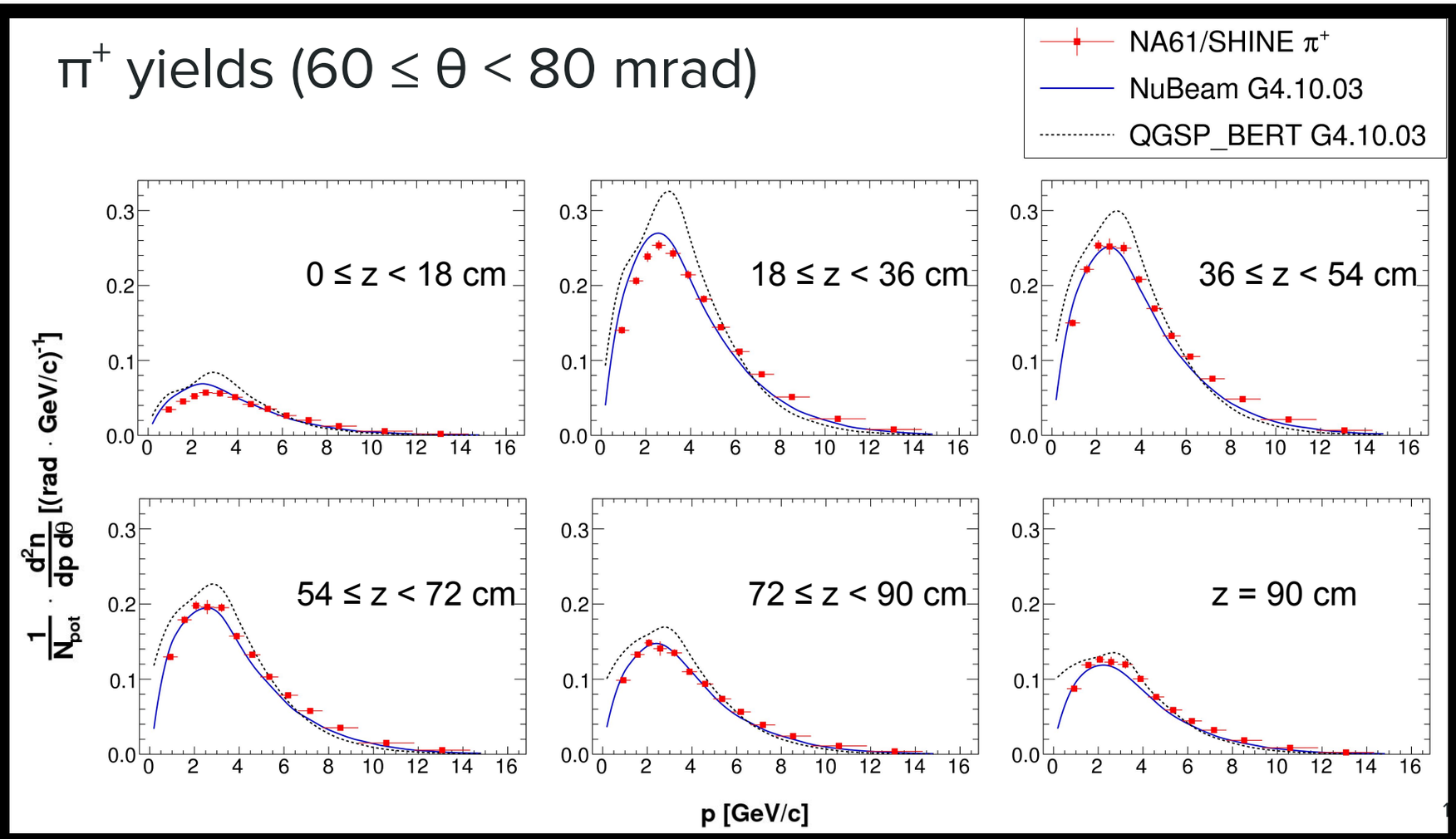
- Detailed beam instrumentation including PID and tracking before the target
- Several large-acceptance TPCs, two superconducting analysis magnets
- Scintillator-based time-of-flight detectors
- Projectile Spectator Detector: forward hadron calorimeter

Neutrino-related accomplishments from NA61's first phase

- NA61/SHINE took thin and thick target data with 31 GeV/*c* protons specifically for T2K in **2007**, **2009**, and **2010**.
- T2K flux prediction (described in Phys.Rev. D87 (2013) no.1, 012001 and J.Phys.Conf.Ser. 888 (2017) no.1, 012064) currently uses thin target data, and incorporation of thick target data is in progress



Recent result: full yields from T2K replica target



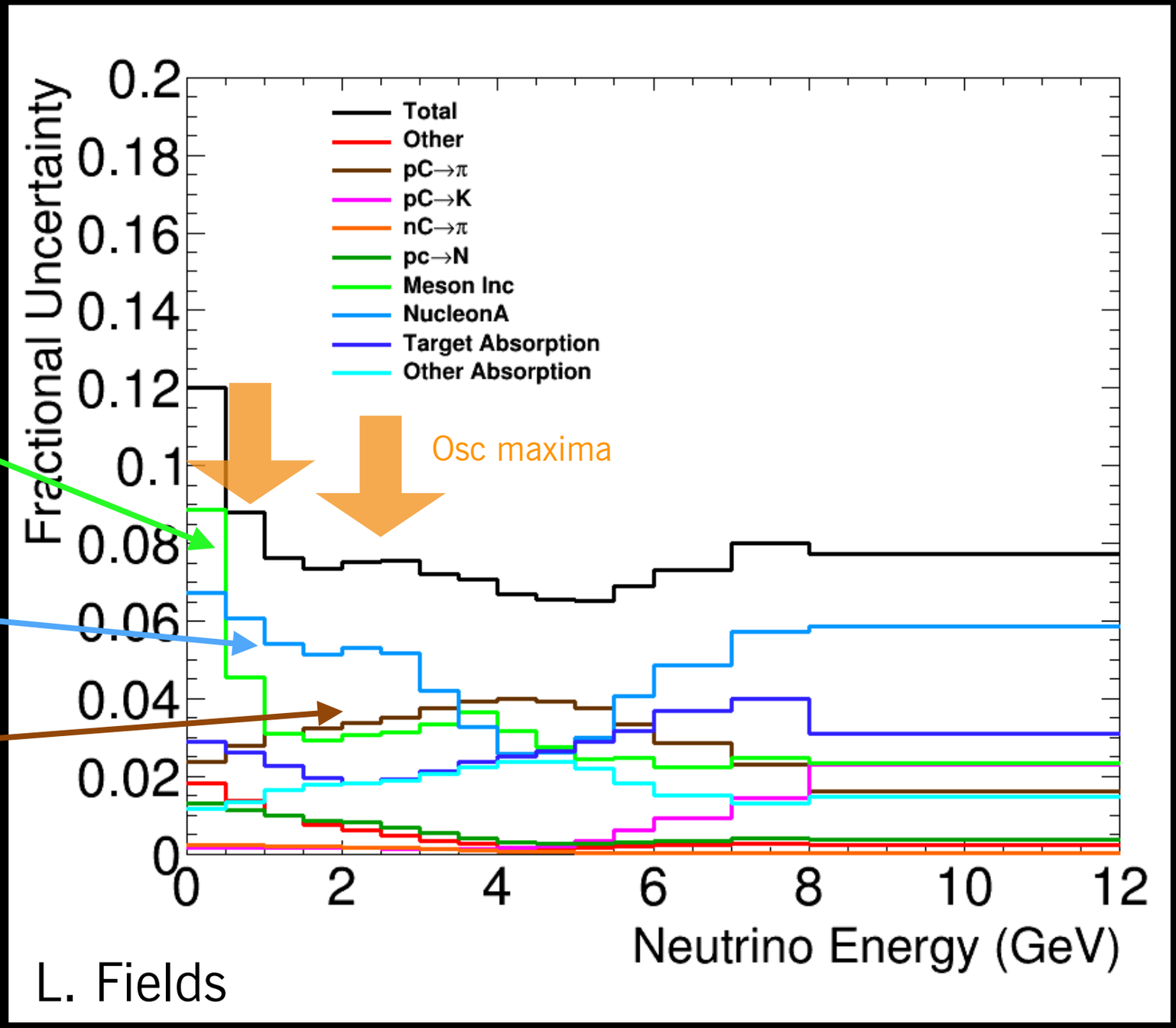
- e-Print: arXiv:1808.04927
- Showing π^+ for illustration. Also have π^-, $K^\pm$, p yields
- One more analysis (high magnetic field run) in progress

A second phase of NA61 neutrino measurements

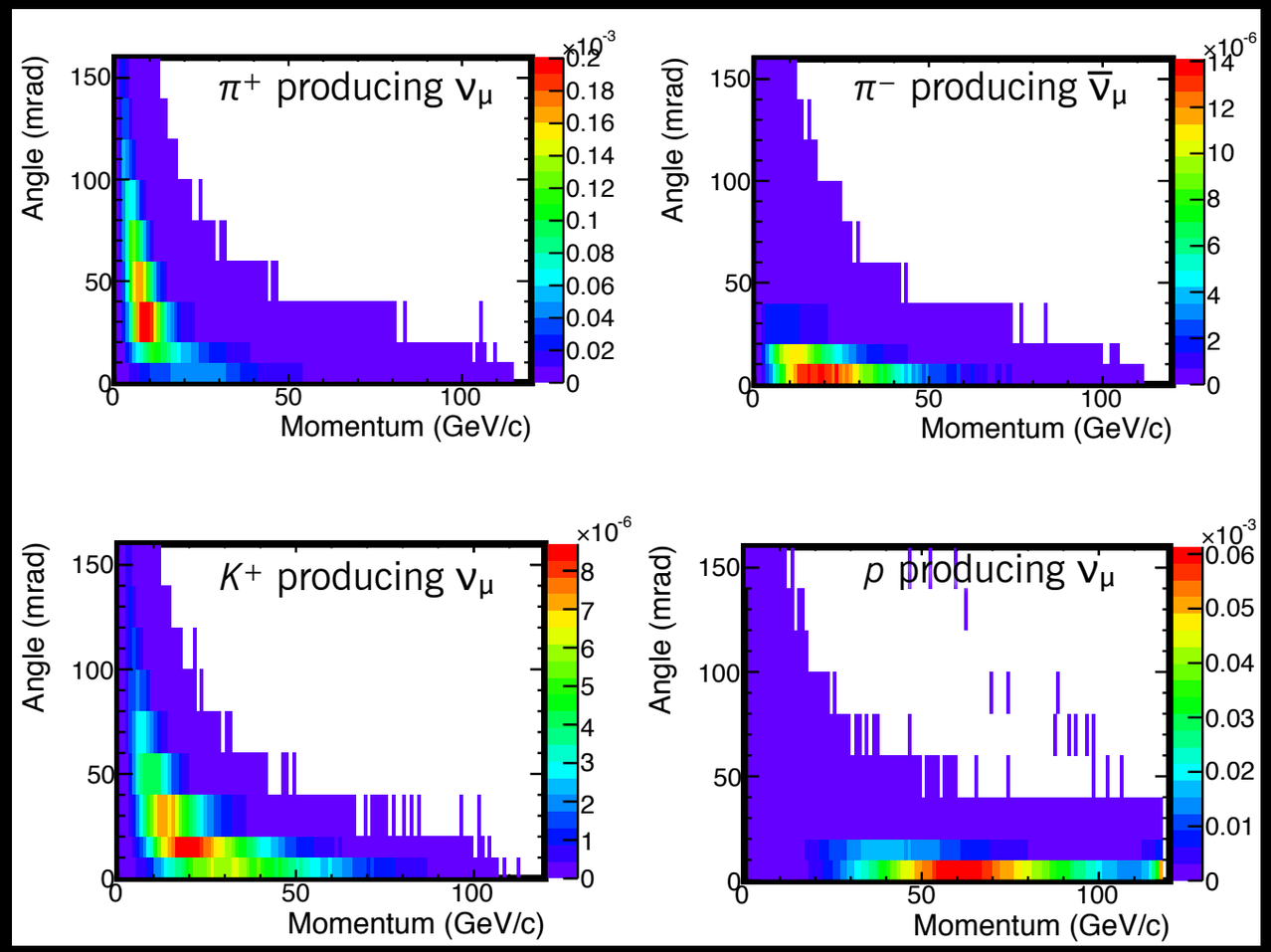
- Four US-based groups joined NA61 in 2014 to make measurements specifically for the FNAL-based neutrino program.
- Motivation: new coverage will be needed for DUNE, can help NuMI as well in shorter term
- US-funded project made specific upgrades:
  - Forward tracking system
  - DRS4-based readout for TOF systems
- Data collection in 2015-18 for this program

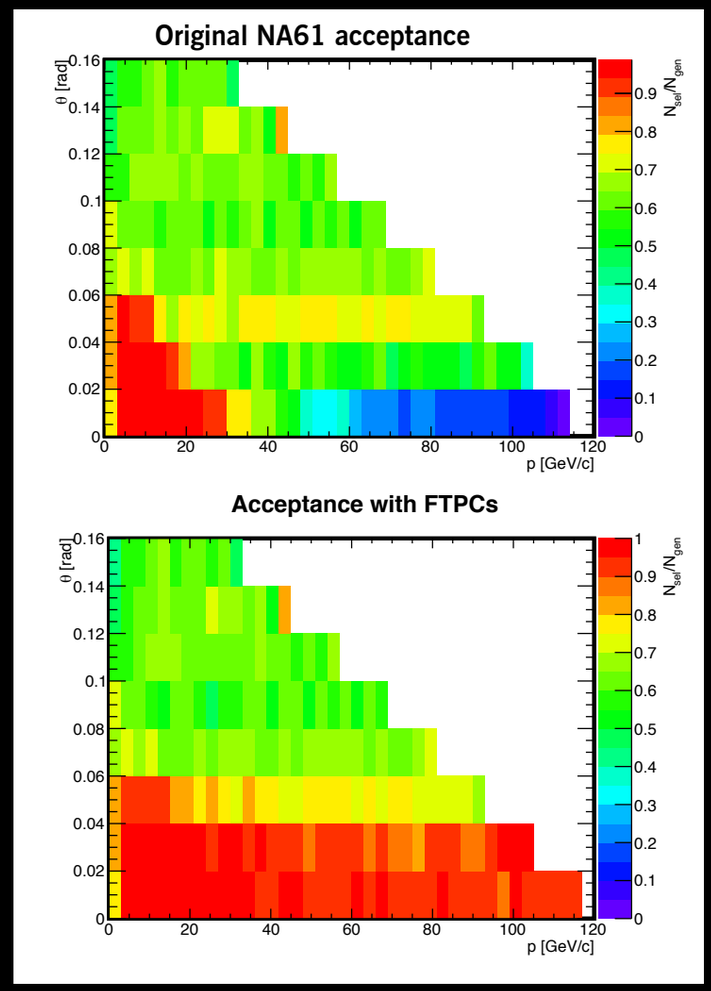
DUNE flux uncertainties with current production data

- Dominated by
  - Pion and Kaon re-interactions
  - Nucleon interactions not covered by data
  - Errors on existing pC data



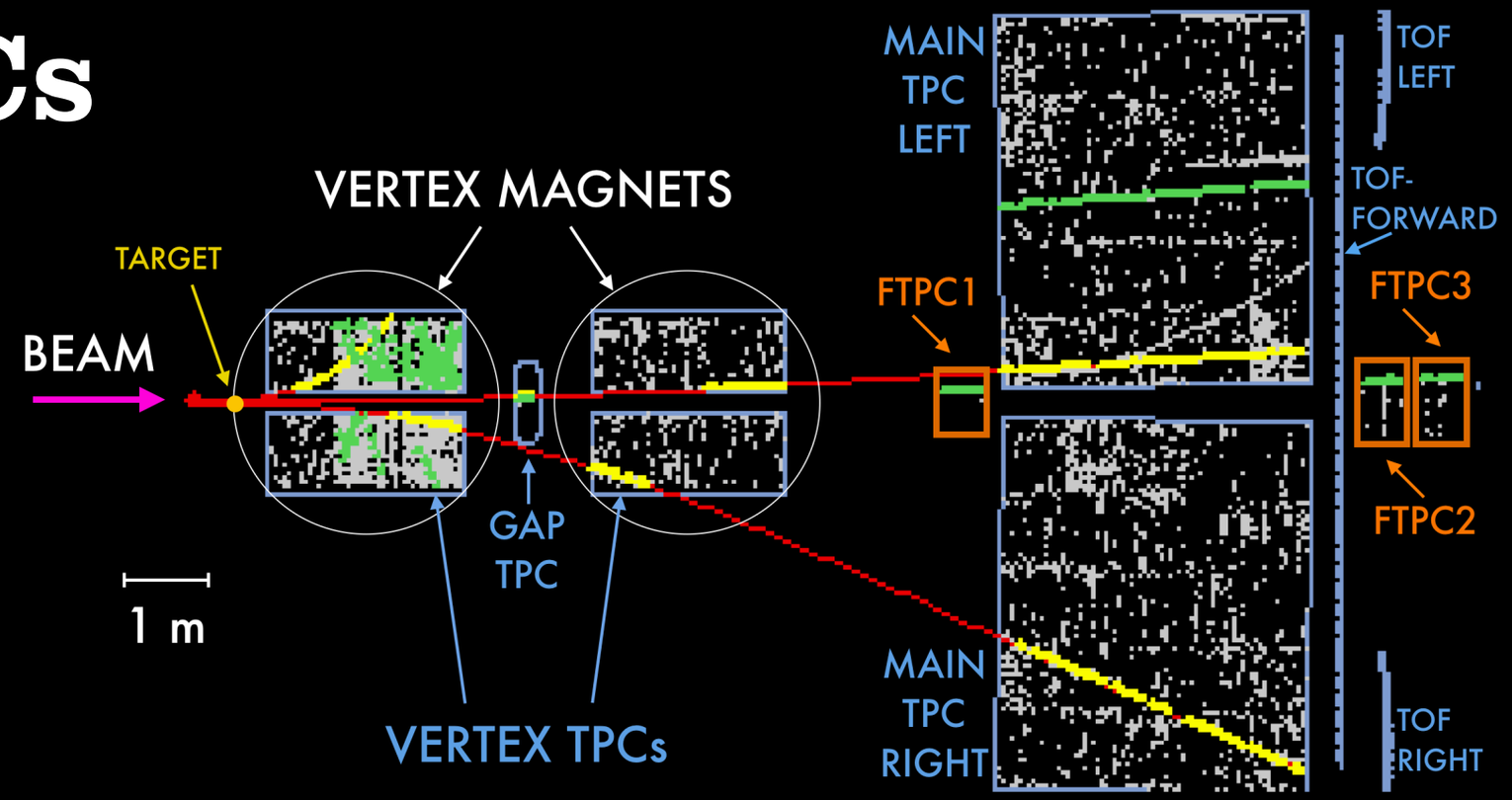
Secondaries Contributing to DUNE Flux





- Weighted by contribution to DUNE FD flux, for Nov 2017 DUNE Optimized and Engineered Beam design (120 GeV/*c* protons)
- New forward TPCs make measurements of important secondary protons possible
- Acceptance is now well-matched to secondaries that generate neutrinos in DUNE

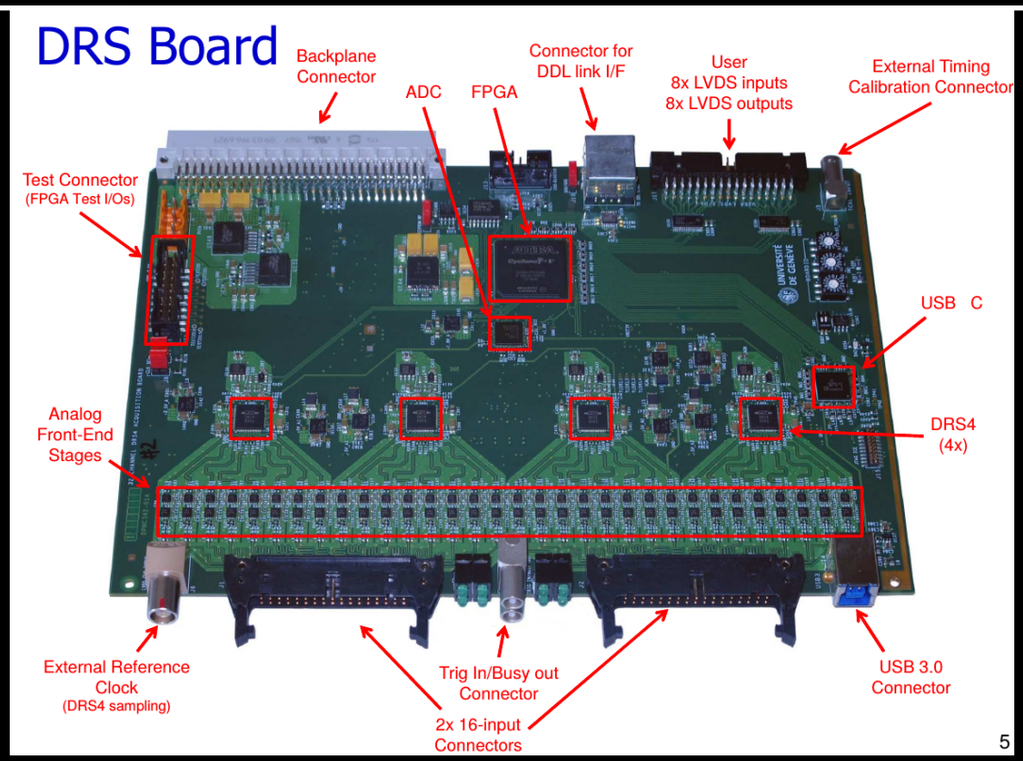
Forward TPCs

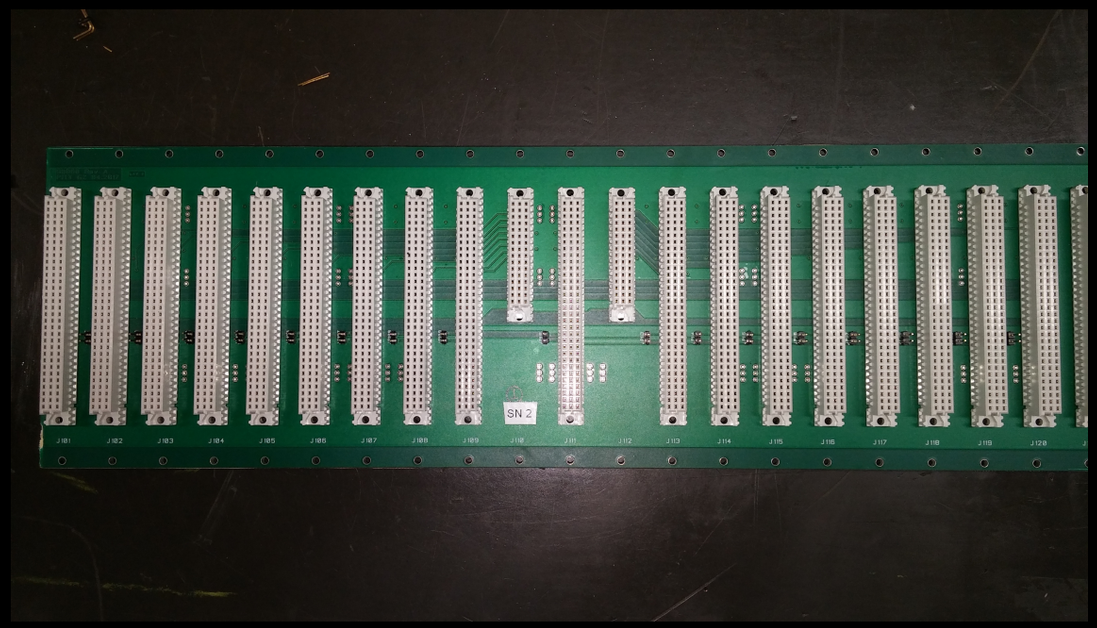


- FTPCs installed 2016-17, used in 2017 and 2018 data run
- Chambers work well
- Event display above from 2017 data with local (green) tracks reconstructed
- New global tracking algorithm in final development stage

Electronics upgrade

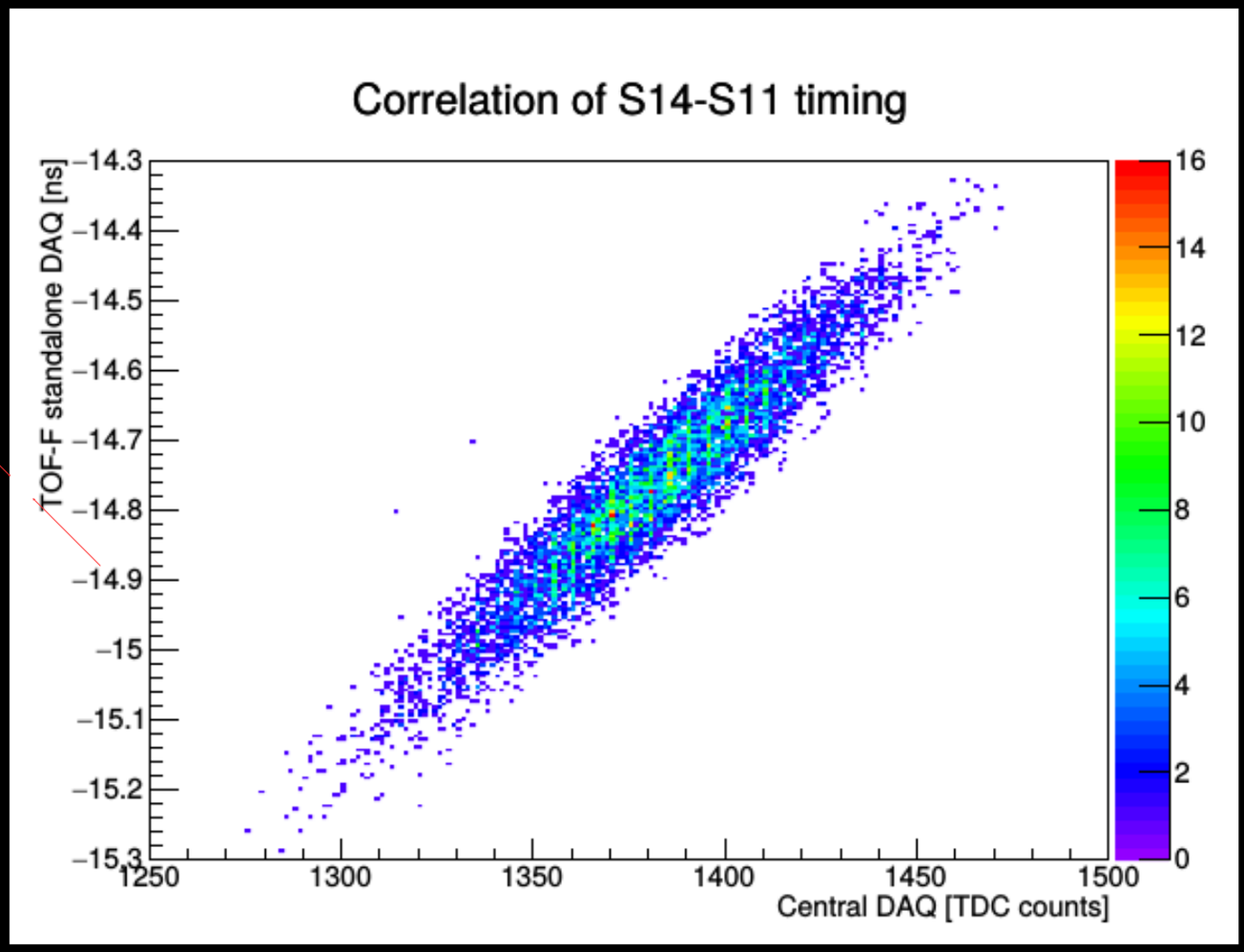
- Replacement of TOF electronics with a modern system based on the DRS4 chip
- Pittsburgh-Geneva collaborative effort
- Goal is to replace 3500 channels during LS2
- Initial deployment in 2017 in Forward TOF wall, where previous system not functional and improved time resolution is most helpful
- Extend to all compatible detectors during Long Shutdown





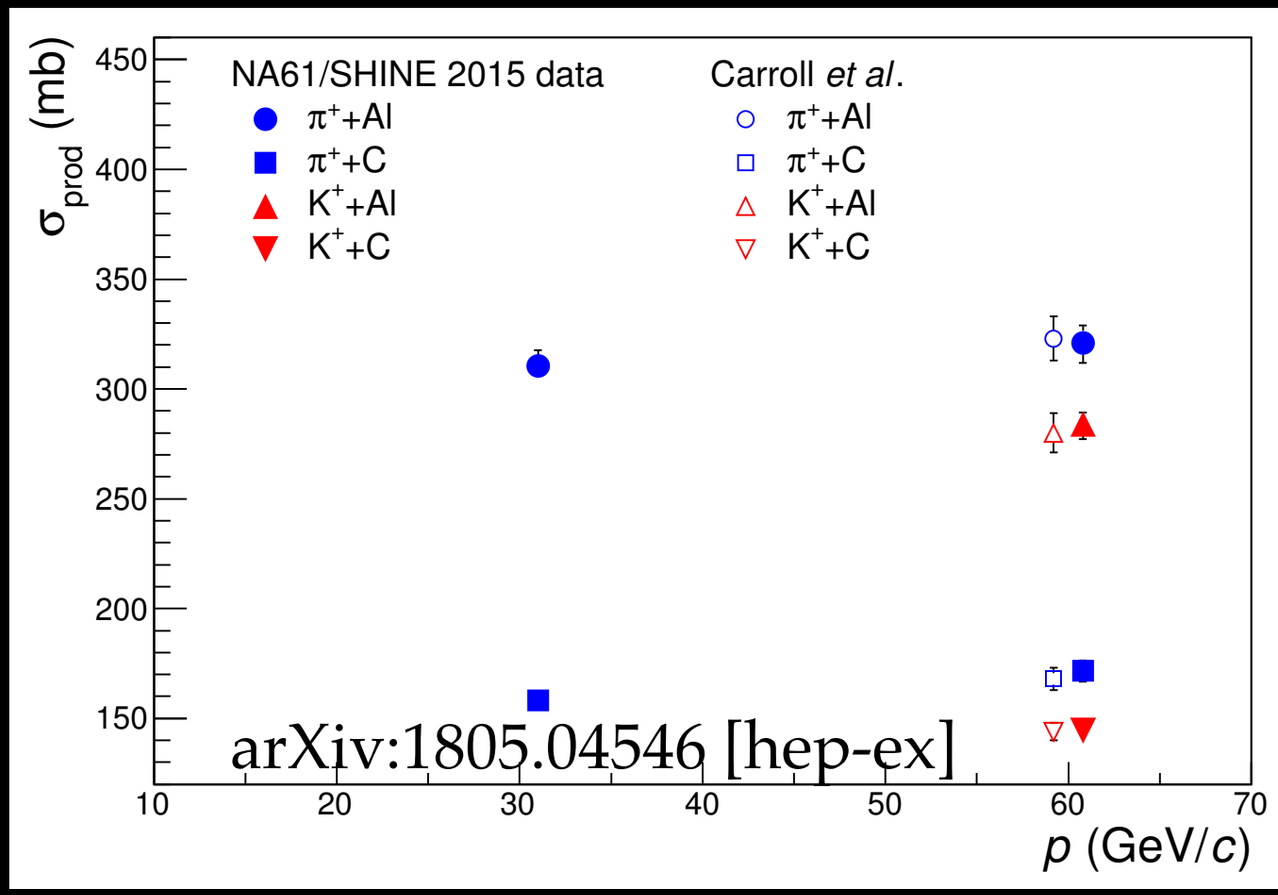
Performance of DRSv4 in 2017 data

- First forward TOF TDC data with DRS4
- After preliminary voltage, local, and global time calibration the timing resolution is ~40ps



First result: total production cross-sections on nuclear targets

- 2015 data set collected with no magnetic field due to failure of old superconducting magnets: no momentum measurements
- Recently published total production and total inelastic cross section measurements for data without magnetic field
- Phys.Rev. D98 (2018) 052001
- Note: here $\sigma_{prod} = \sigma_{total} - \sigma_{el} - \sigma_{qe}$, requires new hadrons to be produced. Also $\sigma_{inel} = \sigma_{total} - \sigma_{el}$. This terminology not always used consistently in community or in hadronic event generators.

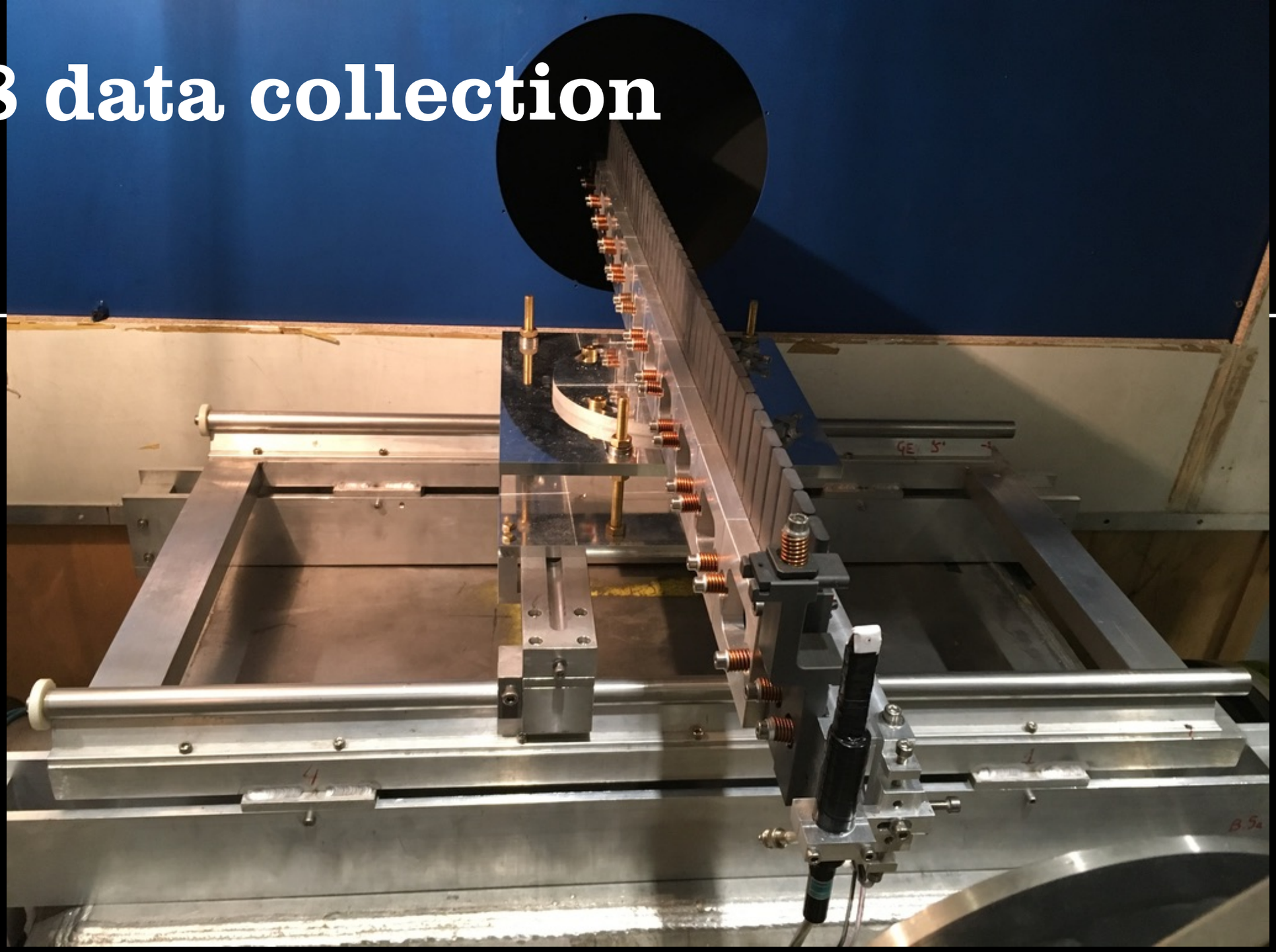


NA61 2016-17 neutrino data
Thin targets

2016	2017
p + C @ 120 GeV/c	π^+ + Al @ 60GeV/c
p + Be @ 120 GeV/c	π^+ + C @ 30 GeV/c
p + C @ 60 GeV/c	π^- + C @ 30 GeV/c
p + Al @ 60 GeV/c	p + C @ 120 GeV/c (w FTPCs)
p + Be @ 60 GeV/c	p + Be @ 120 GeV/c (w FTPCs)
π^+ + C @ 60GeV/c	p + C @ 90 GeV/c (w FTPCs)
π^+ + Be @ 60 GeV/c	

Highest analysis priority

2018 data collection



- 120 GeV *p* on NOvA replica target provided by Fermilab
- 15M events recorded in summer; a final run next week should add 30-50%

Post-2020 plans

- Previously-approved run ends this year; Long Shutdown 2 begins
- NA61 is working with CERN SPSC and European Strategy Update on proposed data collection beyond LS2
- SPSC recommends 2021 running
- European Strategy update will address 2022-24 runs

NA61 running beyond 2019-20 accelerator shutdown

- Many measurements motivated by strong interactions (esp. open charm) and cosmic ray physics
- Neutrino-related measurements in 2021-22 era:
  - When available (could be after 2022): replica target for LBNF/DUNE
  - New measurements for T2K-II/Hyper-K to reduce flux uncertainties to ~3%
    - New ceramic target material?
    - Replica target data with improved upstream tracking
    - Study of low-energy secondary interactions (needs work on beam)
  - More secondary processes for LBNF; beryllium if needed
    - Detailed list to be developed as current analysis efforts proceed, LBNF beam MC develops and needs are better known
  - Low-energy measurements for atmospheric neutrino flux
- See talks at workshop on NA61 Beyond 2020 workshop at Geneva, August 2017: https://indico.cern.ch/event/629968/

Post-2020 plans

- NA61 is planning significant upgrades to the detector for 2021+
  - New forward Projectile Spectator Detector module, reconfiguration of existing detector
  - Replacement of old TPC electronics with system from ALICE
  - New silicon vertex detector for open charm studies
  - RPC-based replacement for TOF-L/R walls
  - New close-in tracking detectors for improved vertex resolution in long targets
  - New trigger/DAQ, combined with new electronics, will give a major upgrade in data collection rate

Relevant for neutrino running

Post-2020 plans

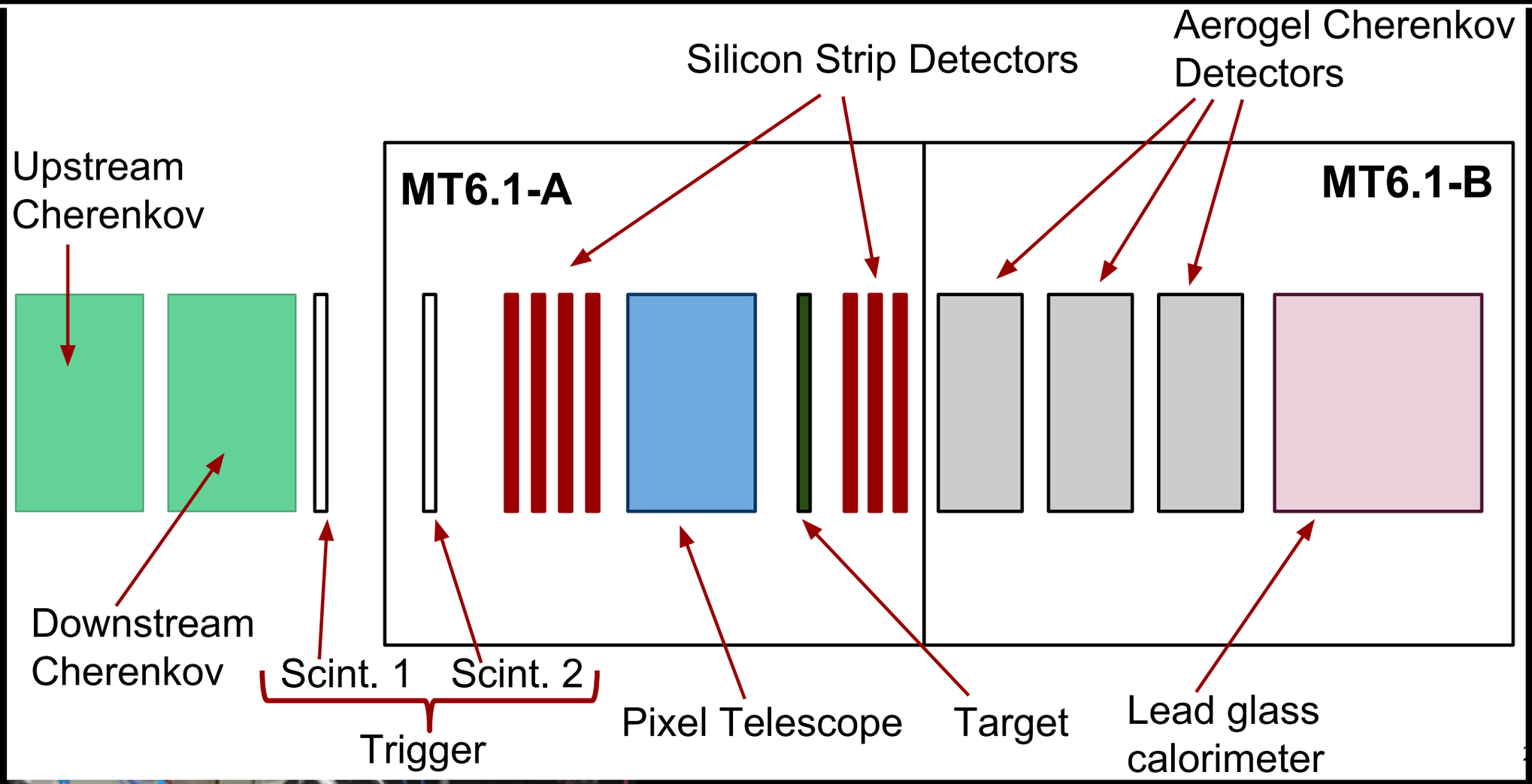
- These upgrades are not fully funded yet. Some funding agency applications are under review, others to be submitted.
- They are, however, essential if we are to preserve NA61 as a resource for the neutrino community.
- New collaborators are welcome to join: opportunities to work on the upgrade as well as to analyze existing data.

A new hadron production experiment: EMPHATIC

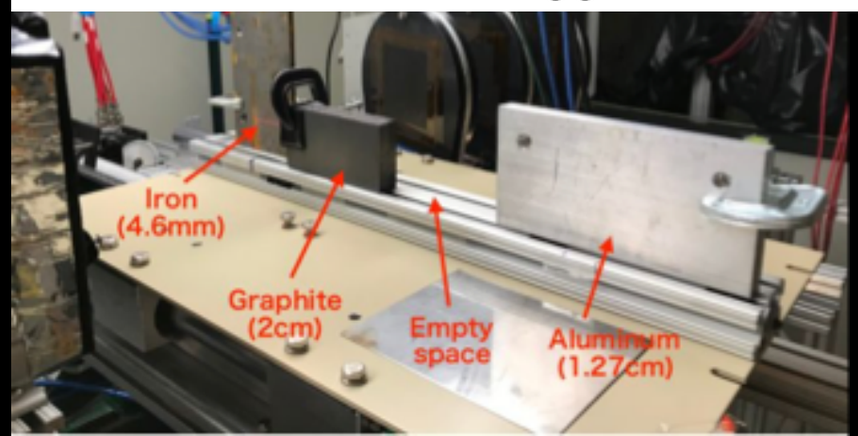
Experiment to **M**easure the **P**roduction of **H**adrons **A**t a **T**estbeam **I**n **C**hicagoland

- "Tabletop-scale" hadron production experiment
- First version took data in a Fermilab test beam in January 2018
- Goal is to measure
  - the reactions important to T2K that aren't covered by existing NA61 data
  - hadron production for atmospheric neutrino flux modeling
- Mostly means low energy (<15 GeV) that NA61's beam can't deliver as currently configured. Beam has momenta 2-120 GeV/c
- Complementary to NA61

EMPHATIC layout in 2018 run



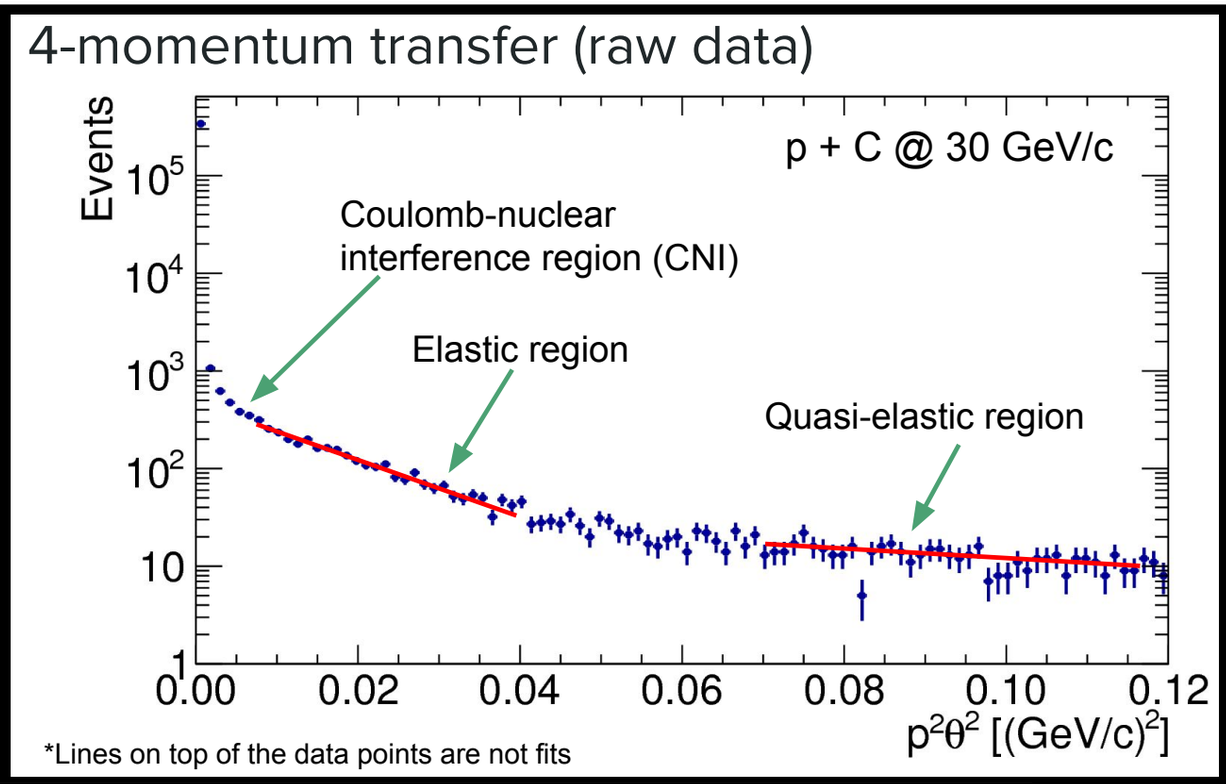
M. Pavin, NOW2018



- Graphite, aluminum, steel targets
- Emulsion targets with grapite

Physics goals of current detector

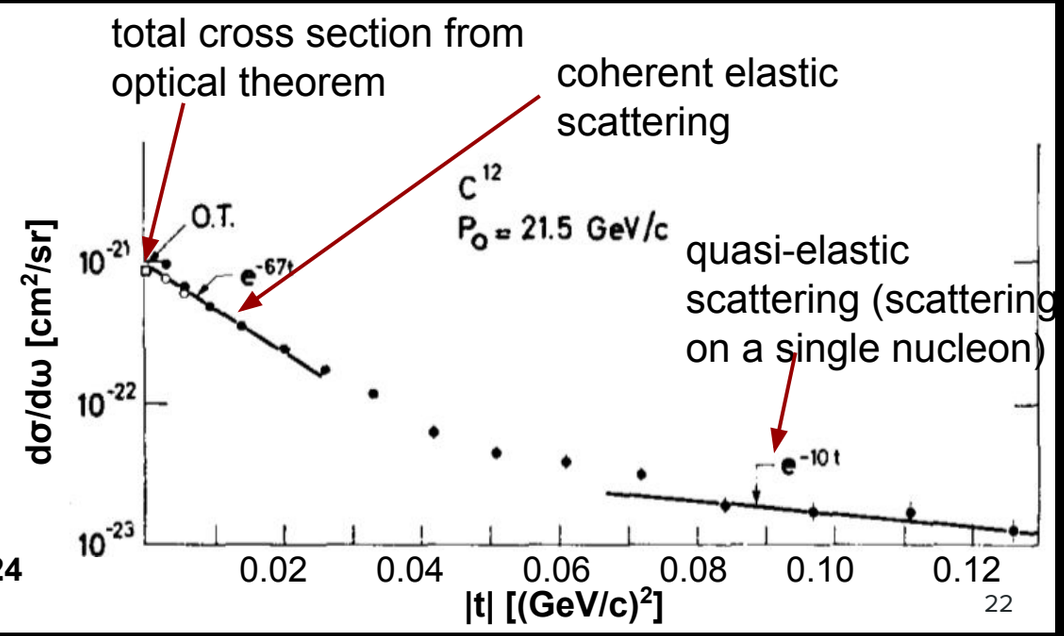
- Measurement of total, elastic and quasi-elastic cross section
- (No magnetic field yet — similar situation to NA61 2015)



$$|t| \approx p^2\theta^2$$

Beam momentum

Scattering angle



Bellettini et al., Nucl.Phys. 79 (1966) 609-624

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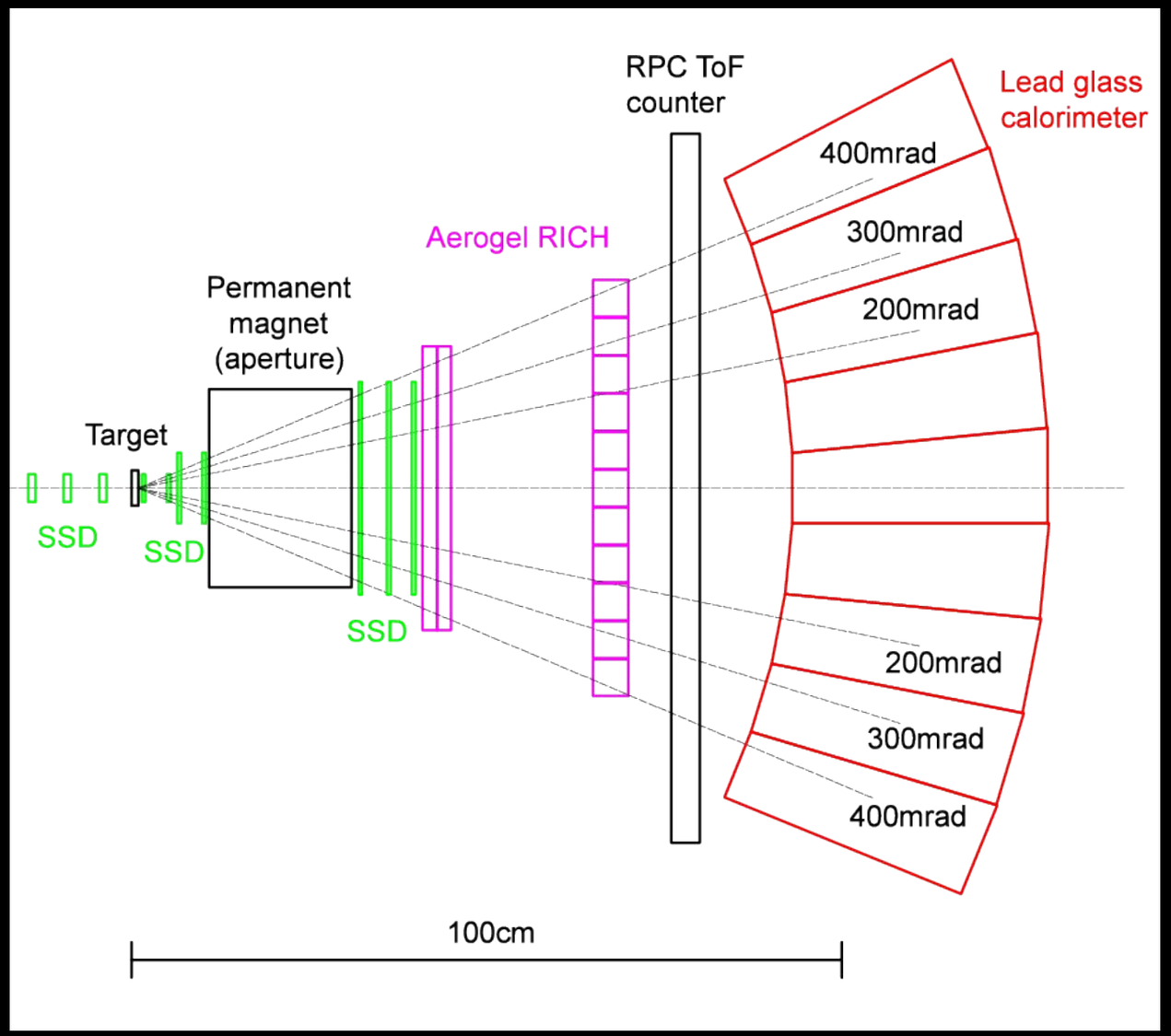
Future EMPHATIC configuration

- Permanent magnet (Halbach array)
- With Si strip detectors, momentum resolution of 2% possible
- TOF + aerogel RICH for particle ID
- Plan to run with B, BN, B_2O_3 for atmospheric flux studies
- More C, Al, Fe for accelerator neutrino beams, including beam proton survival probability measurements



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Summary

- Dedicated hadron production experiments have proven essential to bringing flux errors down to manageable sizes in current neutrino experiments
- NA61/SHINE's program of T2K-related measurements is almost done; next-to-last result in publication
- NA61 is concluding its current program of neutrino measurements with data for NuMI experiments, including replica NOvA target and thin-target measurements useful for DUNE
- Plan to run with further detector upgrades after LS2, with several high-priority measurements planned including LBNF/DUNE replica target when available — but resources are still necessary
- New experiment EMPHATIC is joining the game: complementary to NA61