TRIUMF

Hadron production measurements for neutrino experiments

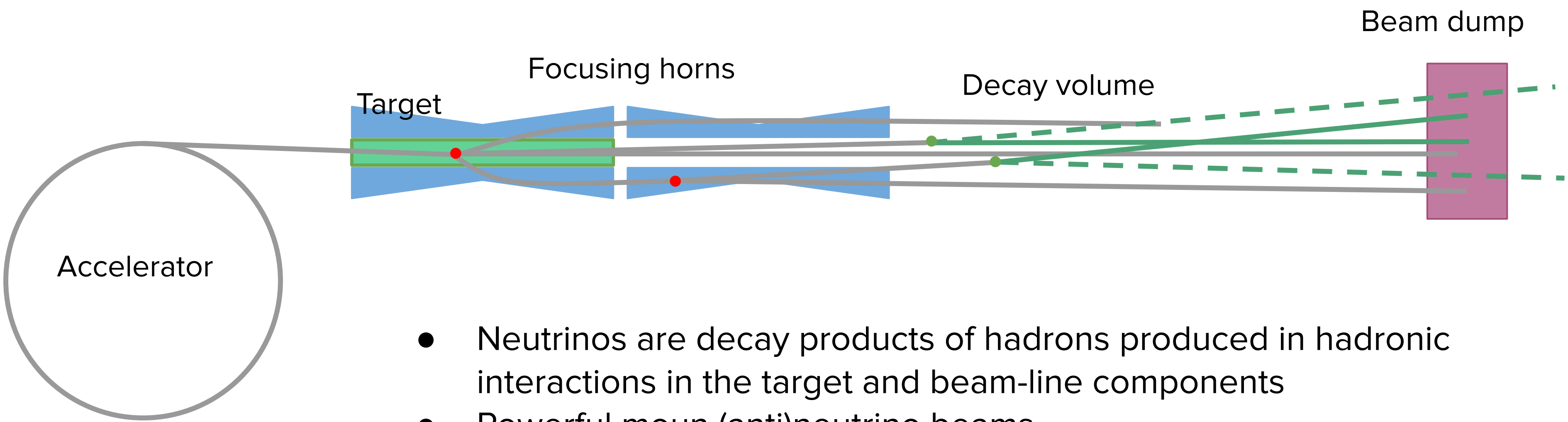
Matej Pavin,

Neutrino 2020
June 29, 2020

Outline

- A brief introduction to the hadron production measurements for neutrino experiments
- Why we need hadron production measurements?
- NA61/SHINE and EMPHATIC

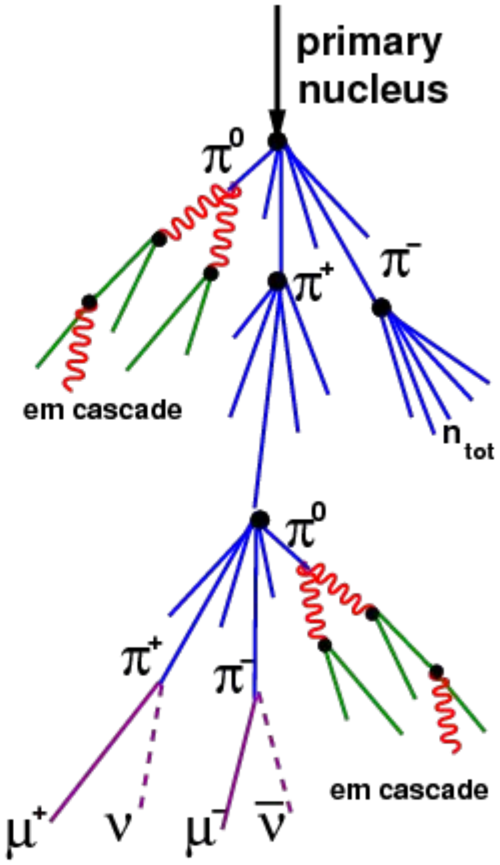
Accelerator-based neutrino beams



- Neutrinos are decay products of hadrons produced in hadronic interactions in the target and beam-line components
- Powerful moun (anti)neutrino beams
- Proton beams: 8 GeV/c, 31 GeV/c, 120 GeV/c

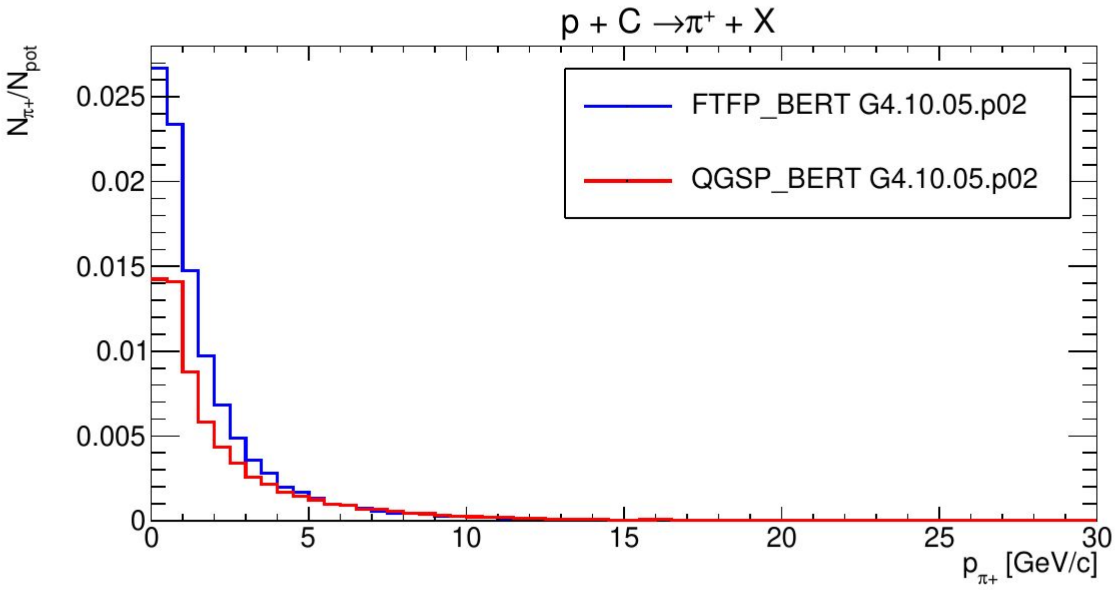
Atmospheric neutrinos

- Hadronic shower in the atmosphere caused by cosmic ray interactions
- Neutrinos are decay products of daughter particles created in the shower



How to estimate neutrino flux?

- Hard to measure directly ➔ we rely on hadronic interaction models
- Large differences between models (20% - 30%) ➔ in some cases order of magnitude
- External hadron production data is used to constrain the models



Is neutrino flux uncertainty important? - Accelerator neutrinos

- 3-flavor oscillation measurements ➜ far to near detector ratio ➜ flux uncertainty cancels out in ideal conditions
    - In reality neutrino source does not look the same in near and far detectors
    - Flux uncertainty comes into play indirectly through neutrino cross-section measurements
- Measurements with a single neutrino detector (cross-sections, sterile neutrino searches, ...) are limited by neutrino flux
- Important for ν-prism technique in upcoming experiments

	Statistics [%]	**Flux [%]**	Cross-section model [%]	Detector [%]
σ(ν)	0.87	**9.14**	1.16	2.63
σ(anti-ν)	3.22	**9.37**	2.13	1.82
σ(anti-ν)/σ(ν)	3.22	**3.58**	1.56	1.11

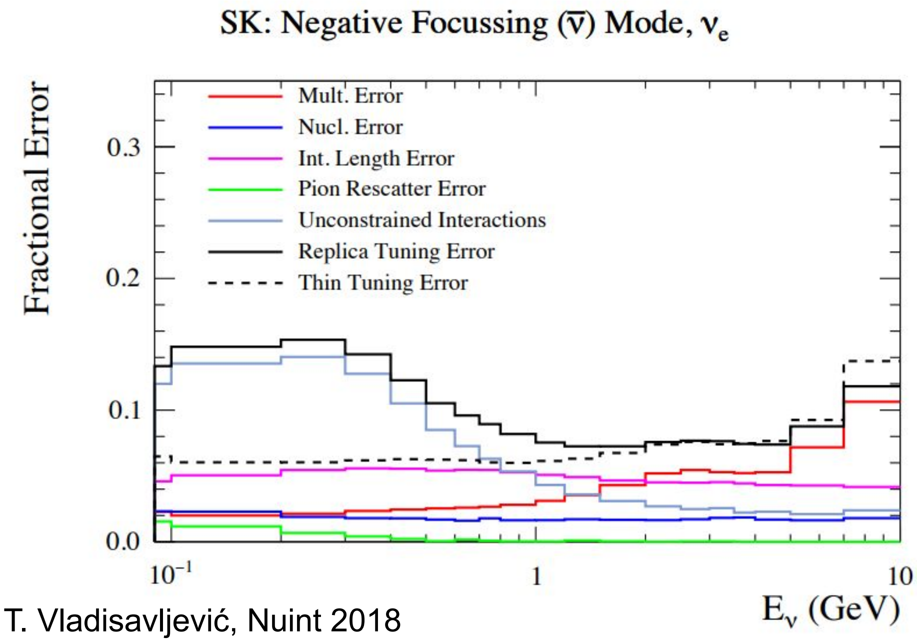
Measurement of (anti)ν_μ charged current inclusive cross-sections

Phys.Rev. D96 (2017) no.5, 052001

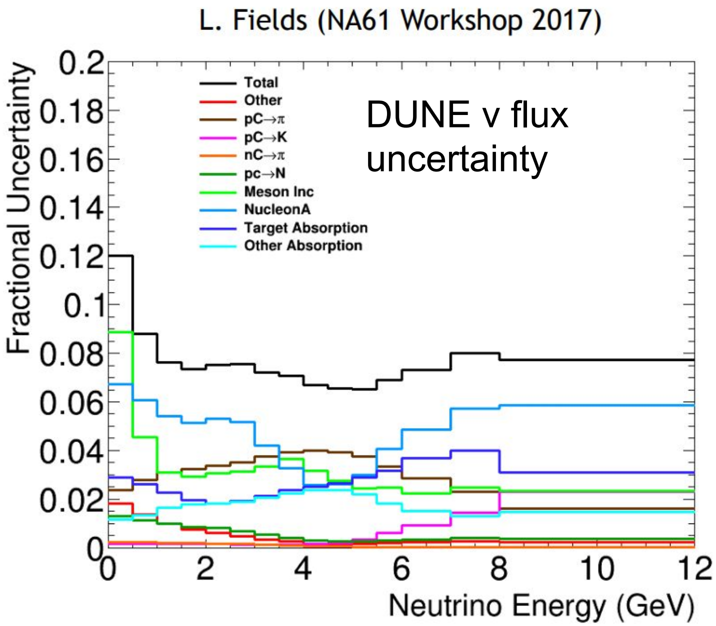
T2K measurements

Flux uncertainty at T2K(T2HK) and DUNE

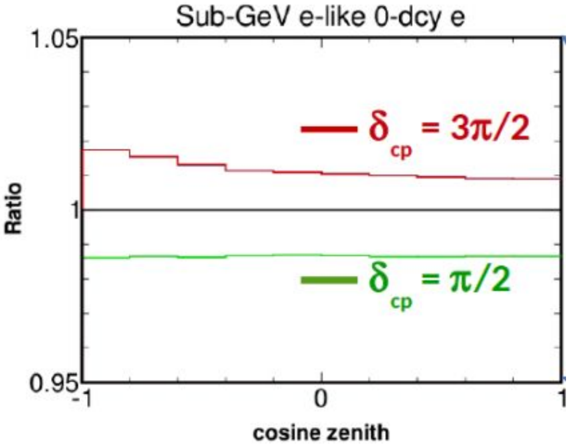
- T2K ν_e flux uncertainty at low energies is limited by the untuned interactions outside of the target ($\pi^\pm$ + Al → $\pi^\pm$ + X, $K^\pm$ + Al → $K^\pm$ + X)
    - Untuned → not covered by hadron production measurements
- Nearly 50% of wrong-sign neutrinos come from interactions outside of the target



T. Vladisavljević, Nuint 2018



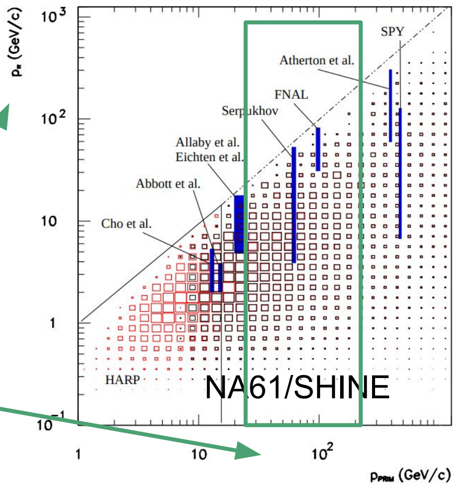
Is neutrino flux uncertainty important? - Atmospheric neutrinos

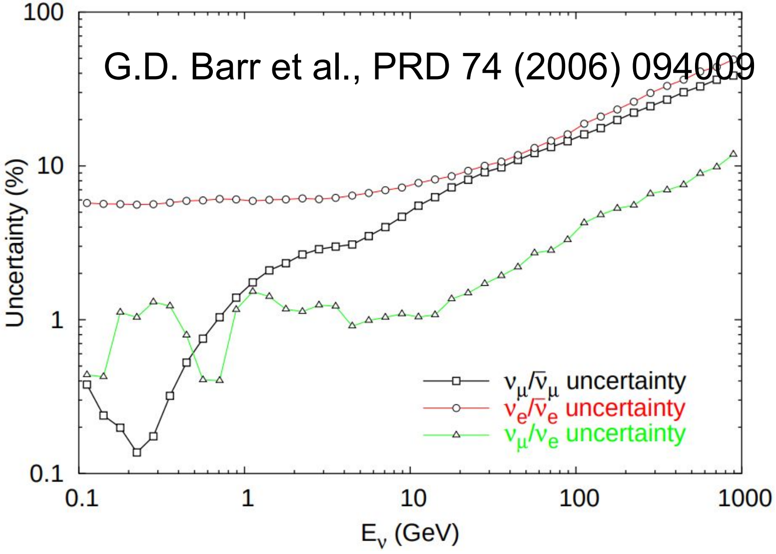


- CP violation measurements ➔ small effect (~2%) in sub-GeV neutrino sample
- The uncertainty is dominated by hadron production below 15 GeV (π^+/π^- ratio)
- Only HARP data covers the important region

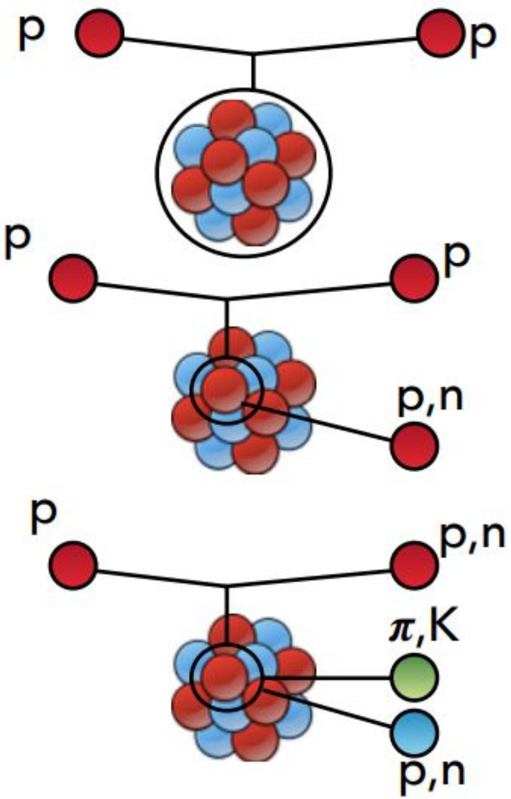
Momentum of secondary pions

Momentum of primary cosmic ray





Hadron interactions (simplified)



Coherent elastic interactions (σ_{el})

$$\sigma_{\rm tot} = \sigma_{\rm el} + \sigma_{\rm qel} + \sigma_{\rm prod}$$

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

Quasi-elastic interactions (σ_{qel})

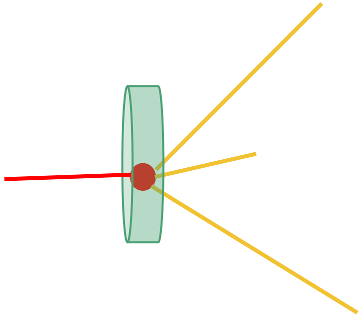
Particle production (σ_{prod})

Inelastic interactions (σ_{inel})

Hadron production measurements

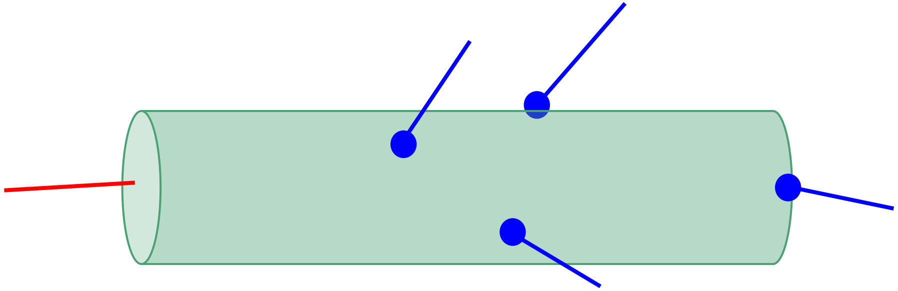
- **Hadron production measurements can be used to tune models**

1 Thin target measurements



- Total, elastic, inelastic and production cross-section measurements
- Differential cross-section
- Useful for model tuning
- **Useful for all experiments**

2 Replica target measurements

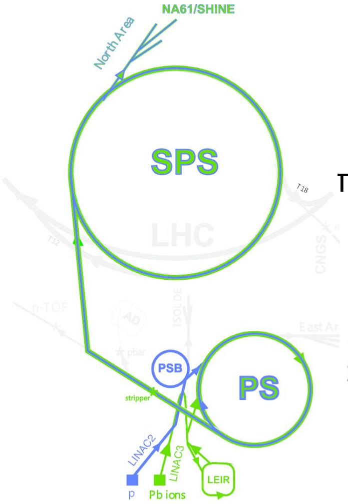


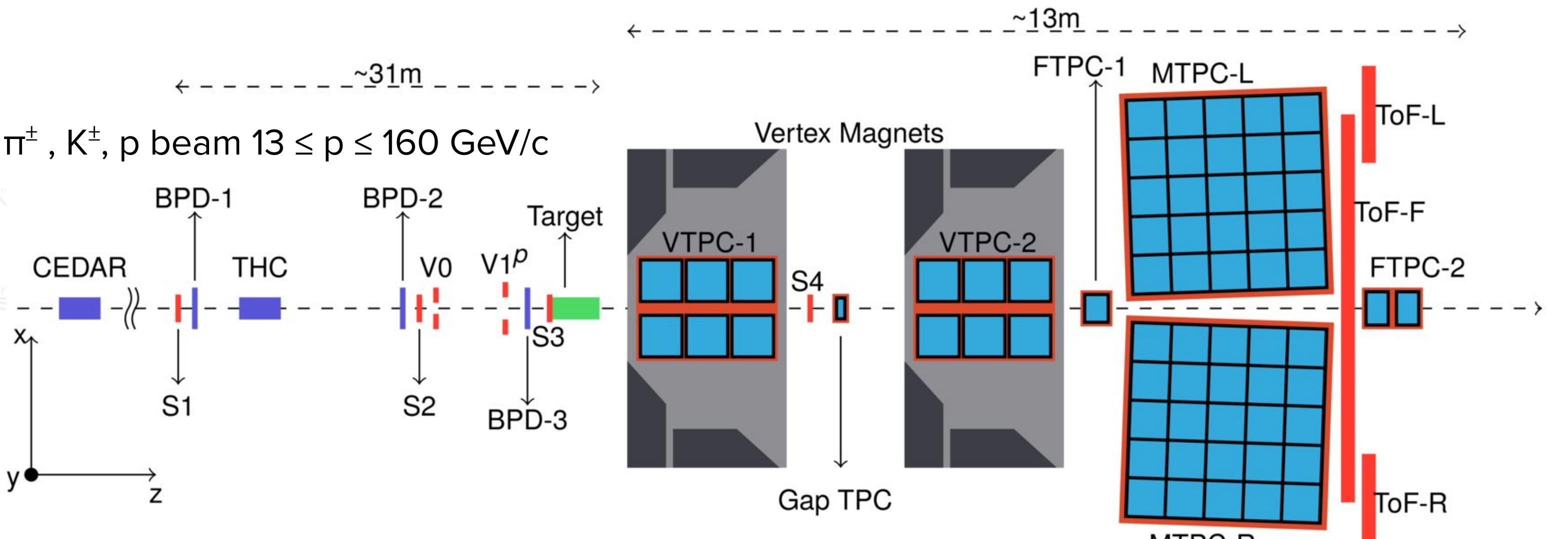
- Measuring hadron multiplicities coming from the target surface
- Whole particle shower in the target is taken into account
- **Beam and target specific measurement**
- Necessary to achieve < 5% flux uncertainty

A brief history of hadron production measurements

- Many measurements are quite old (1960s - 1980s)
  - Thin target data
- Good data, but many things are missing (lost):
  - How systematic uncertainties are calculated
  - Covariance matrices
  - Data points (only log plots available)
  - Definitions of what is measured not clear due to terminology changes over the year
- Majority of the recent measurements were done by NA61/SHINE collaboration
- Upcoming experiment: EMPHATIC
- **We need a consistent way of publishing hadron production data**

North Area 61 / SPS Heavy Ion and Neutrino Experiment
NA61 / SHINE



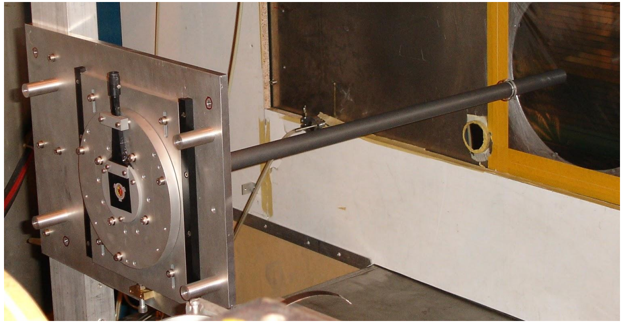


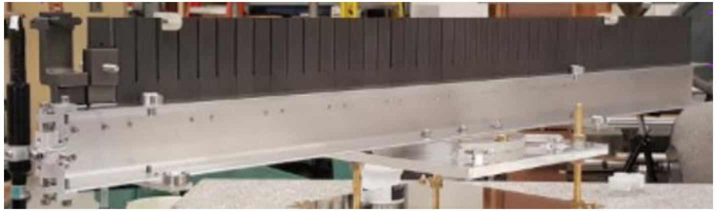
*Setup used in hadron production measurements for neutrino experiments

- Precise hadron production measurements for neutrino flux re-weighting in T2K, HyperK, and Fermilab neutrino experiments

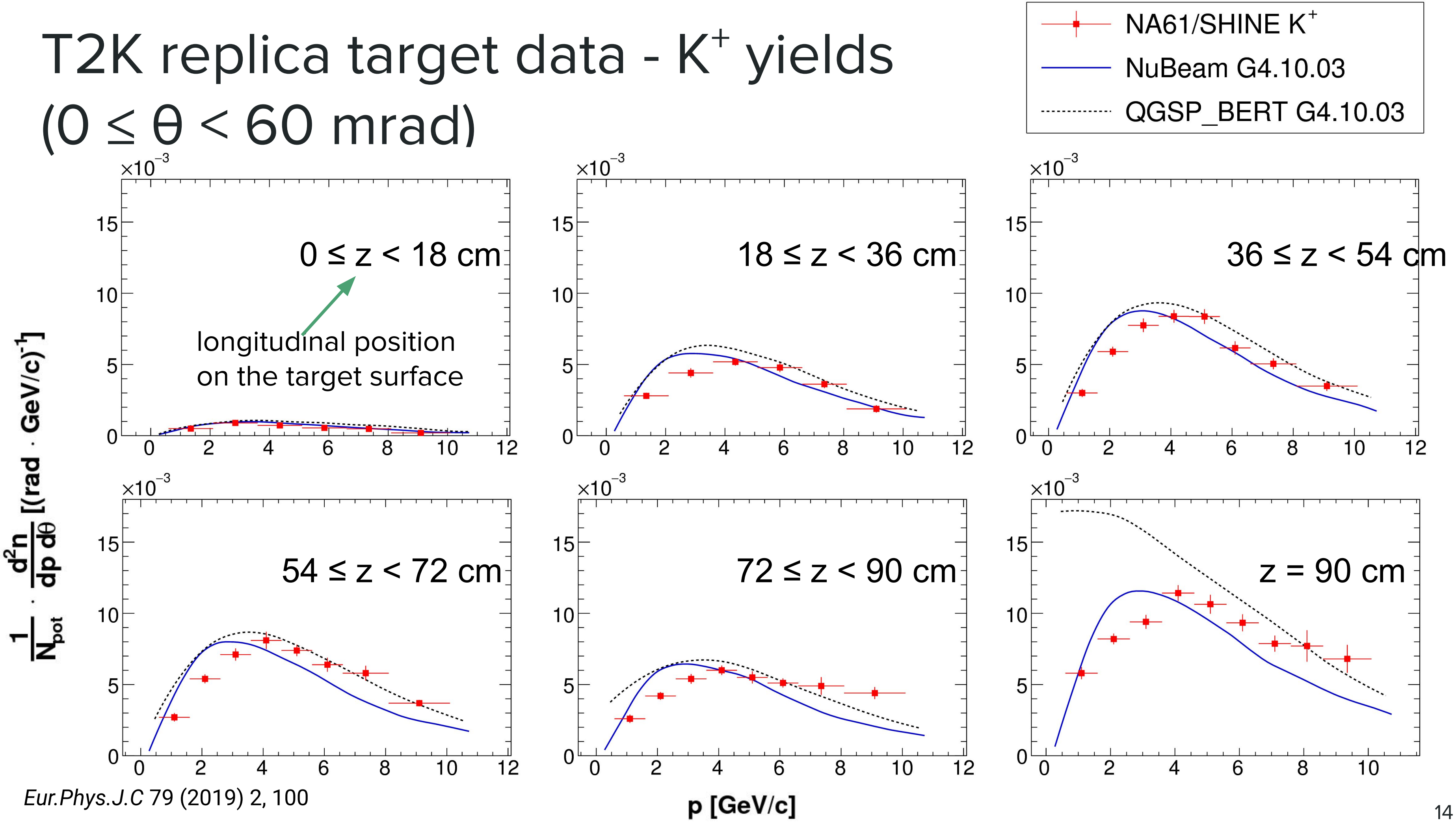
NA61/SHINE hadron production measurements

- Thin and replica target measurement
- NA61/SHINE data played important role in the success of the T2K programme
  - Replica target data allowed reduction of the flux uncertainty from 10% to 4%-5% for (anti)ν_μ flux
- Huge data-taking campaign for the US neutrino programme
  - Proton/pion/kaon interactions in carbon/ beryllium/ aluminium / NOVA replica target (31-120 GeV/c)
  - Analysis ongoing / some of the results are published





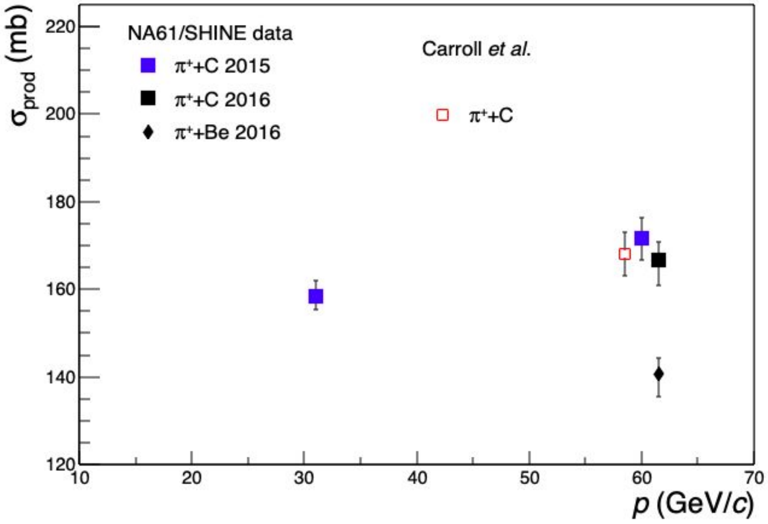
T2K replica target data - K^+ yields ($0 \leq \theta < 60$ mrad)



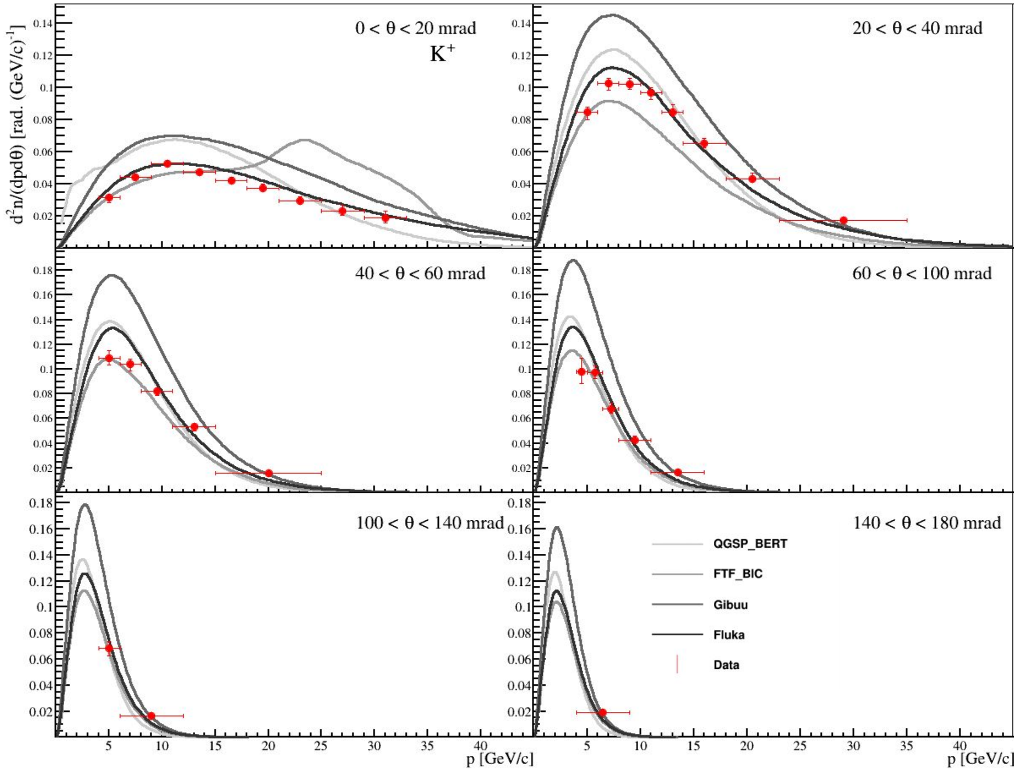
Eur.Phys.J.C 79 (2019) 2, 100

Measurements of hadron production in π^+ + C and π^+ + Be interactions at 60 GeV/c

- Production of $\pi^\pm$, $K^\pm$, p, K^0_s, Λ



Phys. Rev. D 100, 112004 (2019)



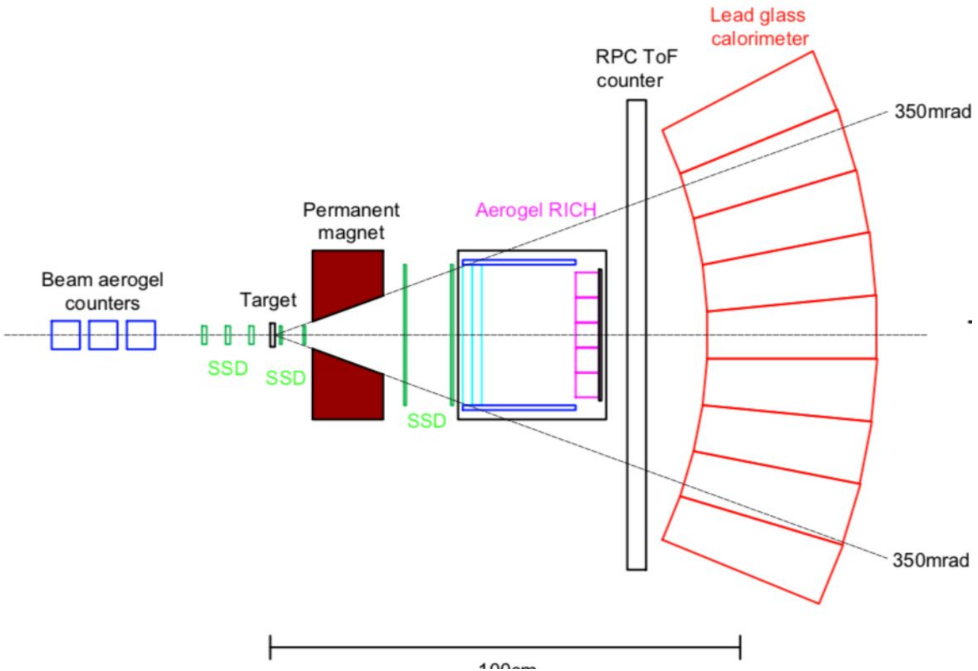
NA61/SHINE upgrades

- Important for hadron production measurements:
  - Forward TPCs (already installed)
  - TPC readout electronics from ALICE ➔ 1 kHZ readout speeds
  - Silicon vertex detector
- New replica target measurements for T2K and HyperK are already approved by SPSC
- MC studies ongoing for low momentum beamline for NA61/SHINE
  - Current NA61/SHINE beamline is limited > 13 GeV/c

EMPHATIC

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

- **Tabletop experiment run by neutrino physicists (T2K, SK, HK, DUNE, NOVA) + E50 experiment**
- USA (magnet, silicon strips, ARICH), Japan (RPC, calorimeter, T0) and Canada (magnet, ARICH, DAQ)
- Complementary to NA61/SHINE (physics programme and detector technology)
- **Approved by Fermilab PAC**
- Fermilab Test Beam Facility (FTBF) ➔ secondary beam 2 - 120 GeV/c
- Compact hadron spectrometer
- Angular acceptance 400 mrad



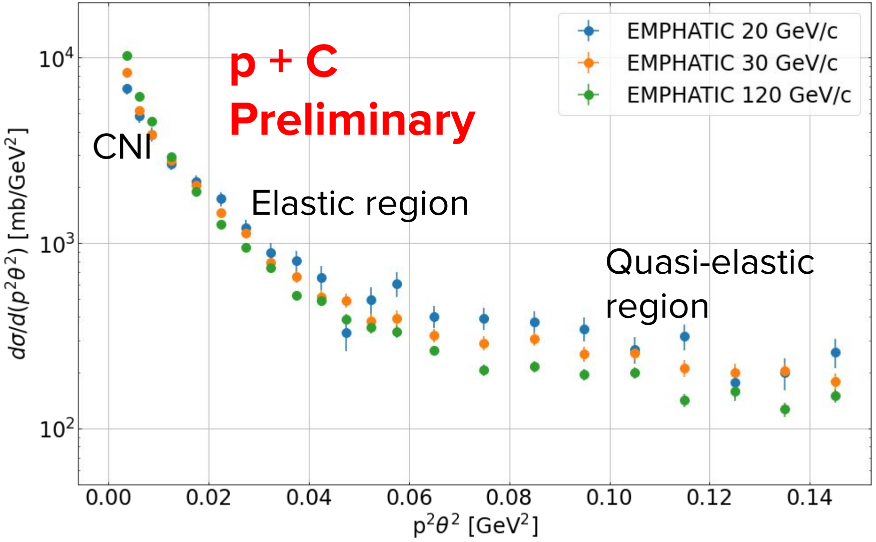
arXiv:1912.08841 **[hep-ex]**

EMPHATIC - what do we want to measure?

- Measurements for T2K, NOVA, DUNE, HyperK, …
- 2-15 GeV/c pion, proton, kaon scattering on beryllium, carbon, aluminium, iron, boron nitride and boron oxide
- Better understanding of differences between thin and replica target data measurements

Test run in 2018

- Goal: prove that silicon strips can be used for forward scattering measurements
- Measurement of forward proton-carbon scattering
- No secondary PID or momentum measurements

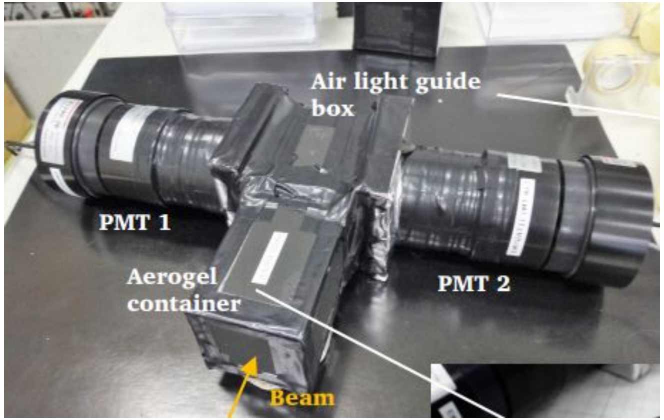


EMPHATIC next data-taking campaign

- Phase 1 data-taking was planned for April 2020
    - **Postponed until next winter or early spring**
    - 3-4 week run ➔ DAQ rate 10k per spill (1 spill = 4s each minute)
    - Limited acceptance 150 mrad ➔ because existing SSDs will be used
    - Small acceptance magnet, RPCs, and ARICH detector
    - Pion, kaon and proton beams
    - Beryllium, carbon, aluminum, titanium, iron, composite targets for atmospheric neutrinos
- Phase 2 ➔ full acceptance
    - 400 mrad permanent magnet, large silicon strip detectors, full acceptance ARICH

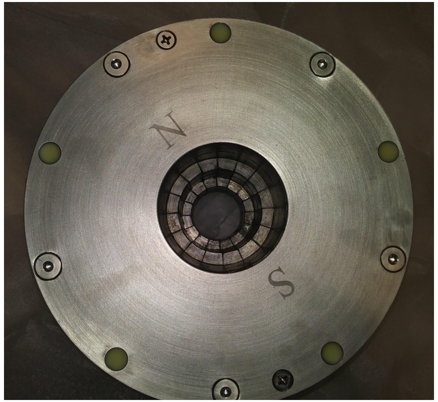
EMPHATIC ➜ phase 1 detector development

Aerogel threshold Cherenkov detector

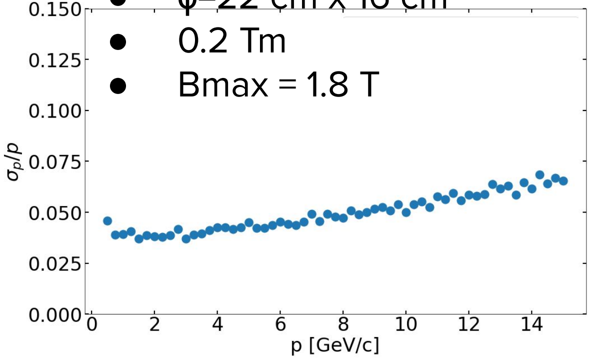


n	π threshold [GeV/c]	K threshold [GeV/c]	p threshold [GeV/c]
1.004	1.6	5.5	10.5
1.012	0.9	3.2	6.0

Magnet

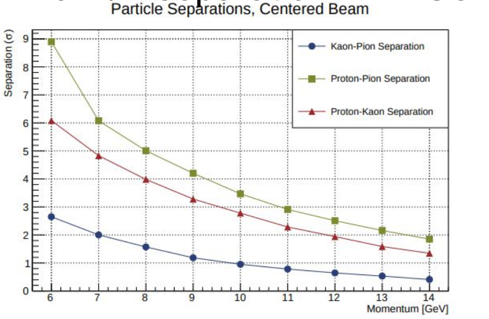


- ϕ=22 cm x 16 cm
- 0.2 Tm
- Bmax = 1.8 T



ARICH

- 2σ π/K separation < 7 GeV/c
- 1σ π/K separation < 11 GeV/c



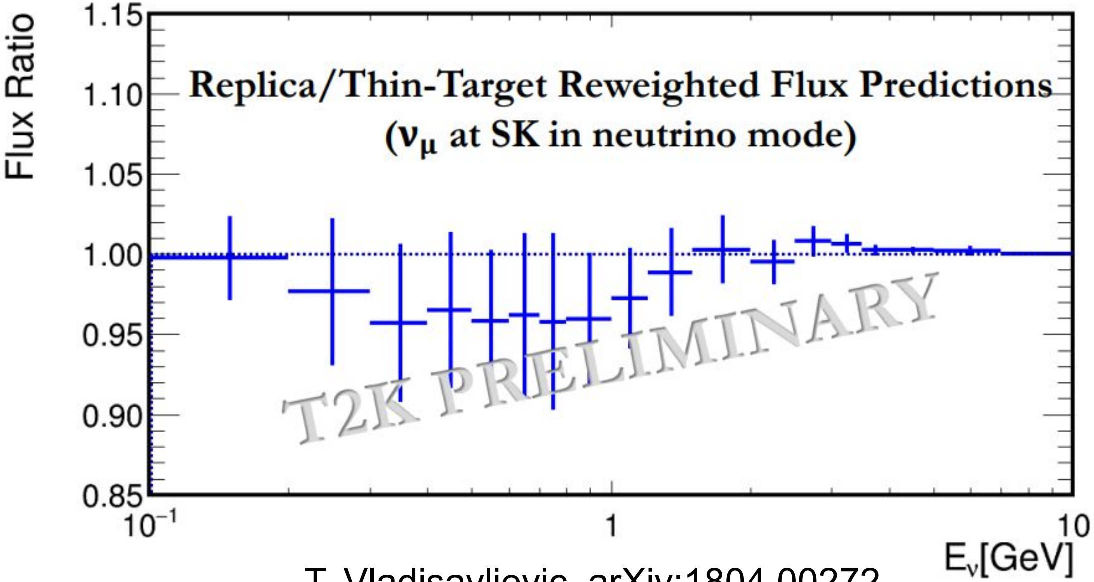
Conclusions

- **Hadron production measurements are limiting factor in neutrino measurements done by a single detector**
- **Both, thin and replica target data are needed for <5% neutrino flux uncertainty**
- Data covering hadron interactions below 15 GeV/c are sparse
- We need a consistent way to measure and publish hadron production data
- **NA61/SHINE and EMPHATIC are planning new data-taking campaigns**
- NA61/SHINE is the only experiment currently running that can take replica target data
- EMPHATIC has been designed with a very specific goal ➔ this allows for a cleaner, more effective design, at reduced cost.

BACKUP

Thin vs. replica target tuning in T2K

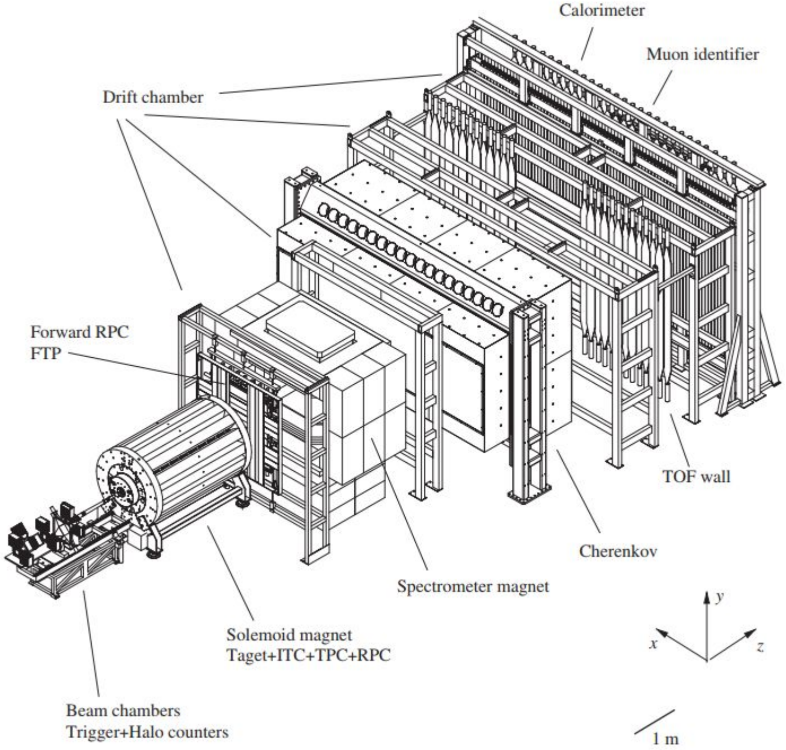
- T2K neutrino flux simulation with the NA61/SHINE replica target tuning predicts 5% lower flux
- Issues with interaction probability?



T. Vladisavljevic, arXiv:1804.00272

HARP (Hadron Production Experiment)

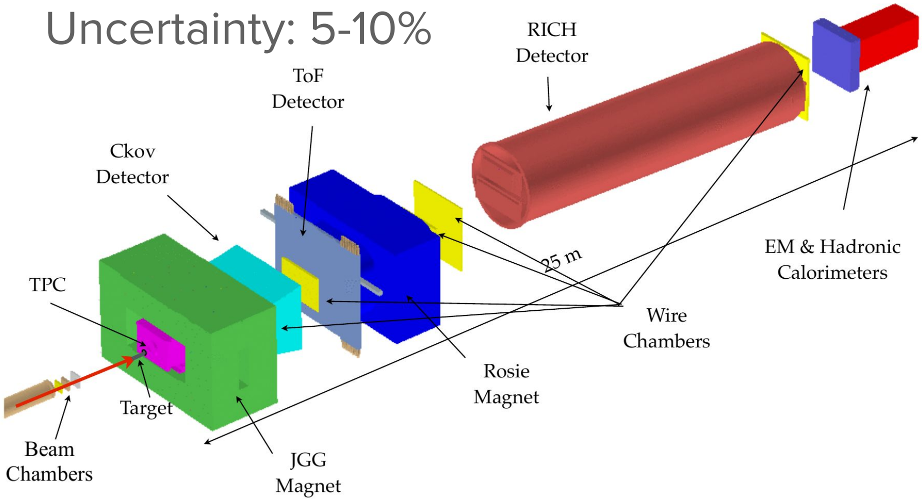
- CERN PS
- Beam momentum: 1.5-15 GeV/c
- Targets: A = 1-200
- **p+A→ $\pi^{\pm}$ (3-12 GeV/c):** Phys.Rev. C80 (2009) 035208
- **$\pi^{\pm}$+A→ $\pi^{\pm}$ (3-12 GeV/c):** Nucl.Phys. A821 (2009) 118-192)
- **p+N2, O2→ $\pi^{\pm}$ (12 GeV/c):** Astropart.Phys. 30 (2008) 124-132)
- Low angle configuration 0-250 mrad
- High angle configuration 350 - 2150 mrad
- Systematics : 5% due to re-interactions

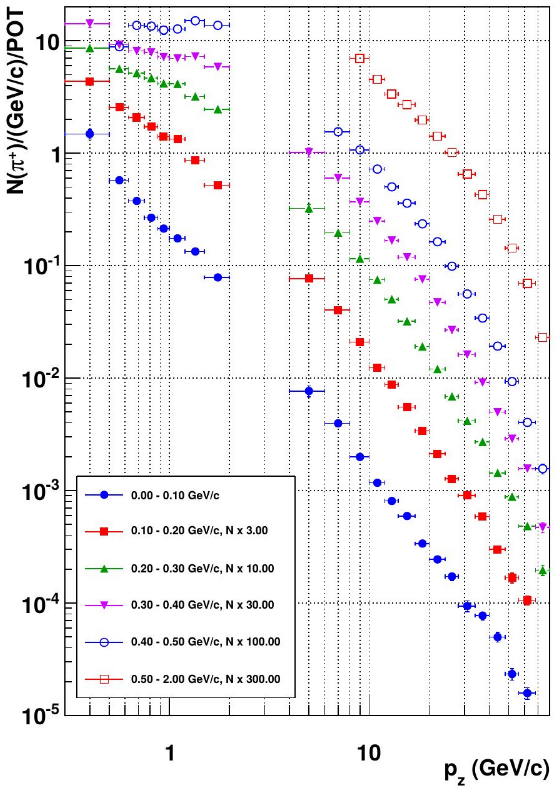


Nucl. Instr. Meth. A 571(2007) 527 13

MIPP (The Main Injector Particle Production Experiment)

- Secondary beam from the Main Injector
- Targets: H, D, Be, C, N, Cu, Bi, U, NuMI
- Beam: π, K, p, beam momentum: 5 - 120 GeV/c (primary and secondary beam)
- p_t: 0-2 GeV/c
- p_z: 0-80 GeV/c
- Uncertainty: 5-10%

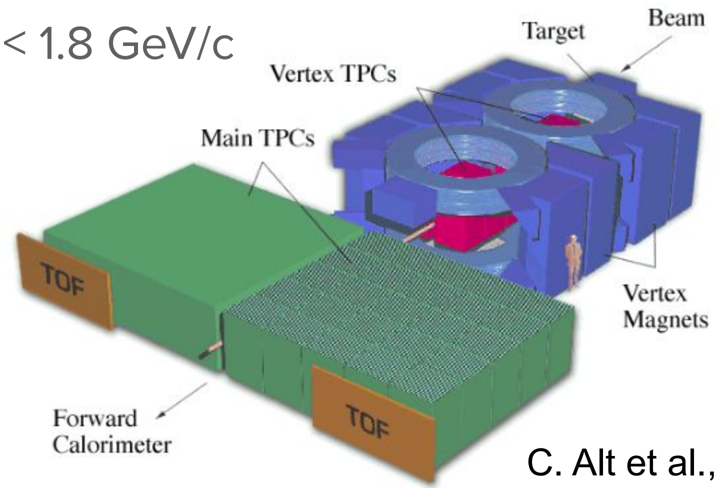


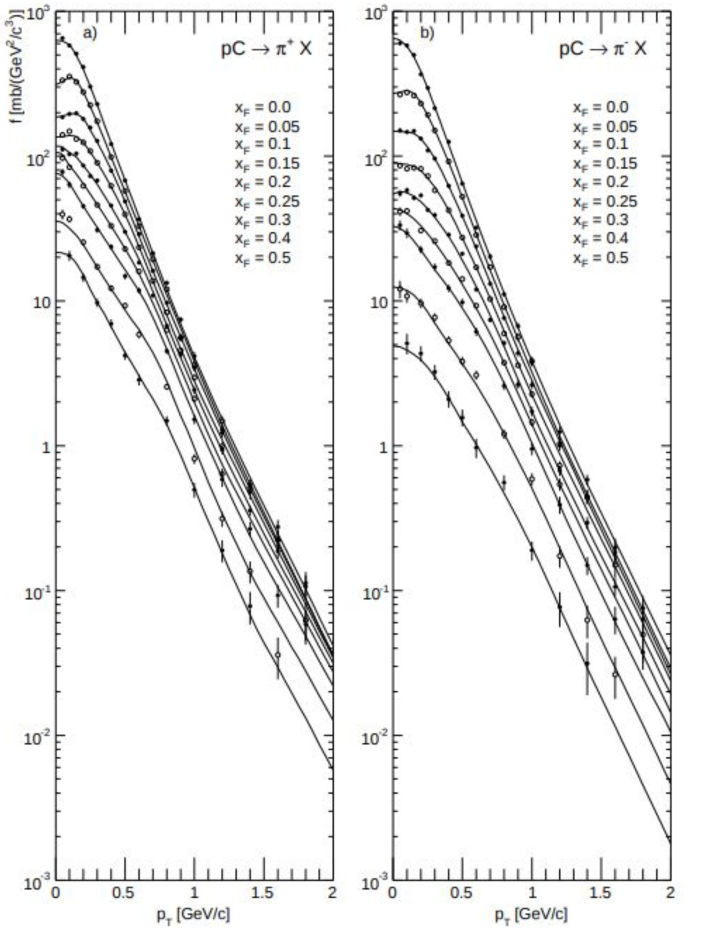


Phys.Rev. D90 (2014) 032001

NA49

- CERN SPS
- Main physics goal is not related to neutrino physics
- Beam: 158 GeV/c
- p+p, p+A, A+A collisions
- p+C measurements are useful for NuMI flux predictions
- Systematics: 3-8%
- x_F: -0.1 - 0.5, $p_t < 1.8$ GeV/c





C. Alt et al., Eur.Phys.J. C49 (2007) 897-917