Implementation of experimental data in PPFX

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ICARUS flux note completed

Prediction of NuMI electron and muon neutrino flux in ICARUS

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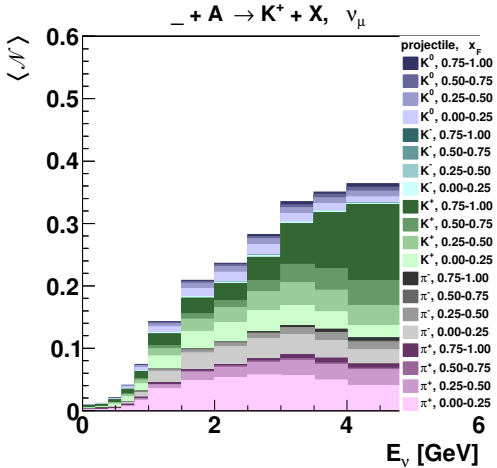
Abstract

The NuMI neutrino flux prediction for ICARUS is extracted using Package to Predict the Flux (PPFX). Systematic effects on the flux due to modeling of the beamline and hadronic interactions are studied. Validity of the simulation's uncertainty characterization for high off-axis angles is evaluated, and potential avenues for improving the prediction and reducing the uncertainties are identified. The predicted electron and muon (anti–)neutrino flux for both forward and reverse horn operating modes is presented with its expected uncertainties. Covariance matrices were calculated and a principal component analysis (PCA) was performed to reduce statistical noise and remove degeneracies. The total uncertainty on the flux in the 0–20 GeV range of neutrino energy was found to be 11.5% (7.0%) for ν_μ (ν_e) incident on the ICARUS detector.

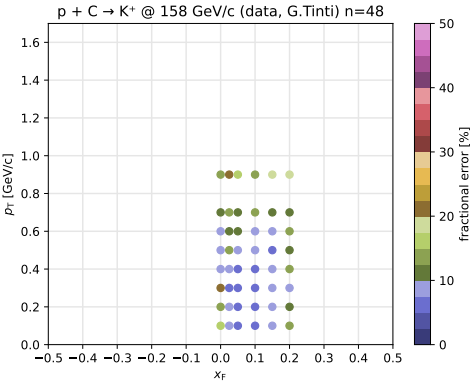
SBN Document 27384

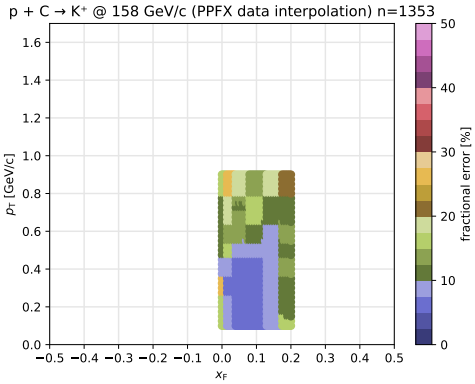
Impact of hadron production on neutrino flux



- Hadrons produced in various x_F bins contribute similarly to all energies of the neutrino flux
- Hadron production variation in various kinematic bins averages out in neutrino flux

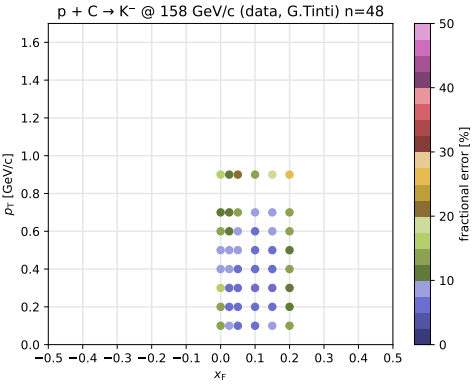
K^+ (G.Tinti) interpolation

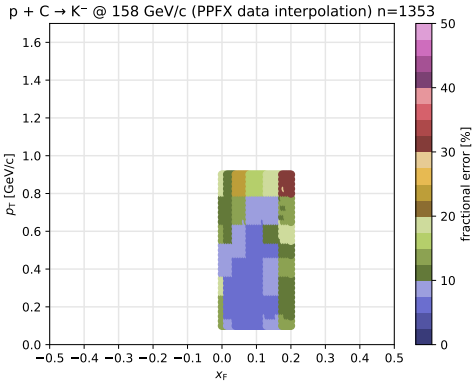




- NA49 p+C $\rightarrow$ K + X dataset from G.Tinti PhD Thesis (2010) was interpolated when implemented in PPFX
- Minor artifacts in interpolation (irregular patterns in the right plot) $\rightarrow$ not really significant
- Number of statistically independent points was increased $1353/48 = 5.3^2$ times
  - PPFX **underestimates** the **statistical** error contribution to the ν flux by factor of order of **5.3**
- I believe that G.Tinti's thesis reported **total** errors, while PPFX interprets them as statistical
  - **slight overestimation** of statistical errors

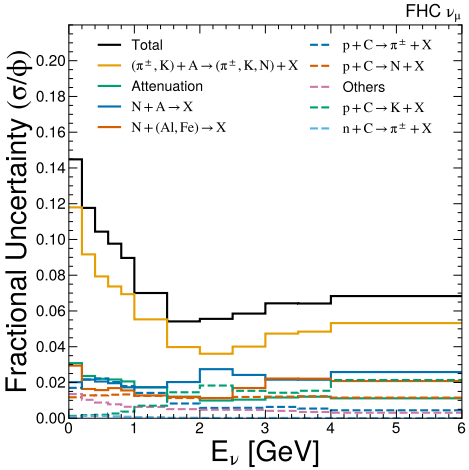
K^- (G.Tinti) interpolation



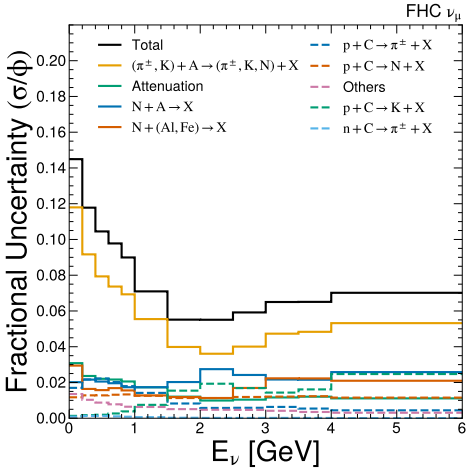


Impact on the flux uncertainties (ICARUS)

regular PPFX



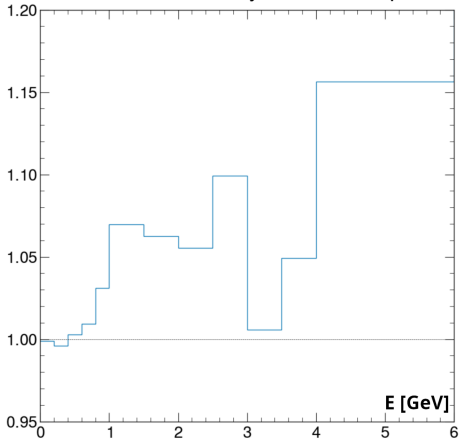
my attempt to bypass interpolation



- p+C $\to$ K + X contribution (dashed green line) increase by up to 1% at the top energy

Relative impact on the flux uncertainty

Ratio of p+C $\rightarrow$ K + X contribution uncertainty without interpolation to with interpolation:



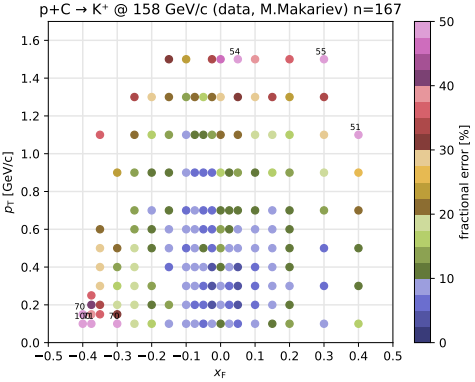
- Contribution to flux increases, by (relative) 5–10%, rather than by factor of 5
- Only statistical uncertainties are affected
  - Systematic uncertainties dominate the flux error

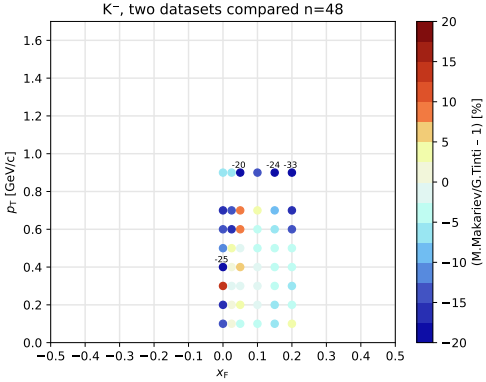
Proposed way to implement data in PPFX

1. Take experimental data using published variables and binning
   - For NA49 data some bins need to be assumed, as they are not clearly published
2. Generate MC in the same binning as the experimental data
   - For NA49 data, which are corrected for the spectrum variation within the bin, a high statistics MC, fine binned MC should be used, and the large bins should be filled with values from fine bins in the middle
3. Apply collision energy scaling separately, in (x_F, p_T) bins (as usual)

- Requires some modification of PPFX code, and the already implemented data
- But makes adding new dataset much easier
- Avoids issues caused by interpolation, described earlier
- Discontinuities in PPFX hadron spectrum corrections resulting from lack of interpolation will average out in the neutrino spectrum, and will not introduce a systematic bias
- ROOT TH2Poly class can facilitate storing data in irregular binning

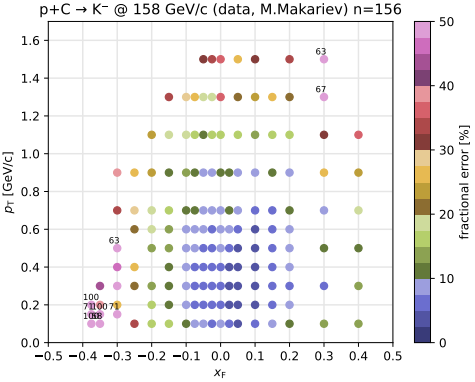
K^+ newer analysis from M.Makariev

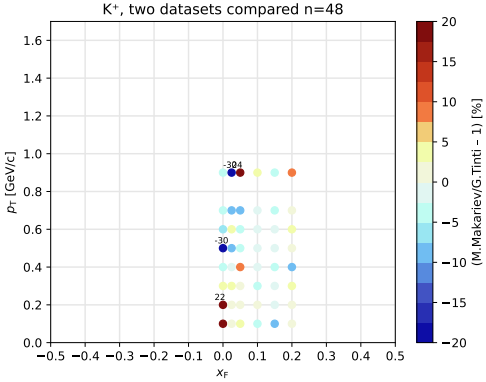




- NA49 **preliminary**, more advanced analysis (EPS HEP 2013 → [slides], [poster], never published in a paper)
- Significantly larger (x_F, p_T) phasespace coverage
- Some disagreement with the results of G.Tinti
- Areas below 20% (blue and green) could be a valuable addition to PPFX, especially at $-0.1 < x_F < 0$
- Only statistical errors given. From MM: At (x_F>0 systematic errors should be similar to p+p with 1% addition to the normalization error. At At (x_F<0 larger errors expected due to the dE/dx crossover

K^- newer analysis from M.Makariev





New effort to generate updated NuMI MC

- Ongoing effort
  - Up to date “1MW” beam and target parameters
  - New Geant version
  - Relevant list of beam systematics to study, with statistics suitable for off-axis experiments
- PPFX changes might be required
  - Needed review of target geometry hard coded in PPFX
  - New MC spectra coming from the same Geant version

Conclusions

1. Interpolating data leads to underestimation of flux uncertainties
   - This is a different (and larger) issue from the one discussed in 2021
   - The issue could be avoided while preserving the interpolation, but it might be complicated $\rightarrow$ potential for more errors
   - Other PPFX datasets affected too e.g., NA49 p+C$\rightarrow\pi^{\pm}$+X 270 experimental bins interpolated into 9801 PPFX bins
   - At present, the overall effect is small, as the dominant contribution are the non-measured interactions
   - But the mistake should be avoided when including new data
   - Also effect might be more significant with any older datasets with larger statistical errors
2. A method to handle data without interpolation was presented
3. Preliminary NA49 data on p+C$\rightarrow$K$^{\pm}$+X from M.Makariev could be a valuable addition to PPFX
4. Systematic uncertainties have the dominant effect on neutrino flux
   - We need to request new experiments to calculate the systematic uncertainties carefully
5. Ongoing effort to produce up to date NuMI MC simulation