Understanding the Off-Axis Flux of Neutrinos from Neutral Kaons

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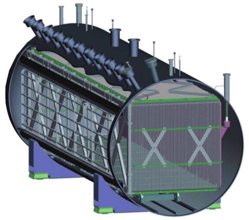
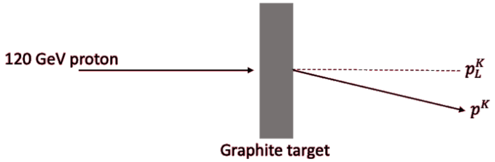
Overview

- The MicroBooNE experiment



- Why υ_es and why kaons?

- Method



$$x_F = \frac{2p_L^K}{\sqrt{s}}$$

- Results

p-p

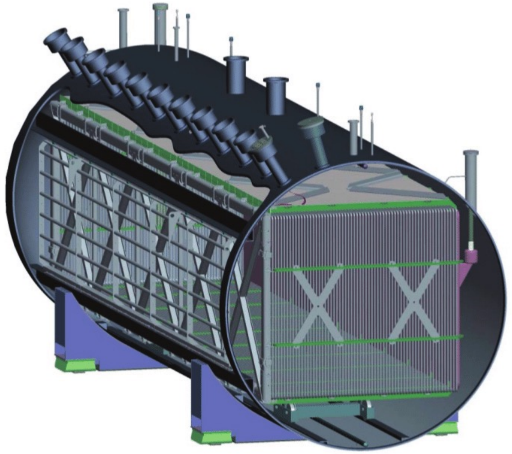
$$\boxed{N(K^0_{L(S)}) = \frac{N(K^+) + 3N(K^-)}{4}}$$

p-C

$$\boxed{N(K^0_{L(S)}) = \frac{3N(K^+) + 5N(K^-)}{8}}$$

The MicroBooNE Experiment

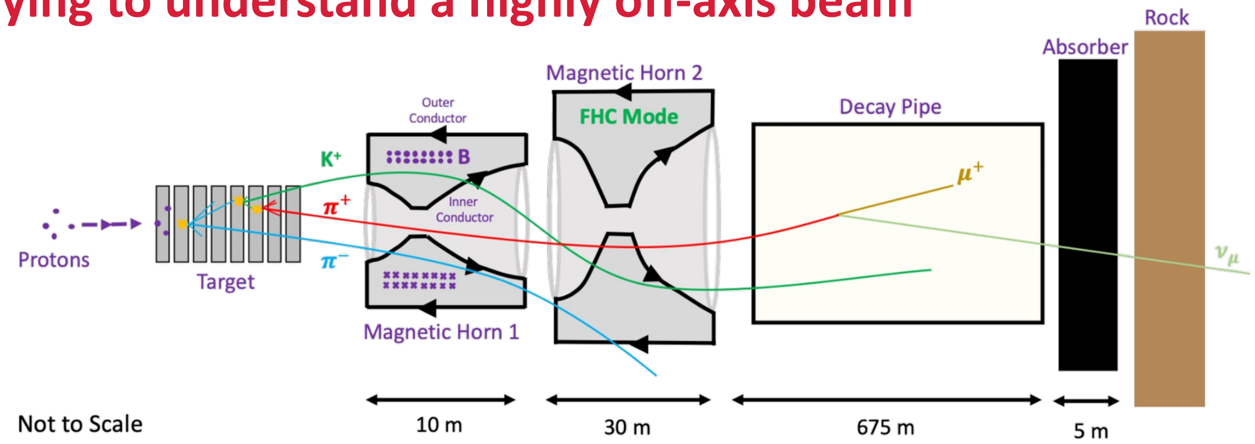
- MicroBooNE is a liquid-argon time projection chamber (LArTPC) neutrino detector, based at Fermilab (Batavia, IL)
  - Active volume of 85 tonnes of LAr
  - Took five runs of data between 2015 and 2021
- Investigating **low-energy excess**
- Measuring **neutrino-argon cross sections**

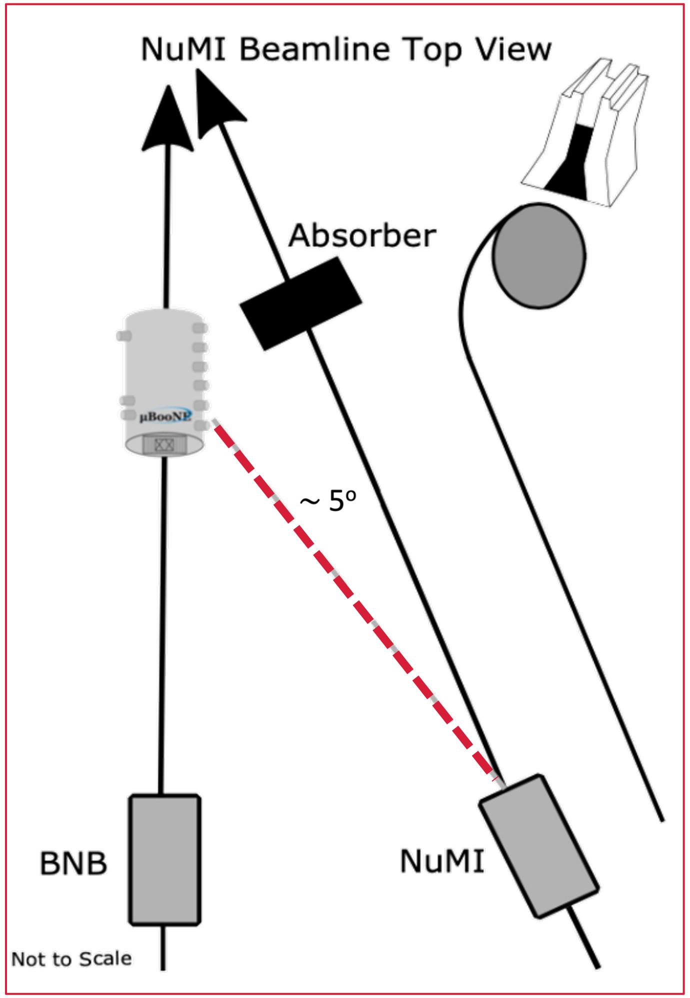


The MicroBooNE Experiment

- MicroBooNE receives neutrinos…
  - on-axis from the Booster Neutrino Beam (BNB)
  - off-axis from Neutrinos from Main Injector **(NuMI) beam**
- NuMI provides a higher flux of v_e and $\overline{v_e}$ (~4 % of flux) than BNB

  →**We are trying to understand a highly off-axis beam**

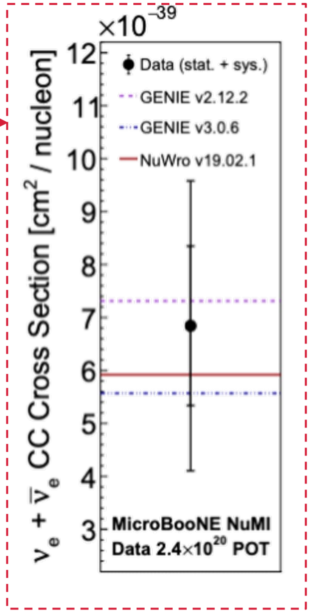




K. Mistry

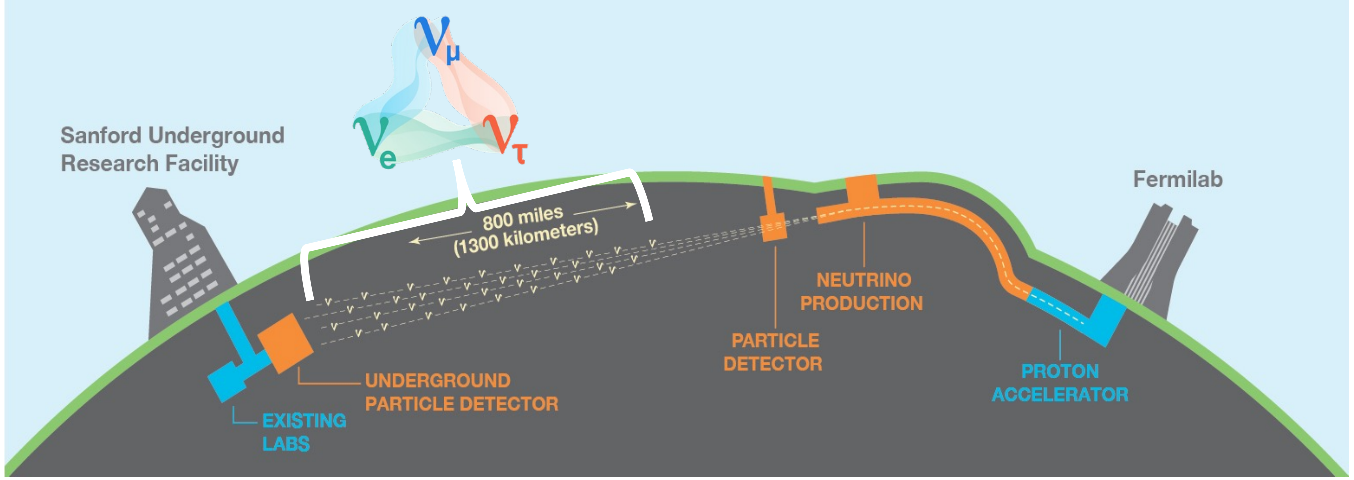
Motivation: why ν_e and $\overline{\nu_e}$?

MicroBooNE have published ν_e cross section papers here and here!



- Measurements of the electron-neutrino cross sections are crucial for furthering our understanding of neutrino physics
  - Mass ordering, sterile neutrinos, CP violation

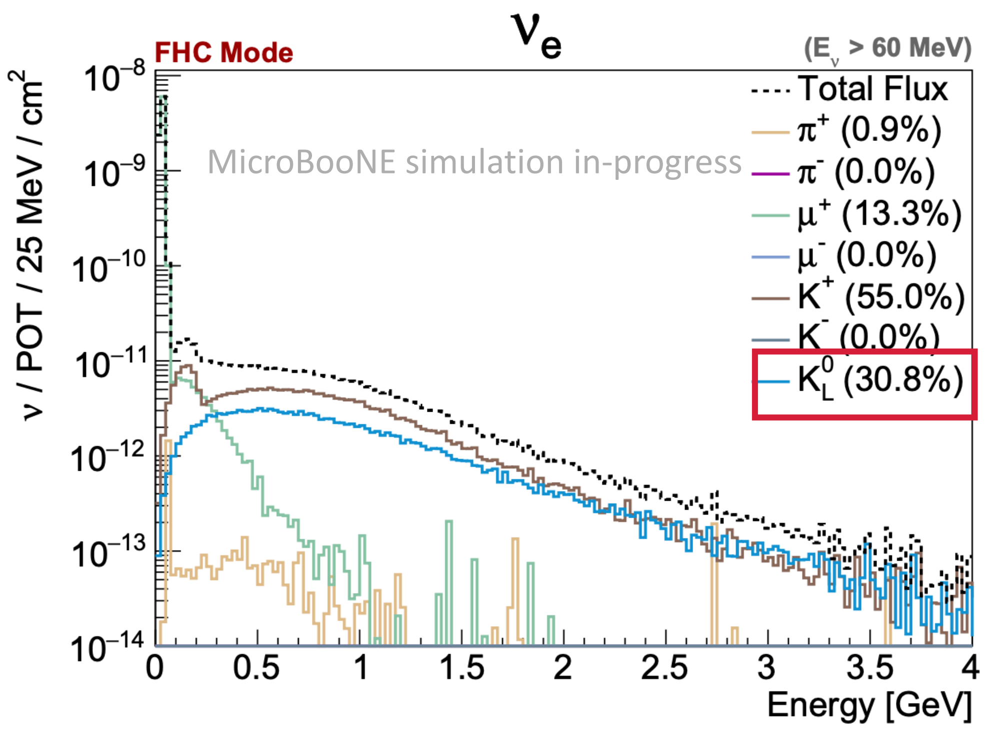
- Needed for oscillation experiments, which will be using liquid argon
  - Electron neutrinos involved in disappearance and appearance channels

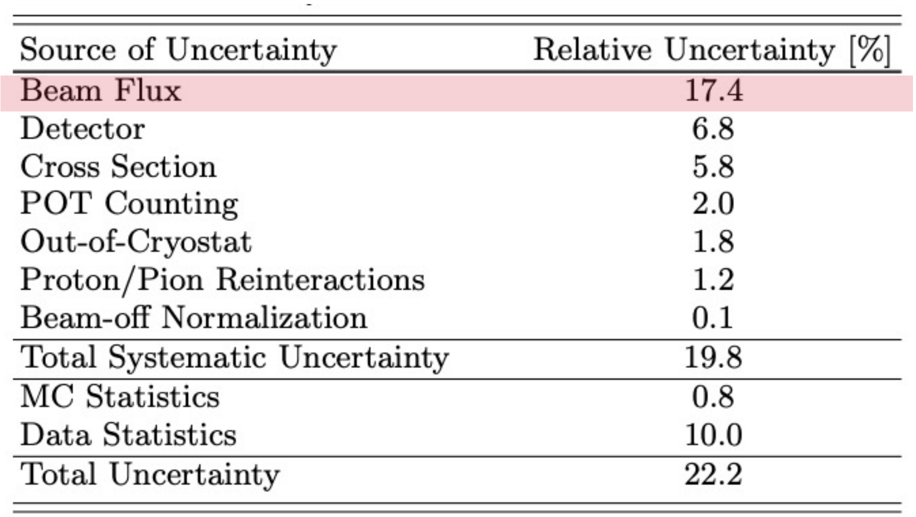


Kaon flux at NuMI

- Approx. 30 % of ν_e flux at MicroBooNE from NuMI comes from K_L^0 decays
    - Important to simulate accurately and precisely for ν_e cross sections
    - Flux is largest systematic uncertainty

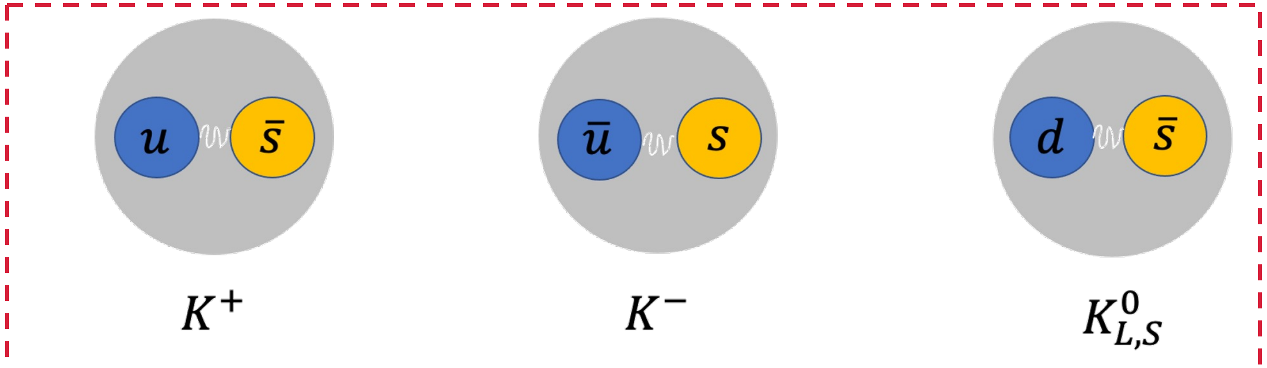
$$\langle\sigma\rangle = \frac{N - B}{\epsilon \times N_{\text{target}} \times \Phi_{\nu_e + \bar{\nu}_e}}$$





Source of Uncertainty	Relative Uncertainty [%]
Beam Flux	17.4
Detector	6.8
Cross Section	5.8
POT Counting	2.0
Out-of-Cryostat	1.8
Proton/Pion Reinteractions	1.2
Beam-off Normalization	0.1
Total Systematic Uncertainty	19.8
MC Statistics	0.8
Data Statistics	10.0
Total Uncertainty	22.2

Particle physics 101 – what's a kaon?



A meson consisting of one strange quark/antiquark and one up or down quark/antiquark

K^0 has 2 eigenstates: one **short lived, K^0_S**, and one **long lived, K^0_L**

$$K^0_L \rightarrow \pi^\pm e^\mp \nu_e$$

40.5% of K^0_L decays result in the production of an electron neutrino

The current picture

- Uncertainty on ν_e yield from K^0_L currently comes from PPFX
  - a particle production, transportation and decay package also used by MINERvA and NOvA, more on-axis

- K^0_L yield calculated with hadron production data through use of the **Gatignon Wachsmuth formula**, derived assuming isospin symmetry:

$s_s = \bar{s}_s$

$u_s = \bar{u}_s = d_s = \bar{d}_s$

$$\boxed{N\left(K^0_{L(S)}\right) = \frac{N(K^+) + 3N(K^-)}{4}}$$

($N(X)$ = number of X produced in an interaction)

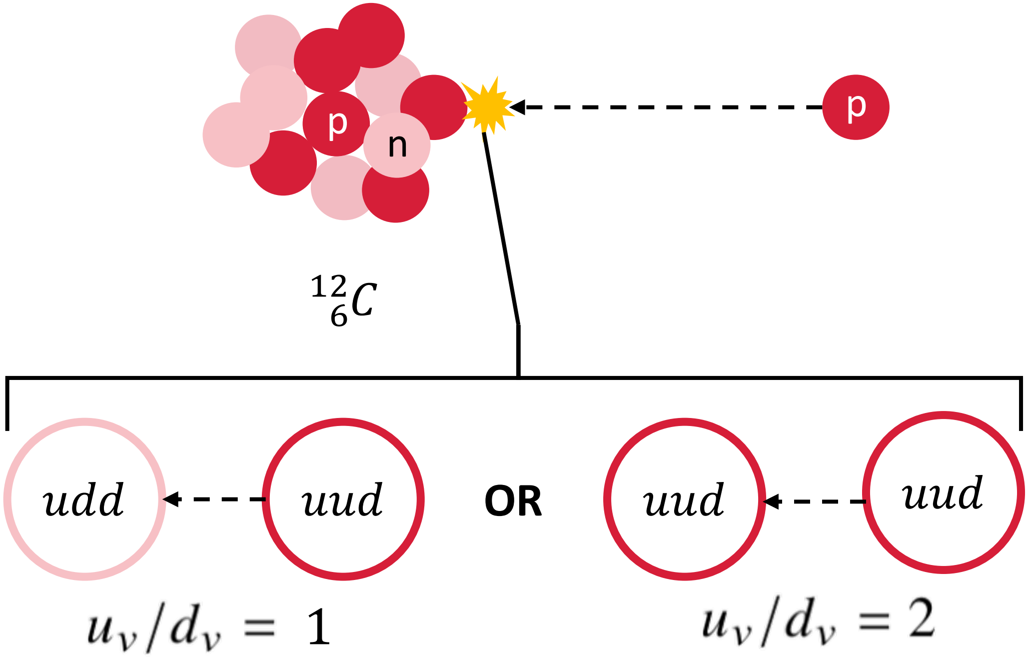
$u_v / d_v = 2$

Derivation!

Application to NuMI

- To create the NuMI beam, a proton beam hits a **graphite** target, so we have a **proton-carbon collision**
  - Equal likelihood of a proton-proton or proton-neutron interaction

  - Average the two equations for those two cases:



$$\boxed{N\left(K^0_{L(S)}\right) = \frac{3N(K^+) + 5N(K^-)}{8}}$$

proton-carbon collision

Derivation!

Aim

- Use charged kaon data from NA61/SHINE to find the percentage difference between K^0_L yield values calculated with the two models (proton-proton and proton-carbon)

Measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton–carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS

Abgrall et al. (2016)

- This will be **an additional model uncertainty** on our current flux model
  - Currently no uncertainty on equation

p-p $N(K^0_{L(S)}) = \frac{N(K^+) + 3N(K^-)}{4}$

p-C $N(K^0_{L(S)}) = \frac{3N(K^+) + 5N(K^-)}{8}$

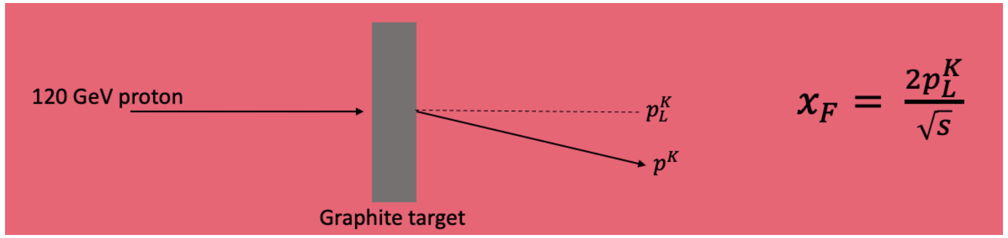
Method

1. ‘Translate’ charged kaon data
   → currently binned in p and θ

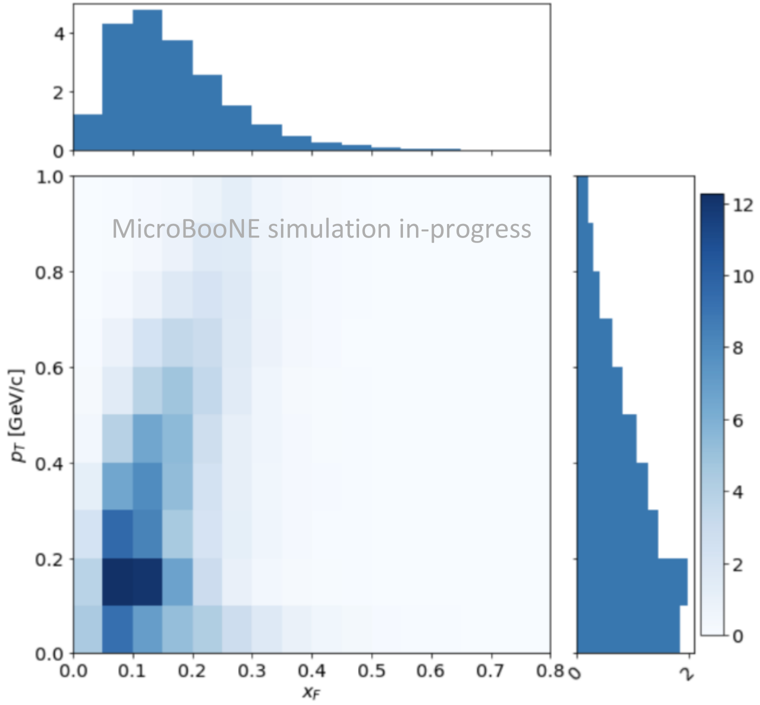
1: ‘Translate’ charged kaon data

$p_T = p\sin(\theta);\ x_F = \frac{2p\cos(\theta)}{\sqrt{s}}$

- cross section is invariant under (x_F, p_T)
  - we can apply NA61/SHINE to NuMI despite different energies (31 vs 120 GeV/c)



- Bonesini et al: isospin model shown to be accurate for $0.18 < x_F < 0.36$, and agrees with direct production measurements within 15% for $x_F < 0.5$



2D distribution of transverse momentum and Feynman-x for K^0 that generate electron neutrinos traversing the MicroBooNE detector from NuMI Run 1, with area normalised histograms for individual distribution; each bin is weighted such that the weights sum to 1.

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Method

1. 'Translate' charged kaon data ☑
   → currently binned in p and θ
2. Fit (x_F, p_T) distributions of charged kaons with a continuous polynomial function
   → reduces statistical uncertainty

p-p

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p-C

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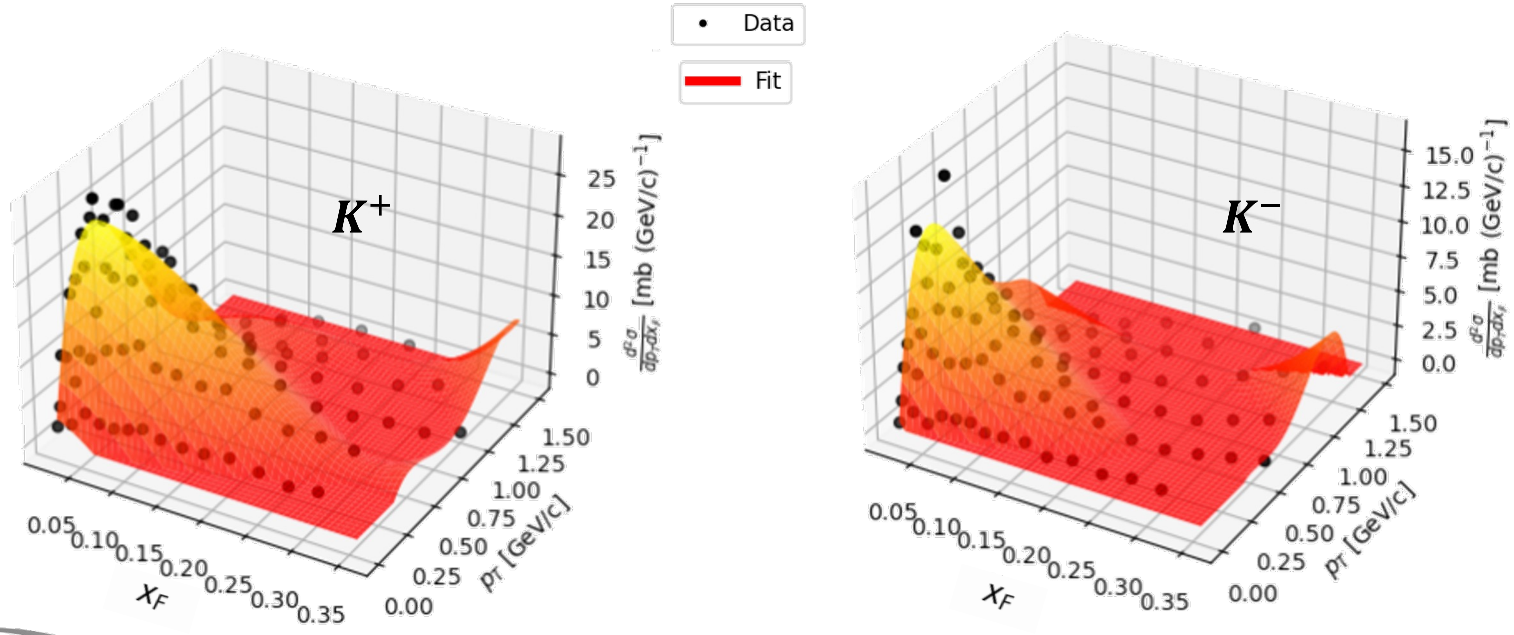
2: Fit charged kaon yield functions

- Data from NA61/SHINE for K$^+$ (left) and K$^-$ (right) yield as a function of Feynman-x and transverse momentum, shown in black, fitted with a polynomial function, shown in red.



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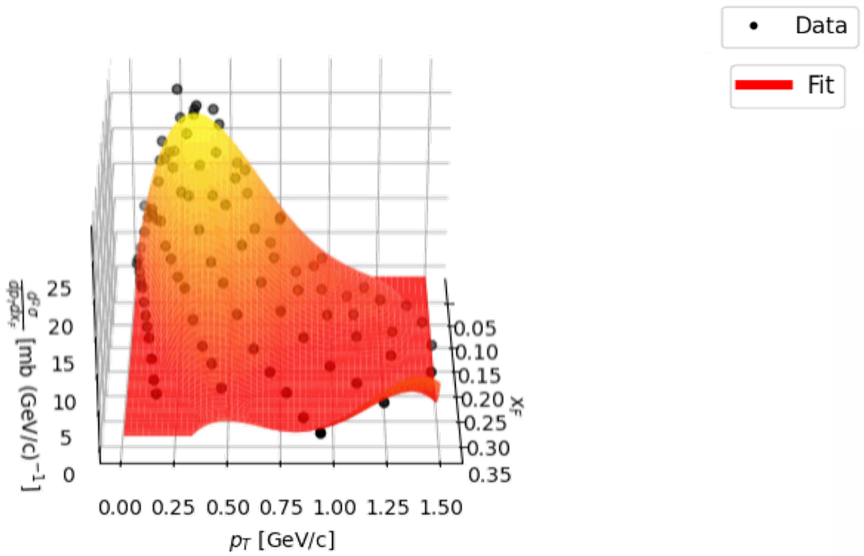
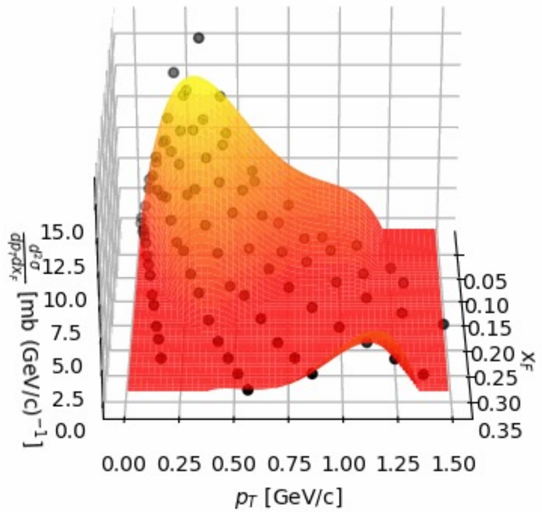


K^+



K^-

p-p

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1. ‘Translate’ charged kaon data ☑

   → currently binned in p and θ

2. Fit (x_F, p_T) distributions of charged kaons with a continuous polynomial function ☑

   → reduces statistical uncertainty

3. Use K^+ and K^- functions to find K_L^0 yields using the two equations

3: Functions of the equations

p-p $N(K^0_{L(S)}) = \frac{N(K^+) + 3N(K^-)}{4}$

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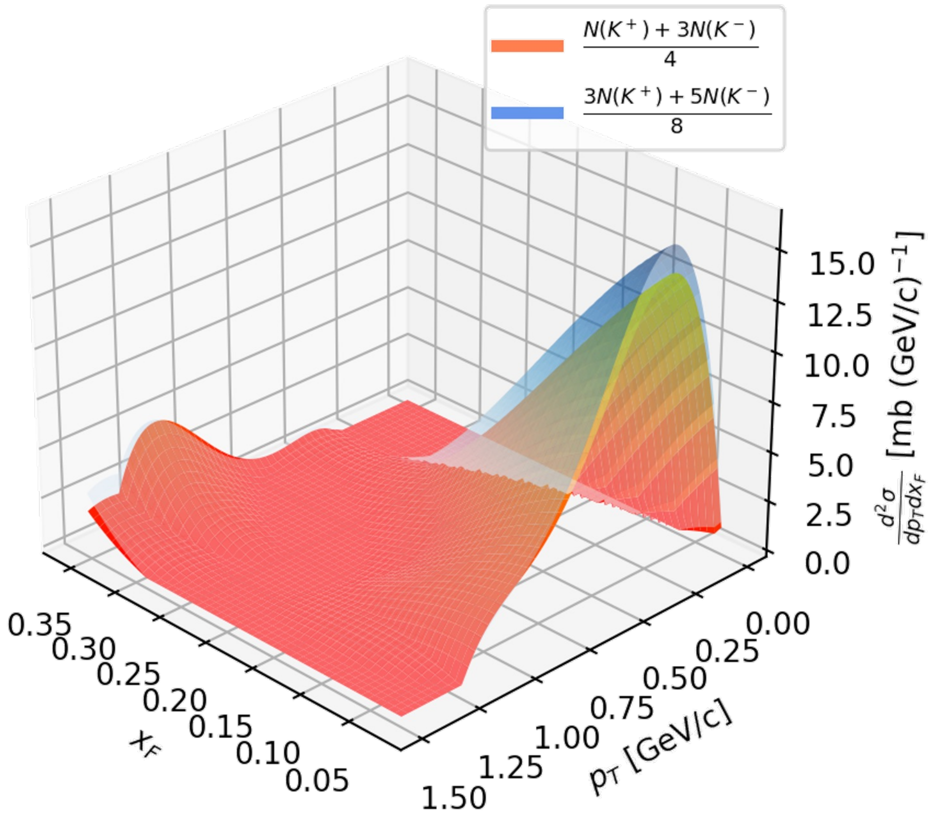

K^0_L yield as a function of x_F and p_T computed using the fitted functions (previous slide) applied to the two equations, p-p (red) and p-C (blue).

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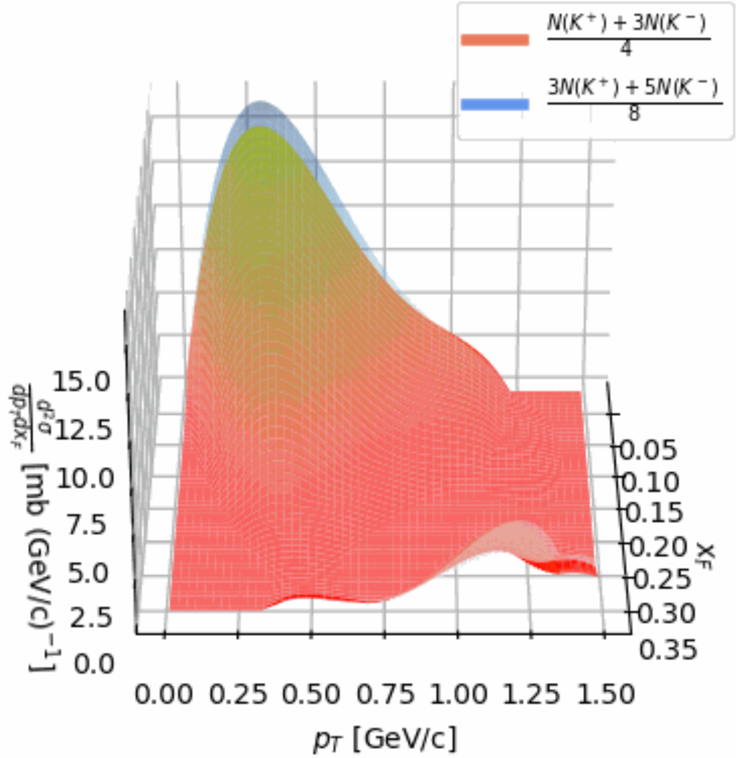

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Method

1. ‘Translate’ charged kaon data ☑
   → currently binned in p and θ
2. Fit (x_F, p_T) distributions of charged kaons with a continuous polynomial function ☑
   → reduces statistical uncertainty
3. Use K^+ and K^- functions to find K^0_L yields using the two equations ☑
4. Percentage difference between model equations can be computed as continuous function of (x_F, p_T)

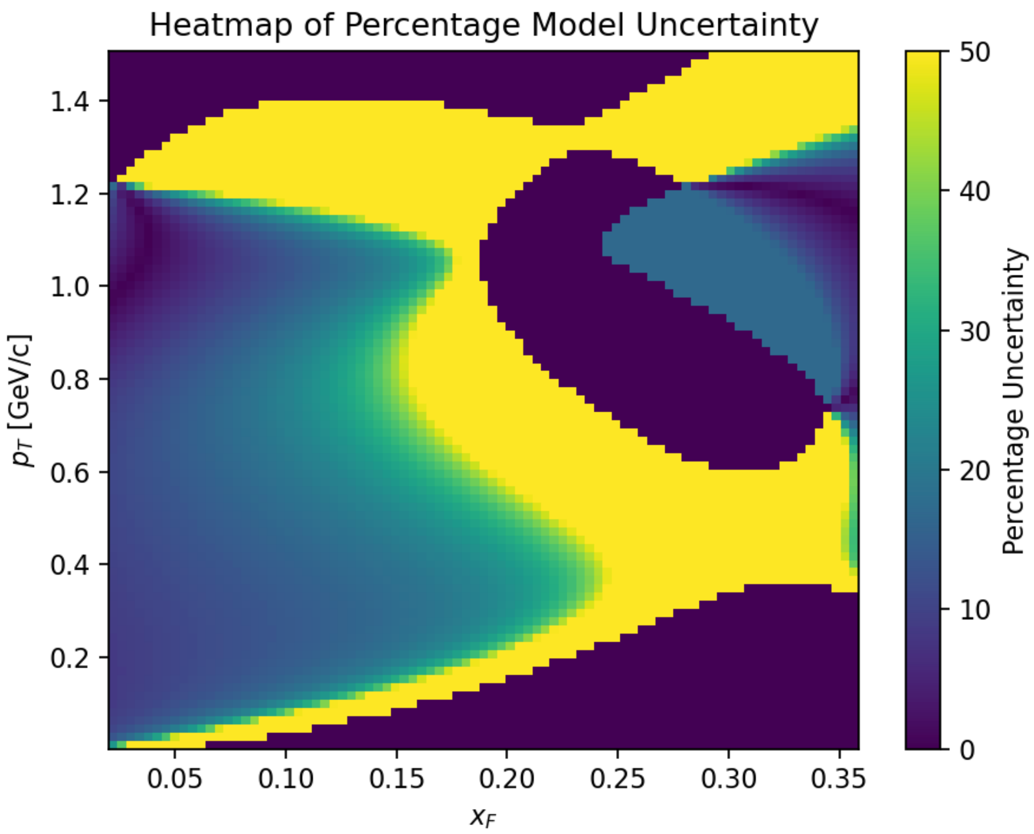
→ **this will be our model uncertainty** p-p $N(K^0_{L(S)}) = \frac{N(K^+) + 3N(K^-)}{4}$

p-C $N(K^0_{L(S)}) = \frac{3N(K^+) + 5N(K^-)}{8}$

4: Percentage model difference

percentage difference = $\frac{|(p-p)-(p-C)|}{(p-p)} \times 100$

- →**where both charged kaon functions functions are at 0**, the percentage difference is **0 %**
- →**where one function is at zero and the other is not**, the percentage difference is **50 %**



Heatmap showing the percentage difference between the K^0_L yield calculated using the two models (p-p and p-c collision) for a given (x_F, p_T) coordinate.

4: Percentage model difference

p-p $N(K^0_{L(S)}) = \frac{N(K^+) + 3N(K^-)}{4}$

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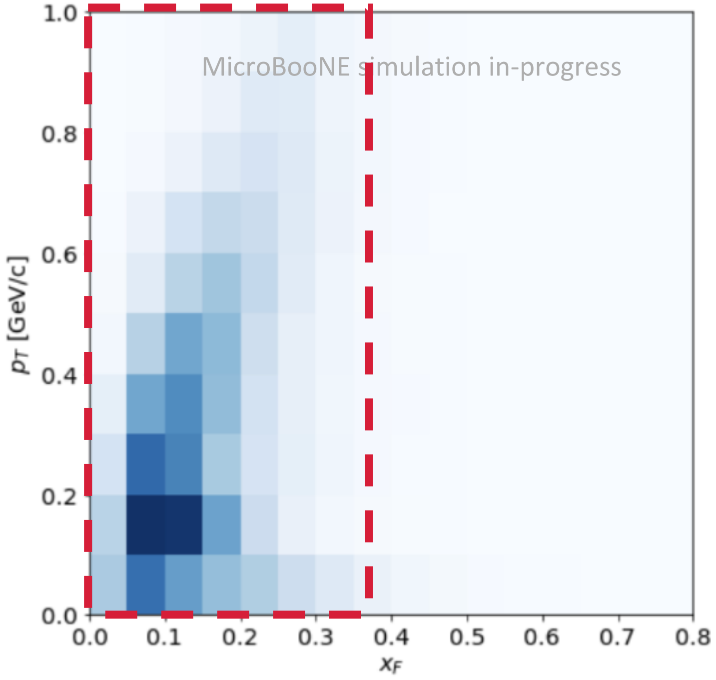

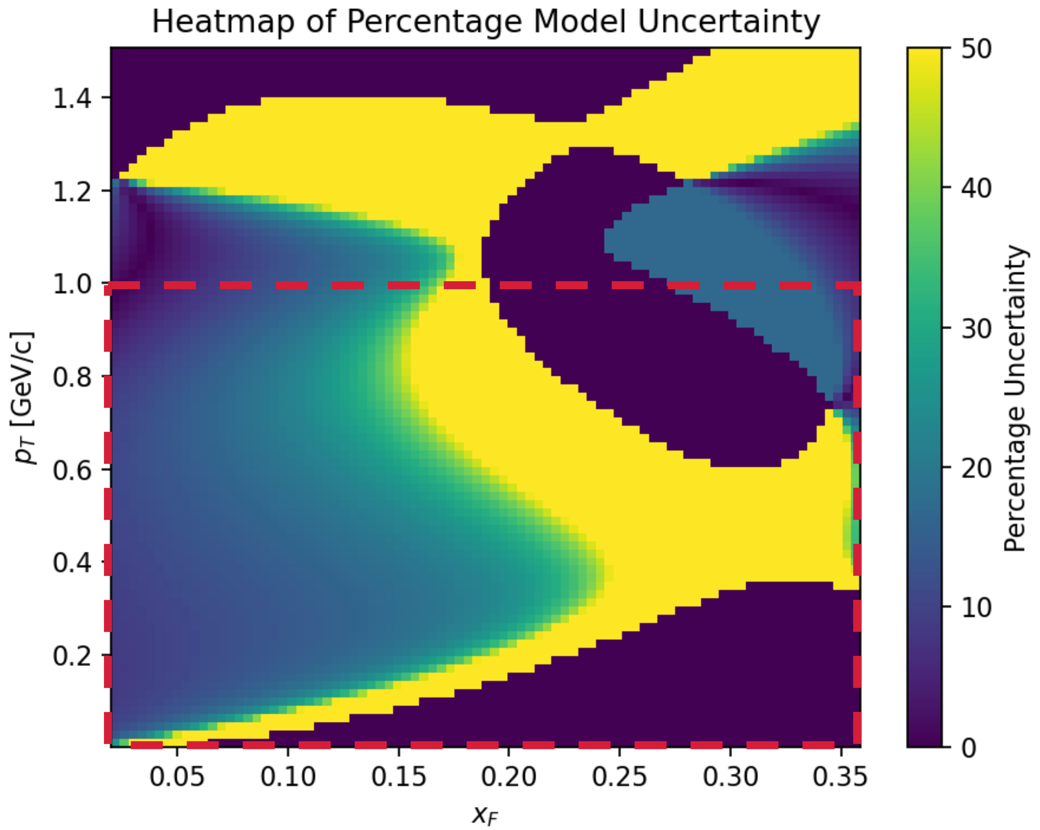

Heatmap showing the percentage difference between the K^0_L yield calculated using the two models (p-p and p-c collision) for a given (x_F, p_T) coordinate.

Summary

- NA61/SHINE charged kaon data has been used to determine an **additional model uncertainty on the $\mathbf{K_L^0}$ yield for NuMI**
  - Continuous function in (x_F, p_T)
  - Can be implemented to MicroBooNE software

- Correctly simulating kaon flux and its uncertainty is crucial for electron neutrino cross section measurements and oscillation experiments

- Publication in the works!

Thank you for listening!

Backup

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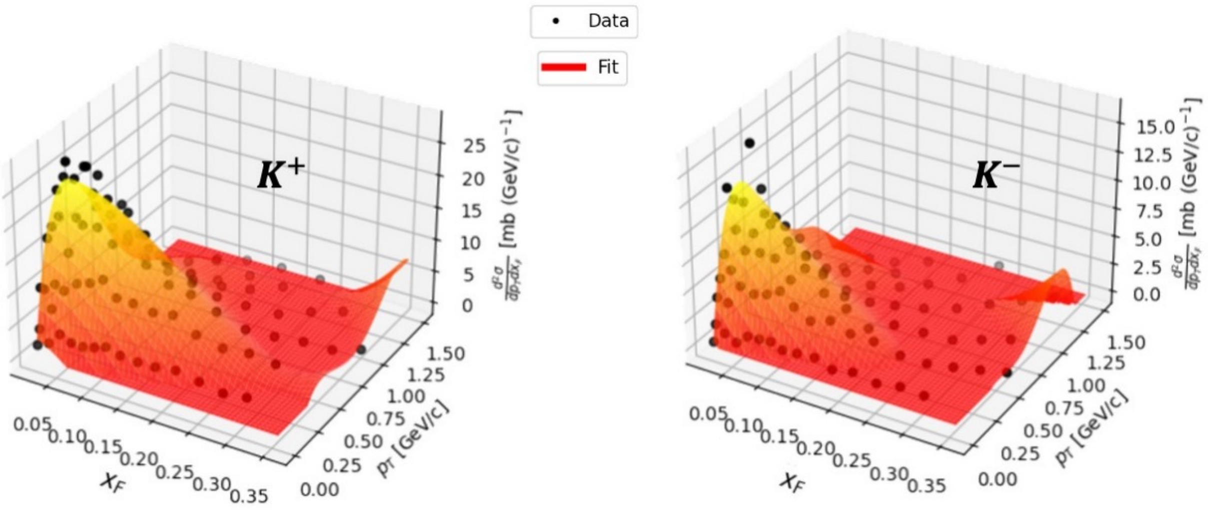
Charged kaon yield functions



NA61/SHINE K+ (left) and K- (right) yield data, shown in black as a function of Feynman-x and transverse momentum, fitted with a polynomial surface, in red.

- RMSE suggests good fit, but fit parameter errors are large: could suggest **overfitting**

  → could try simpler polynomial, but overfitting uncertainty is likely less than the statistical uncertainty that fitting removes