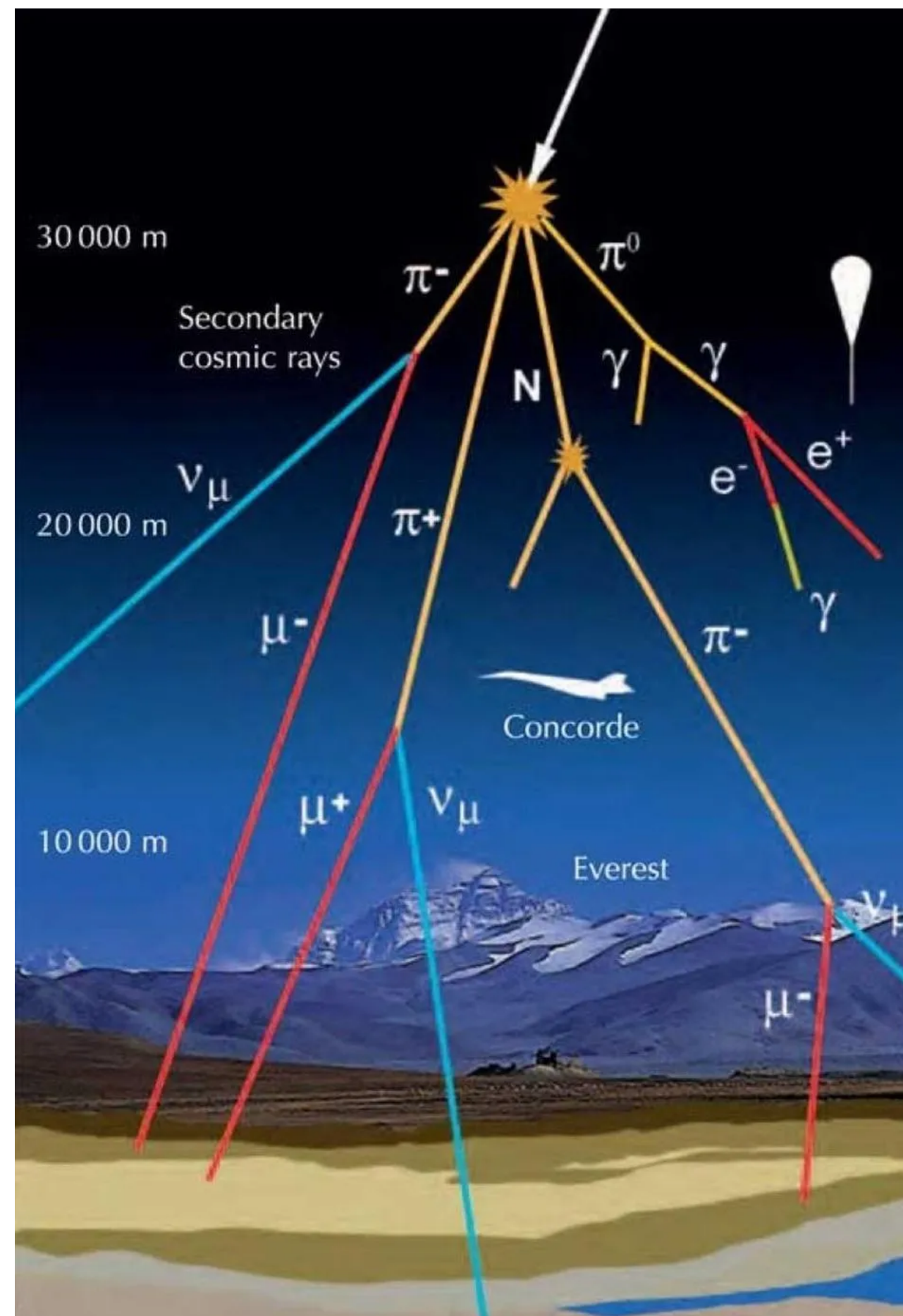


# Tuning the BARTOL Atmospheric Neutrino Flux Calculation to Hadron Production Measurements

Trystan Coveney

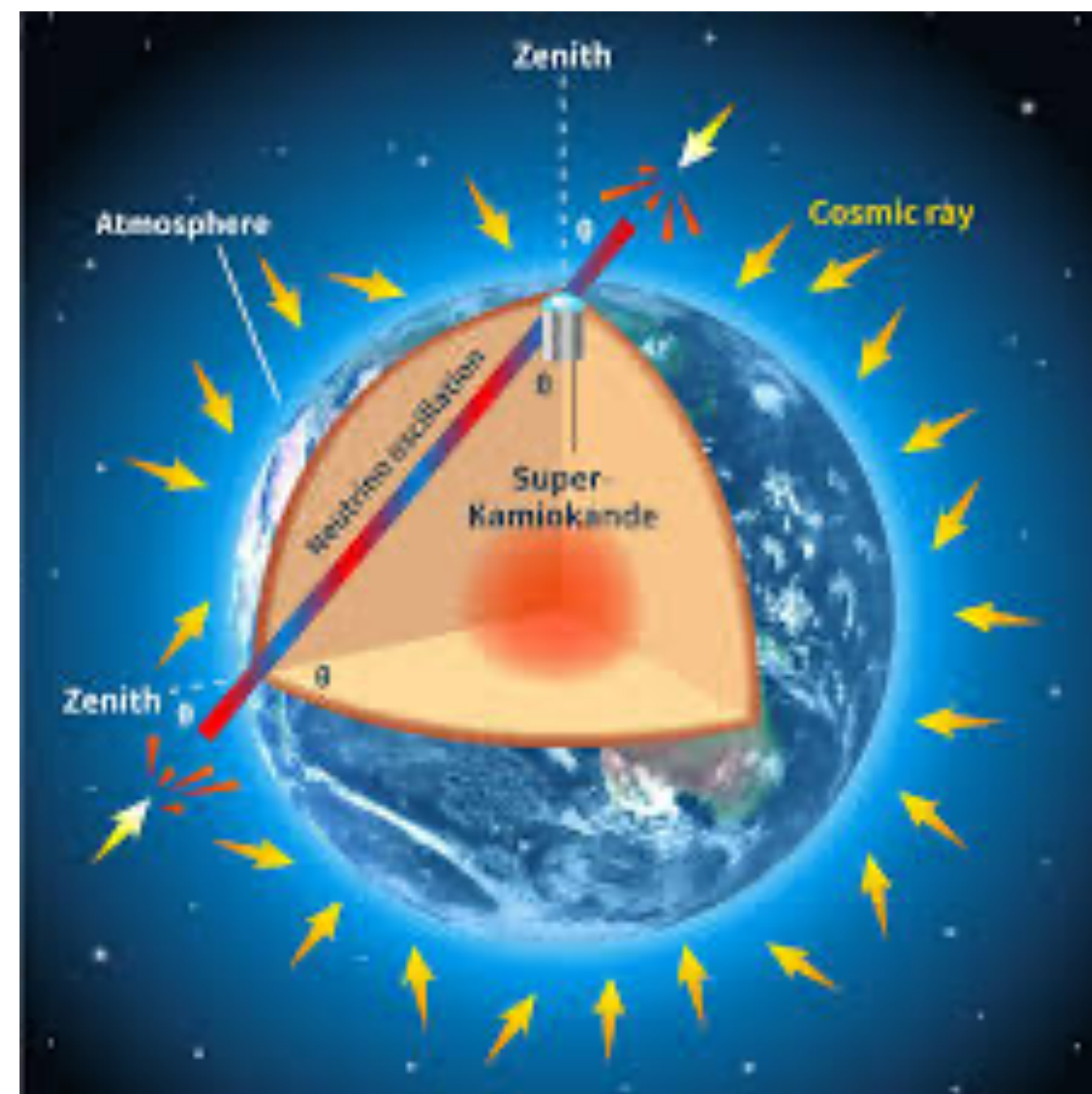
# What Are Atmospheric Neutrinos?

- Atmospheric neutrinos are produced in the decay of mesons that result from cosmic rays interacting with nuclei in the atmosphere

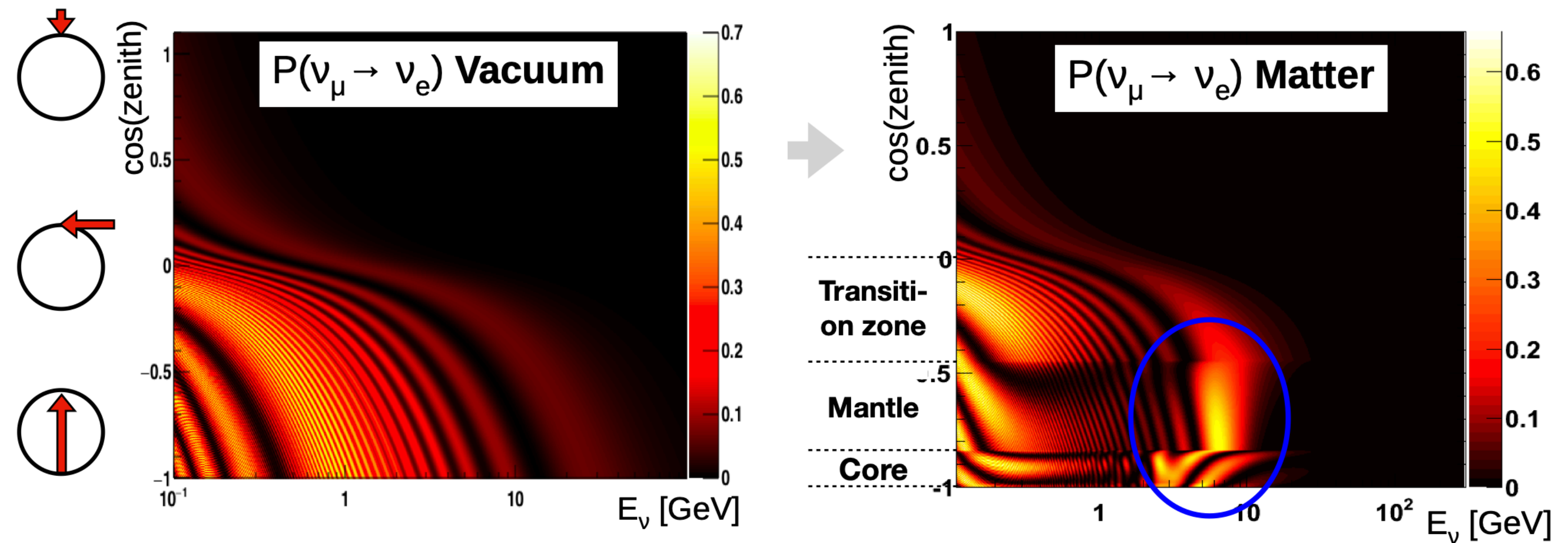


# Why Study Atmospheric Neutrinos?

- Important background for dark matter and proton decay searches
- Oscillations have good sensitivity to mass hierarchy

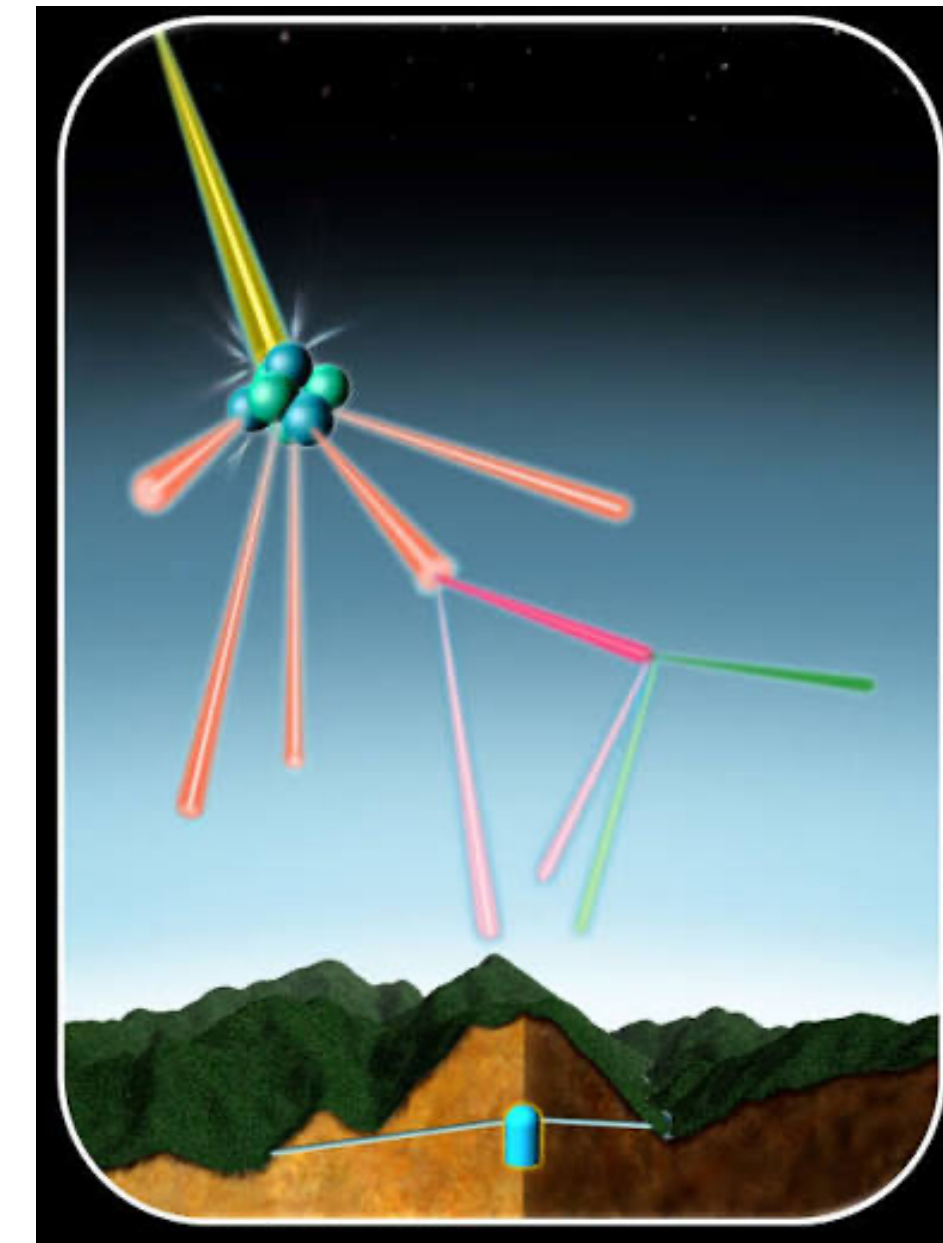


## For Normal Ordering



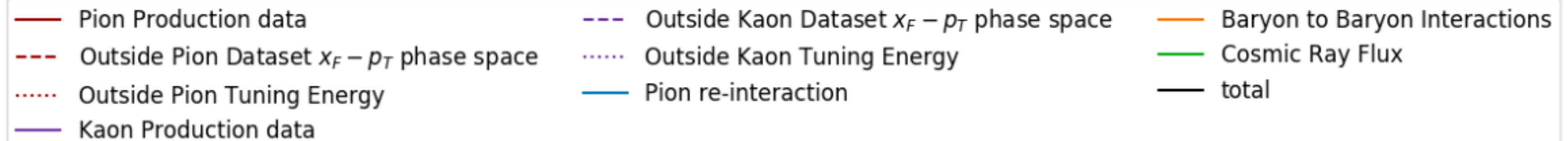
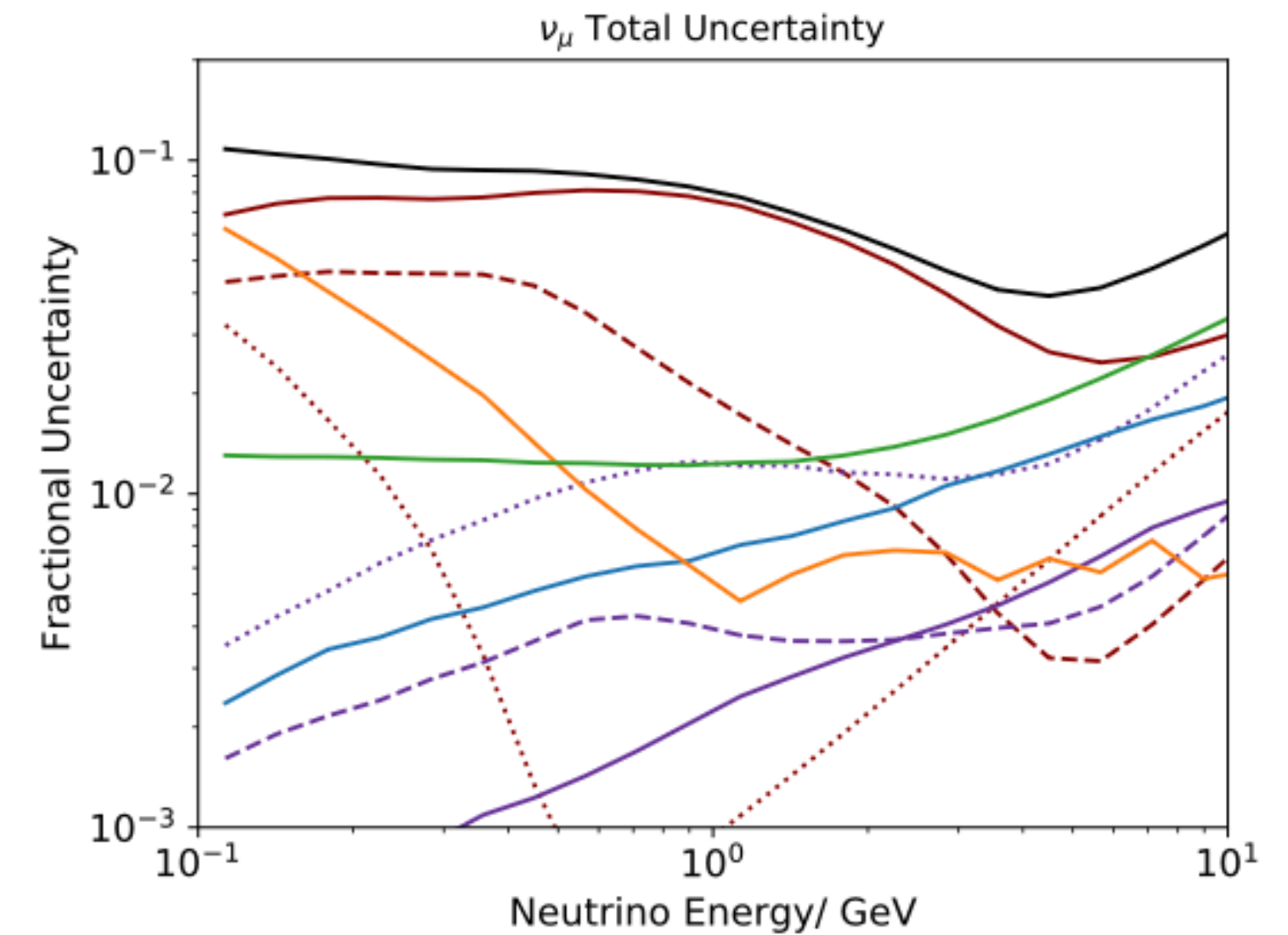
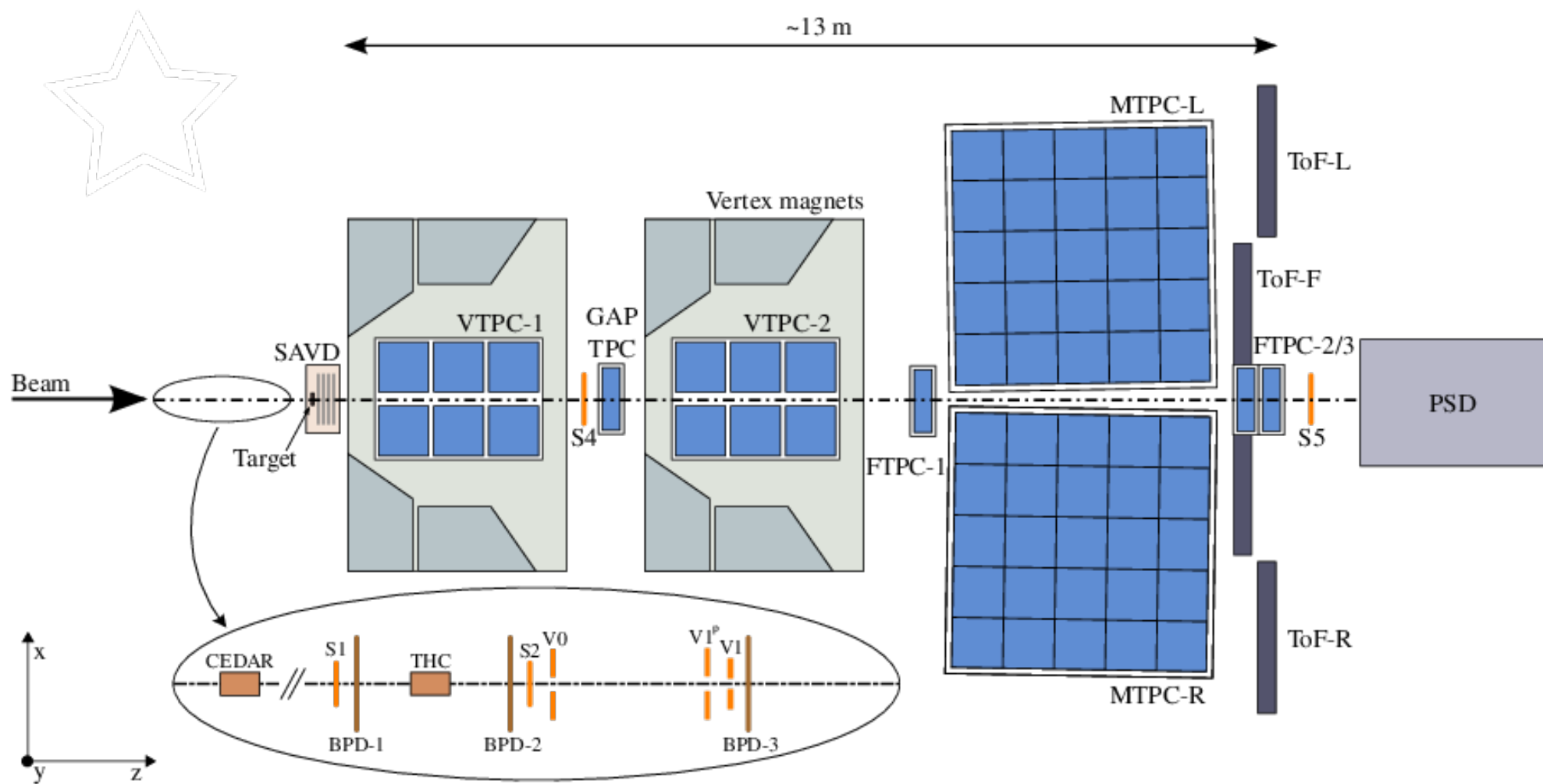
# BARTOL Flux Model

- 3D Monte-Carlo simulation used to predict flux of atmospheric neutrinos as a function of energy and incoming direction
- Inject Cosmic Primaries at a height of 80km in atmosphere of energies 1GeV-10TeV
- Simulate Hadronic Interactions using TARGET and track outgoing particles and their decays
- Count neutrinos at detector location
- Calculate Flux



# Hadron Production Uncertainties

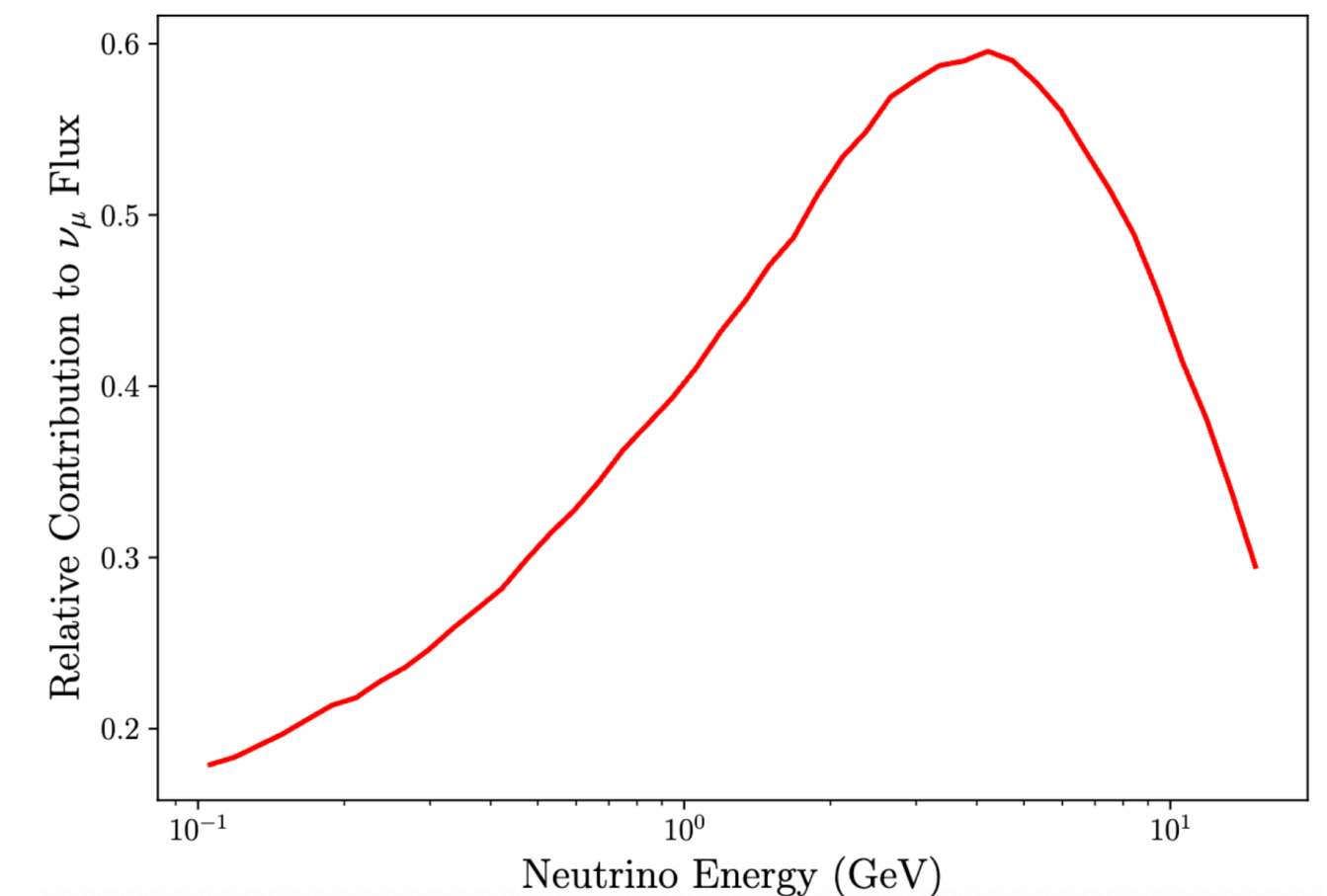
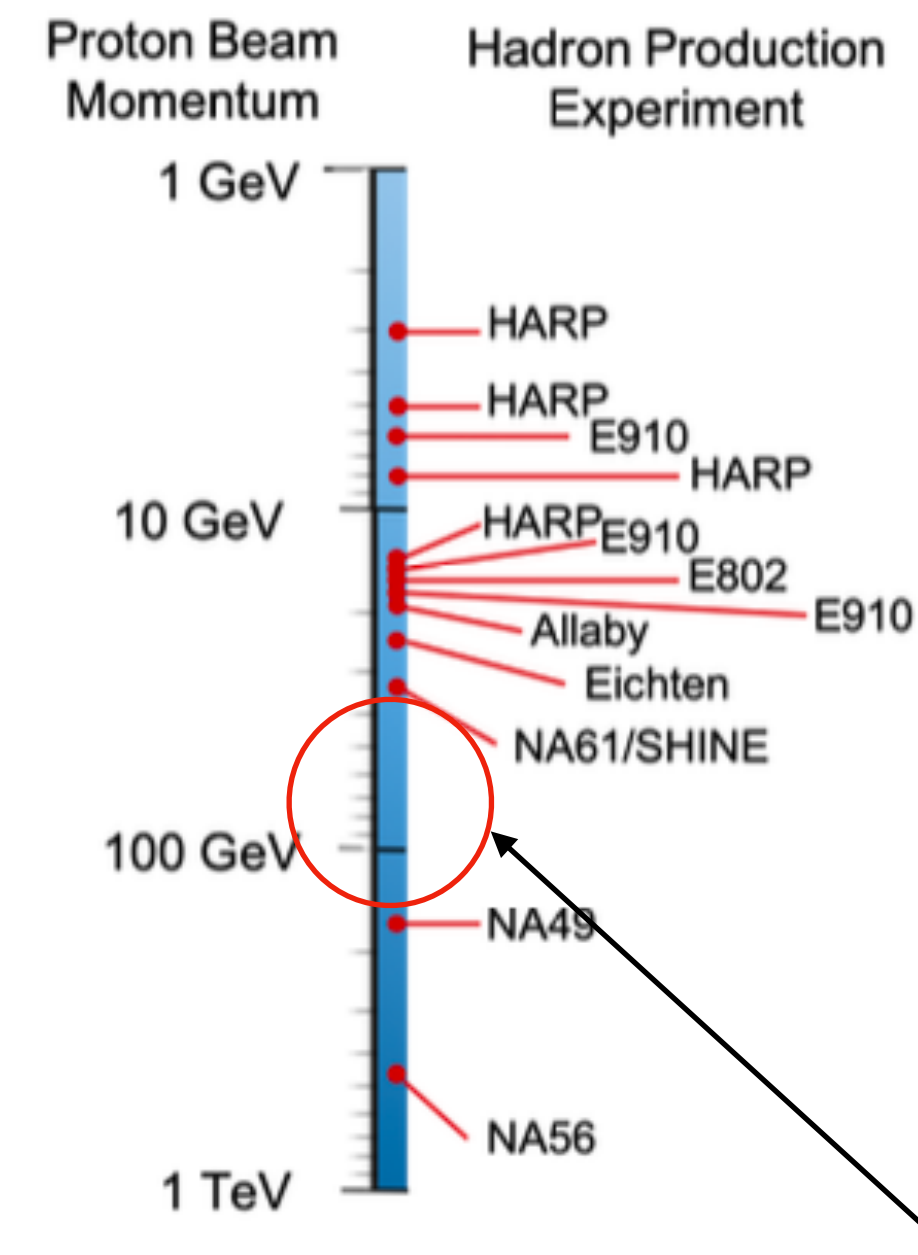
- **Dominant Uncertainties** comes from poor understanding of hadron production
- Previous student developed data-driven method to tune flux prediction to measurements from fixed target experiments to reduce these



From L Cook's PhD thesis

# This Work

- When previous work was conducted, a large range of energies between NA61's 31 GeV/c beam momentum and NA49 at 158 GeV/c
- NA61 recently released data for 120 GeV/c and 90 GeV/c momentum protons on a thin-carbon target (60 GeV/c analysis also underway)
- **Today will be presenting work on incorporating 120 GeV/c data in the flux prediction**



# Modelling Meson Production

- Loosely based on Feynman Scaling which states that the Lorentz-invariant cross section should depend only on  $x_F$  and  $p_T$  of outgoing meson, but not on energy of the collision

$$E \frac{d^3\sigma(p + N \rightarrow \pi^+ + X)}{dp^3}(x_F, p_T)$$

longitudinal momentum of meson as a fraction of the maximum possible magnitude in the CoM frame (between -1 and 1).

$p_T$  is transverse momentum of daughter meson



# Cross Section Parameterisation

- Modified version of the BMPT parameterisation to charged pions and kaons is fit

$$E \frac{d^3\sigma}{dp^3} = \left( \frac{A}{A_{Be}} \right)^{\alpha_1(x_F, p_T)} \left( \frac{A_{Be}}{2} \right)^{\alpha_2(x_F, p_T)} \left( E \frac{d^3\sigma(x_R, p_T)}{dp^3} \right)_{BMPT}$$

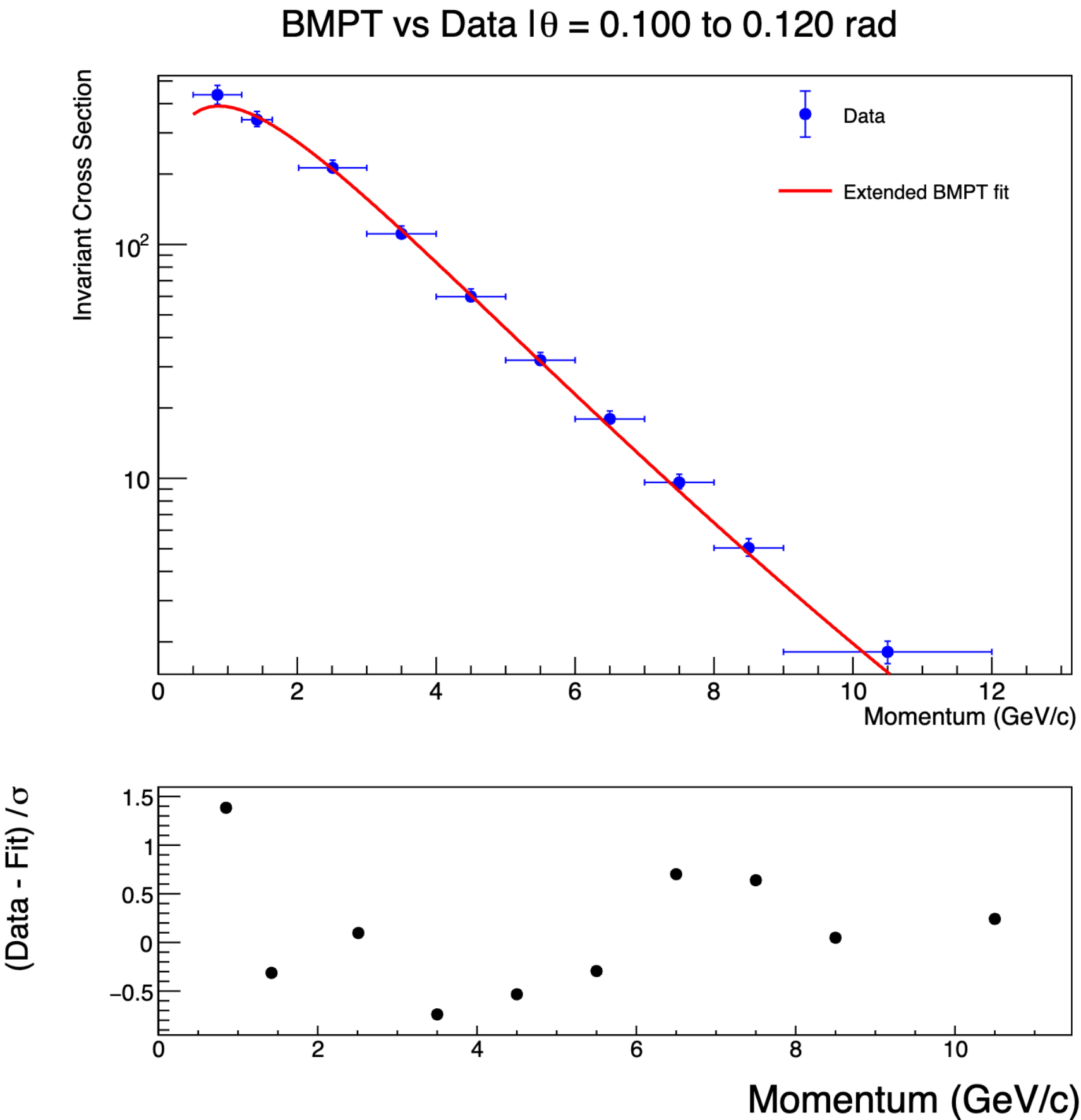
Atomic mass of Beryllium

Atomic mass of deuteron

- $x_R$  is a quantity symmetric in  $x_F \implies x_F$ -dependent A-Scaling terms break forward-backward asymmetry for collision between high energy proton and stationary nucleus
- A-Scaling terms allow extrapolation from carbon to nitrogen and oxygen

# Fits to 120GeV/c p+C data

$$\pi^{-}$$



|           |                       |
|-----------|-----------------------|
|           | $\chi^2/\text{d.o.f}$ |
| $\pi^{+}$ | 76.8/184              |
| $\pi^{-}$ | 193.6/181             |
| $K^{+}$   | 30.7/38               |
| $K^{-}$   | 49.2/45               |

# Tuning Procedure - 1

Construct differential multiplicity to air derived from fits

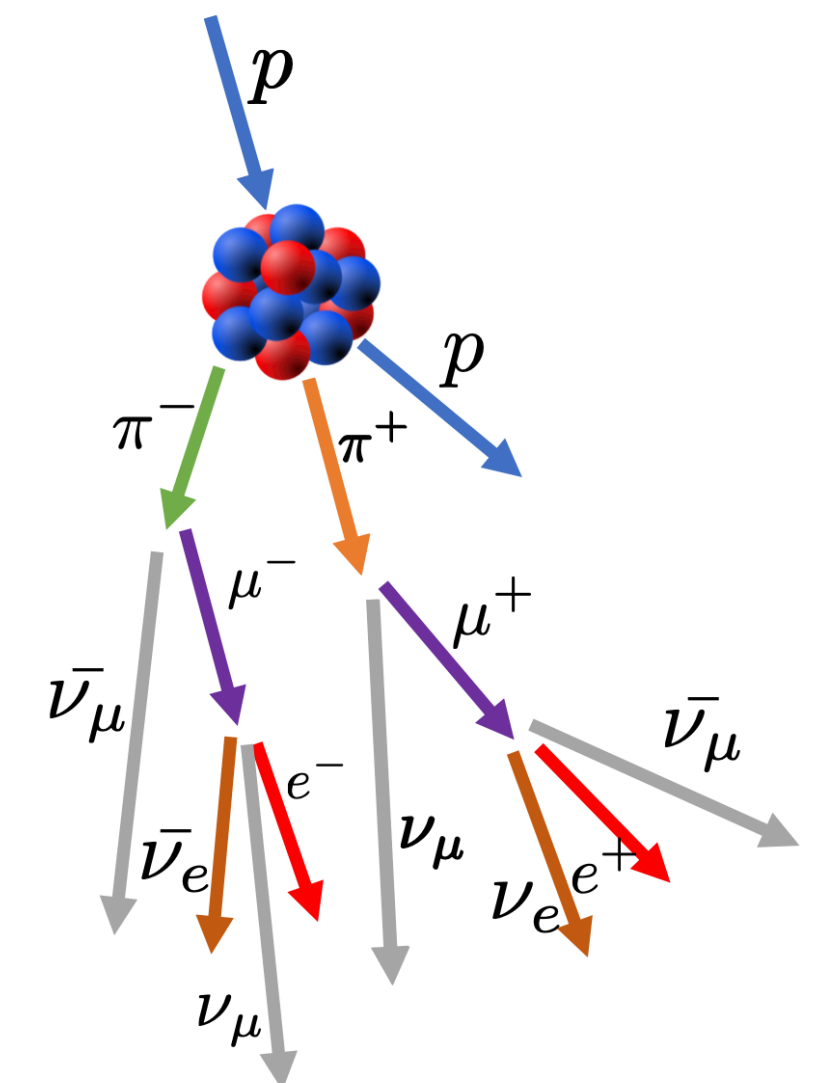
$$\left( \frac{d^2 n_{air}}{dx_F dp_T} \right)_{Data} = \frac{0.21 \sigma_O \left( \frac{d^2 n}{dx_F dp_T} \right)_O + 0.79 \sigma_N \left( \frac{d^2 n}{dx_F dp_T} \right)_N}{0.21 \sigma_O + 0.79 \sigma_N}$$

Run Particle Gun of TARGET event generator used in the BARTOL Monte-Carlo to estimate differential multiplicity for air for matching proton momentum

$$\left( \frac{d^2 n_{air}}{dx_F dp_T} \right)_{MC}$$

**Assign weight for neutrinos at energy range based on meson kinematics and parent energy in decay chain**

$$w = \frac{\left( \frac{d^2 n}{dx_F dp_T} \right)_{Data}}{\left( \frac{d^2 n}{dx_F dp_T} \right)_{MC}}$$



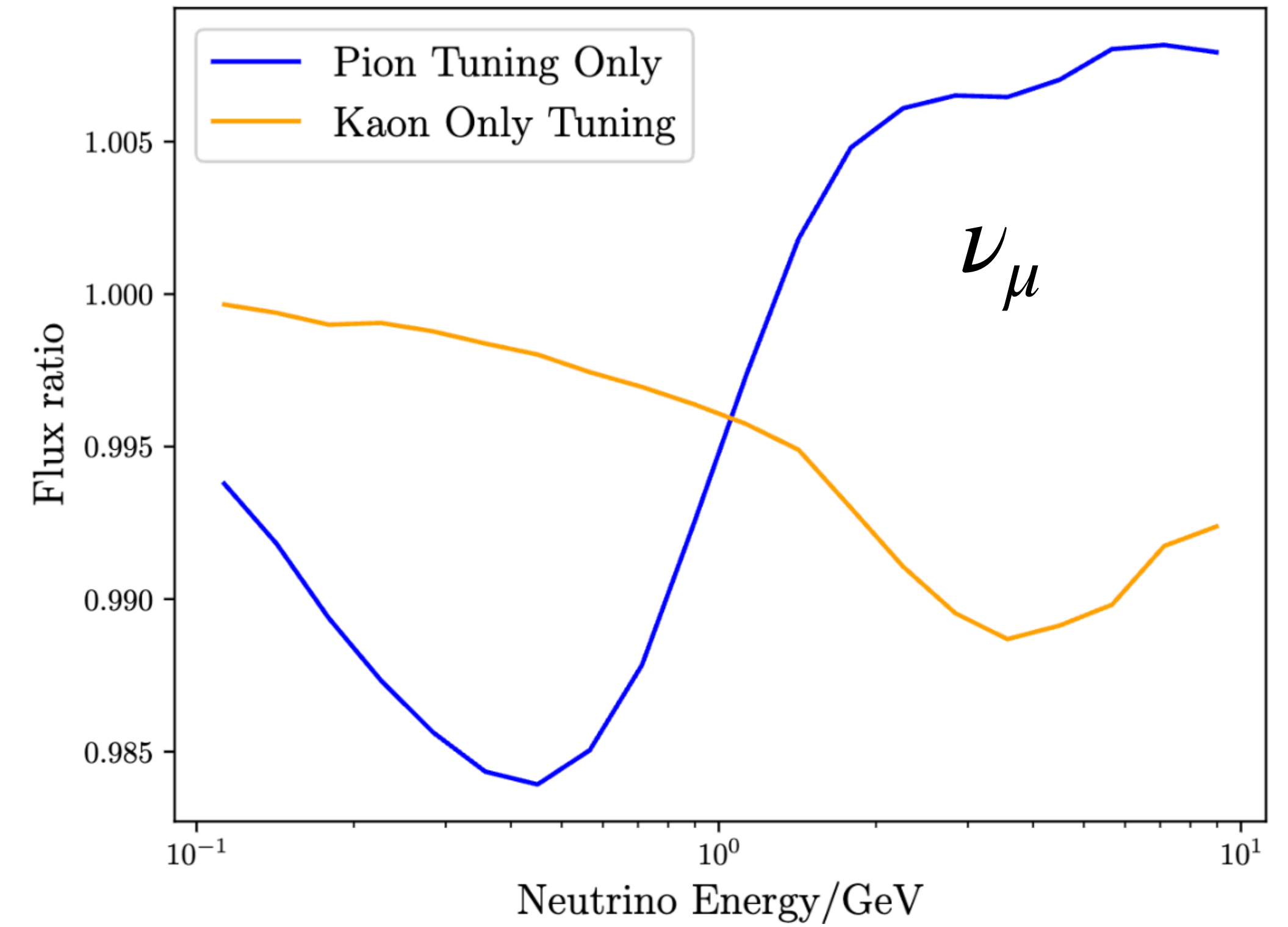
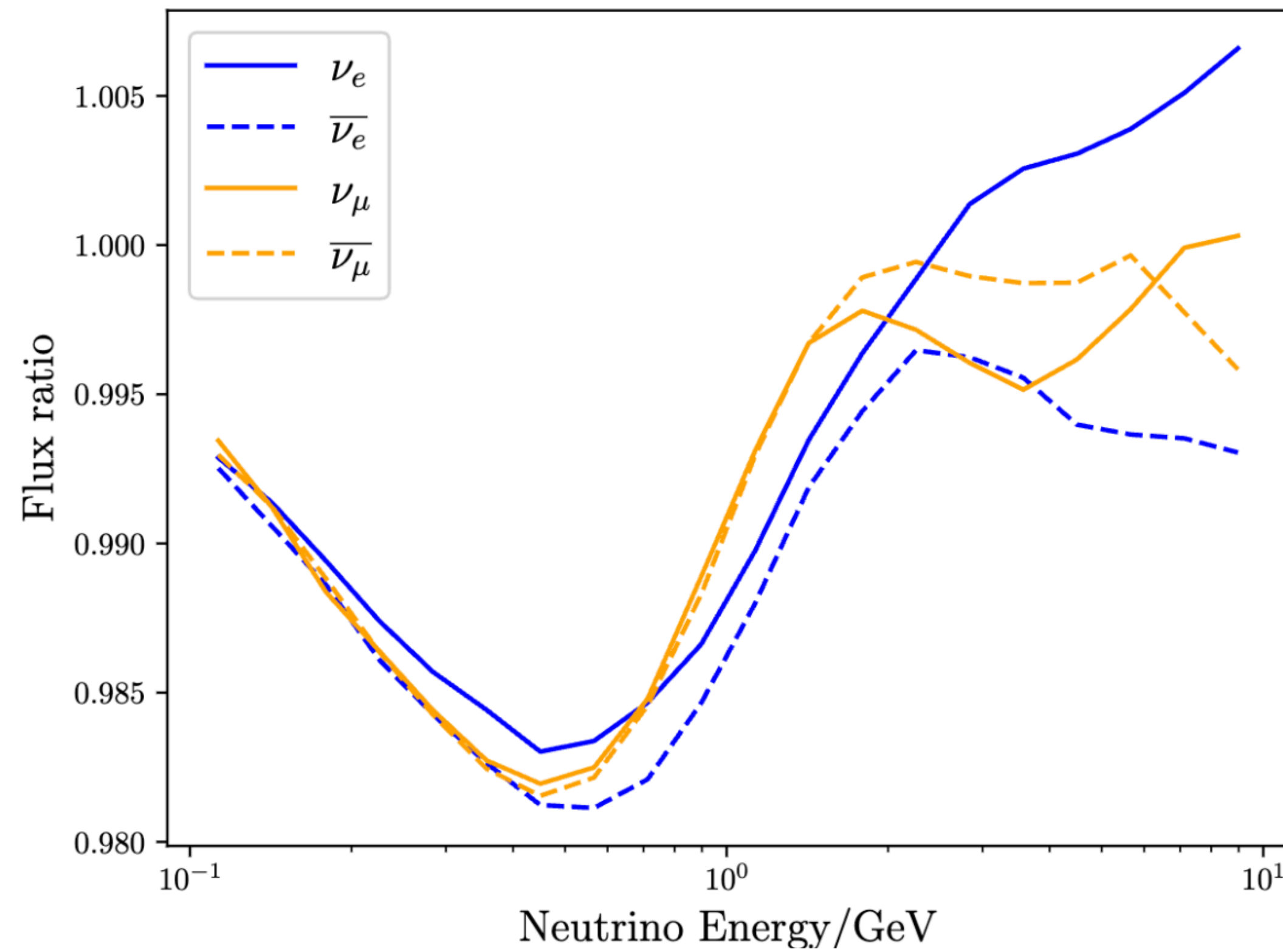
# Tuning Procedure - 2

- Experiments are at fixed energies but atmospheric neutrinos produced in spans wide range of energies of primaries  $\implies$  **for primary nucleons in between dataset energies, interpolate the weights between experiments based on the  $\sqrt{s}$  value.**
- ~10% of cosmic rays are nuclei such as helium which contain neutrons
- **Isospin symmetry used to obtain cross-sections for processes induced by on neutrons**

$$\sigma(p + N \rightarrow \pi^{\pm} + X) = \sigma(n + N \rightarrow \pi^{\mp} + X)$$

- **Arguments based on simple Quark-Parton Model used to obtain  $K_S^0$  and  $K_L^0$  cross sections from charged kaon cross-sections**

# Impact on Neutrino Flux



# Conclusion and Outlook

- Fits to 120GeV/c data have been incorporated into the BARTOL model
- Impact on sub-GeV is largest - somewhat unexpected

## Future Work

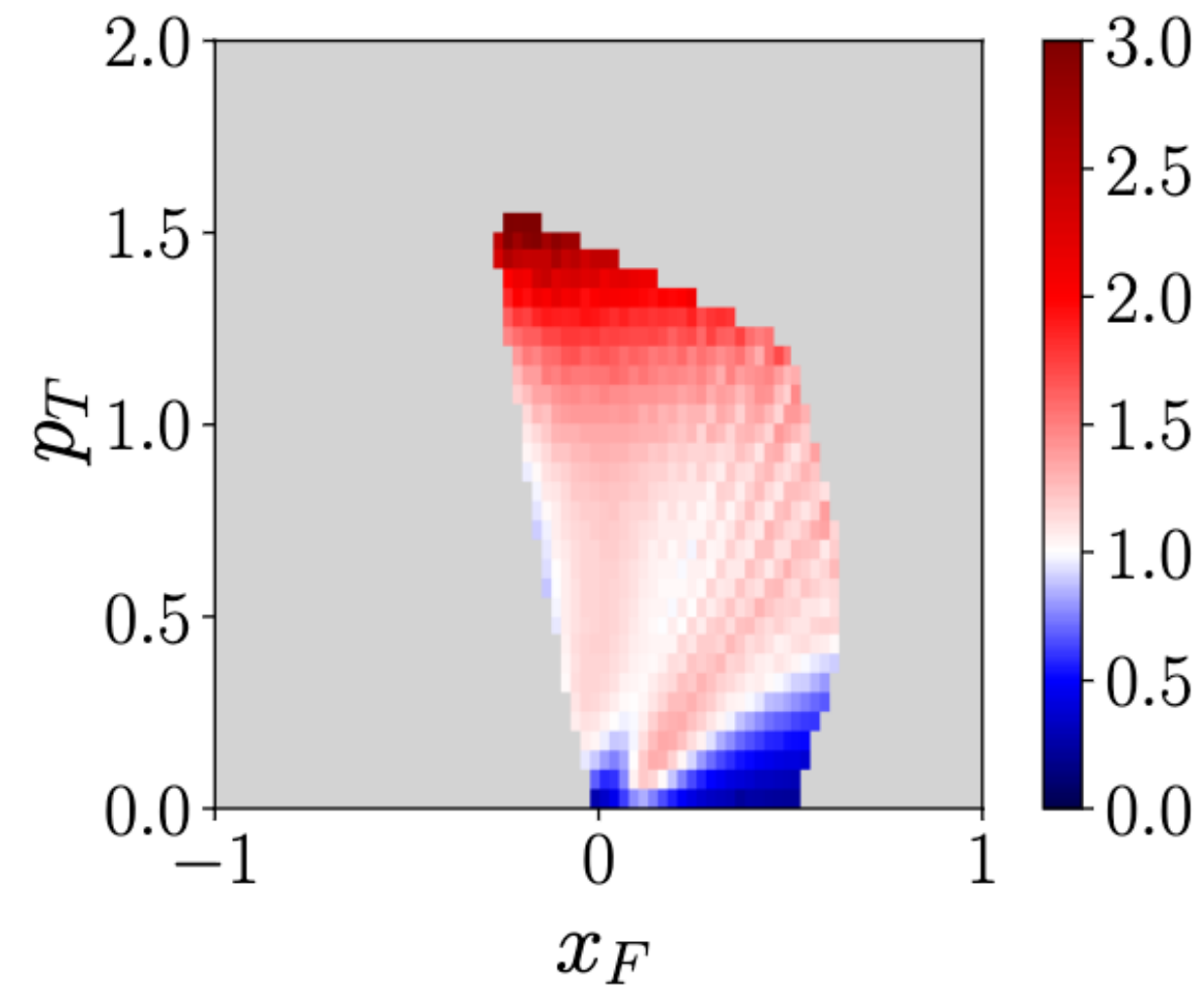
- Benchmark generators that agree best with the data to tune outside of experiment phase space coverage
- Review tuning procedure to better deal with issues encountered in correlation matrices for pion data bins and more robust error propagation
- Expand to 90GeV/c and 60GeV/c
- Evaluate Systematics and Interpolation Uncertainties

**Thank You!**

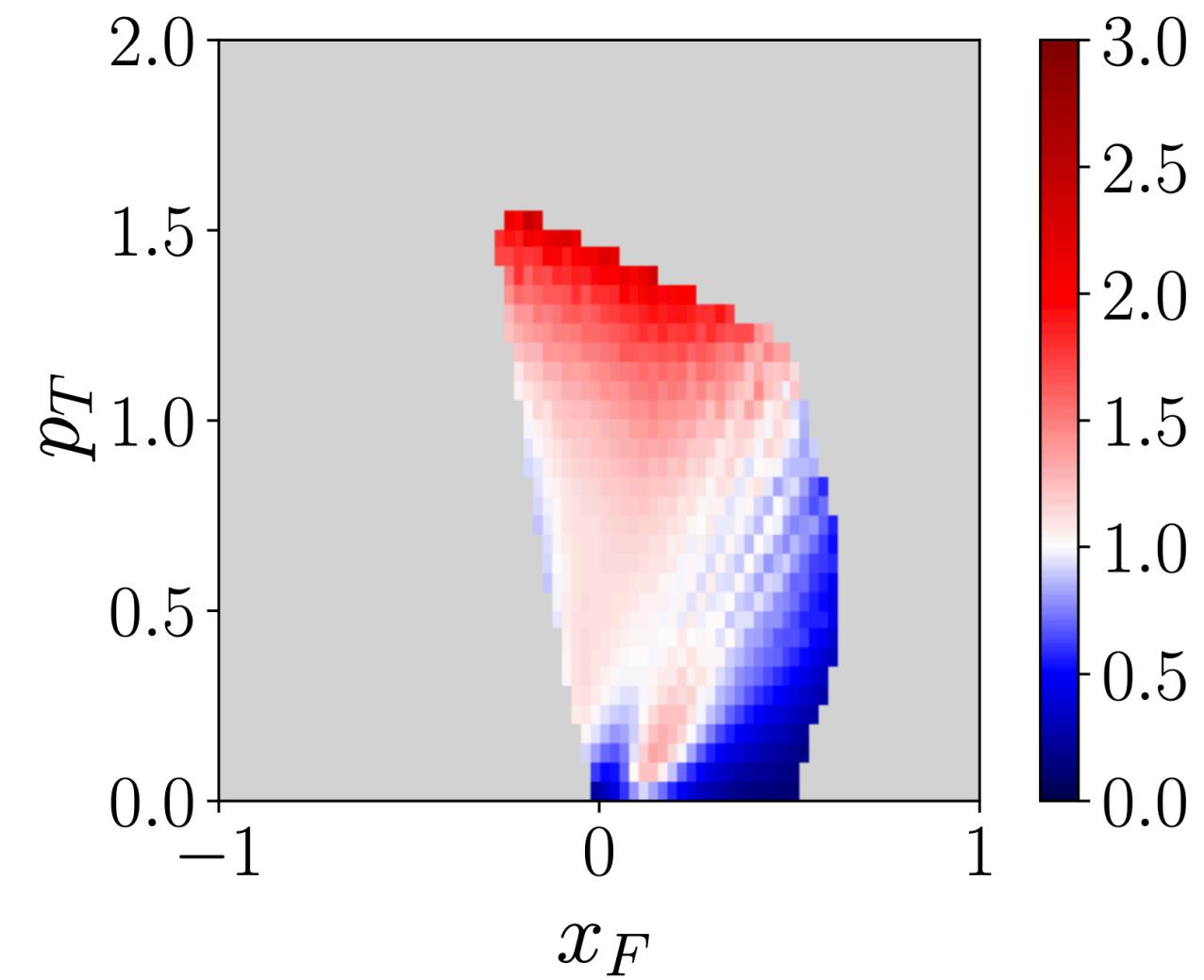
# Back-Ups

# Multiplicity Weights at 120GeV/c

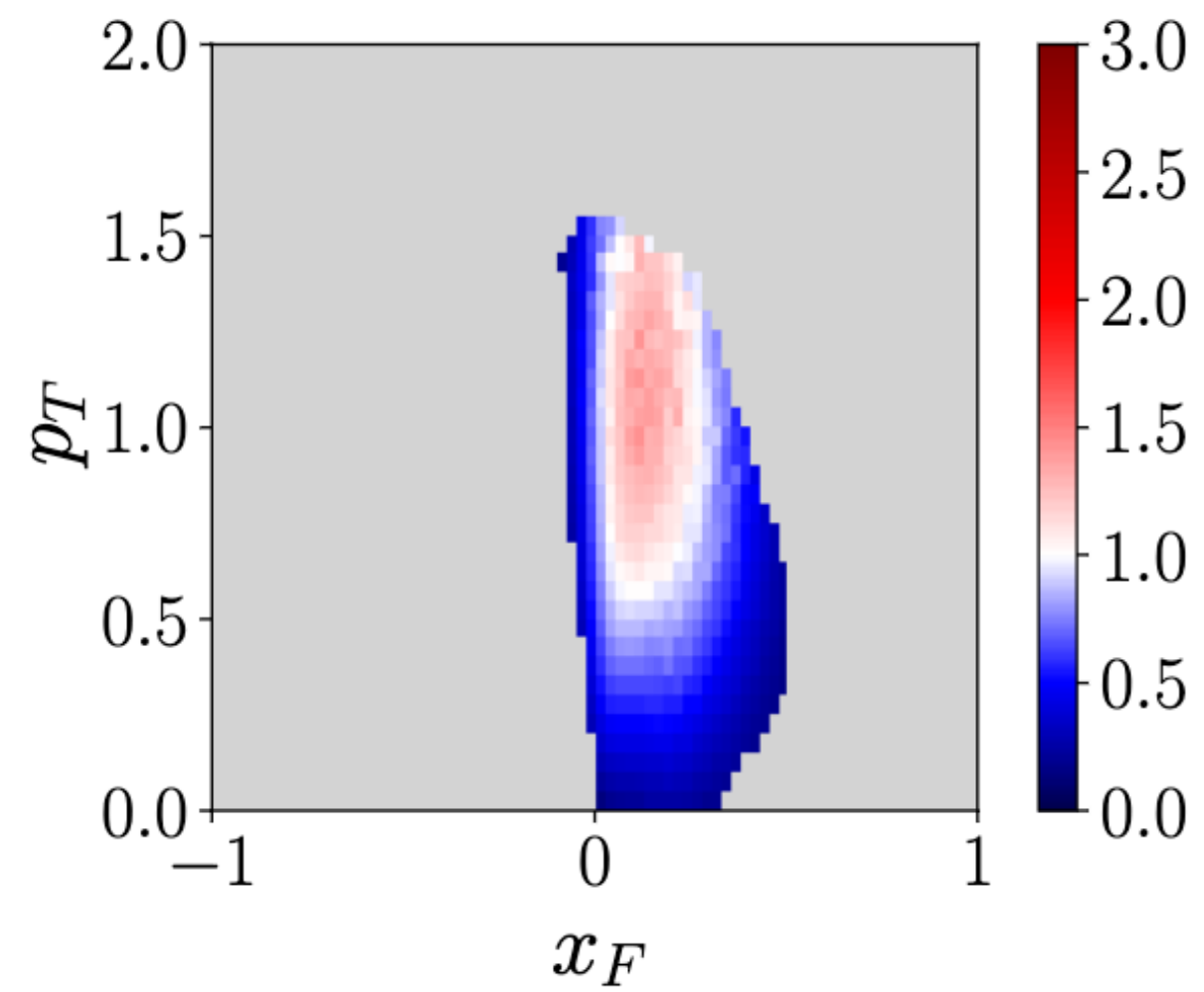
$$p + N \rightarrow \pi^+ + X$$



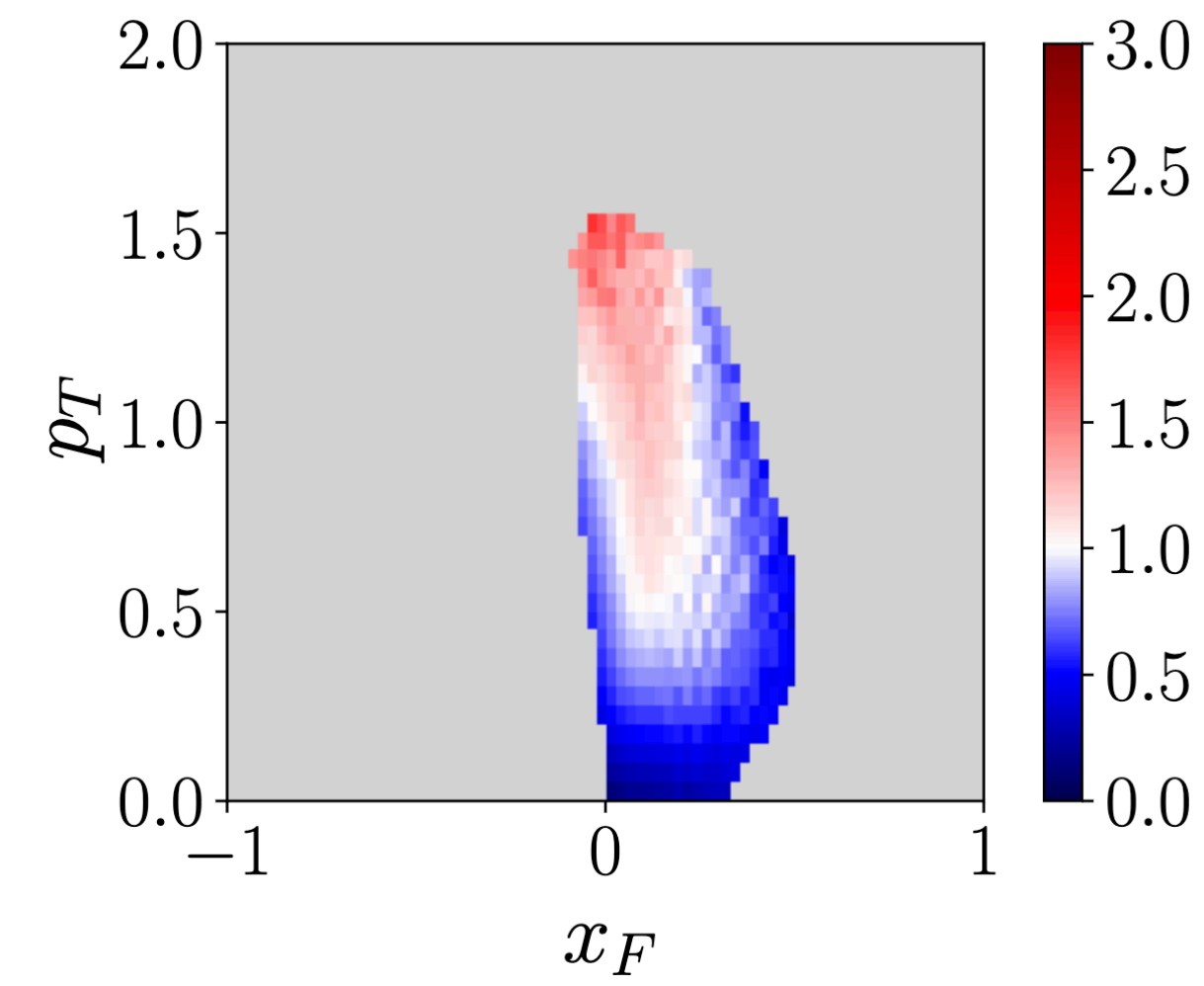
$$p + N \rightarrow \pi^- + X$$



$$p + N \rightarrow K^+ + X$$



$$p + N \rightarrow K^- + X$$



# BMPT Parameterisation

$$x_R = \frac{E^*}{E_{max}^*}$$

$$E \frac{d^3\sigma}{dp^3} = A(1 - x_R)^\alpha (1 + Bx_R)x_R^{-\beta} \times \left[1 + \frac{a}{x_R^\gamma} p_T + \frac{a^2}{2x_R^\delta} p_T^2\right] e^{-\frac{ap_T}{x_R^\gamma}}.$$

$$(0.74 - 0.55x_F + 0.26x_F^2)(0.98 + 0.21p_T^2).$$

$\alpha_2(x_F, p_T)$  takes the form

$$\frac{2}{3} + a_0x_F + a_1p_T + a_2x_F^2 + a_3p_t^2 + a_4x_Fp_T,$$

# Neutron Interactions and Neutral Kaons

Use Isospin symmetry to obtain cross-section for processes induced by neutrons

$$\sigma(p + N \rightarrow \pi^{\pm} + X) = \sigma(n + N \rightarrow \pi^{\mp} + X)$$

$$\sigma(nN \rightarrow K^{+}) = \frac{1}{4}(3\sigma(pN \rightarrow K^{+}) + \sigma(pN \rightarrow K^{-}))$$

$$\sigma(nN \rightarrow K_{L/S}^0) = \frac{1}{2}(\sigma(pN \rightarrow K^{+}) + \sigma(pN \rightarrow K^{-}))$$

$$\sigma(nN \rightarrow K^{-}) = \sigma(pN \rightarrow K^{-})$$

$$\sigma(nN \rightarrow K^{+}) = \sigma(pN \rightarrow K^0)$$

$$\sigma(nN \rightarrow K_{L/S}^0) = \frac{1}{2}(\sigma(pN \rightarrow K^{+}) + \sigma(pN \rightarrow K^{-}))$$

$$\sigma(nN \rightarrow K^{-}) = \sigma(pN \rightarrow \bar{K}^0)$$

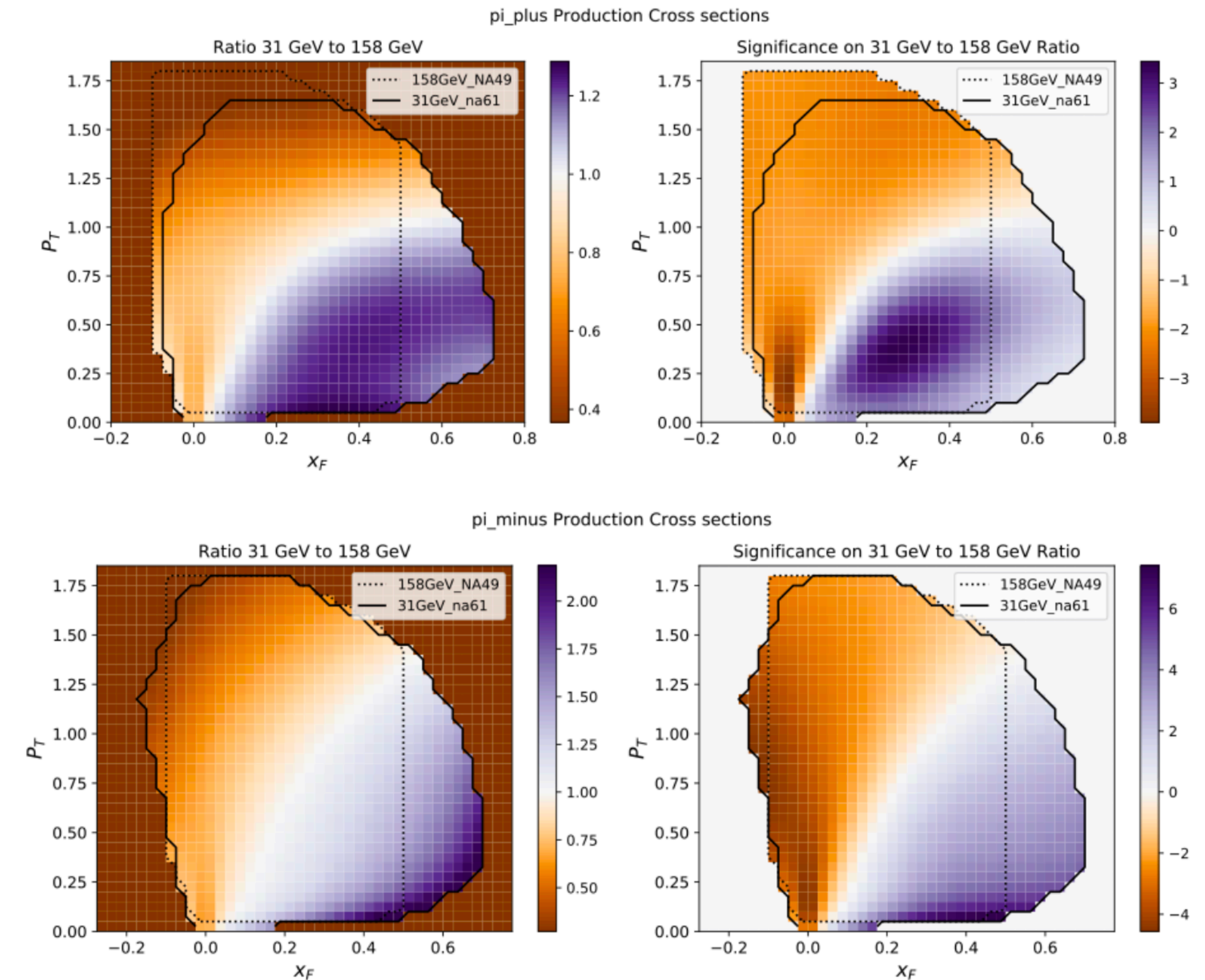
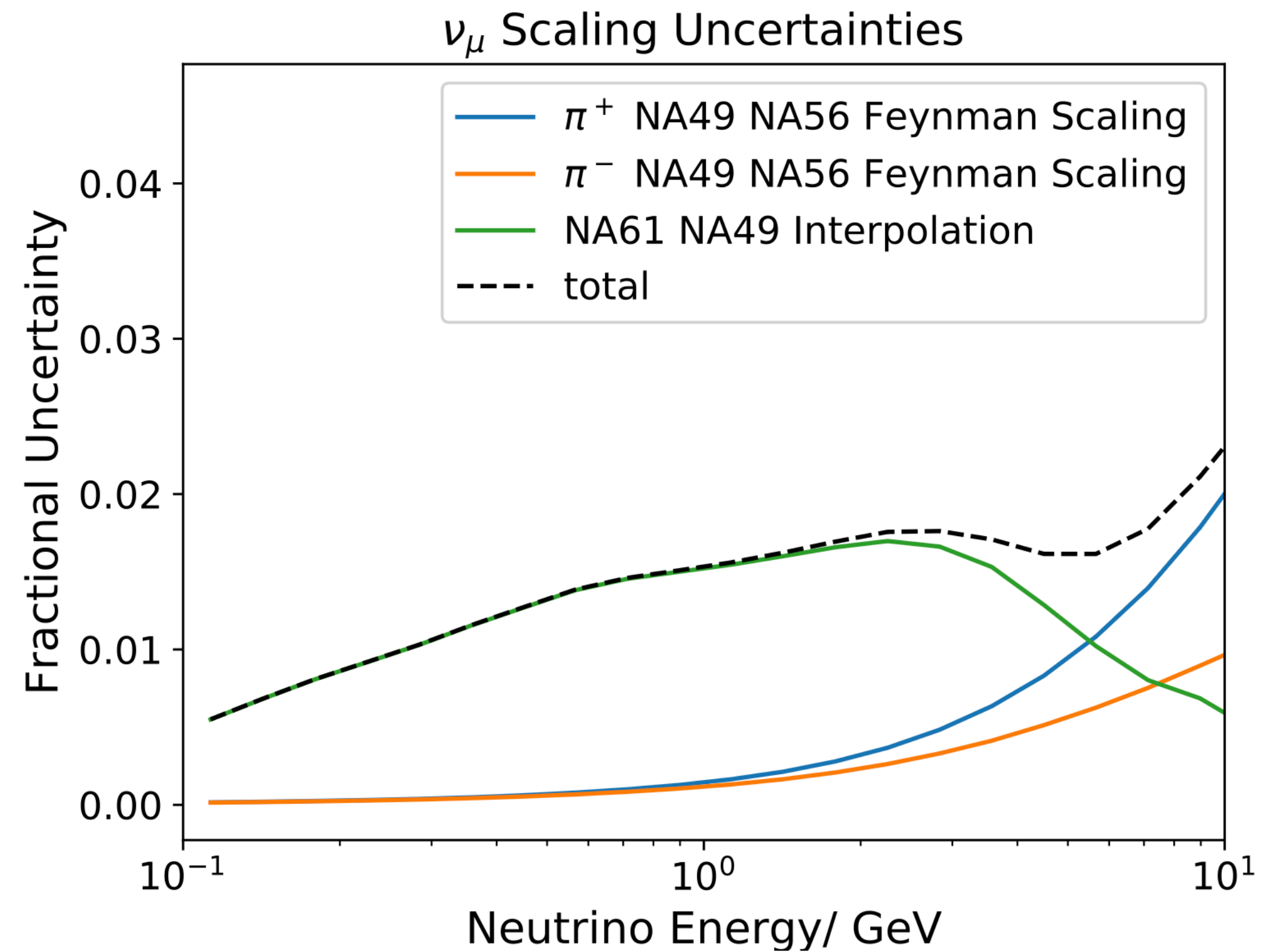
Quark-Parton Model used to predict neutral kaon cross-sections in terms of charged Kaon cross-sections:

$$n = \frac{u_v}{d_v}$$

$$\sigma(K_L^0) = \sigma(K_S^0) = \frac{1}{8}(3\sigma(K^{+}) + 5\sigma(K^{-}))$$

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

# Previous Estimate for Interpolation Uncertainty



From L Cook PhD Thesis

# Issues with Pion Matrices

- Both 120 GeV/c and 90GeV/c correlation matrices for bins that are not positive semi-definite. Difficult to use in fits
- Will probably look into using A-scaled bin multiplicities to deal with these
- 90GeV/c fits to data have been poor so far. Would also be improved from this approach
- Would need to decide on how to interpolate between bins separated in phase space

# Multiplicity to Air Construction

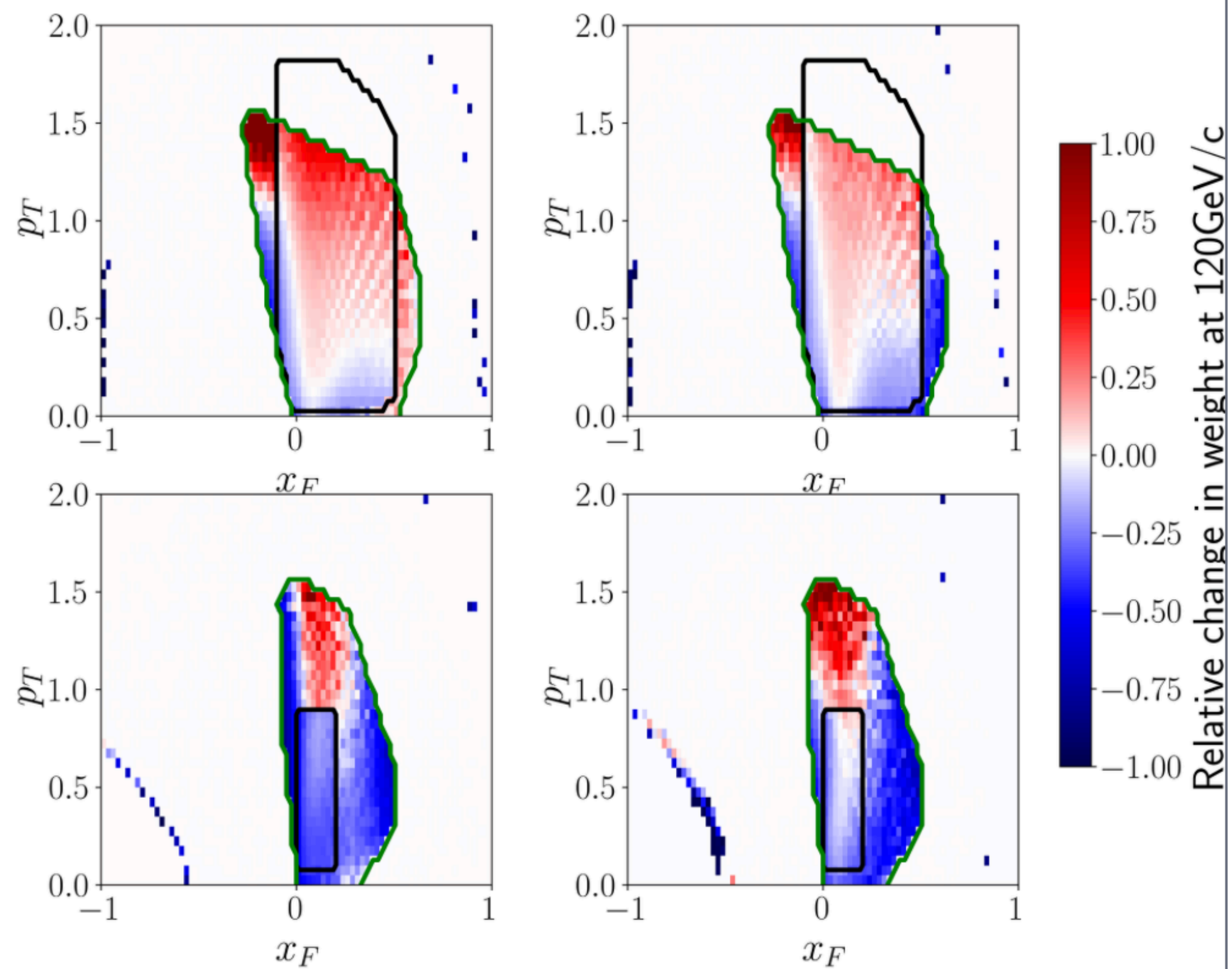
From BMPT parameterisation

The diagram illustrates the derivation of the air construction formula. It features a central equation with four arrows pointing to its components: one from 'From BMPT parameterisation' to the oxygen and nitrogen terms in the numerator, and two from 'Relative abundance of N and O in atmosphere' to the coefficients 0.21 and 0.79 in the denominator.

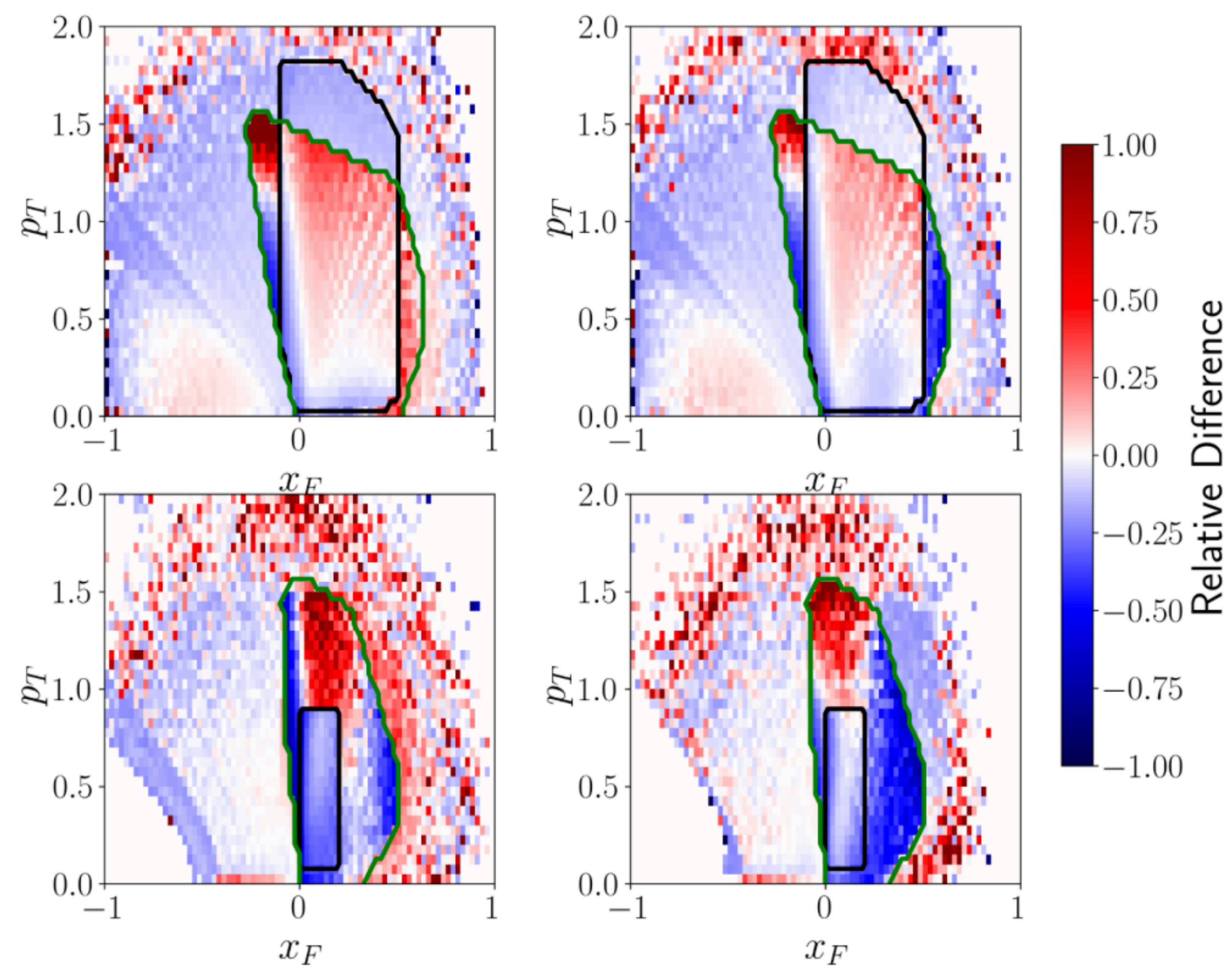
$$\left( \frac{d^2 n}{dx_F dp_T} \right)_{air} = \frac{0.21 \sigma_O \left( \frac{d^2 n}{dx_F dp_T} \right)_O + 0.79 \sigma_N \left( \frac{d^2 n}{dx_F dp_T} \right)_N}{0.21 \sigma_O + 0.79 \sigma_N}$$

Relative abundance of N and O in atmosphere

Deviation from Linear Interpolation



Relative Difference Between Weights at 158GeV/c and 120GeV/c



# Hadron Production Tuning - Basic Idea

- Experiments have measured differential cross-sections for charged meson production with protons of fixed energy incident on thin carbon-targets
- Extrapolate these to nitrogen and oxygen to obtain differential cross-sections for air
- Assign a weight to each neutrino event so its contribution to the flux calculation matches measured data
- For parent energies in between dataset energies, linearly interpolate weights based on the  $\sqrt{s}$  of neighbouring experiments

