Bartol Atmospheric Neutrino Flux Calculation: Tuning Hadronic Interactions

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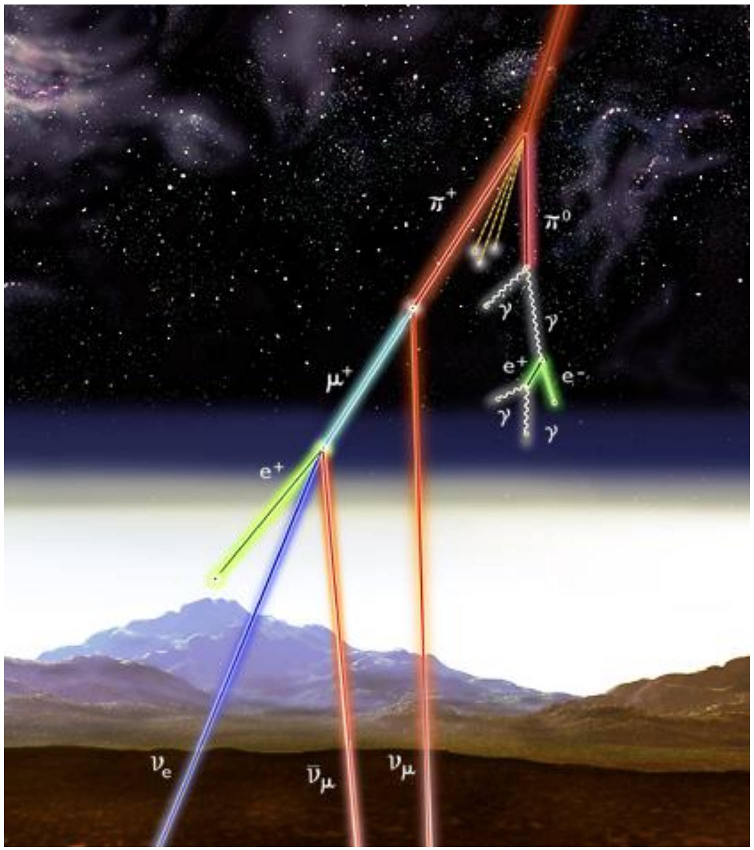
Introduction

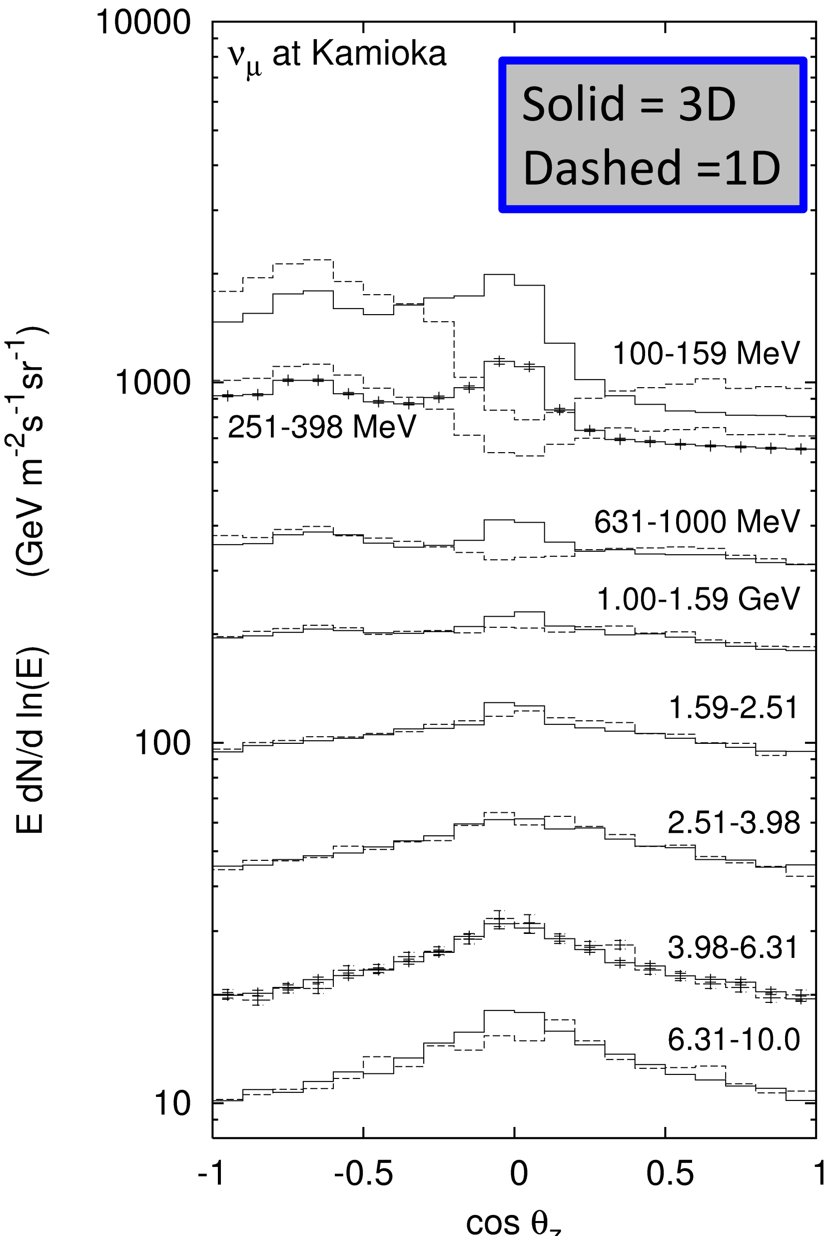
- Update on the work from the Bartol group:
  - Oxford/IPMU: L.Cook, G.Barr, M.Hartz
  - University of Delaware: T. Gaisser, T.Stanev, S.Tilav
- Bartol Monte Carlo last major flux update from 2004
- Use of fixed target cross section data to tune neutrino flux
- Dataset driven approach to Hadron Tuning and Error Propagation
- Use beam neutrino modelling techniques on the atmospheric flux
- Recent hadron production dataset releases (e.g. NA61 NA49)

Overview of Bartol Calculation



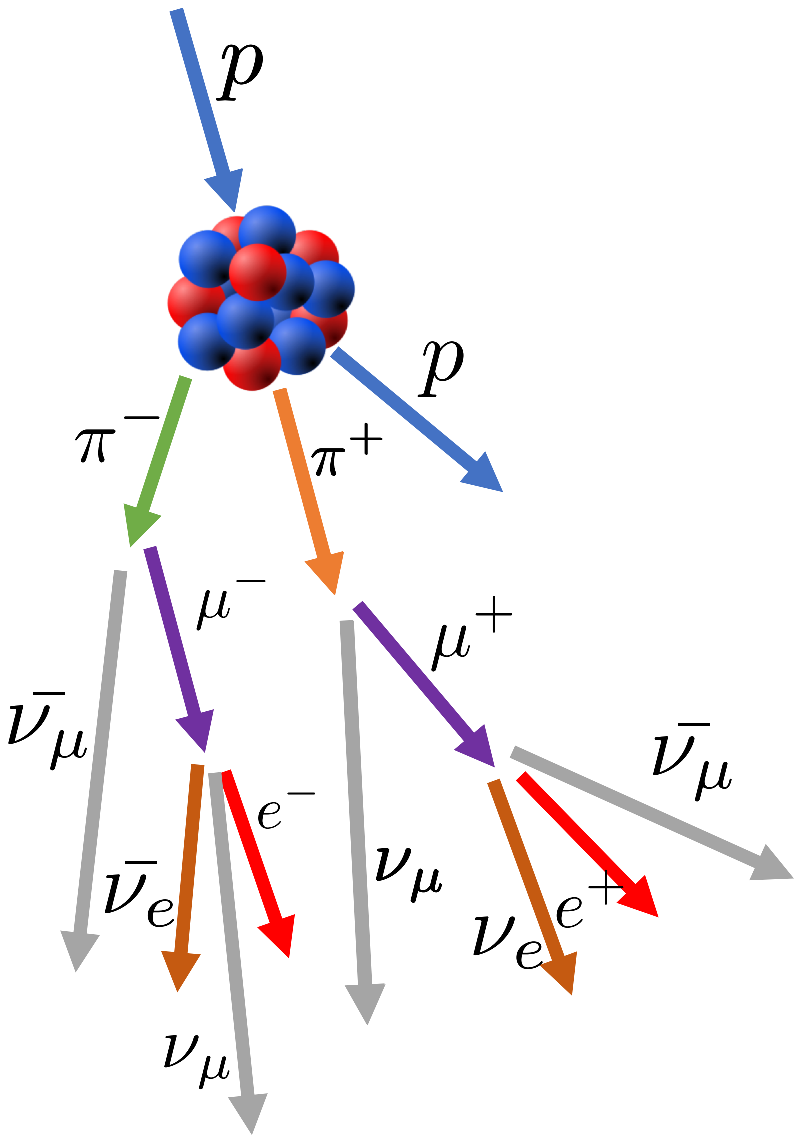
- Primary cosmic rays generated at 80 Km
- Mostly free protons and alpha particles
- Tracked and shower through variable density atmosphere
- Fluxes Tuned to primary cosmic ray data

Overview of Bartol Calculation



- 3D Calculation
- Target2.4 used as hadron production generator
- Not previously tuned to muon flux data
- Primary cosmic rays generated between 1 GeV and 10 TeV
- Output un-oscillated muon and electron neutrino flux at the detector site
- Primary cosmic ray fluxes and hadronic interactions are major uncertainties

Hadronic Interactions



- Showers origin of neutrinos
- Interactions considered in terms of inclusive cross sections:

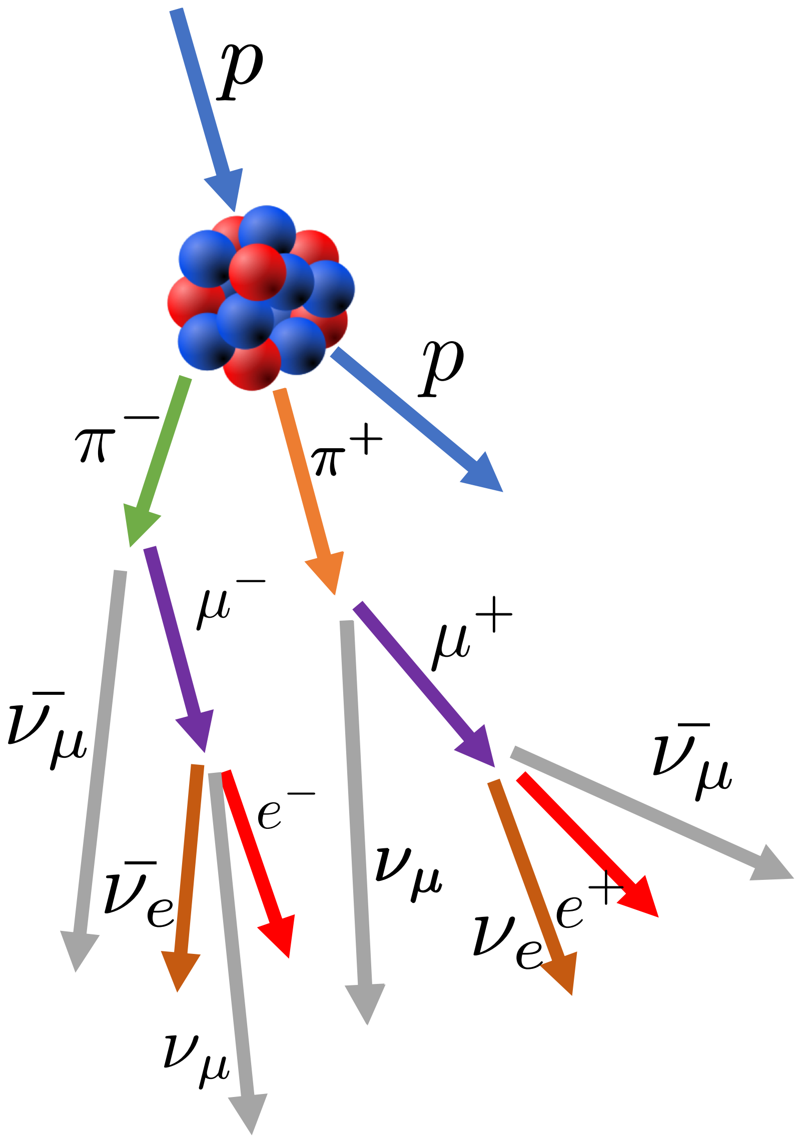
$$p + N_2 \rightarrow \pi^+ + X$$

- Phase space of interactions considered at a particular beam energy in outgoing pion kinematics:

$$\frac{d^2\sigma}{dx_F dP_T}$$

- Isospin arguments used to deduce the corresponding Neutron cross sections

Tuning Method and Aims

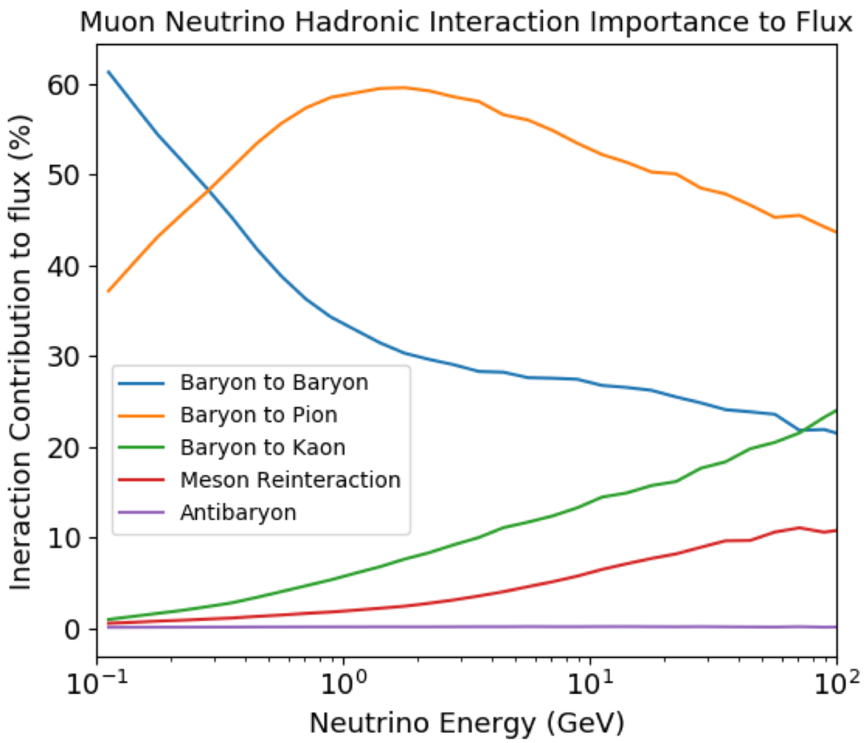


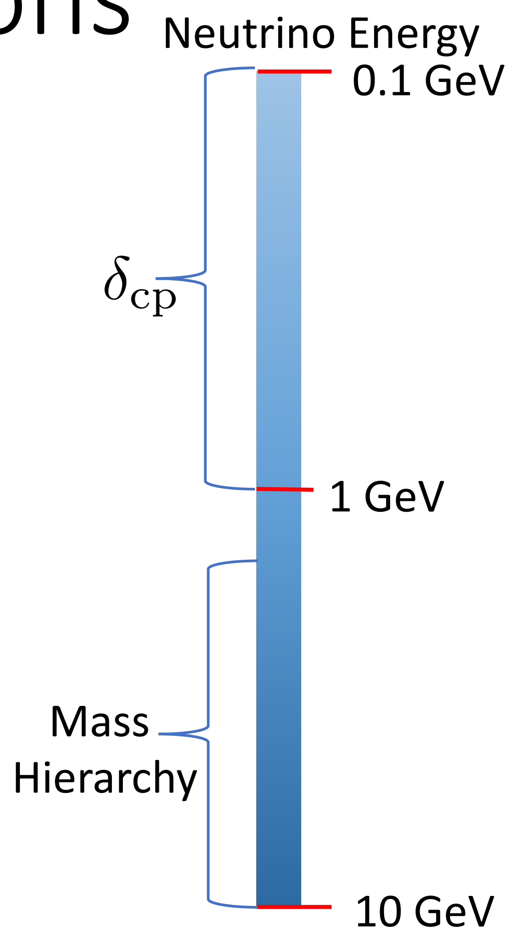
1. Run Atmospheric Monte Carlo recording hadron interaction chain
2. Reweight flux by weighting neutrinos according to hadron production
3. Weight

$$W = \frac{d\sigma_{\text{Data}}(\pi^+)}{dx_F dP_T} / \frac{d\sigma_{\text{MC}}(\pi^+)}{dx_F dP_T}$$

Relevant Hadronic Interactions

- Focus on Neutrinos from 0.1-10 GeV



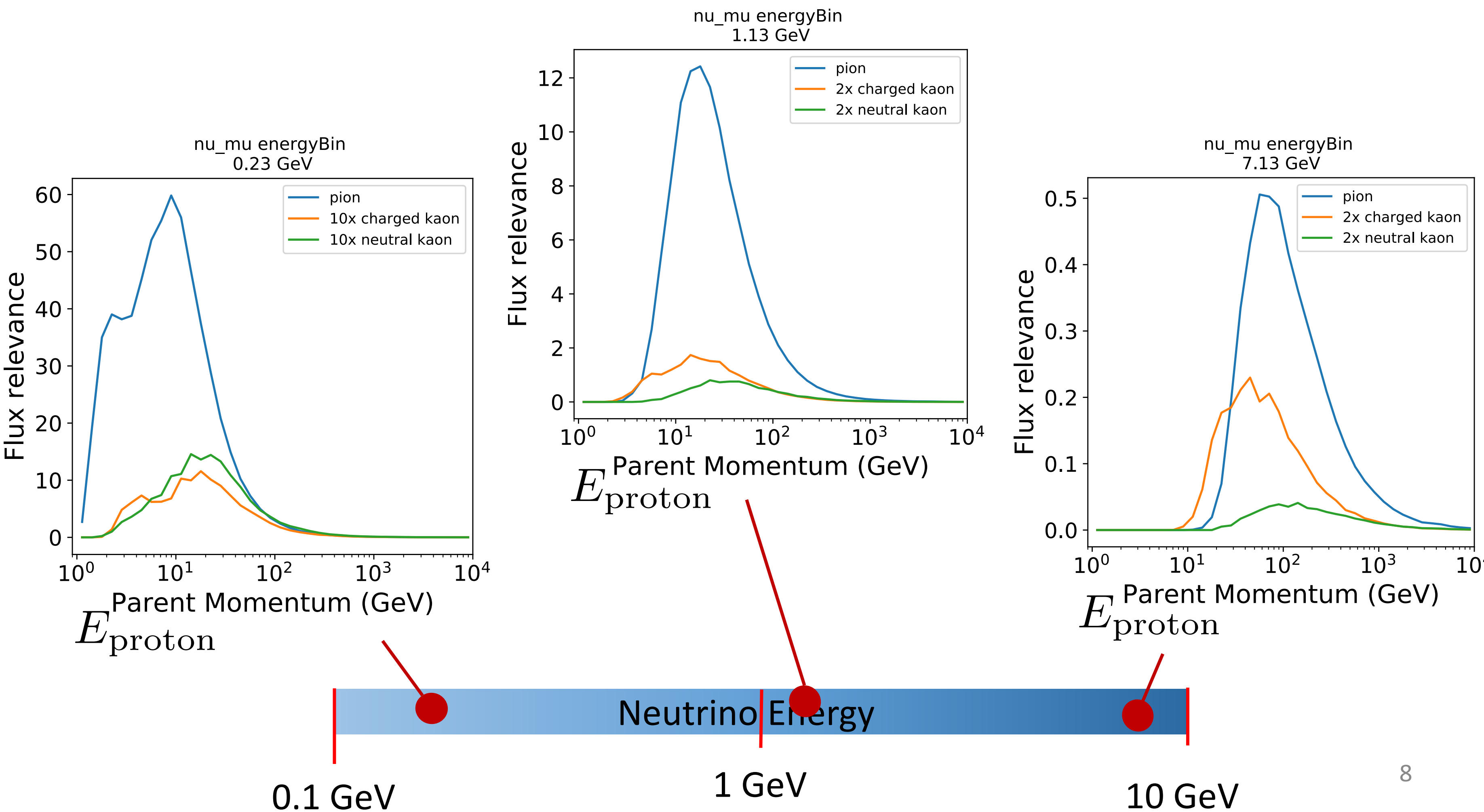


- Baryon to Baryon Interactions are less crucial as governed by conservation numbers
- Pion production dominates in regions we are interested in

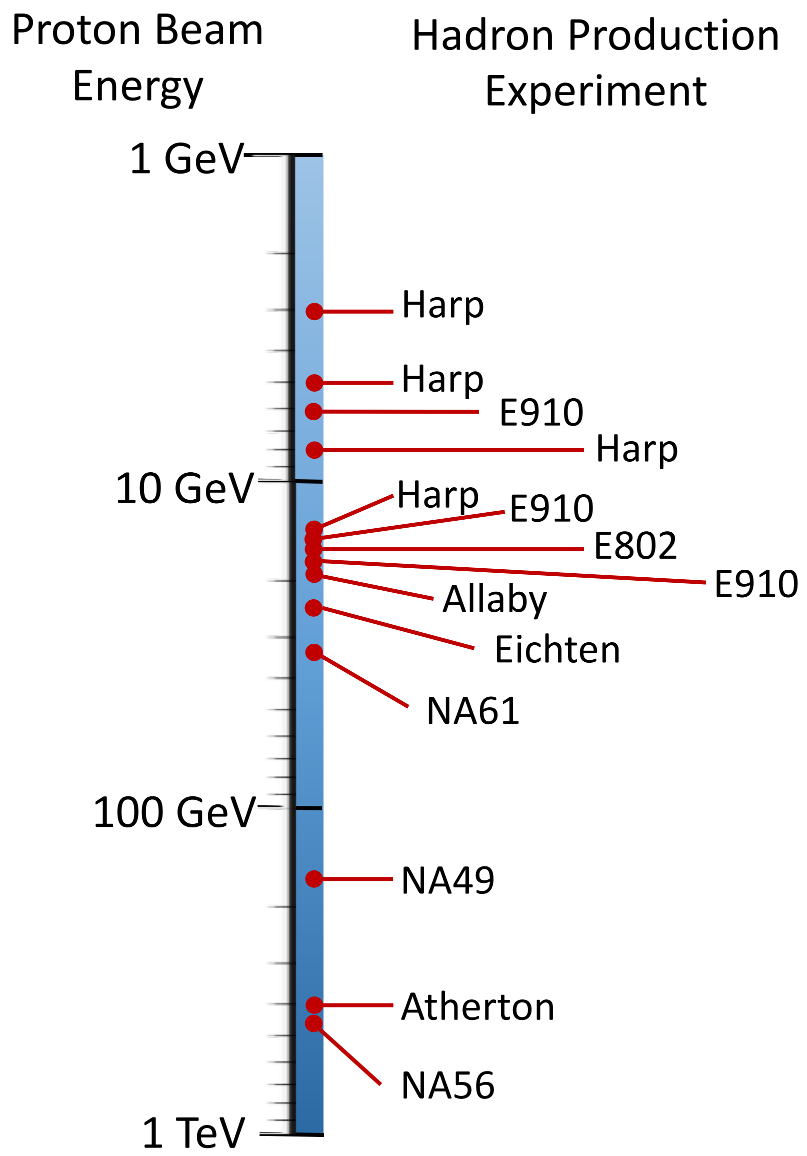
Graphs for fluxes at SK detector site

Primary Particle Energies

- Primary (proton) interaction flux contributions



Hadron Production Datasets



- Harp (2009) 3,5,8,12 GeV/c pC -> $\pi^{\pm}/K^{\pm}$
  - High angle and low angle separately
- Eichten et al. (1972) 24 GeV/c pAl -> $\pi^{\pm}/K^{\pm}$
- Allaby et al. (1970) 19.2 GeV/c pAl -> $\pi^{\pm}/K^{\pm}$
- E910 (2008) 6.4,12.3,17.5 GeV/c pBe -> $\pi^{\pm}$
- E802 (1991) 14.6 GeV/c pAl -> $\pi^{\pm}/K^{\pm}$
- NA61 (2016) 31 GeV/c pC -> $\pi^{\pm}/K^{\pm}$
- NA49 (2006) 158 GeV/c pC -> $\pi^{\pm}$
- Atherton et al. (1980) 400 GeV/c pBe -> $\pi^{\pm}/K^{\pm}$
- NA56/SPY (1999) 450 GeV/c pBe -> $\pi^{\pm}/K^{\pm}$

A-Scaling

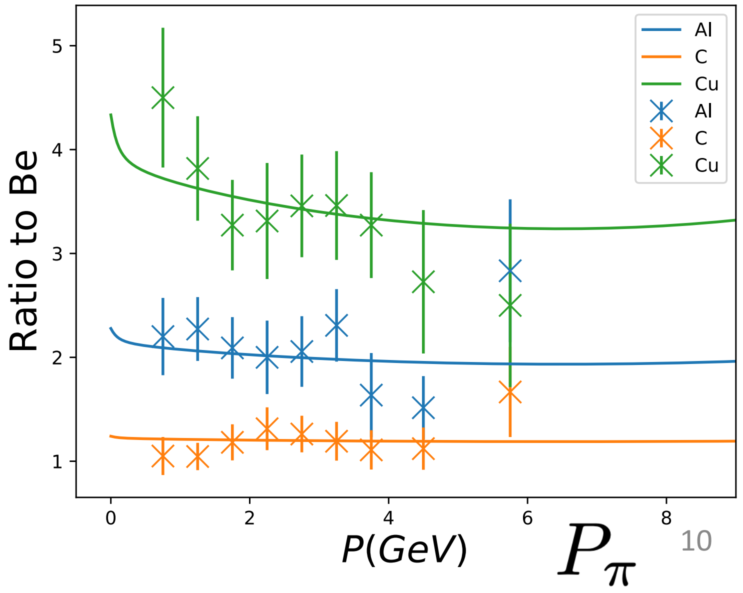
- Data on a variety of Target Nuclei
- Simple version of cross-section scaling
  - $\alpha = 2/3$
- Instead try empirical fit to data ratios of the form

  $\alpha(x_F, P_T)$ where alpha is quadratic in xf pt

$$\frac{d^2\sigma_{A_1}}{dx_F dP_T} = (\frac{A_1}{A_2})^{\alpha} \frac{d^2\sigma_{A_2}}{dx_F dP_T}$$

- Use to interpolate to Nitrogen/ Oxygen Targets

E.g. Harp 12 GeV Data Fit 125 mRad



Fitting and A-Scaling

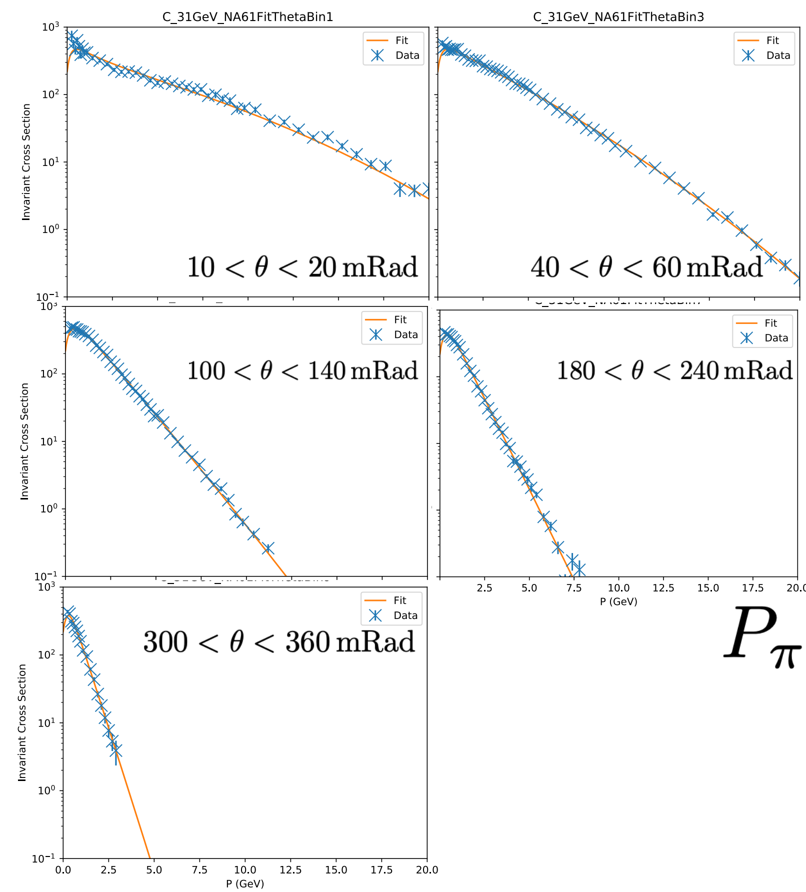
- BMPT parameterisation Fit to each of the datasets in X_F - P_T space
- Included additional free parameters to improve the Fits
  - BMPT has inherent forward backward symmetry in Feynman X_R dependence
  - Additional free parameters to model scaling from deuterium to target nuclei

$$\frac{d^2\sigma(A)}{dx_F dP_T} = \frac{A}{2}^{\alpha(x_F, P_T)} \frac{d^2\sigma_{\mathrm{BMPT}}}{dx_F dP_T}$$

Results from BMPT fitting

χ^2 per d.o.f.	π^+ BMPT	π^+ BMPT + asymmetry parameters
31 GeV NA61	594.4/407	524.2/402
158 GeV NA49	1081.2/263	487.0/258
	π^- BMPT	π^- BMPT + asymmetry parameters
31 GeV NA61	1133.8/438	638.2/433
158 GeV NA49	1166.2/261	353.6/256

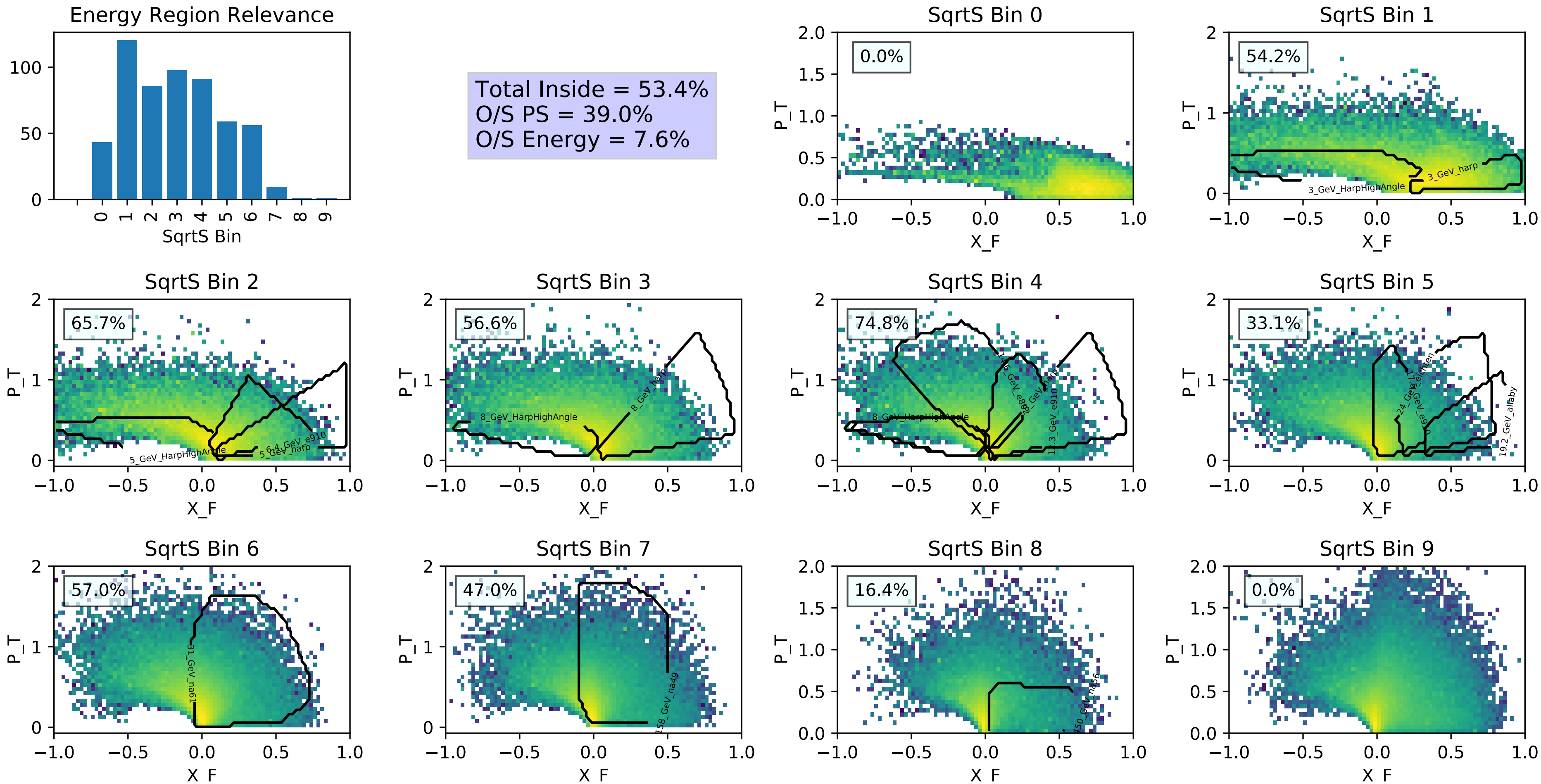
NA61 π^+ - Fits



Data Set Coverage

- Lower Energy Datasets have lower coverage
- Combine datasets at similar beam (interaction) energies:
  - Region 1 – 3GeV Harp
  - Region 2 - 5 GeV Harp, 6.4 GeV E910
  - Region 3 - 8 GeV Harp
  - Region 4 – 12 GeV Harp, 12.3 GeV E910, 14.6 GeV E802
  - Region 5 – 17.5 GeV E910, 19.2 GeV Allaby, 24 GeV Eichten
  - Region 6 - 31 GeV NA61
  - Region 7 – 158 GeV NA49
  - Region 8 – 450 GeV NA56
- Explore interaction phase space of pion production for neutrino energy bins
- Explore phase space parameterised by X_F P_T of outgoing pion
  - Attempting to model multiple dimensions in 2D plots!

Pion Creation phase space E_ν = 0.2 GeV



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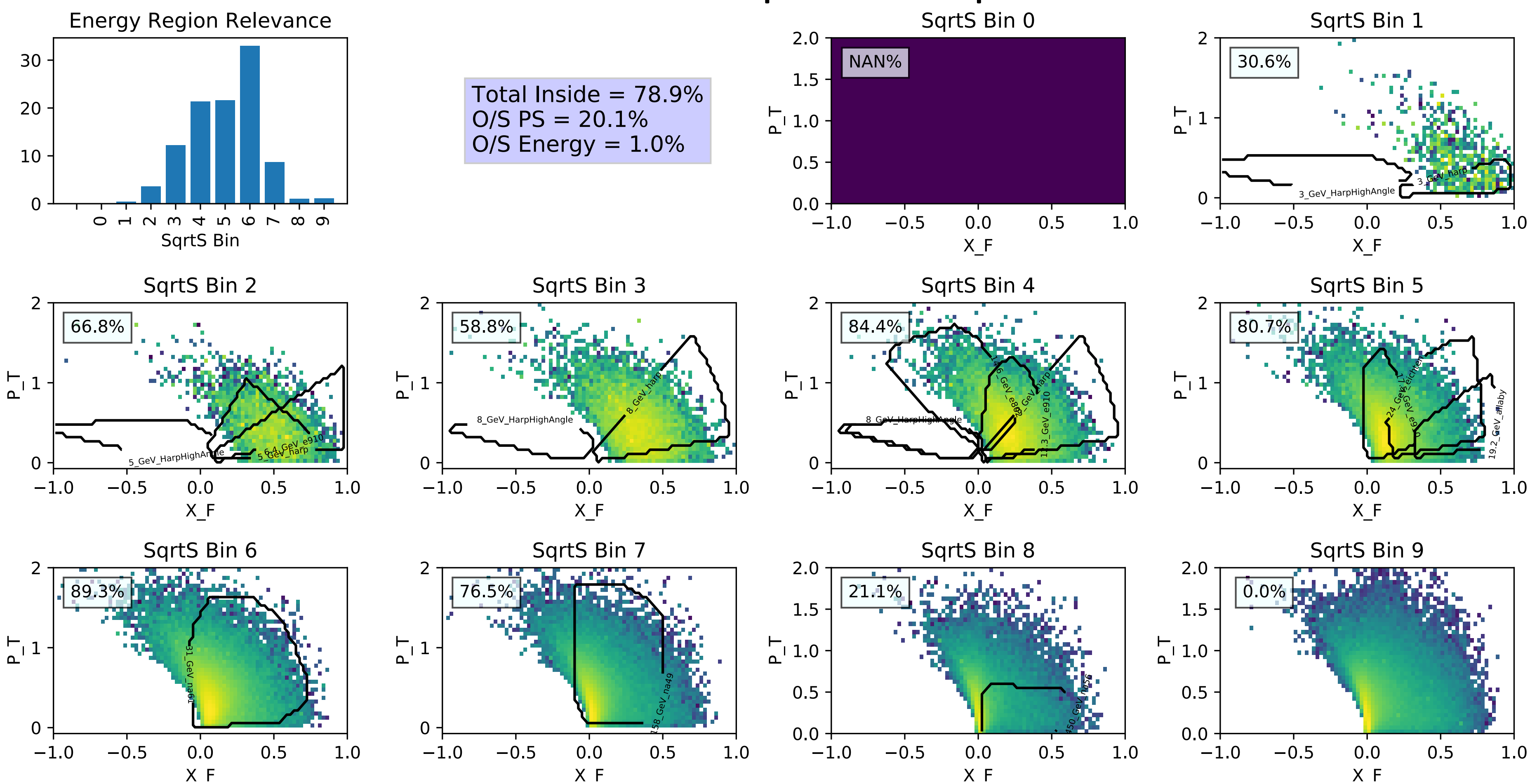
Pion Creation interaction phase space $E_\nu = 1.1$ GeV



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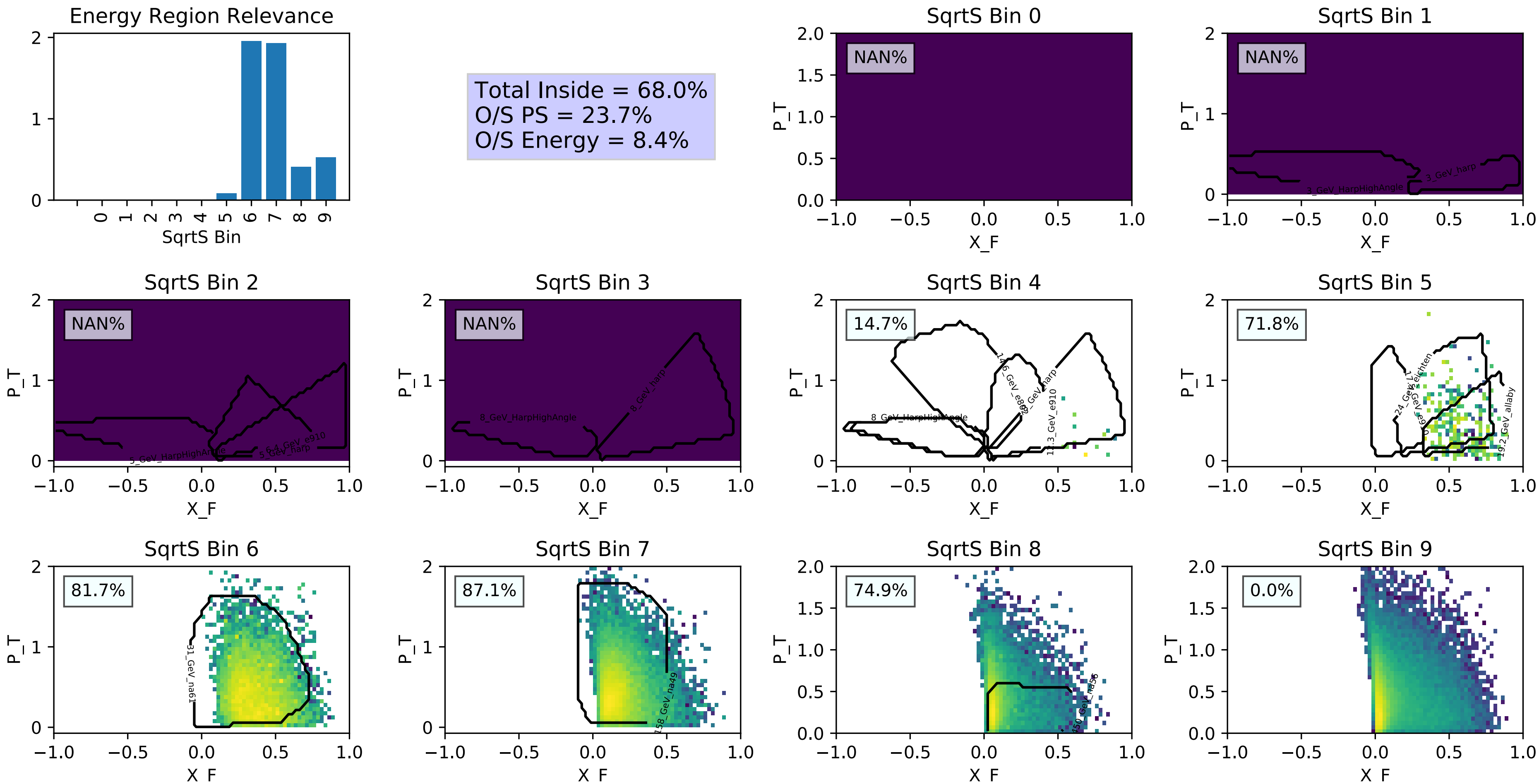
Pion Creation interaction phase space E_ν = 7.1 GeV



- Region 1 – 3GeV Harp
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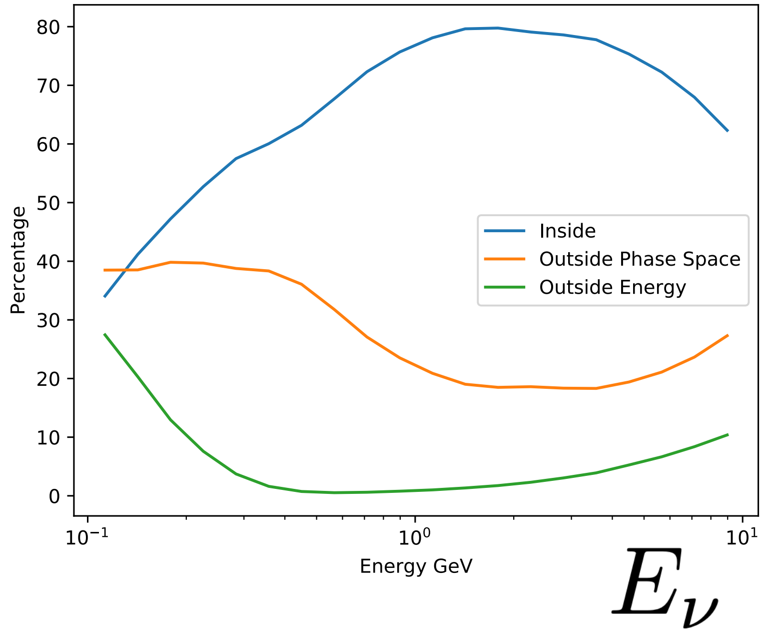
- Region 8 – 450 GeV NA56

Data Set Coverage

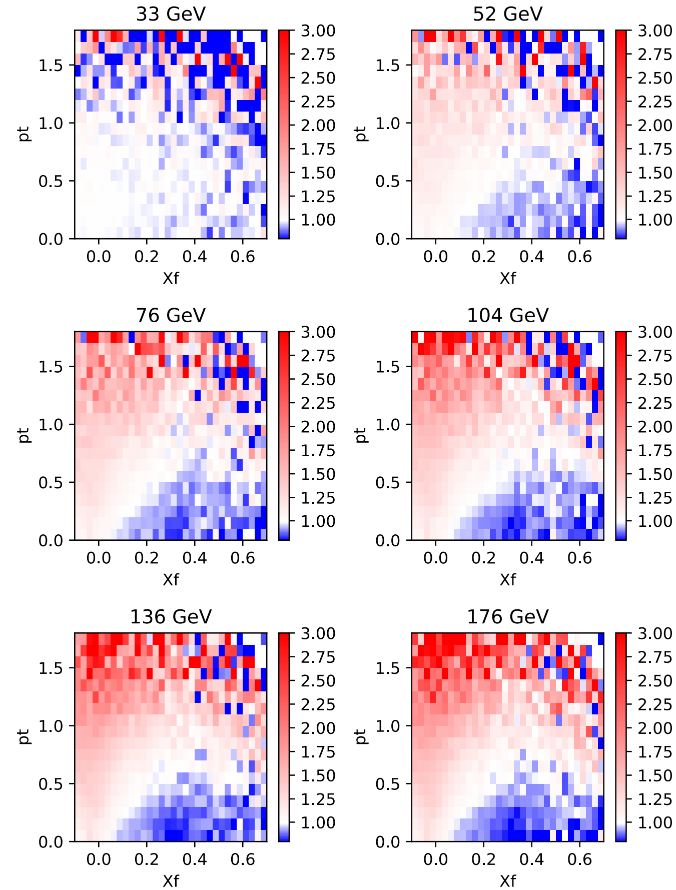
- Proportion of interactions occurring outside coverage of experiments
  - High angle data is important for atmospheric neutrinos
- For low energy neutrinos: < 3GeV beam energy increasingly important
  - Care needed as this is region where resonances dominate
- These will both be improved with advent of new hadron production experiments

Fraction of Pion Production interactions covered by experimental datasets



Uncertainties

- Dataset experimental uncertainties
  - Propagated through to the final flux via the BMPT parameterisation
  - Creating toy datasets using the uncertainty on the bins and rerunning BMPT joint fits.
  - Reasonable estimates for correlation
- Outside phase space uncertainties
  - Constraint from data via energy conservation
  - Use different hadron production generators to estimate cross section and use variance between the models to estimate the uncertainty
- A-Scaling uncertainties
- Energy scaling uncertainties
  - 31 GeV to 158 GeV scaling uncertainty

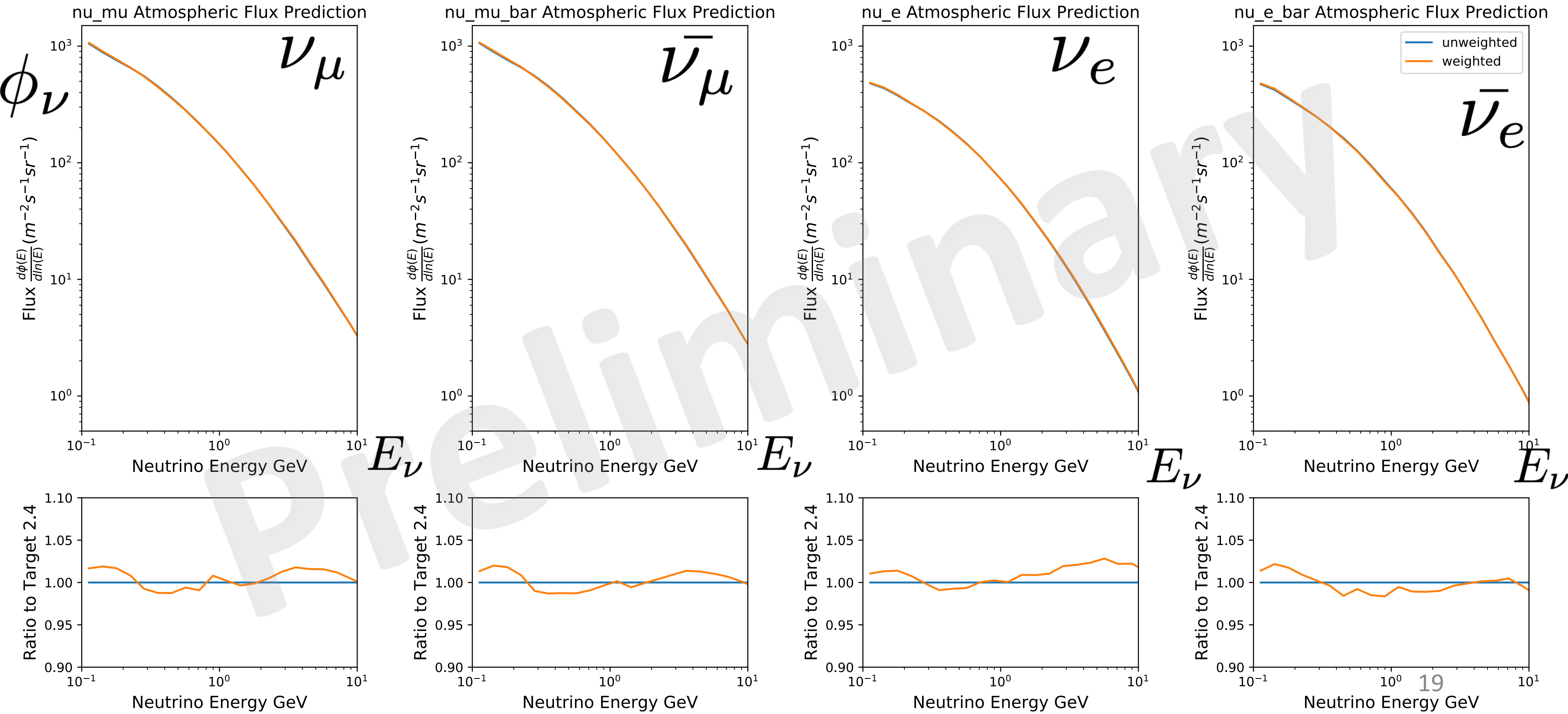


Geant4 Nu Beam MC Generator π^+

ratios from 31 GeV Beam Energy

Preliminary results – neutrino fluxes

- Results of tuning to dataset fits
- Tuning pions from 3 - 170GeV/c within experimental phase spaces

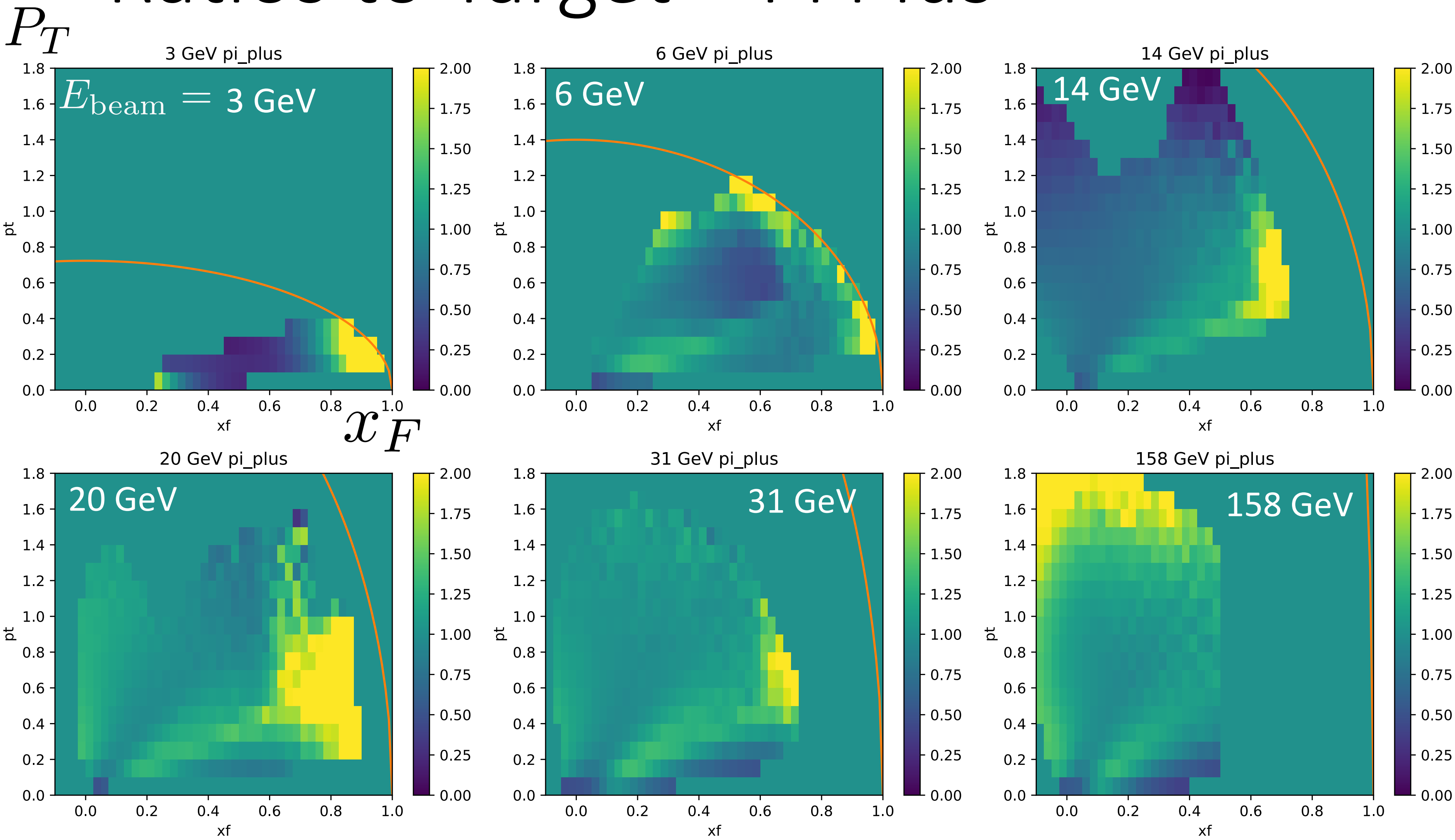


Conclusions and Next stages

- Work largely finished for pions, repeat for kaon production interactions
- Ensuring each relevant uncertainty is accounted for
- Releasing the tuned result and uncertainties with correlations between bins
- Other large area of uncertainty is primary cosmic ray fluxes

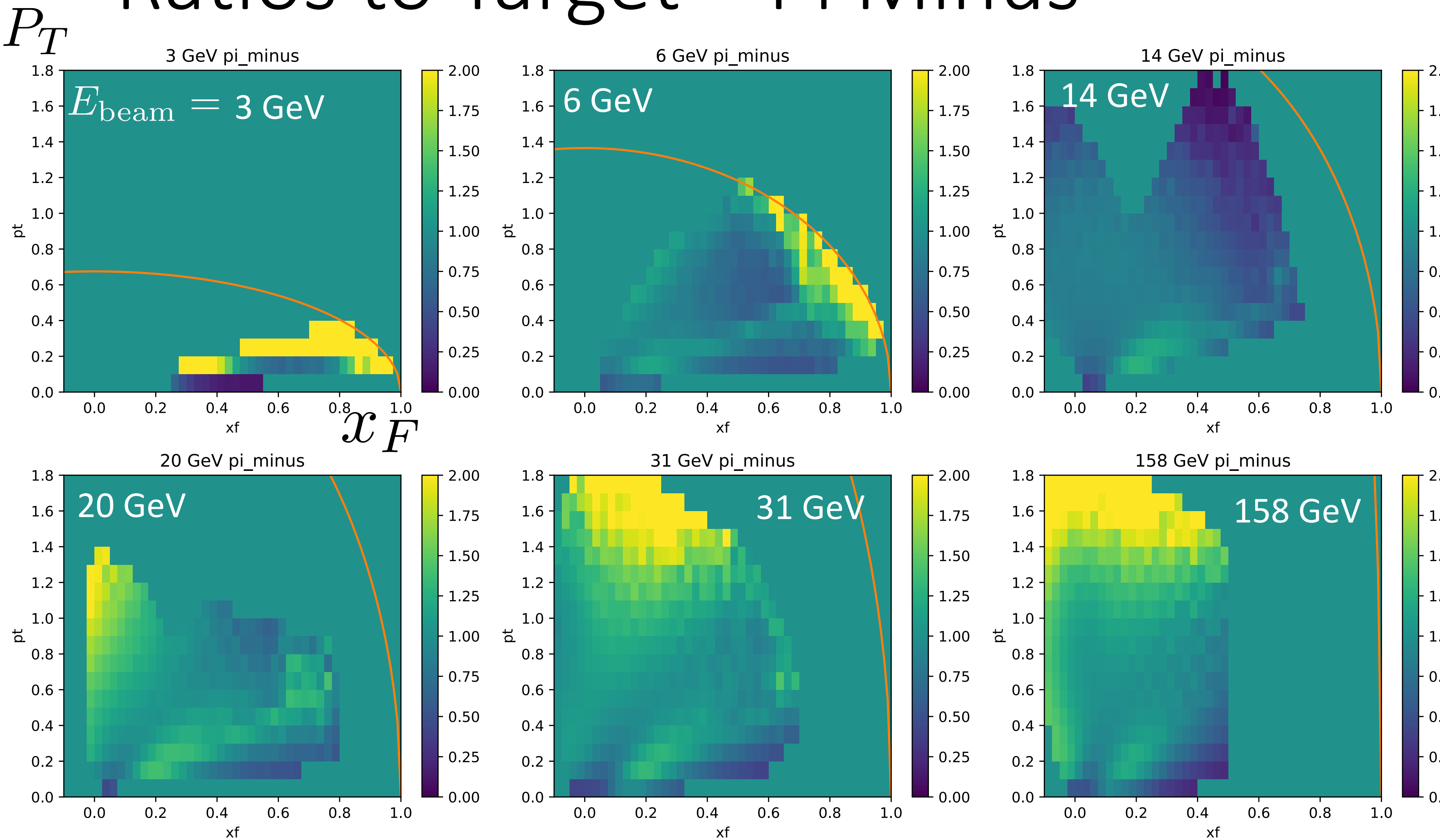
Additional Slides

Ratios to Target – Pi Plus



Ratio of data cross section to target cross section
Allowed kinematic region indicated by contour

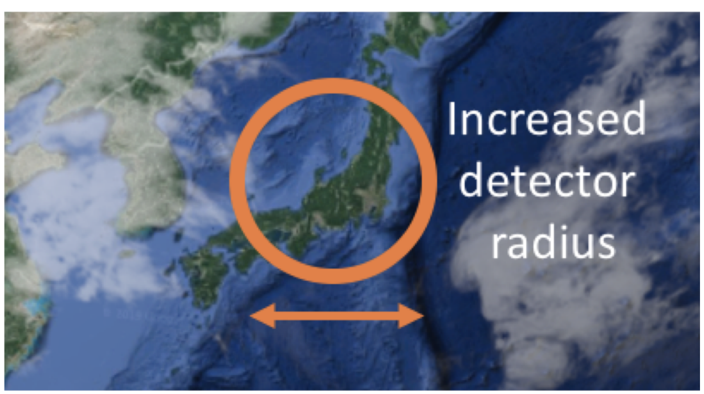
Ratios to Target – Pi Minus



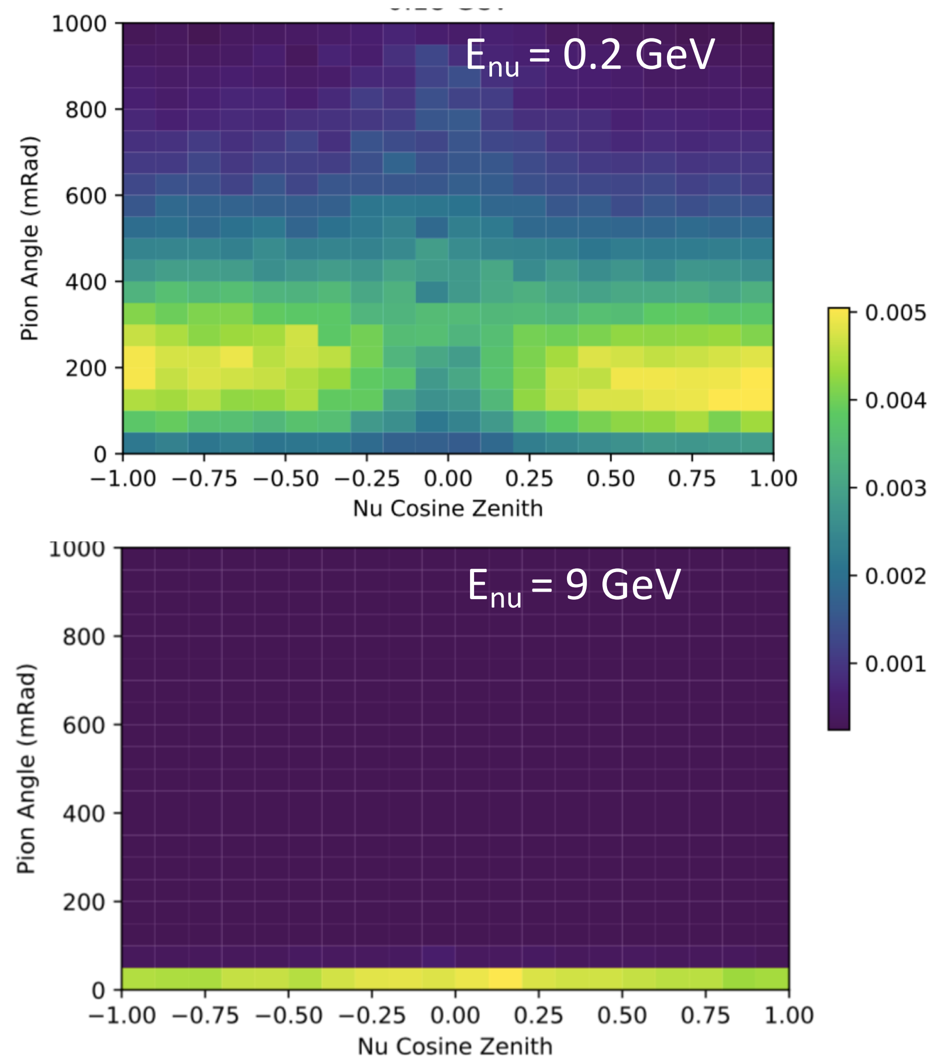
Ratio of data cross section to target cross section
Allowed kinematic region indicated by contour

Near Horizonal Neutrinos

- Consider Pion production angle phase space in neutrino cosine zenith bins
    - 3D effect geometrical effect at play near horizontal
- Similarly flat detector model in Monte Carlo begins to break down at these low energies



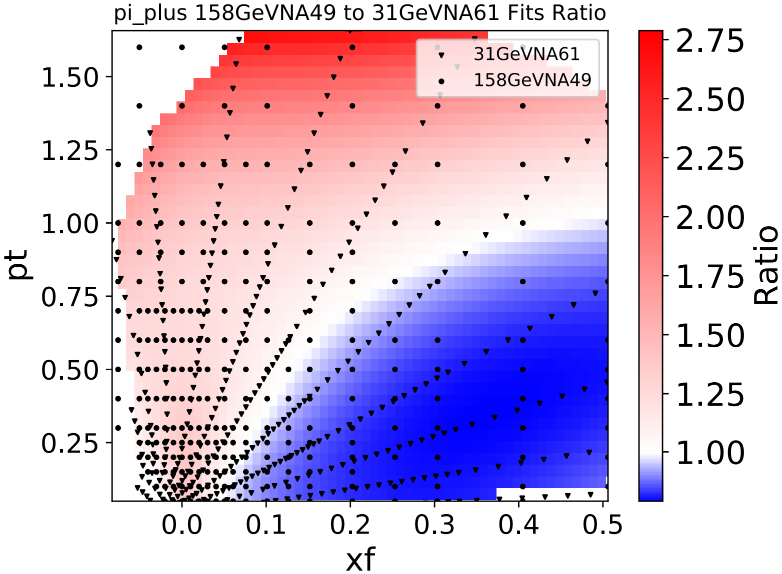
Interaction phase space in pion angle



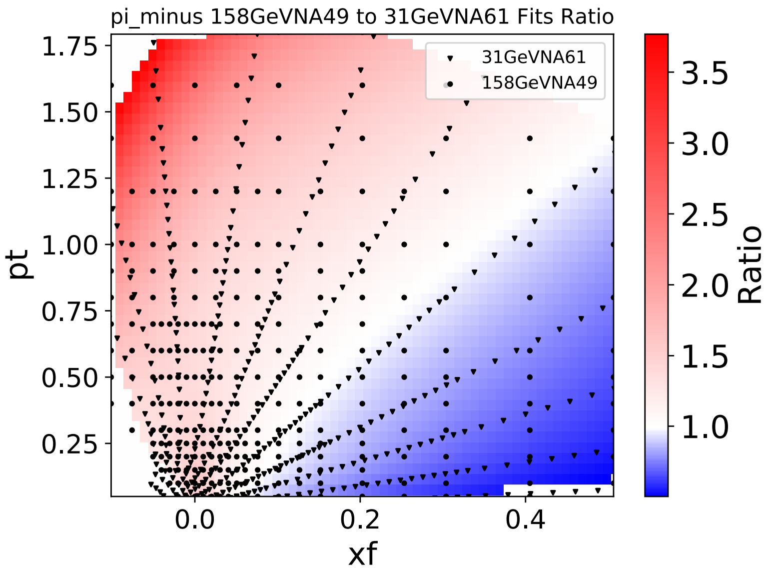
Normalised by cosine zenith angle bin

Energy Scaling NA61 to NA49

π^+



π^-



- Feynman Scaling is not particularly affective

- Lower energy scaling can be used to determine where dataset differences come from physical energy scaling or systematic uncertainties