Image: ESA

Atmospheric Neutrino Fluxes

NA61++/SHINE: Physics opportunities from ions to pions

15th December 2022

Giles Barr
University of Oxford

&

Laurence Cook
University of Oxford
IPMU, University of Tokyo

Overview

- Physics with atmospheric neutrinos
- Hadron production – key component of flux modelling
- Energy regions
- More measurements please! – Low energy especially

Oscillation of Atmospheric Neutrinos

Superkamiokande 1998 T.Kajita

Neutrino 1998 Takayama, Japan

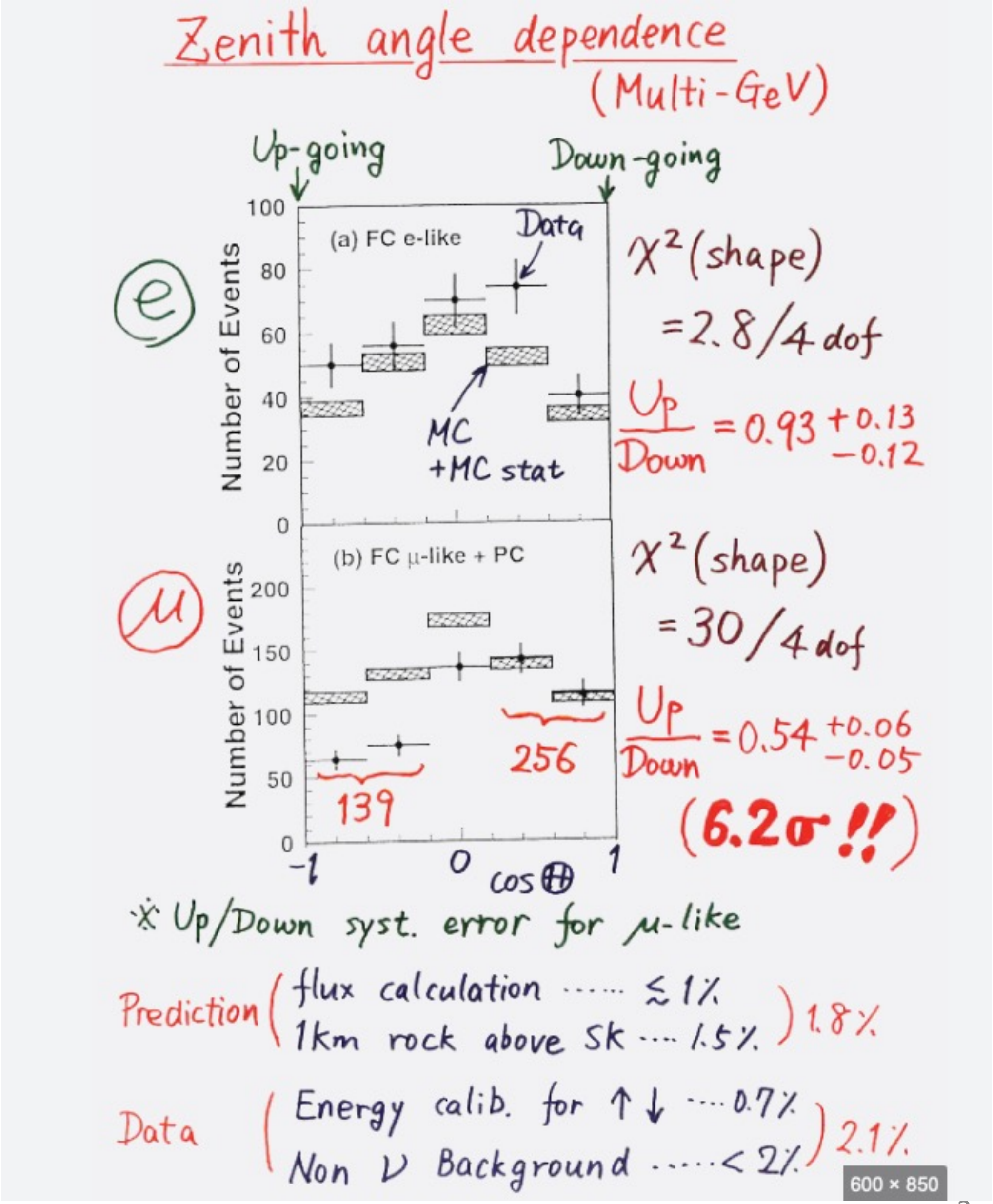
Historically important for identifying $\nu_\mu \to \nu_\tau$ oscillations.

- Evidence of neutrino oscillations

- This slide shows the first measurements at SuperKamiokande from 1998. Now operated for > 25 years, high statistics.

- Other important measurements at
  - MINOS (magnetic field = lepton charge)
  - ICECUBE (higher energy measurements)

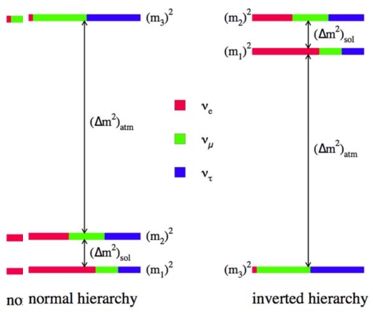
- Important part of physics programs at
  - Hyper-K (higher statistics)
  - DUNE (liquid argon)



Oscillation of Atmospheric Neutrinos

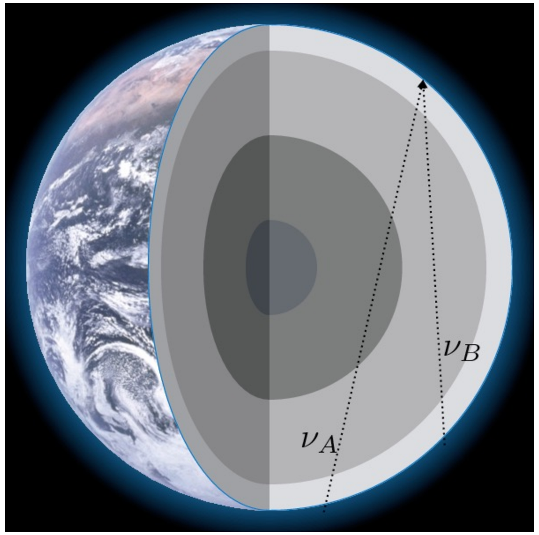
- Baseline: $\mathcal{O}\ 20 - 10,000\ \mathrm{km}$
- High statistics 3 flavour oscillation analysis is now sensitive to :
- Mass Ordering (2-10 GeV)
  - Resonant matter effects
  - $m_3 > m_1$?
- δ_{cp} (0.1-2 GeV)

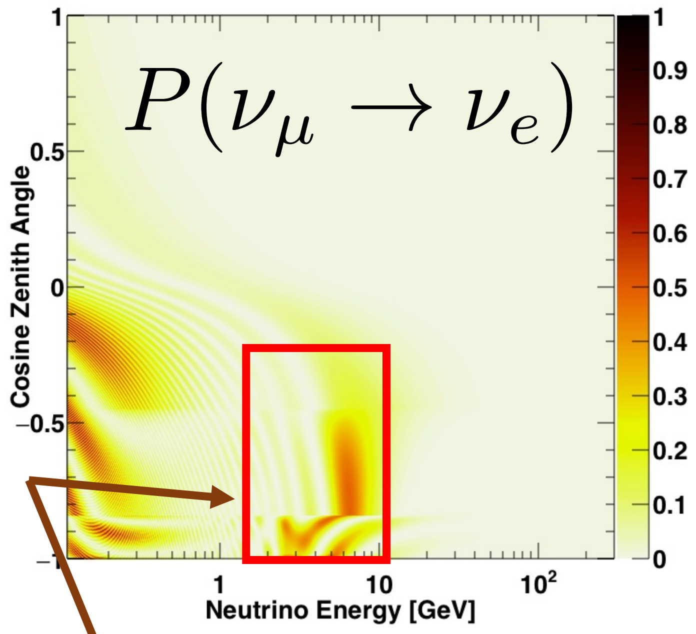
Oscillation analyses require un-oscillated neutrino flux prediction

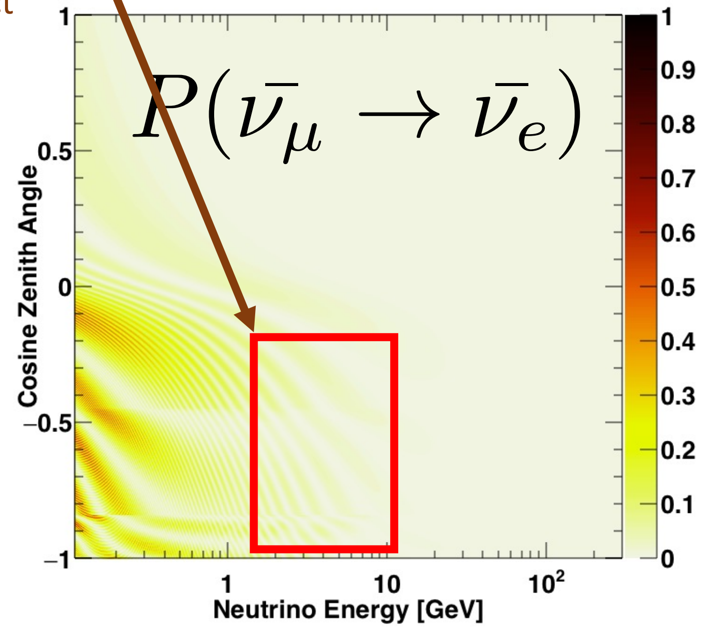


Normal Ordering: resonance only in neutrino oscillation probability

Inverted Ordering: resonance in anti-neutrino oscillation probability, the effect would be in the other plot.







arXiv:1710.09126v2

Energy Spectrum of Atmospheric Neutrinos

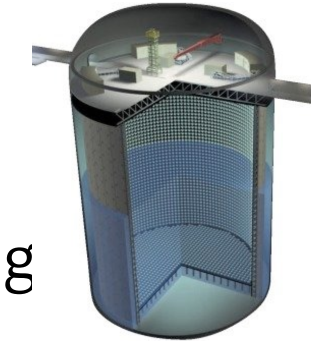
Created when daughter particles from cosmic ray interactions decay

$\sim 10\ \text{MeV}$

- Background to:
  - Diffuse SN Relic Neutrinos
  - Dark Matter Detection

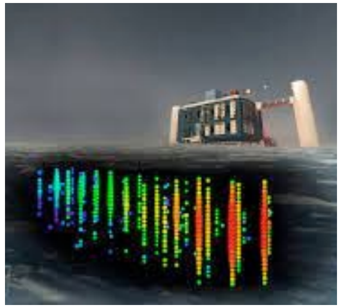
$0.1 - \sim 10\ \text{GeV}$

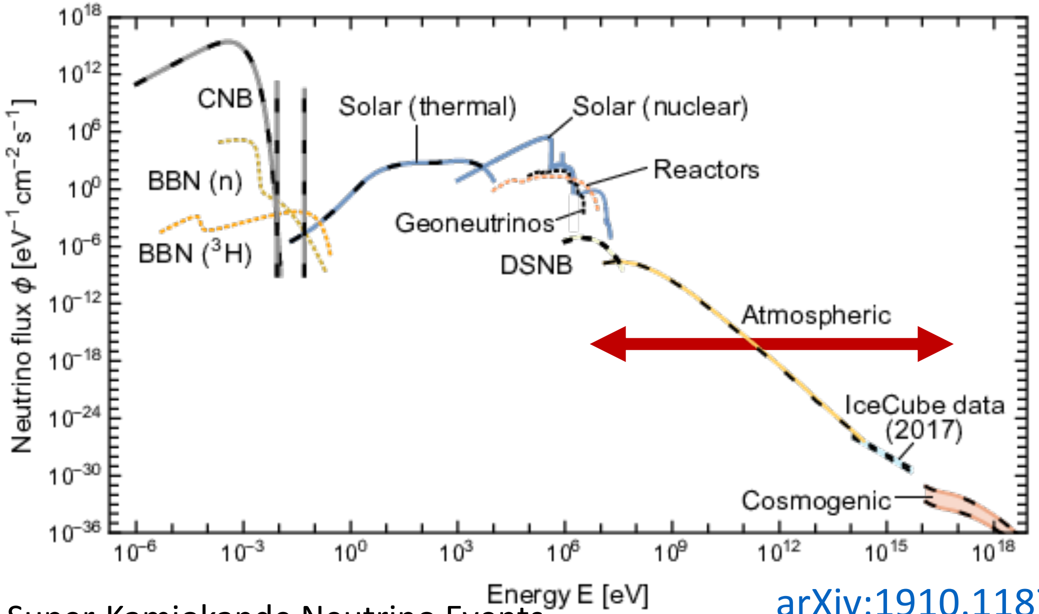
- Measurement of CP violation and mass ordering in oscillation analyses



$> \sim 1000\ \text{GeV}$

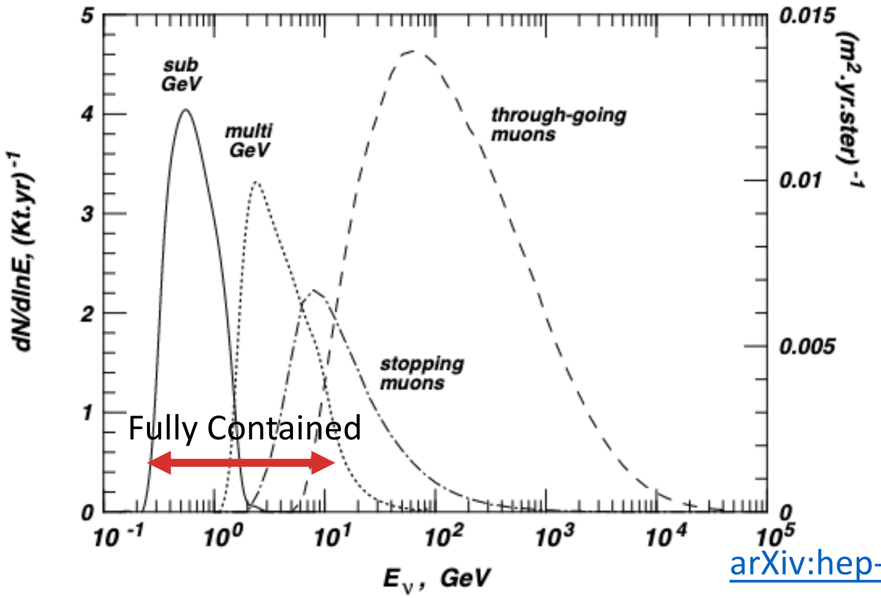
- IceCube Neutrinos
- Galactic Neutrino Energies





arXiv:1910.11878

Super-Kamiokande Neutrino Events



arXiv:hep-ph/0203272

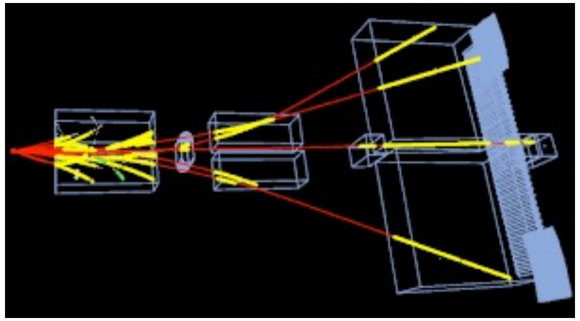
Atmospheric ν Flux Calculation

Un-oscillated fluxes

- Dominant uncertainties:
  - Hadronic Interactions – "soft" QCD region
  - Primary cosmic ray fluxes

Can be reduced by precision…

… Hadron Production Measurements



e.g. NA61/SHINE Fixed Target Hadron Production

- Recent work to incorporate measurements into neutrino flux

  Bartol Group: L.Cook, G.Barr, M.Hartz (T.Gaisser, T.Stanev)

  Honda Group: K. Sato, Y. Itow, H. Menjo (+ M. Honda)

… & Cosmic Ray Flux Measurements

e.g. AMS-02

- Similar efforts with MCEq at higher energies:

  A.Fedynitch, M.Huber

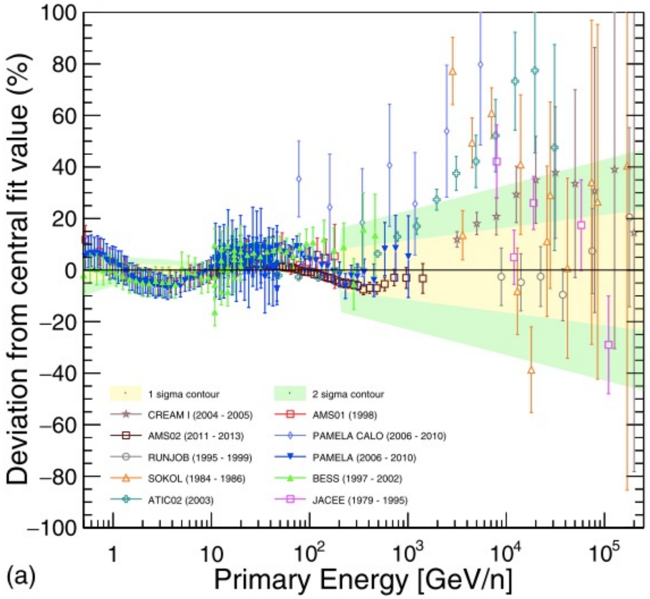
  See "Data-driven hadronic interaction model for atmospheric lepton flux calculations" arXiv:2205.14766

- Also can tune or make cross checks with muon fluxes

Independent models with comparisons at workshops every ~18 months

Cosmic Ray Fluxes

- Significantly reduced uncertainty in recent satellite and balloon datasets (few % level)
  - Higher uncertainty in calorimeter measurements at higher energies (> ~1TeV)
- Bartol : Recent work uses global fit of GSHL parameterisation to cosmic ray flux by Evans et al.
- Similar global fit presented by Honda at ICRC17 conference
- Isotropic flux in deep space travels through **solar** and **geomagnetic fields** before reaching atmosphere

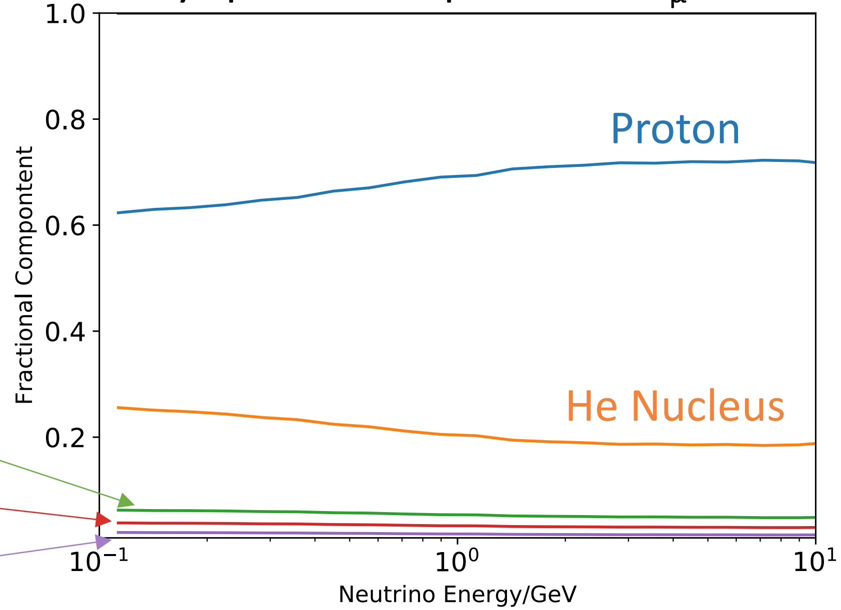


Proton Fit residuals
Evans et al.

arXiv:1612.03219v1

1 sigma uncertainty contour

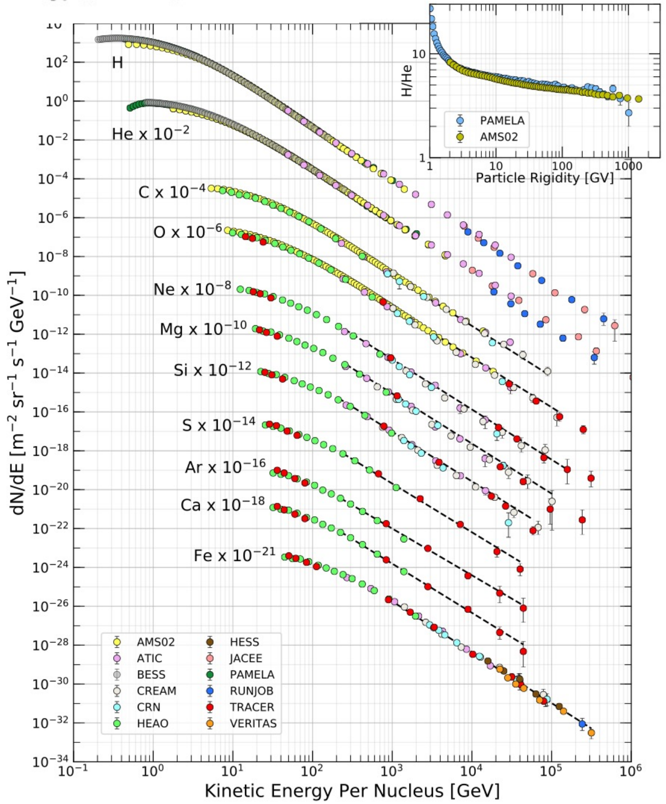
Cosmic ray species component to ν_μ neutrino flux



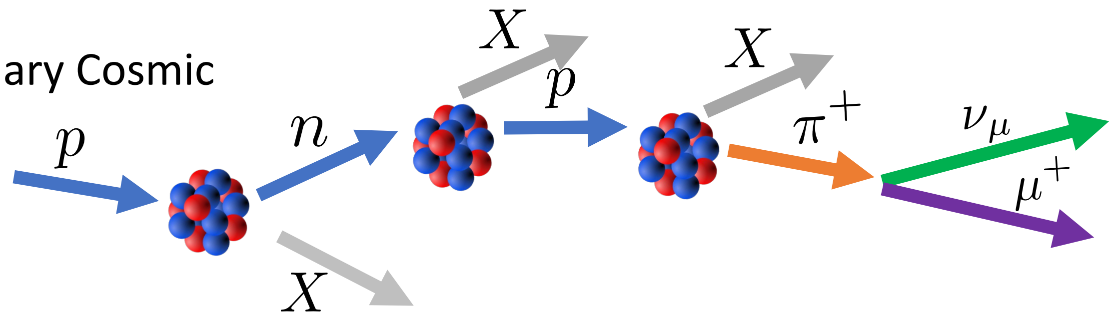
CNO Group

MgSi Group

Fe Group



Hadronic Interactions

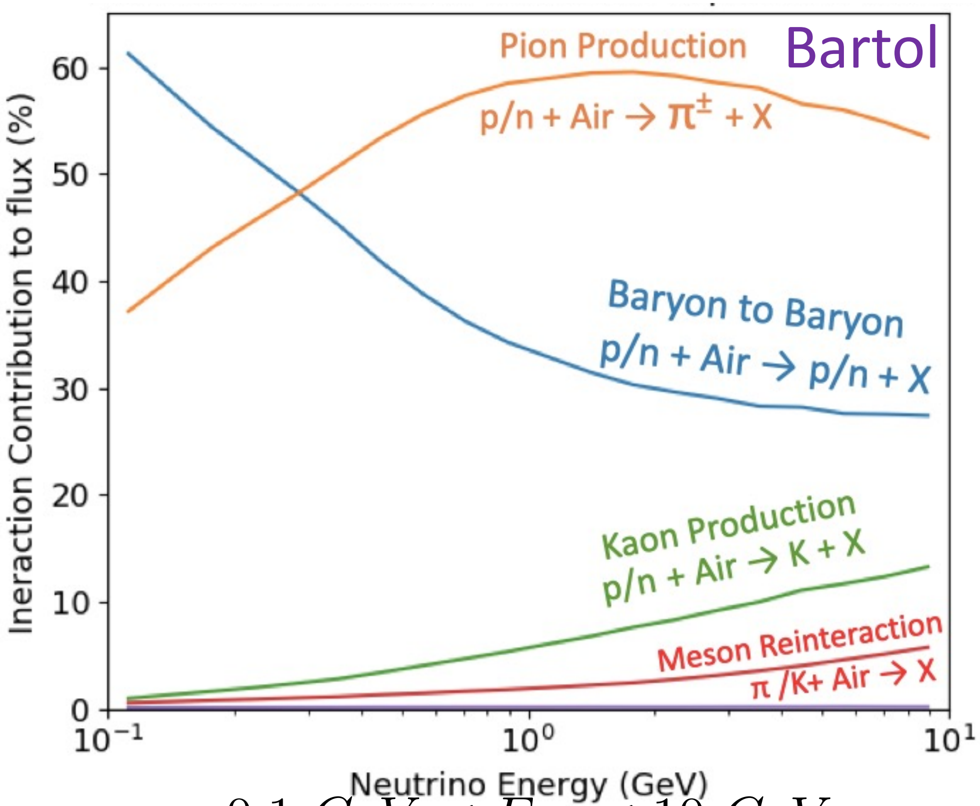


- Interactions considered as inclusive of final states e.g.:

$$pN \rightarrow \pi^+ + X$$

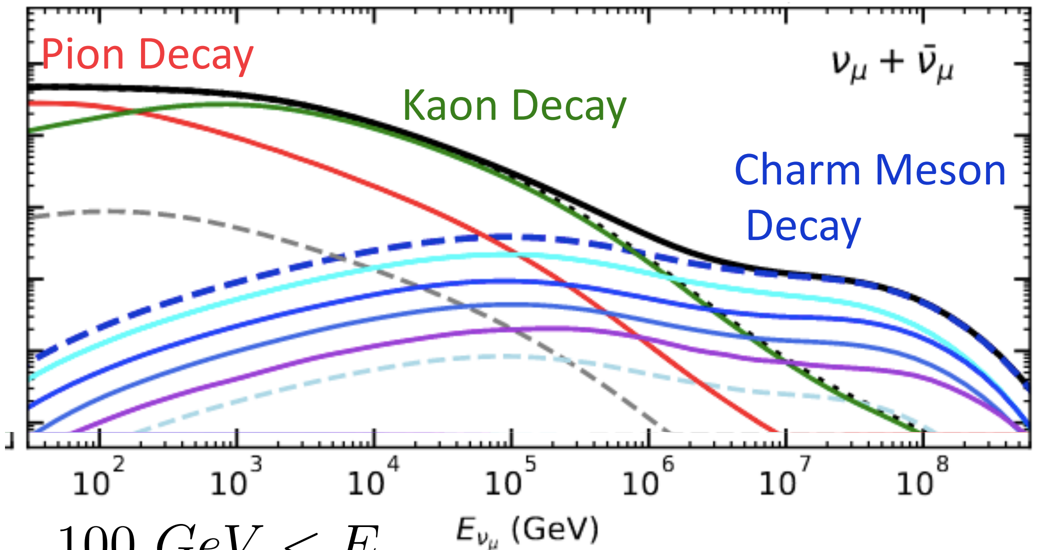
- E_ν < 10 GeV   Most important: **pion** and **kaon** production by baryons
- Baryon number conservation limits effect of baryon to baryon interactions

Fraction of each interaction in chain for ν_μ production



$0.1\ GeV < E_{\nu_\mu} < 10\ GeV$

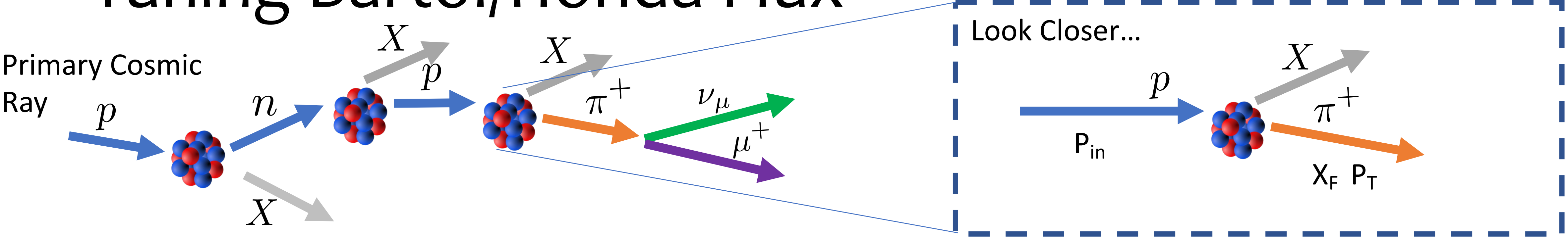
Meson decays in ν_μ flux



$100\ GeV < E_{\nu_\mu}$

A. Fedynitch et al. arXiv:1806.04140

Tuning Bartol/Honda Flux



- 3 dimensions to describe hadron production kinematics:

  Incident Baryon: P_{in}

  Outgoing Pion: x_F P_T

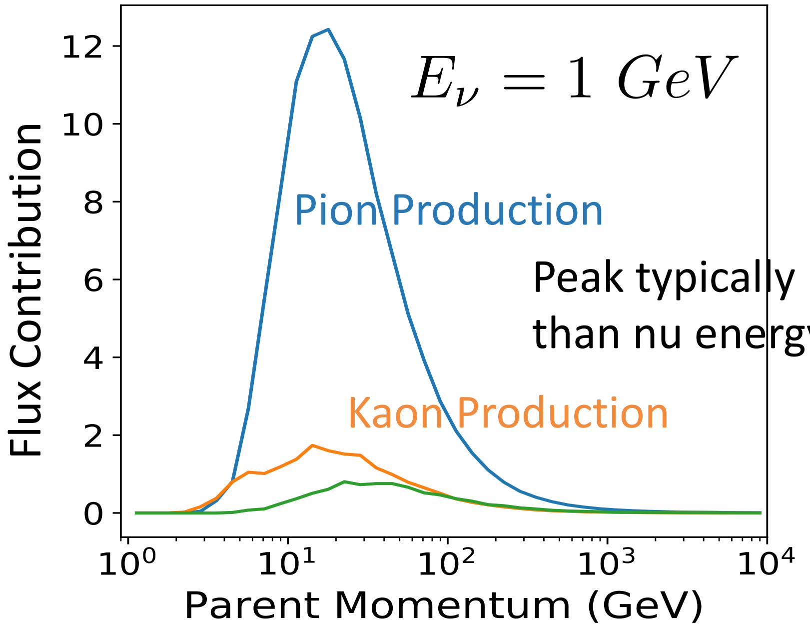
- Feynman Scaling: Does not hold well at low beam energies

$$f(P_{\text{in}}, x_F, p_T) \to f(x_F, p_T)$$

- Hadron production weighted by multiplicity ratio :

$$W = \frac{d^2 n_{\text{data}}(\pi^+)}{dx_F dp_T} \Big/ \frac{d^2 n_{\text{MC}}(\pi^+)}{dx_F dp_T}$$

Interaction Energy Contribution ν_μ

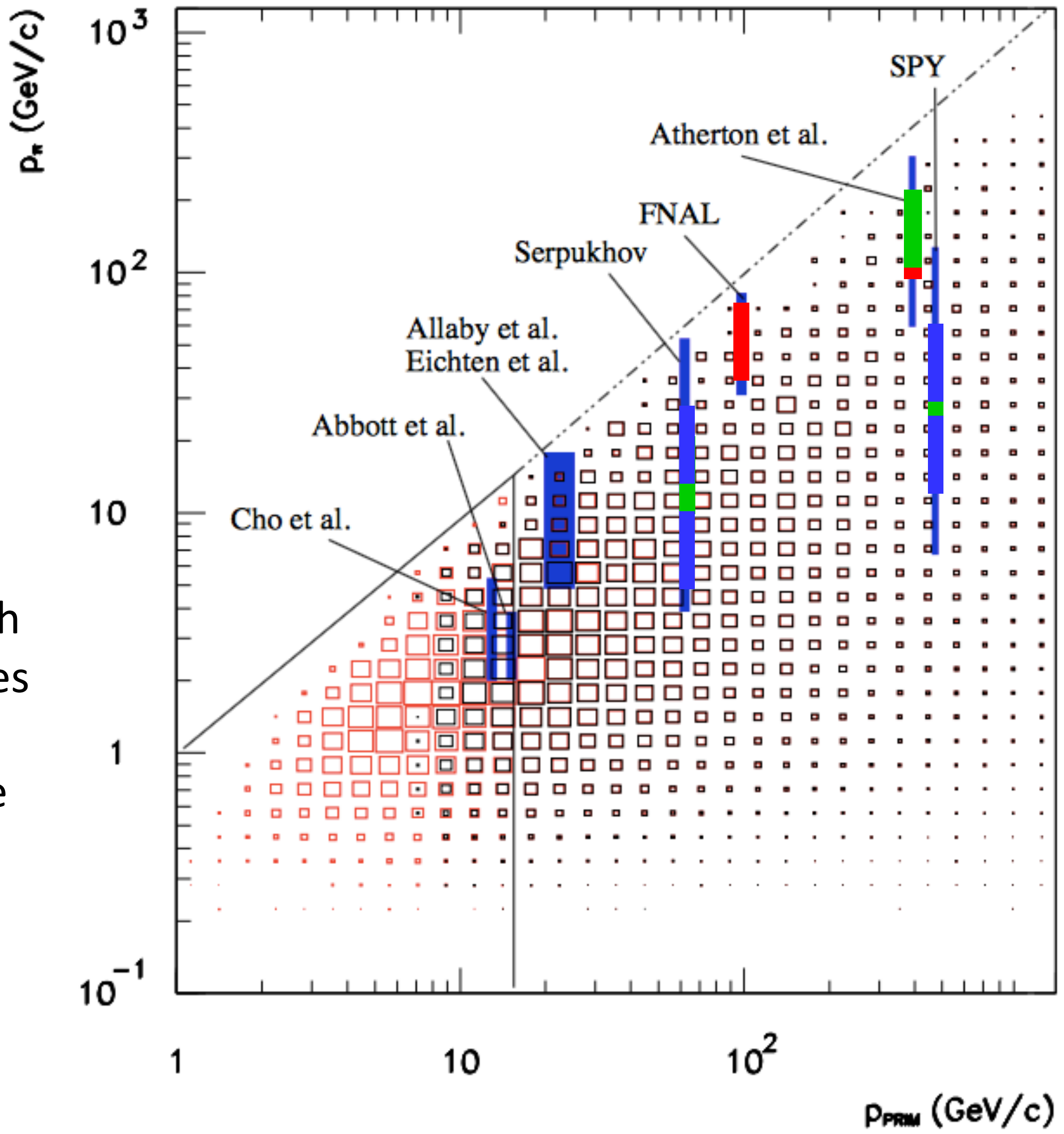


Peak typically 10x higher than nu energy

P_{in}

Very old Hadron production measurements

Small acceptance spectrometers



Red boxes show additional flux at high geomagnetic latitudes where low energy cosmic rays are more important.

i.e. DUNE, MINOS, ICECUBE

Population of hadron-production phase-space for $pA \rightarrow \pi X$ interactions.

ν_μ flux (represented by boxes) as a function of the parent and daughter energies.

Red/black indicate extremes of magnetic latitude.

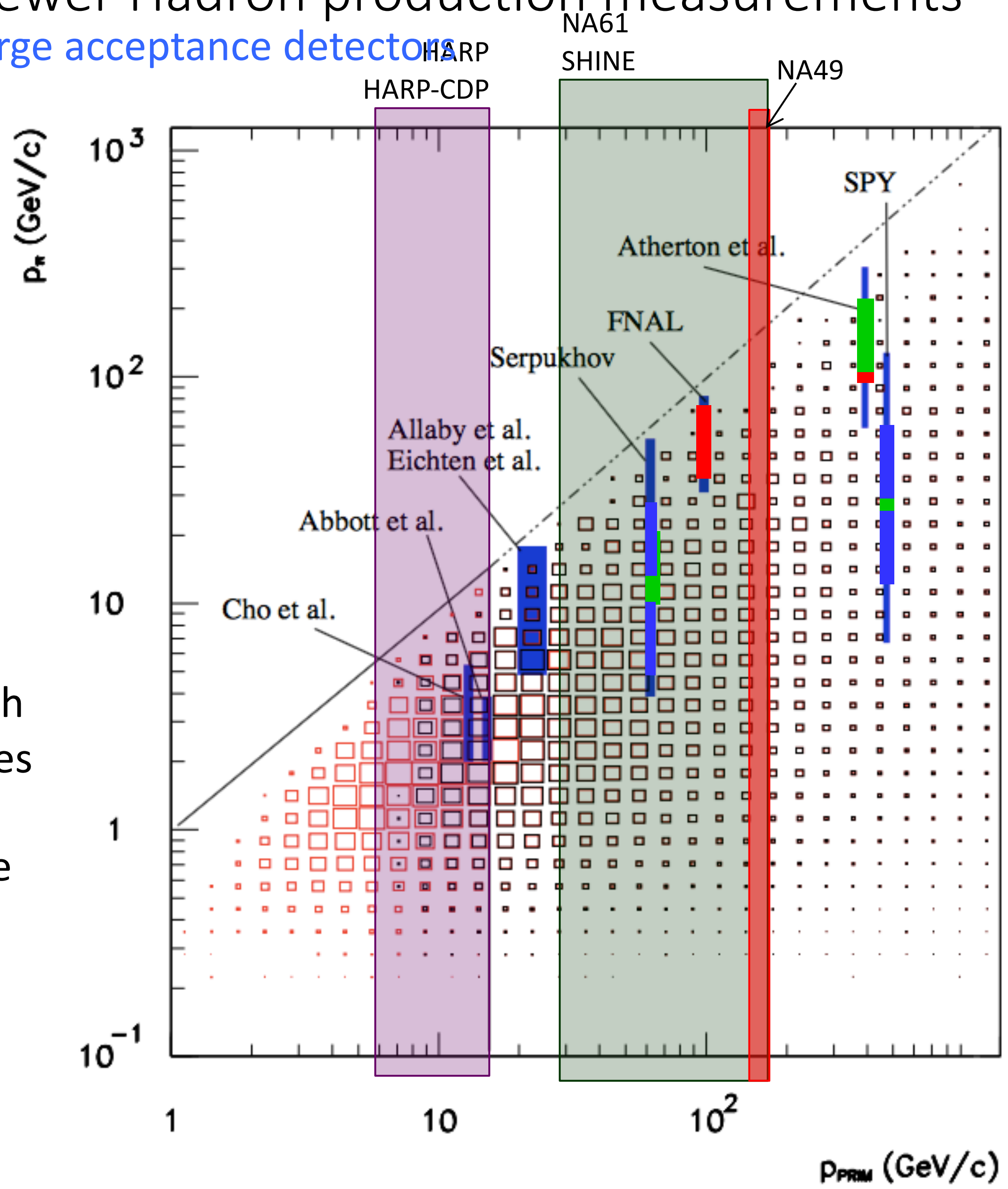
Energies around 1 GeV representing contained events in a SK-sized detector.

Measurements.

- 1-2 p_T points
- 3-5 p_T points
- >5 p_T points

Newer Hadron production measurements

Large acceptance detectors



Red boxes show additional flux at high geomagnetic latitudes where low energy cosmic rays are more important.

i.e. DUNE, MINOS, ICECUBE

Population of hadron-production phase-space for $pA \rightarrow \pi X$ interactions.

ν_μ flux (represented by boxes) as a function of the parent and daughter energies.

Red/black indicate extremes of magnetic latitude.

Energies around 1 GeV representing contained events in a SK-sized detector.

Measurements.

- 1-2 p_T points
- 3-5 p_T points
- >5 p_T points

Bartol Tuning Approach

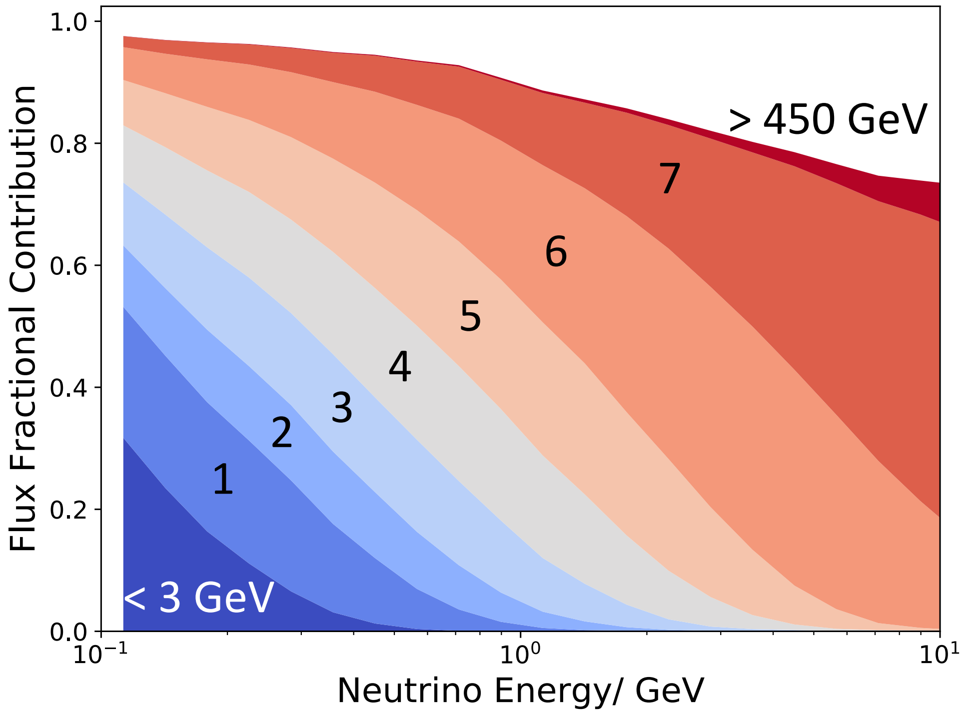
- Group measurements at similar beam energies
- Empirical scaling to interpolate between target material
- Modified BMPT parameterisation at each region
  - Same as T2K flux calculation
- Linear interpolation between Energy Regions:
  - Additional interpolation uncertainties included
  - Feynman scaling between 158 – 450 GeV
- Tune **pion** production:

$$3\ GeV < P_{\rm in} < 450\ GeV$$

- Tune **kaon** production:

$$13\ GeV < P_{\rm in} < 158\ GeV$$

Pion production energy region fractional contribution to ν_μ flux



Bartol Tuning

P_{in}	
1) 3 GeV	3 GeV HARP 3 GeV HARP high angle
2) ~6 GeV	5 GeV HARP 6.4 GeV E910 5 GeV HARP high angle
3) 8 GeV	8 GeV HARP 8 GeV HARP high angle
4) ~13 GeV	12 GeV HARP 12.3 GeV E910 14.6 GeV E802 12 GeV HARP high angle
5) ~20 GeV	17.5 GeV E910 19.2 GeV Allaby et al. 24 GeV Eichten et al.
6) 31 GeV	31 GeV NA61/SHINE
7) 158 GeV -450 GeV	158 GeV NA49 450 GeV NA56

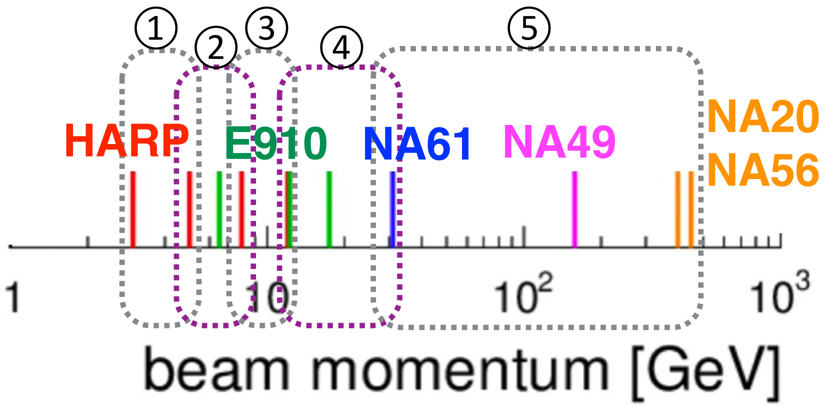
Honda Tuning by Nagoya Group
Thank you to K. Sato for the slides

data fit

Interpolation between discrete beam E is a challenge.

- Feynman scaling is not applicable.

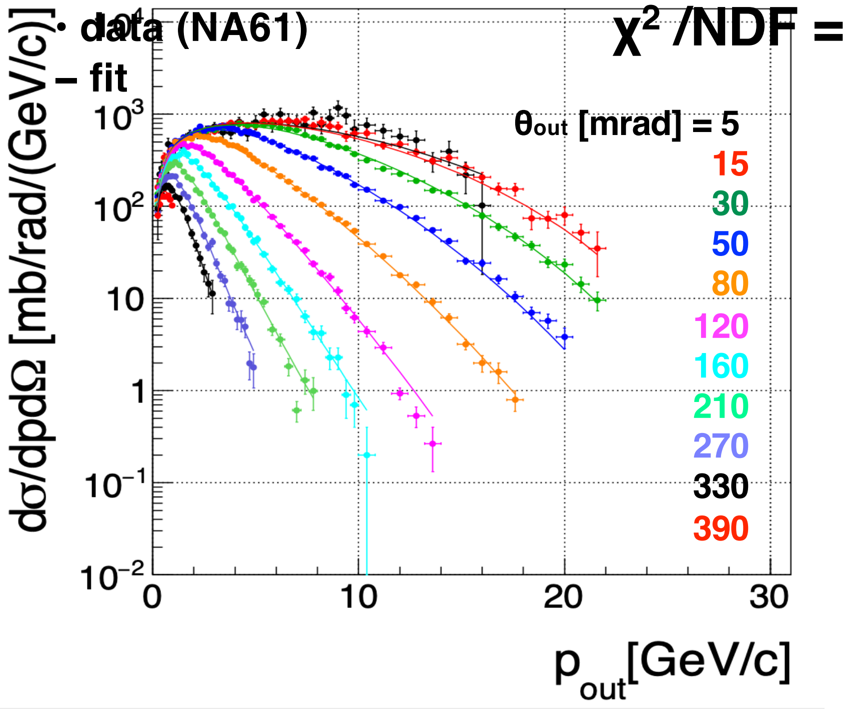
→ grouped beam data into small sections

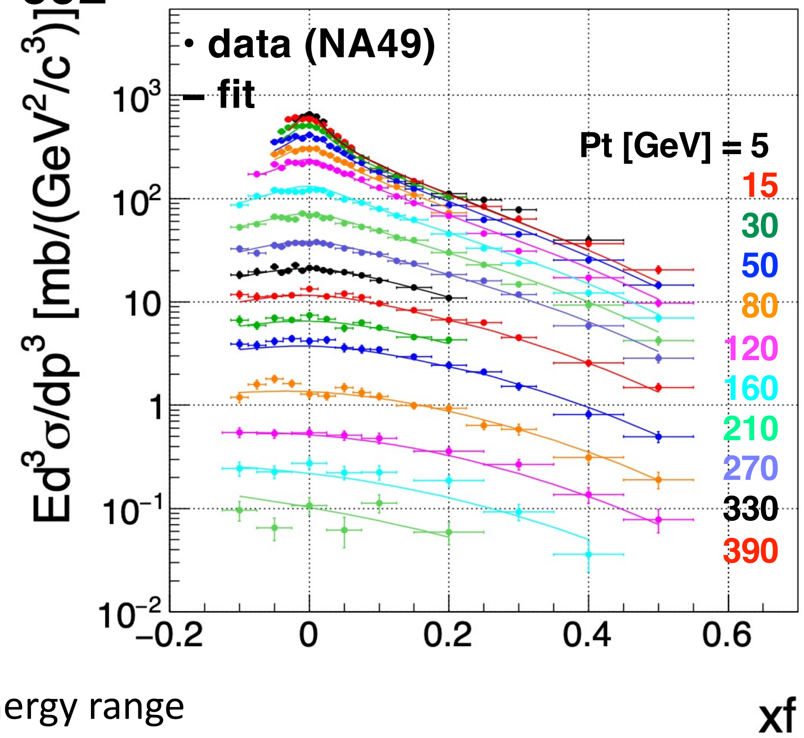


$$f_{fit} = f_{pp} \times f_{pA_0/pp} \times f_{A/A_0} \times \left(1 + C_1 \log_{10} \frac{p_{beam}}{C_2}\right)$$ **beam E dependence**

result of simultaneous fit for π⁺ data in group ⑤ (NA61, NA49, NA56)

χ^2 /NDF = 1227 / 692





based on measurements

weight for tuning:

$$w = \frac{\left(\frac{d\sigma}{dpd\Omega}\right)_{data}}{\left(\frac{d\sigma}{dpd\Omega}\right)_{MC}}$$

used in MC

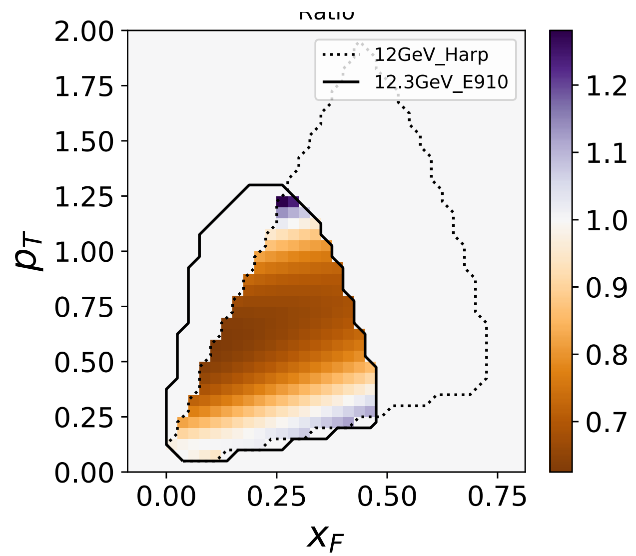
→ reduced $\chi^2 < \sim 2$ in all energy range

Challenges at Lower Energies

- Smaller phase space coverage of the relevant interactions
- Disagreements between dataset multiplicity measurements
  - Differing analyses of HARP high angle data
- Scaling of errors a la PDG

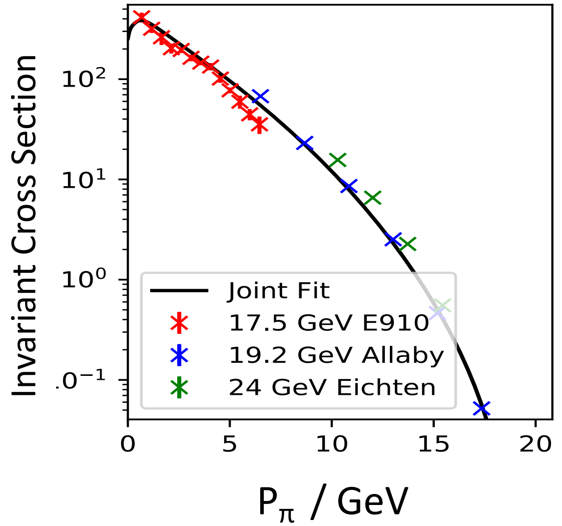
Discrepancies between lower energy datasets

12 GeV Harp to 12.3 GeV E910 π^+ Fit Ratio



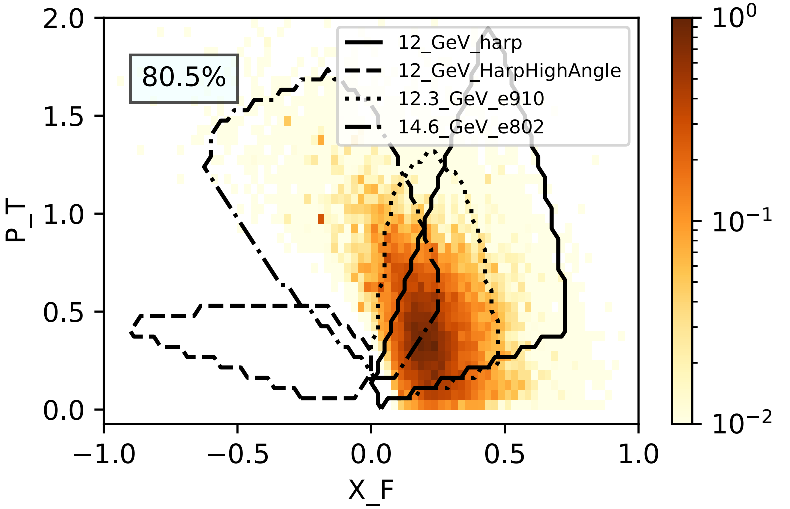
@ ~ 19 GeV

30 - 40 mRad

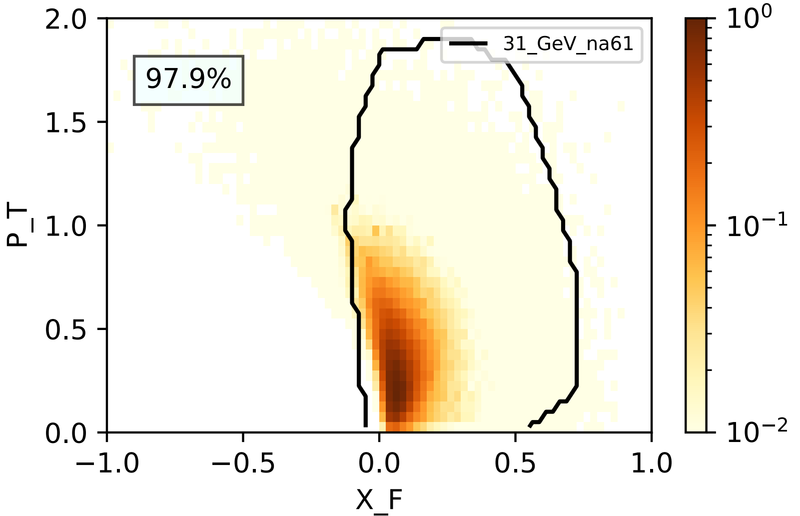


$E_{\nu_\mu} = 1\ GeV$ pion production phase space

Interaction Energy ~ 13 GeV



Interaction Energy ~ 30 GeV



- These effects increase the systematic uncertainties on neutrino flux
- New low energy measurements will lower this uncertainty in the future

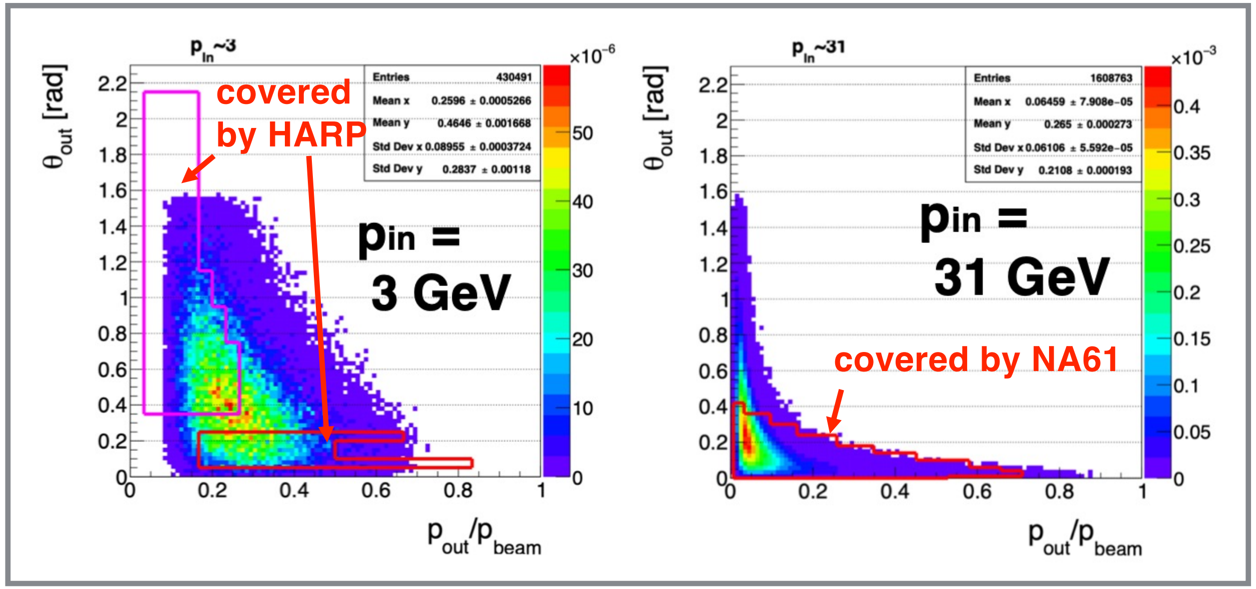
Honda Tuning by Nagoya Group

Slides by K. Sato

phase space coverage

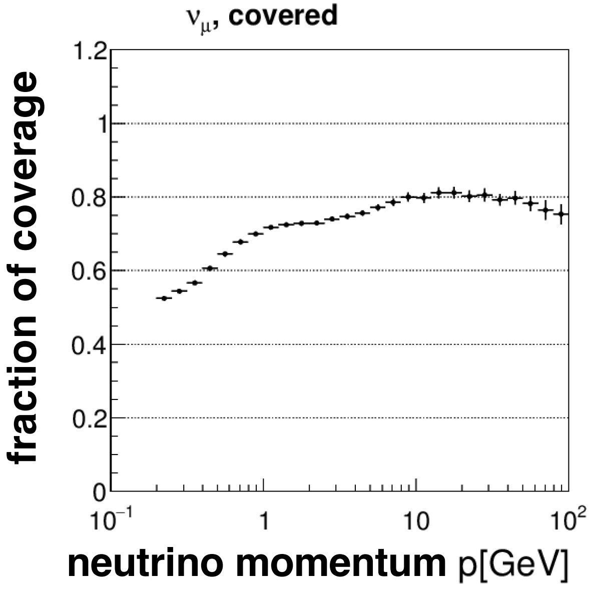
Tuning of:
$p\ N_{\mathrm{Air}} \to \pi K p + X$
Interactions

ex) phase space of π^+ production for 0.3 GeV ν_μ



← hadron production phase space (PS) as a function of p_{in}, p_{out}, θ_{out}

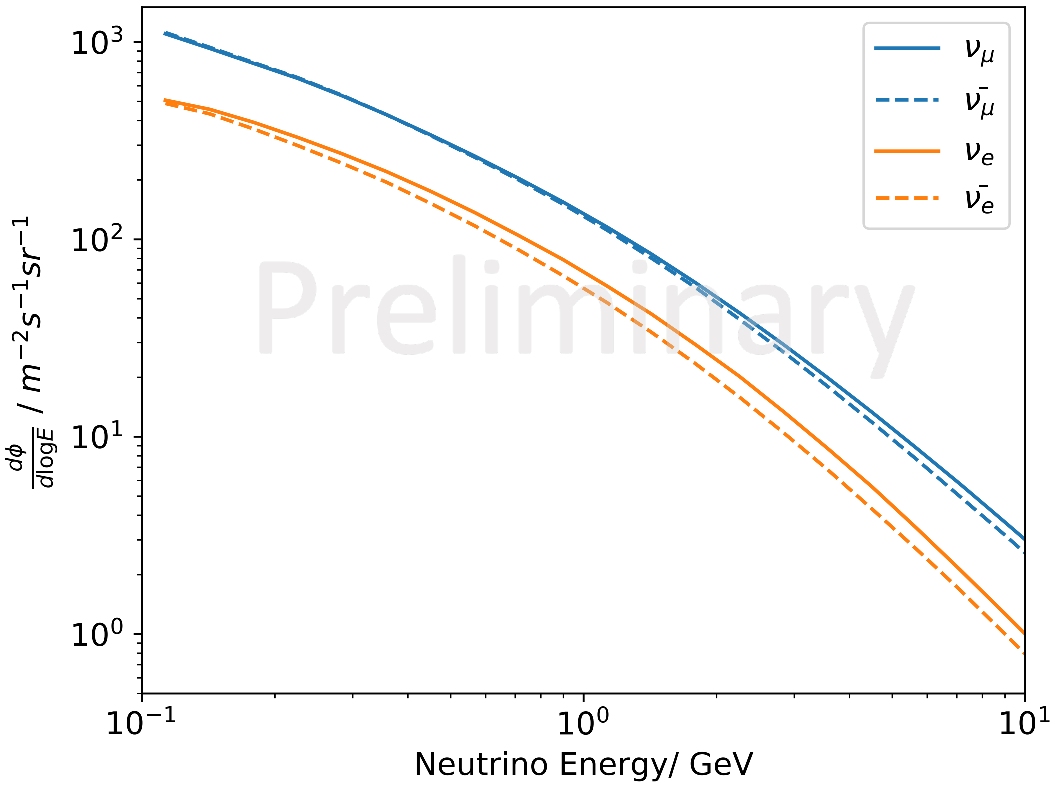
phase space coverage for ν_μ



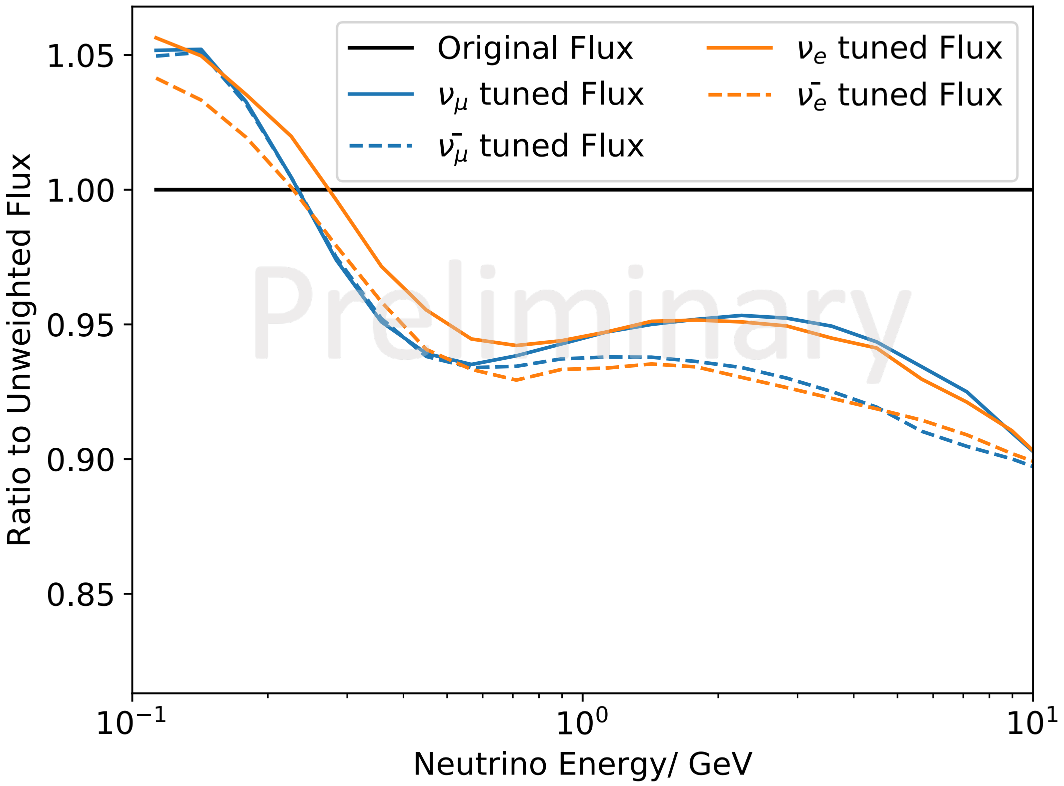
- good (~80%) PS coverage for ~10 GeV ν
  - due to wide PS of NA61 & NA49
- lower coverage in E_ν < 1 GeV
  - due to lack of E_{beam} < 3GeV beam data

→ shortage of phase space is considered as systematic uncertainty of ν flux.

Tuning Flux Results



Ratio to Bartol with TARGET2.4 before Tuning

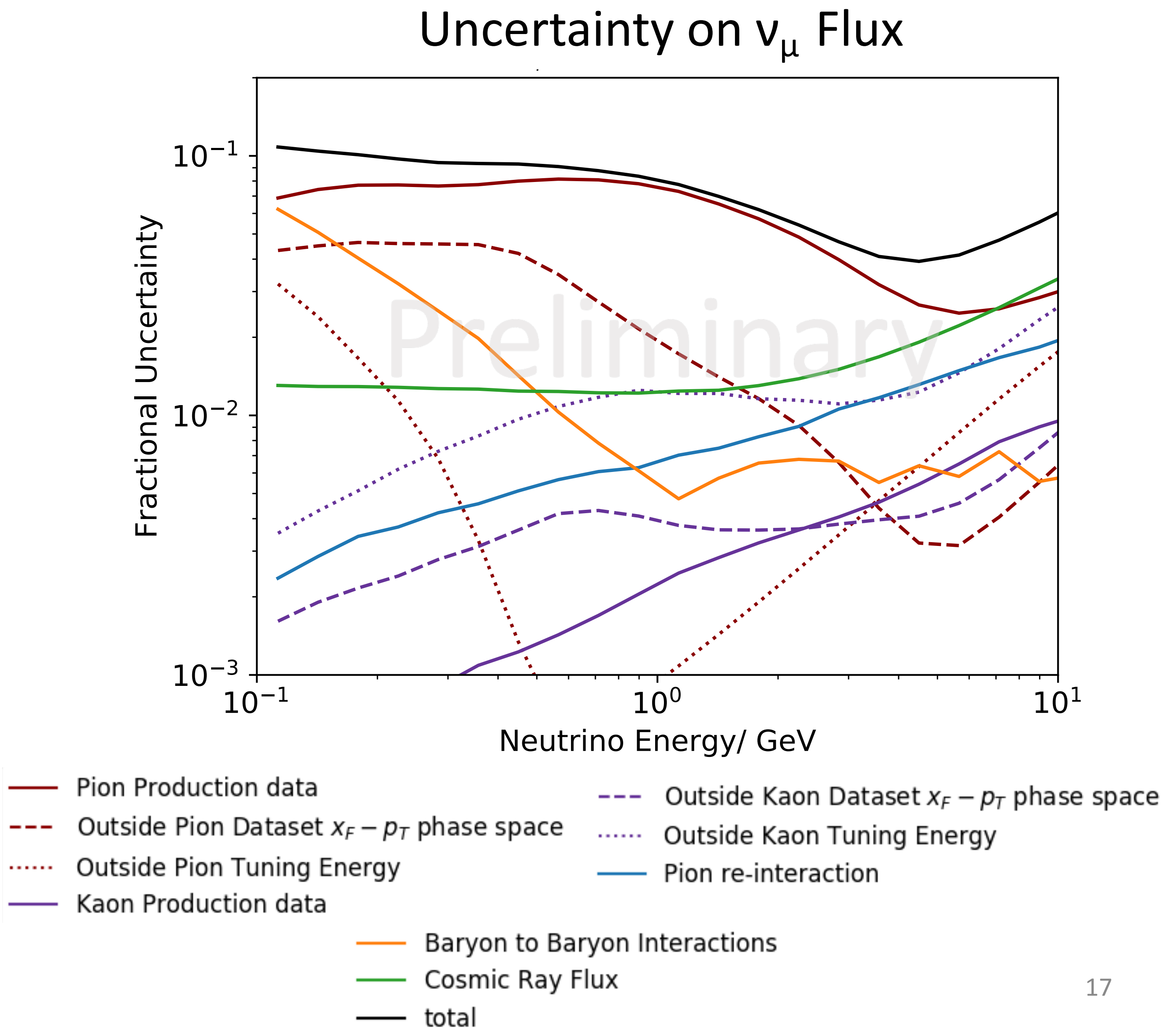


- Tuning both hadronic interactions and cosmic ray fluxes
- Within the original 15% uncertainty

Neutrino Flux Uncertainty

- Reduction in uncertainty from 15% previous estimate
- Total uncertainty is quadrature sum of individual uncertainties
- < 2GeV uncertainty
  - Higher dataset uncertainty
  - Lower coverage of datasets
- > 2GeV uncertainty
  - Reduced uncertainty in region covered by NA61 and NA49

- Additional uncertainties due to:
  - baryon to baryon interactions
  - pion reinteractions

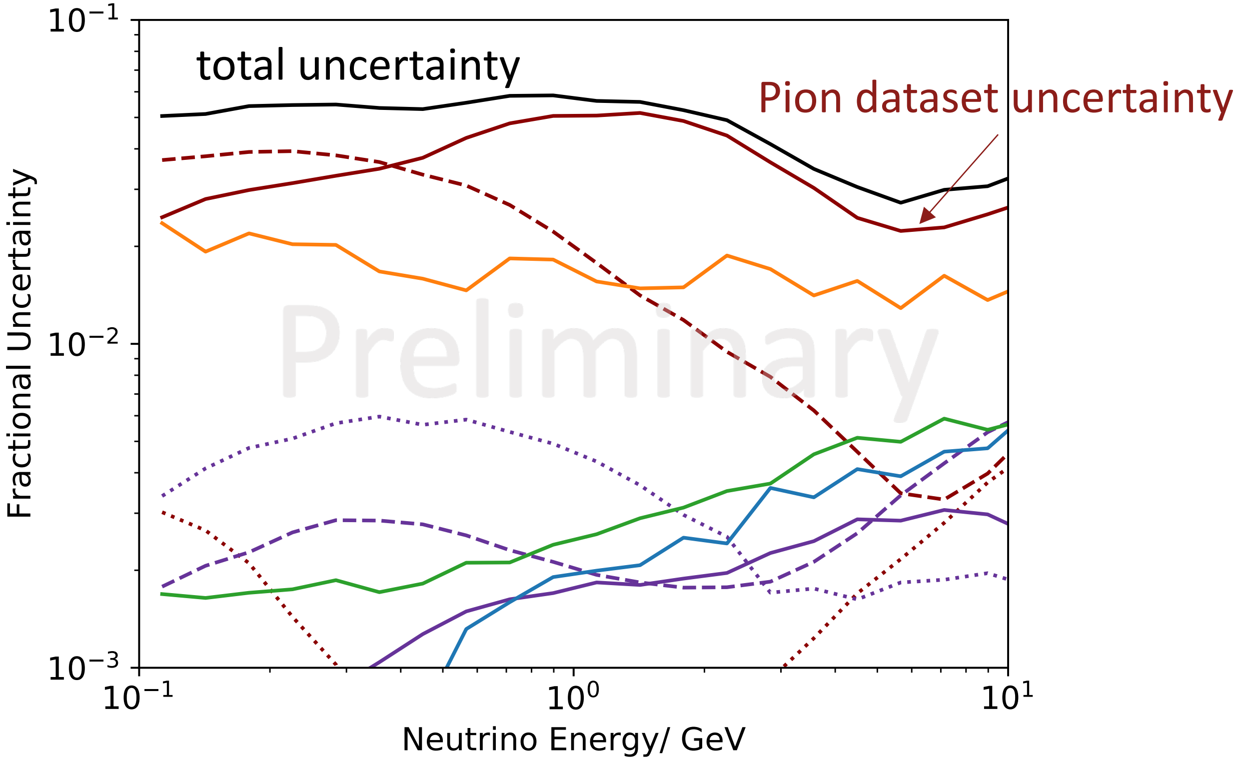


Uncertainty on Flavour Ratios

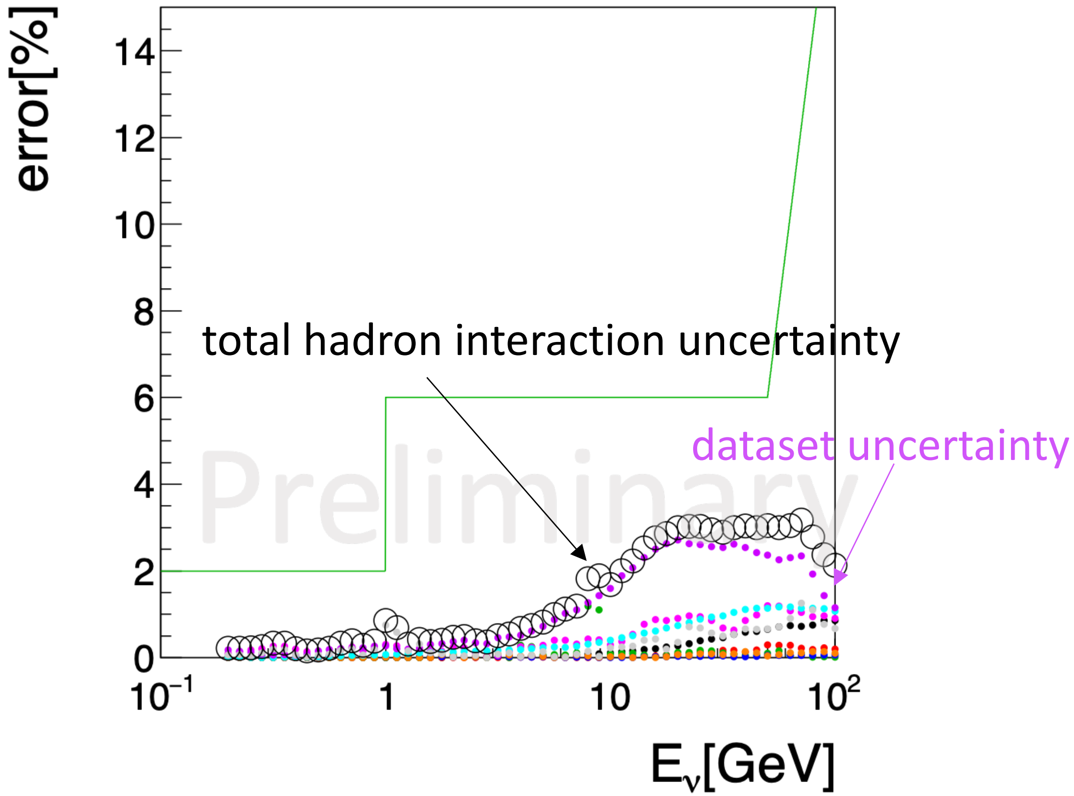
- Reduction in uncertainties when considering flavour ratios
- Correlation between production of different neutrino flavours
    - Cancellation of common systematic errors
- Flavour ratios sensitive to oscillation effects

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\quad\quad \hookrightarrow e^+ + \nu_e + \bar{\nu_\mu}$$

Bartol Tuned Flux $\nu_e / \bar{\nu_e}$ uncertainty

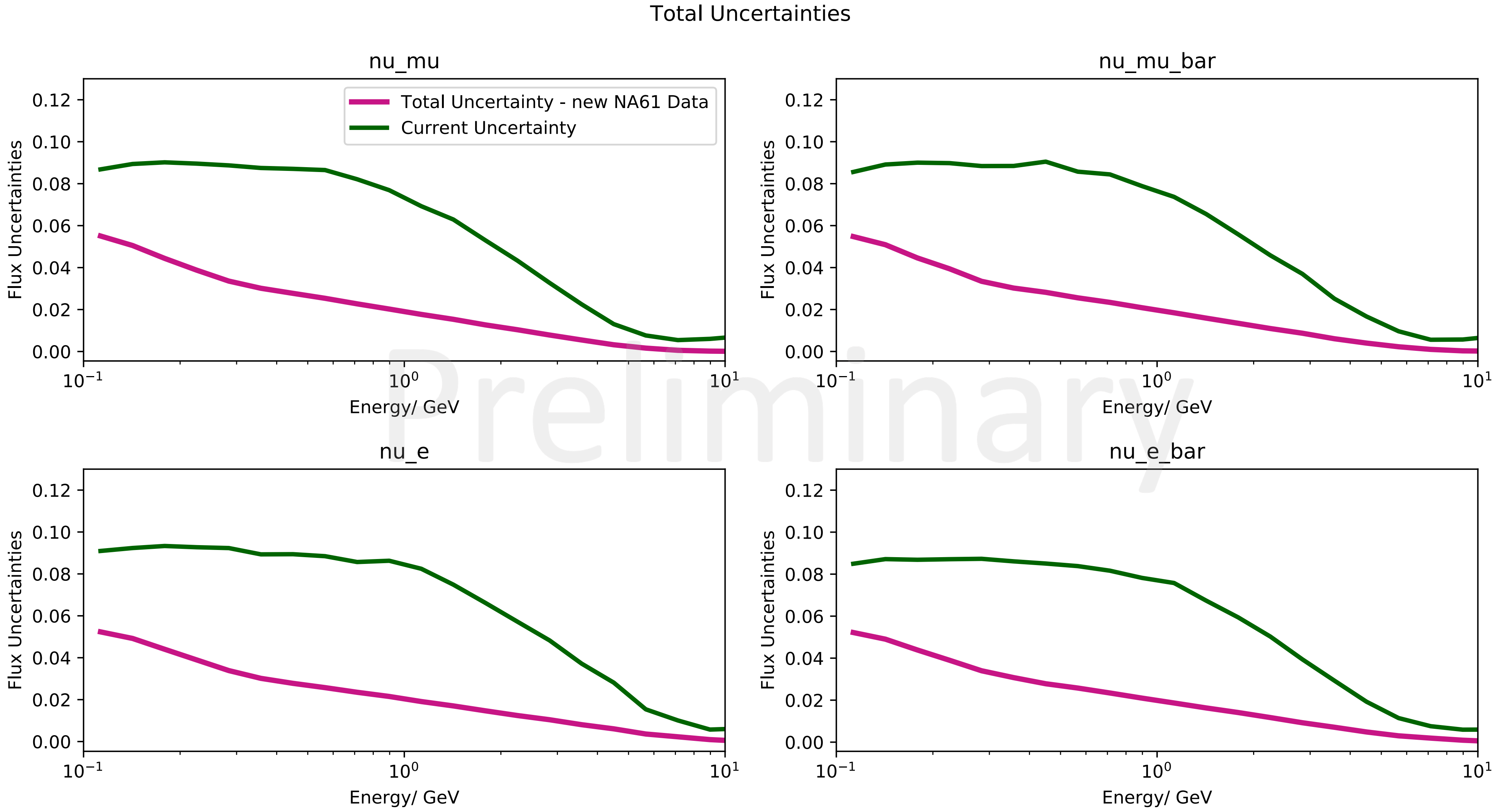


Honda Tuned Flux $\bar{\nu}_\mu / \nu_\mu$ uncertainty



Comparison of original and new uncertainty estimates

Uncertainties from <30 GeV Interactions only

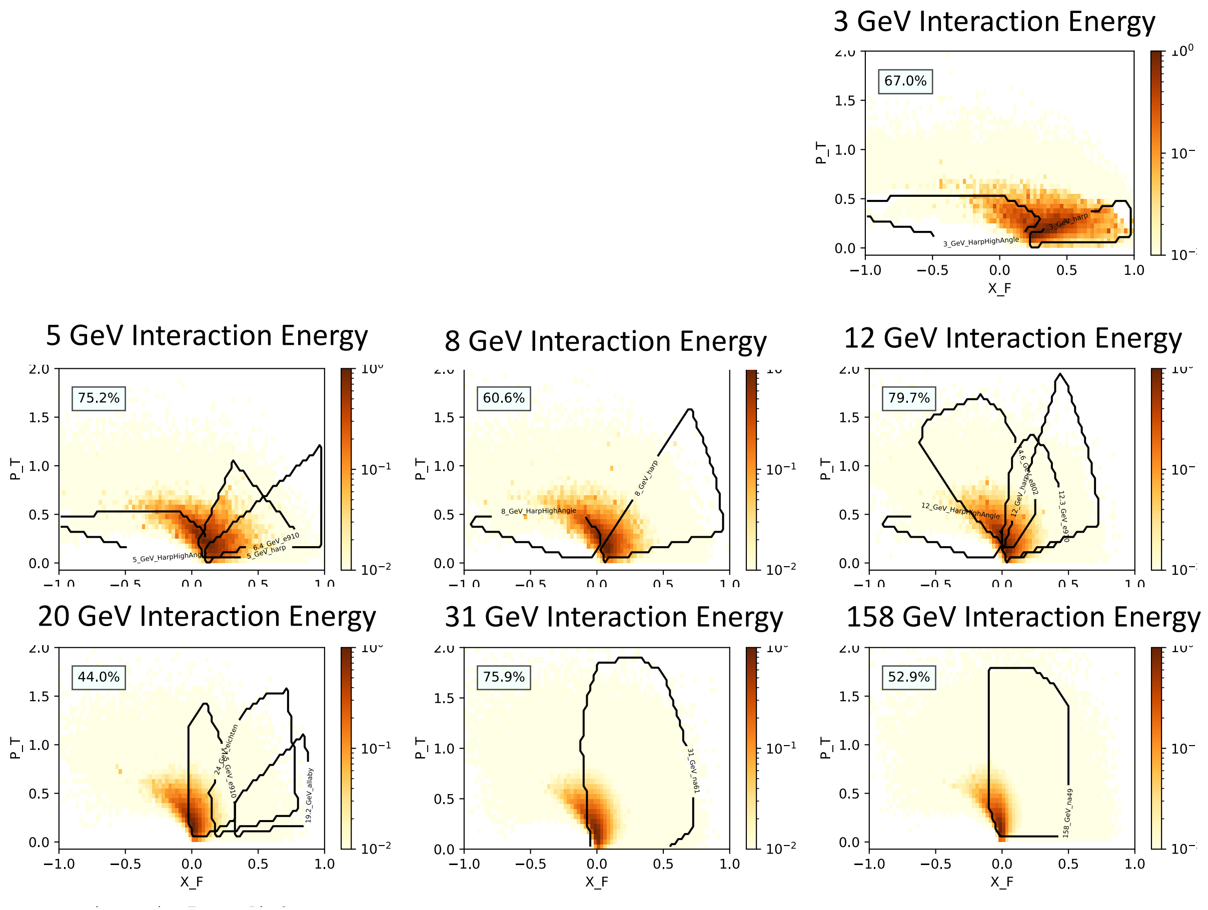


Conclusions

- Atmospheric neutrinos produced very exciting physics in the past, and the future is bright for sub-dominant oscillation studies.
- Hadron production data is crucial in this precision era of atmospheric neutrino studies.
- At low energies (< 20GeV protons), there is data, some of it is good, but it is a struggle to make a consistent overall picture and there are large gaps in the phase space.
- Detailed Bartol and Honda flux model comparisons to take place shortly
- Further reduction in hadron production systematics:
  - 120 GeV NA61/SHINE data – reduce interpolation uncertainty between 31 and 158 GeV
  - Potential for new low energy measurements reduce uncertainty where hadron production is uncertain

Backup

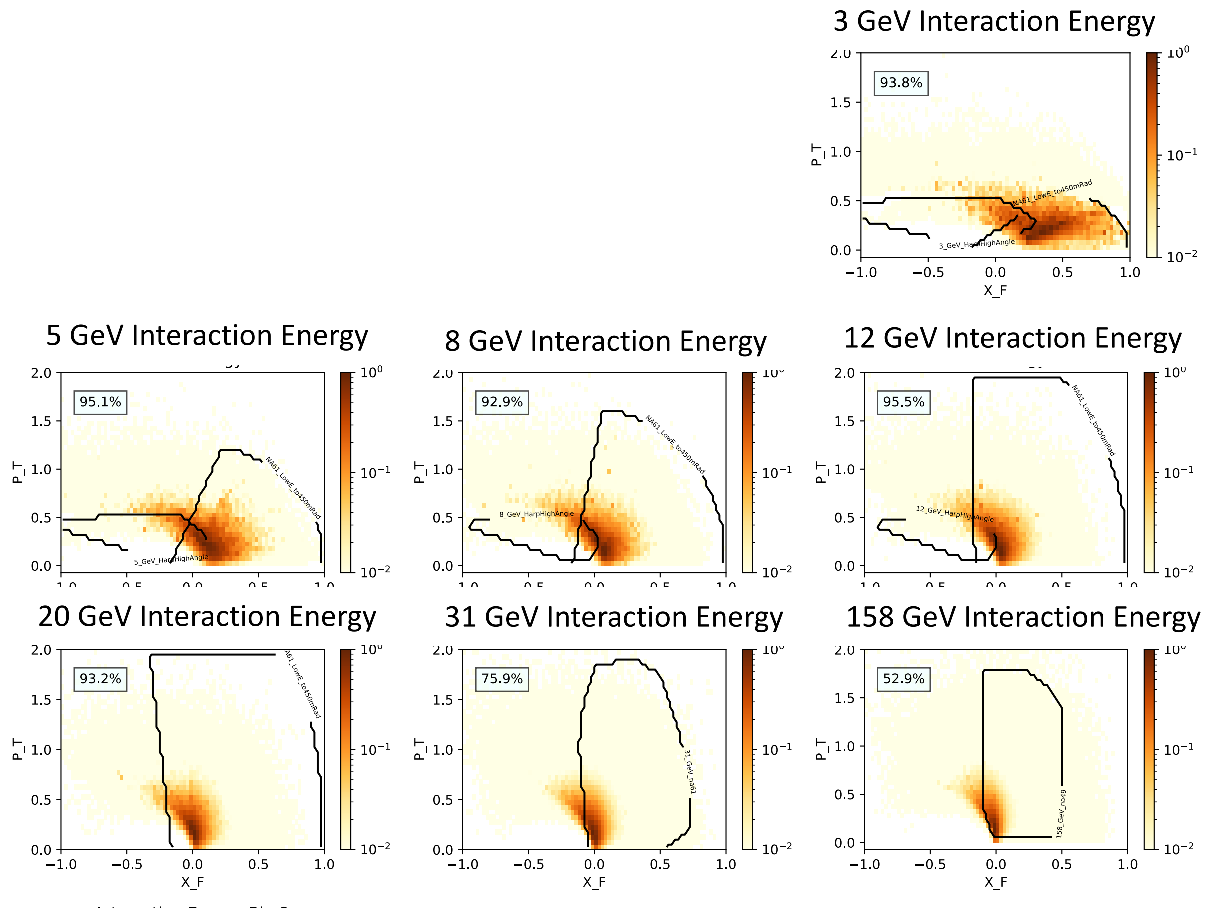
Improvements with new low energy data



- Plots for different primary energies. x_f vs p_T.
- Colours show the importance to atmospheric neutrinos
- Wide range of low energy datasets with significantly poorer coverage than NA61/NA49 region.
- Low energy data sets have significantly worse errors and disagreements.
- Not all measurements use carbon, need to use A scaling model.
- Resonances mean scaling parameterizations are not effective at low energy
- Transition from low-angle to high-angle data difficult at low energies.

0.3 GeV Neutrino phase space coverage

With new NA61 Low Energy Bins



- Regions changed to include the increased NA61++ phase space coverage
- Older measurements removed where covered by NA61++