Pion Reinteraction Uncertainties with Geant 4 Reweight

Christopher Thorpe, Lancaster University

Lancaster University

1. Introduction

A goal of modern neutrino experiments is the measurement of neutrino-nucleus cross sections and understanding the influence of final state interactions, which often relies on observing additional final state particles such as protons and pions.

The detection efficiencies of these particles can depend on whether they undergo secondary interactions such as reabsorption whilst propagating through the detector. These processes are usually simulated by the software package Geant 4 [1].

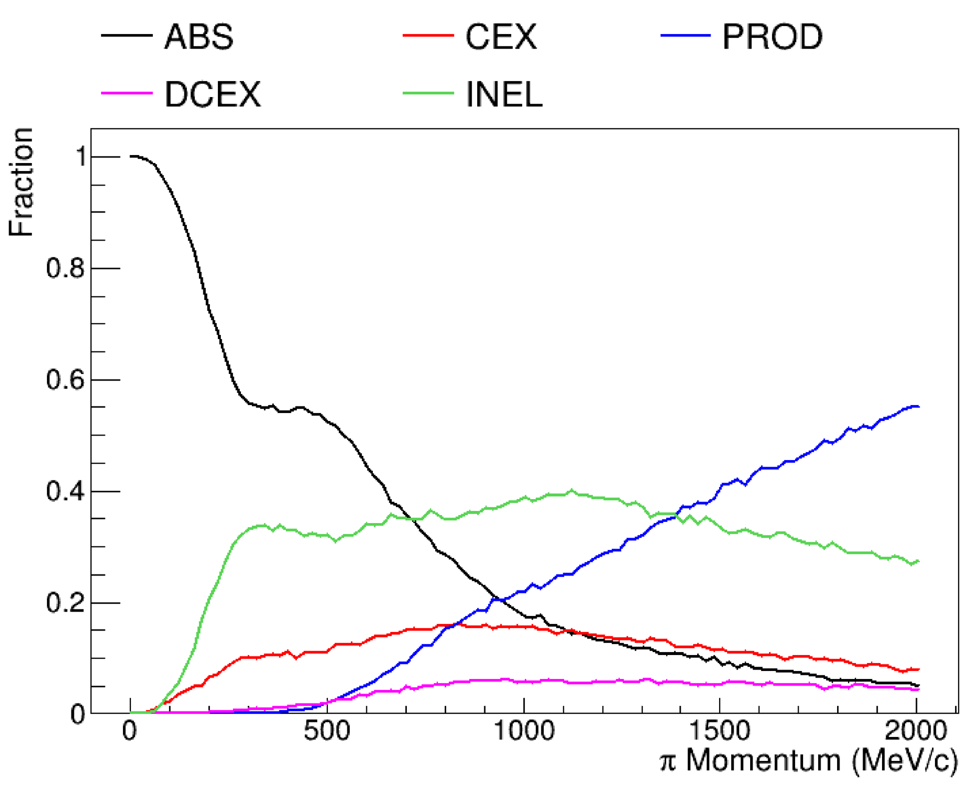
Geant 4 Reweight [2] is a tool used to reweight simulated particle trajectories for the propagation of hadron-nucleus cross section uncertainties. Here we describe a procedure for the extraction of suitable input uncertainties from data.

2. Charged Pion Interactions

We classify charged pion interactions into six channels defined by their final state content:

Channel	Definition
Elastic	$\pi^{\pm} + N \to \pi^{\pm} + N$
Absorption	$\pi^{\pm} + N \to N'$
Inelastic	$\pi^{\pm} + N \to \pi^{\pm} + N'$
Charge Exchange	$\pi^{\pm} + N \to \pi^{0} + N'$
Double Charge Exchange	$\pi^{\pm} + N \to \pi^{\mp} + N'$
Pion Production	$\pi^{\pm} + N \to n\pi + N'$

Elastic is distinguished from inelastic in that the nucleus is left intact in its ground state.



Relative strengths of 5 interaction channels (excl. Elastic) at different pion momenta using an Ar target, estimated from G4.

4. Fitting Procedure

A multi-target, multi-channel fit is performed by introducing a parameter to rescale the Geant 4 cross section of each exclusive channel. We vary these scaling parameters and use the MINUIT routine to minimise the following χ2 score:

$$\chi^2_k = \frac{1}{N_k - p_k} \sum_i^{N_k} \left(\frac{\sigma_i^{\mathrm{Data}} - \sigma_i^{\mathrm{MC}}}{\Delta\sigma_i^{\mathrm{Data}}} \right)^2$$

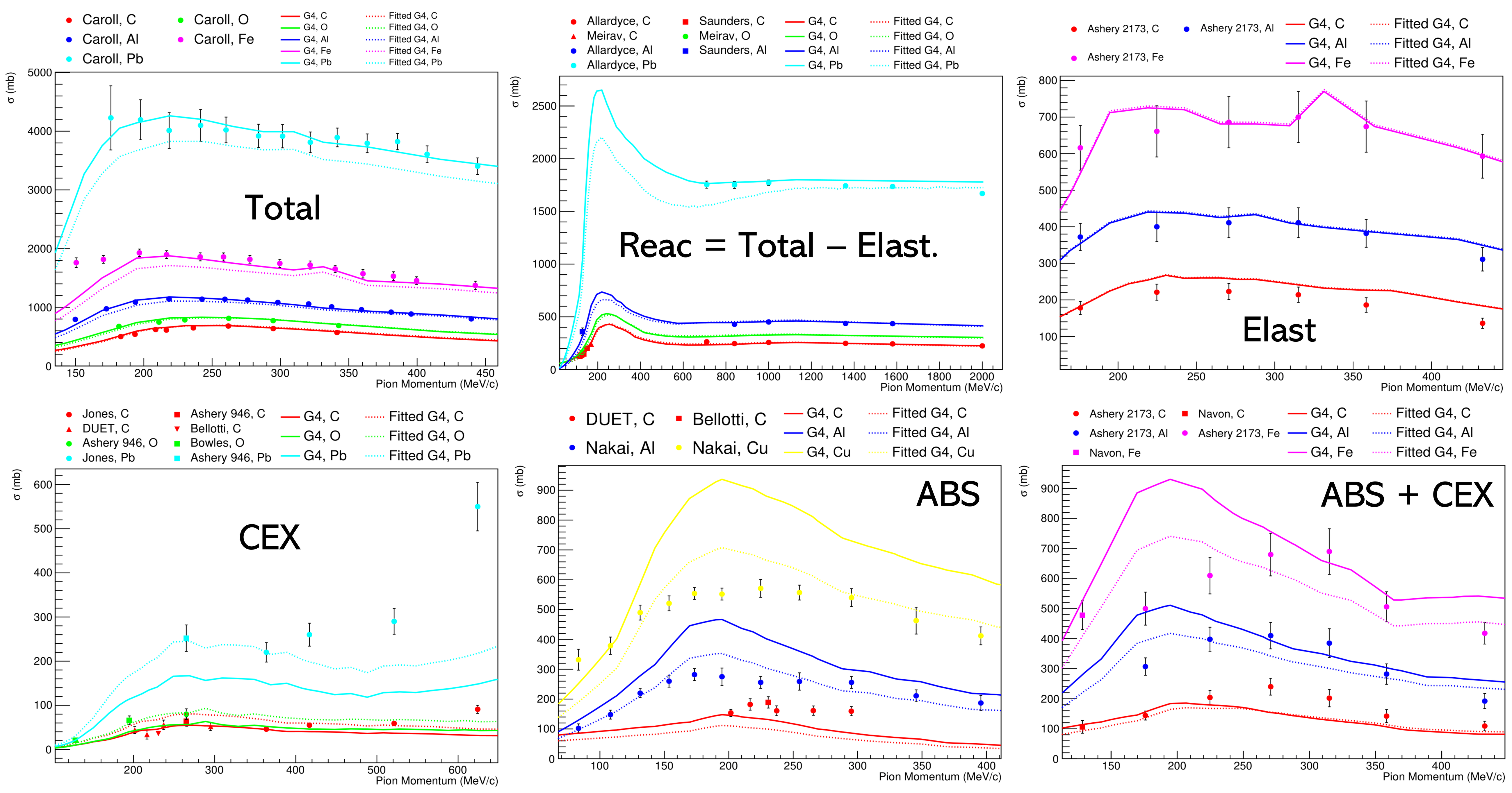
$$\chi^2 = \frac{1}{N_{\mathrm{C}} + f - 1} \left(\sum_k \chi^2_k + f \chi^2_{\mathrm{Total}} \right)$$

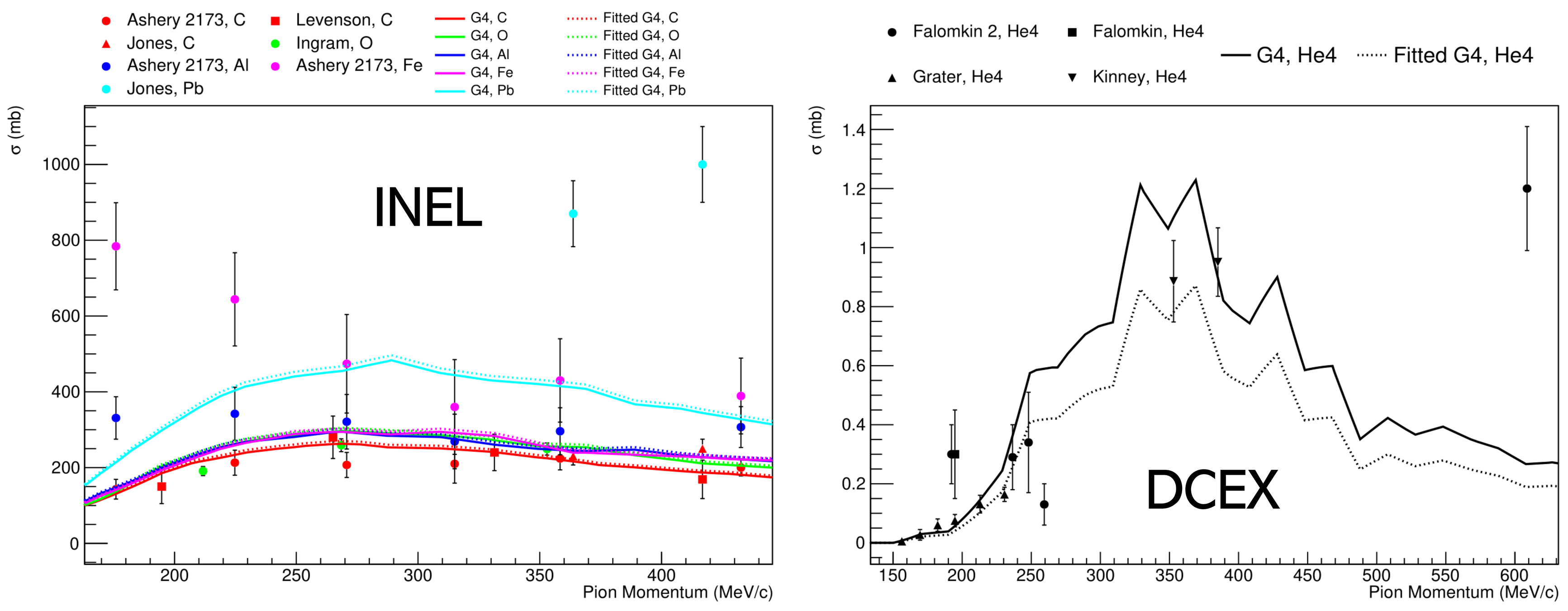
k are different exclusive channels.
N_k is the number of cross section measurements for channel k.
p_k is the number of parameter modifying channel k.
N_C is the number of channels included in the fit.

A separate fit is done to total cross section data to obtain $\chi 2_{\mathrm{Total}}$. f is a weighting factor used to modify the "importance" of total cross section data.

3. The Data

Data available for π^{+} interactions is compared with Geant below. Coverage of targets/channels is inconsistent, and consideration must be made for different quantity of measurements across different channels.



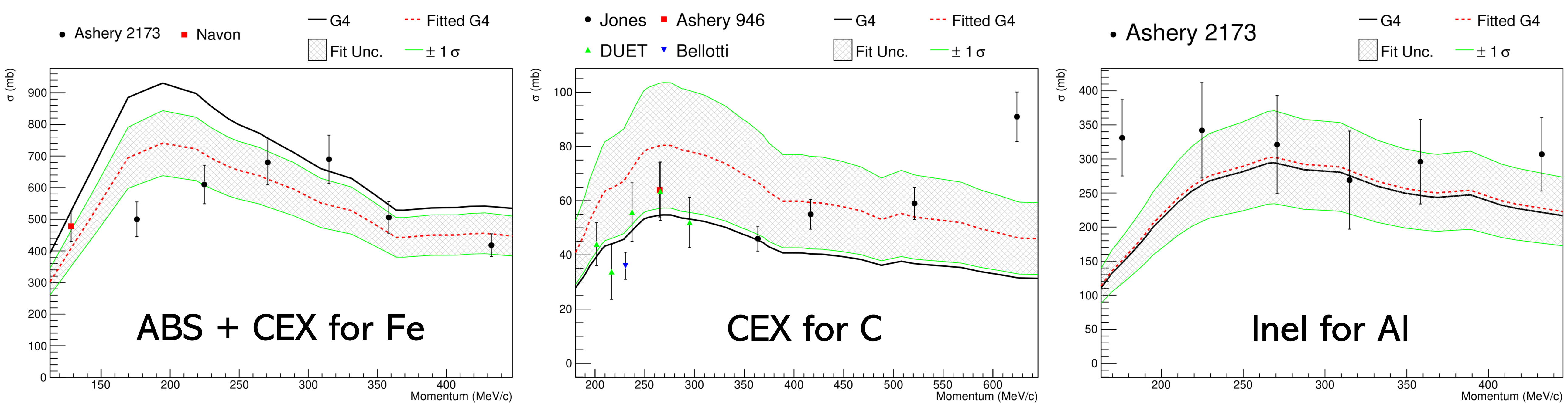


Solid line = Original G4
Dashed line = Fitted G4.

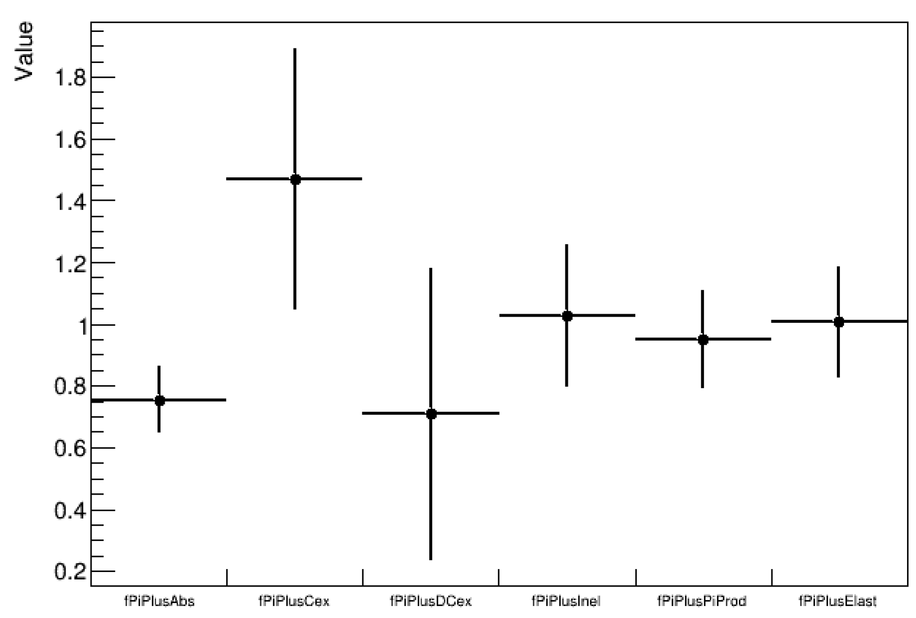
See [2] for references to data.

5. Uncertainty Extraction

MINUIT extracts a covariance matrix by estimating the rate the χ2 changes around the minimum. From this we obtain error bands on corrected cross sections. Examples below:



The extracted scaling parameters are often anti-correlated due to the inclusion of total cross section data. The extracted uncertainties for π^{+} and covariance matrix are below. These can be used to throw universes to propagate uncertainties.



	fPiPlusAbs	fPiPlusCex	fPiPlusDCex	fPiPlusInel	fPiPlusPiProd	fPiPlusElast
fPiPlusElast	-0.00220682	0.00563699	0.010307	-0.020257	0.0116296	0.032517
fPiPlusPiProd	0.00257457	-0.000497861	-0.00262526	-0.0265273	0.024707	0.0116296
fPiPlusInel	-0.00370995	-0.0371577	-0.00864119	0.0537955	-0.0265273	-0.020257
fPiPlusDCex	-0.00580007	-0.0488493	0.224077	-0.00864119	-0.00262526	0.010307
fPiPlusCex	-0.0126346	0.178324	-0.0488493	-0.0371577	-0.000497861	0.00563699
fPiPlusAbs	0.011569	-0.0126346	-0.00580007	-0.00370995	0.00257457	-0.00220682

6. Summary

A technique for performing fits with multiple channels/targets has been developed to extract uncertainties from pion interaction data. These fits can be used as input uncertainties for Geant 4 Reweight to propagate them through various physics analyses.

See [2] for more details.

[1] Nucl. Instrum. Meth. A 506 (2003),472 pp. 250–303 [2] JINST 16.08 (2021), P08042.