Modelling the Axial Form Factor (F_A) in CCQE interactions

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DUNE and Cross-section Measurements

- One goal of DUNE is to precisely measure the ν oscillation parameters, with the aim of determining CP-violation in the lepton sector
- To achieve this goal, we need precise estimates of E_ν and to increase our understanding of ν-nucleus cross-sections (σ)
- ν−nucleus CCQE interactions are the largest background in the ν_μ flux, and are currently the largest systematic uncertainty for ν oscillation experiments

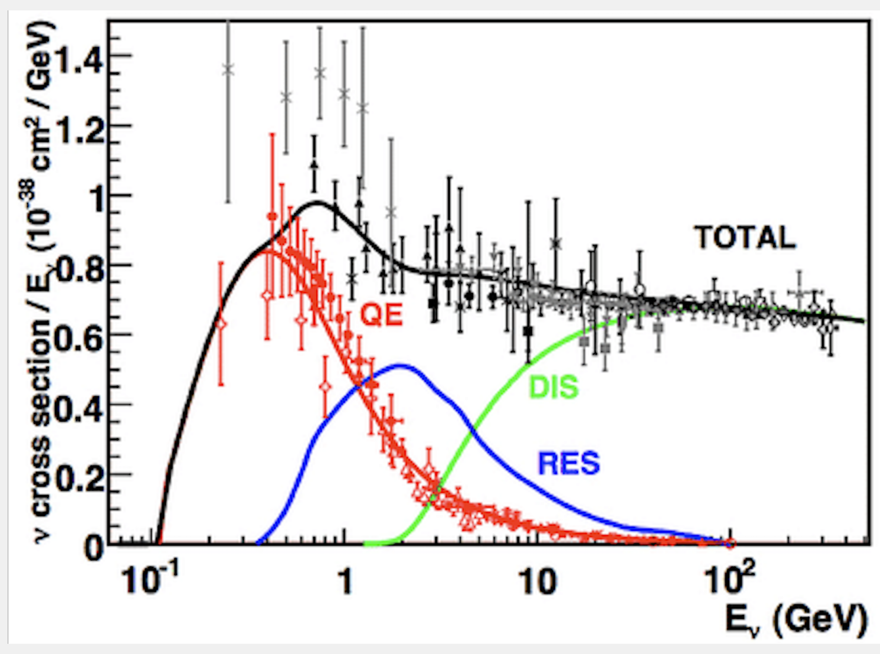


Figure 1. Total $\sigma(E_\nu)$ decomposed in QE, RES and DIS plot shown for ν_μ measurements [4].

Modelling CCQE interactions: F_A and z Expansion

- F_A characterises the weak charge distribution, and is measured in scattering experiments
- In a precision era of ν physics, we need sophisticated parameterisations, such as the z expansion for F_A [1]:

$$F_A(q^2, z) = \sum_{k=0}^{k_{max}} a_k z(q^2)^k$$

- The best z-expansion parameterisation available is a joint fit of ν-H scattering data [2]

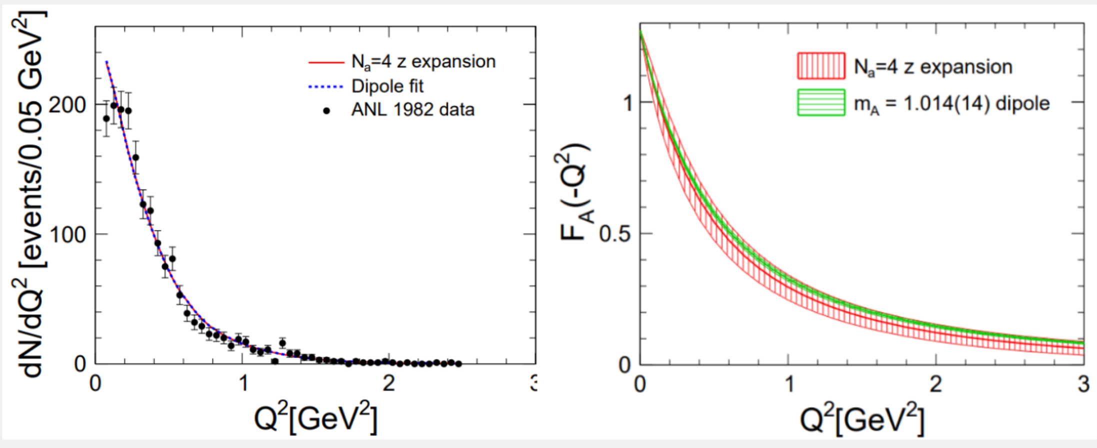


Figure 2. L: Bubble chamber data from the ANL 1981 experiment and the best fit cross section predictions corresponding to dipole and $N_a = 4z$ expansion. R: The best fit predictions from z expansion and dipole F_A parameterisations with uncertainty bands. Figures [2].

Factorisability of $F_A(q^2)$

- Modern oscillation analyses sample from likelihoods with 100s of parameters
- To make this procedure computationally tractable, it often helps to treat nuisance parameters as factorisable
- a_k are not factorisable from F_A
- *Approximating* a_k as factorisable means that a_k can be treated as independent variables
- The correlation matrix from [2] demonstrates that a_k are correlated: $\begin{bmatrix} 1 & 0.350 & -0.678 & 0.611 \\ 0.350 & 1 & -0.898 & 0.367 \\ -0.678 & -0.898 & 1 & -0.685 \\ 0.611 & 0.367 & -0.685 & 1 \end{bmatrix}$
- Treating a_k as independent is not sufficient for the level of precision required by high-precision experiments such as DUNE

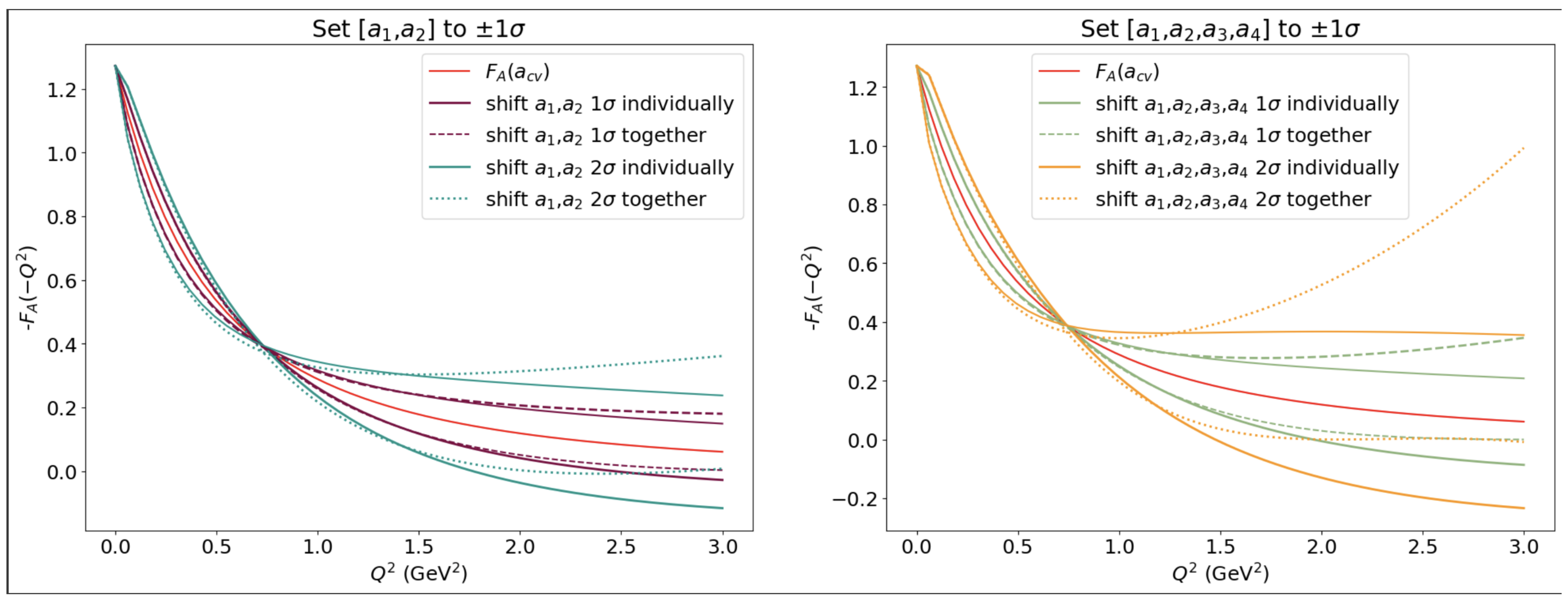
Improvement: Principal Component Analysis (PCA)

- Transforms a_k to an uncorrelated basis (b_i):

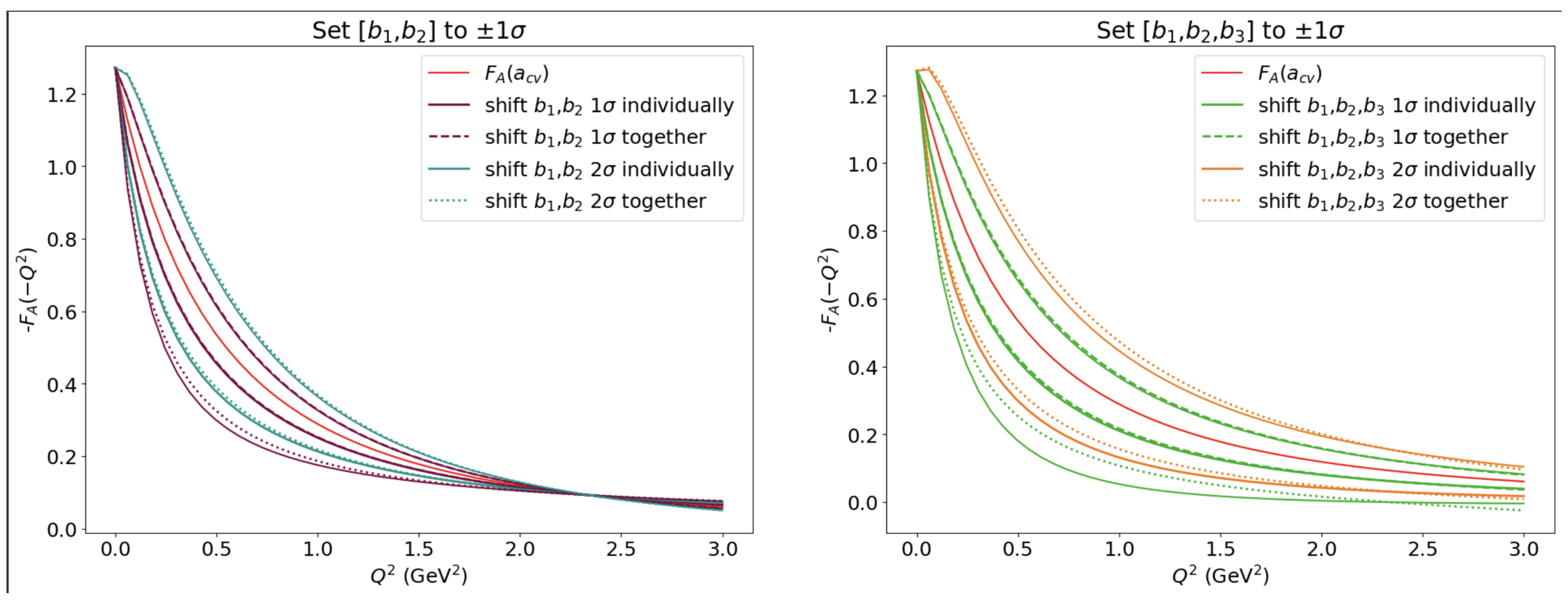
$$\lceil a_i \rceil = \text{Diag}\left(\sqrt{\lambda_i}\right) \lceil \hat{v}_i \rceil^T \lceil b_i \rceil$$

λ_i, v_i are the eigenvalues and eigenvectors of the covariance matrix

- Examples of applying the fractional change from varying each of several parameters 'independently' and the value of F_A fully calculated at that set of parameters is shown in Figure 3(a)



((a)) Original parameterisation

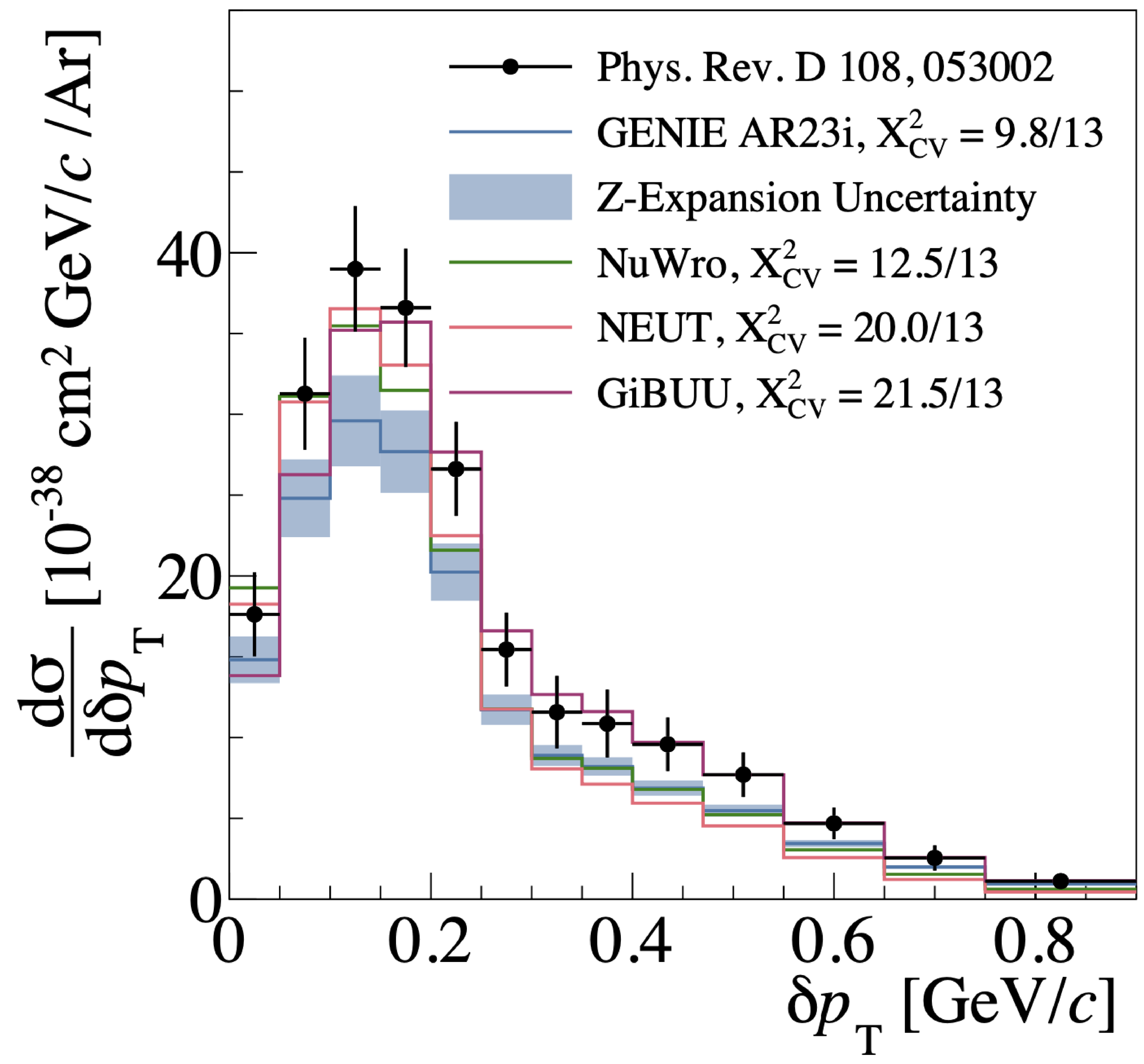


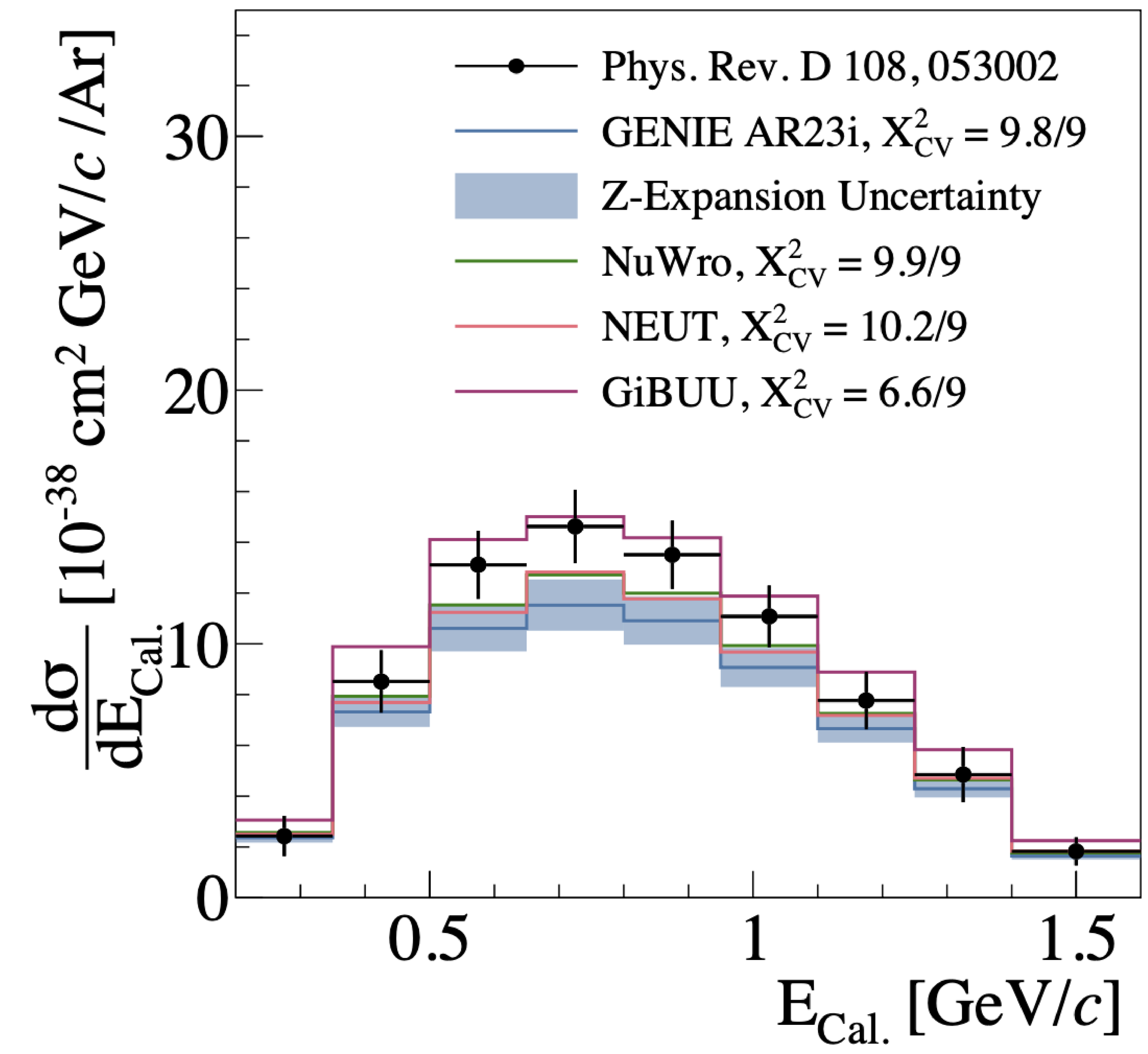
((b)) PCA

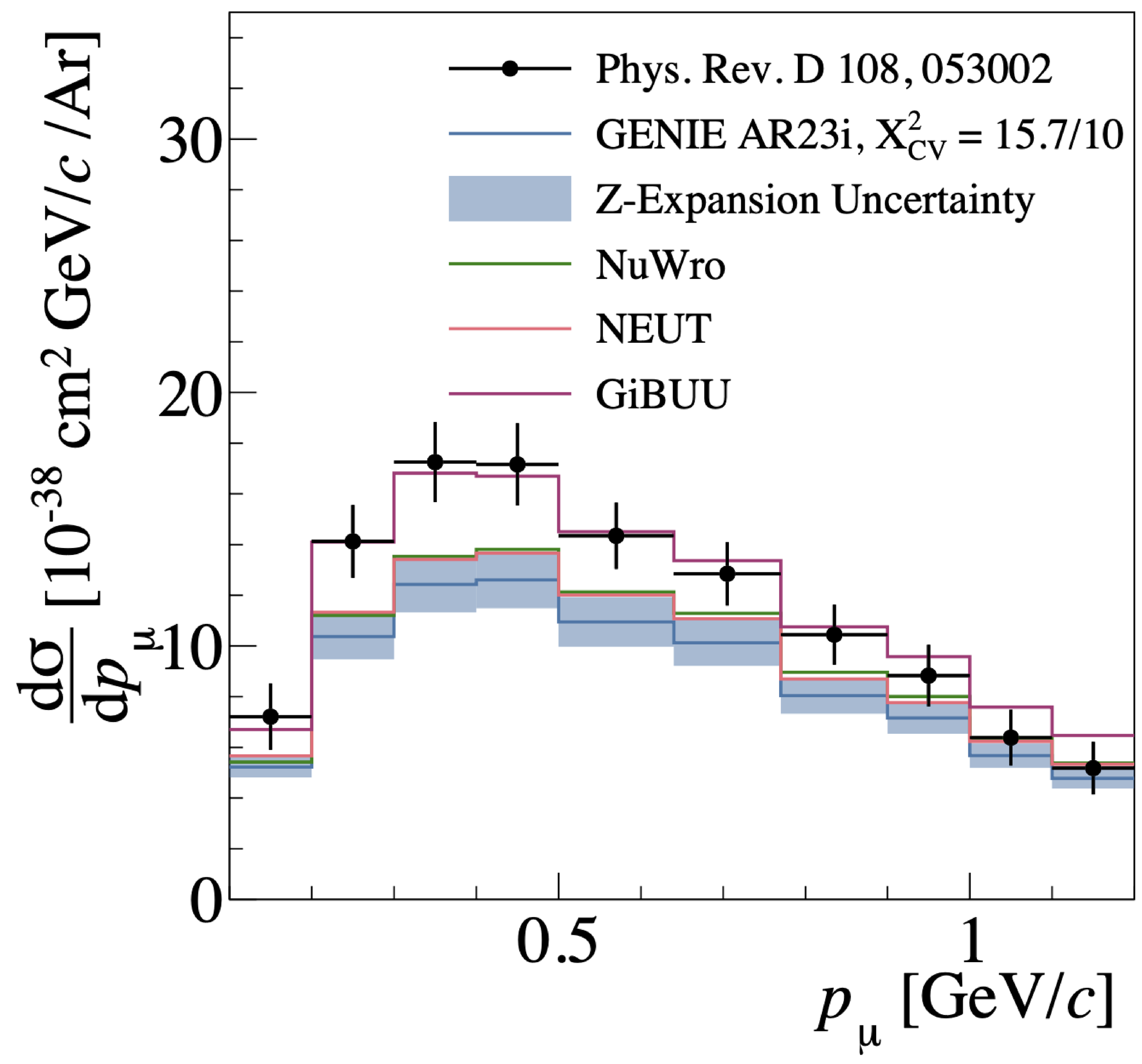
Figure 3. Assuming that the a_k parameters a factorisable from F_A leads to large divergences from F_A^{CV} in the original parameterisation. This affect is reduced in the new transformed basis.

Comparison to MicroBooNE data

- MicroBooNE is a liquid Argon TPC positioned in the Booster ν beamline at Fermilab, and is therefore the most relevant data set for studying cross-section measurements.
- Using the MicroBooNE flux-integrated multidifferential measurements of charged-current μ ν scattering on Argon with 1 in the final state [3].
- Implemented z-expansion NuSystematics and used Nuisance to compare to MicroBooNE data.







[1] Model independent determination of the axial mass parameter in quasielastic neutrino-nucleon scattering. *Phys. Rev. D*, 84:073006, 2011.

[2] Deuterium target data for precision neutrino-nucleus cross sections. *Phys. Rev. D*, 93:113015, Jun 2016.

[3] Multidifferential cross section measurements of ν_μ-argon quasielasticlike reactions with the microboone detector. *Phys. Rev. D*, 108:053002, Sep 2023.

[4] J. L. H. et. al. Fundamental physics at the intensity frontier, 2012.