Cross section model + uncertainties for ICARUS oscillation analysis and thoughts on SBN

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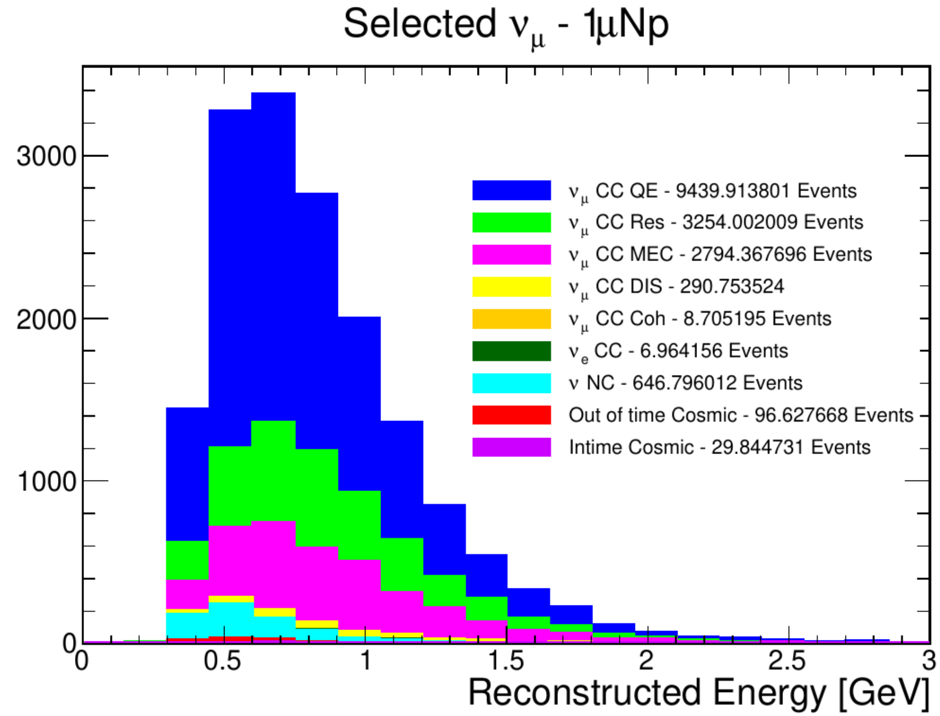
Outline

- Definitions: base model, central value, systematic uncertainties, fake data studies
- What is the ICARUS base model? Why?
- Should we tune the CV?
- Are our current systematics adequate?
- Differences between ICARUS only and SBND+ICARUS
- Conclusions & recommendations

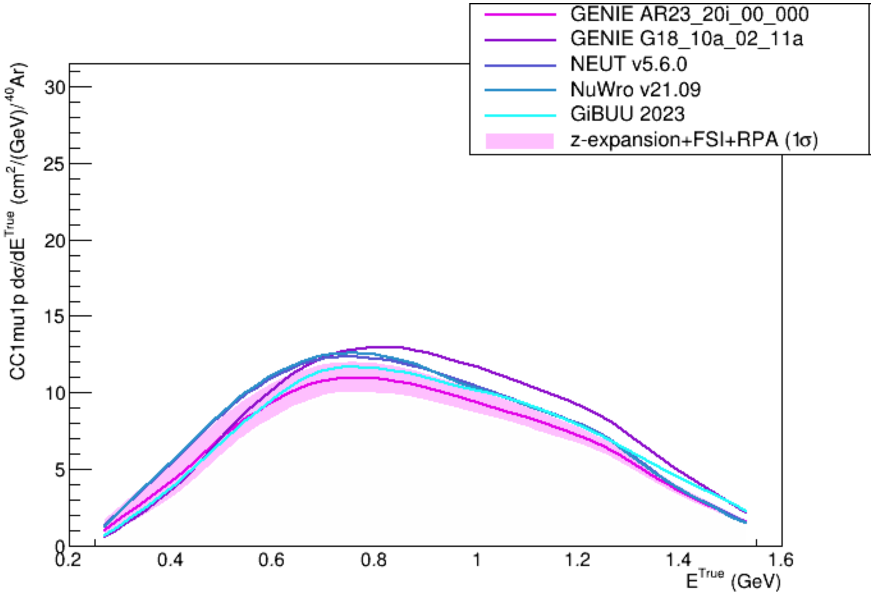
How cross sections enter OA

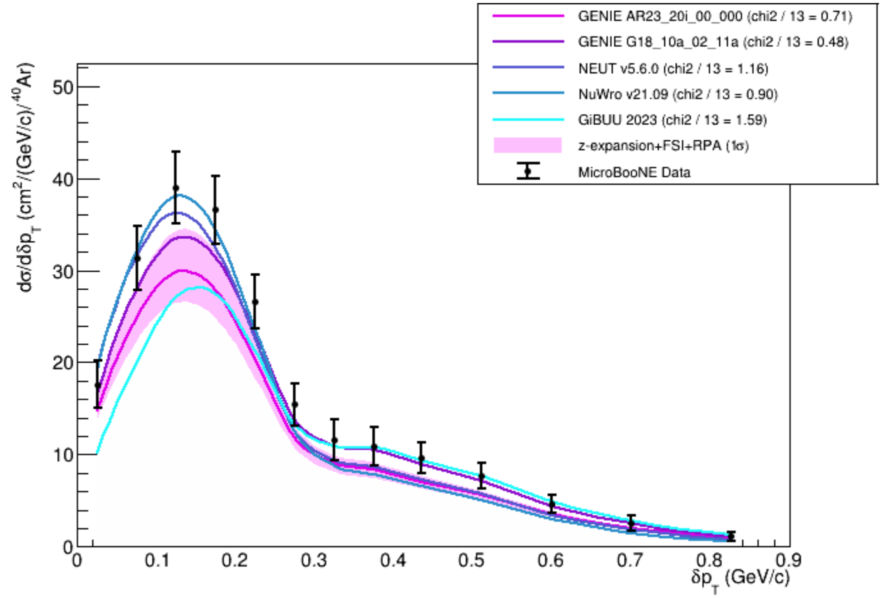
- Make predictions of neutrino energy distribution for selected 1μNp events in ICARUS, for different values of oscillation parameters (e.g. Δm^2, $\theta_{\mu\mu}$)
- Compare prediction to data to infer oscillation parameters
- Cross section model affects event rate and shape as a function of E_ν (or any other observable)



Definitions

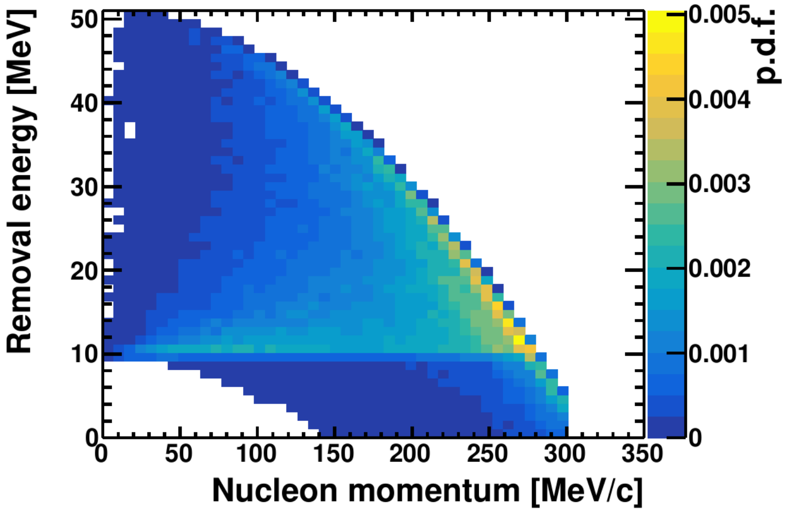
- **Base model** = the out-of-the-box generator prediction
- **Central value** = we could decide to **reweight** the base model, for example by comparing it to data from another experiment
- **Uncertainties** = free parameters of the model are varied to produce alternate predictions, which form an error band





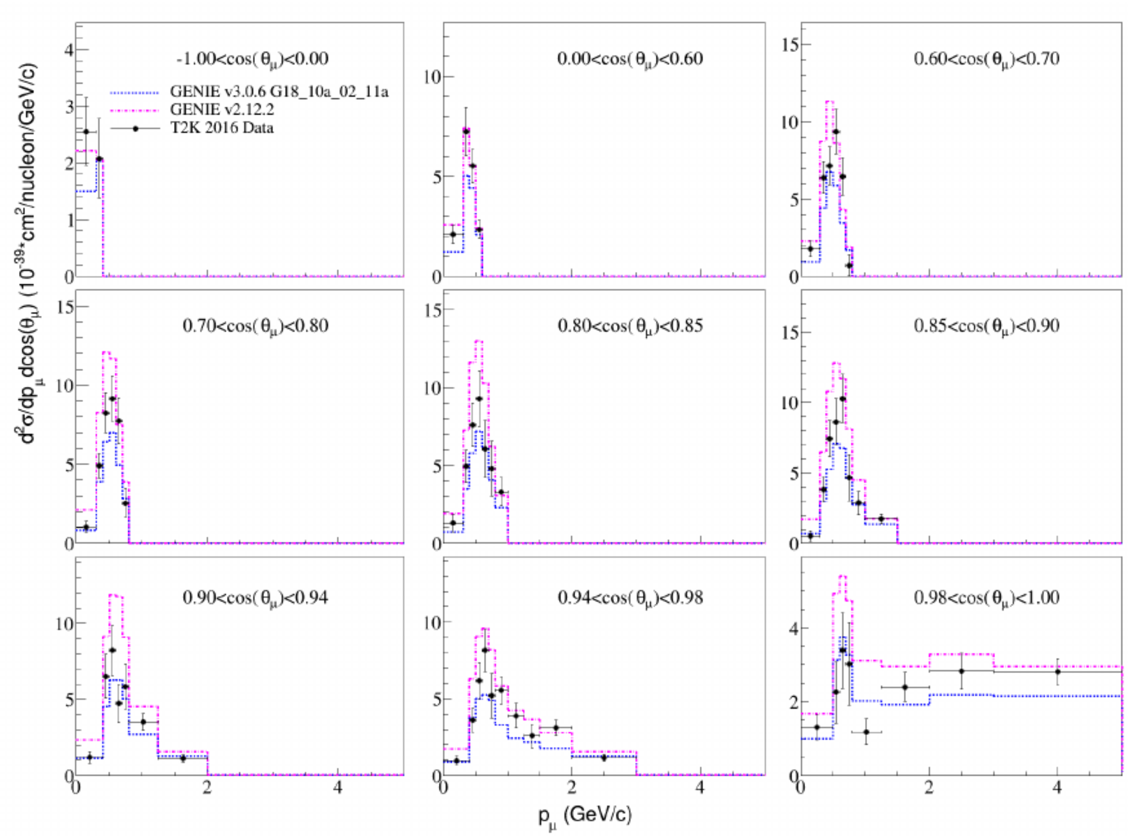
The base model: "AR23"

- New GENIE "tune" called AR23 developed by DUNE NIUWG
- Philosophy: maximize reweightability to make model flexible



- Updated ground state model (pictured)
- Valencia 1p1h with Z-expansion, SuSav2 2p2h, Berger-Seghal RES and COH, hA2018 FSI
- DUNE has also developed uncertainty "dials" that extend GENIE ReWeight, can be trivially used in ICARUS

Tuning the CV



- It is possible to further tune the CV to external data
- MicroBooNE tuned its G18-based model to T2K 2016 CC0π data as a function of lepton kinematics
- This could make the model better describe data

An argument *for* tuning

- In the ICARUS-only analysis, if the XS model is wrong, we could attribute this to oscillations
- Tuning to external data is the best way to get the best model prediction

An argument *against* tuning

- ICARUS will search for oscillations in the L/E range of ~0.3-3 km/GeV
- All modern neutrino-nucleus cross section measurements are made using short-baseline detectors in O(1 GeV) beams
- T2K is 0.2-2 GeV at 280m → L/E 0.15-1.4
- MINERvA (LE) is 1.5-4 GeV at ~1km → L/E 0.25-0.7
- If there is ν_μ disappearance that ICARUS would see, it will be present in the cross section data

Example: 10% ν_μ disappearance

- Suppose there is a 10% disappearance to steriles at all energies, for example $\sin^2 2\theta \sim 0.1$ and $\Delta m^2 = 100$ eV^2
- Flux-integrated cross sections will divide by a flux that is 10% too large, so XS results will be 10% too small
- ICARUS tunes to those results, decreases the XS prediction by 10%
- ICARUS observes no disappearance, because we decreased the cross section by 10% so our tuned MC + no oscillations is in perfect agreement with the data

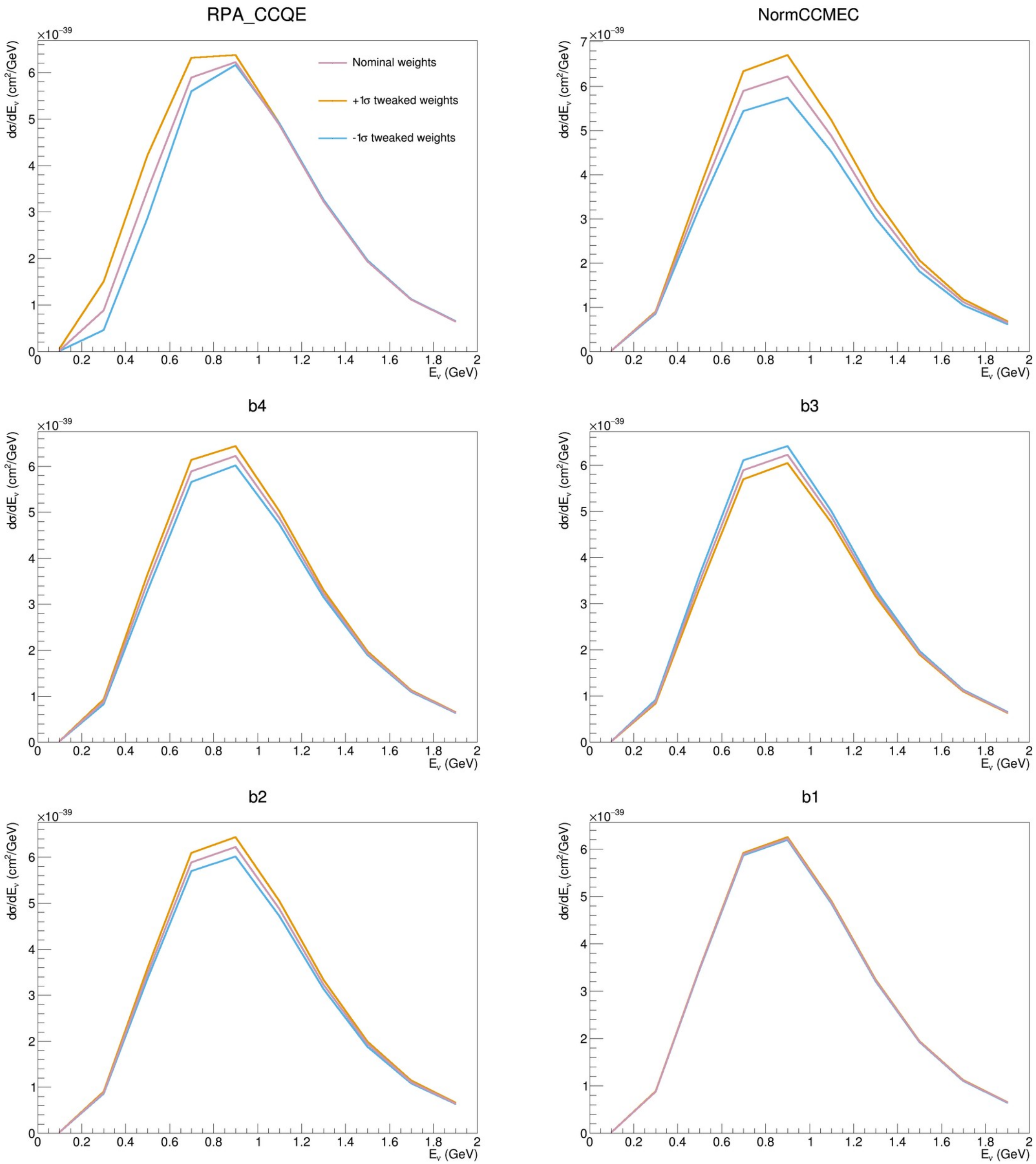
Summary: we should *not* tune

- There is no way to tune without potentially biasing the oscillation analysis against oscillations
- We should ensure that our model and its uncertainties are sufficiently robust that it can describe external data
- We should test our model using dedicated fake data samples to ensure that our cross section uncertainties cover discrepancies, and they are not attributed to oscillations

Tuning for model robustness

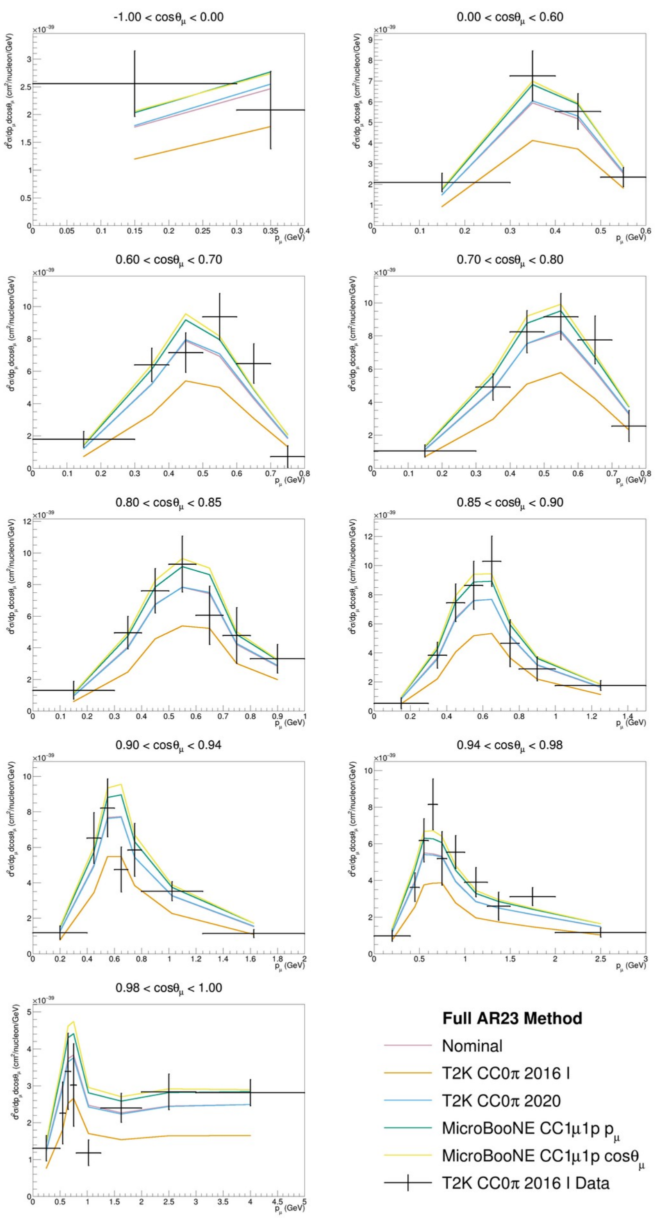
- This section of the talk describes work done by Jeanie Wolfs

Tuning for model robustness



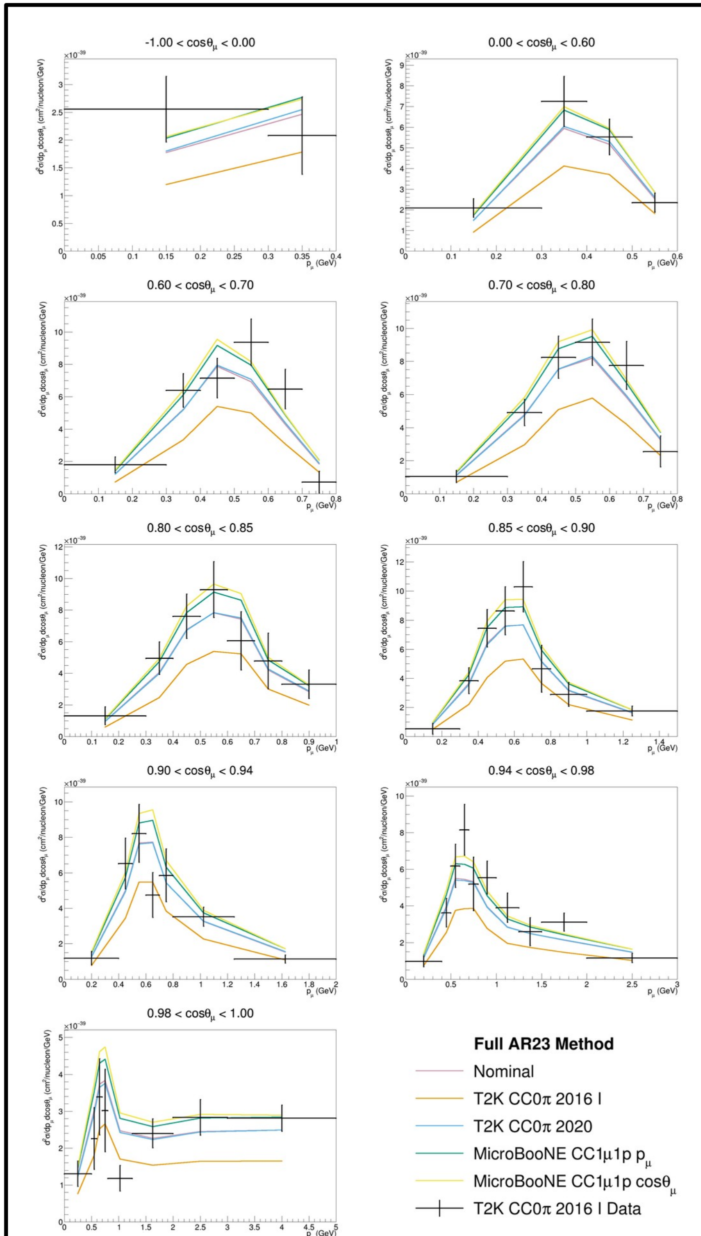
- Step 1: identify model parameters that actually matter
- The model has dozens of free parameters, many of which only affect high-W processes that do not occur often in BNB
- For AR23 model: four z-expansion parameters (1p1h), RPA, and 2p2h normalization

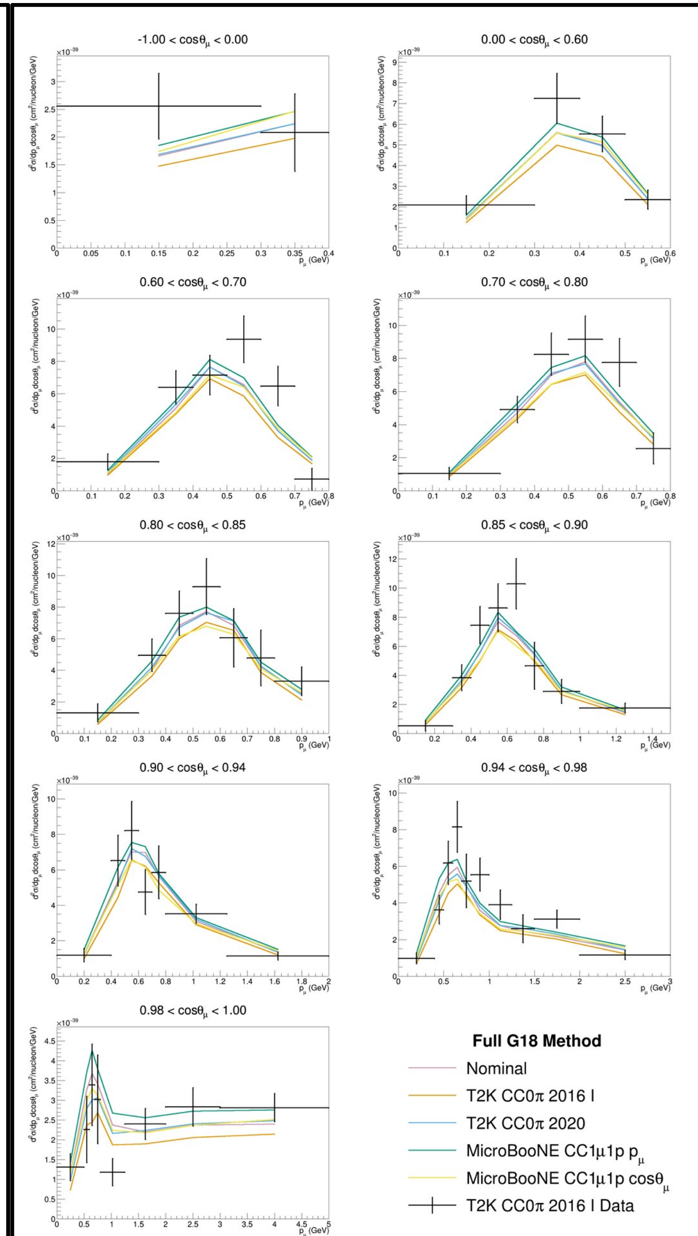
Tuning for model robustness

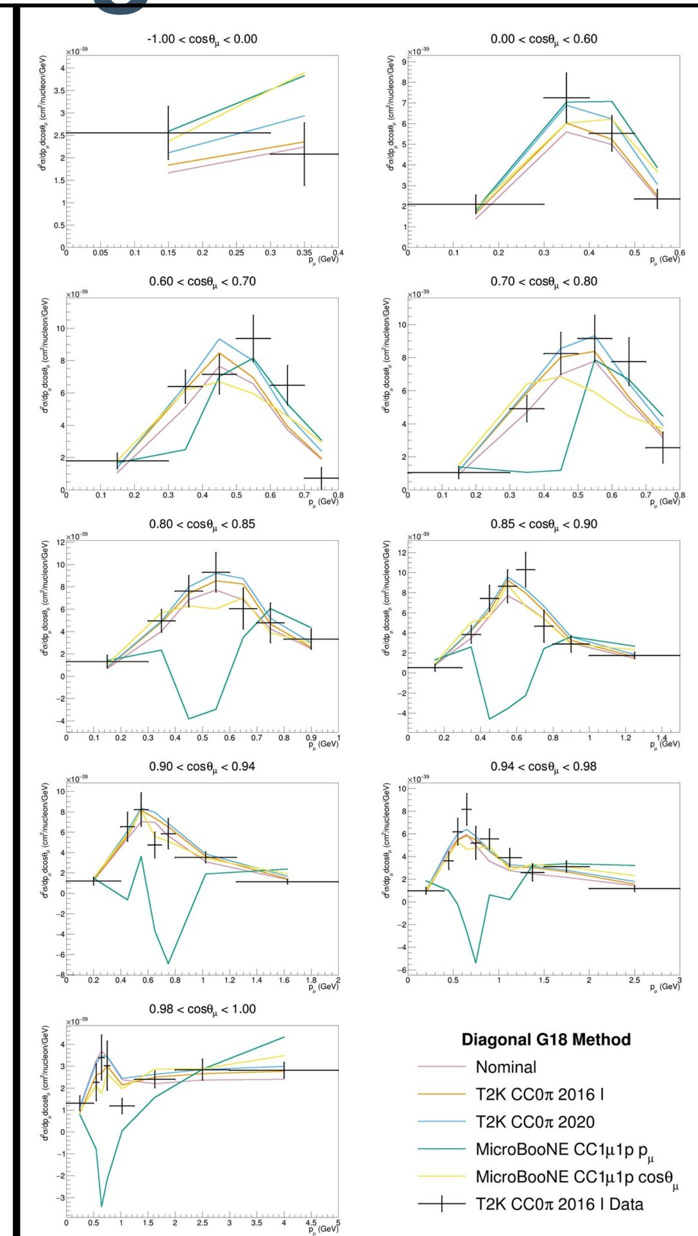


- Use NUISANCE to tune a model to one data set, and then compare it to another
- We used four measurements:
  - T2K 2016 CC0π (T_μ, θ_μ)
  - T2K 2020 CC0π (T_μ, θ_μ)
  - μBooNE 1μ1p p_μ
  - μBooNE 1μ1p p_p
- If the model is correct, we should get a good fit without tuning parameters
- If the model uncertainties are adequate, we should get a good fit, potentially with different best-fit parameter values
- If we get a poor fit, the model does not have adequate freedom to describe the data

AR23 vs. G18 vs. “diagonal”



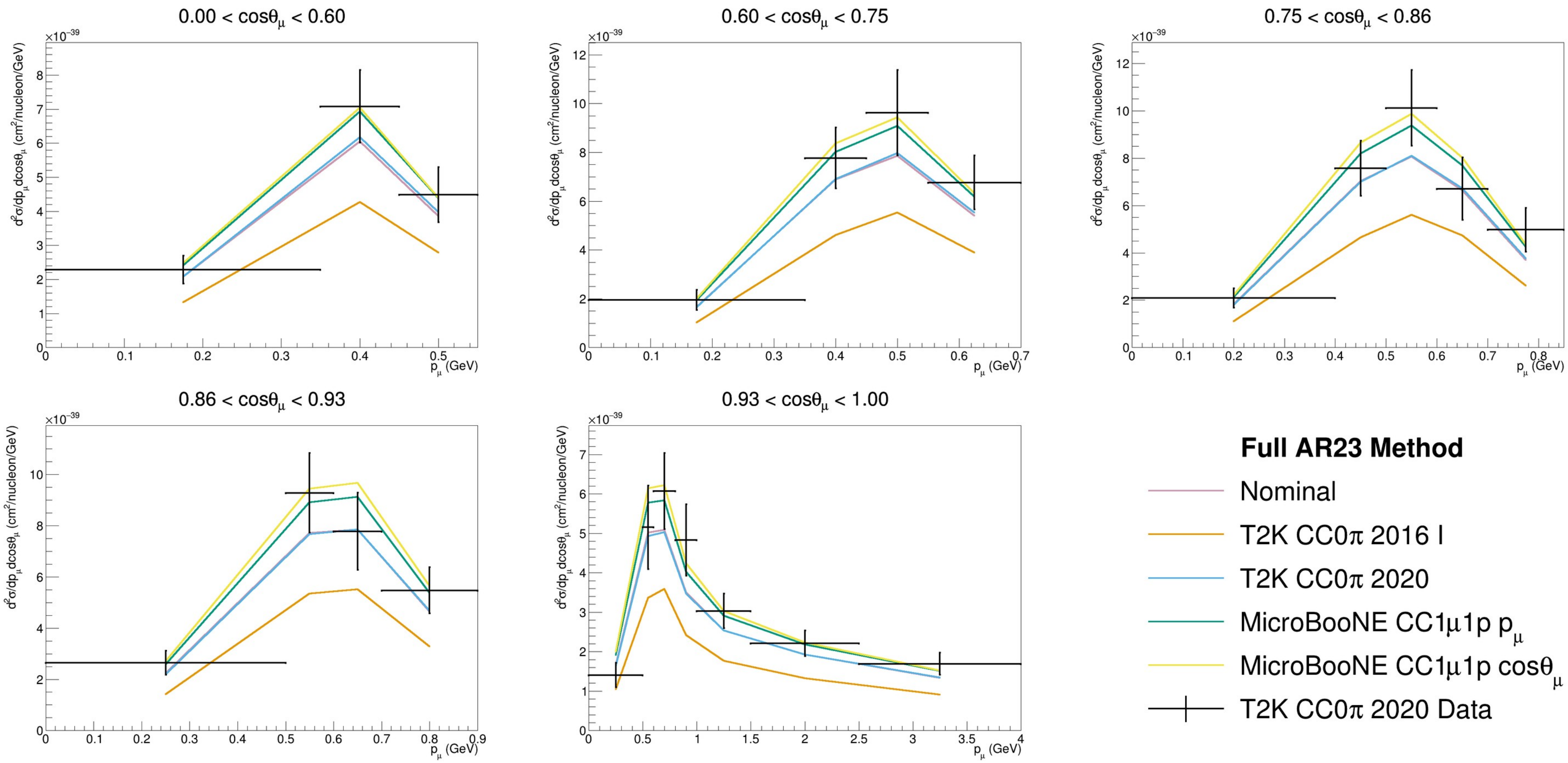




Discussion

- μBooNE's tune used G18 as the base model, and tuned to T2K 2016 data (Phys. Rev. D 105, 072001 (2022))
- They found a poor fit quality – fit decreases total XS despite data being above the prediction
- The "solution" was to use a "diagonal" covariance matrix, essentially ignoring the (real) correlations in T2K's systematics → resulted in a better fit, better agreement with μBooNE data
- But applying this same method and tuning to μBooNE's own data gives absurd result → the method is not robust, it just happened to work in this one case

Comparing to newer T2K data



- Comparison to T2K 2020 data: AR23 model is reasonably describing all but the T2K 2016 data
- This is odd; there is a high overlap between T2K's two data samples

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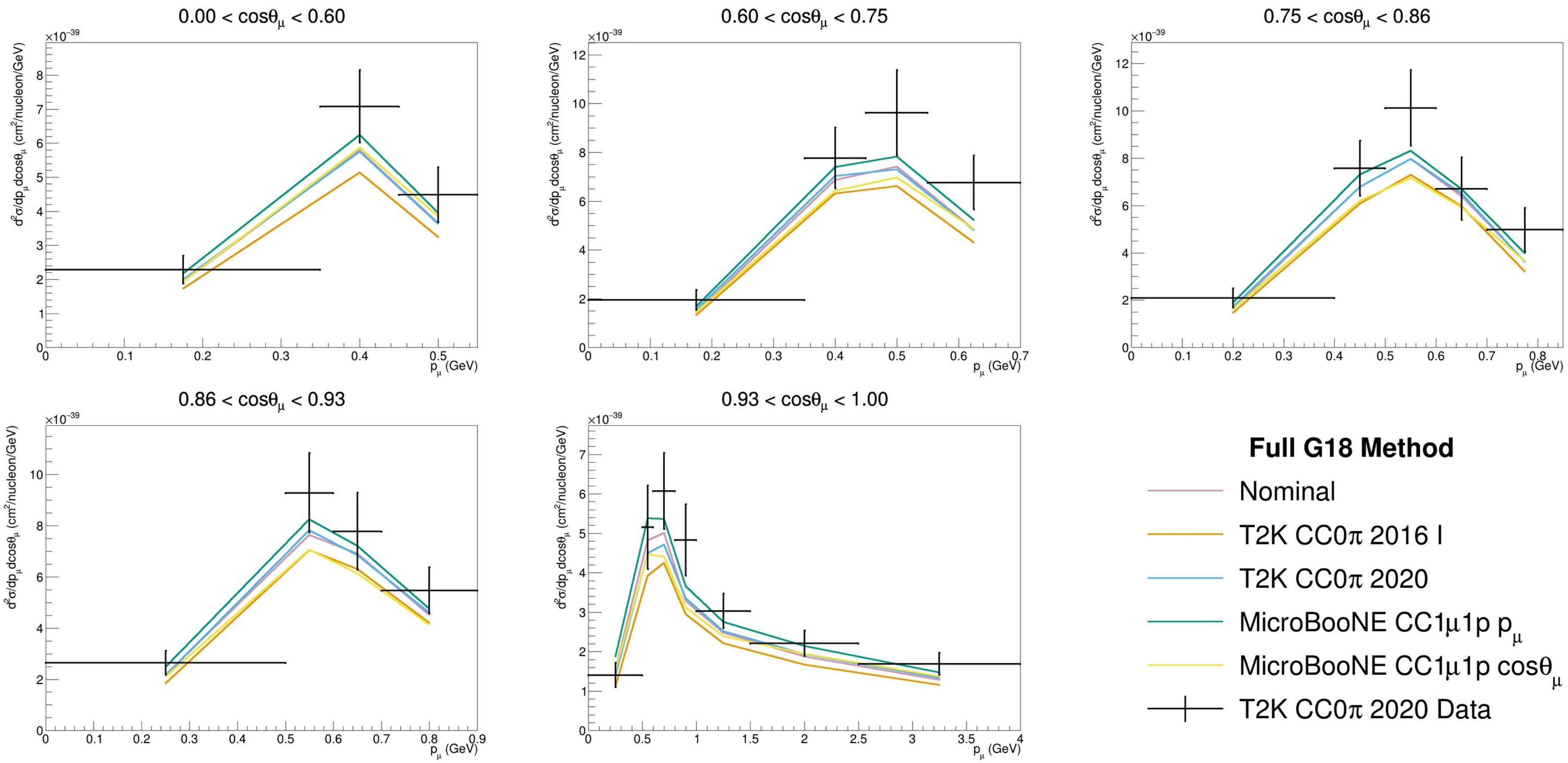
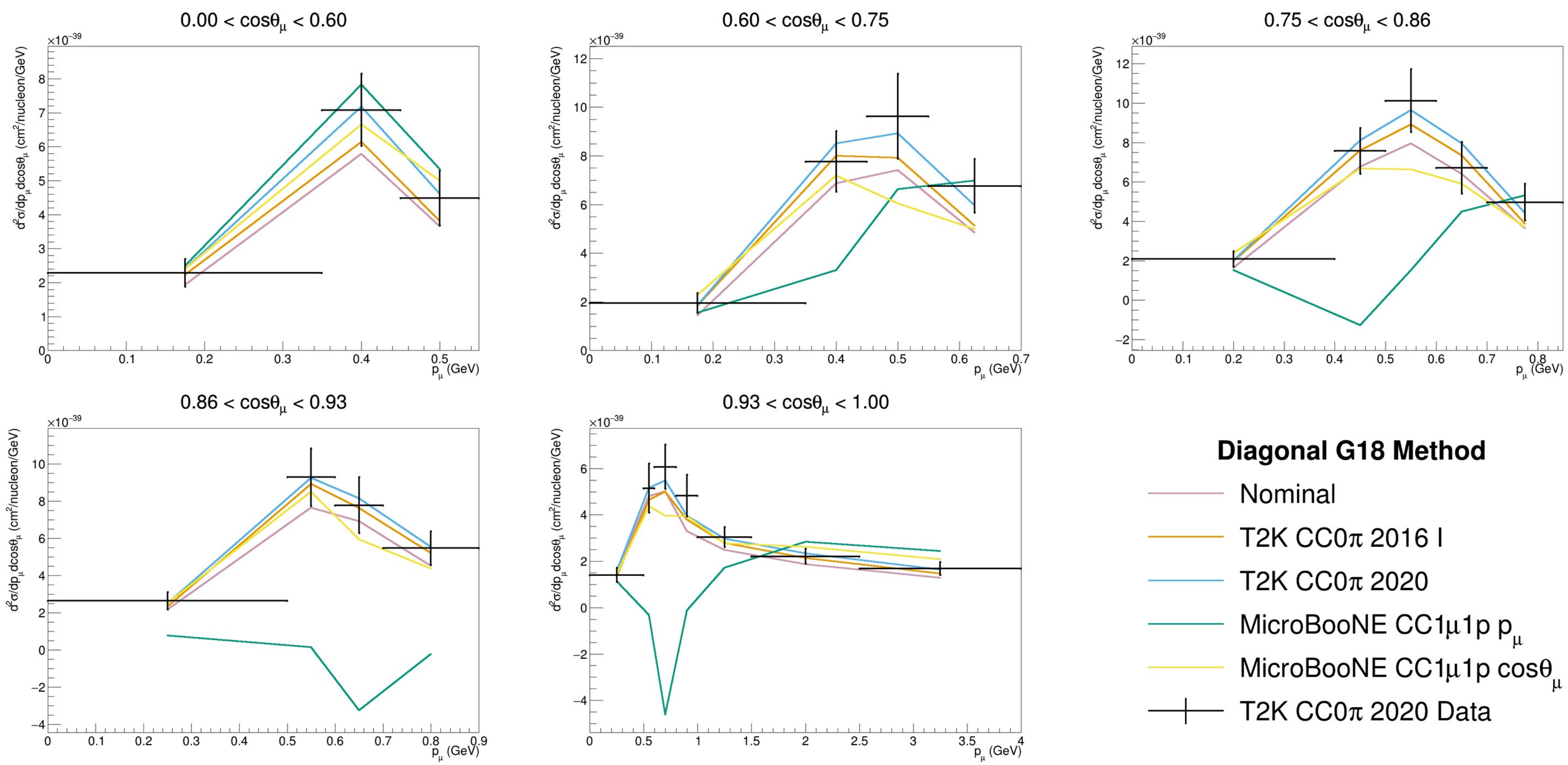
Comparing to newer T2K data



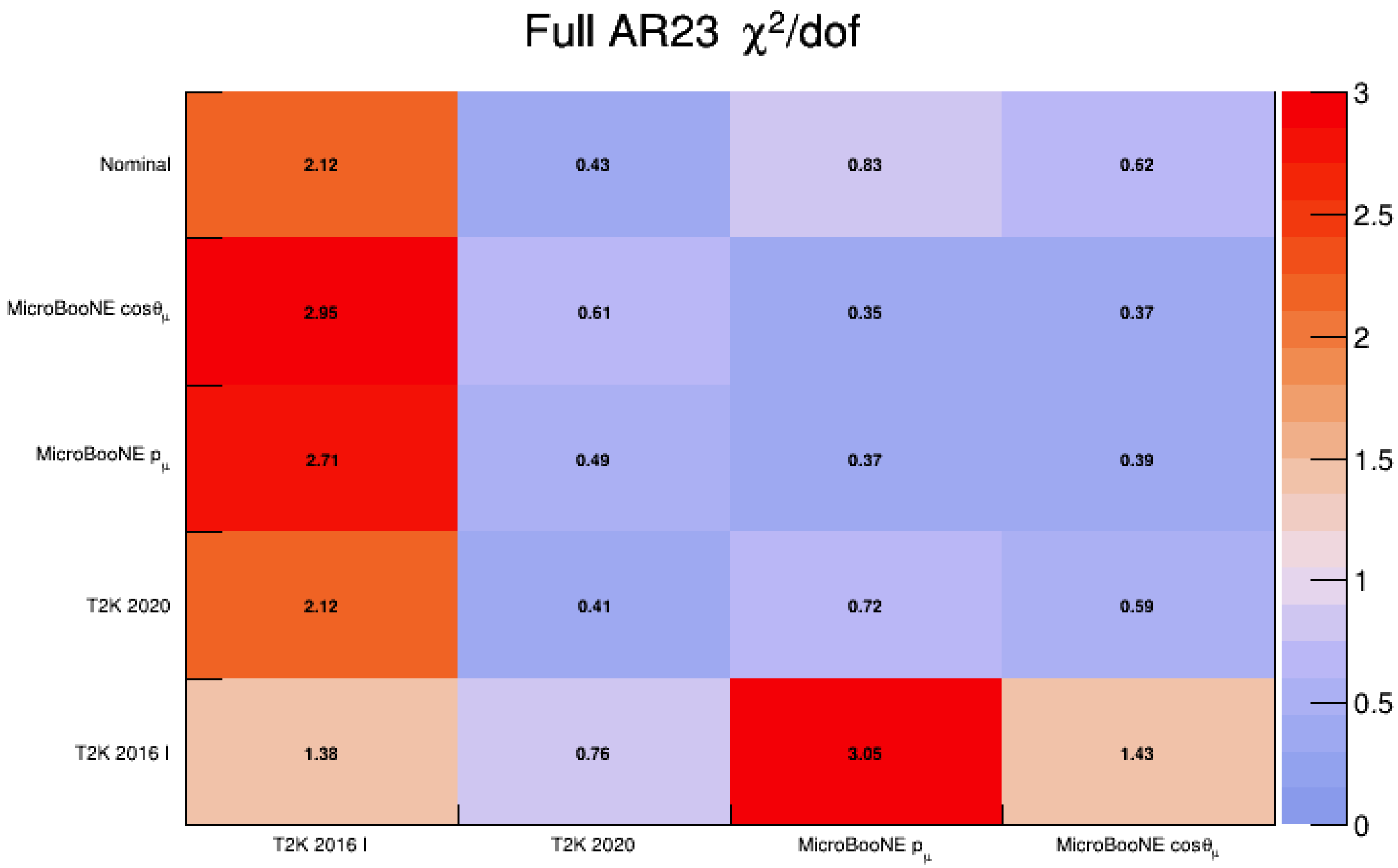
- Same thing but using G18 tune, with M_AQE instead of z-expansion

Tuning for model robustness



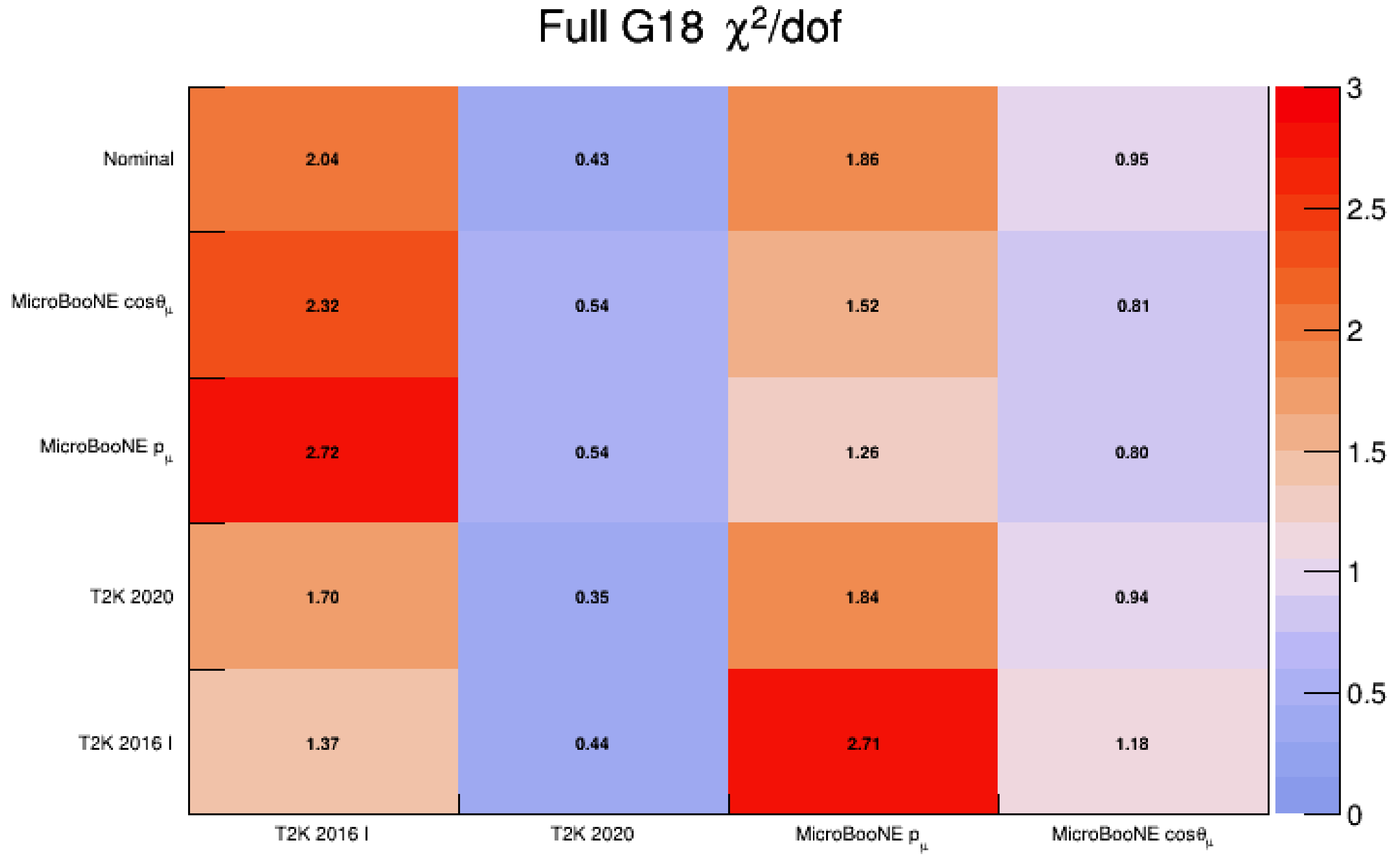
- Using the “diagonal covariance” of MicroBooNE you get silly results when tuning on MicroBooNE data

Summary



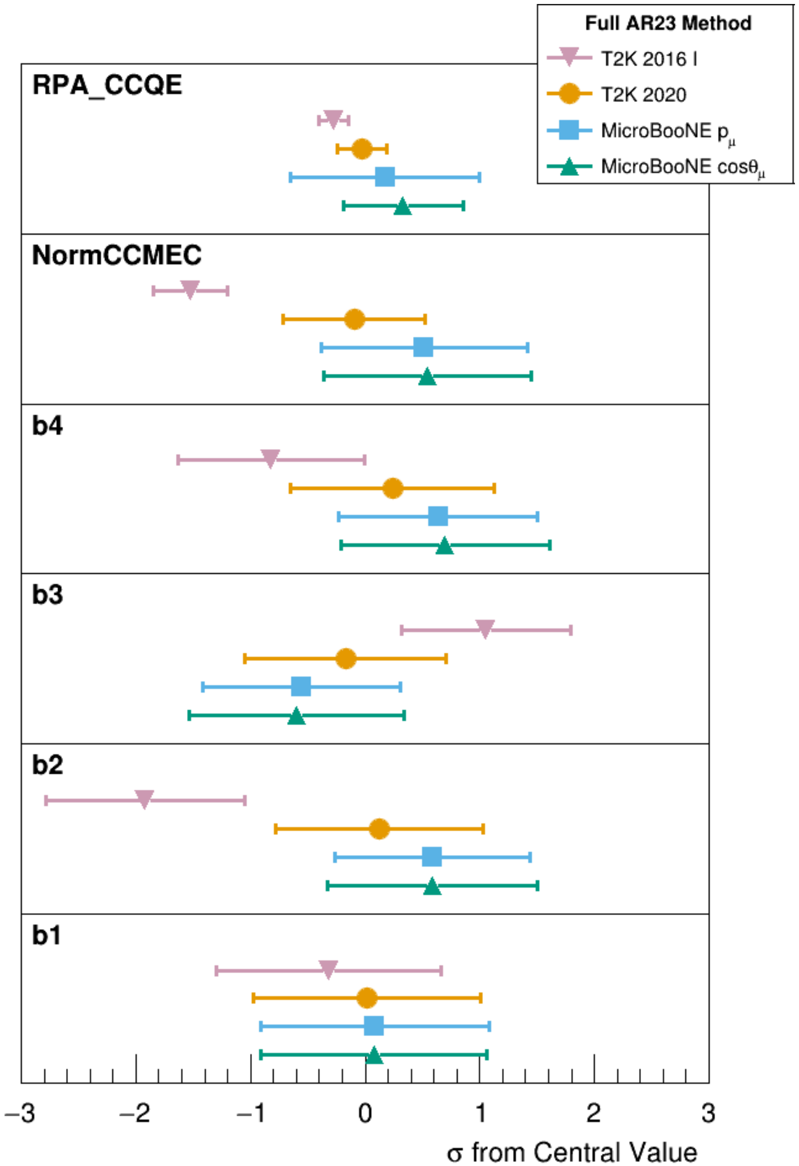
- A robust model would be all blue → can tune with one dataset and describe another with small χ^2
- There is a clear issue with T2K 2016 (it is inconsistent with every other data set, including T2K 2020) but otherwise, AR23 is doing OK with lepton kinematics

Summary (G18)



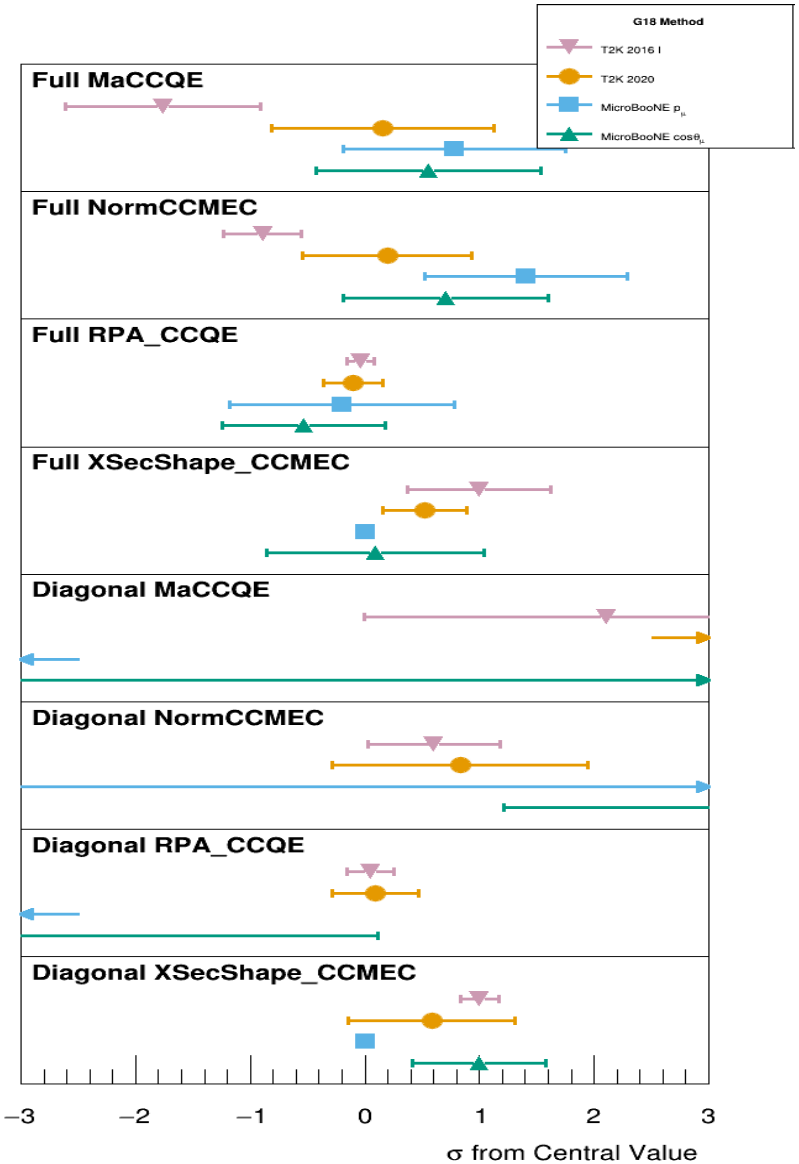
- G18 also does reasonably well, but AR23 is more flexible in simultaneously fitting T2K and μBooNE

Parameter pulls



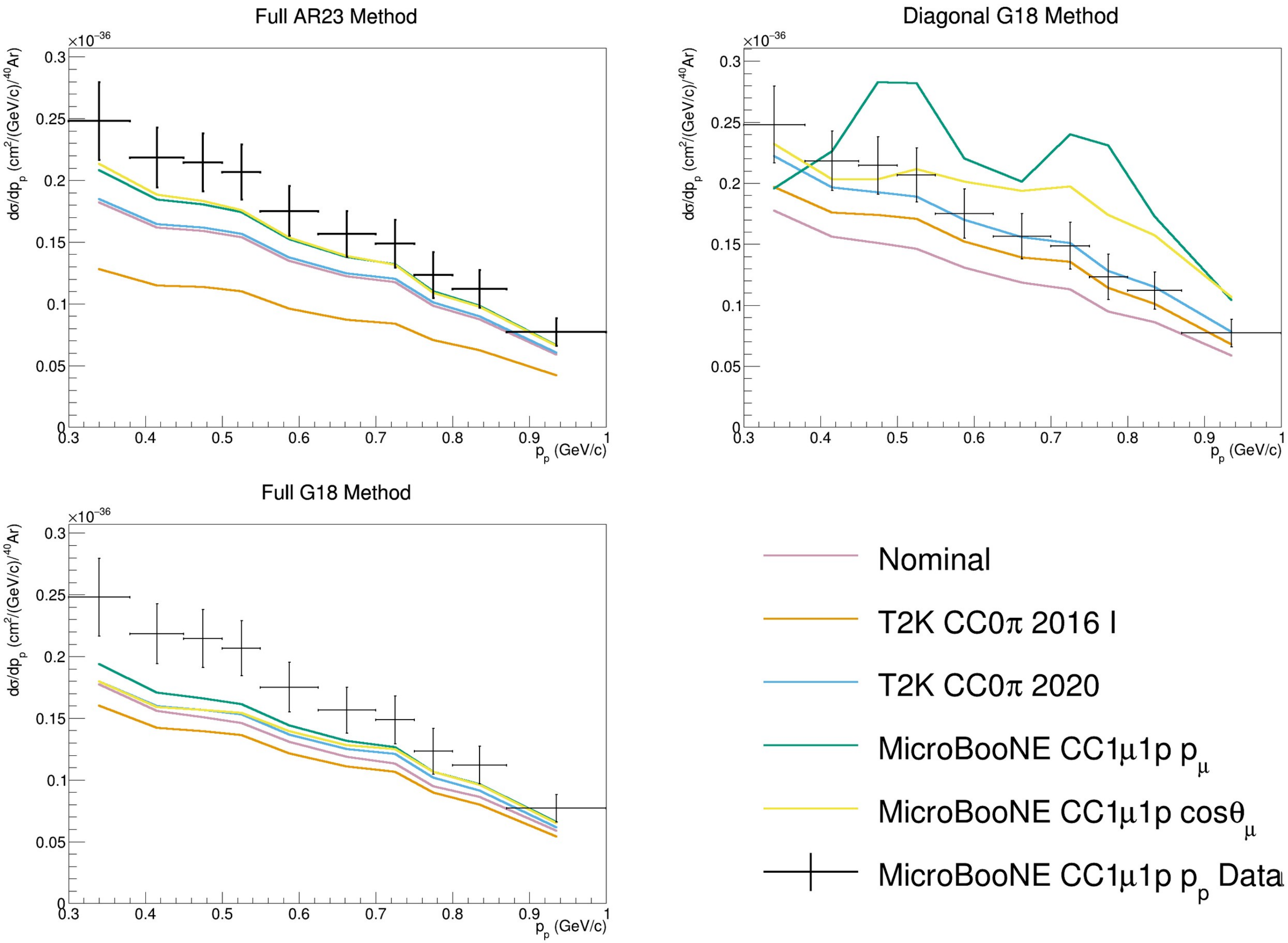
- We can see what the best-fit values and post-fit uncertainties are for fits to different data sets
- We don't expect much constraint on the prior 1σ uncertainties
- Except for T2K2016, pulls are all <1σ, but some differences between T2K2020 and μBooNE
  - This means that the same model is not simultaneously describing T2K and μBooNE, but there is enough flexibility in the uncertainties to describe both of them

Parameter pulls (G18)



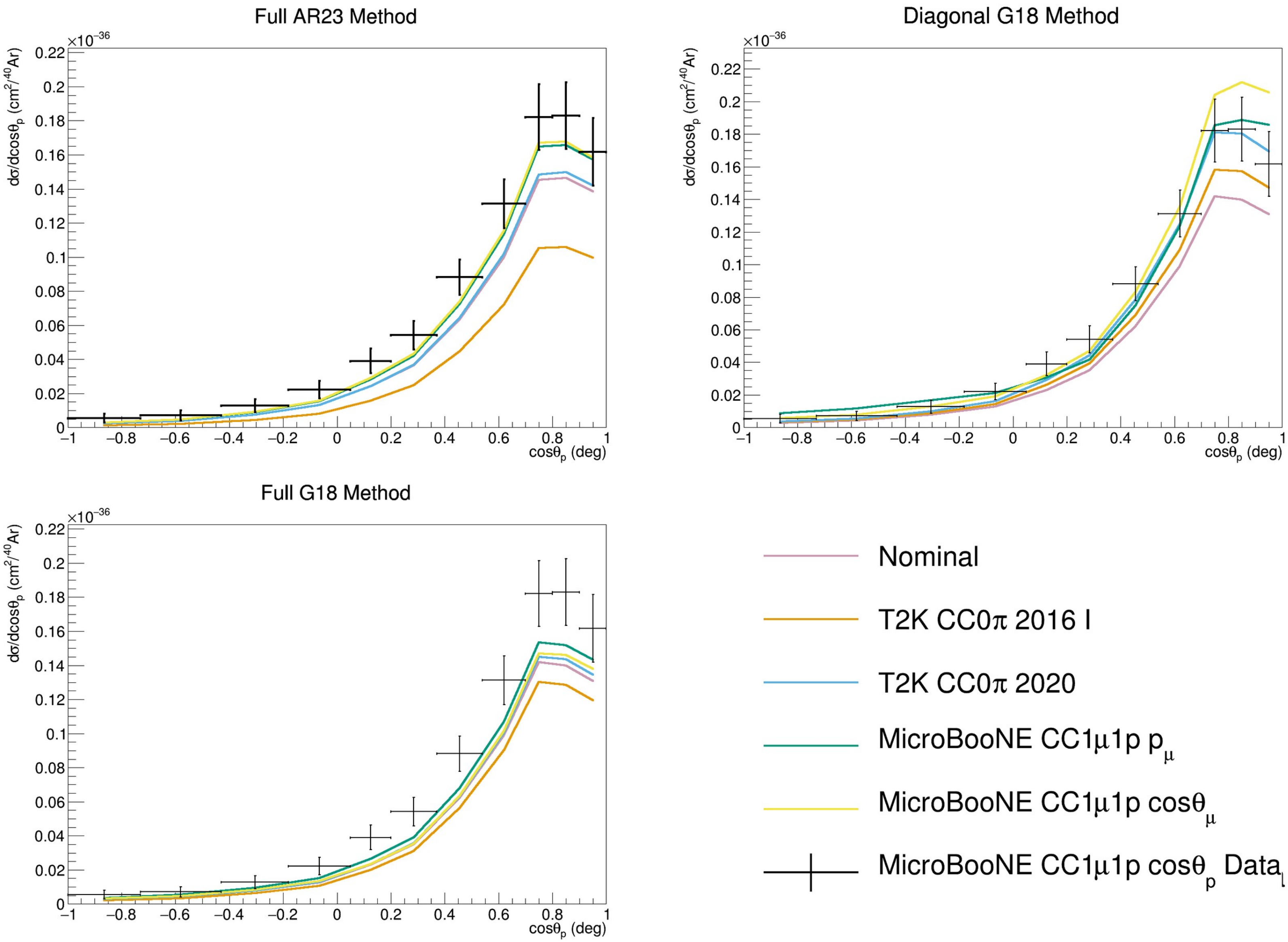
- The G18 model with full covariance also reasonably describes T2K2020 and μBooNE
- Note parameters are different, and some parameters get unrealistically well constrained
- The diagonal fits are all over the place

µBooNE proton kinematics



- None of the tunes to lepton kinematics describes the µBooNE proton data
- AR23 does the best job (obviously tuning to µBooNE lepton and comparing to the same events' proton kinematics is not statistically robust)

µBooNE proton kinematics



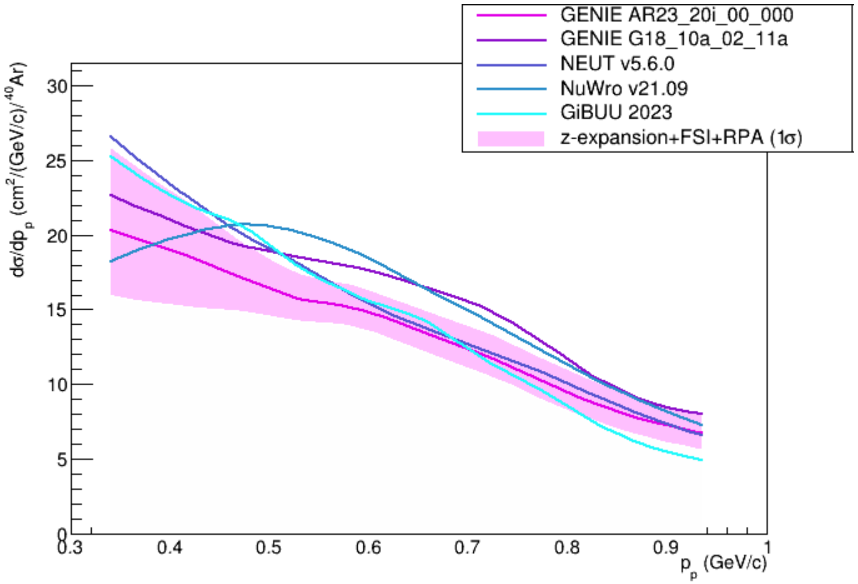
- Similar conclusion when comparing to proton angle

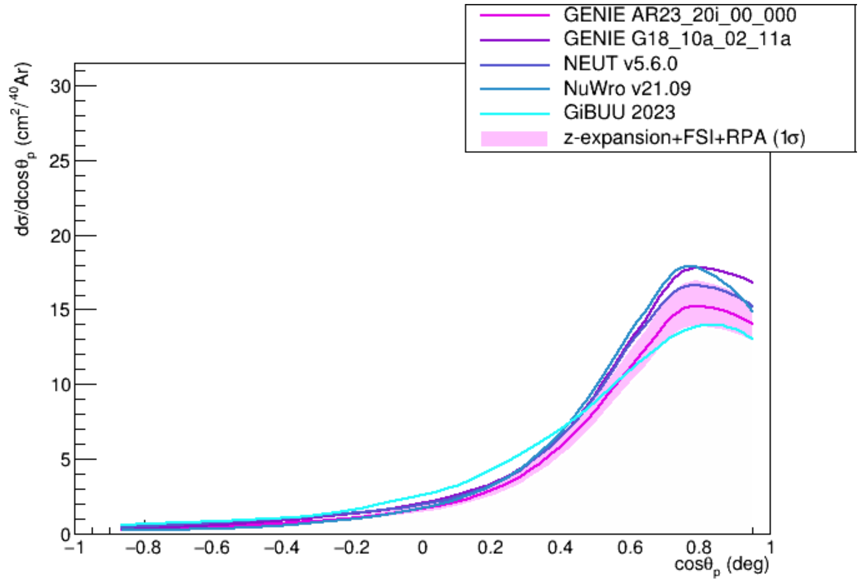
Proton kinematics matter for ICARUS

- Since we are planning to use an exclusive 1μNp (N>0) selection for the OA, the modeling of proton kinematics is important
- In particular, the selection efficiency is a strong function of the (uncertain) proton energy distribution
- We may need additional uncertainties in this space

Fake data studies for protons

- Can use generator comparisons to generate out-of-model fake data samples
- For example, we can reweight our prediction to another generator vs. p_p and maybe also θ_p
- Idea would be to run oscillation fits on the fake data
- If our existing uncertainties cover this, we should get best-fit oscillations of zero; if we see fake oscillations, we may need additional systematics





Summary: are our systemtaics adequate?

- Current systematics are reasonably describing lepton kinematics in T2K and μBooNE, including shape
  - Six parameters in AR23 are especially important
- Some indication of deficiencies in proton kinematics
  - Some new dials developed by DUNE may help → we plan to include these once we respin CAFs
  - Mock data studies motivated by alternate generators as a test of the impact of varied proton kinematics on oscillation fit

What is different with SBND?

- When we include SBND, the argument against tuning the CV becomes stronger
  - We will effectively tune the model with SBND data, correctly accounting for short-baseline oscillations
- It is likely that second-order cross section effects will become more important
  - Differences in efficiency for SBND and ICARUS
  - Differences between ν_μ and ν_e cross sections
  - Subtle energy dependence effects
  - etc.

Conclusions & recommendations:

- We should continue to use AR23
- We should **not** tune it to external data
- We should always ensure that the model is robust, flexible enough to describe multiple external datasets, fake data, etc.
    - This is in OK shape, lepton kinematics look OK
- We should pursue fake data studies, especially varying proton kinematics to test the robustness of our OA
- The argument against tuning becomes stronger with SBND, but cross section uncertainties will need some revisiting