Challenges in cross section measurements and global fits

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Challenges for cross section measurements

Model dependence, and how we bias our data

Cross section extraction

Signal events in *j*th reco. bin

Pesudoinverse of the reco./true smearing matrix

Predicted background events in *j*th reco. bin

$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}_{ij}^{-1}\left(N_j - B_j\right)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

Eff. correction in *i*th true bin

Variable of interest

Bin width

Integrated flux

 # targets

Cross section model dependence

The signal definition and background subtraction can be model dependent

Some unfolding methods introduce bias

$$\frac{d\sigma}{\boxed{dx_i}} = \frac{\sum_j \boxed{\widetilde{U}^{-1}_{ij}}\,(\boxed{N_j - B_j})}{\Phi_\nu T \Delta x_i \boxed{\epsilon_i}}$$

Choice of variables

Efficiency corrections couple to model in complex ways

Choice of variables

- **Model-independent:** final state particle kinematics, or some combination of them (e.g., Q^2_{QE}). *Combinations are prone to subtle efficiency issues!*
- **Model-dependent:** interaction-level kinematics, Q^2, E_ν W…
- Perception that theorists will prefer interaction-level variables because they are easier to use… very shortsighted view...
- Often it’s unclear to experimentalists which variables are of interest to the theory community, *and can be measured...*

Cross section model dependence

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$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}^{-1}_{ij}\,(N_j - B_j)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

Choice of variables

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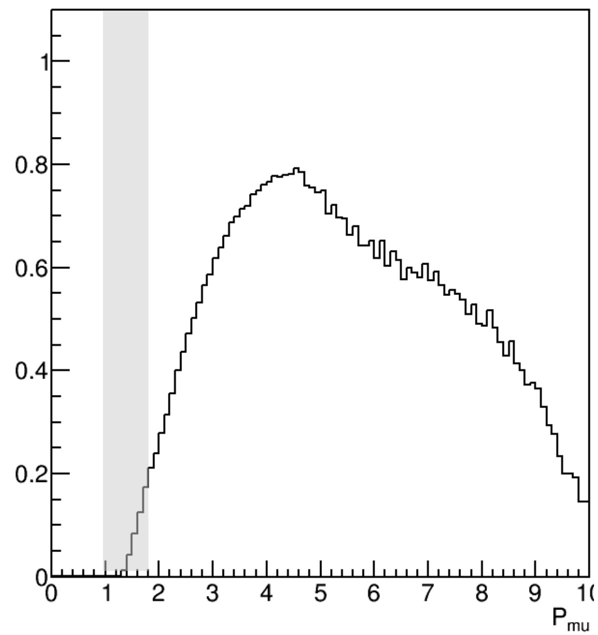
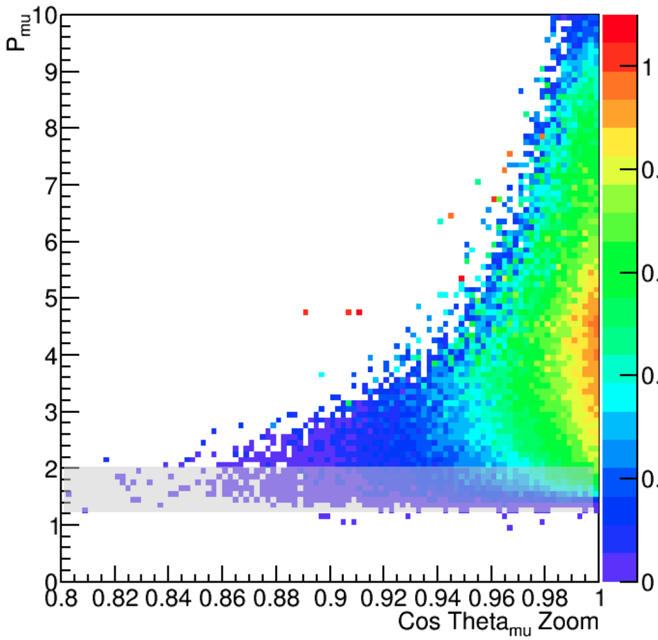
Efficiency corrections

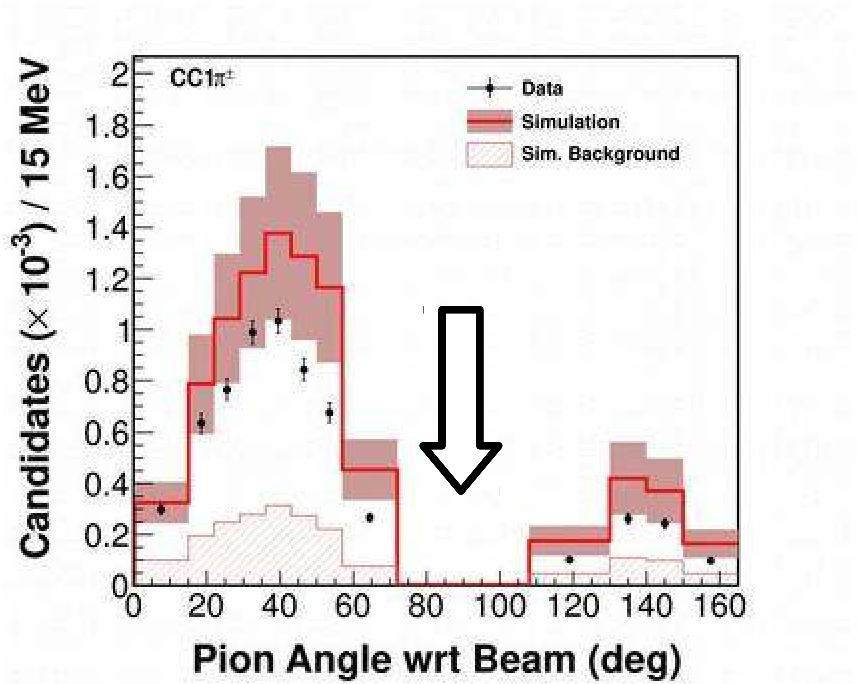
- **Basic problem:** efficiency corrections are typically done on a bin-by-bin basis. Other degrees of freedom have been integrated out.
- Binning efficiency in p_μ only integrates out $\cos\theta_\mu$ variation: all events in a p_μ bin are assigned the same efficiency correction.

- If data more/less forward than MC, result biased up/down
- Sometimes regions of zero efficiency are “corrected for”

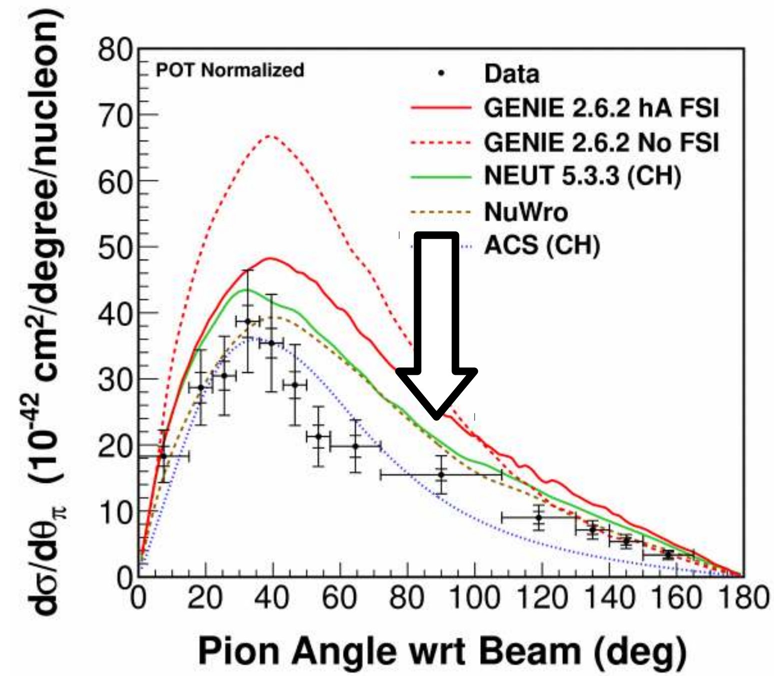


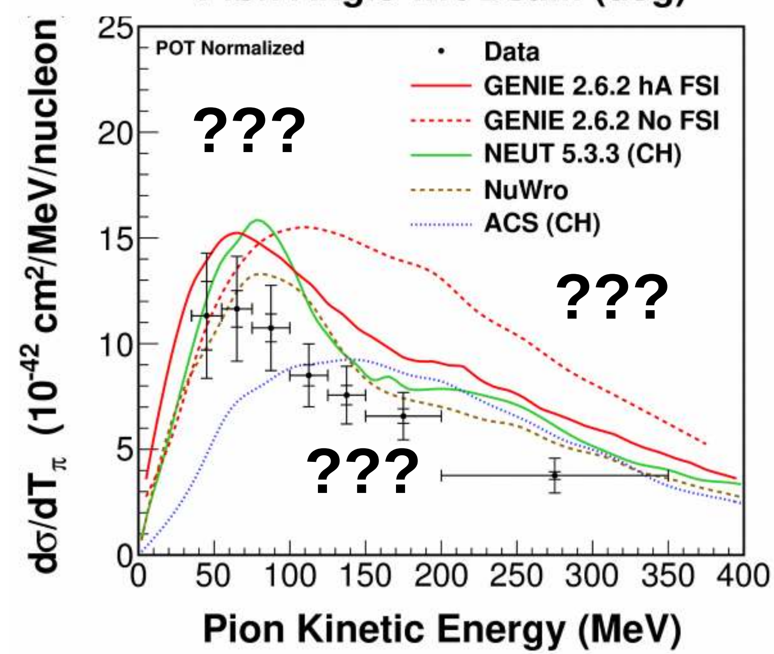


MINERvA CC1$\pi^{\pm}$



- One angular bin filled with MC… unclear where this affects the KE spectrum
- Also, signal defined as $\pi^{\pm}$. But, Michel required! So π^{-} effectively filled in with MC…
- Unclear how much MC (GENIE) has biased the result...

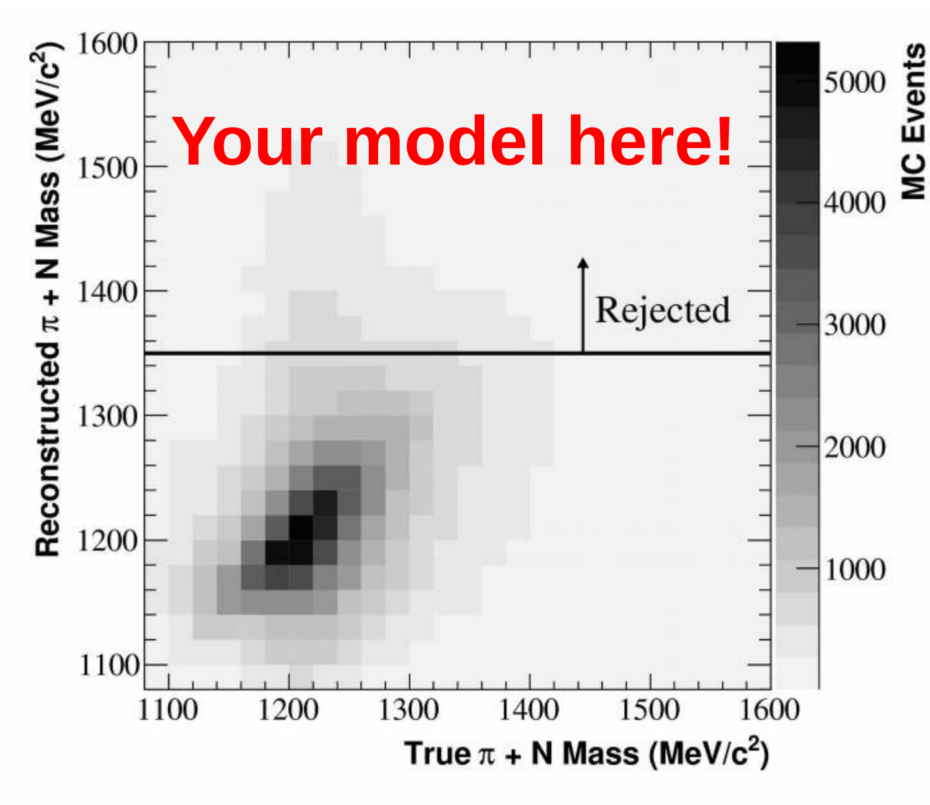




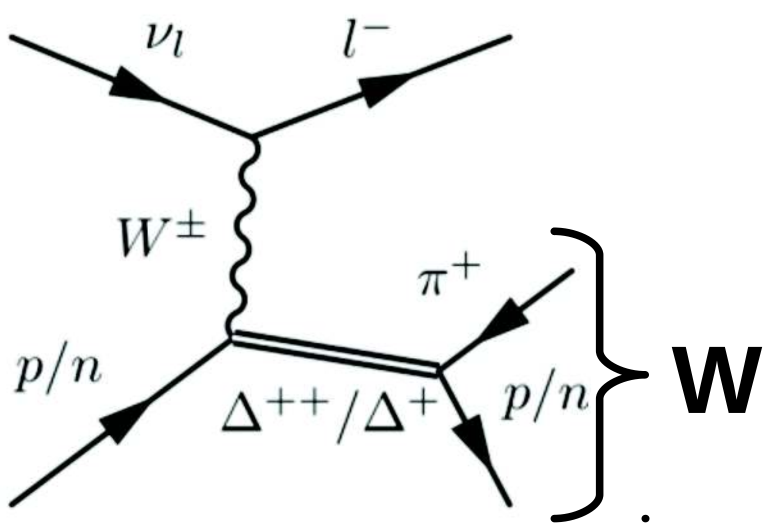
PRD 92 (2015) 092008

MiniBooNE CC1π^+

- Cut made on reconstructed invariant mass, but not reflected in signal definition
- ~30% correction to published cross section comes from MB MC.



PRD 83 (2011) 052007



- Cannot assess where this bias lives… it might dominate some kinematic bins.
- **Hidden efficiency correction!**

Cross section model dependence

The signal definition and background subtraction can be model dependent

Some unfolding methods introduce bias

$$\frac{d\sigma}{dx_i} = \frac{\sum_j \widetilde{U}^{-1}_{ij}\left(N_j - B_j\right)}{\Phi_\nu T \Delta x_i \epsilon_i}$$

Choice of variables

Efficiency corrections couple to model in complex ways

Unfolding methods

- Discussion at PhyStat-nu conferences highlighted unfolding as another critical source for model-dependence
- Unfolding is an inverse problem:

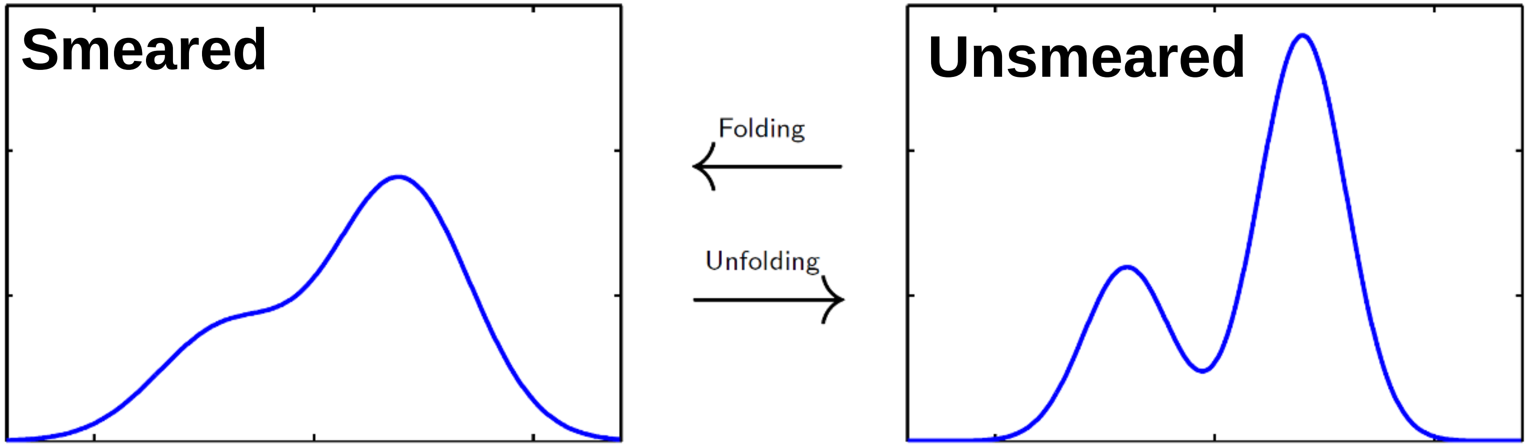


Figure from M. Kuusela

- Some commonly used methods lead to biased results:
  - D'Agostini unfolding with low (< 10) # iterations **(common!)**
  - Bin-by-bin efficiency corrections
  - ***Impossible to quantify bias after the fact***

Unfolding methods

- **Solution #1:** use data driven regularization methods.
  - Regularization makes *some* assumptions about expected result
  - No regularization be harder to interpret (large bin-bin variation)
- **Solution #2:** not unfolding (MB NCEL, MINERvA CC-inc ratios)
  - Present results in reconstructed variables, provide smearing matrix to smear theory to match data
  - Harder to use… some concern that this will lead to results *not being used*
  - Unambiguous advice from statisticians…

Cross section model dependence

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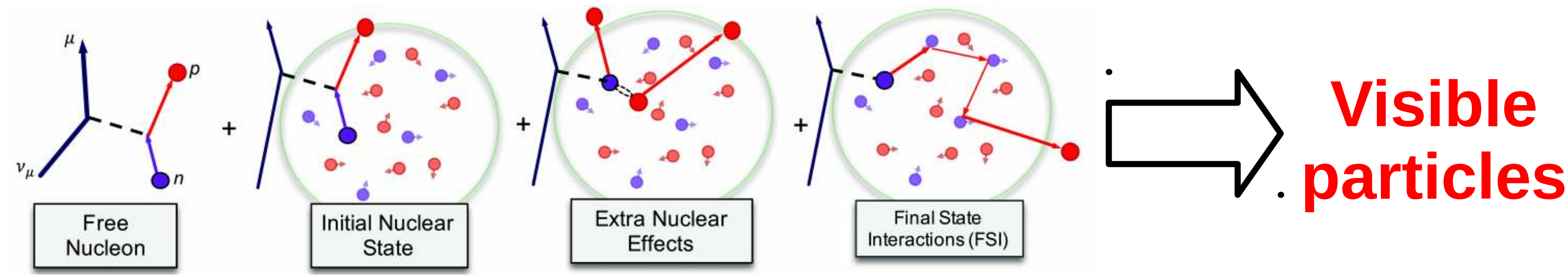
Model-independent signal definitions



- Experiments can only measure final state particles, e.g., 1μ 0π:

CC0π = CCQE + npnh(0π) + CC1π(+abs) + …

- Many previous measurements try to correct for irreducible backgrounds to make the result easier to use...

… but trying to recover CCQE introduces model dependence

$$\mathbf{CCQE} = \underbrace{\mathbf{CC0\pi}}_{\textbf{Data}} \mathbf{-} \underbrace{\mathbf{npnh(0\pi) - CC1\pi(+abs) - \ldots\ ???}}_{\textbf{Generator}}$$

What can we actually measure?

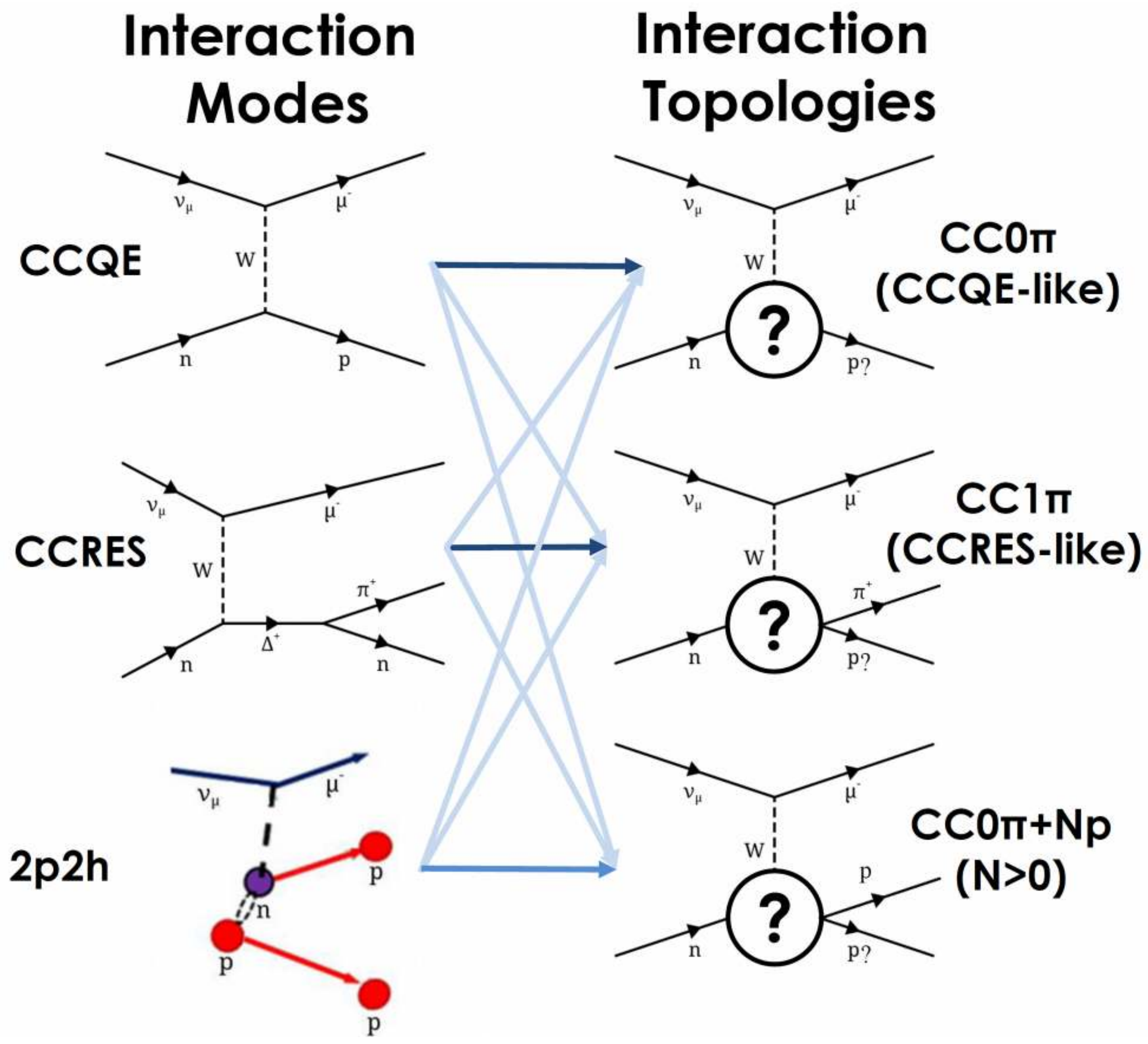
- Only ***post-FSI*** cross sections are model-independent:

$$\widetilde{\sigma}_k(\vec{\mathbf{y}}) = \sum_i \int_{E_{min}}^{E_{max}} \sigma_i(E_\nu, \vec{\mathbf{x}}) \times \mathrm{FSI}(\vec{\mathbf{x}}, \vec{\mathbf{y}}) dE_\nu$$

CC0π = 1p1h + 2p2h + CC1pi(+abs) + ...

- Need to integrate out all degrees of freedom other than ***y*** **FSI** makes this difficult analytically
- Some results will become very difficult to compare to outside a generator (e.g., MINERvA 1π^+, with any number of π^0s allows)

What can we actually measure?



Many modes contribute to any measurement

Integrated over broad ω region

Difficult to tune models!

Graphic from S. Dolan

Challenges for global fits

Tuning models to data

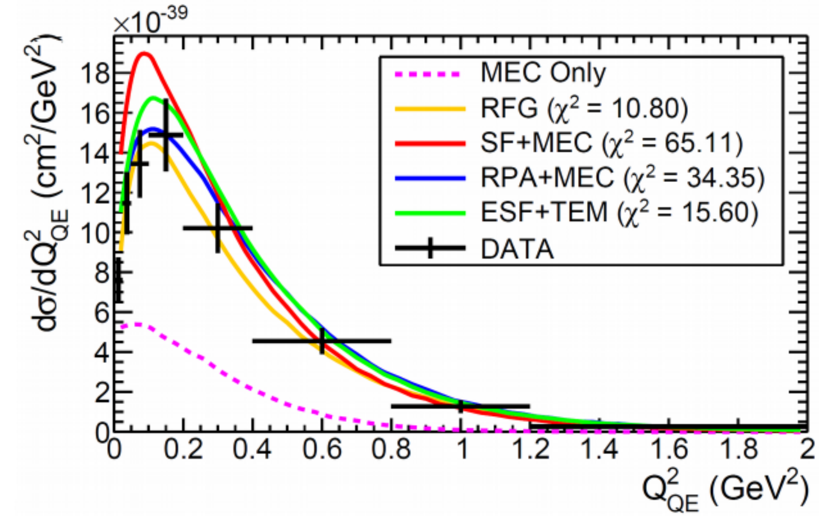
- Tuning σ_i parameters requires many post-FSI datasets to break degeneracies!
  - Multiple fluxes
  - Different acceptance
  - Detector technologies
  - Multiple targets

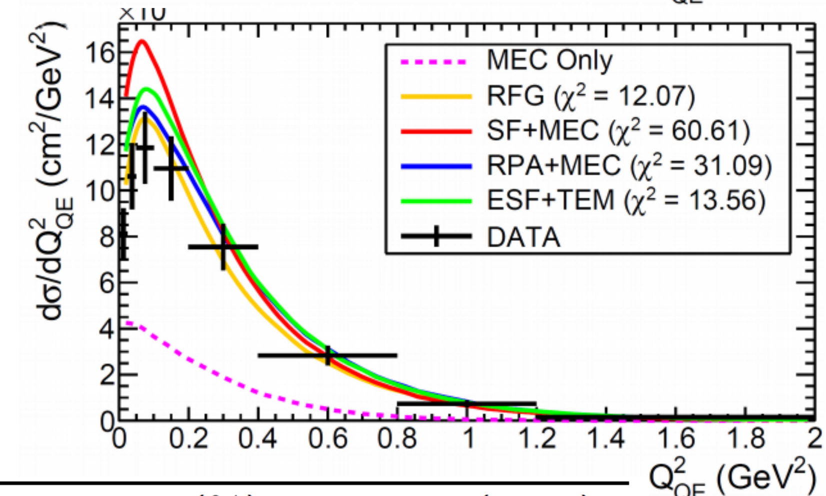
- Cannot fit parameters of a single interaction channel, without making assumptions about (or fitting) others

- **Tuning or validation of a model is really challenging!**

Previous T2K CC0π attempt

- Attempt to fit all CC0π data:
  - MiniBooNE T_μ-$\cos\theta_\mu$ ν_μ
  - MiniBooNE T_μ-$\cos\theta_\mu$ $\bar{\nu}_\mu$
  - MINERvA Q^2 ν_μ & $\bar{\nu}_\mu$ (with corr.)
- Many NEUT model improvements: SF, 2p2h,…
- Unable to fit the data, **surprising** and **unsatisfactory** results.

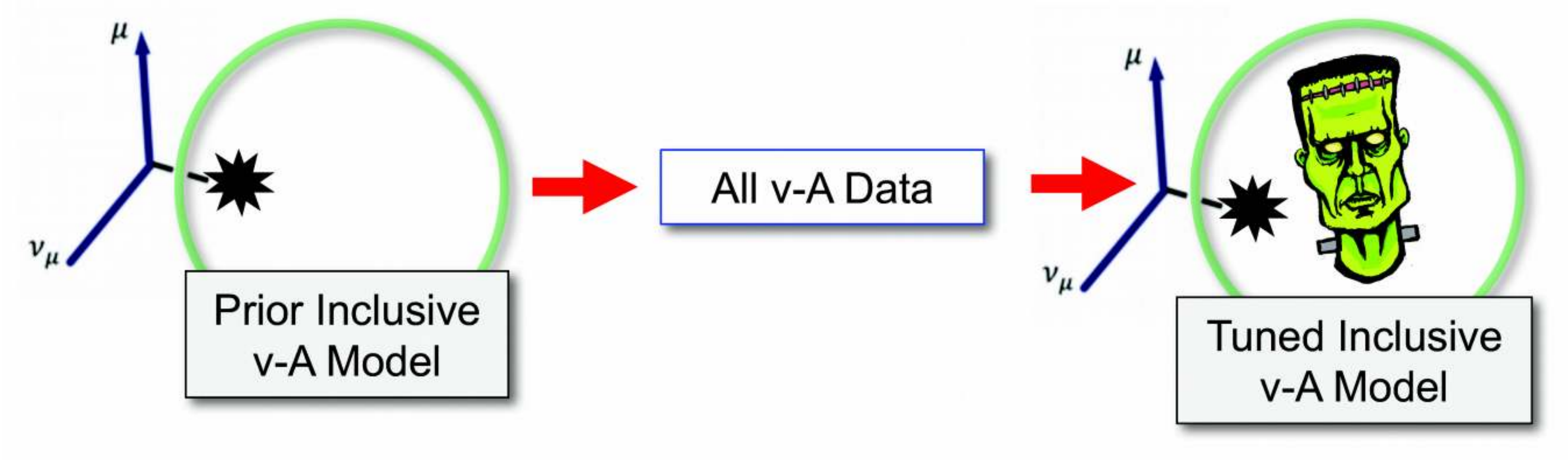




Model	χ^2/DOF	$\mathbf{p}_1$: M_A (GeV)	$\mathbf{p}_2$: 2p2h (%)	$\mathbf{p}_3$: p_F (MeV)
Theory expectation		$\sim$1.00	$\sim$100	$\sim$217
A: SF+2p2h	97.5/228	1.33±0.02	0 (at limit)	234±4
B: RFG+RPA+2p2h	97.8/228	1.15±0.03	27±12	223±5

See PRD 072010 (2016) for the gory details!

Frankenmodels

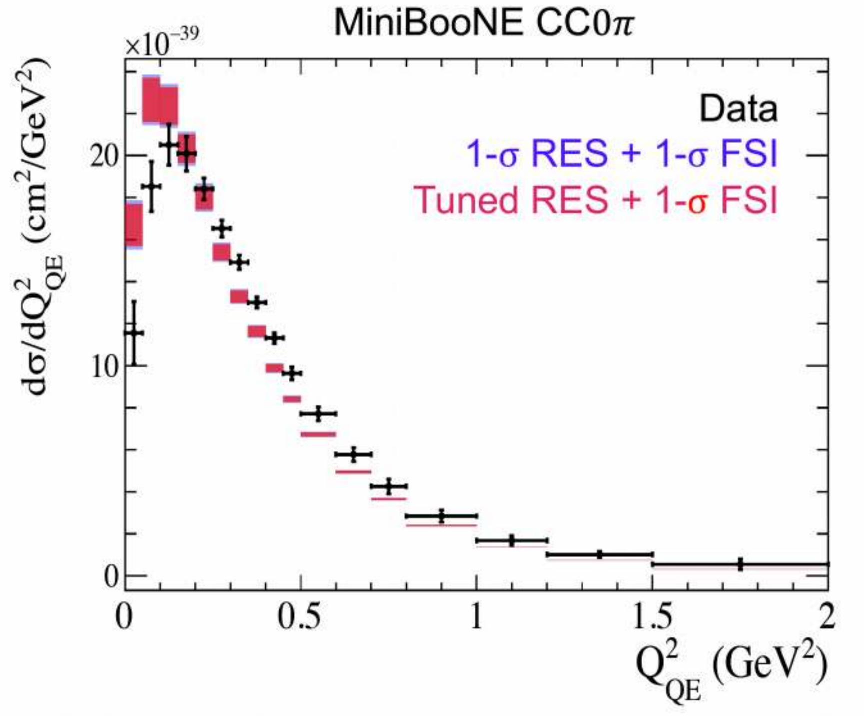


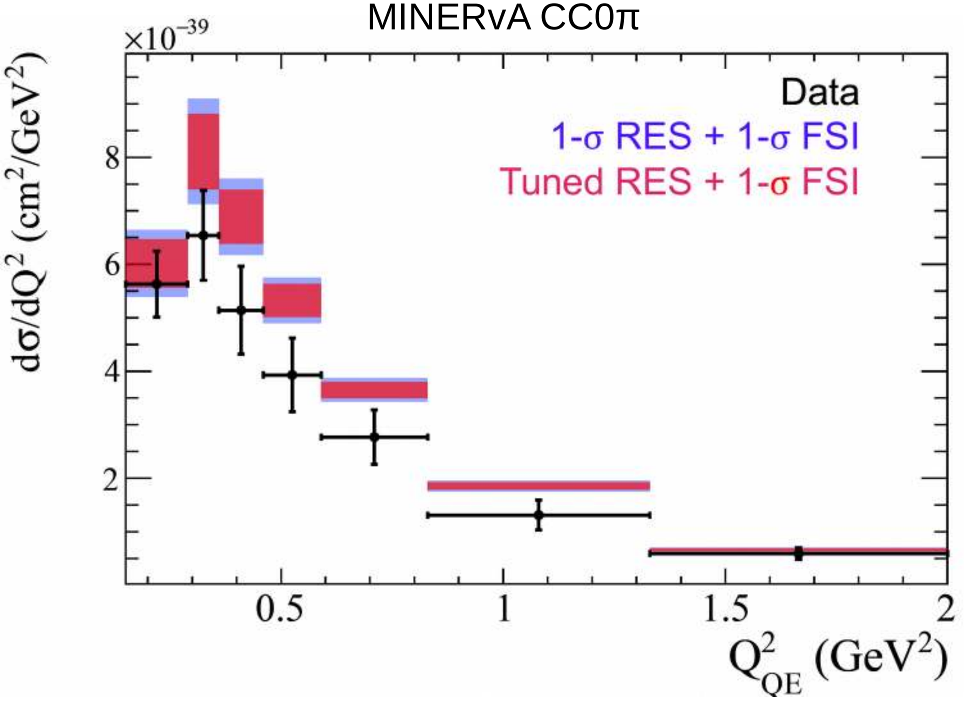
- Incomplete models lead to unphysical ***effective*** parameters (large axial mass!)
- Not clear where the deficiency lies
- Common issue for all neutrino experiments and model tunings!

Unclear where deficiency lies

- We know that we can't isolate CCQE for ν-A data → CC0π

- But there's still a temptation to fit CCQE parameters to CC0π data

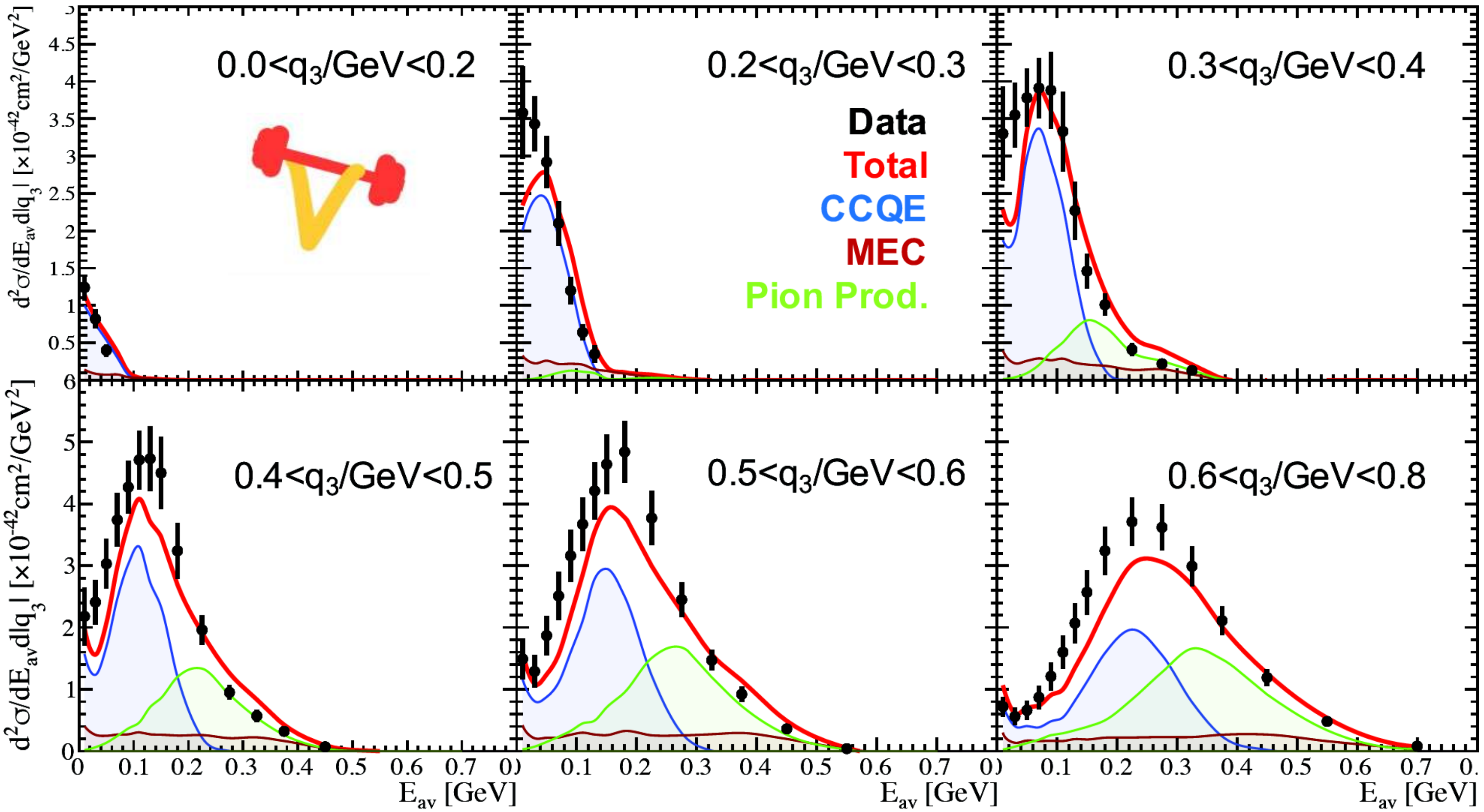




- RES parameters in NEUT clearly have a large effect on CC0π data

- But, this makes theory challenges outside generators very challenging!

Another example (sort of)



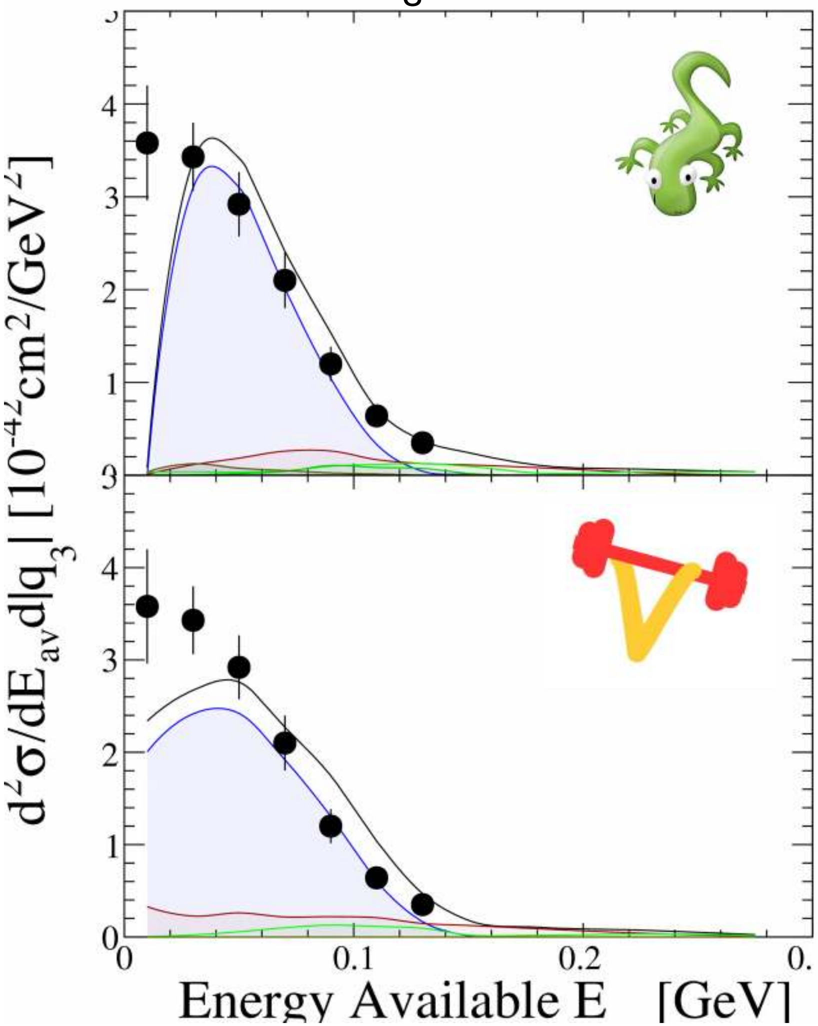
PRL 116 (2016) 071802

$$E_{av} = \sum_{i=p,\pi^{\pm}} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

Is disagreement due to the CCQE model? MEC? Pion production?

Partial exception

0.2 < q_3/GeV < 0.3



$$E_{av} = \sum_{i=p,\pi^\pm} T_i^K + \sum_{i=\pi^0,e,\gamma} E_i$$

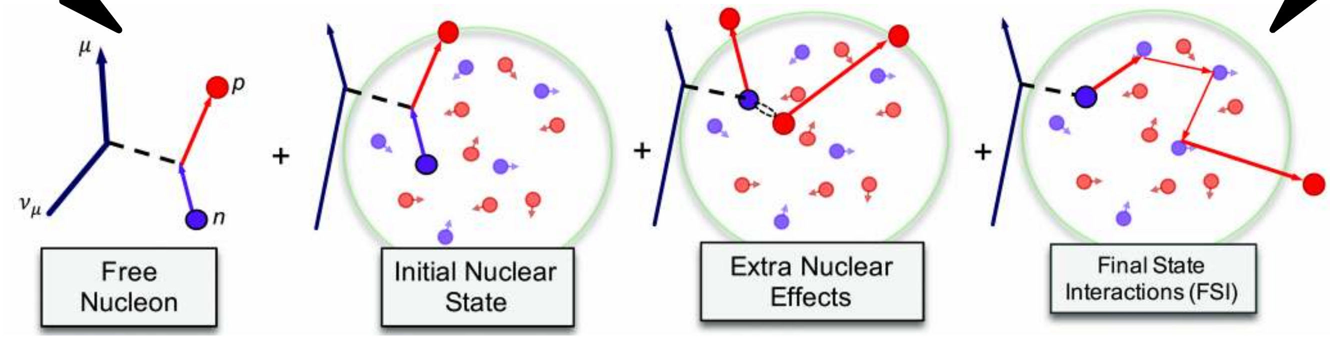
- Inclusive data can still highlight model deficiencies
- NEUT clearly deficient at very low energy transfers (QE-dominated)
- Difference in the nuclear model → motivated further NEUT development
- Limited use, but important cross check!

External cross section model constraints

ν-D_2 bubble chamber
(1970s-1980s)

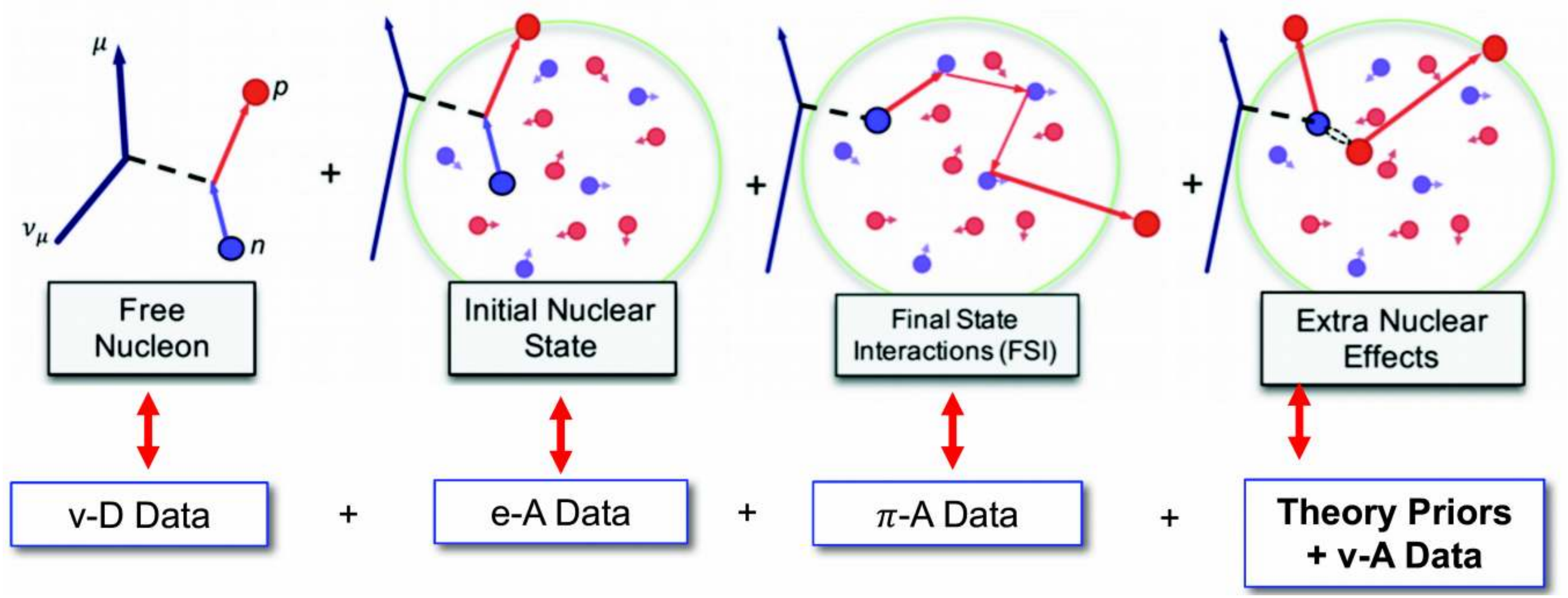
e-A scattering
(1970s-present)

Pion/nucleon



Neutrino heavy
target experiments

Modular approach on T2K



- Tune different aspects of the model to ***appropriate data***
- Develop *ad hoc* models in the generators (NEUT) to include new theory where possible / fill in the gaps
- **Theory and generator co-ordination essential to improve this horrible situation!**

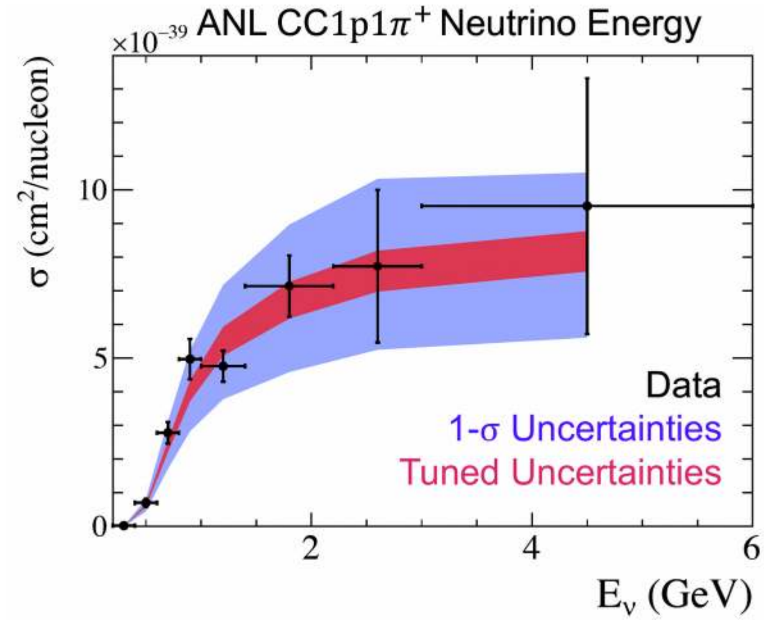
Outlook

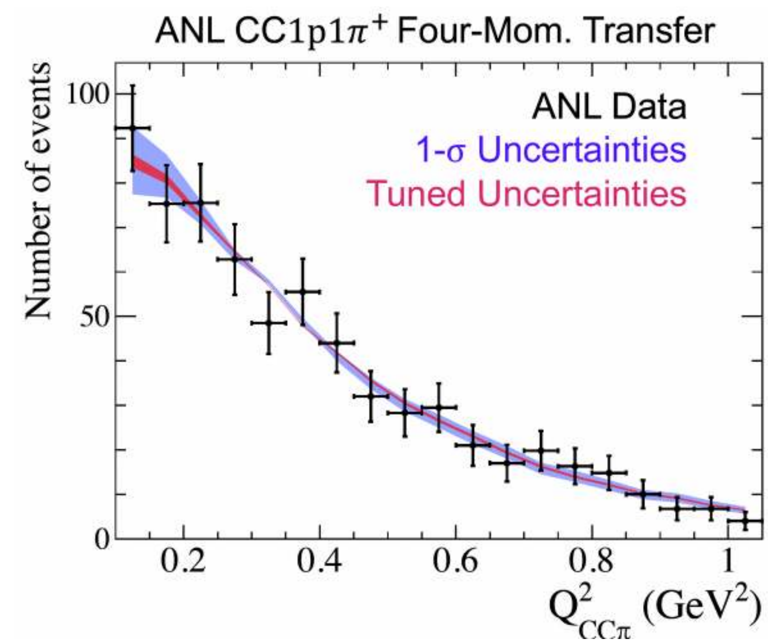
- Difficult road ahead to reduce cross systematics for future experiments.
- Situation is improving, a lot of new, higher quality data.
- Alternative generators and models essential for that
- Challenge to using that data to constrain models. Bad data may also spoil the picture…
- Need new theory models in generators rather than simply fiddling with effective generator parametrizations.

Backup

Tuning the R-S model

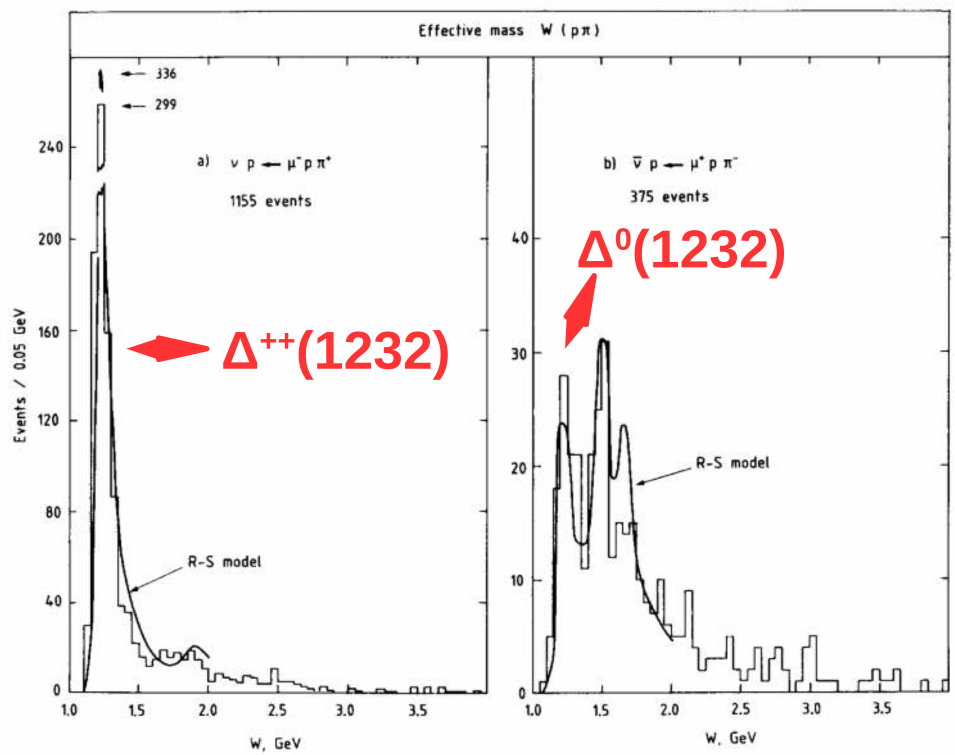
- Parameters tuned to 10% level by limited set of BC data:
  - ANL and BNL, E_ν and Q^2
  - $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^0 + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^+ + n$
- **Caveats:**
  - D_2 data, FSI may not be negligible
  - CC used to predict NC model
  - Many known limitations to R-S model!





ν-N resonance production

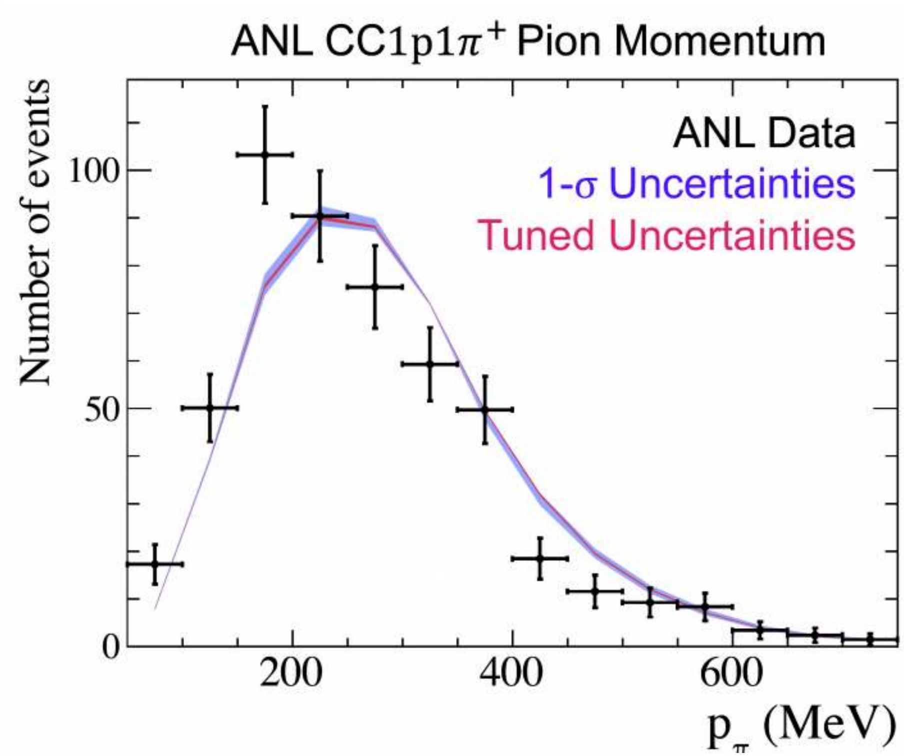
Nucl. Phys. B264 221 (1986)



$$W^2 = (\Sigma E)^2 - |\Sigma \mathbf{p}|^2$$

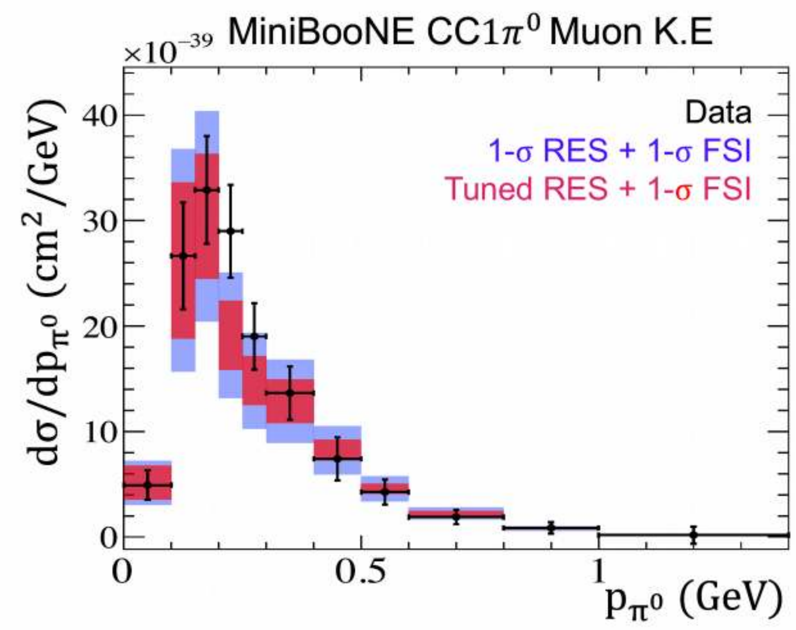
- Not clear that the R-S model fits all available kinematics.
- Little flexibility in model to cover possible discrepancies.

- Higher order resonances also contribute, insufficient data to constrain model for them
- Current experiments can't do better, can't reconstruct W well enough.



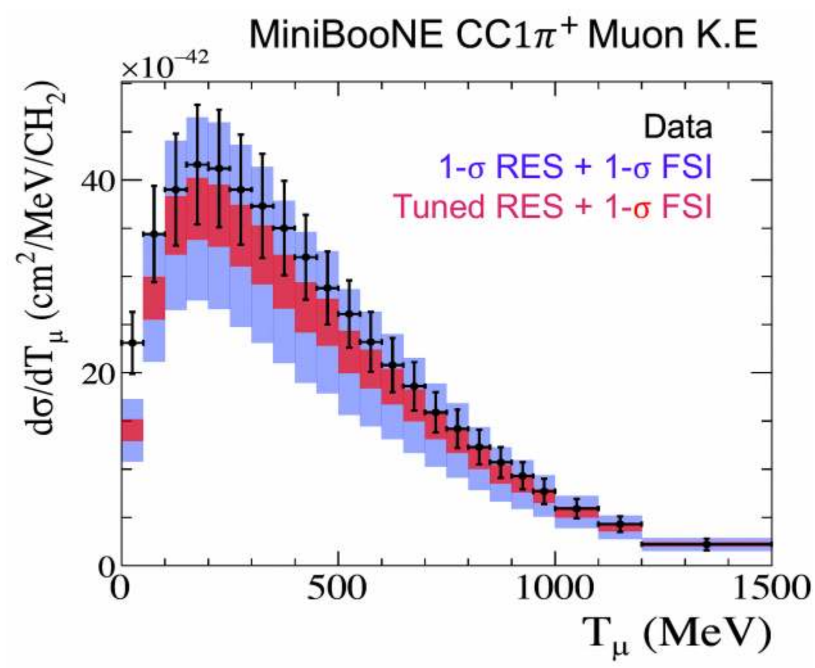
Comparison with nuclear data

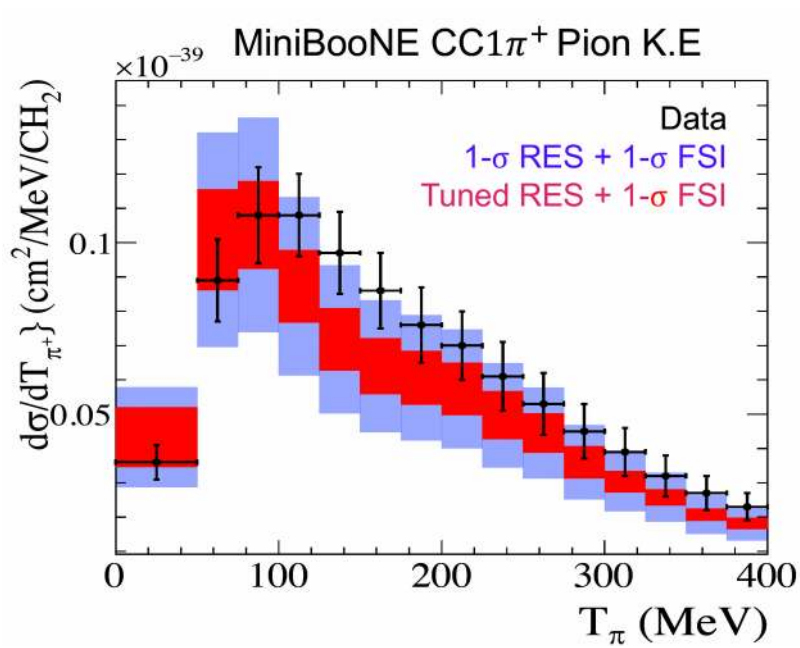
- Reasonable agreement with outgoing **muon kinematics**
- Not for pion kinematics. Inadequate FSI model? … but poor for ν-N data too!



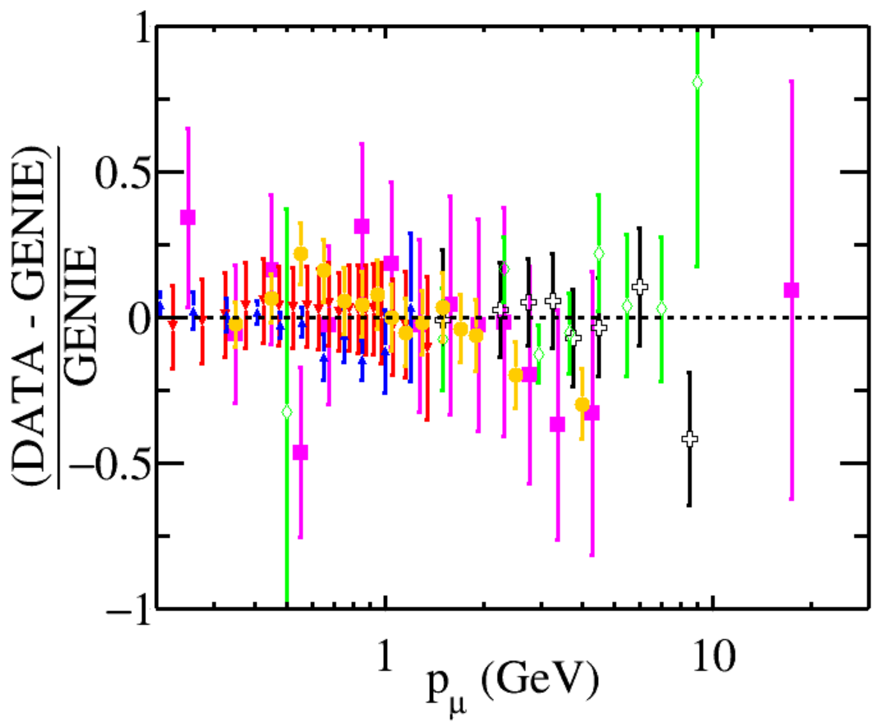
MB ν_μ-CH_2 CC1π^0
PRD 83 (2011) 052009

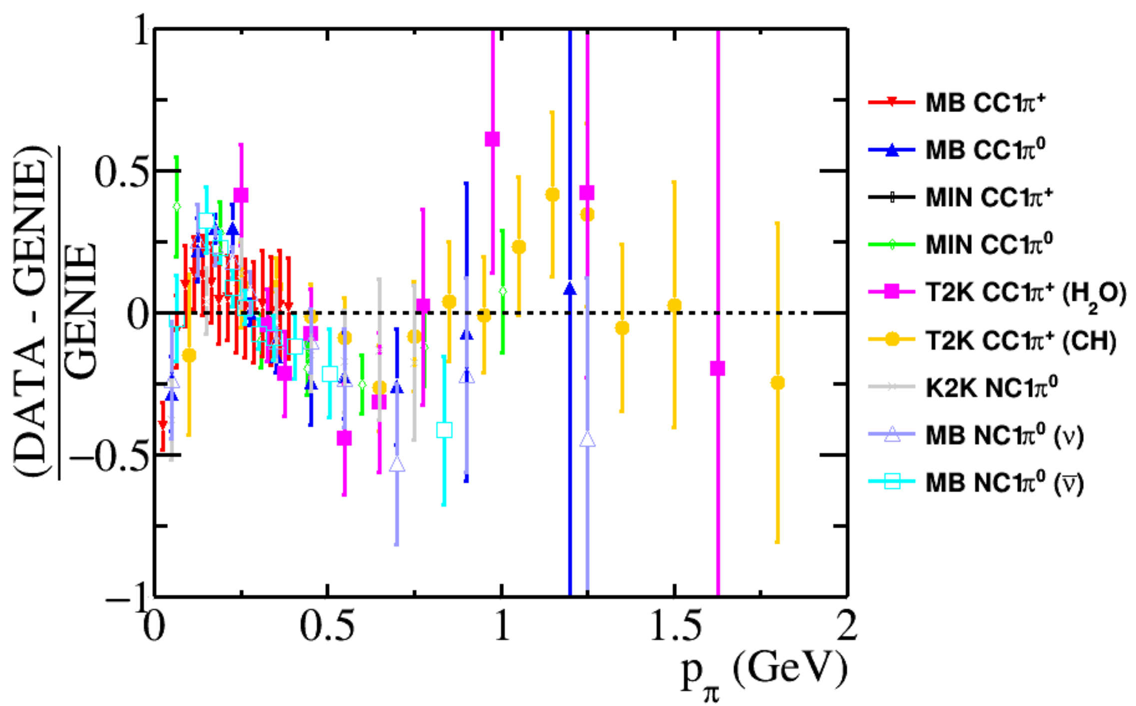
MB ν_μ-CH_2 CC1π^+
PRD 83 (2011) 052007





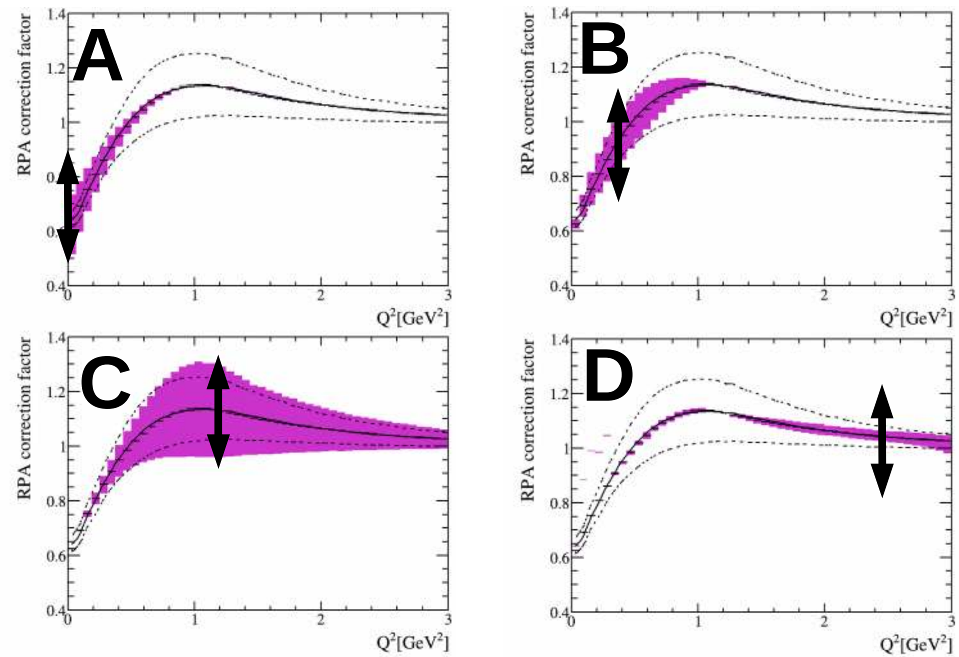
ν-A data-MC disagreement





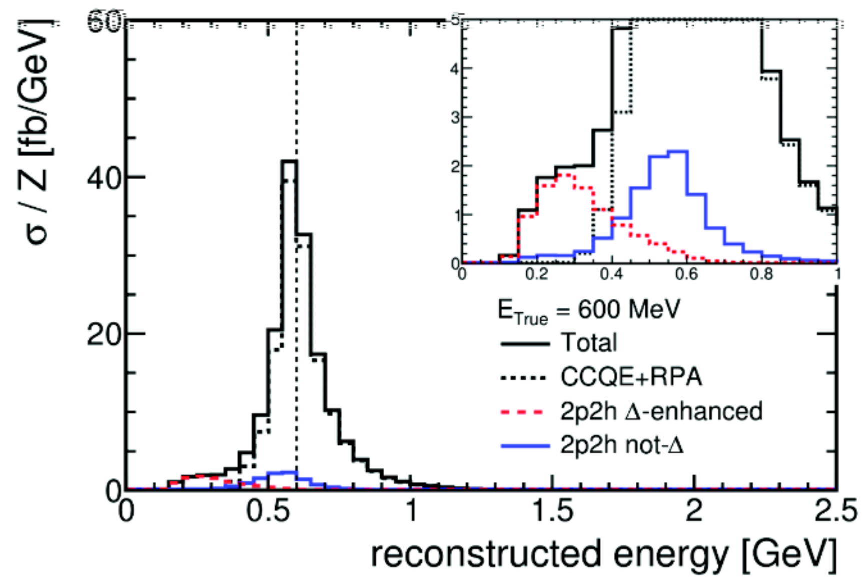
- Fractional deviation of data from reference model (shape-only)
- Good agreement for muon kinematics, poor for pion kinematics
- Difficult to resolve… simply tuning cascade model parameters is clearly inadequate...

Developing new parameters



- **BeRPA:** effective model to mock up Nieves RPA, but introduce flexibility.
- Approximates theoretical error band.

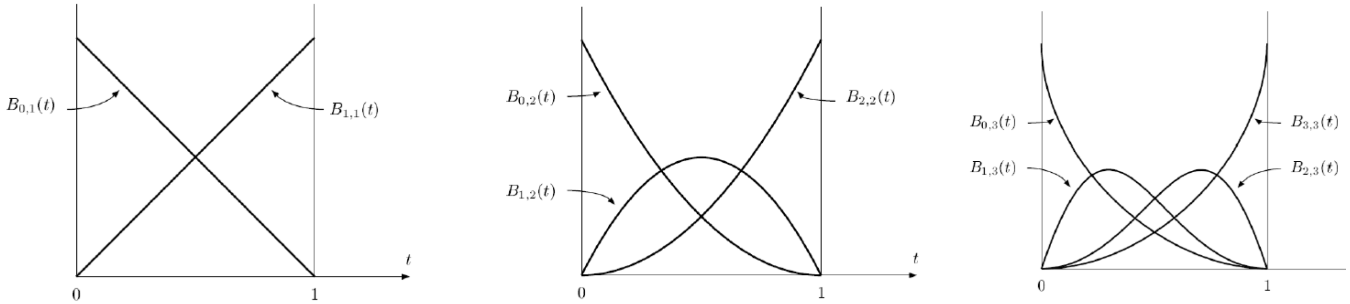
- **2p2h shape:** separate terms
  - **Delta-component (PDD)**
  - **Non-Delta**
  - **Interference**
- Vary relative strength of the Delta-component, but preserve total 2p2h norm.



Bernstein polynomials

- Bernstein polynomials of degree *n* form a basis for the power polynomials of order *n*:

$$B_{i,n}(x) = \binom{n}{i} x^i (1-x)^{n-i}$$



- The n Bernstein polynomials peak at different values of x and can reproduce any nth order power polynomial by varying their normalizations.
- The same cubic to exponential form expressed with Bernstein polynomials gives:

$$f(x) = \begin{cases} A(1-x')^3 + 3B(1-x')^2 x' + 3C(1-x')x'^2 + Dx'^3, & x < U \\ 1 + E\exp(-F(x-U)), & x > U \end{cases}$$

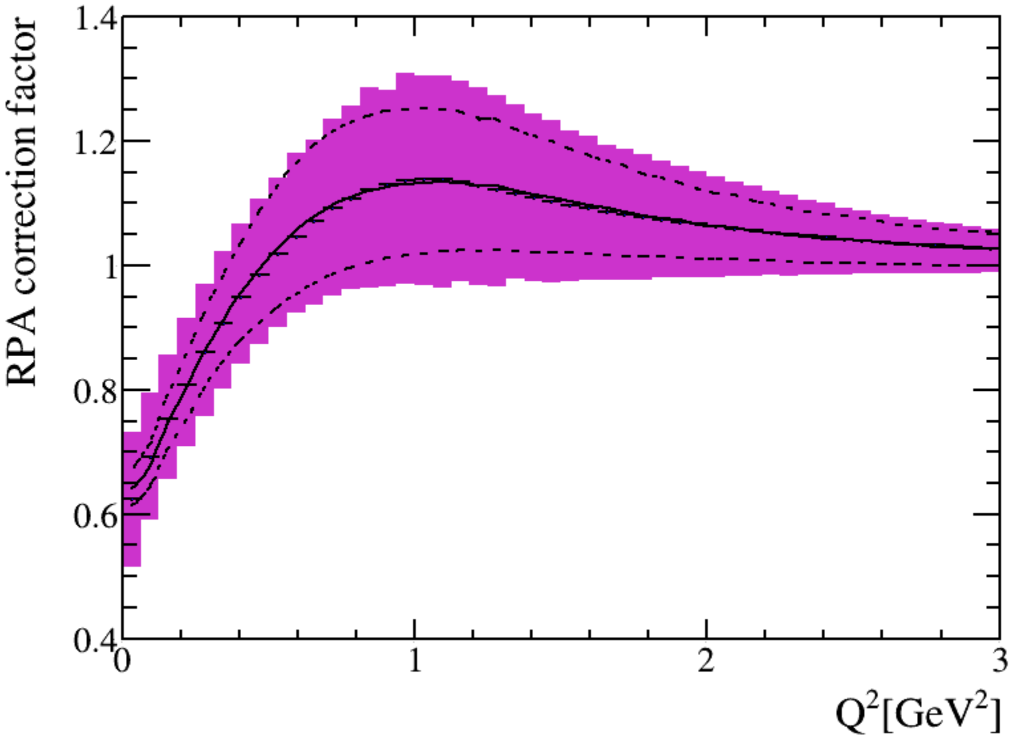
where $x = Q^2$, $x' = x/U$

- Looks awful! But, the continuity conditions are much less problematic:

$$E = D - 1$$

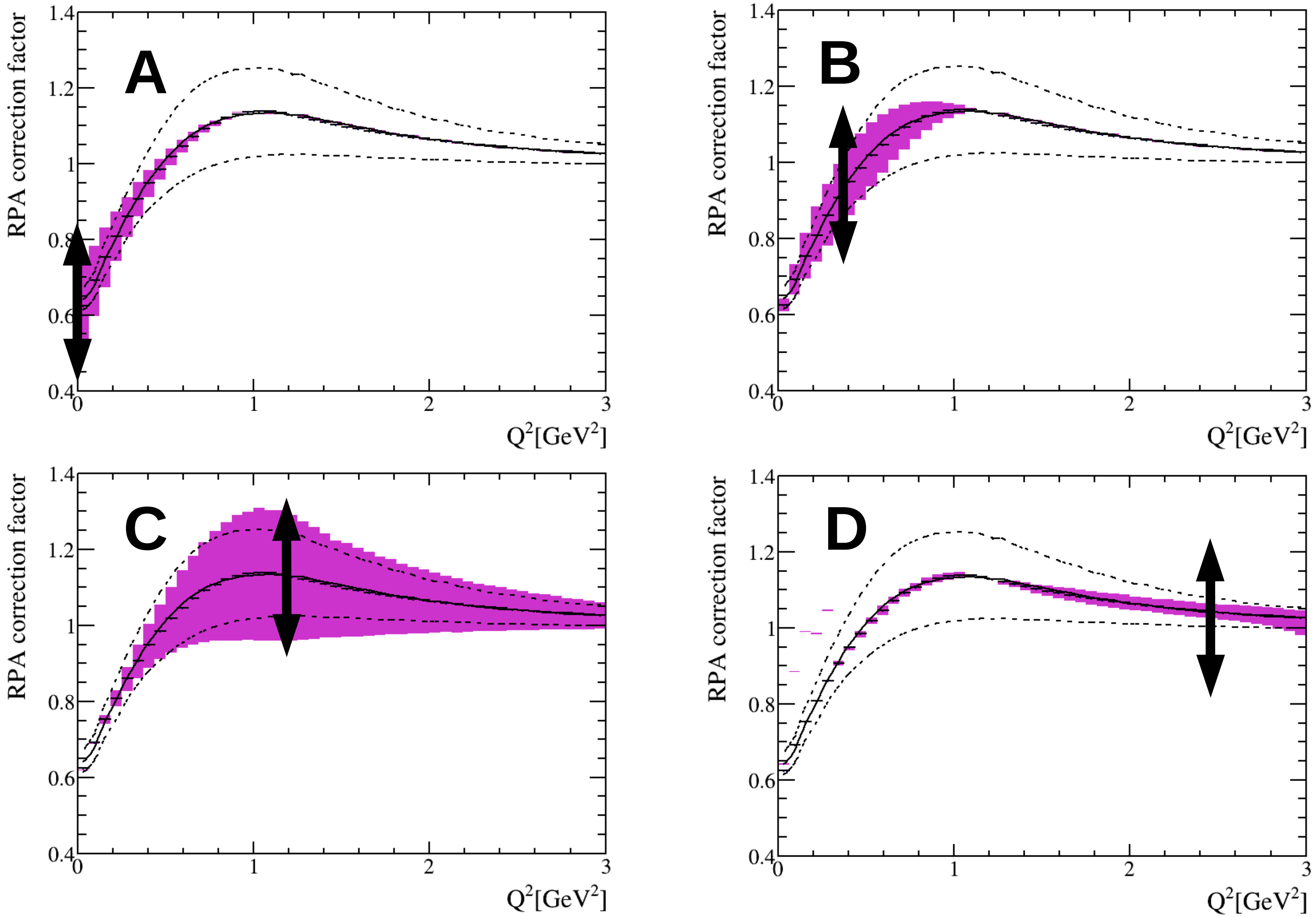
$$C = D + \frac{UF(D-1)}{3}$$

BeRPA (1)



- **Be**rnstein polynominals used to approximate the Nieves **RPA** model, with additional freedom.
- Fit (blue) to nominal Nieves RPA (solid black).
- Guesstimate errors (purple band) which cover the Nieves error (dashed).

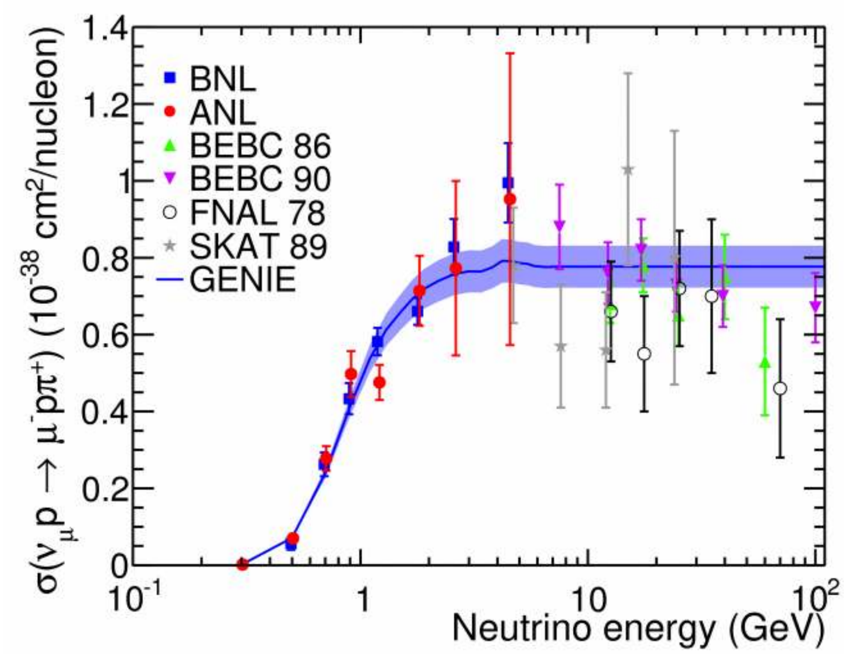
BeRPA (2)

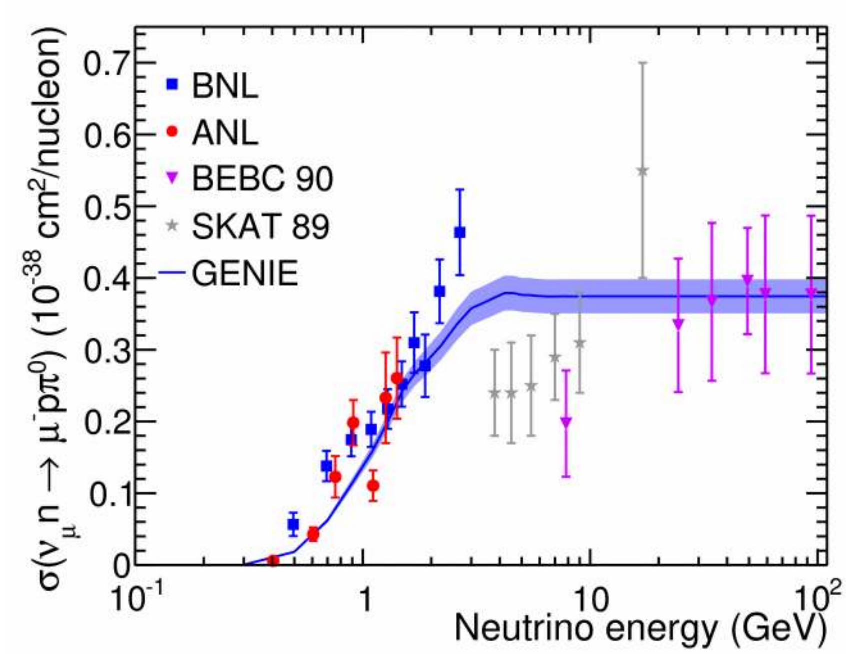


BeRPA parameters affect different regions of Q^2 → more flexibility

Bubble chamber tuning

- Parameters tuned to a limited set of bubble chamber data:
  - ANL and BNL, E_ν and Q^2 distributions
  - $\nu_\mu + p \rightarrow \mu^- + \pi^+ + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^0 + p$
  - $\nu_\mu + n \rightarrow \mu^- + \pi^+ + n$
- Similar to tuning of the GENIE model for MINERvA (pictured)





EPJC 76 (2016) 76:474