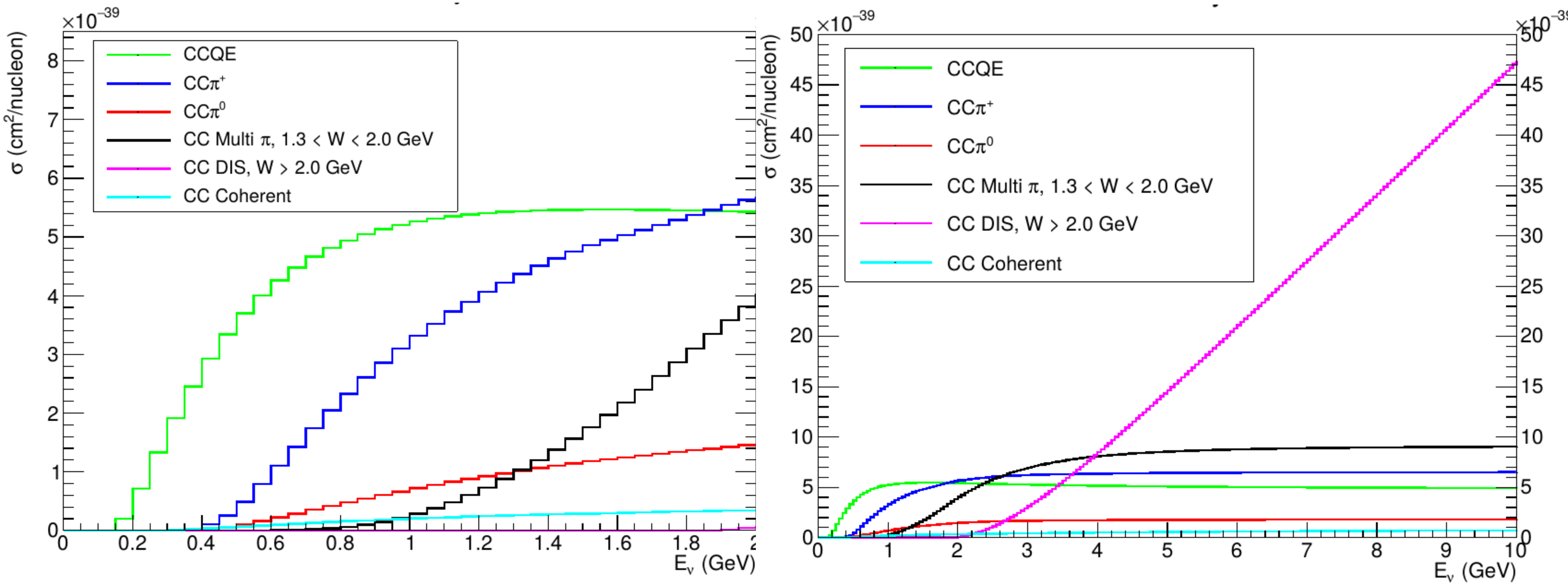
Single pion cross-sections in NEUT



Everything is work in progress, nothing is propagated anywhere yet!
(and I do not speak on behalf of anyone but myself)

Clarence Wret, c.wret14@imperial.ac.uk
Nu-Tune 2016, Liverpool
12 July 2016
Imperial College London
T2K

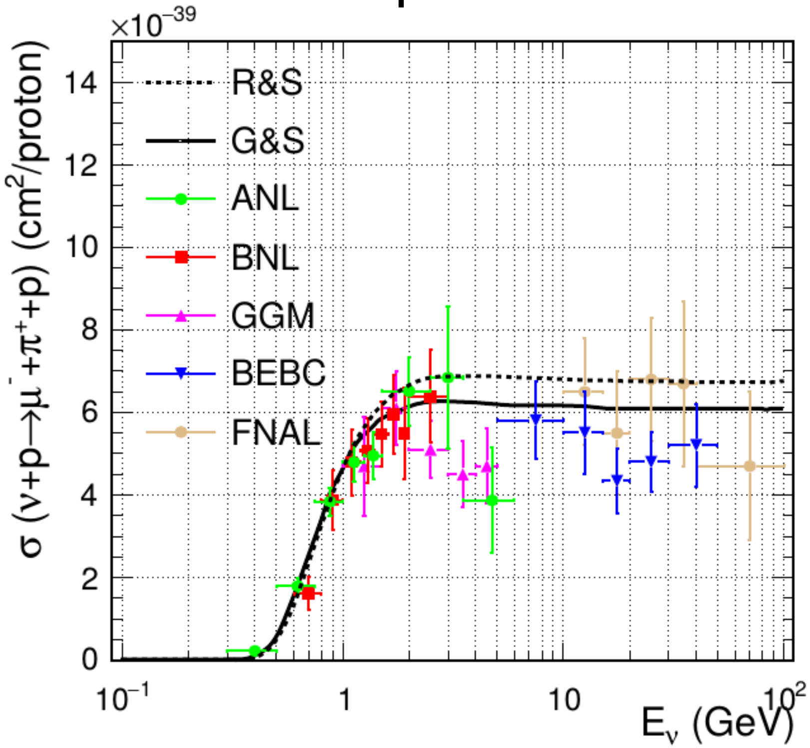
Outline

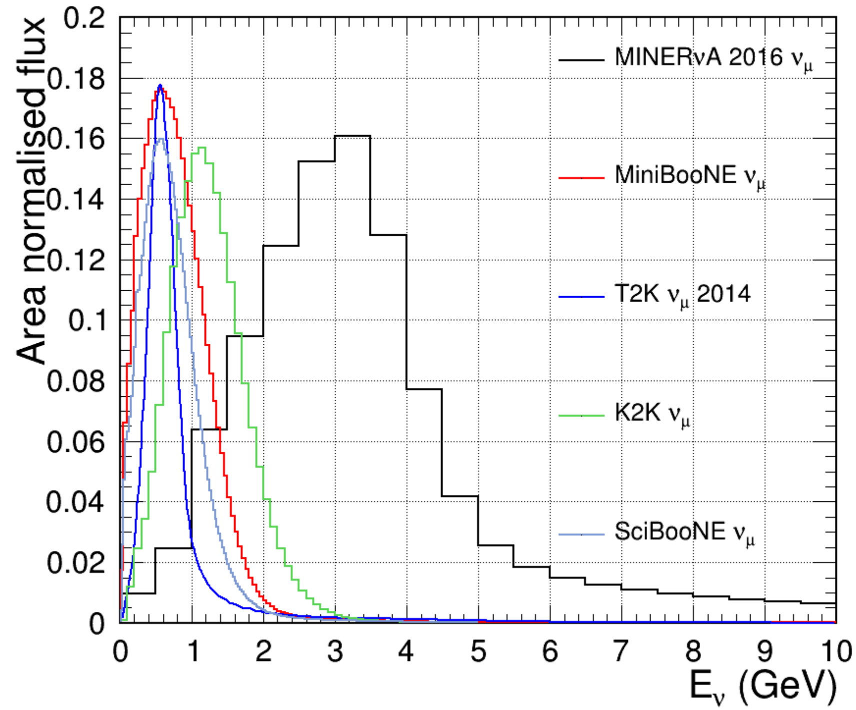
- Modelling single pion production in NEUT
- Bubble chamber fits
- Nuclear target complications and my approach
- Nuclear fits
- General comments on how we might make this easier…

- Interlaced with random comments about the data

External data

- There's a tonne of data available!
  - Ranging from the 60s to present day
  - Variety of targets with a variety of fluxes in many different kinematic variables
- Bubble chamber experiments with clean nucleon interactions





- Nuclear experiments with complicated nuclear environments
  - Nucleon models might become effective, how do we feel about that?

Imperial College London

T2K

External data

- Most have some subtleties
  - Cutting phase space and then unfolding with MC
  - Correct for phase space cuts by overall normalisation
  - Fluxes which are "published" as conferences proceedings
  - Specific data not available in publication but in PhD theses
- I'll go through a few of these and why I think care needs to be taken… Also a humbling reminder from FKR:

ficing theoretical adequacy for simplicity. We shall choose a relativistic theory which is naive and obviously wrong in its simplicity, but which is definite and in which we can calculate as many things as possible – not expecting the results to agree exactly with experiment, but to see how closely our "shadow of the truth" equation gives a partial reflection of reality. In our attempt to maintain simplicity, we shall evidently have to violate known principles of a complete relativistic field theory (for example, unitarity). We shall attempt to modify our calculated results in a general way to allow, in a vague way, for these errors.

(Borrowed from K. Graczyk)

…

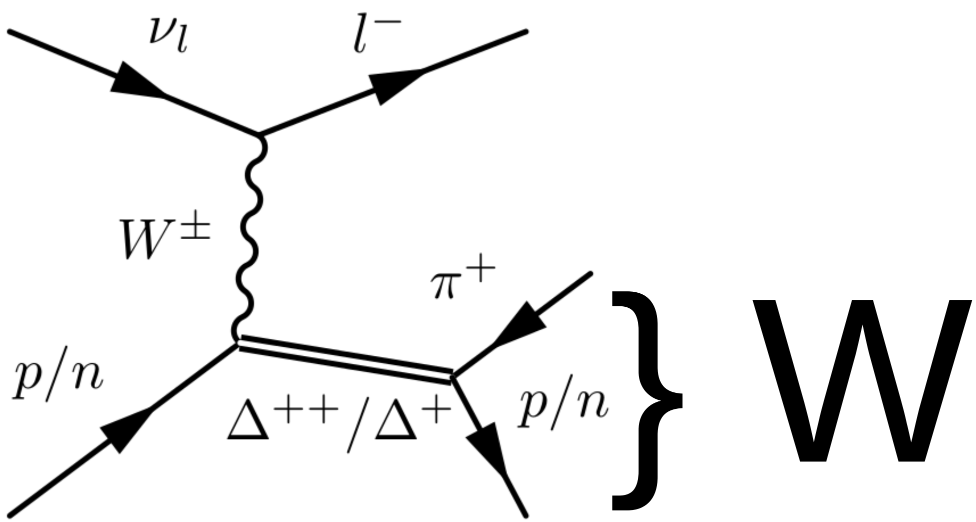
the slope of the Regge trajectories, and the masses of the particles, 75 matrix elements are calculated, of which more than $\frac{3}{4}$ agree with the experimental values within 40%. The problems of extending this calculational scheme to a viable physical theory are discussed.

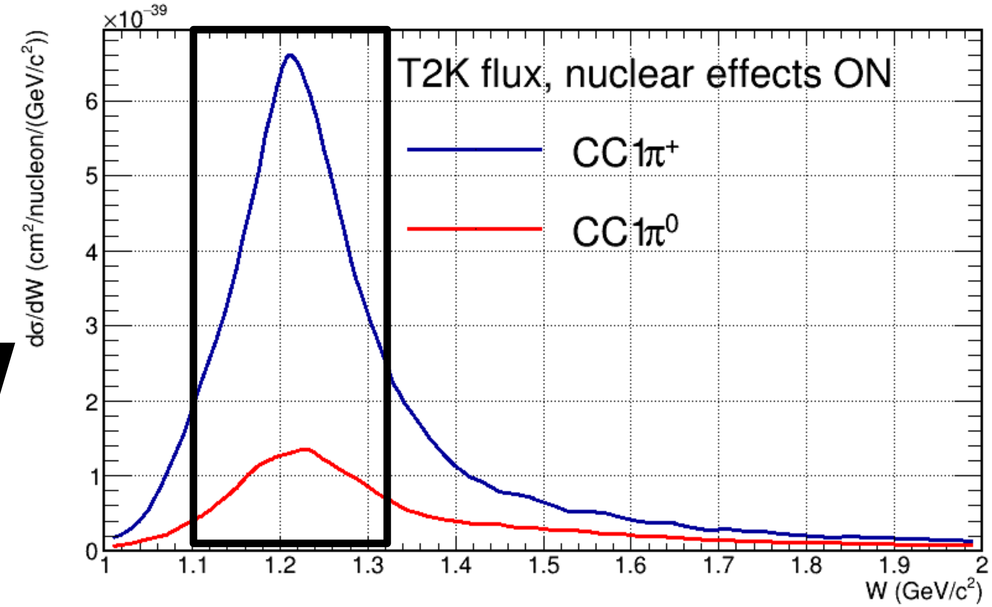
NEUT single pion model

- Rein-Sehgal model (highlighting differences to GENIE):
  - Form-factor tuned to the Delta resonance $C_A^5(0)$, Graczyk-Sobczyk
  - Lepton mass effects, Berger-Sehgal (I think GENIE has this?)
  - Includes resonance-resonance interferences
  - Includes a non-interfering non-resonant I½ background, as prescribed by Rein-Sehgal (no DIS scaling)
  - Outgoing pion generated **an-isotropically** from P(1232) amplitude and spherical harmonics, as prescribed by Rein-Sehgal
- Three parameters: M_A^{RES}, $C_A^5(0)$, non-resonant scaling
- In nuclear environment add pion FSI parameters and DIS scaling
  - Tricky to tune using only 1π data; will need priors from "tunes" to Nπ data from bubble chambers (+MINERvA?)

Fitting the model

- Three parameters: M_A^{RES}, $C_A^5(0)$, non-resonant I=½ scaling
- T2K care mostly about E_ν < 5 GeV region
  - Delta dominated region for single pion production

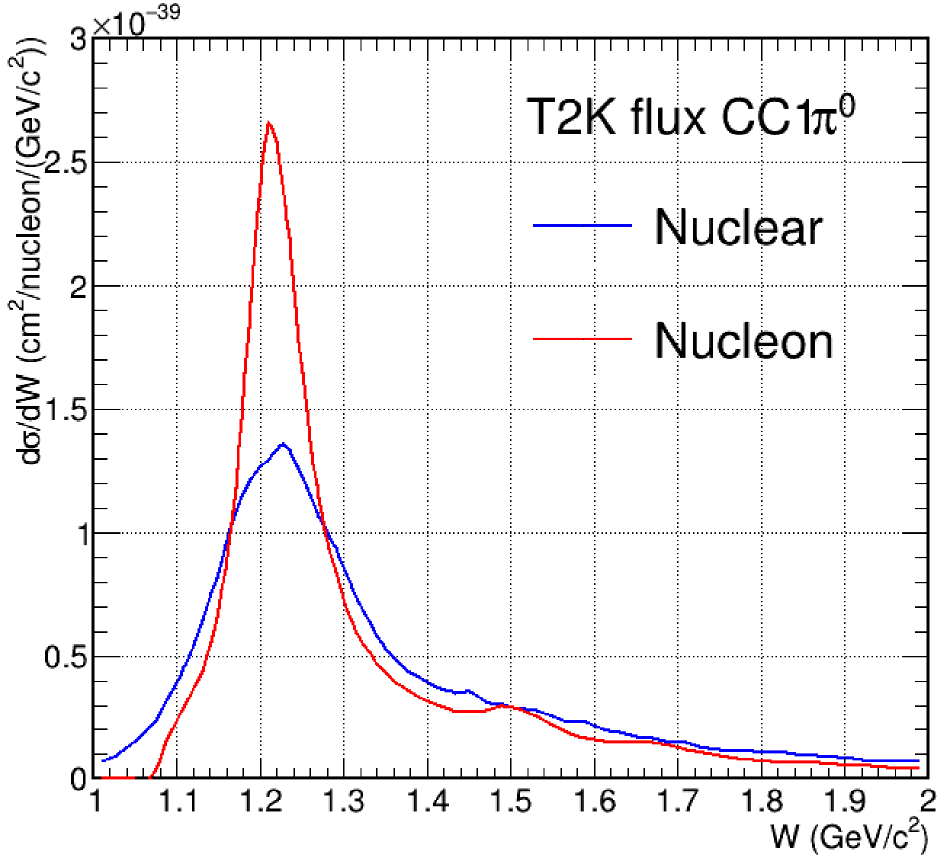


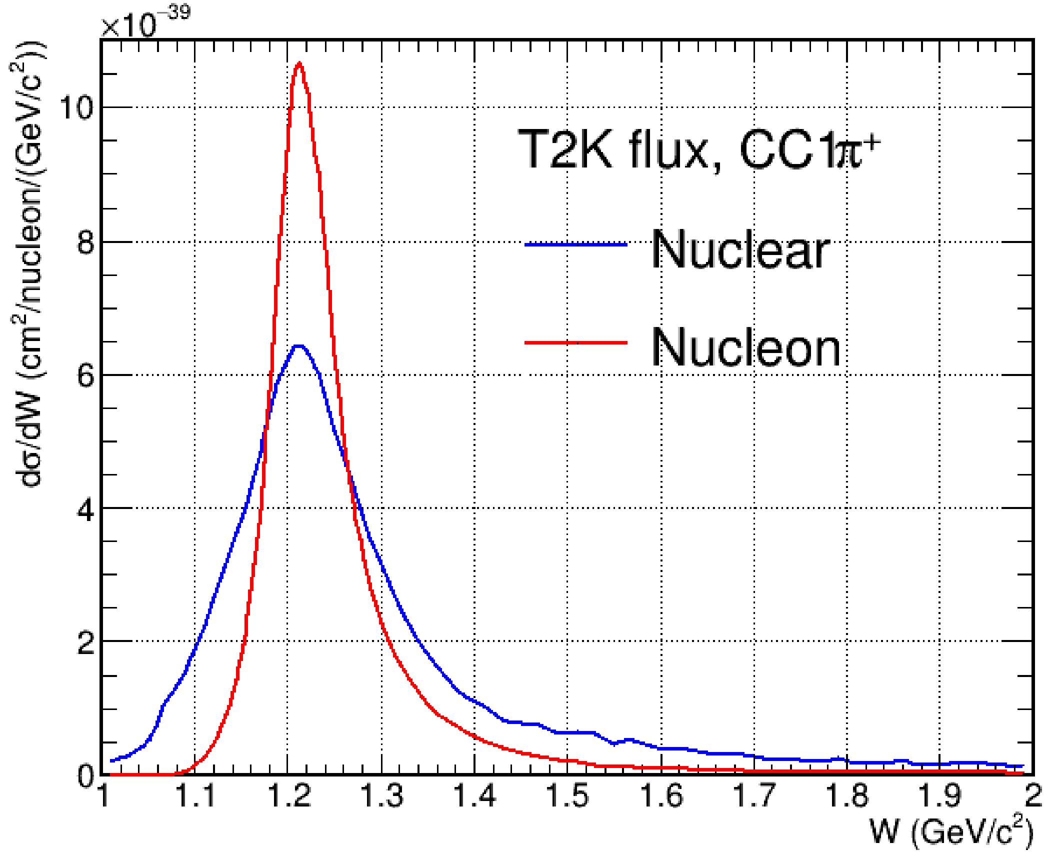


  - See small effects from higher resonances; partly E_ν, partly FSI
  - **Use W < 1.4 GeV data when possible**
- Built on previous work by P de Perio, Phil Rodriguez and Callum
- Have used fitter developed by Patrick, Callum, Luke and myself

Fitting the model

- In nuclear targets we see strong modifications to the hadronic mass

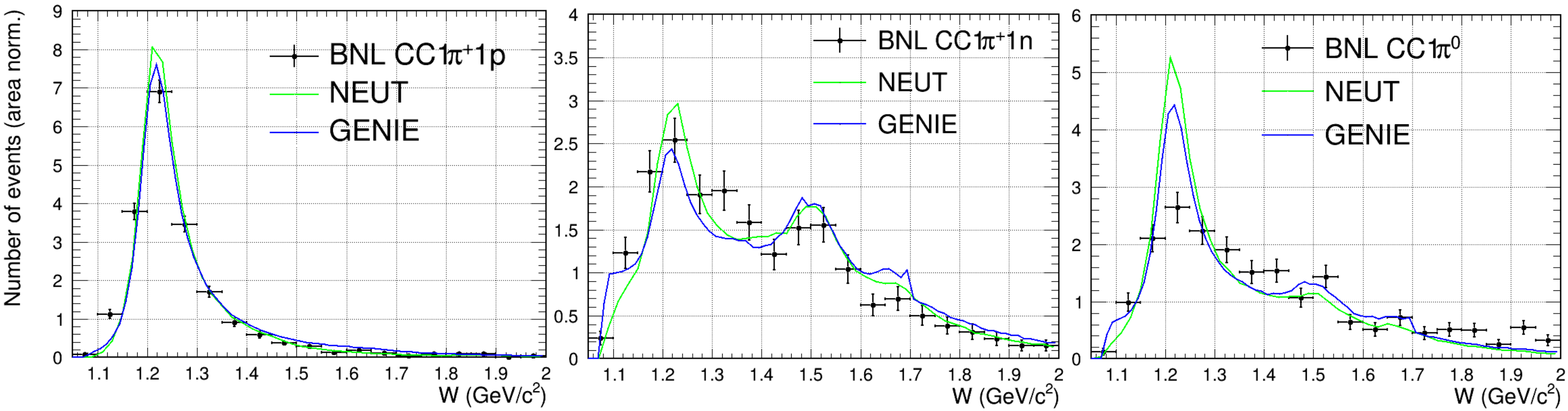




- Come from pion re-interactions and initial state modelling
- At T2K flux, higher resonances (already small) get washed out; Delta peak significantly widened

Bubble chambers

- ANL, BNL and Gargamelle sit in the right E_ν range for T2K
- Have three ν-CC channels from bubble chambers: $CC1\pi^+1p$, $CC1\pi^+1n$ and $CC1\pi^0$ (exists some NC and anti-nu data, but low-ish stats)
- $CC1\pi^+1p$ (I=3/2) pure resonance interaction, dominated by Δ(1232)



- $CC1\pi^+1n$ and $CC1\pi^0$ more complicated resonance, and non-resonant I½
- All clearly see a dominant Δ(1232) peak below W < 1.4 GeV
- Higher resonances more excited at higher E_ν; larger cross-section

Bubble chambers

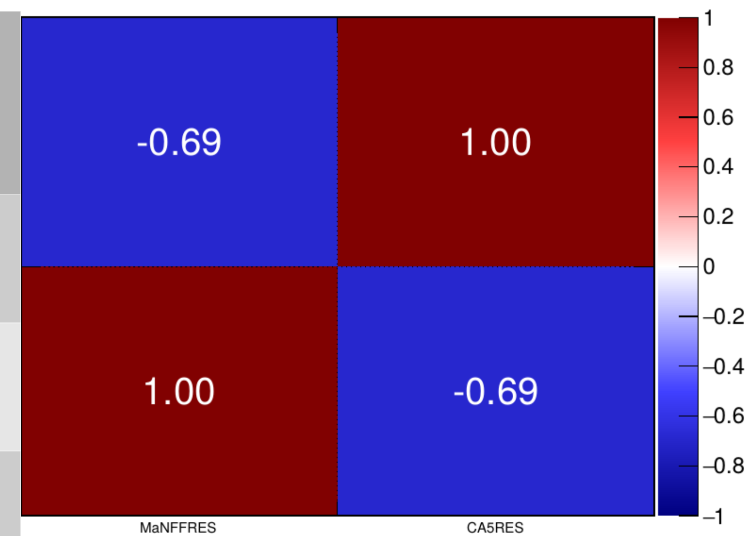
- Three parameters: M_A^{RES}, $C_A^5(0)$, non-resonant I=½ scaling
- Makes good sense to fit M_A^{RES}, $C_A^5(0)$ to W < 1.4 GeV data
  - Either do CC1π^+1p for pure I=3/2 (non-res. background free)
  - **Or** all CC channels, with or without I½ background
  - **Or** can use fit from W < 1.4 GeV on W < 2.0 GeV, with the intent on better constraining I½ background (larger contribution at high W)
- ...However, T2K near detector fit (“BANFF”) cares little about the theory justification and happily fit all 1π parameters to all 1π events…
  - Are we doing external fits solely to give priors?
  - How much do we care about the underlying physics?
  - I think the latter is difficult; it seems like Rein-Sehgal is unable to predict wide range of E_ν cross-sections; acts as effective model?

ANL and BNL CC1π⁺1p

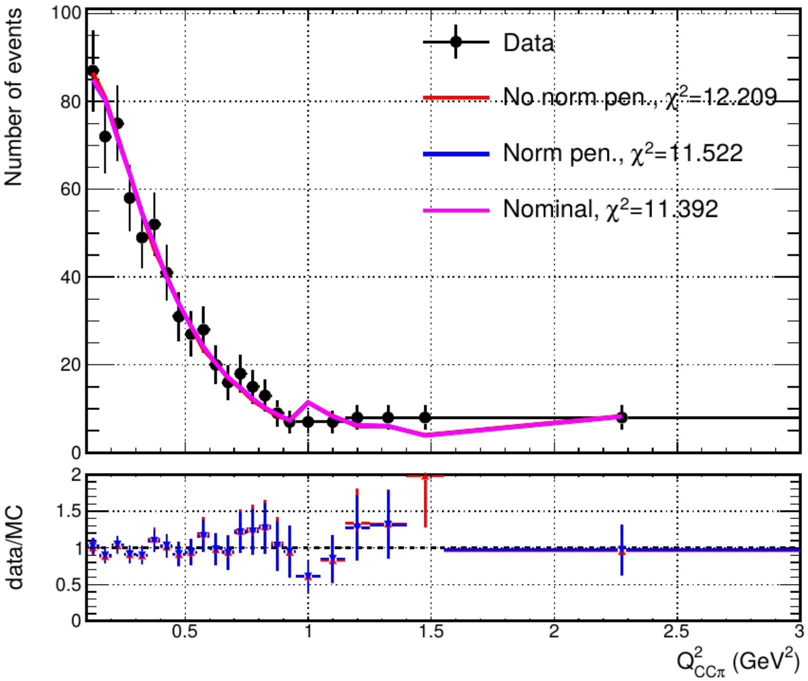
- Simplest fit is to ANL and BNL CC1π⁺1p channels: σ(E_ν) (Phil & Callum corrected), N(Q^2) shape
- Test statistic pdf: Poisson for N(Q^2) and Gaussian for σ(E_ν)

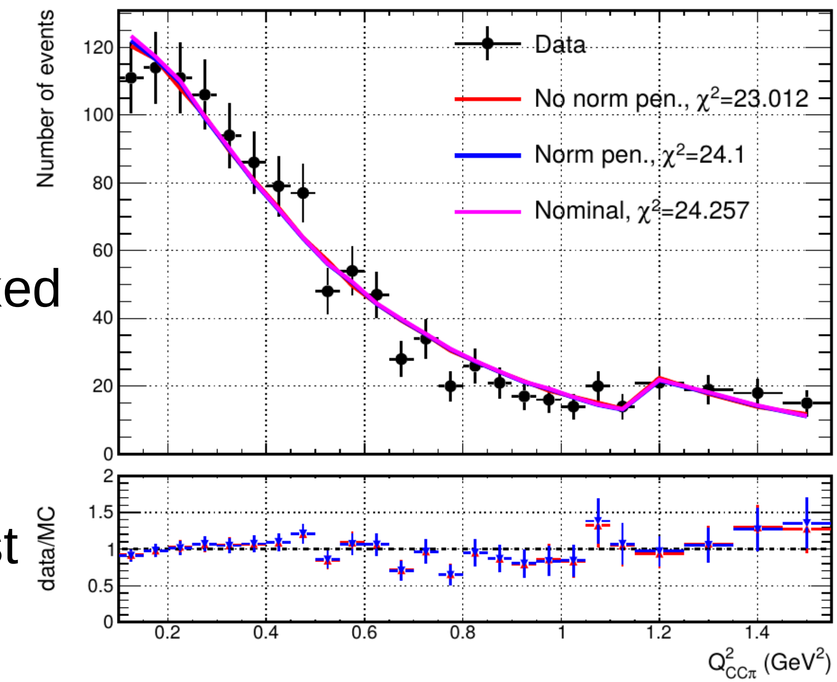
$$\chi^2 = \sum_{Q^2\ \mathrm{expt.}}^{\mathrm{Shape}} \left\{ 2\sum_{i=1}^{N} \left(\mu_i(\vec{x}) - n_i + n_i \log\frac{n_i}{\mu_i(\vec{x})} \right) \right\} + \sum_{E_\nu\ \mathrm{expt.}}^{\mathrm{Abs.}} \left\{ \sum_{i=1}^{N} \frac{\left(n_i - \frac{\mu_i(\vec{x})}{p_{\mathrm{expt}}} \right)^2}{\sigma_i^2} + \left(\frac{p_{\mathrm{expt}} - 1}{\Delta p_{\mathrm{expt}}} \right)^2 \right\}$$

Parameter	Nominal	CC1π⁺1p w/ norm	CC1π⁺1p w/o norm
M_A^{RES}	0.95 ± 0.15	**0.92 ± 0.10**	**1.00 ± 0.08**
$C_A^5(0)$	1.01 ± 0.12	**0.89 ± 0.22**	**0.95 ± 0.09**
ANL norm.	1.00 ± 0.20	**0.94 ± 0.14**	**1.00**
BNL norm.	1.00 ± 0.20	**1.04 ± 0.10**	**1.00**

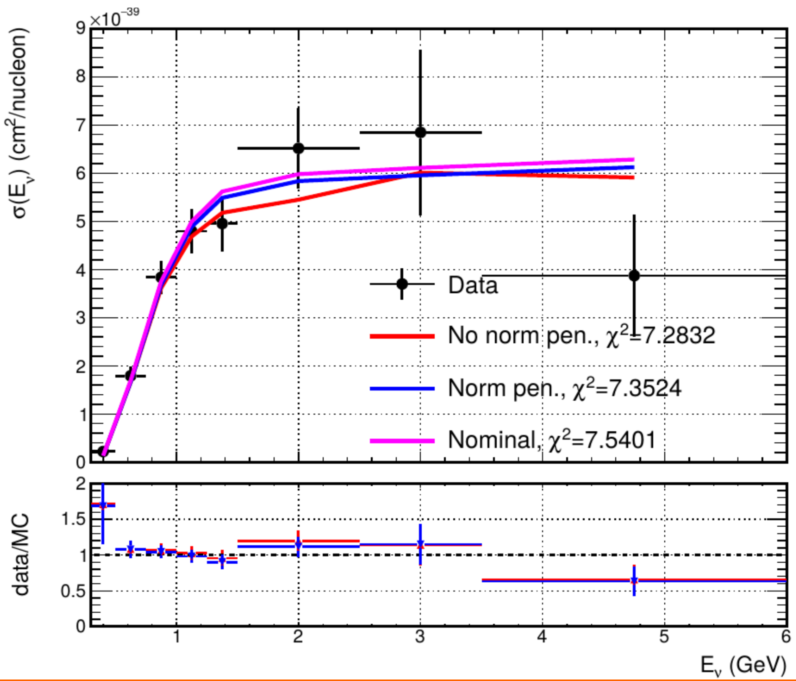


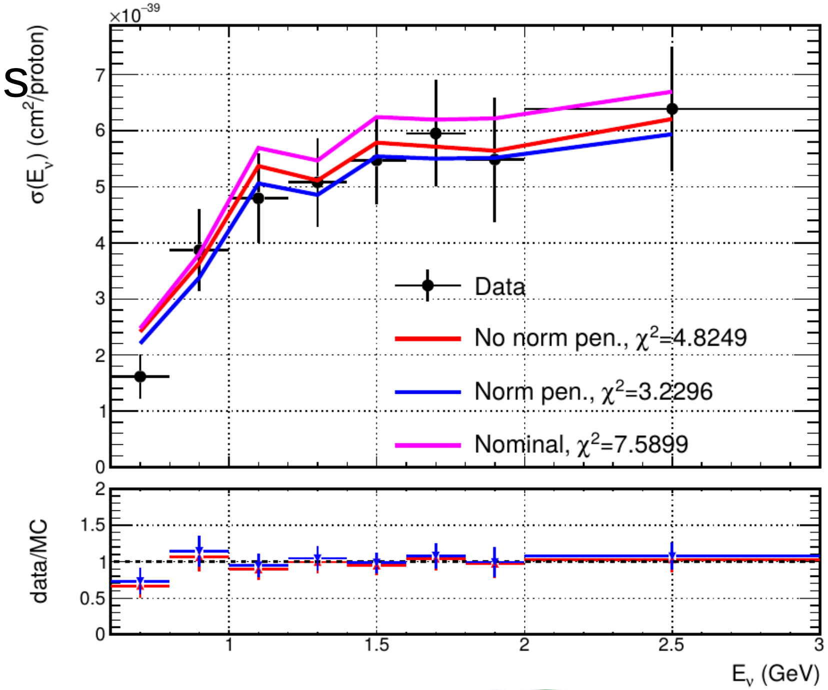
ANL and BNL CC1π^+1p





- See small differences between normalisation penalty and fixed
- ANL barely changes
- BNL sees most improvement
- Nominal parameter set is roughly adequate

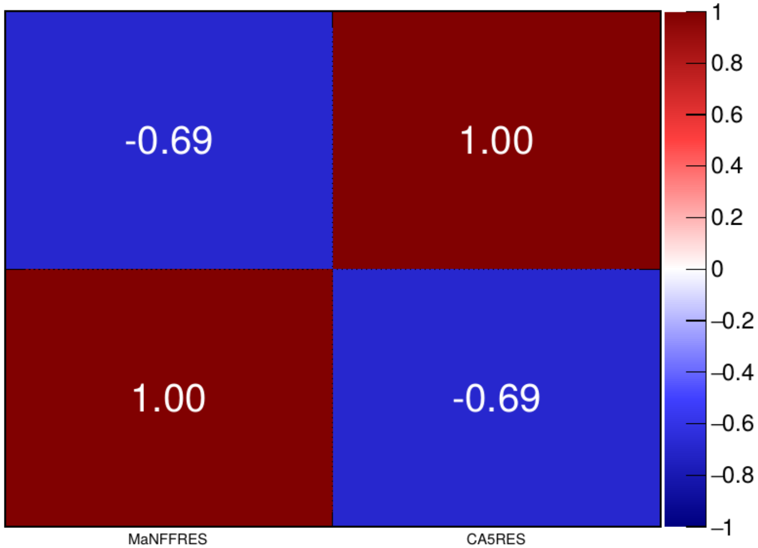




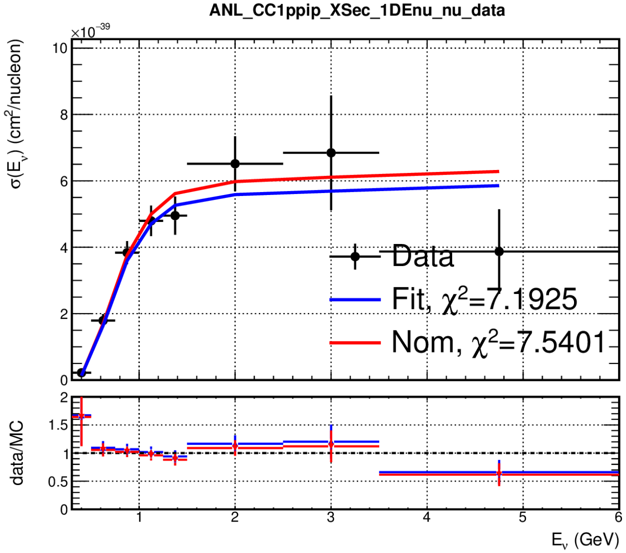
Bubble chambers

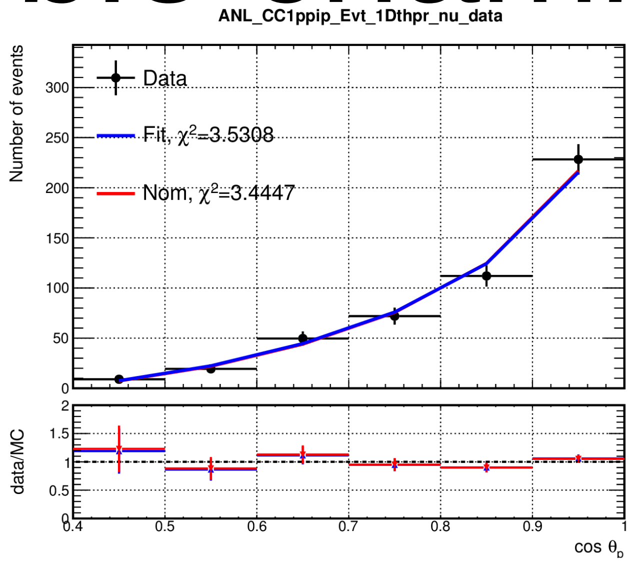
- Moving along, can do a "kitchen sink" $CC1\pi^+1p$, as suggested by Bob Cousins and Louis Lyons at Phystat-nu Tokyo
- Same test-statistic as before, no normalisation

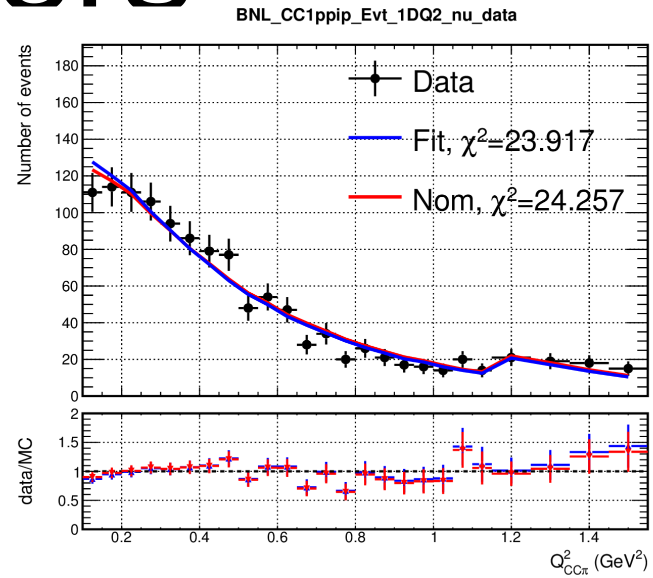
Parameter	Nominal	**$CC1\pi^{\pm}1p$ w/ norm**	**$CC1\pi^{\pm}1p$ w/o norm**	**$CC1\pi^{\pm}1p$ kitchenSink**
M_A^{RES}	0.95 ± 0.15	**0.92 ± 0.10**	**1.00 ± 0.08**	**0.89 ± 0.04**
$C_A^5(0)$	1.01 ± 0.12	**0.89 ± 0.22**	**0.95 ± 0.09**	**1.02 ± 0.05**
ANL norm.	1.00 ± 0.20	**0.94 ± 0.14**	**1.00**	**1.00**
BNL norm.	1.00 ± 0.20	**1.04 ± 0.10**	**1.00**	**1.00**



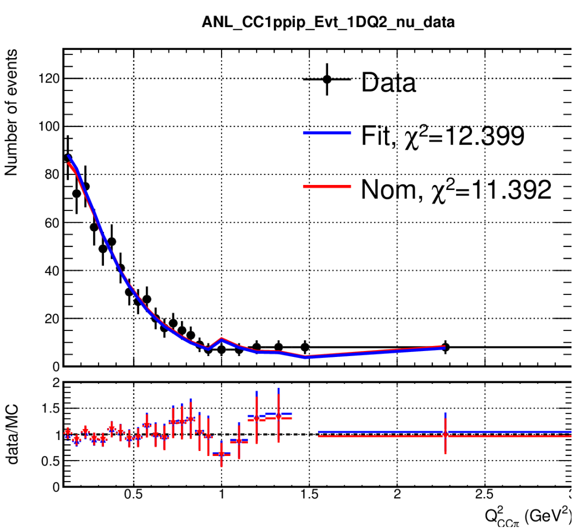
Bubble chambers

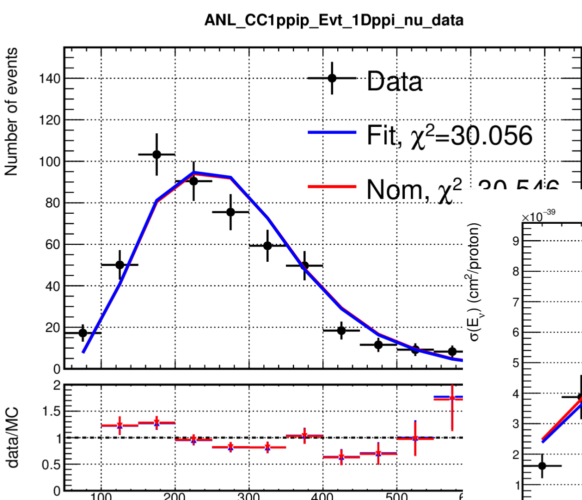


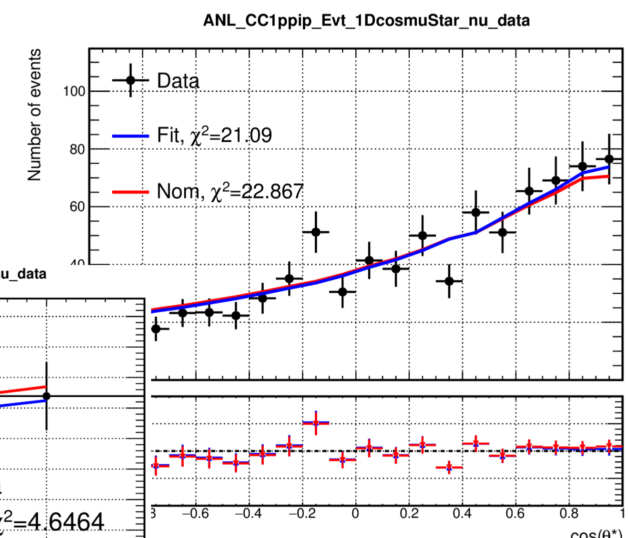


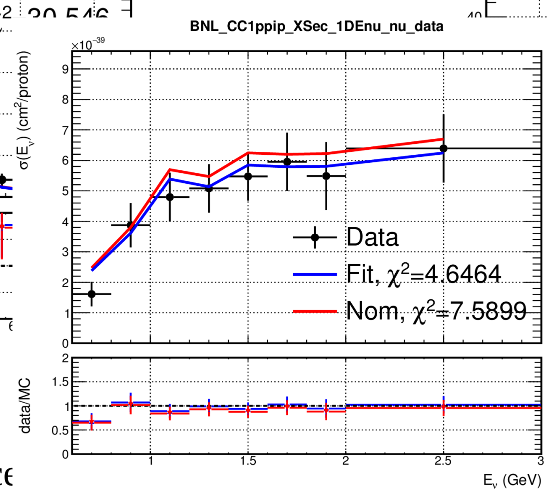


- Adding kinematic distributions allow for less wiggle in parameters, no real surprises; smaller uncertainties





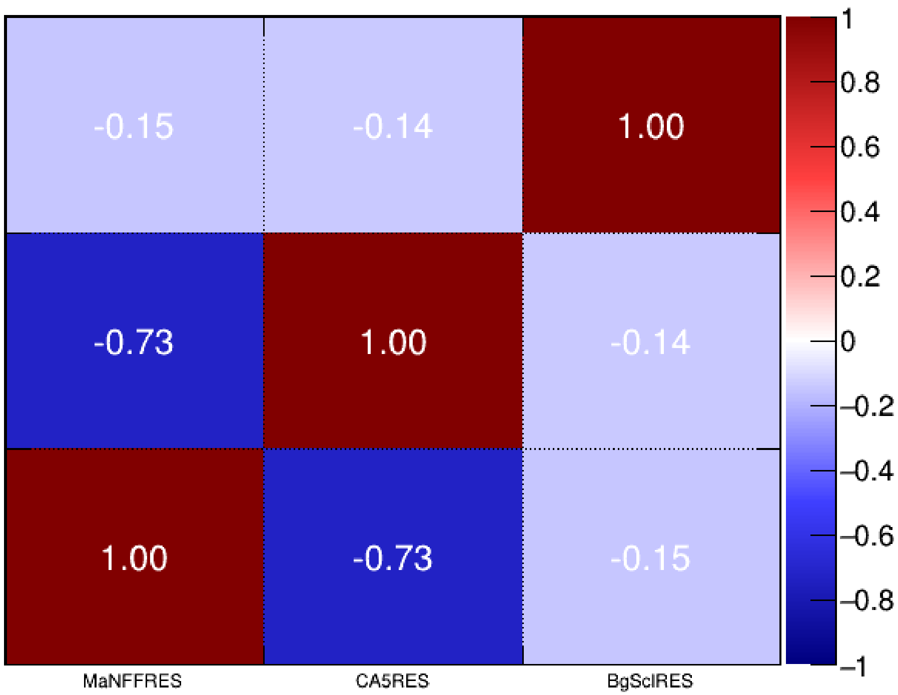


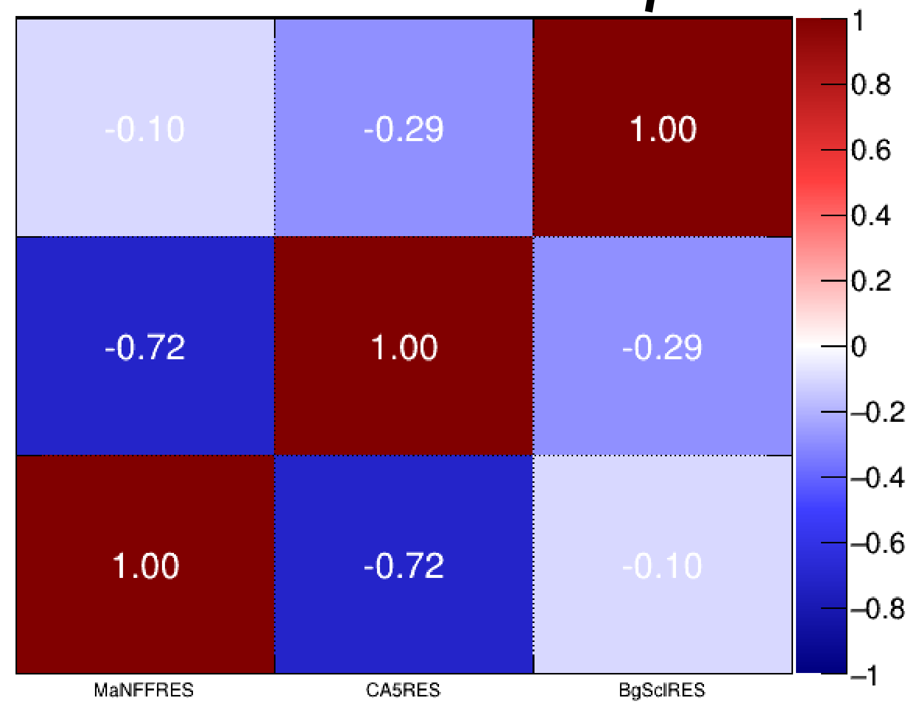


Bubble chambers

- Including all CC channels with W < 1.4 GeV + kitchen-sink

Parameter	Nominal	$CC1\pi^{\pm}1p$ w/ norm	$CC1\pi^{\pm}1p$ w/o norm	$CC1\pi^{\pm}1p$ kitchen	all $CC1\pi$ $\sigma(E_{\nu})$ $N(Q^2)$	all $CC1\pi$ kitchen
M_A^{RES}	0.95 ± 0.15	**0.92 ± 0.10**	**1.00 ± 0.08**	**0.89 ± 0.04**	**0.82 ± 0.08**	**0.87 ± 0.05**
$C_A^5(0)$	1.01 ± 0.12	**0.89 ± 0.22**	**0.95 ± 0.09**	**1.02 ± 0.05**	**1.04 ± 0.12**	**1.18 ± 0.08**
I½ bckgd	1.30	1.30	1.30	1.30	**1.66 ± 0.25**	**1.33 ± 0.26**
ANL norm.	1.00 ± 0.20	**0.94 ± 0.14**				
BNL norm.	1.00 ± 0.20	**1.04 ± 0.10**				





ce Wret

Conclusions on BC

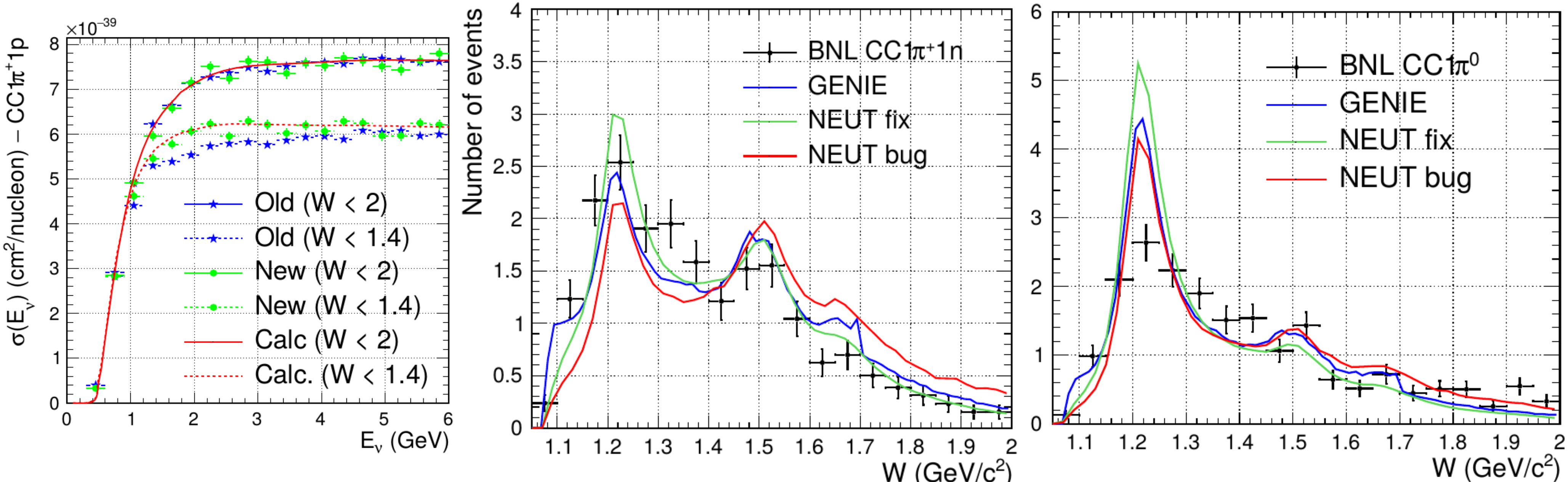
- Have found distributions constraining the kinematics in BC, not seen fit prev.
- See relatively large correlations between M_A and C^A_5; broken by including more kinematic distributions. A bit concerned about Minuit2; MCMC future?
- Not complete body of work:
  - Fit W < 1.4 GeV for M_A and C^A_5, 1.4 < W < 2.0 for I½ and use priors
  - Will have to subtract the ANL data to get 1.4 < W < 2.0 range; also only have BNL CC1π^+1p W < 1.4; rest are W < 2.0 GeV
- There's been a lot of previous work on this (e.g. Adler, Rein-Sehgal, Ravndal, Lalakulich, Graczyk-Sobczyk, Berger-Sehgal, Nieves, Martini, Phil-Callum)
- Generally find M_A = 0.9~1.2 GeV/c^2, C^A_5 (or similar) = 0.95~1.20
  - My fits seem to agree
- Difficult to tell if model accurately predicts all the data; statistical fluctuations are certainly an issue, mismodelling is a possibility too
  - Haven't showed higher E_ν data yet, but joint fit goes horribly wrong
  - Might be higher resonances mismodelled, might be FKR

Bubble chambers, problems

- BNL flux was never properly published, had to dive into KEK paper history database to find NuInt02 proceedings
- BNL n-channel data is only available with W < 2.0 GeV cuts
  - Makes the fit dominated by ANL data in W < 1.4 GeV
- Shape-only for a lot of distributions: no systematics applied
- $CC1\pi^{+}1p$ dominates in statistics so dominates the fit too
  - Many $CC1\pi^{+}1p$ event rates and kinematic variables (e.g. muon direction in CM frame, pion momentum, proton momentum, Adler angles…)
- There's also GGM, “light propane-freon mixture”, with high free-proton density, selected by “kinematical fit”
  - Should still technically see nuclear effects, so excluded here
- Re-binning of N(var) distributions somewhat arbitrarily (N_{evt} > 5)

Bubble chambers, problems

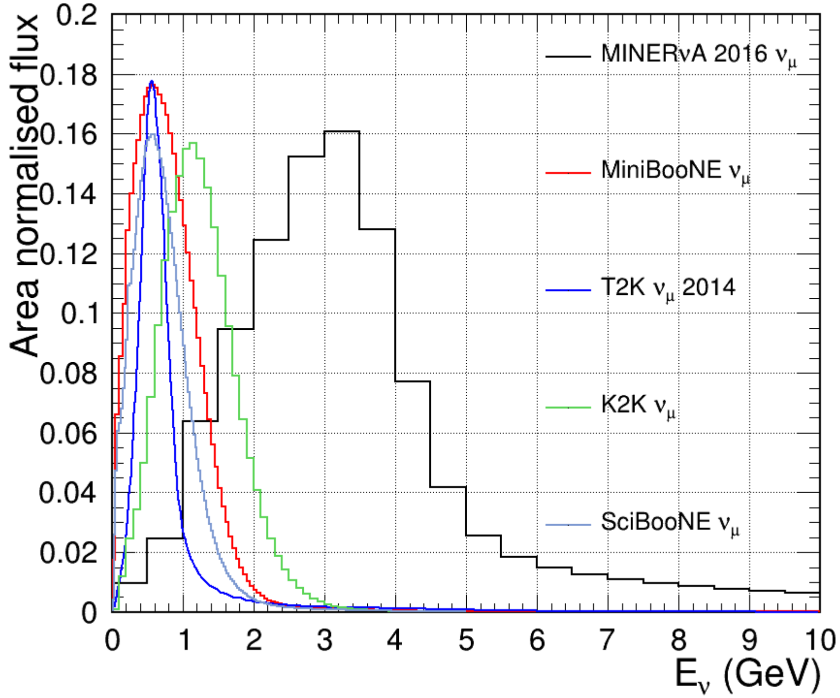
- Low Q^2 bins are problematic – I cut these out
  - Nuclear effects seep in; region which is most sensitive to params
- Bug in NEUT which wrongly sampled the W Q^2 phase space
  - Problem when cutting into W and/or Q^2



- Please contact me if you run into any of the above; all have been fixed/mitigated in one way or another c.wret14@imperial.ac.uk
  - You might have a better fix!

Nuclear experiments

- MiniBooNE, MINERvA and T2K are the main factories
  - CCN/1π^+ (nu), CC1π^0 (nu, nubar), CC coherent
- K2K has CC1π^+/CCQE ratio, NC1π^0 momentum shape
- SciBooNE has NC1π^0 momentum and angle shape
- All sit in an awkward place to constrain the I½ background
  - MINERvA CC1π^0 is best bet, future MINERvA CC1π+
- (New MiniBooNE results?!)
- Attempt to avoid effective model
  - Careful selection of distributions

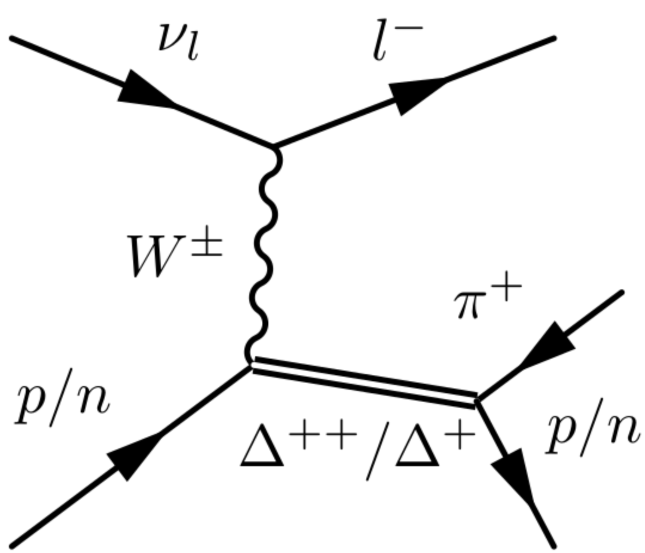


Fitting nuclear data

- Rein-Sehgal model predicts $d\sigma/dWdQ^2$
  - Q^2 is the natural variable to fit in
  - W isn't a bad idea, but is difficult to reconstruct in nuclear

$$Q^2 = -m_\mu^2 + 2\boxed{E_\nu}\left(E_\mu - p_\mu \cos\theta_\mu\right)$$

$$W = \sqrt{m_N^2 + 2m_N\left(\boxed{E_\nu} - E_\mu\right) - \boxed{Q^2}}$$



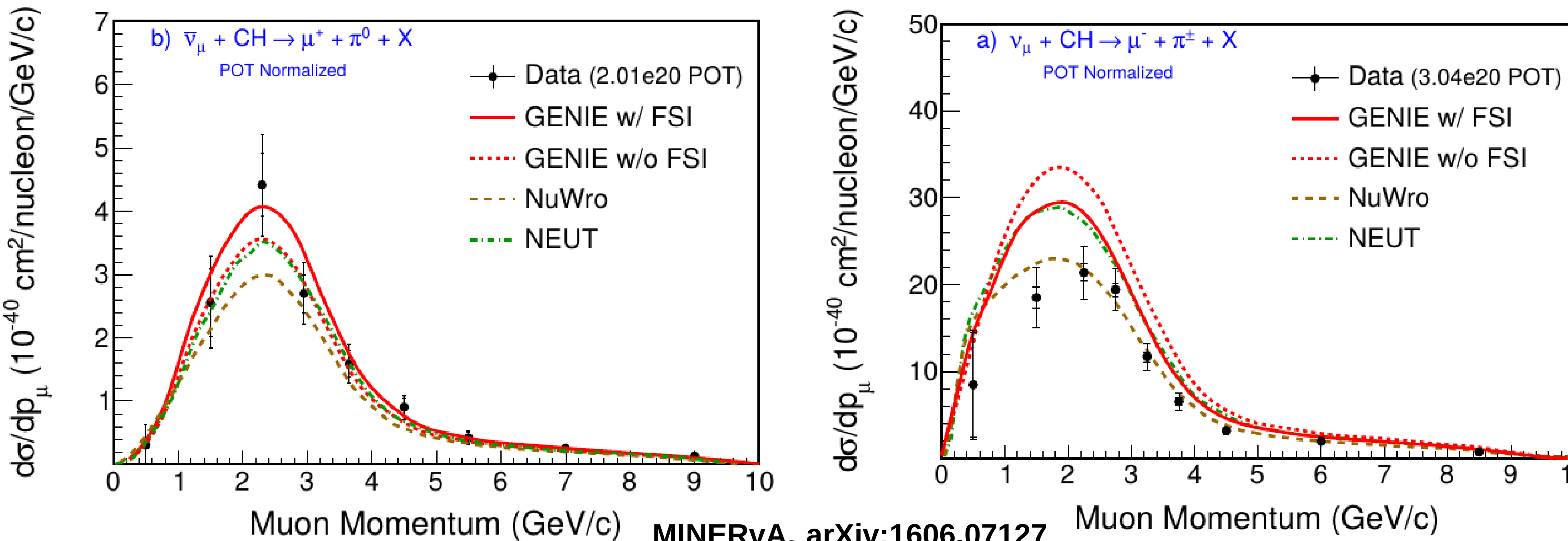
- Q^2 needs E_ν and E_μ and $\cos\theta_\mu$
  - E_μ is (hopefully) an observable
  - E_ν is not; will involve MC dependence in $E_\nu^{obs} \rightarrow E_\nu^{true}$
  - The effect is considerable; both pions and nucleons undergo FSI
- Q^2 and W will rely on Monte-Carlo in experiments; kinematics (hopefully) don't, unless they unfolded over nuclear effects…

Fitting nuclear data

- Fit in T_μ (p_μ) $\cos\theta_\mu$
  - This is the only direct probe of the vertex interaction
  - Relatively “FSI-free” – muons exit nucleus ~cleanly
  - Could potentially agree quite well with predictions using fits from nucleon data
- Getting T_π (p_π) $\cos\theta_\pi$ correct is not quite as easy
  - Use the “vertex” best-fits from muon and apply these to pion variables; should tell you about pion kinematic mismodelling
  - Fit FSI parameters with priors on 1π parameters from fits to muon kinematics
- Hopefully these are not unfolded!

Fitting nuclear data

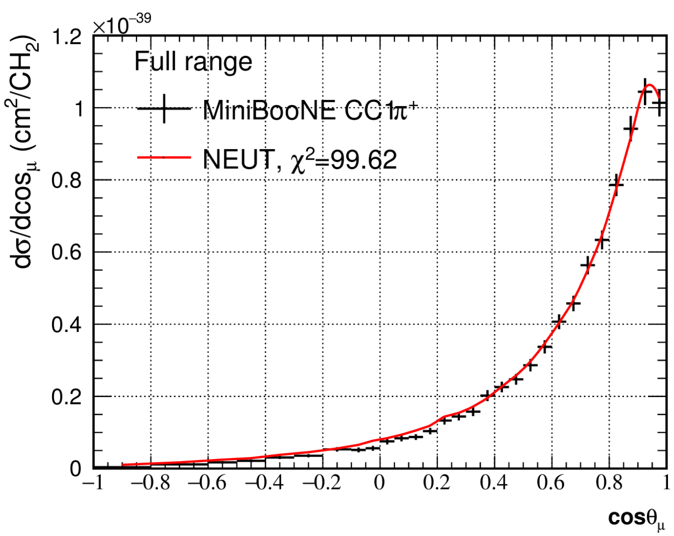
- Difference between CC1π^+ and CC1π^0 can come from non-resonant background, pion propagation, and DIS mismodelling
  - Can gauge impact by confronting CC1π^0 muon data with predictions from fitting to CC1π^+ muon data
  - GENIE, NEUT and NuWro see difficulty in agreeing
  - Generally, if CC1/Nπ^+ is well modelled, CC1π^0 is probably not

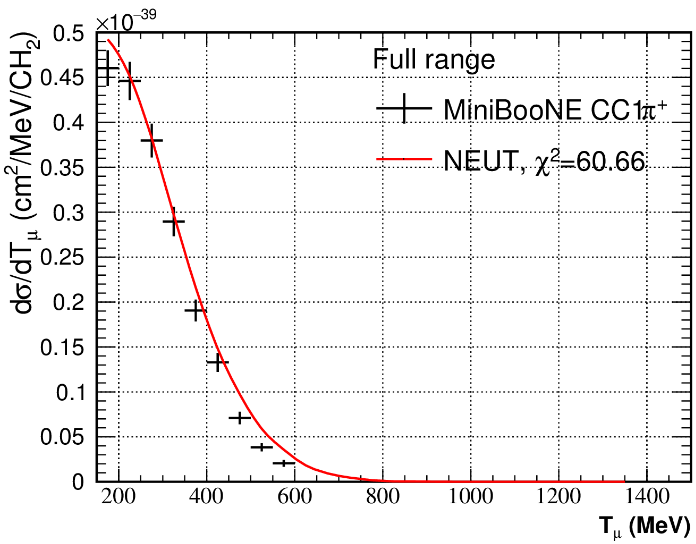


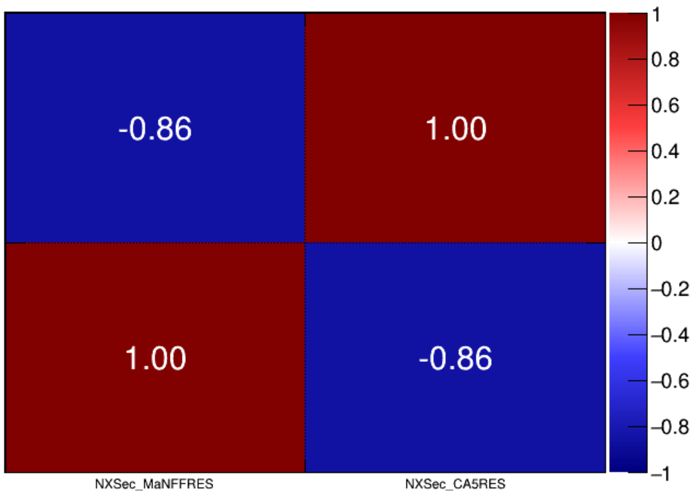
MINERvA, arXiv:1606.07127

MiniBooNE CC1π^+

- Very pure sample, and largest sample on tape (48322)
  - Asks for two Michel electrons (muon and pion contained)
  - All sorts of great distributions; kinetic variables, Q^2 E_ν







Parameter	Nominal	BC CC1$\pi^\pm$1p w/o norm	BC CC1$\pi^\pm$1p kitchen	MiniBooNE 2D μ CC1$\pi^\pm$
M_A^{RES}	0.95 ± 0.15	**1.00 ± 0.08**	**0.89 ± 0.04**	**0.88 ± 0.03**
$C_A^5(0)$	1.01 ± 0.12	**0.95 ± 0.09**	**1.02 ± 0.05**	**0.87 ± 0.03**

MiniBooNE CC1π^+ problems

- No covariance matrix
- Data looks suspicious, stats err?
  - Unfolding issues?
- Some confusions on W cut:

The absence of a Δ mass constraint also means that the $\pi^+ + N$ invariant mass, which is dominated by the Δ resonance, can be measured. Fig. 9 shows the reconstructed

...

$m_{\pi+N}$ is shown in Fig. 15. Beyond reconstructed masses of 1350 MeV/c^2, the population of misreconstructed events begins to dominate, so a cut is implemented to remove these events. Fig. 16 shows the improvement

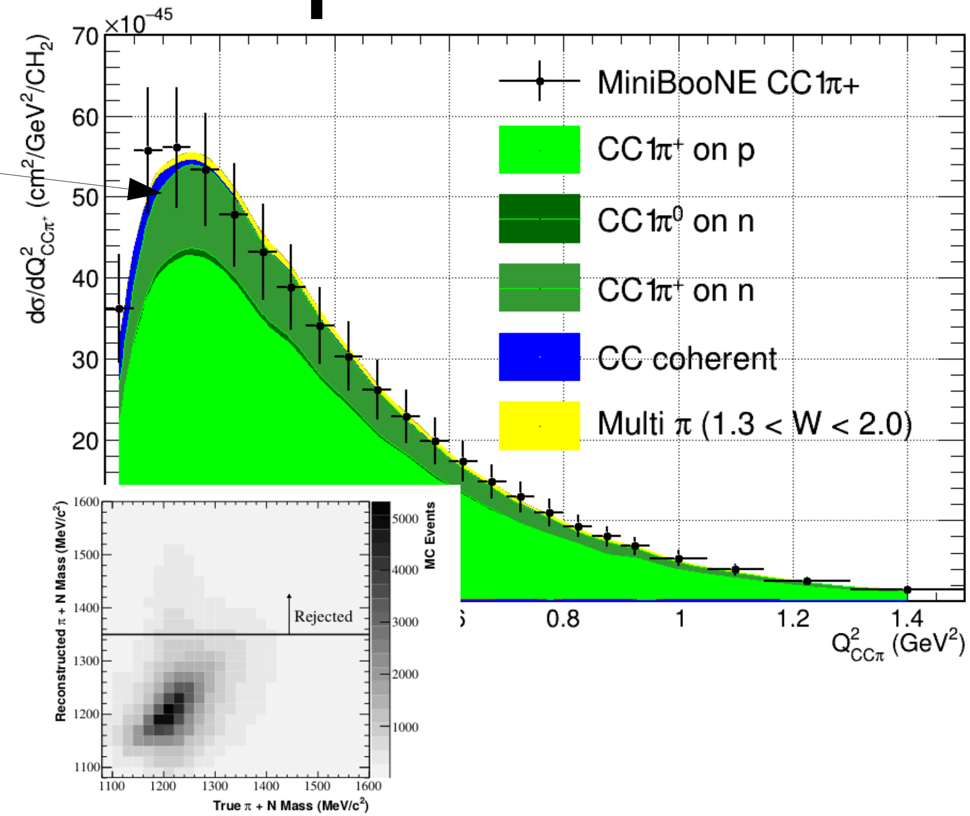


FIG. 15: The Monte Carlo m_{pi+N} distribution shows a correlation between the reconstructed and true distributions at low mass. At high reconstructed mass, the distribution is dominated by events with a high energy muon misidentified as a pion. A cut is placed at 1350 MeV/c^2 to remove these events.

- Mike replied about it:

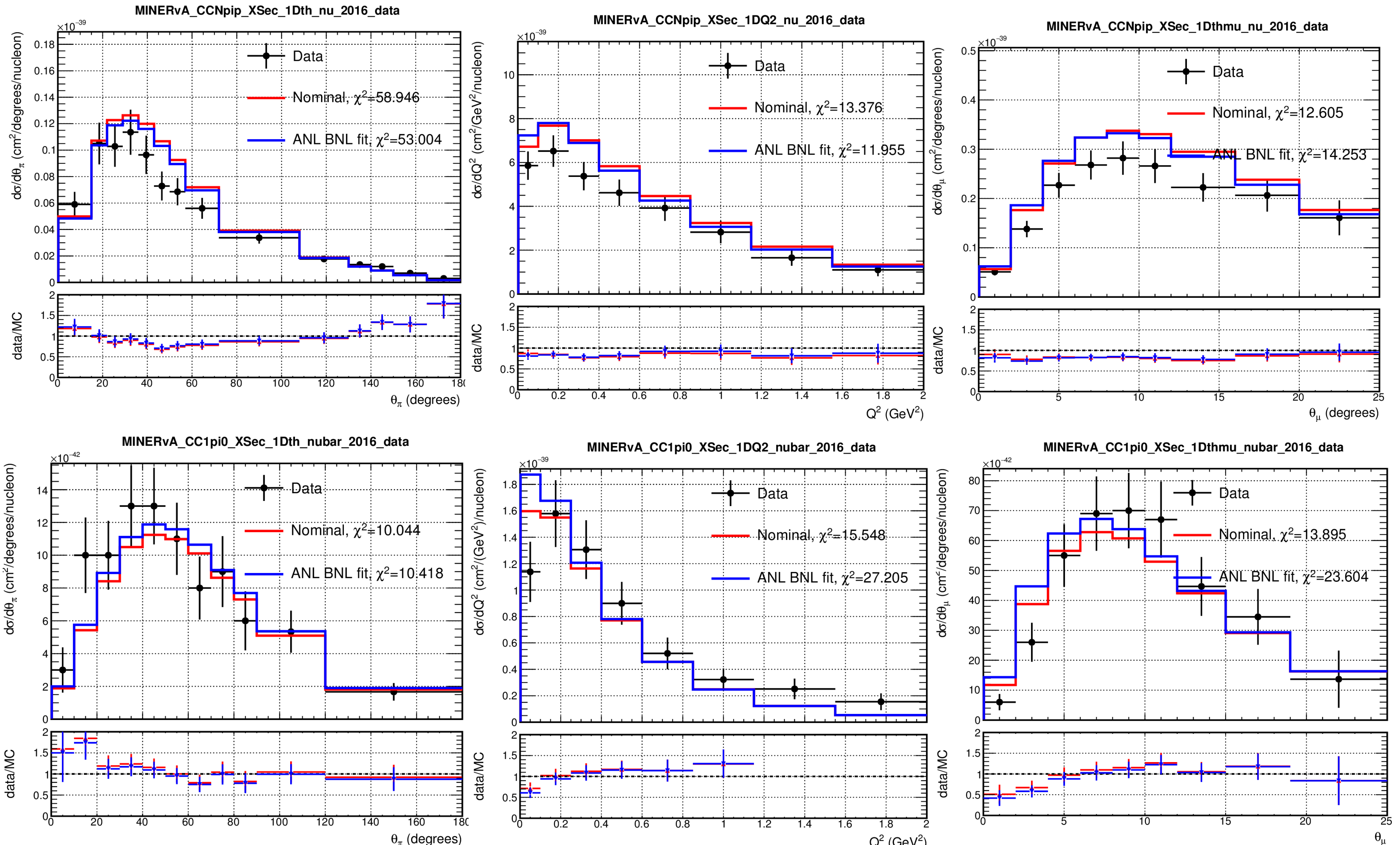
On 01/07/15 17:14, Michael Wilking wrote:

> Hi Clarence,
>
> Sorry for the slow reply. I am doing a lot of traveling at the moment.
>
> Indeed this issue can be confusing. For the publication, there is a cut on W, as stated, but we then efficiency correct (Minerva does not do this). This means we are essentially using the Nuance model to fill in the reconstructed high W events. This is needed because most of the events that are reconstructed at high W are really just muons misidentified as pions (this is also the reason for imposing the cut in the first place).

- **The largest CC1$\pi^\pm$ data-set is NUANCE above W ~ 1.35 GeV...**

Predicting nuclear using nucleon

- Can use previous nucleon fits to predict nuclear cross-sections



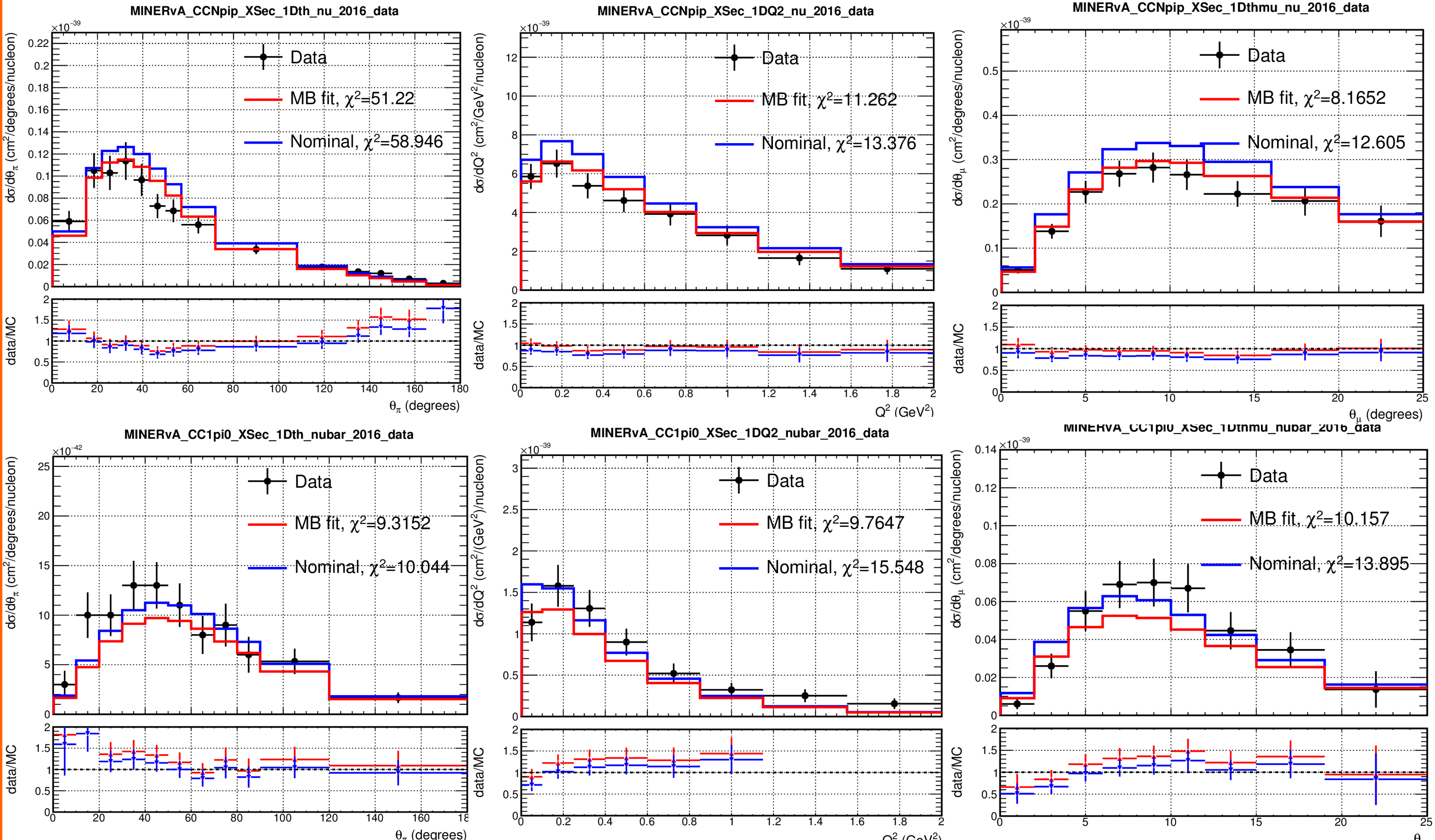
Predicting nuclear using nucleon

- Doesn't do all too well; nominal is sometimes better
- See fairly large differences in the best-fits from nucleons; only shown one of many variations here to predict the nuclear data
- MINERvA CC1π^0 will see a large non-resonant background contribution and DIS components, not constrained from nucleons

- Will (hopefully) improve once I'm happy with the nucleon fits
- Alternatively, can feed nucleon priors into a nuclear fit
  - Will probably need to inflate errors from nucleons for prior

Predicting nuclear using nuclear

- Can use prediction from MiniBooNE muons to predict MINERvA



Predicting nuclear using nuclear

- Doesn't look too bad: χ^2 improves in every distribution
- Good place to start for a global nuclear fit
- Brings up another problem that Patrick also sees
  - MINERνA covariance seems too put very strong constraints on the shape of distributions rather than the normalisations
  - Very difficult to judge goodness of fit by eye
  - Is this actual effect in data or unfolding side-effect?
- Combining MiniBooNE and MINERvA doesn't seem to come for free in the pions either

Nuclear experiments, problems

- MiniBooNE lacks covariances; enforces fairly tight constraints on the normalisation of the distributions
- MINERvA's covariances seem to instead enforce strong constraints on the shape of the distribution rather than the normalisation
- Some broken covariances (e.g. MINERvA CC1π^0, CC coherent)
- Not always clear from one read what event selection is
  - MINERvA CC1$\pi^\pm$ uses a Michel tag, effectively making it CC1π^+; only briefly mentioned. Large difference if you use abs(PID) = 211 rather than PID = 211 for signal
  - MINERvA CCN$\pi^\pm$ data release; also never explicitly states highest pion selected. Not clear from publication if restricted phase space used throughout selection or only for plotting p_μ $\cos\theta_\mu$
  - MiniBooNE CC1π^+ W < 1.35 GeV cut, previously mentioned
- Probably need internal checks of cross-section before publishing

Nuclear conclusions

- A global fit is much harder in the nuclear environment
- Experiments might have done slightly disagreeable things
  - Is the data actually data? How much is MC dependent?
- Need to be careful in selecting data-sets to minimise chance of model becoming effective, or letting experiment MC determine fitted MC
- Data releases are moving in the right direction
  - Multiple distributions, more correlations
  - Less unfolding, more observables; don't be afraid of low acceptance
  - Making an anti-ν cross-section? Publish the ν contamination, and even anti-ν + ν cross-sections; don't rely on your MC or sideband too much
- I probably won't be using any nuclear data in my fits other than gauging error and $\Delta\chi^2$ inflation; subject to change
- Much more data to come; MINERvA, NovA, T2K, LAr experiments

Vision for the future!

- Rein-Sehgal beautifully models a lot of resonances, but there certainly are short-comings and approximations
- Get a “full Rein-Sehgal” model into generators that predict ejection angles from all resonances (Minoo)
  - Run this through a generator with nuclear effects on top
  - Any improvements? Nucleus washes out fine distributions?
- Start looking into alternative descriptions, e.g. Nieves Delta excitation, Ghent group
- **Need to help our experiments to produce useful data releases; once it's analysed it's analysed**
- **Need to get theorists on experiments**

Shameless advertising

- We learnt a lot at Phystat-nu Tokyo: buffs like Bob Cousins, Louis Lyons, Michael Betancourt gave some advice
  - “Fit everything that you're given”
  - “You can't do much without correlations”
  - “If they unfolded, they screwed you over”
  - “I've never unfolded in my life and I hope I never have to!”
- If you're in/close to the US, I'd recommend the Fermilab equivalent, Phystat-nu Fermilab (it's $35!)
  - https://indico.fnal.gov/conferenceDisplay.py?ovw=True&confId=11906

PhyStat-ν Fermilab 2016

Community to-dos

- Build up a comprehensive open library of x-sec results
  - Similar to the old Durham bubble chamber data-base (only bubble chambers, and doesn't include all BC dists by miles)
  - Include comments on how much we trust the data and why; what problems we've found (let's not re-invent the wheel...)
- Make comparisons with models and/or generators on an open framework for anyone to look at
  - Important that experimenters know difference between GENIE, NEUT, NuWro, etc rather than thinking they know the differences and then publishing (MINERvA has unfortunately done this)
- Keep pushing for folded data with detector smearing matrices!
  - Aka "fold your MC to data, don't unfold your data to MC"
  - Stephen Dolan, Callum, Kendall, Kevin et al are advocating at T2K
  - **Many novel cross-section experiments coming up: let's make them useful for as long as possible**

Community to-dos

- Experiments seem interested in multiple-generators, which is great! Full production in GENIE, NEUT and NuWro (GiBUU?)
  - Would ease future joint oscillation analyses
  - But, needs to be more of us committed to generator work
  - And, more effort for experiment to write general framework
- **Need to make generators interesting to students…**
- Pushing for more exposed NEUT
  - Tutorials, documentation, much more commented code
- Hope for more meetings like this; the more we talk the better

General conclusions

- Spent a lot of time O(1yr) getting to know the data and NEUT
- We're now moderately good friends: road-map in place to mitigate for issues in the data and model degeneracies
- Similar to what ATLAS MC covered yesterday, LEP → Tevatron:
  - Use bubble chamber data to constrain fundamental interaction; much trust because of reconstruction
  - Propagate to reasonable nuclear distributions; choose to minimise possible MC dependence in data
  - Try to explain the observed differences, inflate error?
- More pion models in generators would be great; we know quite little about how FSI and initial state affect observed kinematics

Thanks!

What's in the kitchen sink?

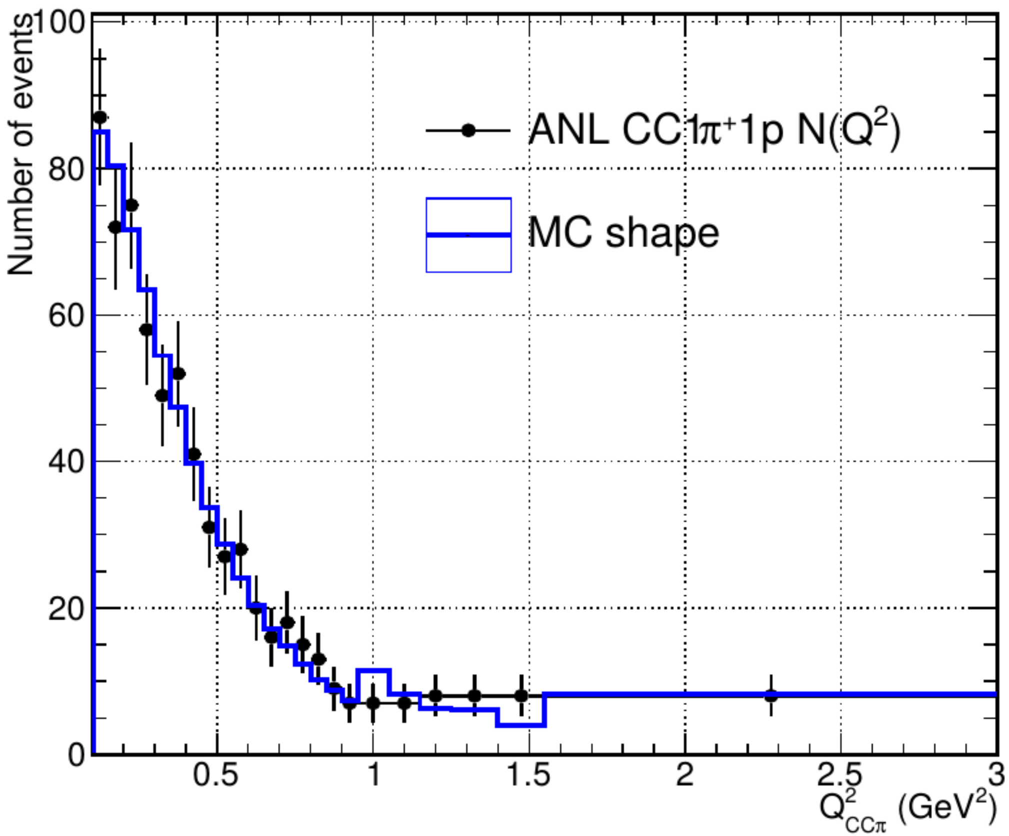
- Only W < 1.4 GeV data included:
- ANL CC1ppip
  - $\sigma(E_\nu)$, Q^2 ($d\sigma/dQ^2$ or $N(Q^2)$), $\cos\theta^*_\mu$, p_π, θ_{prot}, φ_{Adler}, $\cos\theta_{Adler}$
- ANL CC1pi0
  - $\sigma(E_\nu)$, $N(Q^2)$, $\cos\theta^*_\mu$
- ANL CC1npip
  - $\sigma(E_\nu)$, $N(Q^2)$, $\cos\theta^*_\mu$
- BNL CC1ppip
  - $\sigma(E_\nu)$, $N(Q^2)$

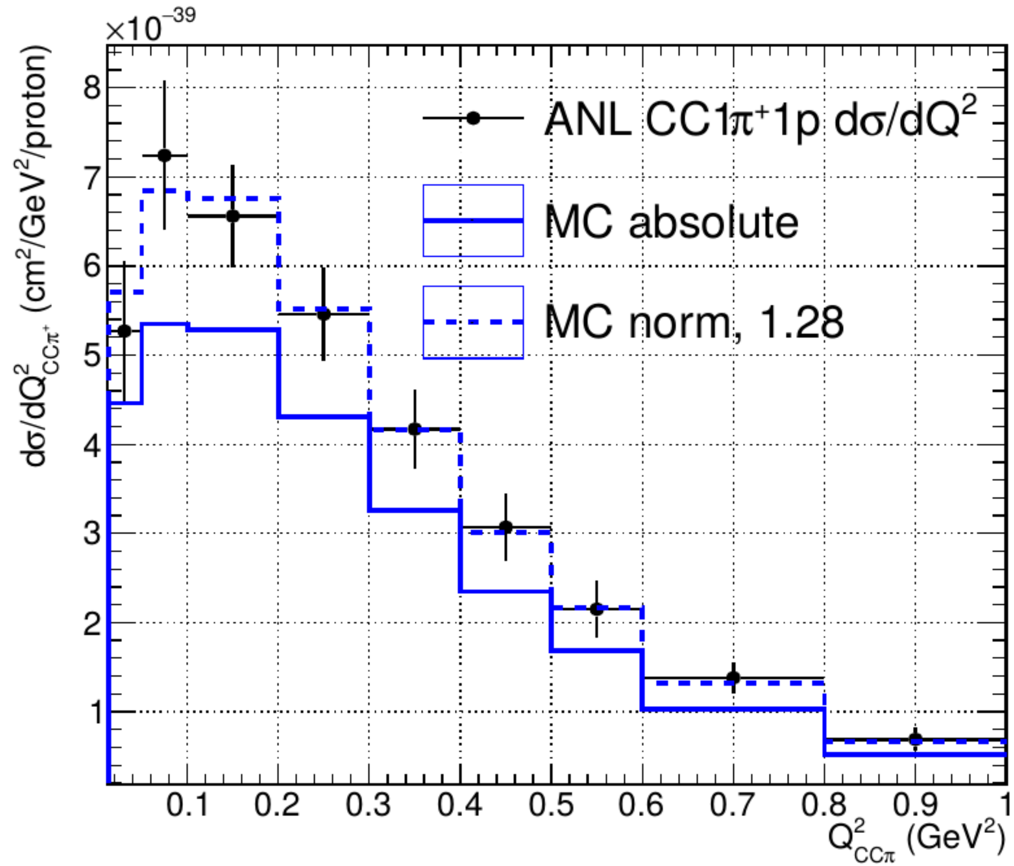
What's in the nuclear data?

- MiniBooNE
  - CC1pi+: Enu, Q2, Tmu cosmu, Tpi cospi, Tmu, Tpi, Q2 Enu, Enu Tpi, Enu Tmu
  - CC1pi0: Enu, Q2, cosmu, cospi, ppi0, Tmu
  - CC1pi+/CCQE(-like): Enu
  - NC1pi0: (nu, nubar, nu+nubar in both modes): ppi0, cospi0
- MINERvA
  - CC1pi+ (old):
  - CC1pi0 (nubar new, old)
  - CCNpi+ (new, old)
- K2K
  - CC1pi+/CCQE
  - NC1pi0
- SciBooNE
  - NC1pi0
- T2K
  - CC1pi+ H2O
  - CC1pi+ CH coming
  - CC1pi0 coming

Concern about Q2 shape-only bias

- A lot of information available in Q^2 distributions, we but miss good chunks because ANL and BNL only published $N(Q^2)$, not $d\sigma/dQ^2$
- NEUT over-estimates MiniBooNE and MINERvA $d\sigma/dQ^2$ but underestimates nucleons

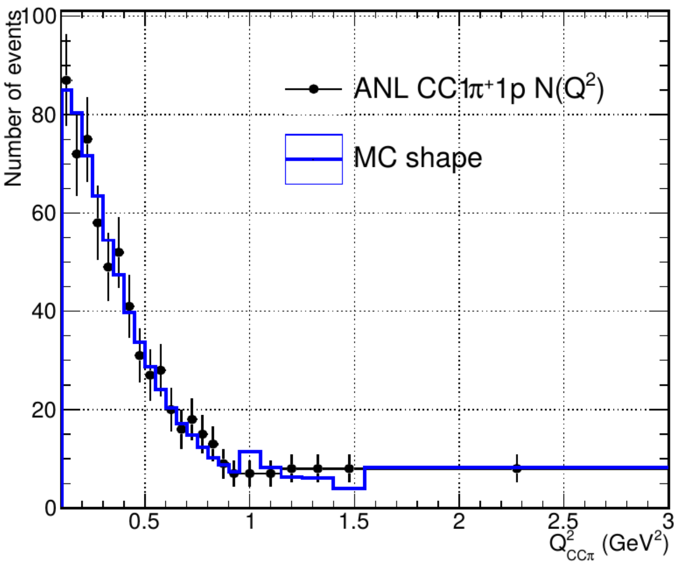


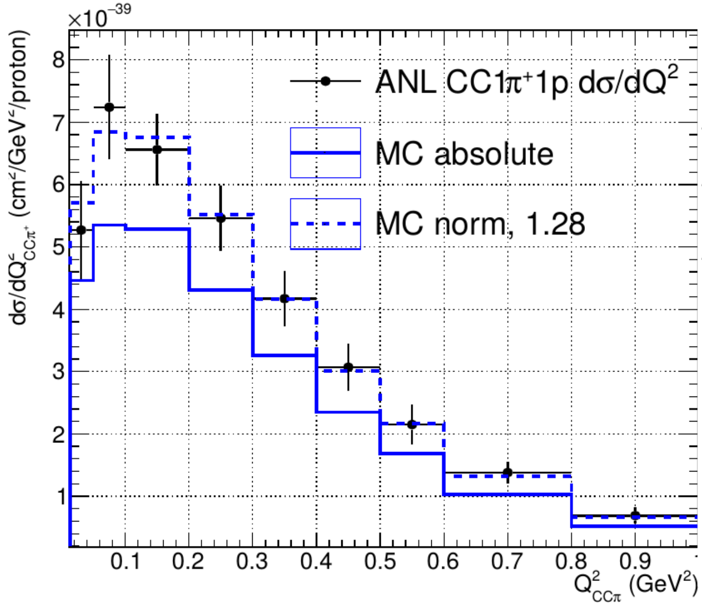


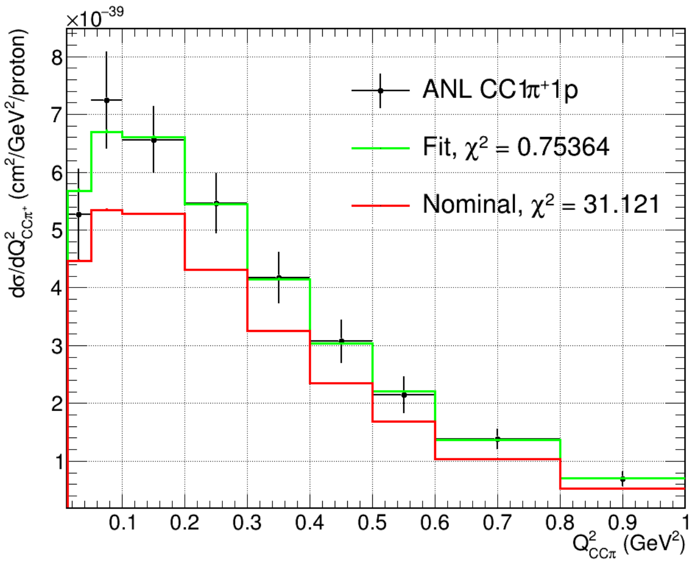
- Try fit only ANL $d\sigma/dQ^2$ instead

ANL dσ/dQ^2 fit

- A lot of information available in Q^2 distributions, we but miss good chunks because ANL and BNL only published N(Q^2), not dσ/dQ^2
- NEUT over-estimates MiniBooNE and MINERvA dσ/dQ^2 but underestimates nucleons







- Try to fit only ANL dσ/dQ^2; M_A = 1.03±0.08 (0.95±0.16), C_A^5 = 1.14±0.16 (1.01±0.25)
- Change in M_A and C_A^5 almost perfectly becomes a normalisation change...
- Would have had nuclear predictions if computers cooperated...