NUISANCE tutorial

NeUtrino Interaction Systematics ANalyser by Comparing Experiments
NeUtrino Interaction Synthesiser Aggregating Constraints from Experiments
NeUtrino Interaction Systematics from A-Neutrino sCattering Experiments

https://nuisance.hepforge.org/




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T2K WS, Toronto
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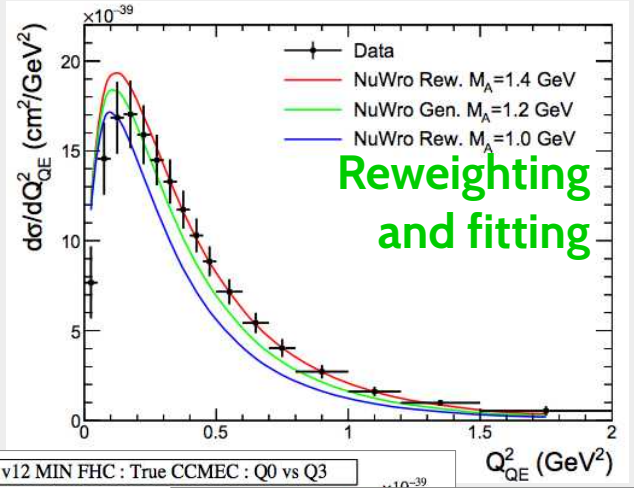
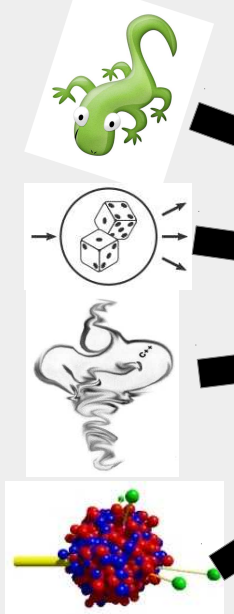
The low-down of NUISANCE

- Interfaces with neutrino interaction generators to give you event distributions
- Confront with data
- Play-time!

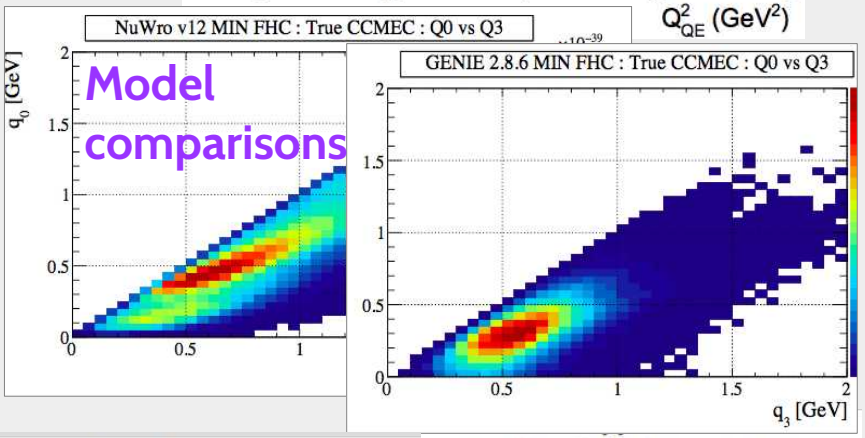
Event selection, cross-section scaling, reweight

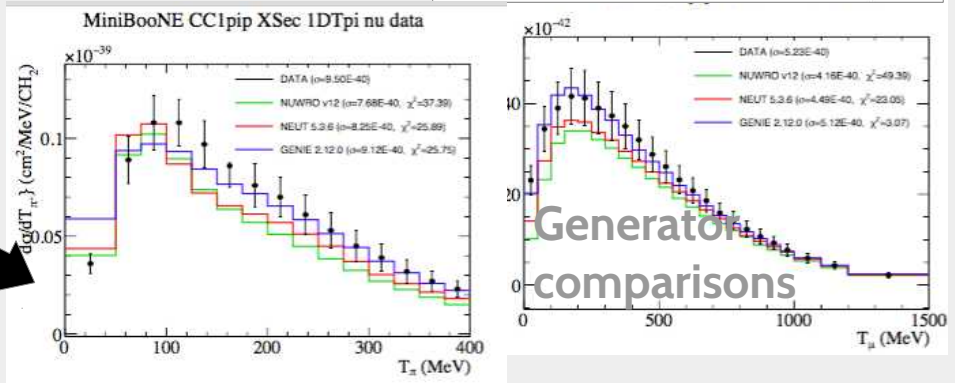


Particle kinematics, interaction targets, etc



Common event format

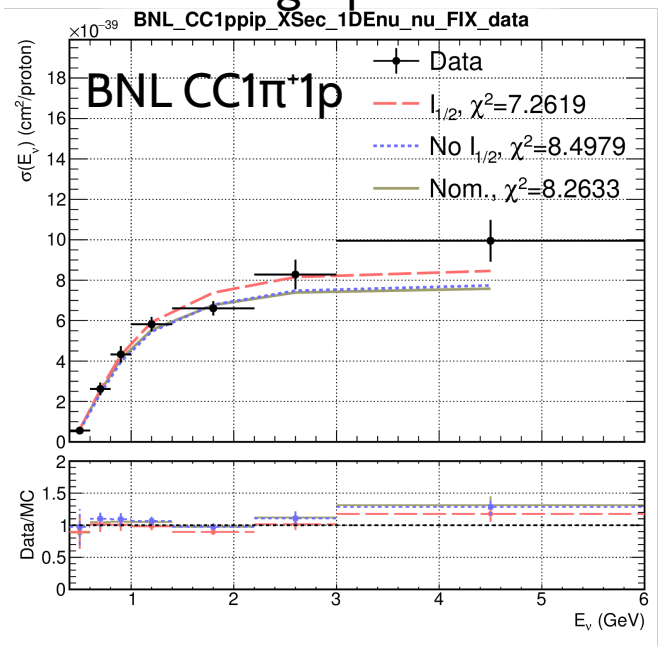




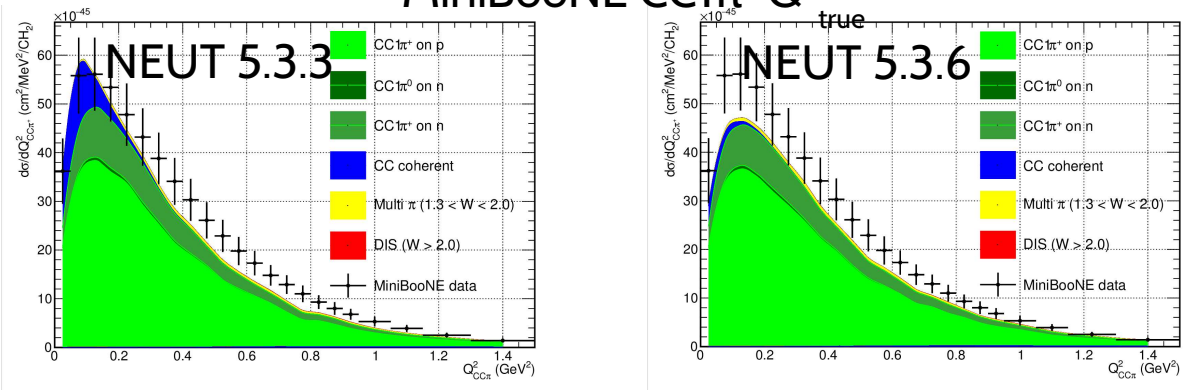
The low down of NUISANCE

- Developed for NEUT model selection and giving OA central values and uncertainties
  - Grew to support all generators and reweighting libs

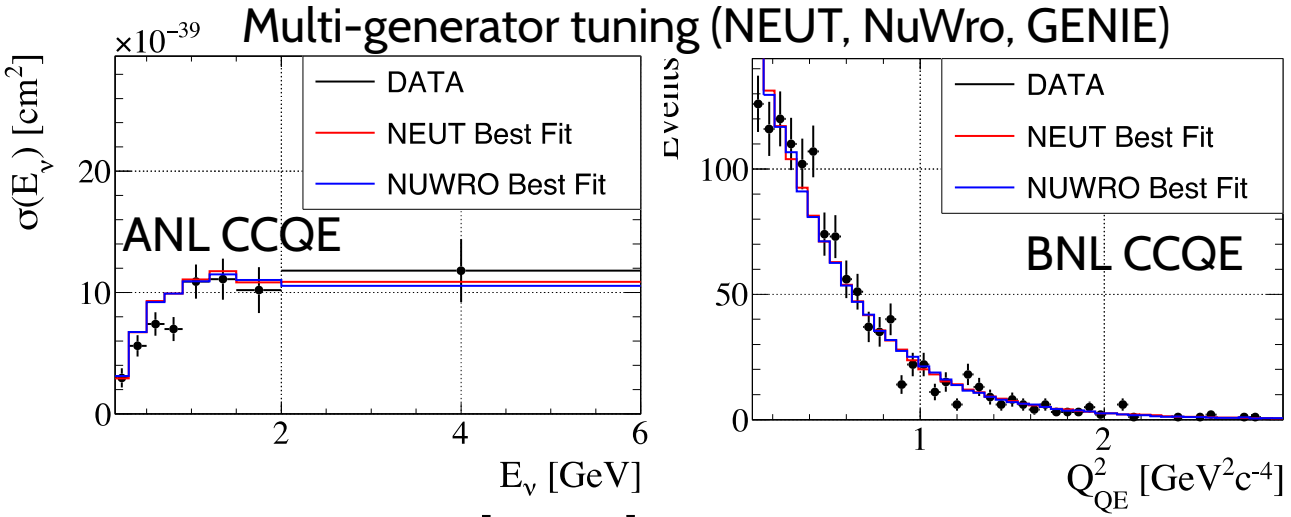
Tune all single pion channels



MiniBooNE CC1π⁺ Q^2



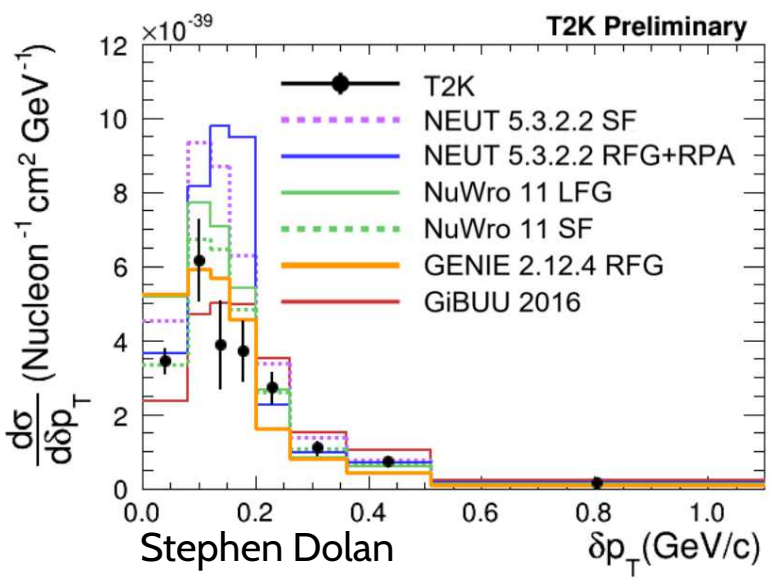
Multi-generator tuning (NEUT, NuWro, GENIE)



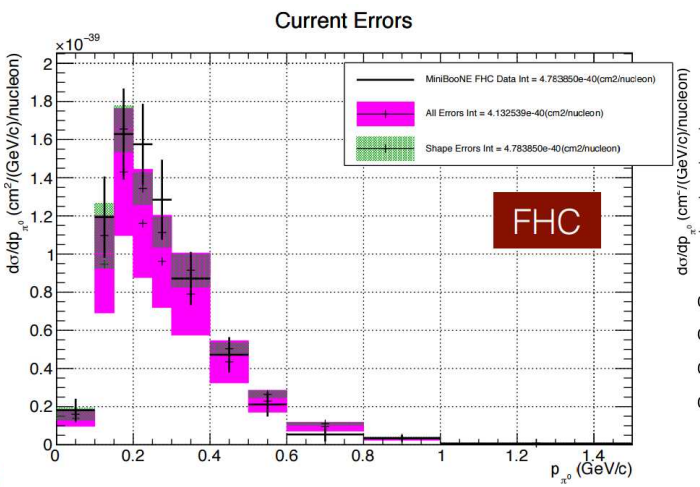
- **<u>Lots of fun for for the cross-section analyser! :D</u>**

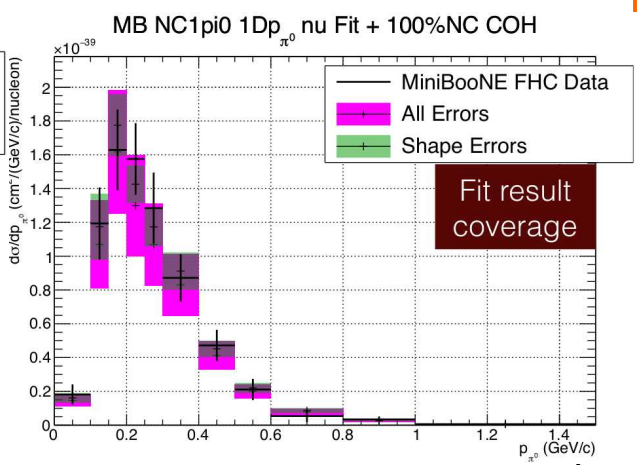
How can NUISANCE help you?

- Challenge the systematics in your analysis
  - Vary 1σ of M_A^{QE}: what does that actually mean?
  - Dominated by an interaction which you don't have a sideband? Get informed from external data?
- What do previous measurements say?
  - Tensions? Interesting distributions? Where do the models differ?
  - Become comfortable with the effects of theory on distributions



Stephen Dolan





Pierre Lasorak

This tutorial

- Patrick set up a virtual box with all the software built
- MC files are also available from us

- We'll start with NEUT and MiniBooNE FHC generated events
- Will probably only have time for simple Data/MC comparisons
- Might have time for a quick fit
- How to make flat trees
- Some details about the framework

- Callum and I will walk around and help out

- Need 10GB+ free space, 3GB+ of RAM
- Please give feedback! Always room for improvement

Setting up the virtual box

- If you don't have Oracle VirtualBox set it up:
  - Get it here
- In the meantime, download the virtual disk image:
  - Get it here
- And also download MiniBooNE FHC NEUT 5.3.3 events:
  - Get it here
- Start up the VirtualBox, give about 3GB ram, mount disk image:
  - Linux Other 64-bit
  - Instructions here
  - Password is **neutrino**
- If you finished fast, check our website

Ok, let's make some nuisance

- Make a shared folder between host and guest
  - On host: `cd ~ && mkdir Share`
  - On host in VirtualBox window: Devices → Shared folders → Settings → "+" box → Add Share folder
  - On guest: `cd ~ && mkdir Share && sudo mount -t vboxsf Share ~/Share`
  - On guest: `ls ~/Share`
- Set up a shared clipboard, Devices → Shared Clipboard → Bidirectional
- Source the environments
  - Open terminal
  - `cd ~/NUISANCEMC && source setup.sh`
- You've now sourced ROOT, GENIE, NuWro, NEUT, their reweighting libraries, T2KReWeight, NIWGReWeight and all dependencies

Getting NUISANCE

- `cd ~/NUISANCEMC/nuisance/branches`
- Get NUISANCE v2r0
  - `source getnuisance.sh v2r0`
  - This will take some time because making on VM is a little slow
- After this is done, do
  - `cd ~/NUISANCEMC/nuisance/branches/v2r0 && source setupnuisance.sh`
  - This sources all of the environment variables, from generators to T2KReWeight to ROOT
- Whilst NUISANCE is building, let's just look a little at how the build system is set up...

NUISANCE versions and build

- NUISANCE is under git version control
  - `git branch -a` and `git tag` are your friends!
- Our build system is CMake, which operates under the principle of making a build directory and generating Makefile(s) for your specific system
  - Won't need for this particular tutorial, here for completeness
  - Make the makefiles with define flags `-D`, e.g. `-DUSE_NEUT=1 -DUSE_GENIE=0`
  - `cd ~/nuisance && mkdir build && cmake ../ -DUSE_YOUR_DEFINES`
  - There should now been generated makefiles
  - `make && make install`

Running NUISANCE

- NUISANCE has a few parameter settings (`parameters/config.xml`) which can be overridden by `-q` when running executables

- Uses "card files" for user input, e.g. what experiment distributions to use, where the output MC is located, what systematics should be varied

- link explaining card files on our wiki

```
- sample SampleName Generator:Location
- parameter ParameterName cent min max step
  FREE/FIX
```

- I'll use the simple card-file format rather than xml

Card files

- Get a list of sample names

```
- nuissamples MiniBooNE
- nuissamples | wc -l
```
gives 216 samples, woop

- Let's choose MiniBooNE CCQE Q2 cross-section for neutrino

```
- vim example_ccqe.card
- sample MiniBooNE_CCQE_XSec_1DQ2_nu
  NEUT:~/Share/MB_numu_fhc_533Aut_merge.root
```

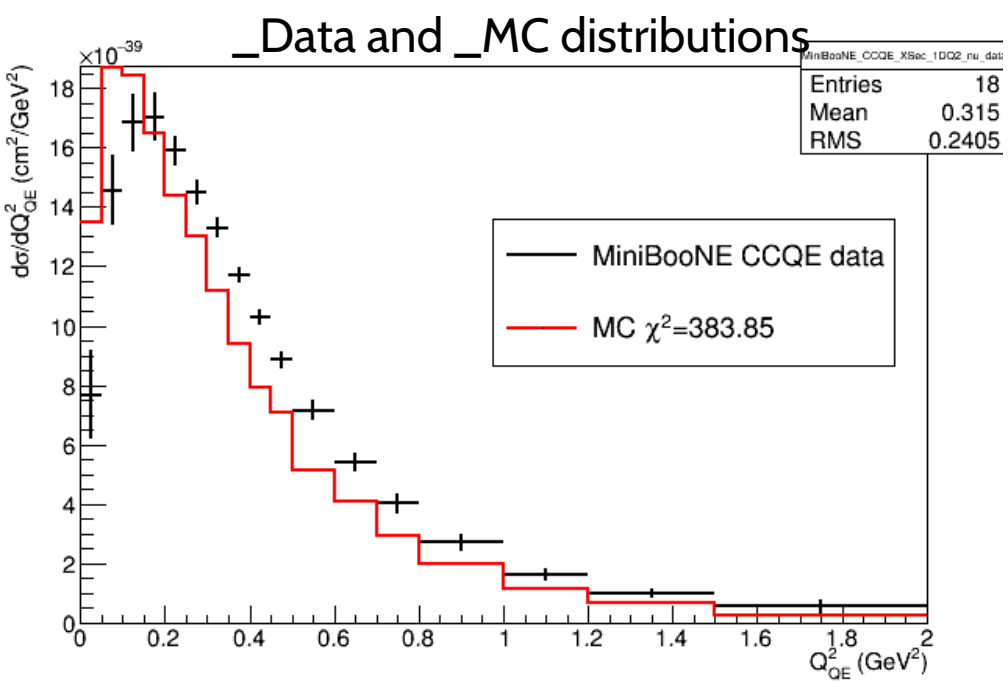
- Now let's produce the data/MC comparison

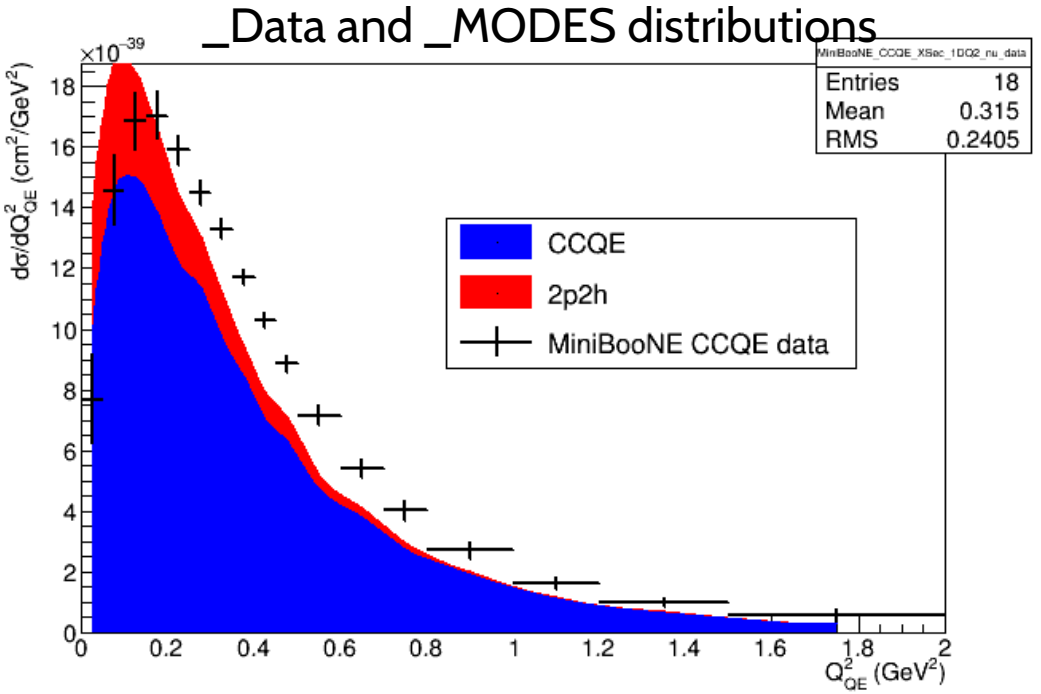
```
- ./nuiscomp -c example.card -o
  my_MiniBooNE_Q2_test.root -q
  MAXEVENTS=50000
```

- `-q MAXEVENTS=50000` says we only load the first 50k events, just a matter of speed. **Always use as many as possible!**

Inspecting the output

- `_Data` and `_MC` are the two important distributions
- Also saves the mode-by-mode distributions
- That's pretty much as simple as it gets!





Varying systematics

- Let's try varying some systematics for MiniBooNE CCQE
- This requires a bit more digging into the generators :(
- `vim ~/NUISANCEMC/neut/branches/neut_5.3.3_Eb_patch/src/reweight/NSyst.h`
- Differs from generator to generator
- Let's vary MaQE between -1 and +1 in steps of 0.5
- NEUT requires VecFFQE 2 (RFG) to be set too

Varying systematics

- Add this to the card file in any place

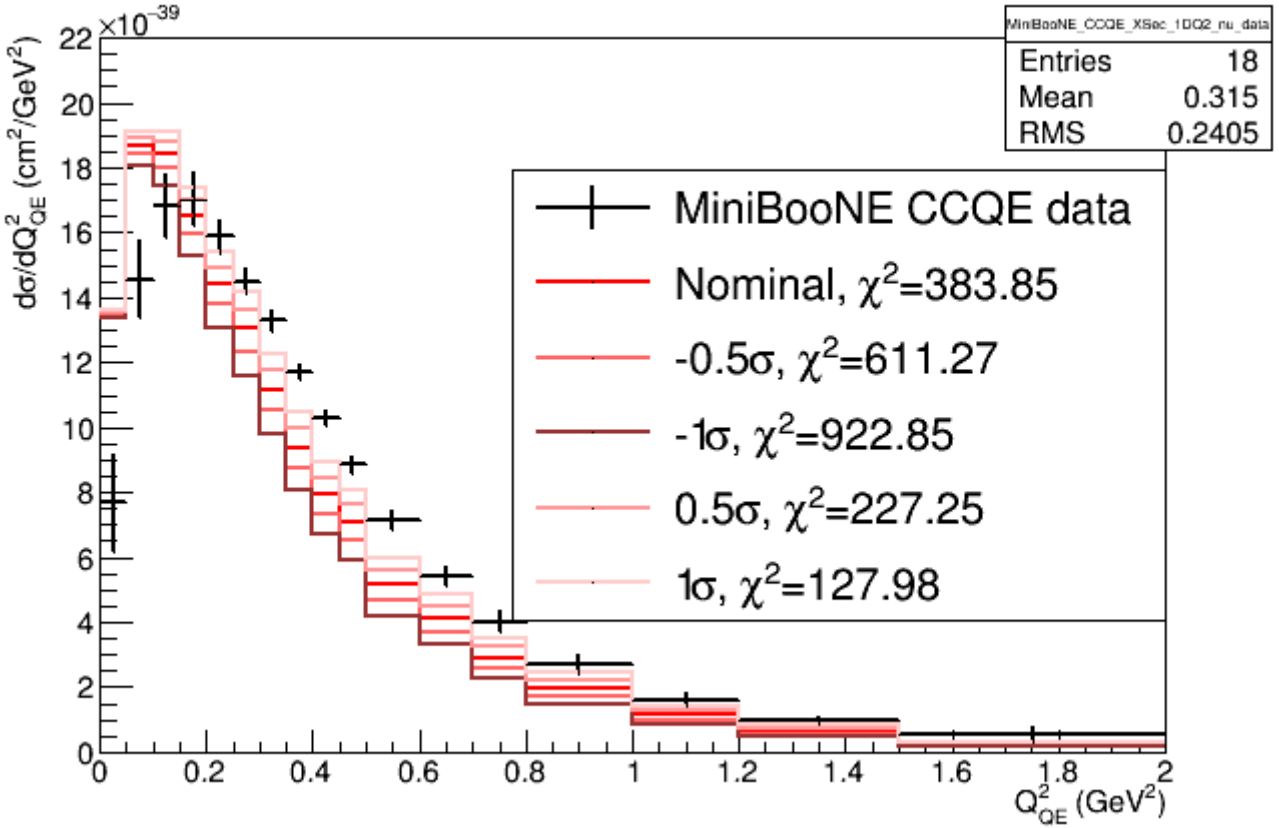
```
• neut_parameter MaCCQE 0.0 -1.0 1.0 0.5 FREE
• neut_parameter VecFFCCQE 2
```

- `neut_parameter` tells the reweight interface that we're about to feed it a NEUTReWeight parameter
  - `genie_parameter, t2k_parameter, niwg_parameter , nuwro_parameter` are the systematic parameters types
  - Also others supported (`ReWeight/WeightUtils.cxx`)
    - e.g. sample normalisations

Varying systematics

- `./nuissyst -c example_ccqe.card -o miniboone_ccqe_var.root -f PlotLimits`

- Now instead get different folders for each variation



- Seems to indicate MiniBooNE CCQE likes a higher M_A^{QE}, wow!

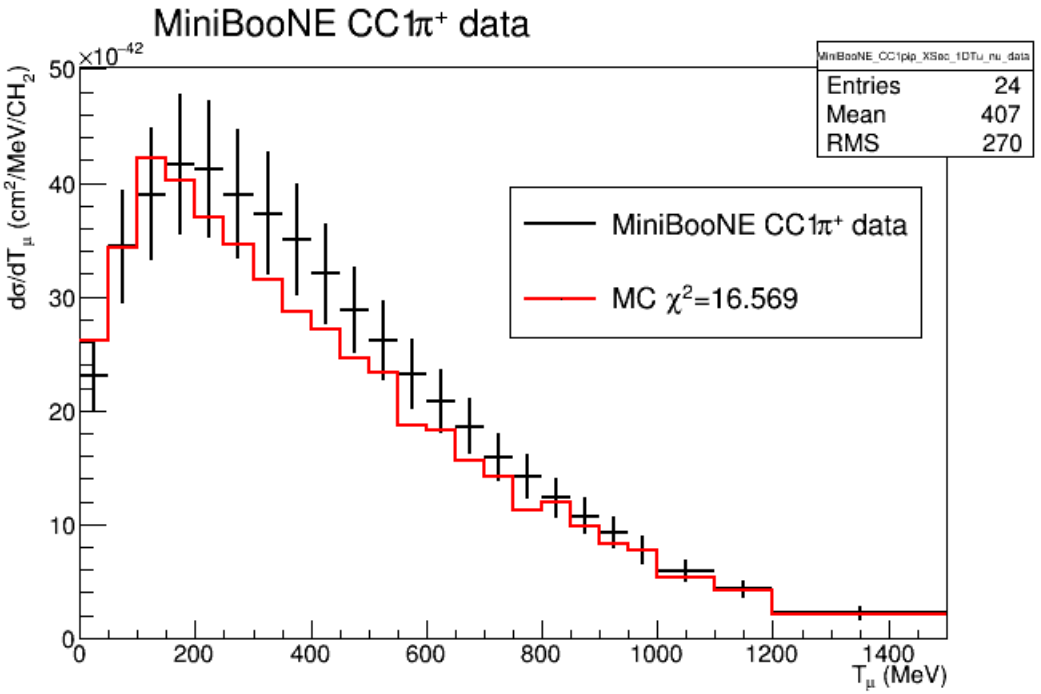
Single pion example

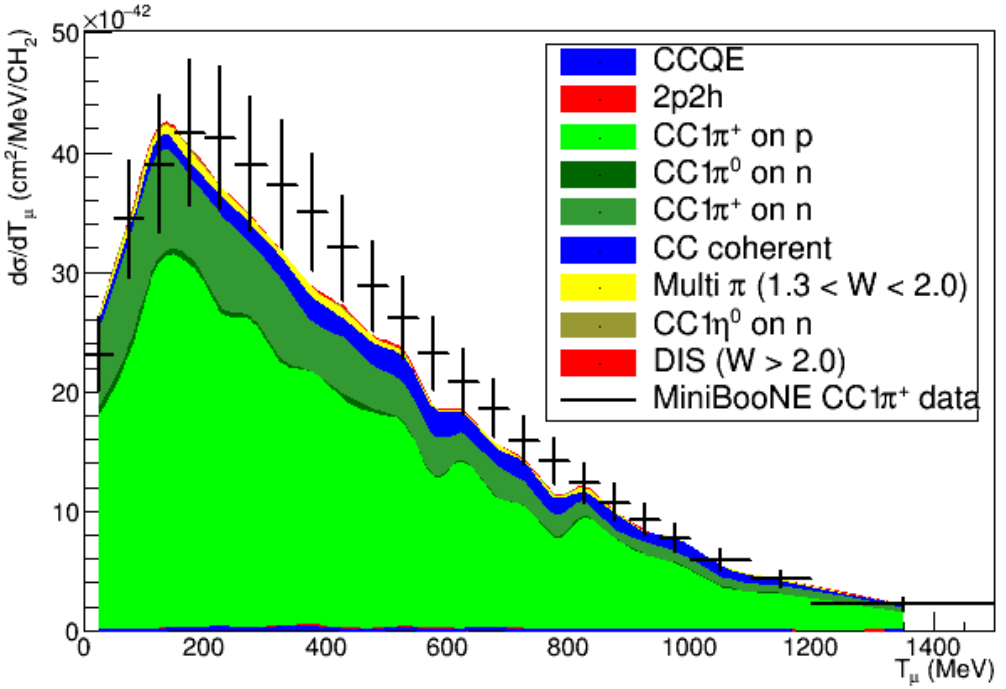
- Let's try a more complicated signal definition, MiniBooNE CC1π^+ T_μ
  - Has a topology-defined signal rather than true interaction mode
  - Will have many contributions to final state

- `vim example_cc1pip.card`
- `sample MiniBooNE_CC1pip_Xsec_1DTu_nu NEUT:~/Share/MB_numu_fhc_533Aut_merge.root`
- `./nuiscomp -c example_cc1pip.card -o miniboone_cc1pip_tmu.root -q MAXEVENTS=50000`

Inspecting the output

- Make similar plots for these distributions





- N.B. we could reuse the same generated NEUT events because
  - Generated with all interaction modes
  - Measurements use same flux on MiniBooNE

Let's start a fit in the background

- Fit MiniBooNE CCQE Q^2 distribution with M_A^{QE}
- First, give larger range to M_A^{QE} in our card file

```
• vim example.card
• neut_parameter MaCCQE 0.0 -3.0 3.0 0.5 FREE
• ./nuismin -c example.card -o
  miniboone_ccqe_q2_fit.root -q MAXEVENTS=50000
```

- Should end up with fit value 2.10 → **M_A^{QE} = 1.61 GeV**
  - This is a slightly unfortunate conversion in NEUT ReWeight and GENIE ReWeight: `real units = nominal*(1+num*1sig)`
  - `nominal` is found in `NFortFns.cc` and `1sig` is found in `NSystUncertainity.cc`

Basic structure of NUISANCE

- Load up a series of `MeasurementBase` derived classes specified by user
  - `Measurement1D, Measurement2D, JointMeas` classes controlling 1D, 2D or joint data format
- Loop over generated MC events, provided in a ROOT file `MeasurementBase::Reconfigure()`
  - Interface with the generator libraries to covert to common format `MeasurementBase::cust_event`
  - Get the dependent variable for each event, e.g. Q^2 `MeasurementBase::FillEventVariables`
  - Does event pass signal definition? `MeasurementBase::isSignal`
  - Fill the histograms, `MeasurementBase::FillHistograms()`
- Calculate a likelihhod, `MeasurementBase::GetLikelihood()`

Adding a measurement

- `Constructor`
  - Set what the sample is (e.g. naming, shape only), point to data, etc
- The dependent variable (`FillEventVariables`)
  - Are we doing $d\sigma/dQ^2$, $d\sigma/dp_\mu$, etc
  - How do we define the dependent variable
- Signal definition (`isSignal`)
  - What events in the input MC do we add to the histogram, which do we discard?

- Let's look closer at these in the implementation of `src/MiniBooNE/MiniBooNE_CC1pip_XSec_1DQ2_nu`

The constructor

Measurement descriptors

E_ν^{true} range

Target

Set data

Set scaling, e.g. /neutron, /nucleon /MeV^2 to /GeV^2

```
//*****************************************************************
MiniBooNE_CC1pip_XSec_1DQ2_nu::MiniBooNE_CC1pip_XSec_1DQ2_nu(nuiskey samplekey) {
//*****************************************************************

  // Sample overview ---------------------------------------------------
  std::string descrip = "MiniBooNE_CC1pip_XSec_1DQ2_nu sample. \n" \
                        "Target: CH \n" \
                        "Flux: MiniBooNE Forward Horn Current nue + nuebar \n" \
                        "Signal: Any event with 1 muon, any nucleons, and no other FS particles \n";

  // Setup common settings
  fSettings = LoadSampleSettings(samplekey);
  fSettings.SetDescription(descrip);
  fSettings.SetXTitle("Q^{2}_{CC#pi} (GeV^{2})");
  fSettings.SetYTitle("d#sigma/dQ_{CC#pi^{+}}^{2} (cm^{2}/MeV^{2}/CH_{2})");
  fSettings.SetAllowedTypes("FIX,FREE,SHAPE/DIAG/NORM/MASK", "FIX/DIAG");
  fSettings.SetEnuRange(0.0, 100.0); // No energy range given in v1r0
  fSettings.DefineAllowedTargets("C,H");

  // CCQELike plot information
  fSettings.SetTitle("MiniBooNE CC1pi");
  fSettings.SetDataInput(  FitPar::GetDataBase() + "MiniBooNE/CC1pip/ccpipXSec_Q2.txt" );
  fSettings.DefineAllowedSpecies("numu");

  FinaliseSampleSettings();

  // Scaling Setup -----------------------------------------------------
  // ScaleFactor automatically setup for DiffXSec/cm2/Nucleon
  fScaleFactor = GetEventHistogram()->Integral("width")*double(1E-38)/double(fNEvents)*(14.08)/TotalIntegratedFlux("width")/1E6;
  // Added /1E6. comes from Q2 being in MeV^2, not GeV^2

  // Plot Setup --------------------------------------------------------
  SetDataFromTextFile( fSettings.GetDataInput() );
  SetCovarFromDiagonal();

  // Final setup  ------------------------------------------------------
  FinaliseMeasurement();

};
```

- Other calls are to helper functions to allocate memory to e.g. TH1Ds
- Inherits from `Measurement1D` class (`MeasurementBase`)

The dependent variables

```
//*********************************************************************
void  MiniBooNE_CC1pip_XSec_1DQ2_nu::FillEventVariables(FitEvent *event){
//*********************************************************************

  if (event->NumFSParticle(211) == 0 ||
      event->NumFSParticle(13) == 0)
    return;

  TLorentzVector Pnu  = event->GetNeutrinoIn()->fP;
  TLorentzVector Ppip = event->GetHMFSParticle(211)->fP;
  TLorentzVector Pmu  = event->GetHMFSParticle(13)->fP;

  // No W cut on MiniBooNE CC1pi+
  double Q2CC1pip = FitUtils::Q2CC1piprec(Pnu, Pmu, Ppip);

  fXVar = Q2CC1pip;

  return;
};
```

Common event format

Check number of final state particles with PDG 211 (positive pion) and PDG 13 (muon)

Get the incoming neutrino

Get the highest momentum particles

Get the reconstructed Q^2

Set the dependent variable of class to be reconstructed Q^2

- The important thing is that `fXVar` gets set at the end of the `FillEventVariables` call

The signal definition

- Signal definition uses a number of helper functions

Define signal as:

incoming numu
CC (outgoing muon)
outgoing positive pion
EnuMin < Enu < EnuMin

To achieve this, we:

Check it's CC-inclusive
Check there's only one pion and that pion is the only meson
Check there's only one charged lepton which agrees with incoming numu

```
//*****************************************************************************
bool MiniBooNE_CC1pip_XSec_1DQ2_nu::isSignal(FitEvent *event) {
//*****************************************************************************
  return SignalDef::isCC1pi(event, 14, 211, EnuMin, EnuMax);
}
```

```
// Require one meson, one charged lepton. types specified in the arguments
bool SignalDef::isCC1pi(FitEvent *event, int nuPDG, int piPDG,
                        double EnuMin, double EnuMax){

  // First, make sure it's CCINC
  if (!SignalDef::isCCINC(event, nuPDG, EnuMin, EnuMax)) return false;

  int nMesons  = event->NumFSMesons();
  int nLeptons = event->NumFSLeptons();
  int nPion    = event->NumFSParticle(piPDG);

  // Check that the desired pion exists and is the only meson
  if (nPion != 1 || nMesons != 1) return false;

  // Check that there is only one final state lepton
  if (nLeptons != 1) return false;

  return true;
}
```

```
bool SignalDef::isCCINC(FitEvent *event, int nuPDG, double EnuMin, double EnuMax) {

  // Check for the desired PDG code
  if (!event->HasISParticle(nuPDG)) return false;

  // Check that it's within the allowed range if set
  if (EnuMin != EnuMax) {
    if (!SignalDef::IsEnuInRange(event, EnuMin*1000, EnuMax*1000)) {
      return false;
    }
  }

  // Check that the charged lepton we expect has been produced
  if (!event->HasFSParticle(nuPDG > 0 ? nuPDG-1 : nuPDG+1)) return false;

  return true;
}
```

Making flat trees

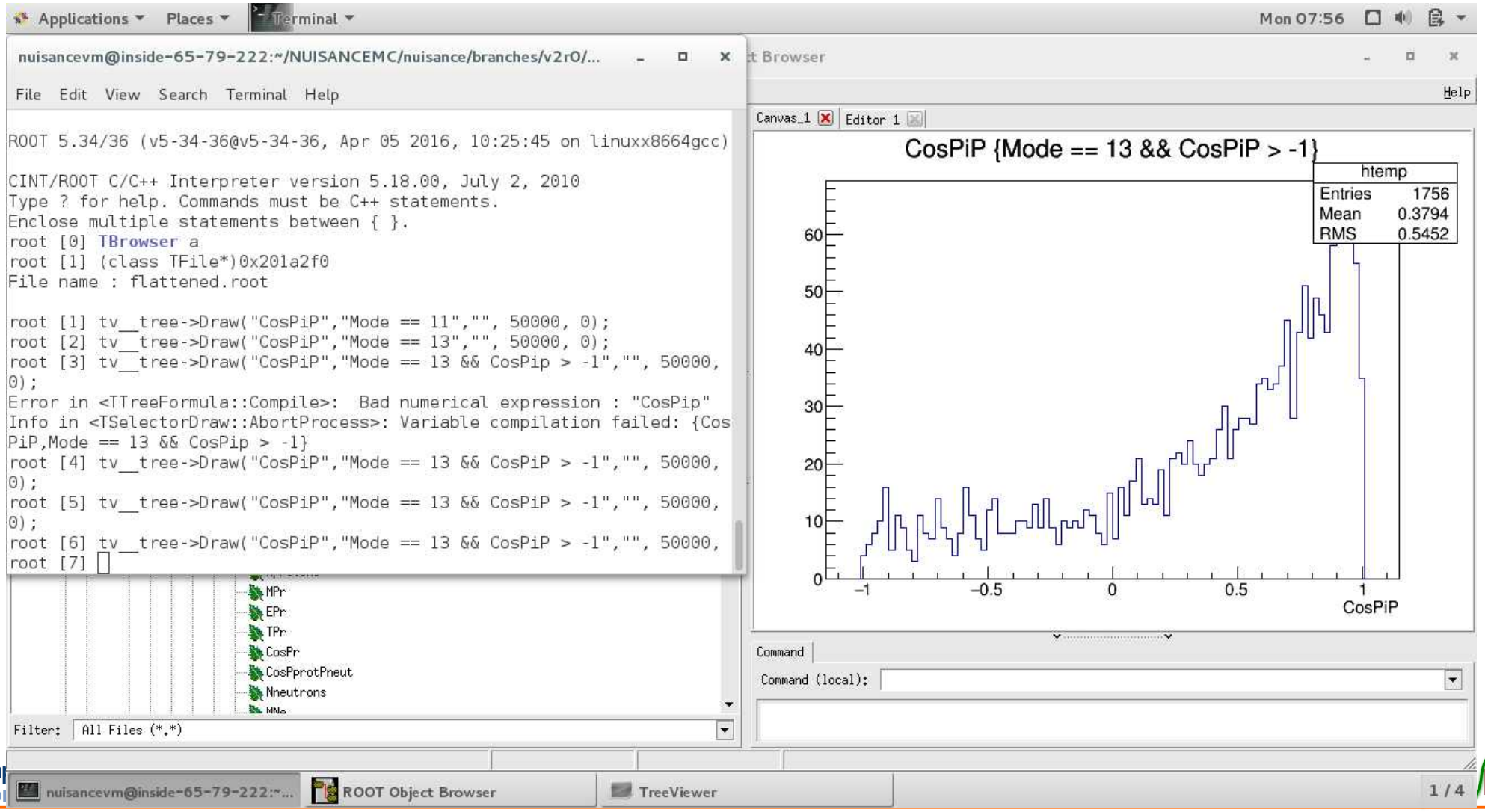
- The `GenericFlux_` class makes flat trees out of the input MC
  - Useful if you don't necessarily want to do data comparisons
  - Or want to learn what distributions are interesting
  - Compare MC with MC
    - e.g. NEUT flat trees with GENIE flat trees

```
• vim flat.card
• sample GenericFlux_Tester
  NEUT:~/Share/MB_numu_fhc_533Aut_merge.root
• ./nuiscomp -c flat.card -o myflattree.root -q
  MAXEVENTS=50000
```

- Can add in systematic parameters too, e.g.
  - `neut_parameter MaCCQE 0.7`

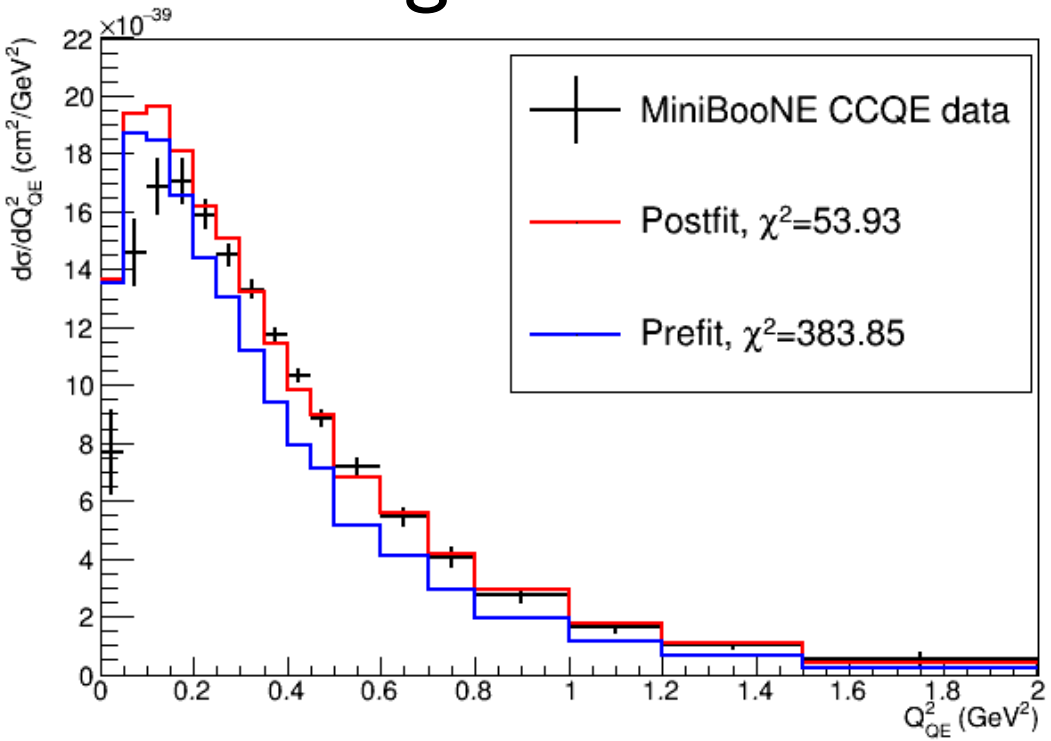
Looking at the flat trees

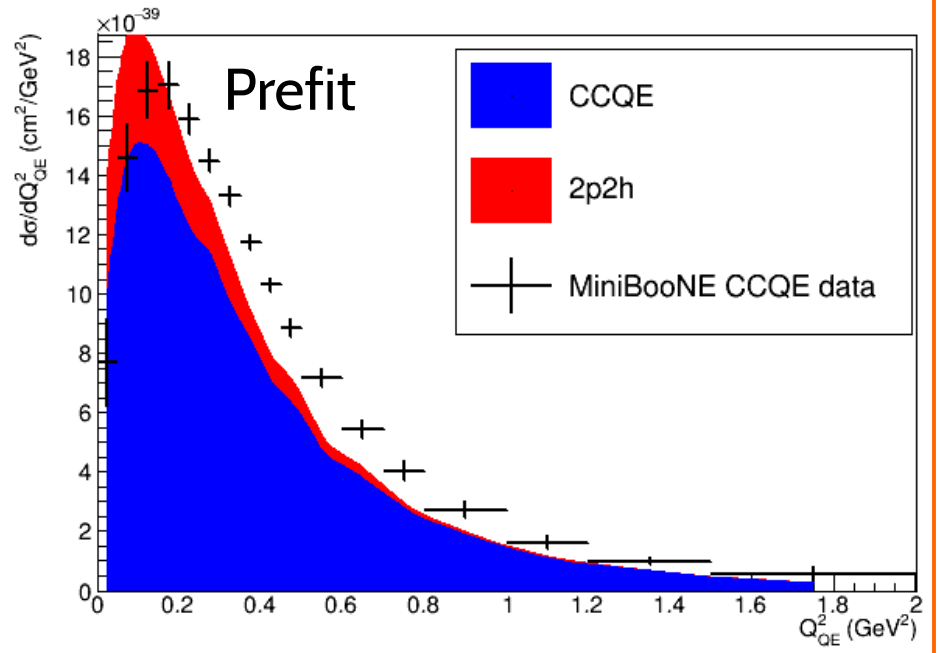
- Produces normal ROOT trees with kinematic variables, modes, etc
- Also a few generic signal definitions
- Here's $\cos\theta_\pi$ for CC1π+1n (NEUT mode 13)

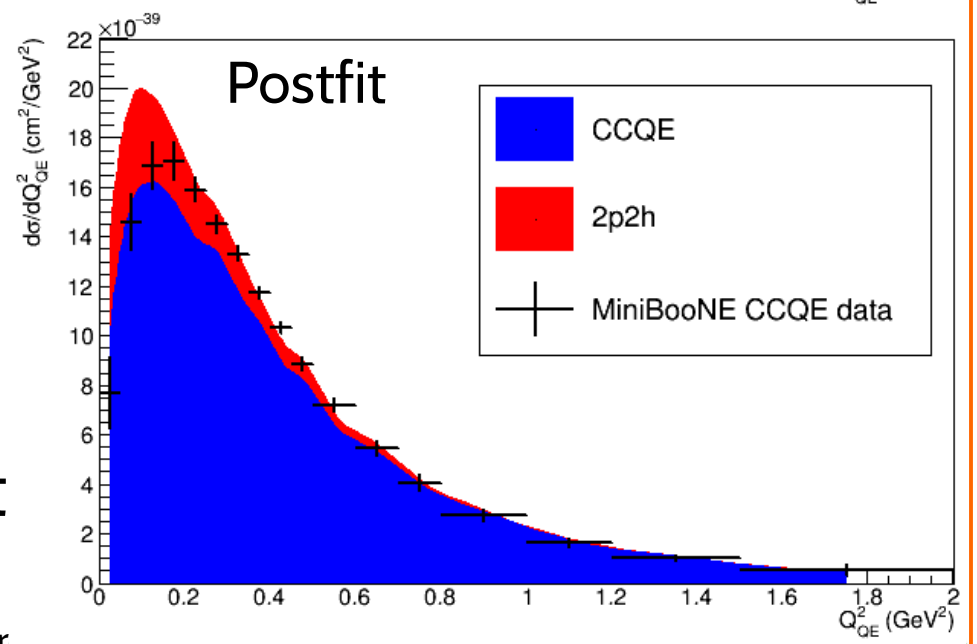


Going back to the fit we sent off

- Looking at the post-fit the low Q^2 behaviour is still not convincing





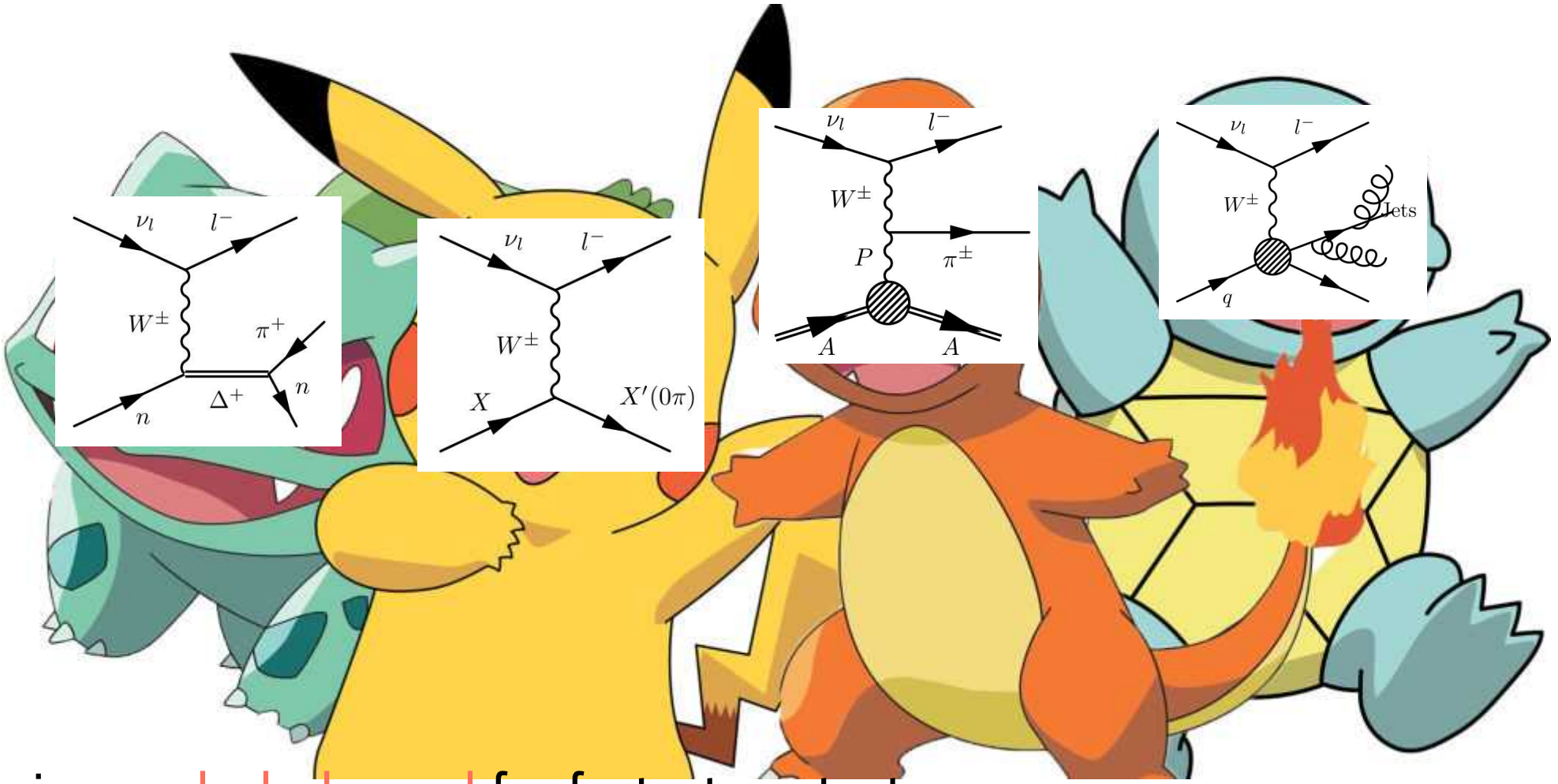


- RPA?
  - Quenches low Q^2 by ~0.6, but not included in the input file

Continuing these studies

- Have all the other generators set up in the virtual box
- Also have pre-generated events here
  - Could download GENIE, GiBUU or NuWro events too
- Try similar studies using the GENIE interface
  - Replace `NEUT:~/Share/MyNEUTfile.root` with `GENIE:~/Share/MyGENIEfile.root` in cardfile
  - Also update `neut_parameter` to `genie_parameter`
- And then you'll be fitting GENIE!
- Generate your own events with alternate models
- **Go catch em all!**

Thanks



- Join our slack channel for fastest contact
- shoot us an email
- Have a glance at our paper describing NUISANCE
- Or just bother us later!