NUISANCE and you

JINST 12 P01016 (2017)
nuisance.hepforge.org
github.com/NUISANCEMC/nuisance/
nuisance-xsec.slack.com


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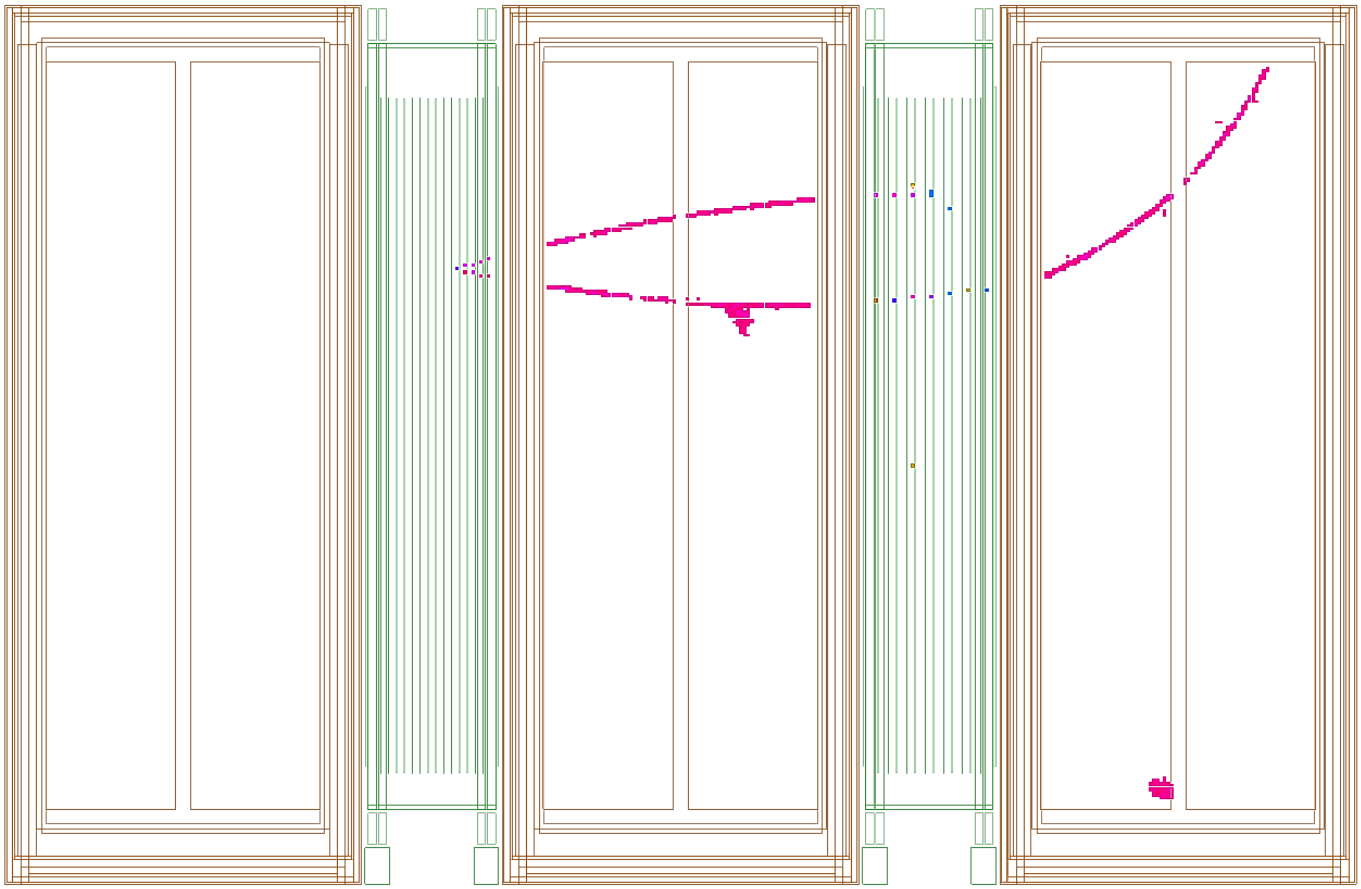
25 October 2022

And thanks Ciro Riccio, Kirsty Duffy, Andy Mastbaum, Steven Gardiner, Daniel Ruterbories, Kendall Mahn, Kevin McFarland, Yoshinari Hayato, Jan Sobzcyk, Kajetan Niewczas, Ulrich Mosel, and many more contributors!

Introduction

- Why do we need neutrino cross-section dependence at all?
  - Can't reliably measure the fundamental interaction quantities (E_ν, Q^2, W, q_0, $\mathbf{q_3}$, **...**)



- Need to relate observed event to the true quantity through some model

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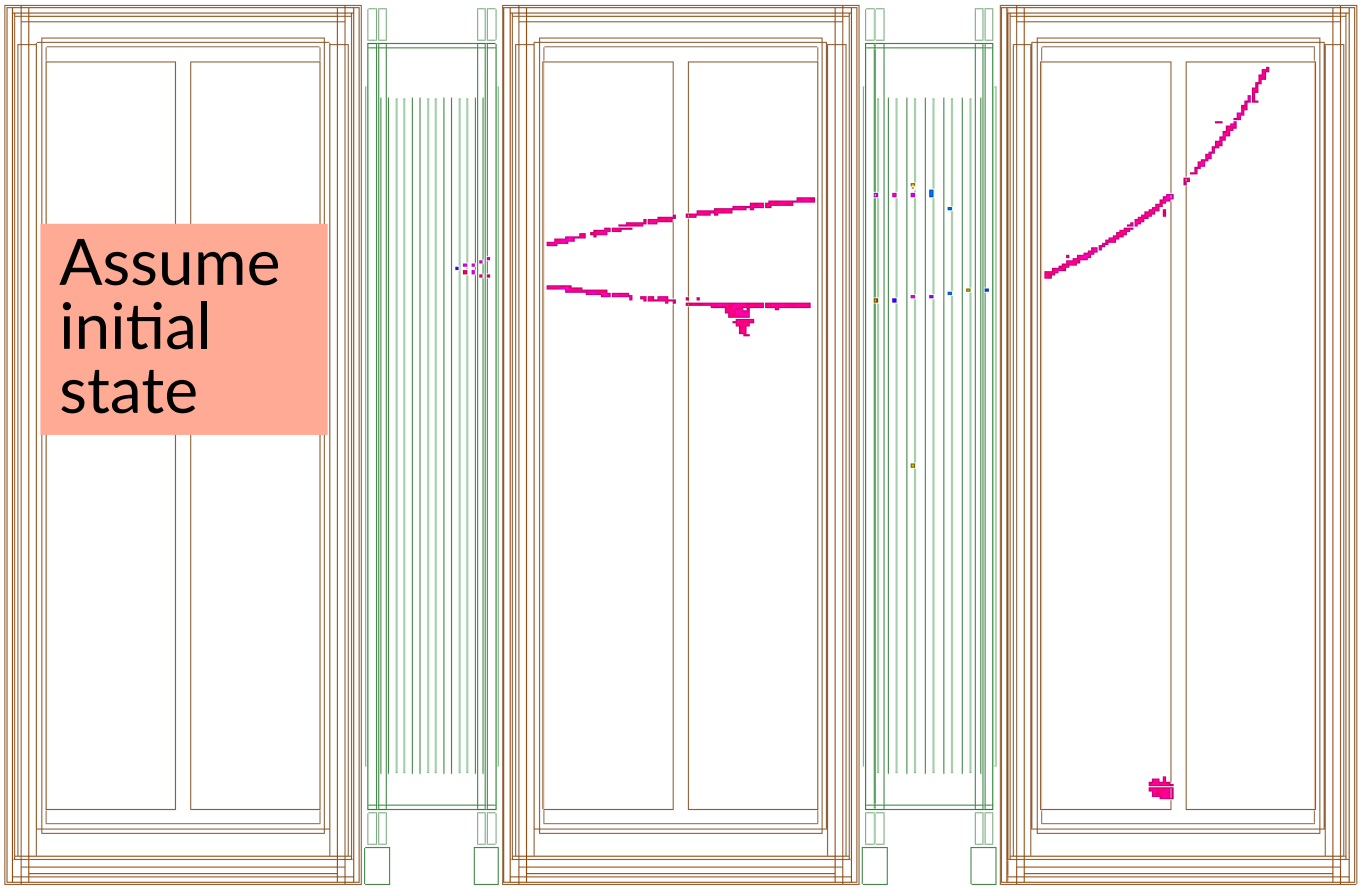

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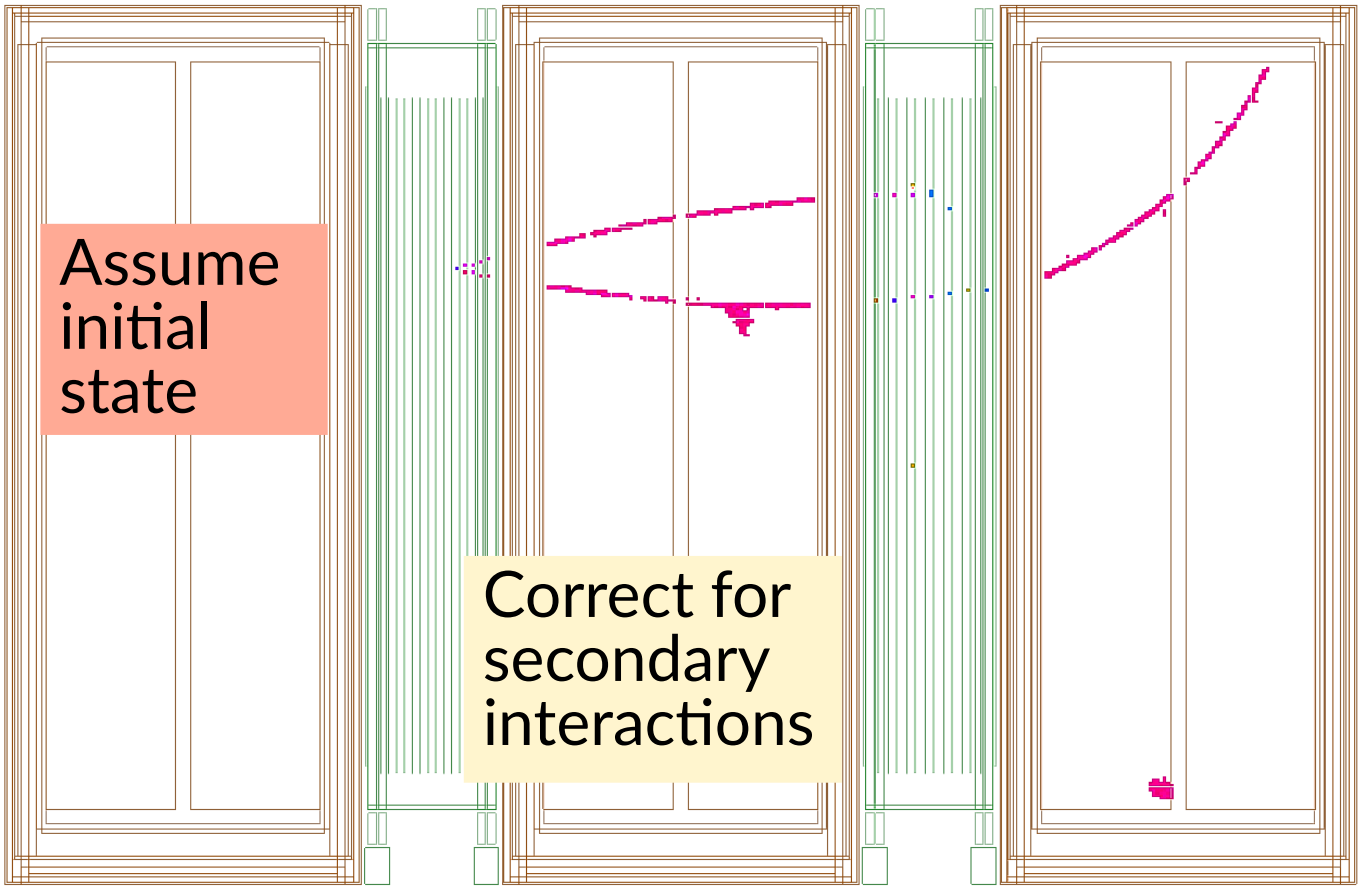

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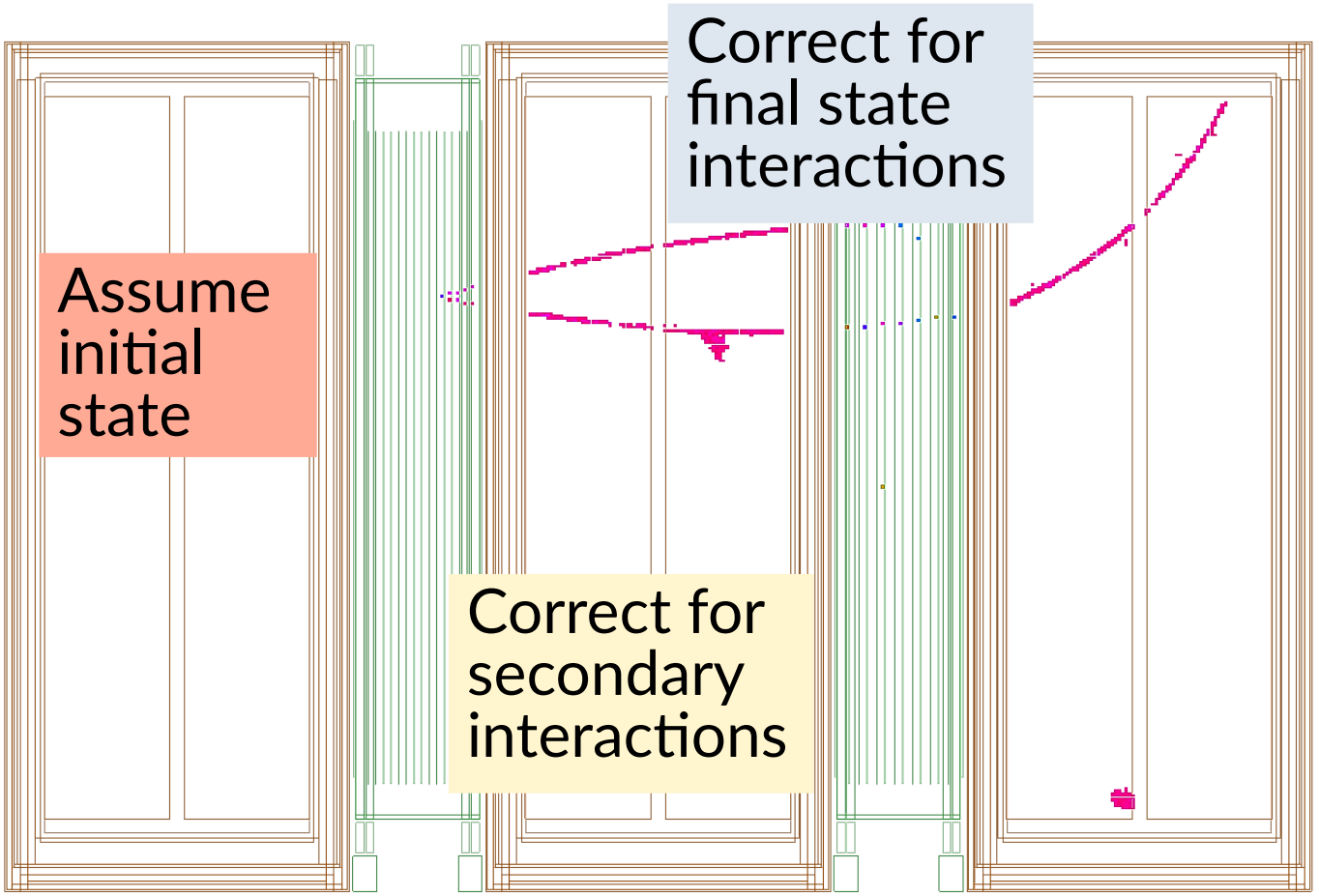

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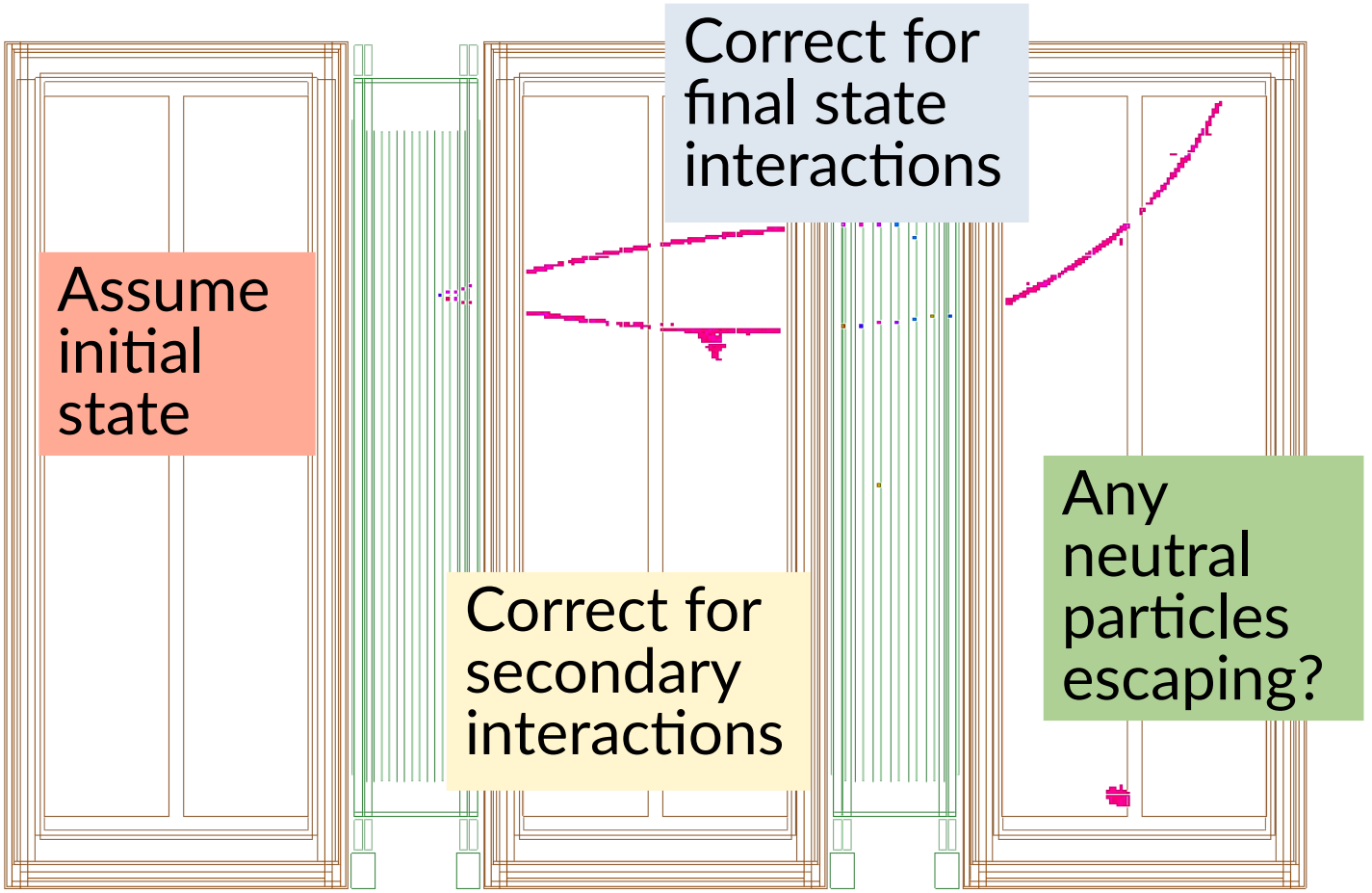


- Need to relate observed event to the true quantity through some model

Introduction

- Can we escape model dependence? Arguably not
  - Even a perfect detector won't be able to tell you about final-state interactions, or the initial state
- But we can **remove dependence on models that have shaky foundations**!
  - Does the model fail to describe reliable data?
  - Is the model prediction very different to currently approved approaches?
  - Etc...
- The community needs tools to inform us of where models are doing well, and where they aren't
  - Design physics analyses to expose weaknesses in modelling
  - Avoid physics analyses that depend on unreliable model predictions
  - Rinse, repeat, and get more robust and valuable measurements!

Introduction

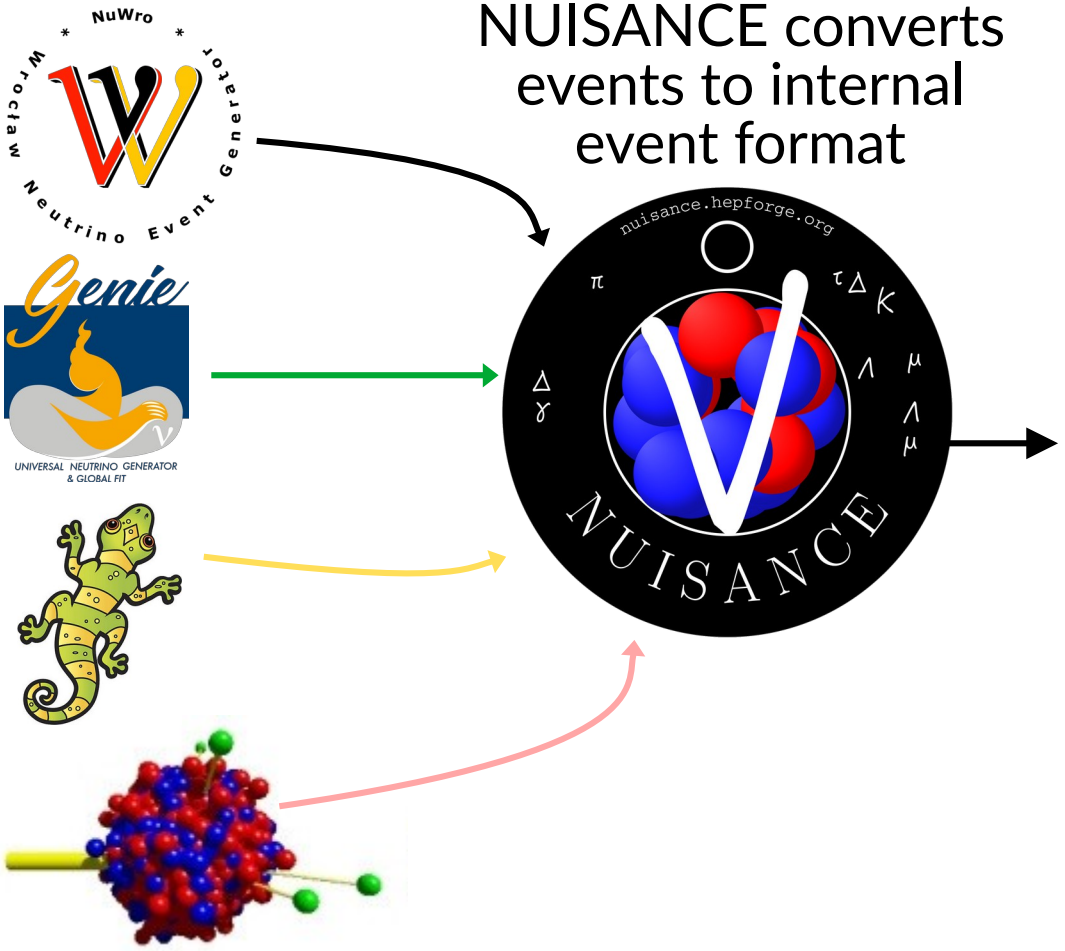
- Identified a need to easily compare **different** generator predictions to each other and to data
  - Develop and estimate uncertainties in analyses, using both generators and external data
  - Expose differences between generators and models for improved analyses
  - Identify interesting measurements for experimentalists to pursue
  - Check effects of theory and phenomenology implementations against data and previous calculations
  - Get an idea of how model-dependent measurements may be
- The generator market is quite vast, and expanding!
  - GENIE, NEUT, NuWro, GiBUU, Achilles, NUANCE, …
  - No clear winner for experiments: some generators have excellent integration into experiments, others have very detailed nuclear model implementations but less developed uncertainty model, and so on

The NUISANCE process

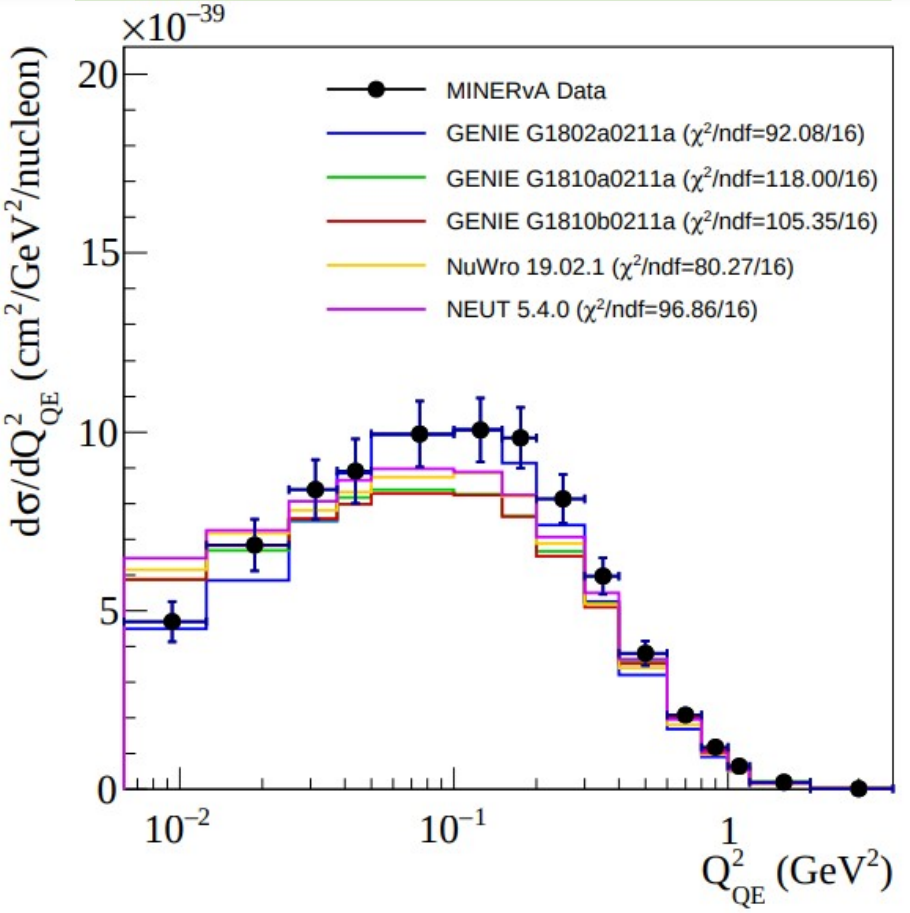
- All driven by simple commands, where a config file with the measurement and systematic parameters are provided

Generate events

NUISANCE converts events to internal event format



Compare generators to data



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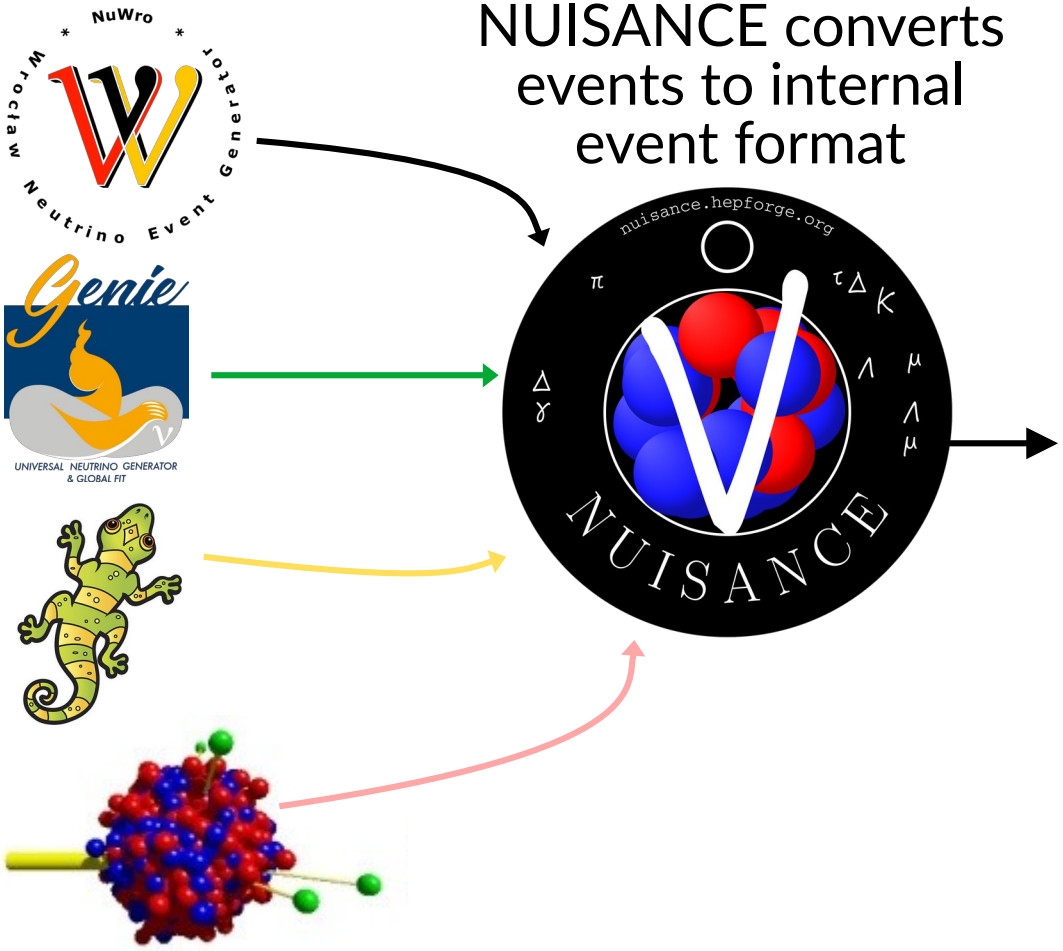
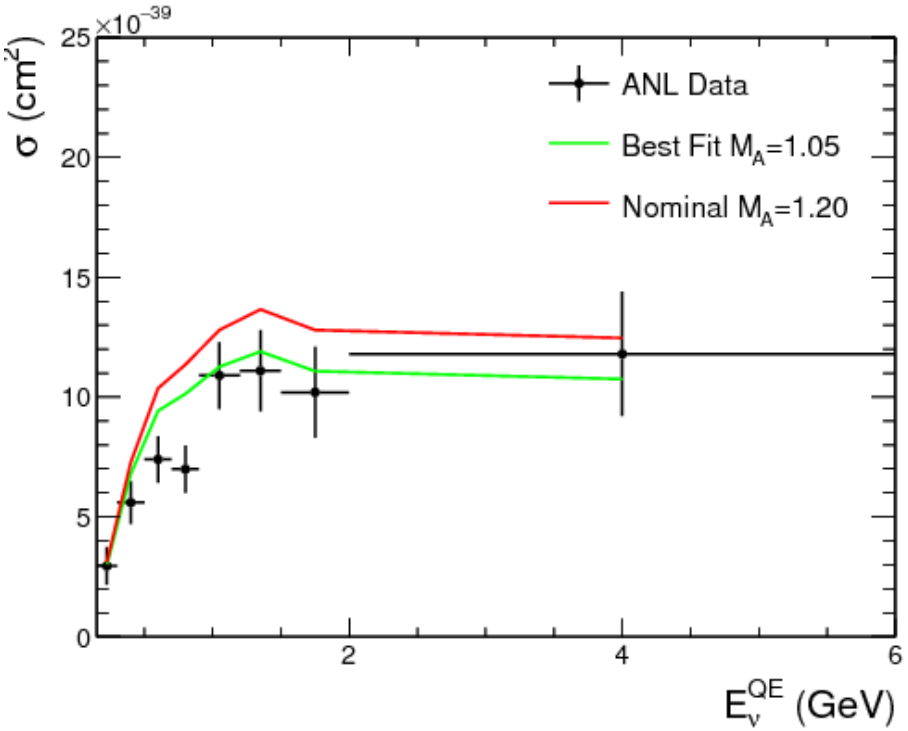
Fit generators model parameters to specific data





The NUISANCE process

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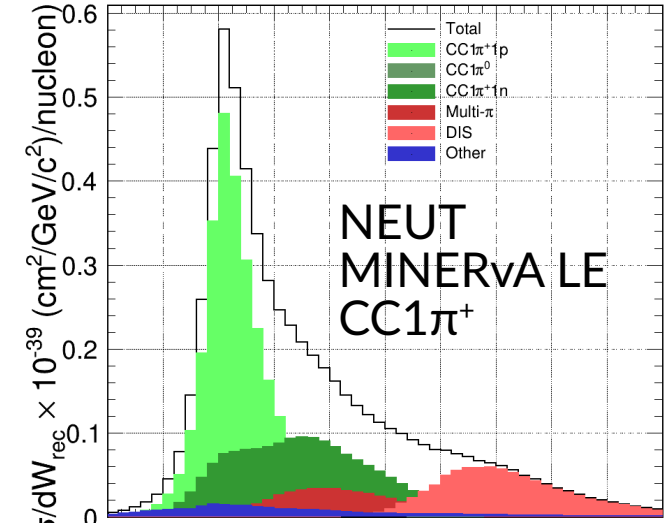
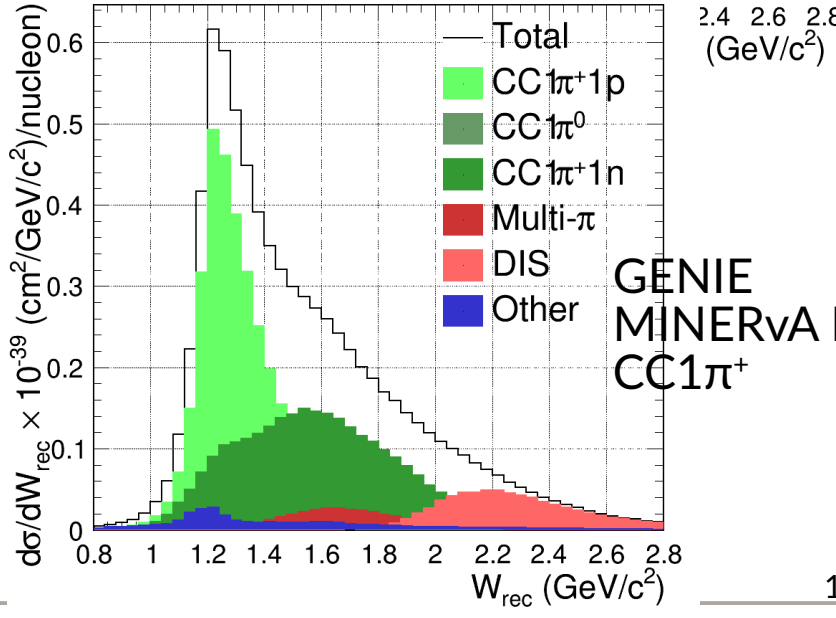
Compare generator features





The NUISANCE process

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Generate events

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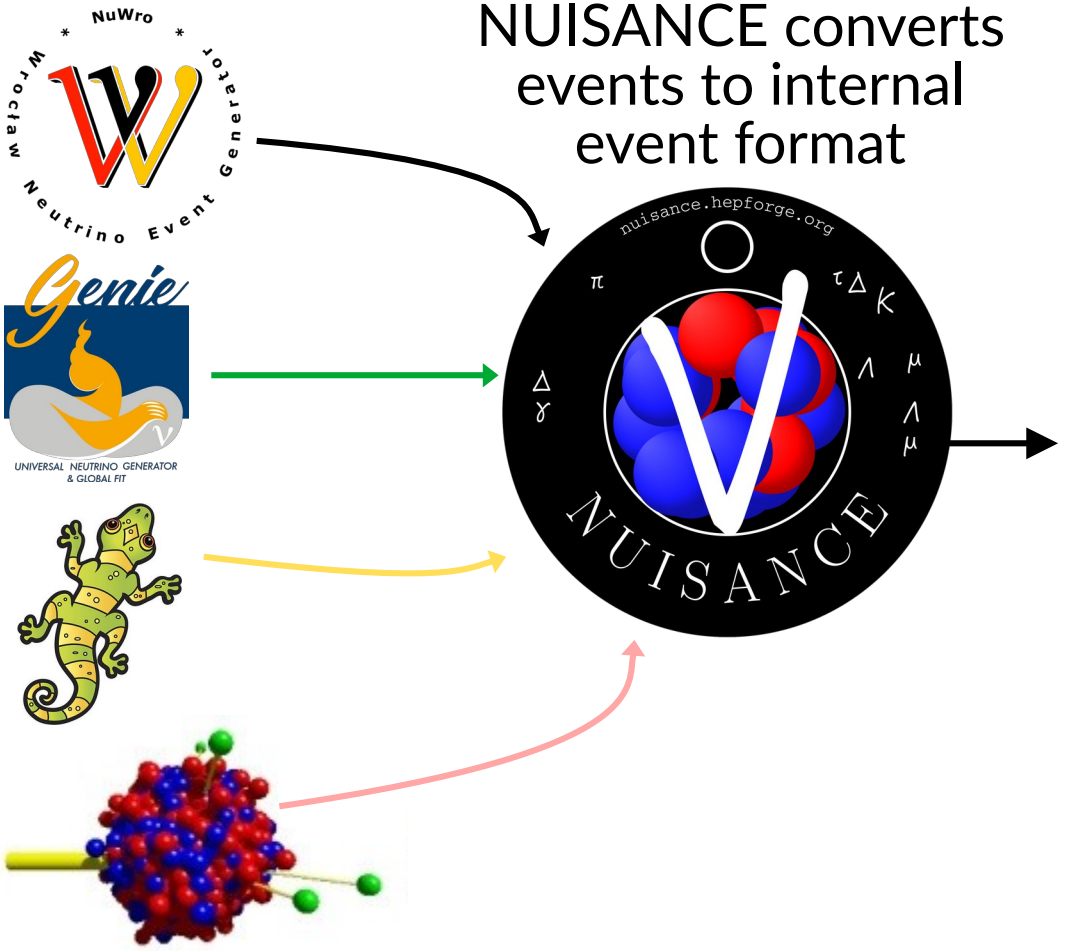
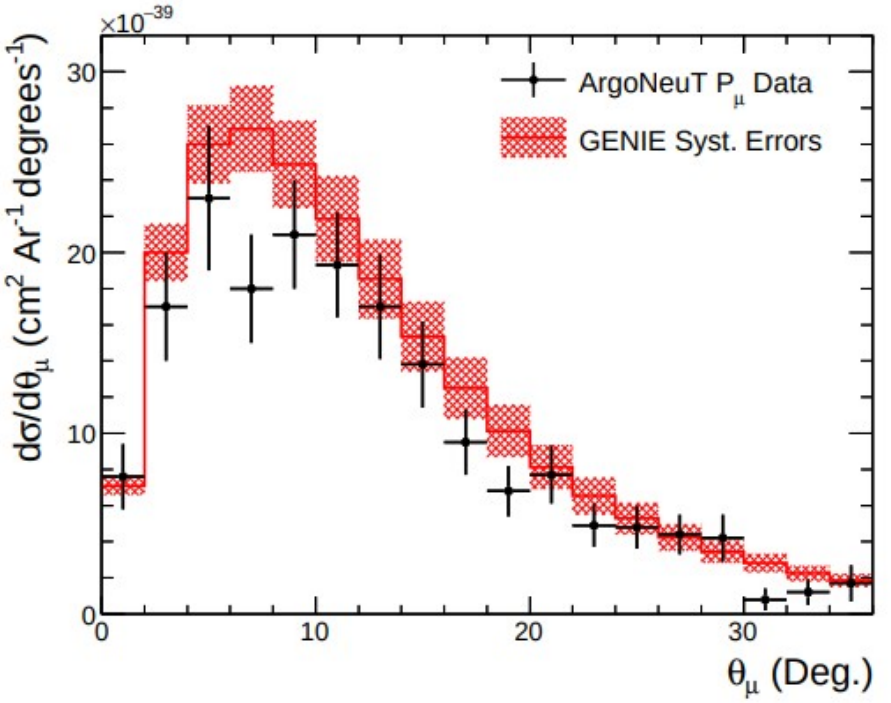
Evaluate uncertainty of model against data





What can NUISANCE do?

- At its heart, NUISANCE is an event converter, **but does much more than just convert events**
- Compare your generators to over **350 implemented data sets**
- Interfaces with **reweighting engines**
  - GENIE ReWeight, custom reweighting, MINERvA reweighting, DUNE's systematics packages, etc
  - You can also add your own!
- Estimate the **uncertainty band of your model** against a vast array of data
- Interfaces with an array of minimisers to **fit your model to data**
  - Fit whatever model you want, to whatever data you want
  - Can also fit GENIE model to NuWro fake data, and so on
  - NUISANCE does **not** ensure that your physics is approved

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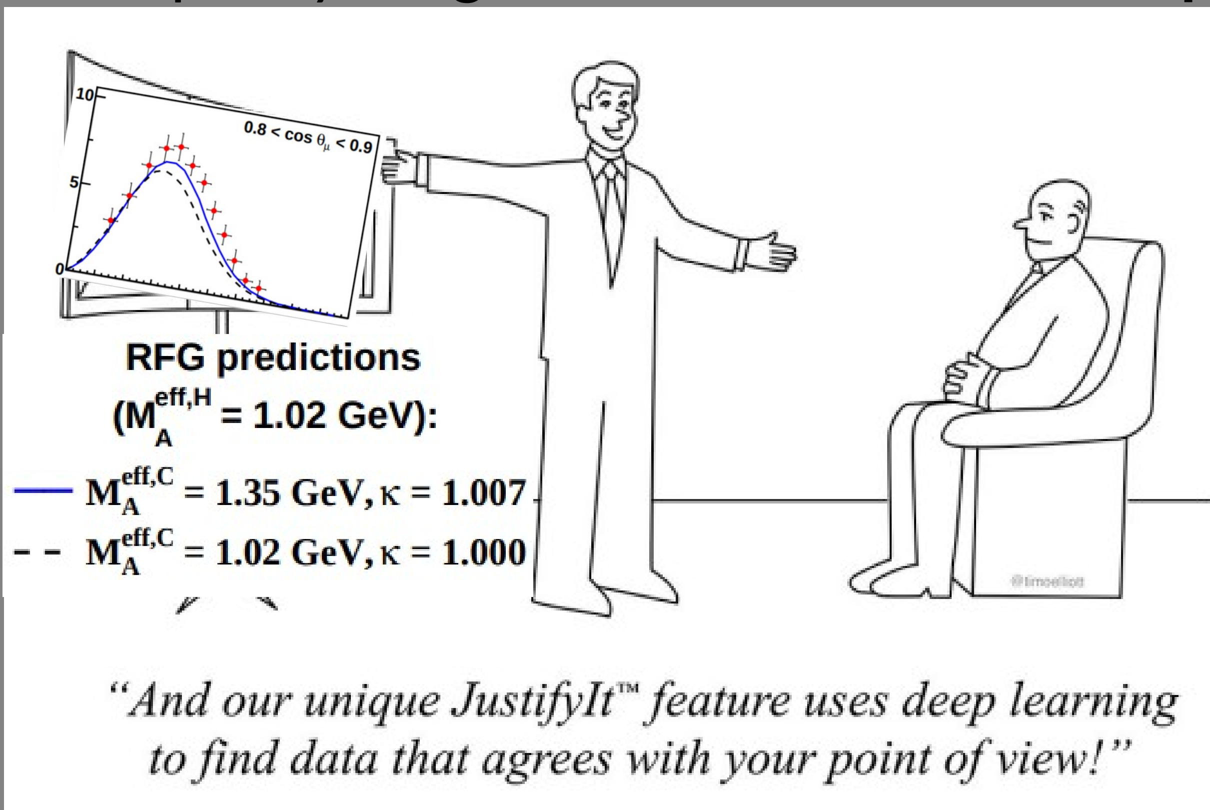


– NUISANCE does **not** ensure that your physics is approved

Typical implementation

- Open to collaboration, with open source code base, operating on a pull request basis
- At last NuInt we had ~200 measurements implemented, we now have 360
  - In part due to the work of people here, producing new interesting cross-section measurements!
  - Some collaborators have implemented their own measurements into NUISANCE and used it for multi-generator predictions in publication, excellent!

- A NUISANCE implementation needs to only define
  - The signal definition
  - The dependent variable(s)
  - An interface to the data and covariance matrix
- All the generator conversions, event loops, reweighting procedures, etc is all done internally, under the hood
  - Shouldn't have to be an expert to perform studies!

Typical implementation

- At last NuInt we had ~200 mea

```
//****************************************************************
void MINERvA_CC0pi_XSec_2D_nu::FillEventVariables(FitEvent *event)
  //****************************************************************
  // Checking to see if there is a Muon
  if (event->NumFSParticle(13) == 0)
    return;

  // Get the muon kinematics
  TLorentzVector Pmu = event->GetHMFSParticle(13)->fP;
  TLorentzVector Pnu = event->GetNeutrinoIn()->fP;

  Double_t px = Pmu.X() / 1000;
  Double_t py = Pmu.Y() / 1000;
  Double_t pt = sqrt(px * px + py * py);

  // y-axis is transverse momentum for both measurements
  fYVar = pt;

  // Don't want to assume the event generators all have neutrino c
  // z pz is muon momentum projected onto the neutrino direction
  Double_t pz = Pmu.Vect().Dot(Pnu.Vect() * (1.0 / Pnu.Vect().Mag(
  // Set Hist Variables
  fXVar = pz;
};
```

Example of MINERvA CC0π 2D $p_t p_z$ implementation

```
//****************************************************************
bool isCC0pi_MINERvAPTPZ(FitEvent *event, int nuPDG, double emin, double emax) {
  //****************************************************************
  // Check it's CCINC
  if (!SignalDef::isCCINC(event, nuPDG, emin, emax))
    return false;

  // Make Angle Cut > 20.0
  TLorentzVector pnu = event->GetHMISParticle(14)->fP;
  TLorentzVector pmu = event->GetHMFSParticle(13)->fP;
  double th_nu_mu = FitUtils::th(pmu, pnu) * 180. / M_PI;
  if (th_nu_mu >= 20.0)
    return false;

  int genie_n_muons = 0;
  int genie_n_mesons = 0;
  int genie_n_heavy_baryons_plus_pi0s = 0;
  int genie_n_photons = 0;

  for (unsigned int i = 0; i < event->NParticles(); ++i) {
    FitParticle *p = event->GetParticle(i);
    if (p->Status() != kFinalState)
      continue;

    int pdg = p->fPID;
    double energy = p->fP.E();

    if (pdg == 13) {
      genie_n_muons++;
    } else if (pdg == 22 && energy > 10.0) {
      genie_n_photons++;
    } else if (abs(pdg) == 211 || abs(pdg) == 321 || abs(pdg) == 323 ||
               pdg == 111 || pdg == 130 || pdg == 310 || pdg == 311 ||
               pdg == 313 || abs(pdg) == 221 || abs(pdg) == 331) {
      genie_n_mesons++;
    } else if (pdg == 3112 || pdg == 3122 || pdg == 3212 || pdg == 3222 ||
               pdg == 4112 || pdg == 4122 || pdg == 4212 || pdg == 4222 ||
               pdg == 411 || pdg == 421 || pdg == 111) {
      genie_n_heavy_baryons_plus_pi0s++;
    }
  }
```

Link to source code

Typical implementation

- Actively collaborate with experiment on implementations
- Validate against the generator prediction that is published using same generator
- Signal definition clarifications, defining variables, etc
- Work together on data releases, or at least identify needs
  - Avoids revisiting data release due to broken covariance matrix, unclear signal definitions, typos in papers… (all of which have happened)

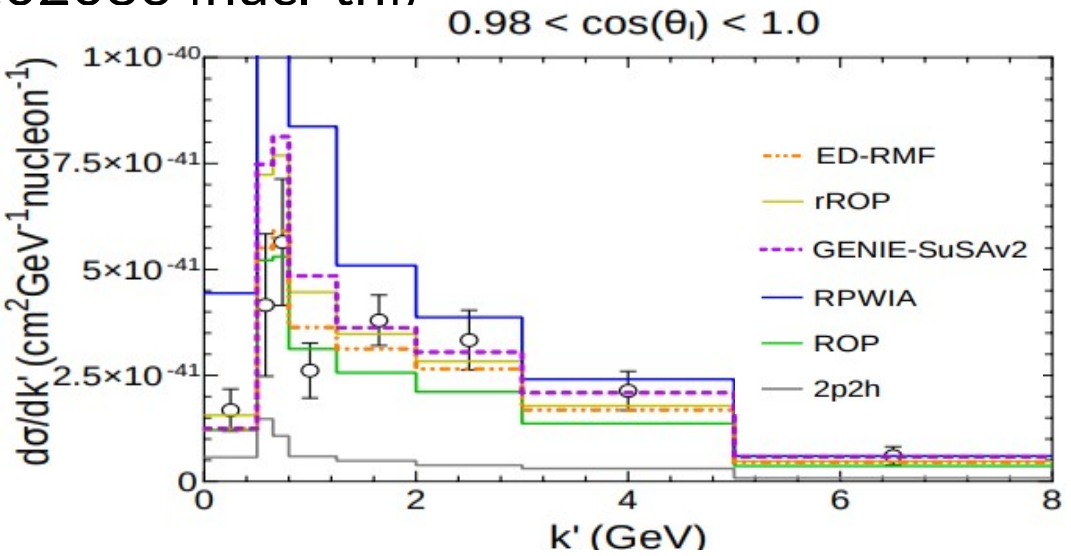
Carefully validated and implemented data release, ensuring physics usage for years

Uninvertible covariance matrix, where student leaves for industry after graduation, leaving a measurement without practical application

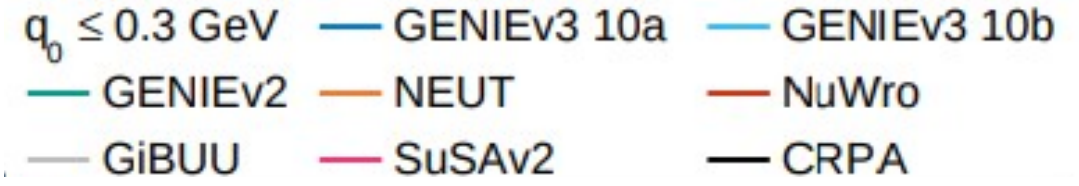
Recent examples

- Use GENIE predictions with SuSAv2 and compare to other 1p1h calculations (J.M. Franco-Patino et al. 2207.02086 [nucl-th])

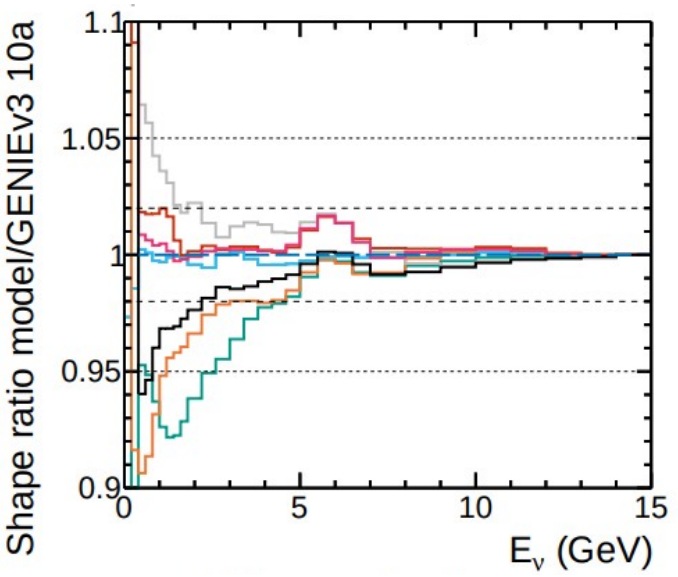
See Raul's NuInt talk



- Studies of low-ν method using multiple generators (C. Wilkinson et al. Eur.Phys.J.C 82 (2022) 9, 808)



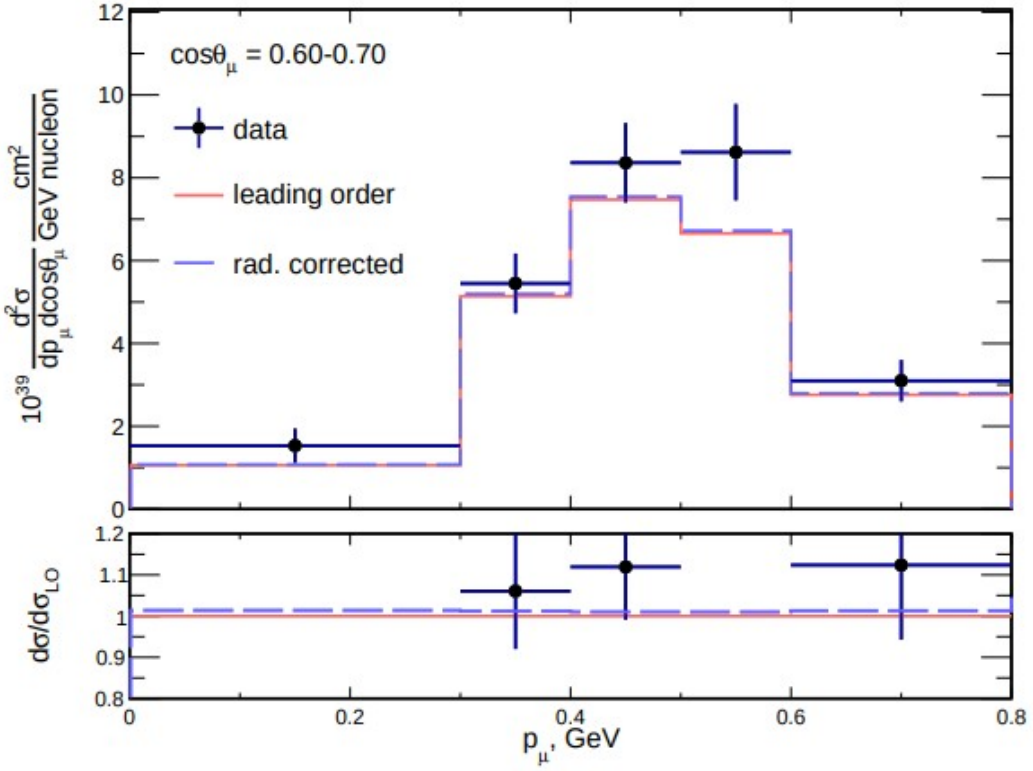
See Callum's NuInt talk

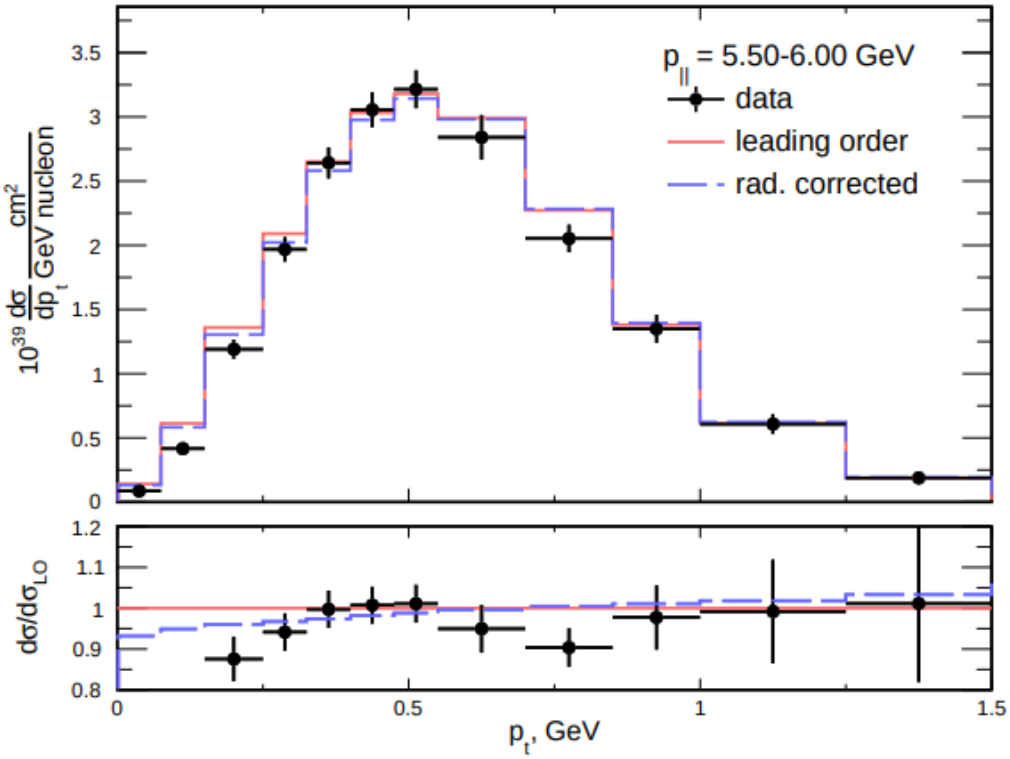


Recent examples

- Radiative corrections (O. Tomalak et al., 2204.11379 [hep-ph])
  - Found large effect for MINERvA, smaller effect for T2K
  - Implemented in NUISANCE; **<u>you can test it too!</u>**

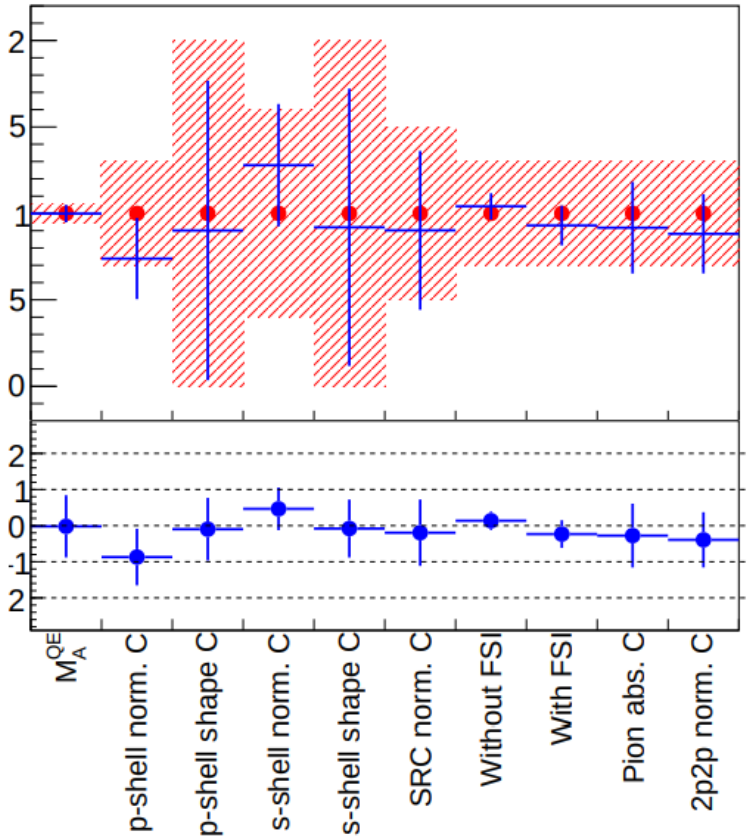
See Sasha's NuInt talk

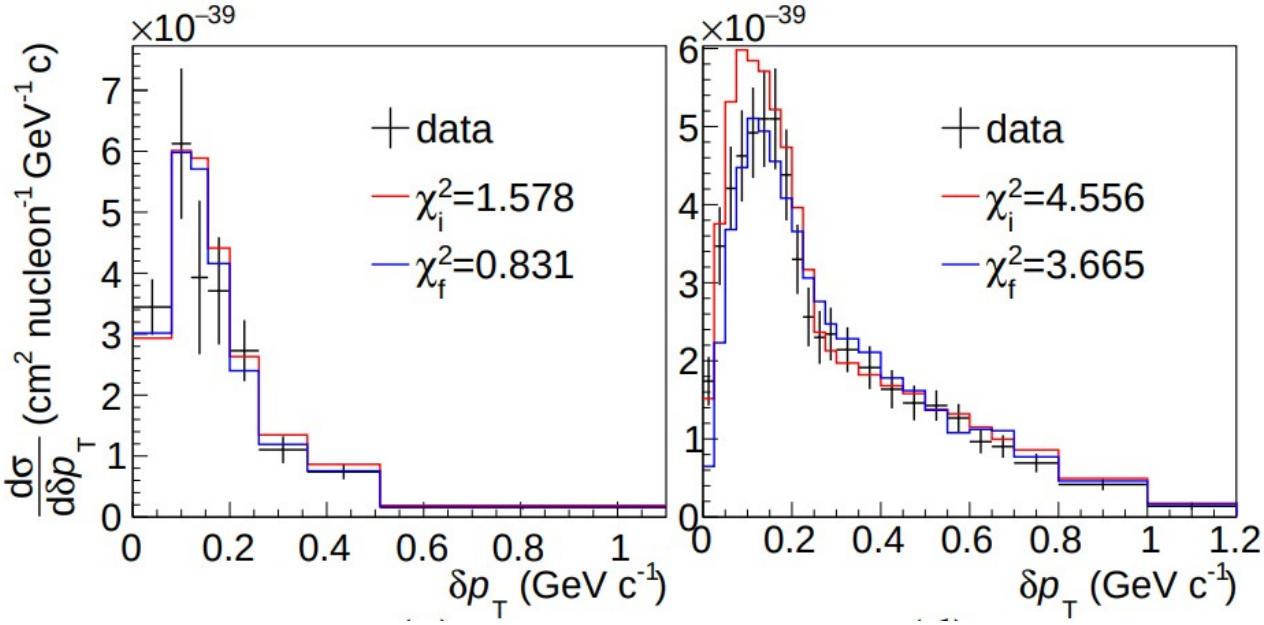




Recent examples

- ND280 Upgrade sensitivity studies and development of T2K interaction model (J. Chakrani et al. arXiv:2202.03219 [hep-ph])
  - Found a good parametrisation against published T2K data, but not MINERvA data

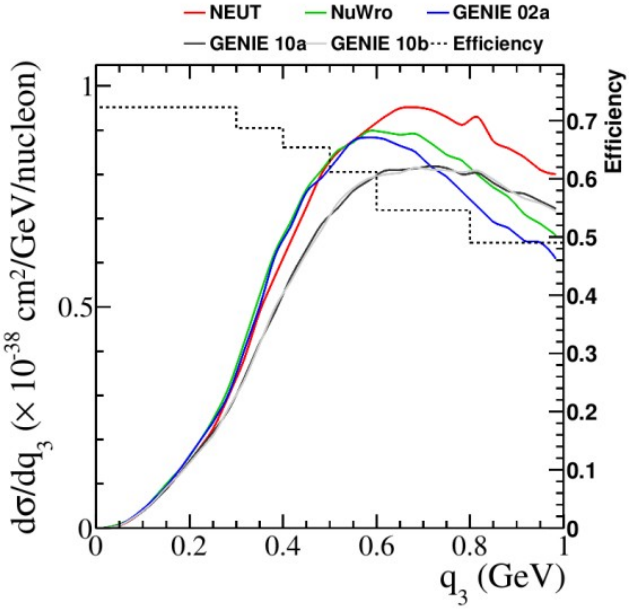


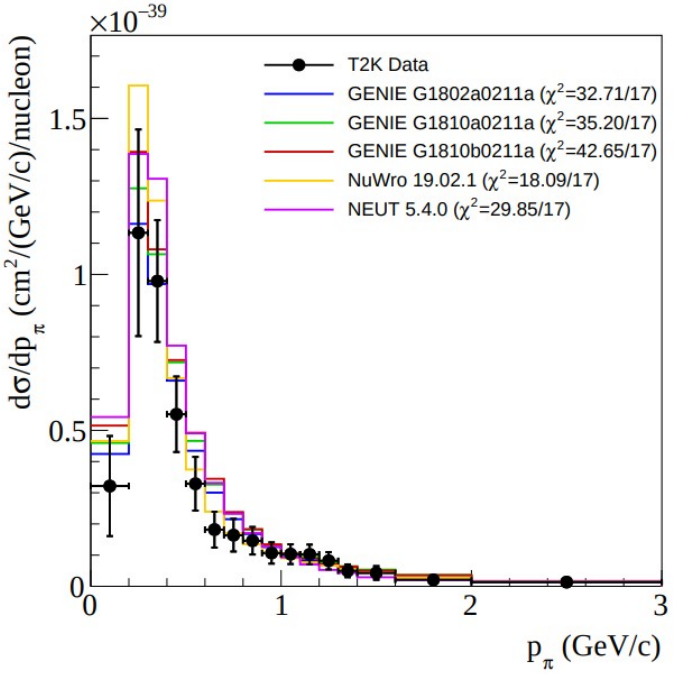


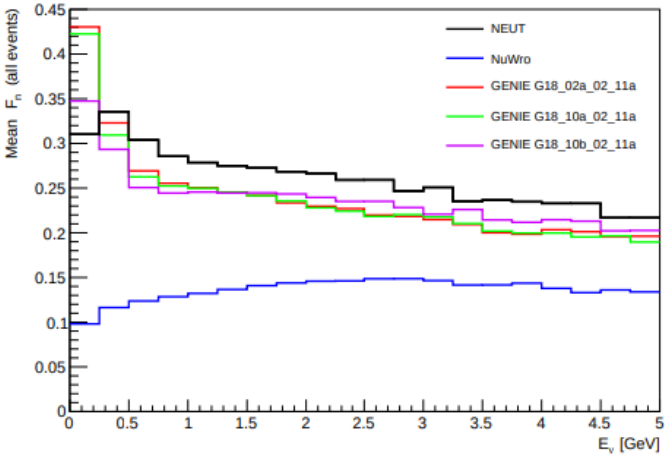
See Laura's ND280 upgrade NuInt talk

Recent examples

- Pittsburgh tensions workshop (M. Buizza Avanzini et al., Phys.Rev.D 105 (2022) 9, 092004)
  - Aimed to get experiment and generator experts together to understand model dependence and current experimental data (amongst others!)
  - Used multiple generators to form predictions against data, against efficiency curves, and how much energy carried away by neutral particles



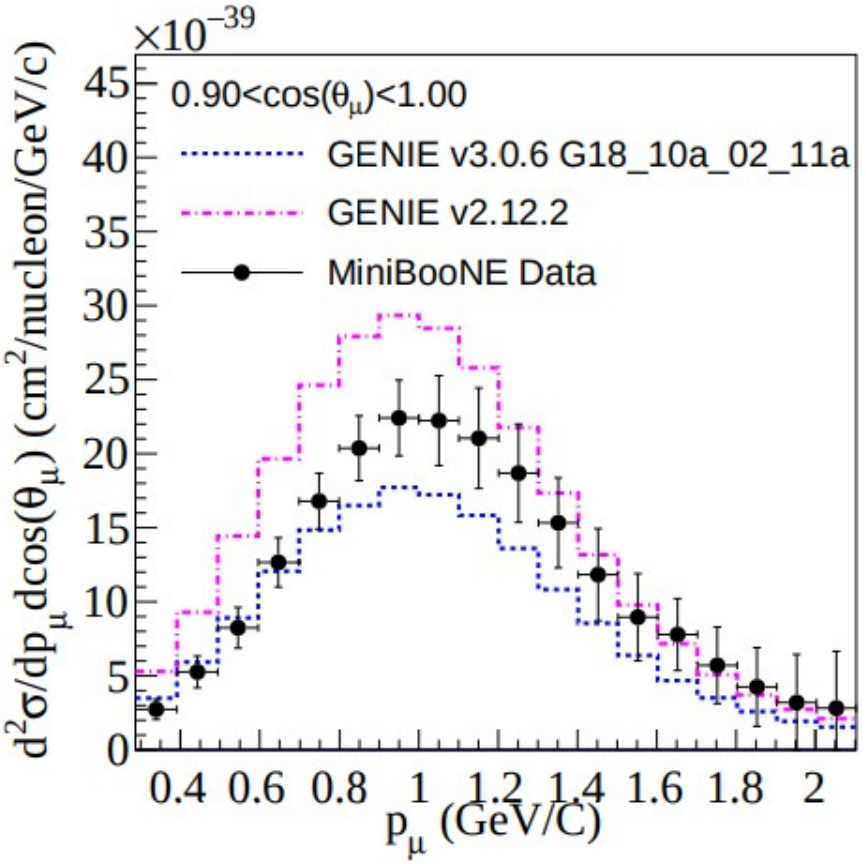


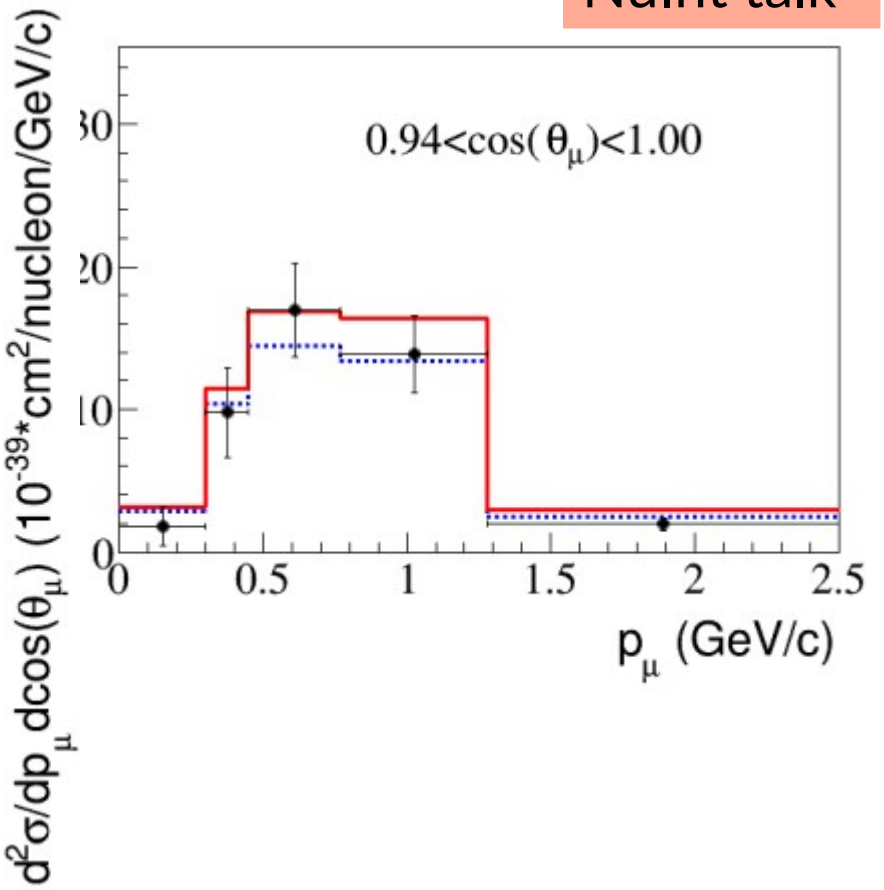


Recent examples

- MicroBooNE CCQE model tuning (P Abratenko et al. Phys.Rev.D 105 (2022) 7, 072001)

See Xin's NuInt talk

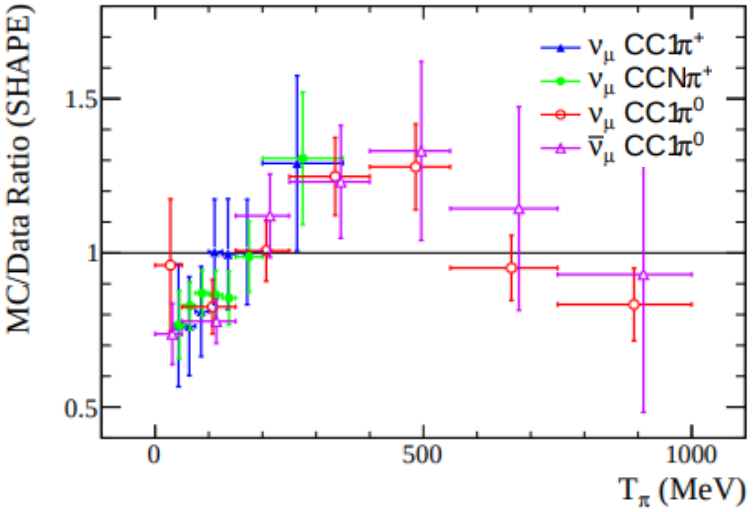


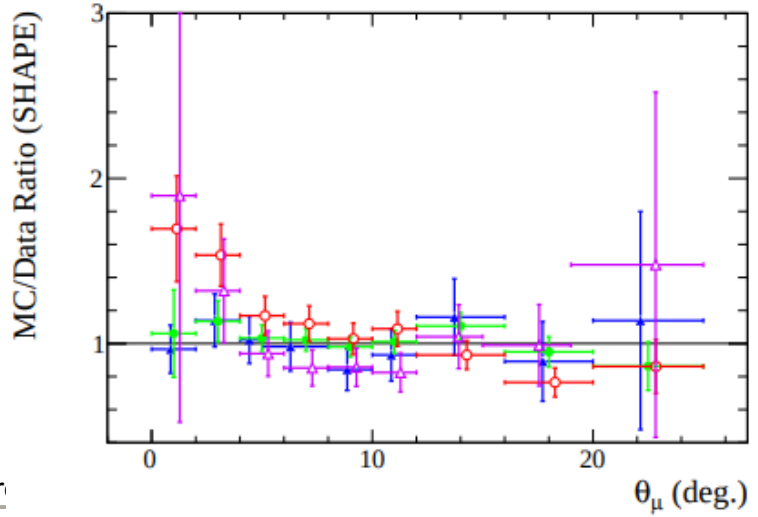


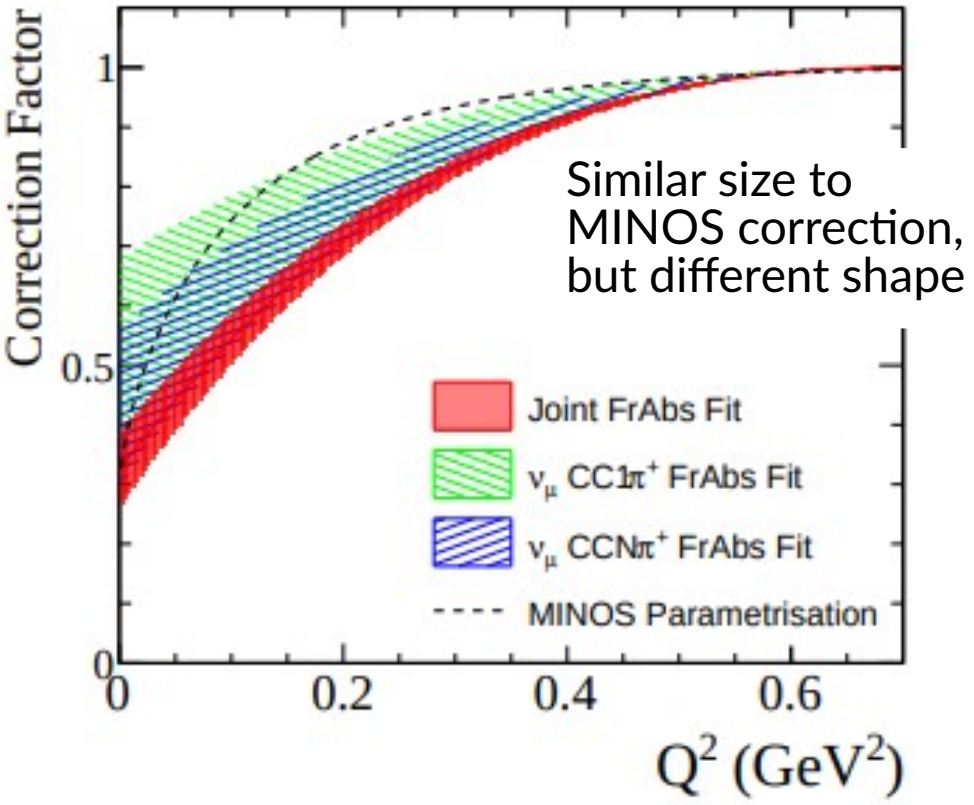
  - Tuned CCQE and 2p2h model to T2K CC0π to estimate input uncertainty into oscillation ananlysis

Recent examples

- MINERvA single pion tune (P. Stowell et al., Phys.Rev.D 100 (2019) 7, 072005)
  - Used publicly available CC pion data from MINERvA to develop a low Q^2 suppression for GENIE v2







Similar size to MINOS correction, but different shape

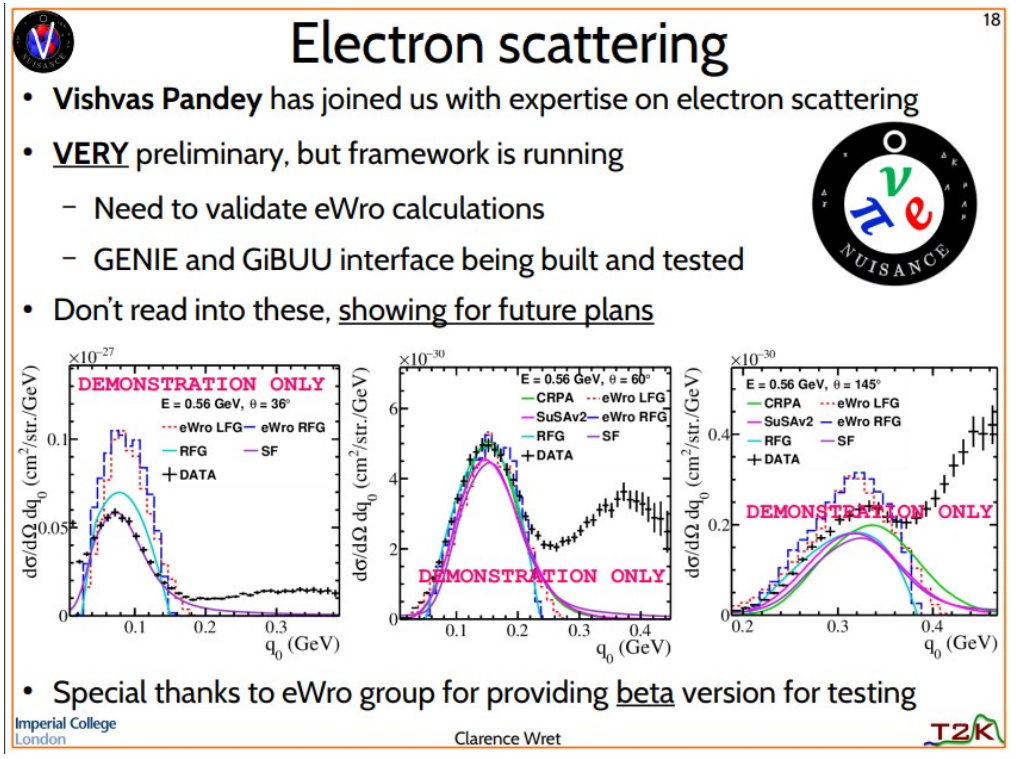
What is needed from community

- Full and reliable covariance matrices
  - If you don't understand the covariance matrix, we probably won't either
- Better understanding of the measurements
  - If the χ^2 for your measurement is huge, where does it come from?
- Clearly defined signal definitions
- Prefer a well understood selection efficiency over maximising the phase space coverage
  - If you can't measure it, don't claim to measure it
  - Avoid model-dependent cross-section extraction
- Let's have more NuInt! More dedicated conferences and workshops to continue to foster cross-experiment and experiment-theory collaboration!

Future

- Continue implementing measurements as they are released
- Support the generators as they expand
- Include new generators as they become available
- Officialise a set of containers to further simplify user experience
  - Possibly also include large MC samples if this is of interest
- Work on expanding NUISANCE for electron and pion scattering has started and was working, but needs some love

NuInt 2017



Summary

- NUISANCE compares neutrino interaction generators to themselves and external data
- Open source tool (GPLv3) developed for the community, and open to collaboration and use
- Interfaces to reweighting libraries and supports its own reweighting machinery
- Talks to minimisation routines (e.g. Minuit, MCMC) to fit models to data or fake data
- Builds uncertainty bands against selected data or generators
- (Hopefully) making your voyage across the seas of neutrino interaction uncertainties a little smoother!

Thanks

nuisance-xsec.slack.com