

GENIE Systematic Errors



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OUTLINE

- 1) History/Context
- 2) Neutrino-Nucleon Interaction Modeling
 - Free nucleon cross section model
 - Free nucleon hadronization model
- 3) Neutrino-Nucleus Interaction Modeling
 - The intranuclear rescattering model
- 4) Lessons Learned / Thoughts for the Future

Q: Where do GENIE's estimates for systematic errors come from?

A: This is Easy!!!
\$GENIE/src/GSystUncertaintycxx

```

//_
void GSystUncertainty::SetDefaults(void)
{
    this->SetUncertainty( kXSecTwkDial_MaNCEL,          0.25, 0.25);
    this->SetUncertainty( kXSecTwkDial_EtaNCEL,         0.30, 0.30);
    this->SetUncertainty( kXSecTwkDial_NormCCQE,        0.20, 0.15);
    this->SetUncertainty( kXSecTwkDial_MaCCQEshape,     0.10, 0.10);
    this->SetUncertainty( kXSecTwkDial_MaCCQE,          0.25, 0.15);
    this->SetUncertainty( kXSecTwkDial_ZNormCCQE,        0.20, 0.15);
    this->SetUncertainty( kXSecTwkDial_ZExpA1CCQE,      0.14, 0.14);
    this->SetUncertainty( kXSecTwkDial_ZExpA2CCQE,      0.67, 0.67);
    this->SetUncertainty( kXSecTwkDial_ZExpA3CCQE,      1.00, 1.00);
    this->SetUncertainty( kXSecTwkDial_ZExpA4CCQE,      0.75, 0.75);
    this->SetUncertainty( kXSecTwkDial_NormCCRES,       0.20, 0.20);
    this->SetUncertainty( kXSecTwkDial_MaCCRESshape,    0.10, 0.10);
    this->SetUncertainty( kXSecTwkDial_MvCCRESshape,    0.05, 0.05);
    this->SetUncertainty( kXSecTwkDial_MaCCRES,          0.20, 0.20);
    this->SetUncertainty( kXSecTwkDial_MvCCRES,          0.10, 0.10);
    this->SetUncertainty( kXSecTwkDial_NormNCRES,        0.20, 0.20);
    this->SetUncertainty( kXSecTwkDial_MaNCRESshape,    0.10, 0.10);
    this->SetUncertainty( kXSecTwkDial_MvNCRESshape,    0.05, 0.05);
    this->SetUncertainty( kXSecTwkDial_MaNCRES,          0.20, 0.20);
    this->SetUncertainty( kXSecTwkDial_MvNCRES,          0.10, 0.10);
    this->SetUncertainty( kXSecTwkDial_MaCOHpi,          0.40, 0.40);
    this->SetUncertainty( kXSecTwkDial_R0COHpi,          0.10, 0.10);
    this->SetUncertainty( kXSecTwkDial_RvpCC1pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvpCC2pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvpNC1pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvpNC2pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvnCC1pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvnCC2pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvnNC1pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvnNC2pi,         0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarpCC1pi,       0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarpCC2pi,       0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarpNC1pi,       0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarpNC2pi,       0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarnCC1pi,        0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarnCC2pi,        0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarnNC1pi,        0.50, 0.50);
    this->SetUncertainty( kXSecTwkDial_RvbarnNC2pi,        0.50, 0.50);

    // From Debdatta's thesis:
    //   Aht = 0.538 +/- 0.134
    //   Bht = 0.305 +/- 0.076
    //   CV1u = 0.291 +/- 0.087
    //   CV2u = 0.189 +/- 0.076

    this->SetUncertainty( kXSecTwkDial_AhtBY,             0.25, 0.25);
    this->SetUncertainty( kXSecTwkDial_BhtBY,              0.25, 0.25);
    this->SetUncertainty( kXSecTwkDial_CV1uBY,             0.30, 0.30);
    this->SetUncertainty( kXSecTwkDial_CV2uBY,             0.40, 0.40);

    this->SetUncertainty( kXSecTwkDial_AhtBYshape,        0.25, 0.25);
    this->SetUncertainty( kXSecTwkDial_BhtBYshape,         0.25, 0.25);
    this->SetUncertainty( kXSecTwkDial_CV1uBYshape,        0.30, 0.30);
    this->SetUncertainty( kXSecTwkDial_CV2uBYshape,        0.40, 0.40);

    this->SetUncertainty( kXSecTwkDial_DISNuclMod,        1.00, 1.00);
    this->SetUncertainty( kSystNucl_CCQEPAULISupViaKF, 0.30, 0.30);
    this->SetUncertainty( kHadAGKYTwkDial_xF1pi,          0.20, 0.20);
    this->SetUncertainty( kHadAGKYTwkDial_pT1pi,          0.03, 0.03);
    this->SetUncertainty( kHadNuclTwkDial_FormZone,      0.50, 0.50);

    // From INTRANUKE pi+A and N+A mode comparisons with hadron
    scattering data:
    //

    this->SetUncertainty( kINukeTwkDial_MFP_pi,           0.20, 0.20);
    this->SetUncertainty( kINukeTwkDial_MFP_N,              0.20, 0.20);
    this->SetUncertainty( kINukeTwkDial_FrCEEx_pi,         0.50, 0.50);
    this->SetUncertainty( kINukeTwkDial_FrElas_pi,         0.10, 0.10);
    this->SetUncertainty( kINukeTwkDial_FrInel_pi,         0.40, 0.40);
    this->SetUncertainty( kINukeTwkDial_FrAbs_pi,          0.30, 0.30);
    this->SetUncertainty( kINukeTwkDial_FrPiProd_pi,       0.20, 0.20);
    this->SetUncertainty( kINukeTwkDial_FrCEEx_N,          0.50, 0.50);
    this->SetUncertainty( kINukeTwkDial_FrElas_N,          0.30, 0.30);
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    this->SetUncertainty( kINukeTwkDial_FrAbs_N,           0.20, 0.20);
    this->SetUncertainty( kINukeTwkDial_FrPiProd_N,         0.20, 0.20);

    this->SetUncertainty( kRDcyTwkDial_BR1gamma,          0.50, 0.50);
    this->SetUncertainty( kRDcyTwkDial_BR1eta,             0.50, 0.50);
}

```



THE BEATLES

stereo

HELP!

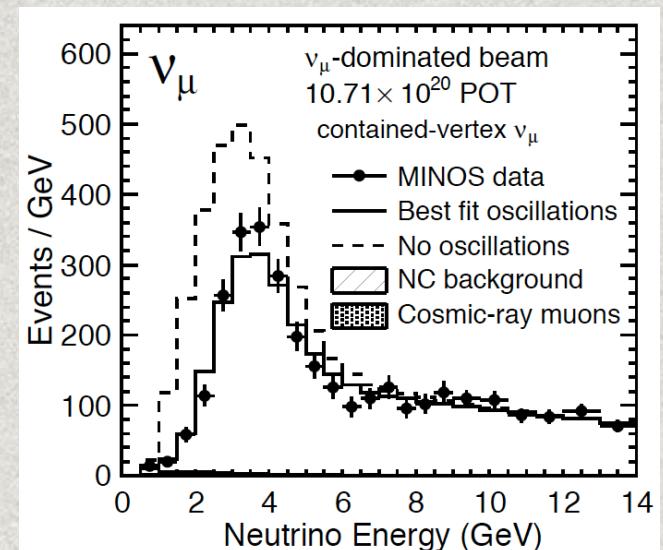


History

neugen3: HG, Nucl.Phys.Proc.Suppl. 112 (2002) 188-194

Many of the core GENIE models were first implemented in the *neugen3* generator in 2005-2006:

- $\nu\bar{\nu}$ -Free nucleon cross section model
- $\nu\bar{\nu}$ -hA intranuclear rescattering model
 - S. Dytman, HG, M. Kordosky, arXiv:0806:2119 (2008).
- $\nu\bar{\nu}$ -AGKY hadronization model
 - T. Yang et al., Eur.Phys.J. C63 (2009) 1-10.
 - T. Yang and J. Boehm Ph. D Theses (MINOS).



Adamson et al., Phys.Rev.Lett. 110 (2013) 251801

Like GENIE, *neugen3* was publicly available, but unlike GENIE, was not ‘universal’, and development was focussed on the needs of its main user, **MINOS**.

As a ‘single user’ activity, effort was available, but deadlines were pretty strict.

History

Since MINOS is an oscillation experiment and has a Near Detector, the generator was essentially providing an ‘effective model’.

Two bursts of activity:

- Development of models that could reasonably accurately describe the Near Detector data (CC inclusive, hadronization model).
- Discussions about the assignment of systematic errors for these models.

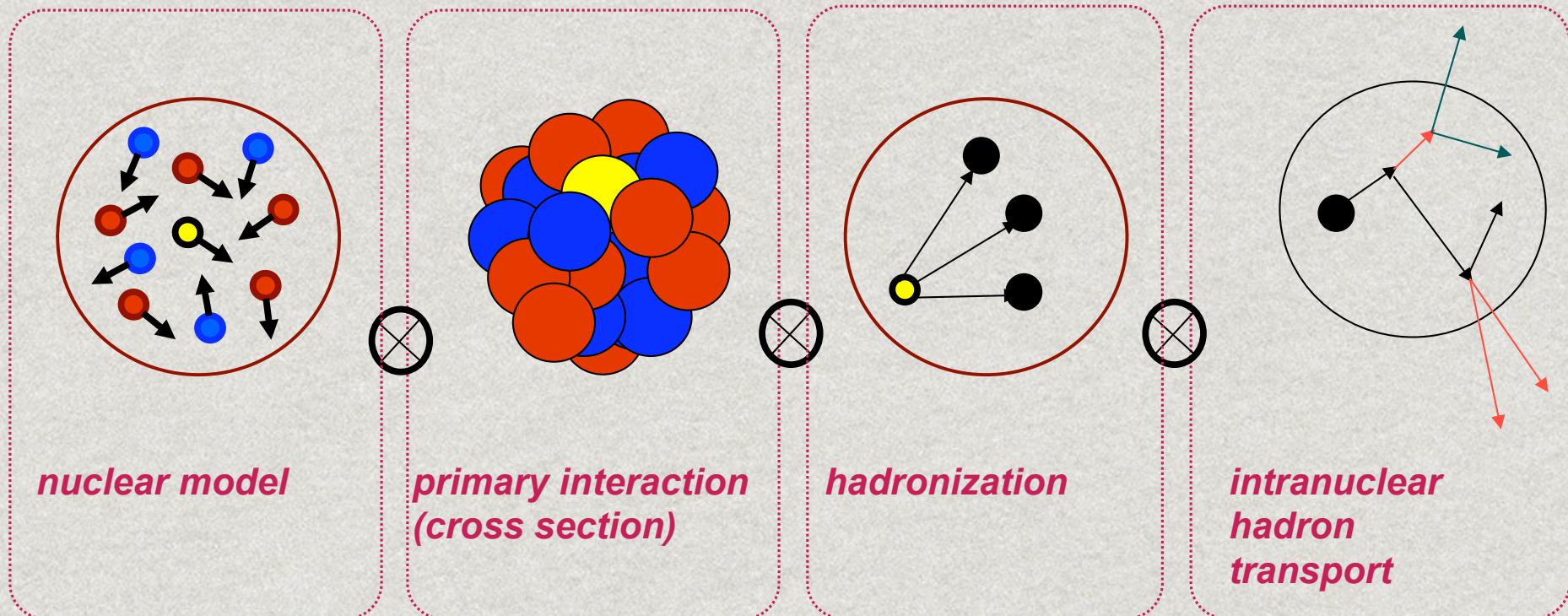
In the context of an oscillation fit, the question was not ***how good the model is***, but ***how wrong it could be***.

Involved many Minoans: C. Andreopoulos, D. Bhattacharya, J. Boehm, S. Dytman, HG, R. Gran, R. Hatcher, M. Kordosky, T. Mann, D. Michael, S. Mishra, J. Morfin, D. Naples, T. Yang.

Incorporated into GENIE and updated in T2K studies (2010) by C. Andreopoulos, J. Dobson +.

Stages of Generation

C. Andreopoulos



```

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    this->SetUncertainty( kINukeTwkDial_FrPiProd_N,            0.20, 0.20);

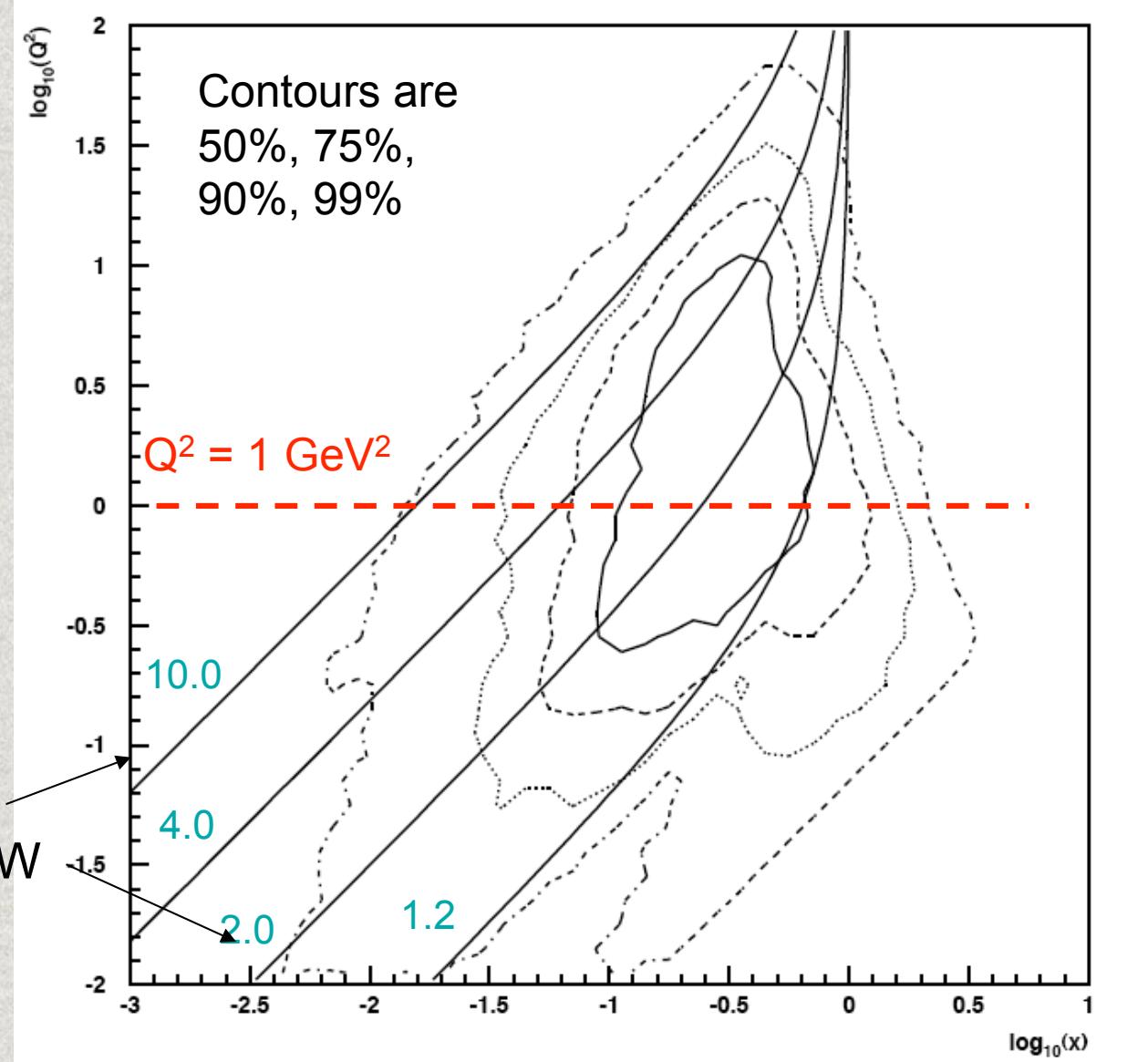
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    this->SetUncertainty( kRDcyTwkDial_BR1eta,                0.50, 0.50);
}

```

3 Ingredients: QEL, Resonance, "DIS"

Kinematic Coverage of the NuMI LE beam

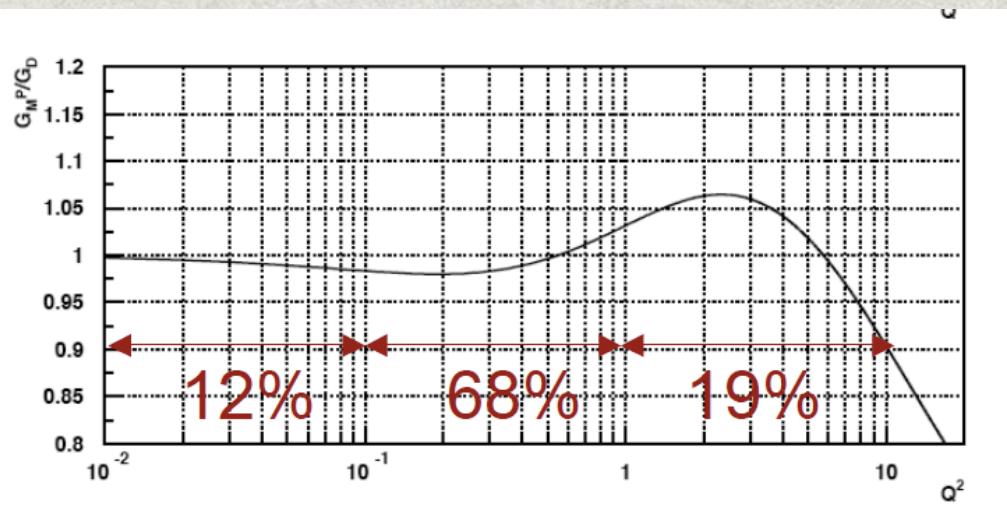
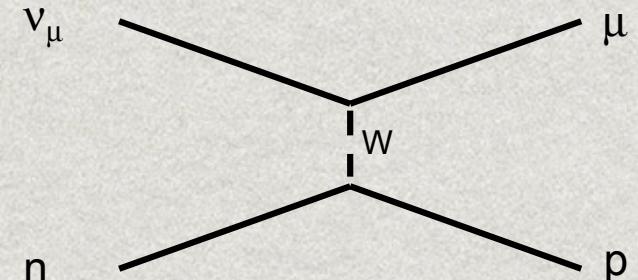
Lines of constant W



Quasi-Elastic

C.H. Lwellyn-Smith
Phys.Rept. 3 (1972) 261-379

$$\langle p(p_2) | J_\lambda^+ | n(p_1) \rangle = \\ \bar{u}(p_2) \left[\gamma_\lambda F_V^1(q^2) + \frac{i\sigma_{\lambda\nu} q^\nu \xi F_V^2(q^2)}{2M} + \gamma_\lambda \gamma_5 F_A(q^2) + \frac{q_\lambda \gamma_5 F_P(q^2)}{M} \right] u(p_1)$$



BBBA05 form factors (hep-ex/0602017) with dipole for axial: $M_A=0.99 \text{ GeV}/c^2$.

$$\frac{d\sigma}{dQ^2} = \frac{G_F^2 M^2}{8\pi E_\nu^2} \left[A \mp \frac{(s-u)}{M^2} B + \frac{(s-u)^2}{M^4} C \right]$$

$$A = \frac{(m^2 + Q^2)}{M^2} \left[(1 + \tau) F_A^2 - (1 - \tau) F_1^2 + \tau (1 - \tau) F_2^2 + 4\tau F_1 F_2 - \frac{m^2}{4M^2} ((F_1 + F_2)^2 + (F_A + 2F_P)^2 - \left(\frac{Q^2}{M^2} + 4 \right) F_P^2) \right]$$

$$B = \frac{Q^2}{M^2} F_A (F_1 + F_2)$$

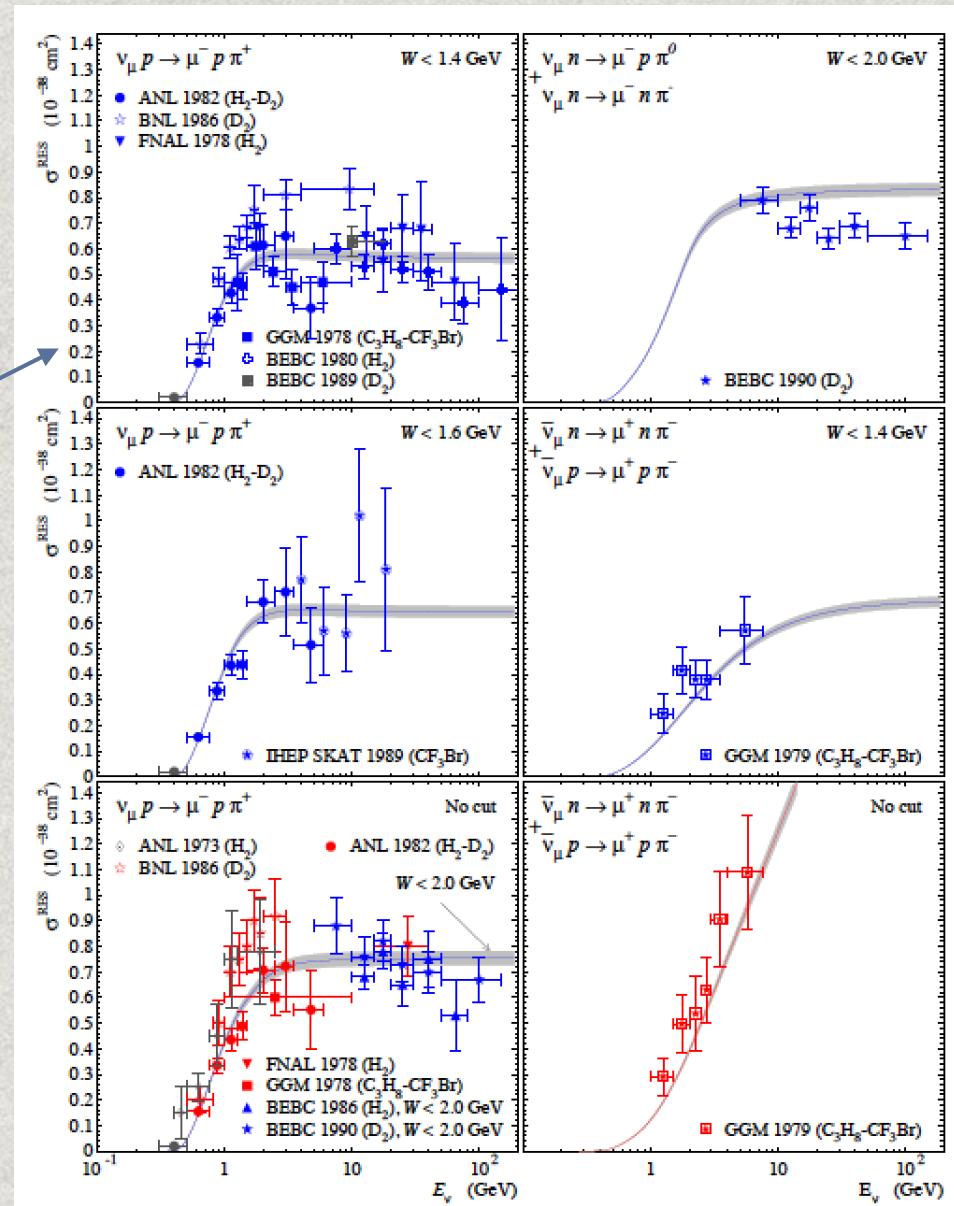
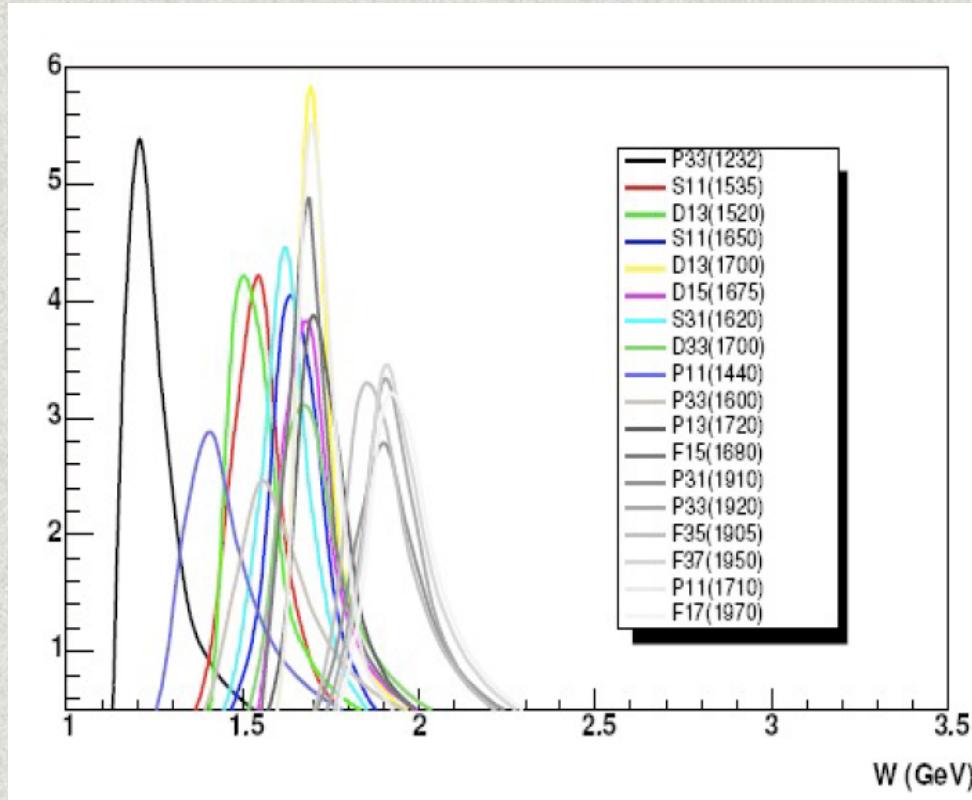
$$C = \frac{1}{4} (F_A^2 + F_1^2 + \tau F_2^2)$$

Resonances

Model from Rein-Sehgal [1]
calculates hadronic resonances
up to $W=1.7 \text{ GeV}/c^2$.

$$M_A^{\text{RES}} = 1.12 \pm 0.03 \text{ GeV} \quad (\chi^2/\text{ndf} = 1.14).$$

[2].



[1] D. Rein and L. Sehgal, Annals Phys. 133: 79, 1981.

[2] K. Kuzmin et al., Acta Phys.Polon. B37 (2006) 2337-2348.

Bodek / Yang model

Based on LO cross section models with new scaling variable to account for higher twists and modified PDFs to describe low-Q² data

$$\xi_w = \frac{2x(Q^2 + M_f^2 + B)}{Q^2[1 + \sqrt{1 + (2Mx)^2/Q^2}] + 2Ax}$$

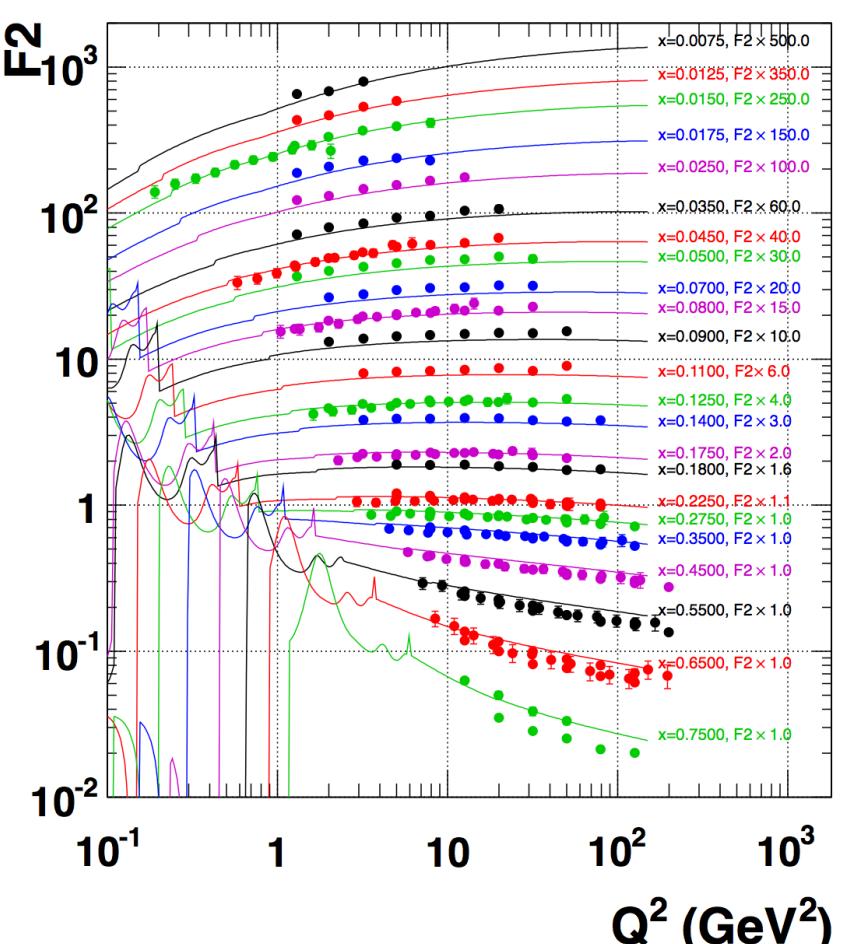
$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}$$

$$K_{valence}(Q^2) = [1 - G_D^2(Q^2)] \times \left(\frac{Q^2 + C_{v2}}{Q^2 + C_{v1}} \right)$$

Fits based on GRV98LO and free nucleon charged lepton data

[[hep-ph/0411202](#)]

“Deep” Inelastic Scattering



M_A Uncertainty

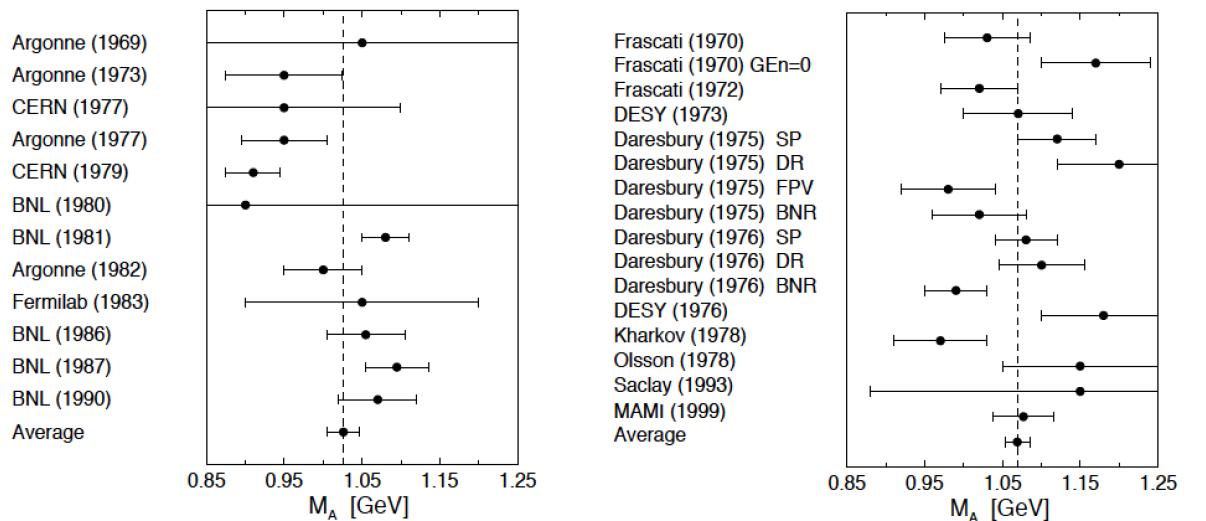


Figure 1. Axial mass M_A extractions. Left panel: From (quasi)elastic neutrino and antineutrino scattering experiments. The weighted average is $M_A = (1.026 \pm 0.021)$ GeV. Right panel: From charged pion electroproduction experiments. The weighted average is $M_A = (1.069 \pm 0.016)$ GeV. Note that value for the MAMI experiment contains both the statistical and systematical uncertainty; for other values the systematical errors were not explicitly given. The labels SP, DR, FPV and BNR refer to different methods evaluating the corrections beyond the soft pion limit as explained in the text.

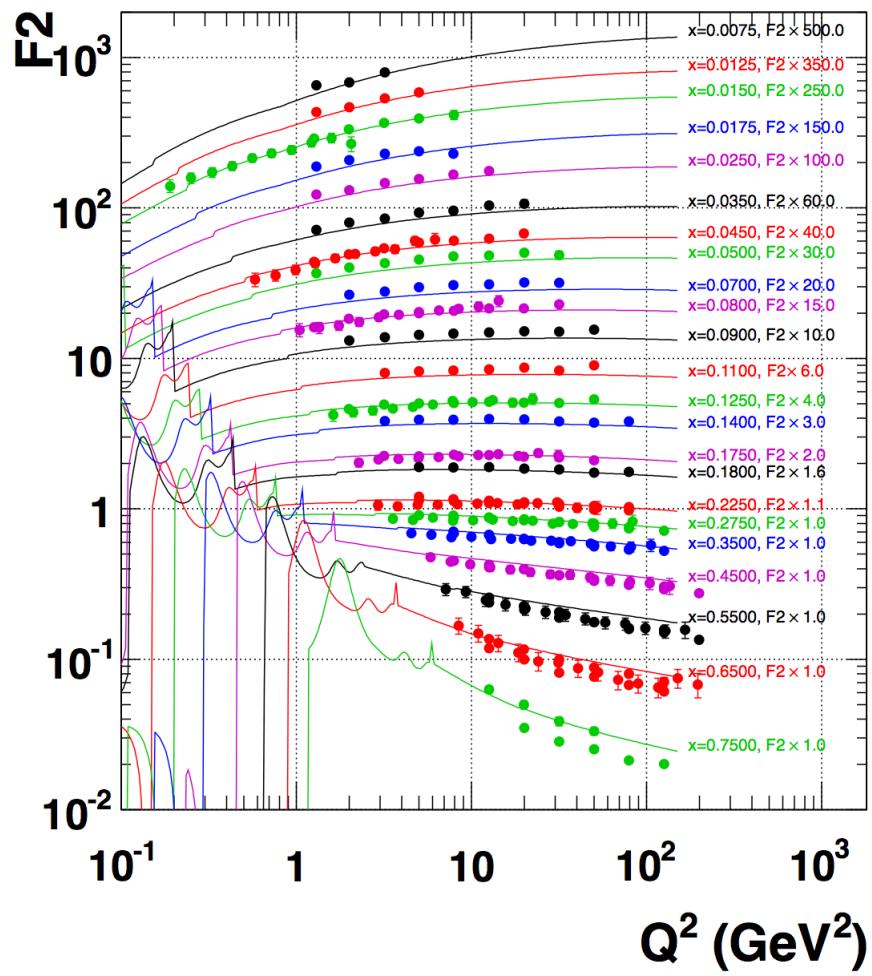
The average of the corrected measurements of M_A from Table 3 is $M_A^{deuterium} = 1.016 \pm 0.026$ GeV/c^2 . This is in agreement the average value of $M_A^{pion} = 1.014 \pm 0.016$ GeV/c^2 extracted from pion electroproduction experiments after corrections for hadronic effects. [12]. The average of the ν_μ and electroproduction values is

$$M_A^{world-average} = 1.014 \pm 0.014 \text{ GeV}/c^2.$$

V. Bernard et al.,
J.Phys. G28 (2002) R1-R35

A. Bodek et al.,
Eur.Phys.J. C53 (2008) 349-354

Bodek-Yang Model



Parameter	Value	Error
A	0.538	0.134
B	0.305	0.076
C_{v1u}	0.291	0.087
C_{v2u}	0.189	0.076
C_{v1d}	0.202	small
C_{v2d}	0.255	small
C_{su}	0.363	small
C_{sd}	0.621	small

Table 5.3: Parameters for the DIS model used in NEUGEN. The right hand column shows the errors on these parameters. The parameters have been taken from Ref.[5].

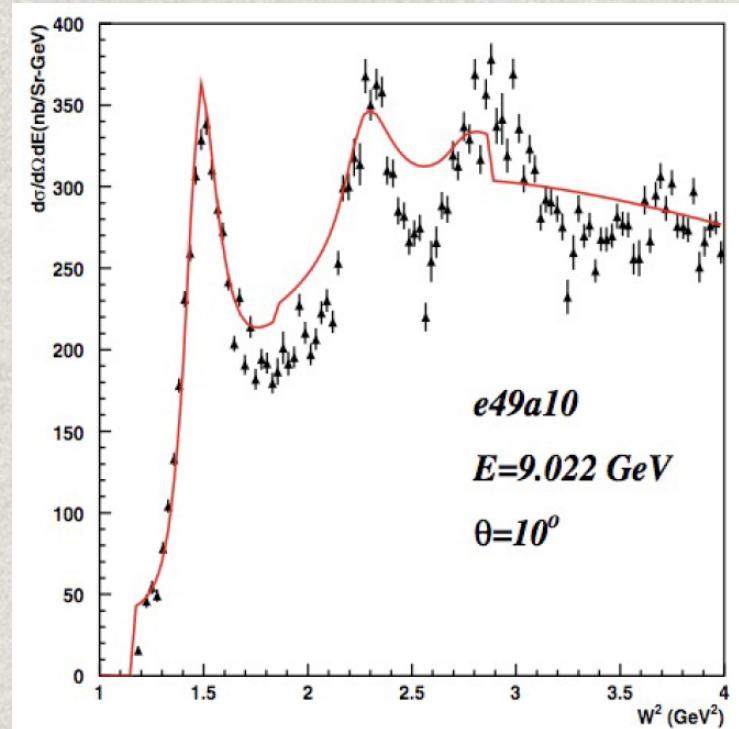
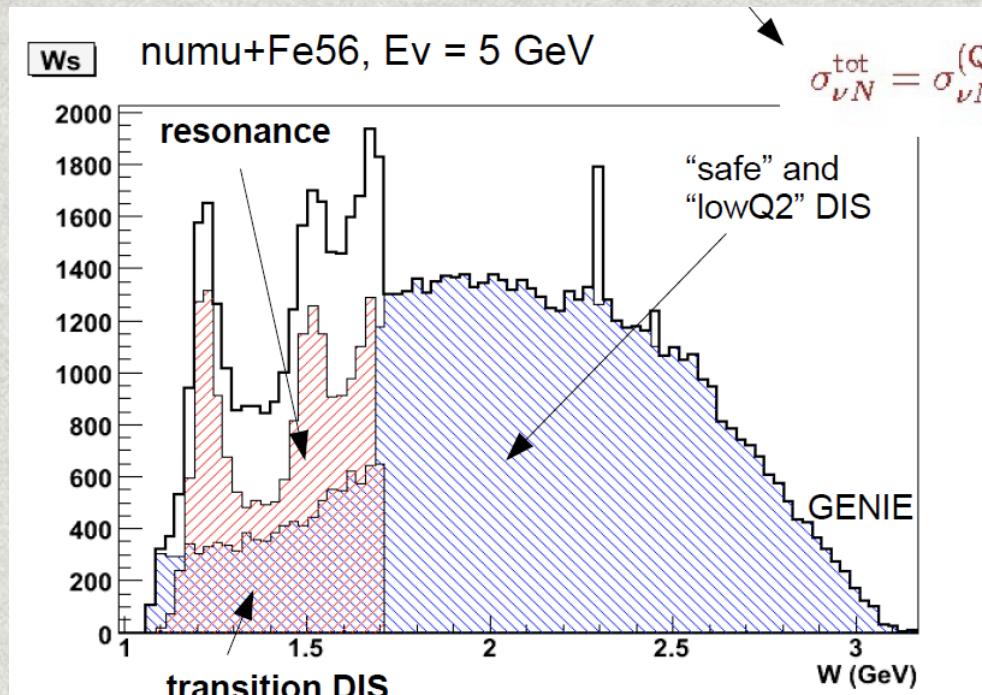
D. Bhattacharya Ph. D Thesis (2009).
J.Phys. G28 (2002) R1-R35

Stitching it Together

For each (CC/NC=i) and (initial state=j), calculate the BY contribution to each exclusive channel (=k).

Dial down the contribution by a factor (r_{ijk}) so that the sum of this contribution and the Rein-Sehgal prediction fits the data for this channel.

Treat four as independent: $r_{112}=0.1$, $r_{122}=0.3$, $r_{113}=1.0$, $r_{123}=1.0$.



Stitching it Together

For each of CC/NC
nu/nubar, n/p

$$\frac{d\sigma}{d\theta dE'}^{RES} = \sum_{i=1}^{17} \frac{d\sigma}{d\theta dE'}^i \Theta(W_{cut} - W)$$

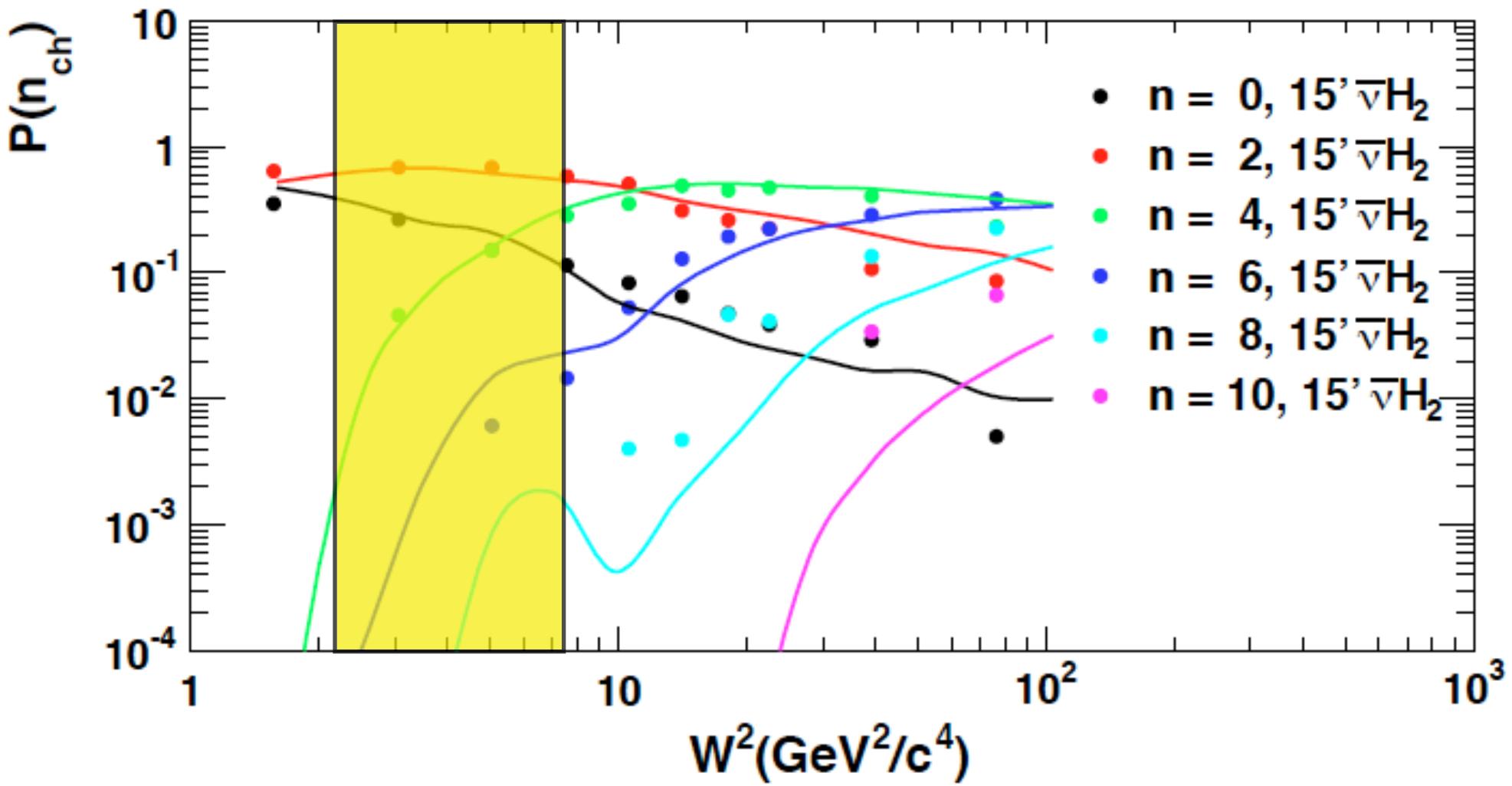
$$\frac{d\sigma}{d\theta dE'} = \frac{d\sigma}{d\theta dE'}^{RES} + \frac{d\sigma}{d\theta dE'}^{DIS}$$

$$W_{Cut} = 1.7 \text{ GeV}/c^2$$

$$\frac{d\sigma}{d\theta dE'}^{DIS} = \frac{d\sigma}{d\theta dE'}^{DIS-BY} \Theta(W - W_{cut}) + \frac{d\sigma}{d\theta dE'}^{DIS-BY} \Theta(W_{cut} - W) \sum_k f_k$$

$$f_k = r_k P_k^{KNO}$$

P_k : Probability of hadronization into channel k
 r_k : Reduction factor to avoid double counting with resonances



Resonance model, parameters like m_A .

$d\sigma/dW$ for the non-resonant inclusive model

The assignment of $d\sigma/dW$ into particular multiplicities (Levy function).

The parameters that remove part of the low multiplicity non-resonant inclusive cross section.

The branching ratio for multiplicity m to channel X.

Original Tuning

- 1) Electron scattering data
- 2) Pin Down Exclusive channels

Coherent model

QEL-MA from global fits

RES-MA from global fits

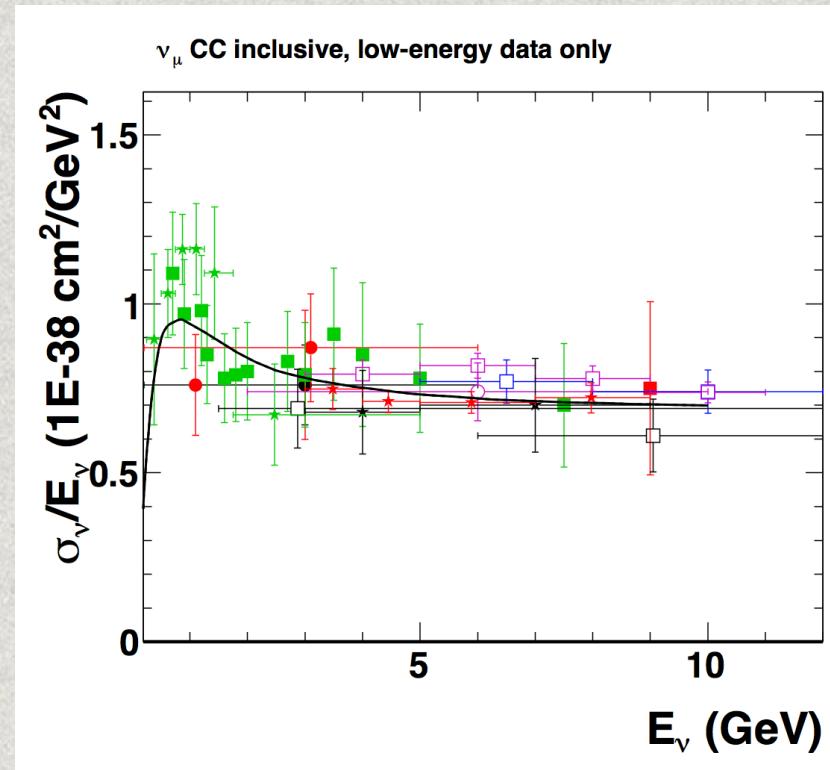
- 3) High energy

Compare F_2 and xF_3 to charged lepton and neutrino data.

Compare to known cross sections at high energy.

- 4) “Transition region”

Finalize tune to inclusive and exclusive (1 and 2 π) channels at intermediate energy (1-10 GeV).



Problem: DIS Scale Factor

Oct 2006

Overall DIS scale factor is 1.032. Applied uniformly to all DIS processes (NC,ubar). Determined from matching the world average neutrino cross section at 100 GeV.

$$\sigma/E = 0.677 \pm 0.014$$

$$\bar{\sigma}/E = 0.334 \pm 0.008$$

$$r = \bar{\sigma}/\sigma = 0.493$$

	σ/E 100 GeV	$\Delta(\%)$	$\Delta(\sigma)$	$\bar{\sigma}/E$ 100 GeV	$\Delta(\%)$	$\Delta(\sigma)$	r
MODBYRS-2	0.673	-0.6	-0.29	.316	-5.4	-2.3	0.470
MODBYRS-4	0.678	+0.1	+0.07	.325	-2.7	-1.1	0.479

Problem: Single pion parameters

Oct 2006

r_{112} =CC single pi on proton //// r_{122} =single pi on neutron

The MODBYRS-4 model has more difficulty in fitting existing data.
Basic issue is that new DIS cross section approaches scaling more quickly than old.

Total cross section data prefers higher values for r_{112} and r_{122} :

$$r_{112} = r_{122} = 0.31 \pm 0.18$$

$$\chi^2 = 79.2/70$$

Single pion data dominate fit but are impossible to fit consistently. BNL only fits (no systematic errors) :

$$r_{112} = 0.01 \pm 0.02$$

$$r_{122} = 0.18 \pm 0.02$$

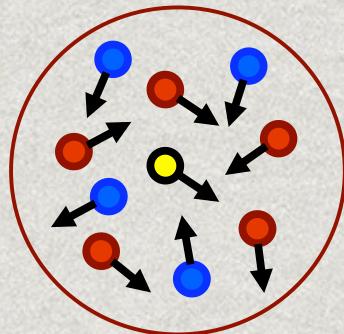
$$\chi^2 = 19.1/15$$

$$\chi^2 = 30.4/13$$

Have taken $r_{112}=0.10$, $r_{122}=0.30$. Single $\pi \sim 10\%$ high.

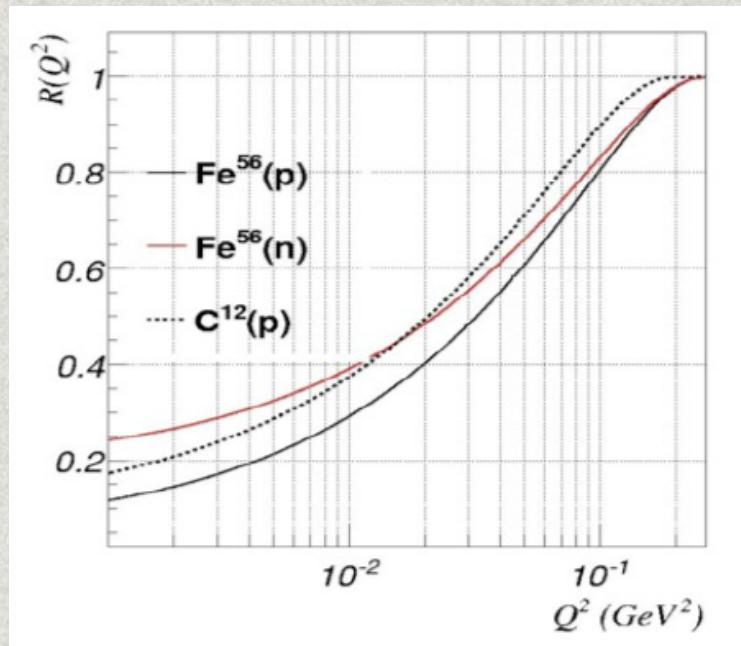
The Nucleus??

```
this->SetUncertainty( kXSecTwkDial_DISNuclMod,      1.00, 1.00);  
this->SetUncertainty( kSystNucl_CCQEPAuliSupViaKF, 0.30, 0.30);
```

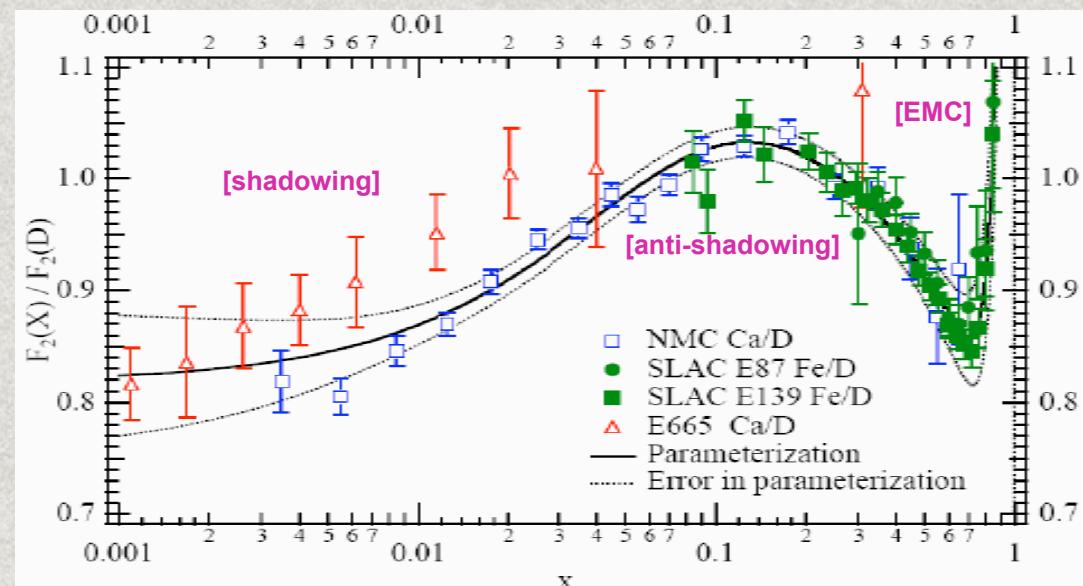


Fermi Motion

QEL: Pauli Blocking



DIS (+ SIS)



MINOS Disappearance

P. Adamson et al., Phys.Rev. D77 (2008) 072002.

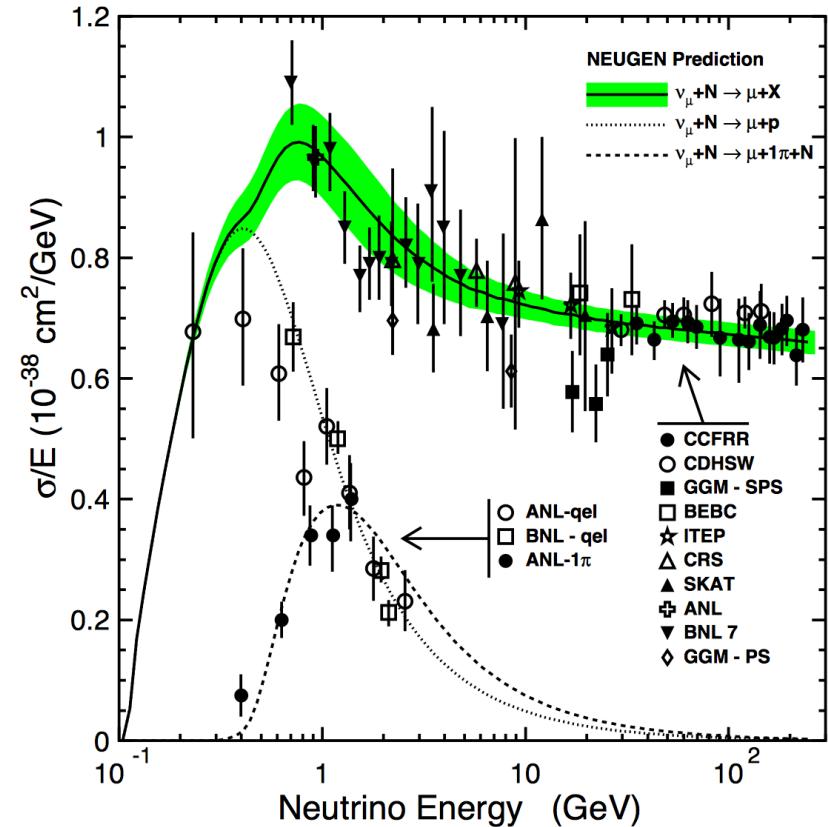


Figure 18 shows the ν_μ charged-current cross-section as a function of neutrino energy in the laboratory frame. Based on a comparison of the model predictions to independent data, some of which [34] is shown in Fig. 18, we assign a systematic uncertainty of 3% on the normalization of the DIS ($W > 1.7 \text{ GeV}/c^2$) cross-section, and a 10% uncertainty in the normalization of the single-pion and quasi-elastic cross-sections. We estimate a 20% uncertainty in the relative contribution of non-resonant states to the 1π and 2π production cross-sections for $W < 1.7 \text{ GeV}/c^2$. This uncertainty was determined from the parameter uncertainties and variations observed in fits to both inclusive and exclusive channel data, and in fits to data in different invariant mass regions. Final state interactions are expected to have a significant effect on the visible energy of the hadronic final state [41]. In particular there are significant uncertainties in the rate of pion absorption, the mechanism for transferring the pion's energy to a nucleon cluster, and the amount of energy eventually visible to the detector. We account for these uncertainties by studying the shift in the reconstructed shower energy when we turn the simulation of final-state interactions off, and when we modify the simulation so that all of an absorbed pion's energy is lost. We find that the predicted response to hadronic showers changes by approximately 10% [41] in these two extreme cases and use this as a conservative estimate of the uncertainty on the absolute hadronic energy scale.

Problem: Nucleon vs. Nucleus

The discussions about the size of these uncertainties took a significant amount of time.

Realization that our simple models might not be able to account for observations on nuclei.

(M_A from K2K, MiniBooNE, ...)

A gradual move towards accepting the role of neugen3 as an “effective model”, and that our overall systematic error treatment should account for real physics *absent* from our model.

Mechanically, errors handled through free nucleon parameters - therefore inflate these uncertainties to account for what we might be missing.

Lessons Learned [1]

It was greatly simplified by the fact it was being done for a single experiment.

This was not a ‘clean’ process.

We probably spent as much FTE on systematic error evaluation as we did on development of the original model. The former was via a broad discussion, the latter focussed work by a smaller group.

Broad expertise in neutrino scattering results (ANL/FNAL bubble chambers, NuTeV, K2K...) was very important.



Lessons Learned [2]

We did not do all the tuning and systematic error evaluation ourselves - made use of dedicated analyses focussed on particular parameters.

Challenge of thinking about models as a microscopic depiction of reality (i.e. like a theorist) vs. as an effective model to describe data (i.e. like a long-baseline experimentalist).

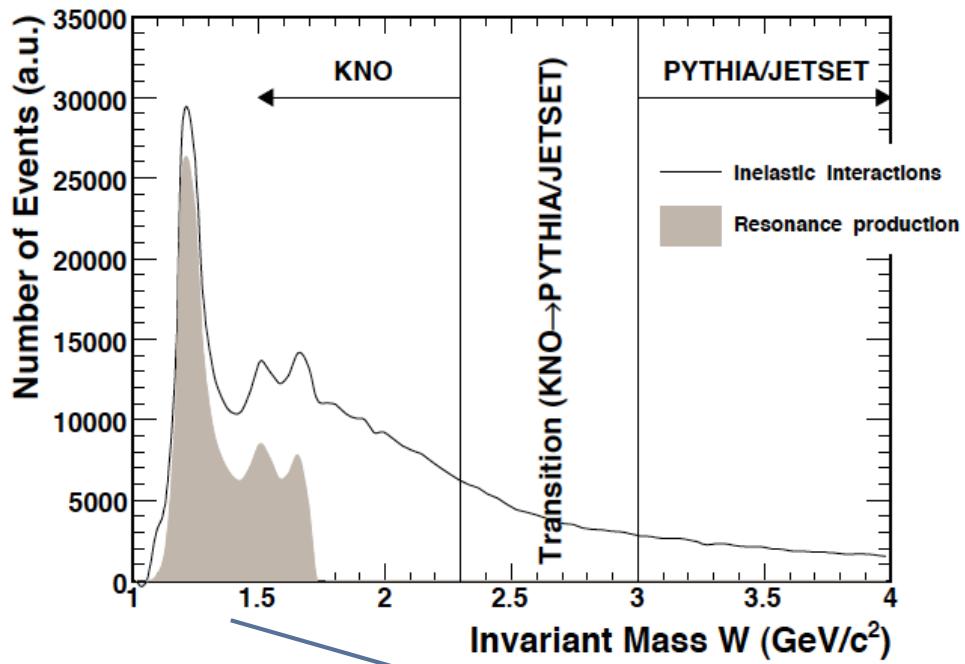
Examples:

- Conflation of free nucleon and nuclear uncertainty statements.
- Agonized over ‘breaking’ models to bring agreement with data.

Hadronization Model

T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)

PYTHIA: . Katori and S. Mandalia,
J.Phys. G42 (2015) no.11, 115004 .



```
// From Debdatta's thesis:  
//   Aht = 0.538 +/- 0.134  
//   Bht = 0.305 +/- 0.076  
//   CV1u = 0.291 +/- 0.087  
//   CV2u = 0.189 +/- 0.076  
  
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this->SetUncertainty( kXSecTwkDial_AhtBYshape,       0.25, 0.25);  
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//  
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this->SetUncertainty( kINukeTwkDial_FrAbs_N,          0.20, 0.20);  
this->SetUncertainty( kINukeTwkDial_FrPiProd_N,        0.20, 0.20);  
  
this->SetUncertainty( kRDcyTwkDial_BR1gamma,        0.50, 0.50);  
this->SetUncertainty( kRDcyTwkDial_BR1eta,          0.50, 0.50);  
}
```

Hadronization Model

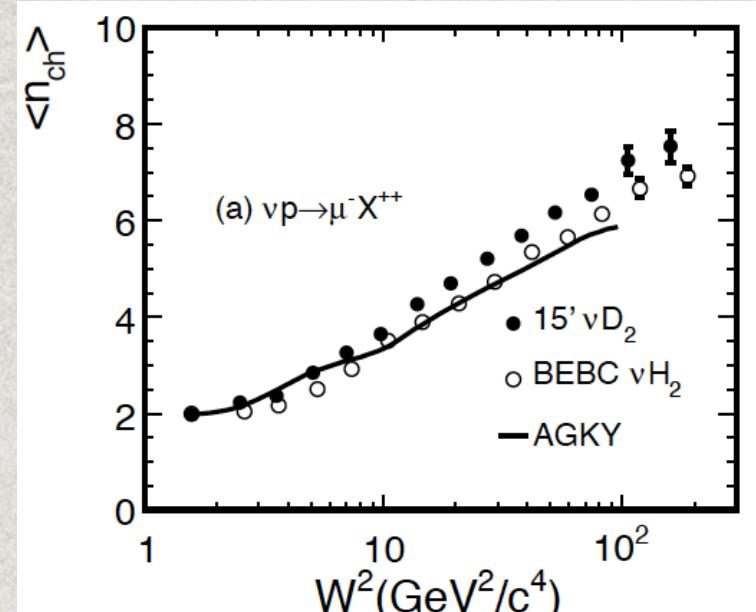
The GENIE model (AGKY) take it in two steps:

1. Decide what particles to create
2. Choose the 4-momenta of each

1.a.) Determine average multiplicity:

*T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)*

	νp	νn	$\bar{\nu} p$	$\bar{\nu} n$
a_{ch}	0.40 [7]	-0.20 [7]	0.02 [13]	0.80 [13]
b_{ch}	1.42 [7]	1.42 [7]	1.28 [13]	0.95 [13]
c_{ch}	7.93 [7]	5.22 [7]	5.22	7.93
$a_{hyperon}$	0.022	0.022	0.022	0.022
$b_{hyperon}$	0.042	0.042	0.042	0.042



$$\langle n_{ch} \rangle = a + b \log W^2$$

$$\langle n_{tot} \rangle = 1.5 \langle n_{ch} \rangle$$

[7] D. Zieminska, et al. Phys. Rev., **D27**, 47 (1983)

[13] S. Barlag, et al. Zeit. Phys., **C11**, 283 (1982)

Hadronization Model

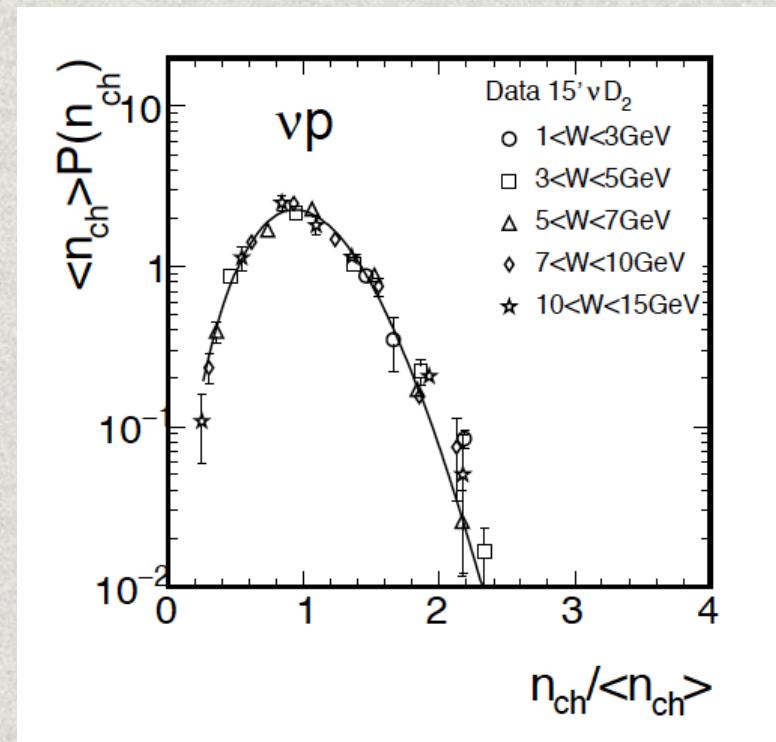
The GENIE model takes it in two steps:

1. Decide what particles to create
 2. Choose the 4-momenta of each
-
- 1.a) Determine average multiplicity.
 - 1.b) Multiplicity distribution determined from KNO scaling.

	νp	νn	$\bar{\nu} p$	$\bar{\nu} n$
a_{ch}	0.40 [7]	-0.20 [7]	0.02 [13]	0.80 [13]
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$b_{hyperon}$	0.042	0.042	0.042	0.042

T. Yang, Ph. D Thesis, Stanford U (2009)

We fit the data points to the Levy function and the best fit parameters are $c = 7.93 \pm 0.34$ for the νp interactions and $c = 5.22 \pm 0.15$ for the νn interactions.



$$\langle n \rangle P(n) = f(n / \langle n \rangle)$$

$$Levy(z; c) = \frac{2e^{-c} c^{cz+1}}{\Gamma(cz + 1)}$$

Hadronization Model

The GENIE model takes it in two steps:

1. Decide what particles to create
 2. Choose the 4-momenta of each
-
- 1.a) Determine average multiplicity.
 - 1.b) Multiplicity distribution determined from KNO scaling.
 - 1.c) Pick the baryon in the event
 - 1.d) Balance charge by creating charged pions
 - 1.e) Create remaining mesons in neutral pairs

	# particles		Probability (%) of choosing a proton for the baryon
	2	>2	
νp	100	67	
νn	33	50	
$\bar{\nu} p$	67	50	
$\bar{\nu} n$	0	33	

Pair	Probability(%)
$\pi^0 - \pi^0$	31.33
$\pi^+ - \pi^-$	62.67
$K^0 - \bar{K}^0$	3
$K^+ - K^-$	3

Hadronization Model

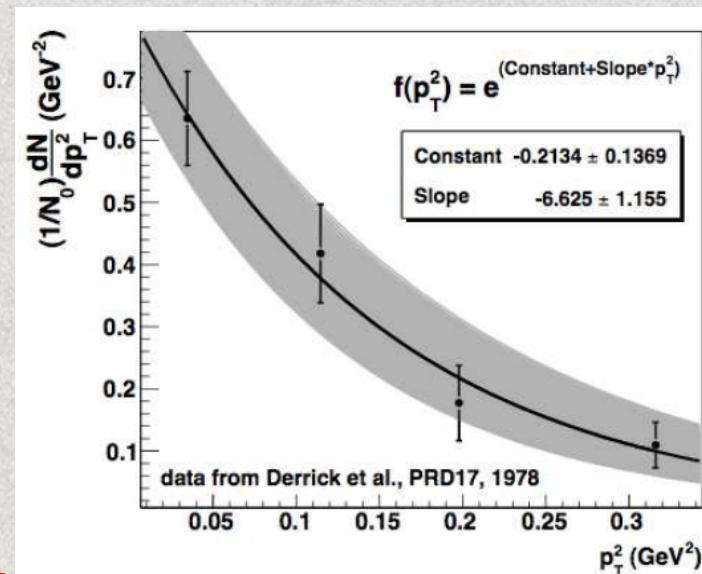
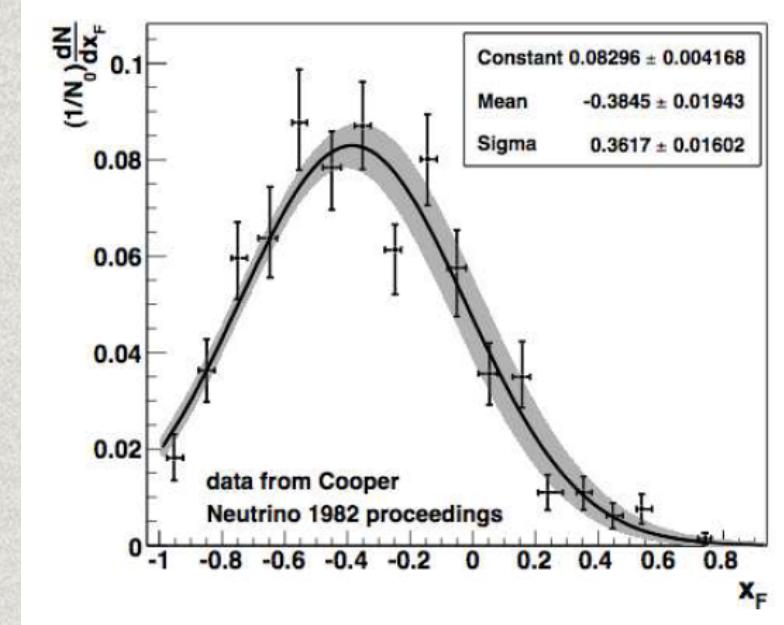
The GENIE model takes it in two steps:

1. Decide what particles to create
2. Choose the 4-momenta of each

2.a) Select baryon 4-momentum from empirical distribution $P(x_F, p_t)$.

2.b) Perform a phase space decay on the remaining particles in the hadronic system, and then “ p_t squeezing” – rejection factor based on p_t for each particle. Clegg and Donnachie, “Description of Jet Structure by p_t -limited Phase Space”, Z. Phys. C 13: 71 (1982).

$$W_i = \exp(-A^* p_t^i)$$



Hadronization Model: Understanding the Data

“Inclusive Charged Hadron Spectra in nu-A and nubar-A Interactions at $E_\nu < 30 \text{ GeV}$ ” - SKAT, ZPC 21, 197-204 (1984)

“The phase space model used reproduces the main features of our data *rather well* up to $W^2 = 25 \text{ GeV}^2$.” (emphasis mine)

“The recoil nucleon is generated with a flat distribution in Feynman x_F in the range $-0.95 < x_F < 0.00$ exponentially decreasing in the forward hemisphere.” [Cooper, Neutrino 1982]

Pictures of Hadronization

For Inelastic Processes:

- * Resonance region, all hadronic distributions calculable in principle from the resonance model. Often treated as phase space decays - isotropic in hadronic c.m.
- * At high energy: ‘current’ and ‘target’ jets.
 P_t is low.
Need to look at the interaction in the hadronic center of mass to understand the dynamics.

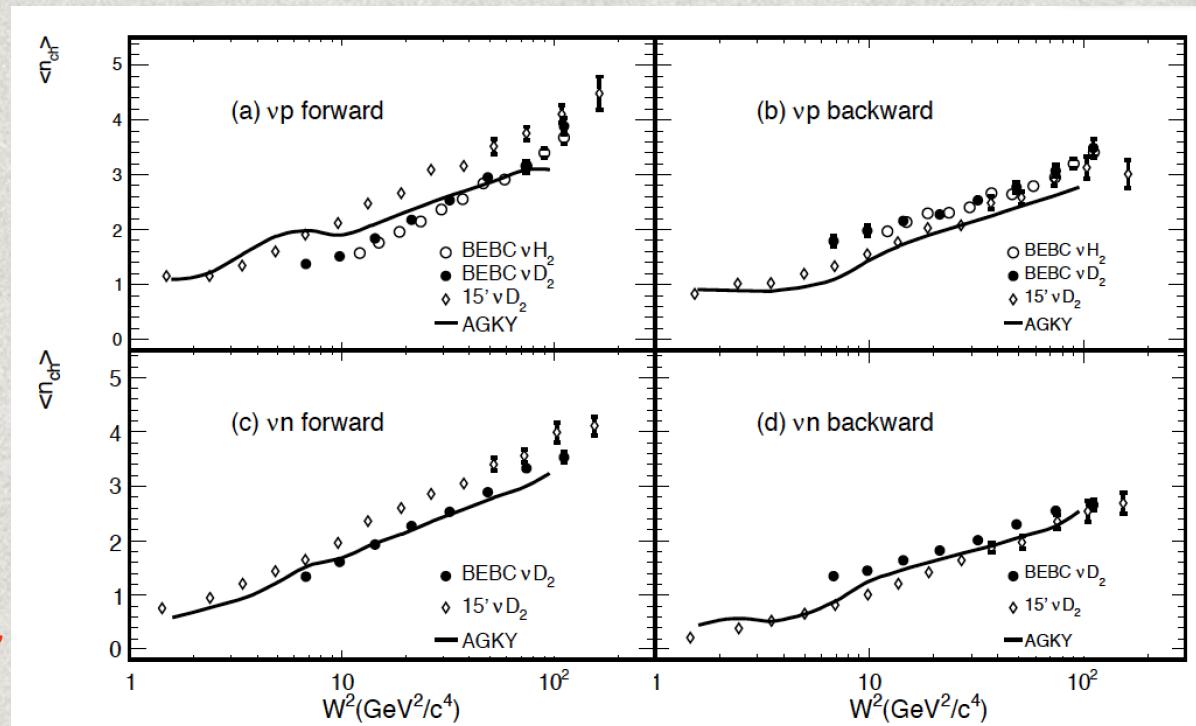
Hadronization Model: Understanding the Data

Grassler, NPB 223 (1982) 269:

"It should be noted that the results presented here for the positive multiplicities in νp scattering differ from our results published previously (Allen et al.). In contrast to ref. [1] $\langle n_{F^+} \rangle$ is now lower than $\langle n_{B^+} \rangle$ over the whole energy range ... The discrepancy is mainly due to particle misidentification which has been corrected for in this, but not in the earlier, analysis."

For nubar-p scattering we find $\langle n_{F^-} \rangle > \langle n_{B^-} \rangle$ and $\langle n_{F^+} \rangle <= \langle n_{B^+} \rangle$. The latter relation may be contrasted with the observation of a previous nubar H2 experiment (Derrick et al, PRD 25 (1982) 624), which did not correct for the $\pi:K:p$ mass assignment ambiguities and which found

$\langle n_{F^+} \rangle > \langle n_{B^+} \rangle$ "



T. Yang, Ph. D Thesis,
Stanford U (2009)

Hadronization Systematics

Because many of the key aspects of the model are ***not reweightable***, experiments often evaluate hadronization related systematics by generating samples with alternate GENIE configurations.

e.g. Replace Steps 2.a and 2.b by phase space decays:

```
<param type="bool" name="KNO-PhaseSpDec-Reweight"> false </param>
<param type="bool" name="KNO-UseBaryonPdfs-xFpT2"> false </param>
```

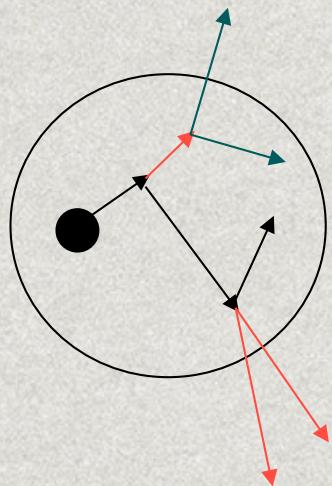
Lessons Learned [3]

Reweighting models are much preferable.

Interpreting previous measurements can *be very hard*. In contrast to the previous case, we had almost no overlap with the community that had produced these measurements.

Again, driven by specific analysis questions faced by experiments. Key studies were carried out by graduate students whose thesis measurements were impacted by these models.

Intranuclear Rescattering Model¹



Hadron in nucleus
produced at a principal
vertex
(e.g. pion production)

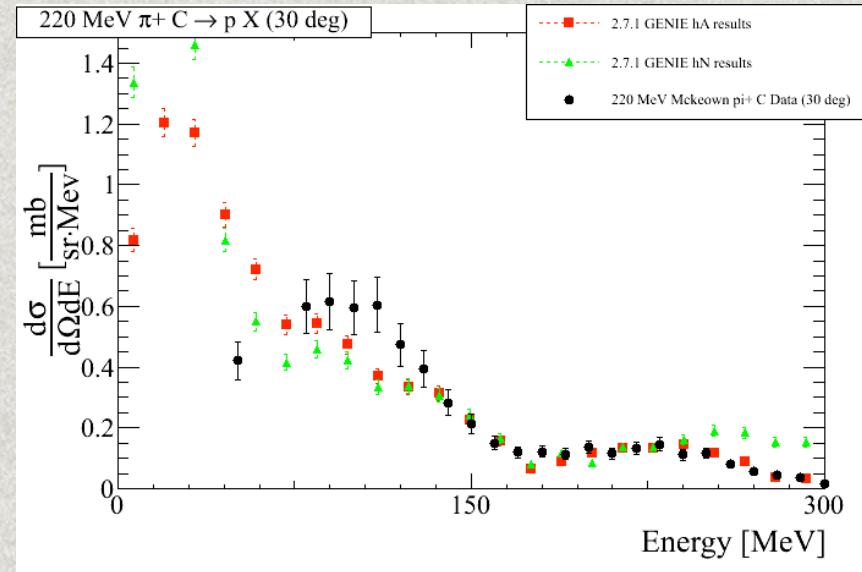
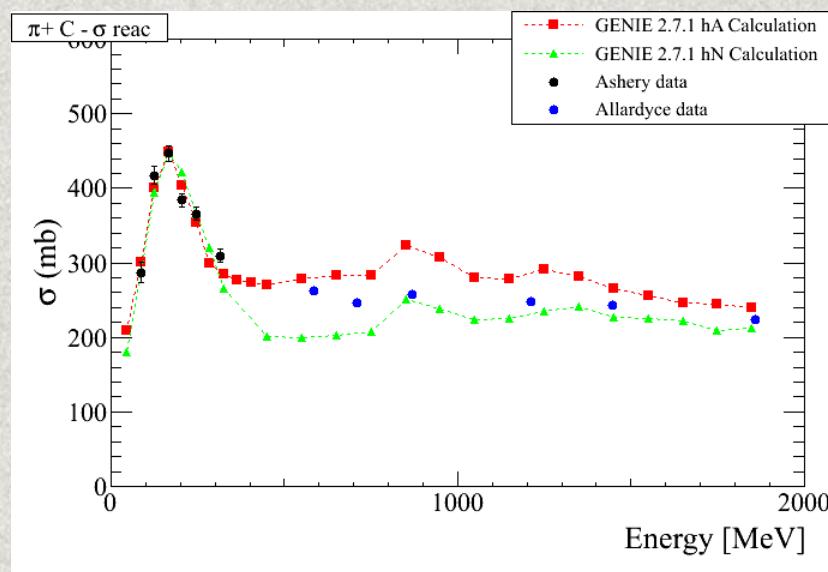
Formation time = **Free step**
Step hadron through nucleus
in 0.1 fm steps.
Assess probability of
interaction with
 $\lambda(E,r) = 1/p(r)\sigma(E)$.

S. Dytman

- Choose interaction from list (data, models, intuition)
- Elas, Inel, CEX, abs (KO), pi prod
- Choose kinematics by models, phase space and exit.

$$\text{formation time}^2 = 0.342 \text{ fm/c}$$

Tuning and Validation



Intranuclear Rescattering Model

Initial studies were focussed on the question of the hadronic energy scale uncertainty for MINOS (S. Dytman, HG, M. Kordosky, arXiv:0806:2119 (2008)).

1) Identify Sources of Uncertainty

- External Data
- Model Assumptions
 - * Treatment of low energy hadrons - changes to EFNUCR parameter
 - * What happens to pion energy in pion absorption events?

2) Quantify Uncertainty

3) Evaluate Impact (in this case, 4-vector level simulations with parametrized detector response).

External Data

branching ratios	
parameter	1σ uncertainty (%)
π charge-exchange	50
π elastic	10
π inelastic	40
π absorption	30
π secondary π production	20
N absorption	20
N secondary π production	20
N elastic	30

cross-sections	
parameter	1σ uncertainty (%)
π total cross-section	10
N total cross-section	15

Table 1: Uncertainties on intranuclear rescattering processes. The N elastic and total cross-section terms are 100% correlated.

In the GENIE model context, these are all reweightable.
Correlations are important!

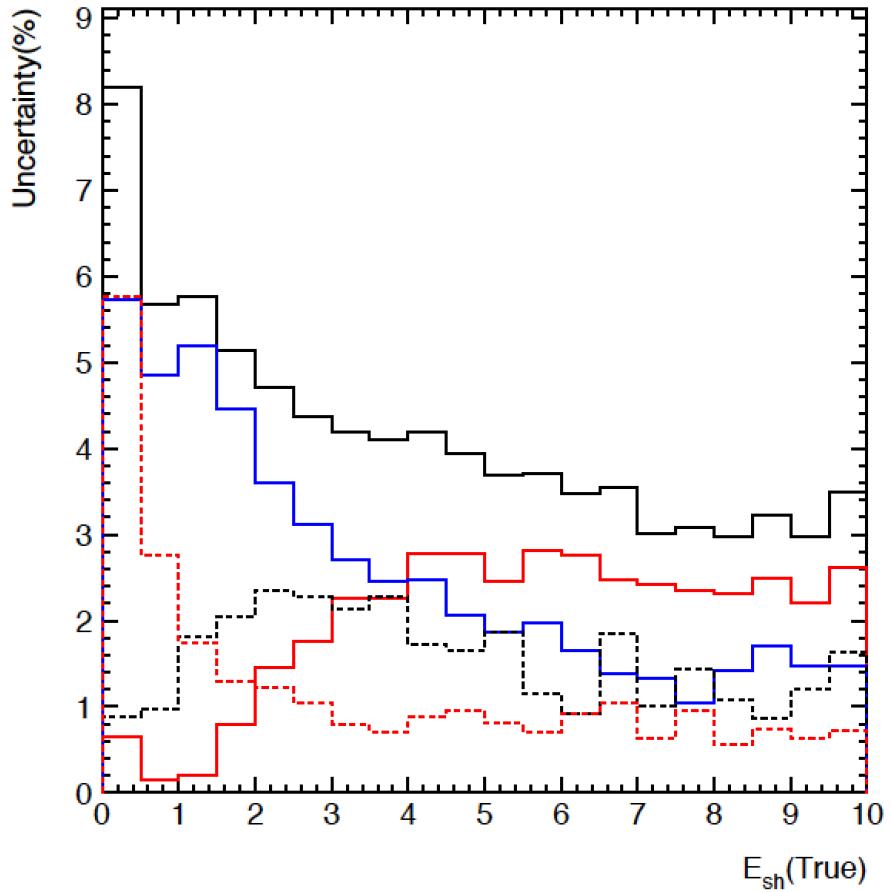


Figure 10: Total uncertainty from all sources (solid black). Contributions from intranuke assumptions (blue), INTRANUKE input (dashed red), hadronization model (solid red), and formation zone (dashed black).

```

// From Debdatta's thesis:
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//   Bht = 0.305 +/- 0.076
//   CV1u = 0.291 +/- 0.087
//   CV2u = 0.189 +/- 0.076

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}

```

S. Dytman, HG, M. Kordosky,
arXiv:0806:2119 (2008)

Lessons Learned [4]

Again: value in having deep expertise with the external data.

Again: advantage of reweightable approaches.

Question of relevant systematics was driven by physics objectives (numu CC disappearance). Analysis specific, not generic!

Understanding the details of the model (in particular, assumptions), were very valuable in thinking about sources of uncertainty.

CONCLUSIONS

Moving away from Impulse Approximation thinking.

The state of the art today has moved far beyond what was done for many of the studies described here! However many themes remain the same:

Tension between ‘theoretically correct and consistent’ and ‘effective model’ views of event generators. e.g. how to determine systematic errors for the kinds of detailed calculations we are now incorporating?

Importance of engaging the experimental communities:

External data - understanding the measurements!

Users - Identifying what really matters to experiments, providing effort when necessary. Discouraging ‘black-box’ thinking. e.g. is NEUT vs. GENIE a valid way of evaluating generator-related systematic errors?