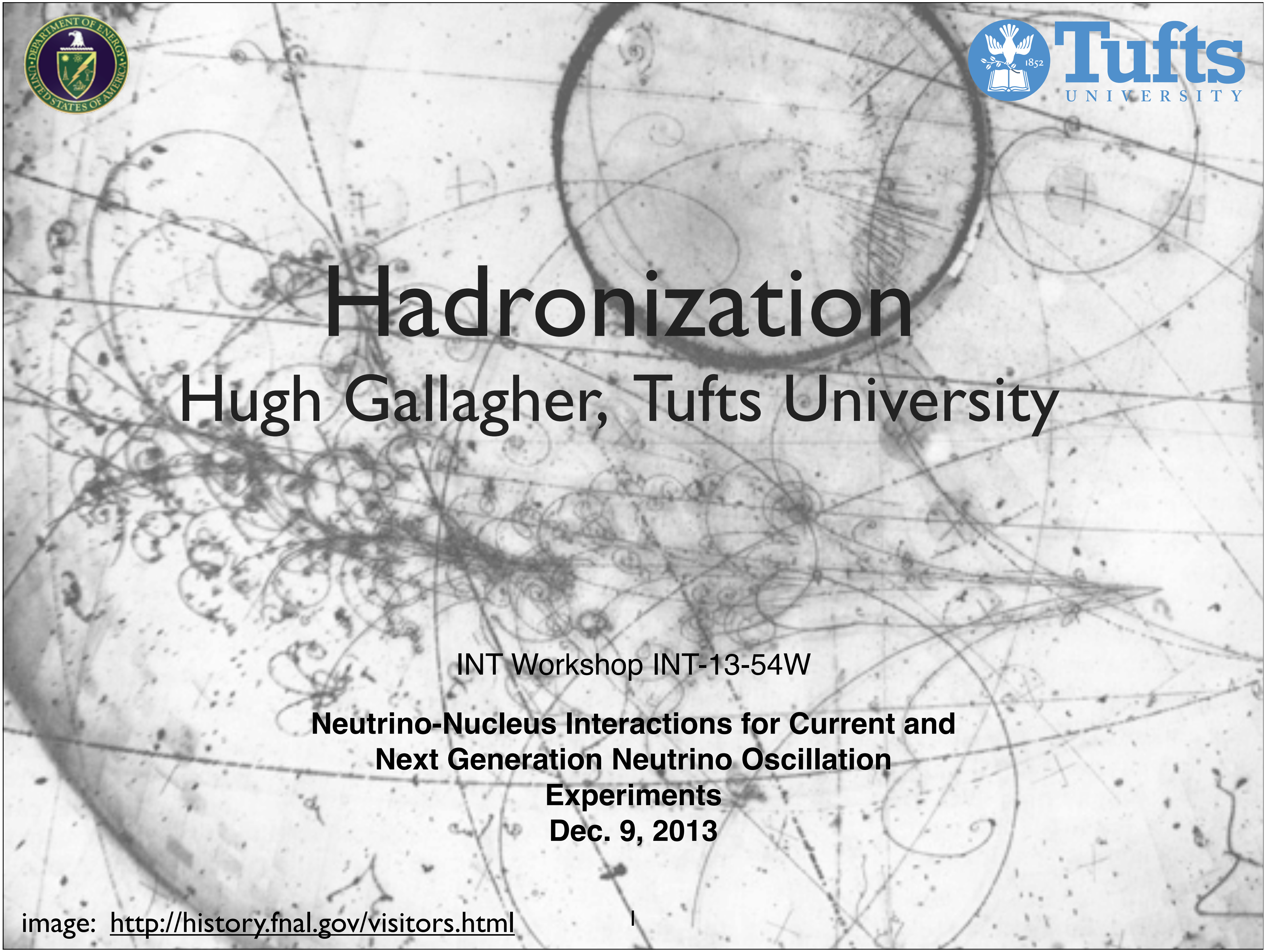


Hadronization

Hugh Gallagher, Tufts University

INT Workshop INT-13-54W

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments
Dec. 9, 2013

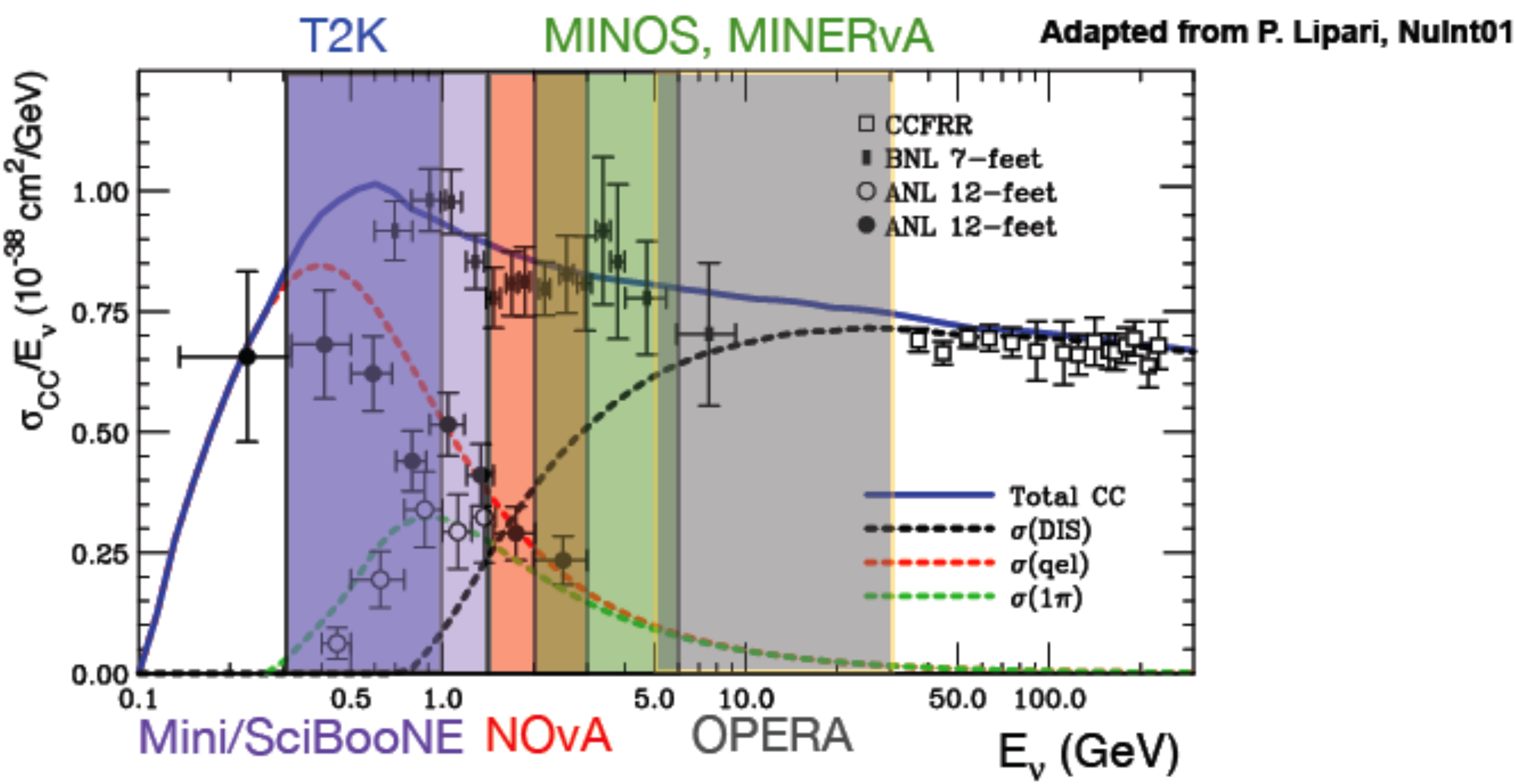
image: http://history.fnal.gov/visitors.html

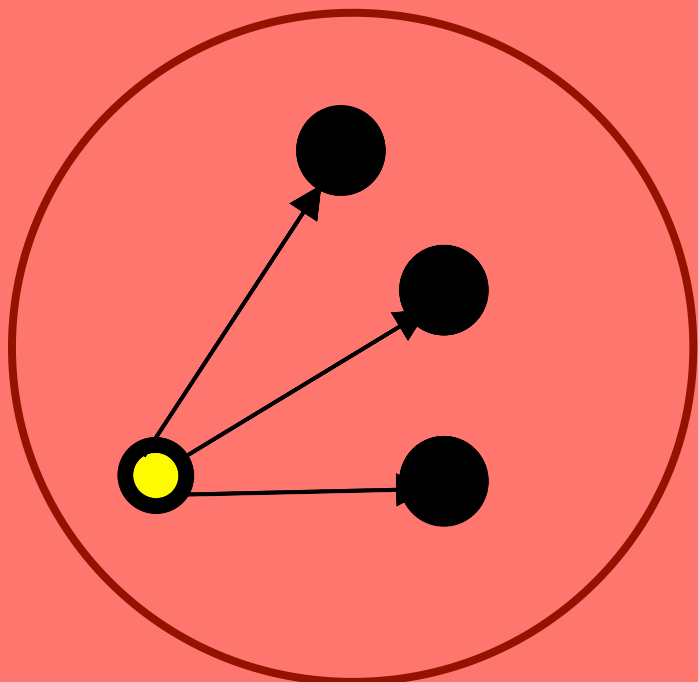
- THE HADRONIC SYSTEM - WHY WE CARE
  - *Example: Minerva*
  - *Example: MINOS muon disappearance*
  - *Example: MINOS electron appearance*
  - *Example: LBNE atmospheric neutrinos*

- FREE NUCLEON HADRONIZATION
  - *External Data - The bounty of the bubble chambers*
  - *Models / Generators*

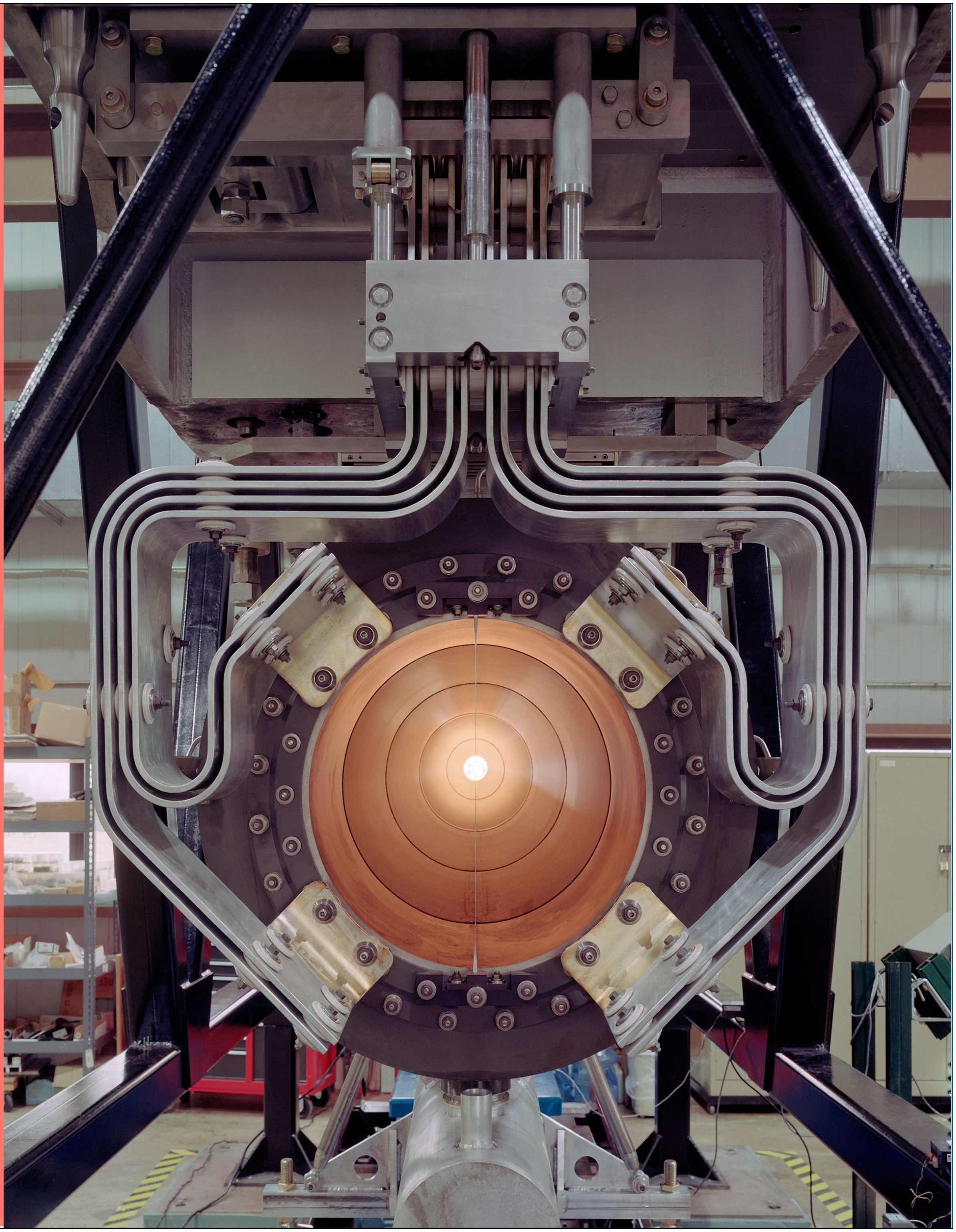
- HADRONIZATION IN NUCLEI
  - *Hadron formation in nuclei*
  - *External Data*
  - *Models / Generators*

H. Tanaka, NuINT09.





HADRONIZATION:
WHY WE CARE



WE DON'T LIKE HADRONS EITHER

- Detectors respond differently to particles present in the hadronic shower: charged/neutral hadrons (e/h ratio) to neutrons (likely undetectable).
- Hadronic calorimetry is, in general, much more difficult than measuring lepton energy.
- Difficult to reconstruct even in high resolution devices.
- Uncertainties in hadronic physics in detector simulations (GEANT).

Analysis strategies try to minimize dependence on hadronic system. BUT, we need to make the most out of the information provided by our apparatus.

GENERAL STATEMENTS ARE HARD

Issues related to hadronization depend very strongly on the beam SPECTRUM of the experiment.

1) Event classification is based on the hadronic system

and/or

2) Event measurement uses the hadronic system
   - Based on total energy deposited by hadrons
   - Based on reconstruction of individual particles within the hadronic shower.

HADRONS ARE HARD

It is very hard to make a general statements about the 'needs of oscillation experiments' with regards to our ability to theoretically describe and simulate hadronic systems.

'Oscillation experiments' in the modern era covers a lot of ground, so one can really only make statements about the needs of particular experiments and measurements.

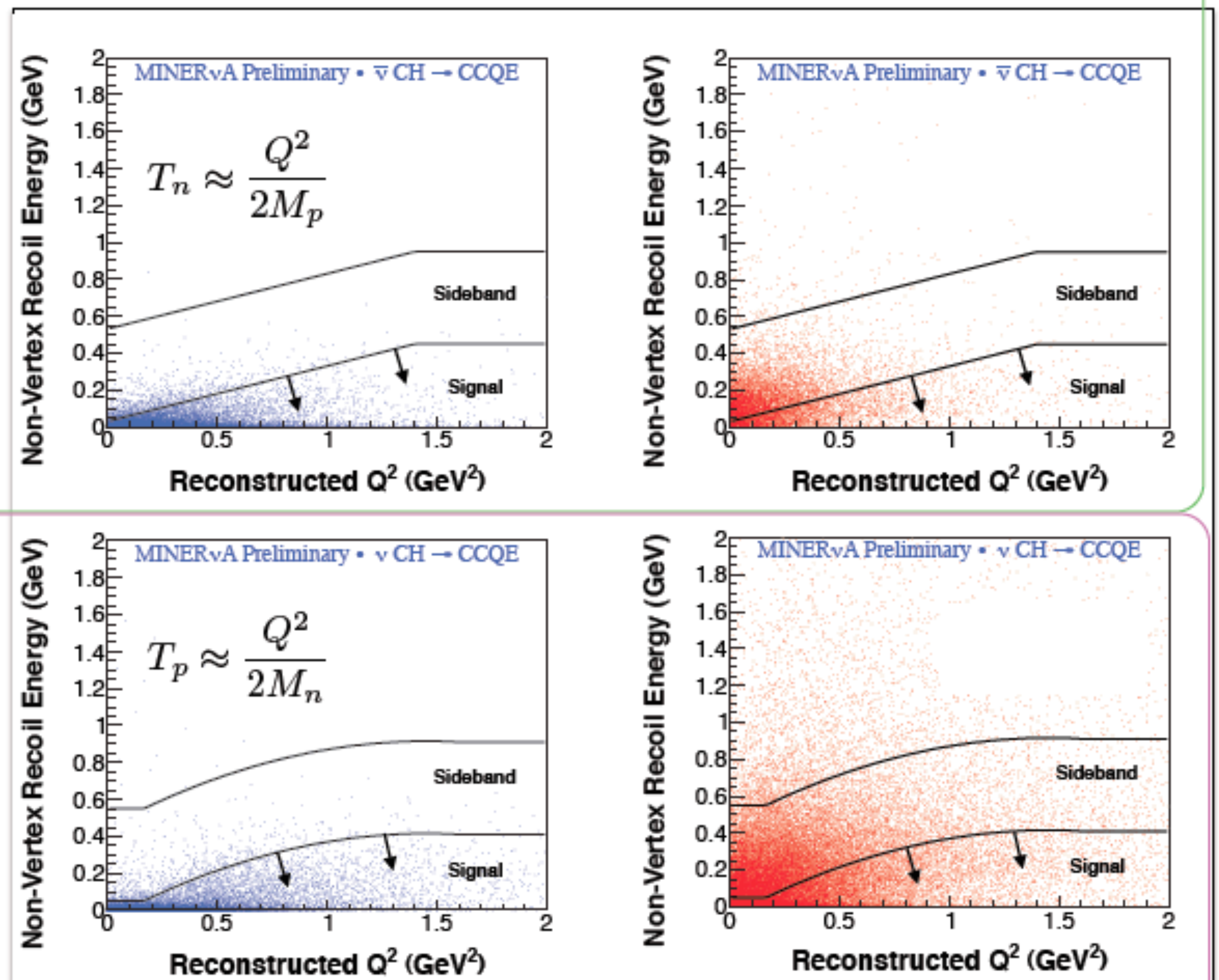
What follows are some examples of why modern experiments, in particular oscillation experiments, care about the hadronic system.

CCQE Selection

Minerva: G. Perdue, this workshop

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

- **Antineutrino**
  - 10 g/cm2 vertex region
    - Contains < 120 MeV KE protons
    - Contains < 65 MeV KE pions
  - ≤ 1 isolated shower outside the vertex.
- **Neutrino**
  - 30 g/cm2 vertex region
    - Contains < 225 MeV KE protons
    - Contains < 100 MeV KE pions
  - ≤ 2 isolated showers outside the vertex.

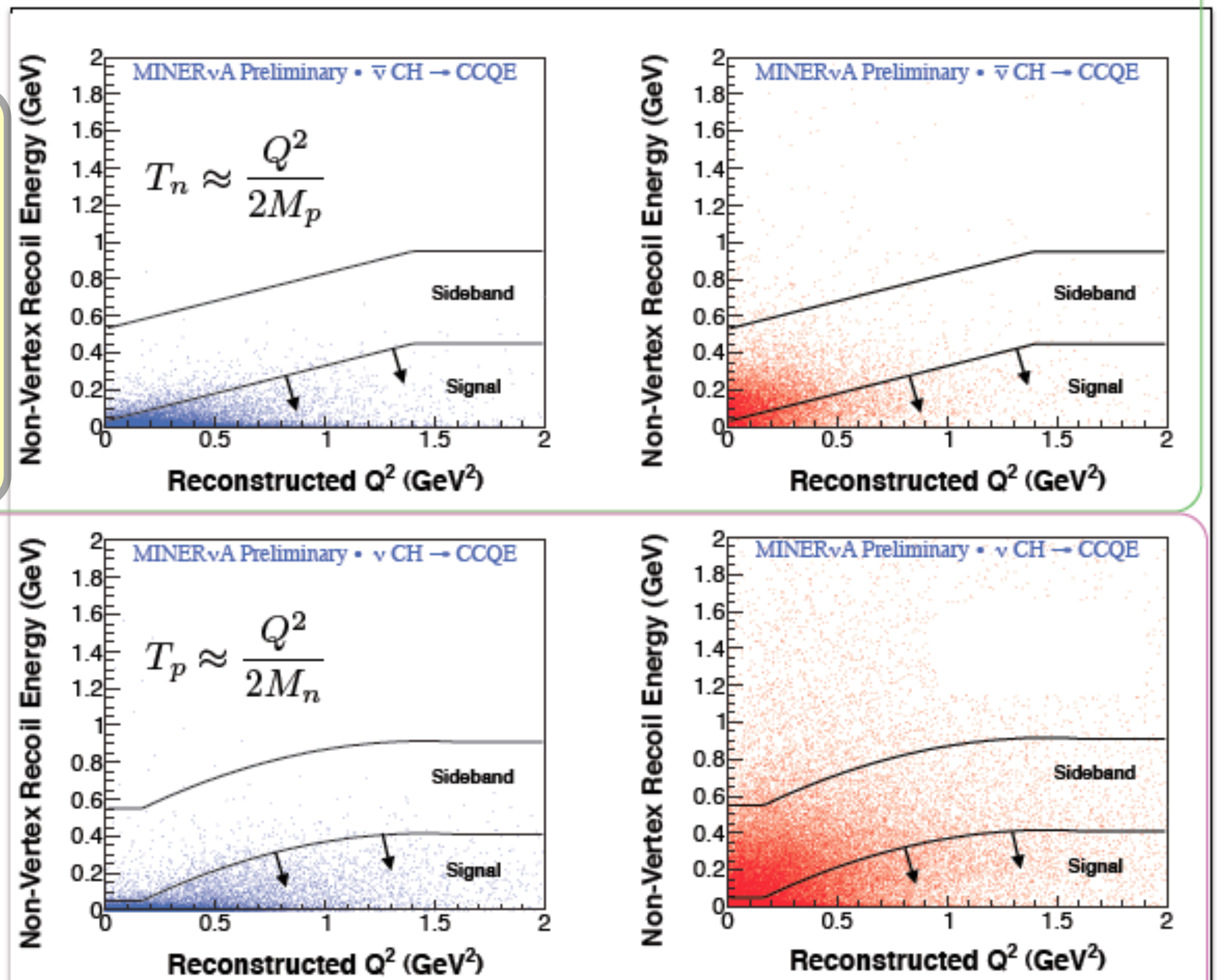


CCQE Selection

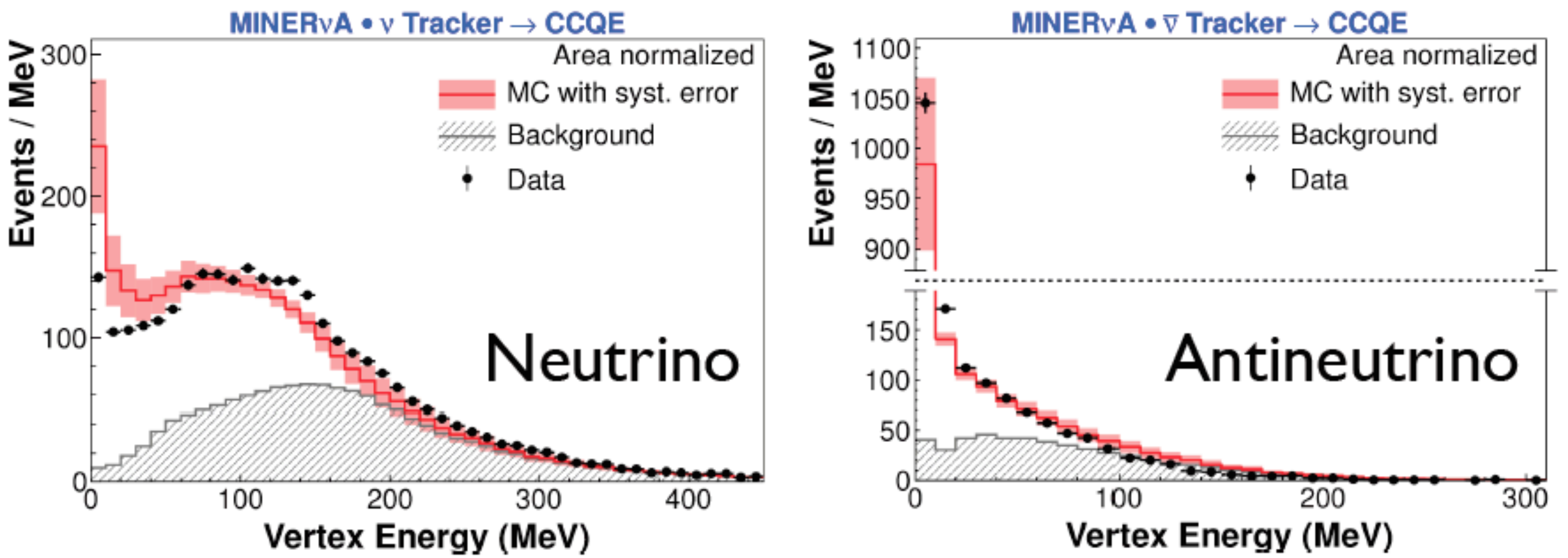
Minerva: G. Perdue, this workshop

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

- **Antineutrino**
  - 10 g/cm2 vertex region
    - Contains < 120 MeV KE protons
    - Contains < 65 MeV KE pions
  - ≤ 1 isolated shower outside the vertex.
- **Neutrino**
  - 30 g/cm2 vertex region
    - Contains < 225 MeV KE protons
    - Contains < 100 MeV KE pions
  - ≤ 2 isolated showers outside the vertex.



Minerva: G. Perdue, this workshop

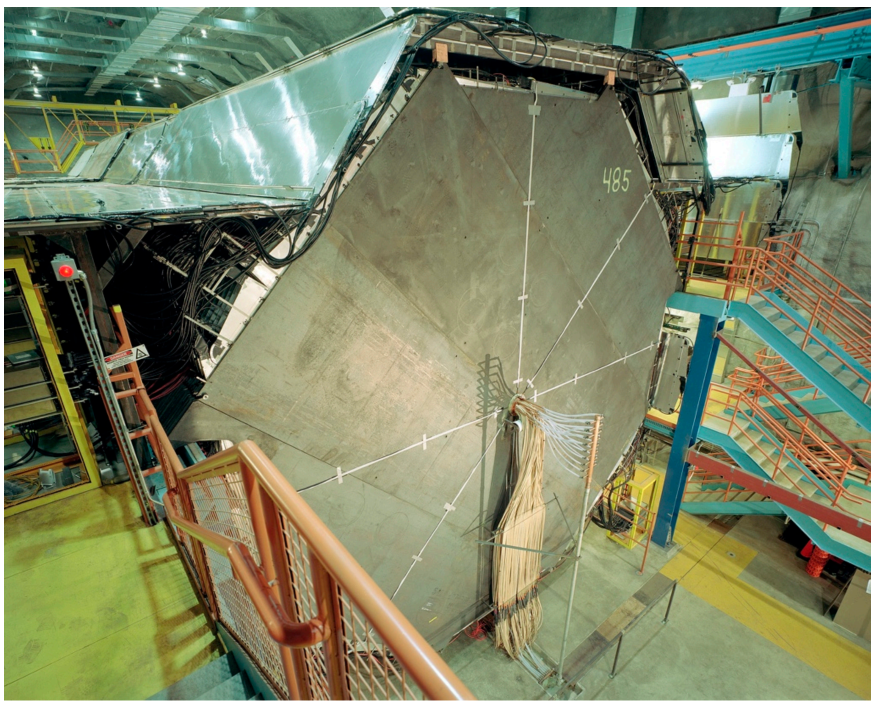


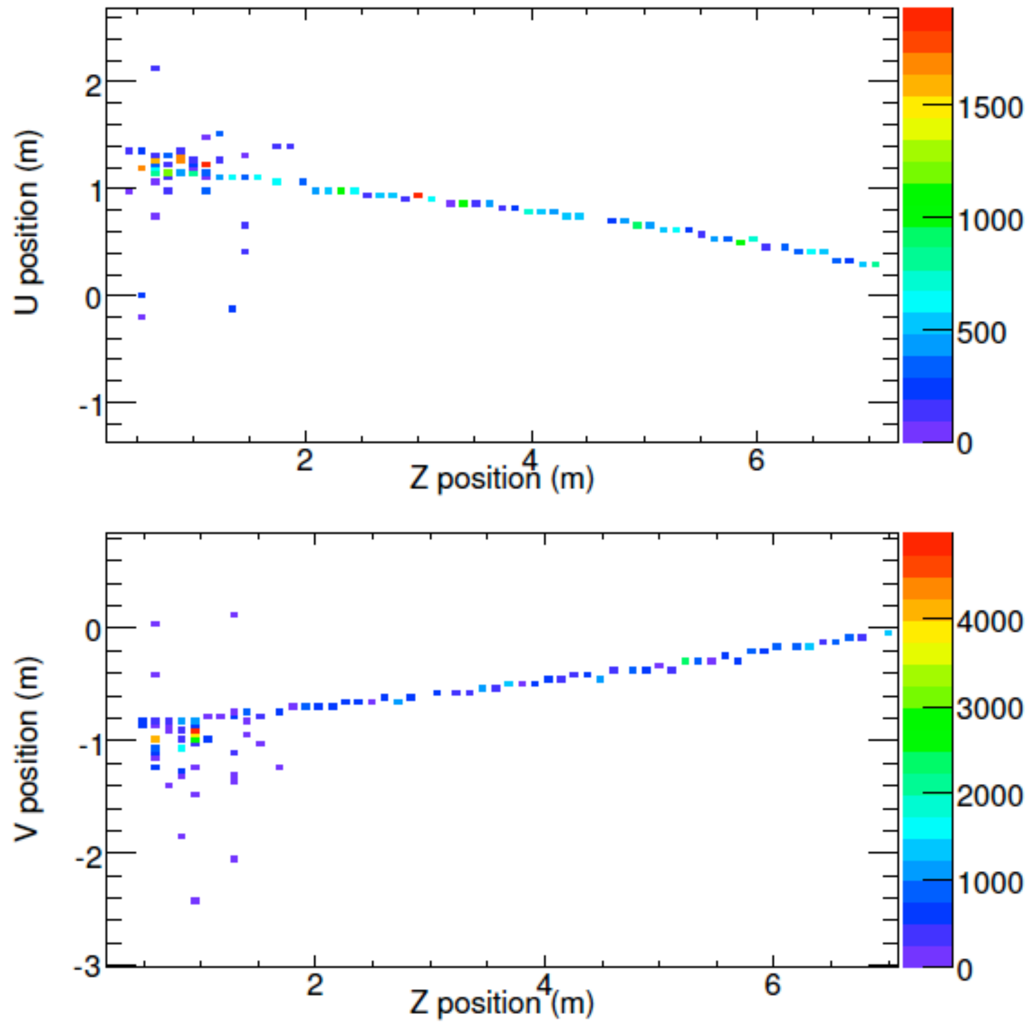
...or... analyzing 'clean' events where the muon exits the Minerva detector but does not go into MINOS.

Example: MINOS Muon Disappearance

A Near/Far comparison, but we need to relate what we see in the detector to TRUE neutrino energy, in order to fit for oscillations.

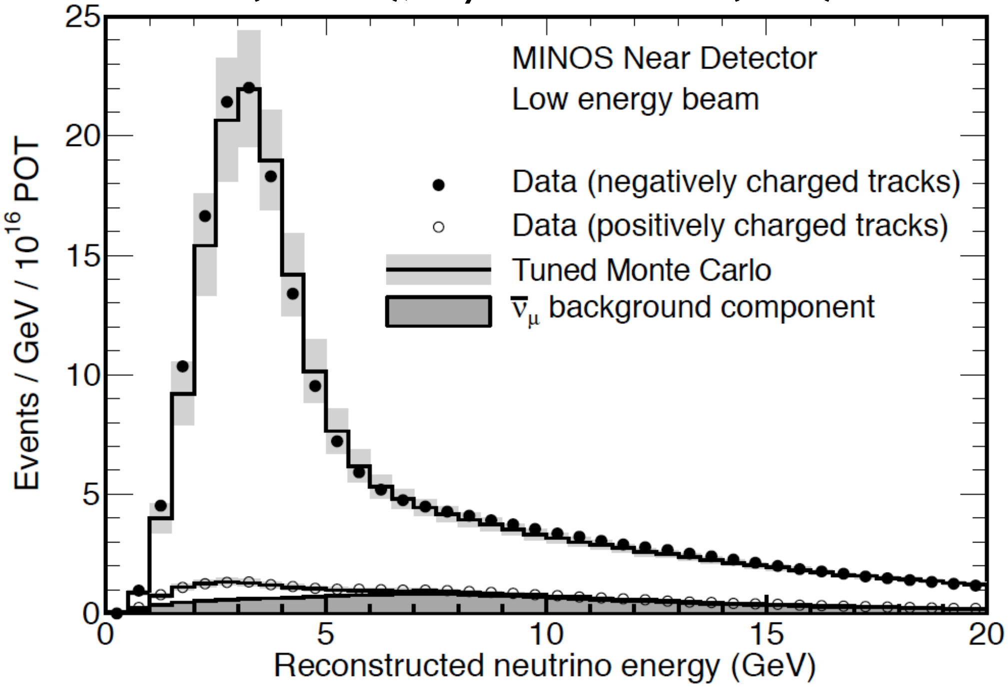
Requires a model - with uncertainty.



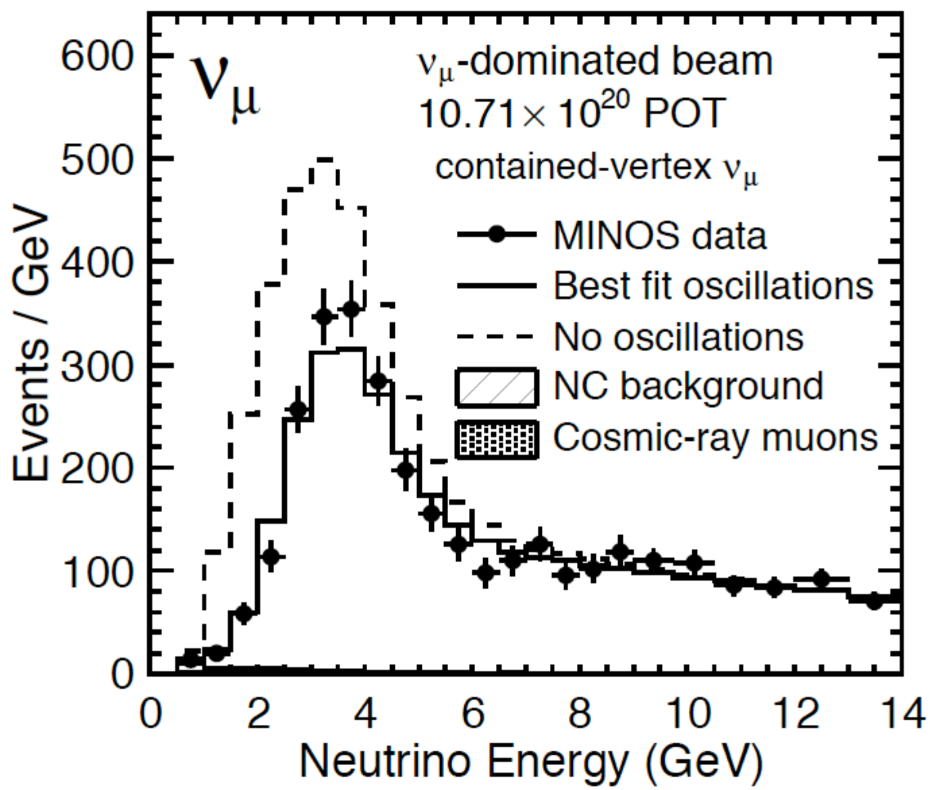


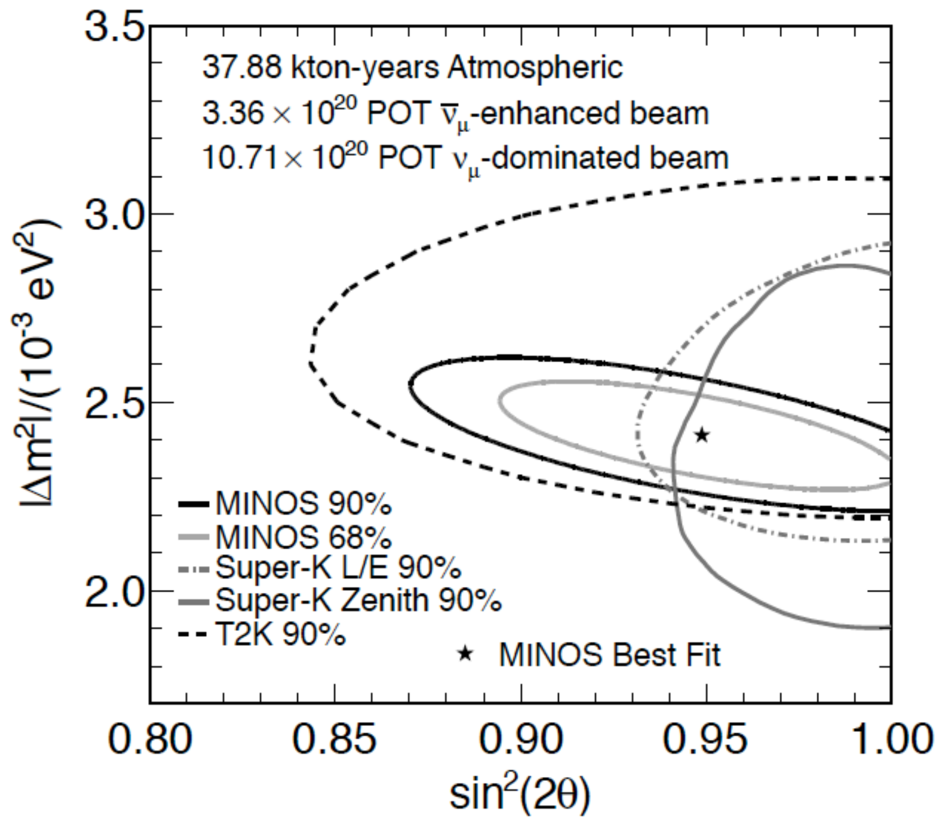
R. Ospanov, Ph. D Thesis (U. Texas, 2009)

Adamson et al. (MINOS), Phys.Rev.Lett. 106 (2011) 181801



Example: MINOS Muon Disappearance





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

Example: MINOS Muon Disappearance

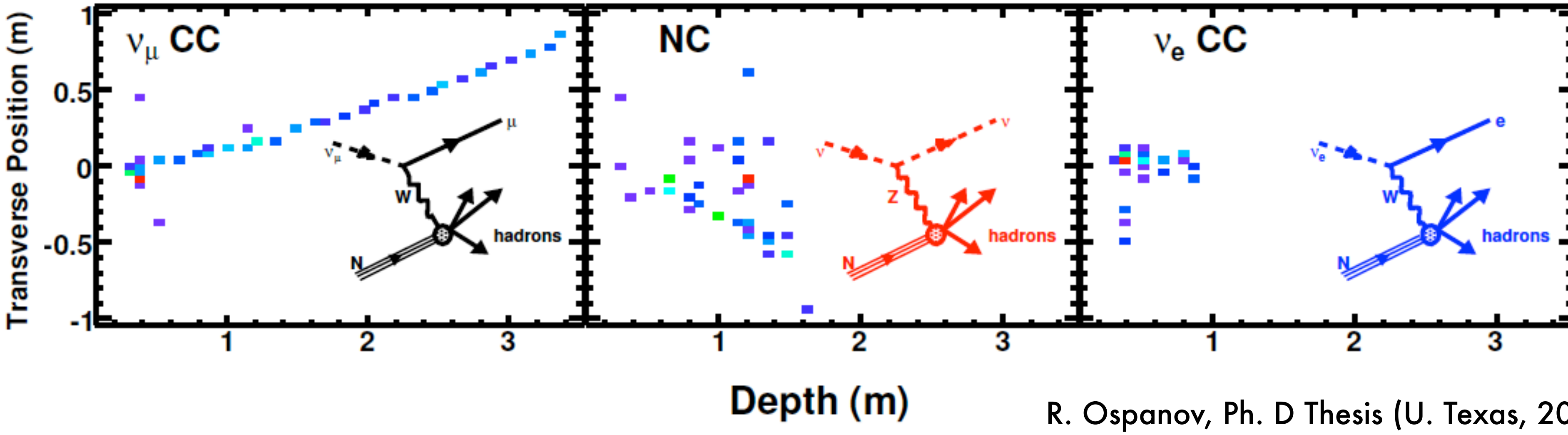
Source of systematic uncertainty	$\delta(\Delta m^2)$ ($10^{-3}\,eV^2$)	$\delta(\sin^2(2\theta))$
(a) Hadronic energy	0.051	< 0.001
(b) μ energy (range 2%, curv. 3%)	0.047	0.001
(c) Relative normalization (1.6%)	0.042	< 0.001
(d) NC contamination (20%)	0.005	0.009
(e) Relative hadronic energy (2.2%)	0.006	0.004
(f) $\sigma_\nu(E_\nu < 10$ GeV)	0.020	0.007
(g) Beam flux	0.011	0.001
(h) Neutrino-antineutrino separation	0.002	0.002
(i) Partially reconstructed events	0.004	0.003
Total systematic uncertainty	0.085	0.013
Expected statistical uncertainty	0.124	0.060

TABLE I: Sources of systematic uncertainties, their one standard deviation variation level, and their impact on fitting oscillation parameters.

Adamson et al. (MINOS), Phys.Rev.Lett. 106 (2011) 181801

- 1" thick steel: proton threshold of around 150 MeV.
- Neutron KE is not completely captured.
- e/h ratio is approximately 1.3.

Example: MINOS Electron Appearance



R. Ospanov, Ph. D Thesis (U. Texas, 2009)

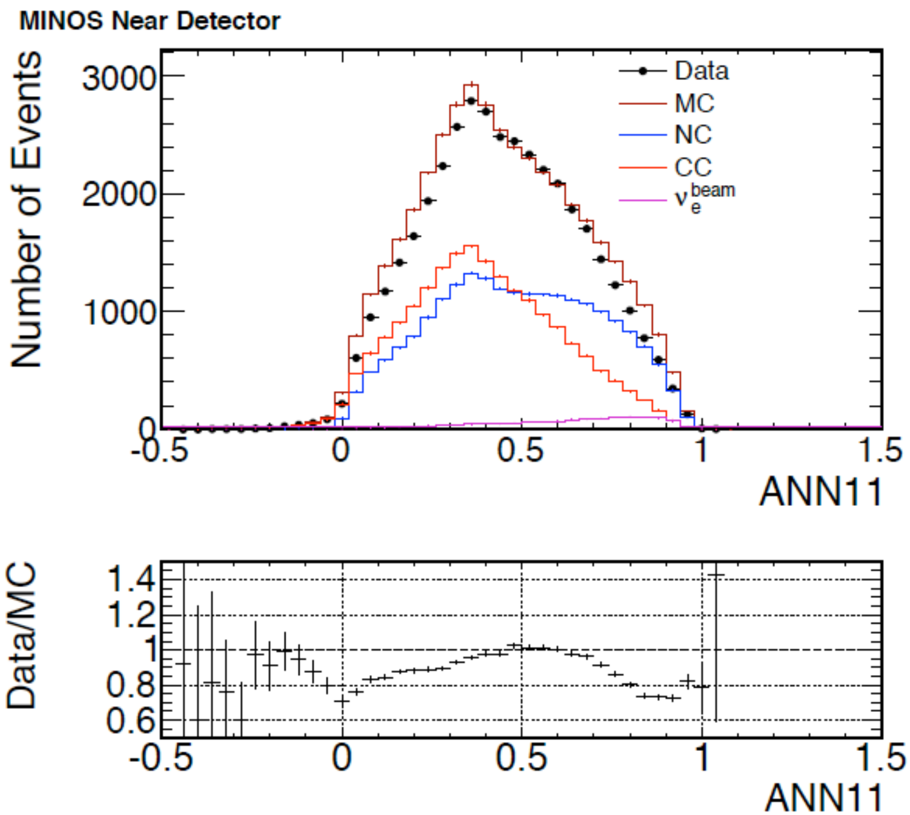
Backgrounds in the Far Detector will come from:

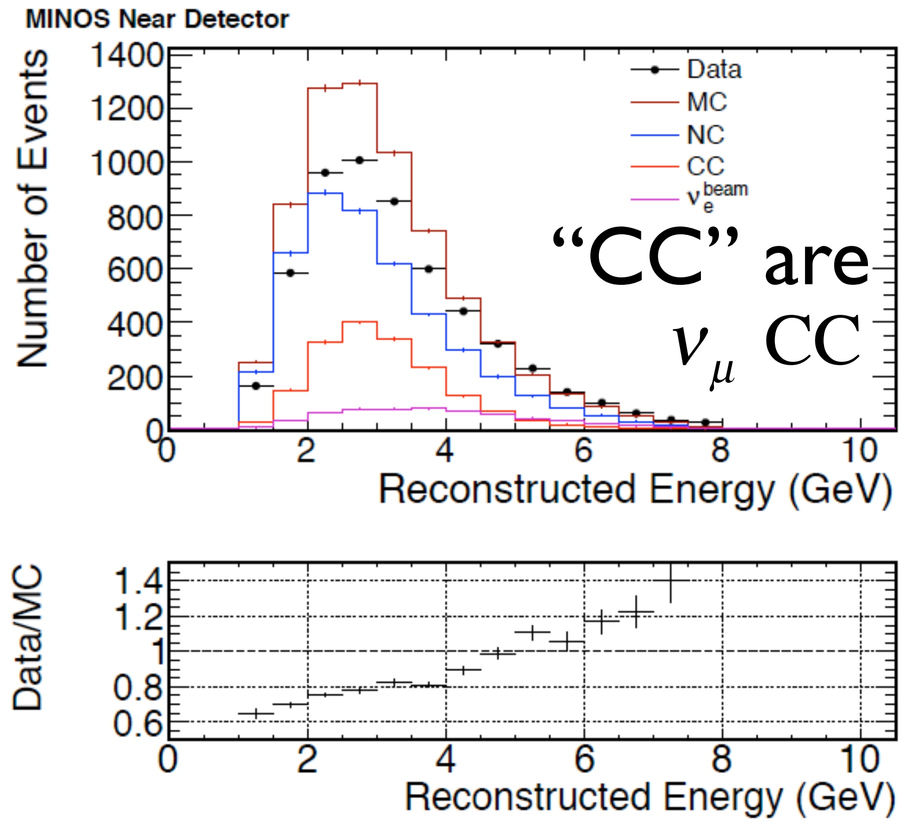
- Intrinsic electron neutrinos in the beam
- NC events with high em content.
- High-y CC events with high em content.

Example: MINOS Electron Appearance

Create a discriminating variable for electron-like events and apply it to the data in the Near Detector.

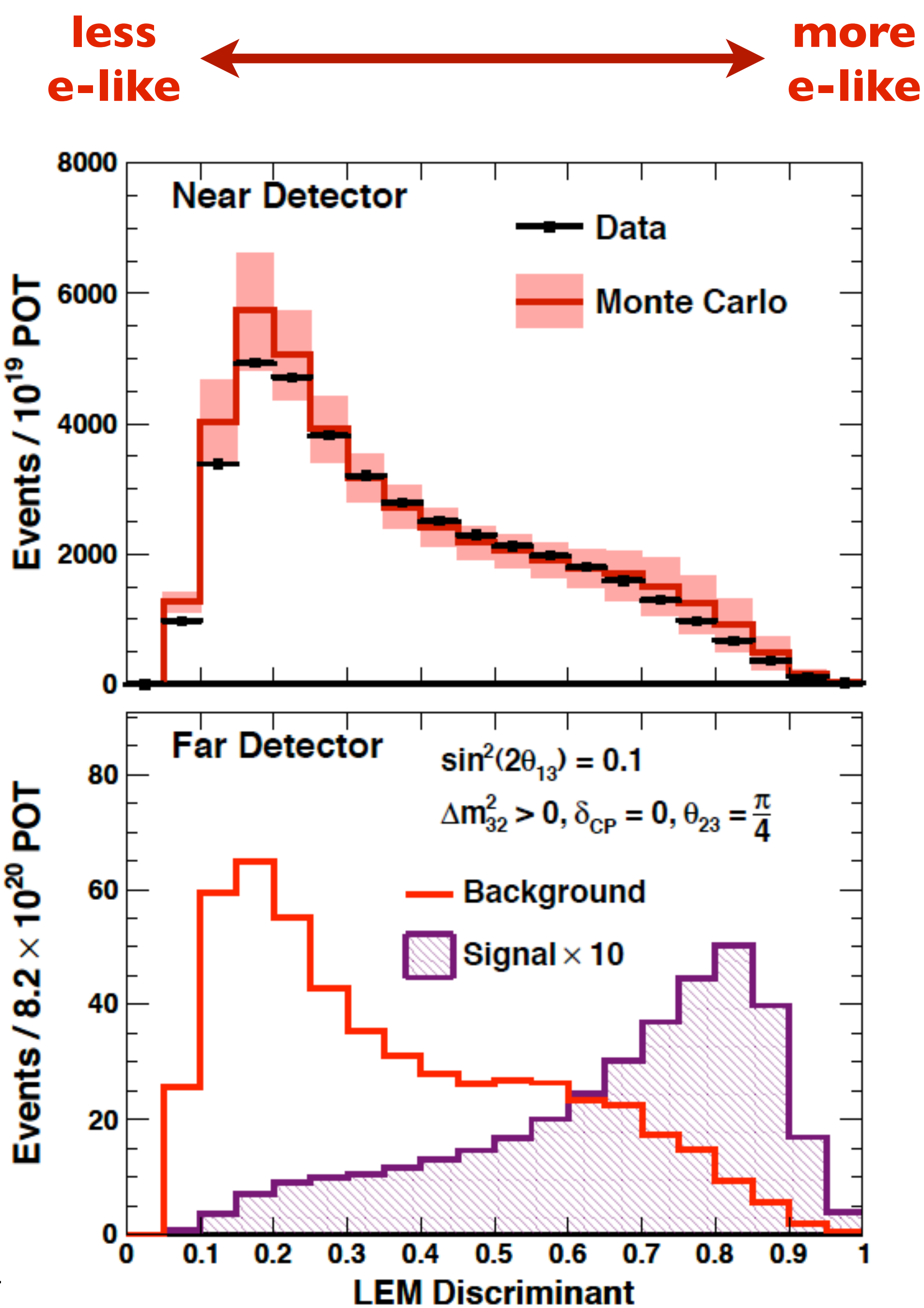
T. Yang, Ph. D Thesis (2009).





Data/MC shape disagreements at the 10's of percent level with 'out of the box' MC.

Example: MINOS Electron Appearance



But how does one go about extrapolating this Near Detector measurement to a Far Detector?

NC backgrounds are not affected by oscillations.

ν_μ CC backgrounds reduced by around 50% by oscillations.

Example: MINOS

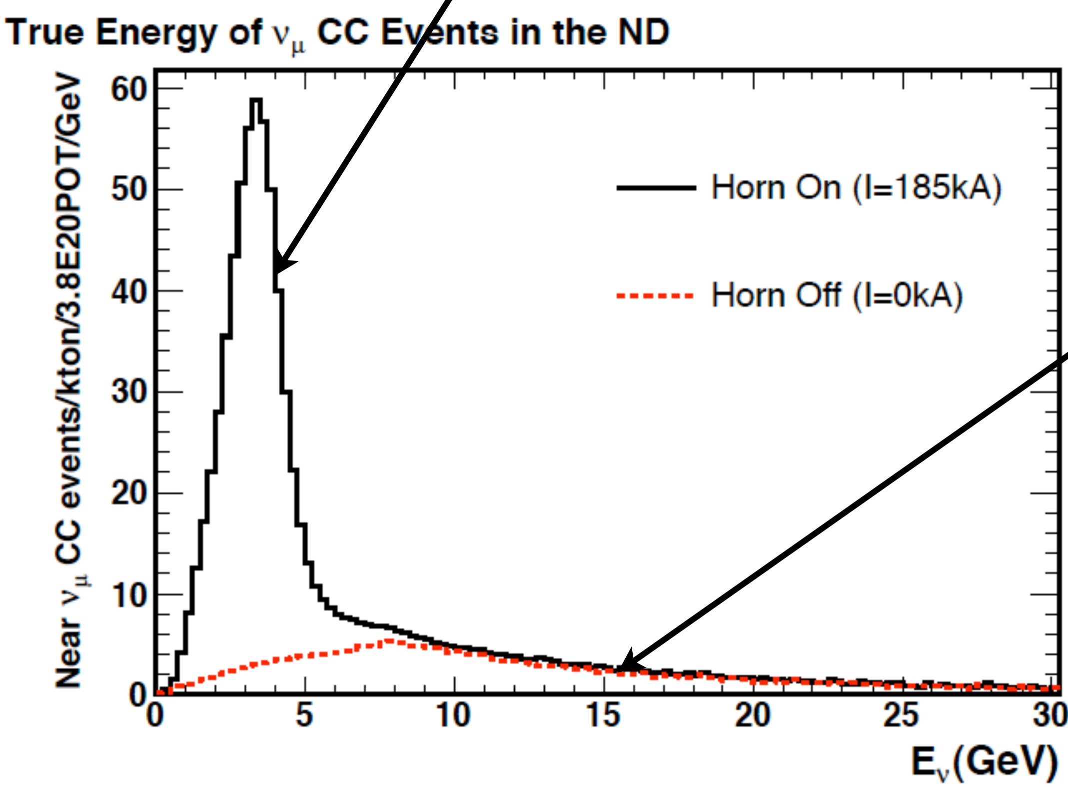
Use a data-driven method with Near Detector data in different beam configurations.

ν_e CC: $15 \pm 1\%$

ν_μ CC: $24 \pm 1\%$

NC: $61 \pm 1\%$

ν_μ CC backgrounds
come from mainly from the peak



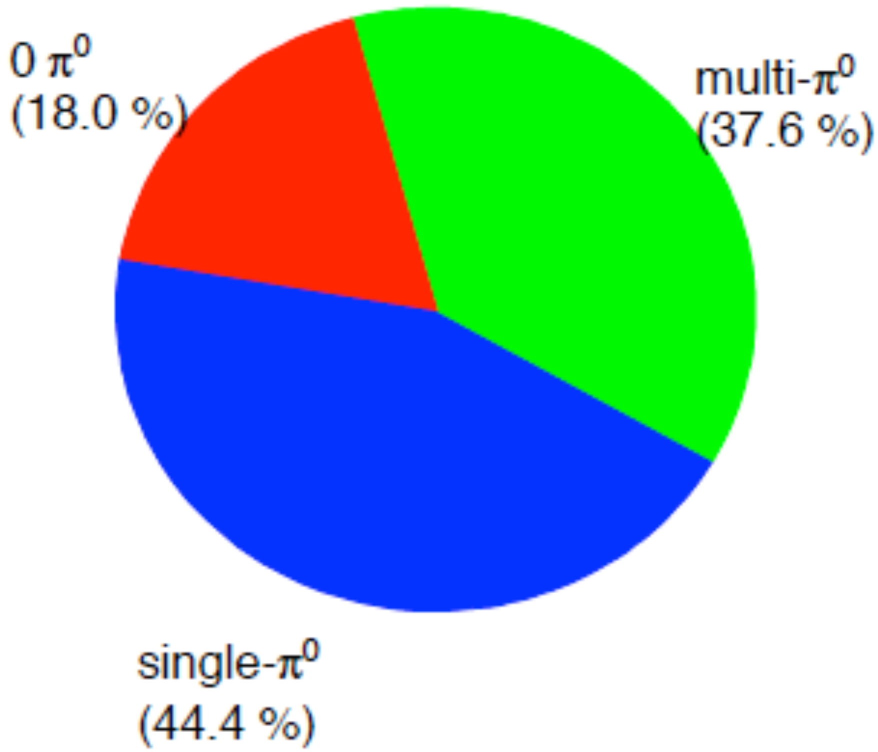
NC backgrounds
come mainly from the tail

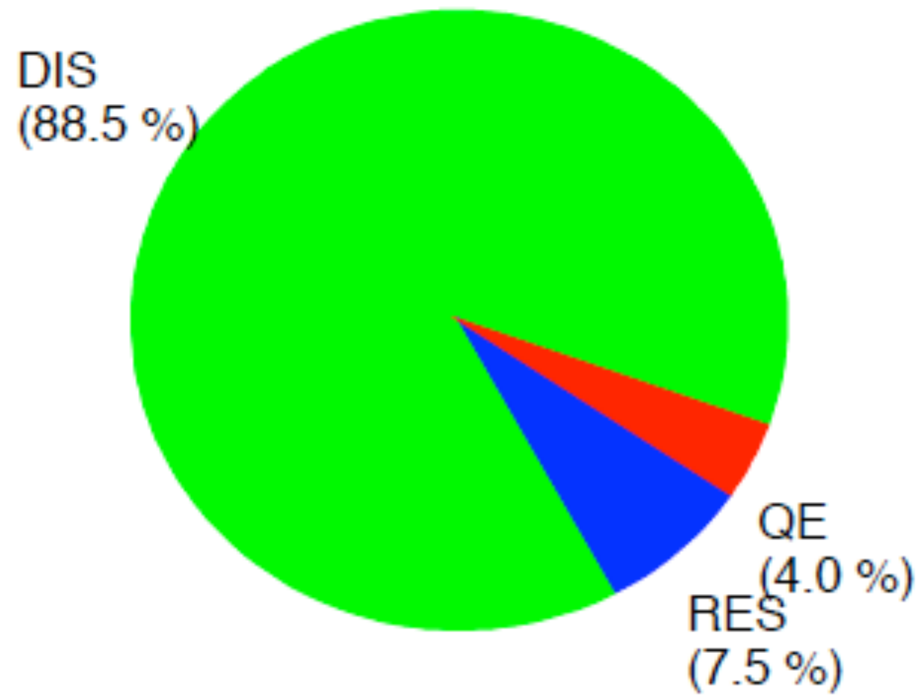
Moral: The Near Detector was not enough!

Size of modeling uncertainties ***also*** require data-driven techniques.

MC Breakdown of Far Detector Backgrounds

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

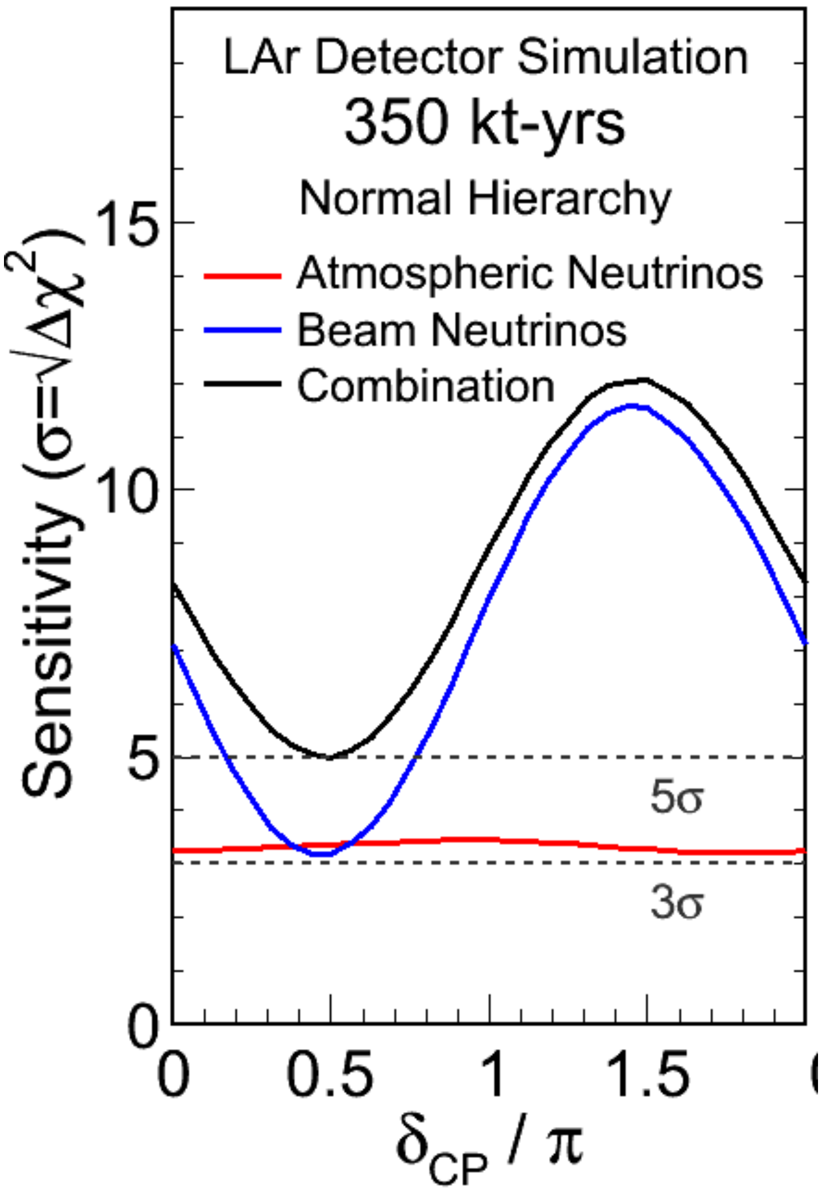


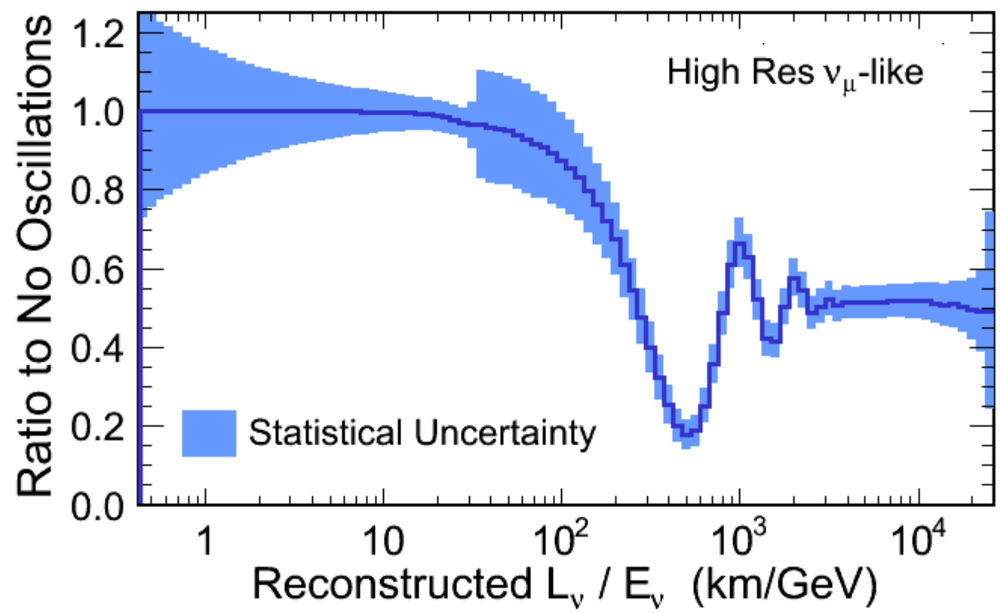


Example: LBNE Atmospheric Neutrinos

LBNE underground can study atmospheric neutrinos - large range of L,E probes 3-flavor oscillation picture.

Mass Hierarchy sensitivity:
Comparable to the beam (for $\delta_{CP} = \pi / 2$).
35 kton LBNE comparable to HyperK





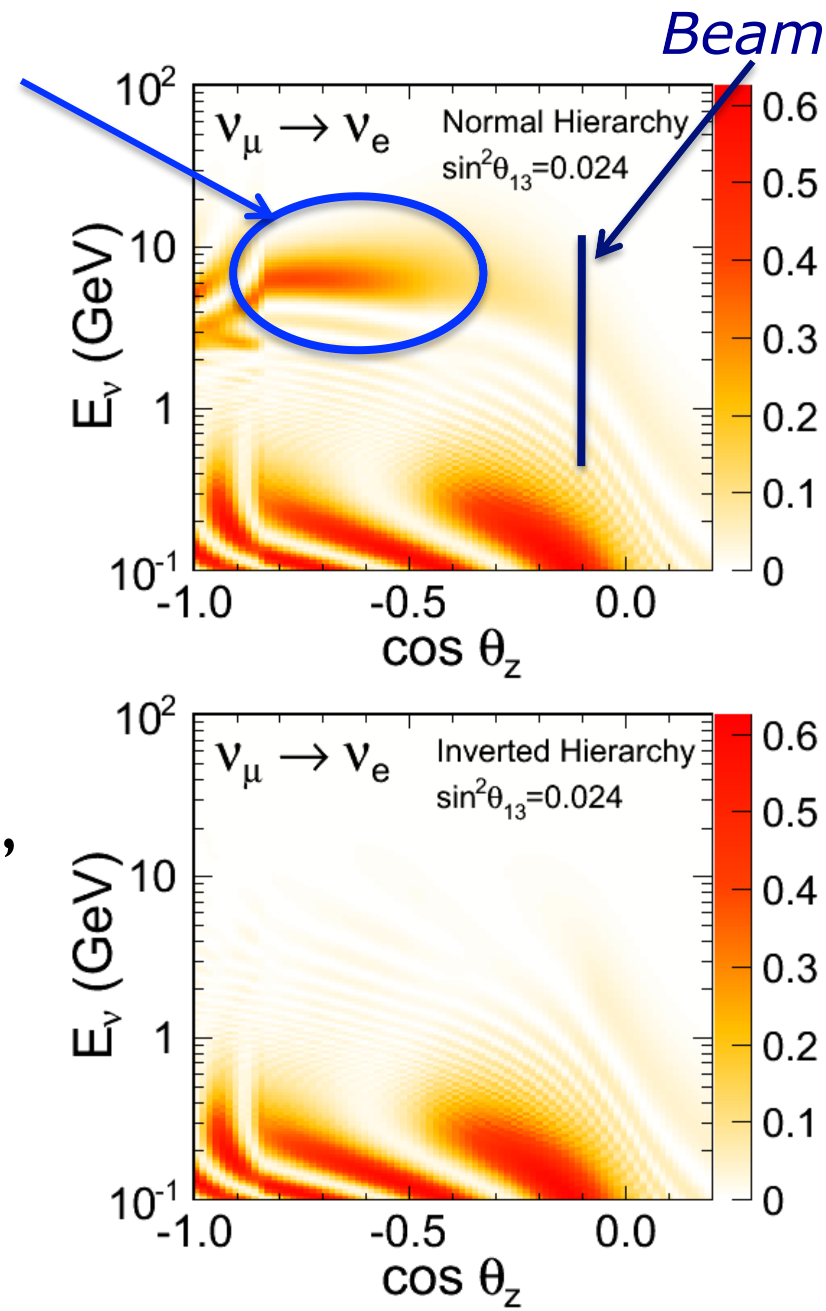
Example: LBNE Atmospheric Neutrinos

Matter effects in the earth produce distinct features in the (L,E) distribution.

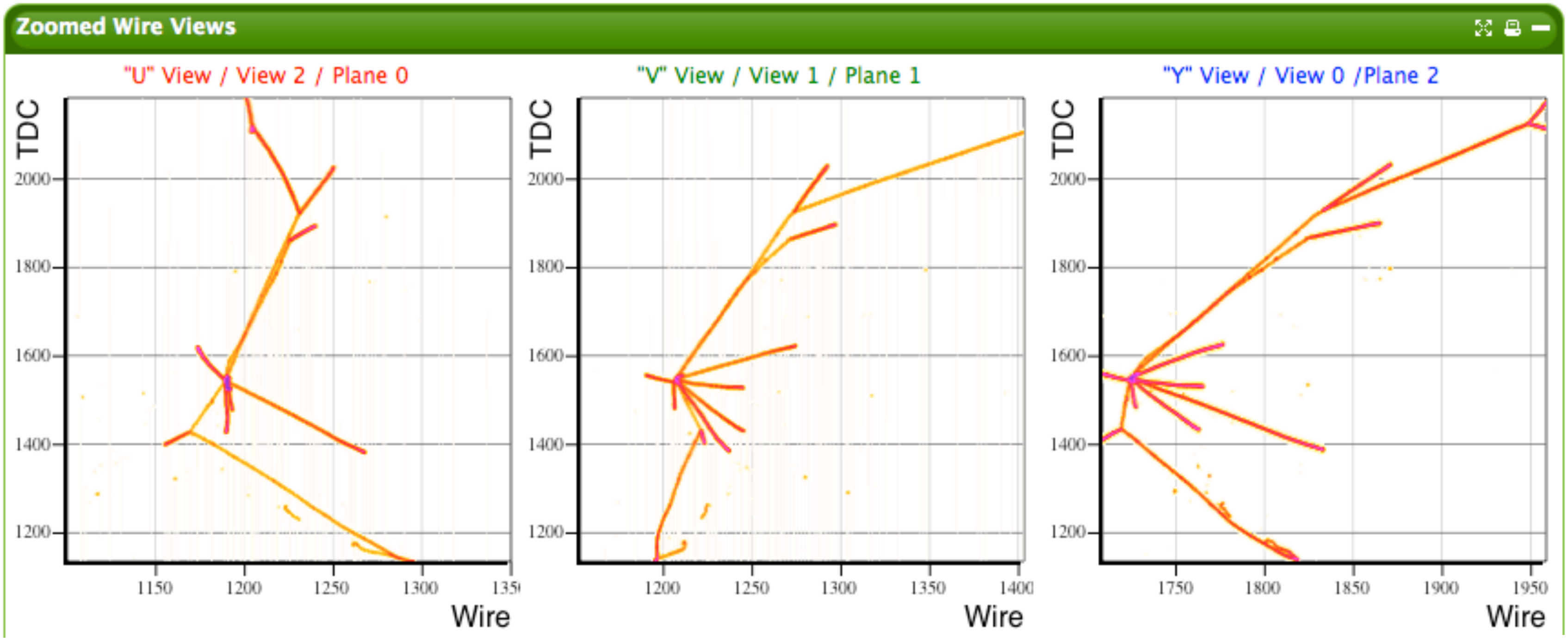
The better they can be resolved, the better the sensitivity.

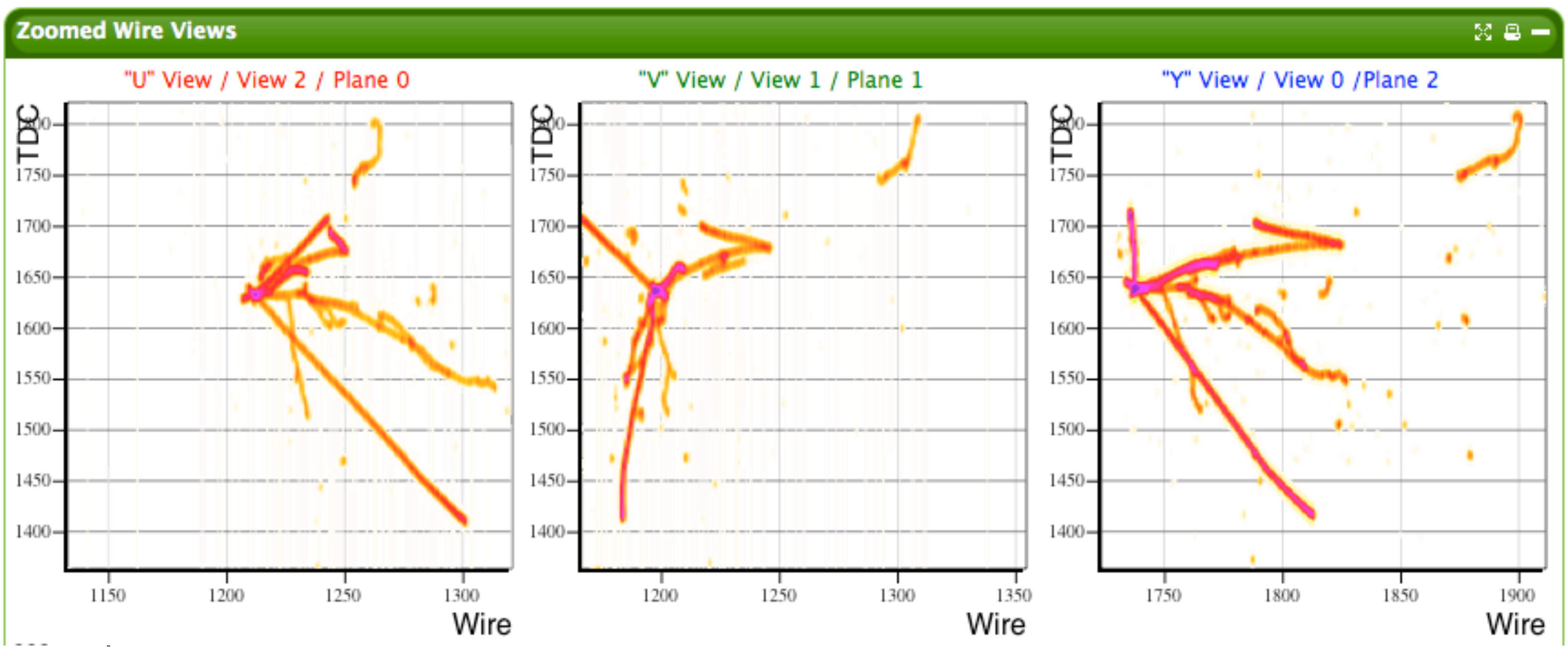
Requires good flavor tagging, **neutrino** energy reconstruction, and **neutrino** direction reconstruction.

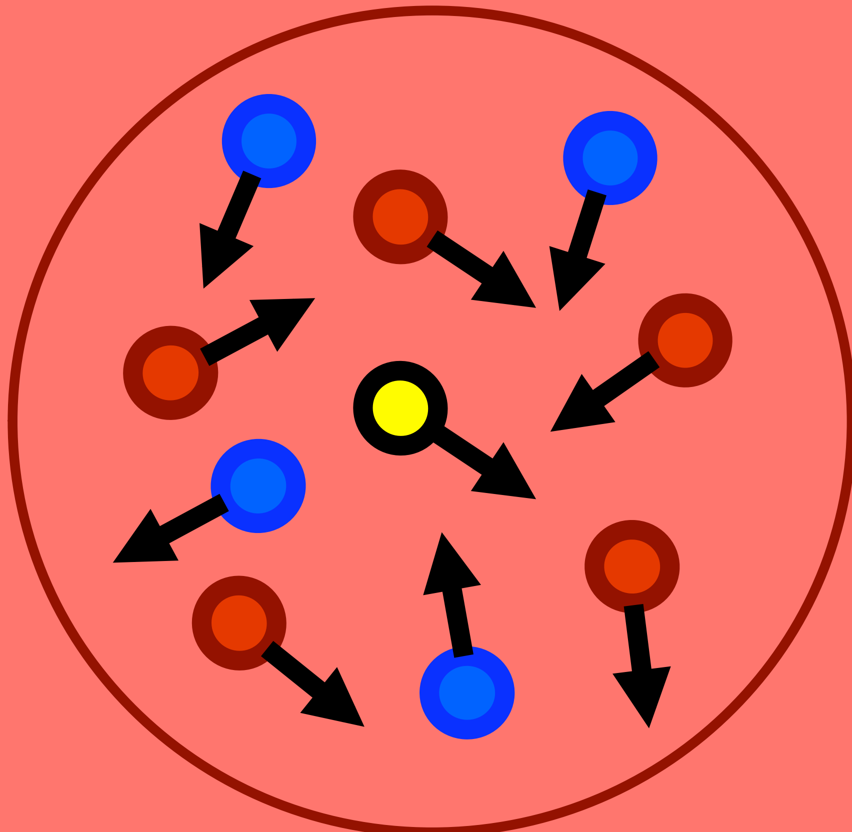
Limited by measurements of the **hadronic** system.



NC, ν_e CC, or ν_μ CC??







FREE NUCLEON
HADRONIZATION

FREE NUCLEON HADRONIZATION

In this section I will describe:

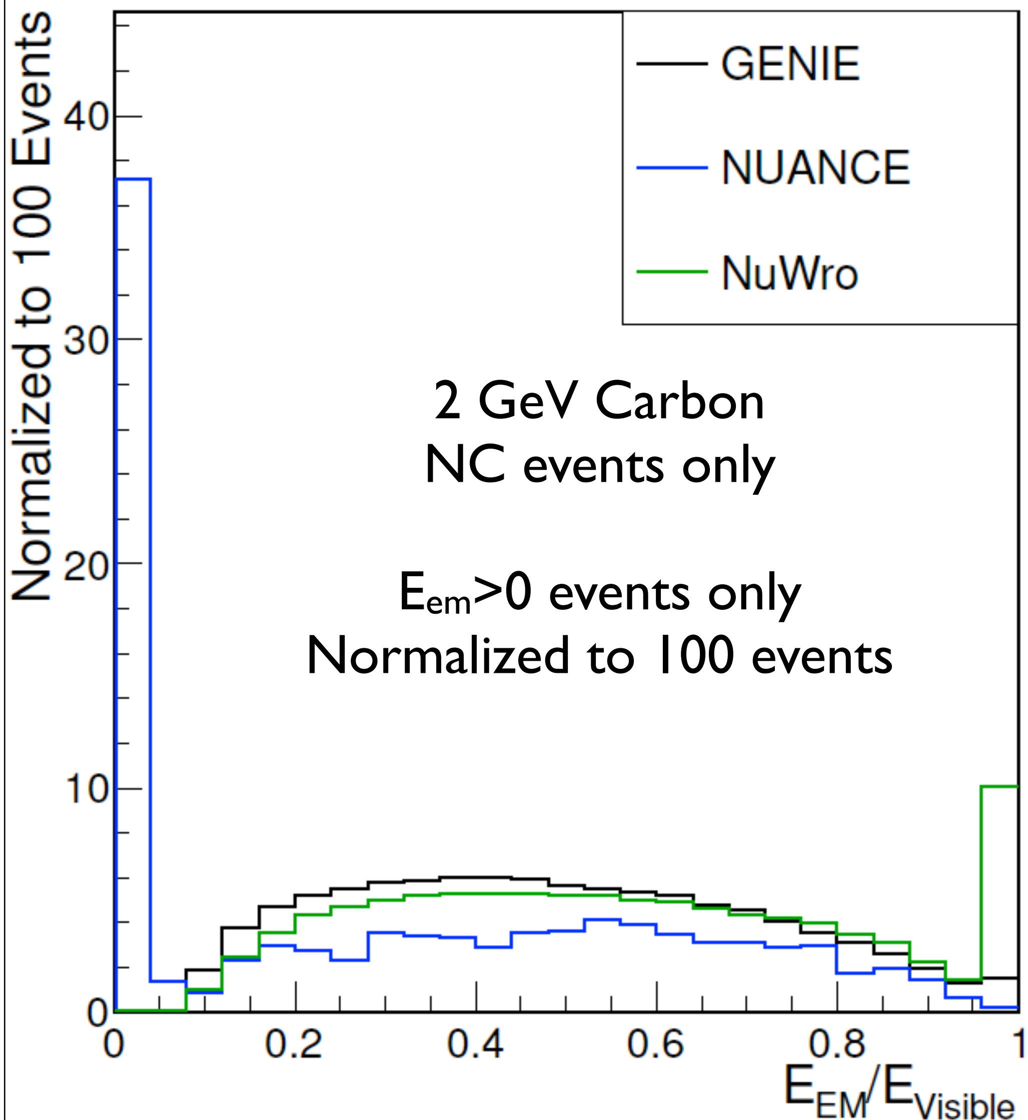
- Data that is available to describe free particle hadronization.
- Models for free particle hadronization.

In comparing differences in generator output, it is easy to heap blame on the nuclear model (FSI) as the source of all difficulty.

In my experience, often surprisingly large differences in the treatment of free nucleon hadronization between generators.

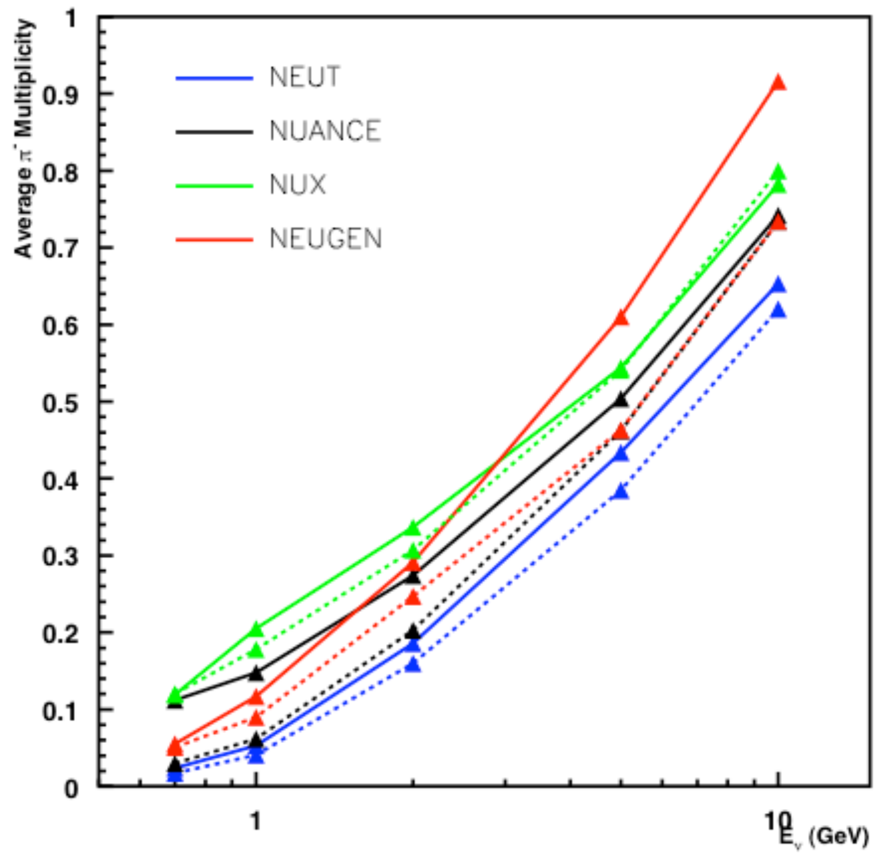
(Don't) Blame it on the Nucleus

N. Mayer, NuINT 12.



HG, NuINT 04

Figure 10. Average π^- multiplicity as a function of neutrino energy for anti-neutrino CC interactions. Solid lines are for free protons, dashed lines are for protons bound in oxygen.



(Don't) Blame it on the Nucleus

S. Dytman et al., NuINT 09

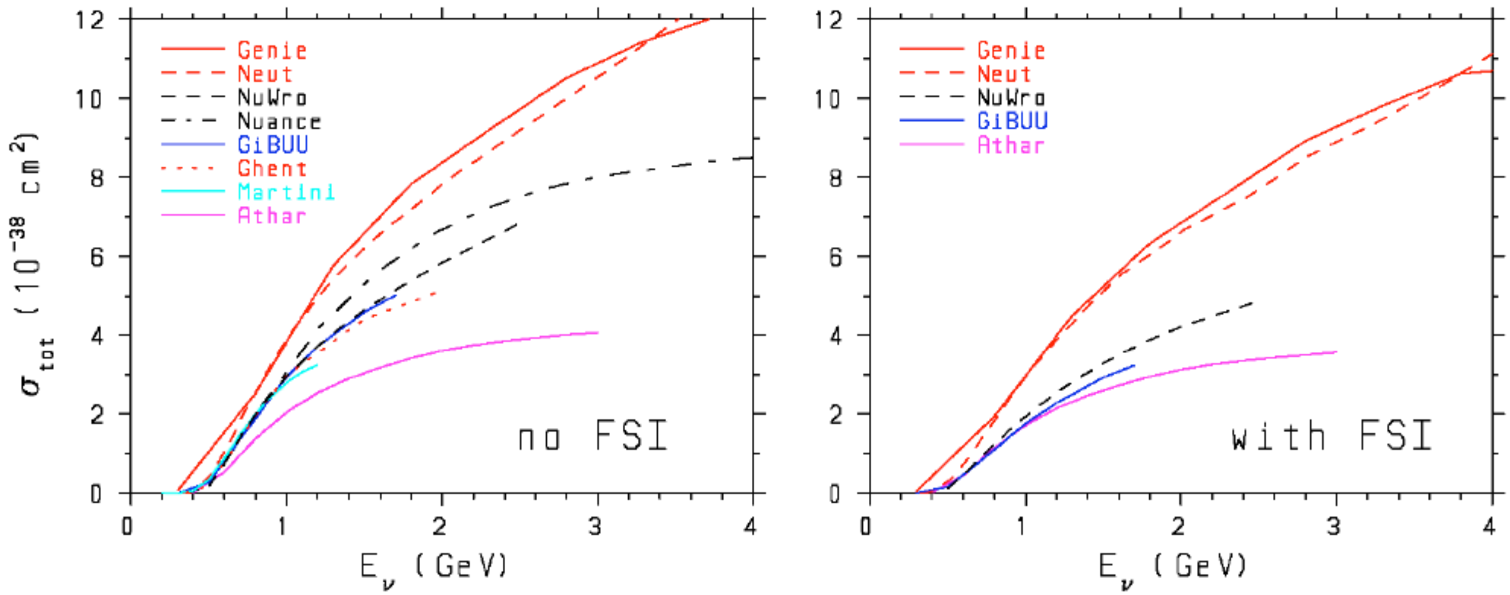


FIGURE 5. Total CC single π^+ production cross section on ^{12}C. All calculations use the CC pion production vertex. All include nonresonant processes except NUANCE. No coherent events are included.

PICTURES OF HADRONIZATION

For Inelastic Processes:

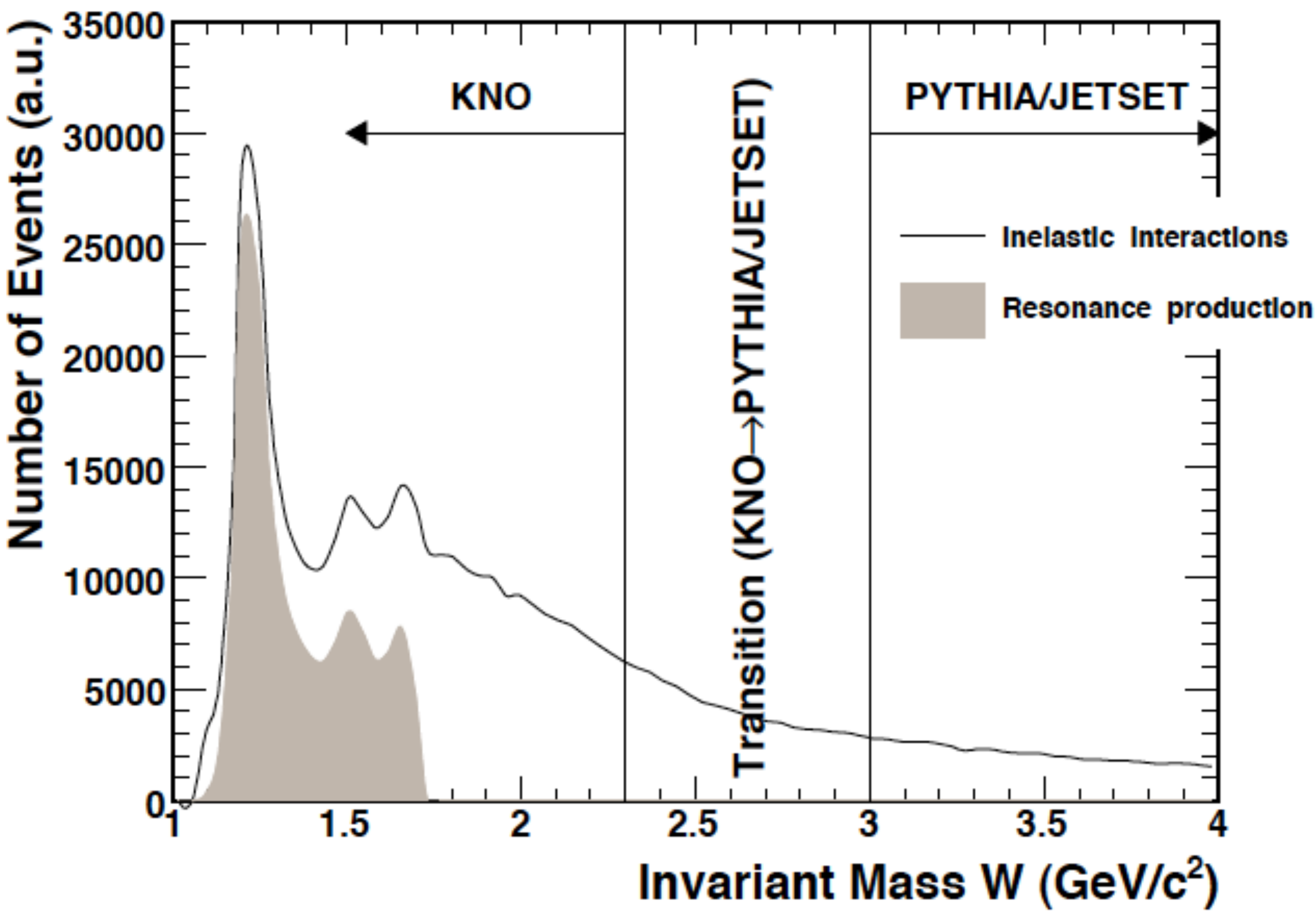
- Resonance region, all hadronic distributions calculable in principle from the resonance model. Often treated as phase space decays - isotropic in hadronic c.m.

- At high energy: ‘current’ and ‘target’ jets.

  Pt is low.

  Need to look at the interaction in the hadronic center of mass to understand the dynamics.

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



The model for the cross section will affect many things.
DIS vs. 'non-resonant background' in the resonance region.

RESONANCES

Model from Rein-Sehgal[1] calculates cross sections for electron and neutrino-production of hadronic resonances up to W=1.7 GeV/c^2.

Basis for the model is the FKR[2] model which is assumes a relativistic harmonic oscillator potential for the 3-quark system.

Current Matrix Elements from a Relativistic Quark Model

"A relativistic equation to represent the symmetric quark model of hadrons with harmonic interaction is used to define and calculate matrix elements of vector and axial-vector currents."

[1] Rein and Sehgal, Annals Phys. 133: 79, 1981
[2] Feynman, Kislinger, and Ravndal, Phys. Rev. D 3, 2706–2732 (1971)

RESONANCES

Model from Rein-Sehgal[1] calculates cross sections for electron and neutrino-production of hadronic resonances up to W=1.7 GeV/c^2.

Basis for the model is the FKR[2] model which is assumes a relativistic harmonic oscillator potential for the 3-quark system.

Current Matrix Elements from a Relativistic Quark Model

"A relativistic equation to represent the symmetric quark model of hadrons with harmonic interaction is used to define and calculate matrix elements of vector and axial-vector currents....75 matrix elements are calculated, of which more than 3/4 agree with the experimental values within 40%."

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

[2] Feynman, Kislinger, and Ravndal, Phys. Rev. D 3, 2706–2732 (1971)

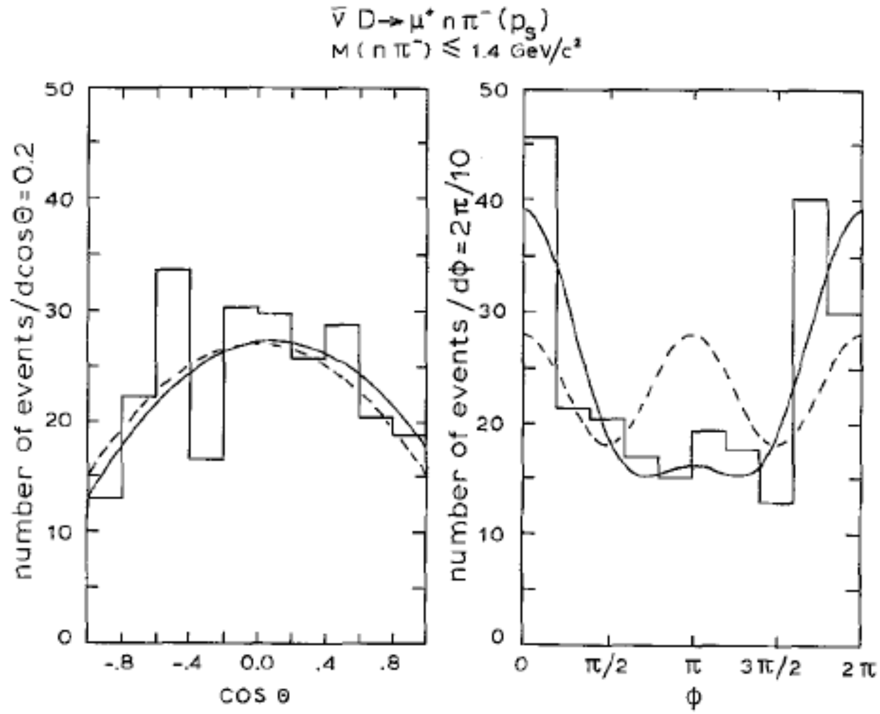


Fig. 2. Decay angular distributions of the π^- in the $n\pi^-$ rest frame for events of reaction (1) with $M(n\pi^-) \leqq 1.4\,\mathrm{GeV/c^2}$, corrected for background. The full curve in the figures is the best fit to the data obtained with the moments method. The dotted curve represents the best fit to the data of the expression given in the text

Allasia et al (BEBC), Z.Phys. C20 (1983) 95-100

$$\frac{dN}{d\Omega} = \frac{N}{\sqrt{4\pi}} \left[Y_0^0 - \frac{2}{\sqrt{5}} (\bar{\rho}_{33} - 0.5)\, Y_2^0 + \frac{4}{\sqrt{10}} \operatorname{Re} \bar{\rho}_{31} \operatorname{Re} Y_2^1 - \frac{4}{\sqrt{10}} \operatorname{Re} \bar{\rho}_{3-1} \operatorname{Re} Y_2^2 \right]$$

Need spin density matrices?

Or parametrizations of the data are enough?

Delta in particular?

Start by reconstructing overall kinematics (E, W, Q^2)

Particle counting:

- Average charged particle multiplicities.
- pizero and neutral strange particle multiplicities.
- charged particle multiplicities.
- (some) neutral - charged multiplicity correlations

Characteristics of the hadronic system (c.m.):

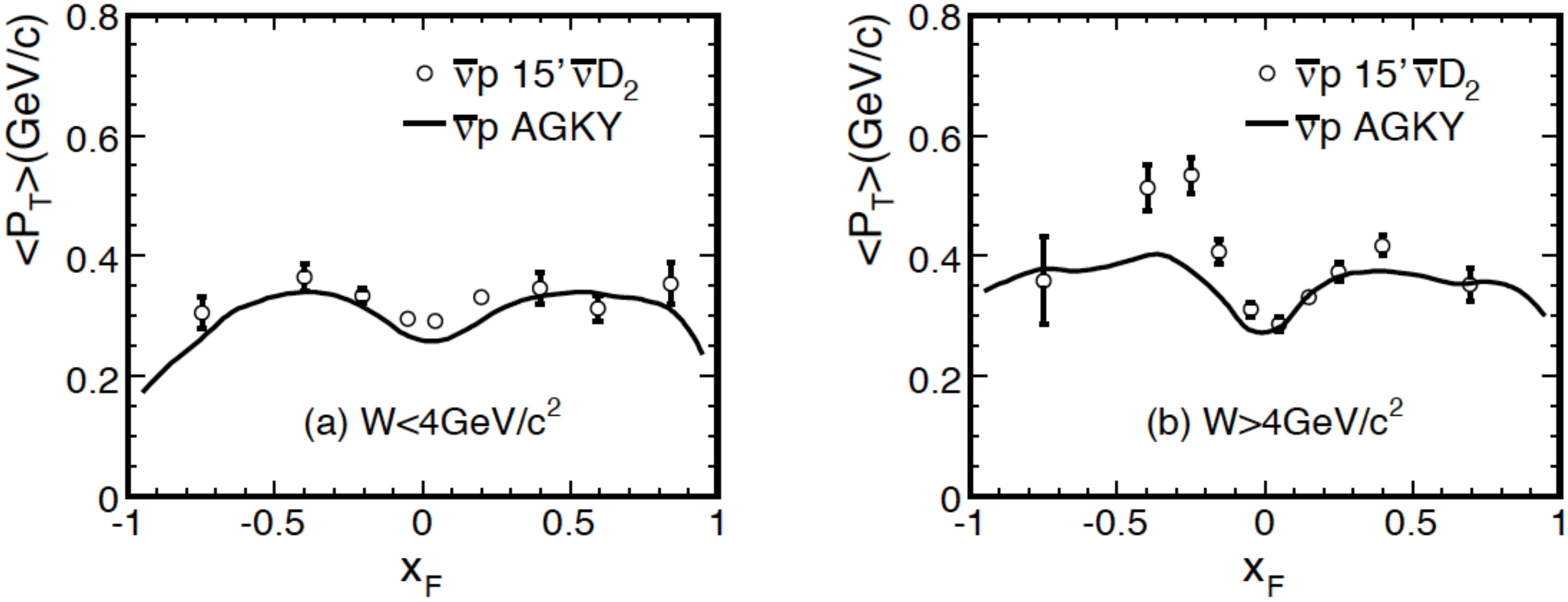
- Multiplicities in forward and backward hemispheres
- Fragmentation functions
- x_F distributions
- Transverse momentum distributions
- x_F-transverse momentum correlations

$$z \equiv \frac{E_{hadron}}{\nu} \qquad D(z) = \frac{1}{N_{\text{events}}} \frac{dN}{dz}$$

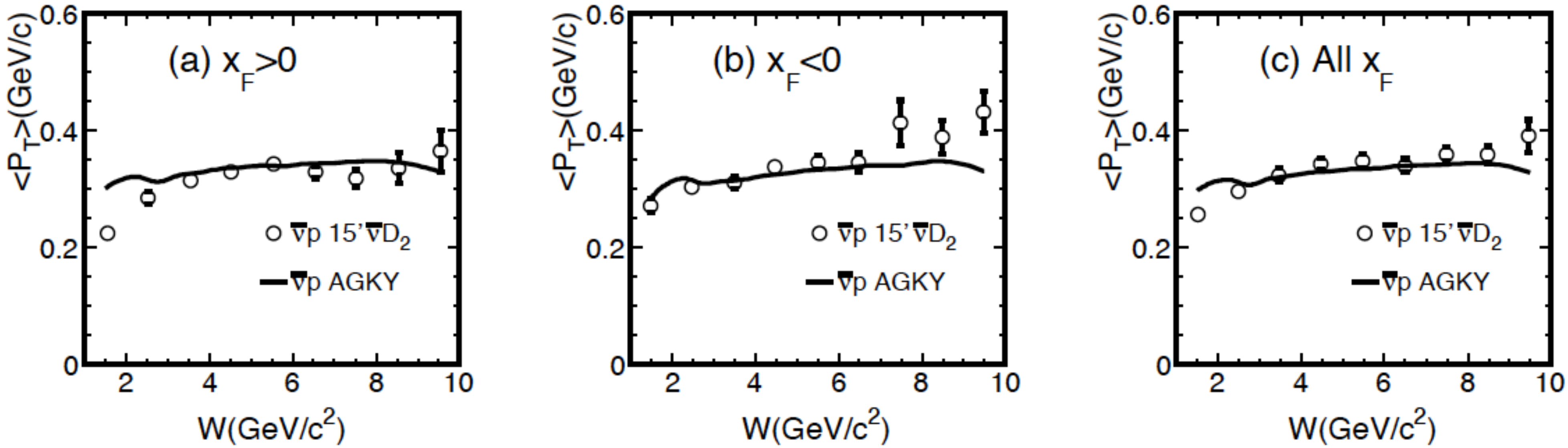
$$x_F \equiv \frac{p_L^*}{p_{L,\max}^*}$$

N. Schmitz, "Production of Hadrons in Charged Current Neutrino and Anti-Neutrino Reactions", Proceedings of Lepton-Photon 1981.

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



$$x_F \equiv \frac{p_L^*}{p_{L,\max}^*}$$



Data: M. Derrick et al., Phys. Rev. D 24, 1071 (1981) [Erratum-ibid. D 30, 1129 (1984)].

$$z \equiv \frac{E_{hadron}}{\nu}$$

Fraction of the energy transfer carried by a particular hadron in the lab frame.

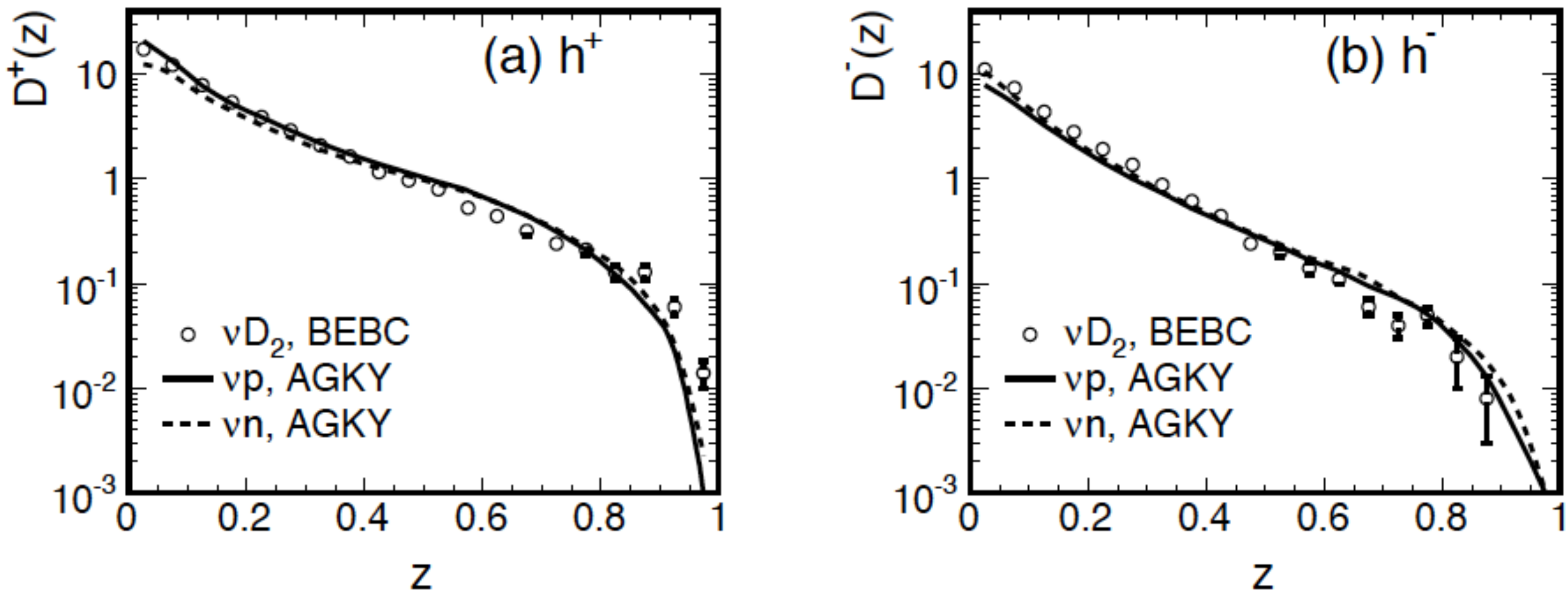


Figure 10: Fragmentation functions for positive (a) and negative (b) hadrons. Applied cuts: $W^2 > 5(GeV/c^2)^2$, $Q^2 > 1(GeV/c)^2$. Data points are taken from [23].

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

The GENIE Hadronization Model (AGKY)

By hadronization model we mean the piece of code that gives a list of final state particles and 4-momenta given an interaction (CC/NC, nu/nubar, n/p) and the event kinematics.

Takes a 4-vector for a hadronic system with some charge produced from a particular neutrino interaction and produces the vector of particles with their 4-momenta.

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

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

NOT THIS GENIE

Codename GENIE: NSA to Control 85,000 "Implants" in Strategically Chosen Machines Around the World by Year End

In Archive, CIA, NSA, NSA Files on August 31, 2013 at 9:57 PM

http://leaksource.wordpress.com/2013/08/31/codename-genie-nsa-to-control-85000-implants-in-strategically-chosen-machines-around-the-world-by-year-end/

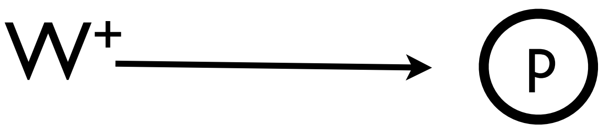
PYTHIA

All generators use PYTHIA for hadronization at high invariant masses.

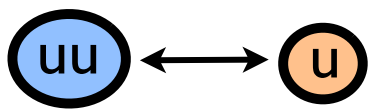
Hadronization is based on the venerable LUND string model.

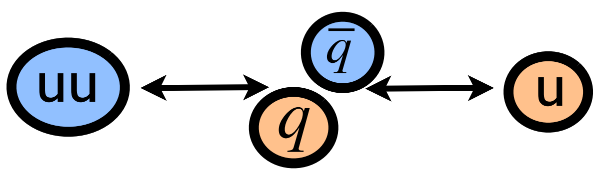
- GENIE: Transition window from 2.3 to 3.0 GeV/c^2
- GiBUU: Uses PYTHIA for hard scattering and hadronization, transition window from 2.0 to 2.4 GeV/c^2
- NEUT: above 2.0 GeV/c^2
- NuWRO: above 1.21 GeV/c^2

e.g nu+p CC



in hadronic c.m.





continues until invariant mass is too low, then cluster fragmentation/collapse.

Q: sea quark scattering?

also GENIE except for

Parameter	Value (Wroclaw)	Value (NUX)	Description
PARJ(2)	-	0.21	(D=0.30) is P(s)/P(u), the suppression of s quark pair production in the field compared with u or d pair production.
PARJ(21)	-	0.44	(D=0.36 GeV) corresponds to the width σin the Gaussian px and py transverse momentum distributions for primary hadrons. See also PARJ(22) -PARJ(24).
PARJ(23)	-	0.01	PARJ(23-24) : (D=0.01, 2.) a fraction PARJ(23) of the Gaussian transverse momentum distribution is taken to be a factor PARJ(24) larger than input in PARJ(21). This gives a simple parametrization of non-Gaussian tails to the Gaussian shape assumed above.
PARJ(32)	0.1 GeV	-	(D=1. GeV) is, with quark masses added, used to define the minimum allowable energy of a colour-singlet jet system.
PARJ(33)	0.5 GeV	0.2 GeV	(D=0.8 GeV, 1.5 GeV) are, together with quark masses, used to define the remaining energy below which the fragmentation of a jet system is stopped and two final hadrons formed. PARJ(33) is normally used, except for MSTJ(11)=2, when PARJ(34) is used.
PARJ(34)	1.0 GeV	-	
PARJ(36)	0.3 GeV	-	(D=2.) represents the dependence on the mass of the final quark pair for defining the stopping point of the fragmentation. Is strongly correlated to the choice of PARJ(33)

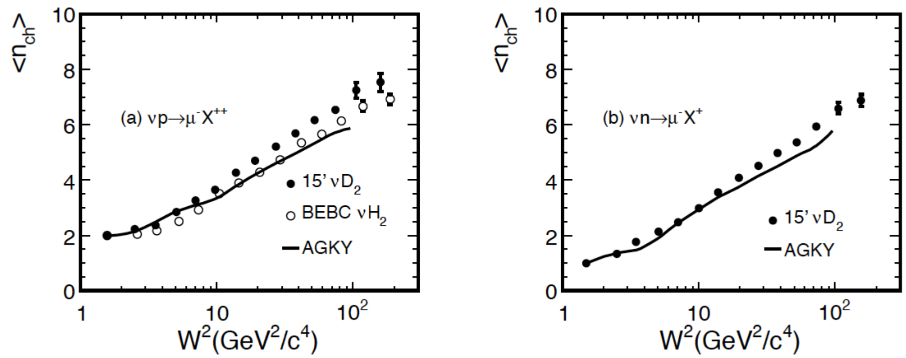
also MSTJ(17)=3 in NuWRO

J. Nowak (NuWRO), Phys.Scripta T127 (2006) 70-72

1) average multiplicity selected from measured multiplicity relations

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

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



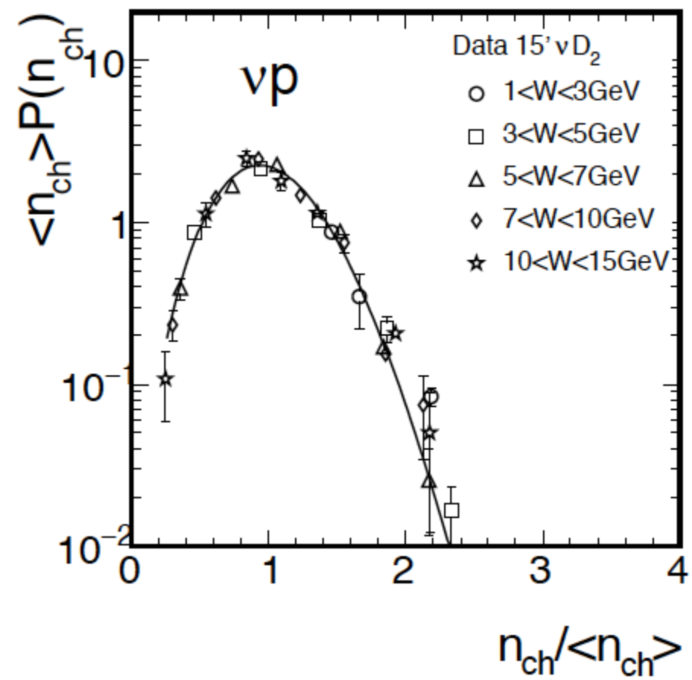
	νp	νn	$\bar{\nu} p$	$\bar{\nu} n$
a_{ch}	0.40 [7]	-0.20 [7]	0.02 [13]	0.80 [13]
b_{ch}	1.42 [7]	1.42 [7]	1.28 [13]	0.95 [13]
c_{ch}	7.93 [7]	5.22 [7]	5.22	7.93
$a_{hyperon}$	0.022	0.022	0.022	0.022
$b_{hyperon}$	0.042	0.042	0.042	0.042

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

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

2) multiplicity for event selected based on KNO scaling

(<n>P(n,W) vs. n/<n> is independent of W)

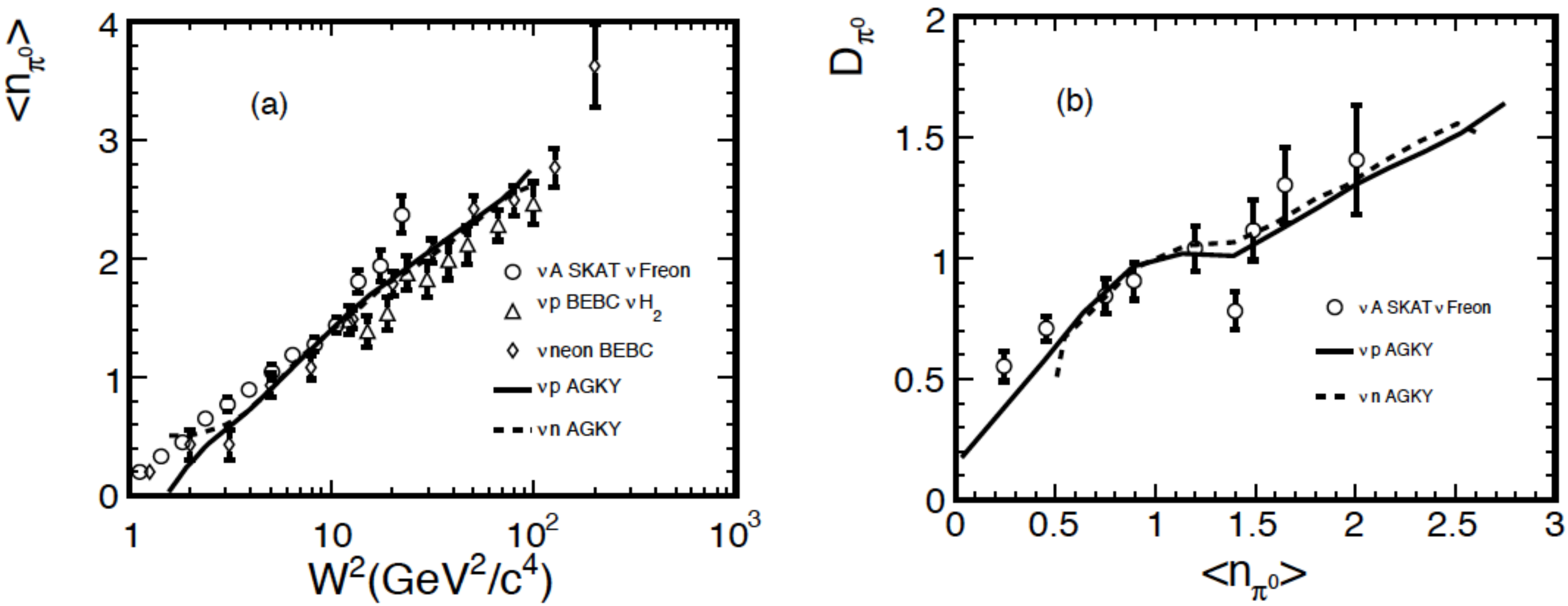


$$\langle n \rangle P(n) = f(n / \langle n \rangle)$$

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

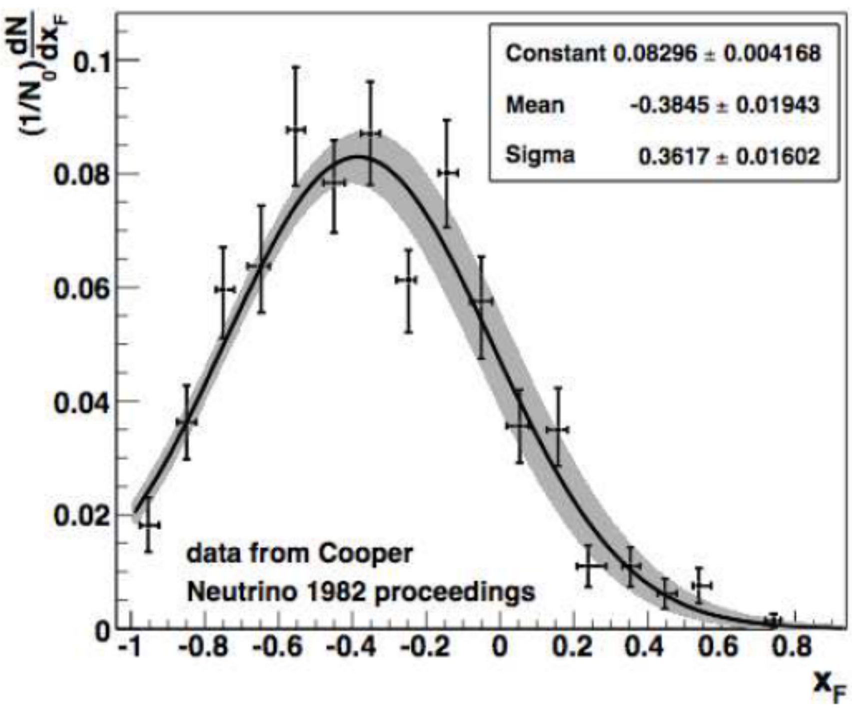
3) Select baryon in the event (probability for selecting a proton depends only on the initial state). Net charge of the system is reduced to zero by creating charged pions. Remaining particle types assigned according to simple pair production probabilities:

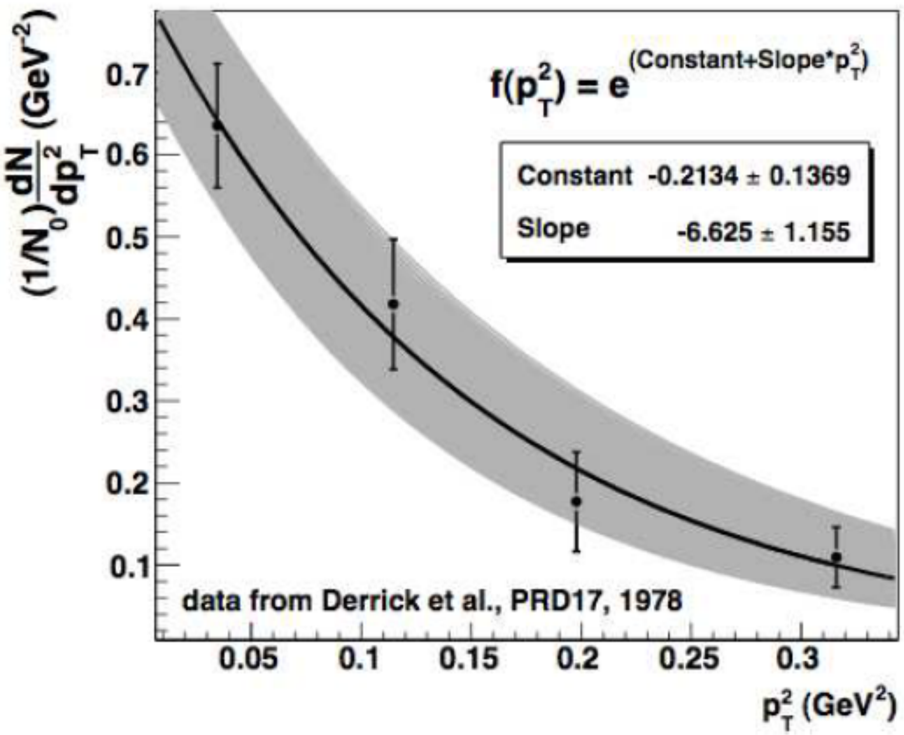
State	Probability
$\pi^0\pi^0$	30%
$\pi^+\pi^-$	60%
K^0 K^-	2.5%
K^+ K^-	2.5%
K^0 K^+	2.5%
K^0 K^0	2.5%

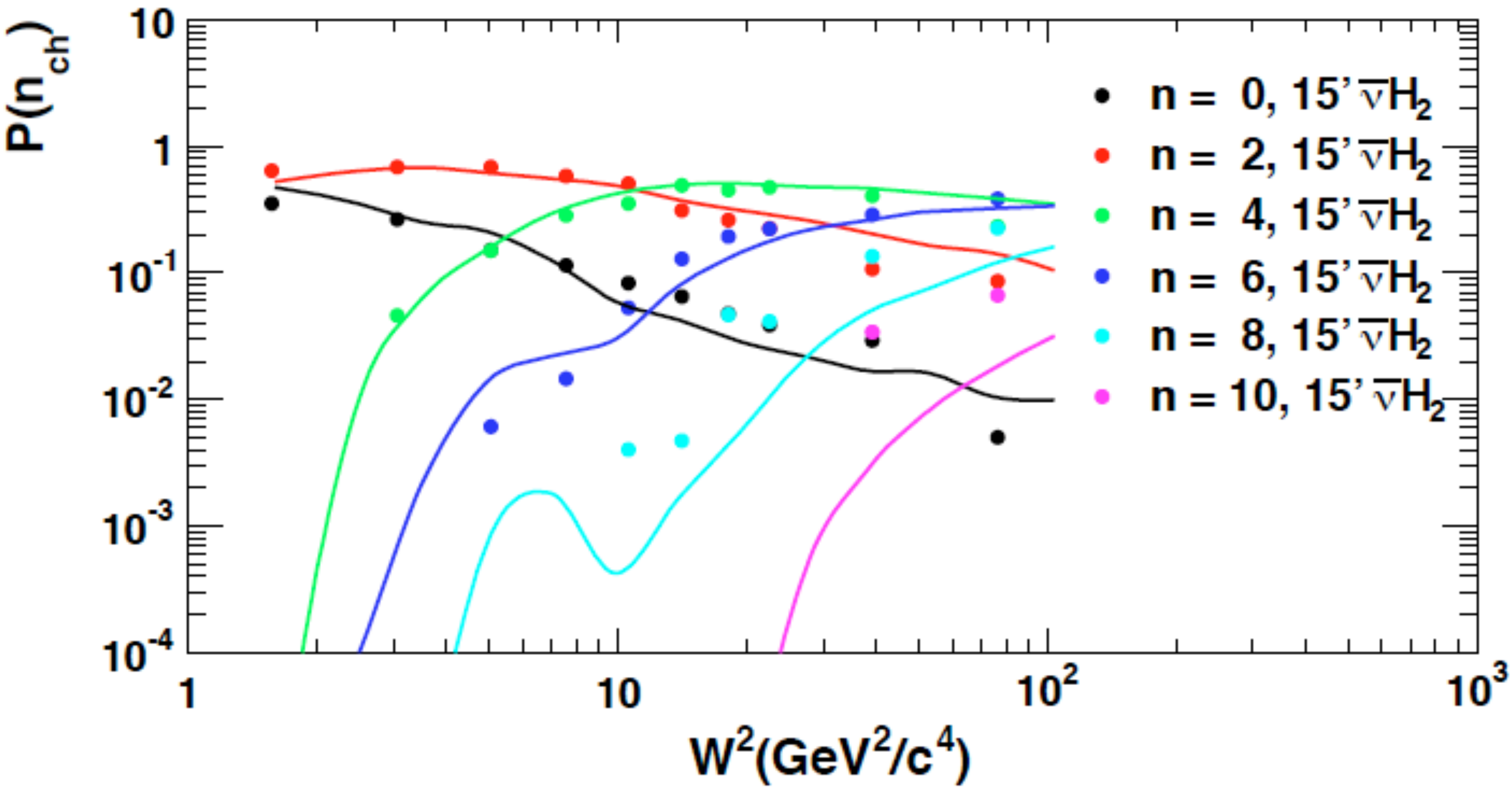


4) Select baryon 4-momentum from empirical distribution $P(x_F, pt)$.

5) 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 pt-limited Phase Space", Z. Phys. C 13: 71 (1982). $W_i=\exp(-A^*p^i_t)$







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.

Y. Hayato, 2009 Wroclaw Neutrino School (http://wng.ift.uni.wroc.pl/karp45/)

9. Deep Inelastic scattering

ν + N → l + hadrons

Avoid double counting : the resonance region to the DIS region

W < 2GeV : Restrict # of mesons to be larger than 1
Exclude 1 meson production
by using multiplicity function <n>(W)
Because non-resonant background is already included
in the single π production.

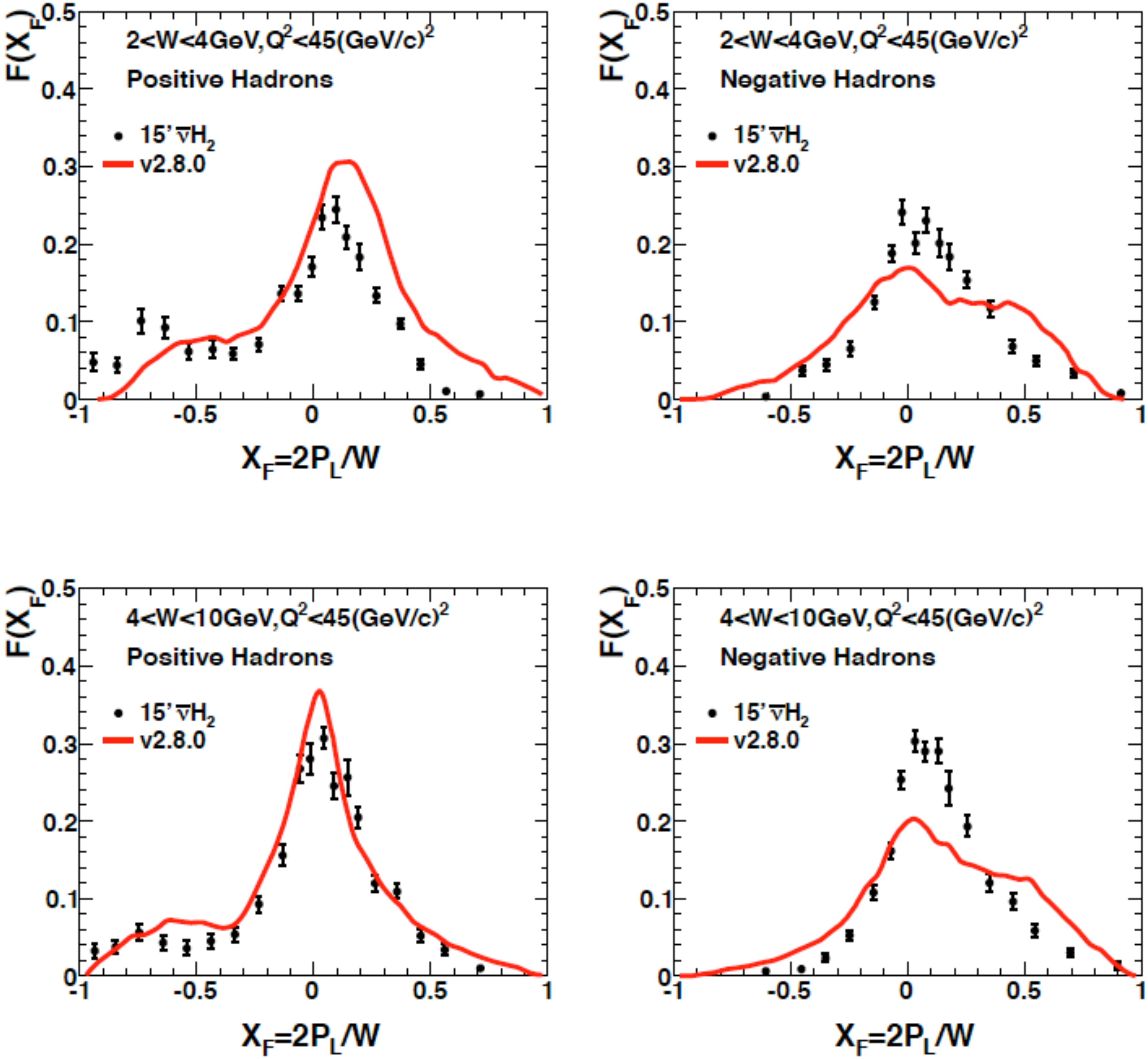
Multiplicity is determined based on the experimental result.
Current version: S. J. Barish et al. Phys. Rev D.17,1 (1978)
(There are recent reports from CHORUS collaboration.
Eur.Phys.J.C51:775-785,2007)

$$\langle n_\pi \rangle = 0.09 + 1.83 \ln(W^2)$$

W > 2GeV : Use PYTHIA to generate vectors.

	W < 2GeV	W > 2GeV
# of π = 1	Rein & Sehgal	PDF + Custom kinematics (Bodek & Yang Corr.)
# of π > 1	Use PDF + PYTHIA (Bodek & Yang Corr.)	Use PDF + PYTHIA (Bodek & Yang Corr.)

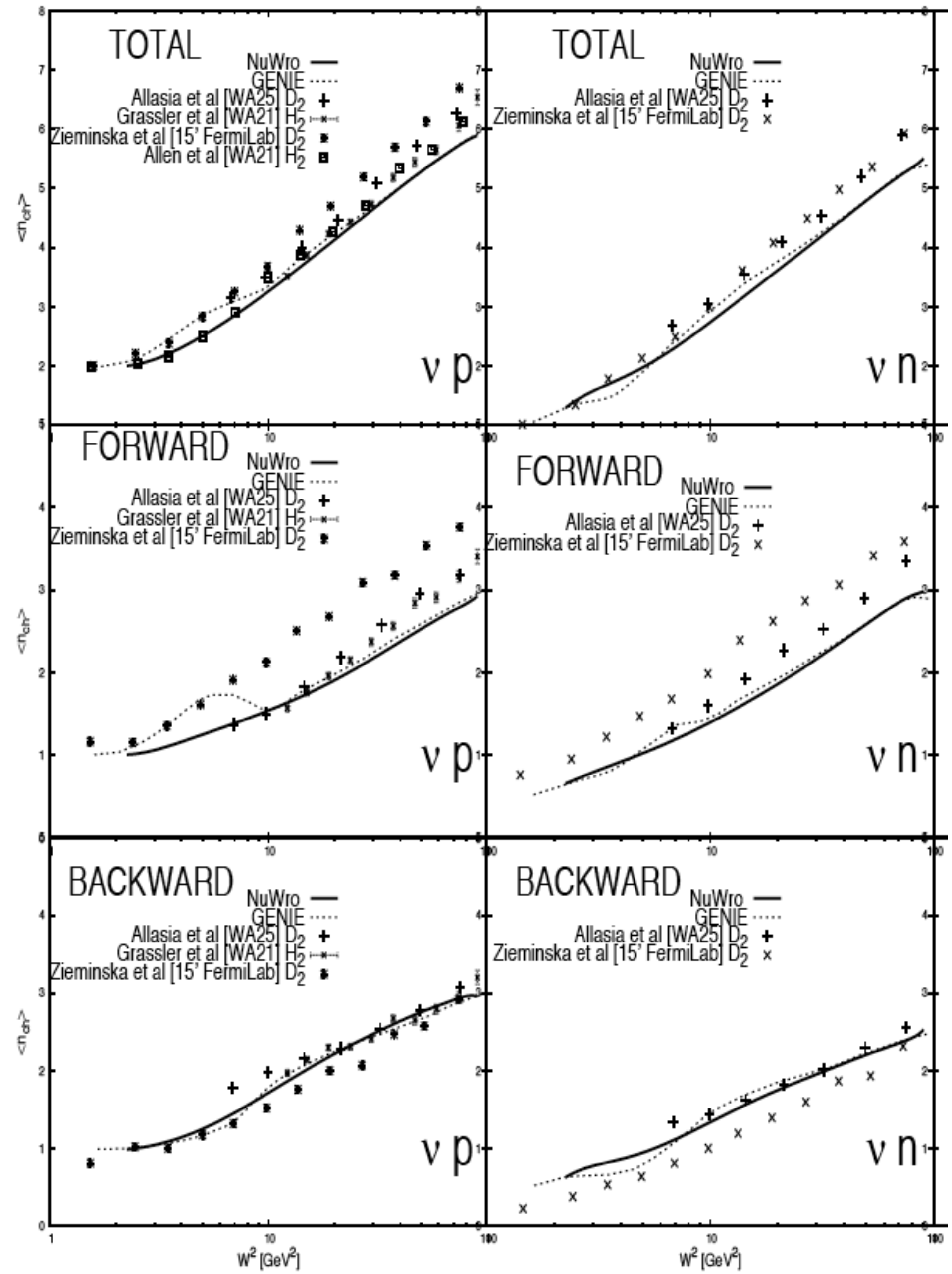
As for the parton distribution function,
we use the correction suggsted by Bodek and Yang.



2<W<4GeV,Q2<45(GeV/c)2
Positive Hadrons
15' νH2
v2.8.0
F(XF)
XF=2PL/W
2<W<4GeV,Q2<45(GeV/c)2
Negative Hadrons
15' νH2
v2.8.0
F(XF)
XF=2PL/W
4<W<10GeV,Q2<45(GeV/c)2
Positive Hadrons
15' νH2
v2.8.0
F(XF)
XF=2PL/W
4<W<10GeV,Q2<45(GeV/c)2
Negative Hadrons
15' νH2
v2.8.0
F(XF)
XF=2PL/W

NuWRO

Careful tuning of PYTHIA parameters to produce agreement with charged particle multiplicities.



J. Sobczyk, PoS(NUFACT08)141

"Mean charged multiplicities in charged-current neutrino scattering on hydrogen and deuterium"

Kuzmin and Naumov, arXiv:1311.4047

Extremely careful examination of data:

- Identifying duplicate data sets
- Only data without kinematic cuts used in fits
- A variety of other careful tests and consistency checks

Suggested fitting functions:

$$\langle n_{\rm ch}\rangle = \begin{cases} a_1 + b_1 \ln X + c_1 \ln^2 X & \text{for } X \le X_0, \\ a_2 + b_2 \ln X + c_2 \ln^2 X & \text{for } X > X_0. \end{cases}$$

$a_1 = 2$
$b_1 = 0$
$c_2 = 0$

gives good fits

Comparisons to generators and pi-p data.

Disagreement between hydrogen and deuterium fits.

$$\frac{\langle n_{\rm ch}^{\nu p}\rangle_{\rm free}}{\langle n_{\rm ch}^{\nu p}\rangle_{\rm bound}} = \frac{\langle n_{\rm ch}^{\nu n}\rangle_{\rm free}}{\langle n_{\rm ch}^{\nu n}\rangle_{\rm bound}}$$

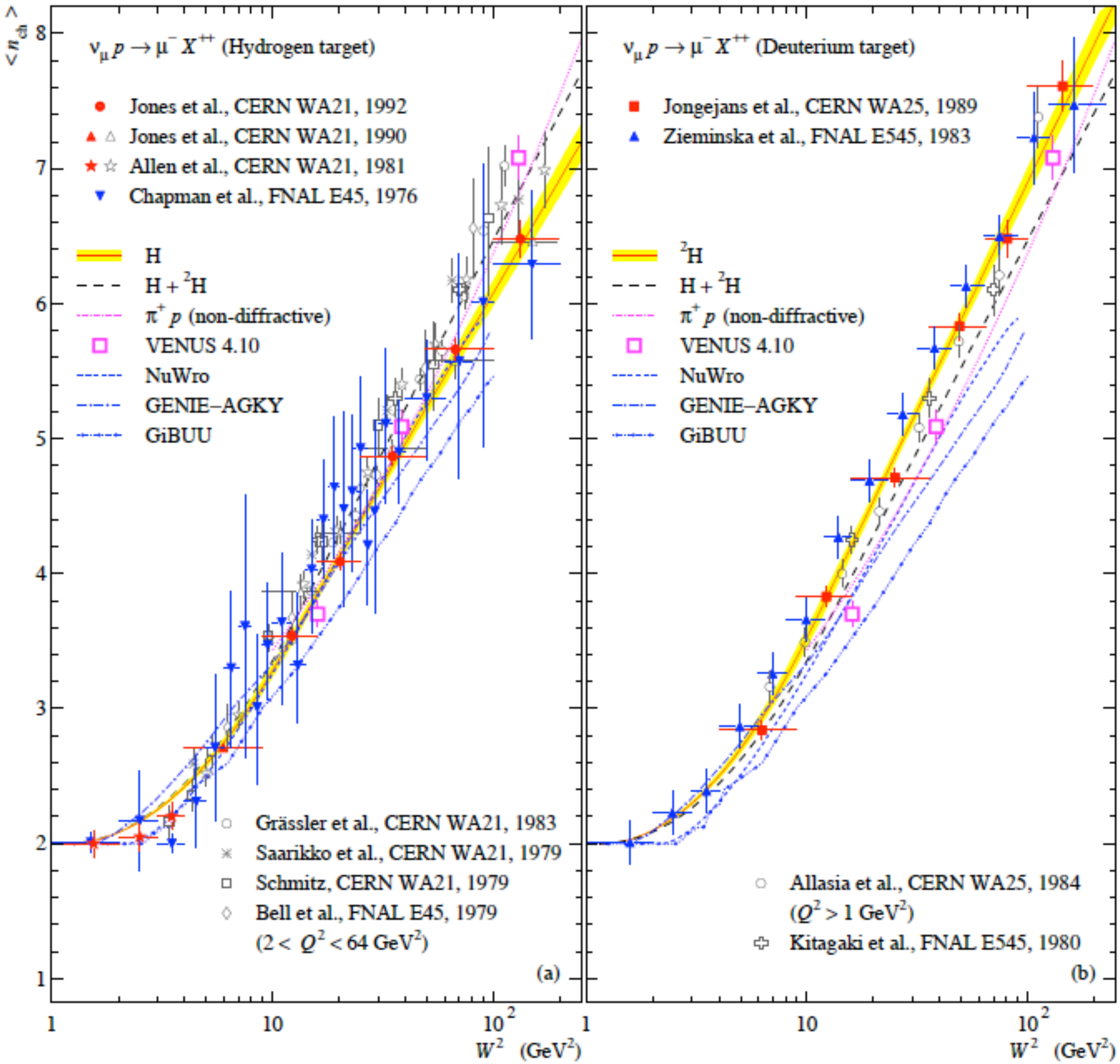
Get from data

Apply to get "free" neutron values

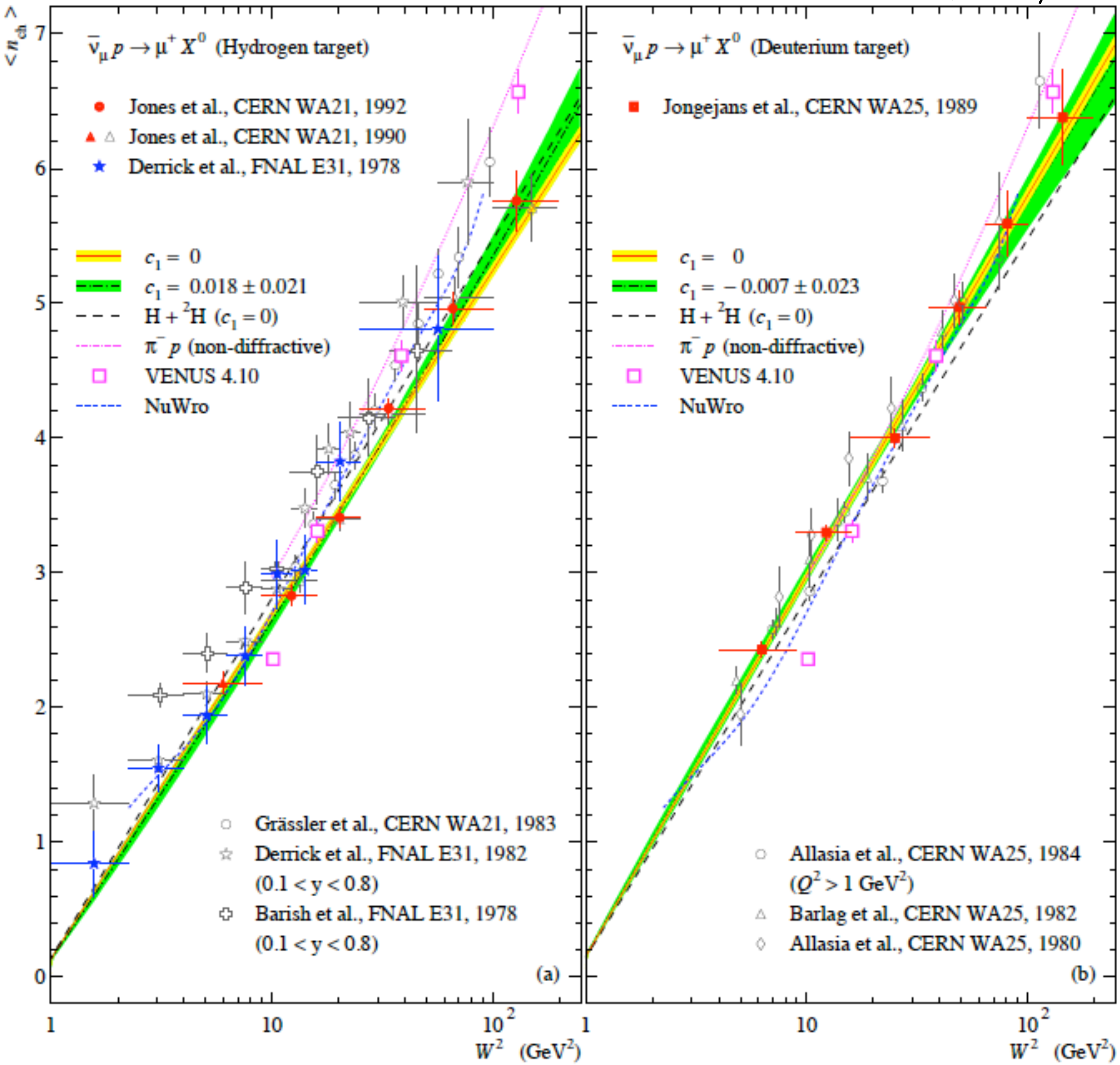
Author(s), experiment, publ. date	Ref.	Target	W range	Kinematic cuts	Intercept a	Slope b
			$\nu_\mu p \to \mu^- X^{++}$			
Coffin *et al.*, FNAL E45, 1975	[21]	H	$4-200$		1.0 ± 0.3	1.1 ± 0.1
Chapman *et al.*, FNAL E45, 1976	[22]	H	$4-200$		1.09 ± 0.38	1.09 ± 0.03
Bell *et al.*, FNAL E45, 1979	[23]	H	$4-100$	$Q^2 = 2-64$ GeV^2	–	1.35 ± 0.15
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	$1-100$		0.80 ± 0.10	1.25 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	$4-225$		0.50 ± 0.08	1.42 ± 0.03
Saarikko *et al.*, CERN WA21, 1979	[28]	H	$3-200$		0.68 ± 0.04	1.29 ± 0.02
Schmitz, CERN WA21, 1979	[29]	H	$4-140$		0.38 ± 0.07	1.38 ± 0.03
Allen *et al.*, CERN WA21, 1981	[30]	H	$4-200$		0.37 ± 0.02	1.33 ± 0.02
Grässler *et al.*, CERN WA21, 1983	[32]	H	$11-121$		-0.05 ± 0.11	1.43 ± 0.04
Jones *et al.*, CERN WA21, 1990	[33]	H	$16-196$		0.911 ± 0.224	1.131 ± 0.086
Jones *et al.*, CERN WA21, 1992	[34]	H	$9-200$		0.40 ± 0.13	1.25 ± 0.04
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$2-60$		1.07 ± 0.27	1.31 ± 0.11
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	0.13 ± 0.18	1.44 ± 0.06
			$\overline{\nu}_\mu p \to \mu^+ X^0$			
Derrick *et al.*, FNAL E31, 1976	[14]	H	$4-100$	$y > 0.1$	0.04 ± 0.37	1.27 ± 0.17
Singer, FNAL E31, 1977	[15]	H	$4-100$	$y > 0.1$	0.78 ± 0.15	1.03 ± 0.08
Derrick *et al.*, FNAL E31, 1978	[16]	H	$1-50$		0.06 ± 0.06	1.22 ± 0.03
Derrick *et al.*, FNAL E31, 1982	[20]	H	$4-100$	$0.1 < y < 0.8$	-0.44 ± 0.13	1.48 ± 0.06
Grässler *et al.*, CERN WA21, 1983	[32]	H	$11-121$		-0.56 ± 0.25	1.42 ± 0.08
Jones *et al.*, CERN WA21, 1990	[33]	H	$16-144$		0.222 ± 0.362	1.117 ± 0.141
Jones *et al.*, CERN WA21, 1992	[34]	H	$9-200$		-0.44 ± 0.20	1.30 ± 0.06
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$7-50$		0.55 ± 0.29	1.15 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	$6-140$		0.18 ± 0.20	1.23 ± 0.07
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	$6-140$		0.02 ± 0.20	1.28 ± 0.08
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	-0.29 ± 0.16	1.37 ± 0.06
			$\nu_\mu n \to \mu^- X^+$			
Kitagaki *et al.*, FNAL E545, 1980	[26]	^{2}H	$1-100$		0.21 ± 0.10	1.21 ± 0.04
Zieminska *et al.*, FNAL E545, 1983	[27]	^{2}H	$4-225$		-0.20 ± 0.07	1.42 ± 0.03
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$2-60$		0.28 ± 0.16	1.29 ± 0.07
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	1.75 ± 0.12	1.31 ± 0.04
			$\overline{\nu}_\mu n \to \mu^+ X^-$			
Allasia *et al.*, CERN WA25, 1980	[35]	^{2}H	$7-50$		0.10 ± 0.28	1.16 ± 0.10
Barlag *et al.*, CERN WA25, 1981	[36]	^{2}H	$4-140$		0.79 ± 0.09	0.93 ± 0.04
Barlag *et al.*, CERN WA25, 1982	[37]	^{2}H	$2-140$		0.80 ± 0.09	0.95 ± 0.04
Allasia *et al.*, CERN WA25, 1984	[38]	^{2}H	$8-144$	$Q^2 > 1$ GeV^2	0.22 ± 0.21	1.08 ± 0.06

Kuzmin and Naumov, arXiv:1311.4047

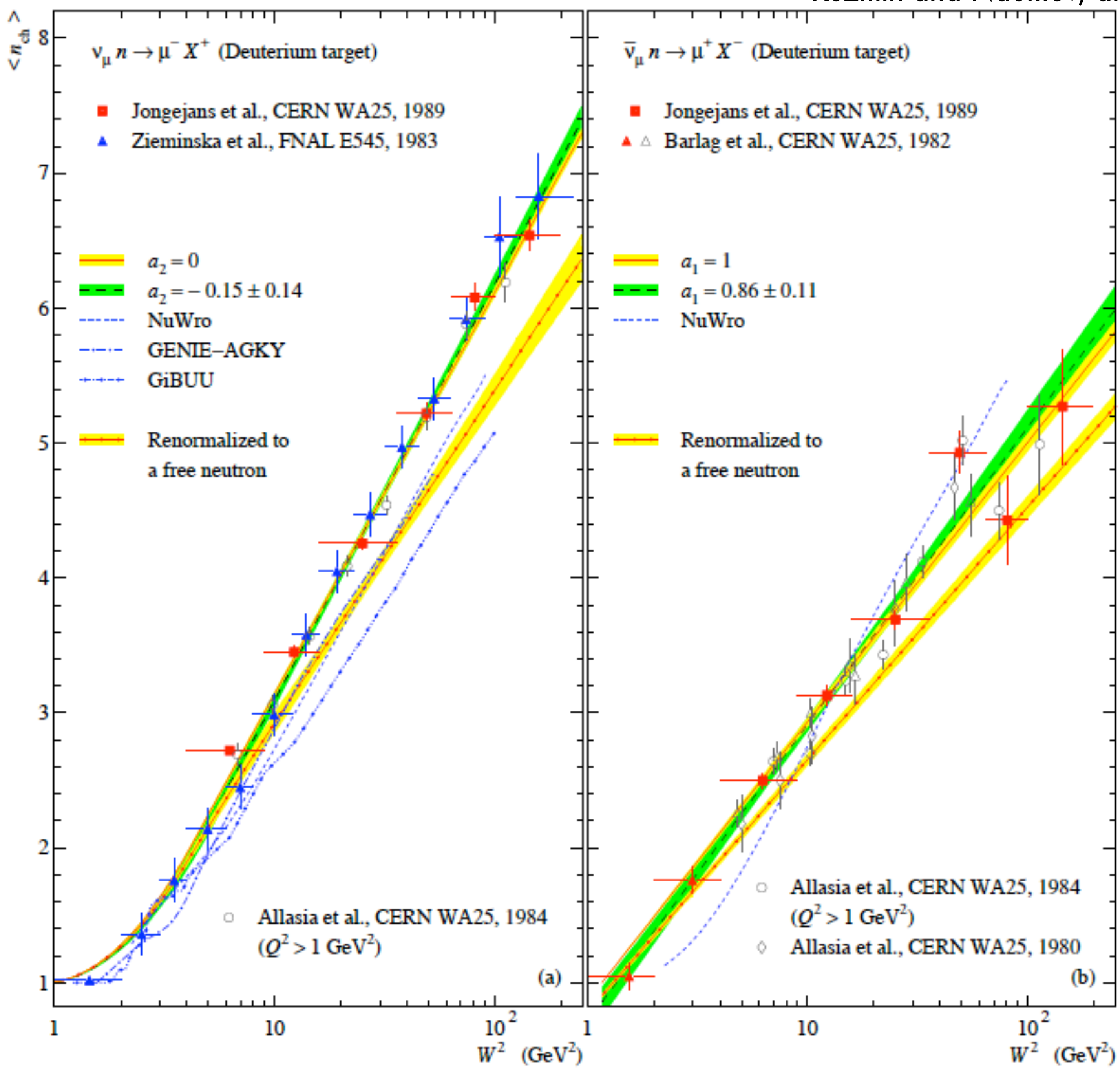
Kuzmin and Naumov, arXiv:1311.4047

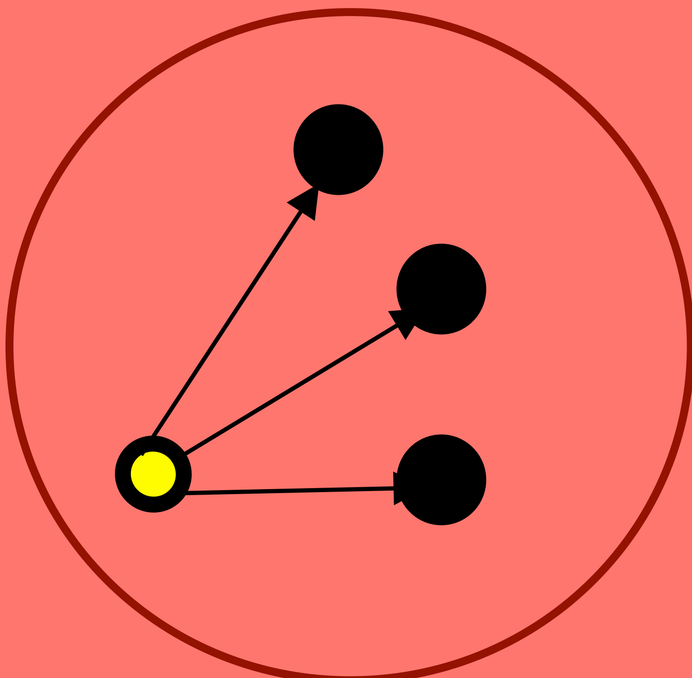


Kuzmin and Naumov, arXiv:1311.4047



Kuzmin and Naumov, arXiv:1311.4047





HADRONIZATION IN NUCLEI

HADRONIZATION IN NUCLEI

A rich theoretical topic that has been studied in some detail in lepton scattering (JLab/Hermes).

QCD Phenomena of Color Transparency (CT). At high momentum transfer, a struck particle is produced with a small size which suppresses its reinteraction cross section.

Detailed QCD models discuss different timescales over which partonic constituents form 'normal' hadrons in the medium.

In many generators, a single "formation time" is often assumed.

Range of Models

Golan et al., Phys.Rev. C86 (2012) 015505

Large differences in treatment of:

- nucleons
- QE/RES events

- Smaller difference in treatment of: pions in DIS events

MC	QE	RES[a]	DIS
NEUT	–	SKAT	SKAT
FLUKA	Coh length	Rantf	Rantf
GENIE	–	–	Rantf-like
NUANCE	1 fm	1 fm	1 fm

[a] Note that every MC has its own slightly different definition of what does RES and DIS terms mean.

TABLE III. FT models in MC event generators

Transparency - Nucleons

D. Rohe et al (E97-006)

$$T_A(Q^2) = \frac{\int_V d\mathbf{p}_m \, dE_m \, N^{exp}(E_m, \mathbf{p}_m)}{\int_V d\mathbf{p}_m \, dE_m \, N^{sim}(E_m, \mathbf{p}_m)}$$

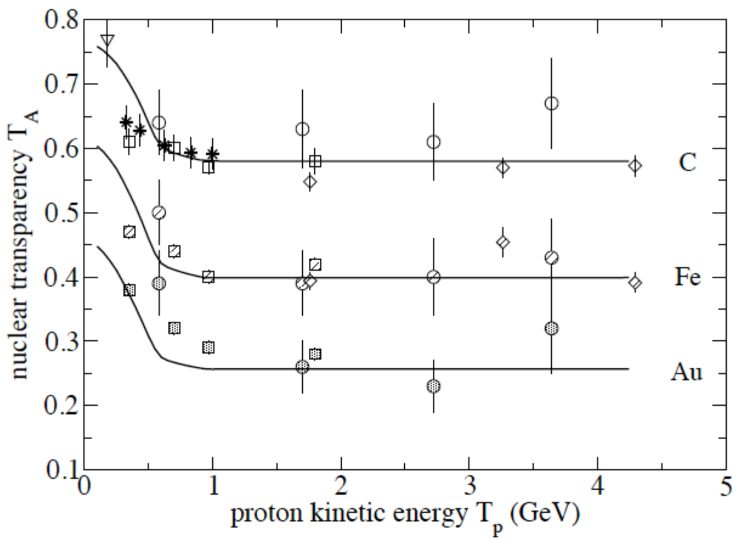


FIG. 4: Nuclear transparency T_A for C, Fe and Au as a function of the proton kinetic energy T_p compared to the correlated Glauber calculations (solid lines). The data indicated by circles are from the NE18–experiment at SLAC [22], squares and diamonds are Jlab data of [23] and [1] and from Bates [3] (triangle down). The result indicated by stars is obtained with the correlated spectral function of [8].

Hadron Attenuation

$$R_M^h(z_h, \nu, p_T^2, Q^2) = \frac{\frac{N_h(z_h,\nu,p_T^2,Q^2)}{N_e(\nu,Q^2)}\Big|_A}{\frac{N_h(z_h,\nu,p_T^2,Q^2)}{N_e(\nu,Q^2)}\Big|_D}$$

EMC, HERMES, JLab

Based on Uncertainty Principle Arguments

QEL: GENIE transports nucleons with the full interaction probability starting from the interaction vertex.

NuWRO uses coherence lengths, no interactions during a time:

$$t_{CL} = \frac{E}{|p \cdot q|}$$

***p* is outgoing nucleon 4-vector**
***q* is 4-momentum transfer**

Sobczyk, nucl-th:1202.4197

RES: GENIE decays resonances at the interaction vertex and transports decay products with the full interaction probability. In GiBUU the delta itself is transported. In NuWRO, before decay transport the delta a distance:

$$t_{\Delta} = \frac{E_{\Delta}}{M\Gamma}$$

Sobczyk, nucl-th:1202.4197

"DIS" Events
(really non-resonant inelastic)

Starting point in the neutrino world for this was the treatment proposed by the SKAT experiment.

$$l = \frac{|\vec{p}|}{\mu^2}$$

SKAT: Baranov et al., PHE 84-04 (1984)

$$\mu = 0.08^{+0.05}_{-0.04}\,\mathrm{GeV}^2$$

DPMJET/NOMAD treatment is based on the equation of Ranft et al.

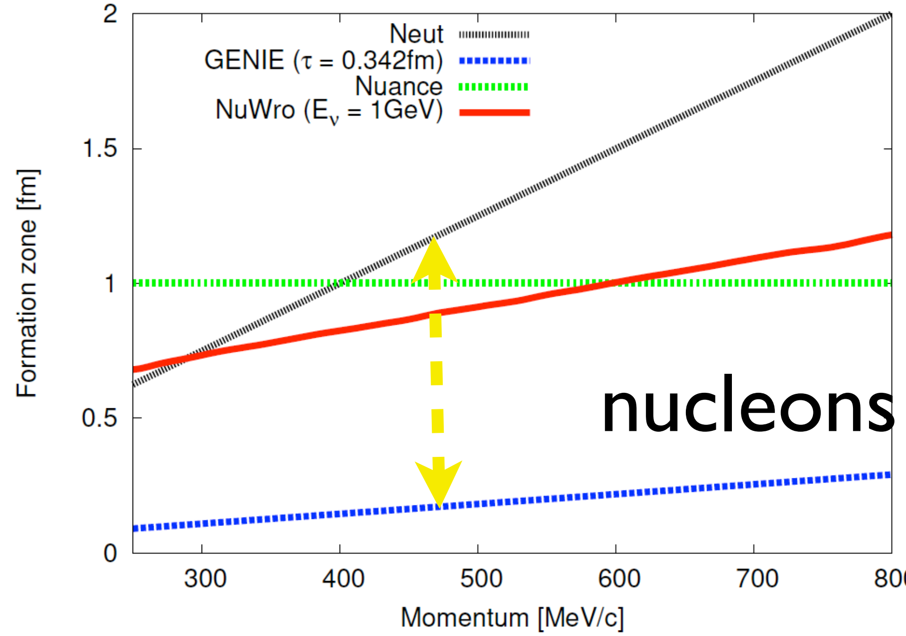
$$l = \frac{|\vec{p}|(c\tau_0)m}{(m^2 + Kp_t^2)}$$

SKAT-equivalent with:

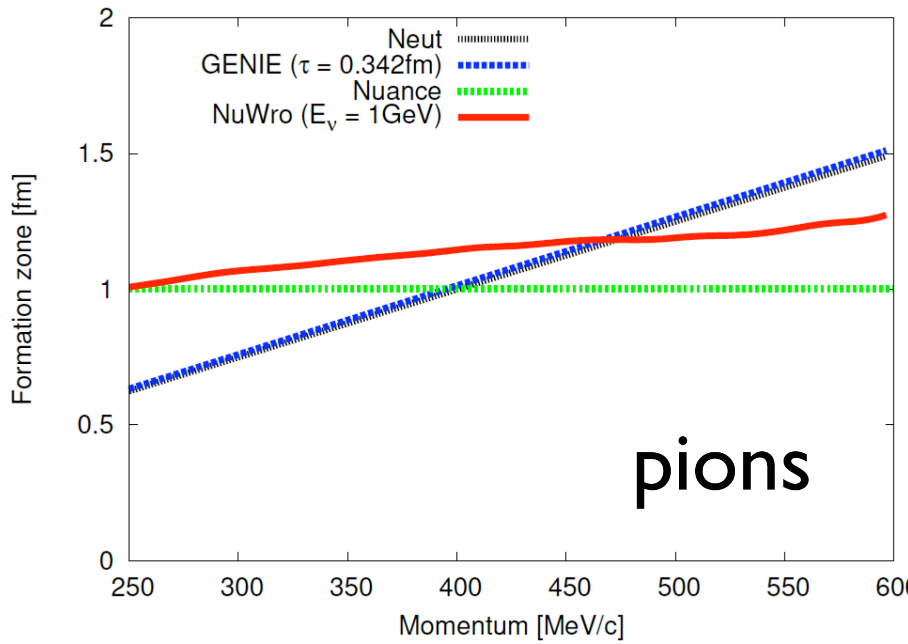
$c\tau_0 = 0.342 \pm 0.171$ fm

K=0

So SKAT expression holds for pions, but not nucleons. To agree with SKAT GENIE needs different formation times for pions and nucleons.



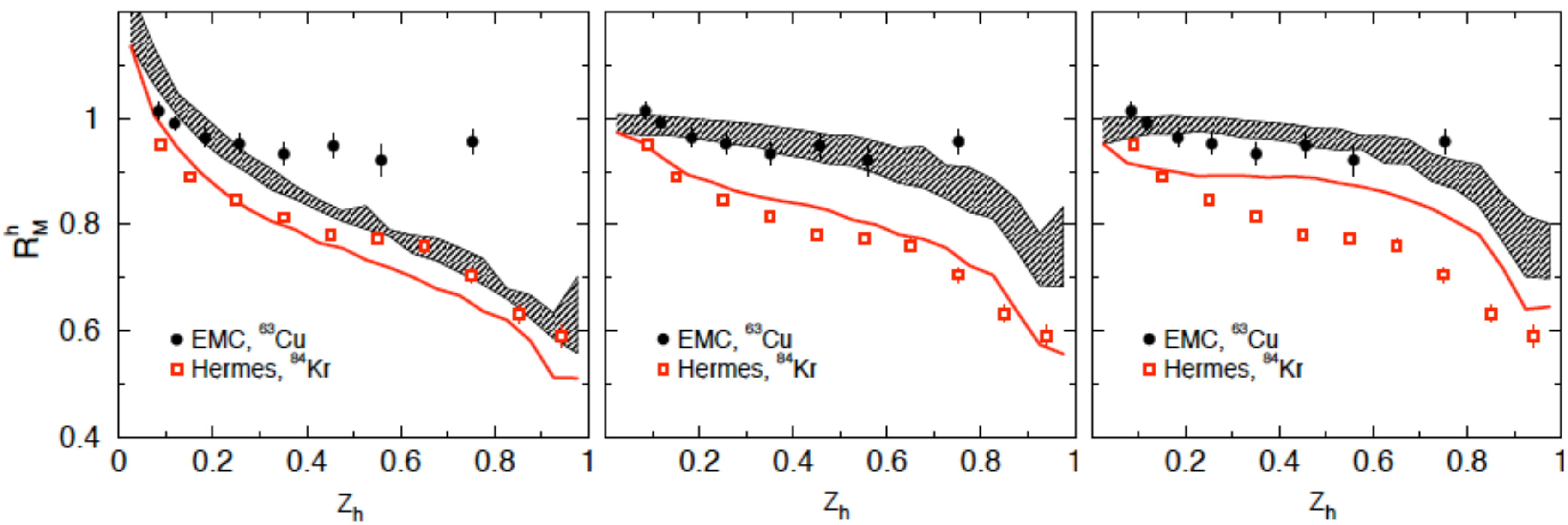
Sobczyk, nucl-th:1202.4197



GiBUU

Hadron attenuation has been one of the many subjects studied with the GiBUU code.

Best description of data is with a hadronic cross section linearly increasing from zero at production time to the normal value at the formation time (as provided by PYTHIA as part of the string fragmentation).



Gallmeister et al., Prog.Part.Nucl.Phys. 61 (2008) 283-289

GiBUU

Gallmeister et al., Prog.Part.Nucl.Phys. 61 (2008) 283-289

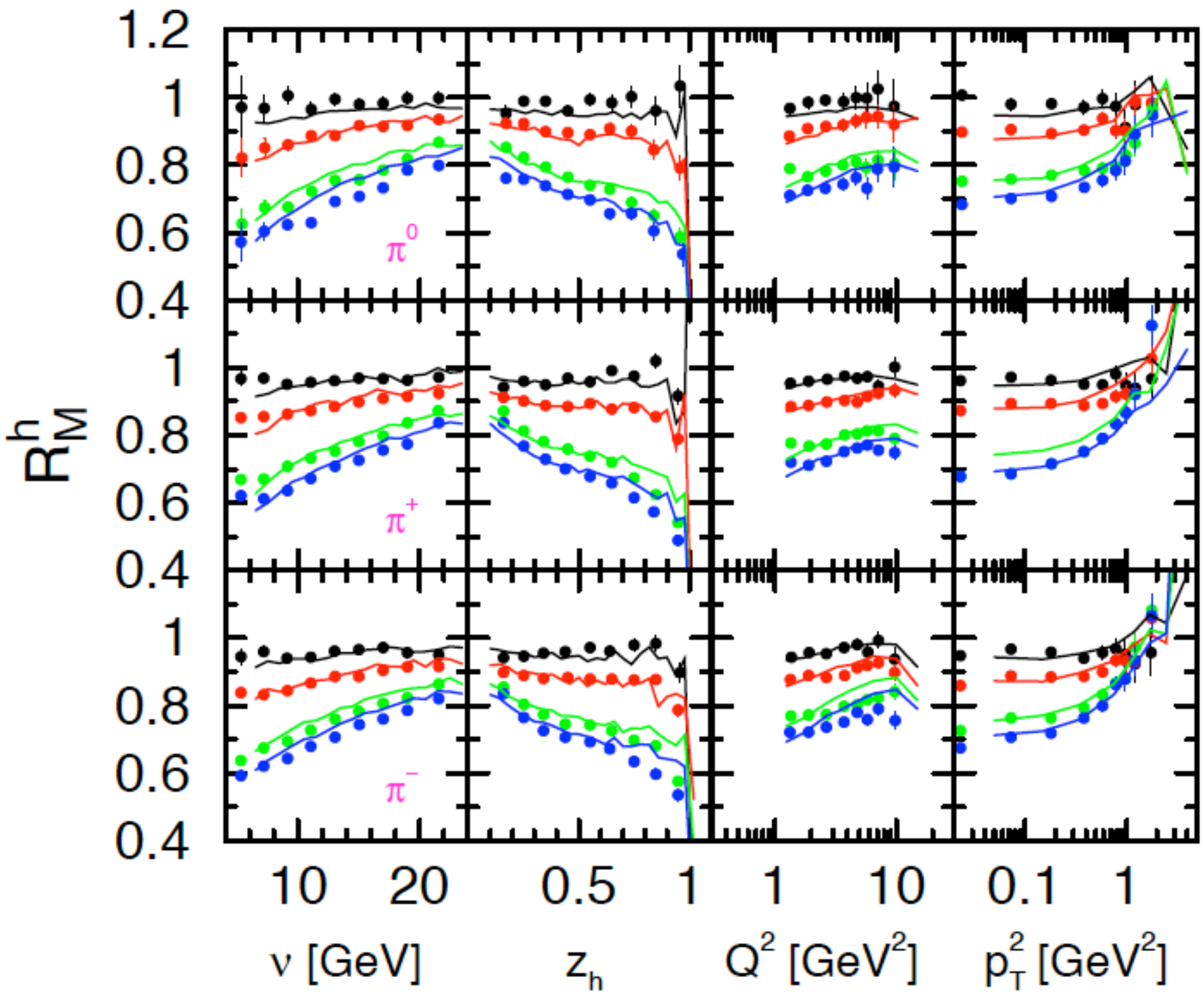


Figure 3: Attenuation of pions in comparison with results of the HERMES experiment. Target nuclei are ^4He,^{20}Ne,^{84}Kr and ^{131}Xe (curves from top to bottom). The calculations have been done with the linear increase of the prehadronic cross sections and a pedestal value for the leading hadrons $\sim 1/Q^2$. Experimental acceptance limitations are taken into account. Data are from [8].

CONCLUSIONS

The ability to simulate hadronic systems in neutrino interactions is important to many neutrino oscillation experiments operating in the few-GeV energy regime.

Abundant data is available from the bubble chamber era for tuning aspects of the free nucleon hadronization model. All generators need to agree with this data. Limitations could perhaps be addressed by CLAS data?

Hadronization in nuclei is more complicated - but here as well significant data exists for generator tuning.

BACKUP

Y. Hayato, 2009 Wroclaw Neutrino School (http://wng.ift.uni.wroc.pl/karp45/)

9. Deep Inelastic scattering

ν + N → l + hadrons

Avoid double counting : the resonance region to the DIS region

W < 2GeV : Restrict # of mesons to be larger than 1
Exclude 1 meson production
by using multiplicity function <n>(W)
Because non-resonant background is already included
in the single π production.

Multiplicity is determined based on the experimental result.
Current version: S. J. Barish et al. Phys. Rev D.17,1 (1978)
(There are recent reports from CHORUS collaboration.
Eur.Phys.J.C51:775-785,2007)

$$\langle n_\pi \rangle = 0.09 + 1.83 \ln(W^2)$$

W > 2GeV : Use PYTHIA to generate vectors.

	W < 2GeV	W > 2GeV
# of π = 1	Rein & Sehgal	PDF + Custom kinematics (Bodek & Yang Corr.)
# of π > 1	Use PDF + PYTHIA (Bodek & Yang Corr.)	Use PDF + PYTHIA (Bodek & Yang Corr.)

As for the parton distribution function,
we use the correction suggsted by Bodek and Yang.

Do not trust F/B data for experiments which do not account for the ambiguity in pi/K/p mass assignment.

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 $\langle n_F^+ \rangle \leq \langle n_B^+ \rangle$. 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 π:K:p mass assignment ambiguities and which found $\langle n_F^+ \rangle > \langle n_B^+ \rangle$"

NuWRO: J. Nowak, Scandinavian Neutrino Workshop (May 2006)

Single pion production cross section has a form

$$\frac{d\sigma^{SPP}}{dW} = \frac{d\sigma^{\Delta}}{dW}(1-\alpha(W)) + \frac{d\sigma^{DIS}}{dW}F^{SPP}(W)\alpha(W) \qquad (1)$$

$$\begin{aligned} \alpha(W) &= \Theta(W_{min}-W)\frac{W-W_{th}}{W_{min}-W_{th}}\alpha_0 \\ &+ \Theta(W_{max}-W)\Theta(W-W_{min})\frac{W-W_{min}+\alpha_0(W_{max}-W)}{W_{max}-W_{min}} \\ &+ \Theta(W-W_{max}) \end{aligned}$$

We observe that the best values of parameters are
$W_{min} = 1.3GeV,\ W_{max} = 1.6GeV$
Non-resonant background is simulated by appropriate DIS contribution. $\alpha_0 \in (0, 0.3)$ (depending on the channel)

“Inclusive Charged Hadron Spectra in nu-A and nubar-A Interactions at E_ν<30 GeV” - SKAT, ZPC 21, 197-204 (1984):

“The phase space model used reproduces the main features of our data *rather well* up to $W^2 = 25 GeV^2$.” (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.” [ref. to Cooper, .

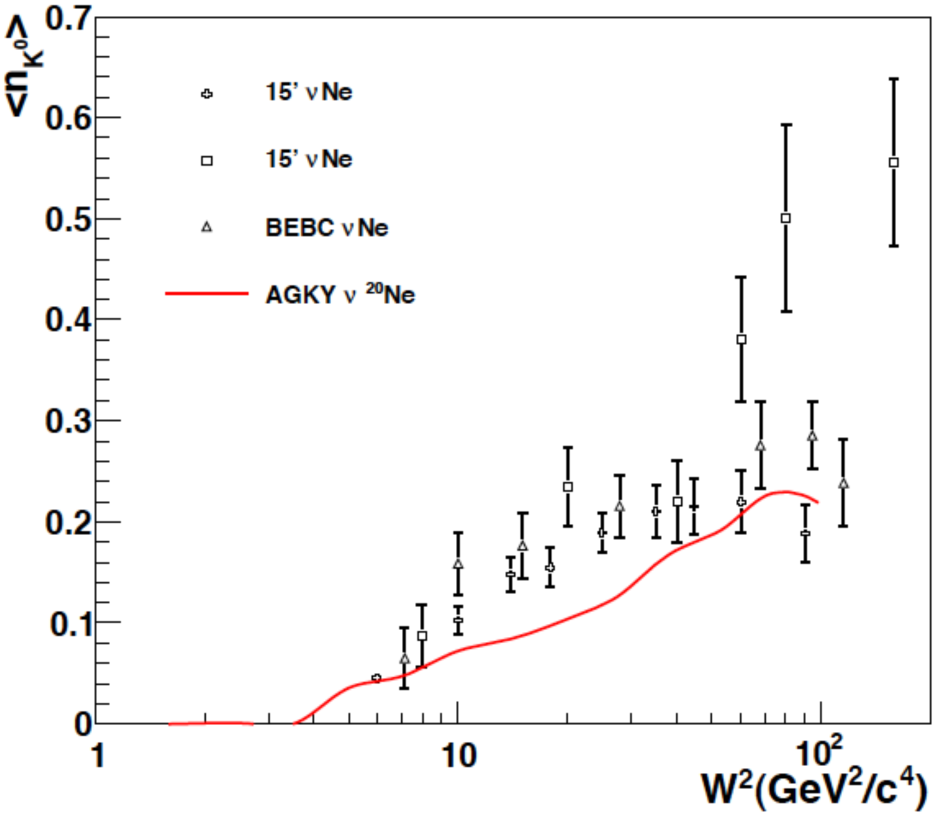
GENIE: Transition Region

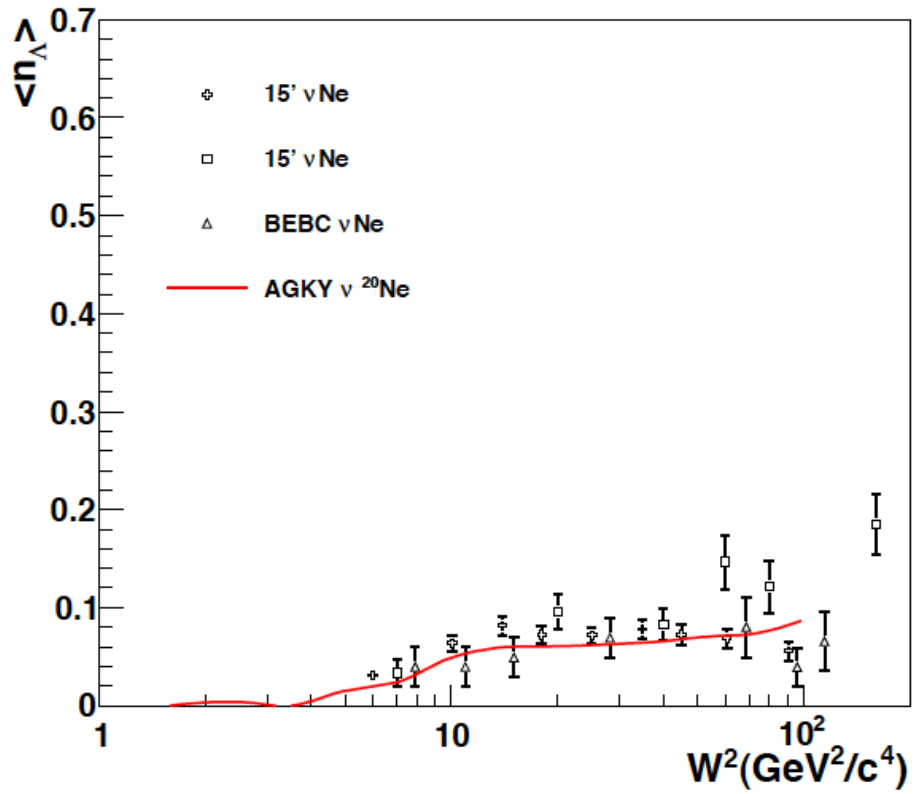
Tune model to give the correct single pion cross section and the correct total cross section (as determined by integrating the DIS model alone).

$$\frac{d\sigma}{d\theta dE'}^{DIS} = \frac{d\sigma}{d\theta dE'}_j^{B-Y} \Theta(W_{cut} - W) \sum_{k=1}^{10} f_k$$

$f_4, f_5\ldots = 1$
f_2 determined from single π fit
f_3 determined from

$$= \int_{W_{min}}^{W_{cut}} dW \int dQ^2 \frac{d\sigma^{R-S}}{dQ^2 dW} + \sum_{k=1}^{10} f_k \int_{W_{min}}^{W_{cut}} dW \int dQ^2 \frac{d\sigma^{B-Y}}{dQ^2 dW}$$


$<n_{K^0}>$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
10^2
$W^2(GeV^2/c^4)$
15' ν Ne
15' ν Ne
BEBC ν Ne
AGKY ν ^{20}Ne


$<n_{\Lambda}>$
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
10
10^2
$W^2(GeV^2/c^4)$
15' ν Ne
15' ν Ne
BEBC ν Ne
AGKY ν ^{20}Ne