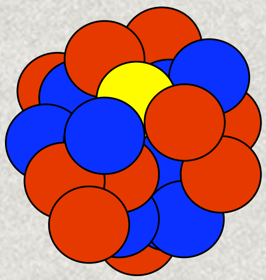
Cross Sections Relevant for Atmospheric Neutrinos

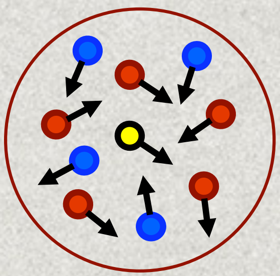
Hugh Gallagher, Tufts University
Advanced Workshop on Physics of Atmospheric Neutrinos

May 28, 2018

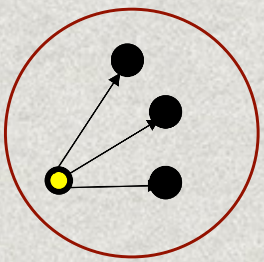
Outline



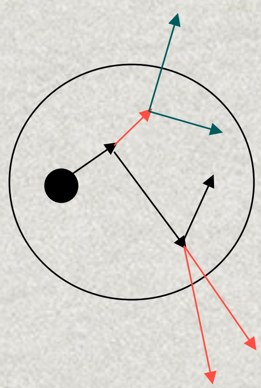
- Neutrino Interaction Physics / Generators



- “Under the Hood” - Free nucleon processes
- “Under the Hood” - Nuclear Physics



- Summary of experimental results
- Examples of interest for atmospheric neutrino measurements

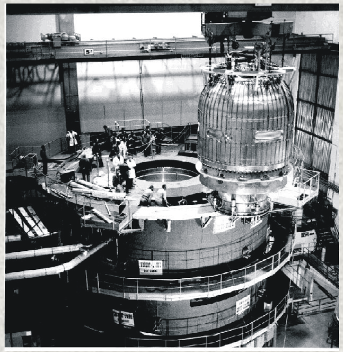


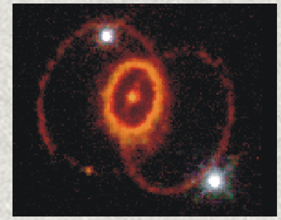
Generators: GiBUU, NuWro, NEUT, GENIE.
General challenges are same, details are different.
GENIE as a specific example (NEUT similarities).

Neutrino Interaction Physics Throughout the Ages

Bubble chambers:
BNL, ANL, FNAL,
CERN, Serpukhov

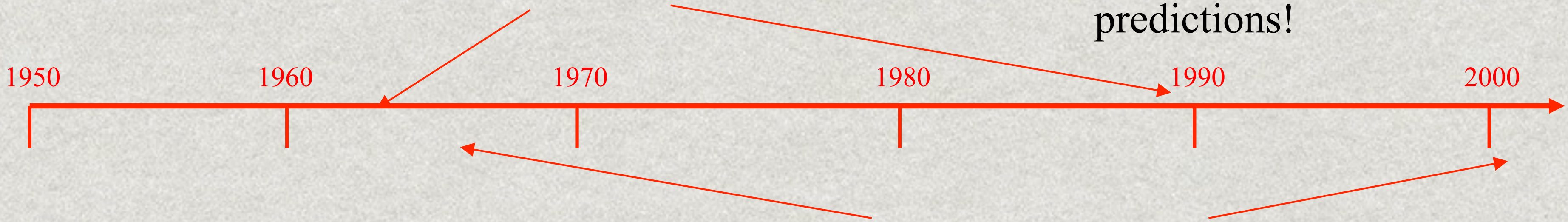
- hadronic weak currents
- observation of neutral currents
- cross section measurements



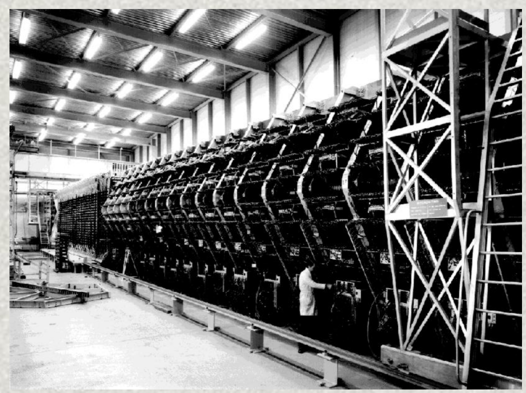


Oscillations →

SN1987A ν detection
confirmed astrophysical
predictions!



high statistics (~100k events)
- structure functions (F_2, F_3)
- parton universality
- Electroweak studies: $\sin^2(\theta_w)$
- strange sea studies
- cross sections
- QCD studies



counter experiments:
CDHS,
CHARM, CHARM II,
CCFR, NuTEV

Neutrino Interaction Physics Throughout the Ages

Bubble chambers:
BNL, ANL, FNAL,
CERN, Serpukhov

- hadronic weak currents
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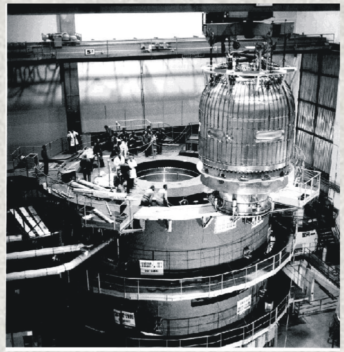
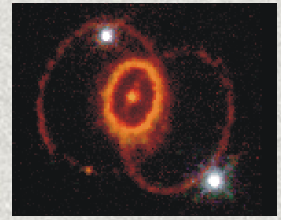
- cross section measurements





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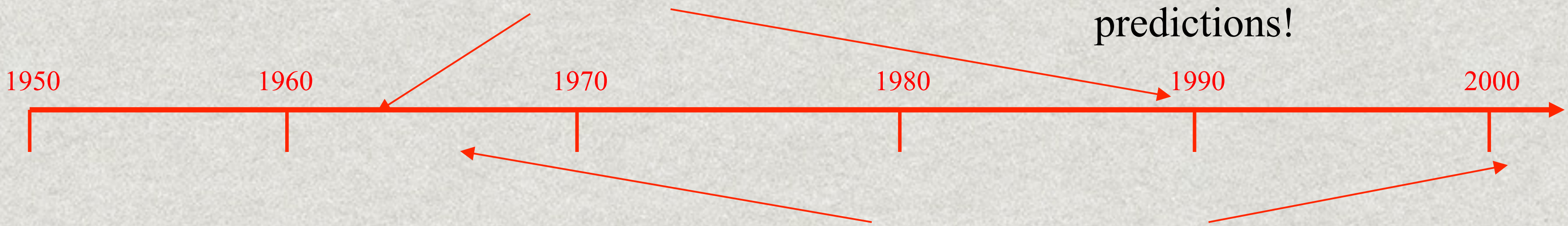


high statistics (
•structure funct
•parton univers
•Electroweak st
•strange sea stu
•cross sections
•QCD studies

Neutrino cross sections and the small atmospheric ν_μ/ν_e ratio

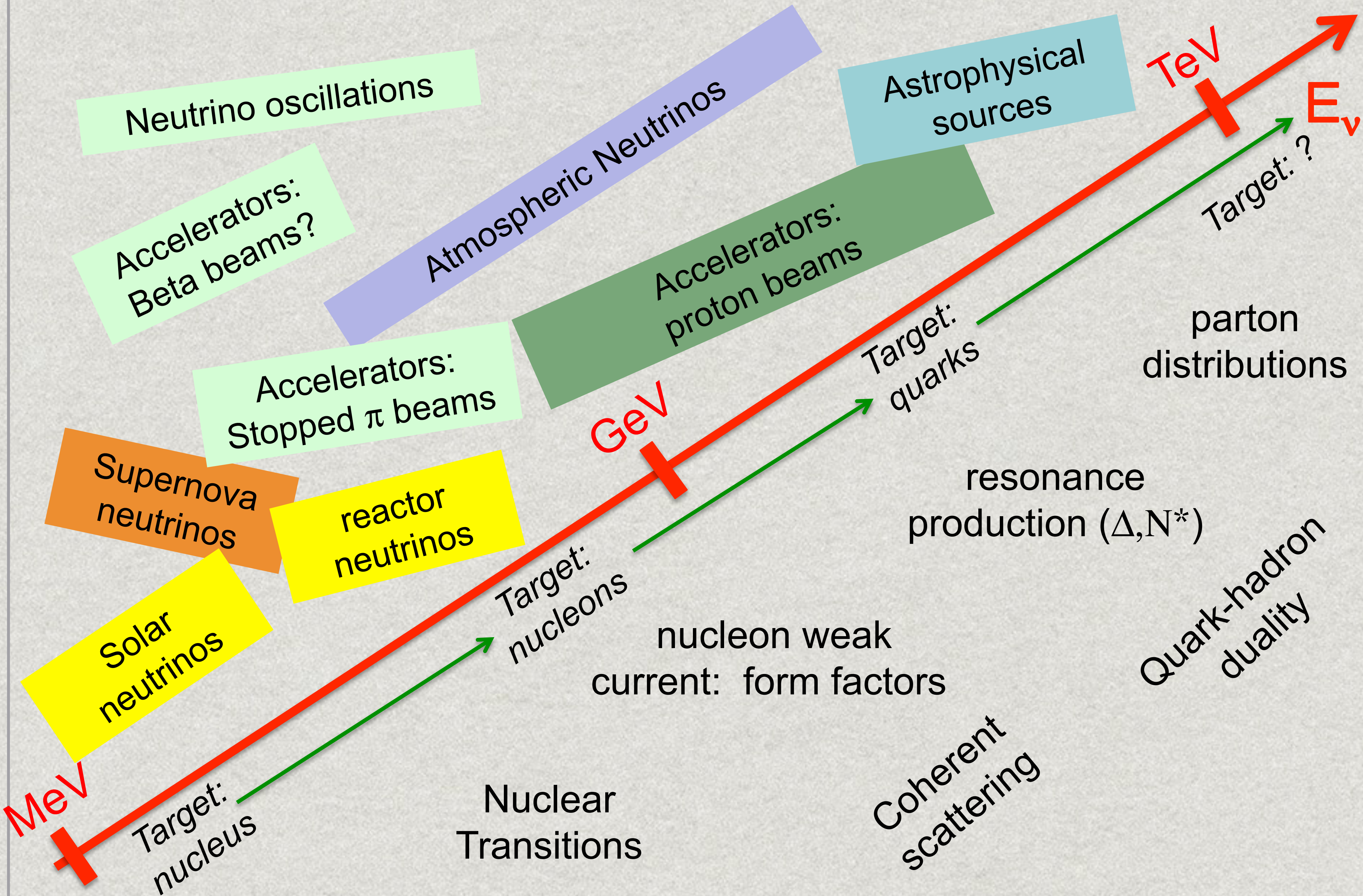
Alfred K. Mann
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 20 January 1993)

From consideration of the energy dependence of the ν_μ- and ν_e-nucleus cross sections and different choices of the momentum thresholds for ν_μ- and ν_e-induced events in underground water Cherenkov detectors, it is argued that the neutrino-nucleus cross sections currently used to calculate the expected atmospheric neutrino-induced event rates do not introduce significant error in comparing the measured and expected muon to electron event ratios.

PACS number(s): 13.15.−f, 14.60.Gh, 25.30.Pt, 96.40.Tv

The Full Spectrum



What matter most? It depends…

MINOS: ν_μ disappearance

K2K: ν_μ disappearance

miniBoone: ν_e appearance

NoVA/T2K: ν_e appearance

CHORUS/OPERA: tau appearance

NOMAD: tau appearance

Future multi-purpose expt
(e.g. SUSY proton decay)

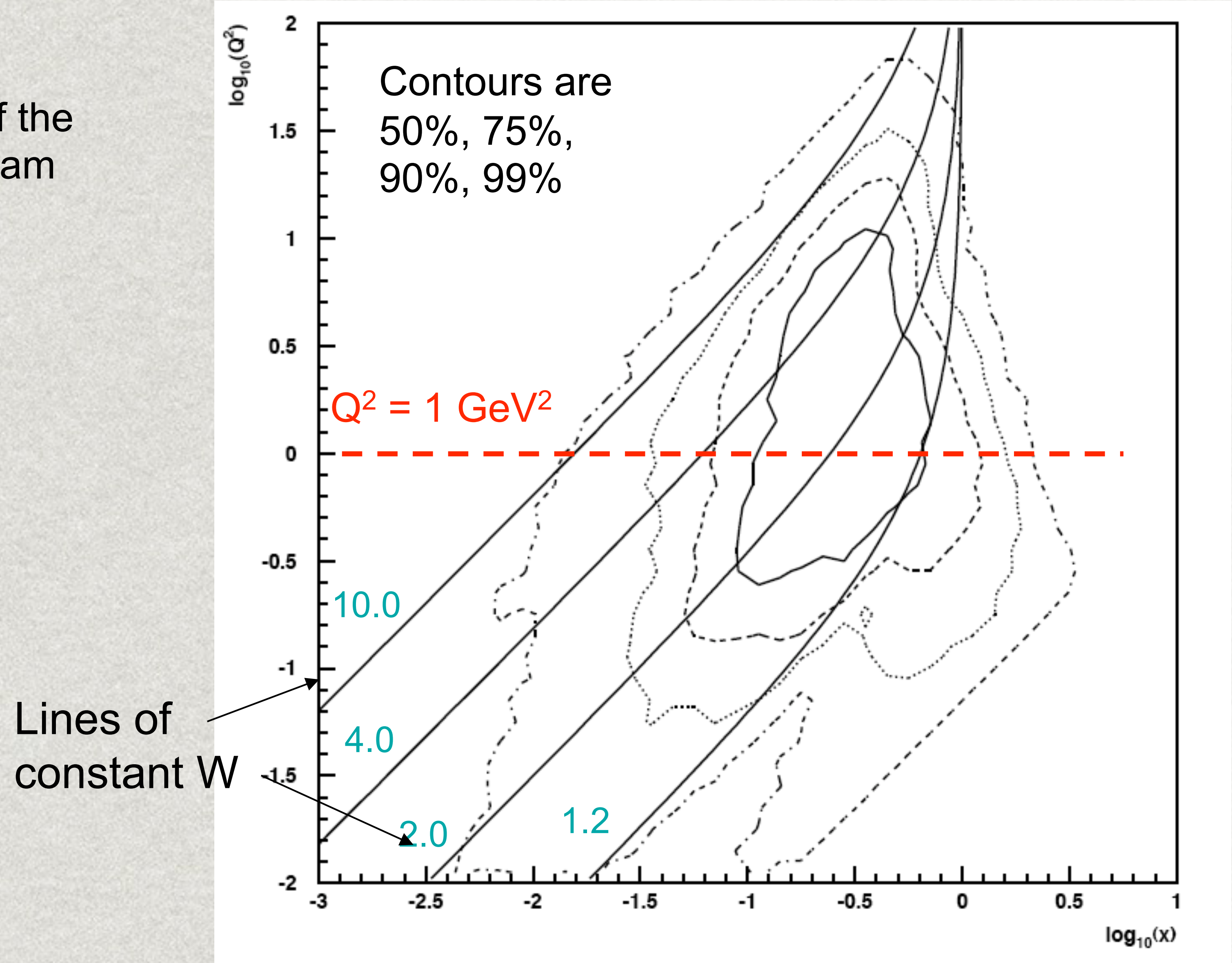
Cross section models:
- Low Q^2 DIS / transition region
- NC
- $\sigma_{1\pi}/\sigma_{qel}$
- Coherent production
- Charm production
- Hadonization modeling

Nuclear model:
- Low Q^2 scattering
- FSI - topology changes
- FSI – effect on calorimetry

Misc:
- Rare electron-like processes
- Tau polarization
- $\Delta S=1$ anti-neutrino modes

Ingredients: QEL + Resonance + "DIS"

Kinematic Coverage of the NuMI LE beam



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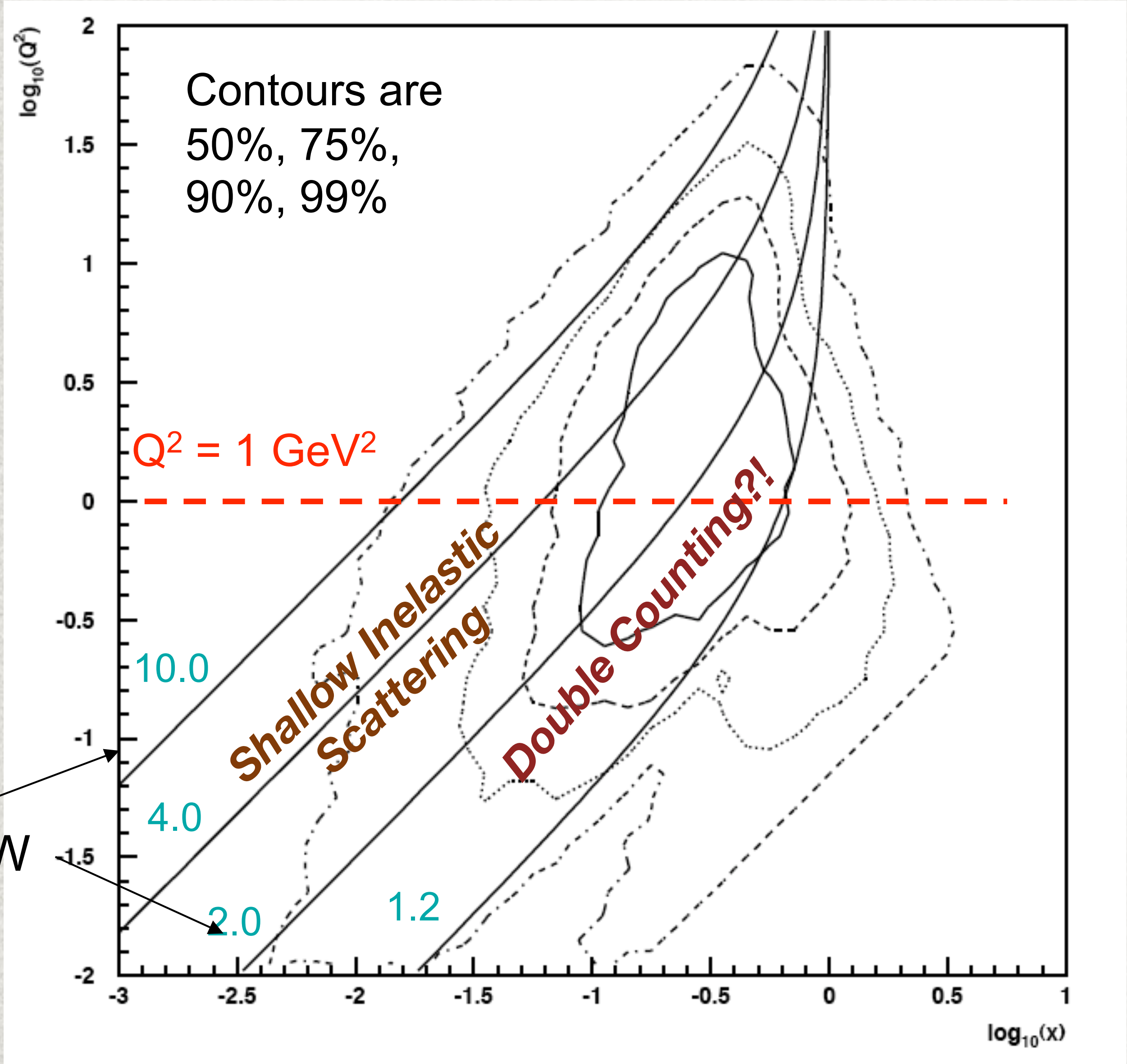
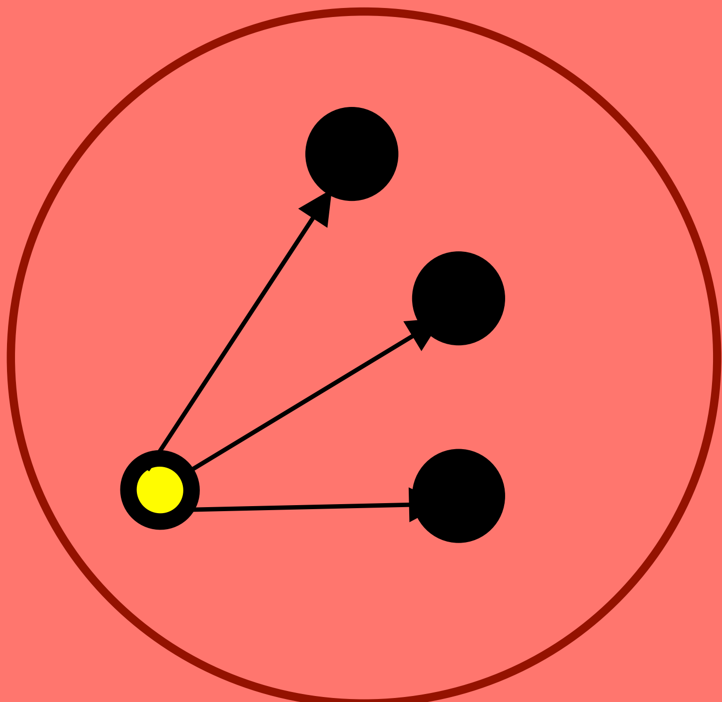
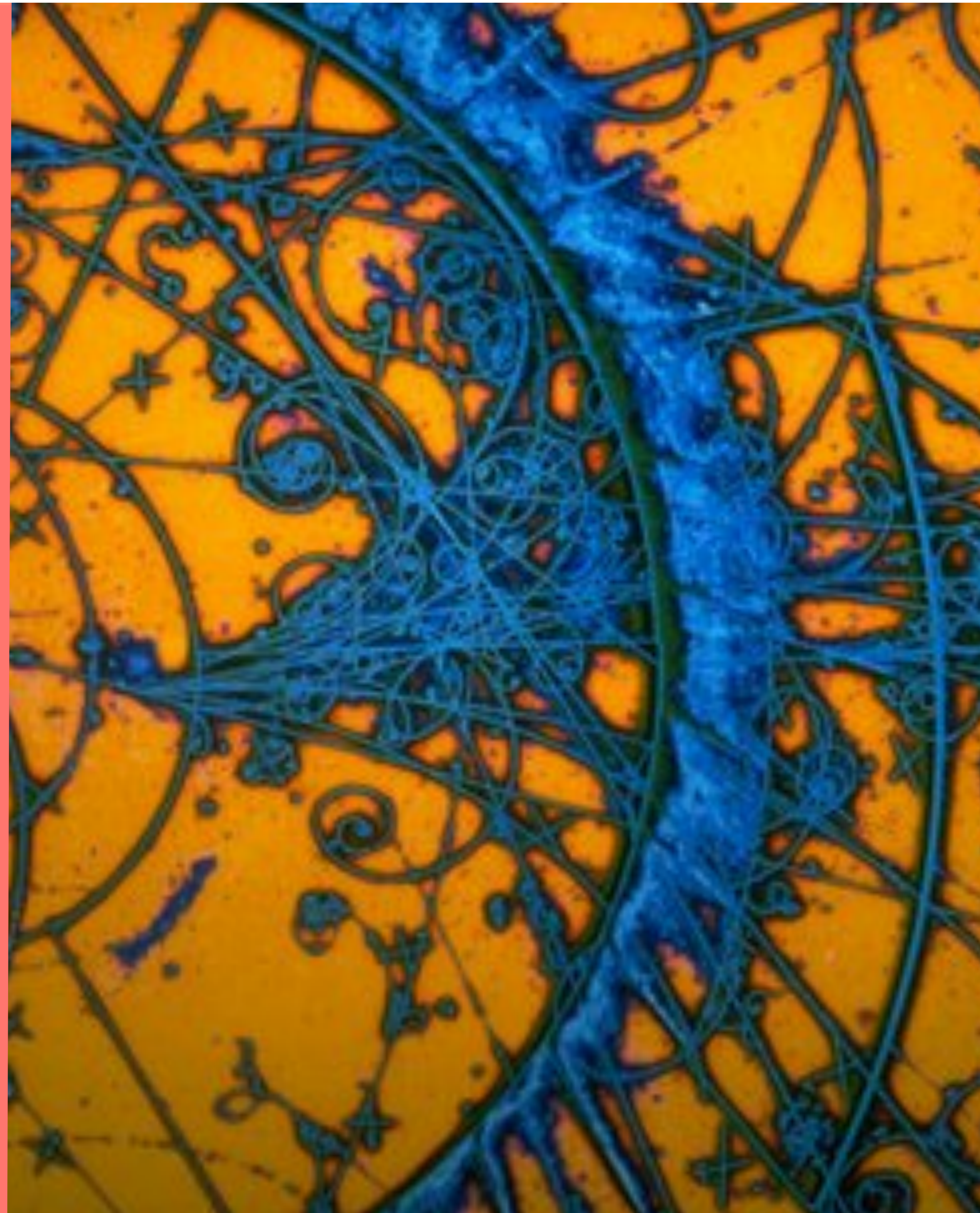


Lines of constant W



FREE NUCLEON PROCESSES

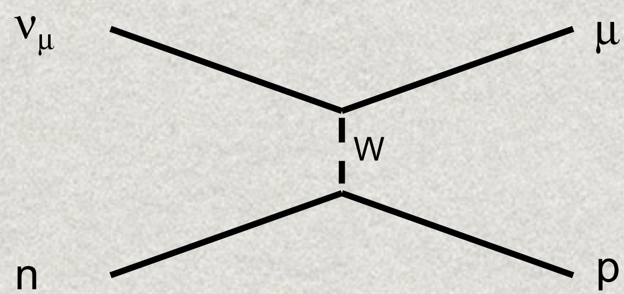


Quasi-Elastic

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

Ignoring ‘second-class’ currents.

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



Axial form factor:

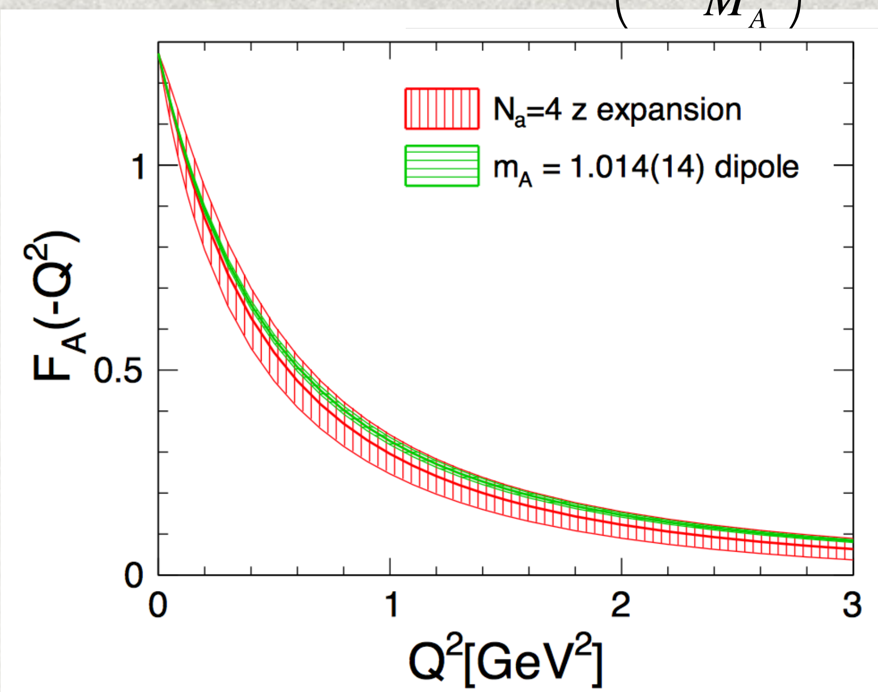
‘dipole form’

$$F_A(q^2) = \frac{F_A(q^2=0)}{\left(1-\frac{q^2}{M_A^2}\right)^2}$$

Modern treatments include more parameters

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

$$\begin{aligned}
A &= \frac{(m^2+Q^2)}{M^2}\Big[(1+\tau)F_A^2 - (1-\tau)F_1^2 \\
&\quad +\tau(1-\tau)F_2^2 + 4\tau F_1F_2 \\
&\quad - \frac{m^2}{4M^2}\left((F_1+F_2)^2 + (F_A+2F_P)^2 \right. \\
&\quad \left. - \left(\frac{Q^2}{M^2}+4\right)F_P^2\right)\Big] \\
B &= \frac{Q^2}{M^2}F_A(F_1+F_2) \\
C &= \frac{1}{4}(F_A^2 + F_1^2 + \tau F_2^2)
\end{aligned}$$

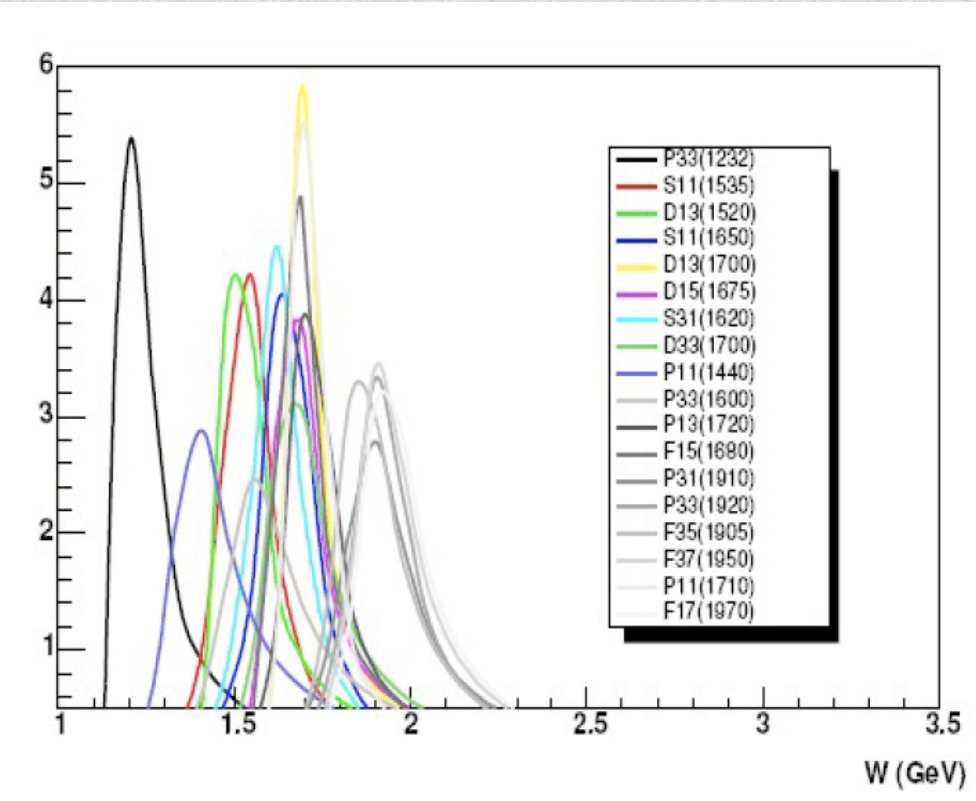


A. Meyer et al., Phys.Rev. D93 (2016) no.11, 113015

Resonances

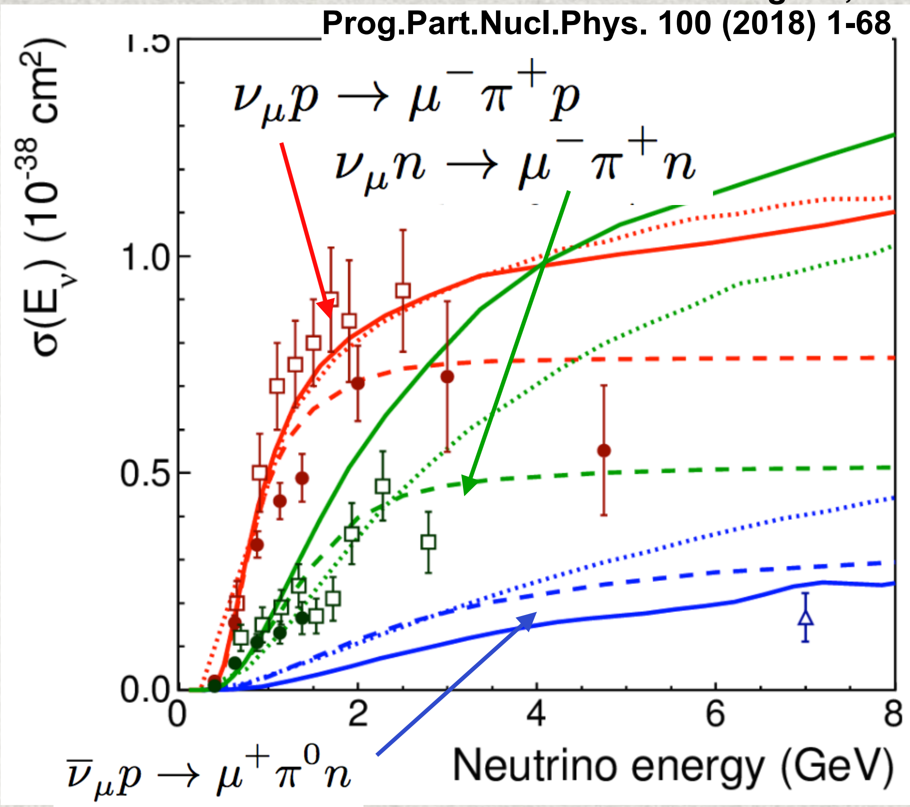
Model from Rein-Sehgal [1] calculates hadronic resonances up to W=1.7 GeV/c².

Axial form factor again determined from fits to light target bubble chamber data.



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

P. Rodrigues, in Prog.Part.Nucl.Phys. 100 (2018) 1-68



GENIE (solid), NEUT (dashed), NuWRO (dotted)

P. Rodrigues et al., Eur.Phys.J. C76 (2016) no.8, 474

[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

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

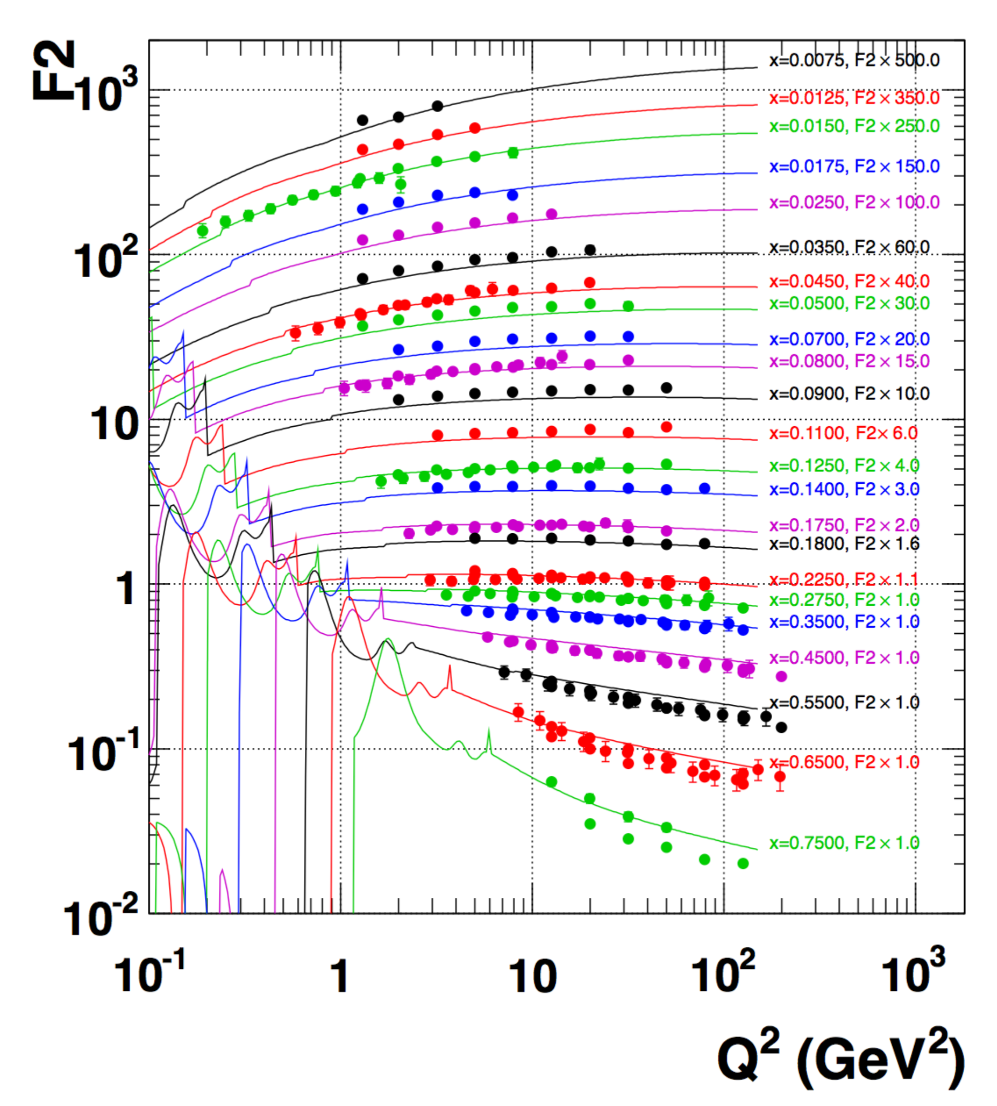
$$K_{sea}(Q^2) = \frac{Q^2}{Q^2 + C_s}$$

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

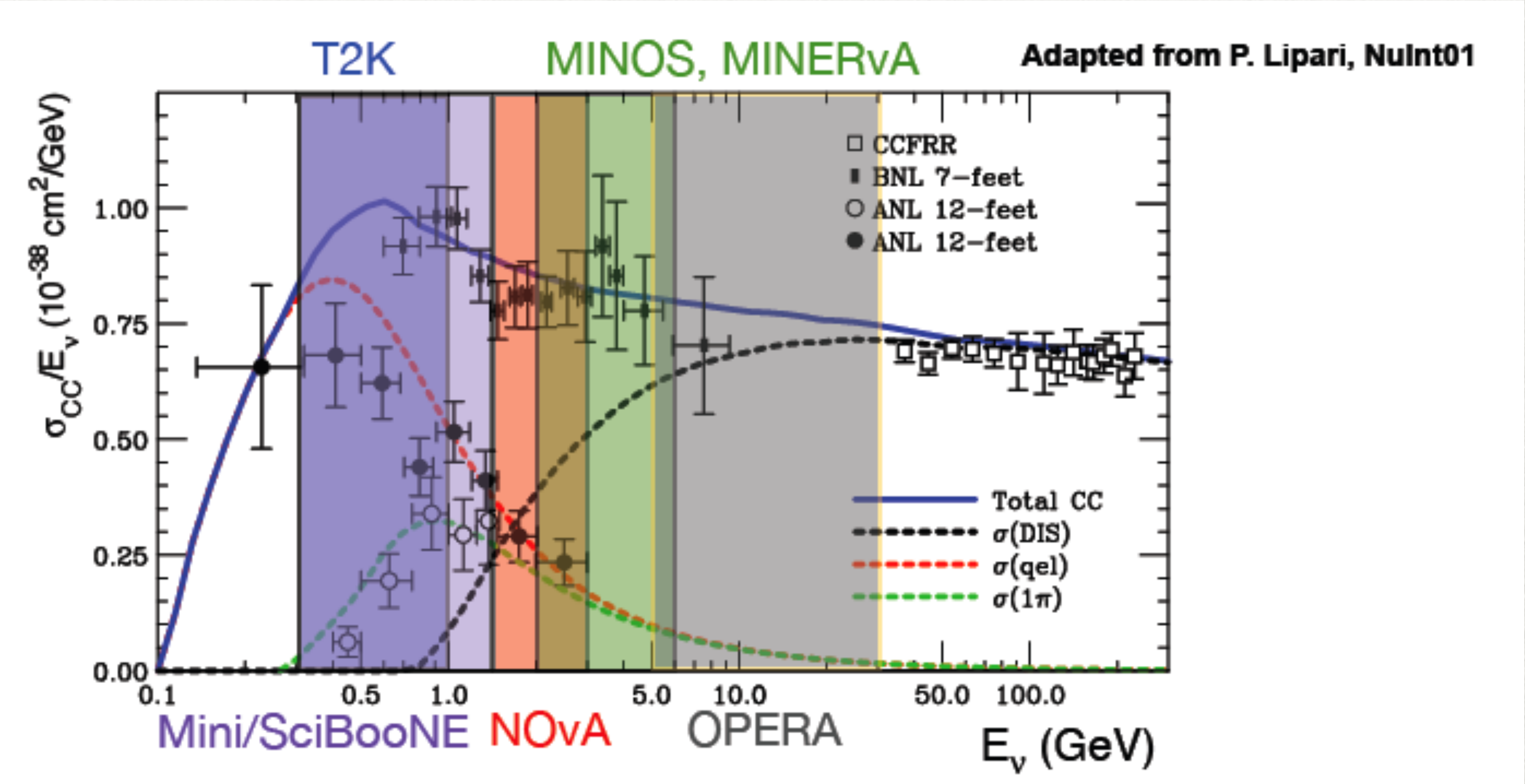
Fits based on GRV98LO and free nucleon charged lepton data

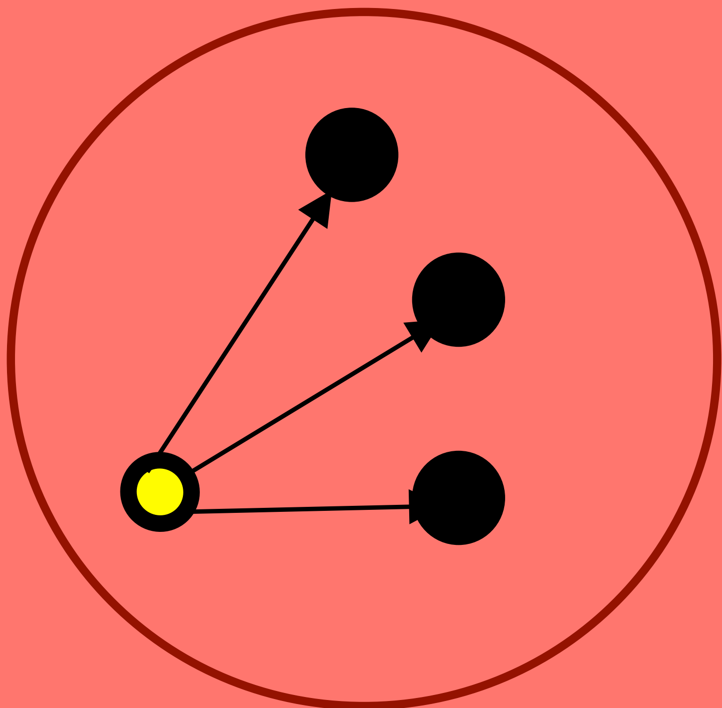
[hep-ph/0411202]

Deep (and Shallow) Inelastic Scattering

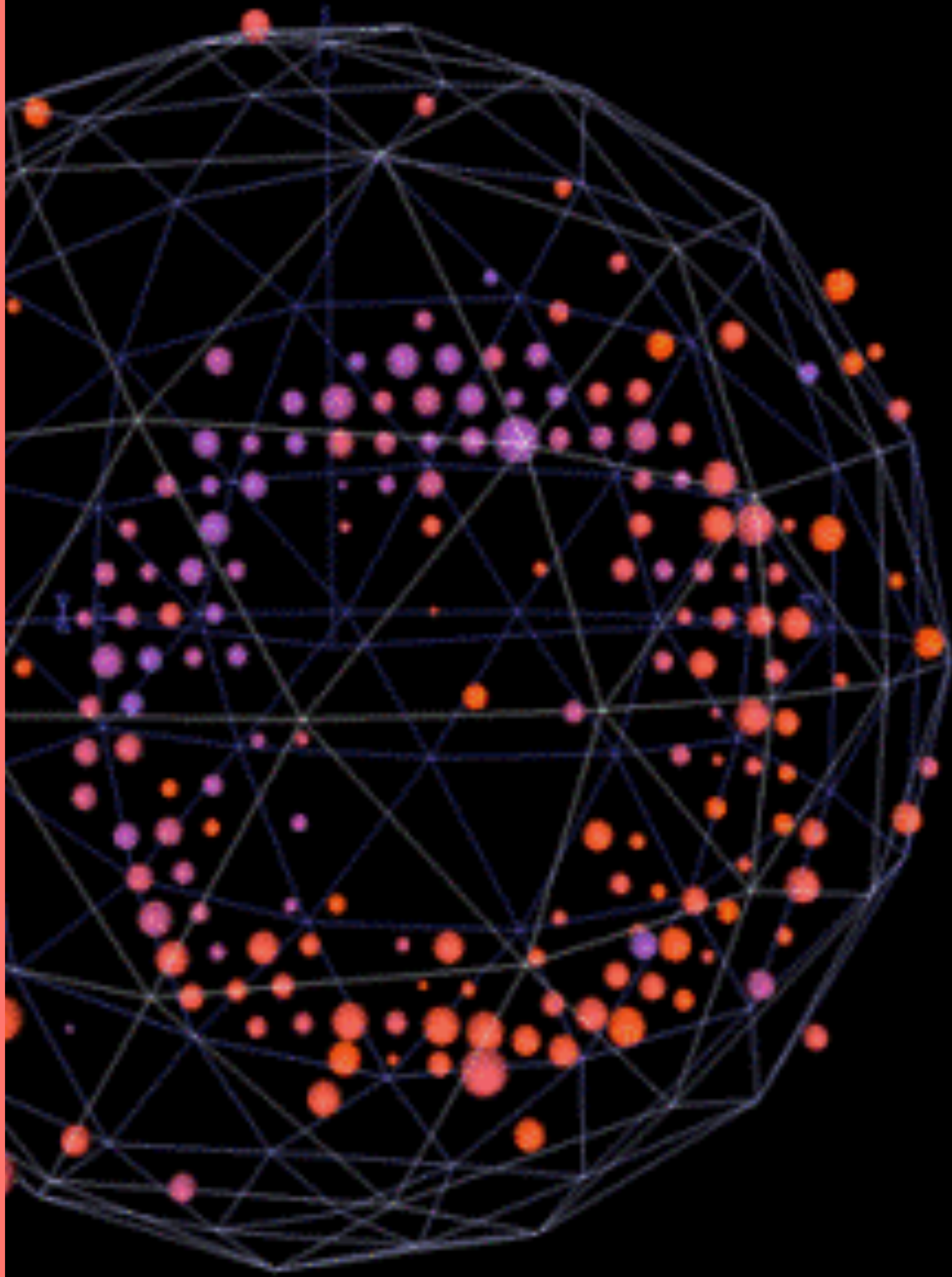


H. Tanaka, NuINT09.





FREE NUCLEON HADRONIZATION



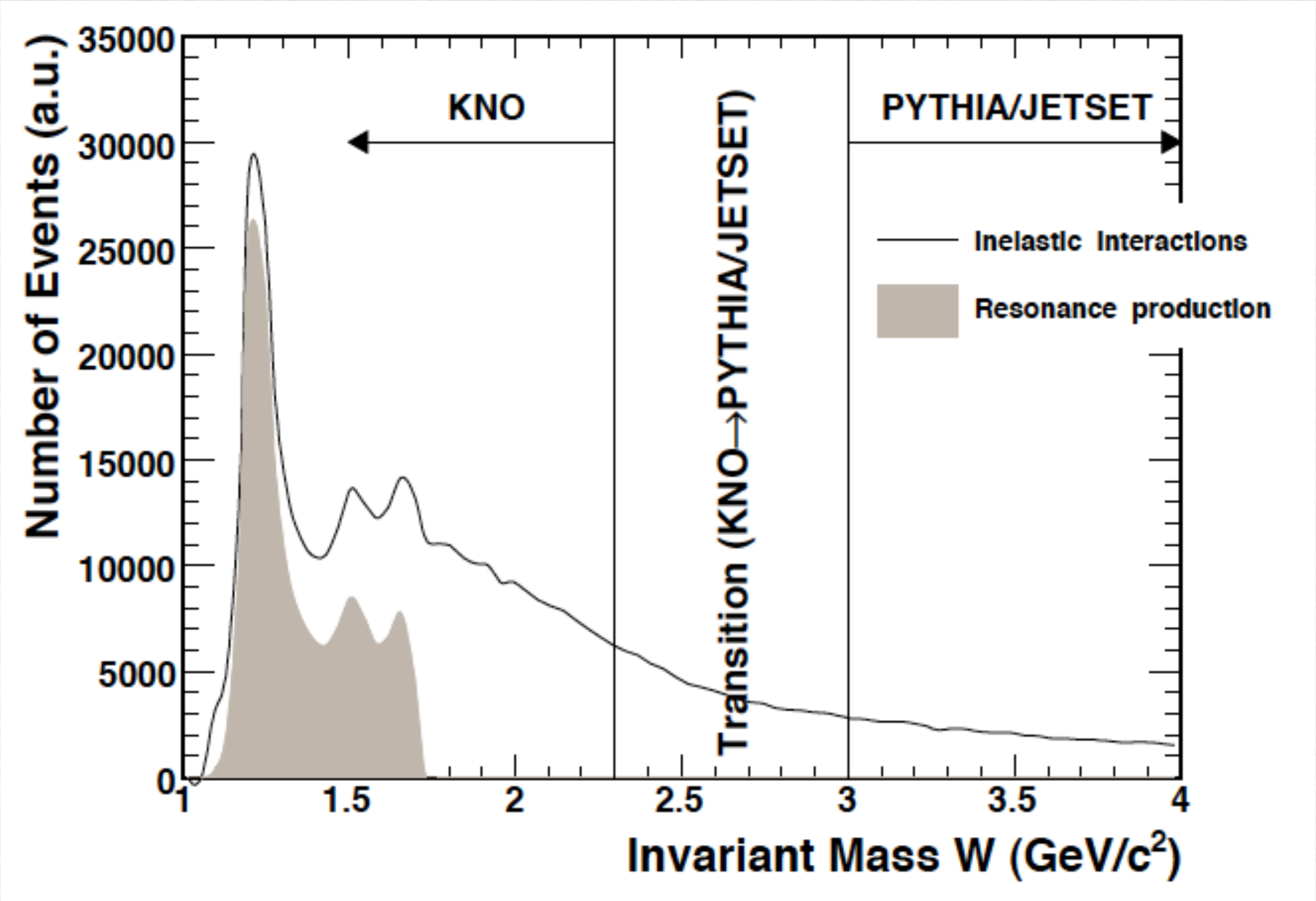
PICTURES OF HADRONIZATION

- Resonances: all hadronic distributions calculable in principle from the resonance model. (Though often treated as isotropic in hadronic c.m.).

- Non-resonant inelastic reactions at low W.
  Empirical models.

- At high energy (W): 'current' and 'target' jets.
  Pt is low. Need to look at the interaction in the hadronic center of mass to understand the dynamics.

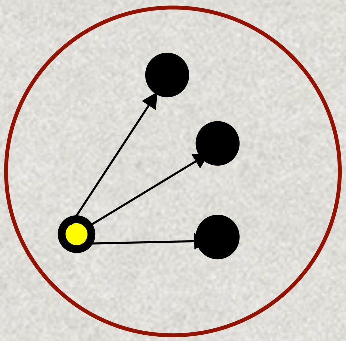
T. Yang et al, Eur.Phys.J. C63 (2009) 1-10.
T. Yang, Ph. D Thesis, Stanford U (2009)



The model for the cross section will affect many things.

DIS vs. 'non-resonant background' in the resonance region.

Hadronization Model[1]



Combining an empirical model ("KNO") with JETSET at high invariant mass, linear transition from W=2.3 GeV/c² to W=3.0 GeV/c².

Particle Content:

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

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

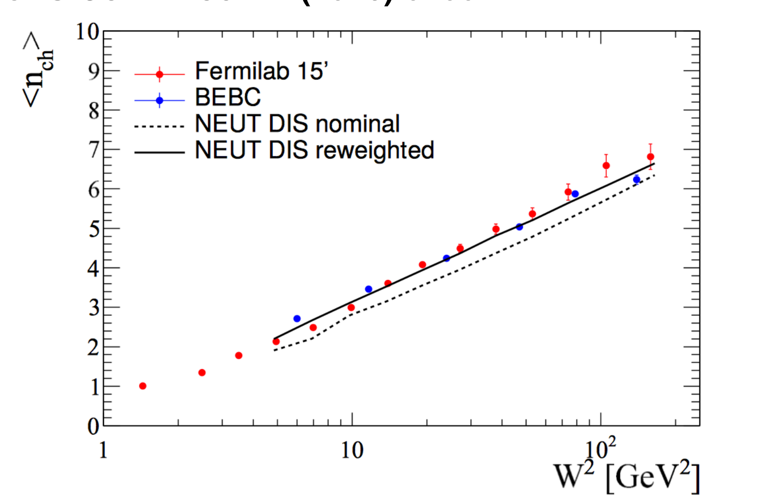
$$\langle n \rangle \times P(n) = f(n / \langle n \rangle)$$

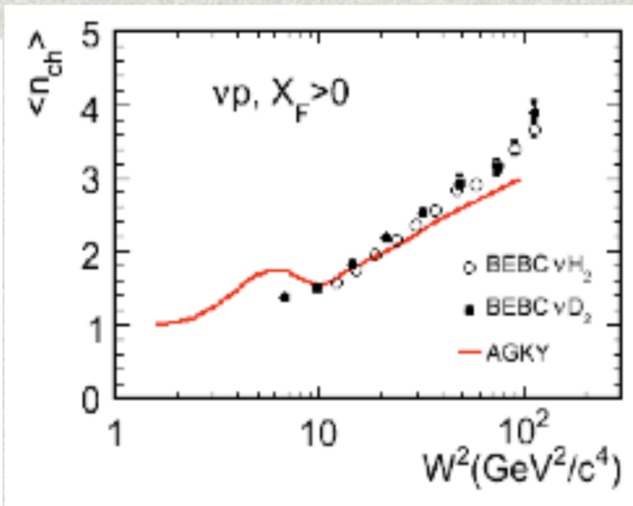
Assign 4-vectors in CM:

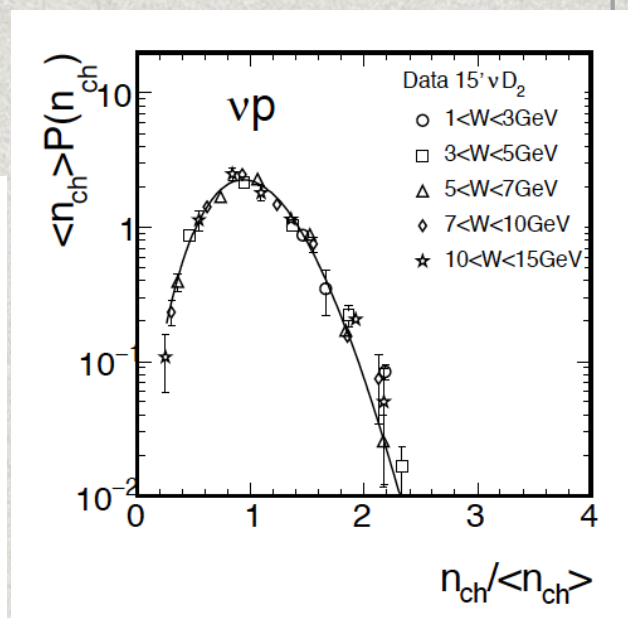
1) Select baryon 4-momentum from empirical distribution $P(x_F, p_t)$.
2) Phase space decay remaining hadronic system
3) "P_T squeezing" – rejection factor

ν Tuning and Validation

NEUT: C. Bronner and M. Hartz, JPS Conf.Proc. 12 (2016) 010041

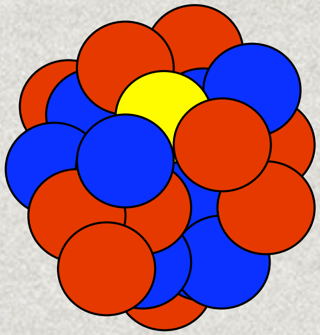






[1] T. Yang et al. *AIP Conf. Proc.967:269-275 (2007).*

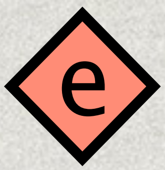
Cross Section model

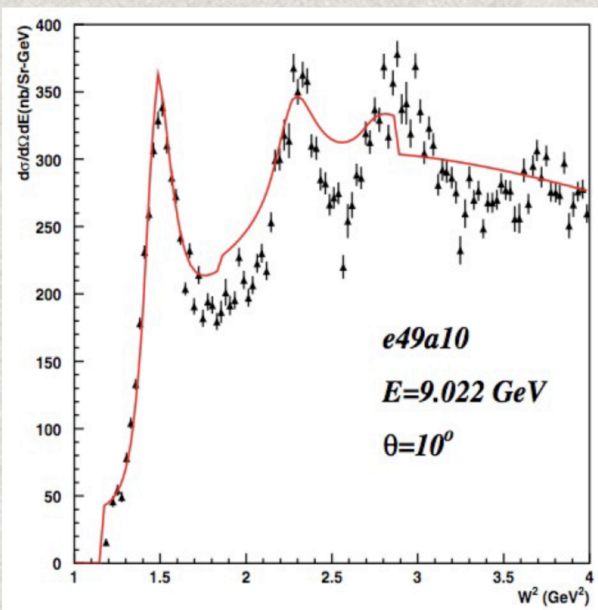


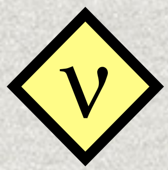
Constructing σ_{TOT}

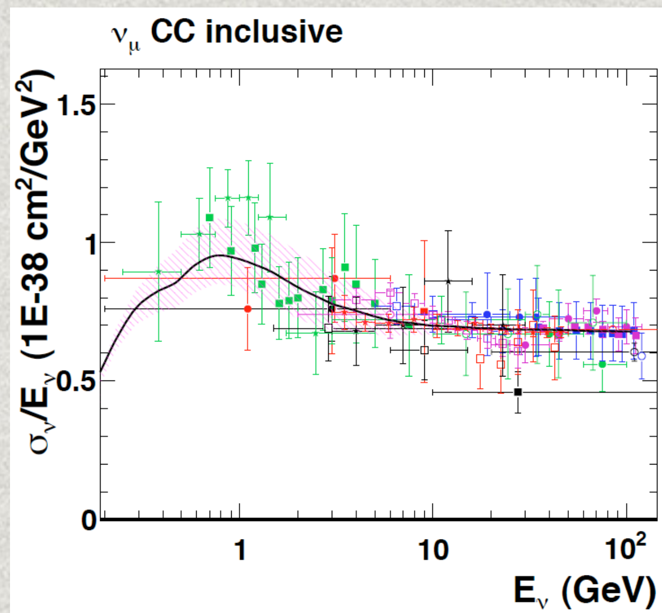
- Tune overall DIS normalization to measured cross section at high energy.
- For each (CC/NC≡i) and (initial state≡j), calculate the BY contribution to each exclusive channel (≡k).
- Dial down the contribution by a factor (r_{ijk}) so that the sum of this contribution and the Rein-Sehgal prediction fits the data for this exclusive channel.
- Treat four as independent: r_{112}=0.1, r_{122}=0.3, r_{113}=1.0, r_{123}=1.0.

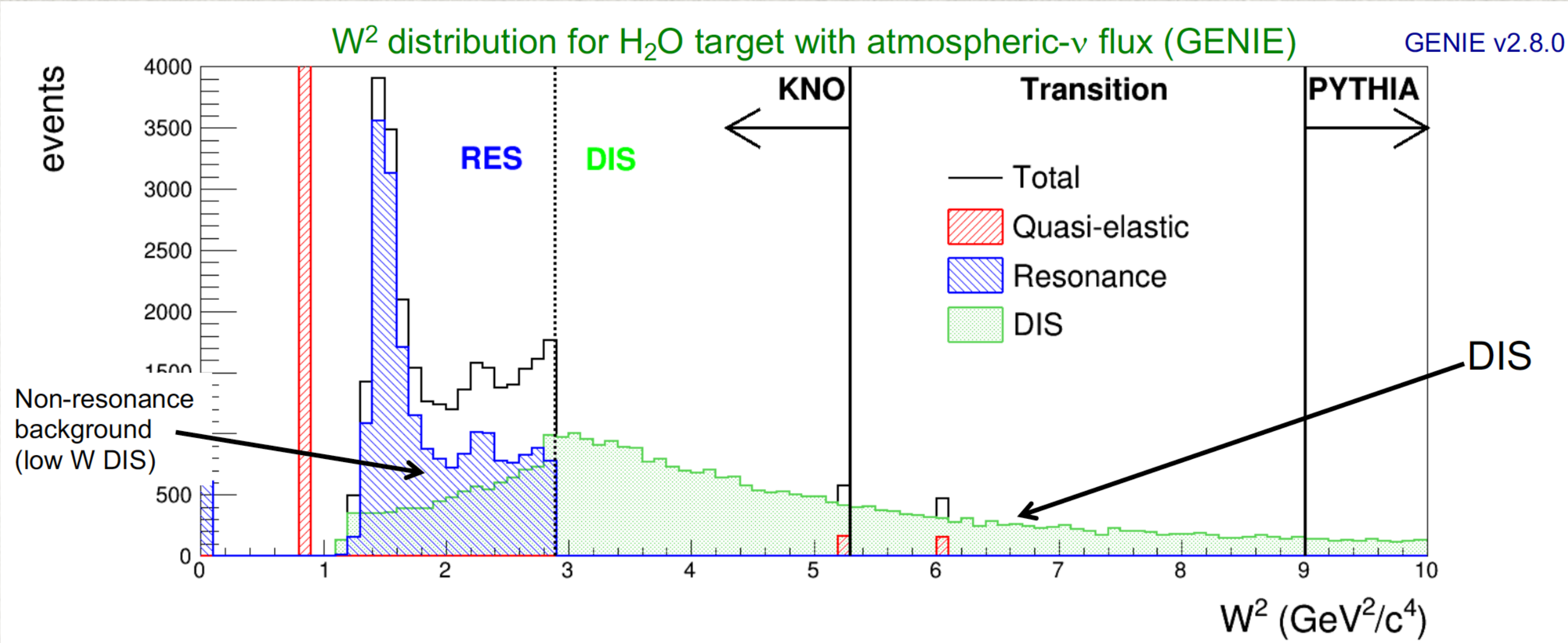
Tuning and Validation



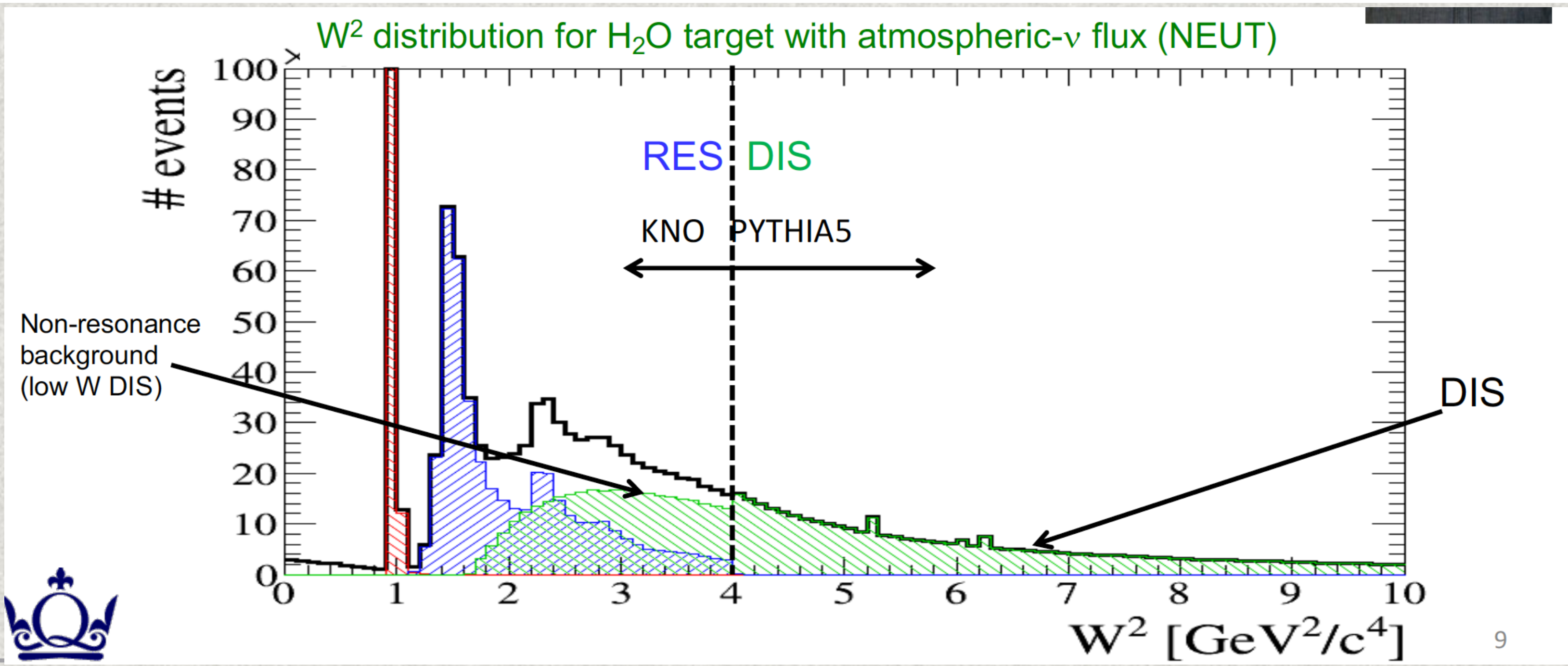






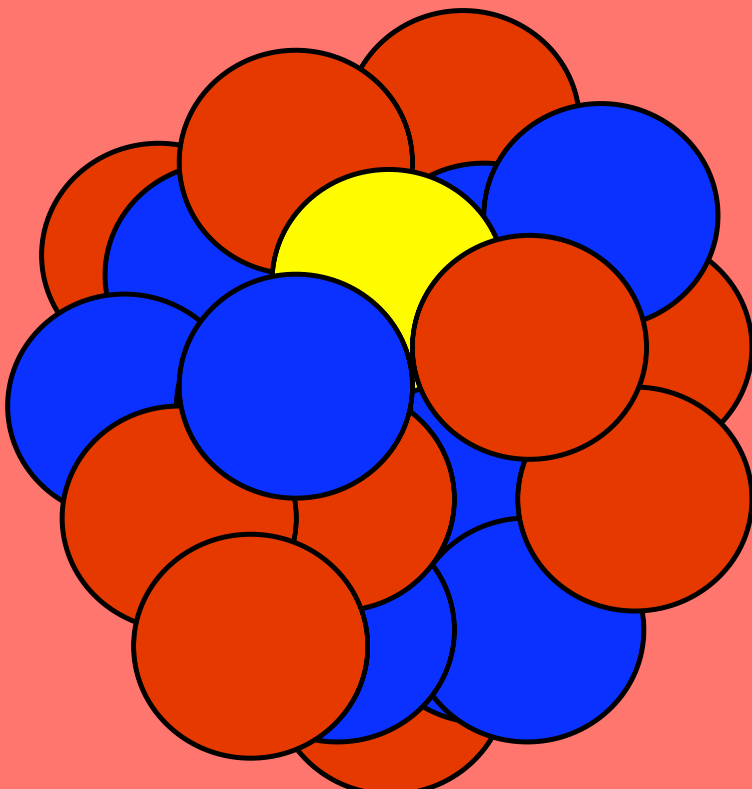


W2 distribution for H2O target with atmospheric-ν flux (GENIE)
GENIE v2.8.0
events
RES
DIS
KNO
Transition
PYTHIA
Total
Quasi-elastic
Resonance
DIS
Non-resonance background (low W DIS)
DIS
W2 (GeV2/c4)



W2 distribution for H2O target with atmospheric-ν flux (NEUT)
events
RES
DIS
KNO
PYTHIA5
Non-resonance background (low W DIS)
DIS
W2 [GeV2/c4]
9

NUCLEAR PHYSICS

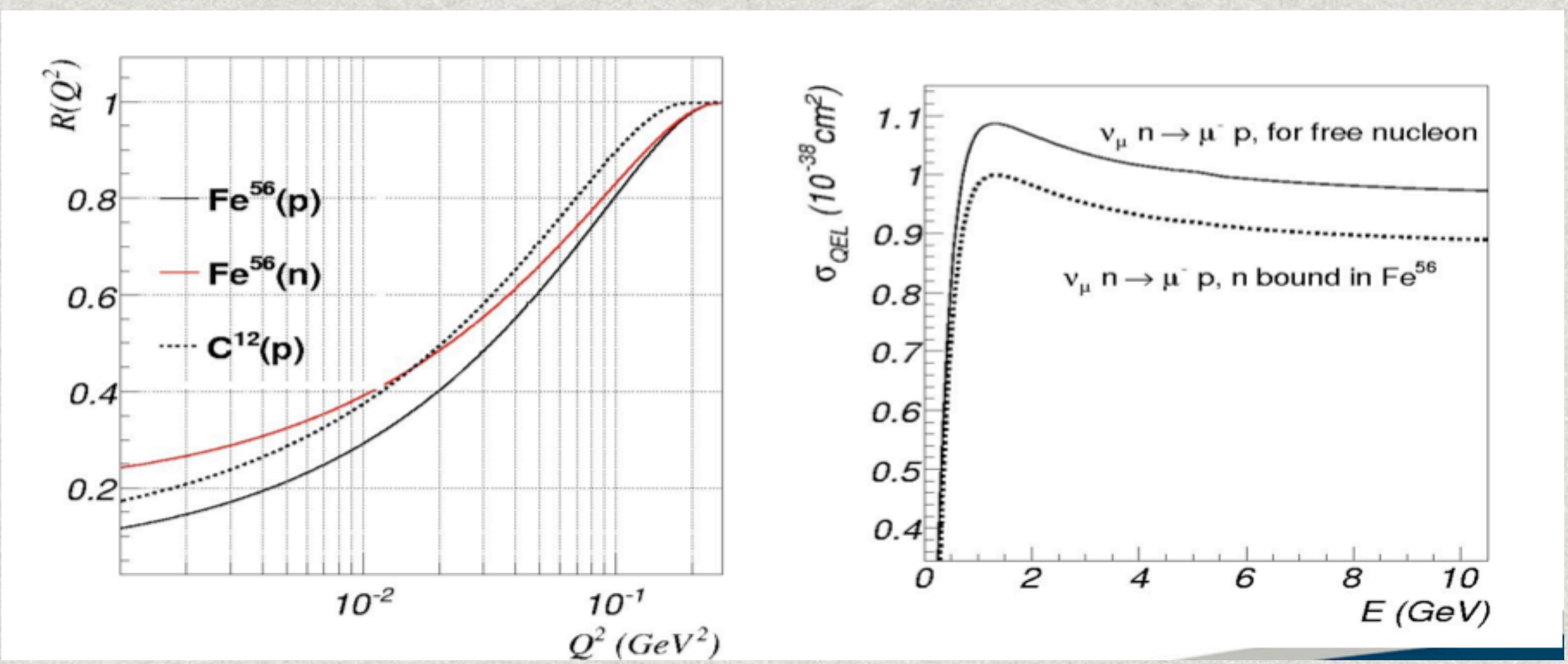


Impulse Approximation

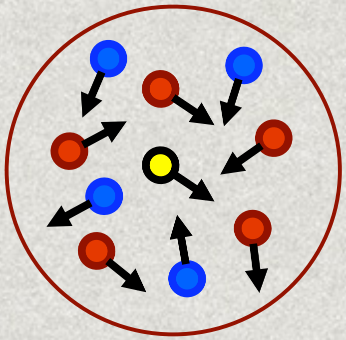
But … modern experiments are on nuclei!

Many nuclear models assume the Impulse Approximation - we are striking a ***single nucleon*** in the nucleus. All we need to know is the distribution of momenta and energy (negative) for these states (1p-1h).

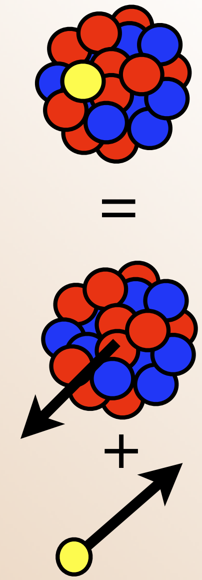
The Fermi Gas Model is the simplest such approach, takes into account Fermi motion and Pauli blocking.



Nuclear model

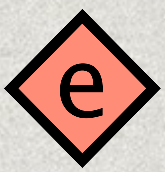


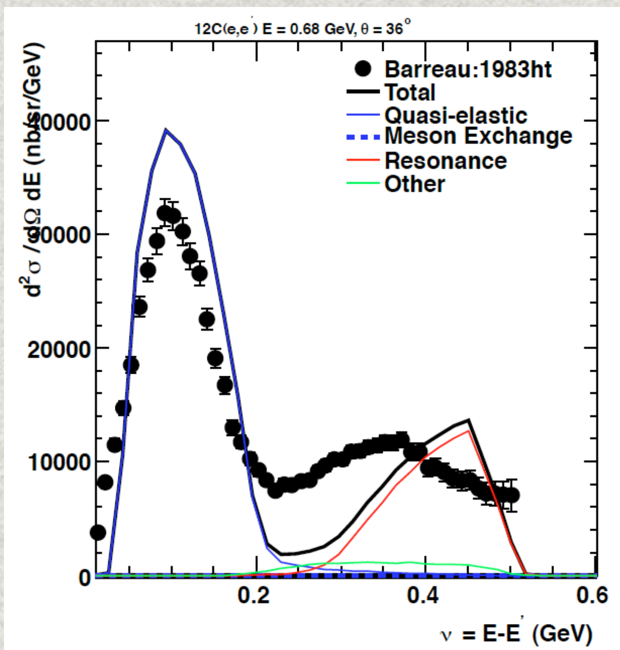
- Momentum distribution from Bodek-Ritchie[1] , a global Fermi Gas Model incorporating a small high momentum tail.
- Scattering from a quasi-deuteron=short-range correlations.
- Pauli blocking applied for QEL events by comparing outgoing nucleon energy to k_F for the nucleus.

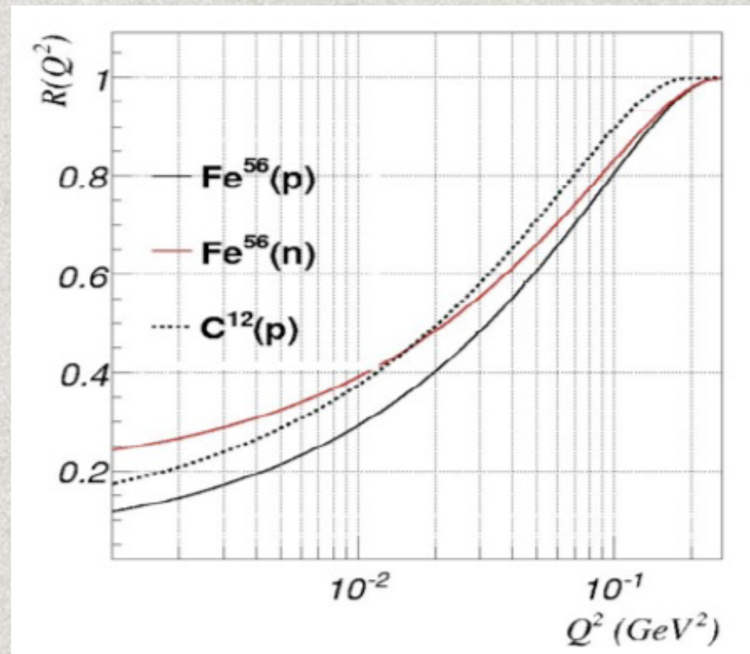


$$E = M_A - \sqrt{M_{A-1}^2 + p^2}$$

Tuning and Validation



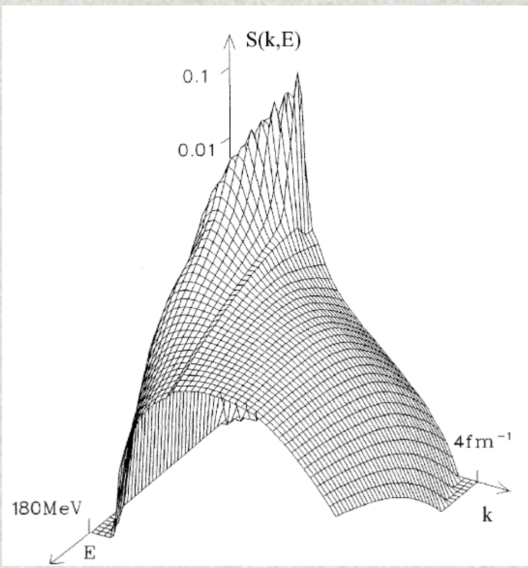




[1] A. Bodek and B. Ritchie, PRD24 (1981) 1400.

Beyond the Fermi Gas

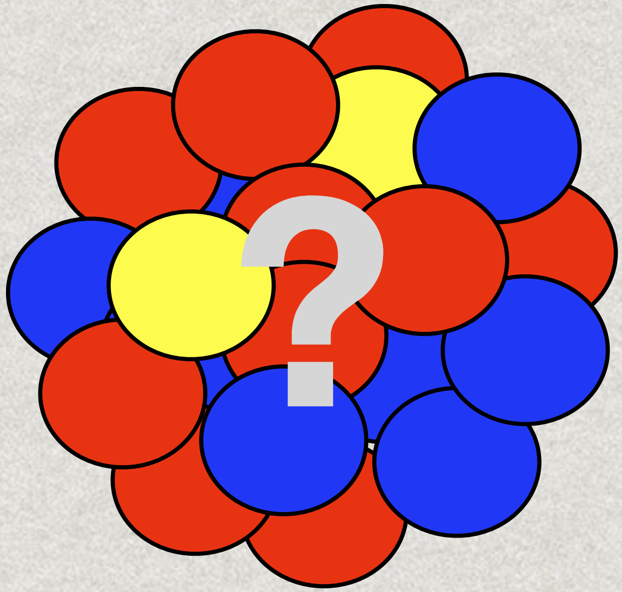
Spectral Functions



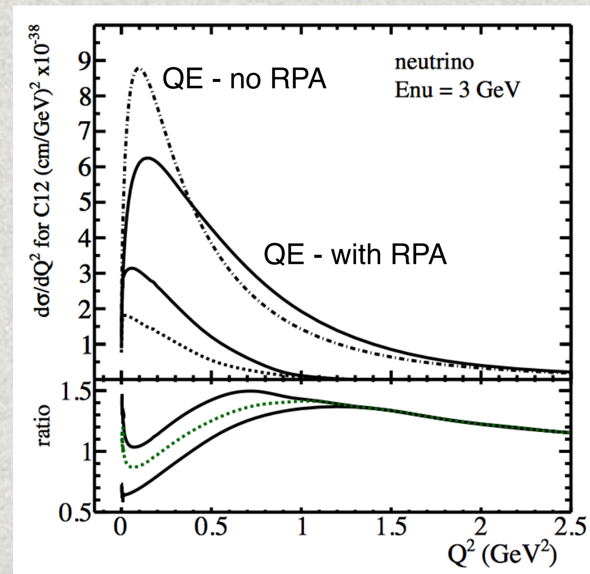
$$\frac{d\sigma_A}{d\Omega_{\ell'} dE_{\ell'}} = \int d^4p\, P(p) \left(\frac{d\sigma_N}{d\Omega_{\ell'} dE_{\ell'}} \right)$$

$$P(\mathbf{p}, E) = \sum_n |\langle \Psi_n^{(A-1)} | a_{\mathbf{p}} | \Psi_0^A \rangle|^2 \delta(E + E_0 - E_n)$$

2p-2h scattering



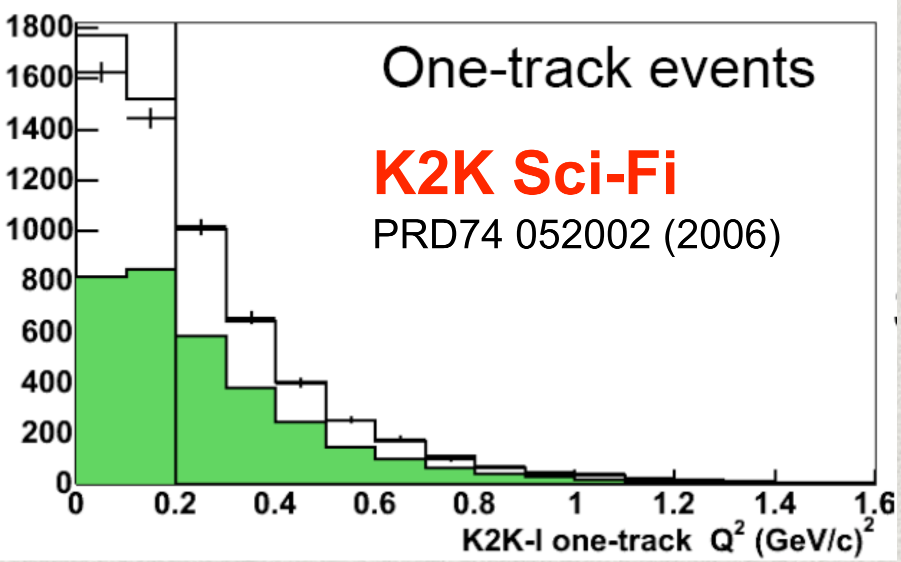
Long-Range correlations (RPA treatment)



R. Gran et al., Phys. Rev. D 88, 113007
Nieves et al., Phys. Rev. D 85, 113008

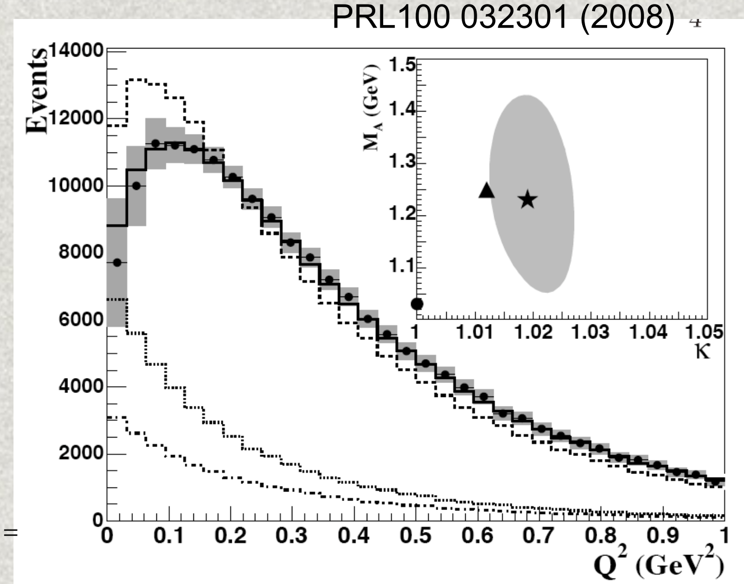
Excellent recent reviews:
T. Katori and M. Martini, J.Phys. G45 (2018) no.1, 013001
L. Alvarez-Ruso et al., Prog.Part.Nucl.Phys. 100 (2018) 1-68

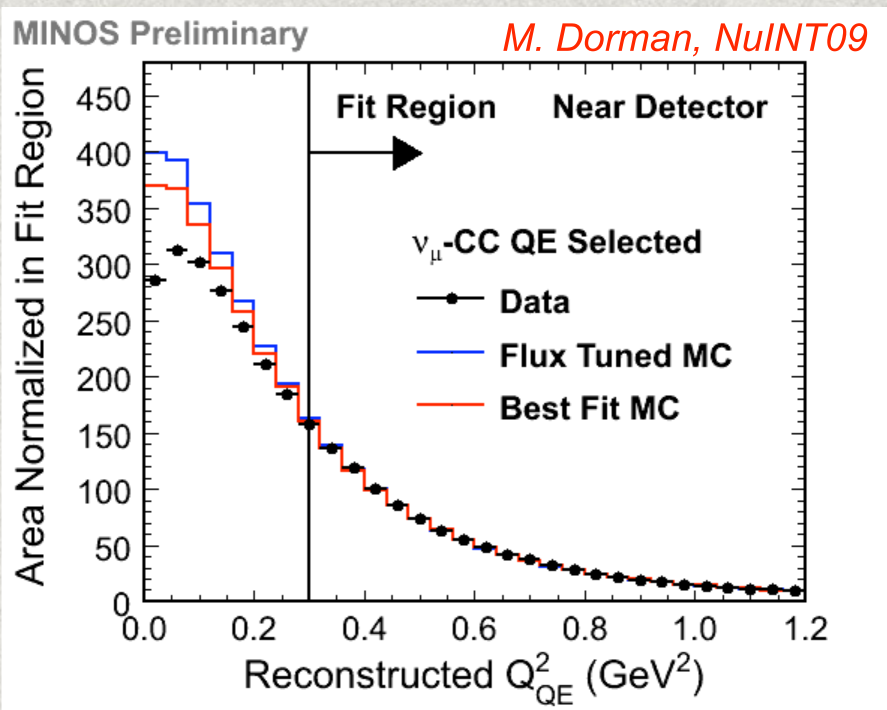
"Quasi-Elastic" Scattering



miniBoone

PRL100 032301 (2008)





Low Q² - nuclear effects

K2K: M_A=1.20±0.12 GeV/c²

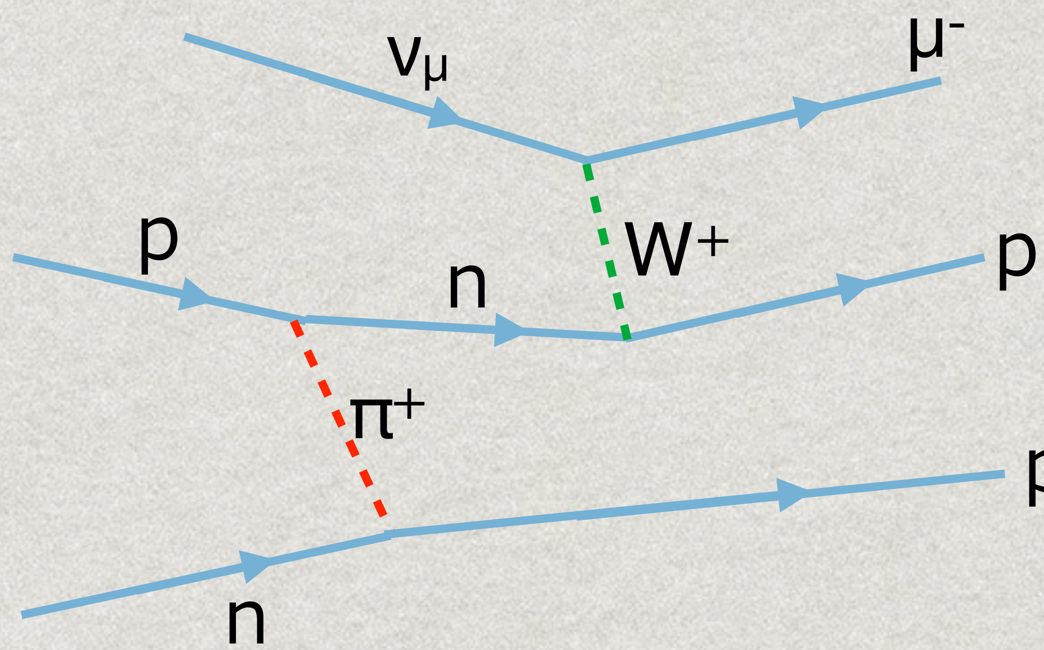
MiniBooNE $M_A = 1.35 \pm 0.17$ GeV/c²

MINOS $1.22^{+0.18}_{-0.11}$ GeV/c²

fit error only

Simplest Explanation

In neutrino-nucleus scattering there are processes which do not occur on free nucleons! (J. Marteau Ph. D Thesis 1998).



Scattering off a quasi-deuteron inside the nucleus is a possibility. Many such diagrams, with n nucleons in the initial and final states.

Electron Scattering

The main reason to believe that such contributions exist and can be potentially large comes from looking at electron scattering.

Phys. Rev. C 80 065501 (2009)
Phys. Rev. C 81 045502 (2010)

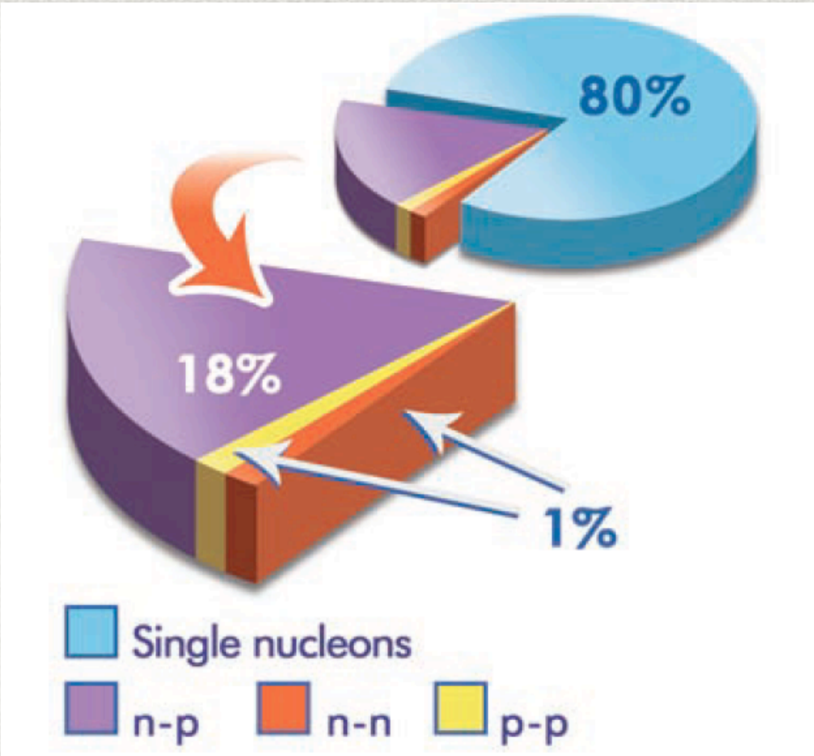
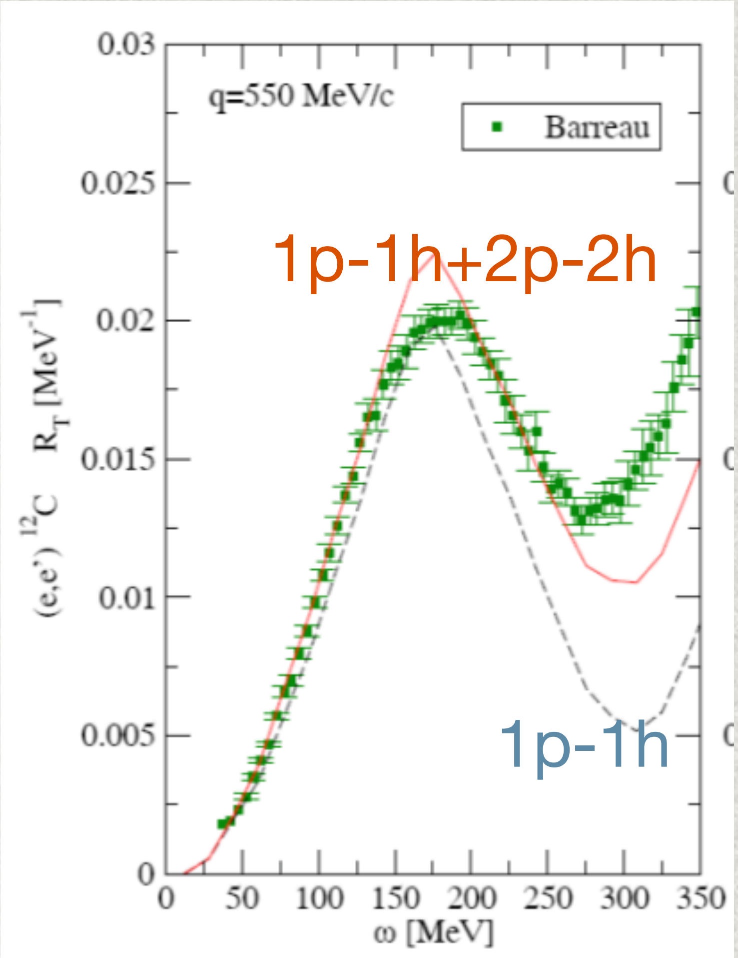


Fig. 3. The average fraction of nucleons in the various initial-state configurations of ^{12}C.

R. Subedi et al.
Science **320**, 1476 (2008);



M. Maltini Seminar, FNAL Sep 30, 2010.

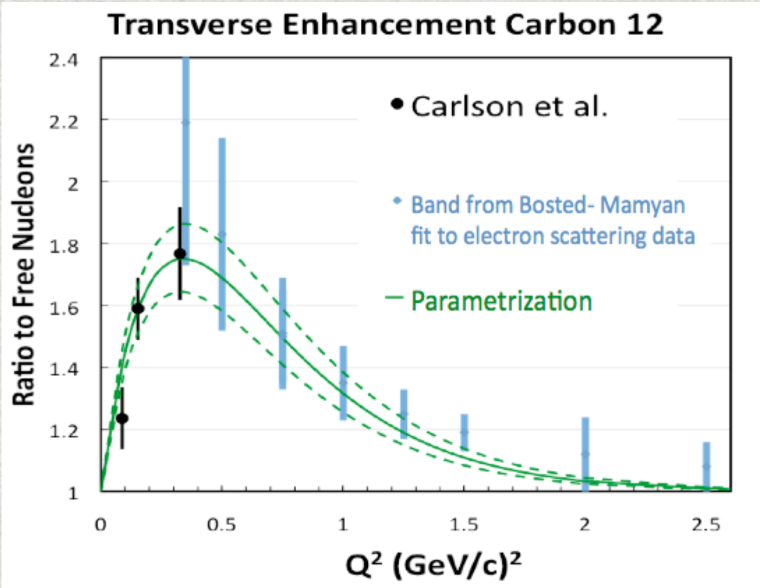
np-nh correlations

Relativistic/Non-Relativistic?
Which diagrams included?
Ground State?
RPA included?

Theoretical Calculations:

- *Martini et al.[1]*
- *Nieves et al.[2]*
- *Amaro et al.[3]*
- *Carlson et al.[4]*

"TEM"



Empirical models:

- *Bodek[5]*

Implementation in Generators:

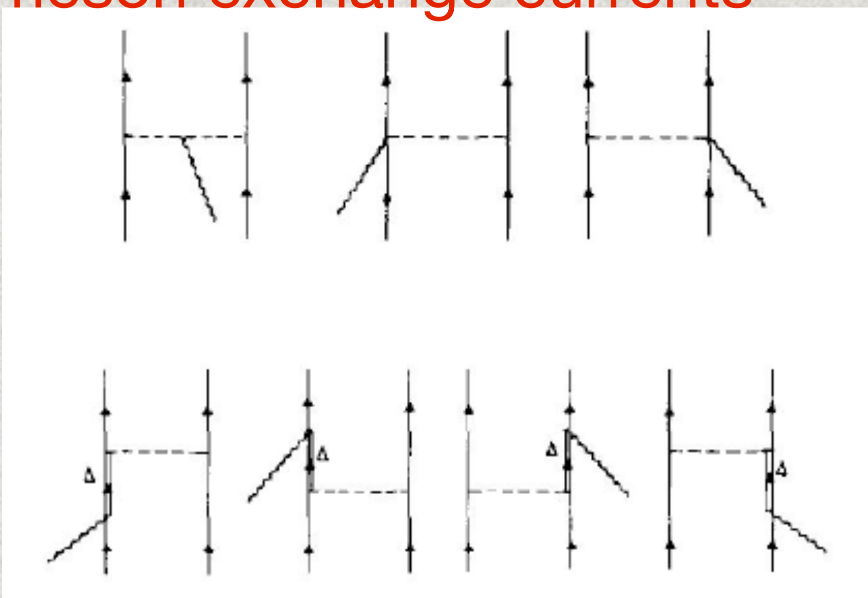
- *GENIE (S. Dytman)*
- *GiBUU*
- *NuWRO*

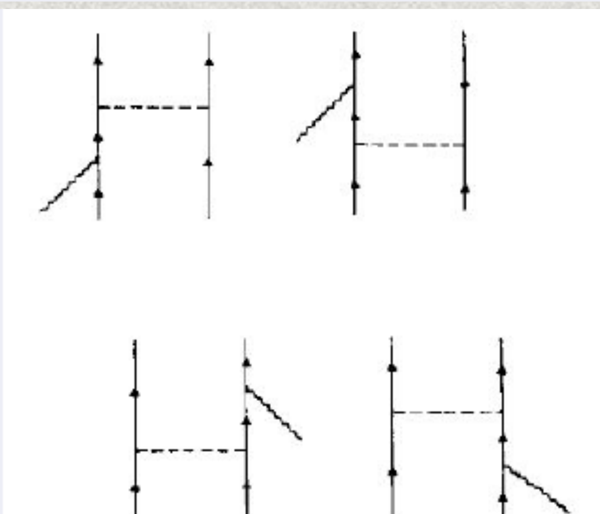
Summary in:
Katori, arXiv:1304.6014

[1] Martini et al. PRC84 (2011) 055502 [2] Nieves et al. Phys Lett. B707 (2012) 72 [3] Amaro et al. PRD84 (2011) 033004
[5] Bodek et al. Eur. Phys. J C71 (2011) 1726

np-nh modeling: so many questions

meson exchange currents





nucleon-nucleon correlations

Hadronic observables?

n:p/n:n ratio in initial state?

Double counting with existing processes? Short-range correlations, pion absorption?

Importance of correct ground state wavefunction?

Neutrino / anti-neutrino predictions?

Alberico et al, Annals Phys. 154 (1984) 356.

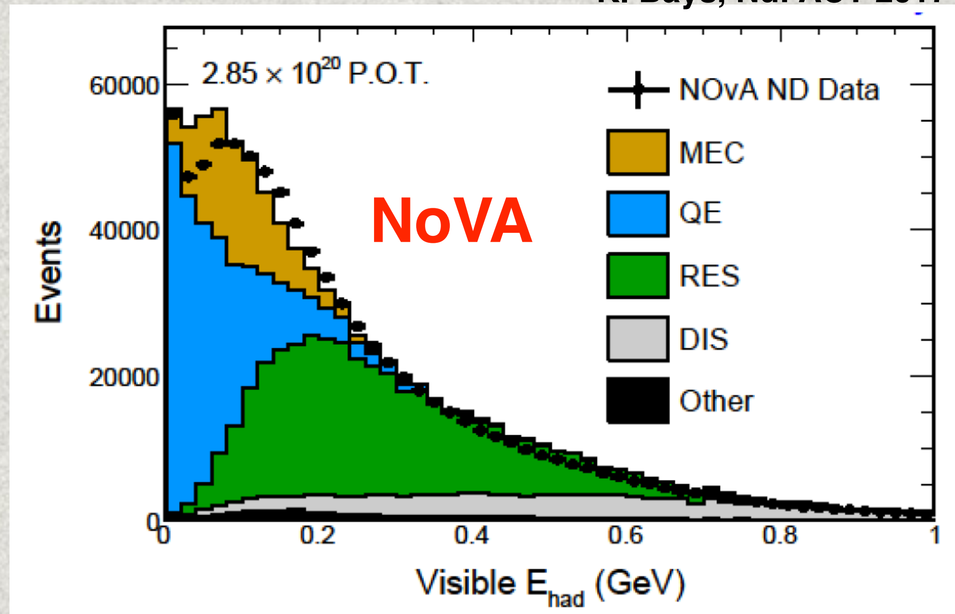
Multi-nucleon processes

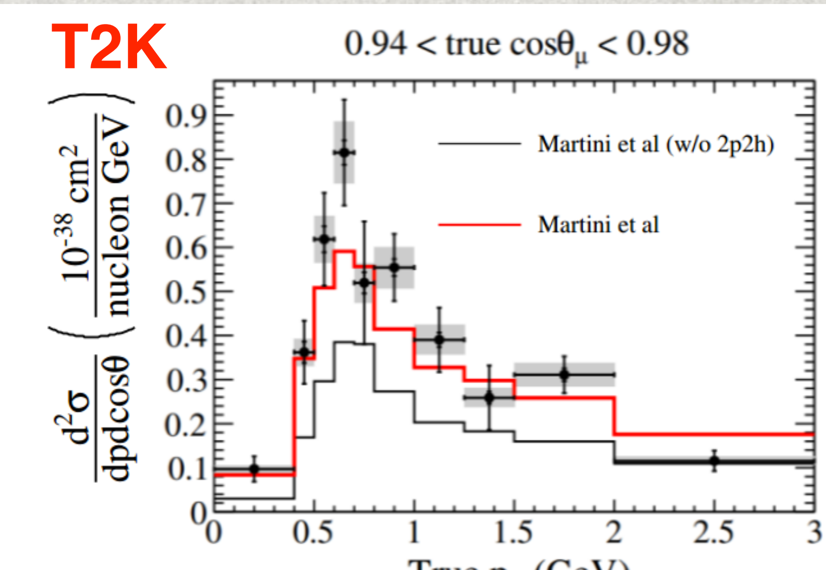
Recent analyses attempt to isolate process in relevant kinematic space.

Disagreements between data and theory.

Empirically adjusted models can consistently describe multiple measurements (e.g. inclusive and exclusive).

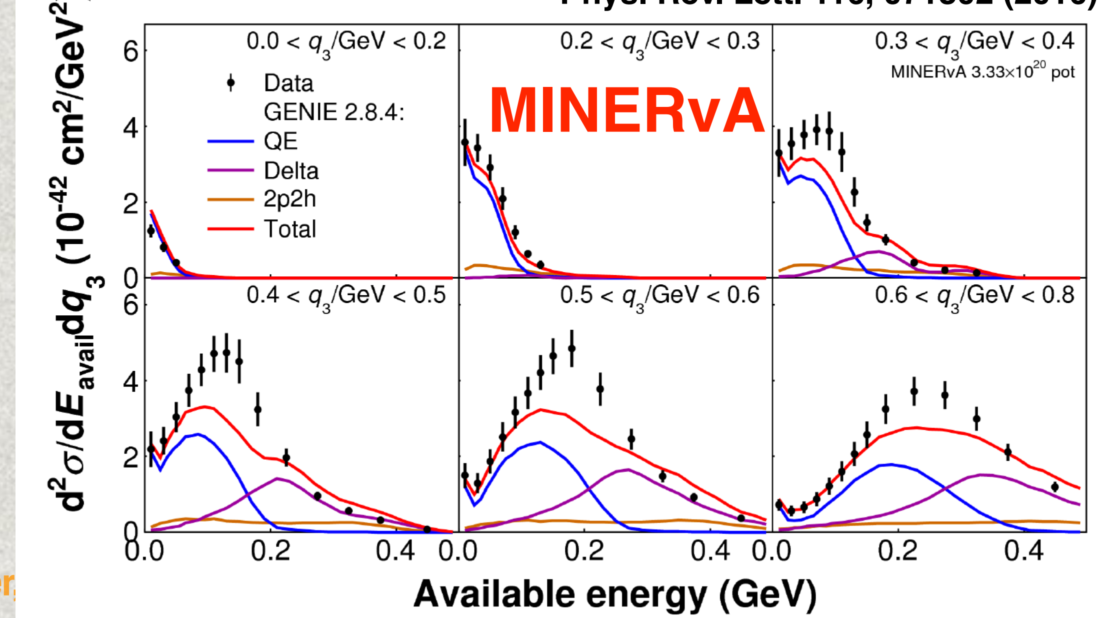
K. Bays, NuFACT 2017





Phys. Rev. D 93, 112012

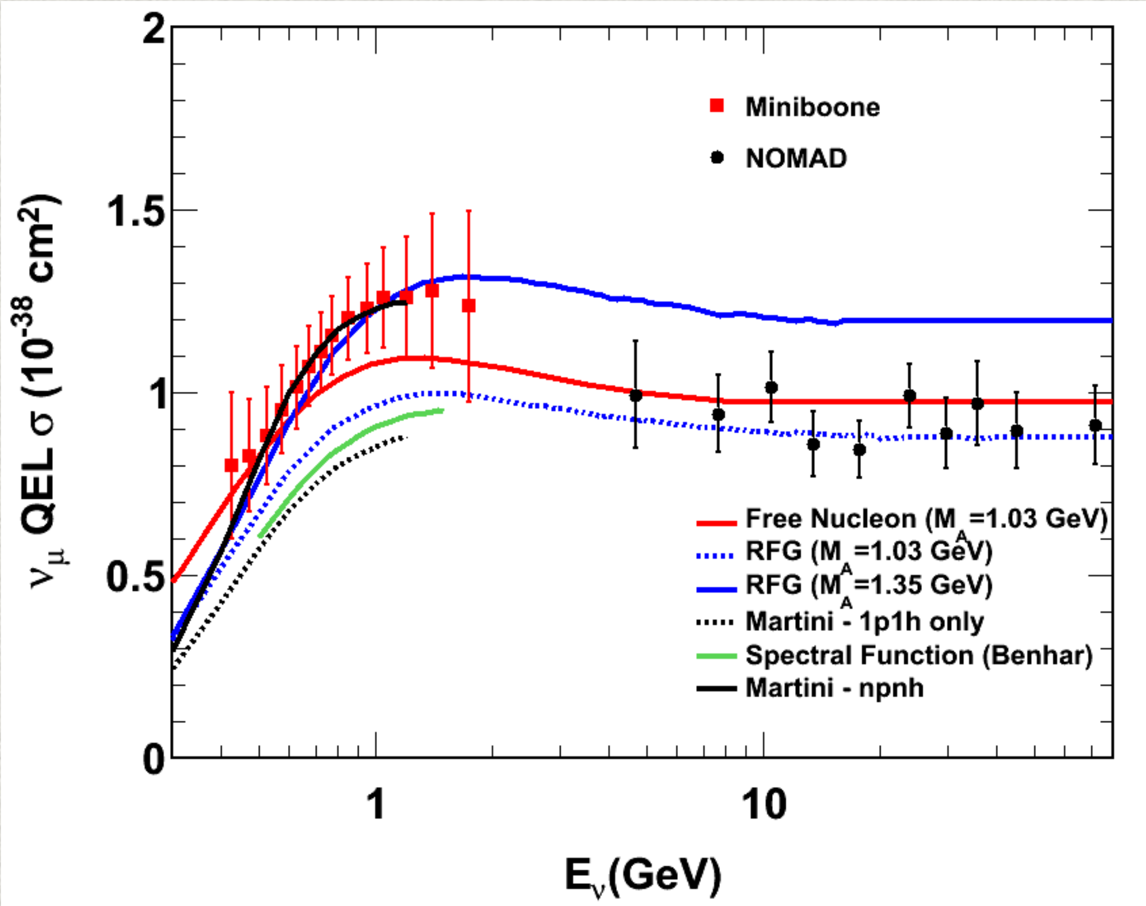
Phys. Rev. Lett. 116, 071802 (2016)



Quasi-Elastics

If this discrepancy is a nuclear effect, it has some curious features:

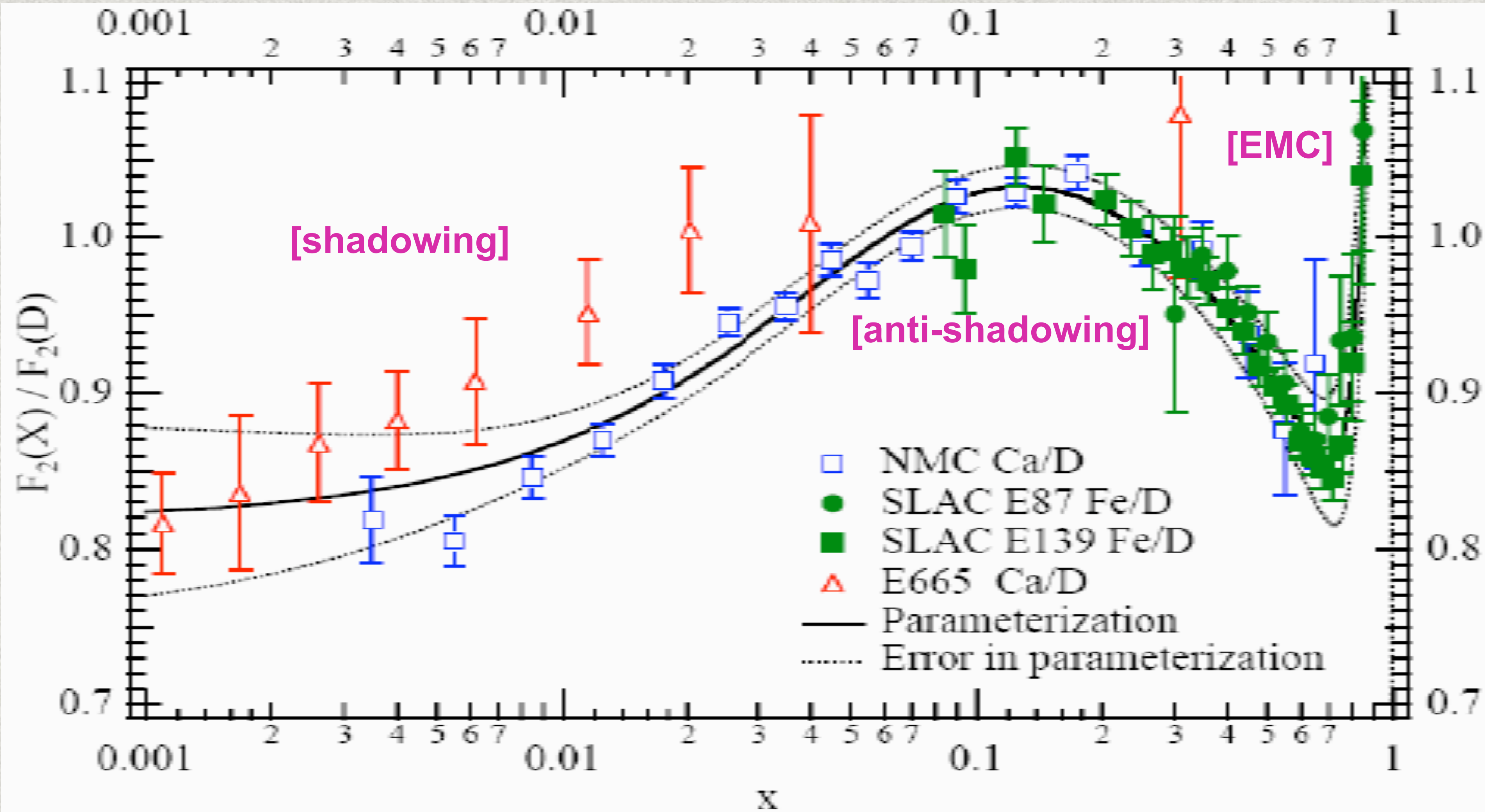
- *Affects shape of Q^2 distribution at moderate Q^2 values.*
- *Increases total QEL-like cross section.*
- *Similar sized discrepancy for iron and carbon.*
- *Less evident in antineutrinos at higher energy (NOMAD).*
- *Less evident in neutrino-carbon at higher energy (NOMAD, but with different selection).*



Our main conclusion is that MiniBooNE data are fully compatible with former determinations of the nucleon axial mass...Besides, we have found that the procedure commonly used to reconstruct the neutrino energy for quasielastic events from the muon angle and energy could be unreliable for a wide region of the phase space, due to the large importance of multinucleon events.

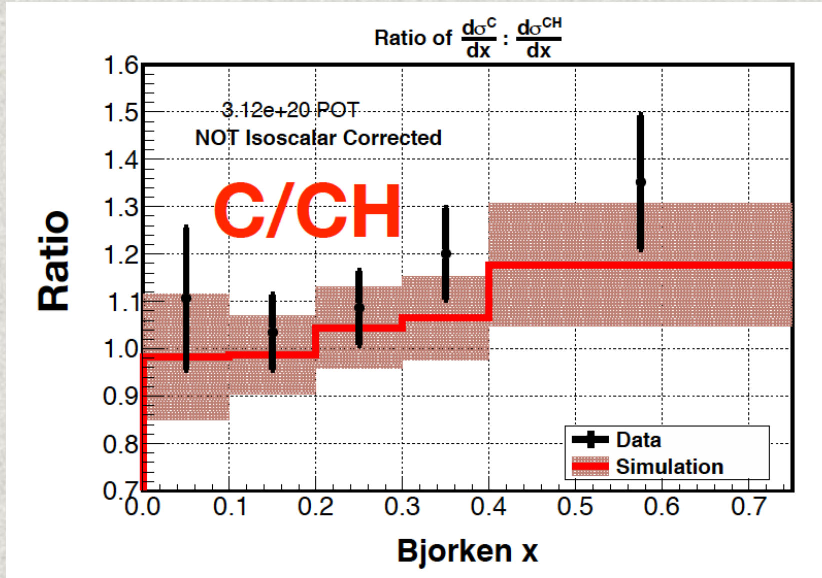
Nieves et al, Phys. Lett. B707 (2012)

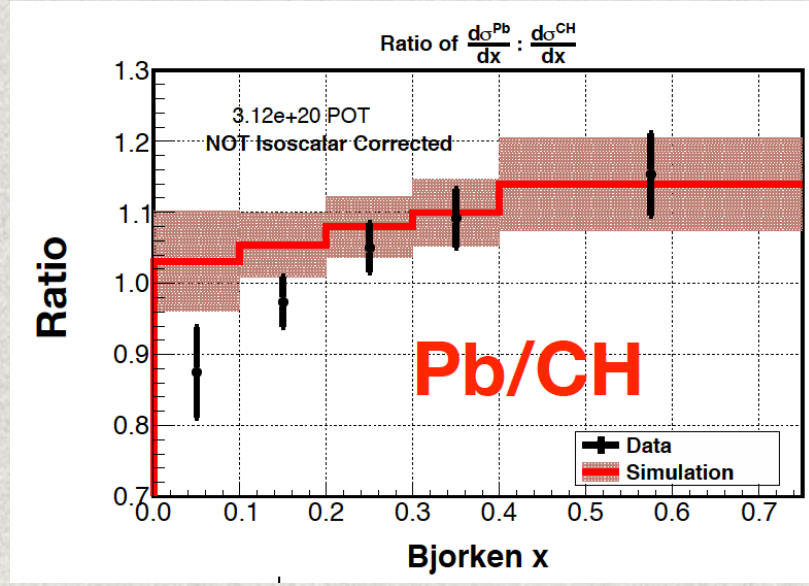
Nuclear Modifications to DIS

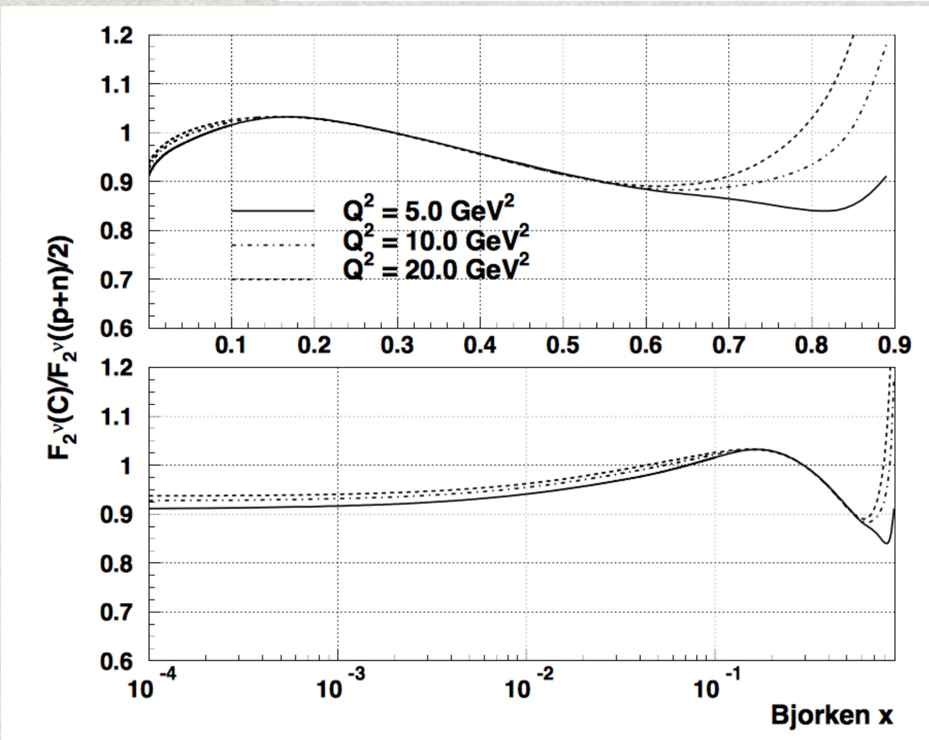


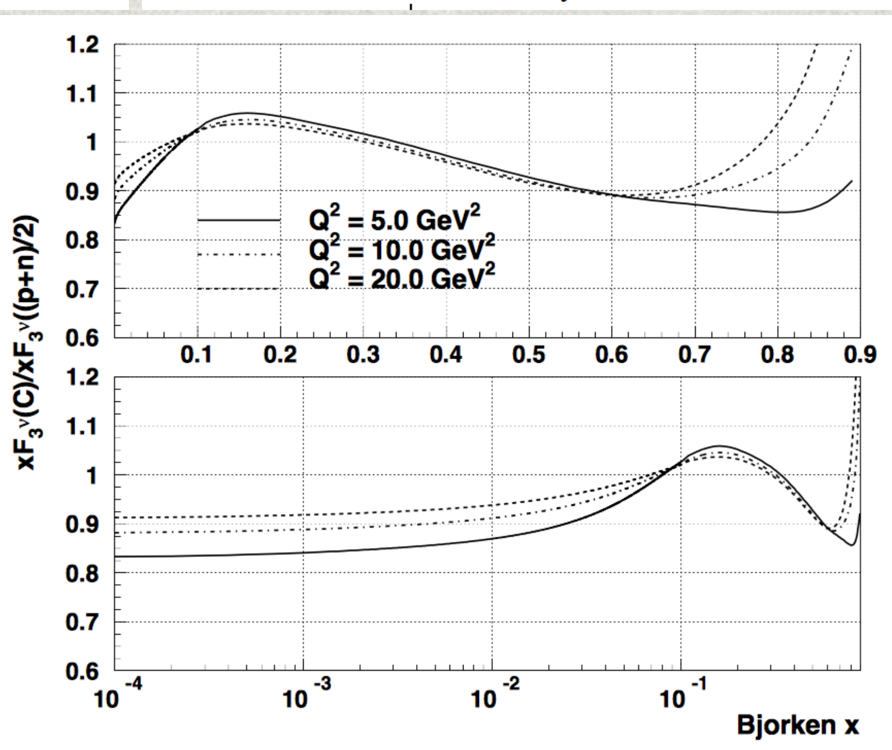
How are A-dependent effects different for neutrinos?

MINERvA, Phys Rev D. 93, 071101 (2016)

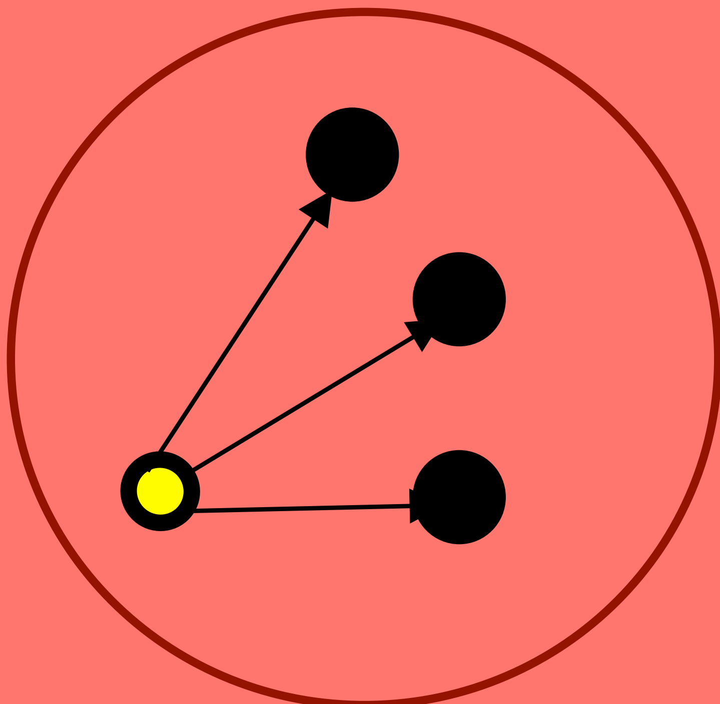








Kulagin and Petti, Nucl.Phys.A765:126-187,2006



HADRONIZATION IN NUCLEI

Hadronization in Nuclei

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

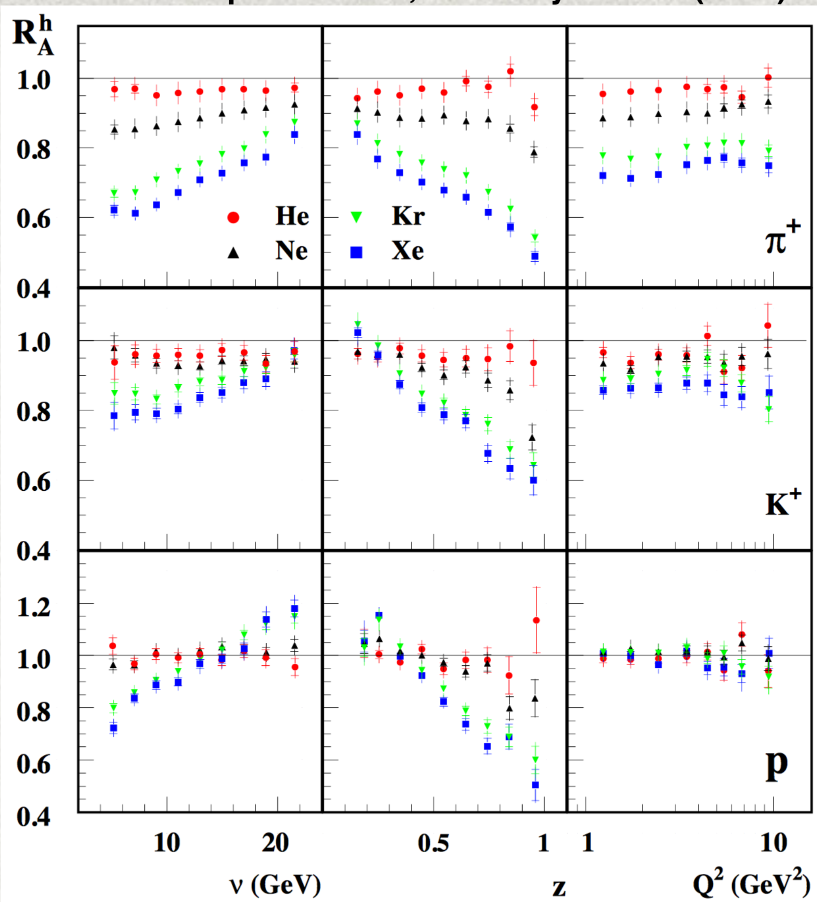
QCD Phenomena of Color Transparency (CT). At high momentum transfer, a struck particle is produced with a small size which suppresses its reinteraction cross section.

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 Data/Models

HERMES: A. Airapetian et al., Nucl.Phys. B780 (2007) 1-27

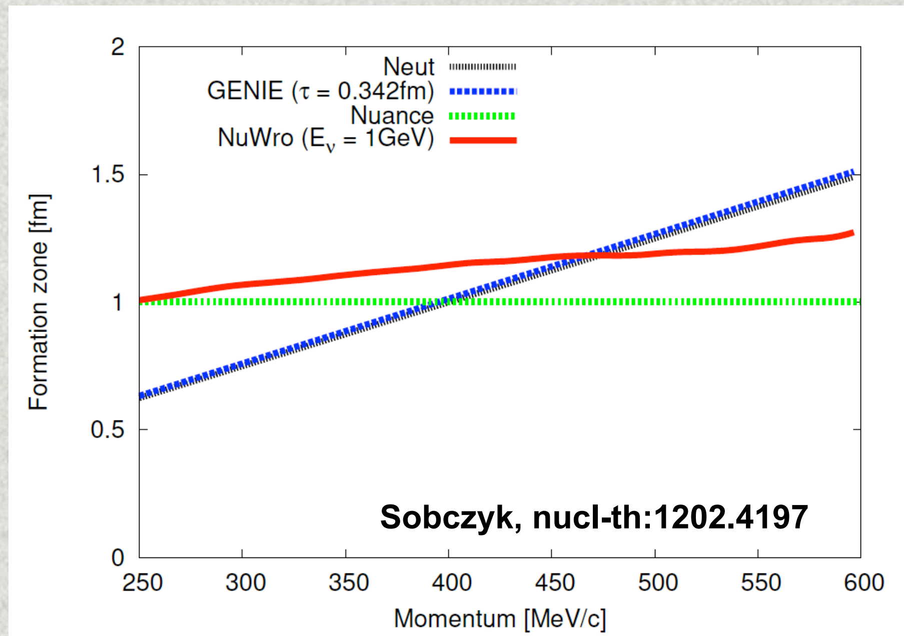


Golan et al., Phys.Rev. C86 (2012) 015505

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



DIS treatment often taken from the SKAT Experiment: *SKAT: Baranov et al., PHE 84-04 (1984)*

Formation time:

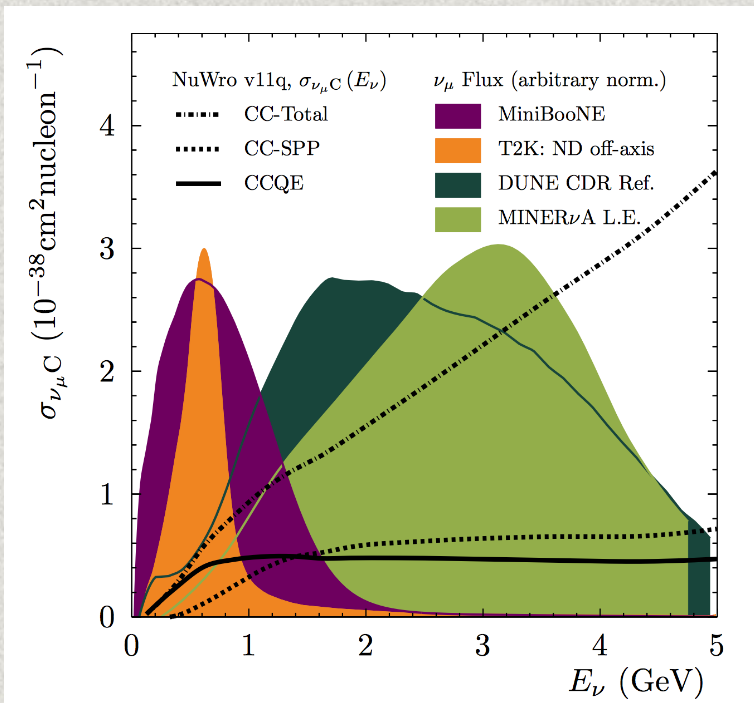
$c t_0$ = 0.342 +- 0.171 fm

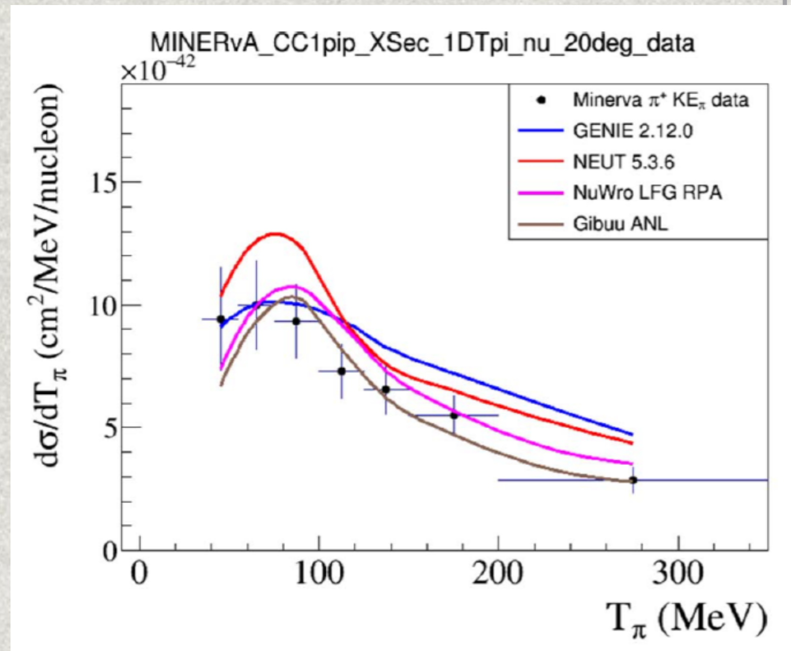
Modern Analyses

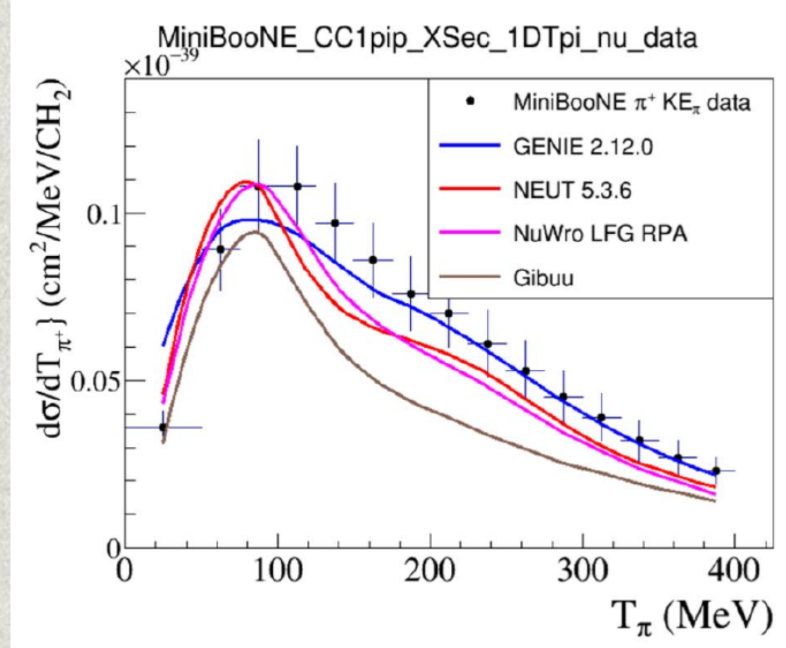
Disagreements between experiments, channels in single pion measurements.

Significant progress towards a comprehensive picture of 0 pion interactions.

Many analysis improvements to reduce model dependence and make results easier to interpret.



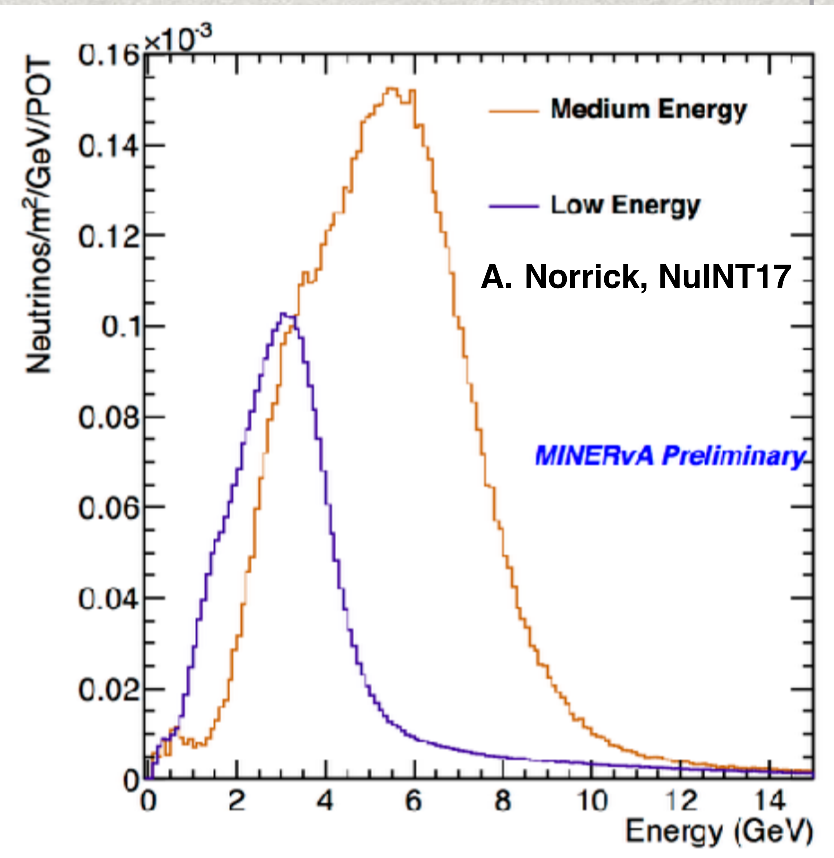




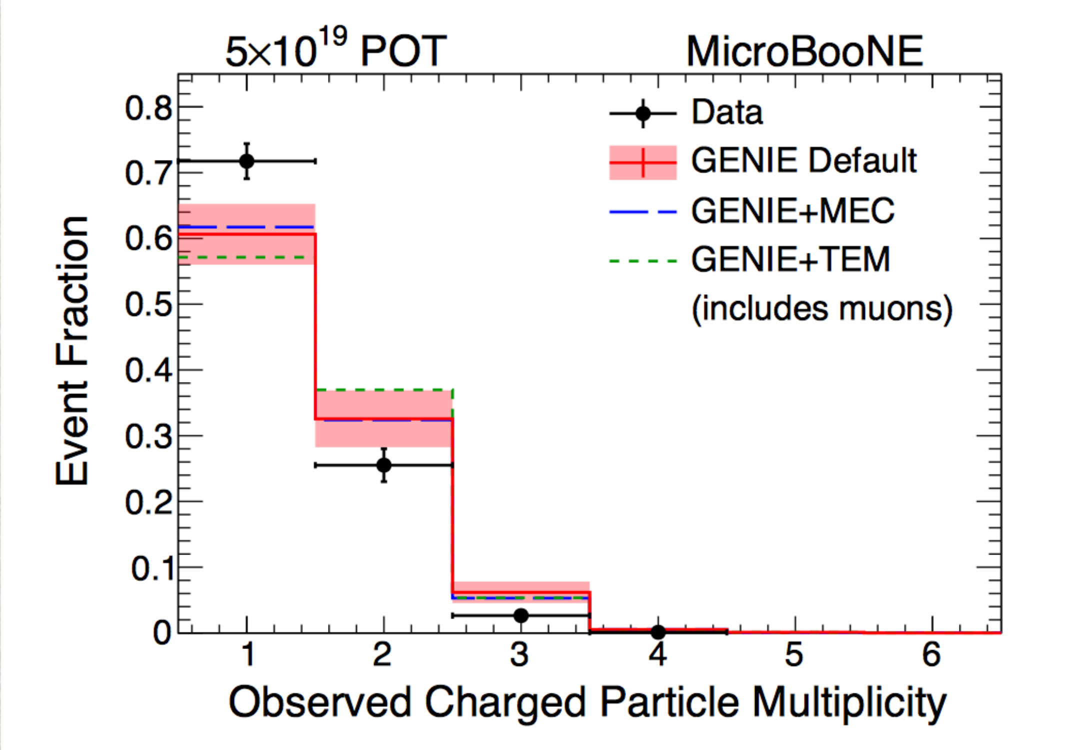
Detailed summary of contemporary situation in:
M. Betancourt et al., arXiv:1805.07378

Future Analyses

More to come from NoVA/ MicroBooNE/SBND. MicroBooNE will make possible detailed measurements of the hadronic system.



MicroBooNE, C. Adams et al., arXiv:1805.06887



\

T2K, MINERvA as well. In particular MINERvA results in the Medium Energy beam will greatly increase statistics in the SIS/DIS regimes.

T. Katori, NuWRO workshop 2017
(+C. Bronner, S. Mandalia,
C. Stanley, L. Hartley)

7. DIS-hadronization errors, summary

- Goal is to make event weight with function of Ev, x, y, etc, for IceCube oscillation program
- Some of systematic errors are identified to be dangerous

	DIS or Hadronization	type of error	approach	size
some study (MSU)	DIS	Bodek-Yang correction	play with Bodek-Yang parameters (by eyes)	maybe large?
done	DIS	differential xs	NuTeV-GENIE comparison (bottom-up)	1-2% by GENIE study
under investigation	DIS	A-scaling	MINERvA-GENIE (bottom-up)	maybe large?
some study (MSU)	DIS	PDF	From nuclear PDF, CT10? nCTEQ? (top-down)	expected to be tiny
under investigation	Hadronization	low W averaged charged hadron multiplicity	play with KNO parameters (by eyes)	maybe large?
done JPhysG42(2015)115004	Hadronization	high W averaged charged hadron multiplicity	bubble chamber-PYTHIA comparison (bottom-up)	1-2% by GENIE study

Sjostrand, Lonnblad, and Mrenna, hep-ph/0108264
Gallmeister and Falter, PLB630(2005)40, TK and Mandalia,JPhysG42(2015)115004

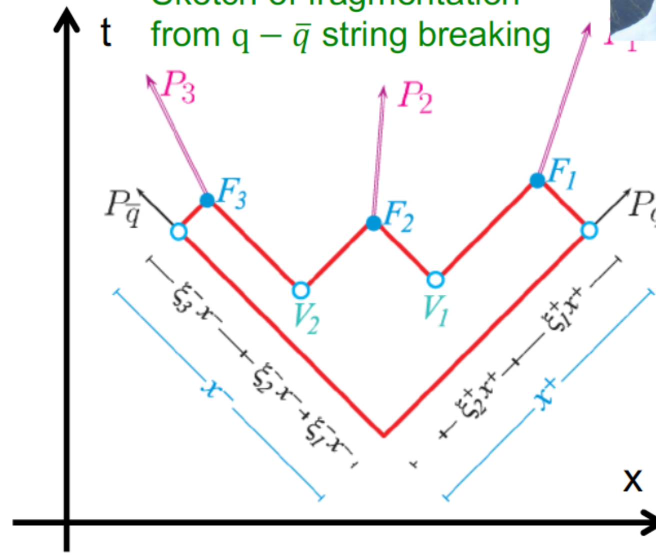
6. High-W hadronization model

Shivesh Mandalia
(Queen Mary)

Averaged charged hadron multiplicity $<n_{ch}>$

- PYTHIA6 with tuned Lund string function can reproduce $<n_{ch}>$ data both neutrino and antineutrino.

Sketch of fragmentation from $q - \bar{q}$ string breaking



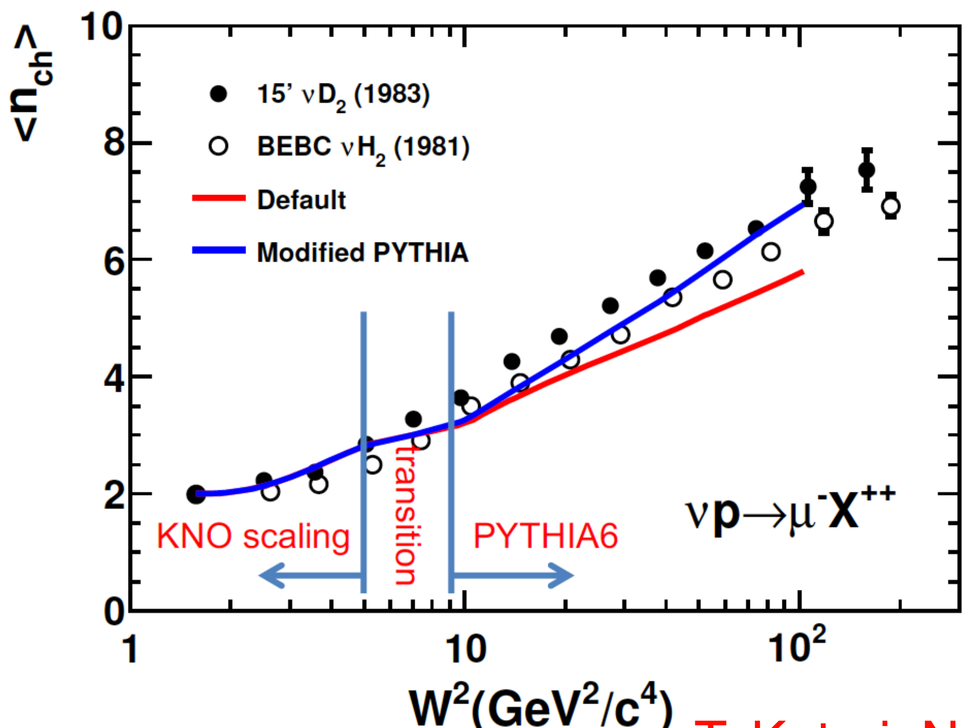
Lund string function

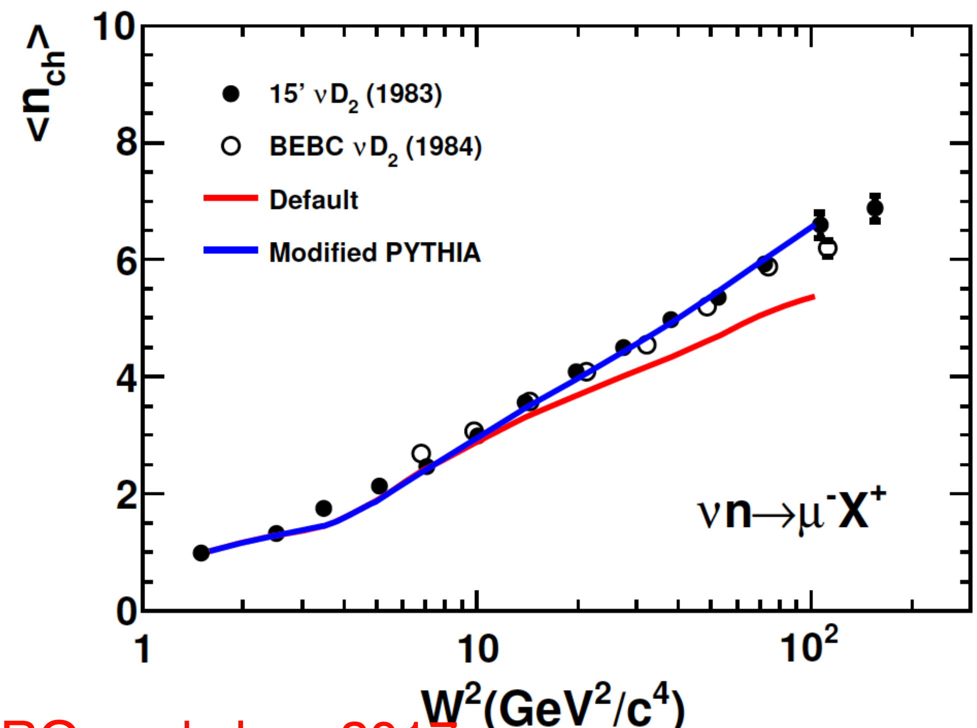
hadron energy distribution from iterative process

tunnelling probability

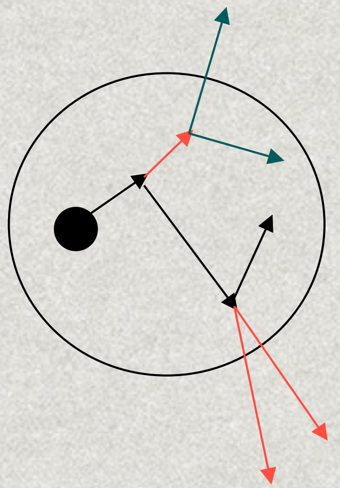
$$f(z) \propto z^{-1}(1-z)^a \cdot exp\left(\frac{-bm_\perp^2}{z}\right)$$

Neutrino average charged hadron multiplicity





Intranuclear Rescattering Model[1]



S. Dytman

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 $\lambda(E,r)=1/\rho(r)\sigma(E)$.

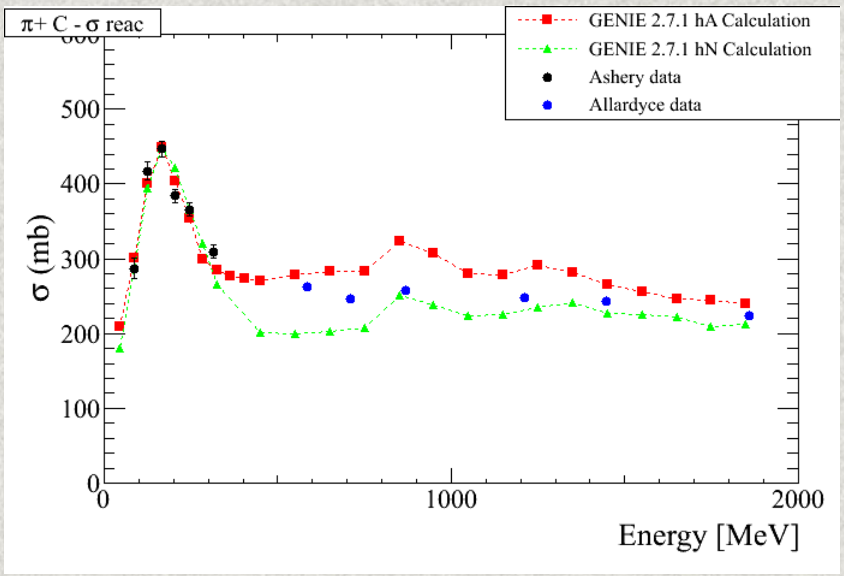
- Choose interaction from list (data, models, intuition)
- Elas, Inel, CEX, abs (KO), pi prod
- Choose kinematics by models, phase space and exit.

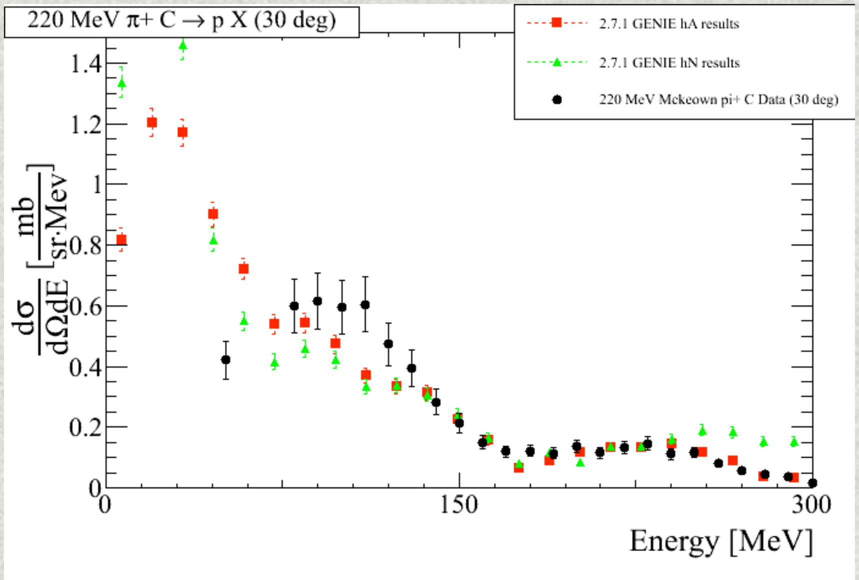
formation time[2]= 0.342 fm/c

Tuning and Validation

π

ν





[1] S. Dytman, AIP Conference Proceedings, Volume 896, pp. 178-184 (2007). [2] V. Ammosov (SKAT), NuINT01

S. Dytman, NuINT2017

Compare to other generators (2.12 default)

Model/generator	GENIE	NuWro	NEUT
QE	Lwlyn-Smith Nieves, Eff MA	Lwlyn-Smith RPA	Lwlyn-Smith Eff RPA
Nuclear model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function
MEC	Valencia Empirical	Valencia Marteau	Valencia
Delta model	Rein-Sehgal (updated)	Home-grown	Rein-Sehgal (update)
Coherent	Rein-Sehgal(corrected) Berger-Sehgal	Rein-Sehgal Berger-Sehgal	Rein-Sehgal Berger-Sehgal
FSI	Schematic Cascade (med corr)	Cascade(med corr)	Cascade(med corr)

- Differences more in detail than fundamental (physics)
- Main difference is that GENIE has larger goals, therefore more ponderous

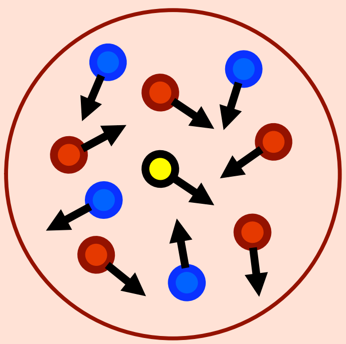
T H E O R Y

- Full nuclear-many body theory
- Relativistic Green's functions
- Spectral functions
- Relativistic Fermi Gas

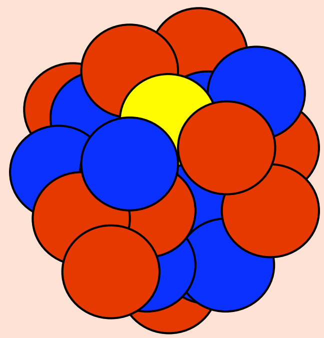
- Elastic/Quasi-elastic
- Production of baryon resonances
- Parton-level inelastic scattering
- + rare processes (coherent, ΔS=1...)

- Resonance decays
- Empirical fragmentation models
- PYTHIA (string fragmentation)
- Formation zones
- Coherence lengths

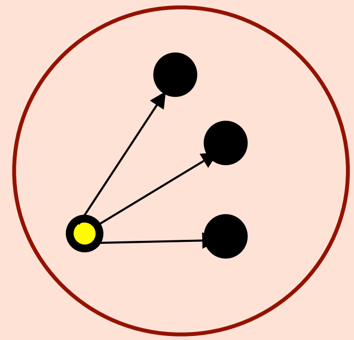
- optical models
- intranuclear cascade simulations
- transport calculations



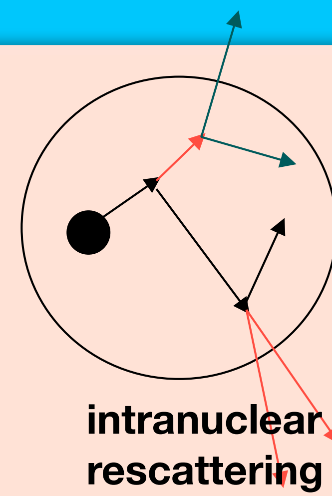
nuclear model



fundamental scattering mechanism



hadronization (in nuclei)



intranuclear rescattering

D A T A

Inclusive electron scattering:

hydrogen/deuterium targets (eN)

nuclear targets (eA)

in the quasi-elastic and resonance regions

hadron attenuation

e/μ : Structure functions

e

Bubble Chambers (ANL, BNL, SKAT, BEBC, FNAL), CCFR, NuTEV, MINOS, T2K, NOMAD, MiniBooNE, SciBooNE, ArgoNEUT, MINERvA, NoVA, MicroBooNE

ν

pion, kaon, hadron - nucleus scattering experiments

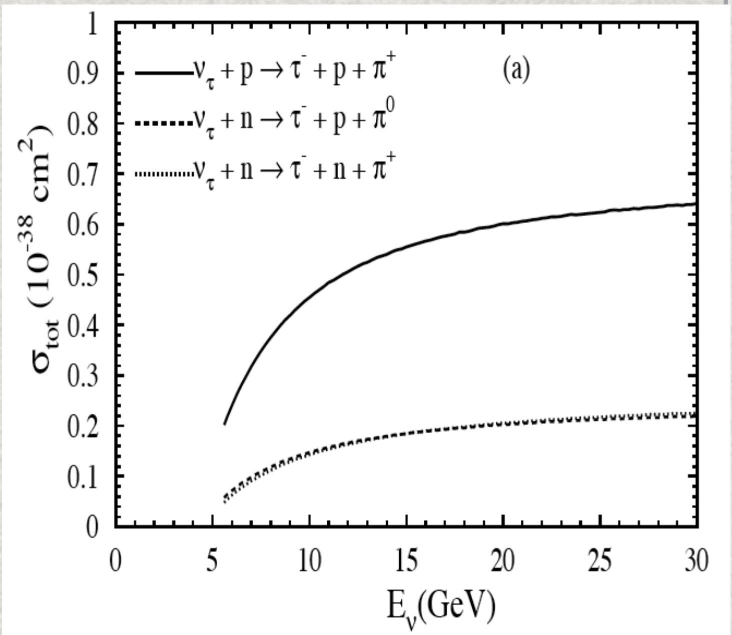
- total and reaction cross sections
- differential distributions of produced particles

π

Tau Cross Sections

Multi-GeV, mainly shower-like, upward going events, important to understand for hierarchy determination.

Paschos and Yu, Phys.Rev.D65:033002,2002



QEL/Resonance uncertainties due to F_P

Uncertainty in resonance production?

- Due to approximate nature of F_P treatment
- Model uncertainty – compare Rein-Sehgal to Paschos-Yu?

DIS Uncertainty?

- F_4 and F_5 are uniquely determined in parton model.

F_P Issues: constrained at low Q^2 by data on radiative muon capture and PCAC.

Not well known at high Q^2. Some suggestions (e.g. Phys. Lett. B591, 113-118 (2004)) lead to large changes.

Tau polarization also relevant for some measurements.

V. Bernard et al., Nucl.Phys. A686 (2001) 290-316

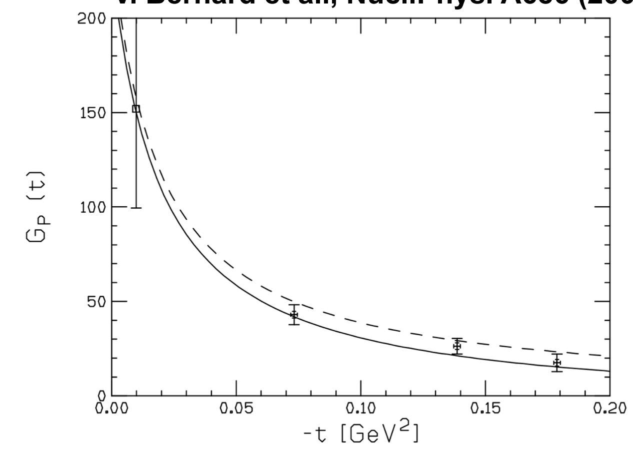


FIG. 7. The "world data" for the induced pseudoscalar form factor $G_P(t)$. Dashed curve: Pion–pole prediction. Solid curve: $\mathcal{O}(\epsilon^3)/\mathcal{O}(p^3)$ SSE/HBChPT prediction. The pion electroproduction data (crosses) are from ref. [8]. Also shown is the OMC result at $t = -0.88m_\mu^2$ from ref. [7] (open square).

Proton Decay Backgrounds

Strange particle production from atmospheric neutrino interactions is the primary background to proton decay searches like p -> K^+ nu.

NC associated production thought to be the dominant mechanism as CC channels can be rejected due to the presence of the charged lepton.

•Requires modeling associated production in shallow inelastic reactions as well as resonance production.

•Kaon FSI also quite important.

Recent data: electron scattering on kaon electroproduction and neutrino data on strange particle production.

BR(N0 (1650)→ Σ−K+) = 3.3%
BR(N+ (1650)→ ΛK+) = 7.5%
BR(N+ (1650)→ Σ0K+) = 1.7%
BR(N0 (1710)→ Σ−K+) = 2.7%
BR(N+ (1710)→ ΛK+) = 13%
…etc

C. Marshall et al. Phys.Rev.Lett. 119 (2017) no.1, 011802

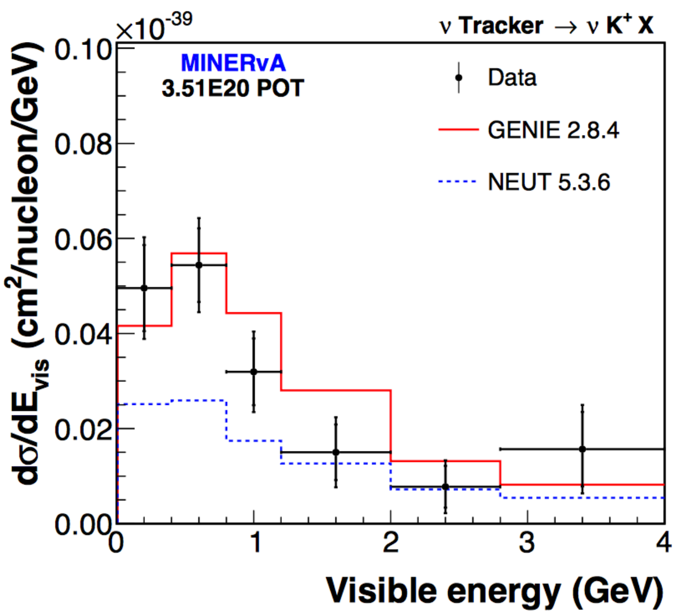


FIG. 4: The differential cross section as a function of non-K^+ visible energy E_{vis}, as defined in the text, compared to GENIE and NEUT. The inner (outer) error bars represent the statistical (total) uncertainty.

mu/e cross section ratio

K. Abe et al., Phys. Rev. D 96, 092006

McFarland and Day, Phys.Rev. D86 (2012) 053003

Accelerator-based experiments are beginning to worry about cross section uncertainties at the few % level, and lepton universality only gets you so far…

Requires detailed calculations and re-evaluation of theoretical assumptions.

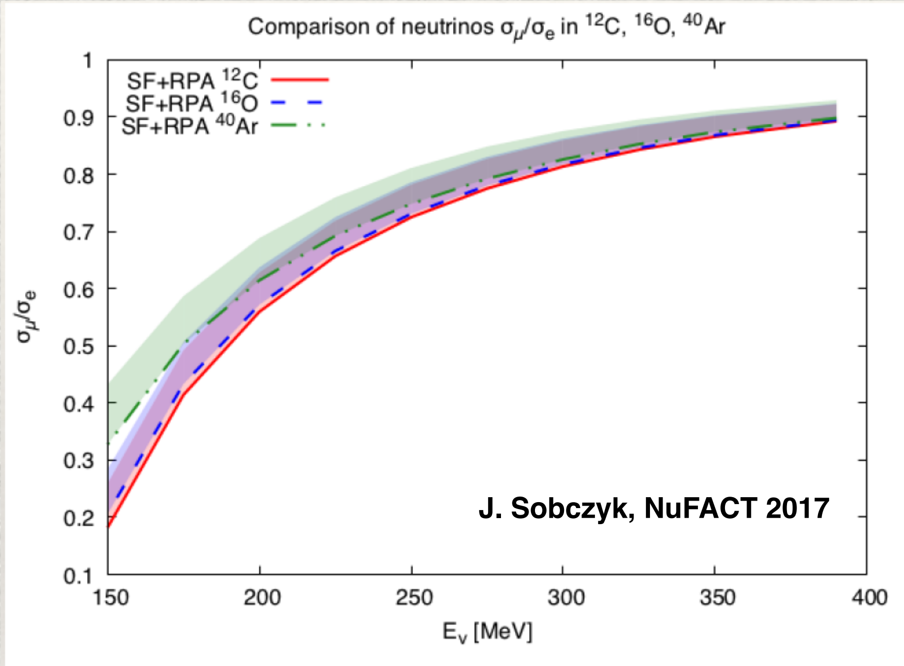
- Second-class currents
- Pseudo-scalar form factor

+nuclear effects (different kinematic thresholds)

Treatment of binding energies?

A. Bodek, arXiv:1801.07975

To account for effects which may potentially affect $\overset{(-)}{\nu}_e$ but not $\overset{(-)}{\nu}_\mu$ cross sections, such as radiative corrections or second class currents (see, for example, Ref. [69]), which are not included in the NEUT cross section model, additional uncertainties which affect $\overset{(-)}{\nu}_e$ have been introduced. These include an uncorrelated 2% uncertainty on the ν_e/ν_μ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross section ratios to account for radiative corrections and an additional 2% uncertainty which is fully anticorrelated between ν_e and $\bar{\nu}_e$ to allow for second class currents.



Radiative Corrections

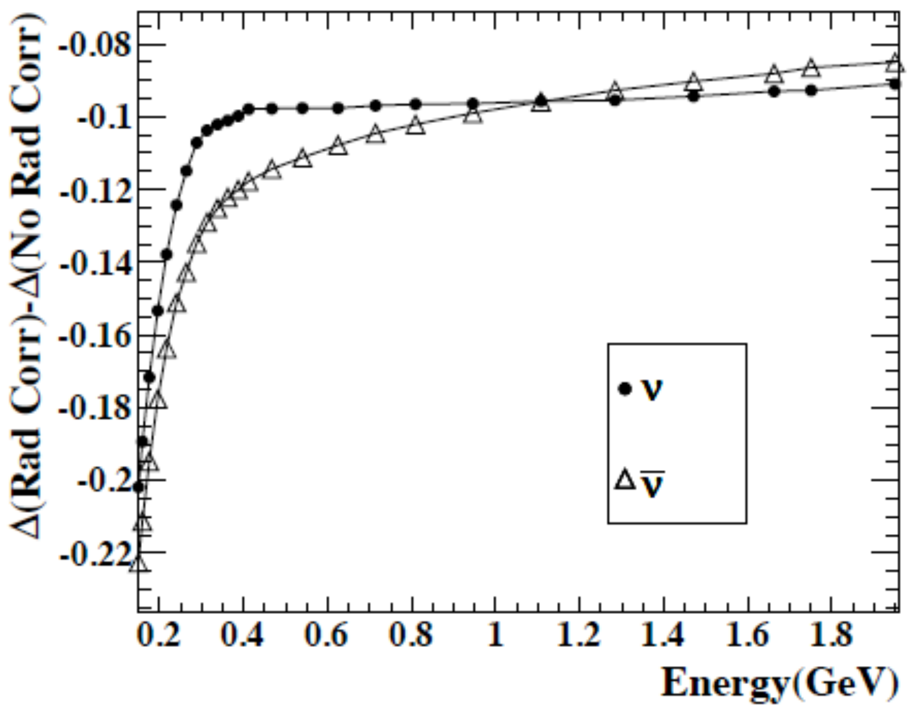


FIG. 2. Our estimate in the lepton leg leading log approximation of the fractional difference between the electron and muon neutrino total charged-current quasi-elastic cross-sections, Δ as defined in Eq. 15, as a function of neutrino energy. The negative difference means that the electron neutrino cross-section is larger than the muon neutrino cross-section.

Free nucleon QEL cross section only!

McFarland and Day, Phys.Rev. D86 (2012) 053003

$$\Delta(E_\nu) \equiv \frac{\int dQ^2 \frac{d\sigma_\mu}{dQ^2} - \int dQ^2 \frac{d\sigma_e}{dQ^2}}{\int dQ^2 \frac{d\sigma_e}{dQ^2}}.$$

$$\frac{d\sigma_{LLL}}{dE_\ell d\Omega} \approx \frac{d\sigma_B}{dE_\ell d\Omega} + \frac{\alpha_{EM}}{2\pi} \log\frac{4E_\ell^{*}}{m^2} \int_0^1 dz \frac{1+z^2}{1-z} \times \left(\frac{1}{z} \frac{d\sigma_B}{d\hat{E}_\ell d\Omega}\Big|_{\hat{E}_\ell = E_\ell/z} - \frac{d\sigma_B}{dE_\ell d\Omega} \right),$$

Photon emission from final state lepton - low energies, co-linear - impact on analysis strongly dependent on detection thresholds and analysis cuts.

NEUT systematic errors for atmospheric neutrino analyses

K. Abe et al., Phys. Rev. D 97, 072001 (2018)

Systematic Error		Fit Value (%)	σ (%)
M_A in QE		-0.56	10
Single π Production, Axial Coupling		-4.5	10
Single π Production, C_{A5}		-3.0	10
Single π Production, BKG		-8.7	10
CCQE cross section[a]		6.6	10
CCQE $\bar{\nu}/\nu$ ratio[a]		9.3	10
CCQE μ/e ratio[a]		0.71	10
DIS cross section		-4.4	5
DIS model comparisons[b]		3.0	10
DIS Q^2 distribution (high W)[c]		8.2	10
DIS Q^2 distribution (low W)[c]		-5.8	10
Coherent π production		-8.6	100
NC/CC		12.1	20
ν_τ cross section		-13.9	25
Single π production, $\pi^0/\pi^\pm$		-20.2	40
Single π production, $\bar{\nu}_i/\nu_i$ (i=e,μ)[d]		-11.1	10
NC fraction from hadron simulation		-0.54	10
π^+ decay uncertainty Sub-GeV 1-ring	e-like 0-decay	-0.18	0.6
	μ-like 0-decay	-0.24	0.8
	e-like 1-decay	1.2	4.1
	μ-like 1-decay	0.71	0.9
	μ-like 2-decay	1.7	5.7
Meson exchange current[e]		-1.8	10
Δm^2_{21} [27]		0.022	2.4
$\sin^2(\theta_{12})$ [27]		0.34	4.6
$\sin^2(\theta_{13})$ [27]		0.11	5.4

[a] Difference from the Nieves [24] model is set to 1.0
[b] Difference from CKMT [42] parametrization is set to 1.0
[c] Difference from GRV98 [43] is set to 1.0
[d] Difference from the Hernandez[44] model is set to 1.0
[e] Difference from NEUT without model from [24] is set to 1.0

Conclusions

With a new generation of experimental and theoretical work, driven by the needs of accelerator-based oscillation experiments, our knowledge of neutrino cross sections is slowly improving, though numerous mysteries remain.

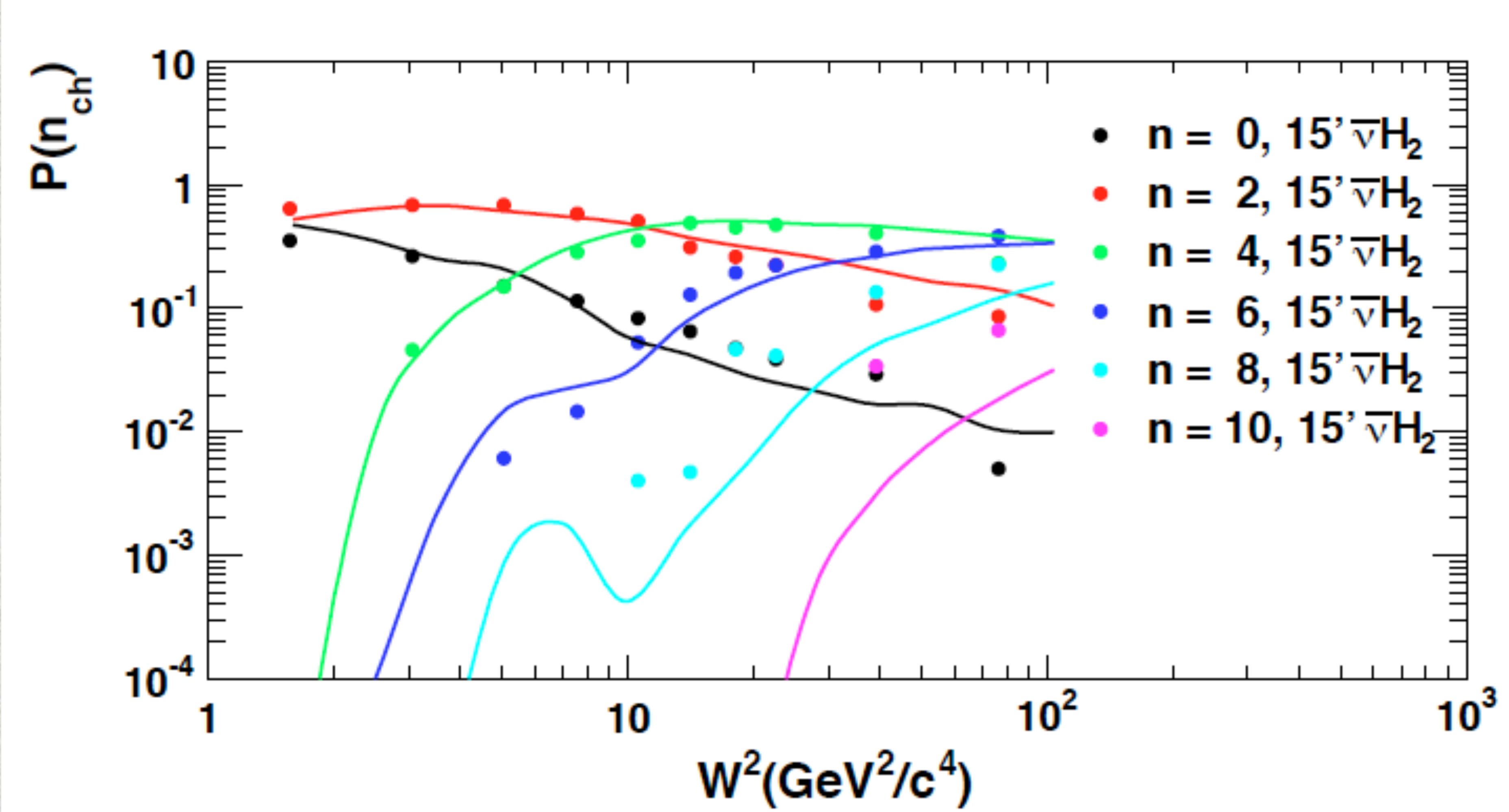
The focus has been on few-GeV energy reactions, in particular 0 and 1 pion final states. Much work remains to be done to understand the SIS/DIS region*.

Neutrino interaction-related systematics have yet to play a limiting role in atmospheric neutrino experiments, but pose some unique questions, e.g. on tau cross sections.

Thank you: Y. Hayato, T. Katori, J. Koskinen, R. Wendell

*dedicated workshop 11-13 October 2018, Gran Sasso Science Institute

BACKUP



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.

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:

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

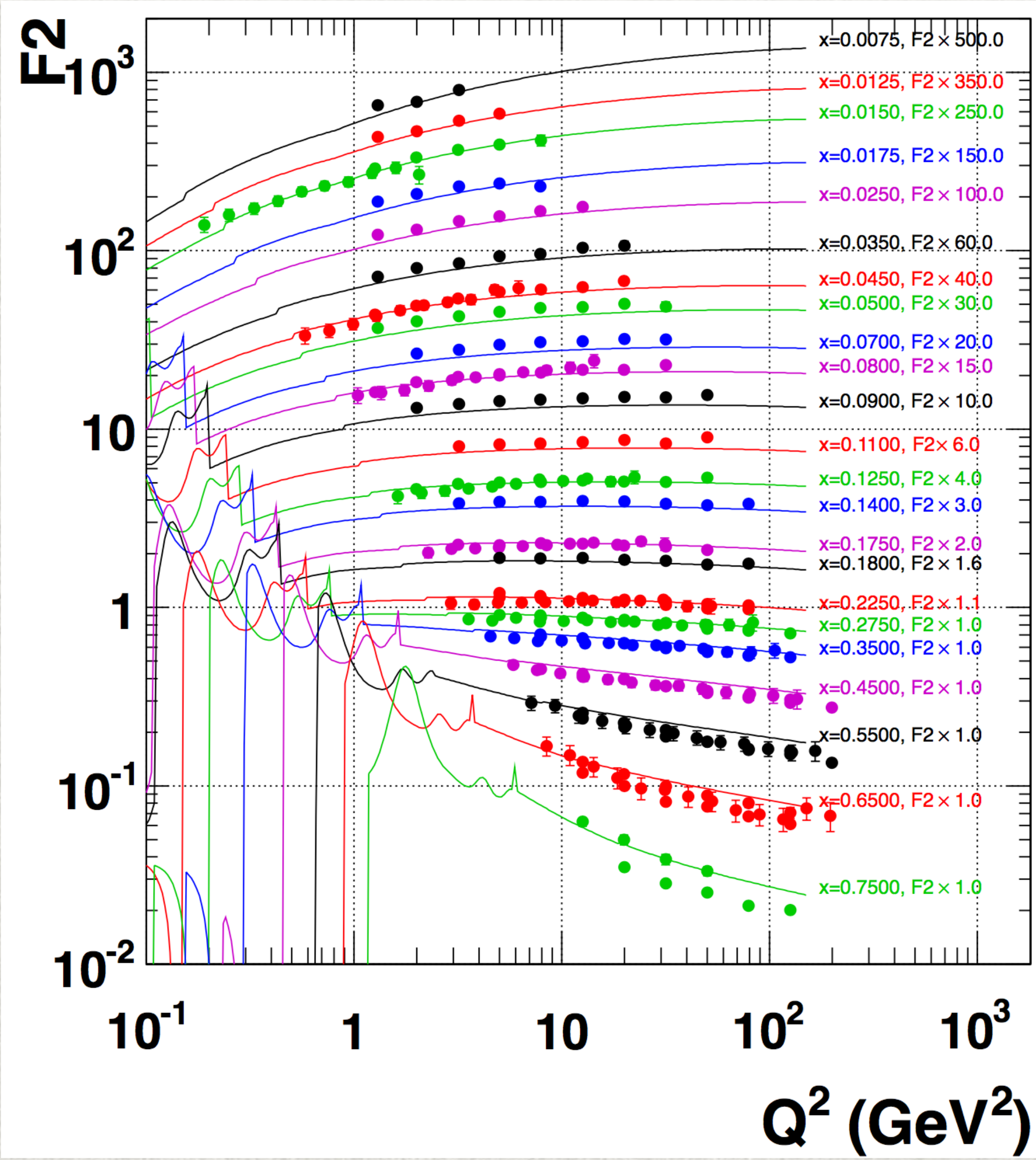
***p* is outgoing nucleon 4-vector**
***q* is 4-momentum transfer**

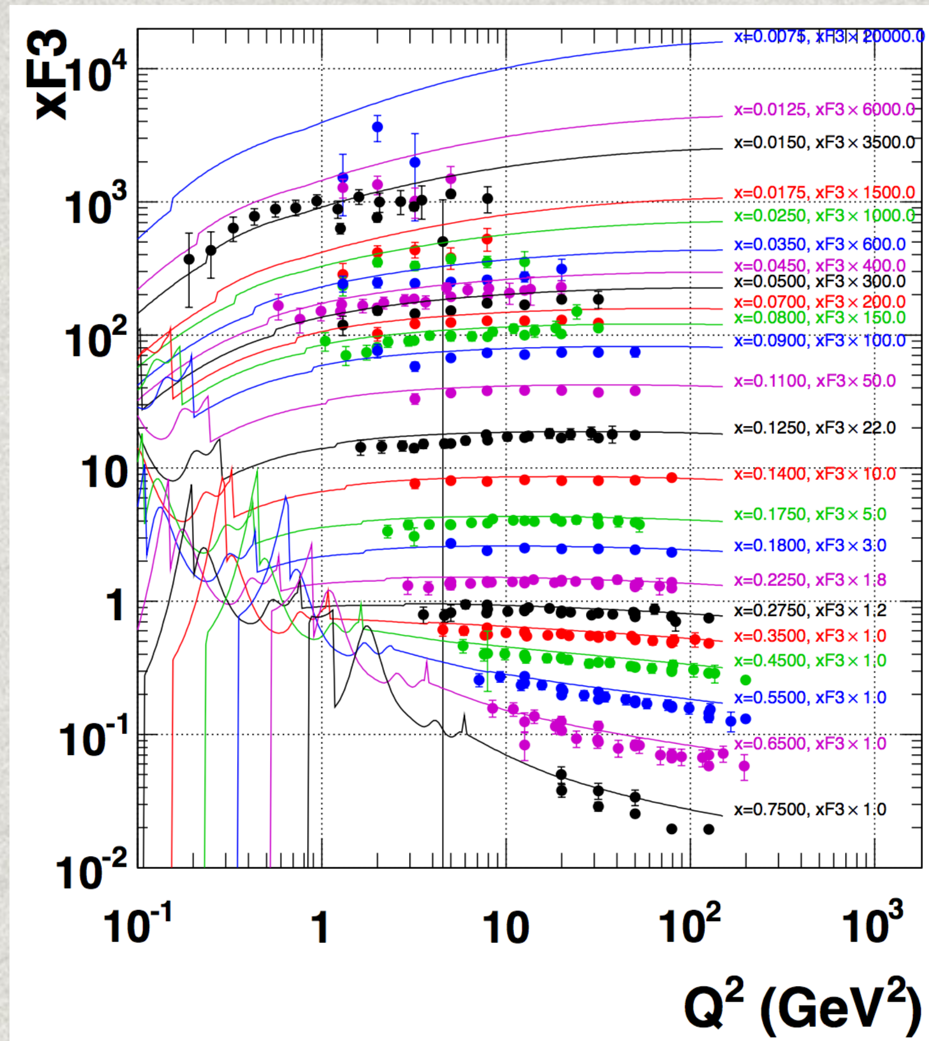
Sobczyk, nucl-th:1202.4197

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


F2
10^3
10^2
10
1
10^-1
10^-2
10^-1
1
10
10^2
10^3
Q^2 (GeV^2)
x=0.0075, F2 × 500.0
x=0.0125, F2 × 350.0
x=0.0150, F2 × 250.0
x=0.0175, F2 × 150.0
x=0.0250, F2 × 100.0
x=0.0350, F2 × 60.0
x=0.0450, F2 × 40.0
x=0.0500, F2 × 30.0
x=0.0700, F2 × 20.0
x=0.0800, F2 × 15.0
x=0.0900, F2 × 10.0
x=0.1100, F2× 6.0
x=0.1250, F2 × 4.0
x=0.1400, F2 × 3.0
x=0.1750, F2 × 2.0
x=0.1800, F2 × 1.6
x=0.2250, F2 × 1.1
x=0.2750, F2 × 1.0
x=0.3500, F2 × 1.0
x=0.4500, F2 × 1.0
x=0.5500, F2 × 1.0
x=0.6500, F2 × 1.0
x=0.7500, F2 × 1.0


xF3
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-1
1
10
10^2
10^3
Q^2 (GeV^2)
x=0.0075, xF3 × 20000.0
x=0.0125, xF3 × 6000.0
x=0.0150, xF3 × 3500.0
x=0.0175, xF3 × 1500.0
x=0.0250, xF3 × 1000.0
x=0.0350, xF3 × 600.0
x=0.0450, xF3 × 400.0
x=0.0500, xF3 × 300.0
x=0.0700, xF3 × 200.0
x=0.0800, xF3 × 150.0
x=0.0900, xF3 × 100.0
x=0.1100, xF3 × 50.0
x=0.1250, xF3 × 22.0
x=0.1400, xF3 × 10.0
x=0.1750, xF3 × 5.0
x=0.1800, xF3 × 3.0
x=0.2250, xF3 × 1.8
x=0.2750, xF3 × 1.2
x=0.3500, xF3 × 1.0
x=0.4500, xF3 × 1.0
x=0.5500, xF3 × 1.0
x=0.6500, xF3 × 1.0
x=0.7500, xF3 × 1.0

Tuning

1) Electron scattering data

2) Exclusive channels

Coherent model

QEL-MA from global fits

RES-MA from global fits

3) High energy

Compare F2 and xF3 to charged lepton and neutrino data.

Compare to known cross sections at high energy.

3) High energy

Compare F2 and xF3 to charged lepton and neutrino data.

Compare to known cross sections at high energy.

4) “Transition region”

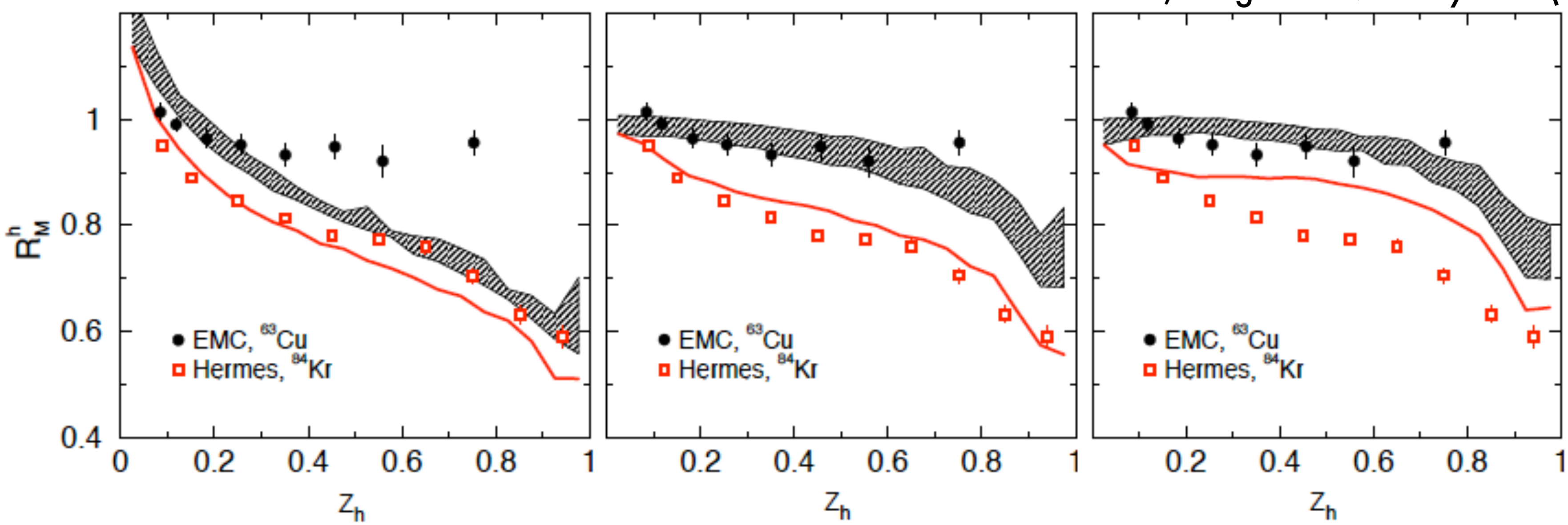
Finalize tune to inclusive and exclusive (1 and 2 pi) channels at intermediate energy (1-10 GeV).

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



np-nh and oscillations

QE Reconstruction in the Impulse Approximation.

$$E_\nu^{QE} = \frac{2\,(M_n - E_B)\,E_\ell - \left[(M_n - E_B)^2 + m_\ell^2 - M_p^2\right]}{2\,[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)]}$$

Doesn't cancel near/far.

Impact on calorimetric measurements?

Requires evaluation -> simulation of hadronic system.

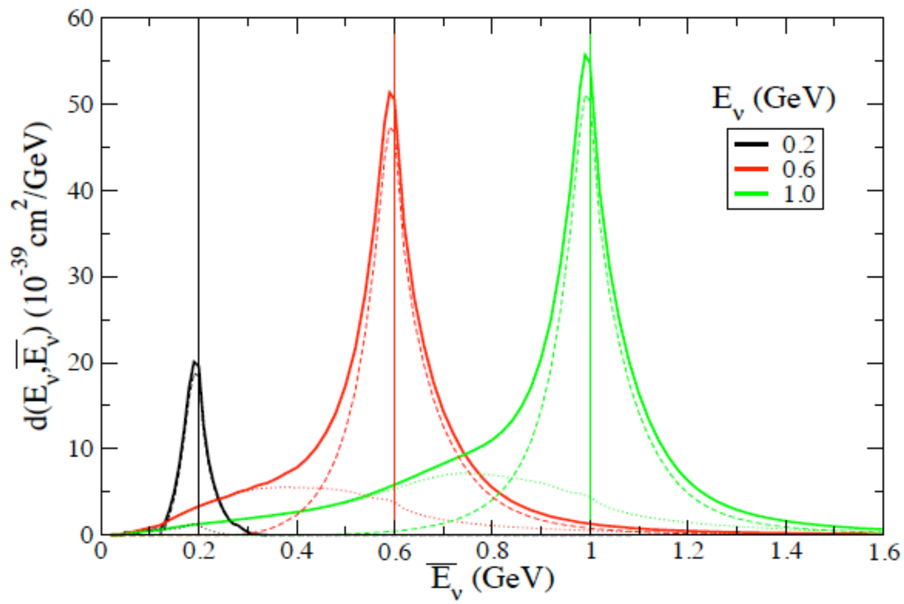


FIG. 1: (Color online) The spreading function $d(E_\nu, \overline{E_\nu})$ of Eq. (4) per neutron of ^{12}C in the case of electrons evaluated for three E_ν values. The genuine quasielastic (dashed lines) and the multinucleon (dotted lines) contributions are also shown separately.

Martini et al., Phys.Rev. D87 (2013) 013009.