Neutrino-nucleus Inelastic Scattering: Where do we go from here.. To-Do list for NuInt14 in May

Christopher Mauger and Jorge G. Morfín

INT Workshop – Dec. 2013

inelastic Neutrino Scattering

Arie Bodek

University of Rochester

December 2013

Modeling Inelastic Low Energy Neutrino Scattering on Nuclear Targets at all values of Q^2

Past, Present and Future

A. Bodek

Resonance Region and Quark Hadron Duality

All scattering is from quarks. However, at low W, final state interaction between the quarks results in nucleon resonances. So nucleon resonance production may be thought of as one of the fragmentation products of the final state quarks .

Elastic electron scattering (quasielastic neutrino scattering), can be thought of an extreme case of FSI where the final state interaction leads to a single nucleon.

So if quark hadron duality works, PDFs can be used to predict the average structure function in the resonance region. Structure functions are just PDFs, modulated by a final state interaction which in the resonance region yields nucleon resonances, and in the DIS region yields a jet of hadrons.

Quark hadron duality (using the Nachtman scaling variable) was found to work in electron scattering for $Q^2>1$ GeV^2, even in the region of the Δ and quasielastic peak.

Questions: (1) What about lower Q^2

(2) What about neutrino scattering.

Quark–Hadron Duality in Neutrino Reactions

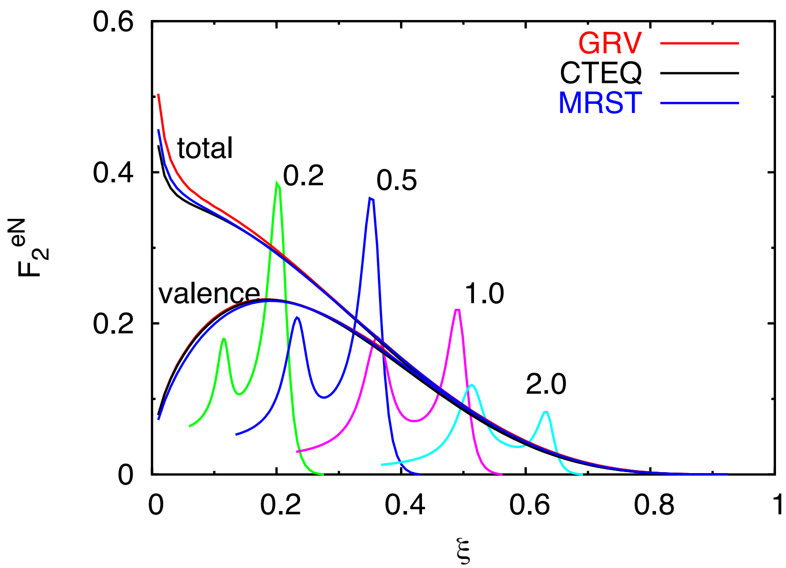
Olga Lalakulich

Department of Subatomic and Radiation Physics
Ghent University, Belgium

+ E.Paschos (Dortmund Uni), W.Melnitchouk (JLab)
+ N. Jachowicz, Ch.Praet, J.Ryckebusch (Gent Uni)

Neutrino-Nucleus Interactions in the Few-GeV Region, 2007

O. Lalakulich – NuInt07



$Q^2 = 0.2,\ 0.5,\ 1.0,\ 2\ \mathrm{GeV}^2$

Resonance structure functions: isobar model with phenominological form factors OL,Paschos, PRD 71, 74 includes the first four low-lying baryon resonances $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$

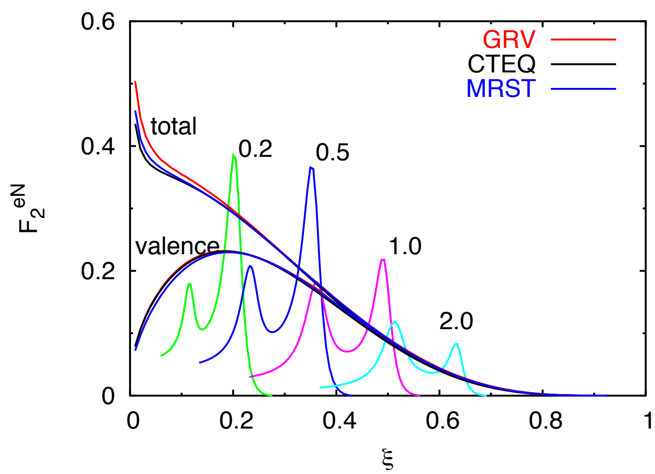
DIS structure functions: leading twist calculation with different parametrizations (GRV, CTEQ, MRST) of the parton distribution functions

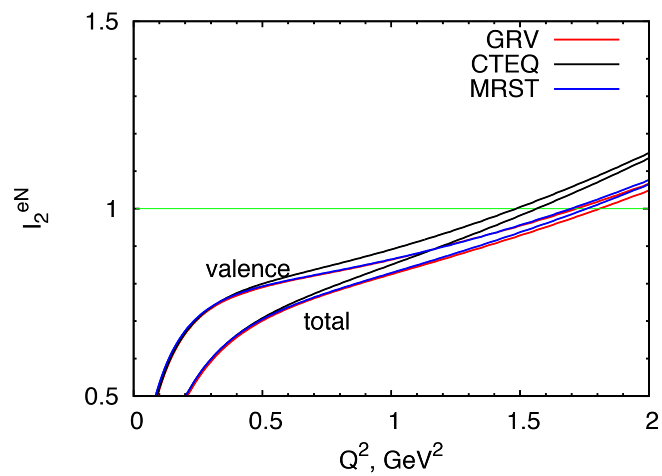
Global duality: on average the resonances appear to oscillate around and slide down the leading twist function

Similar results in Sato-Lee model Matsui,Sato,Lee, PRC 72 ($P_{33}(1232)$ resonance considered so far)

O. Lalakulich – NuInt07

Local duality: ratio of the integrals over the finite interval of ξ





$Q^2 = 0.2,\ 0.5,\ 1.0,\ 2\ \mathrm{GeV}^2$

$$I_2(Q^2) = \frac{\int_{\xi_{\min}}^{\xi_{\max}} d\xi\ \mathcal{F}_2^{(\mathrm{res})}(\xi, Q^2)}{\int_{\xi_{\min}}^{\xi_{\max}} d\xi\ \mathcal{F}_2^{(\mathrm{LeadingTwist})}(\xi, Q^2)},$$

OL,Melnitchouk,Paschos, PRC 75

$$\xi_{\min} = \xi(Q^2, W = 1.6\ \mathrm{GeV}), \qquad \xi_{\max} = \xi(Q^2, W = 1.1\ \mathrm{GeV})$$

Two component duality: resonance curve agrees better with the valence–only structure function. The resonances are dual to the valence quarks, background (not shown here) to the sea quarks

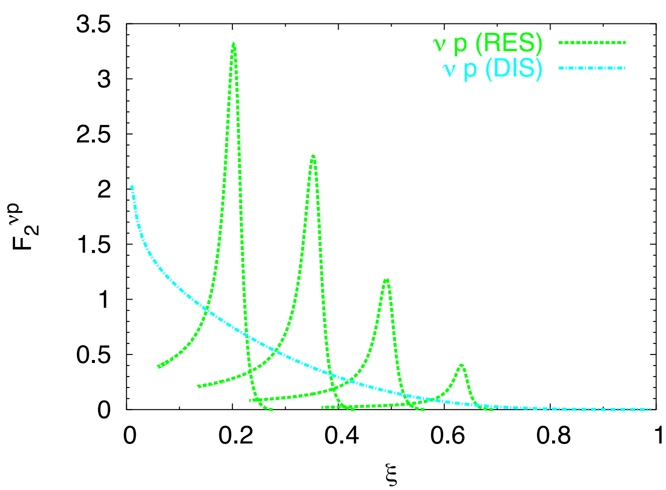
O. Lalakulich – NuInt07

$F_2^{\nu p,\nu n}$: In neutrino–nucleon scattering duality does NOT hold for proton and neutron targets separately

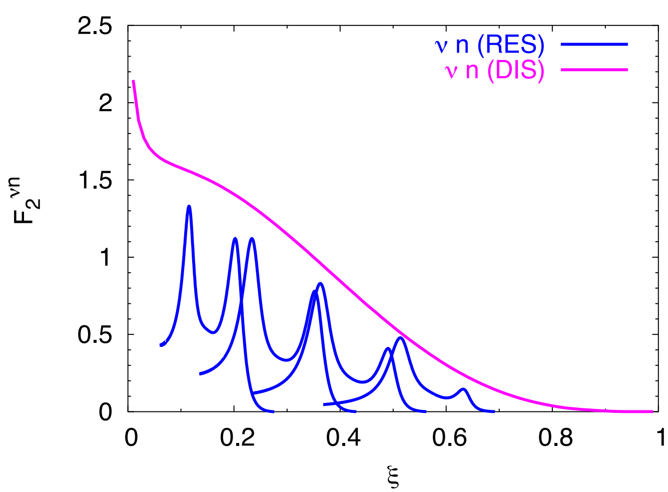
Low-lying resonances: $F_2^{\nu n(res)} < F_2^{\nu p(res)}$, DIS:$F_2^{\nu n(DIS)} > F_2^{\nu p(DIS)}$

$F_2^{\nu p(res-3/2)} = 3F_2^{\nu n(res-3/2)}$
$F_2^{\nu p(res-1/2)} \equiv 0$

$F_2^{\nu n(res)}$: finite contributions from isispin-3/2 and -1/2 resonances



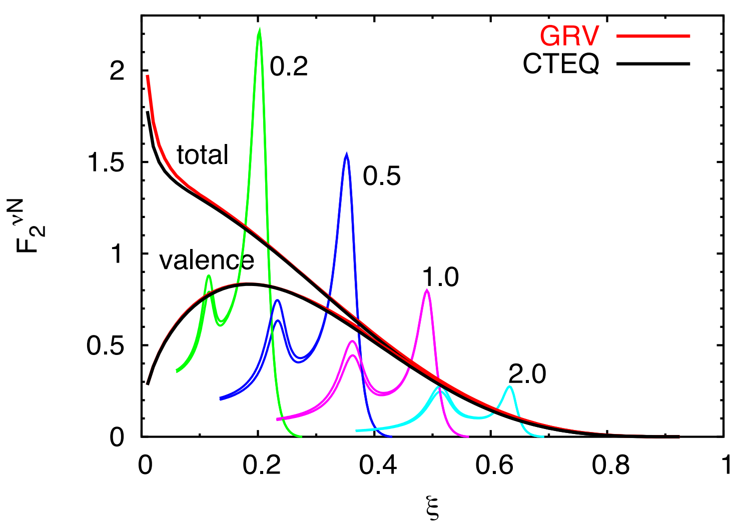
$Q^2 = 0.2,\ 0.5,\ 1.0,\ 2\ \mathrm{GeV}^2$

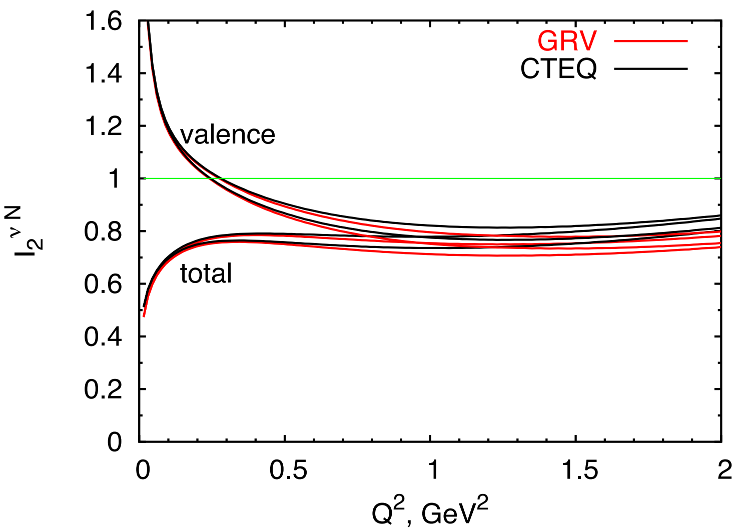


OL, Melnitchouk, Paschos, PRC 75

O. Lalakulich – NuInt07

$F_2^{\nu p,\nu n}$: Duality HOLDS for the averaged structure functions





$Q^2 = 0.2,\ 0.5,\ 1.0,\ 2\ \mathrm{GeV}^2$

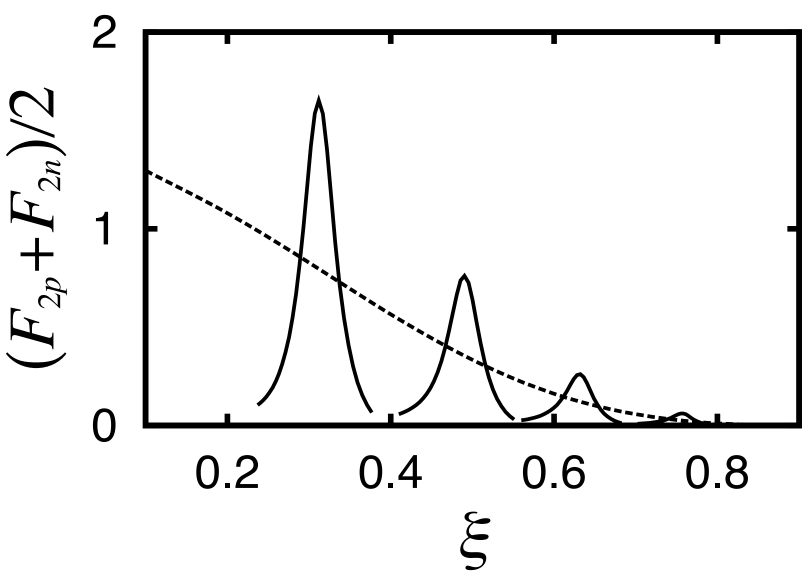
two curves in the second resonance region reflect the uncertainty in their axial form factors

Local duality in neutrino scattering looks better than in electron scattering:

the ratio does not grow appreciably with Q^2

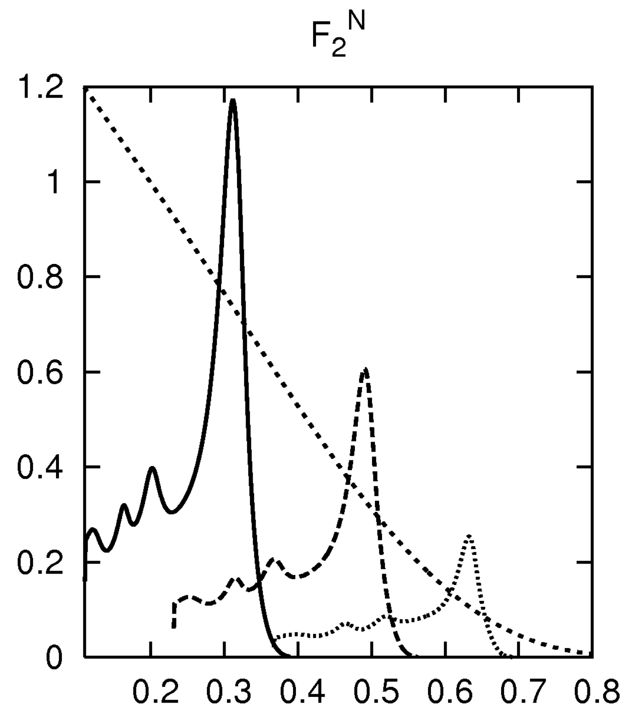
O. Lalakulich – NuInt07

Similar results in Sato-Lee model
Matsui,Sato,Lee, PRC 72
(P_{33}(1232) resonance considered so far)



$Q^2 = 0.4,\ 1.0,\ 2,\ 4\ \mathrm{GeV}^2$

and Rein–Sehgal model
Graczyk, Juszczak, Sobczyk, Nucl Phys A781
(19 resonances included in the model)



$Q^2 = 0.4,\ 1.0,\ 2\ \mathrm{GeV}^2$

O. Lalakulich – NuInt07

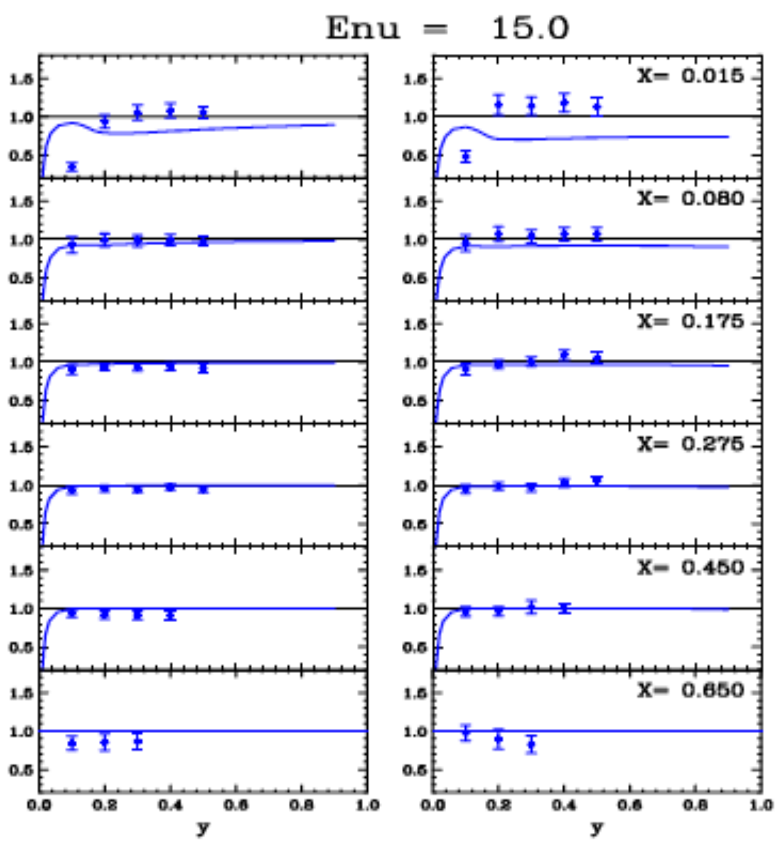
Summary

- For proton and neutron targets separately duality holds in electron-nucleon scattering, but does not hold in neutrino–nucleon scattering
- Global and local duality hold for the average over proton and neutron targets. The accuracy is better for neutrino–nucleon reactions than for the electron–nucleon
- The degree to which the local duality is valid is high for F_2 structure functions. The results are similar within different models of resonance production and different parametrizations of DIS structure function.
- For $2xF_1$ global duality holds and local duality is fair for both electron- and neutrino- nucleon reactions. The quantitative agreement for local duality would require a more elaborate treatment of the target mass corrections for DIS structure functions
- For xF_3 the global duality holds, local duality is sensitive to the Q^2 behaviour of the resonance axial form factors. The accuracy of duality about 30% is consistent with the estimated uncertainly of the form factors.
- Adler Sum Rule holds with the 10% accuracy
- Duality is natural: quite often one relies on duality without making explicit mention of it

A. Bodek
Bodek-Yang on neutron excess targets?

Where do we go from here

Neutrino cross sections should be published as d2-sigma/dxdy



We are accumulating data for neutrino differential on neutrino double differential cross sections, which include both vector and axial contributions to the structure functions

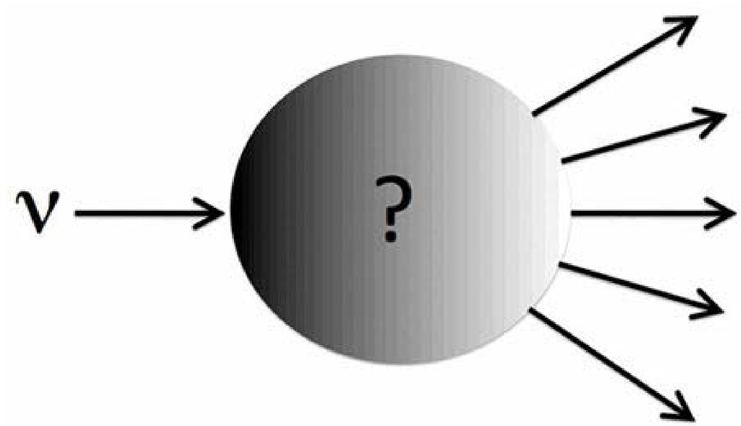
We should look at similar data for electron scattering (from Jlab) for the same nuclear targets to determine the vector structure functions for the nuclear targets.

Structure functions can be parametrized in terms of effective leading order PDFS, or in terms of transition form factors for a multitude of resonances.

When we have many resonances, effective leading order PDFs are a good way to understand the data even in the resonance region.

INT December 3-13, 2013

Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments



Theory of resonance production and decay

Luis Alvarez-Ruso

IFIC, Valencia

L. Alvarez Ruso – Questions?

- Do we need a (drastically) better weak resonance production model?
- Which is the (best) way to take state-of-the-art pheno into account?
- How to deal with the non-resonant background (+interference)?
- How to deal with the RES -> DIS transition?
- Are there going to be new ν-nucleon measurements in the (near) future?
- Will Minerνa help (at the nucleon level)?
- Can we get useful info from PV (e,e') experiments?
- How to avoid the donkey effect?

One of MANY pleas for a high-statistics neutrino-H/D experiment!

Resonance Experiments
S. Dytman

Introduction

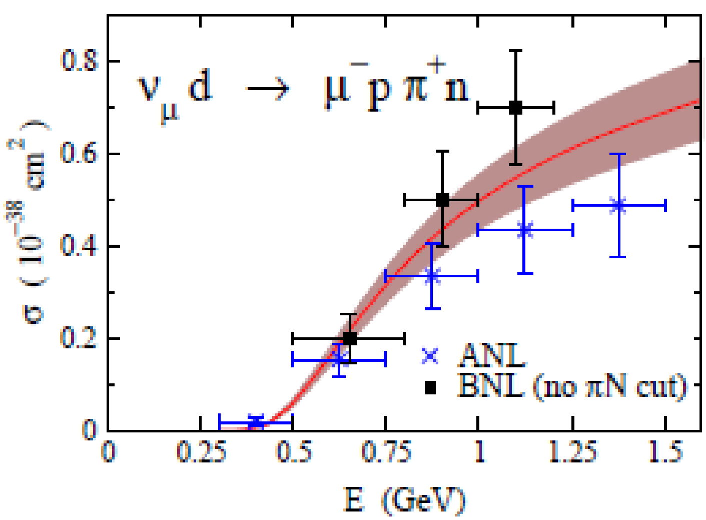
MiniBooNE, new Minerva data

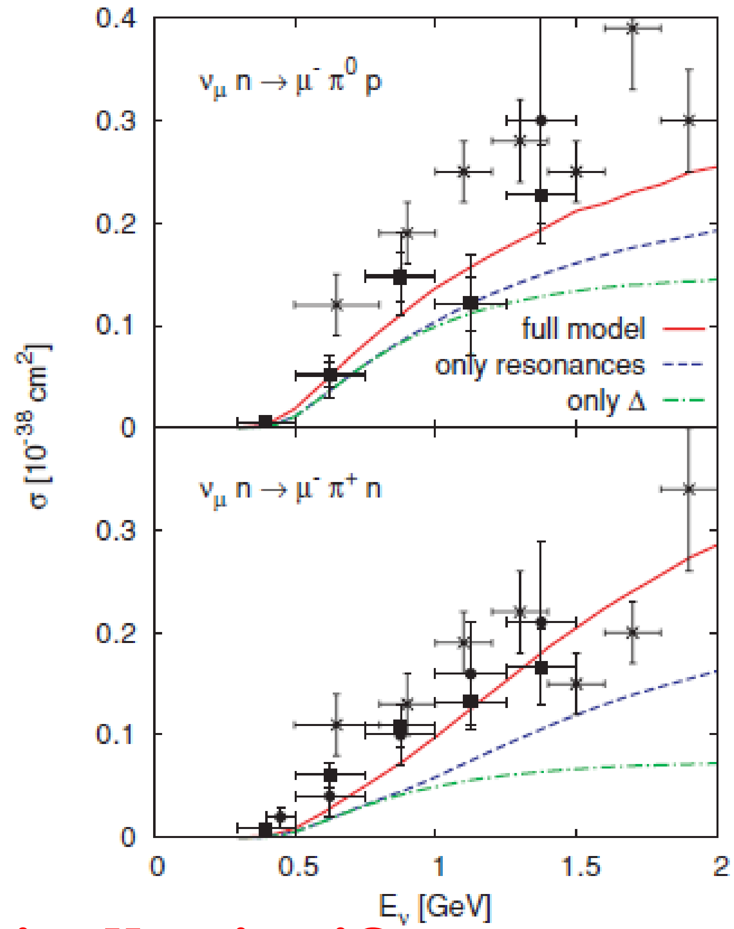
resonances in GENIE (continued from Luis talk Fri)

Cascade, GENIE FSI

And of course controversy **Steve Dytman**

- BNL systematically higher than ANL at low energies.

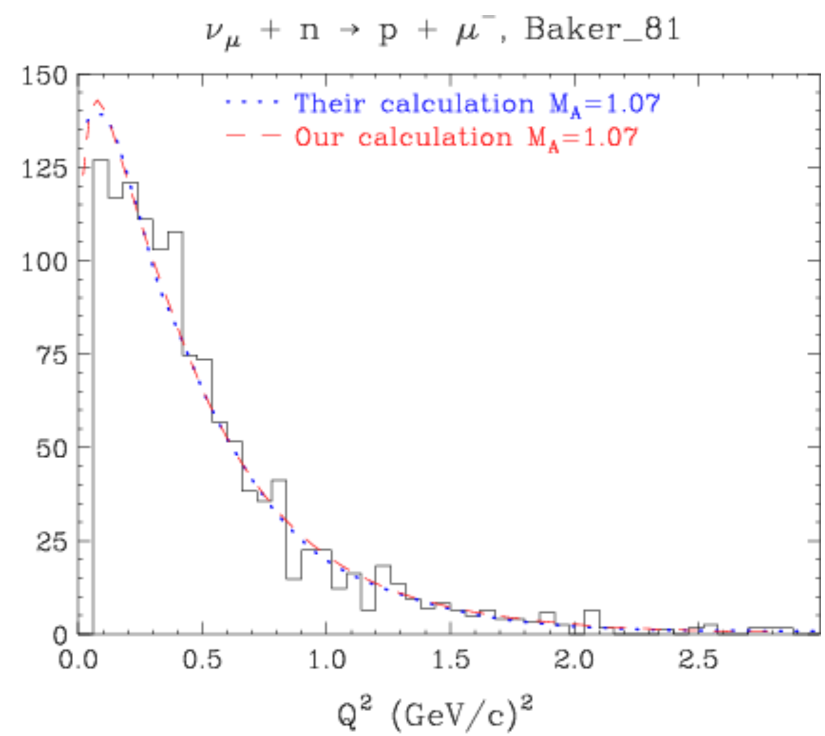




Need for a new statistically significant neutrino experiment off H/D!

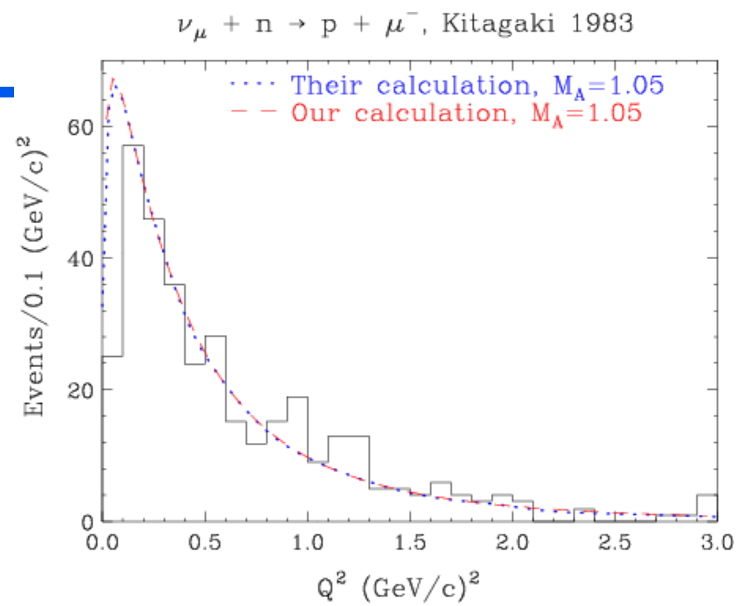
Determining m_A , Baker et al. – BNL deuterium H. Budd - NuInt04

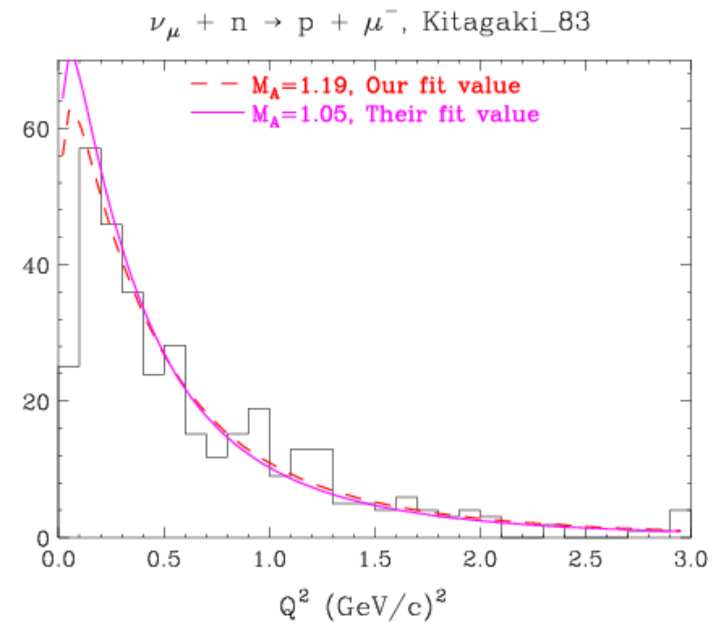
- The dotted curve shows their calculation using their fit value of 1.07 GeV
- They do unbinned likelyhood to get M_A
  No shape fit
- Their data and their curve is taken from the paper of Baker et al.
- The dashed curve shows our calculation using M_A = 1.07 GeV using their assumptions
- The 2 calculations agree.
- If we do shape fit to get M_A
- With their assumptions -- M_A=1.079 GeV
- We agree with their value of M_A
- If we fit with BBA Form Factors and our constants - M_A=1.055 GeV.
- Therefore, we must shift their value of M_A down by -0.024 GeV.
- Baker does not use a pure dipole
- The difference between BBA-form factors and dipole form factors is -0.049 GeV



Kitagaki et al. FNAL deuterium
H. Budd NuInt04

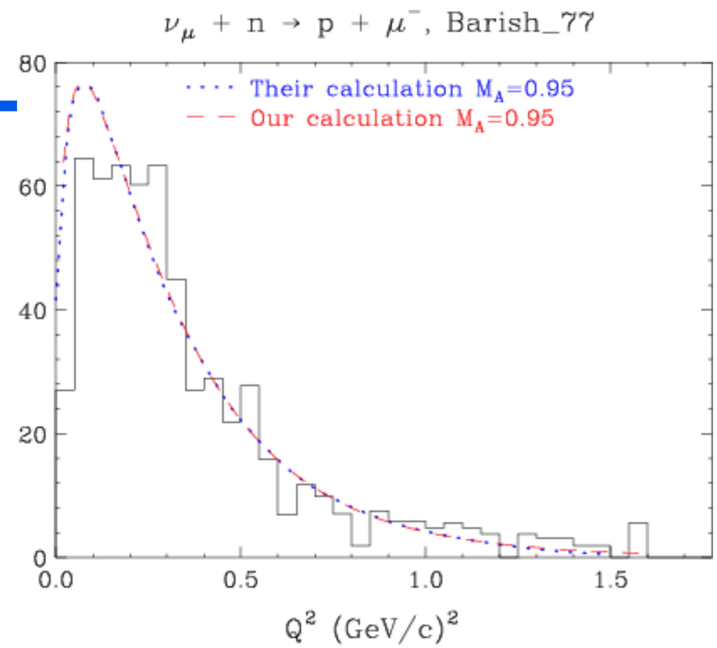
- The dotted curve shows their calculation using their fit value of M_A=1.05 GeV
- They do unbinned likelyhood,
  no shape fit.
- The dashed curve shows our calculation using M_A=1.05 GeV and their assumptions
- The solid curve is our calculation using their fit value M_A=1.05 GeV
- The dash curve is our calculation using our fit value of M_A=1.19 GeV with their assumption
- However, we disagree with their fit value.
- Our fit value seem to be in better agreement with the data than their fit value.
- We get M_A=1.175 GeV when we fit with our assumptions
- Hence, -0.019 GeV should be subtracted from their M_A.

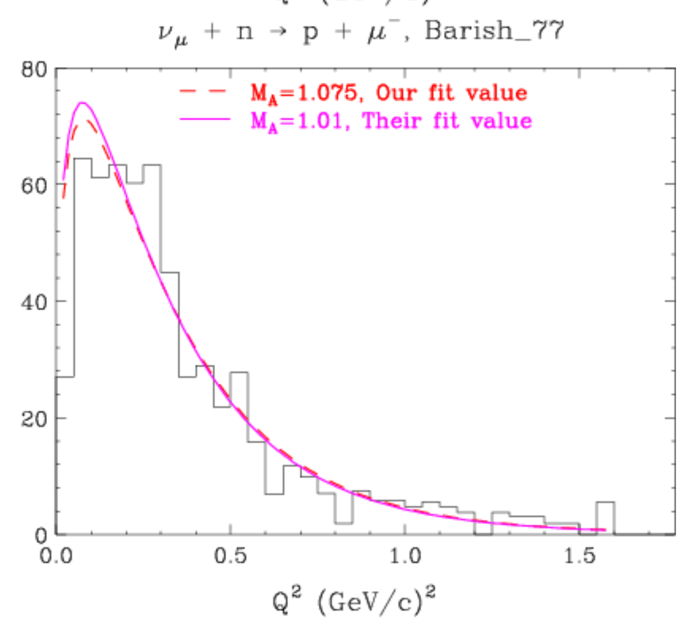




Barish et al. ANL deuterium H. Budd - NuInt-04

- Dotted curve – their calculation M_A=0.95 GeV is their unbinned likelyhood fit
- The dashed curve – our calculation using their assumption
- We agree with their calculation.
- The solid curve – our calculation using theirs shape fit value of 1.01 GeV.
- We are getting the best fit value from their shape fit.
- The dashed curve is our calculation using our fit value M_A=1.075 GeV.
- We slightly disagree with their fit value.
- We get M_A=1.049 GeV when we fit with BBA – Form Factors and our constants.
- Hence, -0.026 GeV must be subtracted from their value of M_A

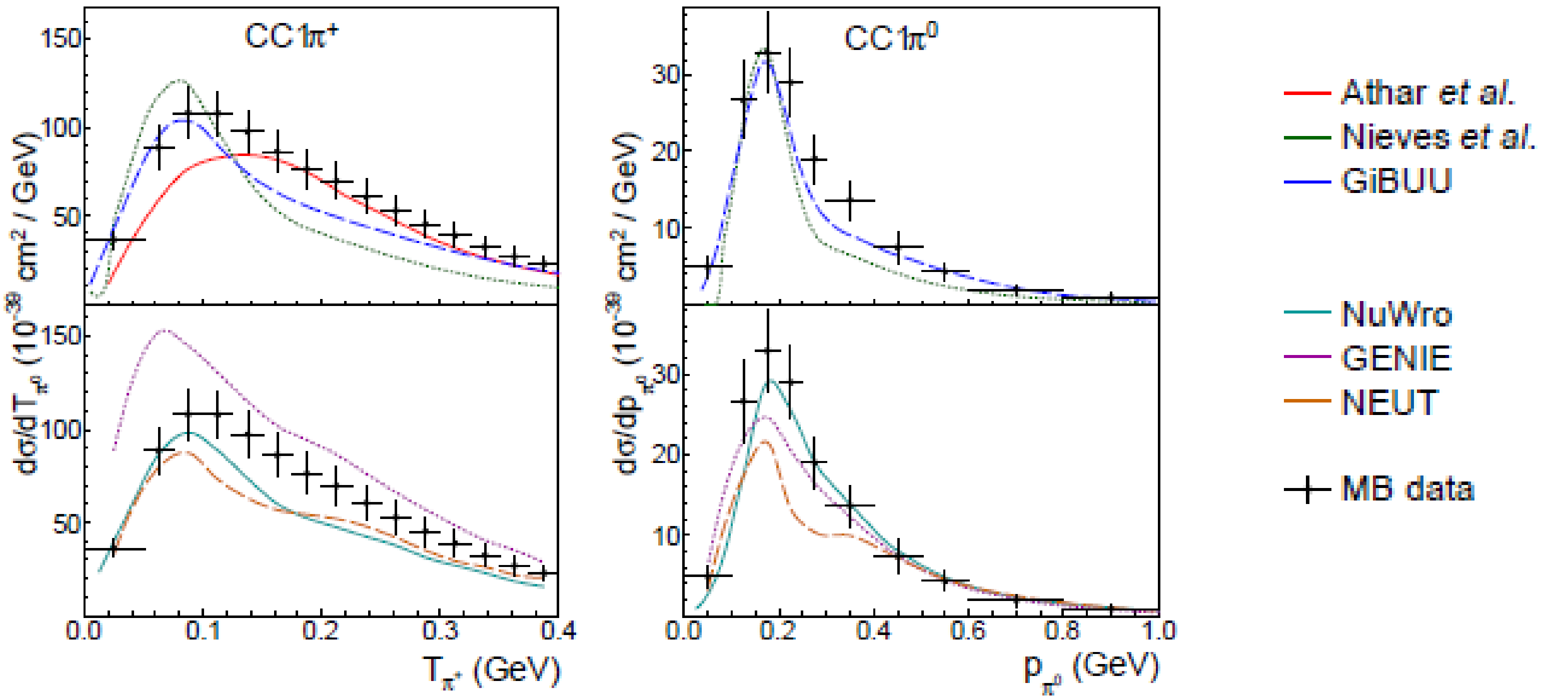




And more controversy

Steve Dytman

- As discussed by Luis on Friday, best theory doesn't agree with pion KE spectrum.
- Modern theory had Δ medium effects, π^+ rescat from piA

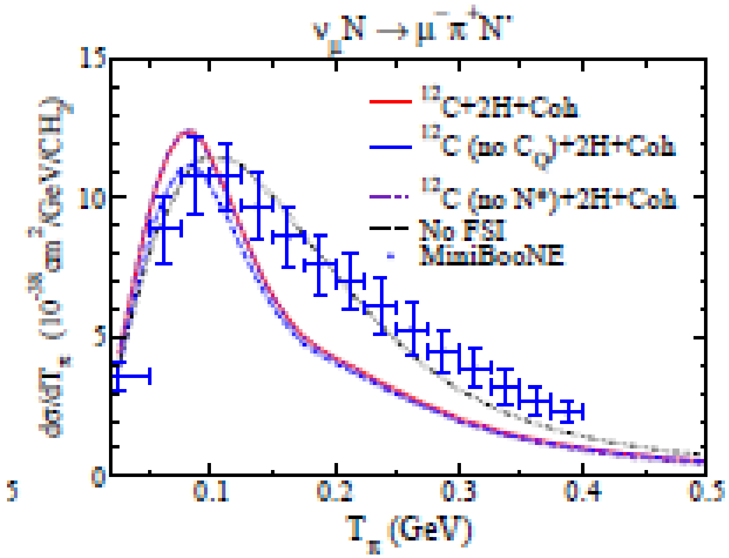


More controversy

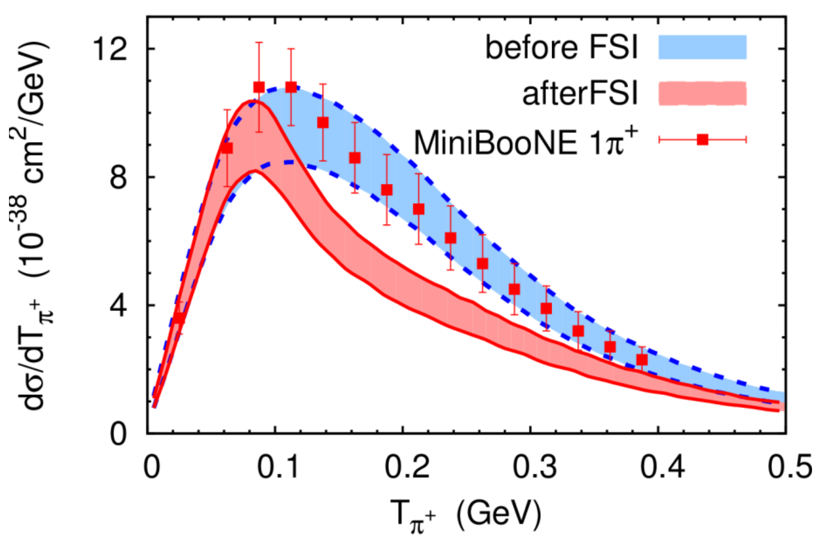
Steve Dytman

- Data prefers calculation with no FSI
- Unrealistic because strong pion absorption expected at Tπ~150 MeV (peak of Δ).
- Theorist: we have best ingredients
- Experiment: we checked our methods carefully, trust errors

Valencia



GiBUU

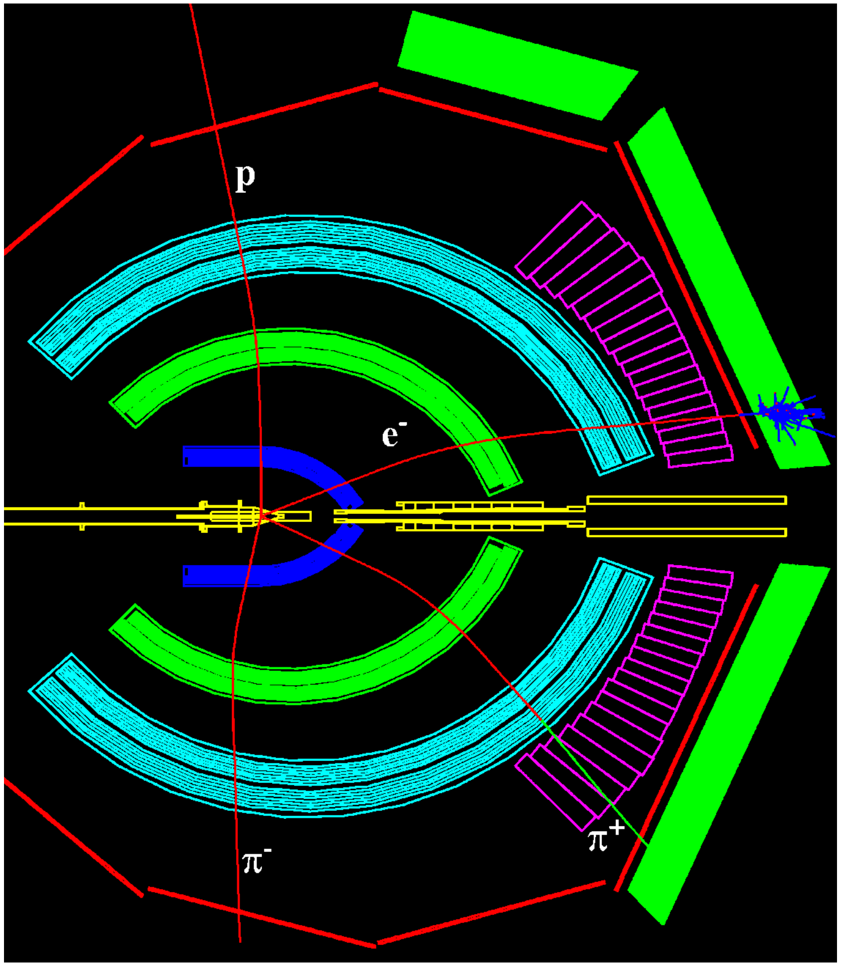


Looking forward

Steve Dytman

- MAID has 11 resonances
- First implementation is ok, but we see problems
  - They fit to (e,e′π) multipoles, we compare with (e,e′) inclusive xs
  - MAID uses different background
- Start communication with Lothar Tiator (Mainz)
  - Make sure we implement resonances correctly
  - Make new nonresonant background to get agreement
- Use Jarek Novak's implementation of Berger-Seghal formalism with muon mass (done).
- Adopt Δ medium correction (take from literature)
- We will then have modern resonance implementation
- As of now, no need to use formalism different than RS

eA pion production at CLAS aimed at neutrinos



S. Manly & Hyupwoo Lee

University of Rochester

Department of Physics and Astronomy

INT Workshop

Seattle, December 2013

Representing the CLAS (EG-2) collaboration

Wish list? **S. Manly**

- Limited capacity to do much beyond this, but …
- If your favorite generator (or new and improved release) has eA mode that produces output we can digest, we can include, *in principle*, comparisons with data in paper (data will be generally available for comparison after paper published). Probably need the MC in ~February (takes a month to generate the events for comparison).
- Conversation with Jan Sobczyk over breakfast: look at W over single pion threshold and use missing mass to measure events with zero pions. Will have low stats, but only two dimensions.

Can the community provide needed help for this analysis if it considers it worthwhile?

– Neutrino-interaction in the resonance region (transition)

Satoshi Nakamura
Osaka University

Collaborators : H. Kamano (RCNP, Osaka Univ.), T. Sato (Osaka Univ.)
T.-S.H. Lee (Argonne Nat'l Lab).

S. Nakamura
Questions/comments

- DCC model for νN ➔ πN, $\pi\pi N$, ηN, $K\Lambda$, $K\Sigma$ being developed (done for Q^2=0)

  first serious 2 π production model (1 π and 2 π are comparable in resonance region)
- Rein-Sehgal model needs to be improved (replaced)
- New deuterium experiment is highly hoped

  deuteron reaction model being developed
- NC photon emission in higher resonance region relevant ?
- Matching with DIS (low-Q^2) needs all coupled-channels ➔ DCC model can do this
- Is making use of QH duality a promising direction to fix axial form factors ?
- Nuclear effects are another difficult problem

Nuclear EMC Effect for Electron and Neutrino Scattering

Sergey Kulagin

Institute for Nuclear Research, Moscow

Talk at the workshop
Neutrino-Nucleus Interactions for Current and Next Generation Neutrino Oscillation Experiments
Seattle, December 9, 2013

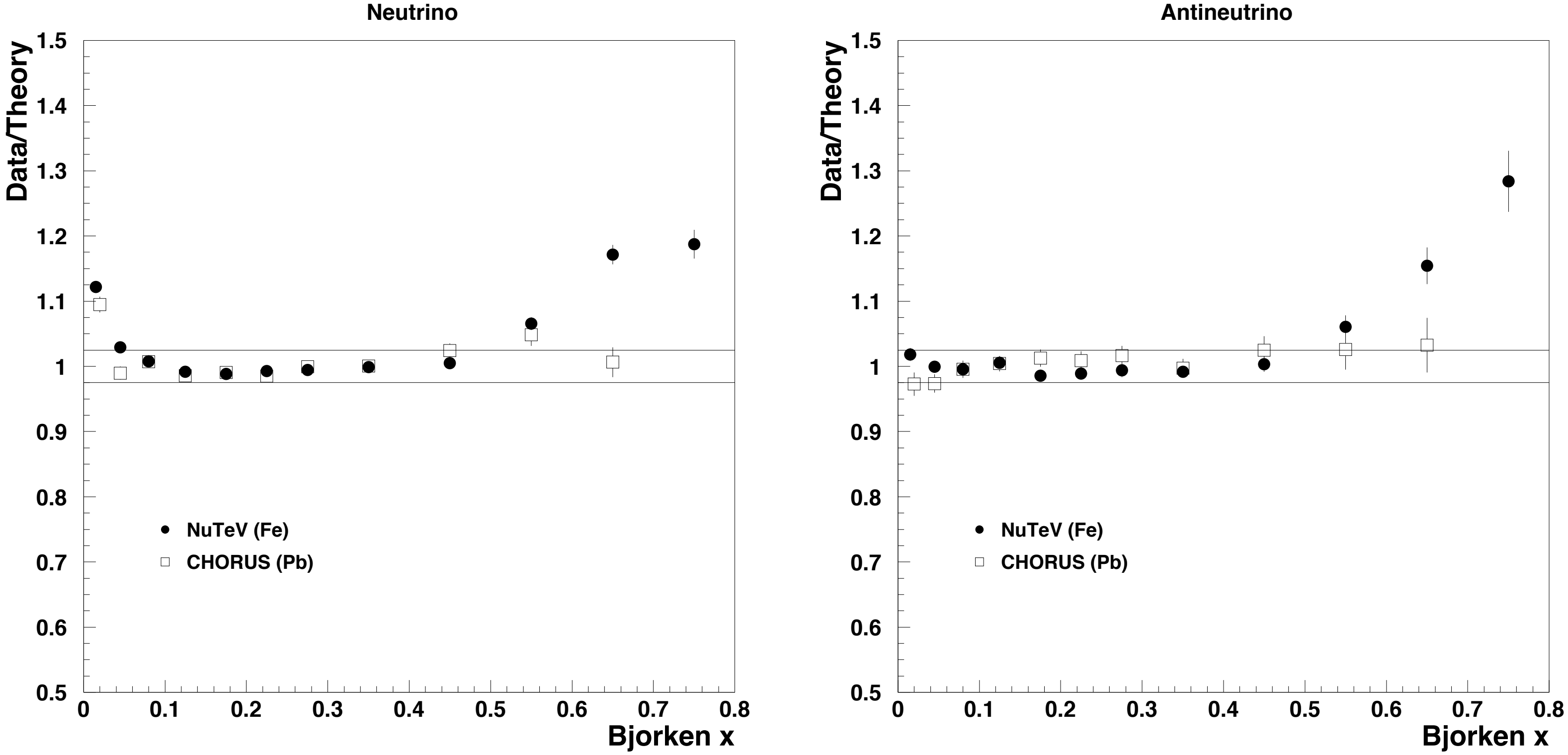
S. Kulagin

Summary for neutrino nuclear DIS

- The presence of a nonconserved axial-vector current is important difference with respect to the charged-lepton DIS. A low-Q^2 region in neutrino scattering is driven by the axial current contribution. Note that for that reason the ratio $R = F_L/F_T$ for neutrino interaction is crucially different from that of the charged-lepton scattering.
- The nuclear corrections depend on the type of the structure function (F_2 vs xF_3). The nuclear corrections are also different for the isoscalar $F_2^{\nu+\bar{\nu}}$ and the isovector $F_2^{\nu-\bar{\nu}}$ combinations.
- Predictions for neutrino cross sections are in a good agreement (within $\pm 2.5\%$ band) with the CHORUS $^{208}\mathrm{Pb}$ data in the whole kinematical region of x and Q^2. We also observe a good agreement with the NuTeV $^{56}\mathrm{Fe}$ data in the region $0.15 < x < 0.55$.
- Note systematic excess of data/theory for the NuTeV data at large $x > 0.5$ for both the neutrino and antineutrino.
- Note also about 10% data/theory excess for small $x = 0.015$ for neutrino scattering for both the $^{208}\mathrm{Pb}$ and $^{56}\mathrm{Fe}$ data.

S. Kulagin

Comparison with CHORUS and NuTeV cross sections



Data/model predictions by *S.K. and R.Petti, NPA 765 (2006) 126; PRD 76 (2007) 094023*. The x-point is the weighted average over available E and y. The solid horizontal lines indicate a $\pm 2.5\%$ band.

Overview of
Nuclear Parton Distribution Functions

Shunzo Kumano

High Energy Accelerator Research Organization (KEK)
J-PARC Center (J-PARC)
Graduate University for Advanced Studies (GUAS)
http://research.kek.jp/people/kumanos/

Neutrino-Nucleus Interactions
for Current and Next Generation Neutrino Oscillation Experiments (INT-13-54W)
December 3-13, 2013, INT, University of Washington, USA
http://www.int.washington.edu/PROGRAMS/13-54w/

Summary of Experimental DIS/transition Neutrino Nuclear Effects

Nuclear Shadowing in Electro-Weak Interactions

Boris Z. Kopeliovich, Jorge G. Morfın, Ivan Schmidt
USA
August 26, 2012

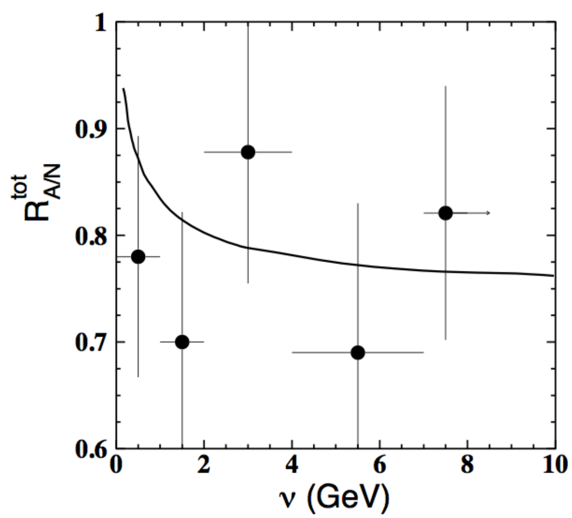
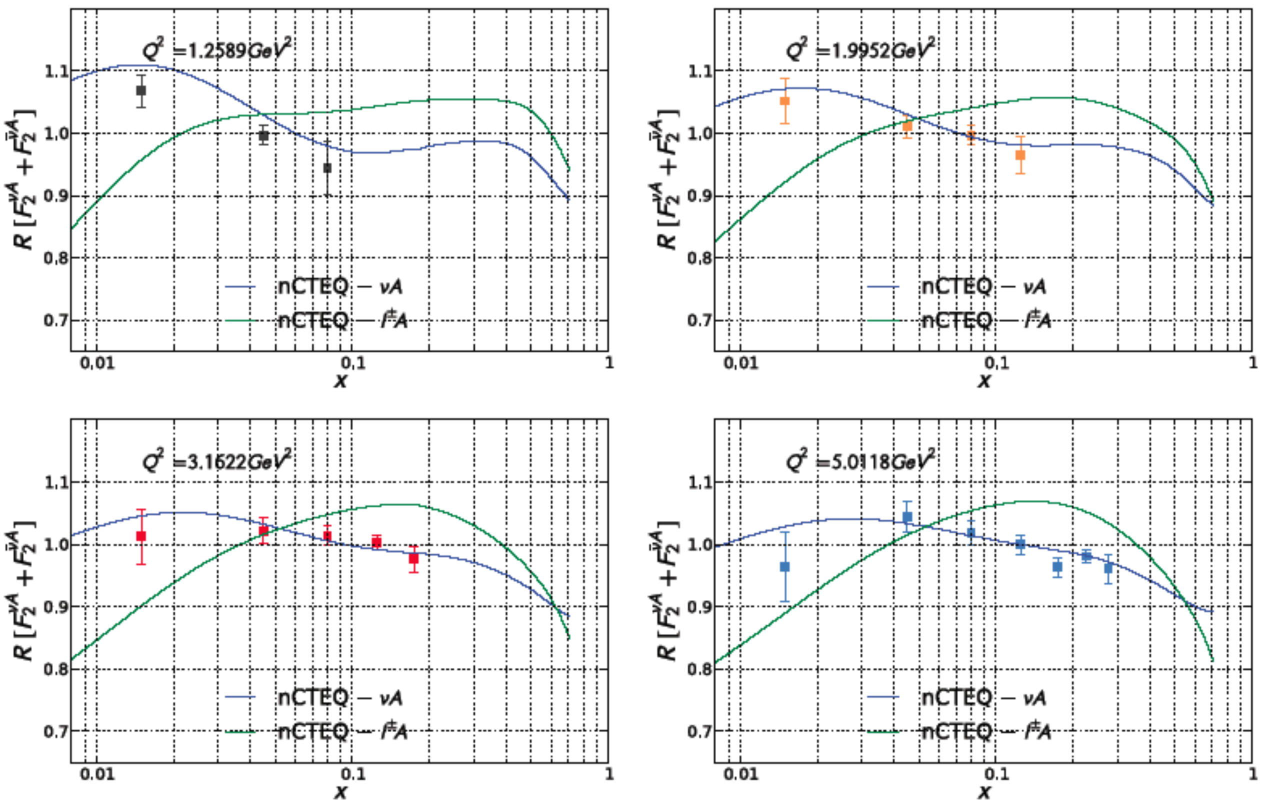


Figure 7: The neon to proton ratio of the total neutrino cross sections, calculated in [33, 34] for $x < 0.2$ and $Q^2 < 0.2\,\mathrm{GeV}^2$. The data present the BEBC results [35].

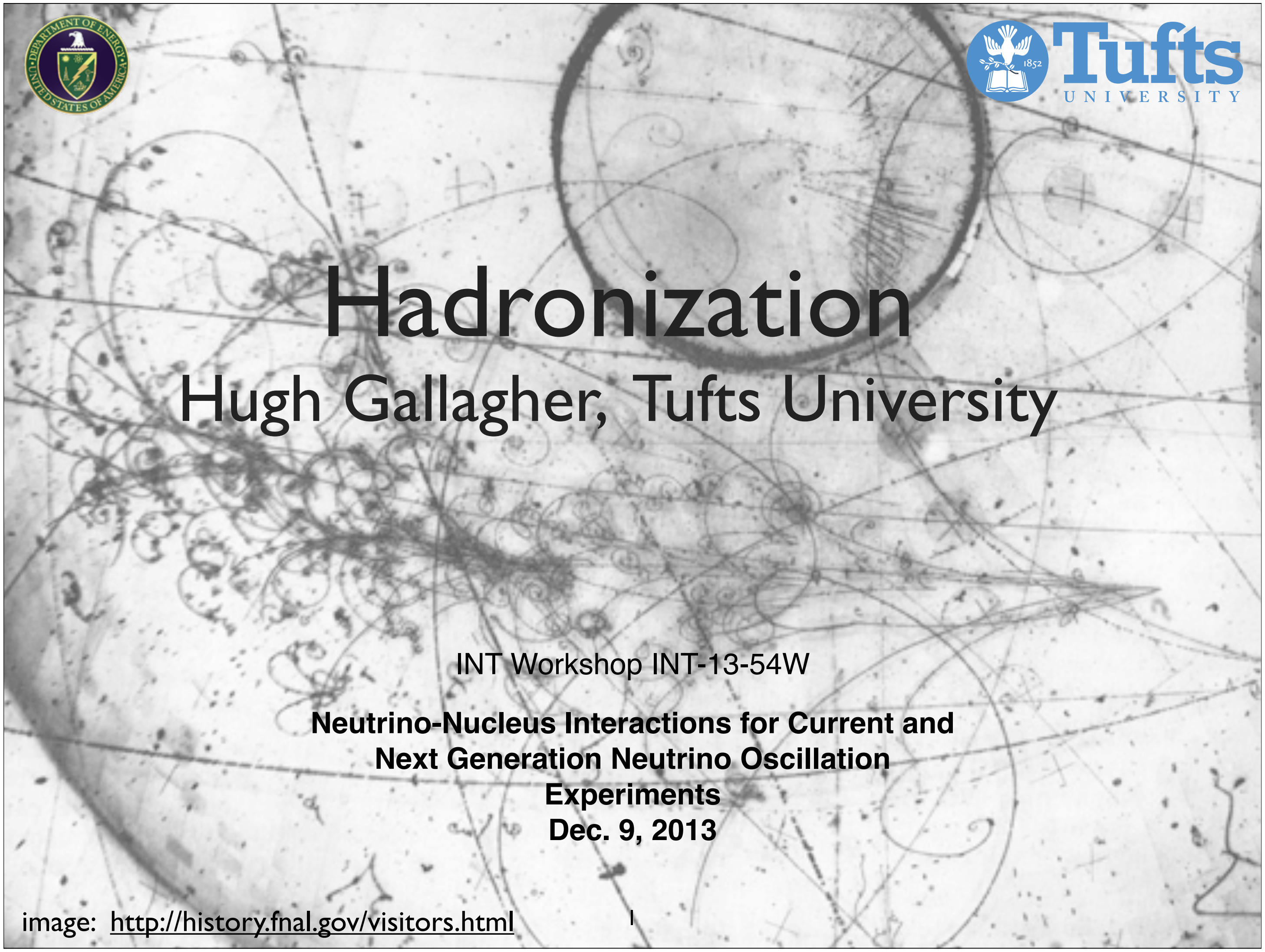
CTEQ nPDFs

A More-Detailed Look at Differences

- NLO QCD calculation of $\dfrac{F_2^{\nu A} + F_2^{\bar{\nu} A}}{2}$ in the ACOT-VFN scheme
  - charge lepton fit undershoots low-x ν data & overshoots mid-x ν data
  - low-Q^2 and low-x ν data cause tension with the shadowing observed in charged lepton data



H. Gallagher


Tufts
UNIVERSITY
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

H. Gallagher

Example: MINOS

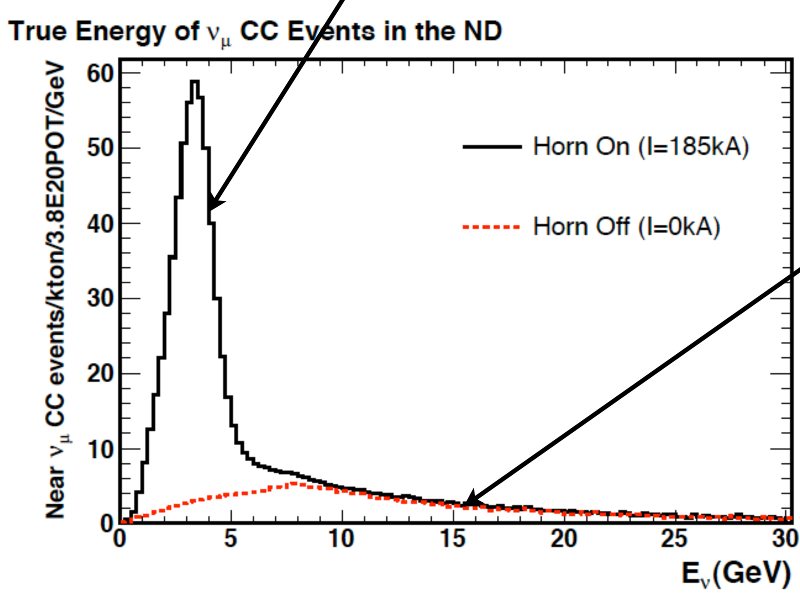
Use a data-driven method with Near Detector data in different beam configurations.

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.

H. Gallagher

(Don't) Blame it on the Nucleus

S. Dytman et al., NuINT 09

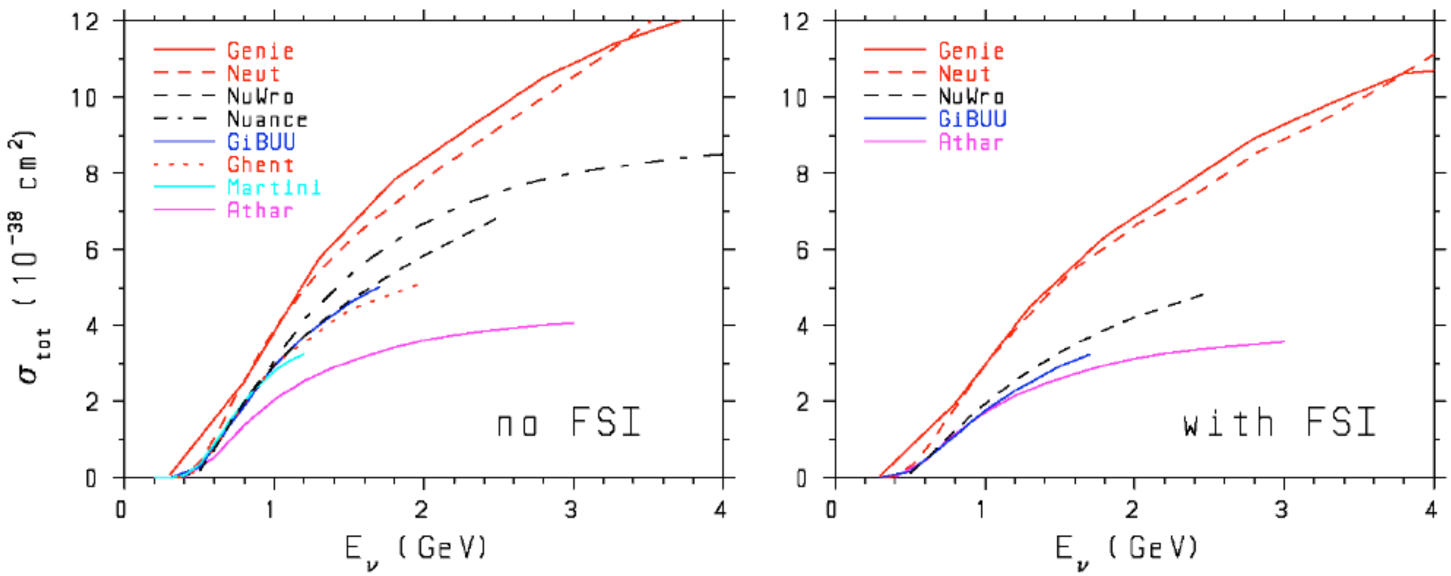


FIGURE 5. Total CC single π^+ production cross section on ^{12}C. All calculations use the CC pion production vertex. All include nonresonant processes except NUANCE. No coherent events are included.

H. Gallagher

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.

Meloni - Mariani

Conclusions

- Energy reconstruction essential for precision determination of neutrino oscillation parameters and neutrino-hadron cross sections

- Impact on neutrino oscilaltion experiments due to nuclear models, what they are and how they are implemented is not negligible (order 10%)
  - comparing systematically generators is important
  - neutrino event generators use almost same data set so there are correlations that are non-negligible
  - using wrong models affect neutrino oscillation parameters determination

U. Mosel

Neutrino Interactions with Nucleons and Nuclei

Olga Lalakulich, Kai Gallmeister and Ulrich Mosel

Institut für Theoretische Physik

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Summary

- Energy reconstruction essential for precision determination of neutrino oscillation parameters
(and neutrino-hadron cross sections)
- Energy reconstruction requires reliable event generators,
of same quality as experimental equipment.
- Precision era of neutrino physics requires much more sophisticated generators and a dedicated effort in theory

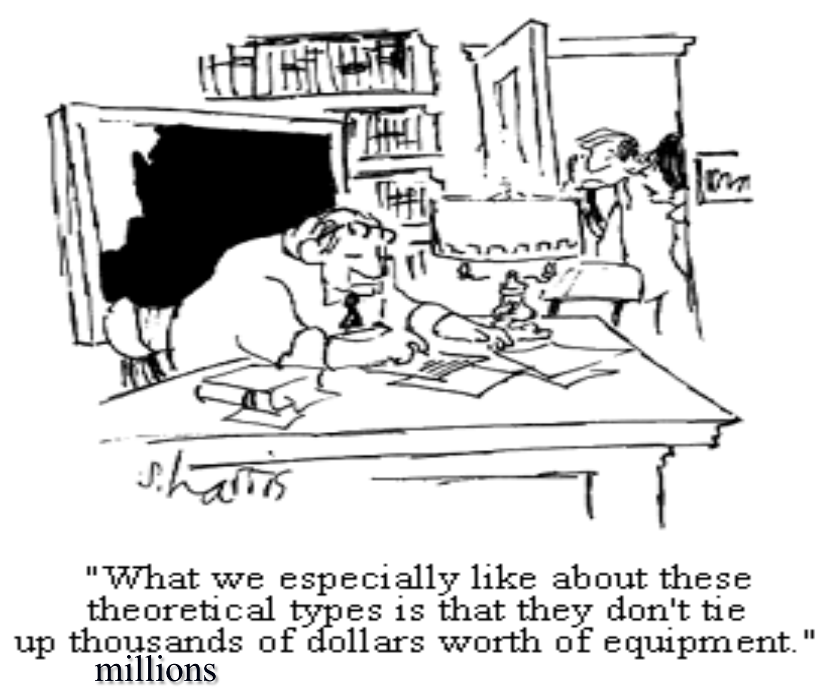
How to proceed

- Generator is an important part of any experiment: at the end of a very sophisticated experiment you do not want to have someone with a ‚crummy' code to mess up your data!
- Generator-Theory support must be integral part of any experiment and its funding!

U. Mosel

Need for solid nuclear physics theory

Generators are a crucial part of any experiment
Must be of same quality as the experimental equipment itself!
Needed resources are relatively small, but still not available



U. Mosel

Precision era requires better generators

1. The community needs NO further generator comparisons
   Instead: Time to not just compare generator results, but clarify origins of differences (e.g. pions)

2. Document theory content and codes of generators (no more black boxes, open code), evaluate generator-TDR as part of exp approval process

U. Mosel

Precision era requires better generators

- Present generators have evolved into a patchwork of theories, recipes and fit parameters without any theoretical justification and loose predictive power

- It is thus time to critically scrutinize existing generators, take the best parts from any of them, supplement them with consistent theory and build a

  ν-Genie

- **How do we get improved ν-nucleon (hydrogen and deuterium) experiments with high statistics data points**

- **New higher energy pion absorption data**
  - **Need more and well-aimed CLAS experiments to provide needed e-A data**

- **Need to bridge the language divide between theorists pure expressions and experimentalists/generator practical patois/ jargon.**