np-nh channel in the MC generators: Status and perspectives

Jakub Żmuda
Institute of Theoretical Physics
University of Wrocław
(jakub.zmuda@ift.uni.wroc.pl)

NuInt14, Surrey, UK
21.05.2014

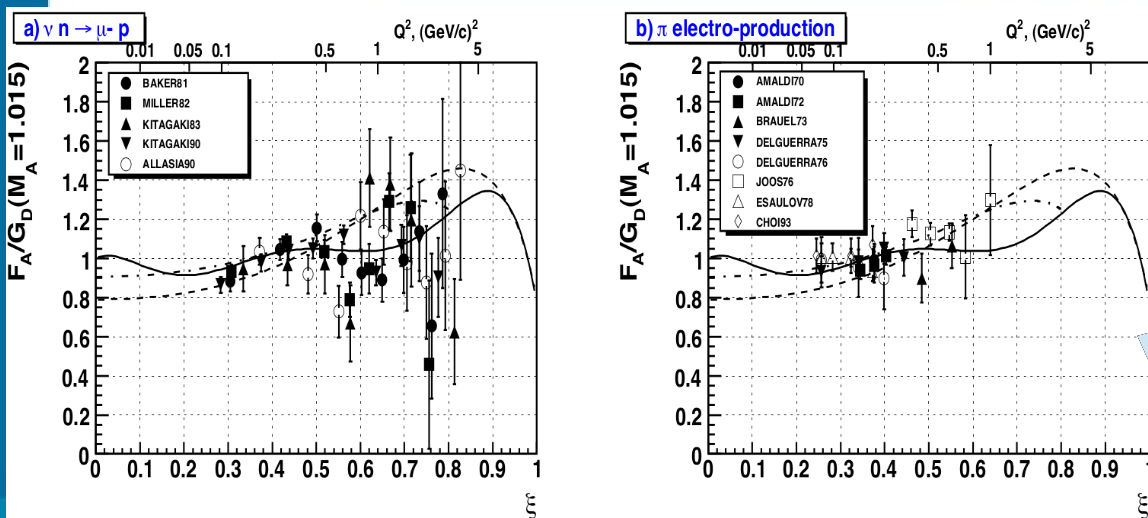
Uniwersytet Wrocławski

Outline of the talk

- Introduction
- Present status of np-nh models in Monte Carlo
- Possible improvements
- Summary

Uniwersytet Wrocławski

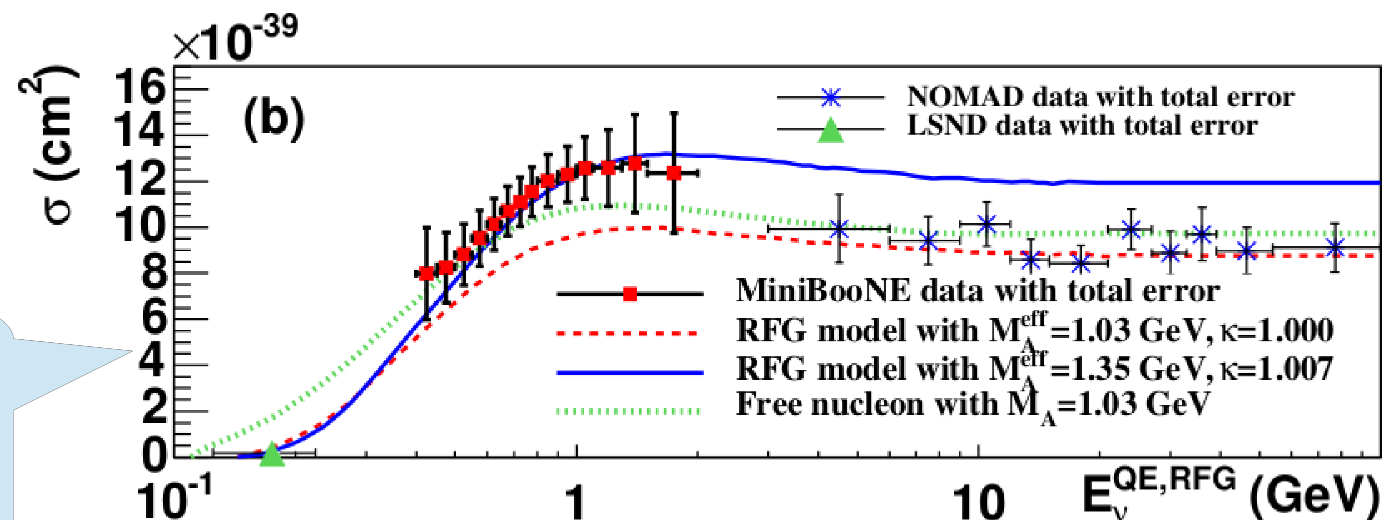
Introduction: large M_A controversy



A. Bodek, S. Avvakumov, R. Bradford, and H. Budd Eur.Phys.J. C53 (2008) 349

The Q^2-dependence of nucleon axial coupling in $\mathbf{M_A}$:

- Old experimental data: dipole axial form factor ~$\mathbf{(1+Q^2/M_A^2)^{-2}}$.
- Approximately **M_A=1.05 GeV**, both from neutrino interactions as well as from independent π electro-production arguments



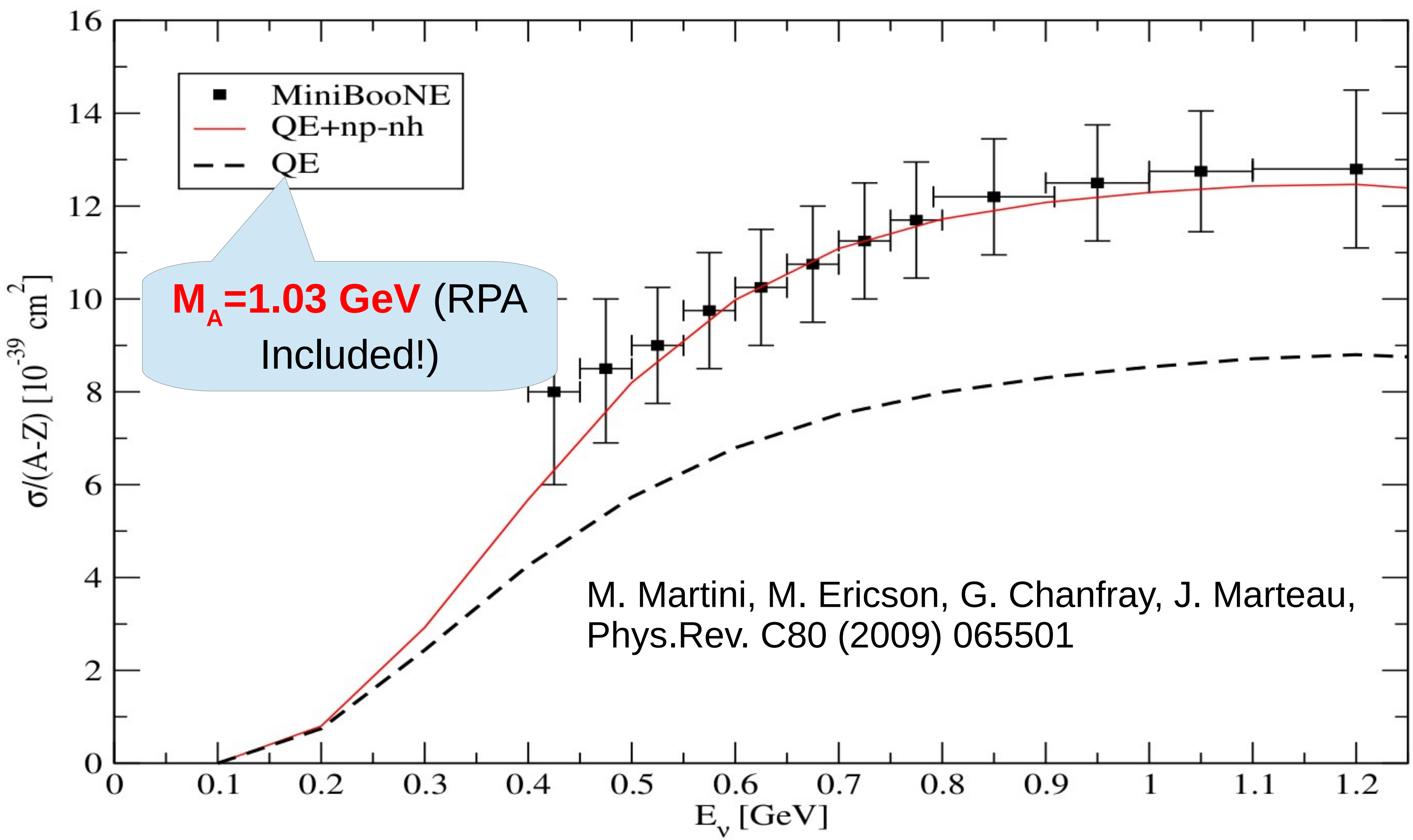
More recent fit to **MiniBooNE** data: **M_A=1.35 GeV** (!)

R. Grange, T. Kator, Mod.Phys.Lett. A29 (2014) 12, 1430011i

Uniwersytet Wrocławski

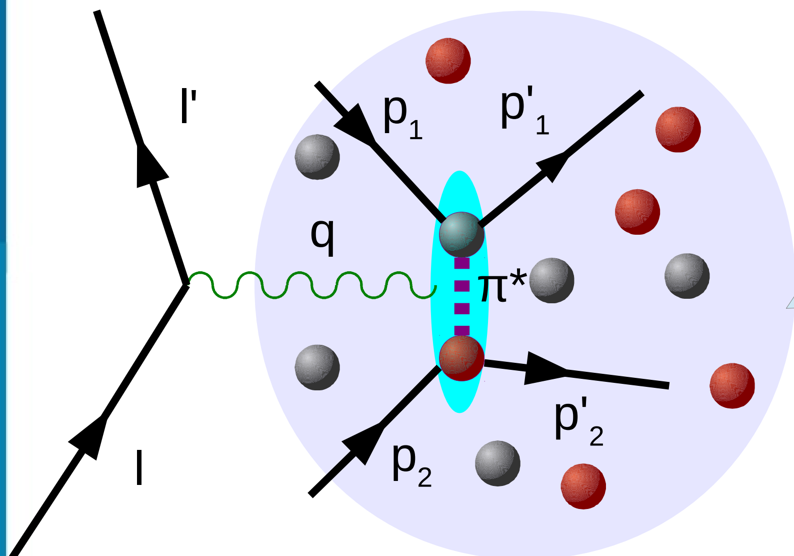
Introduction: large M_A controversy

- Need for an extra neutrino-nucleus interaction channel, possibly mistaken for CCQE in MiniBooNE:



Introduction: np-nh mechanism

- *„np-nh": n-particles n-holes*- interaction with more, than one (n=2 or 3) nucleons correlated by virtual meson exchange
- Terminology in this talk: np-nh= „Meson Exchange Currents (MEC)" = „2p2h"



Theoretical and computational challenge:

- Multiple mechanisms possible
- Non-perturbative nuclear effects
- Realistic treatment of nucleons (np-nh signal)

Only by the means of Monte Carlo!

Experimental challenge:

- Capability of hadron detection
- Final state interaction (FSI): false np-nh signal

  (e.g. single π production → absorption on nucleon pair → multinucleon knockout)
- FSI: absorption of one or more MEC event nucleons → misidentification with CCQE

Uniwersytet Wrocławski

Np-nh in Monte Carlo at present

- So far: np-nh in three neutrino interaction generators:

1) NuWro (two microscopic and one effective model)- first MC generator ever to have MEC!
2) GENIE, GiBUU: effective models
3) NEUT: recent implementation of microscopic IFIC np-nh model, official T2K MC (P. Sinclair's talk)

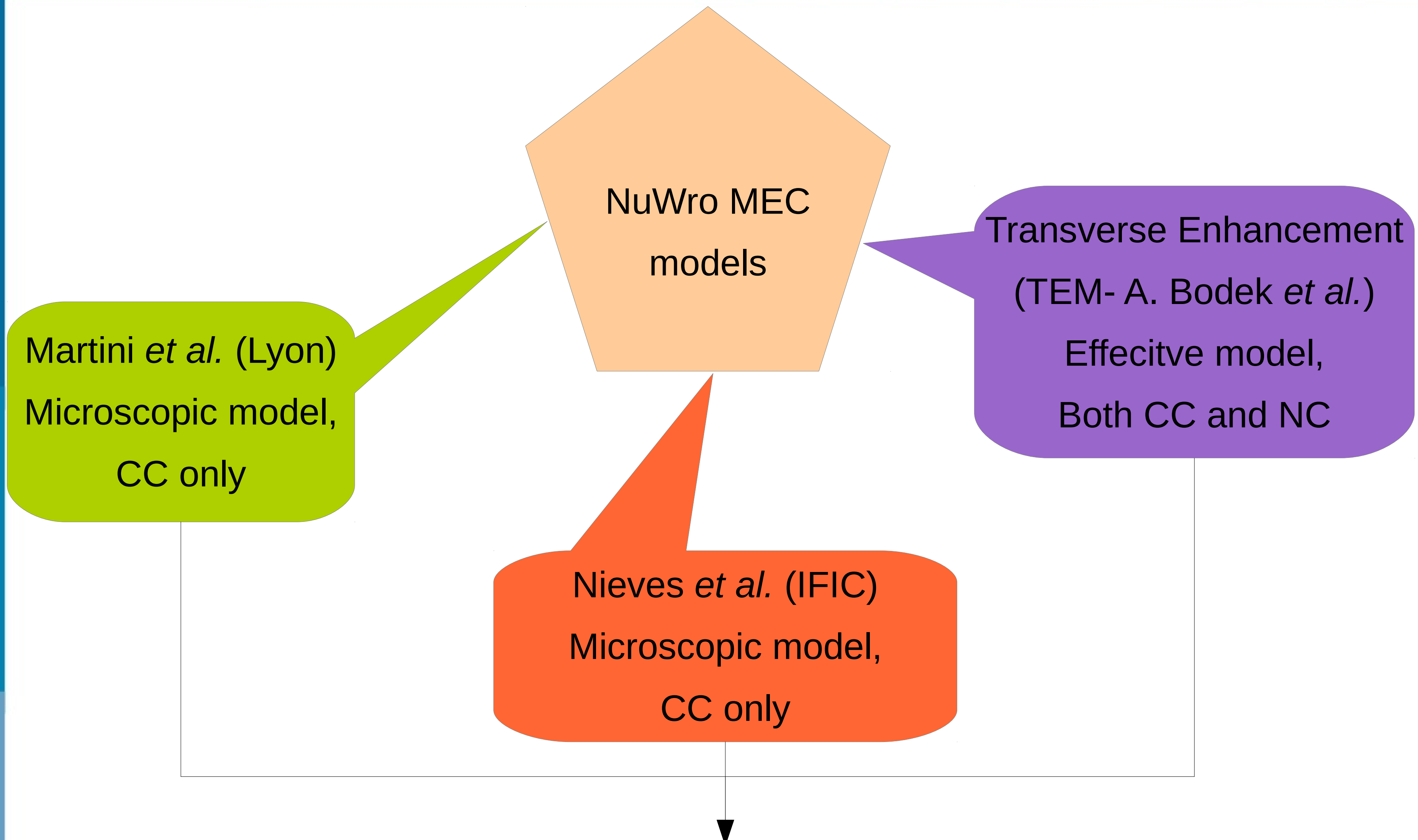
- Core example → implementation in NuWro (more about NuWro in T. Golan's talk)

np-nh in NuWro: general remarks

- Main example during this talk: NuWro, the Wrocław neutrino events generator.
- The project started 2005 at the Wrocław University; an important encouragment from Danuta Kiełczewska from Warsaw
- Main authors: Tomasz Golan, Krzysztof Graczyk, Cezary Juszczak, Jarosław Nowak, Jan Sobczyk, Jakub Żmuda.
- Code written in C++ language.
- First (natural) name: Wrocław Neutrino Generator: WroNG → changed from marketing reasons... (J. T. Sobczyk, J. A. Nowak, K. M. Graczyk „WroNG - Wroclaw Neutrino Generator of events for single pion production” Nucl.Phys.Proc.Suppl. 139 (2005) 266)

Uniwersytet Wrocławski

np-nh in NuWro: general remarks



Prediction: only final state lepton (inclusive cross section)
Nucleon simulation (very important): separate model...

Uniwersytet Wrocławski

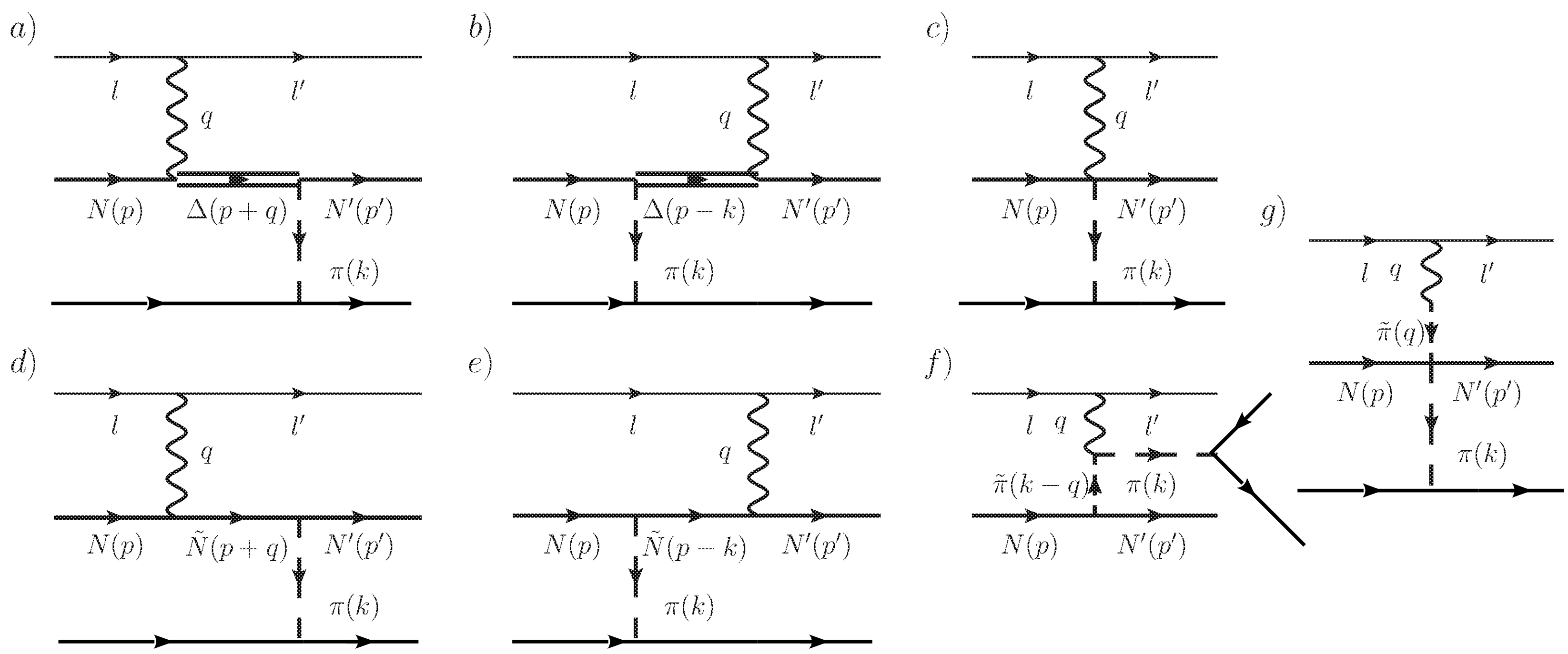
np-nh in NuWro: general remarks

- Some general remarks on Lyon and IFIC microscopic models:

1) Each interaction channel including MEC → contribution to gauge boson self-energy in nuclear matter within (local) Fermi gas model (optical theorem)

2) IFIC model: all diagrams, Lyon: without c), f), g).

3) d), e): nucleon-nucleon correlation diagrams



4) Additional 3p3h from pionless Δ decay (as Δ self-energy)

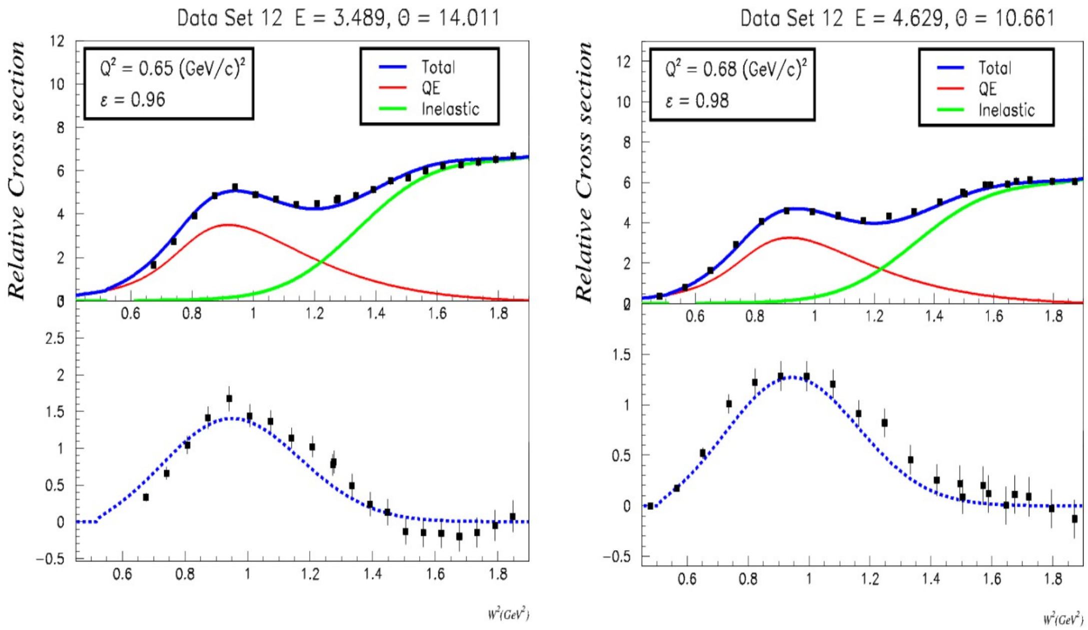
5) Landau-Migdal SRC and RPA

6) More details: other talks in this session

np-nh in NuWro: general remarks

- TEM: np-nh effects as a fit of $G_M(Q^2)$ to electron scattering data (difference between (QE + pion inelastic) and measured cross section)

A. Bodek, H.S. Budd, M.E. Christy, T.N.S. Gautam
arXiv:1310.7669 [nucl-ex]



$$G_M^{TE(p/n)}(Q^2) = R_T^{\frac{1}{2}}(Q^2) G_M^{(p/n)free}(Q^2)$$
$$\mathcal{R}_T(Q^2) = 1 + AQ^2 e^{-Q^2/B}$$

$$\sigma^{MEC} = \sigma_{QE}^{TE} - \sigma_{QE}.$$

- By construction: total and single-differential cross sections
- Recent developments → talk by E. Christy.

np-nh in Nu Wro: inclusive cross section computation

- Example of IFIC MEC model: even with numerical approximations (J. Nieves, I. Ruiz-Simo, M.J. Vicente-Vacas Phys.Rev. C83 (2011) 045501) 5-fold integrals inside double-differential cross section (main model prediction):

$$W^{\mu\nu}_{\rm 2p2h}(q) \;=\; \Theta(q^0)\frac{1}{M^2}\int\frac{d^3r}{2\pi}\sum_{N,N',\lambda}\int\frac{d^4k_\pi}{(2\pi)^4}\Theta(q^0-k^0_\pi)F^2_\pi(k_\pi)\mathrm{Im}\overline{U}_R(q-k_\pi,k_F^N,k_F^{N'})A^{\nu\mu}\times$$

$$\times D^2_\pi(k_\pi)F^2_\pi(k_\pi)\frac{f^2_{\pi NN}}{m^2_\pi}\vec{k}^2_\pi\Theta(k^0_\pi)\mathrm{Im}U_\lambda(k_\pi)$$

„Exact" theory, but no time for that in MC simulation!

Need for an ***effective*** MC implementation, highly nontrivial:

Either cross section tables or „response functions" (now in NuWro)

1) Accuracy of MC

2) Code versatility

3) Code speed

np-nh in Nu Wro: inclusive cross section computation

- Minimal information? Unpolarized inclusive double-differential neutrino cross section:

$$\frac{d^3\sigma}{d\Omega' dE'} = \frac{|\vec{k}'|E' M_i G^2}{\pi^2}\Big\{2W_1(q^0,|\boldsymbol{q}|)\sin^2\frac{\Theta'}{2} + W_2(q^0,|\boldsymbol{q}|)\cos^2\frac{\Theta'}{2}$$
$$- W_3(q^0,|\boldsymbol{q}|)\frac{E+E'}{M_i}\sin^2\frac{\Theta'}{2} + \frac{m_l^2}{E'(E'+|\vec{k}'|)}\Big[W_1(q^0,|\boldsymbol{q}|)\cos\Theta' +$$
$$- \frac{W_2(q^0,|\boldsymbol{q}|)}{2}\cos\Theta' + \frac{W_3(q^0,|\boldsymbol{q}|)}{2}\left(\frac{E'+|\vec{k}'|}{M_i} - \frac{E+E'}{M_i}\cos\Theta'\right)$$
$$+ \frac{W_4(q^0,|\boldsymbol{q}|)}{2}\left(\frac{m_l^2}{M_i^2}\cos\Theta' + \frac{2E'(E'+|\vec{k}'|)}{M_i^2}\sin^2\Theta'\right) +$$
$$- W_5(q^0,|\boldsymbol{q}|)\frac{E'+|\vec{k}'|)}{2M_i}\Big]\Big\}$$

5 nuclear „response functions”

Dependence on nucleus type, channel, energy and momentum transfer **only!** Antineutrino: W_3 sign change

Due to the m_l^2/E^2 dependence of W_4, W_5 → only W_1, W_2, W_3 really matter

Knowledge of W_i = knowledge of double-differential cross sections for each flavor, antineutrinos and with no neutrino energy limits

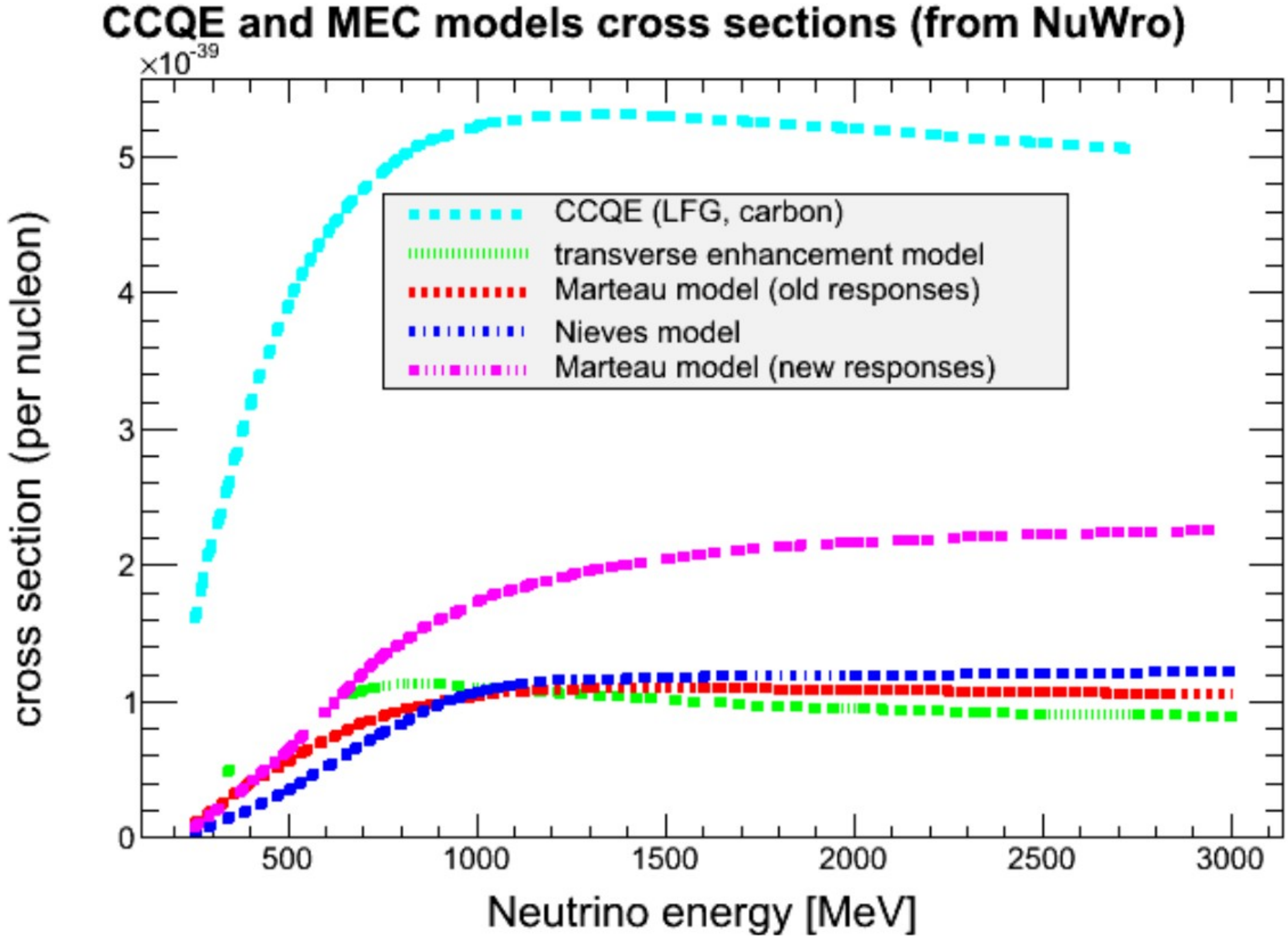
np-nh in Nu Wro: inclusive cross section computation

- IFIC model: thanks to courtesy of J. Nieves and M. J. Vicente-Vacas: fortran code returning 5 elements of hadronic tensor (related directly to response functions)
- Implementation in NuWro (10x10 MeV table in q^0 and $|\mathbf{q}|$ up to 1.2 GeV → momentum transfer limit of the model)
- For Martini et al. model no code available. Approximation worked out and implemented by J. Sobczyk (arXiv:nucl-th/0307047): analytic form of structure functions, „old" implementation from Marteau PhD thesis and „new" implementation extrapolation of electron scattering results from the paper by W. Alberico, M. Ericson, A. Molinari et al.

Uniwersytet Wrocławski

Microscopic MEC cross section implementation

- Comparison of IFIC, Lyon and Transverse Enhancement models:



- Big theoretical uncertainties, (MiniBooNE energy ~2x)

np-nh in NuWro: MEC Hadronic model

- **All theoretical models: information about leptons only**
- **MEC event identification: hadrons needed**

np-nh in NuWro: MEC Hadronic model

- Information about actual nucleon dynamics: unavailable → effective ansatz.
- All models (local) Fermi gas ground state → two (or three) random nucleons from local denstiy distribution (NuWro).
- Vertex position inside the nucleus:

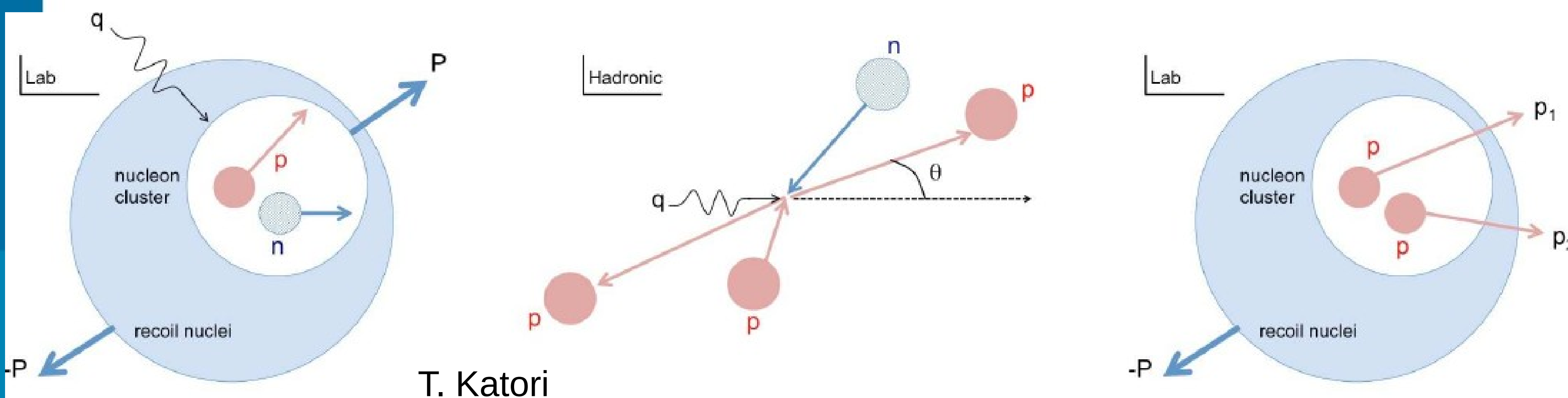
1) Two nucleons at the same point in space, probability ~ρ^2.

2) Two nucleosns at different points in space: both from single-particle distribution ~ρ.

- Second solution: different (local) Fermi momenta, used for IFIC model implementation.
- Isospin content: in NuWro free parameter.

np-nh in NuWro: MEC Hadronic model

- algorithm from J. Sobczyk Phys. Rev. C86 015504 using hadronic CMS:



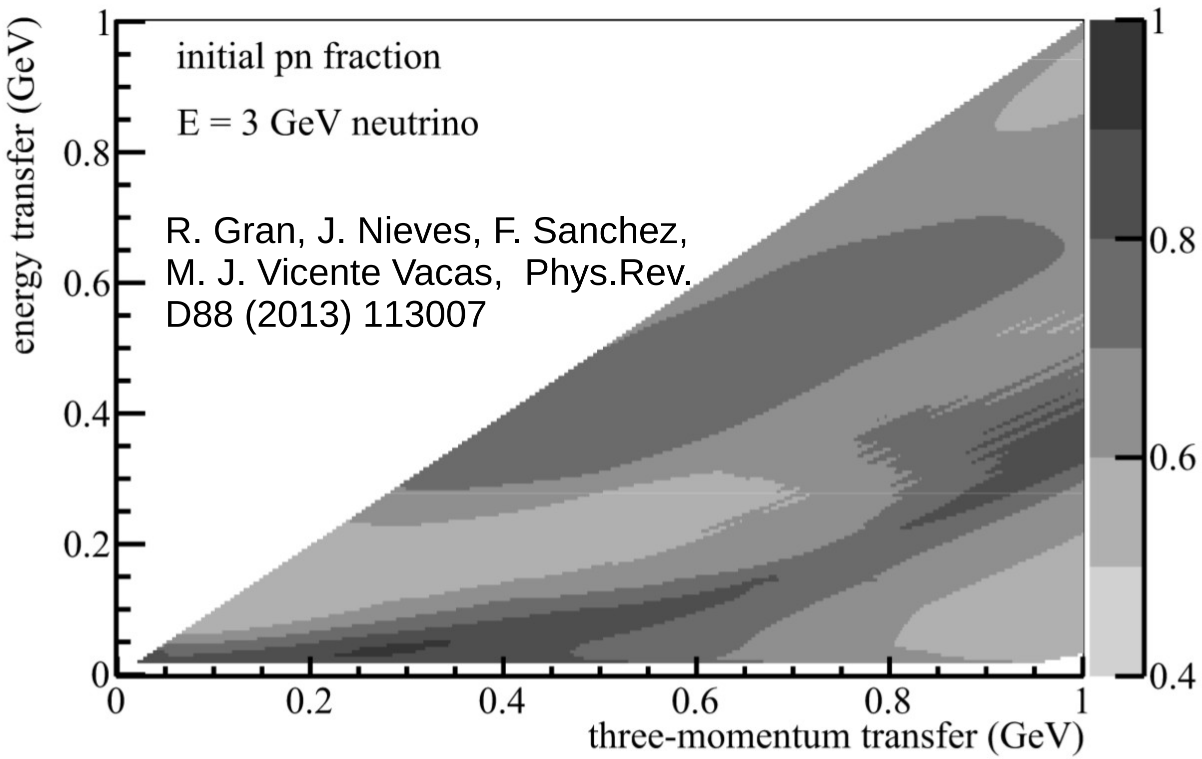
T. Katori

The same phase-space algorithm in each MEC muon inclusive cross section model:

Lepton kinematics/ 4-momentum in laboratory frame → Inclusive cross section (weight) → Random nucleons from Fermi Sea → Hadronic CMS: isotropic decay → Laboratory frame, optional Pauli blocking

Possible improvements

- Hadron model crucial for experimental MEC identification! What can be done?
- Isospin content breakdown of IFIC model:



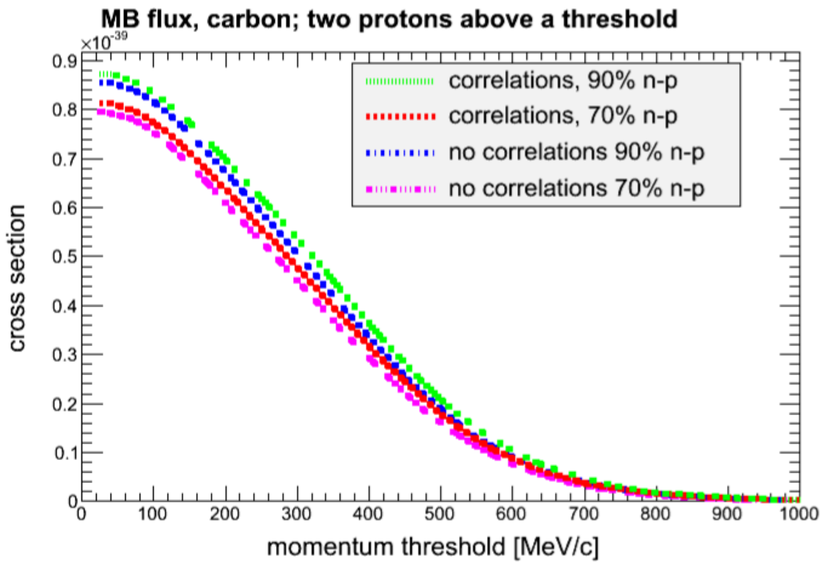
- At average: 67% p-n pairs
- Separate table, like for nuclear responses?

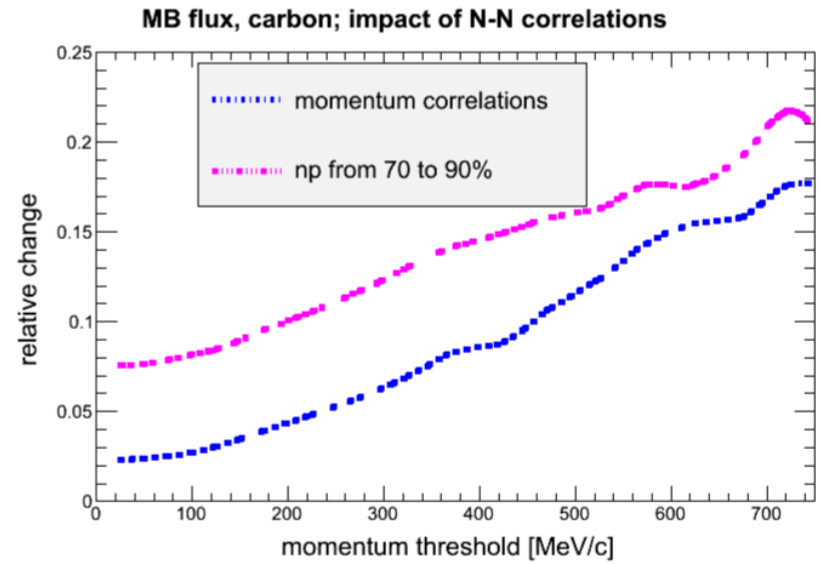
Uniwersytet Wrocławski

Possible improvements

- Problem: around 20% nucleons in strongly correlated proton-neutron pairs with back-to-back momenta → developing version with correlated nucleons with momenta randomized from spectral function (from J. Sobczyk's talk in Seattle)

Impact of correlation effects on number of proton pairs in the final state:





Isospin and momentum correlations are analyzed seperately. A possible confusion: In above figures correlations means initial state nucleon momenta are back-to-back.

Uniwersytet Wrocławski

Possible improvements

- Another possibility: first-principle MEC calculation, realistic nuclear ground state, method: Green's function MC - talk by A. Lovato.
- Changes inclusive cross section, predicts realistic nucleon behavior.
- Problem: need for computational power of Argonne National Laboratory and Los Alamos grids to give predictions for ^{12}C (works of A. Lovato, S. Gandolfi , J. Carlson, S. C. Pieper, and R. Schiavilla) → effective implementation in MC? What about oxygen, calcium, iron...?
- **Huge impact of FSI on outgoing hadrons: improve FSI first? → big effort on initial interaction improvement potentially ruined by bad FSI model...** FSI-potentially „washing out” details of hardonic npnh model as well

- Other theoretical improvements: e.g. fully relativistic treatment, solution to complicated MEC cross section integration problem, constraints on MEC nucleon geometry, I. Ruiz Simo, C. Albertus, J.E. Amaro, M.B. Barbaro, J.A. Caballero, T.W. Donnelly, arXiv:1405.4280 [nucl-th]

Uniwersytet Wrocławski

Summary

- At present only generators with microscopic np-nh models: NuWro and NEUT. Effective np-nh in GENIE and GiBUU.
- All models implemented so far: no realistic nucleon correlations (FG ground state), only lepton inclusive cross section predictions.
- Big theoretical uncertainties on predicted np-nh cross sections → validation against electron data?
- Need for more realistic treatment of hadrons → effective implementation of first-principle calculations? Some theoretical ansatz?
- Good FSI model needed as well
- All the above → impact on MEC event identification in neutrino experiments.