Nuclear Physics in Generators: what needs to be done

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Reaction Types

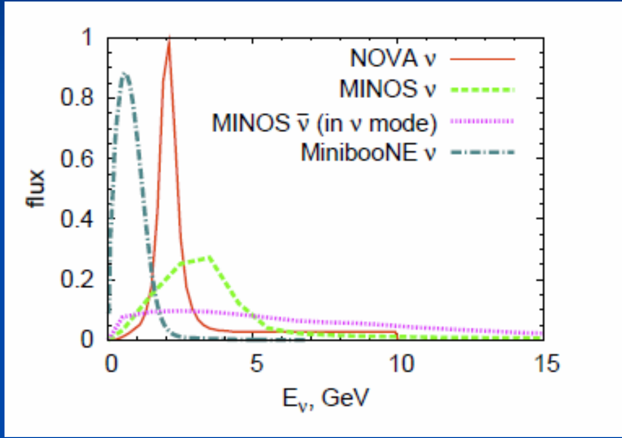
- 3 major reaction types relevant:

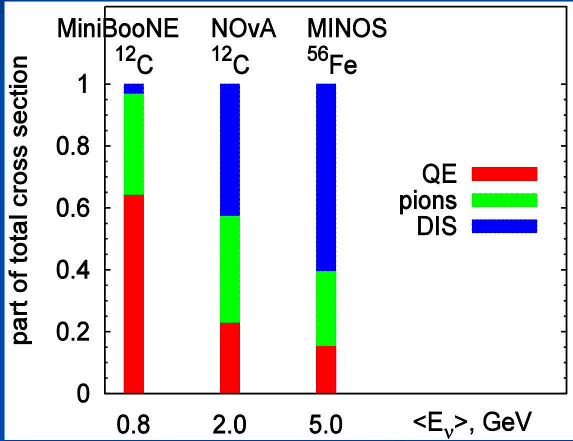
1. QE scattering
   1. true QE (single particle interaction)
   2. many-particle interactions (RPA + 2p2h + spectral functions)
2. Pion production
3. SIS and DIS

- All reaction types are entangled: final states may look the same

Neutrino Beams

- Neutrinos do not have fixed energy nor just one reaction mechanism





Have to reconstruct energy from final state of reaction
Different processes are entangled; final states may look the same

QE Scattering

- Many-body aspects:
  - Spectral functions (selfenergy correction)
  - RPA (selfenergy + vertex correction)
  - 2p-2h interactions (selfenergy + vertex correction)
    Danger: Double Counting
    consistent theory is still being developed (Barbaro, Benhar, Carlson, Martini, Nieves,..)
- Is there a shortcut (*educated* guess) for generators?

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QE: 2p-2h correlations

1. Up to what (Q^2,ν) are existing theories (Martini, Nieves) valid?
2. Dependence on energy (or, better, Q^2 and ν)?
   Do they die off with inv. mass *W* as in the Bosted analysis for MEC contribs in inclusive *e*-scattering?
3. Need parametrization of 2p-2h hadron tensor for generator (educated guess in GiBUU: $H_{\mu\nu} \sim F(Q^2)\, P_T$,strength fitted)
4. Calculate consistently not just inclusive, but also semi-inclusive channels, with knock-out particles

Many-body effects in QE

- SRC in neutrino interactions???
  - All neutrino reactions so far are (semi)-inclusive and $Q^2 < 1$ GeV
  - SRC (or high-momentum tails) for electrons essential at

    $Q^2 > 1.5$ GeV^2 **and** $x_{BJ} > 2$
- Quasideuteron effect is so far more relevant for neutrino physics (electrons couple to dipole moment -> produce *pn* pairs, do neutrinos couple the same?)

Pion Production

- ***Pion-Nucleon-Delta dynamics*** in nuclei well known since 30 years → in resonance region no room (and no need) for generator concepts such as formation times or zones that just add new parameters
- ***Transition currents*** to resonances are still quite uncertain, Rein-Sehgal clearly is bad.
- ***Vector formfactors*** should be taken from em-physics, e.g. MAID analysis, Axial FFs from PCAC

Coherent Pion Production

- ***Coherent pion production***:
  not really part of a MC generator, since coherent process.

  Nakamura, Sato and Lee (PRC81 (2010) 035502) have given (nearly) correct theory. Supersedes oversimplified earlier models, but nowhere used. WHY???

DIS

- DIS well constrained at high neutrino energies (E > 40 GeV).
- Problematic: SIS region around a few GeV, Parameters and X-sections not well determined (2p-2h?, 2 π,..). MINERVA data may help
- Problematic: Switch from resonance model to DIS, can affect pion yield, e.g., in T2K

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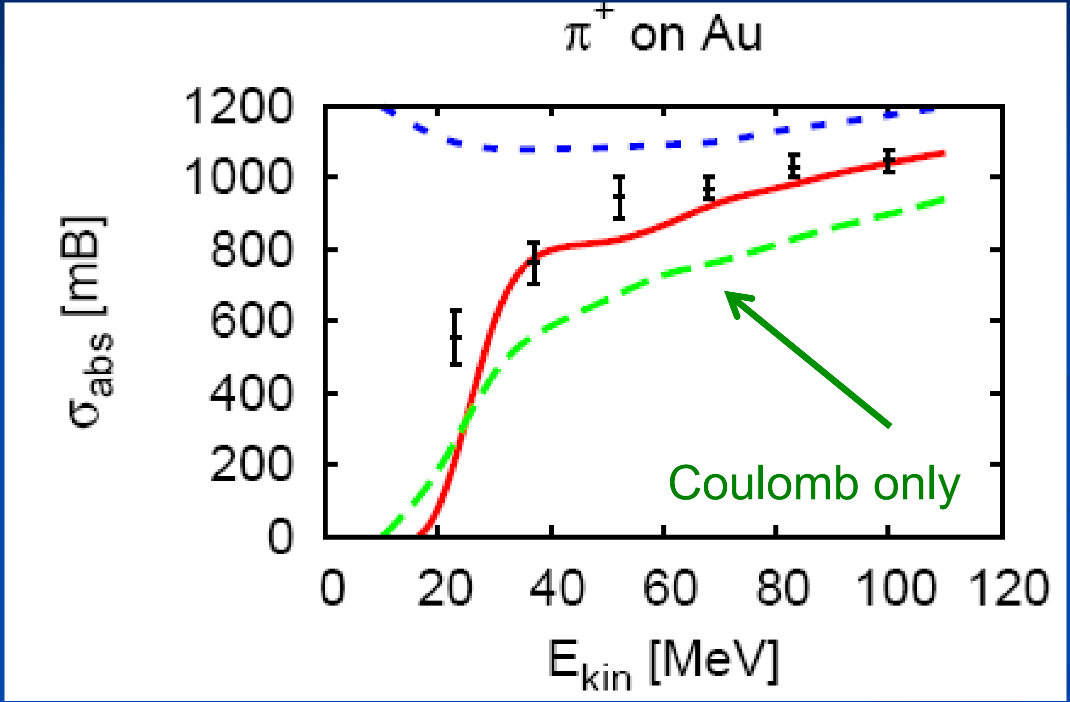
Check: Pion Absorption



Pion potential essential, as well as Coulomb

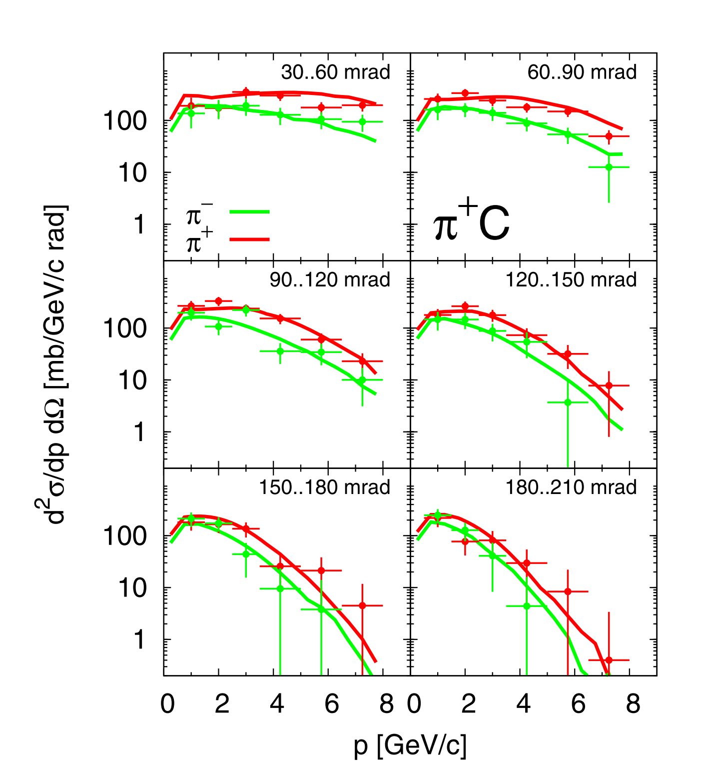
Note: Pion absorption does not provide a sensitive test for fsi with nucleons

Check: pions in HARP

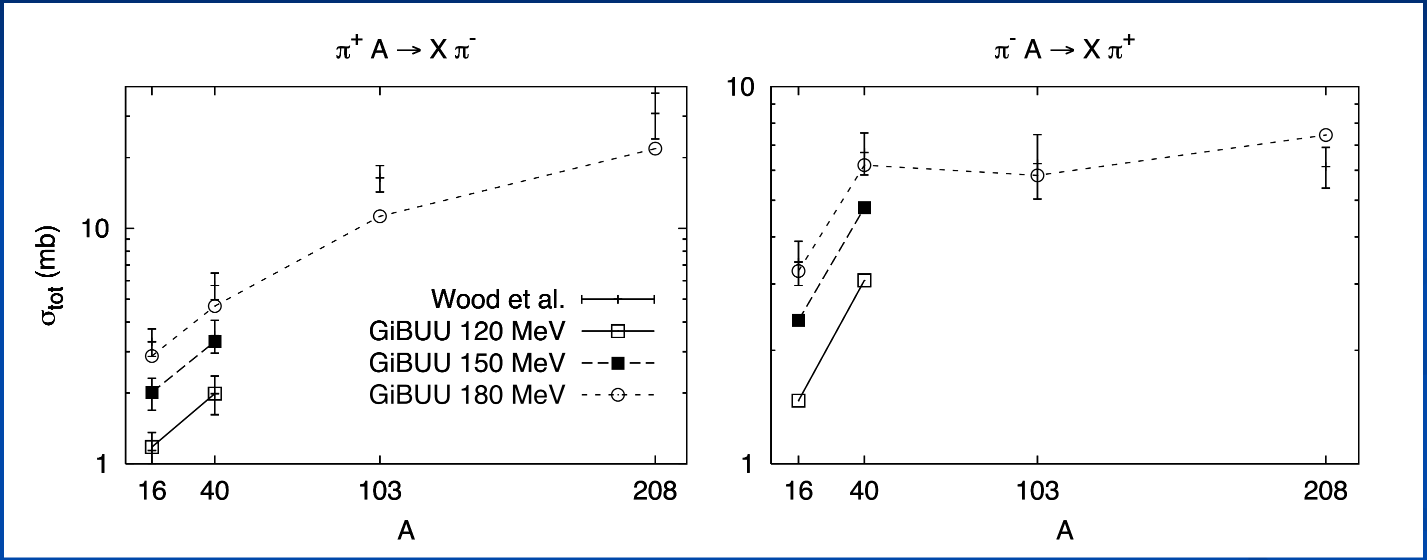
HARP small angle analysis
12 GeV protons

Curves: GiBUU

K. Gallmeister et al, NP A826 (2009)



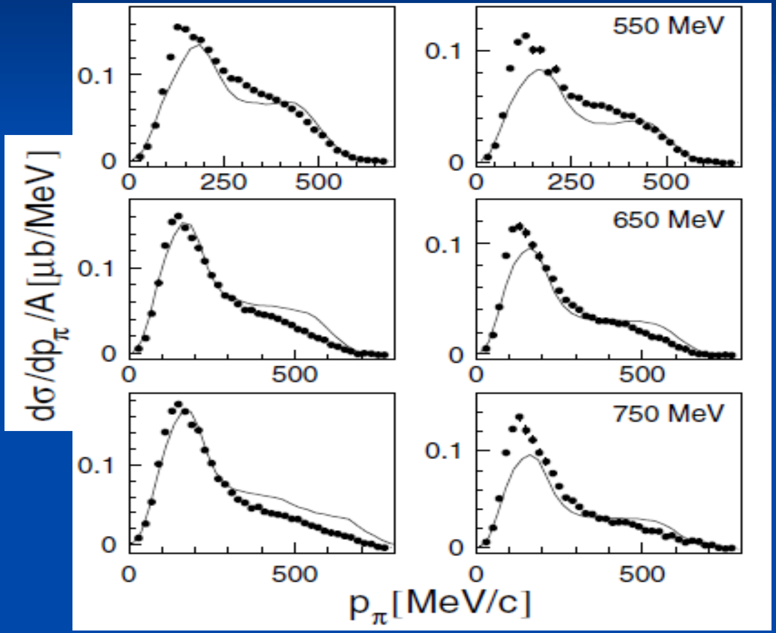
Check: Pion DCE



Data: Wood et al, GiBUU: Buss et al, **Phys.Rev. C74 (2006) 044610**

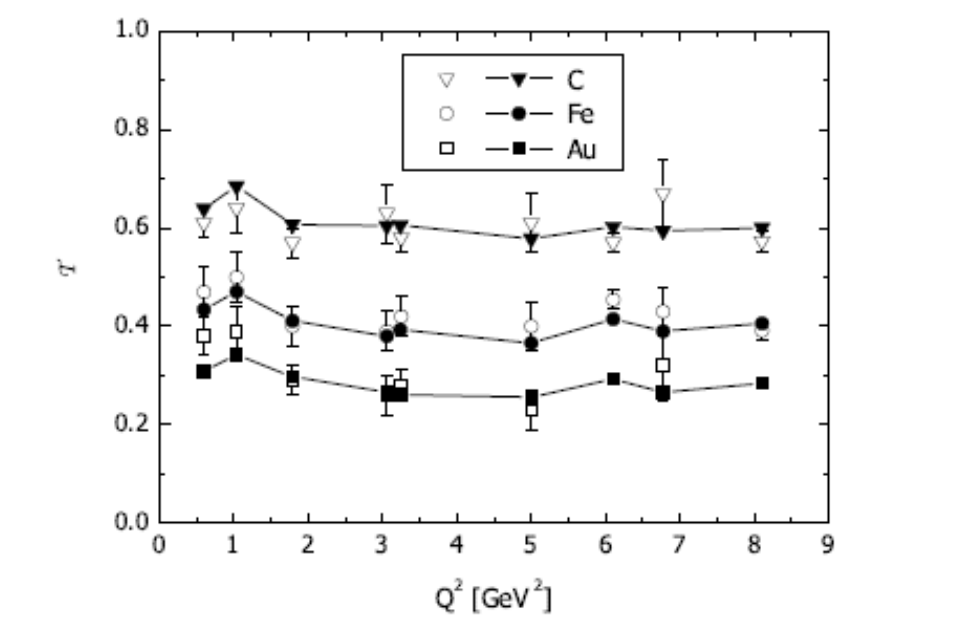
Check: Pions in Nuclei

$\gamma \rightarrow \pi^0$ on Pb



Photons illuminate the whole nucleus, test various pion mean free paths

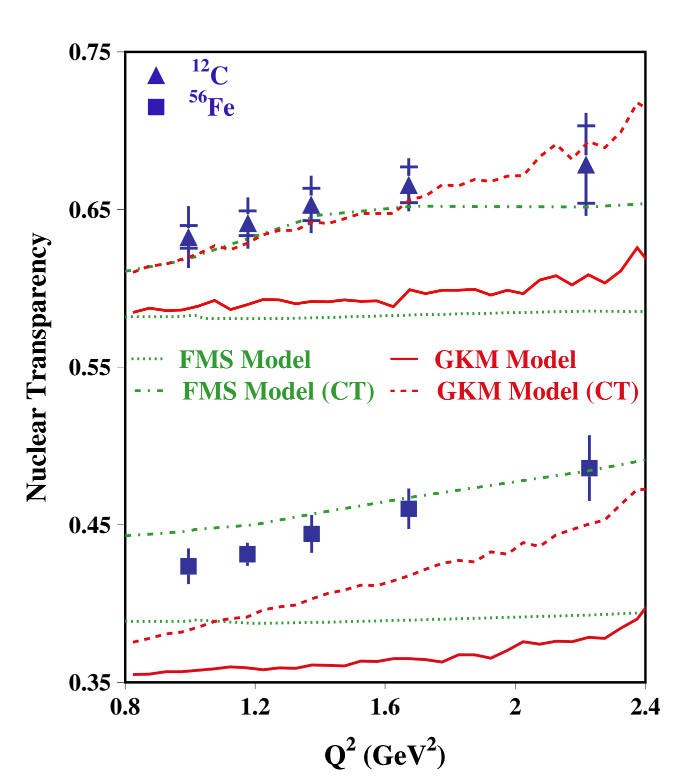
Check: protons



Curves: GiBUU

Proton transparency

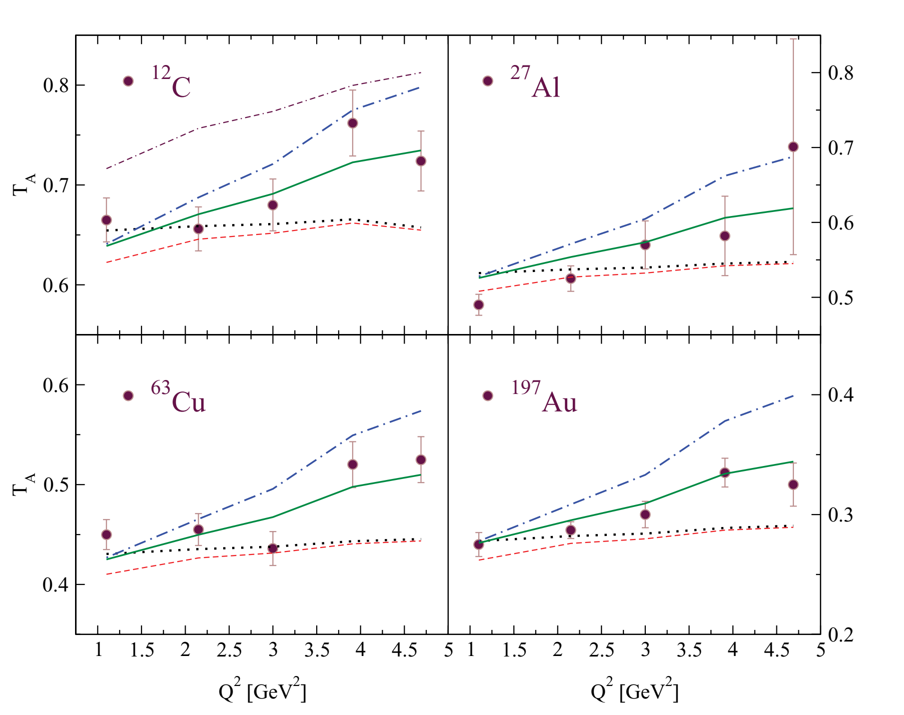
CLAS Rho Production



Exp: Hafidi et al,
Phys.Lett. B712 (2012) 326-330

GiBUU: Gallmeister et al.
Phys.Rev. C83 (2011)

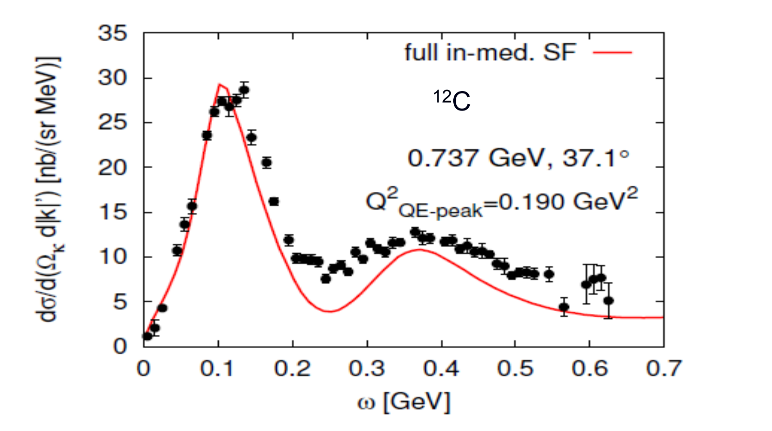
CLAS Pion Production

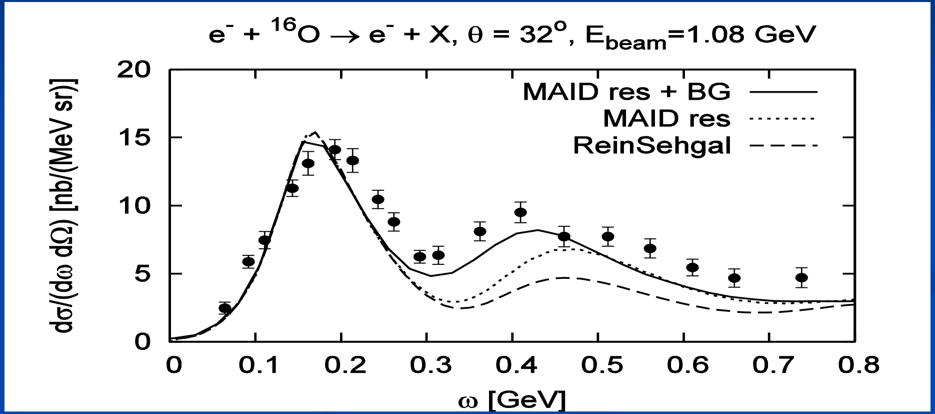


Exp: B. Clasie et al.
Phys. Rev. Lett. 99, 242502 (2007).

GiBUU: Kaskulov et al,
Phys.Rev. C79 (2009) 015207

Electrons as Benchmark for GiBUU



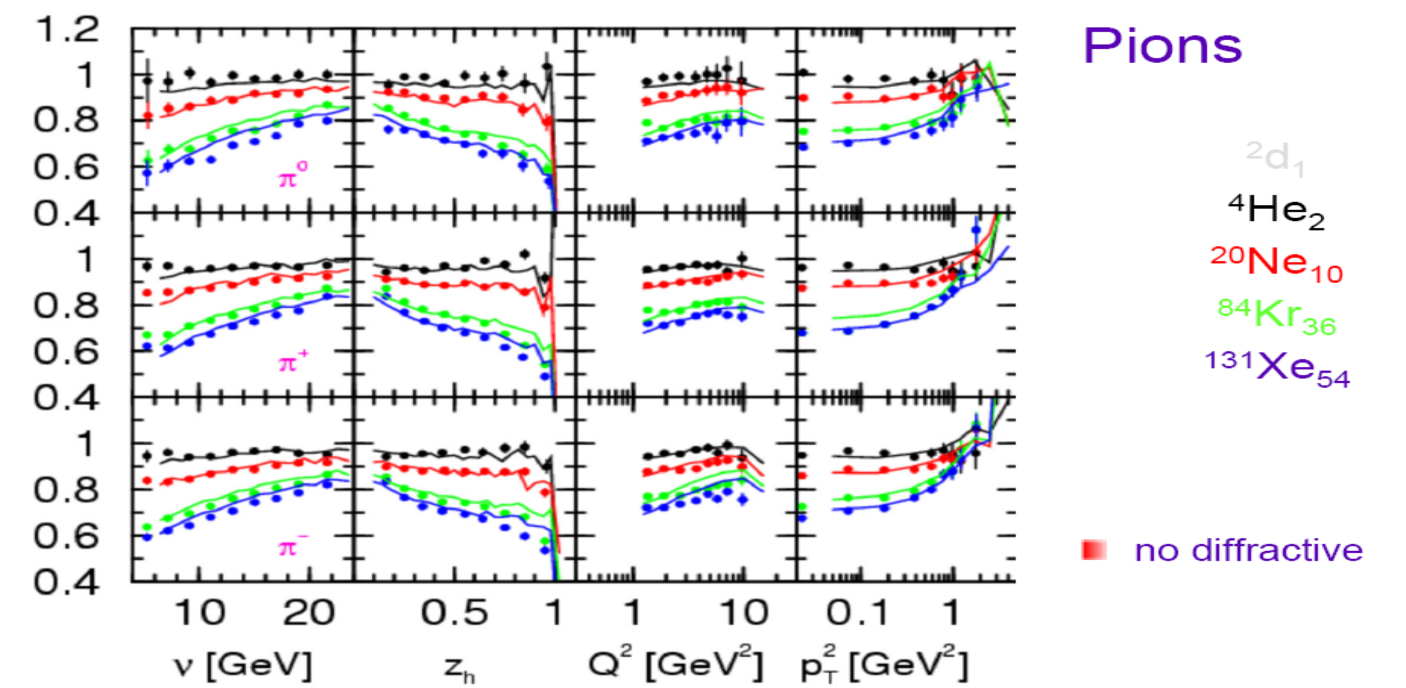


No free parameters!
no 2p-2h, contributes
in dip region and under Δ

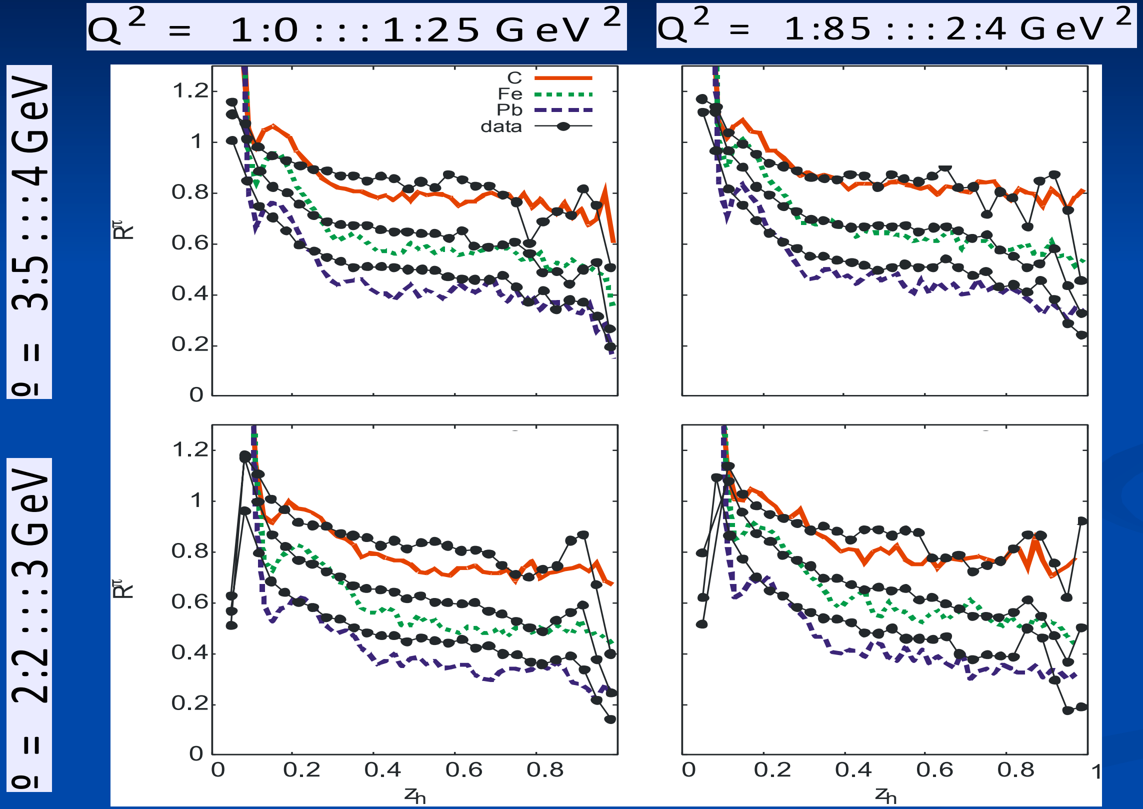
Rein-Sehgal does not work for electrons!
Why should it work for neutrinos?

HERMES@27 GeV and GiBUU

Airapetian et al.



JLAB@5, π^+ : selected (ν,Q^2) bins



Data:

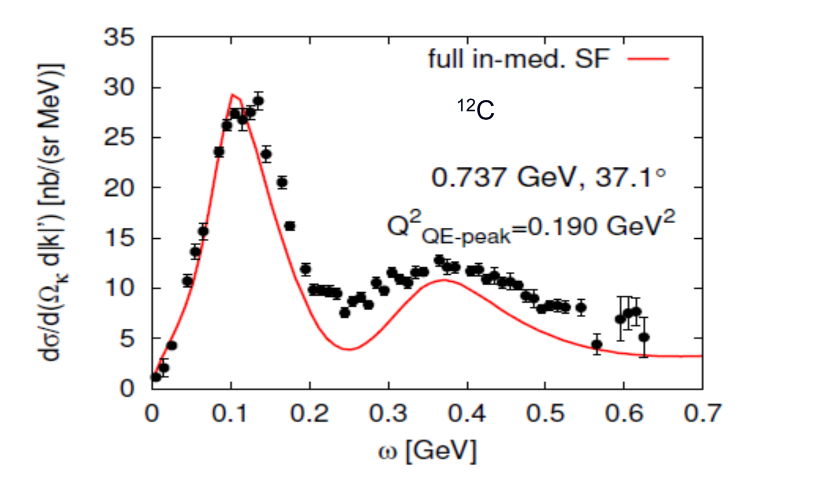
CLAS preliminary
(Brooks et al)
no error bars shown

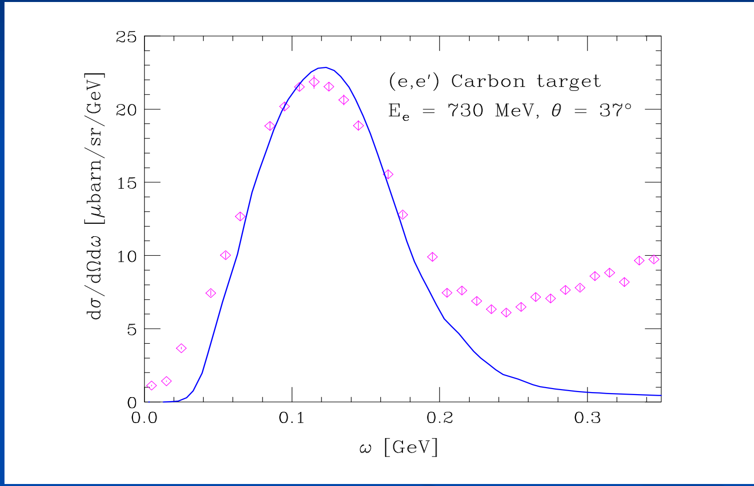
Calculations:

not tuned !!!

no potentials

Electrons as Benchmark for GiBUU



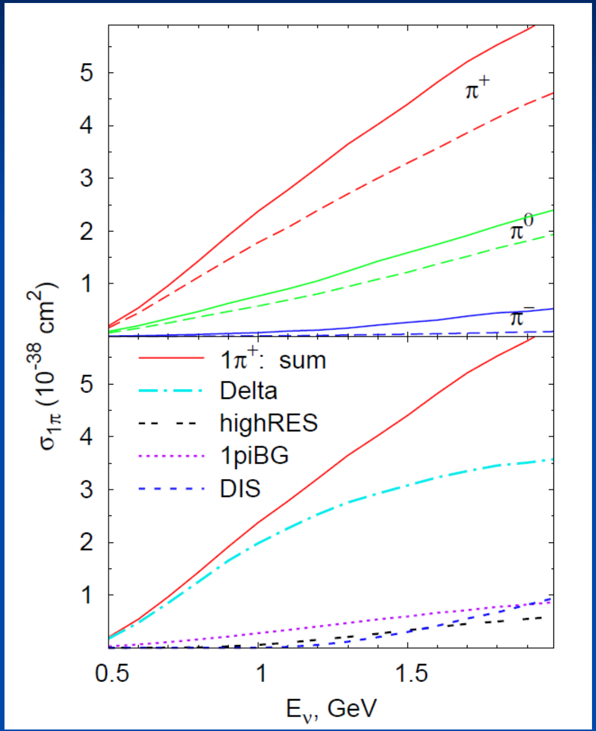


No free parameters!
no 2p-2h, contributes
in dip region and under Δ

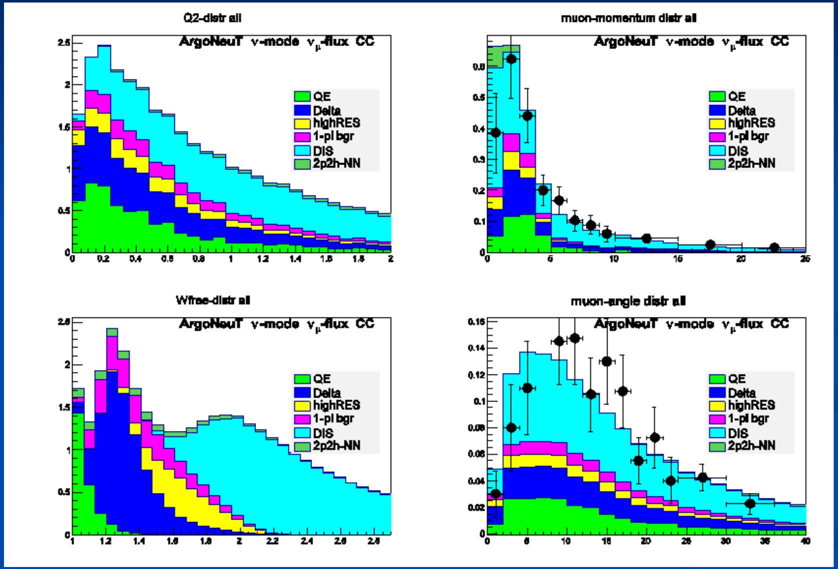
O. Benhar, spectral fctn

Pion Production in SIS and DIS

^{12}C



GiBUU



Thanks to
Ornella Palamara
and her team

many sources for E_ν > 1 GeV

Comparison with experiment only possible if all these sources are taken into account

Energy reconstruction

- Have to identify QE as well as possible (0 π), then treat remaining uncertainty with energy migration matrix *P*

Event Rate:

$$\phi(E_\nu^{\rm rec})\tilde{\sigma}_{0\pi}(E_\nu^{\rm rec}) = \int N(E^{\rm rec}, E^{\rm true})\,{\rm d}E_\nu^{\rm true} = \int \mathcal{P}(E_\nu^{\rm rec}|E_\nu^{\rm true})\,\phi(E_\nu^{\rm true})\,\sigma_{0\pi}(E_\nu^{\rm true})\,{\rm d}E_\nu^{\rm true}$$

MM from one and the same generator

O. Lalakulich, U. Mosel, Phys.Rev. C86 (2012) 054606

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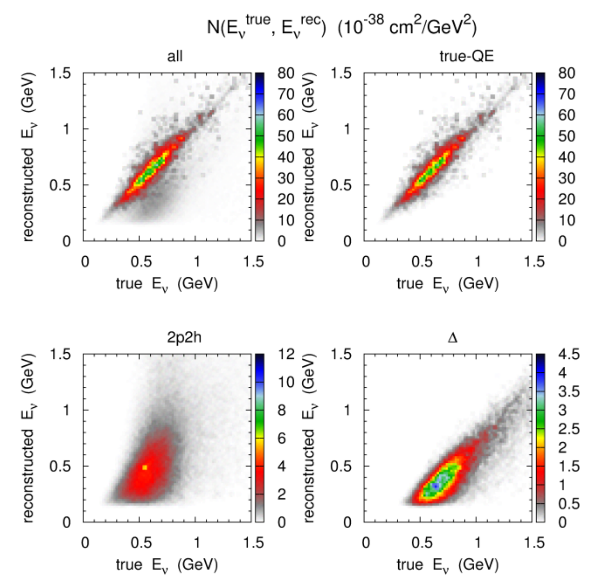
Migration matrix for T2K in GiBUU

Flux x σ



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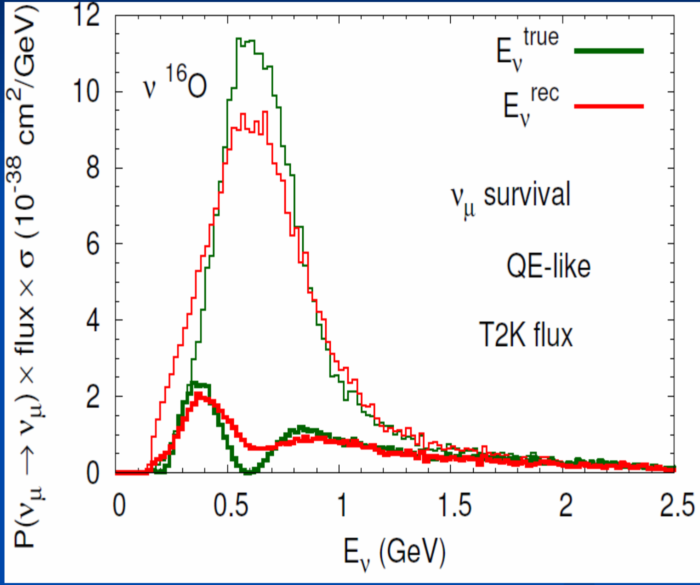
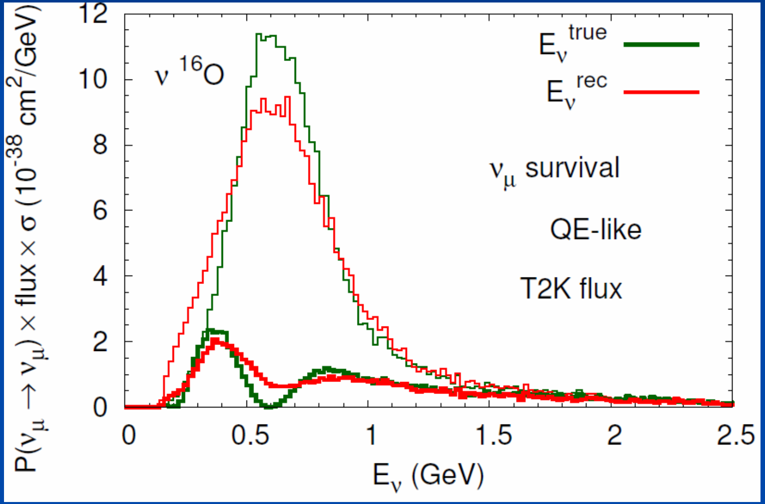


O. Lalakulich, U. Mosel, Phys.Rev. C86 (2012) 054606

Oscillation Signal gets distorted due to mixing of reaction mechanisms

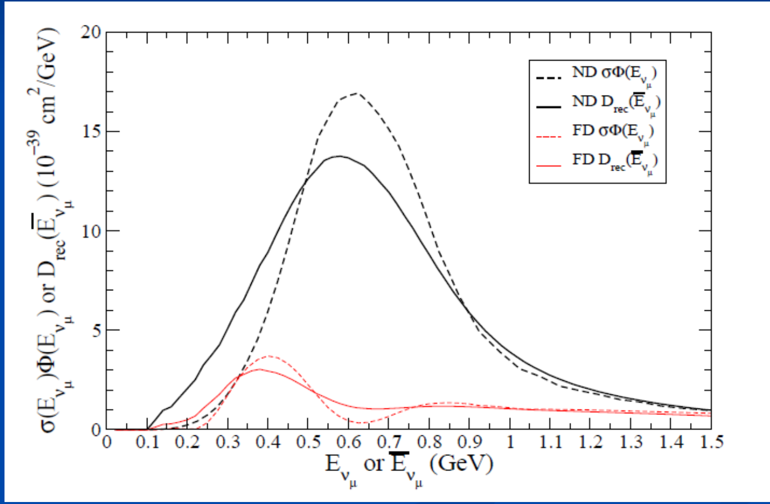
Oscillation signal in T2K
ν_μ disappearance

Two very different models give same result



O. Lalakulich, U. Mosel, Phys.Rev. C86 (2012) 054606

GiBUU



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

Martini

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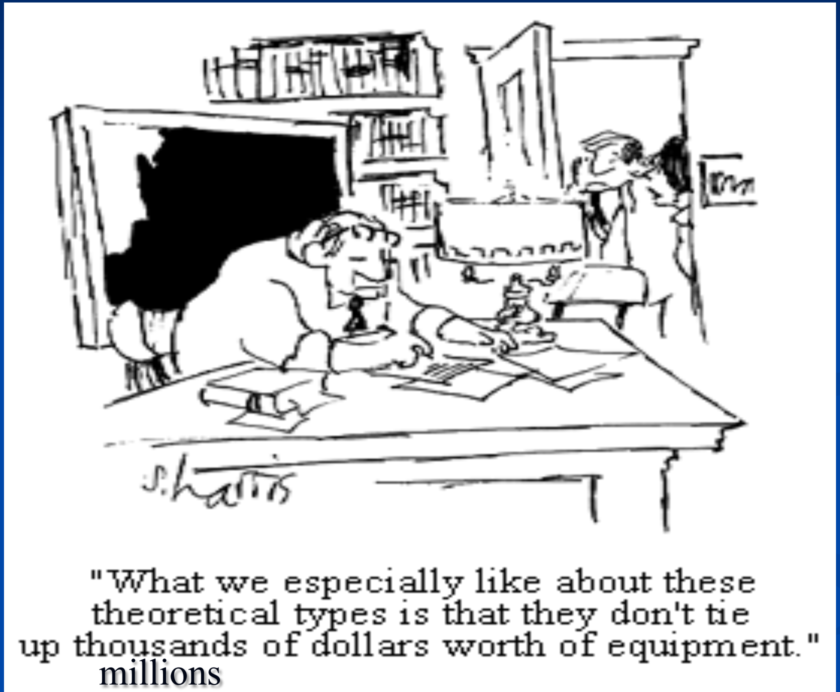
How to proceed

- 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!

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



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

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

Guiding Principles for a new Generator

- ***Consistency:***
  e.g. same ground state for all subprocesses (negative example: combine free uniform Fermi gas with bound state local gas)
- ***Detailed balance:***
  example: Δ + N →NN (pionless Delta decay) must be related to N + N → Δ + N (negative example: just take out 20% Δs)
- ***Relativity:***
  generator collision criterion $\sigma = \pi d^2$
  is incorrect (no Lorentz contraction)

Precision era requires better generators What needs to be done? Theory

1. Develop consistent framework for many-body effects: spectral functions + couplings, consistent groundstates
2. Theory must comprise besides QE also pion and DIS region because all are entangled
3. Parametrize hadron tensors as function of relevant kinematical variables for use in generators
4. Consistency of inclusive and exclusive X-sections
5. Improve all important final state interactions

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2 Final Words

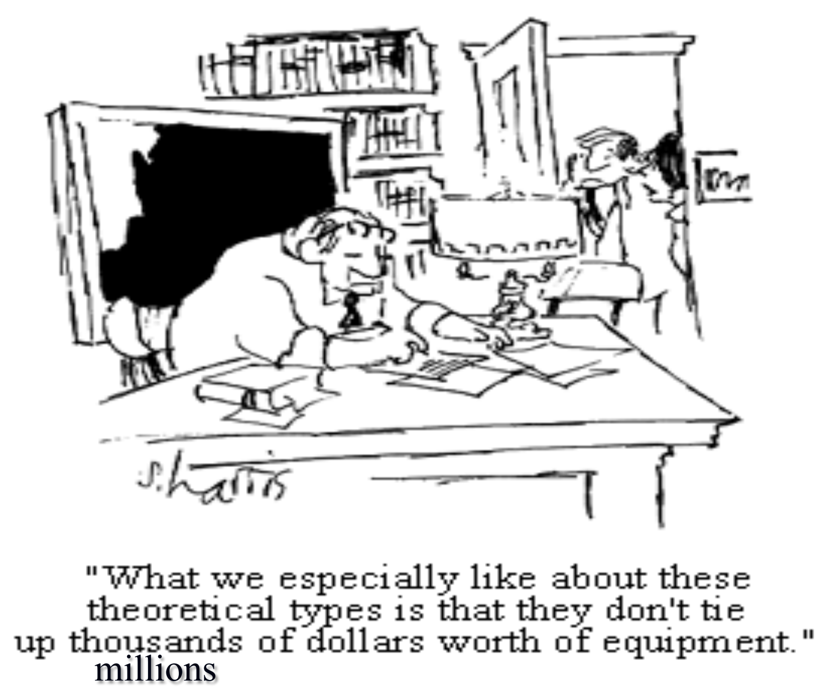
1. A lively discussion scene between experiment and theory is still missing. Exp. papers seldomly quote theoretical work, and never discuss theoretical results in comparison with their data.
2. „We, as a community, would be well advised to share all relevant information and tools freely – instead of reinventing the wheel at every opportunity (see Nuance, GENIE, Neugen, NuWro . . .)“
   P. Huber, NUFACT 2013

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



Importance of Generators

- A good generator does not have to fit the data, provided it is right
- A good generator does not have to be right, provided it fits the data
- Let us strive for a generator that is ‚right‘ and as much state-of-the-art as the experimental equipment is!

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