NuWro * Wrocław Neutrino Event Generator *

Developments in NuWro

Kajetan Niewczas

Uniwersytet Wrocławski

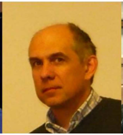
UNIVERSITEIT GENT

NuWro team since 2006

(currently active)

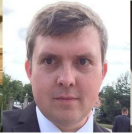
T. Golan

K. Graczyk



C. Juszczak

K. Niewczas



J. Nowak

J.T. Sobczyk

J. Żmuda

Notable supporters

Warsaw

D. Kiełczewska
(passed away in 2016)

P. Przewłocki

General,
many discussions

NuWro at T2K

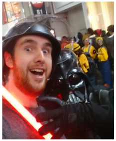
VA, U.S.

A. Ankowski

Spectral function

U.K.

L. Pickering



P. Stowell

Reweightning tools

Project organization

New repository

`https://github.com/NuWro/nuwro`

Releases scheme

`nuwro_[YY].[MM](.[patch])`

User guide

`https://nuwro.github.io/user-guide`

Licence

`GNU General Public Licence v3.0`

Project organization

Current release `nuwro_17.01.1`

Latest patch additions:

- minor bug fixes
- new formation zone option
  `fz-new`
- release tag
  `nuwro --version`
- MacOS support

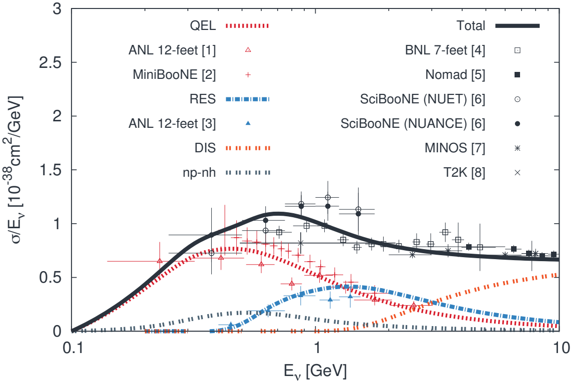
New models

User friendly

Wide applicability

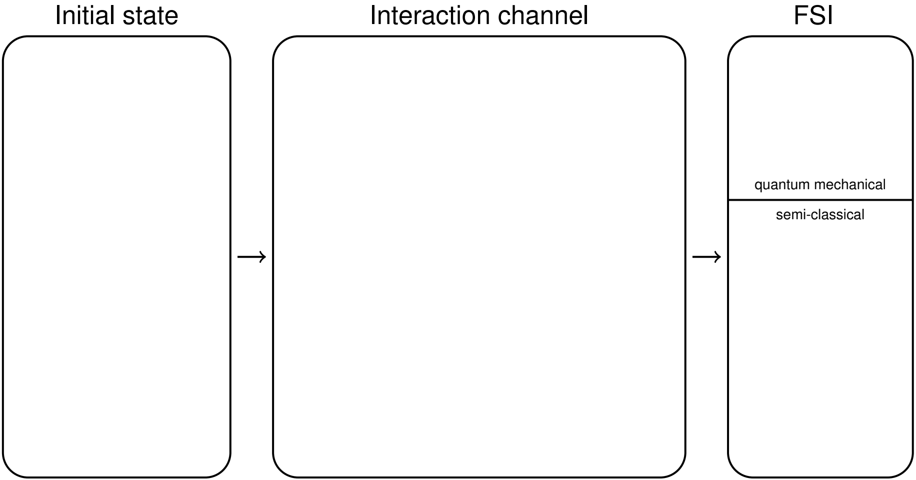
Reliable results

Optimized code

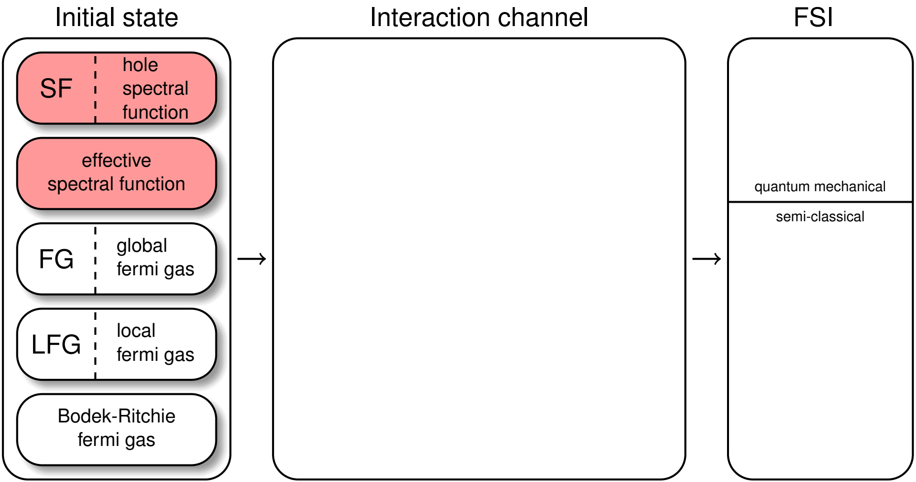


[1] PRD 19 (1979) 2521
[2] PRD 81 (2010) 092005
[3] PRD 16 (1977) 3103
[4] PRD 25 (1982) 617
[5] PLB 660 (2008) 19
[6] PRD 83 (2011) 012005
[7] PRD 81 (2011) 072002
[8] PRD 87 (2013) 092003

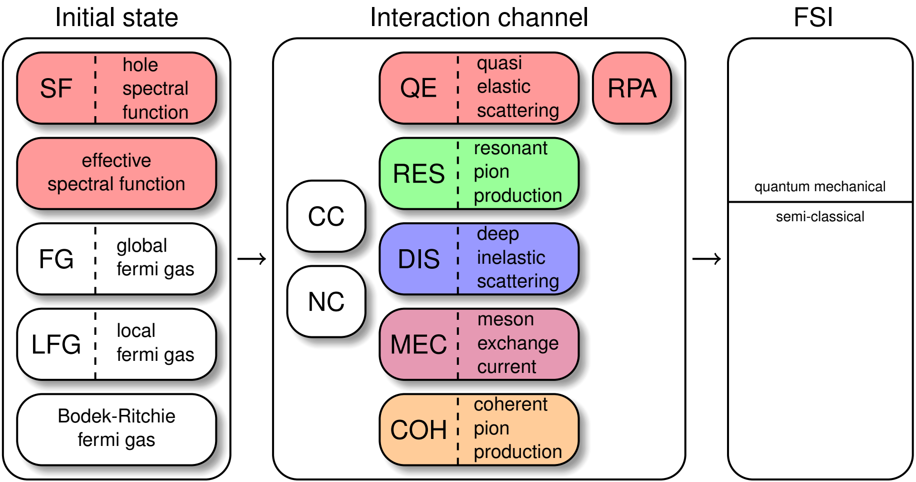
Blueprint


Initial state
Interaction channel
FSI
quantum mechanical
semi-classical

Blueprint


Initial state
Interaction channel
FSI
SF
hole spectral function
effective spectral function
FG
global fermi gas
LFG
local fermi gas
Bodek-Ritchie fermi gas
quantum mechanical
semi-classical

Blueprint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NC
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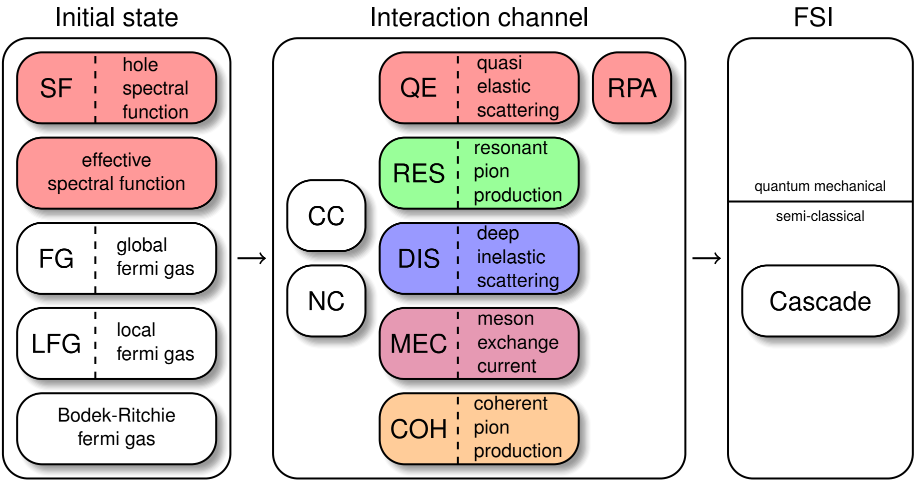
quasi elastic scattering
RPA
RES
resonant pion production
DIS
deep inelastic scattering
MEC
meson exchange current
COH
coherent pion production
quantum mechanical
semi-classical

Blueprint



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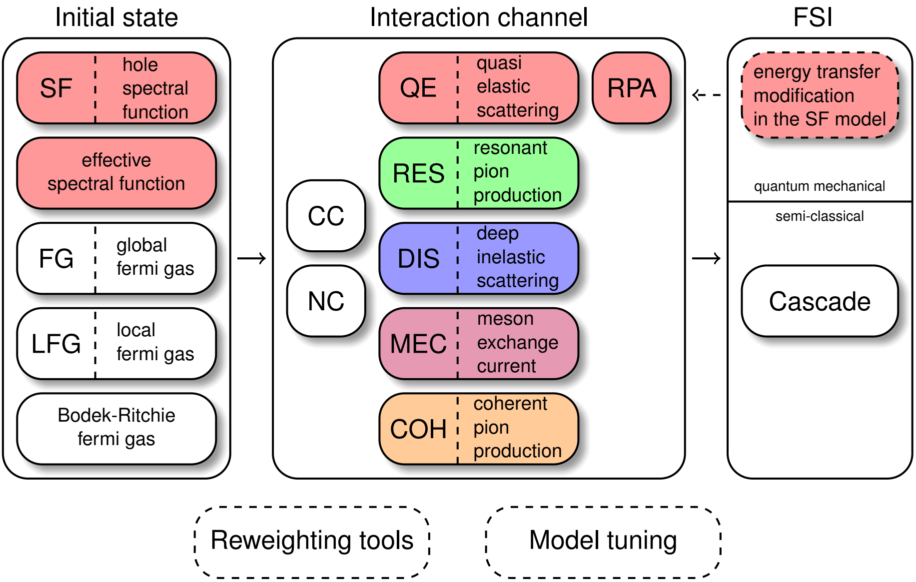
Cascade

Blueprint


Initial state
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Interaction channel
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MEC meson exchange current
COH coherent pion production
FSI
energy transfer modification in the SF model
quantum mechanical
semi-classical
Cascade
Reweighting tools
Model tuning

Hole spectral function

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

*The **probability** distribution of removing a **nucleon** with **momentum** $\vec{p}$ and leaving the residual **nucleus** with the **excitation energy** E.*

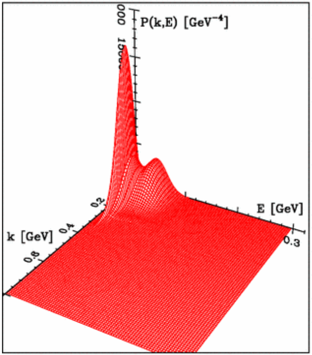
In NuWro available for:

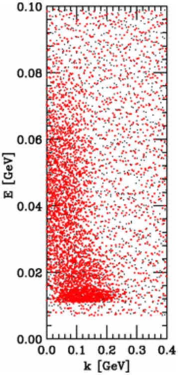
- carbon
- oxygen
- calcium*
- argon*
- iron

*approximation, see

A. Ankowski, J.T. Sobczyk,

Phys.Rev. C77 (2008) 044311





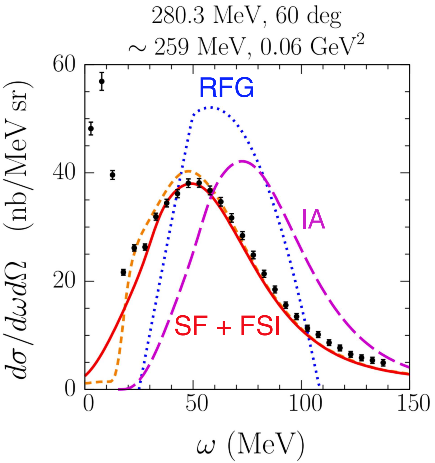
O. Benhar et al., Phys.Rev. D72 (2005) 053005

FSI for SF

The procedure after **O. Benhar et al., Phys.Rev. C44 (1991) 2328**

Different kind of the FSI effects:

- modifies the **inclusive cross section**
- knocked-out **nucleon** is in the **optical potential**
- essential to **reproduce** the inclusive **electron data**



A. Ankowski et al., Phys.Rev. D91 (2015) 033005 (edited)

FSI for SF

The procedure after **O. Benhar et al., Phys.Rev. C44 (1991) 2328**

The cross section is folded as

$$\frac{\mathrm{d}\sigma^{\mathrm{FSI}}}{\mathrm{d}\omega\mathrm{d}\Omega} = \int \mathrm{d}\omega' f_{\mathbf{q}}(\omega - \omega') \frac{\mathrm{d}\sigma^{\mathrm{IA}}}{\mathrm{d}\omega\mathrm{d}\Omega}$$

where the folding function is

$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + (1 - \sqrt{T_A})F_{\mathbf{q}}(\omega)$$

and $F_{\mathbf{q}}(\omega)$ smears the energy transfer according to the **NN cross section** weighted with nuclear **transparency** T_A

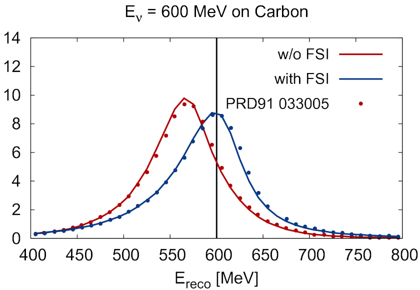
interaction between the knocked-out **nucleon** and the spectator system $\rightarrow$ affects the **conservation of energy** and therefore the **kinematics** of the final **lepton**

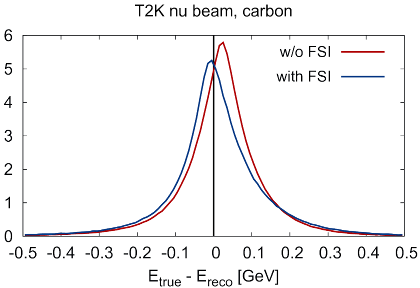
FSI for SF

Implemented for carbon in collaboration with **Artur Ankowski**.

Compared against **A. Ankowski et al., Phys.Rev. D91 (2015) 033005** using the standard energy reconstruction

$$E_\nu^{\rm reco} = \frac{2E_\mu(M-\epsilon) - (m^2 + (M-\epsilon)^2 - M^2)}{2((M-\epsilon) - E_\mu + |\mathbf{k}_\mu|\cos\theta)}$$





Event reweighting

*Reweighting allows to **avoid** a number of **time-consuming** detector **simulations** for **different** model **parametrizations**. **NuWro** is used in the **T2K** experiment, yet without reweighting.*

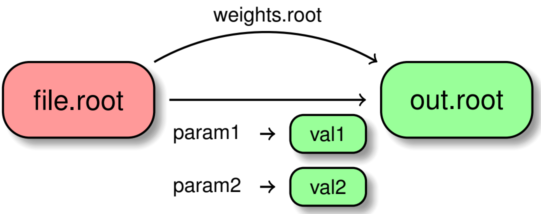
The original code for NuWro by **L. Pickering** and **P. Stowell**.

Usage

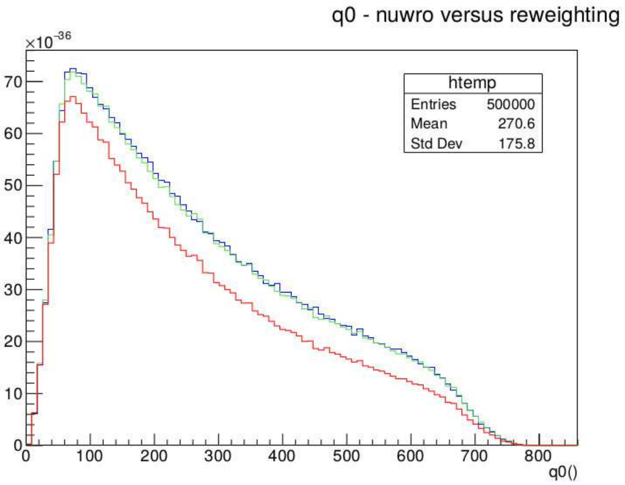
```
reweight_to file.root ( -o out.root | -w weights.root )
      -p param1 val1
      -p param2 val2 ...
```

Implemented:

- parameters affecting the QE channel
- absolute normalizations of interaction channels



Event reweighting



Reweighting of the quasielastic axial mass:
$M_A = 1$ GeV (red), $M_A = 1 \rightarrow 1.2$ GeV (blue), $M_A = 1.2$ GeV (green).

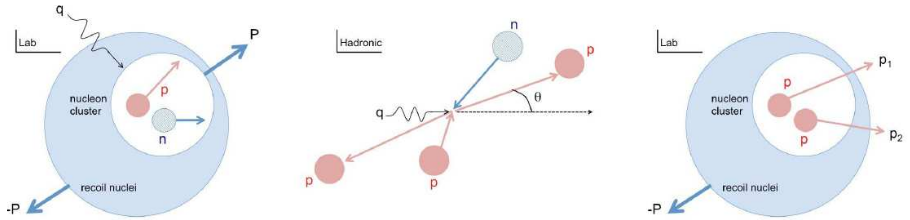
2p2h nucleon final states

*The common **2p2h models** give predictions for the **inclusive** cross section **only**.*

For other soutions, see e.g. Tom Van Cuyck et al., Phys.Rev. C94 (2016) 024611.

Every MC generator uses the **hadronic system phase space model**:

J.T. Sobczyk, Phys.Rev. C86 (2012) 015504



T. Katori

The model is rigid on the initial and final configurations,
yet it is open for tuning.

New parameters – tuning 2p2h

Initial state

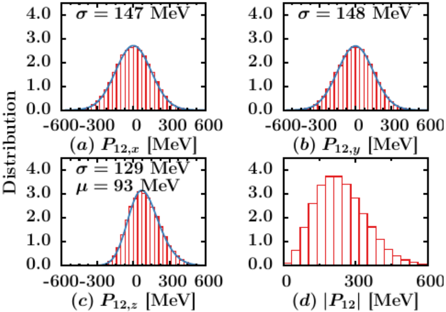
- add nucleon pair **CM momentum**

  `mec_central_motion` parameterizes the gaussian distribution

- add **smearing** of the **back-to-back** configuration (when no CM motion)

  `mec_back_to_back_smearing` parameterizes the gaussian distribution

Nucleon pair CM distributions

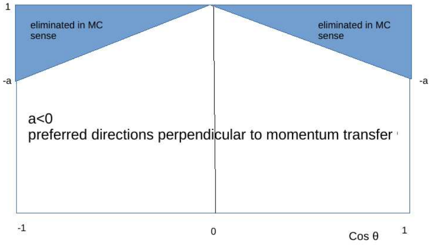


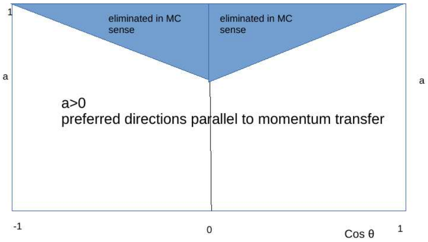
C. Colle et al., Phys.Rev. C89 (2014) 024603

New parameters – tuning 2p2h

Final state

- the nucleon pair **CM distribution** can be **different** than **uniform**
- the **direction** of **momentum transfer** $\vec{q}$ can be distinguished



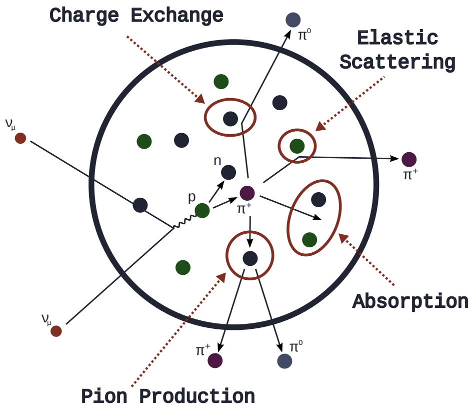


`MEC_cm_direction` (denoted as *a*)
allows for selecting directions on average more parallel or more perpendicular

Intranuclear cascade

- **Propagates particles** through the nuclear medium
- **Semi-classical** – neglect quantum mechanical effects
- **Modifies strength** and **opens** new interaction **channels**
- Implemented for **nucleons** and **pions**

T. Golan, C. Juszczak, J.T. Sobczyk, Phys.Rev. C86 (2012) 015505

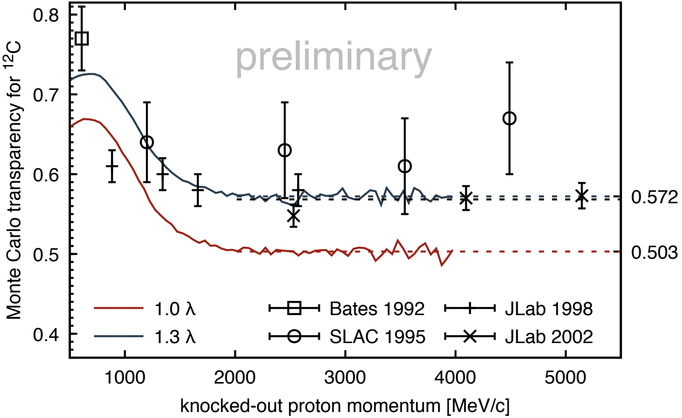


T. Golan

New parameters – tuning FSI

`kaskada_meanfreepath_scale`

scales the mean free path in the cascade



The simplest Monte Carlo transparency **definition** → **no rescattering**.

Future plans

- Event **reweighting** tools
- New models
  $\rightarrow$ close collaboration with **Ghent group**
- Formalization of the **NuWro Collaboration**
- Organization of the **NuWro Workshop**
- Service to the community
- New projects
  $\rightarrow$ **feel free to contribute!**

Backup slides

FSI for SF

Folding function

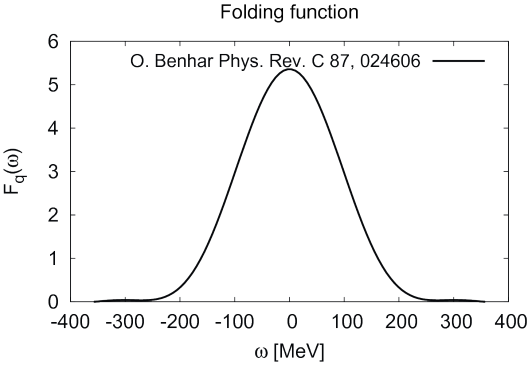
$$f_{\mathbf{q}}(\omega) = \delta(\omega)\sqrt{T_A} + (1 - \sqrt{T_A})F_{\mathbf{q}}(\omega)$$

The optical potential
$U = U_V + iU_W$

Real part is used to account for the modification of the struck nucleon's energy

$$f_{\mathbf{q}}(\omega - \omega') \to f_{\mathbf{q}}(\omega - \omega' - U_V)$$

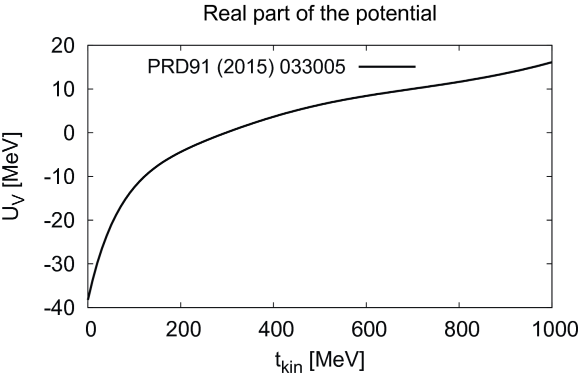
Imaginary part comes into play with $F_{\mathbf{q}}(\omega)$



FSI for SF

Kinetic energy of the knocked-out nucleon from leptonic variables

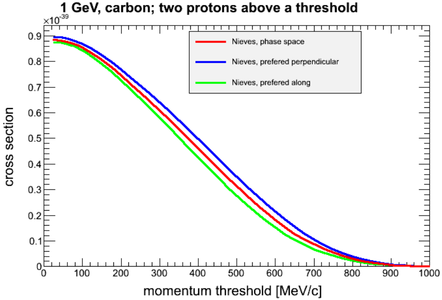
$$t_{\rm kin} = \frac{E_{\mathbf{k}}^2(1-\cos\theta)}{M + E_{\mathbf{k}}(1-\cos\theta)}$$



A. Ankowski et al., Phys.Rev. D91 (2015) 033005

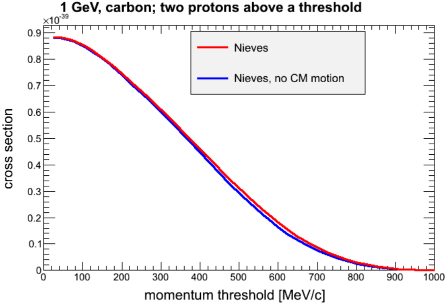
NuWro 2p2h hadronic model uncertainties

CC events with two protons and no π



Impact of the modification of the uniform phase space model.

For a threshold of $\simeq$ 500 MeV/c it is quite large.



Impact of the CM motion.

Negligible.

Transparecy in experiments

Only quasielastic electron scattering experiments: $A(e, e'p)B$

[G. Garino *et al.*, PRC 45 780(1992); T.G. O'Neill *et al.*, PLB 351 87-92(1995); D. Abbott *et al.*, PRL 80 5072(1998); K. Garrow *et al.*, PRC 66 044613(2002)]

$$T = \frac{\sigma_{\mathrm{exp}}}{\sigma_{\mathrm{PWIA}}}$$

One needs to compare:

- what is detected $\rightarrow$ **protons from events with no FSI**
- what should be detected $\rightarrow$ **expectation with no FSI**

Transparency in MC

After **D. Abbott *et al.*, PRL 80 5072(1998)**:

Processes *which make only* ***small shifts*** *in the* ***kinematics*** *of the* ***outgoing proton****, such as elastic proton-nucleus rescattering, low energy nuclear excitations of the residual nucleus, or small angle, low momentum transfer, N-N rescattering (which is constrained by Pauli blocking of the final nucleon states),* ***cannot*** *be* ***separated kinematically*** *from* ***events*** *that have* ***no rescattering****.*

There is some **ambiguity** in the **definition** of **transparency**.

The one with **no proton rescatterings** is clearly **too restrictive**.