NuWro

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Outline:

- NuWro project
- Very (!) preliminary results for 1 TeV ν_μ CC interactions on wolfram ^{184}W target

NuWro project

- Begining $\sim$ 2005 at Wrocław University, Poland
- Optimized for $\sim$ 1 GeV neutrinos!
- Can handle all kind of targets, neutrino fluxes
- Equipped with detector interface
- Used for numerous comparisons and studies by T2K, MINERvA, MicroBooNE experiments

For 1 TeV neutrinos out of several dynamical mechanisms only DIS is of importance together with final state interactions.

NuWro 21.09

DIS

- $W > 1.6$ GeV
- Inclusive cross sections from Bodek-Yang model
- Hadronization with PYTHIA6 fragmentation functions J. Nowak, PhD thesis.
- No shadowing, anti-shadowing, EMC nuclear effects (for reasons explained above).

Some PYTHIA6 parameters adjusted to get better agreement with charged hadron multiplicities data:

- PARJ(32)(D=1GeV) = 0.3 is, with quark masses added, used to define the minimum allowable energy of a colour singlet parton system.
- PARJ(33)-PARJ(34)(D=0.8GeV, 1.5GeV) = 0.5Gev, 1GeV are, with quark masses added, used to define the remaining energy below which the fragmentation of a parton system is stopped and two final hadrons formed.
- PARJ(36)(D=2.0GeV) = 0.3 represents the dependence of the mass of the final quark pair for defining the stopping point of the fragmentation. Strongly correlated with PARJ(33-35)
- MSTJ(17) (D=2) = 3 number of attempts made to find two hadrons that have a combined mass below the cluster mass and thus allow a cluster to decay rather than collapse

Performance: back-up slides.

Intranuclear cascade

- Propagates particles through the nuclear medium
- Probability of passing a distance λ:

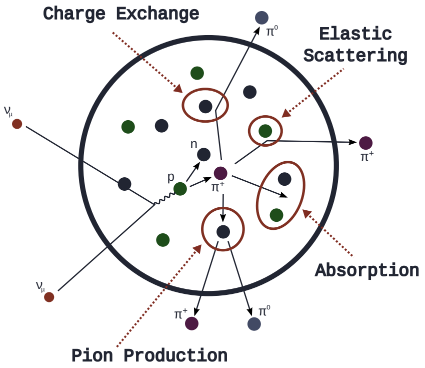
$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

where mean free path
$\tilde{\lambda} \equiv (\rho\sigma)^{-1}$
ρ - local density
σ - cross section

- Implemented for nucleons, pions and hyperons

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

- Semi-classical – includes Pauli blocking, nucleon-nucleon correlation effects



from T. Golan

Intranuclear cascade

Technical details in back-up slides.

Relevant references:

- Correlation effects in NuWro cascade

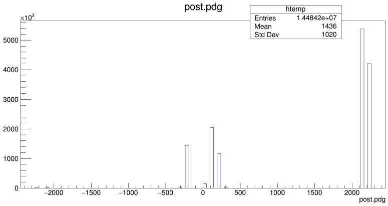
  K. Niewczas and J. T. Sobczyk, Nuclear Transparency in Monte Carlo Neutrino Event Generators, Phys.Rev.C 100 (2019) 1, 015505

- Comparison study of FSI models in NuWro, GENIE and NEUT

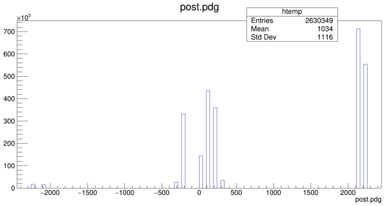
  S. Dytman, Y Hayato, R. Raboanary, J.T. Sobczyk, J. Tena Vidal, Comparison of validation methods of simulations for final state interactions in hadron production experiments, Phys.Rev.D 104 (2021) 5, 053006

Formation zone can be switched on and off - it is a major effect.

Preliminary NuWro results



Without formation zone



With formation zone

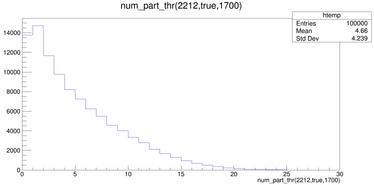
Charged final state particles are mostly protons and charged pions.

See the difference in normalization.

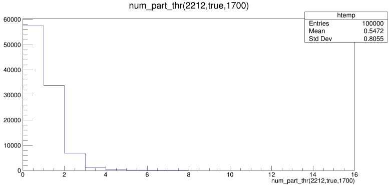
Formation zone (as implemented in NuWro) makes multiplicities much lower ($\sim$ order of magnitude)

Preliminary NuWro results (cont)

Multiplicities of protons with kinetic energy above 1 GeV.



Without formation zone.

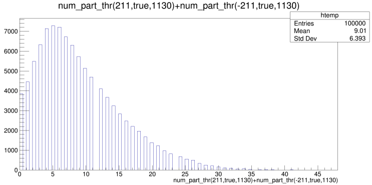


With formation zone.

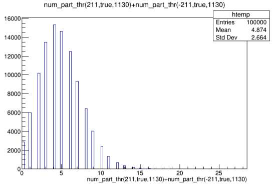
Multiplicity of final state protons is a very good measure of formation zone effects.

Preliminary NuWro results (cont)

Multiplicities of charged pions with kinetic energy above 1 GeV.



Without formation zone.

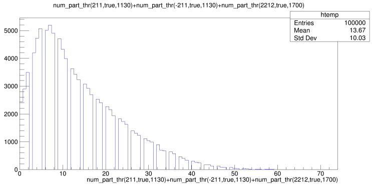


With formation zone.

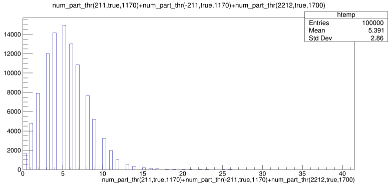
Events with $\sim\geq 15$ charged pions carry information about formation zone effects.

Preliminary NuWro results (cont)

Multiplicities of protons and charged pions with kinetic energy above 1 GeV.



Without formation zone.



With formation zone.

Sorry, I did not have time to investigate impact of formation zone on most energetic protons and charged pions :(.

Thank you!

Back-up slides

NuWro DID model - charged hadrons multiplicities

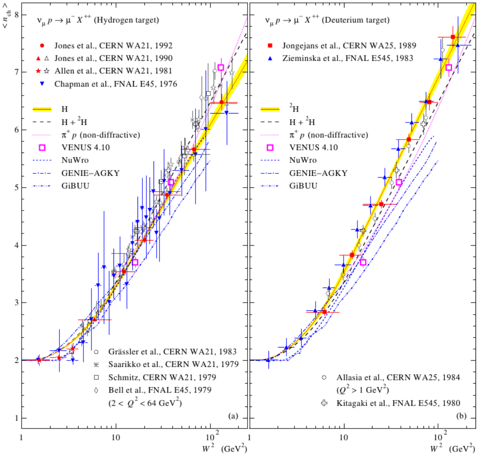
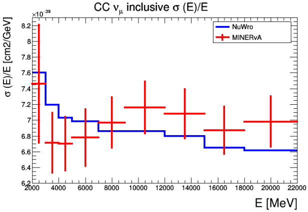
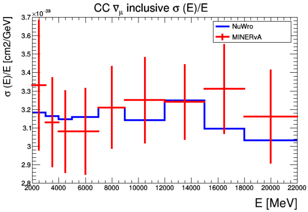


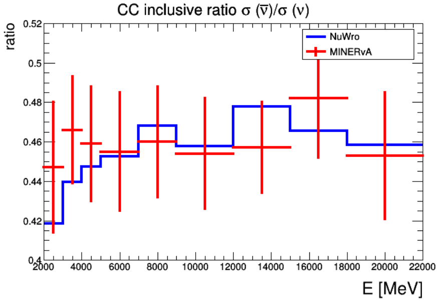
Figure 3. (Color online) A comparison between the fitted and measured charged-hadron multiplicity vs. W^2 for the reaction $\nu_\mu p \to \mu^- X^{++}$ in hydrogen (a) and deuterium (b). The data points are from the experiments FNAL E45 [22, 23], FNAL E545

Kuzmin, Naumov, Phys.Rev.C 88 (2013) 065501

MINERvA inclusive ν_μ, $\overline{\nu_\mu}$, and their ratio Phys.Rev. D95 (2017) 072009



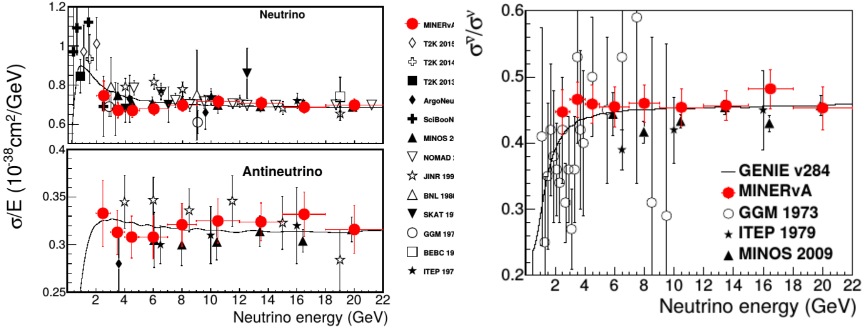




- The agreement is fair.
- MINERvA results are consistent with the previous measurements, see the next slide.

MINERvA inclusive ν_μ, $\overline{\nu_\mu}$, and their ratio

Comparison with the previous experiments



Nucleon cascade – technicalities

- Based on Metropolis at al. algorithm
  N. Metropolis et al., Phys. Rev. 110 (1958) 185-203 and 204-219

- Propagation and interactions of on-shell nucleons

- Nuclear potential from LFG: $V(r) = E_F(r) + E_B$ (nucleons leaving nucleus loose energy)

- Total and elastic free NN cross sections fitted to PDG2016
  M. Tanabashi et al. (Particle Data Group), Phys. Rev. D98 (2018) 030001

- Fraction of 1π production in overall cross section from Bystricky et al.
  J. Bystricky at al, J. Physique 48 (1987) 1901

- Nuclear effects on the top of all that.

Nucleon cascade – in-medium modifications

- V.R. Pandharipande, S. Pieper corrections to the elastic cross section
  - → Reduced relative nucleon velocity and available phase space
  - → Potential obtained from Urbana v_{14} + TNI Hamiltonian

V.R. Pandharipande, S. Pieper, Phys. Rev. C45 (1992) 791-798

- Inelastic cross section modification: $\sigma^{*}_{\mathrm{NN}} = (1 - 0.2\rho/\rho_0)\sigma^{\mathrm{free}}_{\mathrm{NN}}$

Y. Zhang, Z. Li, and P. Danielewicz, Phys. Rev. C75 (2007) 034615

- Nucleon-nucleon correlations effects:
  - → "Effective" nuclear density due to nucleon-nucleon correlations
  - → Correlation function taken from ab initio nuclear matter calculations