NuWro at NUSTEC 2019

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NUSTEC Board Meeting, December 10-12, 2019

NuWro recent and current activities

- New nucleon cascade model
  - K. Niewczas, JTS, Phys.Rev. C100 (2019) no.1, 015505
- Phenomenological 2p2h model
  - T. Bonus, M. Siemaszko, JTS
- CCQE $\bar{\nu}$ hyperon production
  - C. Thorpe, J. Nowak, K. Niewczas, JTS
- New π production model with improved MC algorithm to generate events
  - K. Niewczas, A. Nikolakopoulos
- Long paper - a physics manual and description of all the functionalities
  - NuWro team

The most recent NuWro version is 19.02.1

NuWro cascade model - basic scheme

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

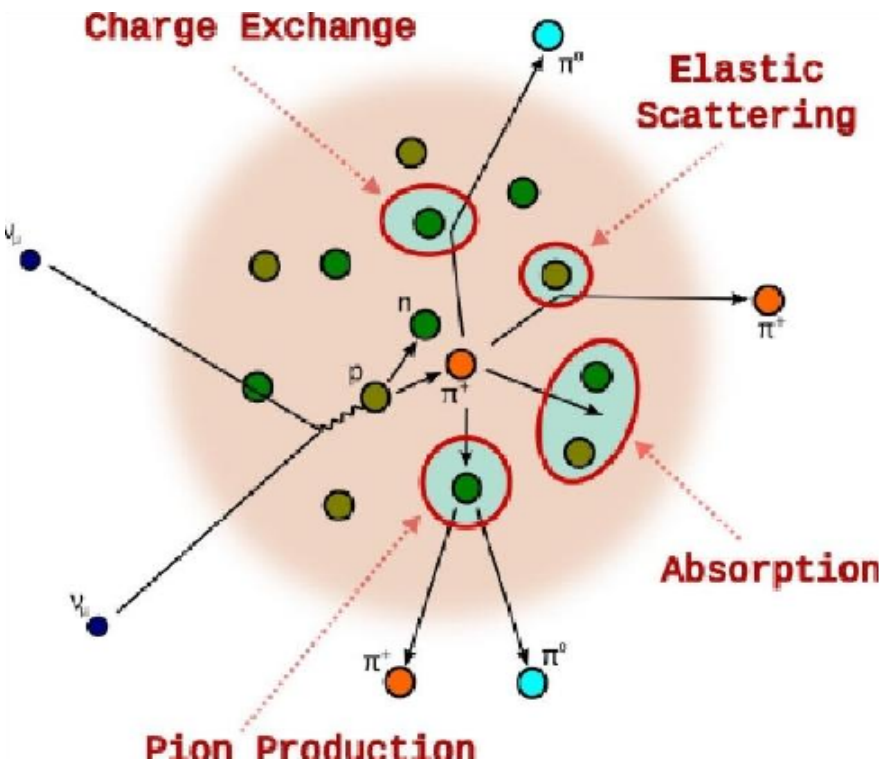
$$P(\lambda) = e^{-\lambda/\tilde{\lambda}}$$

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

- Implemented for nucleons and pions

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

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



from T. Golan

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 of cross sections

- 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

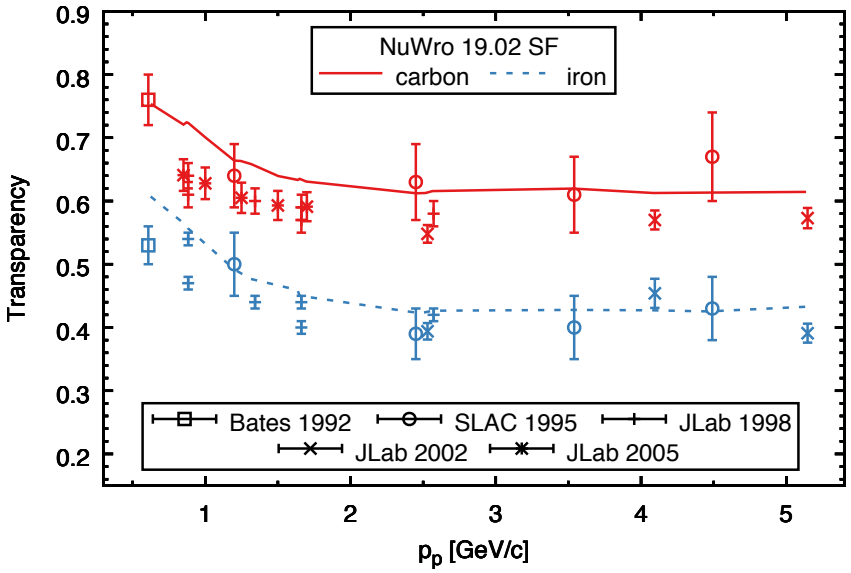
  V.R. Pandharipande, S. Pieper, Phys. Rev. C45 (1992) 791-798

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

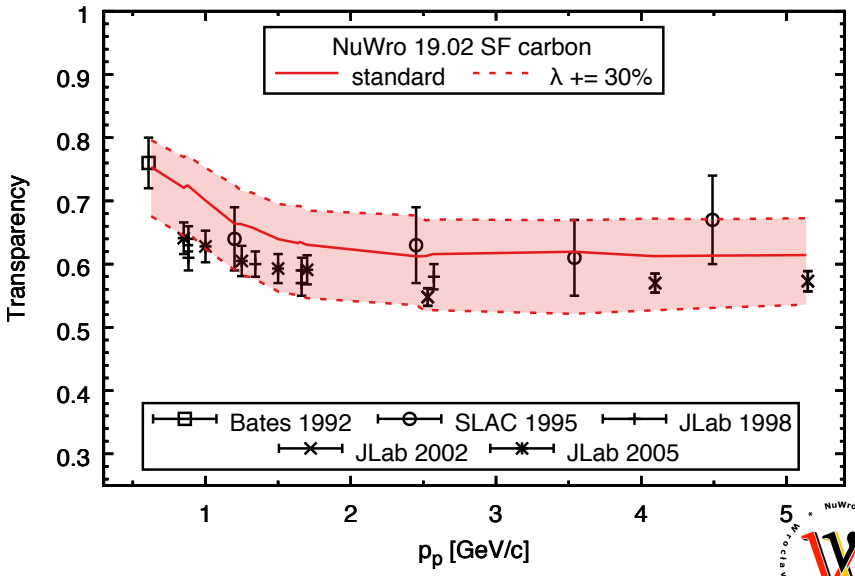
  Y. Zhang, Z. Li, and P. Danielewicz, Phys. Rev. C75 (2007) 034615

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

Nucleon cascade – performance



Top: comparison to transparency data.
Right: estimation of uncertainty (30% scaling of mean free path)

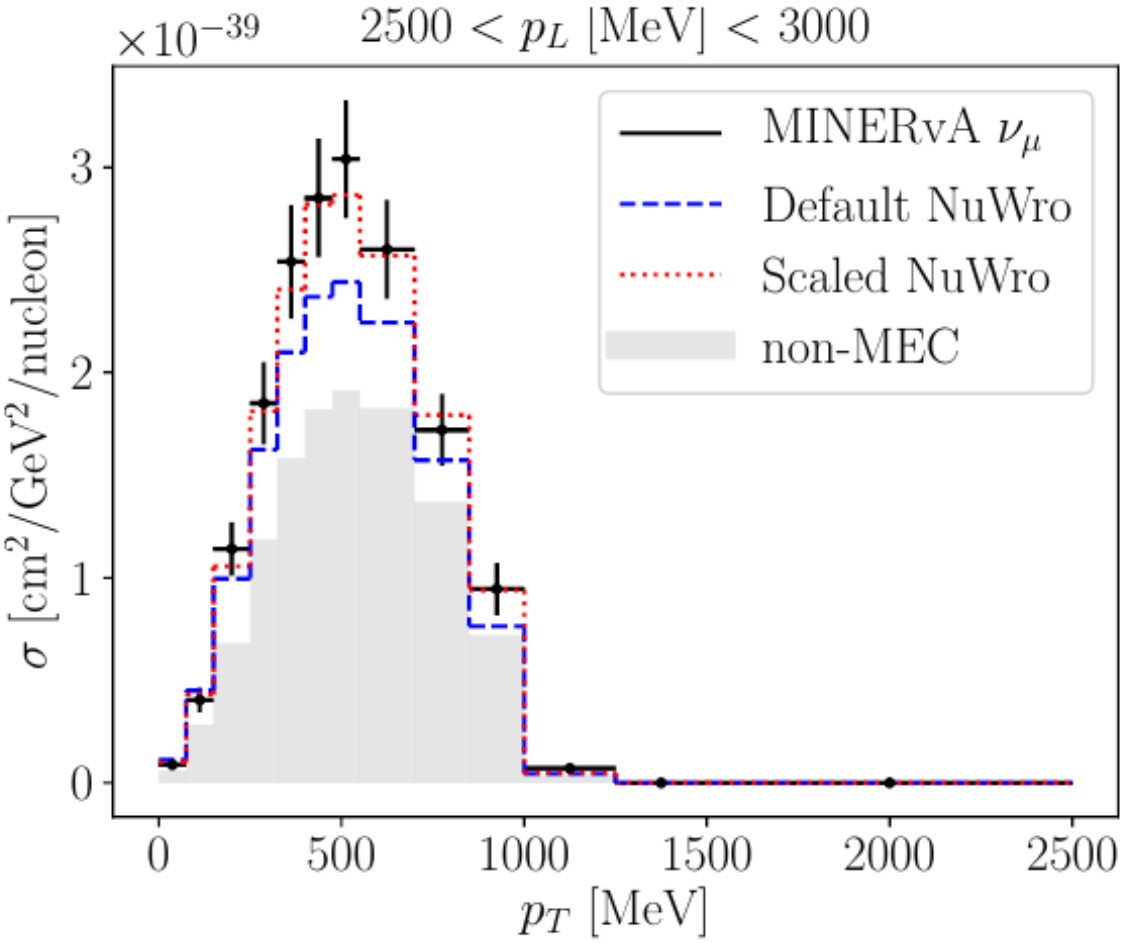


Phenomenological 2p2h model

- Motivation: large differencies between theoretical model predictions.
- An attempt to create a "phenomenological 2p-2h" model based on the Valencia theoretical model.
- T2K and MINERvA CC0π data for ν_μ and $\bar{\nu}_\mu$.
- Results specific to NuWro LFG for CCQE, carbon target.
- The project discussed many times at T2K internal meetings.

Phenomenological 2p2h model

An example of results - still PRELIMINARY!!!



CCQE hyperon production

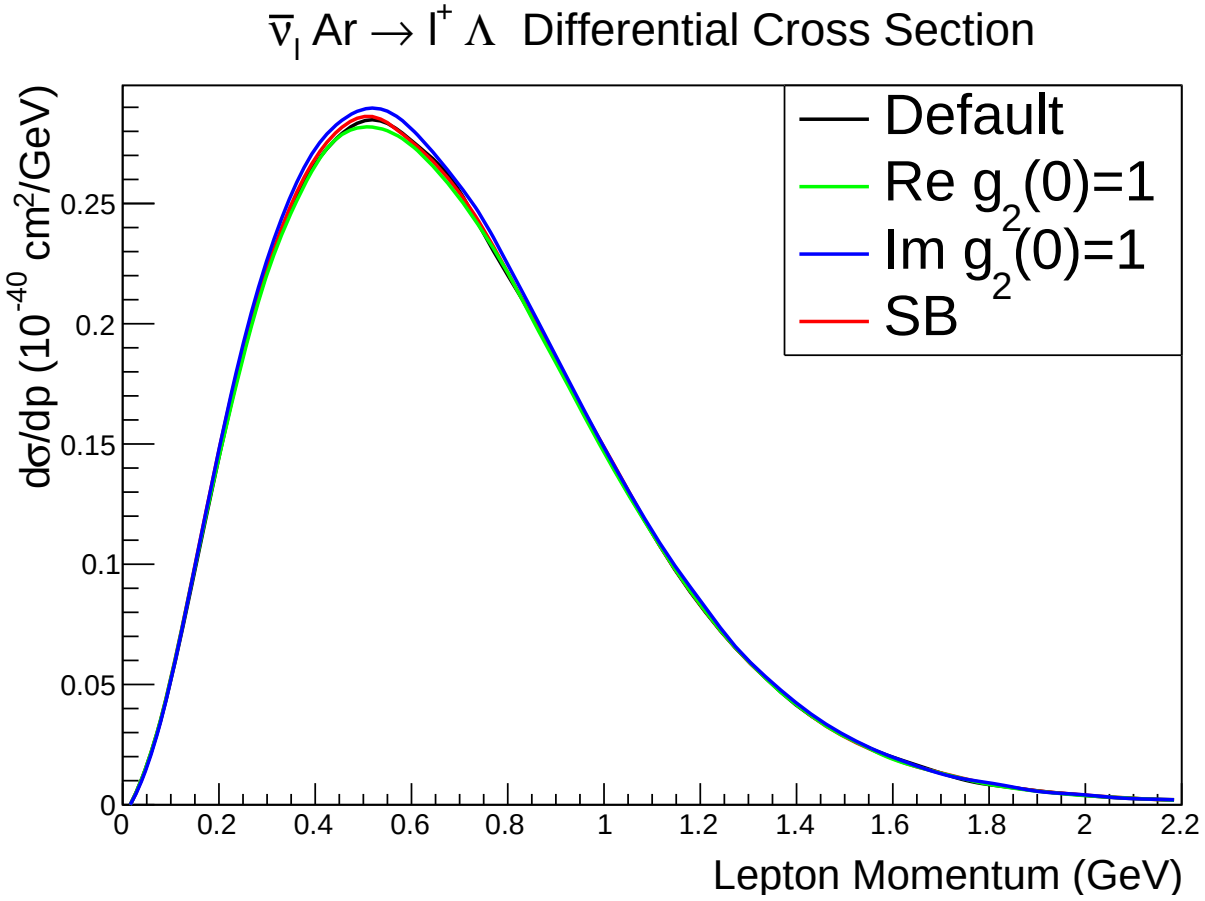
- A missing ingredient in NuWro
- Three channels for $\bar{\nu}$:

$$\begin{aligned} \bar{\nu}_l + p &\rightarrow \Lambda + l^+, \\ \bar{\nu}_l + p &\rightarrow \Sigma^0 + l^+, \\ \bar{\nu}_l + n &\rightarrow \Sigma^- + l^+. \end{aligned}$$

- Suppressed but the process is interesting and is subject of studies, like:

  J.E. Sobczyk, N. Rocco, A. Lovato, and J. Nieves, Phys.Rev. C99 (2019) no.6, 065503
- Hyperons are put into NuWro cascade model.

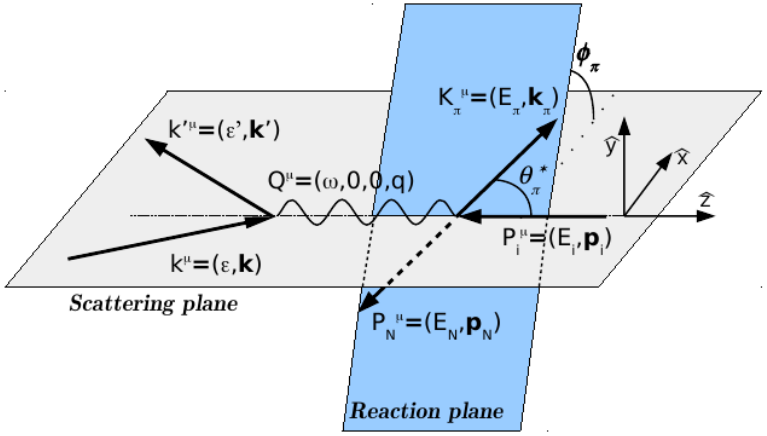
CCQE hyperon production



Ch. Thorpe

Booster beam $\bar{\nu}_\mu$. 4 different sets of theoretical parameters.

Pion production



Within such frame, one can factorize the ϕ^* dependence:

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}Q^2\mathrm{d}W\mathrm{d}\Omega_\pi^*} = \frac{\mathcal{F}^2}{(2\pi)^4}\frac{k_\pi^*}{k_i^2}\left[A + B\cos(\phi^*) + C\cos(2\phi^*) + D\sin(\phi^*) + E\sin(2\phi^*)\right]$$

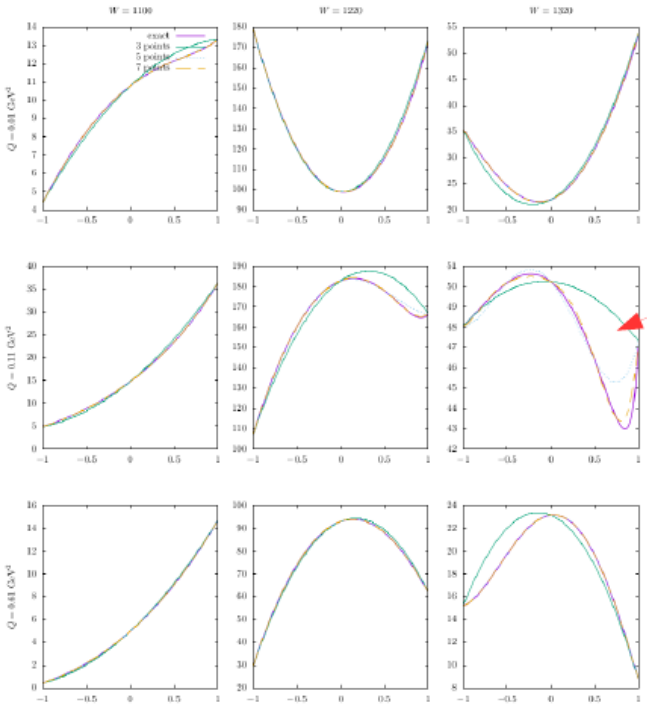
An idea of "cascading" sampling?

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}Q^2\mathrm{d}W} \rightarrow \frac{\mathrm{d}^3\sigma}{\mathrm{d}Q^2\mathrm{d}W\mathrm{d}\cos\theta_\pi^*} \rightarrow \frac{\mathrm{d}^4\sigma}{\mathrm{d}Q^2\mathrm{d}W\mathrm{d}\Omega_\pi^*}$$

Pion production

given a Q2 and W, distribution of cosθ* is determined by A

$$\frac{d\sigma}{dQ^2 dW d\Omega_\pi^*} = \frac{\mathcal{F}^2}{(2\pi)^4}\frac{k_\pi^*}{k_l^2}\times[A + B\cos(\phi^*)\, C\cos(2\phi^*) + D\sin(\phi^*) + E\sin(2\phi^*)]$$



A is a smooth function and can usually be interpolated by a polynomial of degree 2

Calculation of A(cos) for fixed Q2 and W is very cheap

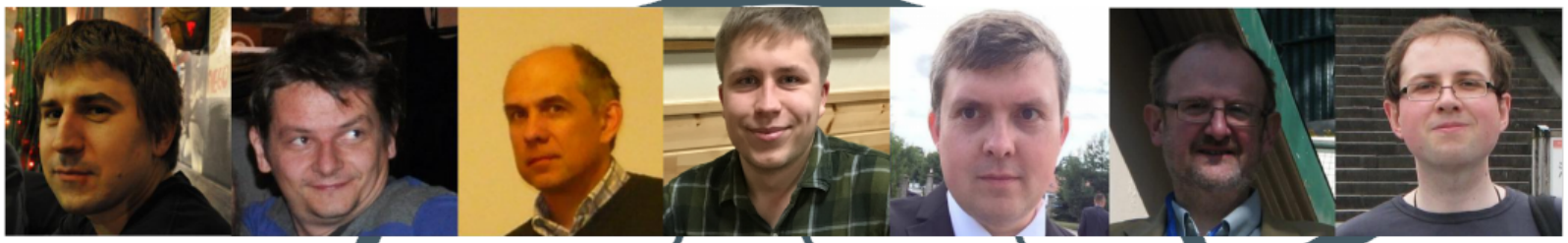
Interpolation with degree 2 polynomial means:

Cumulative distribution function

$$CDF(\cos(\theta)) = \int a_2\cos^2\theta + a1\cos\theta + a_0\, d\cos\theta$$

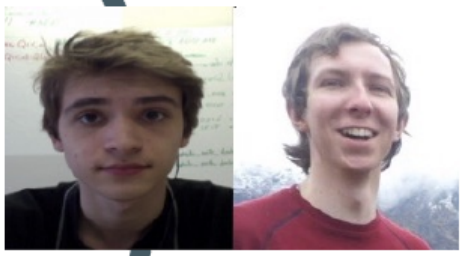
Is a monotonic degree 3 polynomial
→ Can be inverted analytically
→ Inversion sampling

NuWro team



T. Golan | K. Graczyk | C. Juszczak | K. Niewczas | J. Nowak | J.T. Sobczyk | J. Żmuda

new students →



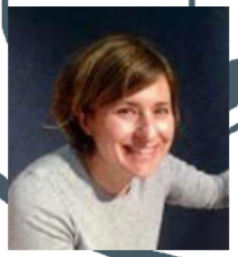
T. Bonus | C. Thorpe

Notable supporters

D. Kiełczewska (passed away in 2016)

Inspiration

P. Przewłocki



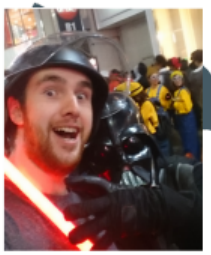
K. Kowalik

NuWro at T2K

A. Ankowski

Spectral function

L. Pickering



P. Stowell

Reweightning tools