Comparison of Validation Methods for Final State Interactions in Hadron Production Experiments

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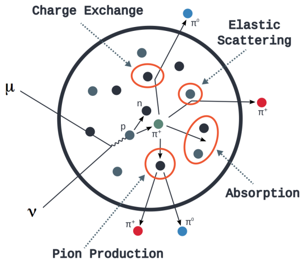
17 March 2021

New Directions in Neutrino-Nucleus Scattering

Introduction

- Neutrino interaction modelling is essential to **address backgrounds** and **systematic errors** in ν measurements
- ν measurements depend on FSI modelling
  - $\rightarrow$ Hard to model and approximations are required
  - $\rightarrow$ One of the largest uncertainty sources
- At $KE_{hadron} < 1$ GeV, the reinteraction probability in Ar
  - p: $40 - 50$ %
  - π^+: $<\sim 75$ (strong E dependence!)%

MC generators are an essential tool



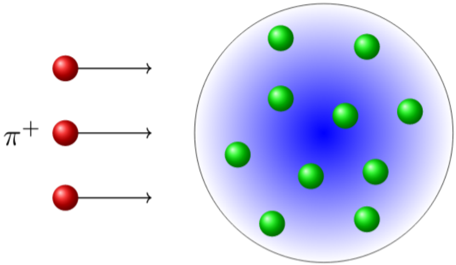
For this work, models are checked against two different general kinds of data

- Total reaction cross section data
- Transparency data

First time to be discussed in detail

Role of hadron-nucleus data

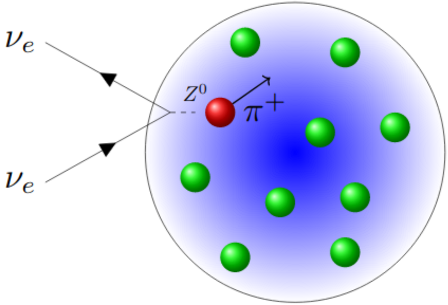
- σ^{reac} provides a general validation method for codes
- σ^{reac} includes all final state channels except elastic
- Measured using hadron beams
- Interaction occurs on the periphery of the nucleus
- Large body of data is available



Role of transparency data

Transparency (T) is defined as the probability of the ejected hadron to not re-interact

- Hadron starting location related to the matter density, same as neutrino experiments
- Until now, no code has been validated against transparency data
  - → First comparison by NuWro [Niewczas and Sobczyk(2019)]
- Some electron data exists for carbon and heavier elements → **No data on argon**



- Understanding relationship between σ^{reac} and transparency is primary goal
  - σ^{reac} and transparency go in opposite directions as function of KE, but how?

Nuclear effects that modify transparency and σ^{reac}

Nuclear effects can significantly alter the transparency and reaction cross section predictions

1. **Formation zone**
   $\rightarrow$ Affects only transparency calculations
2. **Medium effects**
   $\rightarrow$ Different effect on T and σ^{reac}
3. **N-N correlations**
   $\rightarrow$ Negligible effect for σ^{reac}, though significant for T

Different approaches are followed by each MC generator

Goals

- Comparing results from GENIE, NEUT and NuWro:

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- Study FSI effects of p and π^+ in carbon (this talk) and argon (backup slides)
- Comparison between total reaction cross section and transparency from a simulation view point
- Understand the role of the different nuclear effects
  - $\rightarrow$ Different implementations in each MC generator
- Paper available in ArXiv: `https://arxiv.org/pdf/2103.07535.pdf`

Similarities between GENIE, NEUT and NuWro

GENIE hA2018 and hN2018, NuWro, and NEUT share the following characteristics:

- The nucleus is modelled as an ensemble of independent particles
- Nucleon momenta described by a Local Fermi gas distribution
- Nucleons are bound: binding energy corrections are applied
- Other effects at the interaction vertices (Pauli blocking, medium corrections, etc.) are implemented separately

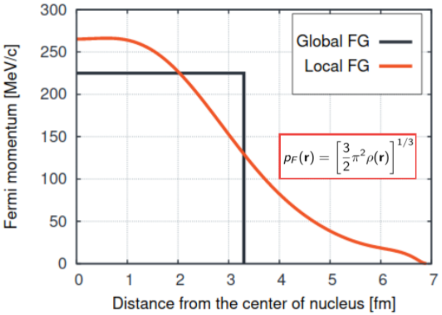
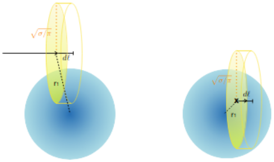


Figure: From Tomasz Golan talk

Similarities between GENIE, NEUT and NuWro

- GENIE hA2018 and hN2018, NuWro, and NEUT are based on **custom cascade models (INC)**:
  - Particles are moved by a small step
    - 0.05 fm in GENIE
    - 0.2 fm in NuWro and NEUT
  - The probability of not interacting is $P(\lambda) = \exp(-\lambda/\tilde{\lambda})$, where $\tilde{\lambda}$ is the mean free path
- In INCL++, the entire hadron-residual system changes through time steps and interactions occur when $d_{min} < \sqrt{\sigma/\pi}$
- Different methods for propagating hadrons (time) in the nuclear medium exist:
  - See next talk by [Isaacson et al.(2020)]
  - The nucleon position/momentum is generated with the QMC method where all nucleons are interacting with realistic potentials.
  - Cylinder interaction approach: probe-nucleon separation doesn't have to be small.



NEUT Specifics

Relevant features:

- **Pauli blocking** is considered
- **Medium corrections** implemented for pions at the delta region only [Salcedo et al.(1988)]
  - → Otherwise, they use free π-N and nucleon nucleon scattering
  - → Same approach followed by NuWro and GENIE

Process	p	π^+
Pauli Blocking	Yes	Yes
Medium Effects	None	$KE_\pi = 85 - 350$ MeV
NN correlations	None	None
Formation zone	None	Yes

- They adjust π-N cross section to get good agreement with $\sigma^{reac}_{\pi N}$ data
- **Formation zone** effect based on SKAT data for pion production

NuWro Specifics

- **Medium corrections** for pions and protons
  For π: same as NEUT
  For p:
  → Elastic: [Pandharipande and Pieper(1992)]
  → Inelastic: in-medium microscopic cross section $\sigma^*_{\mathrm{NN}} = (1 - \eta \cdot \rho/\rho_0)\sigma^{\mathrm{free}}_{\mathrm{NN}}$ being ρ (ρ_0) the local (saturation) density

Process	p	π^+
Pauli Blocking	Yes	Yes
Medium Effects	Yes	Yes
NN correlations	Yes	-

- NN correlations modify the nucleon density

$$\rho^{[1]}_{\mathrm{eff,IPSM}}(\vec{r}_2|\vec{r}_1) = \rho^{[1]}_{\mathrm{A}-1}(\vec{r}_2)g(|\vec{r}_{21}|)N(|\vec{r}_1|)$$

GENIE Specifics - hA2018 and hN2018

hA2018:

- **Empirical approach**
- Single interaction based on hadron-nucleus data
- Medium effects for nucleon-nucleon [Pandharipande and Pieper(1992)]

hN2018:

- **Similar to NEUT and NuWro**
- Nucleons don't propagate below an energy cutoff proportional to $12A^{0.2}$ MeV

Generator	Pauli blocking	medium effects	Cut off
	Proton		
GENIE hA2018	None	Yes	None
GENIE hN2018	None	Yes	$12A^{0.2}$ MeV
	Pion		
GENIE hA2018	None	none	none
GENIE hN2018	None	$T_\pi = 85 - 350$ MeV	None

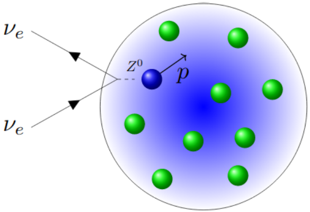
No Pauli Blocking or formation zone considered in any of the models

GENIE Specifics - INCL++

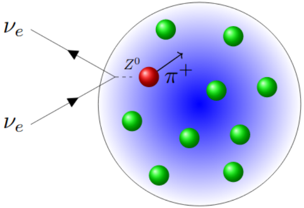
1. **Sophisticated nuclear model:**
    - All nucleons are placed in a square well whose depth and range depends on the nucleon position
2. **Cascade model approach**
3. **Main benefits:**
    - Pauli blocking is applied
    - Improved momentum distribution and binding energy correction
    - Medium corrections applied naturally
    - Propagating hadrons are off-shell
    - The Δ propagates independently with competing interactions and decay possibilities

Event generation for transparency

Proton transparency - NC elastic

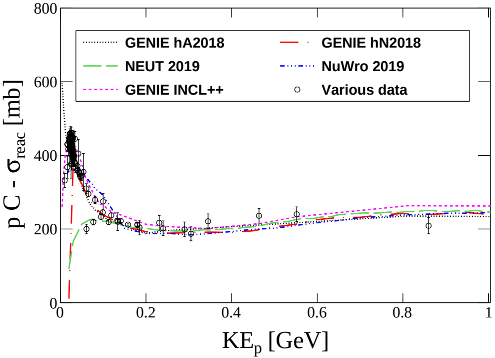


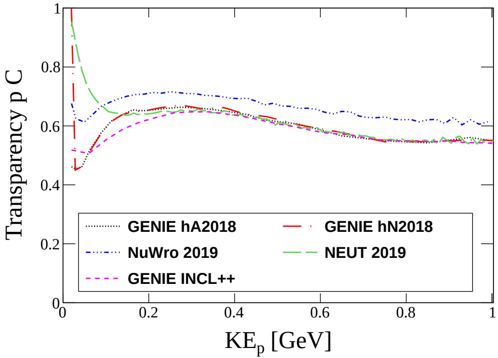
Pion transparency - NC resonance



- Identical interactions are chosen according to same nucleon density distribution
- Neutrino beam: not all codes have electron modes implemented
- NC EL and NC RES interactions to model proton and pion transparency respectively
- In this talk we focus on carbon
- Monte Carlo transparency, i.e. no experimental acceptance applied

Comparisons between σ^{reac} and T of protons on carbon



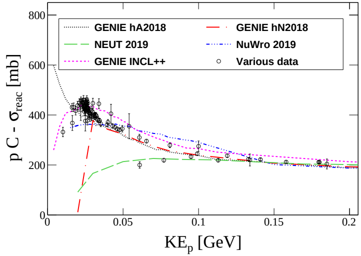


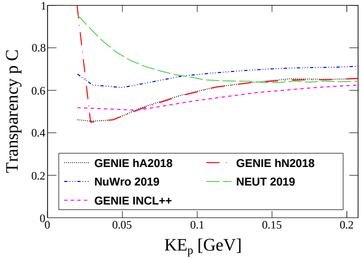
- At high kinetic energies ($KE_p >\sim$ 200MeV), nuclear effects are small
- NN correlations influence transparency and not σ^{reac}
  - $\rightarrow$ NuWro σ^{reac} agrees with the other calculations
  - $\rightarrow$ NuWro T is higher than the others due to NN correlations

Comparisons between σ^{reac} and T of protons on carbon

The models diverge at low kinetic energy where nuclear effects are bigger

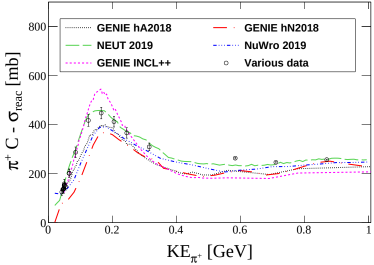
- Rise in σ^{reac} as a consequence of a rise in σ_{pN}
- σ^{reac} peaks and decreases at lower energies due to Pauli blocking and medium corrections
  - Peak at $\sim$ 30 MeV observed for NuWro and INCL++
  - GENIE hA and hN have no Pauli blocking, but GENIE hN cutoff avoids rise in σ^{reac}
  - NEUT starts diverging from others at $\sim$80 MeV due to Pauli blocking
  - INCL++ has the best agreement with σ^{reac} data

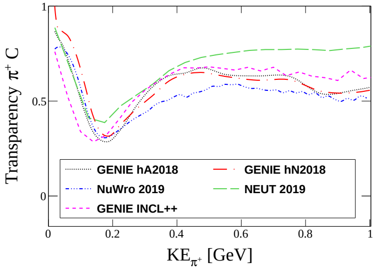




Comparisons between σ^{reac} and T of π^+ on carbon

- The $\Delta(P_{33}(1232))$ resonance effect on σ^{reac} and T is seen at $KE_\pi \sim 165$ MeV
  - $\rightarrow$ In agreement between calculations
  - $\rightarrow$ Underestimating experimental points
- **Spread of π^+ simulations is larger.** Predictions affected by
  1. Formation zone (NEUT only)
  2. Different treatment of high mass resonances (NuWro, GENIE INCL++)
  3. INCL++ predicts a larger σ^{reac} at the Δ peak
     - $\rightarrow$ Treat Δ as a propagating particle
  4. INCL++ Binding energy correction for the propagating particle shifts the delta dip in T
     - $\rightarrow$ Similar to Salcedo-Oset medium corrections but beyond

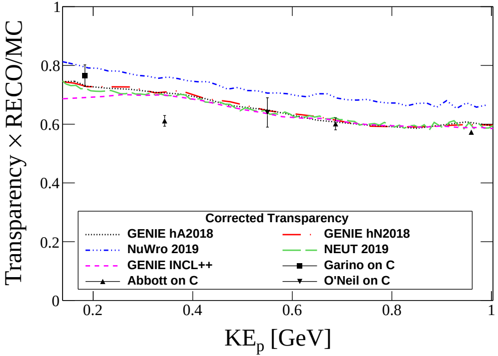




Comparison with proton-carbon transparency data

Computation of **acceptance correction factors** from electron beams is beyond this study

- NuWro made transparency calculations with and without the experimental acceptance
  effects [Niewczas and Sobczyk(2019)].
- The ratio is used to estimate the impact of acceptances on the other model results
- The estimated acceptance corrections put all calculations in **reasonable agreement** with the existing data
  - Short range NN correlations increase NuWro transparency at all KE



Conclusions

- NEUT, NuWro and GENIE codes use **different INC approximations**, esp. nuclear effects
- **Transparency gives information about FSI effects as they would apply neutrino oscillation experiments** - No data on argon. Mostly T data on proton at high KE
- Nuclear effects on σ^{reac} and T are studied for p and π^+ on carbon
- **Strong energy dependence** that has significant effects on T
- **At high KE**,
  - Variations among σ^{reac} and T results are roughly similar
  - Good agreement with carbon proton transparency data for all codes
  - **No major errors** in existing codes against data now available are apparent
- **For low KE protons**, differences between MC generators are notable due to **nuclear effects**
  - $\rightarrow$ GENIE INCL++ has best nuclear model and best agreement with data
  - $\rightarrow$ **Big uncertainty for ν oscillation experiments** depending on models for low KE nucleons
- **Weak A dependence** - No significant changes for argon, see backup

Very **interesting possibilities** for new transparency measurements!

Thank you!

References I

- K. Niewczas and J. T. Sobczyk, Phys. Rev. C **100**, 015505 (2019), 1902.05618.
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- V. R. Pandharipande and S. C. Pieper, Phys. Rev. **C45**, 791 (1992).
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Backup slides

Similarities between GENIE, NEUT and NuWro

GENIE hA2018 and hN2018, NuWro, and NEUT share the following characteristics:

- Custom cascade models (INC)
- Other effects (Pauli blocking, medium corrections, etc.) are implemented separately

Cascade model approach

1. Calculate mean free path: $\tilde{\lambda} = (\sigma_p \rho_p(\mathrm{r}) + \sigma_n \rho_n(\mathrm{r}))^{-1}$
2. Move propagating particle by a small step λ (typically 0.2fm)
3. If particle in nucleus, generate interaction with $P(\lambda) = \exp(-\lambda/\tilde{\lambda})$
4. (*) Apply Pauli blocking (NEUT, NuWro and INCL++)
5. Repeat until the particle leaves the nucleus

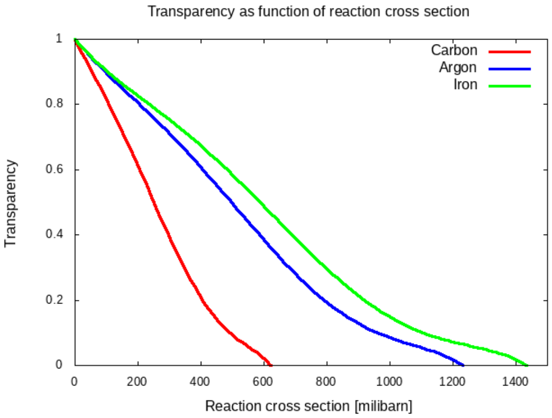
How are reaction cross section and transparency related?

Toy model

- Analitic formulas describe most basic physics
  - $\rightarrow$ Only nuclear density and hadron-nucleon cross section
- The analytic formula for ratio allows the calculation of T from σ^{reac} independent of particle choice.

Expected relationship between T and σ^{reac}:

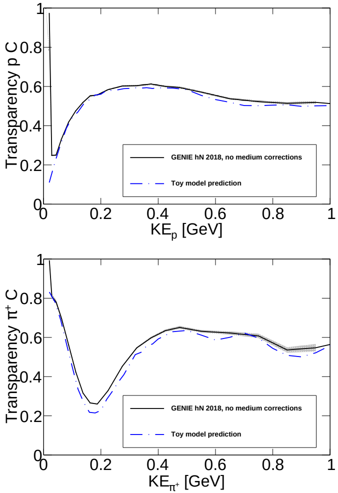
- $\lim_{\sigma^{reac} \to 0} T(\sigma^{reac}) \to 1$
- $\lim_{\sigma^{reac} \to \sigma^{reac\,max}} T(\sigma^{reac}) \to 0$
- T is large when σ^{reac} is small and vice versa



Toy model prediction for GENIE transparency on carbon

- Transparency toy model predictions are obtained from $\sigma^{reac\,GENIE}$
- Stripped-down GENIE agrees well with the predictions for transparency on p and π^+ on carbon

The toy model is a powerful tool to study nuclear effects that modify transparency only



INCL++ in GENIE

- INCL: Intranuclear cascade model
  - It describes the two steps model of a spallation reaction: the cascade stage and the evaporation stage
  - INCL++ is coupled with a set of interface to de-excitation model (Gemini++, ABLA++, ABLA07 (the default), SMM.
  - simulate reactions induced by nucleons, pion and light ion on any target nucleus.
- Included in GENIE as an alternate FSI model
- INCL++ will be available in the GENIE 3.2.0 release
- Also implements the cascade approach
- Used for:
  - Production of hadron-nucleus cross-section.
  - Production of lepton-hadron production interactions.

INCL++ in GENIE

- **Propagation**: stepped in time, all particle are in movement (projectile and nucleon of the target) The time step:

$$t_{step} = -\frac{\vec{d}^0_{ab} \cdot \vec{v}_{ab}}{v^2_{ab}}$$

- $\vec{d}^0_{ab}$: the initial relative position between the two nucleon,
- $\vec{v}_{ab}$: the relative propagation velocity;

- **Collision** happens when two particles reach their minimum distance of approach d_{min}
  - Decision test by $d_{min} < \sqrt{\sigma^{tot}/\pi}$, where σ^{tot} is the total cross section.
- **Stopping time** of the cascade: $t_{stop} = t_0 \cdot f_{stop} \frac{A_T}{208}^{0.6}$, $t_0 = 70 fm/c$, $f_{stop} = 1$

INCL++ stopping time/ (time step)

The distance minimum of approach:

$$d_{min}^2 = (\vec{d}_{ab}^0)^2 + t_{step}\vec{d}_{ab}^0 \cdot \vec{v}_{ab}$$

$t_{stop} = 70(A/208)^{0.6} = 29.8 \cdot A^{0.16}$, A : mass number of the target, and t_{stop} has a unit fm/c.

- If the projectile is a pion $t_{stop} = 30.18 \cdot A^{0.17}$
  - If the projectile is a nucleon $t_{stop} = 29.8 \cdot A^{0.16}$
  - Above 2 AGeV the stopping time depends on the energy $t_{stop} = (5.8E4 - T_{Lab})/5.6E4$ with $T_{Lab} = \frac{E_{Kin}}{A}$, E_{Kin}: Kinetic Energy of the incident particle and A his mass number.
- If the incoming particle is slow: $t_{stop} = 2 \cdot r_{max}/v$ with r_{max} is the universe radius of the projectile particle and v his velocity.

When the cascade stop, all Δ are forced to decay and conservation laws of the number of mass, charge number and the energy are applied.

Nuclear effects on protons

- Nuclear effects are handled in similar ways by the different codes:

Generator	Pauli blocking	medium effects	NN correlations
GENIE hA2018	None	[Pandharipande and Pieper(1992)]	None
GENIE hN2018	None	[Pandharipande and Pieper(1992)]	None
GENIE INCL++	Yes	[Boudard et al.(2013)]	None
NuWro 19.02	Yes	[Pandharipande and Pieper(1992)]	[Pandharipande and Pieper(1992)]
NEUT v5.4.0.1	Yes	None	None

- No formation zone is considered by any of the codes for protons

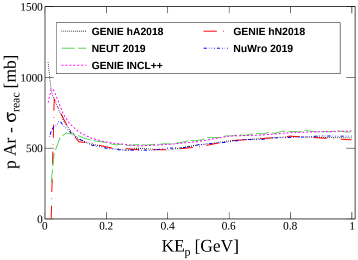
Nuclear effects on pions

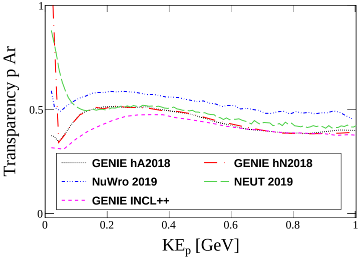
- Nuclear effects are handled in similar ways by the different codes:

Generator	Pauli blocking	medium effects	Formation zone
GENIE hA2018	None	none	none
GENIE hN2018	None	Ref. [Salcedo et al.(1988)]	None
GENIE INCL++	Yes	Ref. [Boudard et al.(2013)]	None
NuWro 19.02	Yes	Ref. [Salcedo et al.(1988)]	None
NEUT v5.4.0.1	Yes	Ref. [Salcedo et al.(1988)]	Yes

Atomic mass dependence

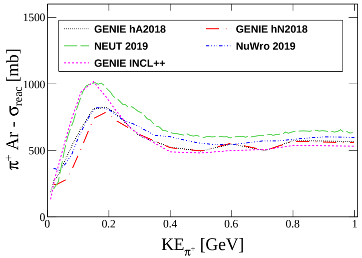
- The calculations can be directly compared with the results shown in the talk.
- The importance of nuclear medium effects can be expected to increase as the size of the nucleus increases. However,
  - The gross features of each model are unchanged
  - Basic effects scale linearly with A
- No data on argon
- The increase in *A* makes the curves spread more extreme
- A dependence is not significant or the models fail to account properly for it

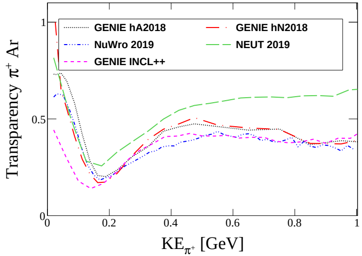




Atomic mass dependence

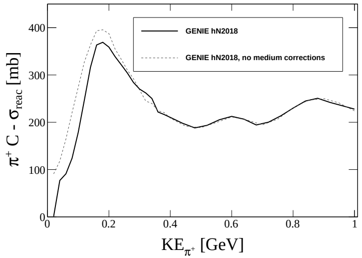
- The calculations can be directly compared with the results shown in the talk.
- No data on argon
- The increase in A makes the curves spread more extreme
- Medium effects make the Δ peak wider for pions with a corresponding effect in transparency.
- A dependence is not significant or the models fail to account properly for it

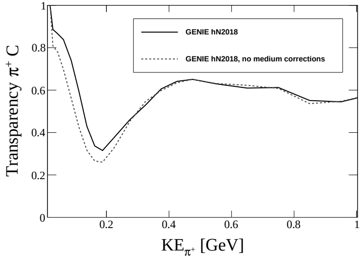




Medium effects in GENIE

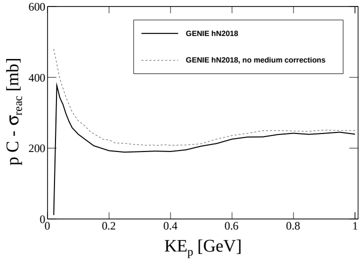
- Here we show the impact of the Salcedo-Oset [Salcedo et al.(1988)] medium effects on π^+ for carbon for σ^{reac} and T
  - The model includes a modification of Δ self-energy due to medium effects via the local density approximation.
  - The 80-350 MeV range of applicability is also allowed to work at $KE_\pi < 80$ MeV (small effects).
  - Small discontinuity at 350 MeV.
- When medium effects are removed, no nuclear effects remain $\rightarrow \sigma_{\pi N}$
- The effect is a reduction about 10% from σ^{reac} at the cross section peak and an increase of about 15% to T.

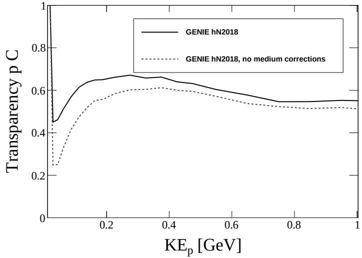




Nucleon-nucleon medium effects in GENIE

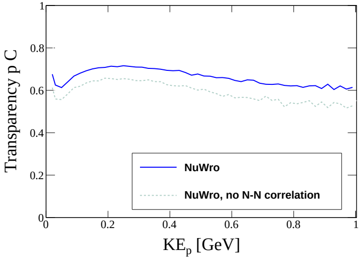
- Nucleon-nucleon medium effects are included with Pandharipande and Pieper [Pandharipande and Pieper(1992)] model (local density approximation)
    - Implemented as a set of look-up tables as a function of nucleon energy and nuclear density for a variety of nuclei
    - Small dependence on nucleus handled with a linear interpolation between tables
- Largest effect is found at low KE where the interaction cross section is large and nuclear effects are important.
- The effect is a decrease in σ^{reac} and increase in T





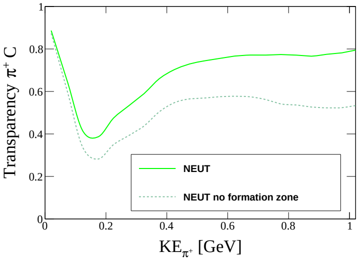
Short N-N correlations in NuWro

- Short N-N correlations increase T by 10-15% in the whole range of proton kinetic energies.
- Because of nucleon-nucleon correlations, the probability of having another nucleon in a sphere of radius ~ 0.8 fm around any nucleon is strongly suppressed.
  - Interactions typically occur in the central region of nucleus with higher density.
  - Due to correlation effects there, nucleons are more likely to leave this region avoiding any reinteraction.
- Correlations do not affect reaction cross section where only the single nucleon density is relevant.



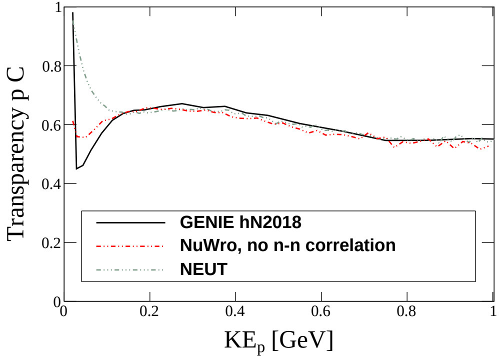
Formation zone in NEUT

- NEUT implements a formation zone effect based on SKAT data for pions
- The pions production point is shifted by $L_{FZ} \cdot (-\log(rand[0,1])$. $L_{FZ} = p/\mu^2$, where p is the momentum and $\mu = 0.08$ GeV/c^2
- Interactions are suppressed by giving the particle a region where it won't interact
- Similar effect to that of correlations
- Increases the π^+ transparency for a wide range of energies
- Could be easily tested in a pion electro-production experiment



"Direct" Comparisons

- Once the NuWro NN-correlations are removed, the results for proton-carbon have a good agreement at $KE_p \sim 200$ MeV
    - Lack of model dependence there
- NuWro and GENIE *hN* are in agreement indicating very similar implementation of the medium corrections.
- NEUT doesn't have the medium corrections that are in both NuWro and GENIE *hN* and this is shown to be a significant effect
    - The agreement must be caused by other differences such as the choice of nucleon-nucleon interactions.



"Direct" Comparisons

- With the NEUT formation zone removed, the comparison for π^+-carbon becomes more straightforward, but it is not simple.
- All calculations have medium corrections but GENIE hN does not agree with the rest
- NuWro and NEUT agree with each other and GENIE *hN* has a different shape and larger magnitude.
  - Preliminary explorations indicate that $\sigma_{\pi N}^{reac}$ employed different
- Calculations agree on the depth of the dip due to the Δ resonance
- At the lowest energies, GENIE *hN* has a larger transparency than the others due to lack of Pauli blocking.