NuWro - recent progress and FSI reweighing

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Outline

1) NuWro - general introduction

2) Examples of performance

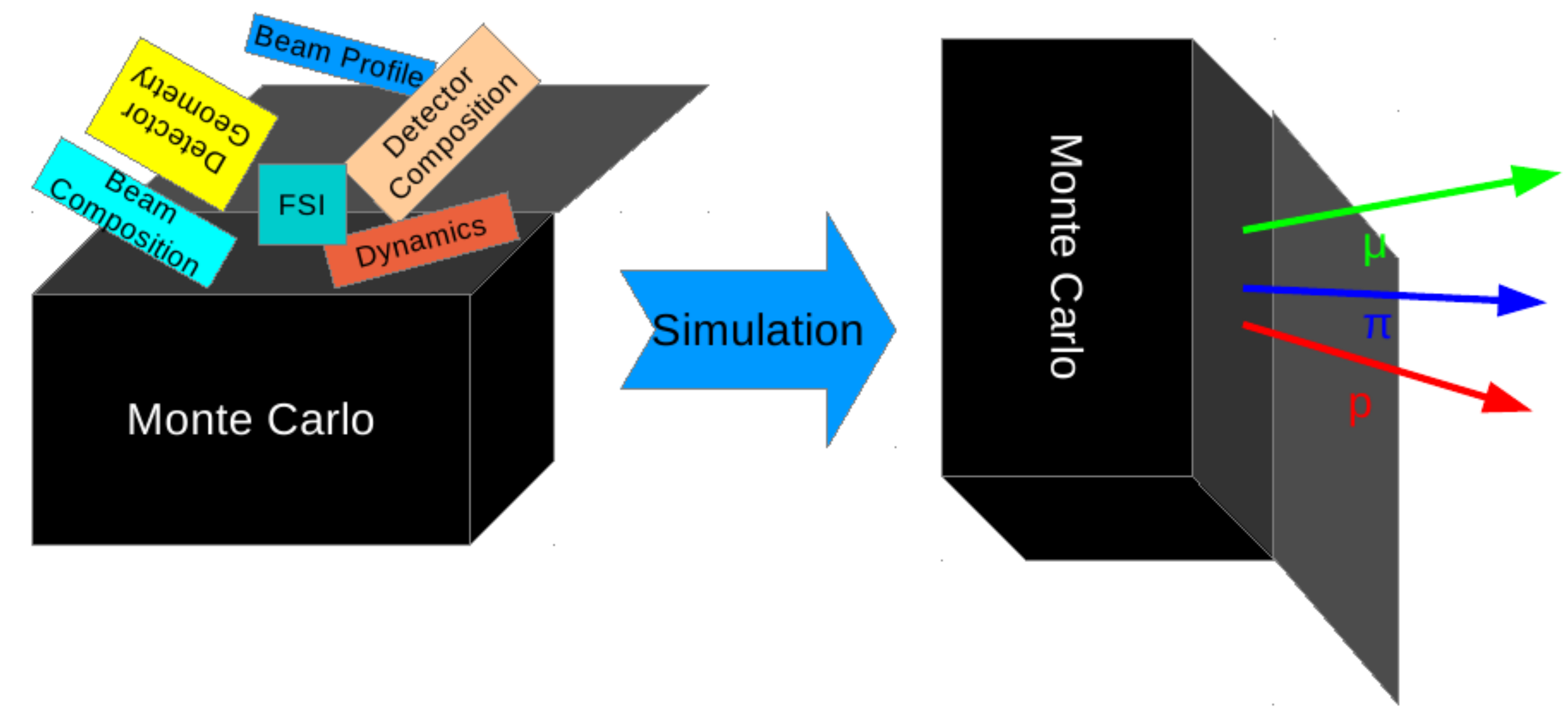
3) NuWro 25.03.1, new features:
- new single pion production model
- new MEC model

4) NuWro FSI model
- tests
- uncertainties

5) FSI reweighting
- generalities
- toy model
- example: NuMi ME flux MINERvA measurement

6) Conclusions

NuWro - general information (1)



- Monte Carlo generator of neutrino interactions
- Beginning ~ 2005 at the University of Wrocław
- Optimized for ~1 GeV
- Can handle all kind of targets, neutrino fluxes, equipped with detector interface
- Written in C++
- Output files in the ROOT format
- PYTHIA6 used for hadronization in DIS
- Open source code, repository: https://github.com/NuWro/nuwro

NuWro - general information (2)

- A major part of NuWro physics models were investigated and implemented by PhD students:

Jarosław Nowak (2006),

Tomasz Golan (2014),

Kajetan Niewczas (2023)

- A structure of the code was constructed by Cezary Juszczak
- Important contributions from Artur Ankowski, Krzysztof Graczyk, Chris Thorpe, Dmitry Zhuridov, Jakub Żmuda.
- Reweighting tools added by Luke Pickering and Patrick Stowell.
- New PhD students: Rwik Dharmapal Banerjee, Hemant Prasad.
- NuWro AI studies: Luis Bonilla, Beata Kowal

Inspiration - credit to Danka Kiełczewska

NuWro - basic interaction modes

Dynamics for neutrino-free target scattering.

Quasi-elastic scattering **(QEL)**

$$\nu_l \, n \to l^- \, p, \quad \bar{\nu}_l \, p \to l^+ \, n$$

and its neutral current counterpart

$$\nu \, N \to \nu \, N$$

RES (for resonance excitation) defined by W < 1.9 GeV, for example

$$\nu_\mu \, p \to \mu^- \, \Delta^{++} \to \mu^- \, p \, \pi^+$$

Also second resonance region is treated properly

``Deep inelastic scattering'' **(DIS)** defined by W > 1.9GeV

Quasi-elastic hyperon production **(HYP)**

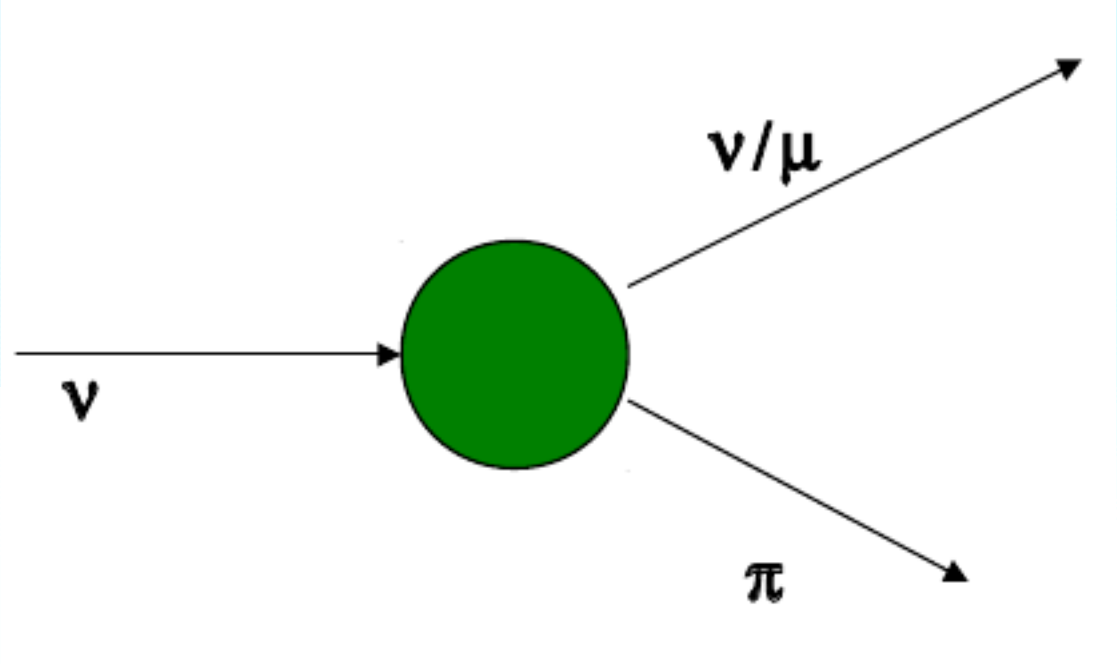
$$\bar{\nu}_l + p \to l^+ + \Lambda, \quad \bar{\nu}_l + p \to l^+ + \Sigma^0, \quad \bar{\nu}_l + n \to l^+ + \Sigma^-$$

Neutrino-electron scattering **(LEP)**

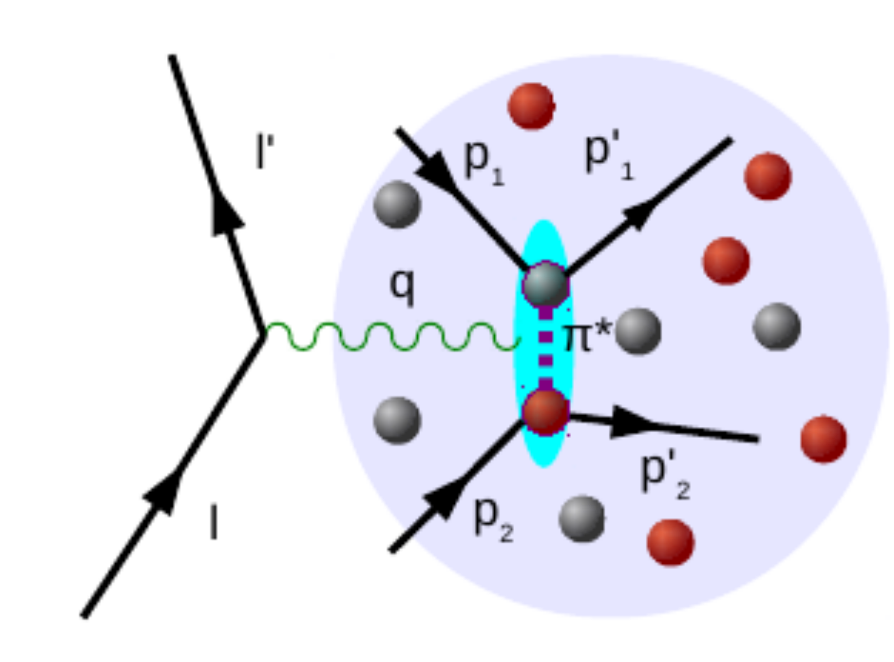
$$\nu_l \, e \to \nu_l \, e, \quad \nu_l \, e \to \nu_e \, l, \quad \bar{\nu}_l \, e \to \bar{\nu}_l \, e, \quad \bar{\nu}_e \, e \to \bar{\nu}_l$$

NuWro - basic interaction modes

In the case of nucleus target there are two other basic dynamics:



Coherent pion production **(COH)**

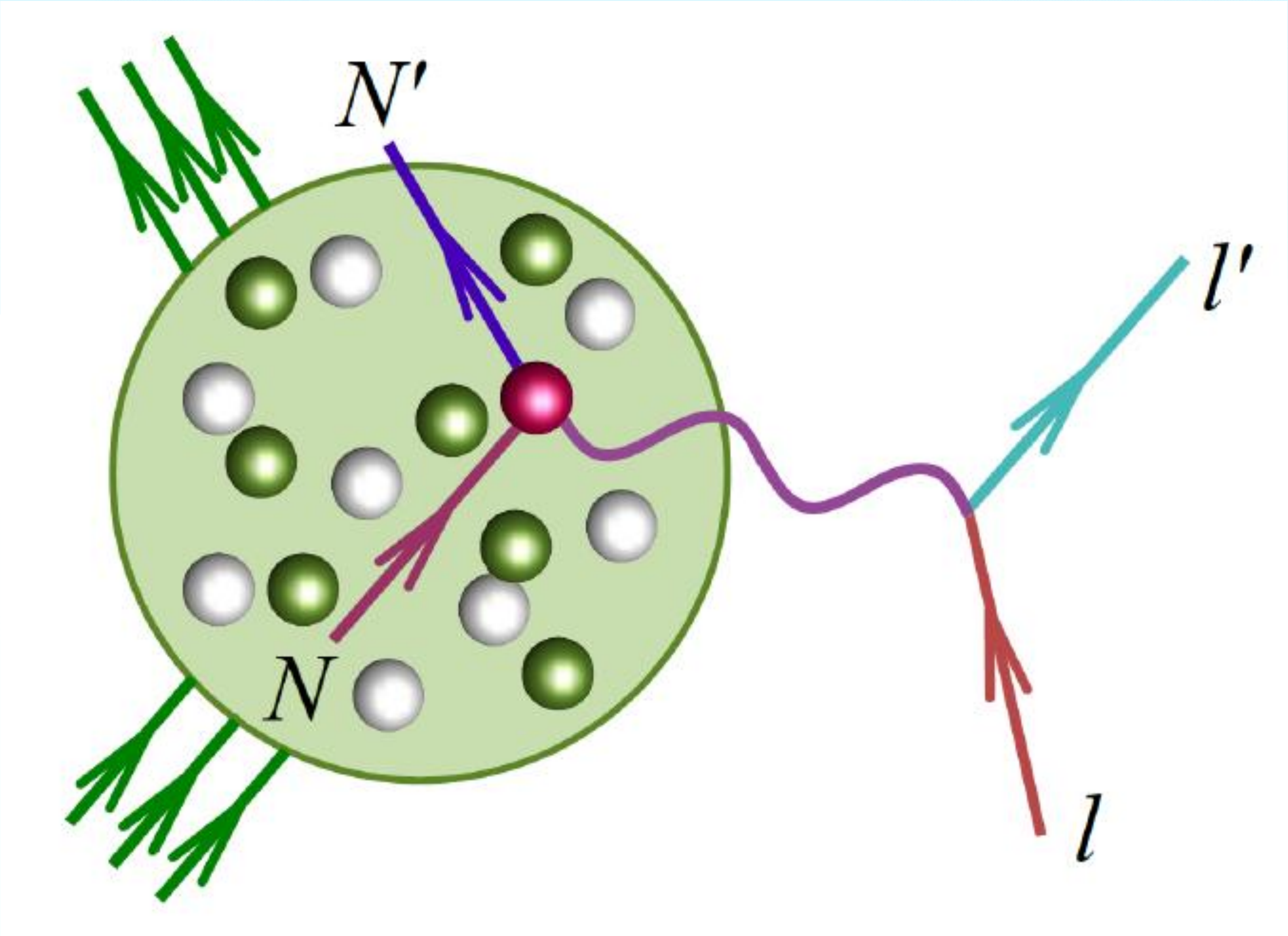


Two body current **(MEC)**

Impulse approximation

Neutrino-nucleus scattering

In the 1~GeV region nuclear effects are treated in the impulse approximation (IA) scheme:



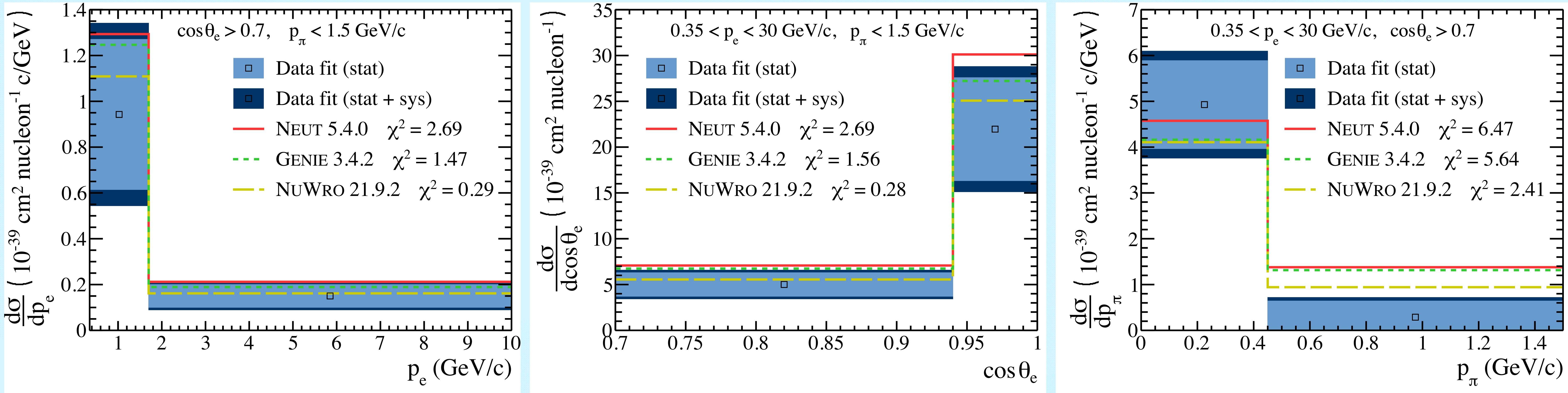
- neutrinos interact with individual bound nucleons
- any interaction is viewed as a two-step process:

1. a primary interaction
2. rescatterings of outgoing hadrons (FSI - final state interactions)

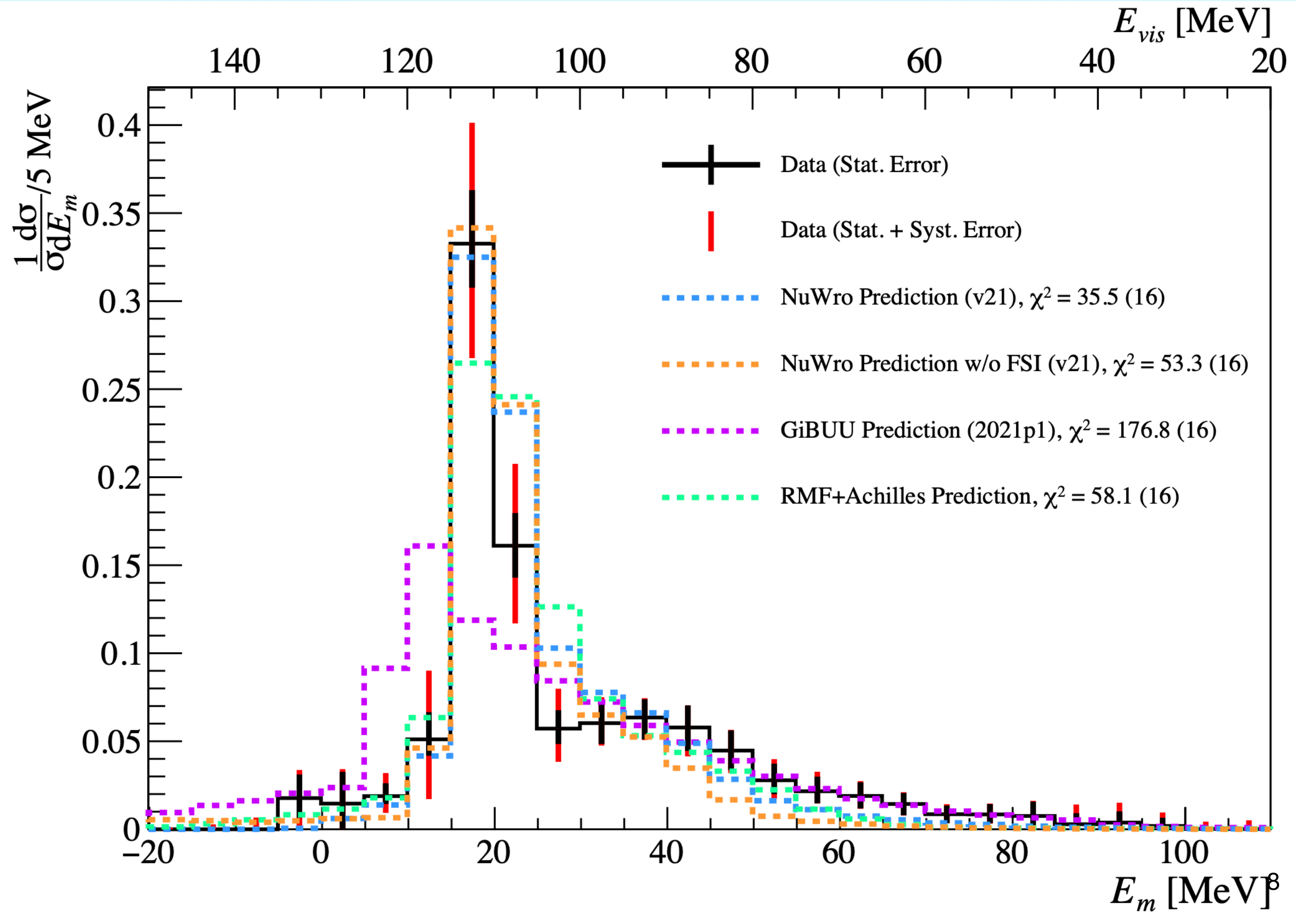
- typically, nucleus is left in an excited state.

Credit: Artur Ankowski

NuWro - examples of performance



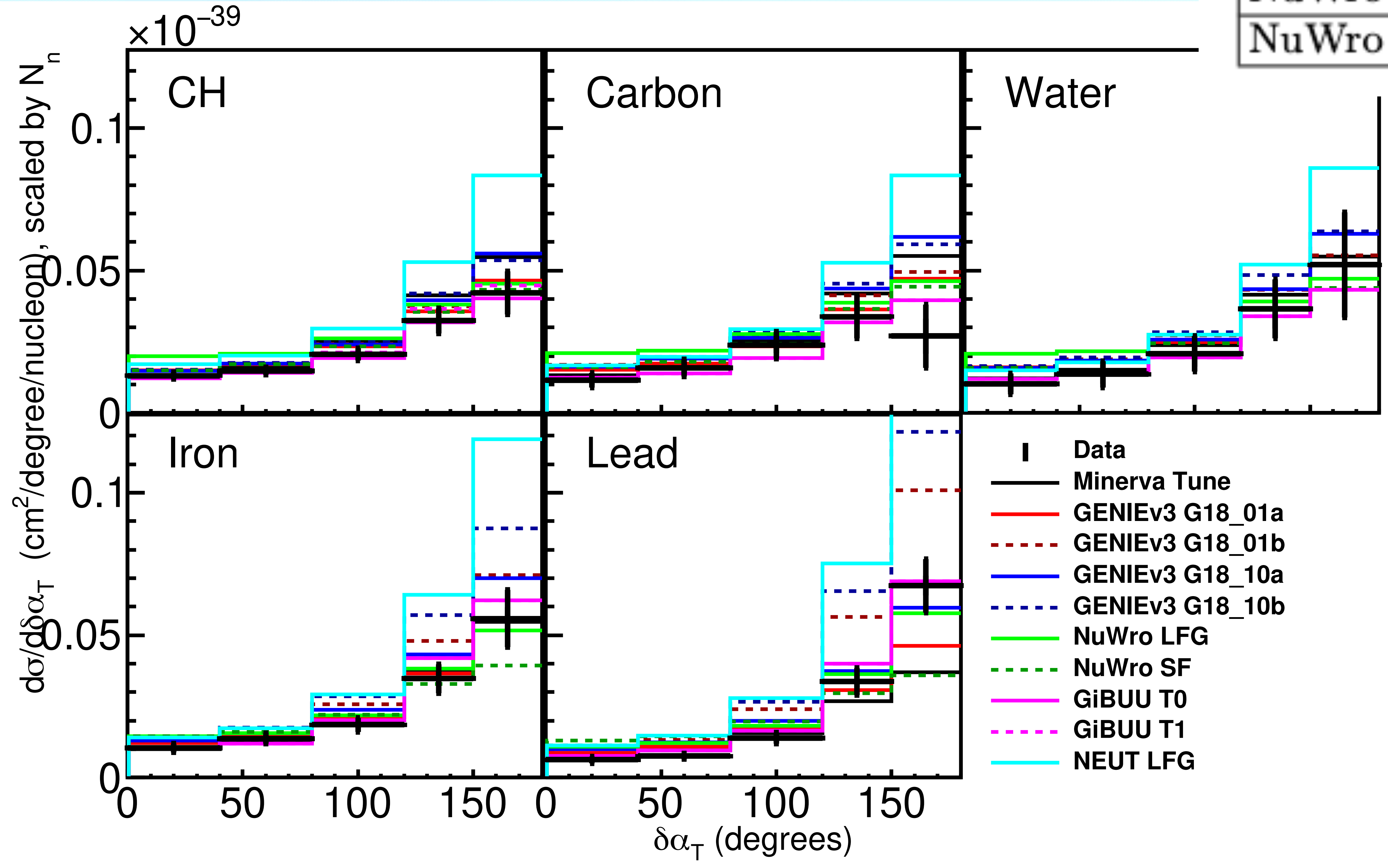
T2K, e-Print: 2505.00516 [hep-ex]



JSNS^2. experiment with KDAR flux
Phys.Rev.Lett. 134 (2025) 8, 081801

NuWro - examples of performance

Model	CH χ^2	C	C/CH	H_20	H_20/CH	Fe	Fe/CH	Pb	Pb/CH
Minerva Tune	26	7.8	5.4	0.51	1.1	5.0	4.5	44	31
GENIEv3 G18 01a	4.3	7.8	5.5	2.6	1.6	1.6	1.8	41	21
GENIEv3 G18 01b	5.3	7.8	6.0	2.8	1.4	9.2	5.4	29	27
GENIEv3 G18 10a	9.2	15	6.2	2.2	1.5	5.1	3.3	45	35
GENIEv3 G18 10b	8.5	12	6.3	3.1	1.7	23	10	53	44
GiBUU T0	6.3	5.2	5.2	0.66	0.92	7.4	8.9	6.7	13
GiBUU T1	19	5.2	6.1	0.66	1.7	7.4	3.3	6.7	10
NEUT LFG	44	32	5.5	4.7	0.77	60	4.1	140	21
NuWro LFG	71	18	5.0	10	1.8	9.9	4.9	49	6.7
NuWro SF	5.1	6.8	5.4	3.4	2.0	17	12	160	88



MINERvA, e-Print: 2503.15047 [hep-ex]

What is new in NuWro 25.03.1?

New single pion production model

- Based on the Ghent theoretical model, R. Gonzalez-Jimenez, N. Jachowicz, et al, *Phys.Rev. D* 95 (2017) 11, 113007
- Implementation described in Qiyu *Yan*, K. Niewczas, A. Nikolakopoulos, R. Gonzalez-Jimenez, N. Jachowicz, X. Lu, JTS, Y. Zheng, *JHEP* 12 (2024) 141

New MEC model

- Based on Valencia group theoretical computations, J.E. Sobczyk, J. Nieves, and F. Sanchez, *Phys.Rev.C* 102 (2020) 2, 024601
- NuWro implementation described in Hemant Prasad, JTS, et al *Phys.Rev.D* 111 (2025) 3, 036032

New single pion production (SPP) model (1)

Motivation

- **NuWro old model** relies on a simple model including explicitly only one $\Delta(1232)$ resonance
- For larger W quark-hadron duality arguments

A. Inclusive cross section from Bodek-Yang

B. Hadronization done by Pythia

C. Linear interpolation

$$\frac{d\sigma^{\text{SPP}}}{dW} = \beta(W)\frac{d\sigma^{\Delta}}{dW} + \alpha(W)\frac{d\sigma^{\text{DIS,SPP}}}{dW}$$

$$\beta(W) = 1 - \alpha(W)$$

$$\alpha(W) = \begin{cases} \dfrac{W - W_{thr}}{W_{min} - W_{thr}}\alpha_0, & W < W_{min}, \\ \dfrac{W - W_{min} + \alpha_0\left(W_{max} - W\right)}{W_{max} - W_{min}}, & W_{min} \leq W \leq W_{max}, \\ 1 & W > W_{max}. \end{cases}$$

$$W_{thr} = M + m_\pi, \quad W_{min} = 1.3GeV, \quad W_{max} = 1.6GeV$$

New SPP model (2)

A model of choice: Ghent model

„Hybrid model” - R. Gonzalez-Jimenez, N. Jachowicz, K. Niewczas, et al, *Phys.Rev. D* 95 (2017) 11, 113007

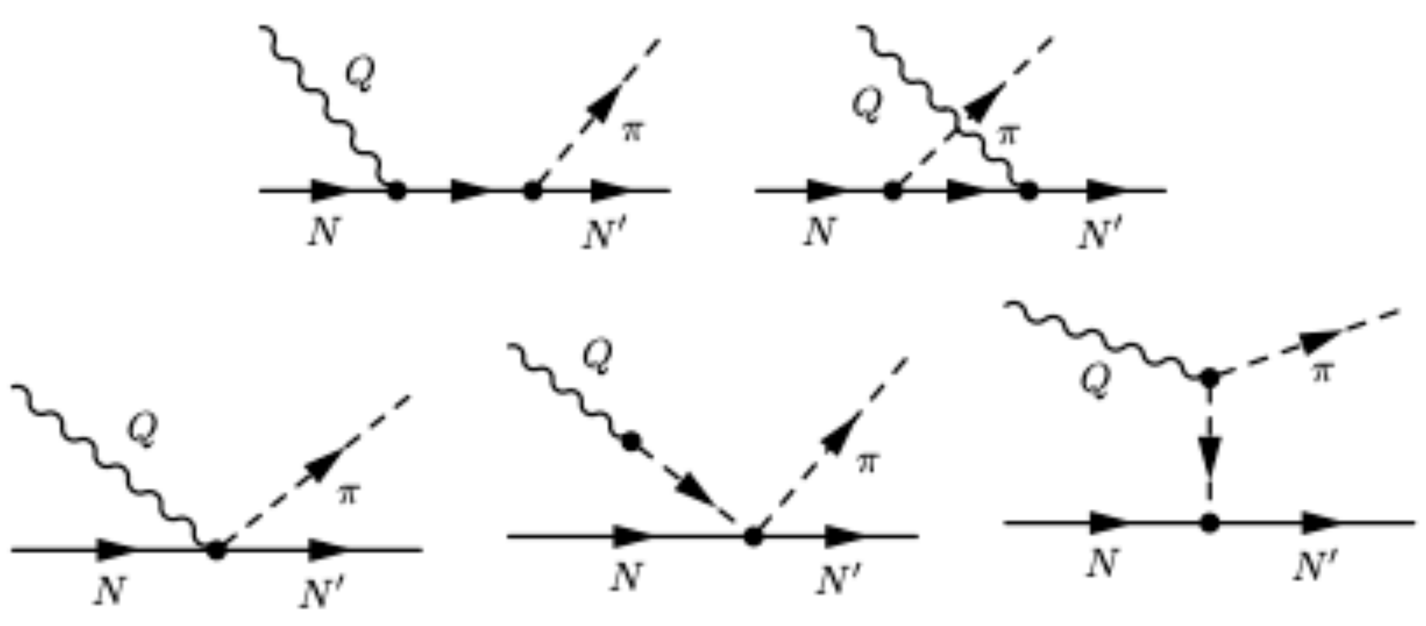
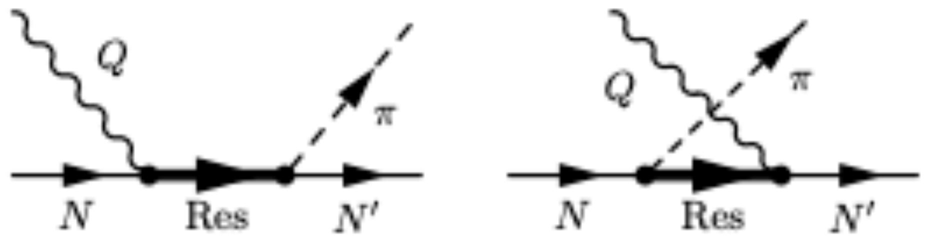


FIG. 5. ChPT-background contributions (from left to right and top to bottom): s channel (nucleon pole, NP), u channel (cross-nucleon pole, CNP), contact term (CT), pion pole (PP), and t channel (pion-in-flight term, PF).



$$J^{\mu}_{\text{Hybrid}} = J^{\mu}_{\text{RES}} + \cos^2\phi(W) J^{\mu}_{\text{LEM}} + \sin^2\phi(W) J^{\mu}_{\text{ReChi}},$$

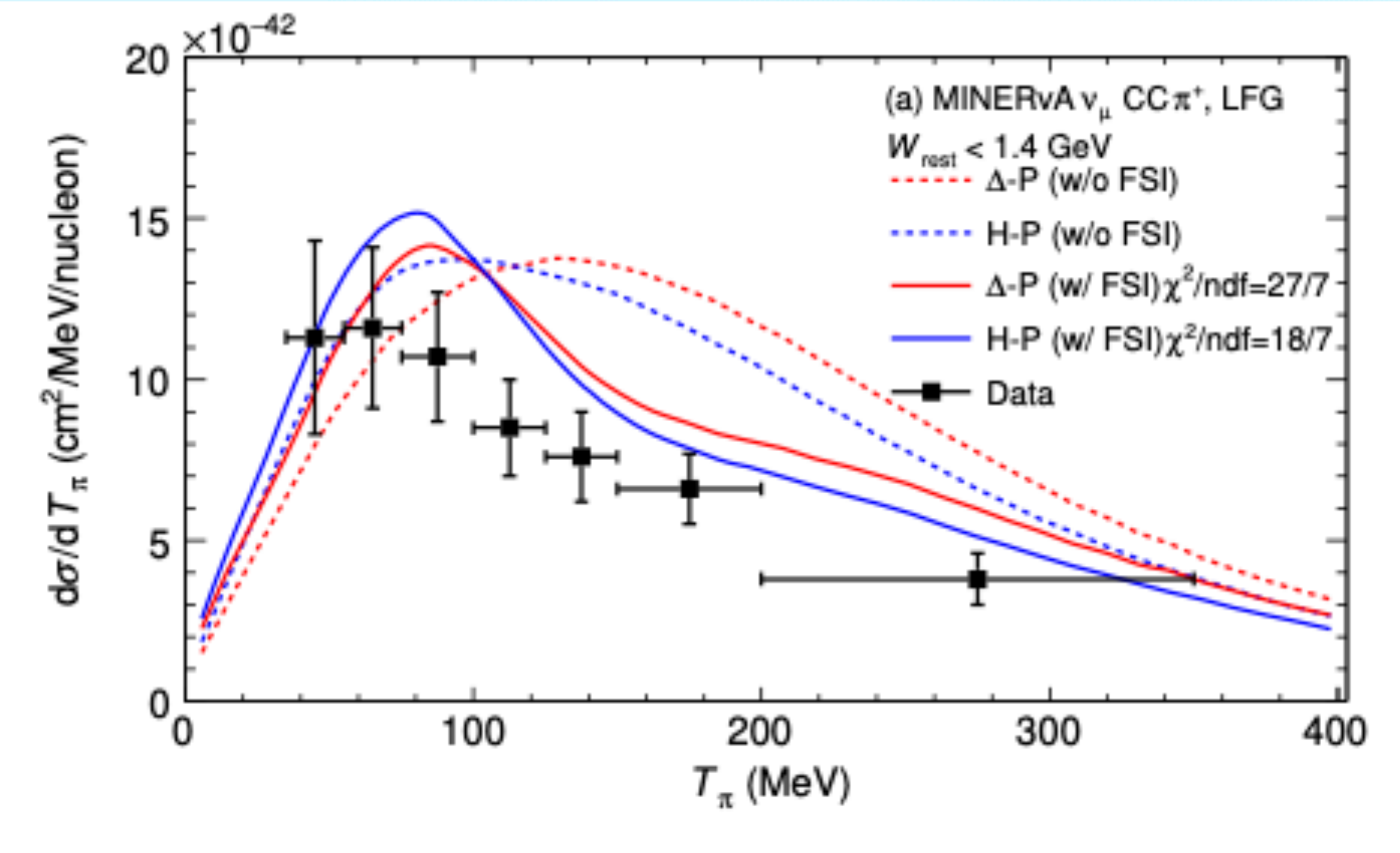
Contributions from resonances $P_{33}(1232)(\Delta),\ D_{13}(1520),\ S_{11}(1535),\ P_{11}(1440)$

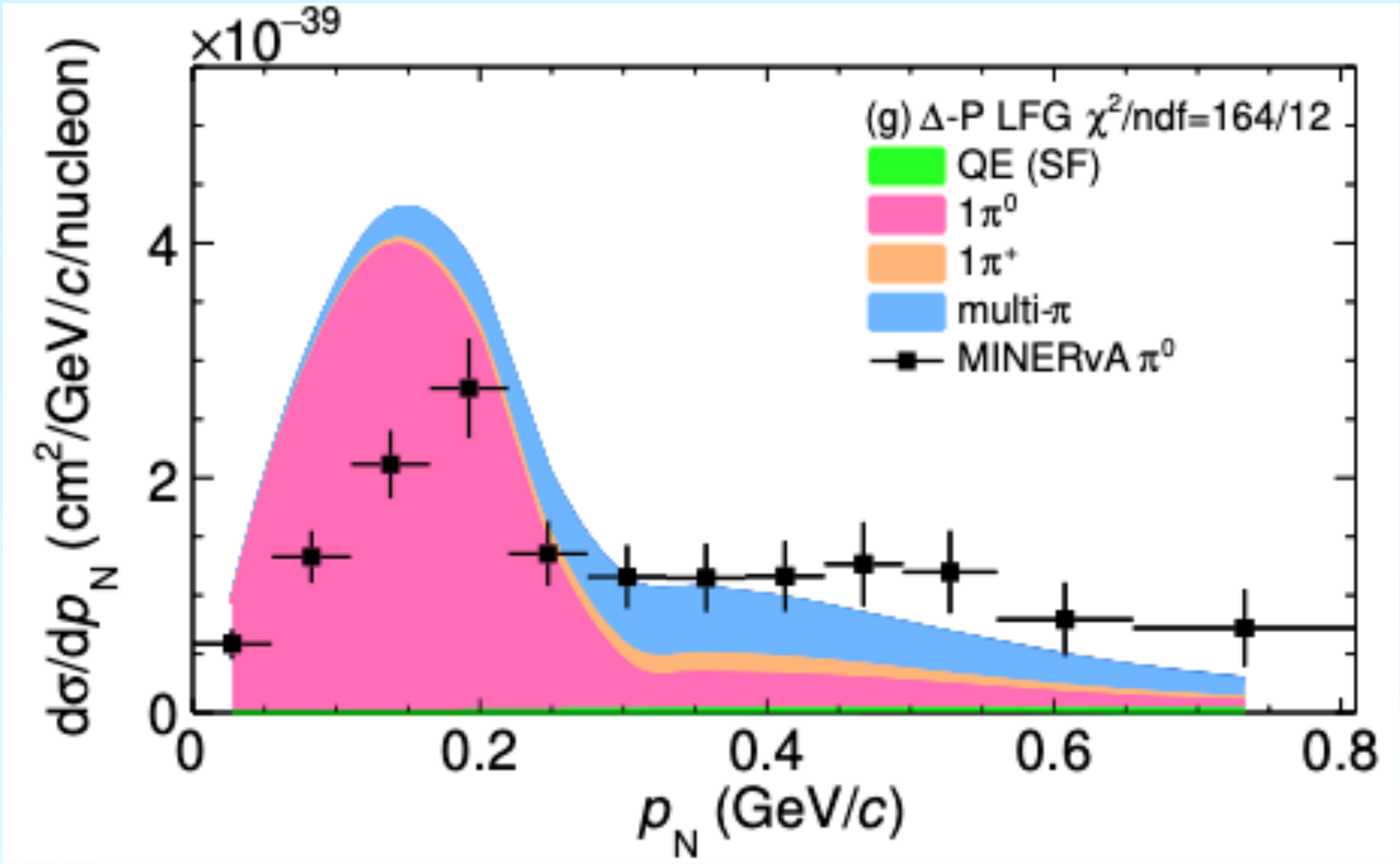
low-energy background, and high-energy background

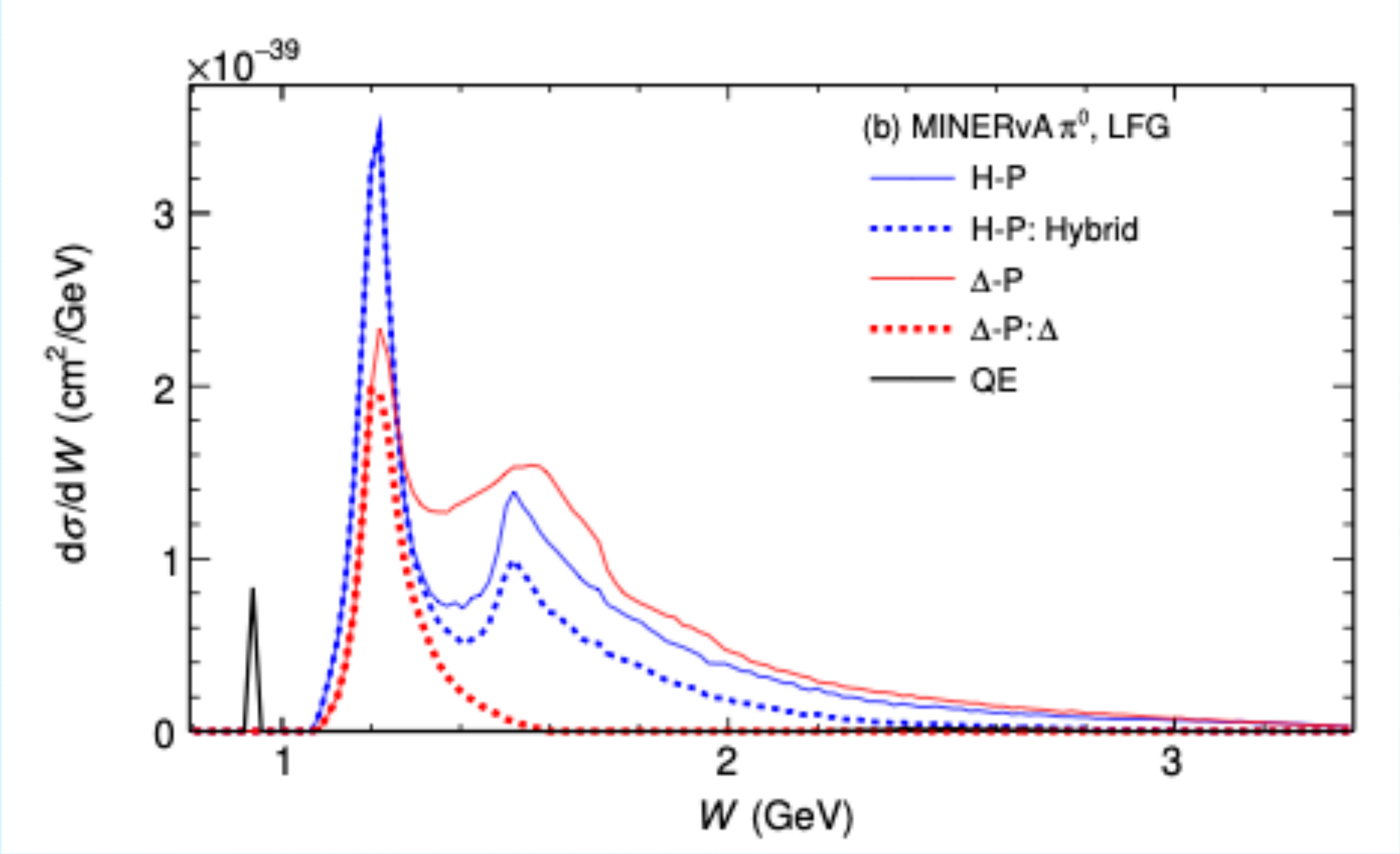
$$\phi(W) = \frac{\pi}{2}\left[1 - \frac{1}{1 + \exp\left(\frac{W - W_0}{L}\right)}\right]; \quad W_0 = 1.5GeV, \quad L = 0.1GeV$$

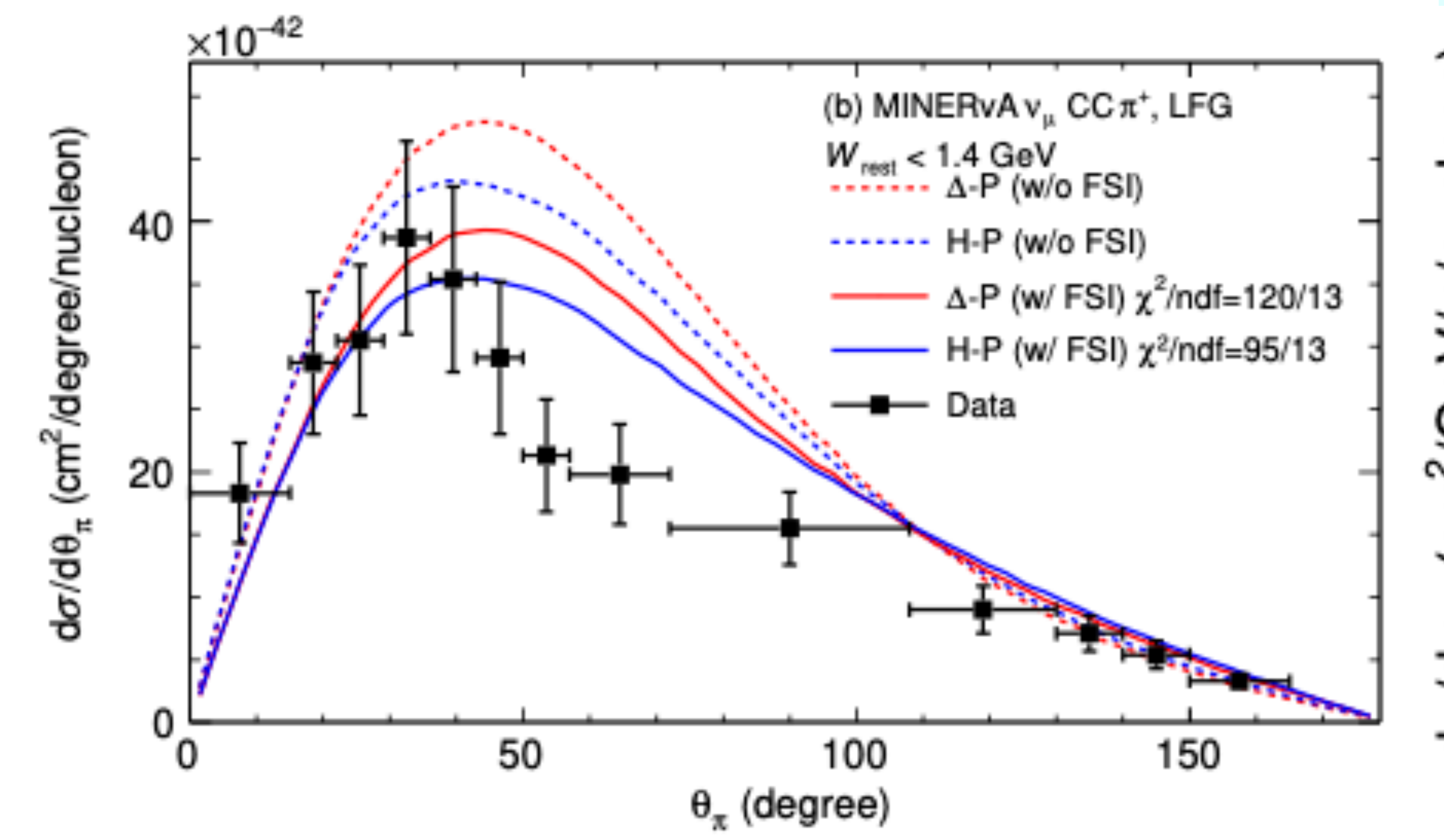
At large W almost entirely ReChi model

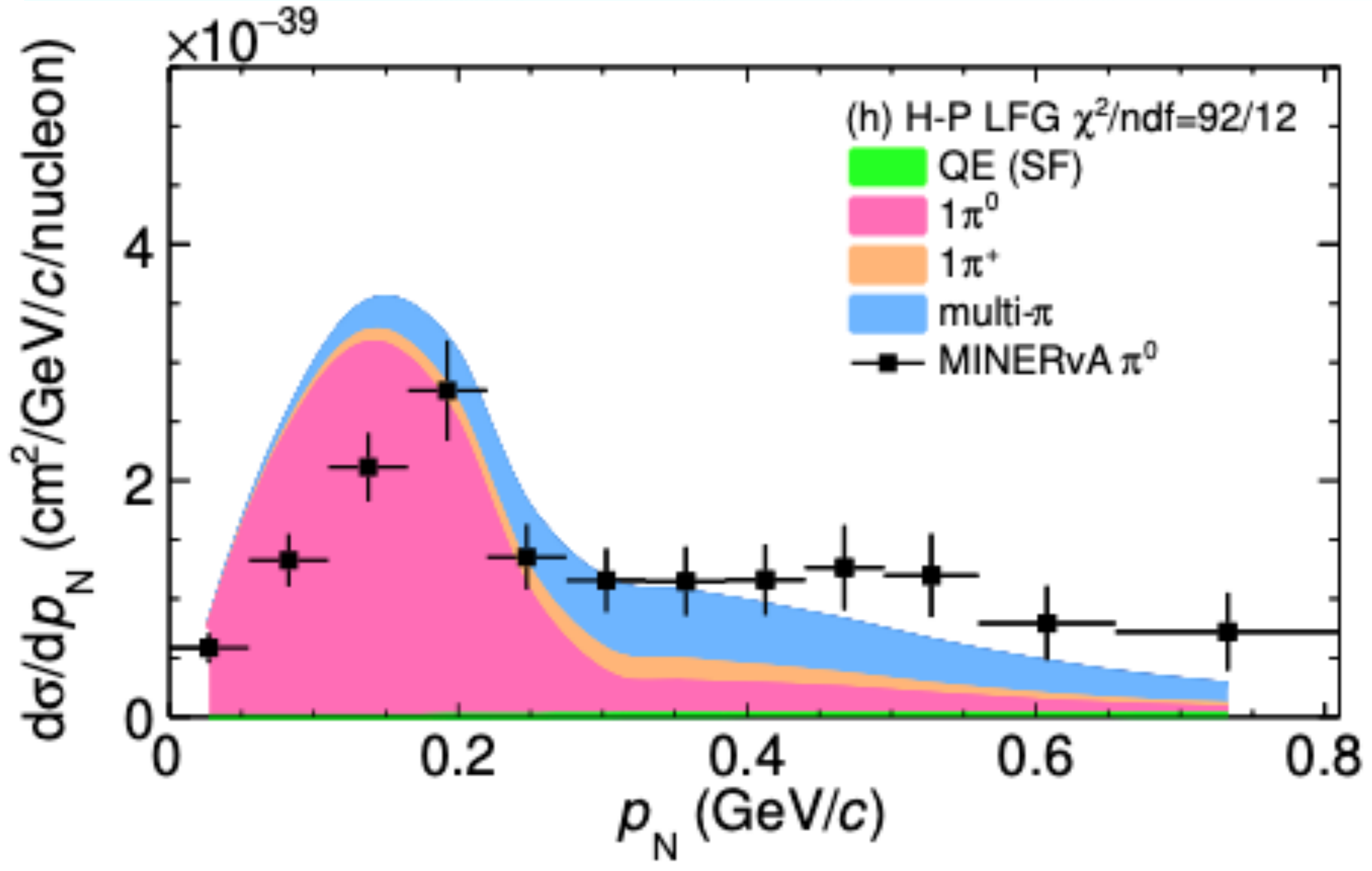
New SPP model (3)











Old model Δ-P
New model H-P

Qiyu Yan,
Kajetan Niewczas,
Alexis Nikolakopoulos,
Raul Gonzalez-Jimenez,
Natalie Jachowicz,
Xianguo Lu,
JTS,
Yangheng Zheng,

Data from: B. Eberly et al. (MINERvA), Phys. Rev. D92 092008 (2015), arXiv:1406.6415 [hep-ex].

Data from: D. Coplowe et al. (MINERvA), Phys. Rev. D 102 072007 (2020), arXiv:2002.05812 [hep-ex].

JHEP 12 (2024) 141

In NuWro 25.03.1 definitions of RES and DIS are changed compared to earlier versions.

NuWro MEC model

Until recently, NuWro relied on an implementation of the Valencia MEC model Nieves, et al, *Phys. Rev.* C83 (2011) 045501

- Only semi-inclusive muon cross section is modeled; only 2p2h final states are predicted
- Semi-inclusive cross section is defined by tabularized response functions $W_j(\omega, q), \quad j = 1,...,5$
- Modeling final state hadrons requires extra assumptions as proposed in JTS, *Phys. Rev.* C86 (2012) 015504

A new Valencia model has become available J.E. Sobczyk, J. Nieves, and F. Sanchez, *Phys. Rev.* C102 (2020) 024601

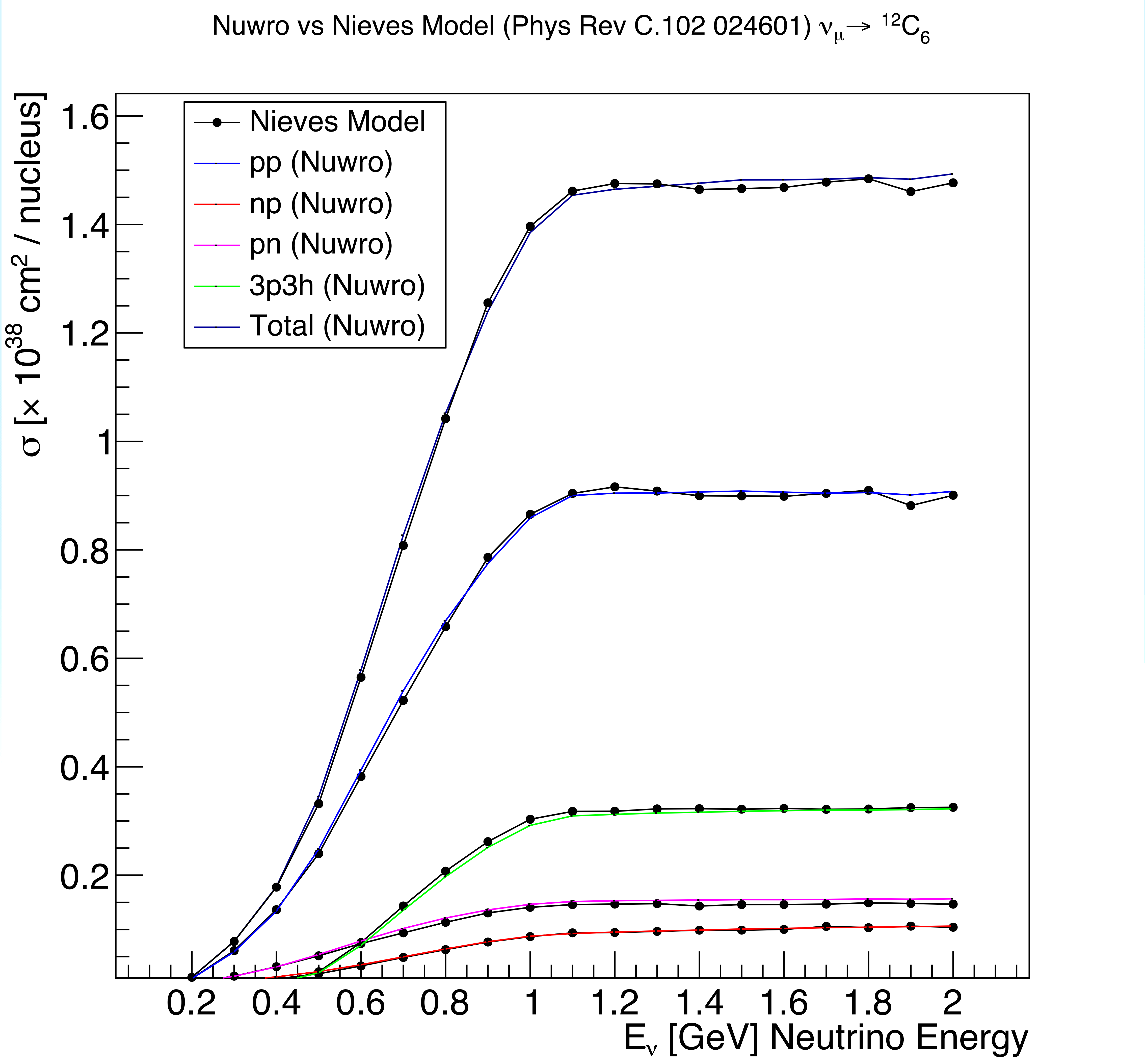
- Includes both 2p2h and 3p3h contributions
- Provides detail predictions for 2p2h including isospin and nucleon momenta
- It is not the last word of the Valencia group!

New MEC model

- There are four distinct contributions: pp, pn, np (for 2p2h) and 3p3h and one needs 4*5=20 tables
- NuWro implementation adopts a factorization scheme in two steps:

1. Muon kinematics (with the tables)
2. Hadronic part (a new algorithm has been developed)

Details will be presented by Hemant next week!



NuWro implementation by Hemant Prasad et al

(using code provided by J.E. Sobczyk)

New vs old NuWro

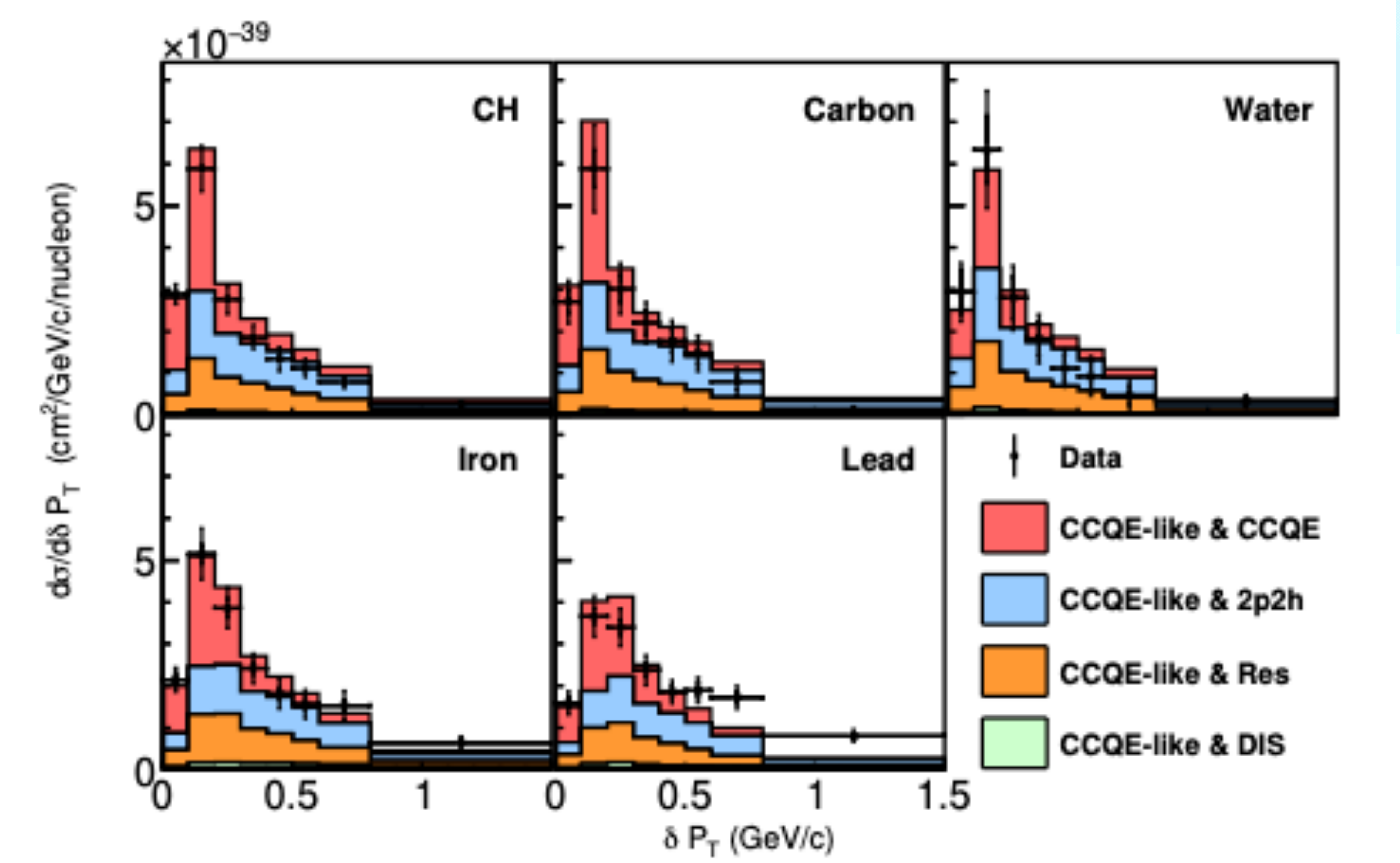
How significant are modifications in 25.03.1?

Recent MINERvA study:

- NuMi ME flux
- $CC0\pi$ signal
- nucleus size dependence (C, O, Fe, Pb)
- contributions from CCQE, RES, DIS,
- an important imprint of FSI

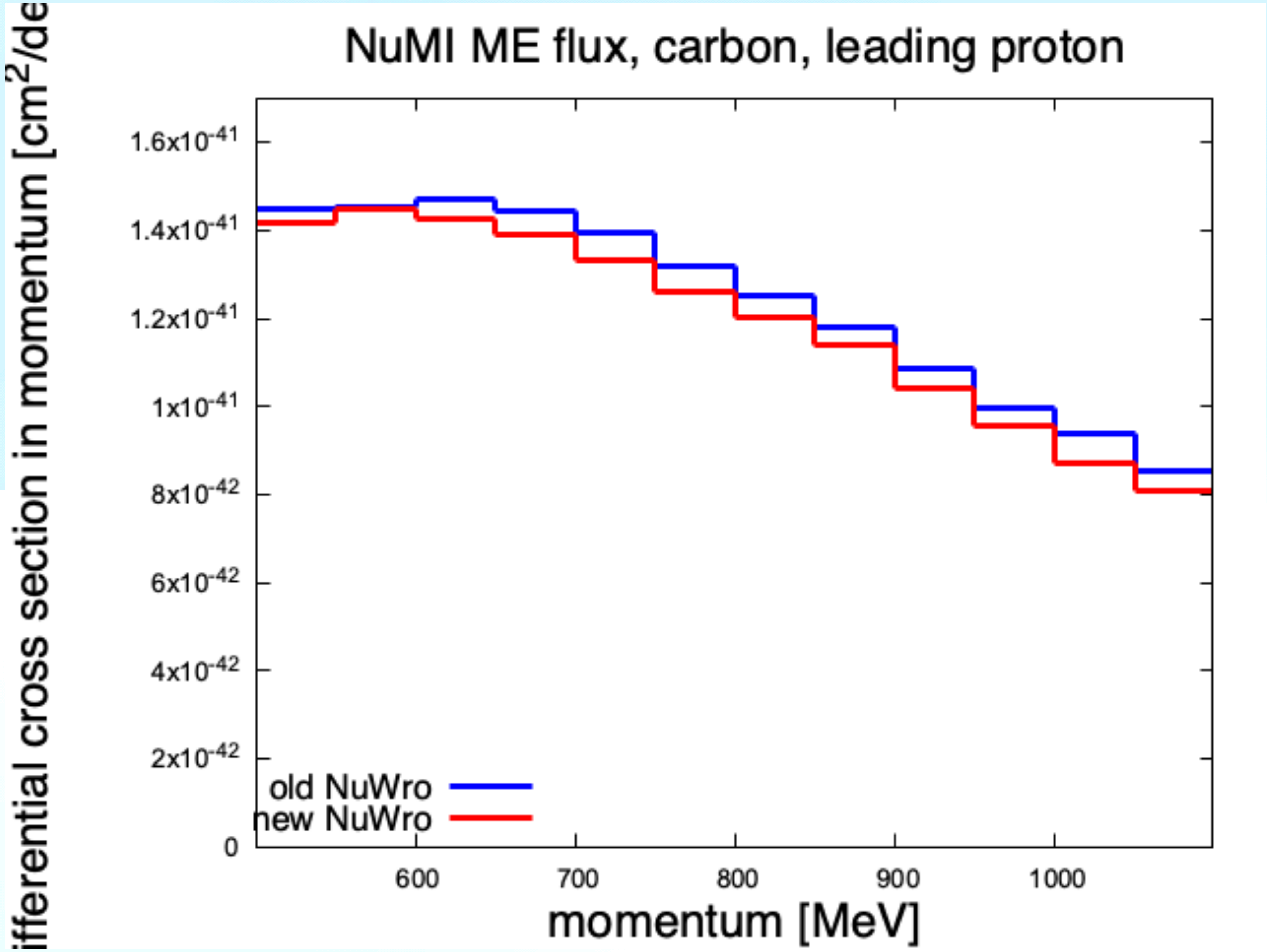
Selection:

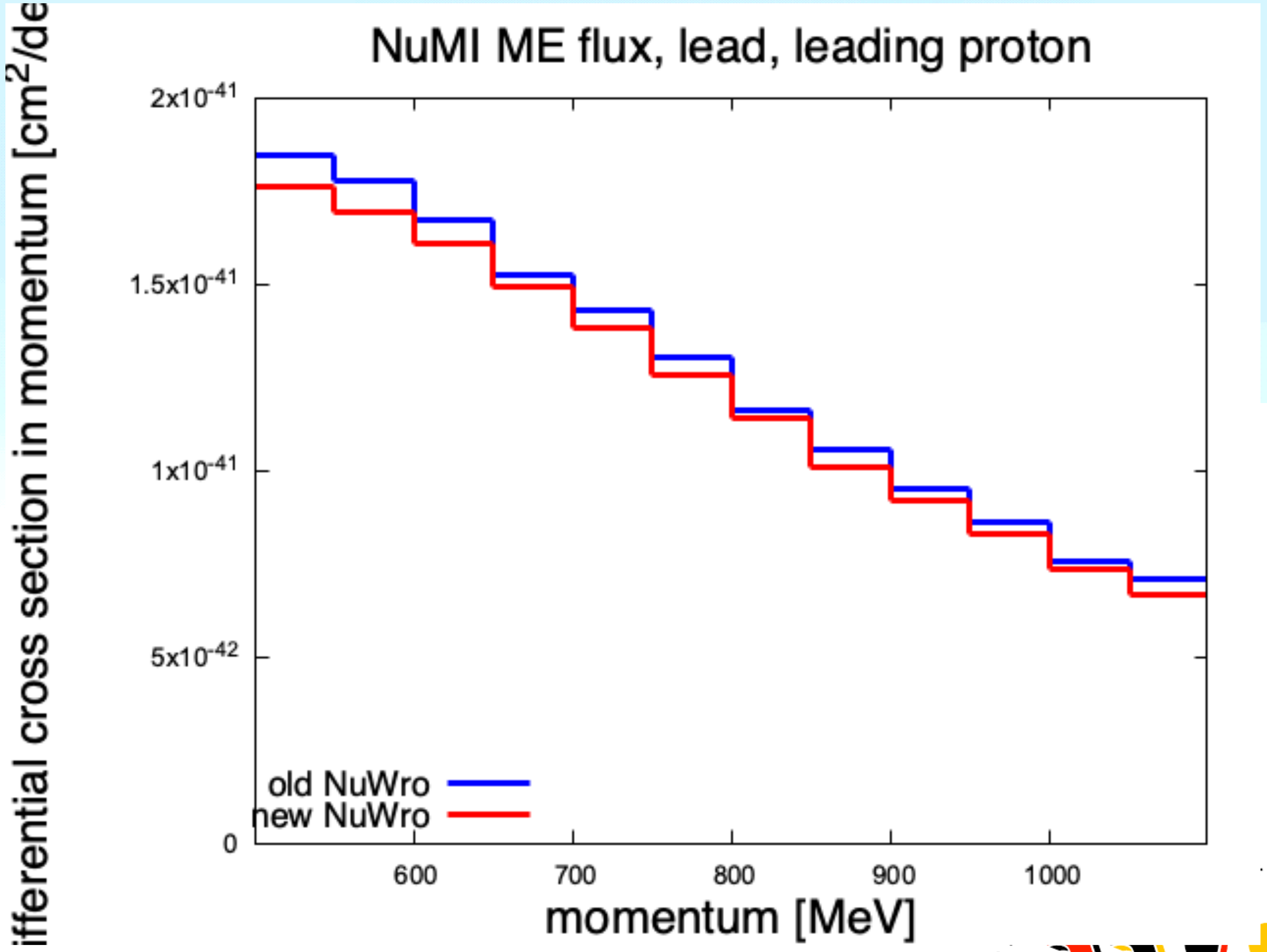
- no pion
- muon $\theta_\mu < 17\ deg$,
  $2\ GeV/v < p_\mu < 10\ GeV/c$
- leading proton $\theta_p < 70\ deg$,
  $500\ MeV/c < p_p < 1100\ MeV/c$



2503.15047 [hep-ex]

New vs old NuWro

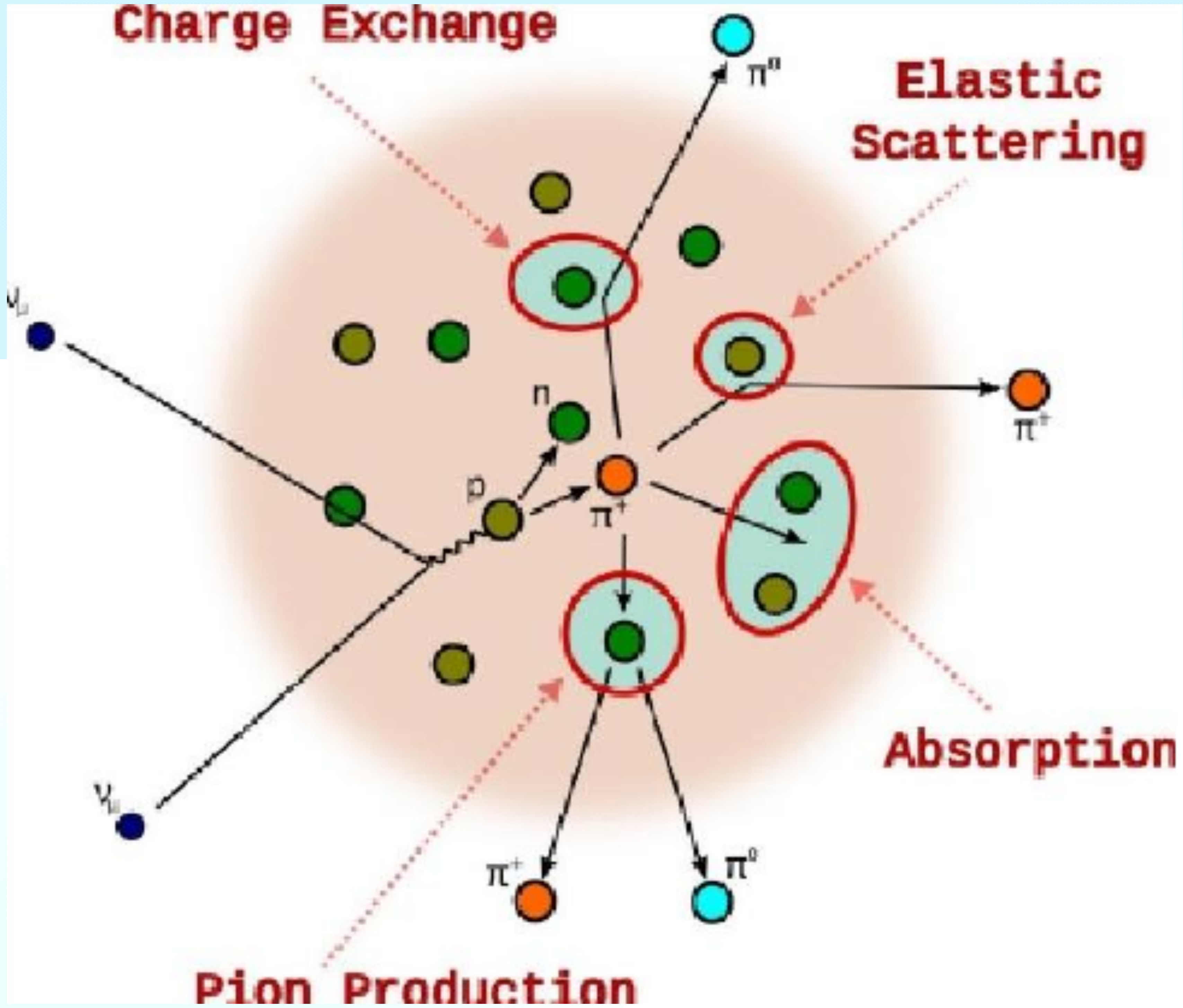




No comparison with the data, we are waiting for data release!

Final state interactions - generalities

In the MC jargon FSI is a unitary transformation connecting hadronic state right after primary interaction and final configuration of hadrons which may be detected experimentally.



Pions...

- can be absorbed
- can be scattered elastically
- (if energetically enough) can produce new pions
- can exchange electic charge with nucleons

A similar picture can be drawn for other hadrons.

Probability to go through nucleus without reinteractions is called hadron transparency.

Some MCs include models of nucleus de-excitation.

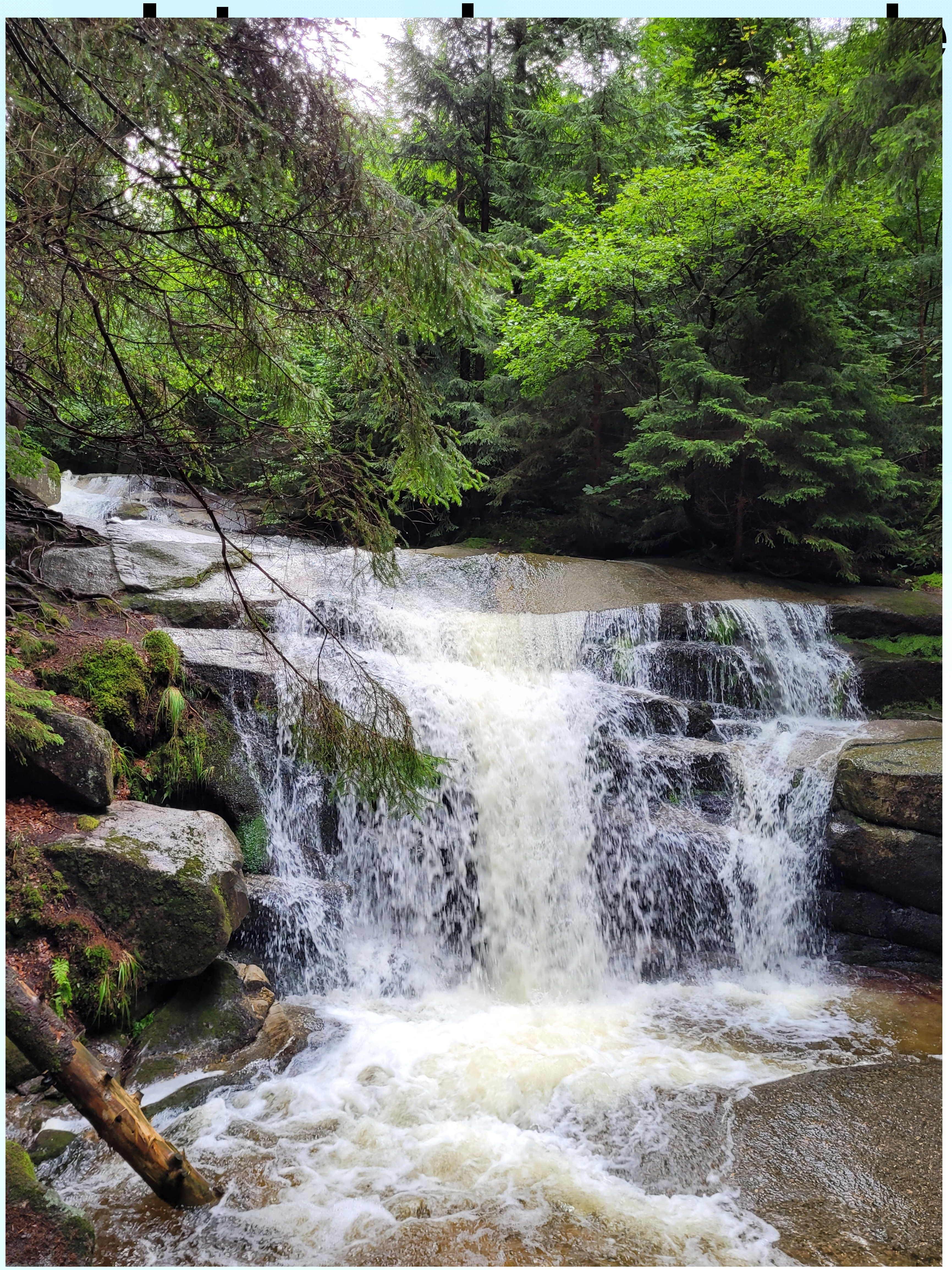
Cascade model

Basic theoretical assumptions (Y. Yariv et al):

- Energies transferred in collisions are large compared to binding energy.
- Hadrons wave-packages have good enough definitions of position and momentum.
- De Broglie wave length is smaller than distances between collisions.
- Scattering from different nucleons can be considered independent.
- With many scatterings interference terms between scattered waves cancel out.

Assumptions are satisfied if nucleon kinetic energy is large enough (>200 MeV).

NuWro FSI model



Hadrons propagate in steps through nuclear medium

- Probability of passing a distance x without interaction

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

$\lambda = \left(\rho\sigma\right)^{-1}$ is mean free path, ρ is local density and σ is hadron-nucleon microscopic cross section.

- Maximal step is 0.2 fm.
- Implemented for nucleons, pions and hyperons.
- Semi-classical approach, includes Pauli blocking, nucleon-nucleon correlation effects.

References:

T. Golan, C. Juszczak, JTS, Phys.Rev. C 86 (2012) 015505;

K. Niewczas, JTS, Phys.Rev. C 100 (2019) 015505

Ch. Thorpe, … , JTS, …, Phys.Rev. C 104 (2021) 035502

NuWro FSI model - technicalities

- Based on the algorithm of Metropolis at al.

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

- Propagation and interactions of on-shell nucleons

- Nuclear potential from LFG: $V(r) = E_F(r) + E_B$

- 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

  J. Bystricky at al, J. Physique 48 (1987) 1901

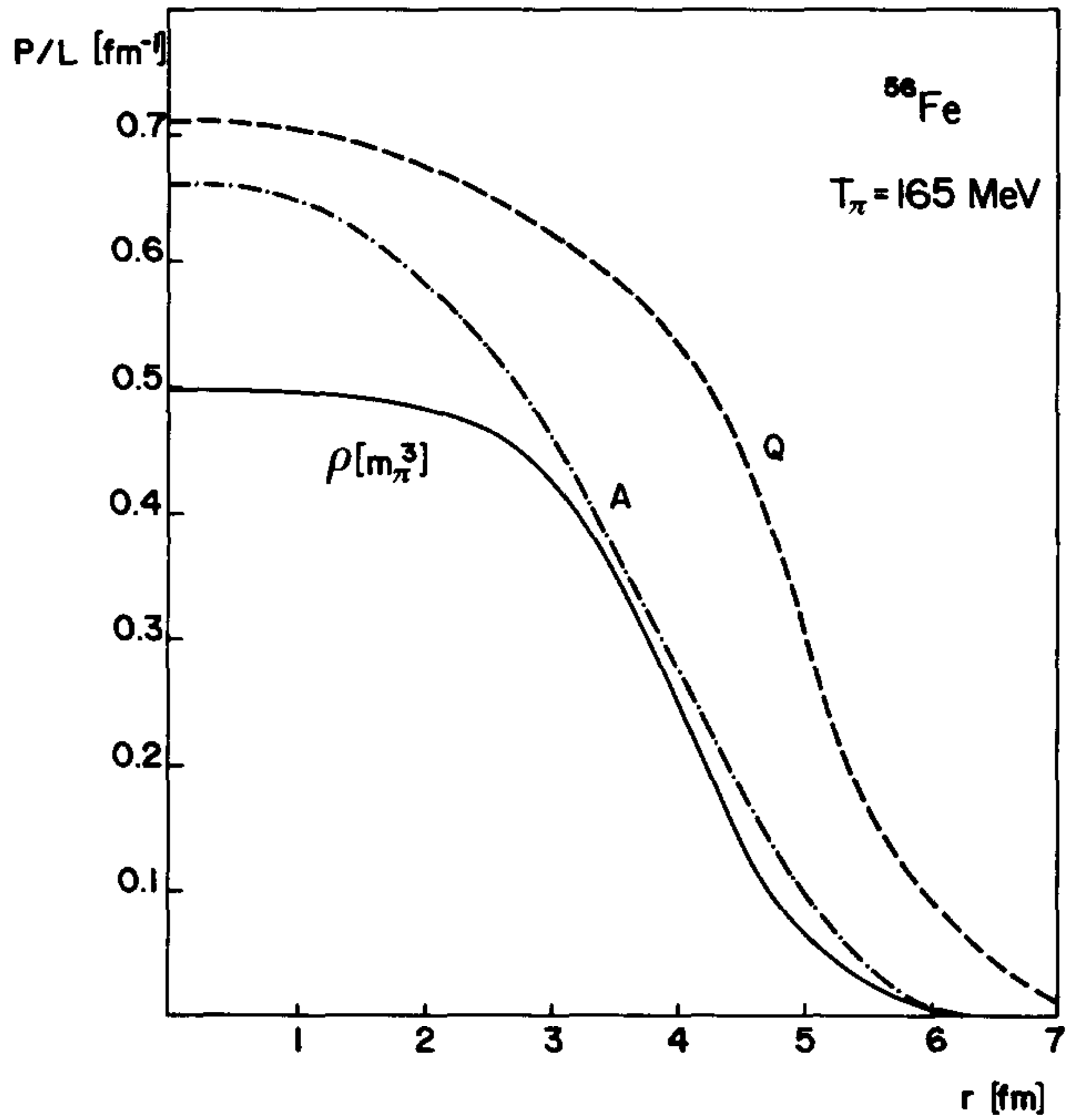
- Nuclear effects on top of all that.

NuWro FSI model - technicalities (2)

Microscopic hadron-nucleon cross sections:

Pions:

LL.Salcedo, E. Oset et al, Nuclear Physics A484 (1988) 557-592



. Probability per fm for quasielastic scattering (dashed line) and absorption (dashed dotted line) and nuclear density (in pion masses) as a function of the radius.

Nucleons:

V. R. Pandharipande and S. C. Pieper, Phys. Rev. C45 (1992)791.

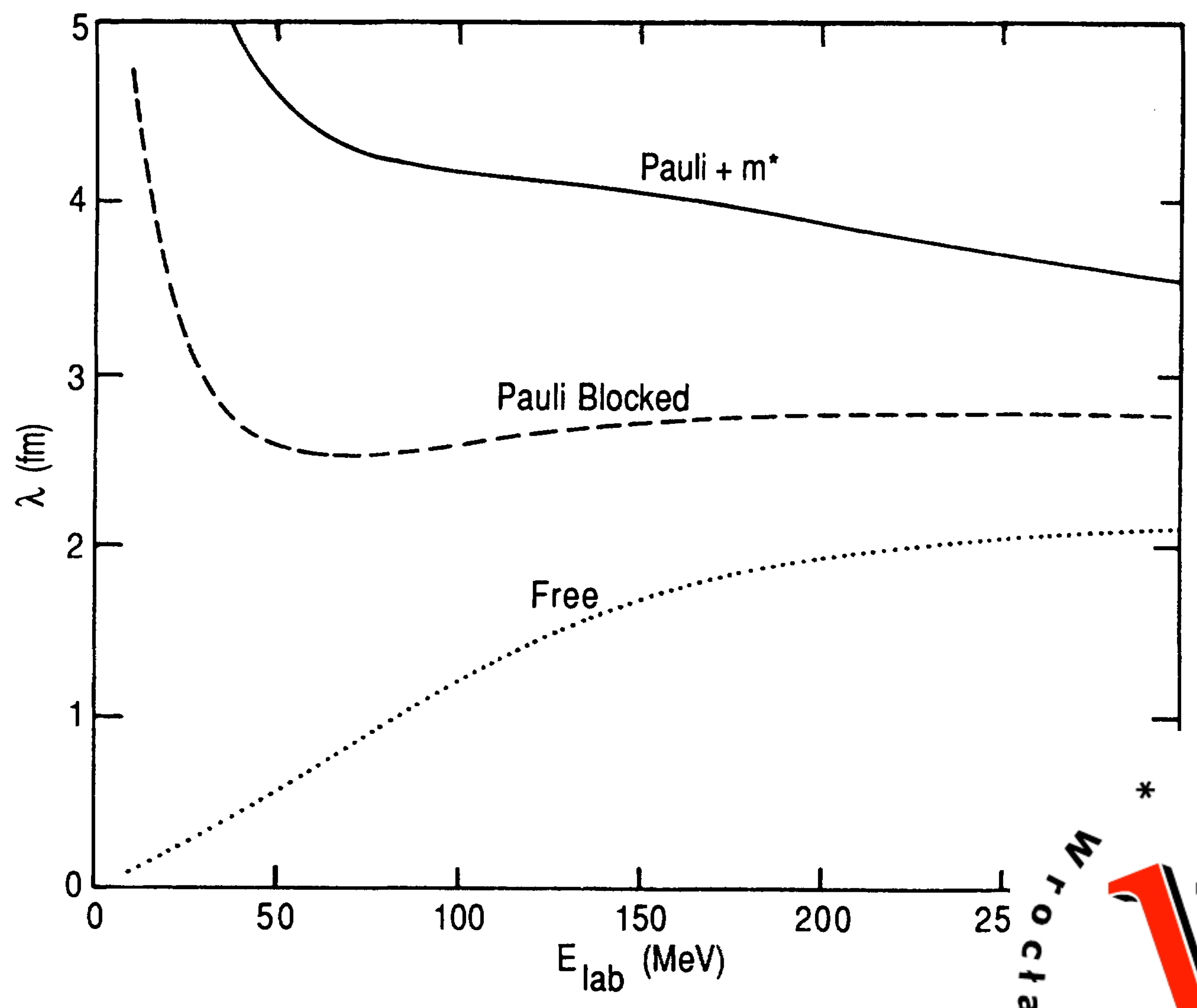


FIG. 3. The mean free path of protons in symmet
matter at saturation density as a function of the proto

NuWro FSI model - technicalities (3)

In-medium modifications

Corrections to the elastic cross section V.R. Pandharipande, S. Pieper, Phys. Rev. C45 (1992) 791

- Reduced relative nucleon velocity and available phase space

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

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

Nucleon-nucleon correlations effects:

- ``Effective'' nuclear density due to nucleon-nucleon correlations
- Mean free path: $\tilde{\lambda} = \left[\rho(\vec{r} + \vec{\lambda})\ g_2(\lambda)\ \sigma(p)\right]^{-1}$
- Correlation function taken from ab initio nuclear matter calculations.

Testing FSI models (1)

Transparency versus reaction cross section

Alternative approaches to cascade lead to distinct relations between transparency and reaction cross section.

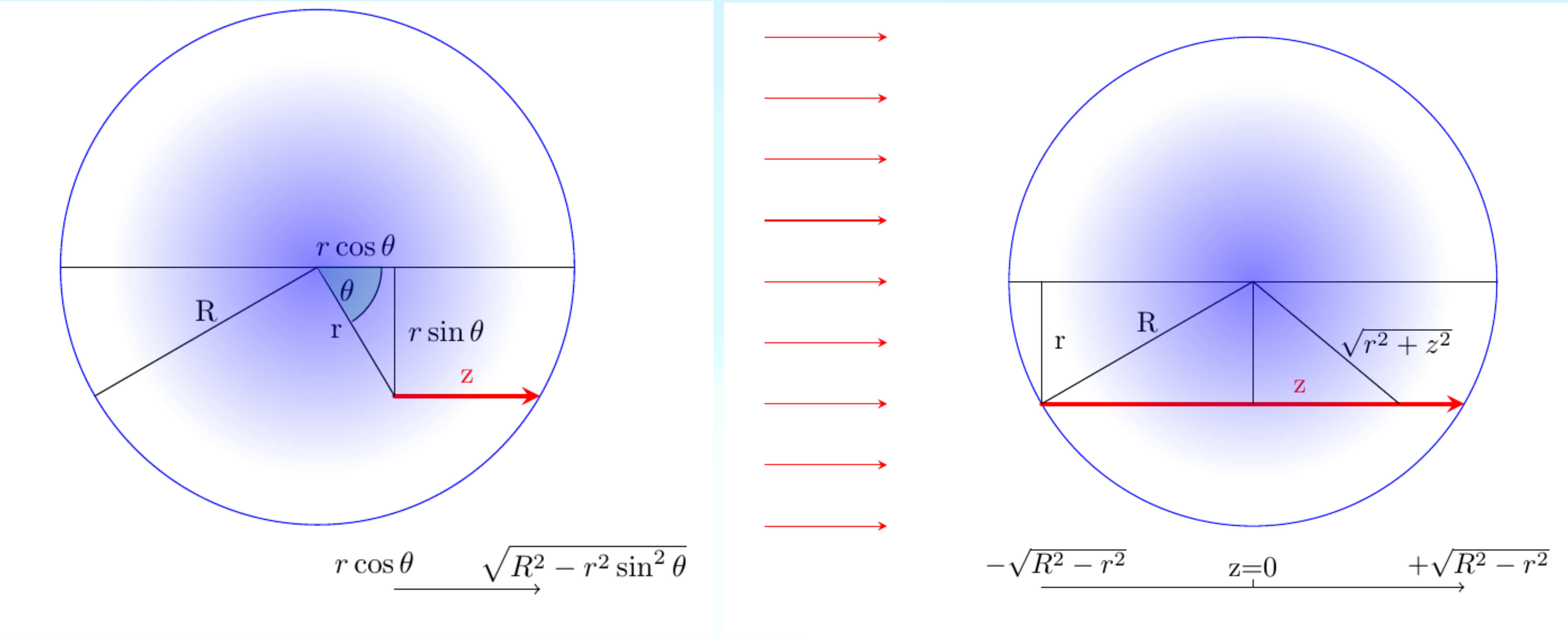
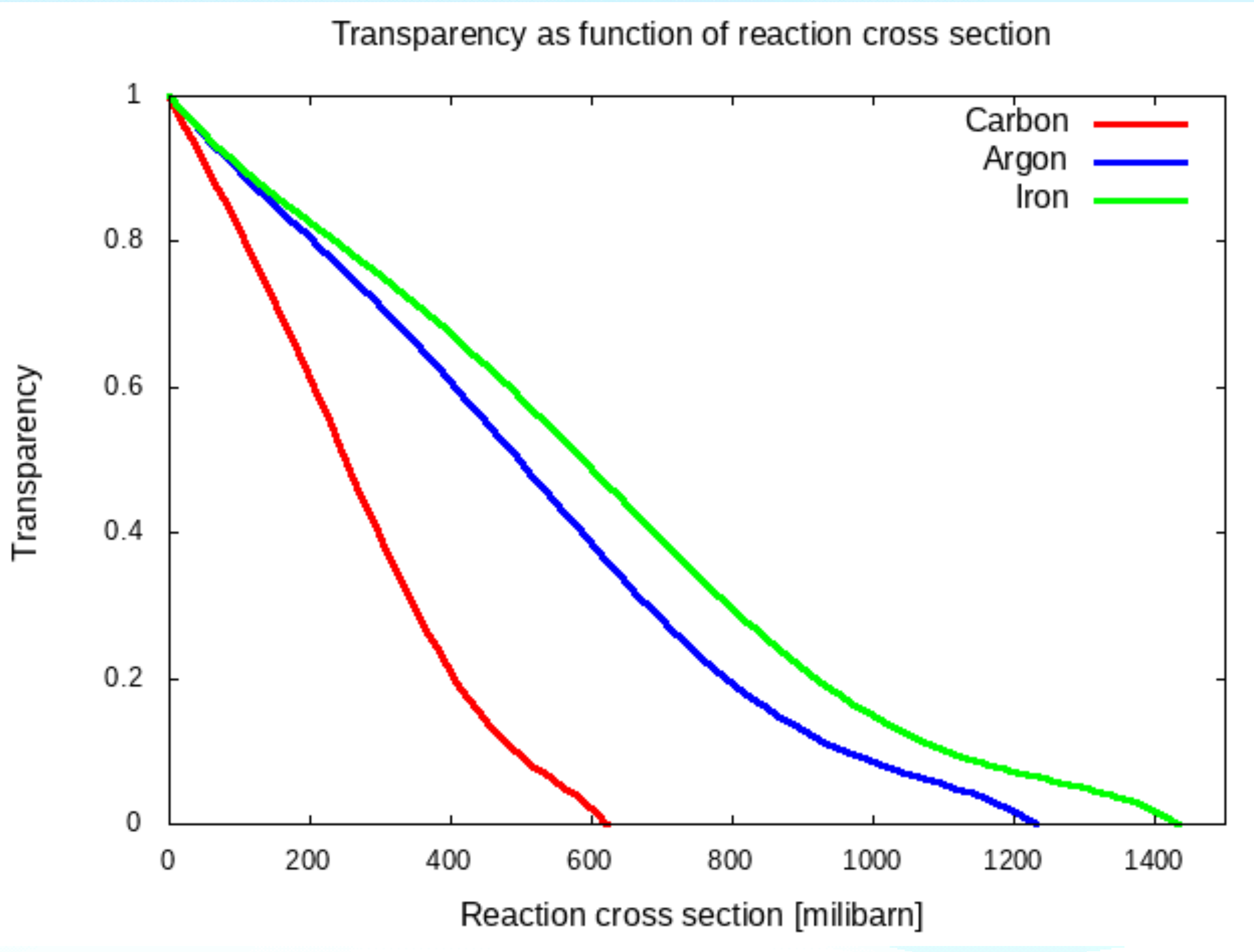


FIG. 1. Computation of transparency (left) and reaction cross section (right) in the toy model.

$$T = \frac{2\pi}{A}\int_{-1}^{+1} d(\cos\theta)\int_0^R dr\; r^2\rho(r)$$
$$\cdot \exp\left\{-\int_{r\cos\theta}^{\sqrt{R^2-r^2\sin^2\theta}} dz\sigma\tilde{\rho}\left(\sqrt{z^2+r^2\sin^2\theta}\right)\right\}$$



Points on the curves correspond to values of microscopic cross section

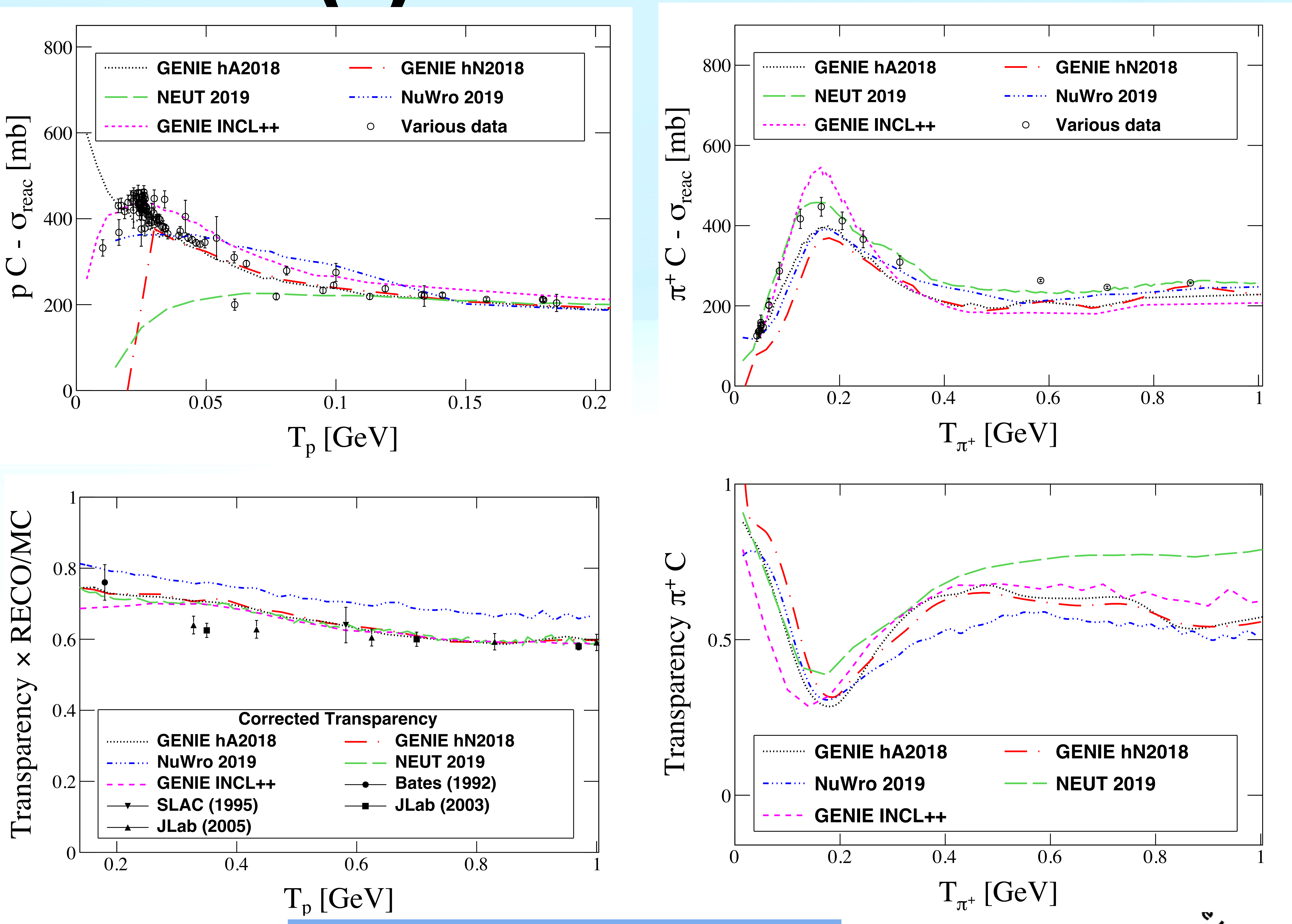
$$\sigma_{reac} = \pi R^2 - 2\pi\int_0^R dr\; r$$
$$\cdot \exp\left\{-\int_{-\sqrt{R^2-r^2}}^{\sqrt{R^2-r^2}} \sigma\rho\left(\sqrt{z^2+r^2}\right) dz\right\}$$

S. Dytman et al, *Phys.Rev.D* 104 (2021) 5, 053006

Testing FSI models (2)

Monte Carlo FSI models can be tested against hadron-nucleus cross section and hadron transparency data.

Technical remark: a correction factor is necessary because „MC transparency” is not the same as experimentally measured transparency (soft scatterings are not seen).

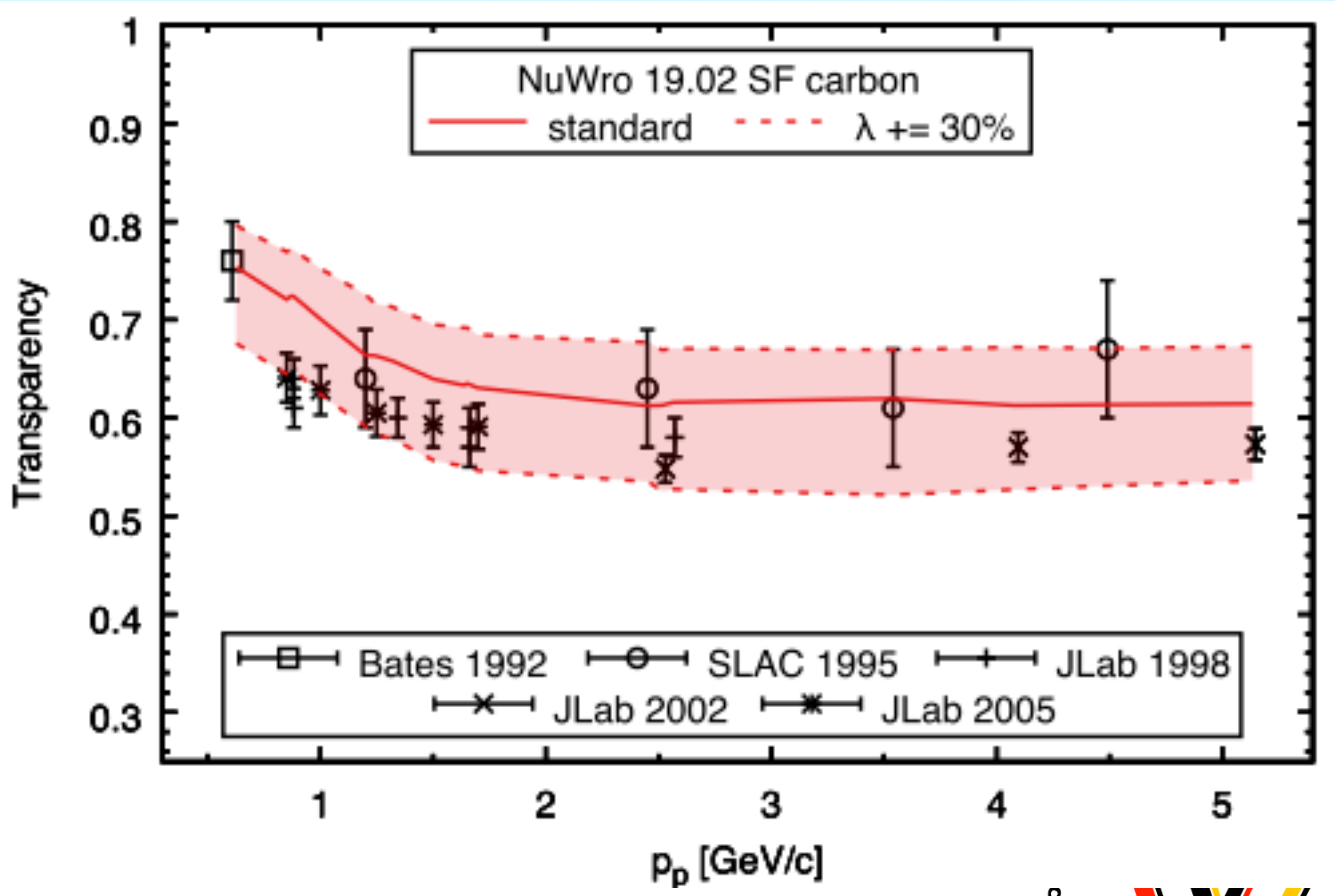


S. Dytman et al, *Phys.Rev.D* 104 (2021) 5, 053006

Uncertainty of NuWro FSI model

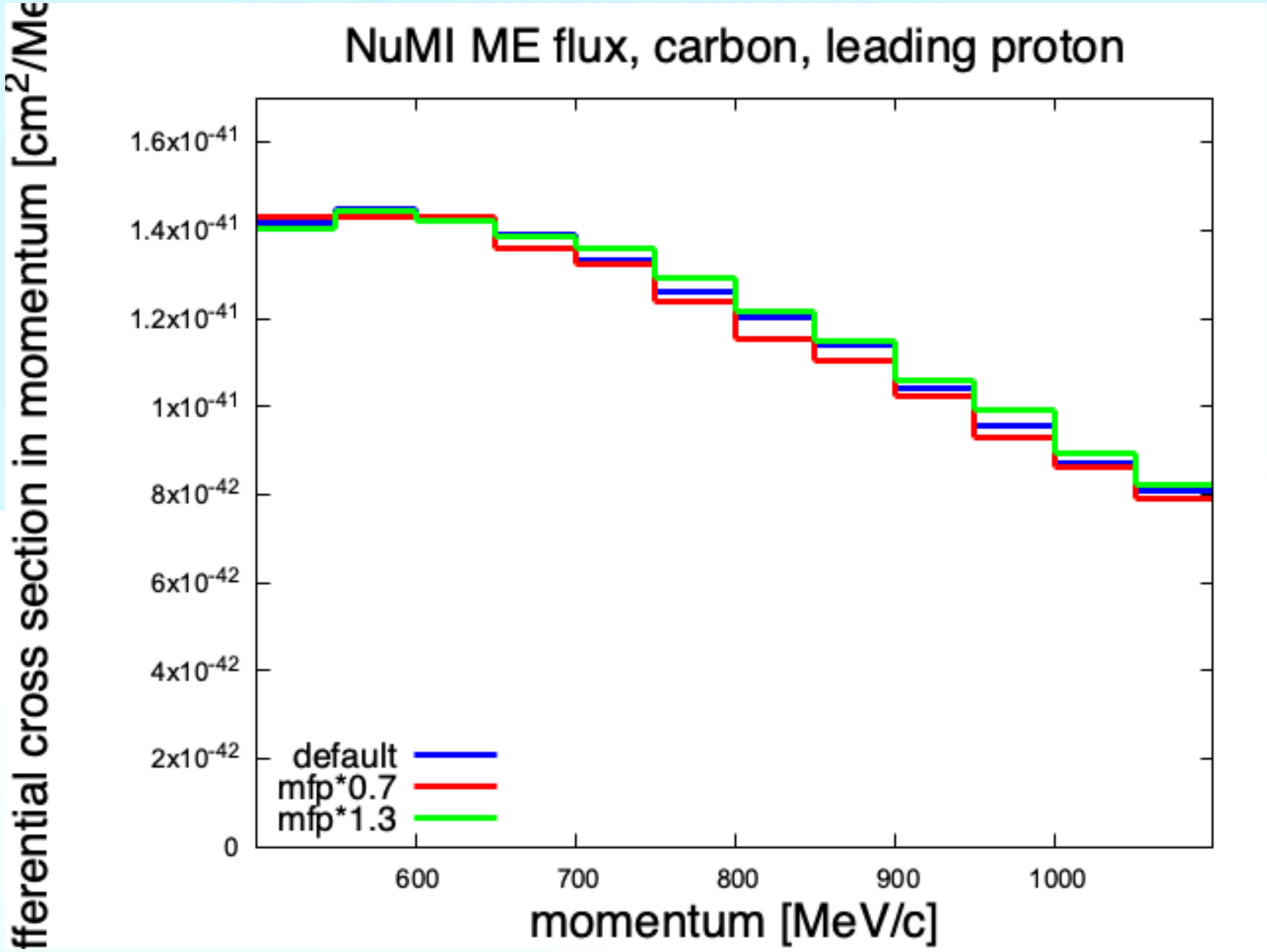
- The most critical ingredient of FSI model is microscopic hadron-nucleon cross section - probability to interact at each step
- In NuWro we estimated uncertainty to be $\pm 30\,\%$
- It is defined as overall multiplicative factor at λ.

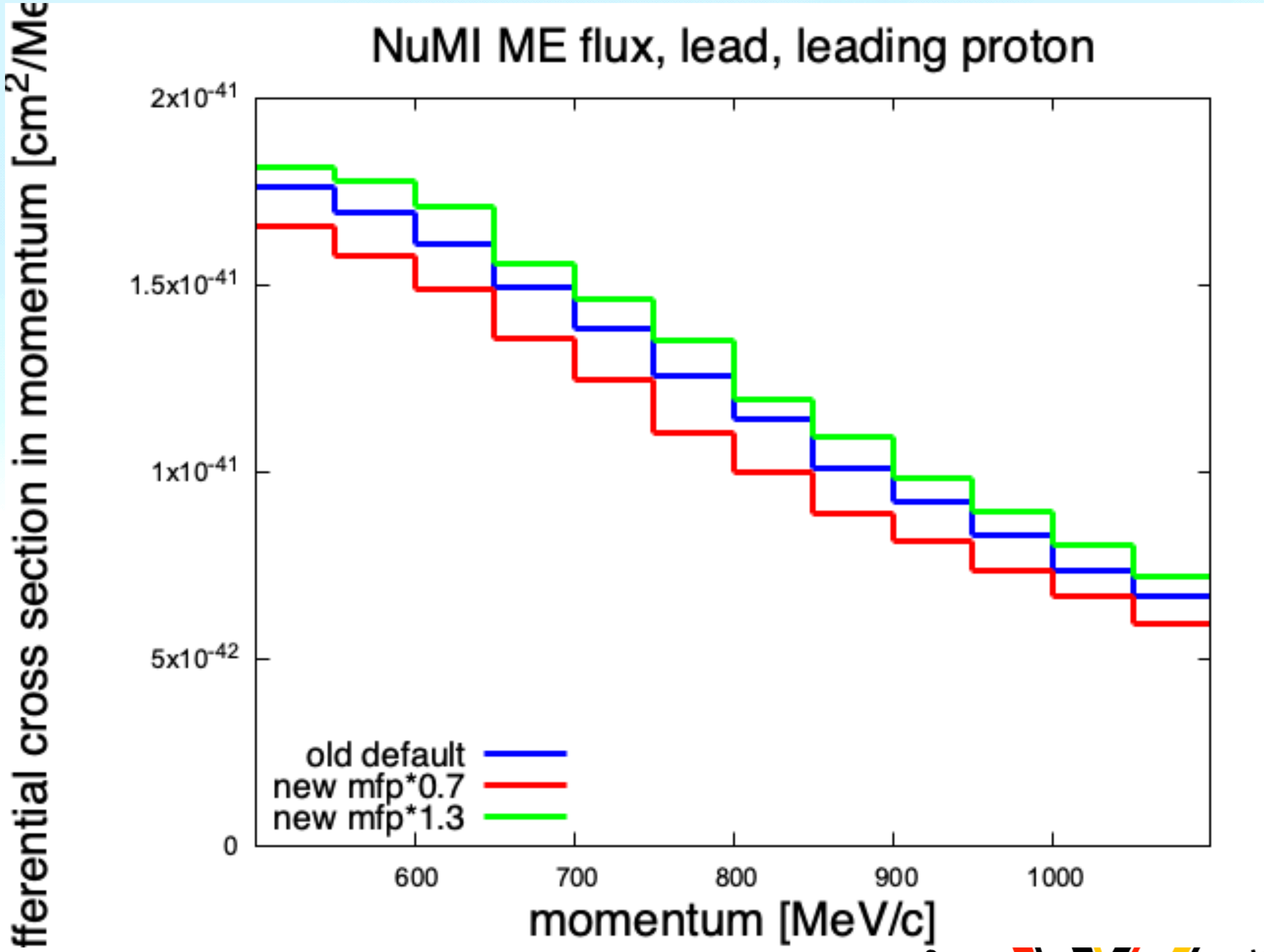
On the next two slides we illustrate its impact on observables.



K. Niewczas, JTS

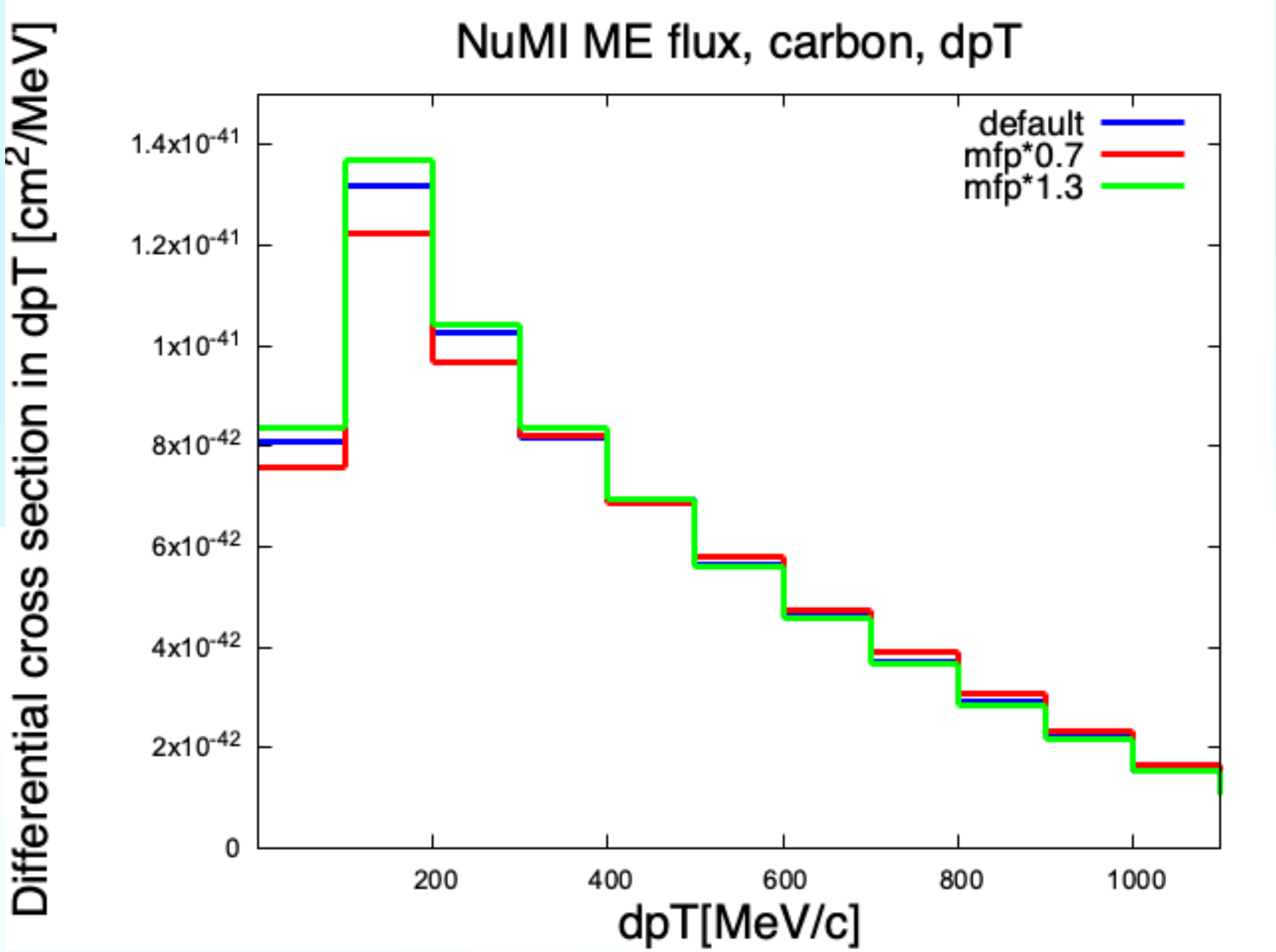
Uncertainty of NuWro FSI model

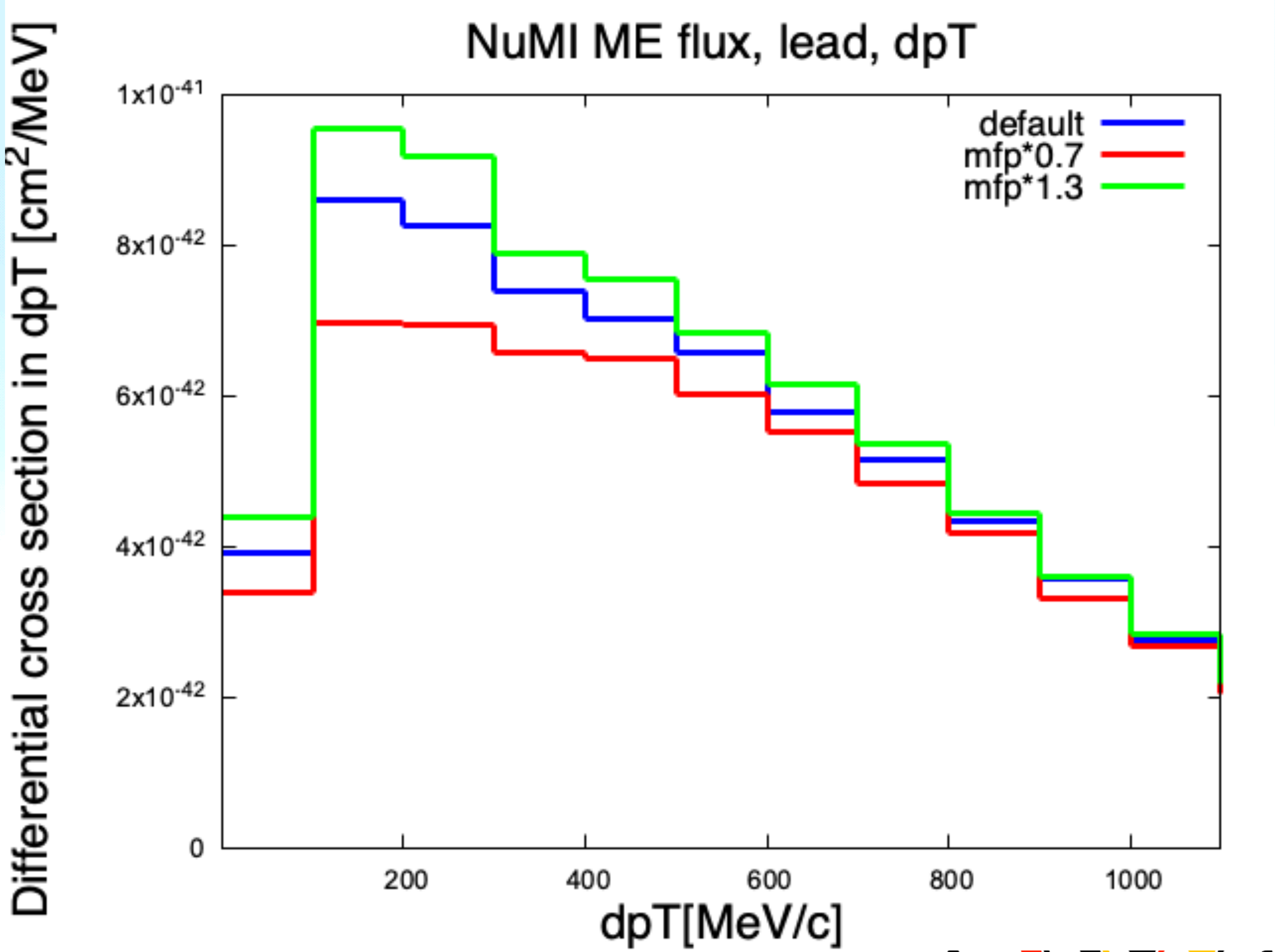




Green means less FSI; red means more FSI

Uncertainty of NuWro FSI model





Green means less FSI; red means more FSI

FSI reweighting tools

Why reweighing?

- Detector simulations are time consuming, usually are done only once
- Uncertainties of MCs should be included in reweighing tools
- FSI uncertainties are very important

We will make an attempt to introduce reweighting scheme for the overall probability of interaction of propagating nucleon - this seems to be the most important feature of FSI models.

Reweighting

What is reweighing?

- In default NuWro configuration the output root file contain events of equal weight
- Reweighting procedure does not change root file but events are assigned with different weights, they become more or less likely

Example: CCQE interaction, axial mass, dipole axial FF

Suppose the events were produced with axial mass M_A and we want to have a sample of events obtained with $\tilde{M}_A$. It is not necessary to run MC again. Reweighting factor $\dfrac{d^2\sigma(\tilde{M}_A, Q^2)/dQ^2}{d^2\sigma(M_A, Q^2)/dQ^2}$ should be applied to each event.

FSI reweighting - toy model

FSI is a complicated process in which many interactions can happen and many particles are involved.

Try to simplify the situation as much as possible to catch the most important features of the reweighting.

A simple model: particles move in equal length steps, typically 0.2 fm, and interactions can occur only at fixed distance points 0.2, 0.4, ...fm (NEUT, and option in NuWro)

FSI reweighting in NEUT was studied before by Patrick de Perio, Tobby Nonnenmacher, Wing Ma, Eldon Pinzon, Martin Hierholzer, Tom Feusels.

FSI reweighting - toy model (2)

Consider a line segment ('a distance from an interaction point to outside nucleus') divided into K identical pieces.

A particle moves along the segment with a fixed probability to interact on each piece.

The process is repeated many times (events)

Every trajectory is described as a set of numbers, like (0,0,0,...0,1,0,... 0,1,0,...,0) where 0 means `no interaction' and 1 means `interaction’. At every step the interaction probability is p.

FSI reweighing - toy model (3)

How to generate trajectories (a technical detail)

Strategy 1: go step by step and select 1 with the probability p and 0 with the probability 1-p.

Strategy 2: if p is very small in most of the cases 0 is selected and we can save computer time by asking question: what is a probability distribution of the first interaction?

Define geometric random number X as a number of the first trial that is a success. Probability distribution is

$$P(X=n) = p(1-p)^{n-1}\,, \quad E[X] = \frac{1}{p}$$

There are standard algorithms to generate X.

FSI reweighing - toy model (4)

We generate M (sufficiently large number) of trajectories.

Sanity test that 'trajectories' are selected correctly:

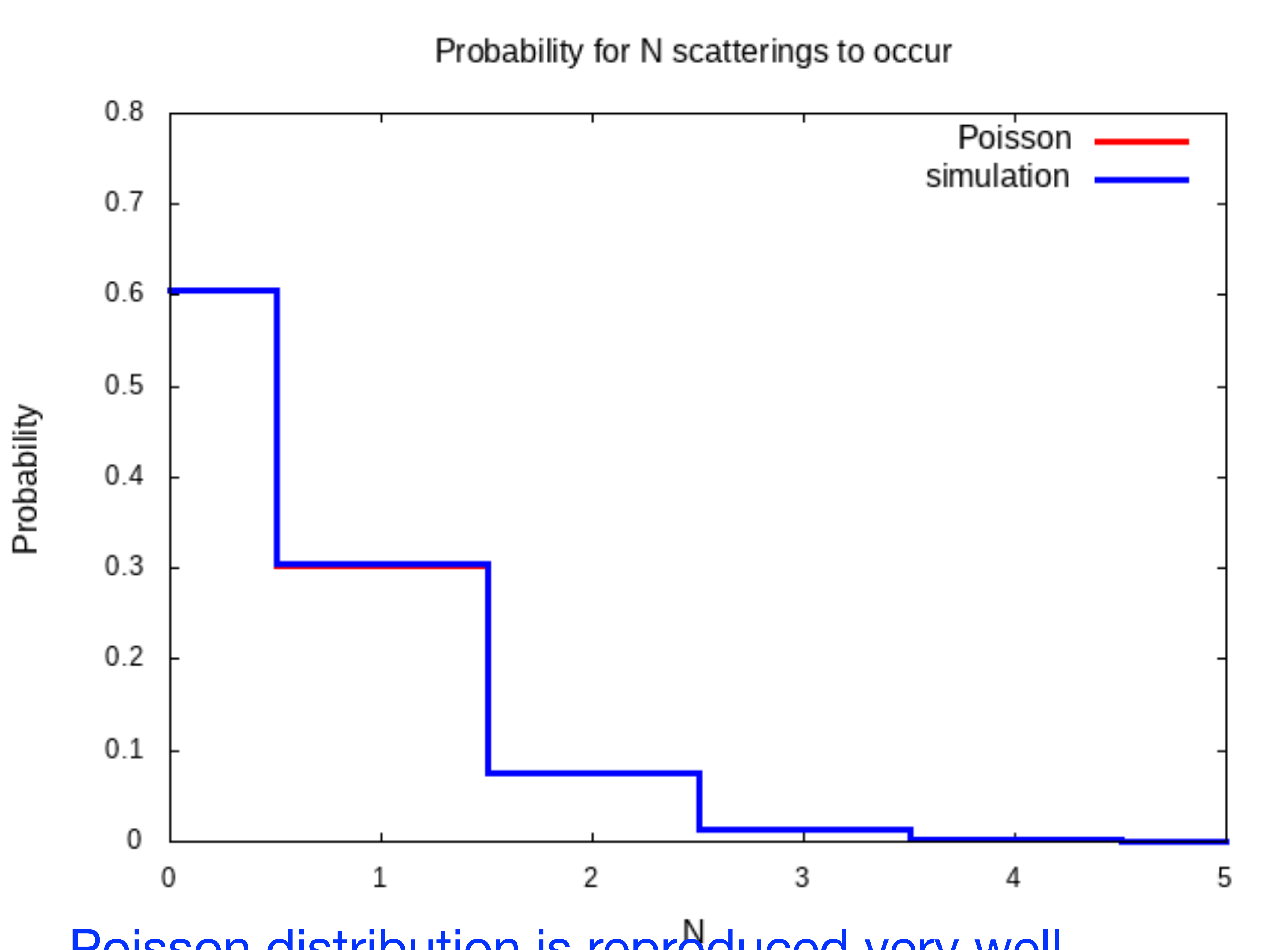
The overall number of interactions N.

It is a binomial random number with probability distribution

$$P(X=N) = \binom{K}{N} p^N (1-p)^{K-N}$$

As p is small and K large,

$$P(X=N) \rightarrow P_{poisson}(X=N) = e^{-\lambda}\frac{\lambda^N}{N!} \text{ with. } \lambda = K \cdot p.$$



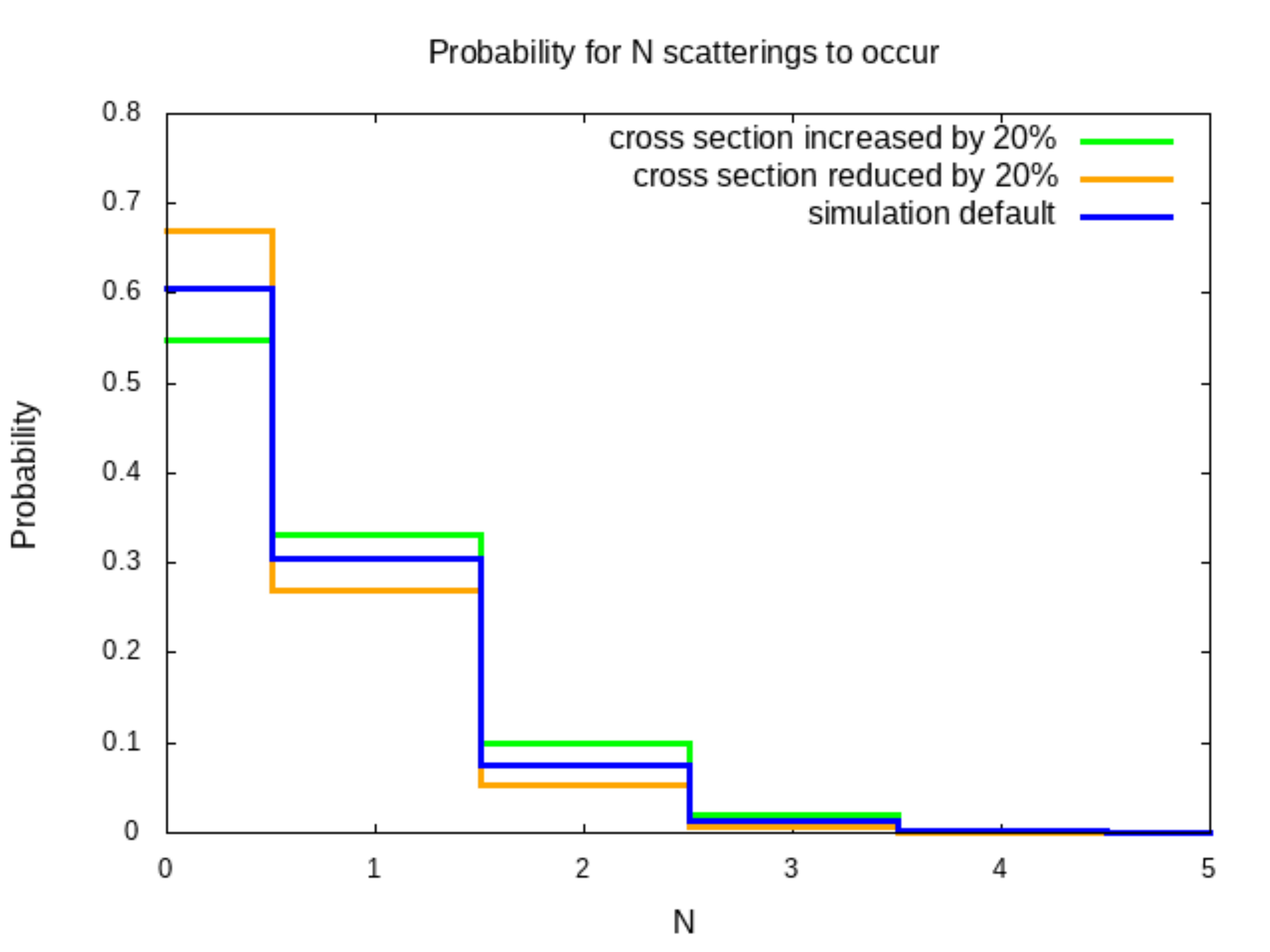
Poisson distribution is reproduced very well.

The parameters are set up so that the value of `nuclear transparency' $P(N=0)$ is realistic :)

Parameters are: p=0.01 K=50

$M = 10^7$ events are generated.

FSI reweighing - toy model (5)



We change interaction probability from p to 0.8*p or 1.2*p.

'Nuclear transparency' is increased if $p \rightarrow 0.8 \cdot p$ and lowered if $p \rightarrow 1.2 \cdot p$.

We want to get the same effect by appropriate reweighting applied to each event separately.

FSI reweighing - toy model (6)

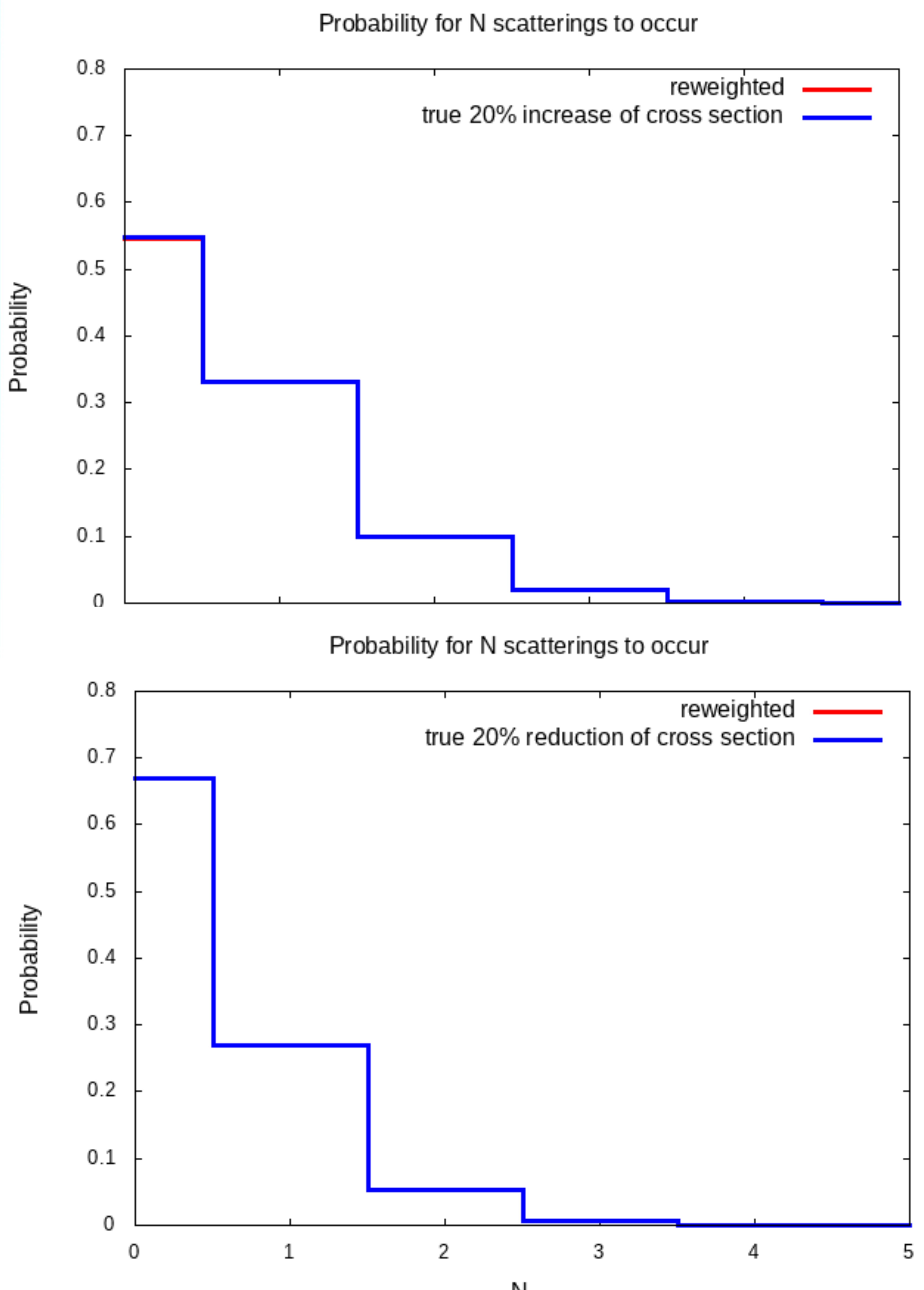
A trajectory is characterized by:

N number of interactions
(K-N)   number of steps without interaction.

Let p be a default probability interaction at each step and p_{new} be a new probability of interaction.

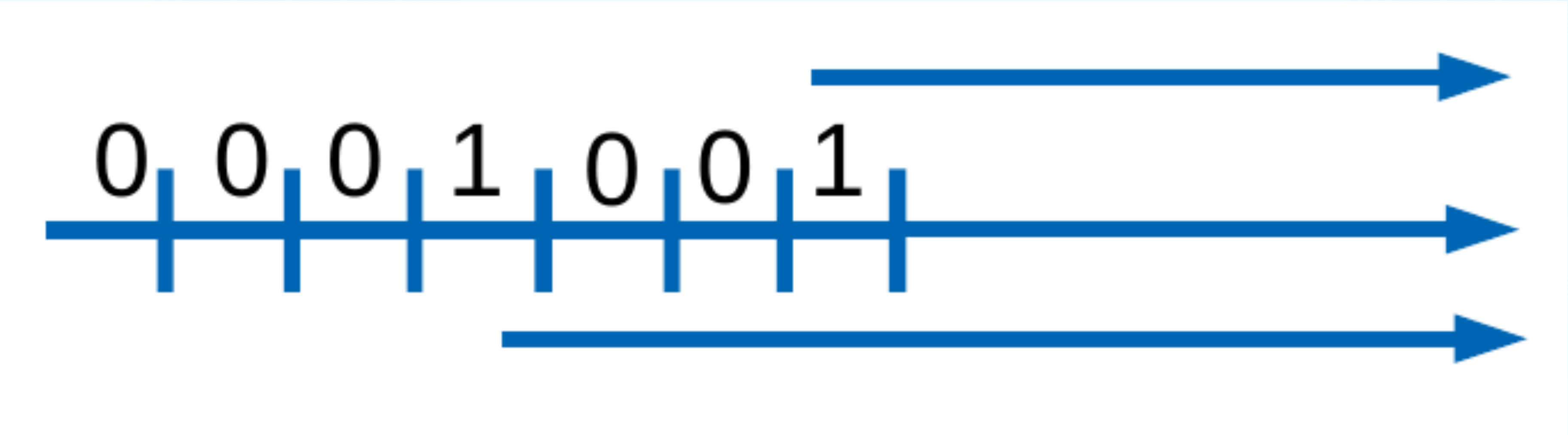
We introduce $R = \left(\frac{p_{new}}{p}\right)^N \left(\frac{1-p_{new}}{1-p}\right)^{K-N}$.

If $R < 1$ the trajectory is removed with the probability $1 - R$
If $R > 1$the trajectory is duplicated with the probability $R - 1$.

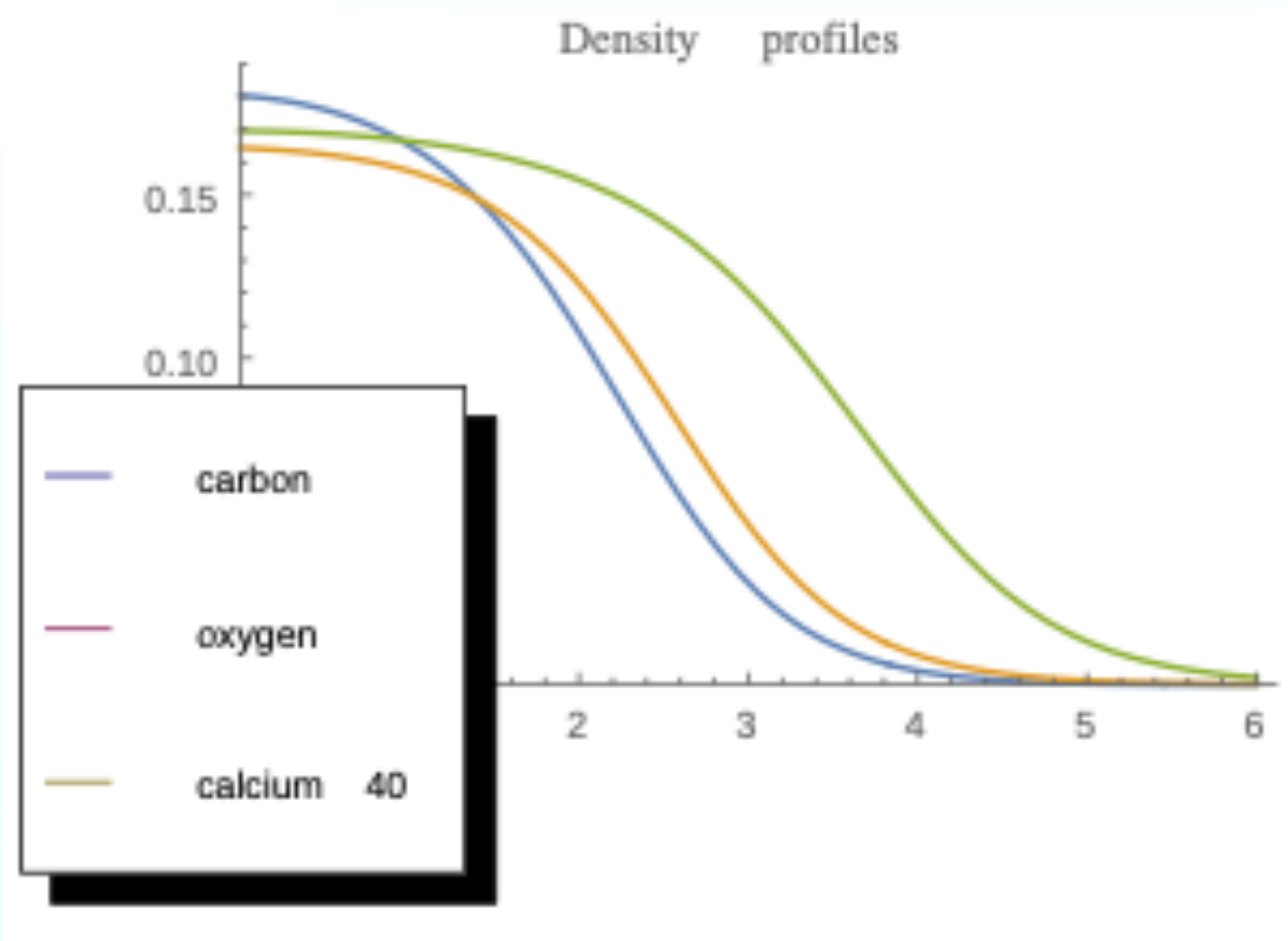


FSI reweighing - toy model (7)

How to make the toy model more realistic?



Each `interaction' starts a new `trajectory' (new particle)
Within the same event. Each event must we reweighed as a whole.



In realistic situation a probability of interaction is at each step different according to local density.

The toy model can be made more sophisticated but we move on to Monte Carlo generator.

FSI reweighing - strategy

We start with the simplest approach. (ALL RESULTS IN THIS SEMINAR ARE PRELIMINARY)

- For each event in a given simulation NuWro stores information about number of nucleon interactions in the cascade and overall number of steps
- With this info we can calculate average probability of interaction $P = \frac{N_{int}}{N_{int} + N_{fail}}$
- $1 - P$ corresponds to probability to travel a distance $\Delta x = 0.2 fm$ without interaction
- $\exp(-\frac{\Delta x}{\lambda})$ which is a basic formula in the NuWro cascade.
- Guided by the toy model we reweight events by modifying $P \to P'$

$$R = \left(\frac{P'}{P}\right)^{N_{int}} \left(\frac{1-P'}{1-P}\right)^{N_{fail}}$$

FSI reweighing - strategy

Caveats:

This approach can only be a good approximation because mean-free-path $\lambda = \dfrac{1}{\rho \cdot \sigma}$ depends on density ρ (position inside nucleus) and on microscopic cross section σ which is a function of nucleon momentum

NuWro FSI uncertainty applies to λ.

Let $\dfrac{P'}{P} = r$. It corresponds to the change of $\lambda \to \lambda' = s\lambda$.

$$P' = rP = 1 - \exp\left(-\frac{\Delta x}{\lambda'}\right) = 1 - \exp\left(-\frac{\Delta x}{s\lambda}\right) \to rP = 1 - (1-P)^{\frac{1}{s}}$$

NuWro FSI reweighing - normalization

In the toy model we checked that $\sum_{j=1}^{N} W_j = N$. Due to approximations of the approach this normalization condition must be verified.

NuMi ME flux carbon target, $P = 0.00805796$; for $P \to 1.3 * P$ we get $\dfrac{N}{\sum_j W_j} = 0.999969$

$P \to 0.7 * P$ we get $\dfrac{N}{\sum_j W_j} = 0.999971$

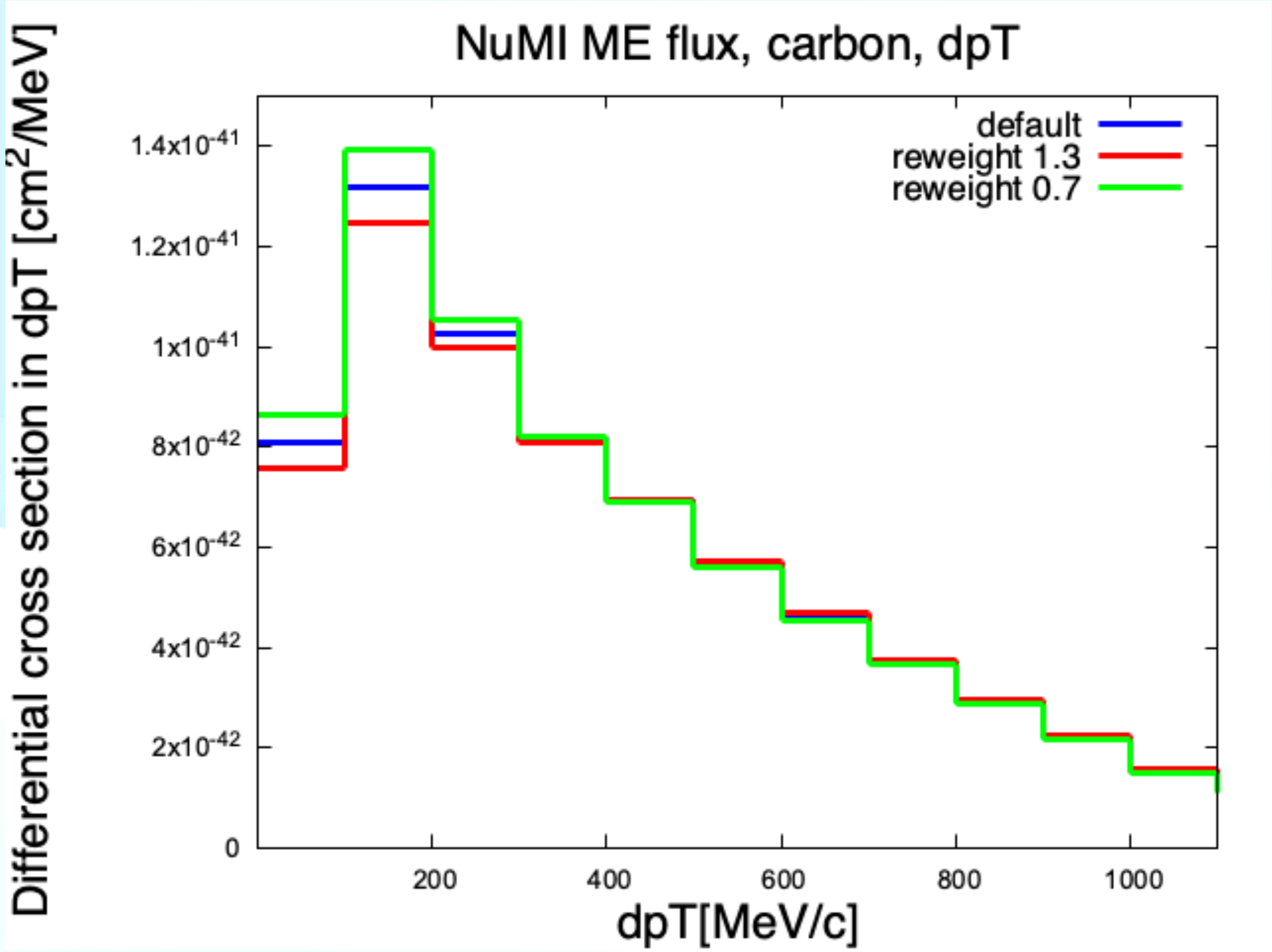
NuMi ME flux lead target, $P = 0.0220029$; for $P \to 1.3 * P$ we get $\dfrac{N}{\sum_j W_j} = 0.935466$

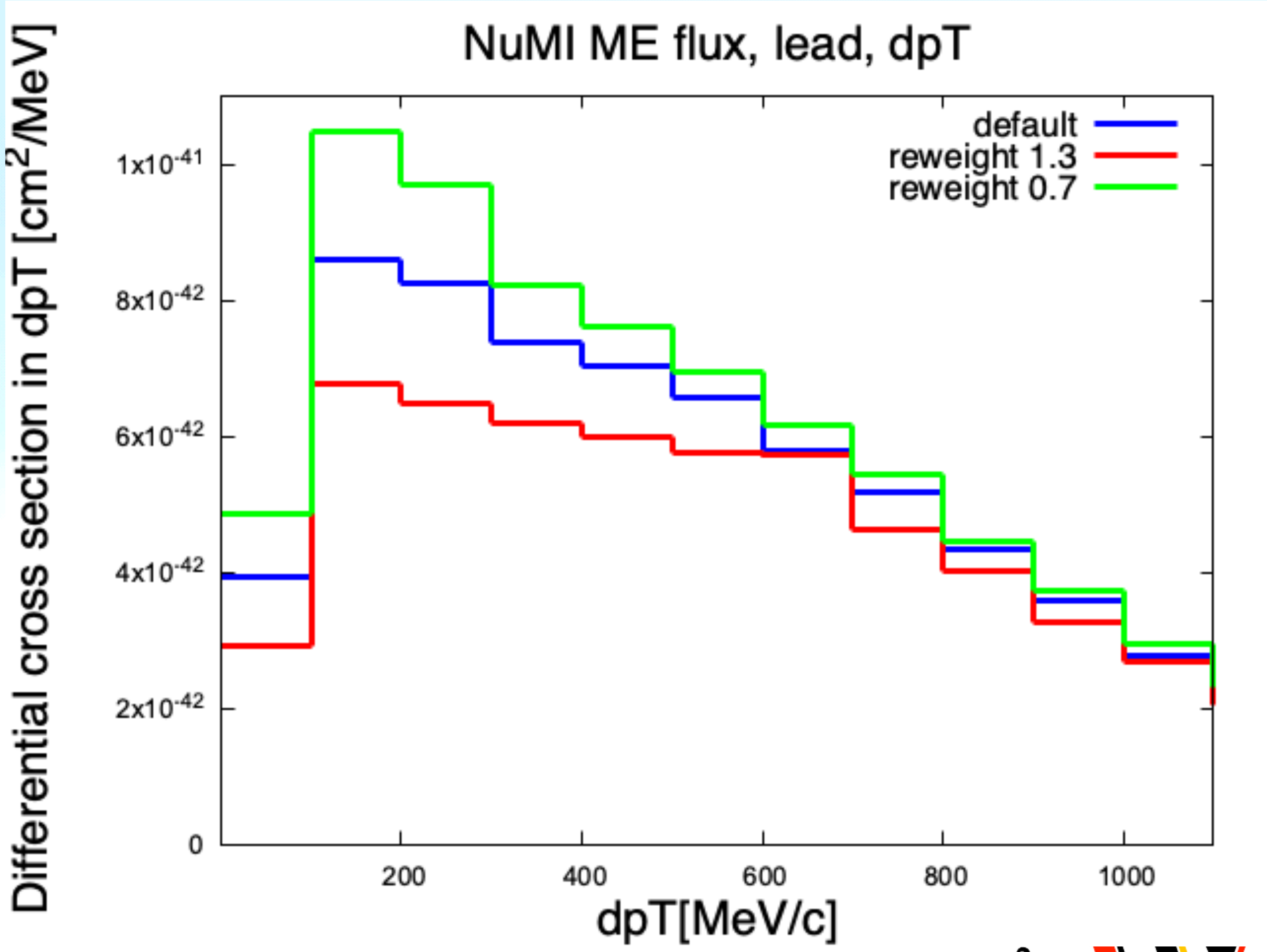
$P \to 0.7 * P$ we get $\dfrac{N}{\sum_j W_j} = 0.958048$

We introduce extra rescaling $W_j \to \tilde{W}_j$ so that $\sum_{j=1}^{N} \tilde{W}_j = N$

NuWro * Wrocław Neutrino Event Generator *

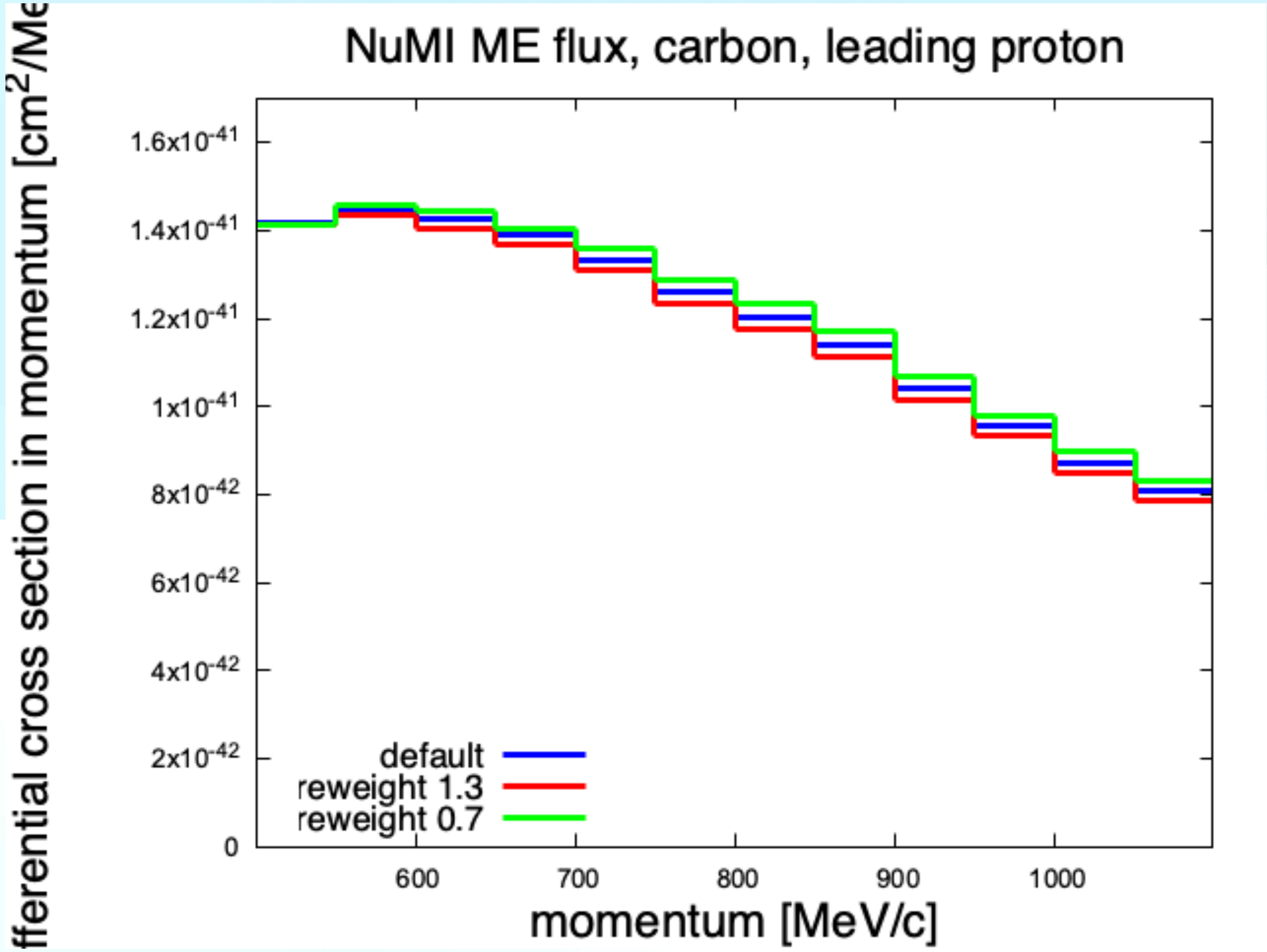
NuWro FSI reweighing - results

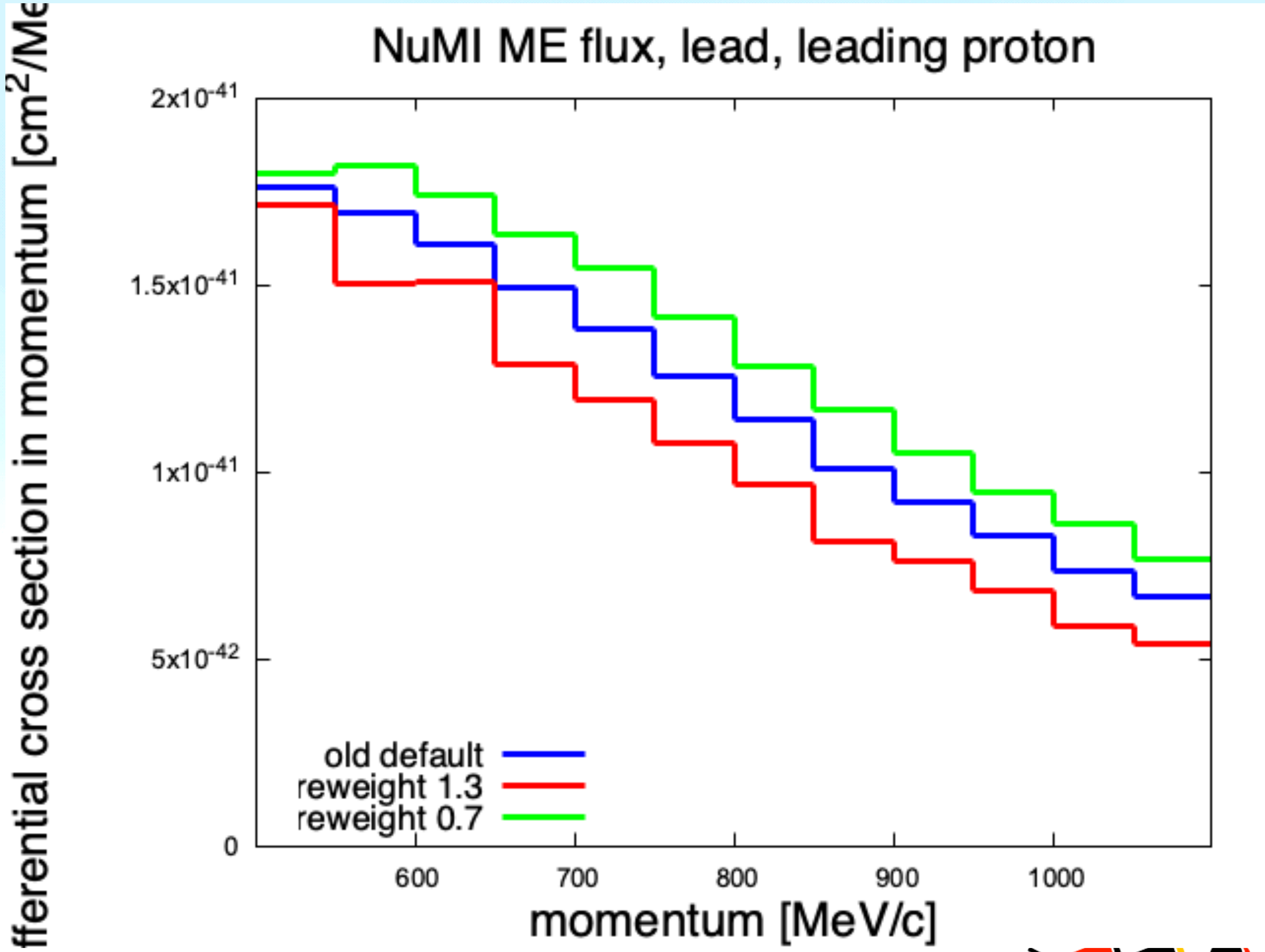




Green means less FSI; red means more FSI

NuWro FSI reweighing - results





Green means less FSI; red means more FSI

Change of mean-free-path and reweighing

What should we expect for reweighting if mean-free-path is scaled by s?

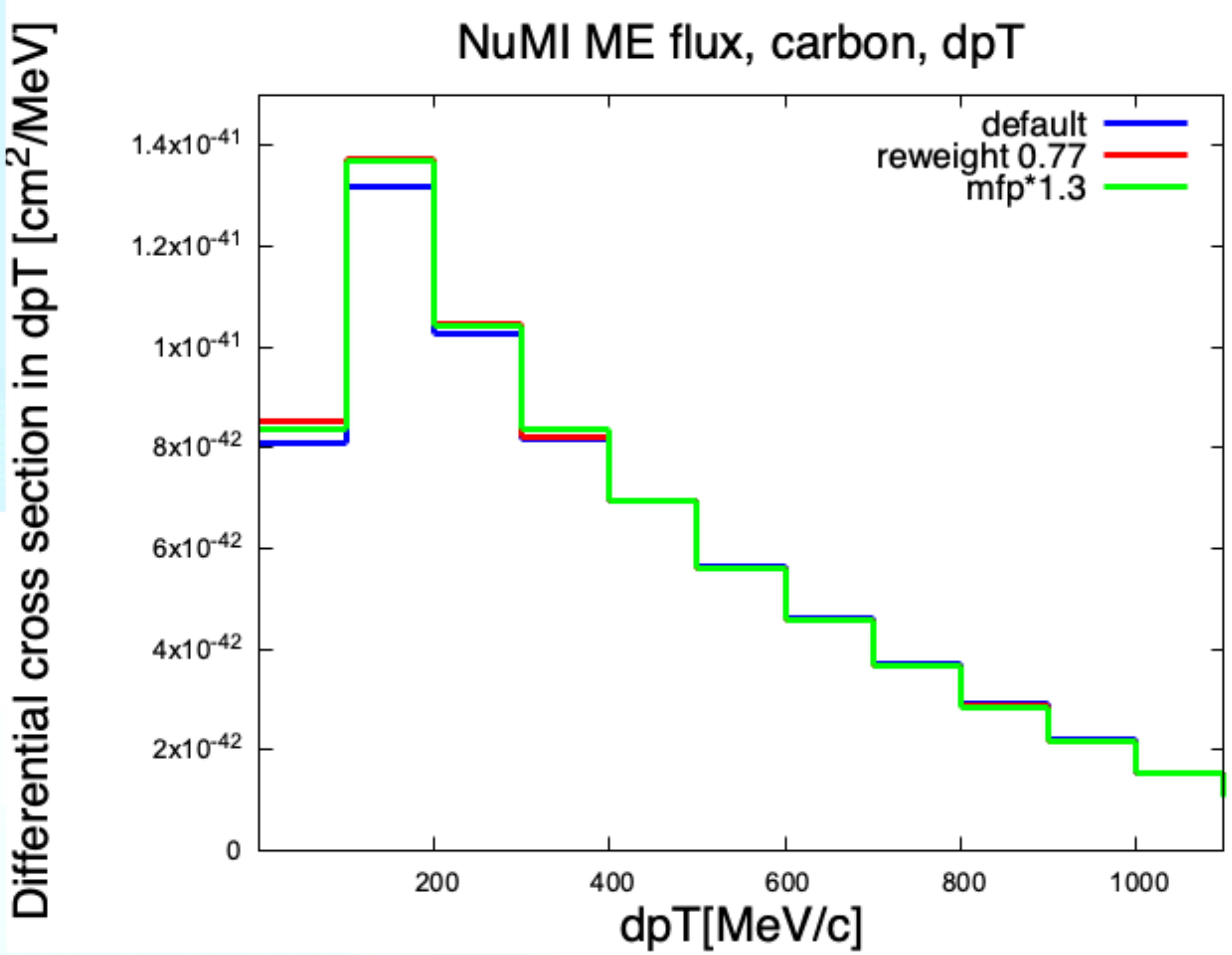
Remember: $P' = 1 - (1 - P)^{\frac{1}{s}}$

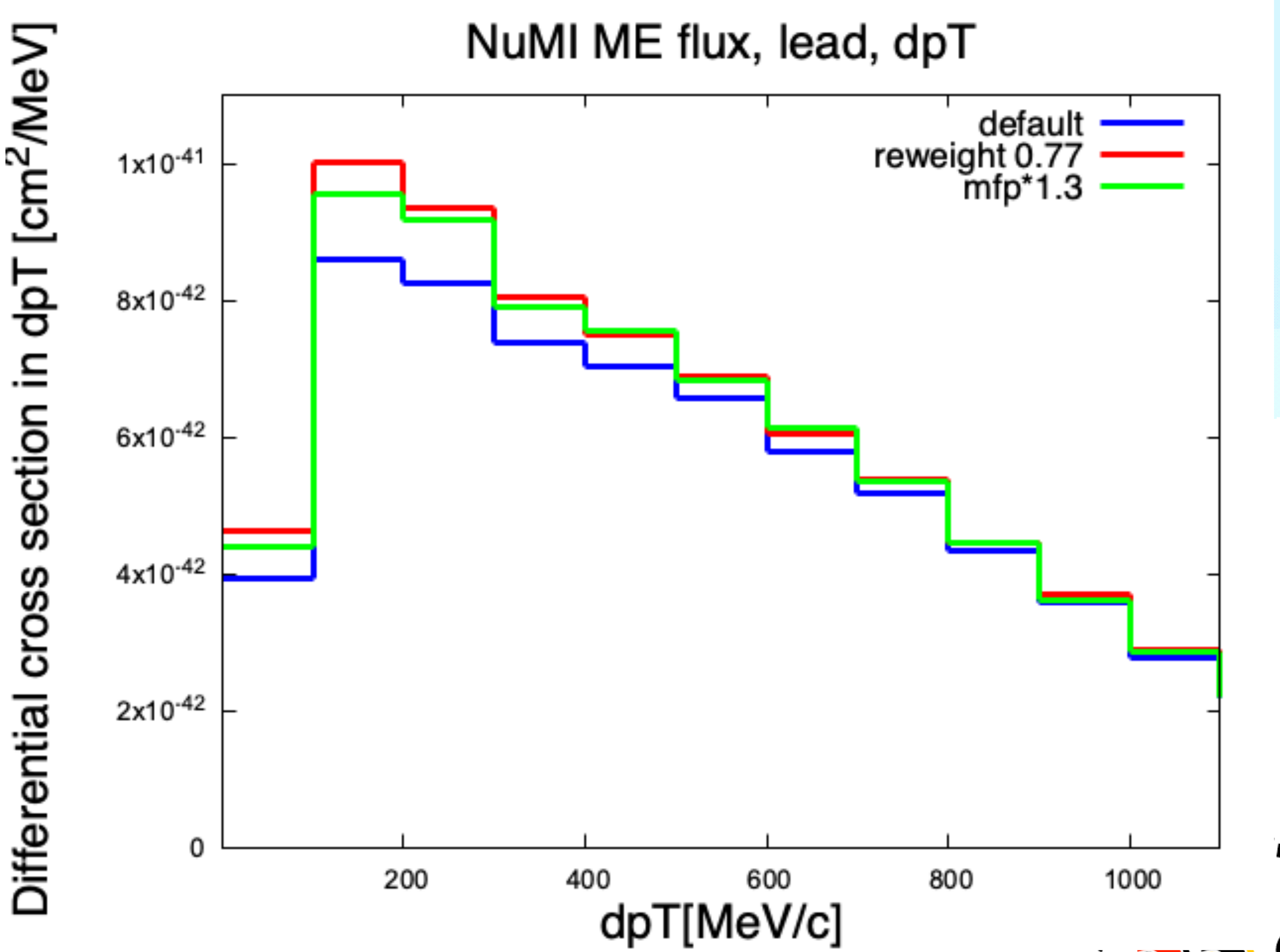
P is very small and $P' = 1 - (1 - P)^{\frac{1}{s}} \approx 1 - \left(1 - P\frac{1}{s}\right) = P\frac{1}{s}$

We expect that for $s = 1.3$ $P \approx 0.77$

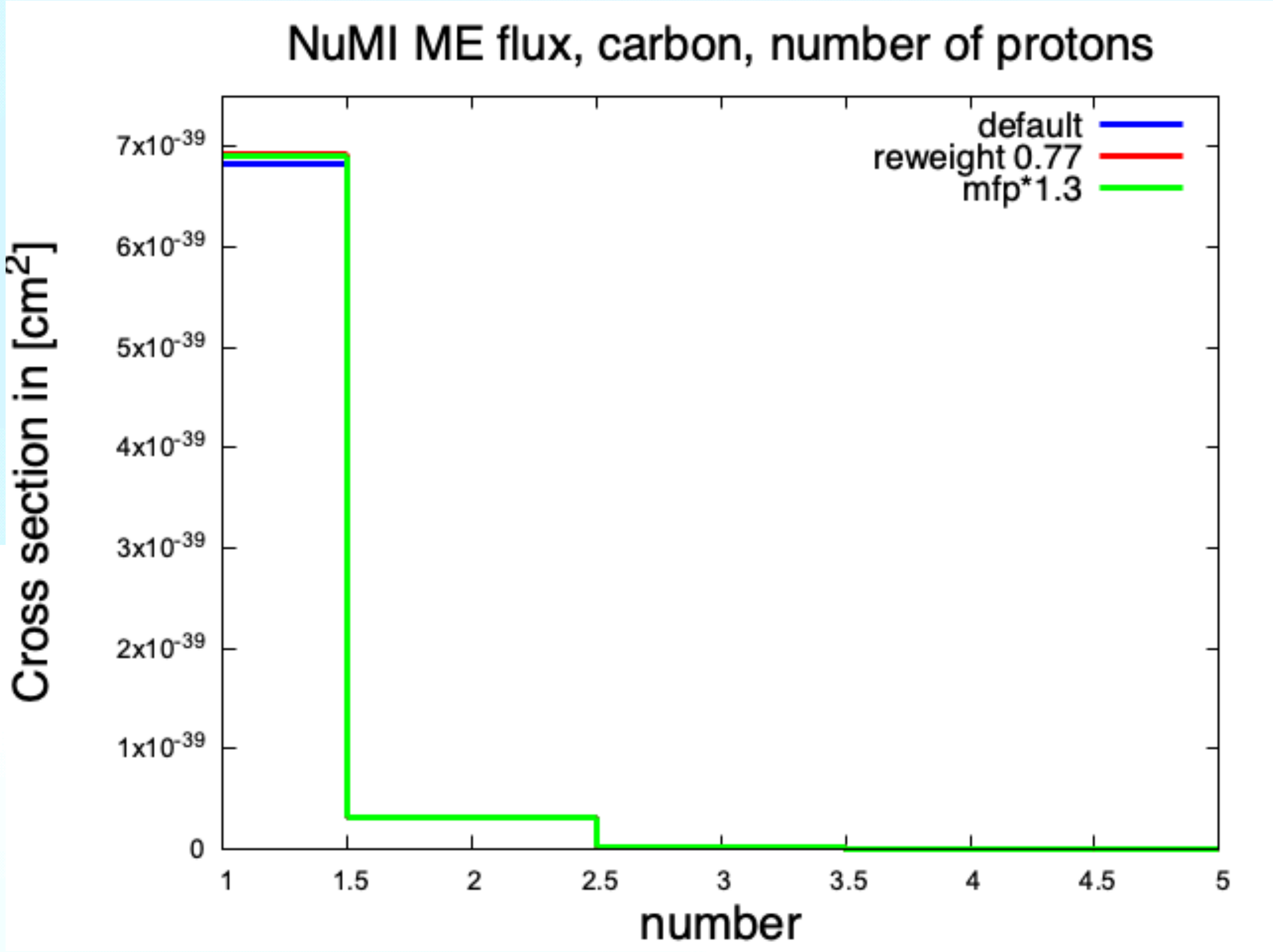
and for $s = 0.7$ $P \approx 1.43$

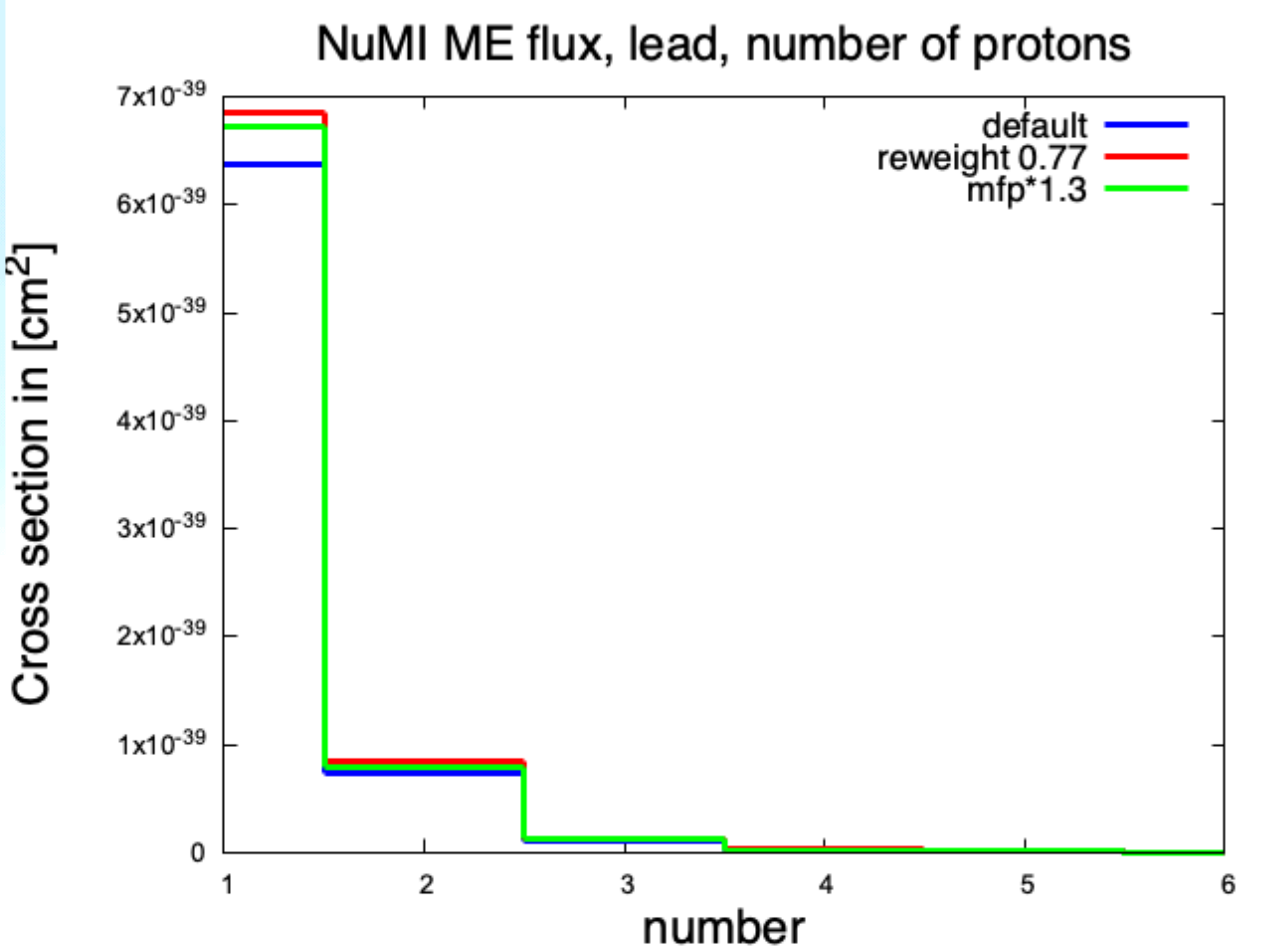
Change of mean-free-path and reweighing





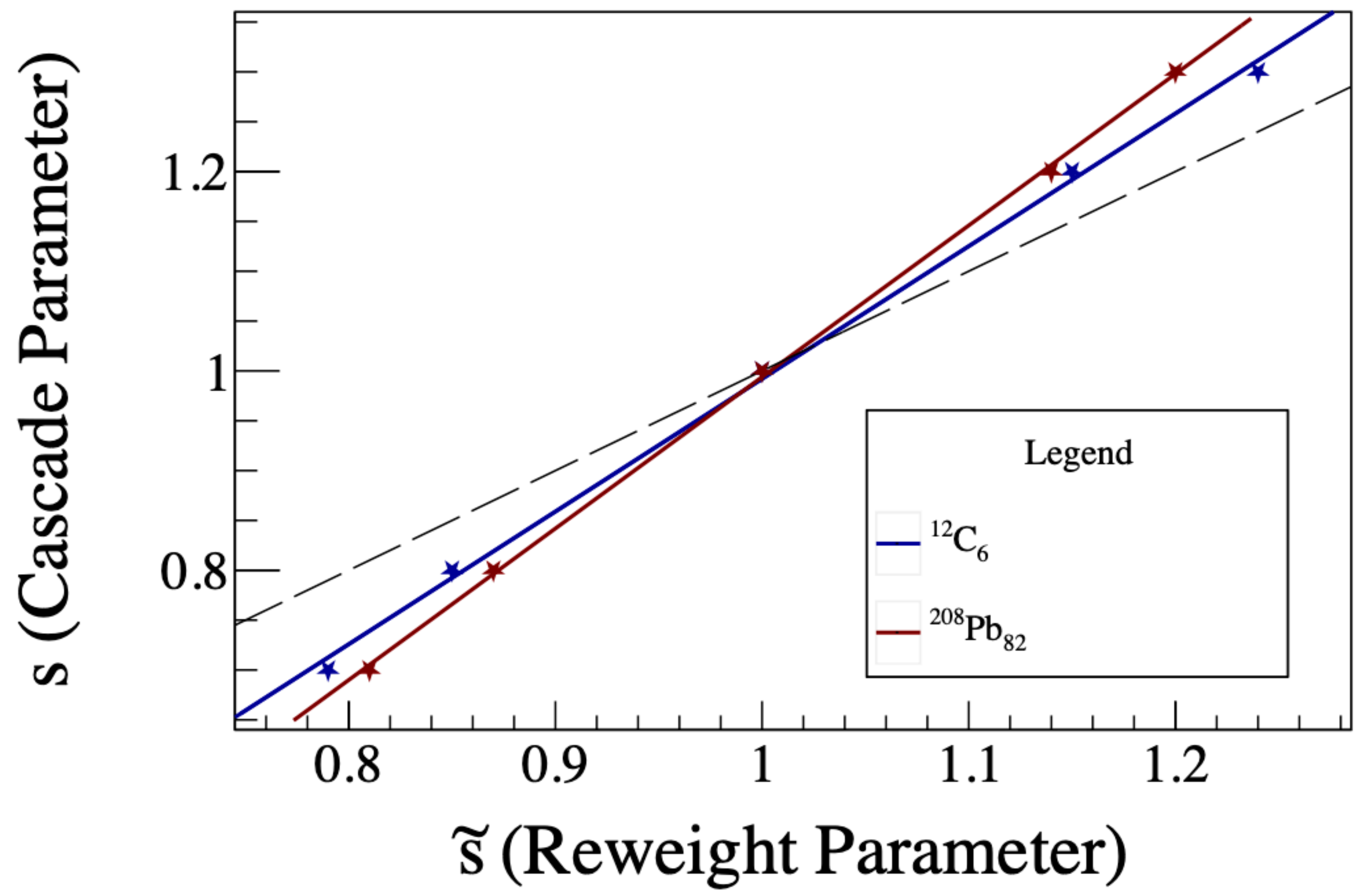
Change of mean-free-path and reweighing





Reweighting by 0.77 is too strong. How to optimize it ? Seems it should be different for carbon and lead.

Change of mean-free-path and reweighing



With NuMi ME flux a fit was done to the distribution of leading proton momentum.

For a given target (C, Pb) and given value of s (NuWro parameter, scales mean-free-path) an optimal $\tilde{s} \approx \dfrac{P}{P'}$ is found.

On the next slides we show the results.

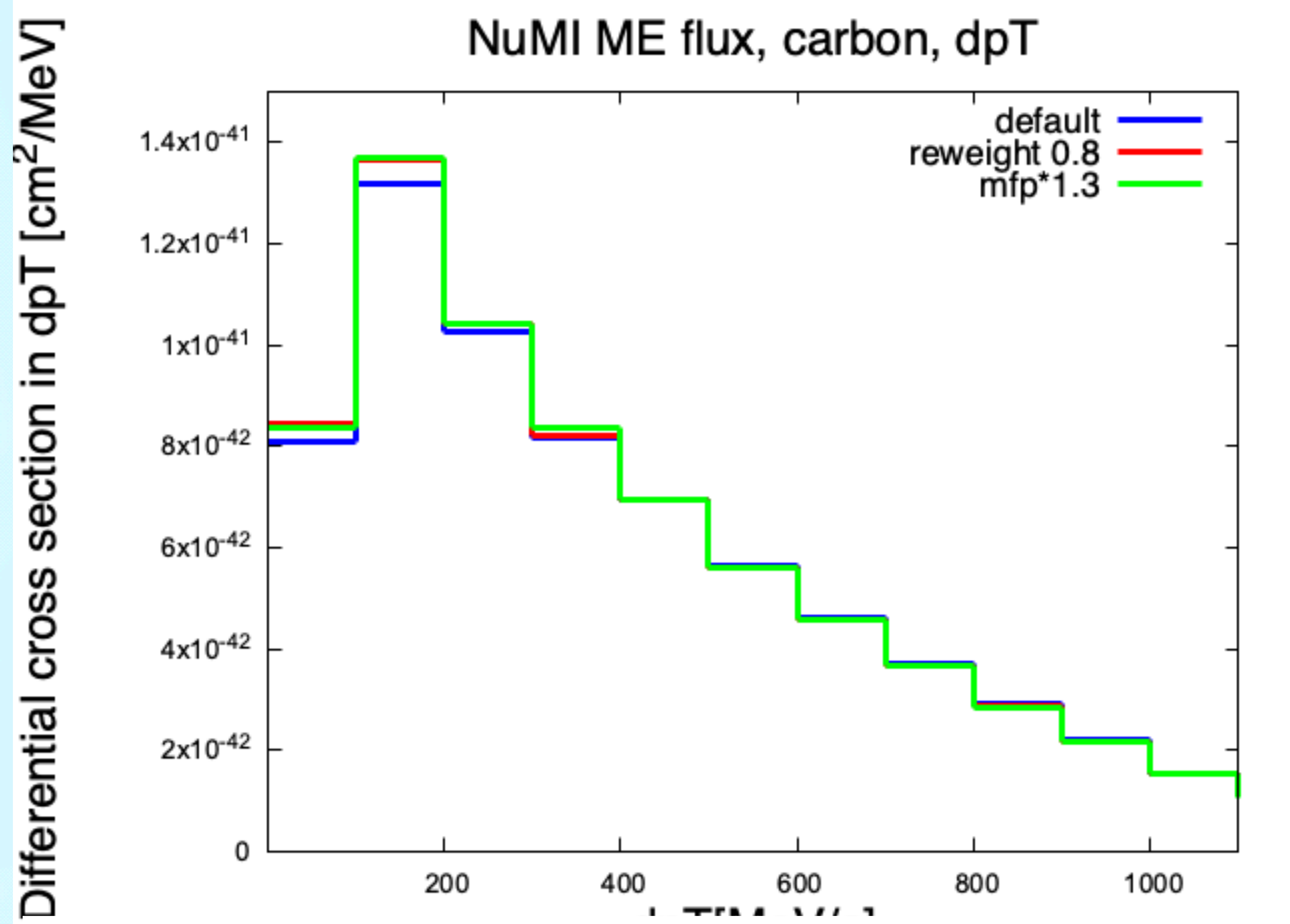
Lead:

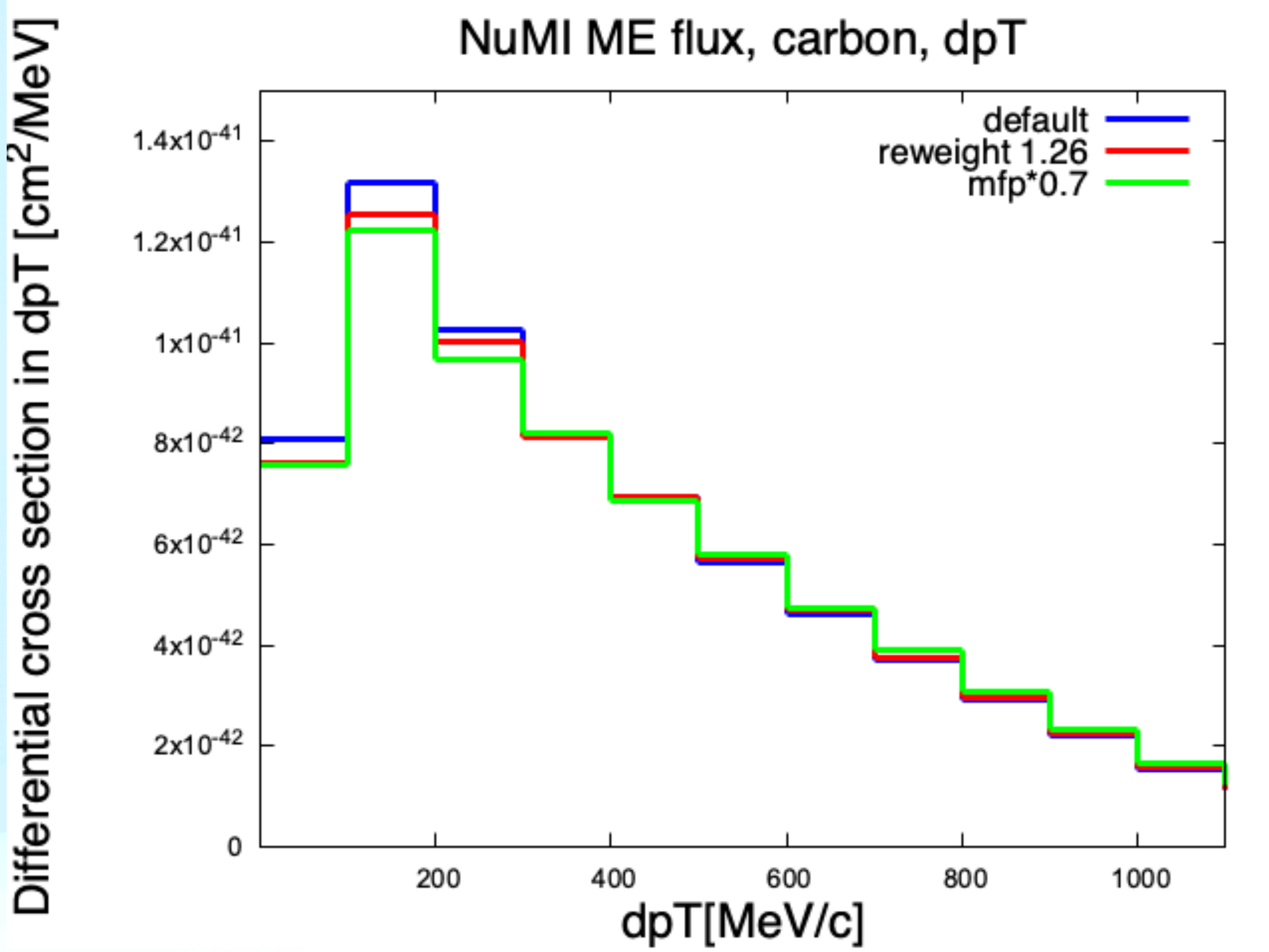
$s = 1.3 \leftrightarrow r = 0.83$, $s = 0.7 \leftrightarrow r = 1.23$

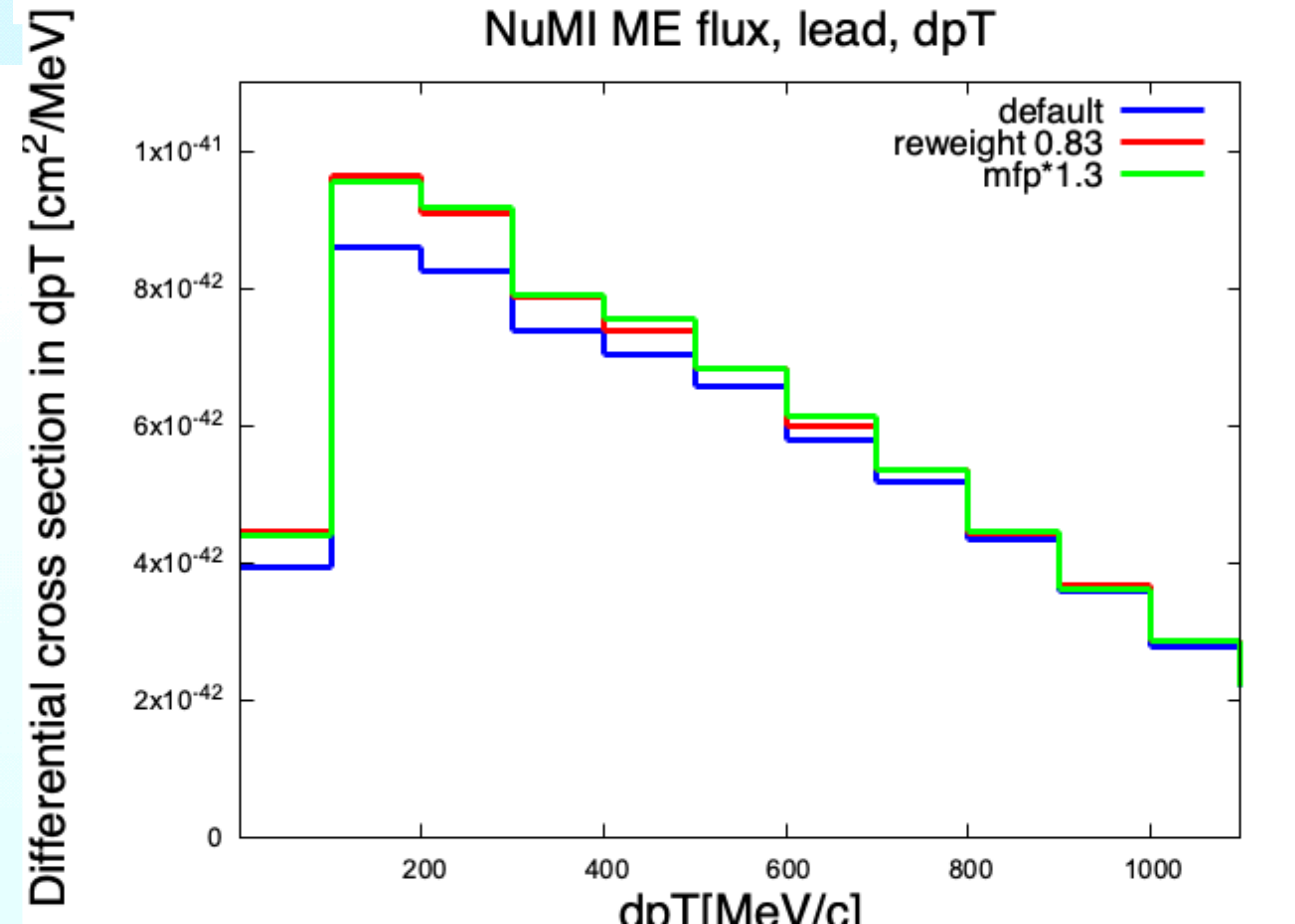
Carbon

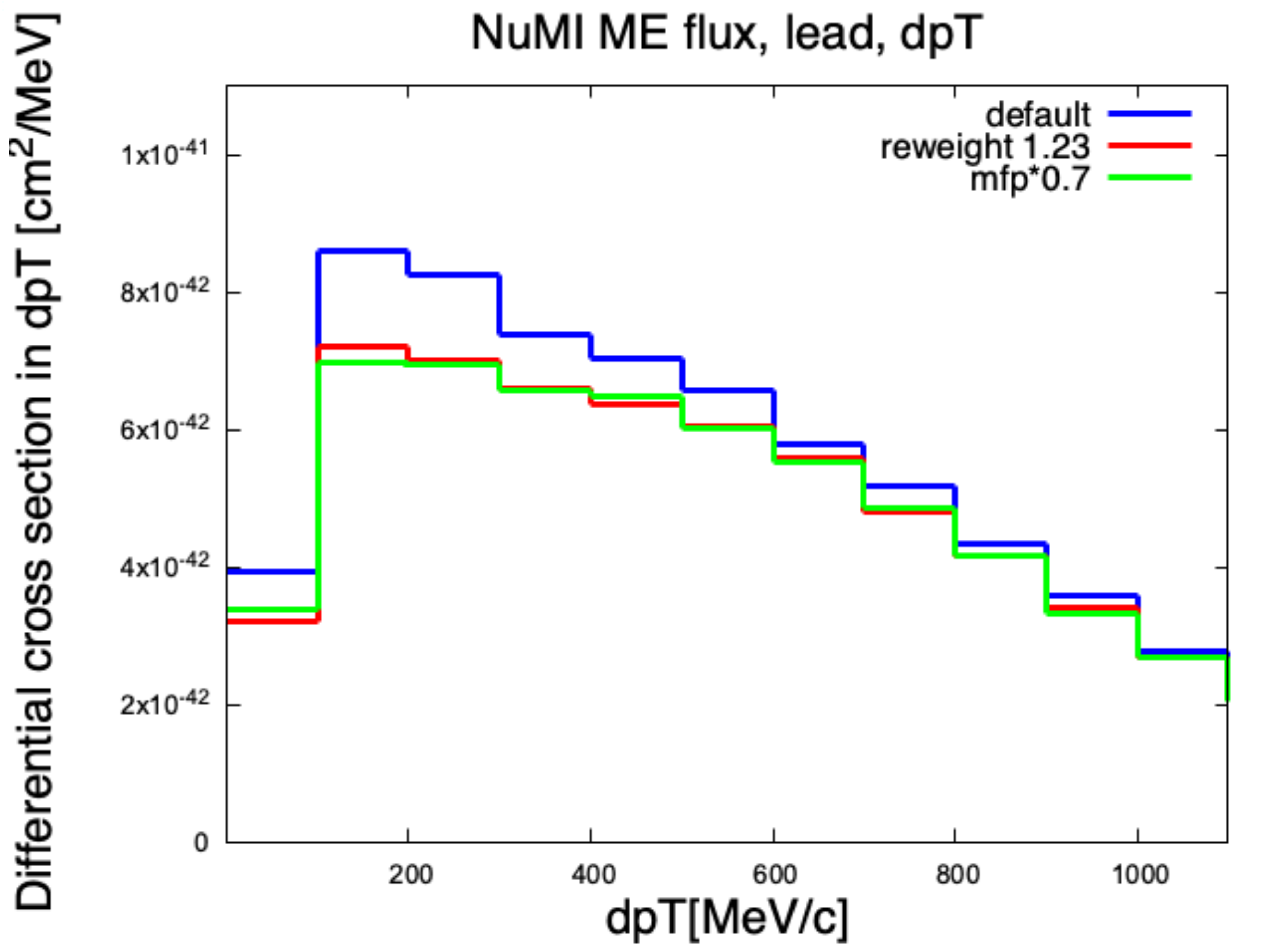
$s = 1.3 \leftrightarrow r = 0.8$, $s = 0.7 \leftrightarrow r = 1.26$

Results (1)

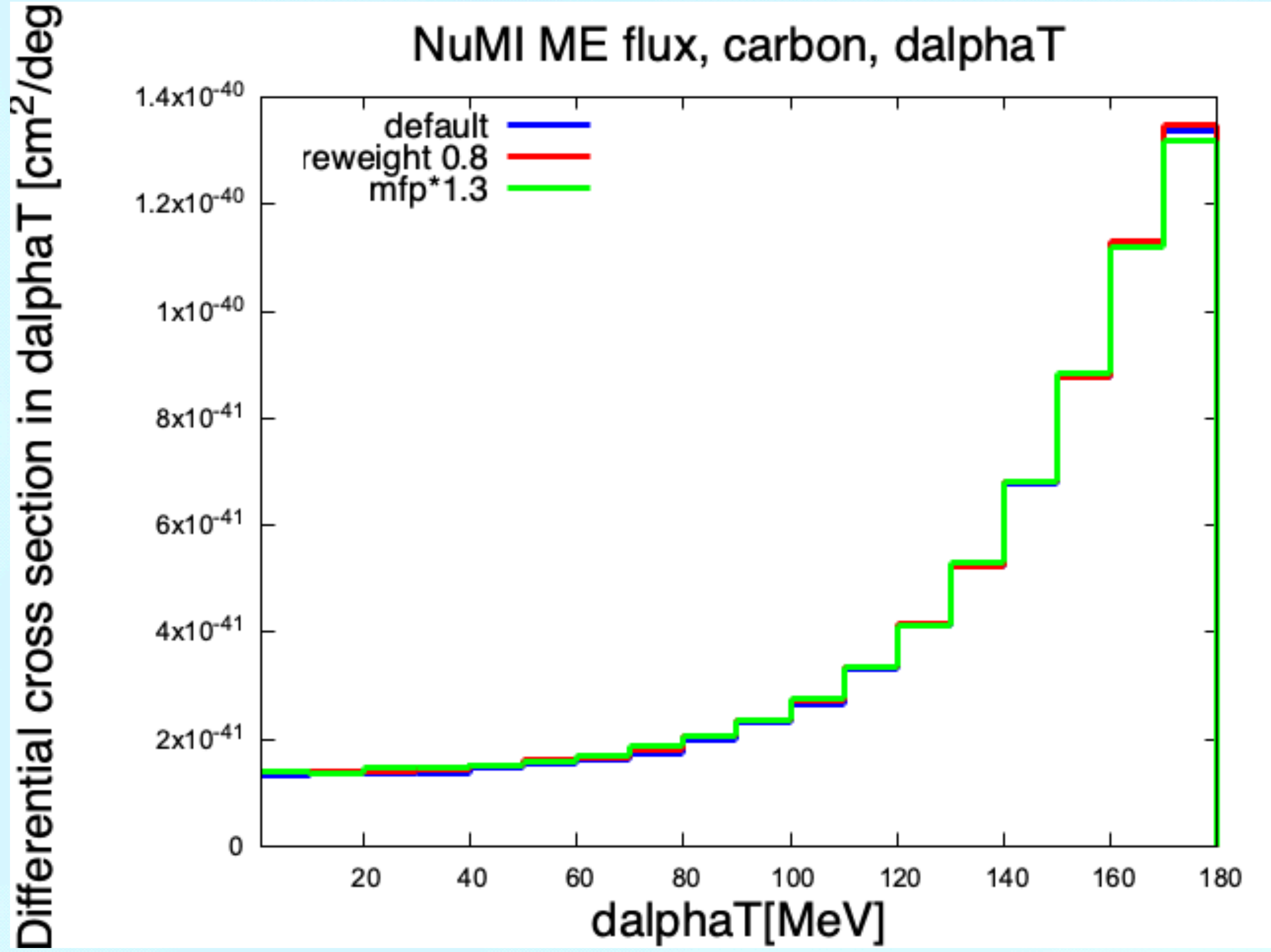

NuMI ME flux, carbon, dpT
default
reweight 0.8
mfp*1.3
Differential cross section in dpT [cm^2/MeV]
0
2x10^{-42}
4x10^{-42}
6x10^{-42}
8x10^{-42}
1x10^{-41}
1.2x10^{-41}
1.4x10^{-41}
200
400
600
800
1000


NuMI ME flux, carbon, dpT
default
reweight 1.26
mfp*0.7
Differential cross section in dpT [cm^2/MeV]
0
2x10^{-42}
4x10^{-42}
6x10^{-42}
8x10^{-42}
1x10^{-41}
1.2x10^{-41}
1.4x10^{-41}
200
400
600
800
1000
dpT[MeV/c]

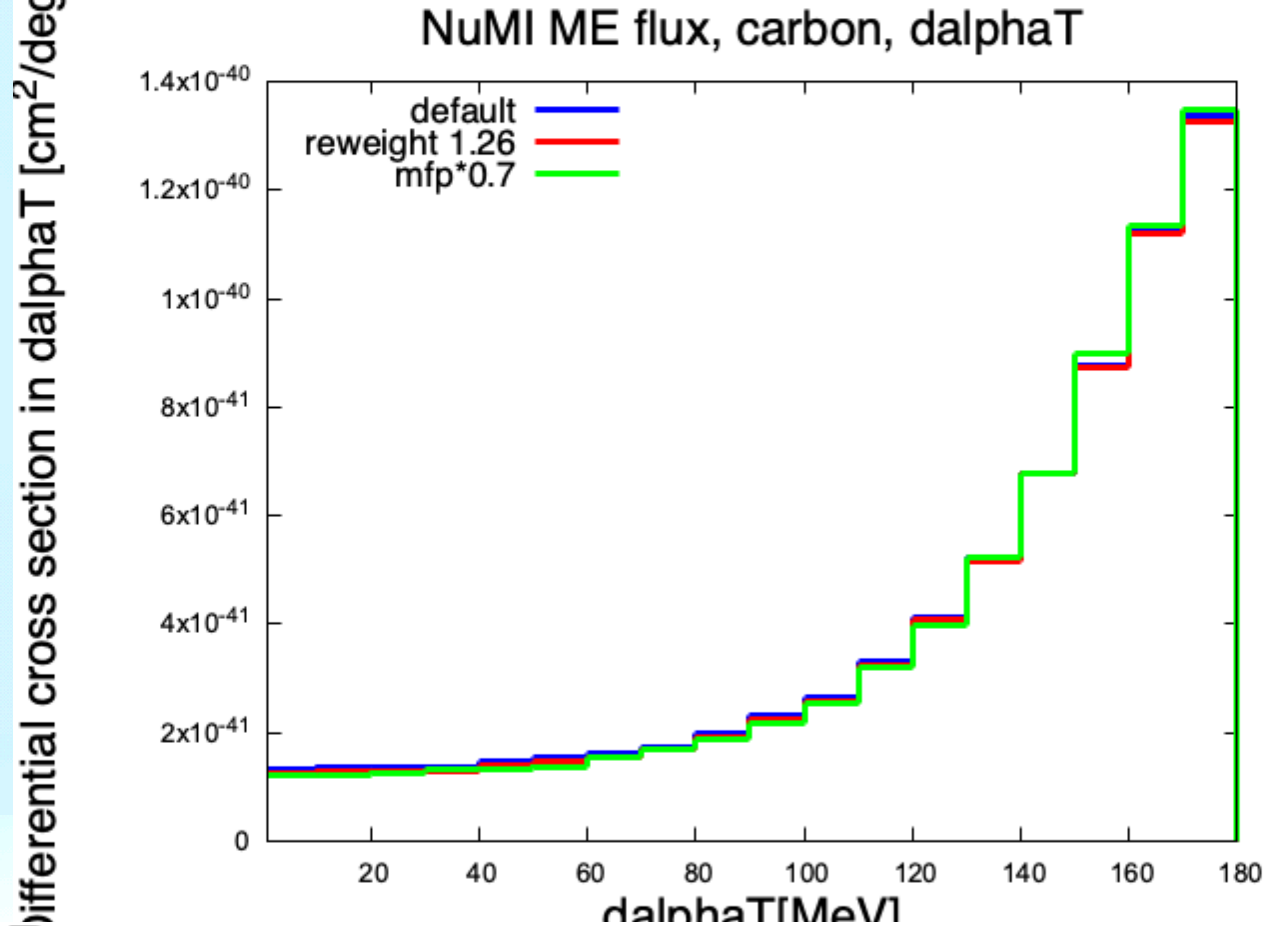

NuMI ME flux, lead, dpT
default
reweight 0.83
mfp*1.3
Differential cross section in dpT [cm^2/MeV]
0
2x10^{-42}
4x10^{-42}
6x10^{-42}
8x10^{-42}
1x10^{-41}
200
400
600
800
1000
dpT[MeV/c]


NuMI ME flux, lead, dpT
default
reweight 1.23
mfp*0.7
Differential cross section in dpT [cm^2/MeV]
0
2x10^{-42}
4x10^{-42}
6x10^{-42}
8x10^{-42}
1x10^{-41}
200
400
600
800
1000
dpT[MeV/c]

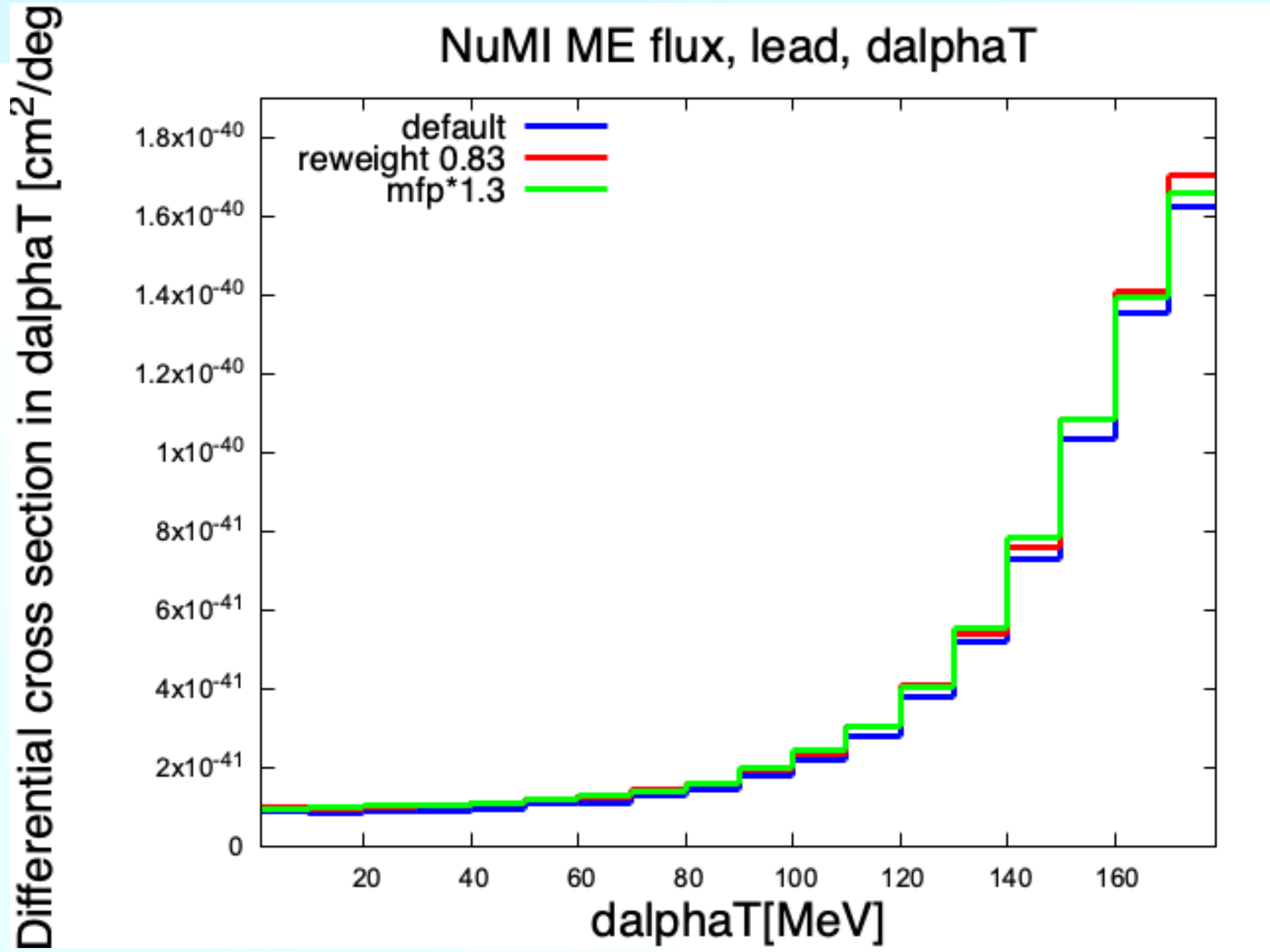
Results (2)



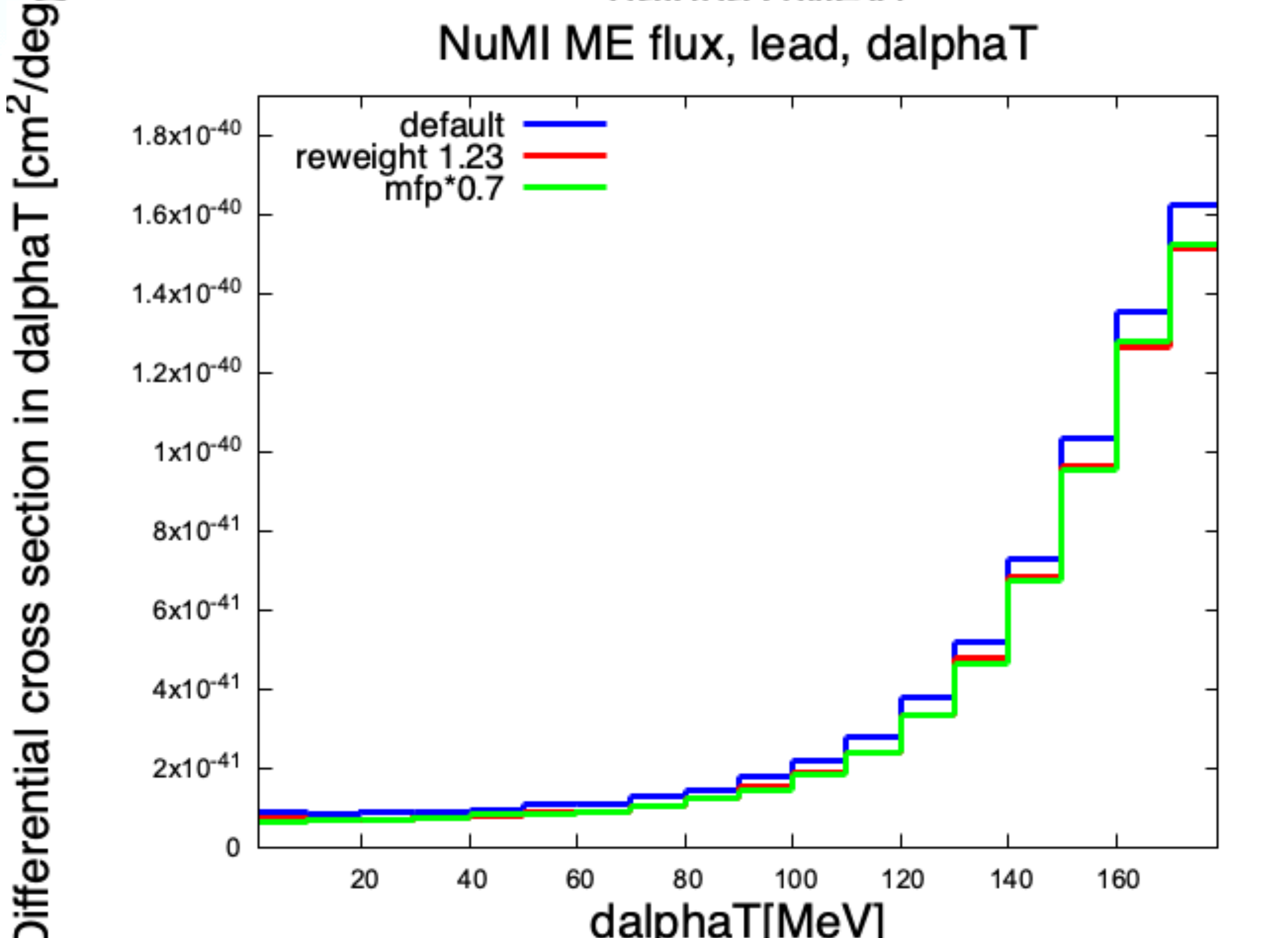
NuMI ME flux, carbon, dalphaT
default
reweight 0.8
mfp*1.3
Differential cross section in dalphaT [cm^2/deg
dalphaT[MeV]



NuMI ME flux, carbon, dalphaT
default
reweight 1.26
mfp*0.7
Differential cross section in dalphaT [cm^2/deg
dalphaT[MeV]

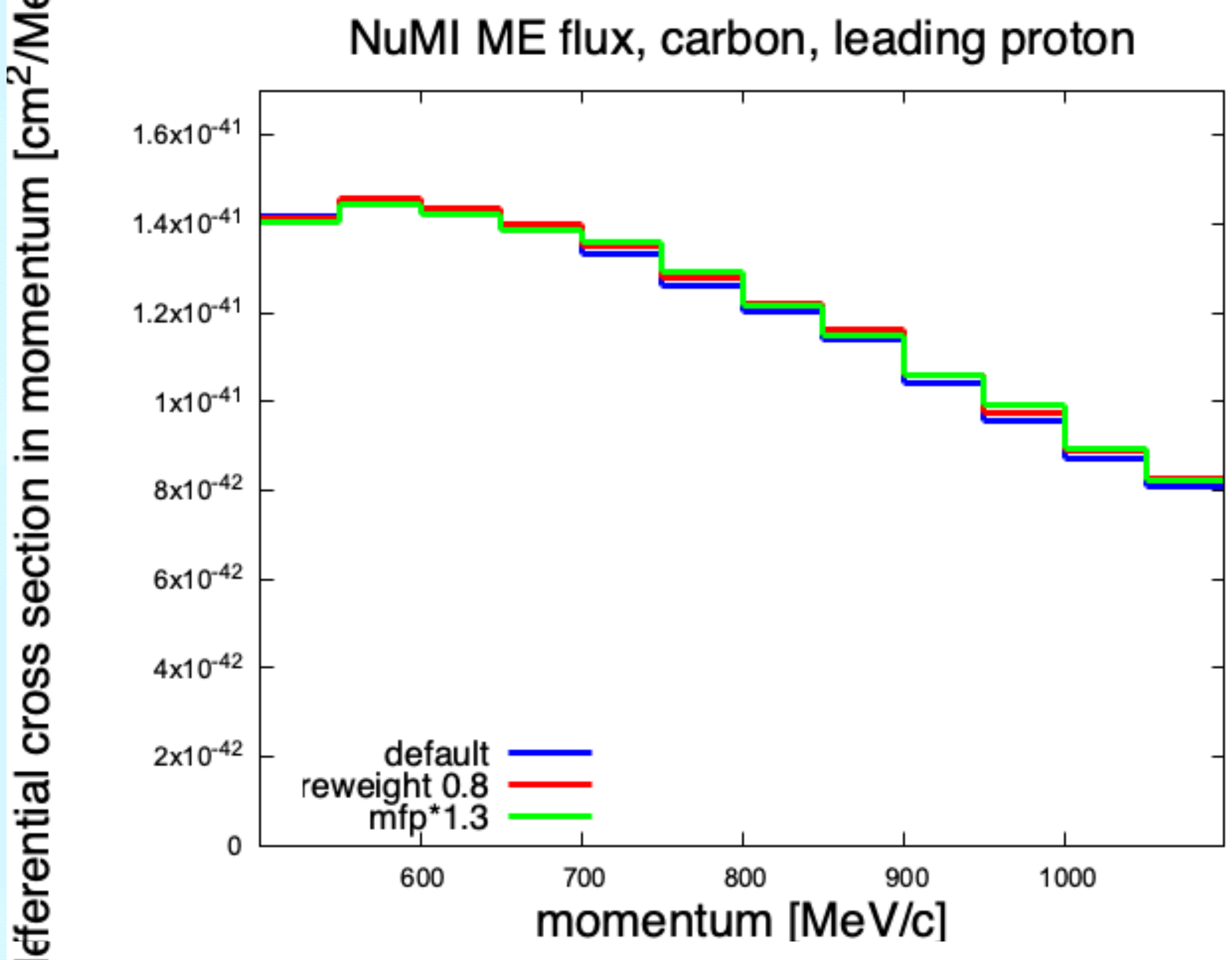


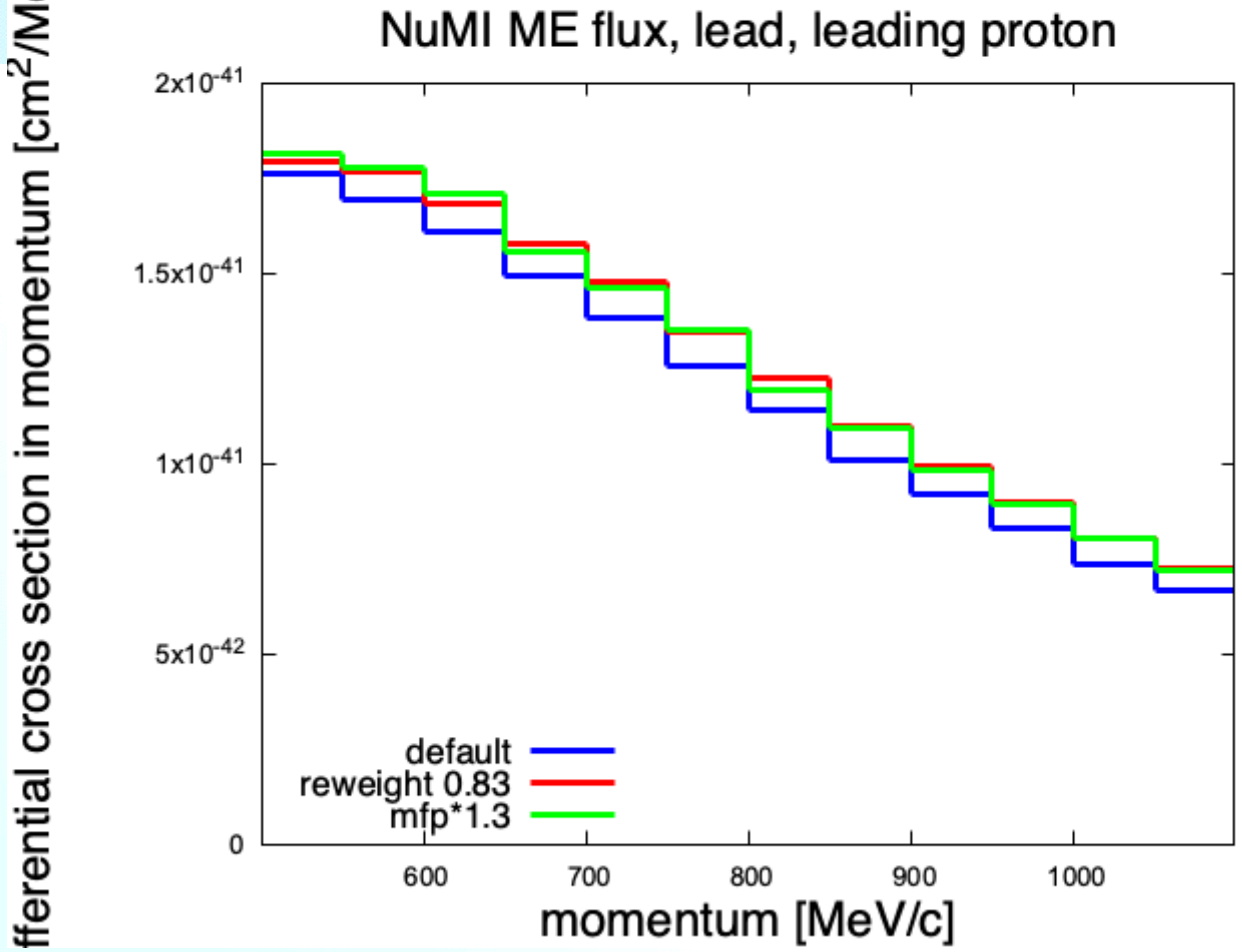
NuMI ME flux, lead, dalphaT
default
reweight 0.83
mfp*1.3
Differential cross section in dalphaT [cm^2/deg
dalphaT[MeV]

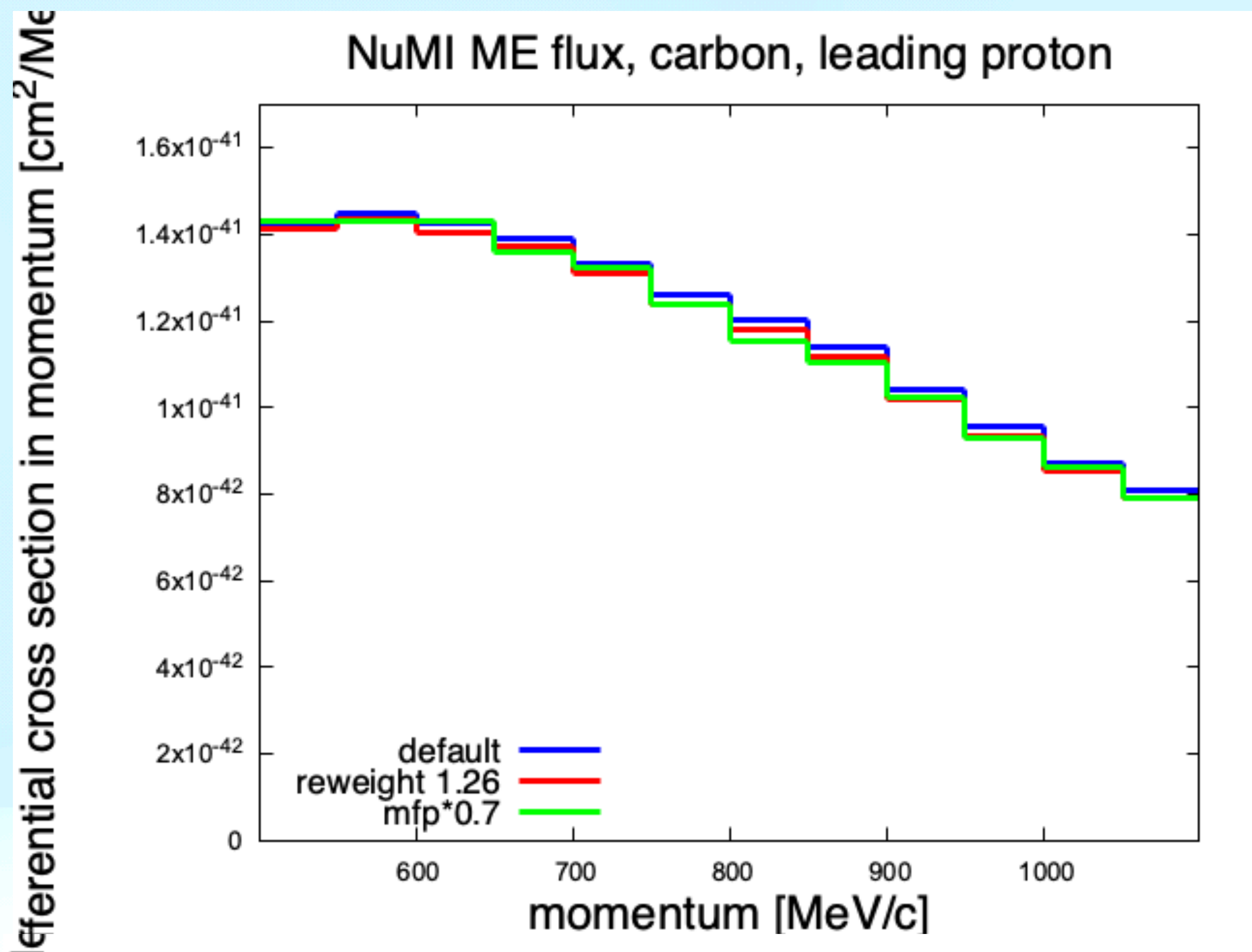


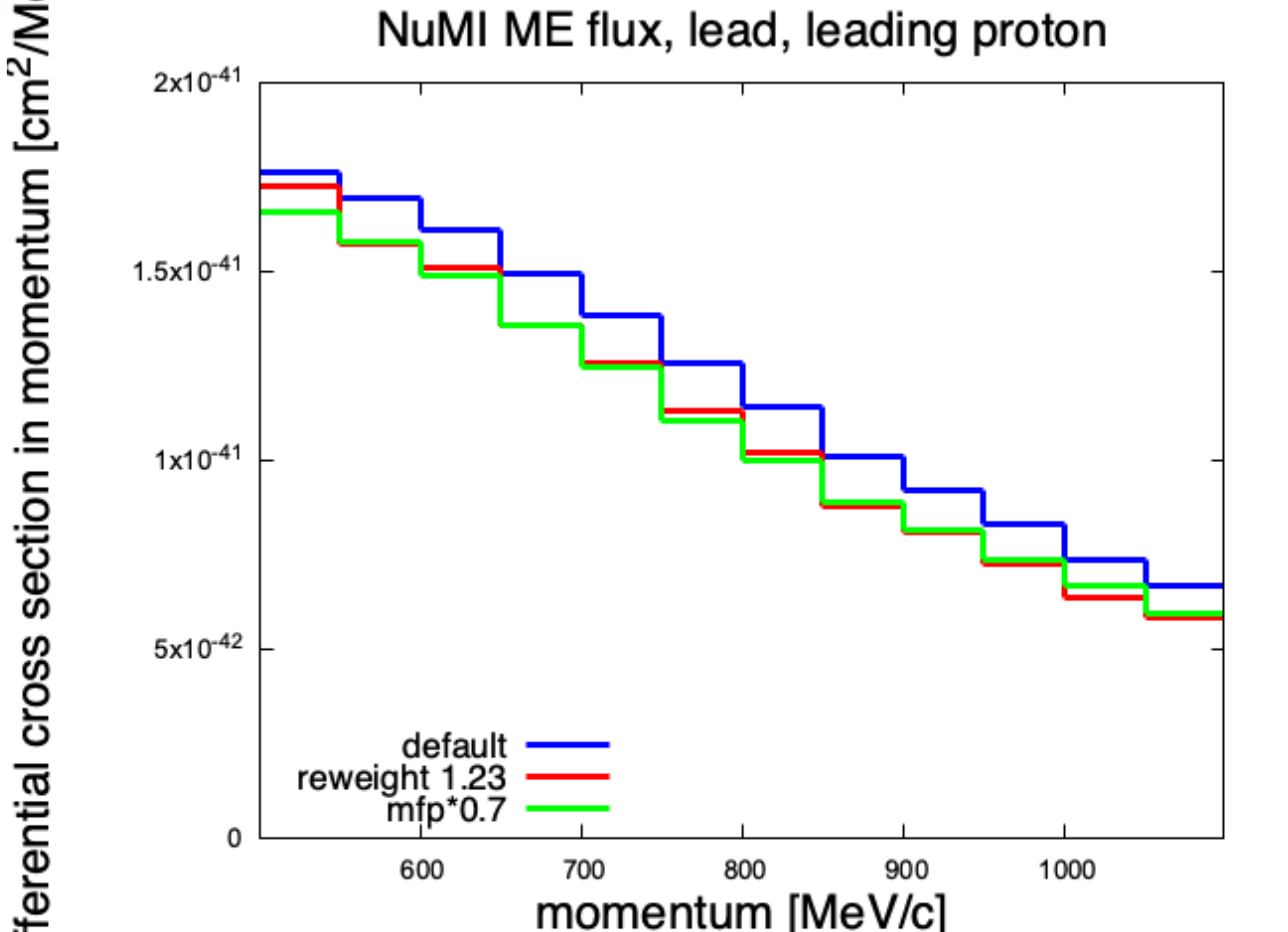
NuMI ME flux, lead, dalphaT
default
reweight 1.23
mfp*0.7
Differential cross section in dalphaT [cm^2/deg
dalphaT[MeV]

Results (3)

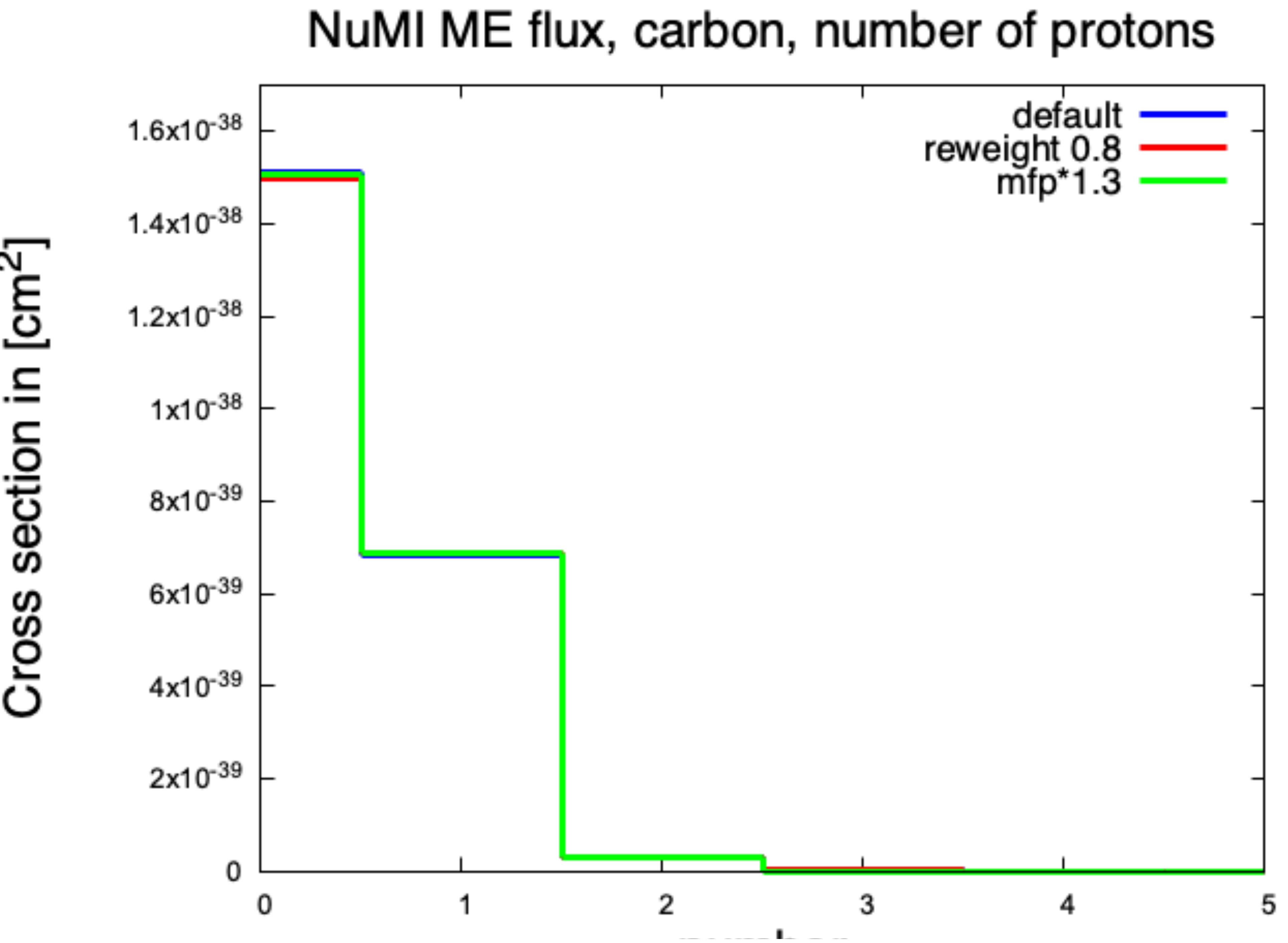

NuMI ME flux, carbon, leading proton
1.6x10^-41
1.4x10^-41
1.2x10^-41
1x10^-41
8x10^-42
6x10^-42
4x10^-42
2x10^-42
0
600
700
800
900
1000
momentum [MeV/c]
default
reweight 0.8
mfp*1.3

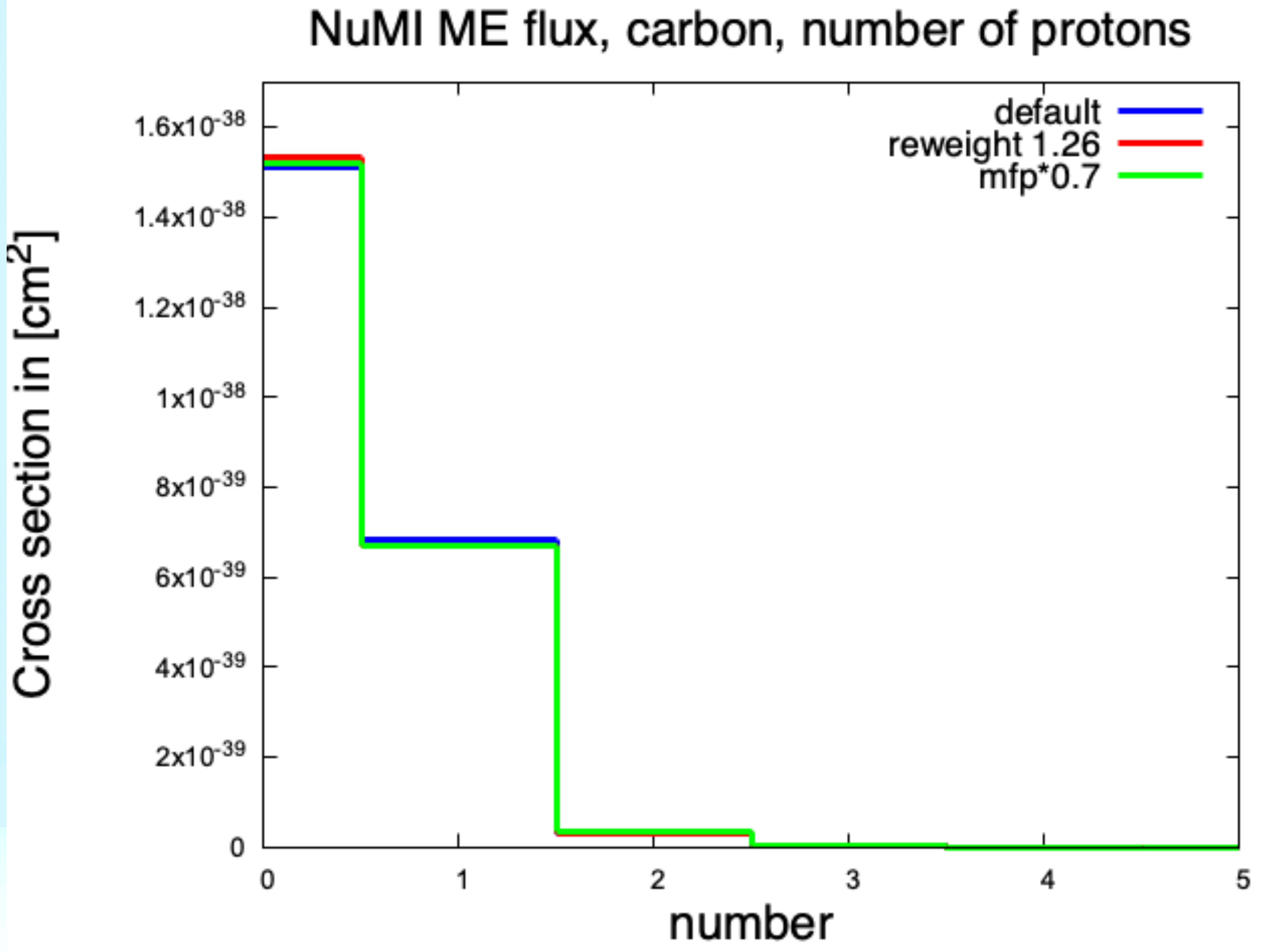

NuMI ME flux, lead, leading proton
2x10^-41
1.5x10^-41
1x10^-41
5x10^-42
0
600
700
800
900
1000
momentum [MeV/c]
default
reweight 0.83
mfp*1.3

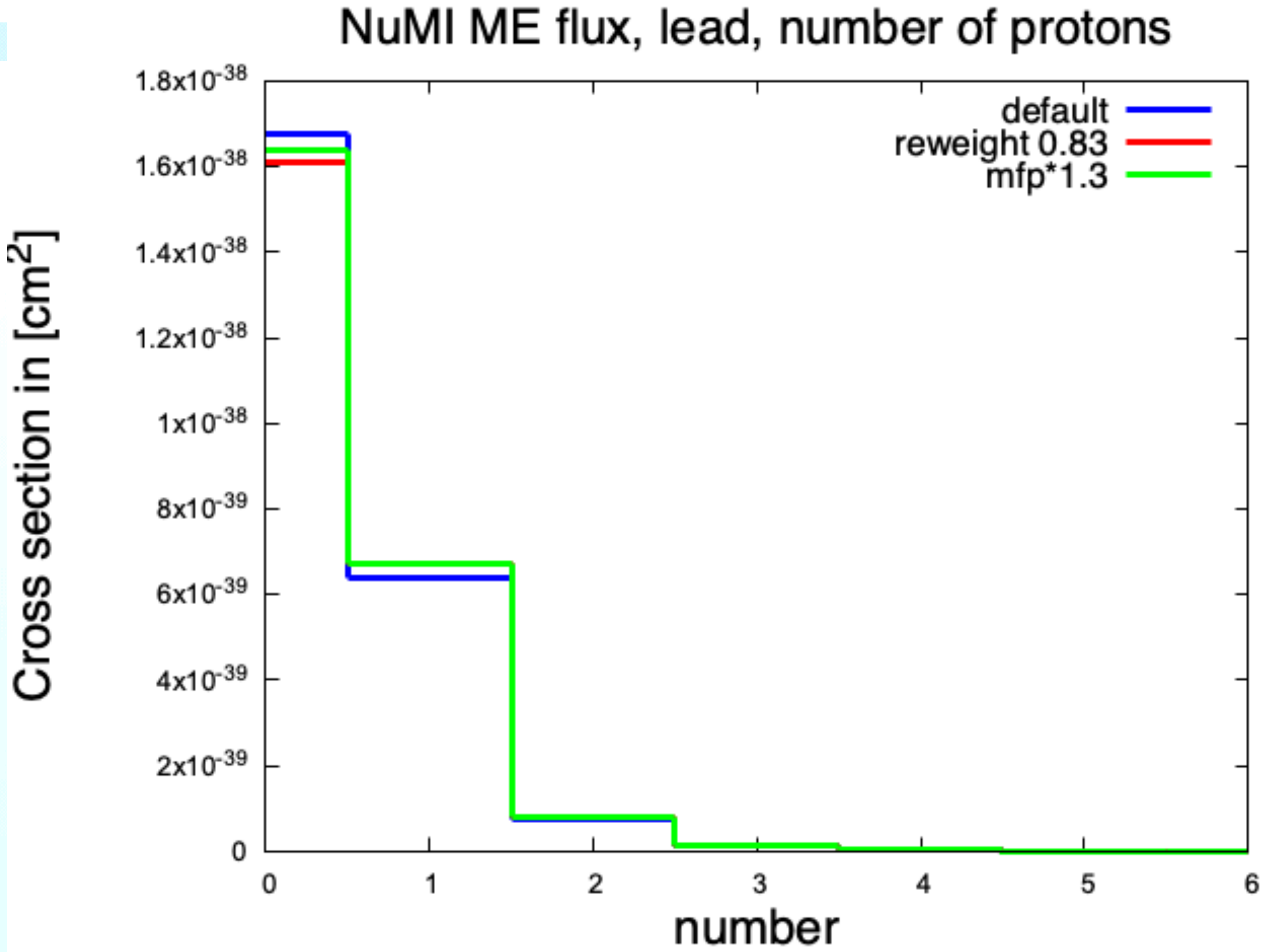

NuMI ME flux, carbon, leading proton
1.6x10^-41
1.4x10^-41
1.2x10^-41
1x10^-41
8x10^-42
6x10^-42
4x10^-42
2x10^-42
0
600
700
800
900
1000
momentum [MeV/c]
default
reweight 1.26
mfp*0.7

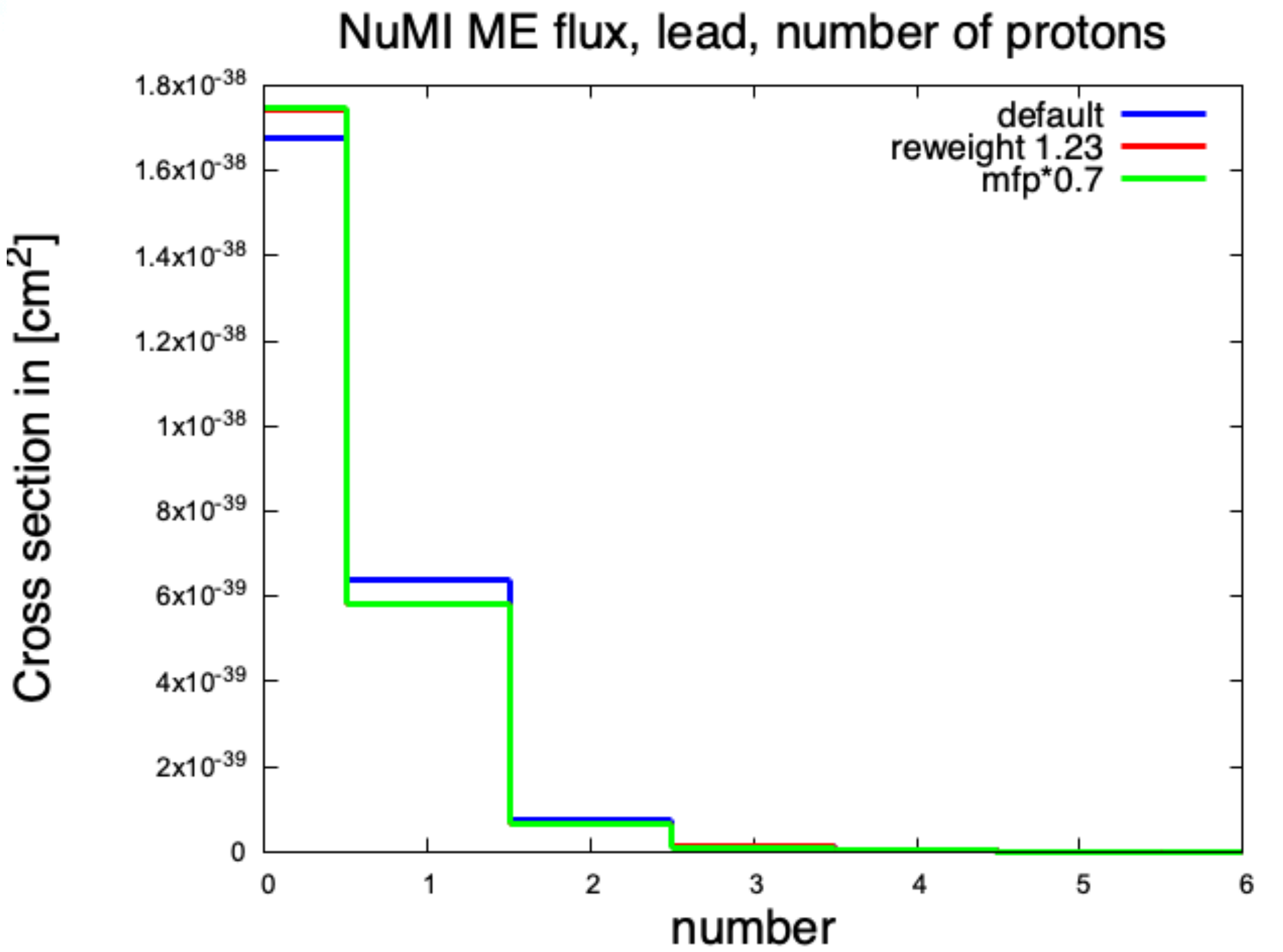

NuMI ME flux, lead, leading proton
2x10^-41
1.5x10^-41
1x10^-41
5x10^-42
0
600
700
800
900
1000
momentum [MeV/c]
default
reweight 1.23
mfp*0.7

Results (4)

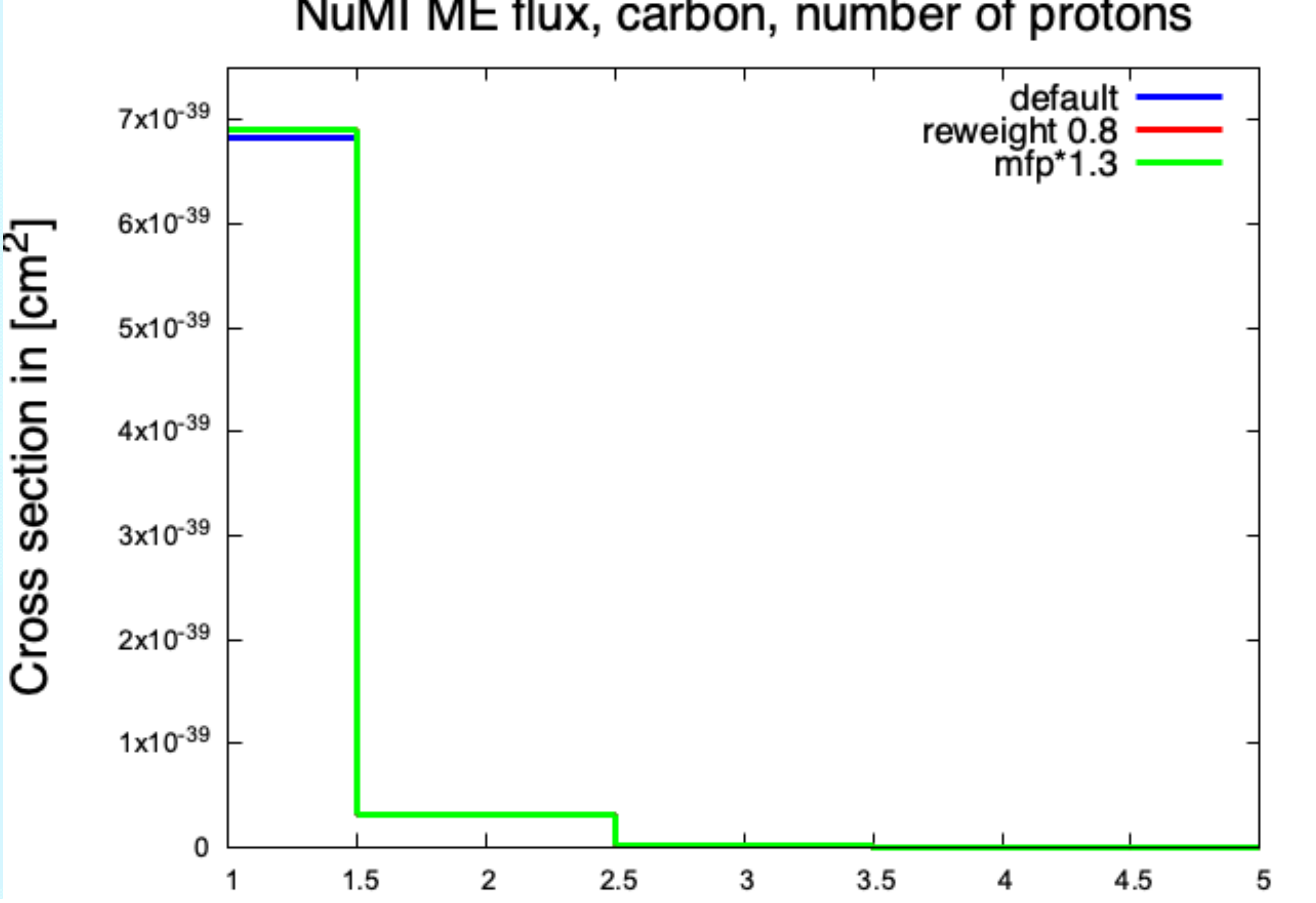

NuMI ME flux, carbon, number of protons
default
reweight 0.8
mfp*1.3
Cross section in [cm^2]

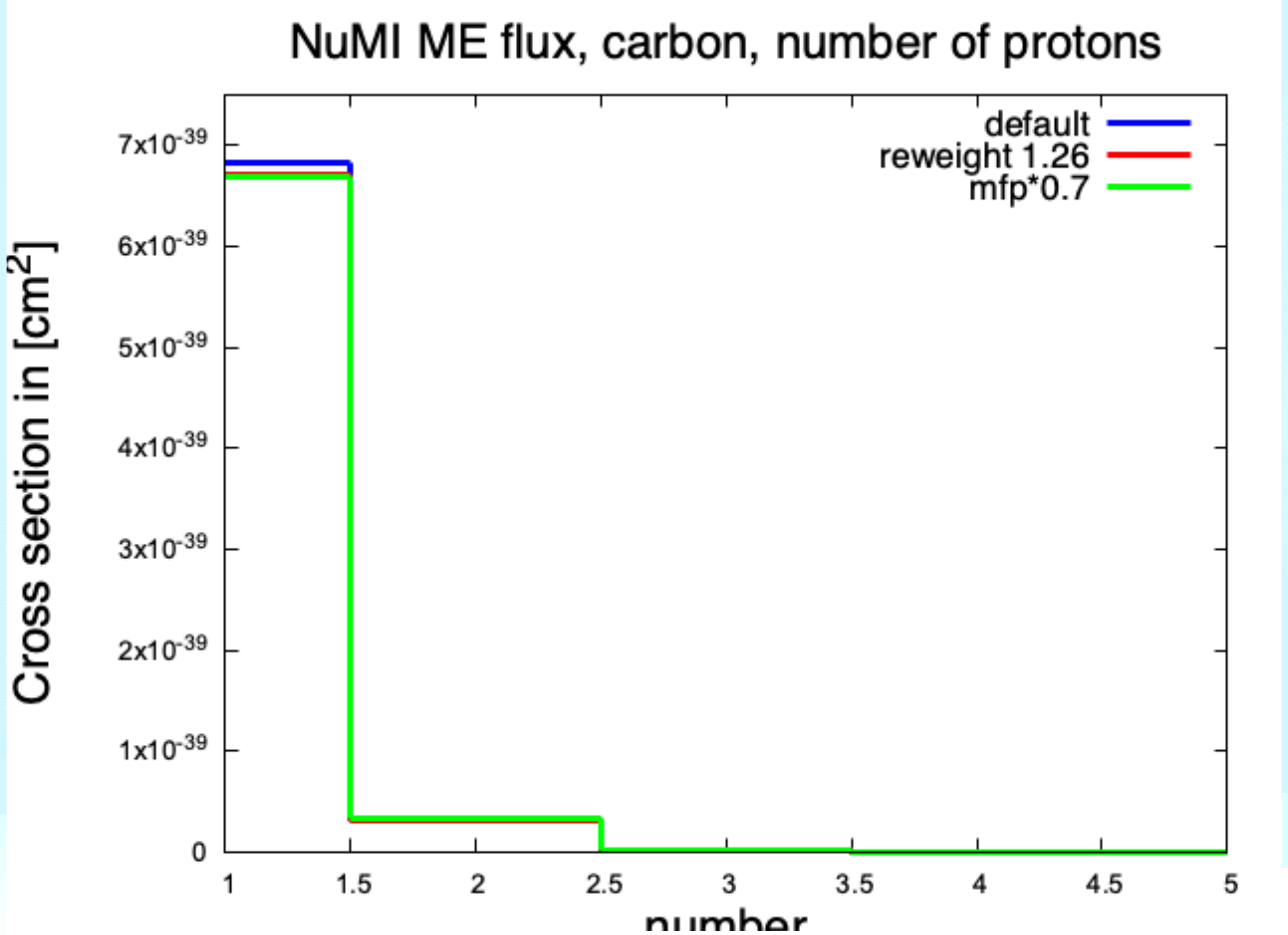

NuMI ME flux, carbon, number of protons
default
reweight 1.26
mfp*0.7
Cross section in [cm^2]
number

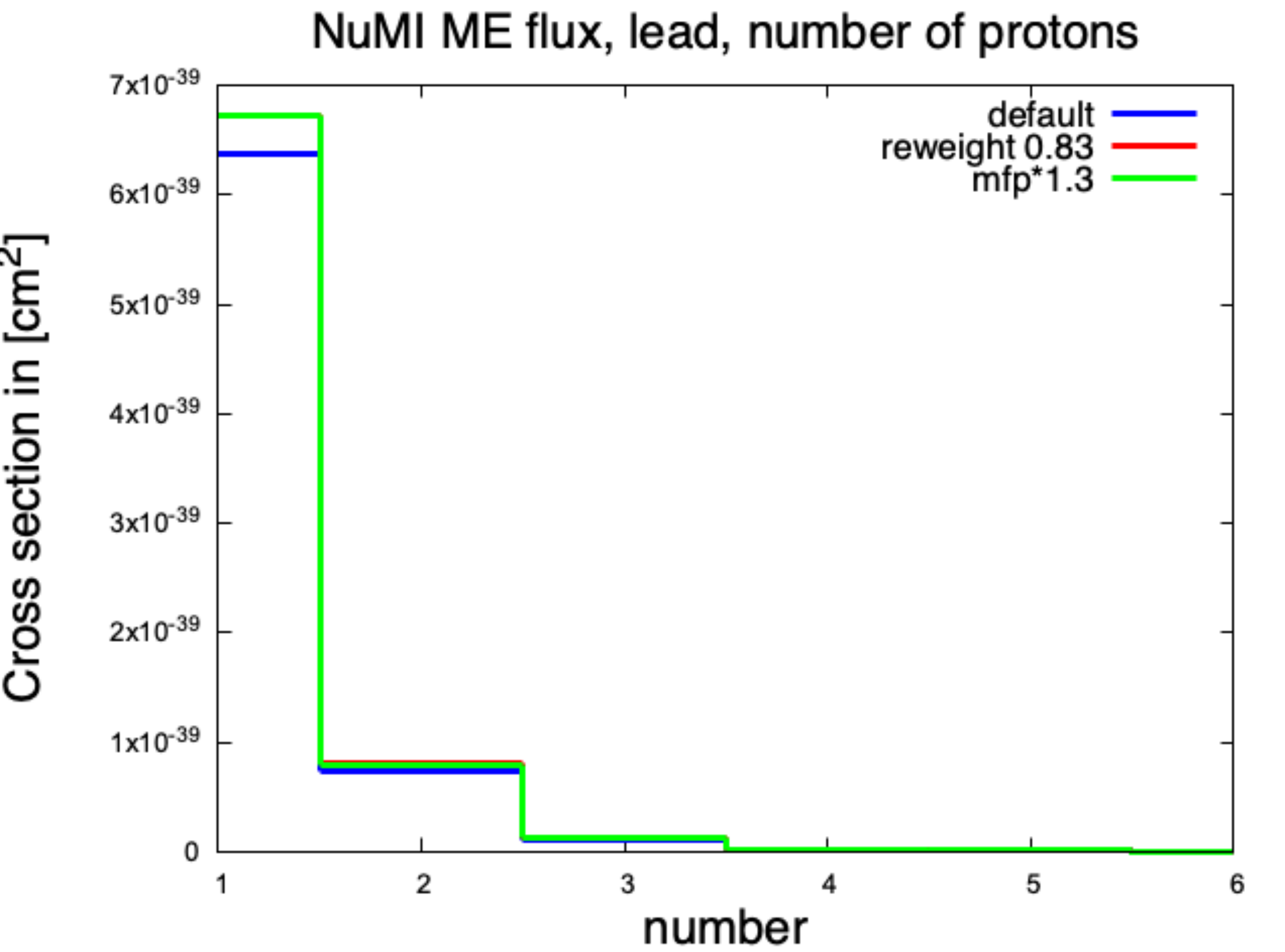

NuMI ME flux, lead, number of protons
default
reweight 0.83
mfp*1.3
Cross section in [cm^2]
number

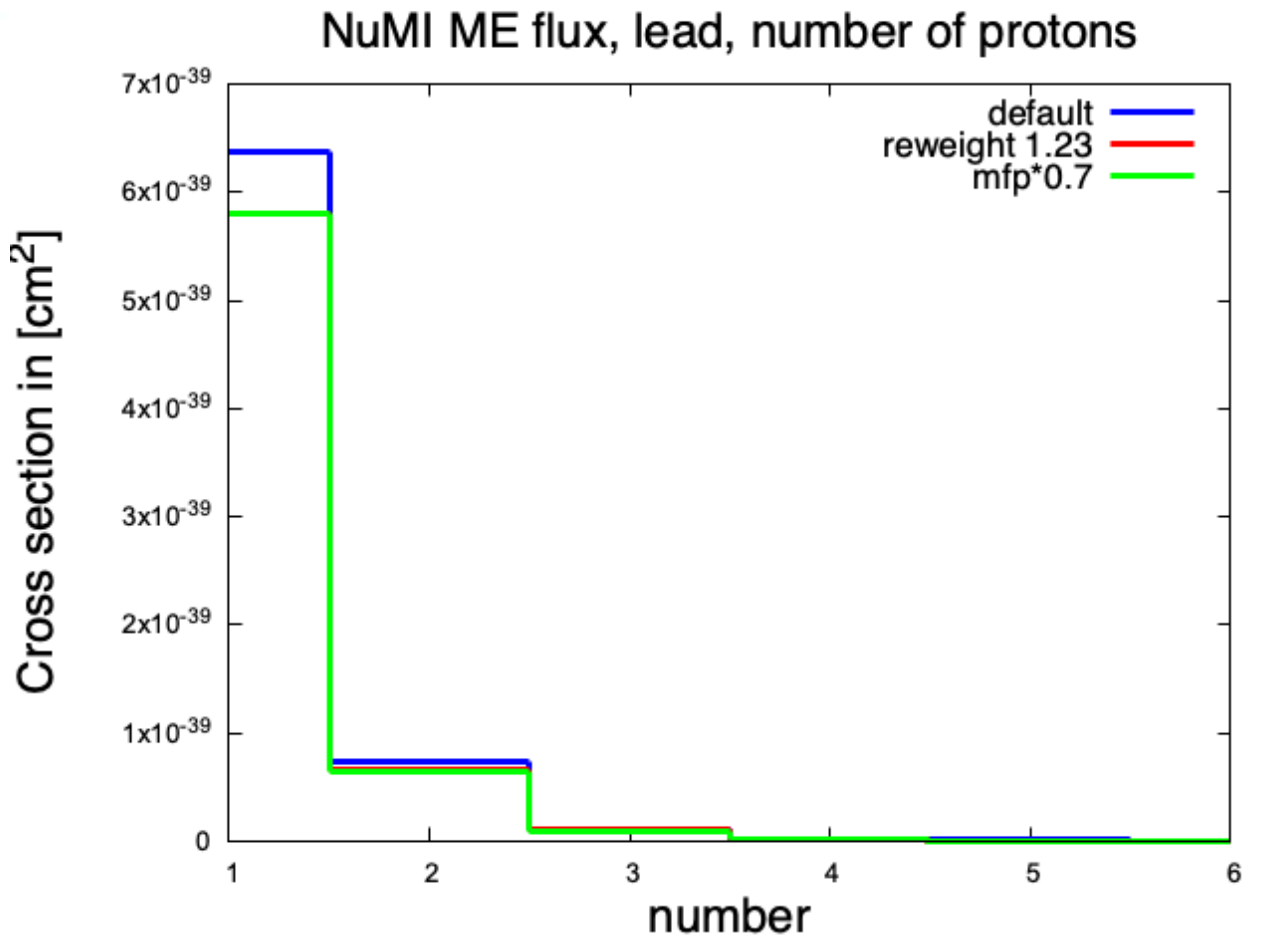

NuMI ME flux, lead, number of protons
default
reweight 1.23
mfp*0.7
Cross section in [cm^2]
number

Results (5)


NuMI ME flux, carbon, number of protons
default
reweight 0.8
mfp*1.3
Cross section in [cm^2]
7x10^{-39}
6x10^{-39}
5x10^{-39}
4x10^{-39}
3x10^{-39}
2x10^{-39}
1x10^{-39}
0
1 1.5 2 2.5 3 3.5 4 4.5 5


NuMI ME flux, carbon, number of protons
default
reweight 1.26
mfp*0.7
Cross section in [cm^2]
7x10^{-39}
6x10^{-39}
5x10^{-39}
4x10^{-39}
3x10^{-39}
2x10^{-39}
1x10^{-39}
0
1 1.5 2 2.5 3 3.5 4 4.5 5


NuMI ME flux, lead, number of protons
default
reweight 0.83
mfp*1.3
Cross section in [cm^2]
7x10^{-39}
6x10^{-39}
5x10^{-39}
4x10^{-39}
3x10^{-39}
2x10^{-39}
1x10^{-39}
0
1 2 3 4 5 6
number


NuMI ME flux, lead, number of protons
default
reweight 1.23
mfp*0.7
Cross section in [cm^2]
7x10^{-39}
6x10^{-39}
5x10^{-39}
4x10^{-39}
3x10^{-39}
2x10^{-39}
1x10^{-39}
0
1 2 3 4 5 6
number

Conclusions

Preliminary results are encouraging? /satisfactory?

More studies will be done to decide if the simplest approach allows for sufficient accuracy

If not…

- in nuclei regions of approximately constant density must be identified
- interaction probabilities must be calculated for every density region separately
- NuWro stores enough information to calculate it (the algorithm to extract it is complicated, though)
- reweighting factors must be defined accordingly
- more sophisticated toy model studies show that indeed better agreement should be achieved.