NuWro

Jan T. Sobczyk

NuInt2024, Sao Paulo, April 15-20, 2024

Outline

- Generał information
- Basic structure (interaction modes, nuclear models, intranuclear cascade)
- eWro
- Examples of performance (T2K CC0π no proton, inferred kinematics; eWro)
- Upgrade - ongoing projects

A. Argon spectral function

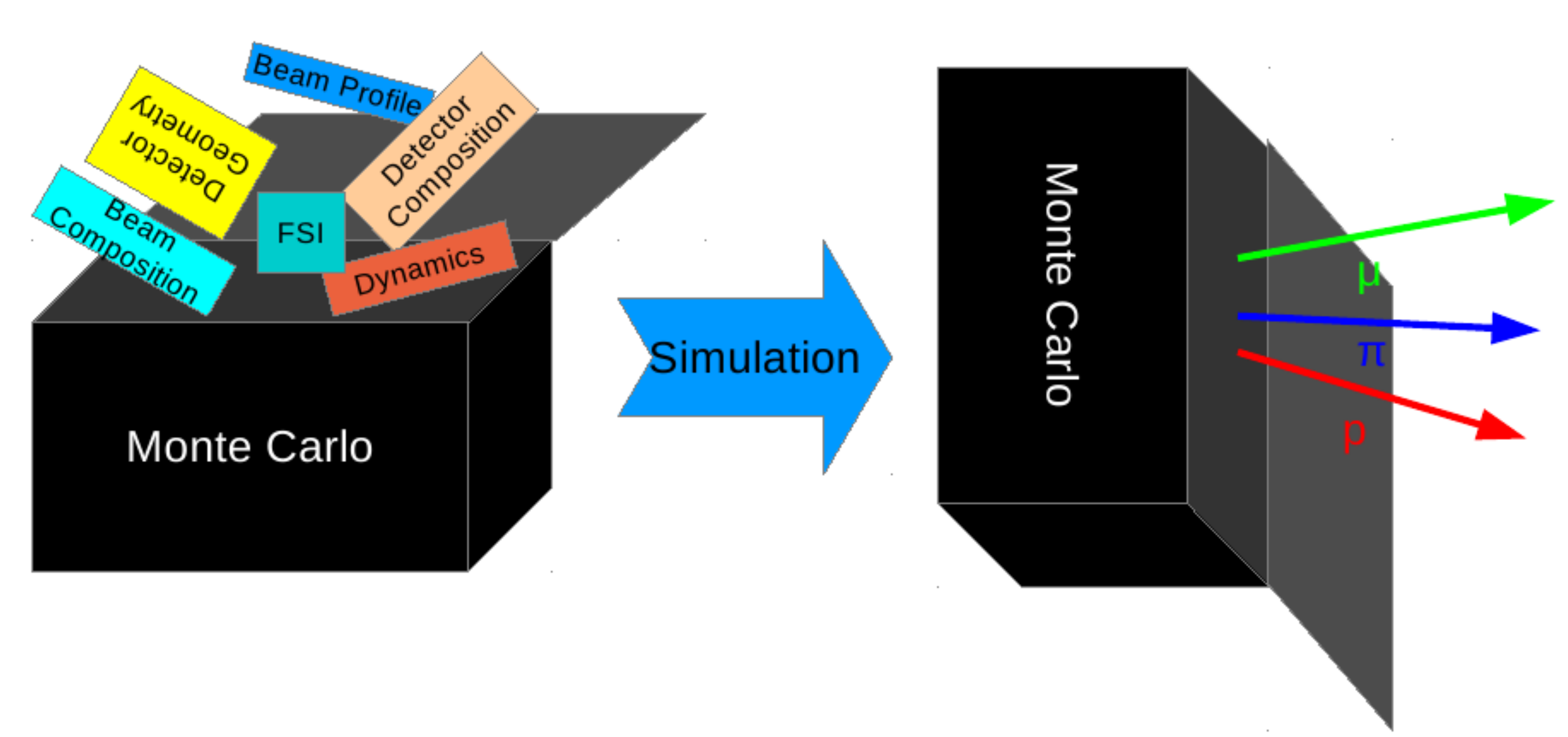
B. Model for MEC nucleons

C. New single pion production model

D. Employiment of ML methods

- Outlook

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.

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

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

Resonance excitation **(RES)** defined by W< 1.6 GeV, for example

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

``Deep inelastic scattering'' **(DIS)** defined by W> 1.6GeV

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

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

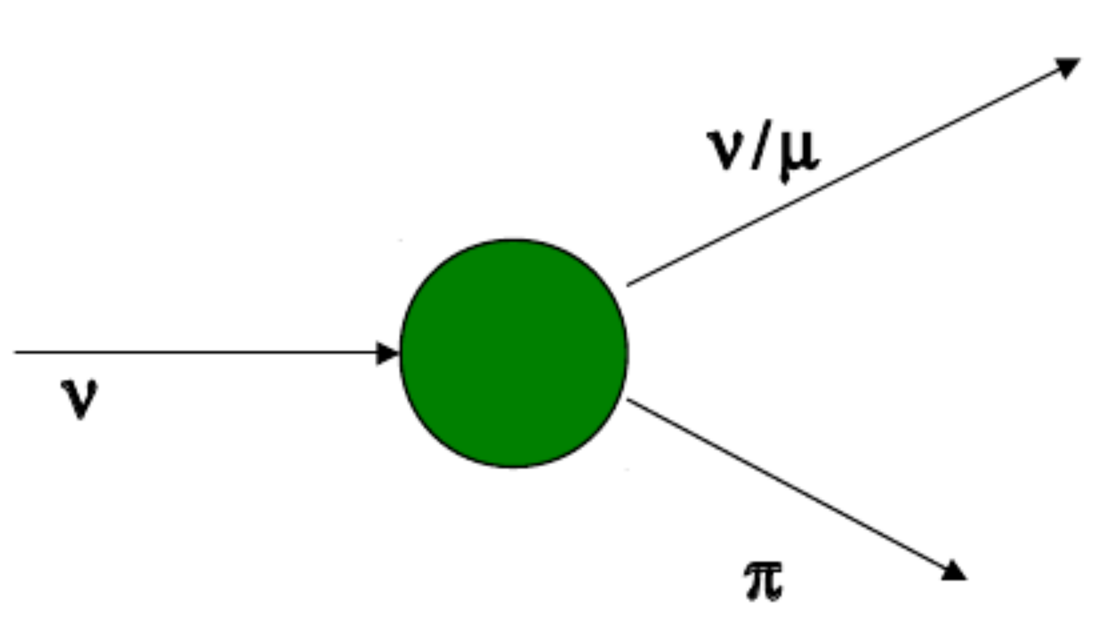
Neutrino-electron scattering **(LEP)**

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

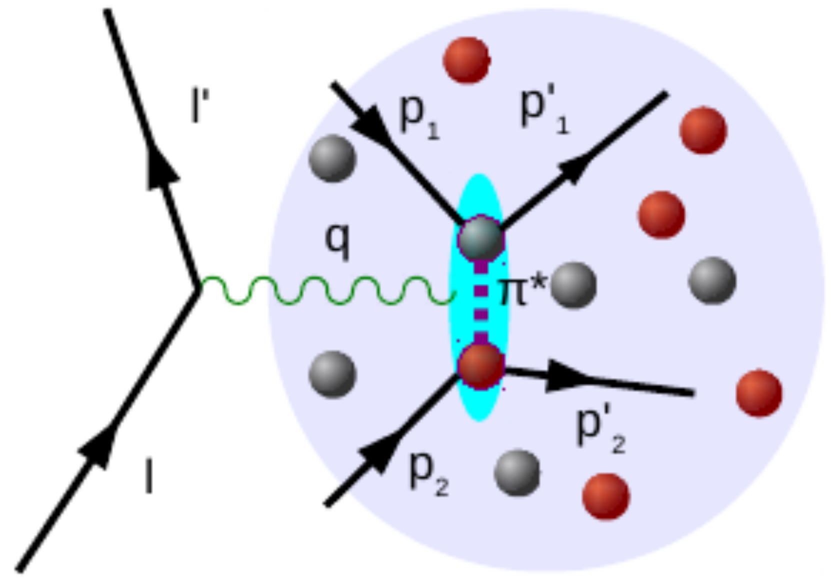
NuWro - basic interaction modes

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

Coherent pion production **(COH)**



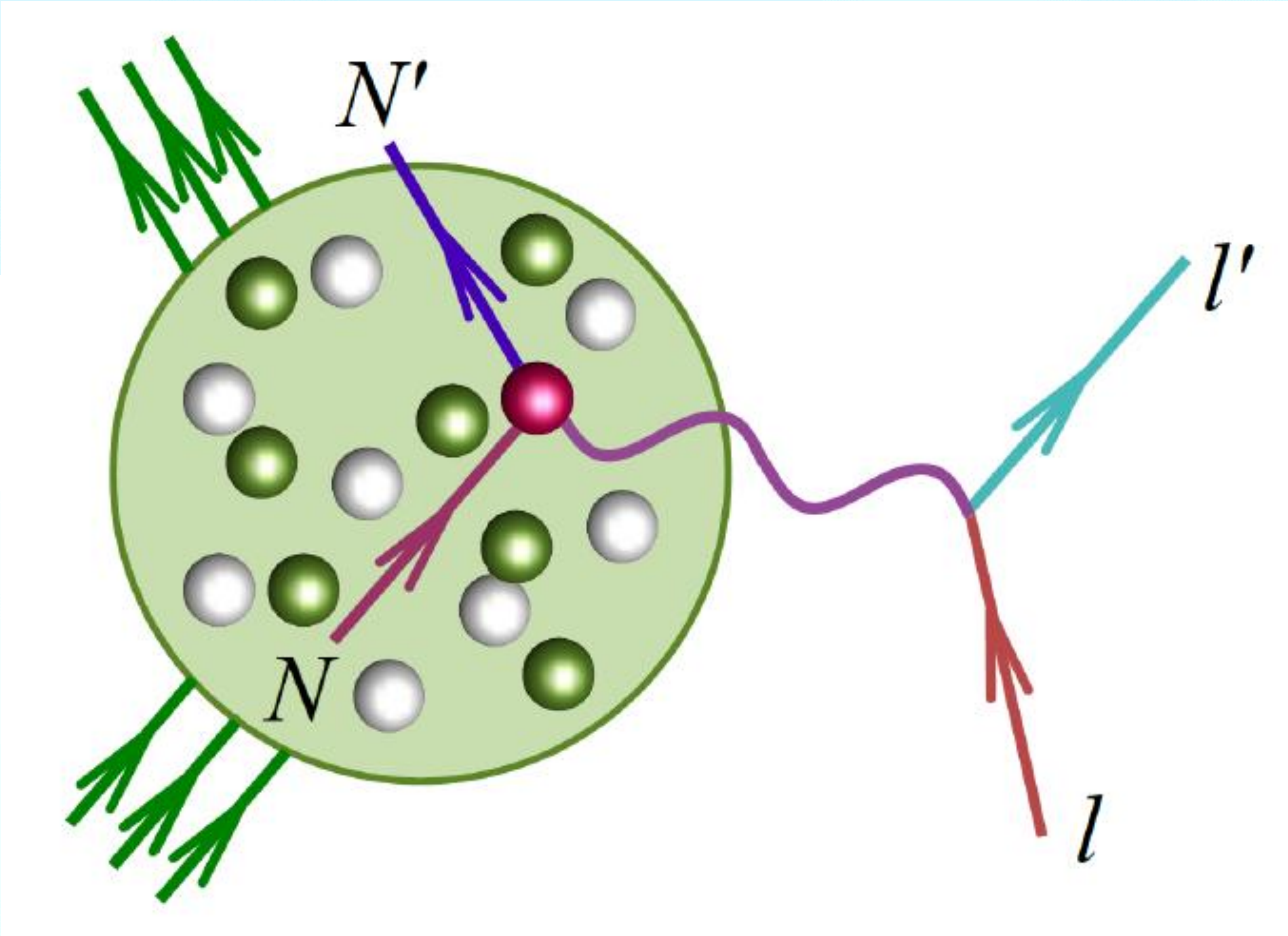
Two body current **(MEC)**



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)

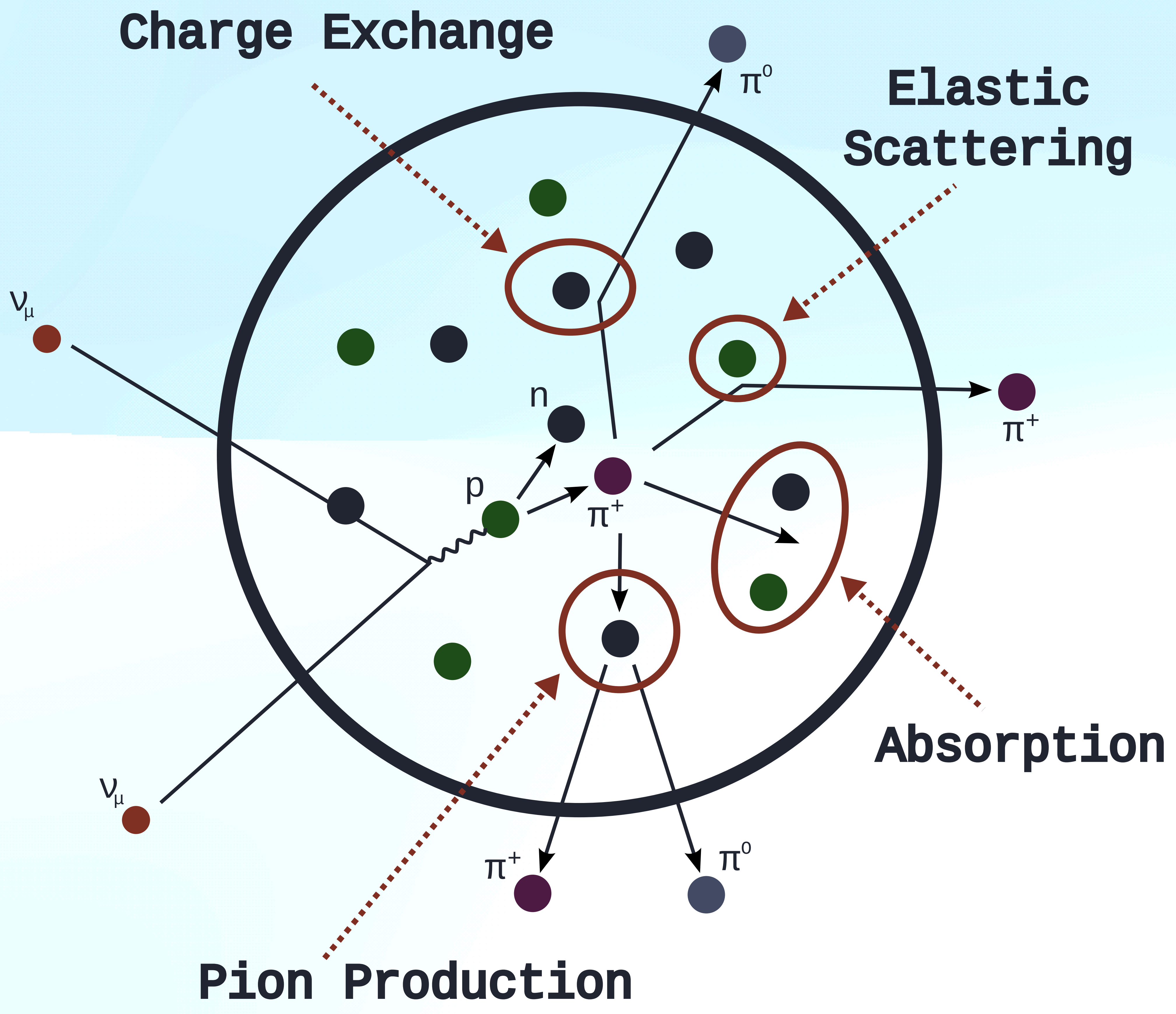
- typically, nucleus is left

  in an excited state.

Credit: Artur Ankowski

Final state interactions

What is observed are particles after FSI



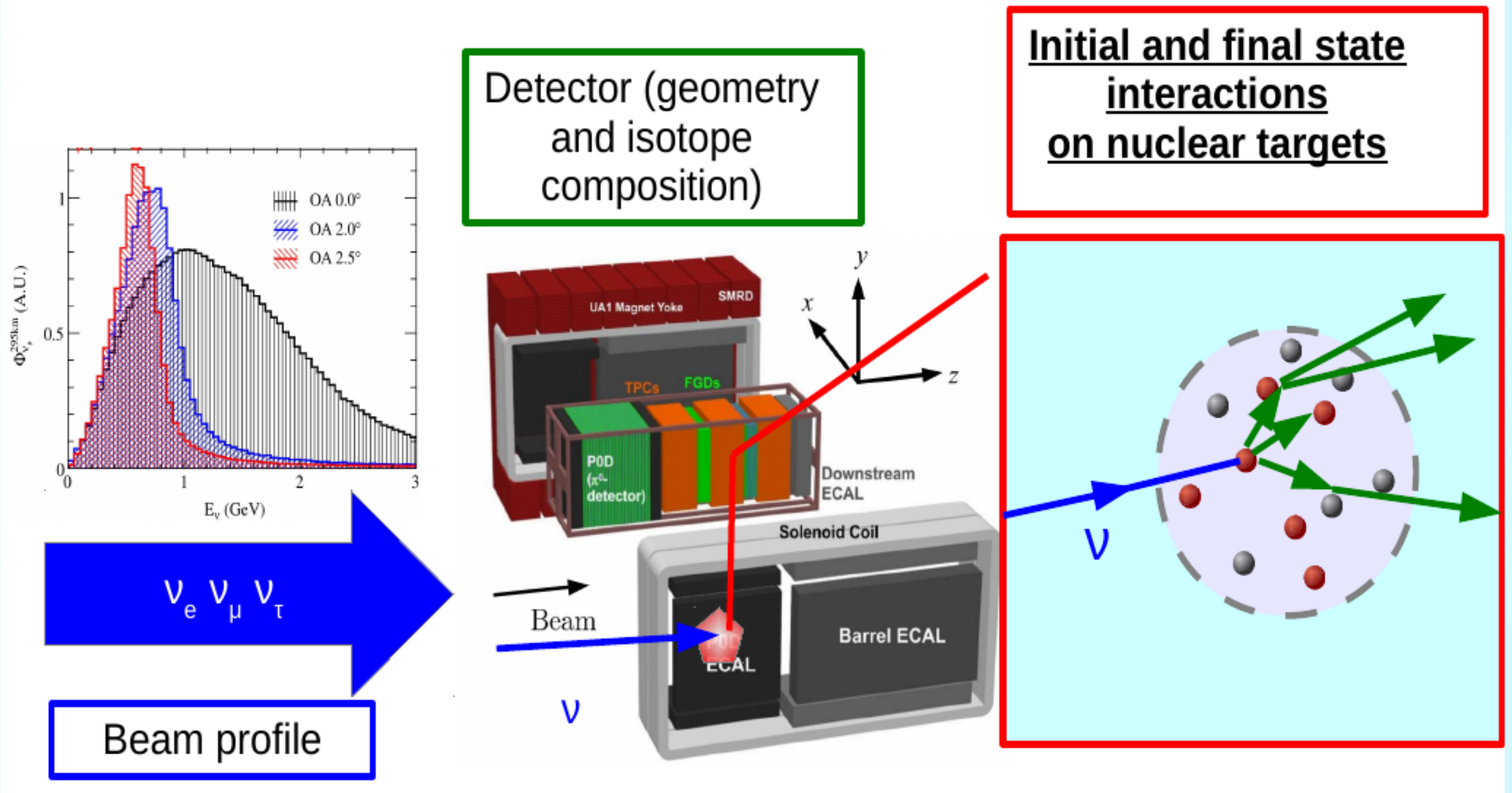
Pions...

- 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 nucleons and hyperons.

Credit: Tomasz Golan

NuWro running



For every run NuWro needs as input:

- information about neutrino flux, energy spectrum, flavor composition, target (free nucleon? nucleus? compoud target?)

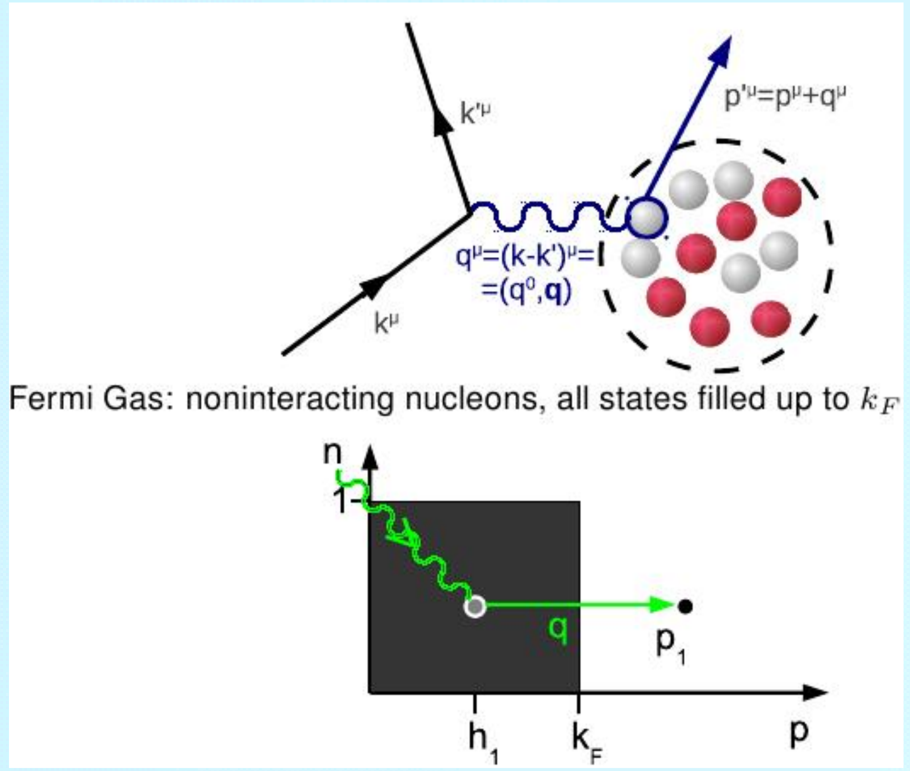
- physics model configuration (defined in the file params.txt)

NuWro provides two pieces of information:

- average cross section (which translates into the expected number of events if flux (POT) and detector size are known; NuWro does not use tabularized cross sections, all the cross sections are calculated in real time

- samples of equal weight events

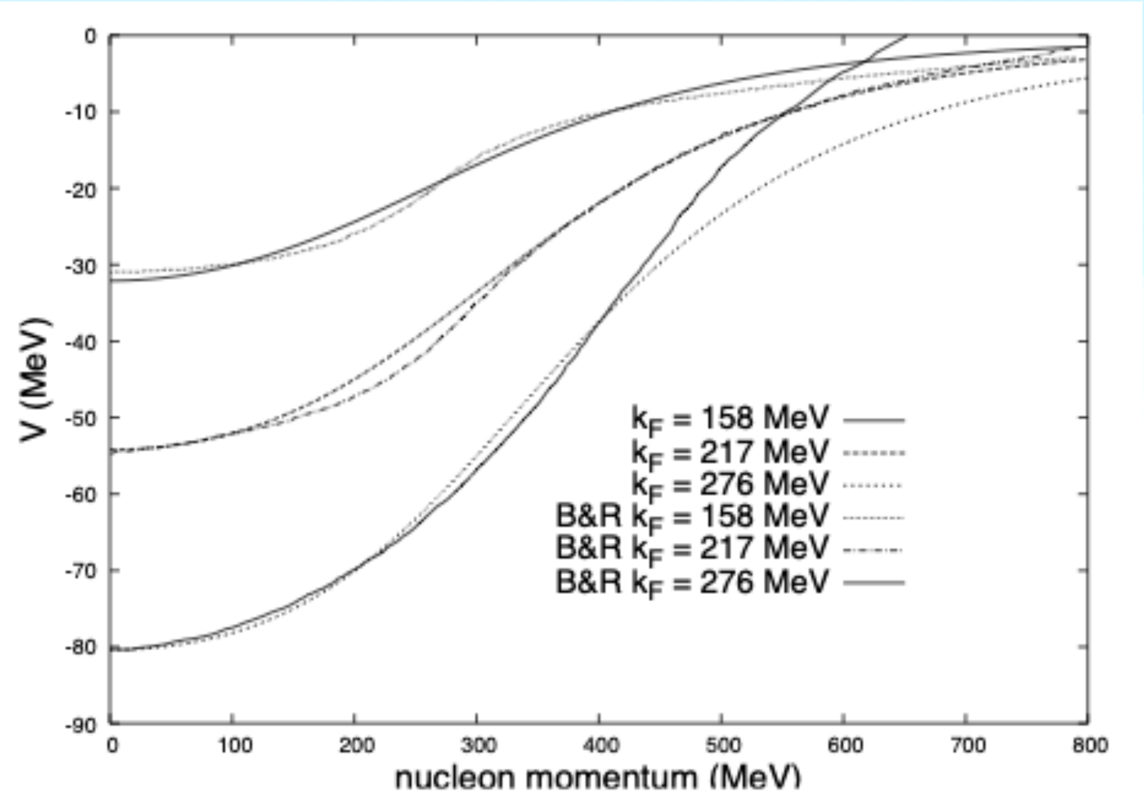
NuWro nuclear models



Fermi gas models (global, local)

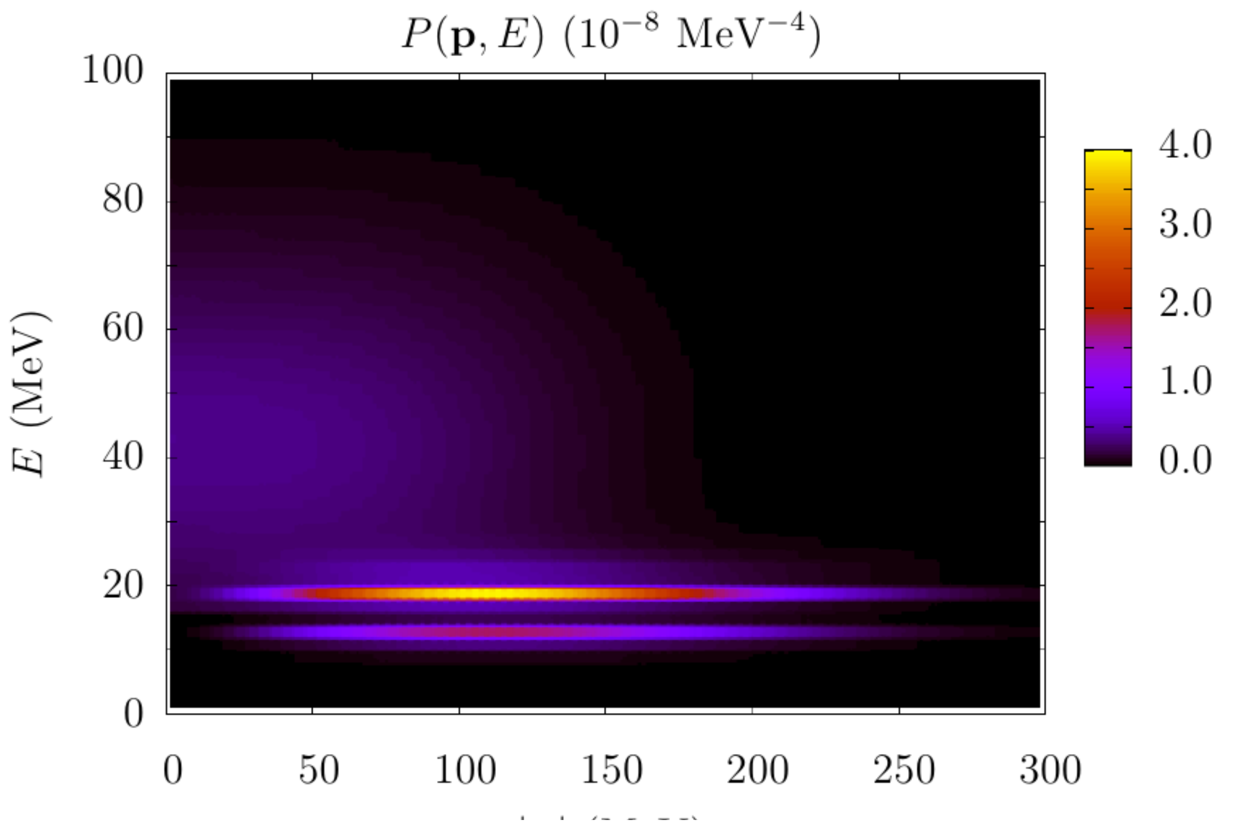
- long range correlations modeled with RPA (random phase approximation) approach can be included

K.M. Graczyk, JTS, Eur.Phys.J.C 31 (2003) 177-185



Momentum and density dependent nuclear potential

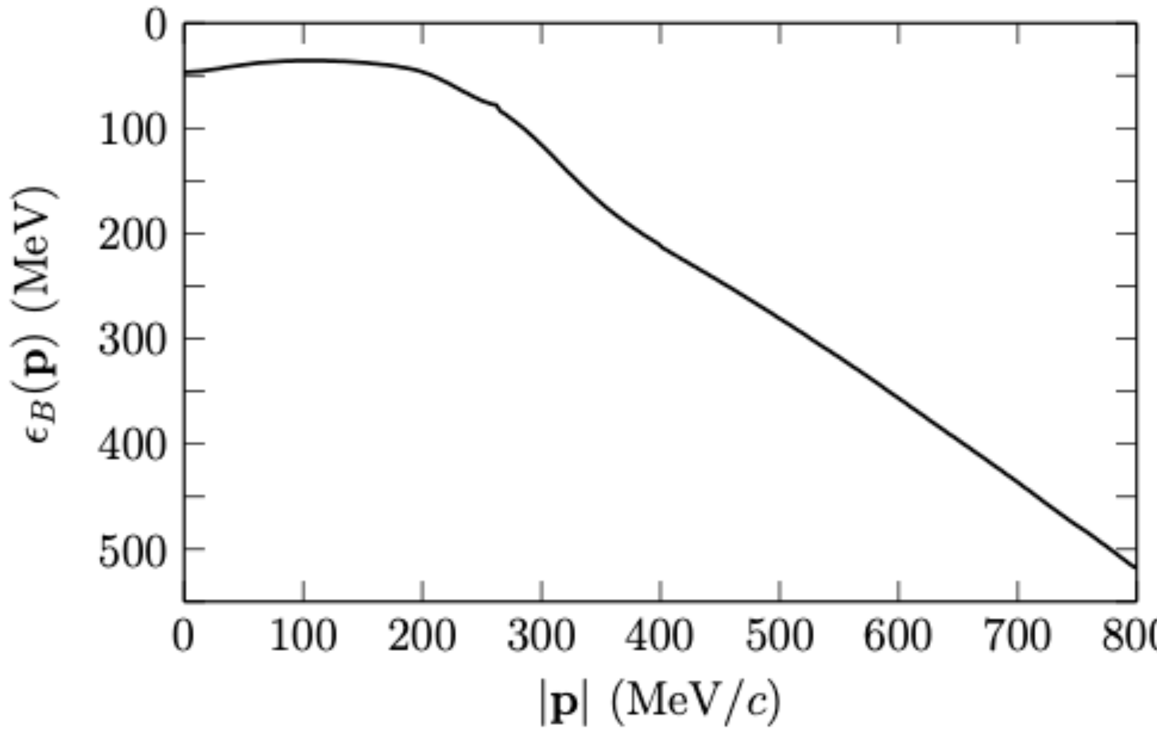
C. Juszczak, J.A. Nowak, JTS, Eur. Phys.J.C 39 (2005) 195-200.



Hole spectral function

- the approach developed by Omar Benhar and collaborators
- available for carbon, oxygen, calcium, iron, argon
- FSI and Coulomb effects affecting outgoing lepton included according to

A.M. Ankowski, O. Benhar, M. Sakuda, Phys.Rev.D 91 (2015) 3, 033005



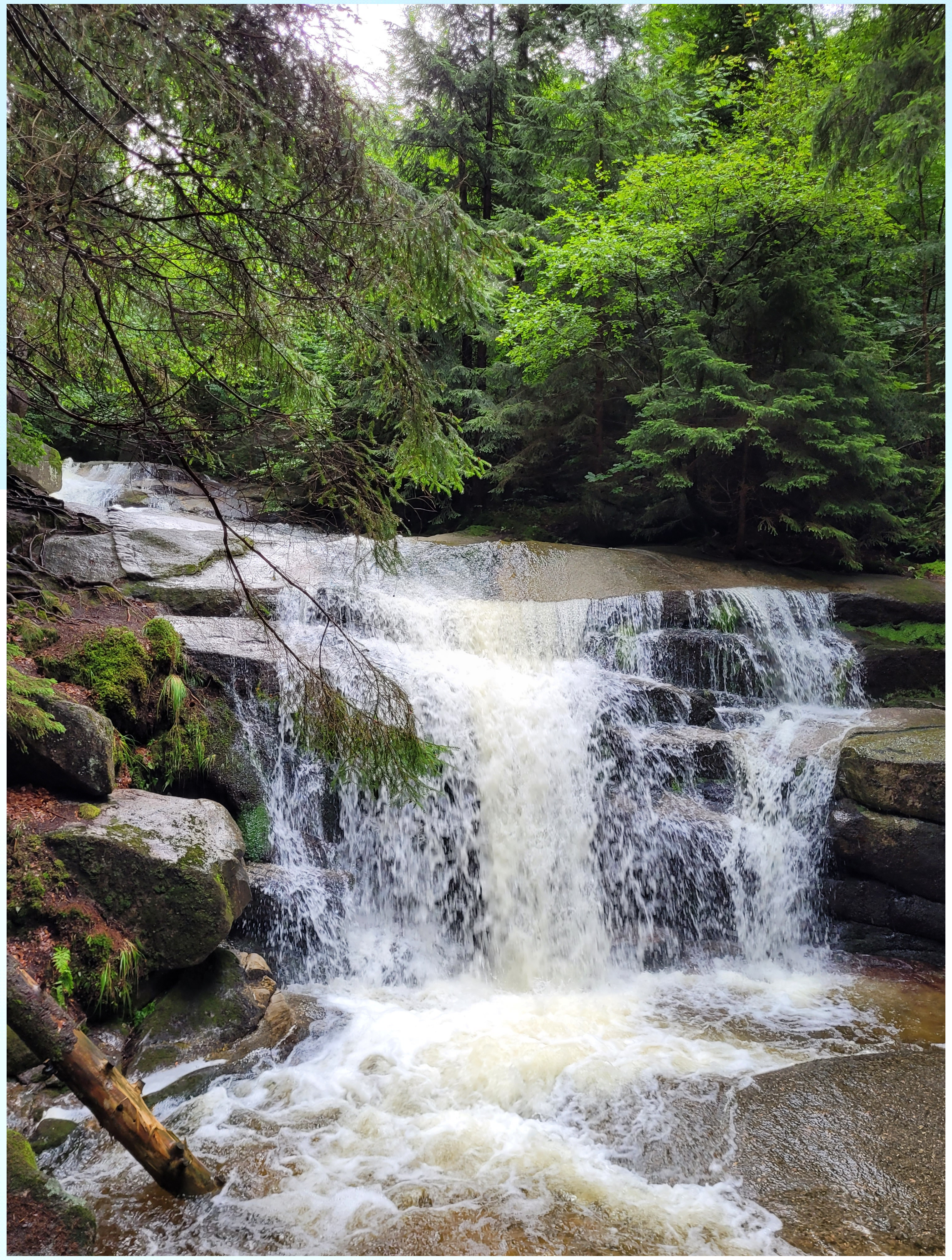
Effective spectral function

A.M. Ankowski, JTS, Phys.Rev.C 74 (2006) 054316.

NuWro Event Generator

NuWro FSI model

Intranuclear cascade



Hadrons propagate in steps through the nuclear medium

- Probability of passing a distance x without interaction

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

$\lambda = (\rho\sigma)^{-1}$ is mean free path, ρ is local density and σ is hadron-nucleon 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:

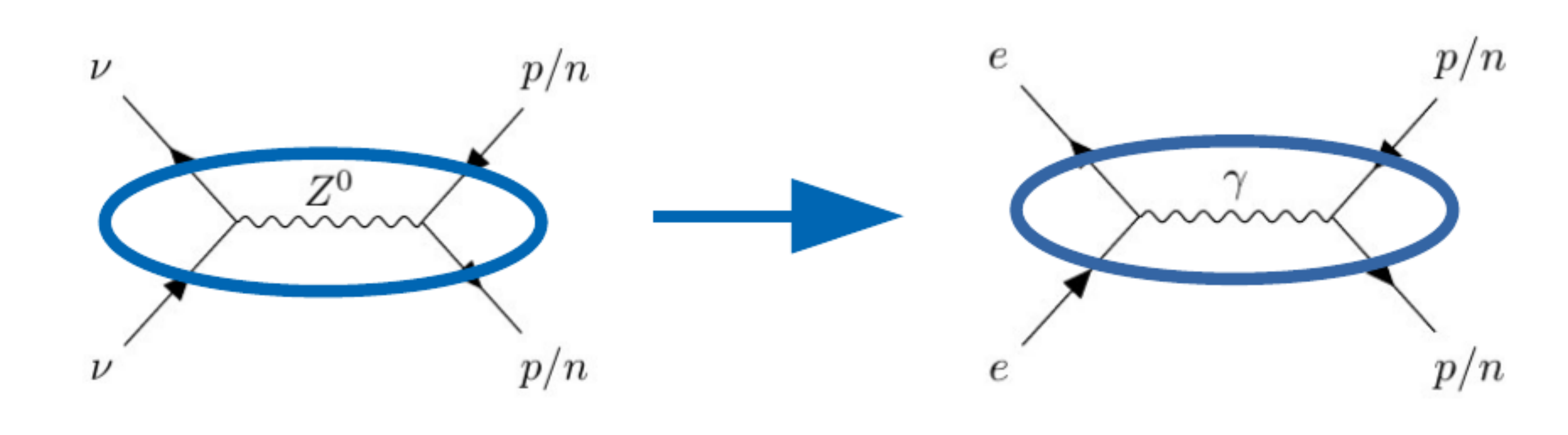
T. Golan, C. Juszczak, JTS, Phys.Rev. C86 (2012) 015505;

K. Niewczas, JTS, Phys.Rev.C 100 (2019) 1, 015505

eWro

NuWro framework applied to electron scattering

A general idea is to use precise electron scattering data to test implemented models.



As much as possible is left untouched, in particular

- procedures to select initial nucleon, generate events, assign kinematics
- FSI.

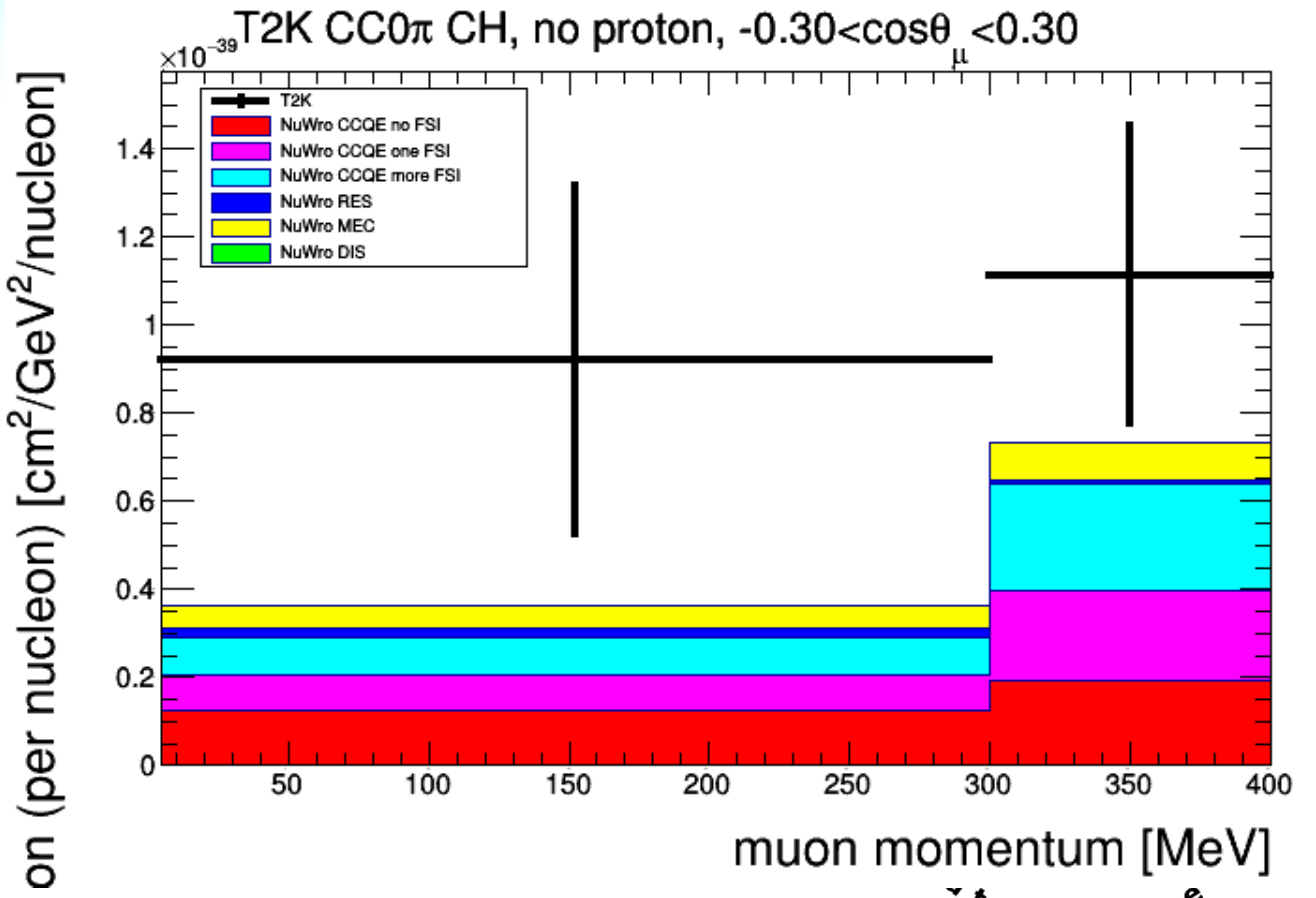
Currently, eWro is available for QE dynamics only

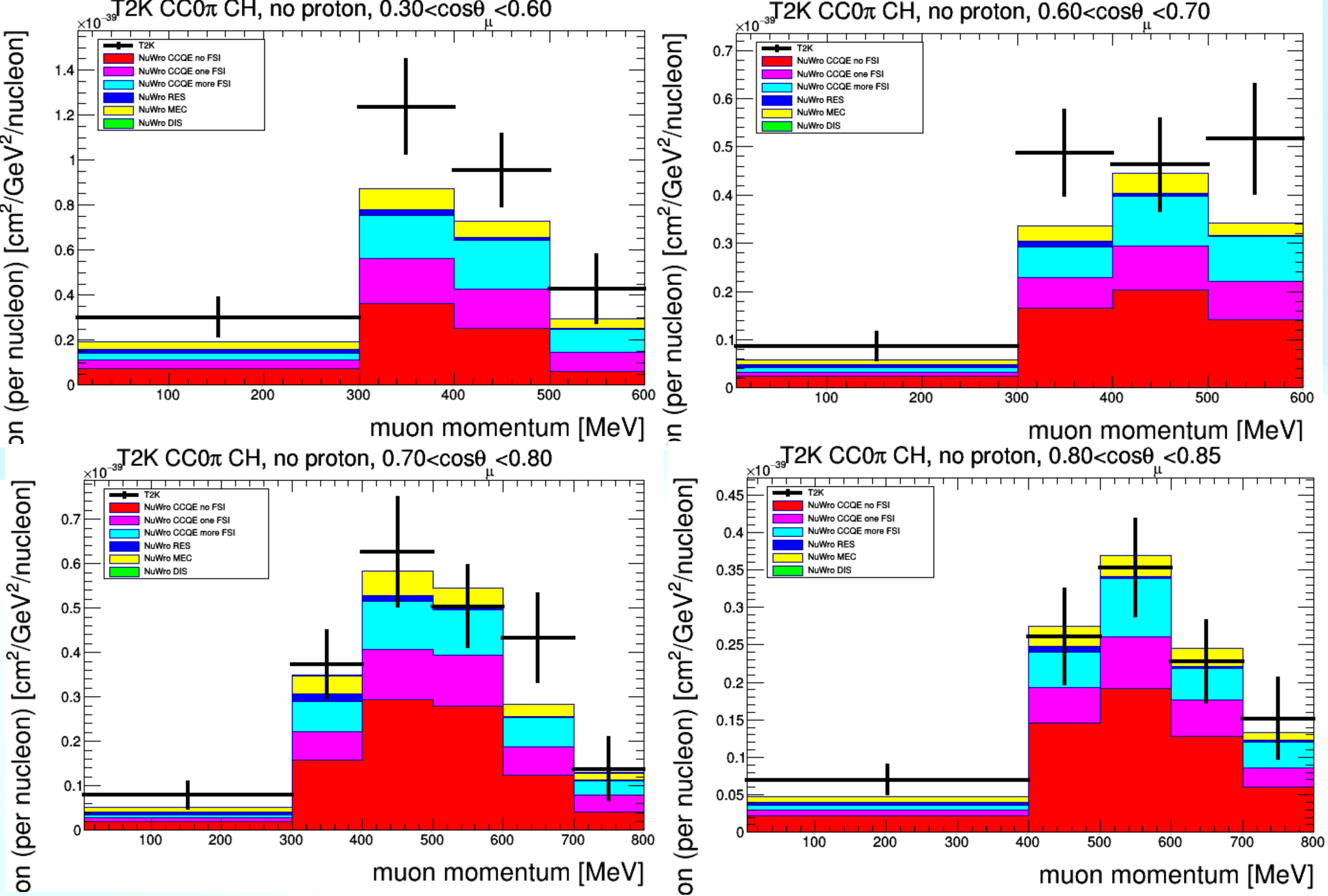
NuWro - performance

T2K CC 0π, no detected proton above a threshold of 450 MeV/c (*Phys.Rev. D98 (2018) 032003)*

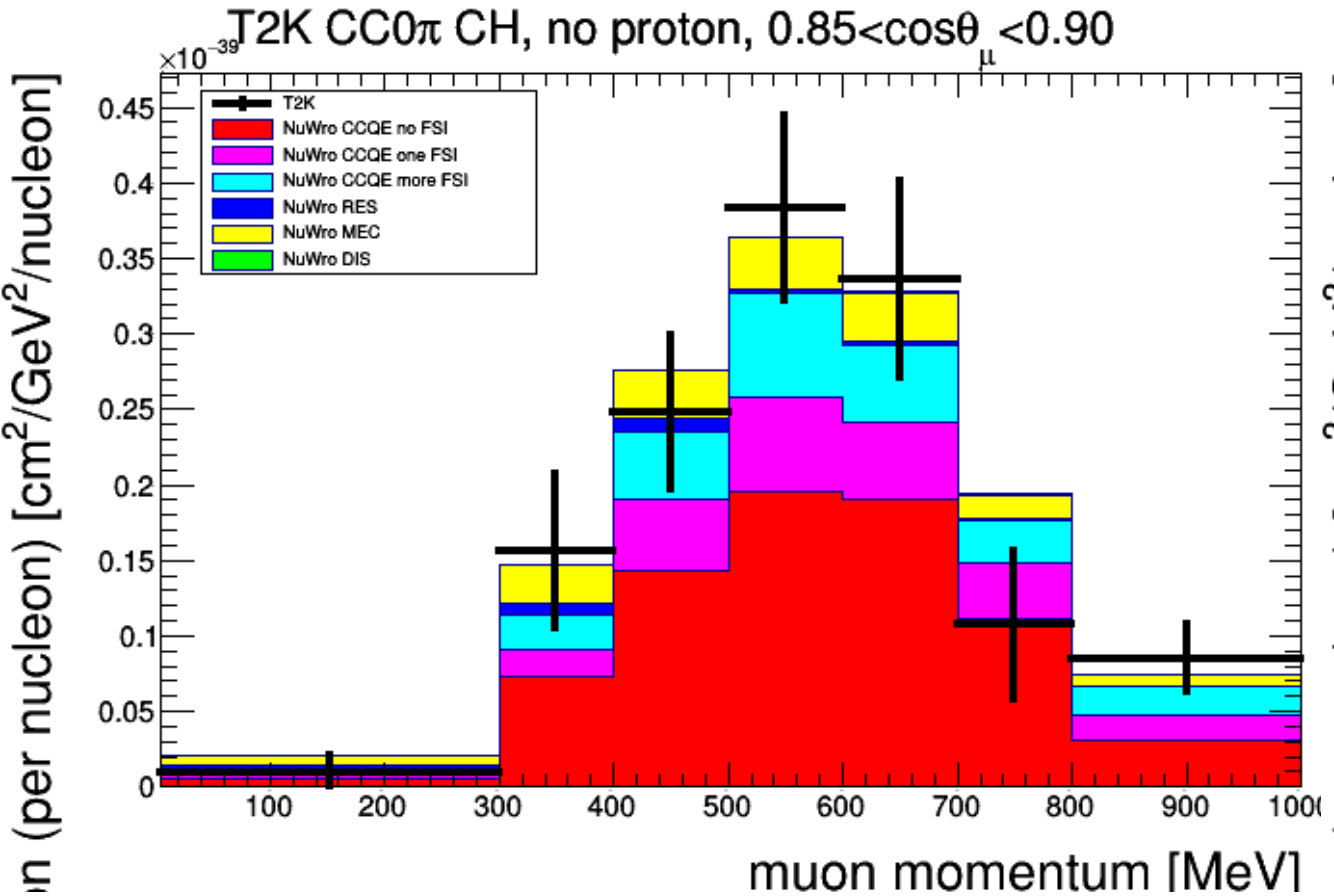
On next slides individual contributions from particular interaction modes/scenarios are shown, as modeled by NuWro:

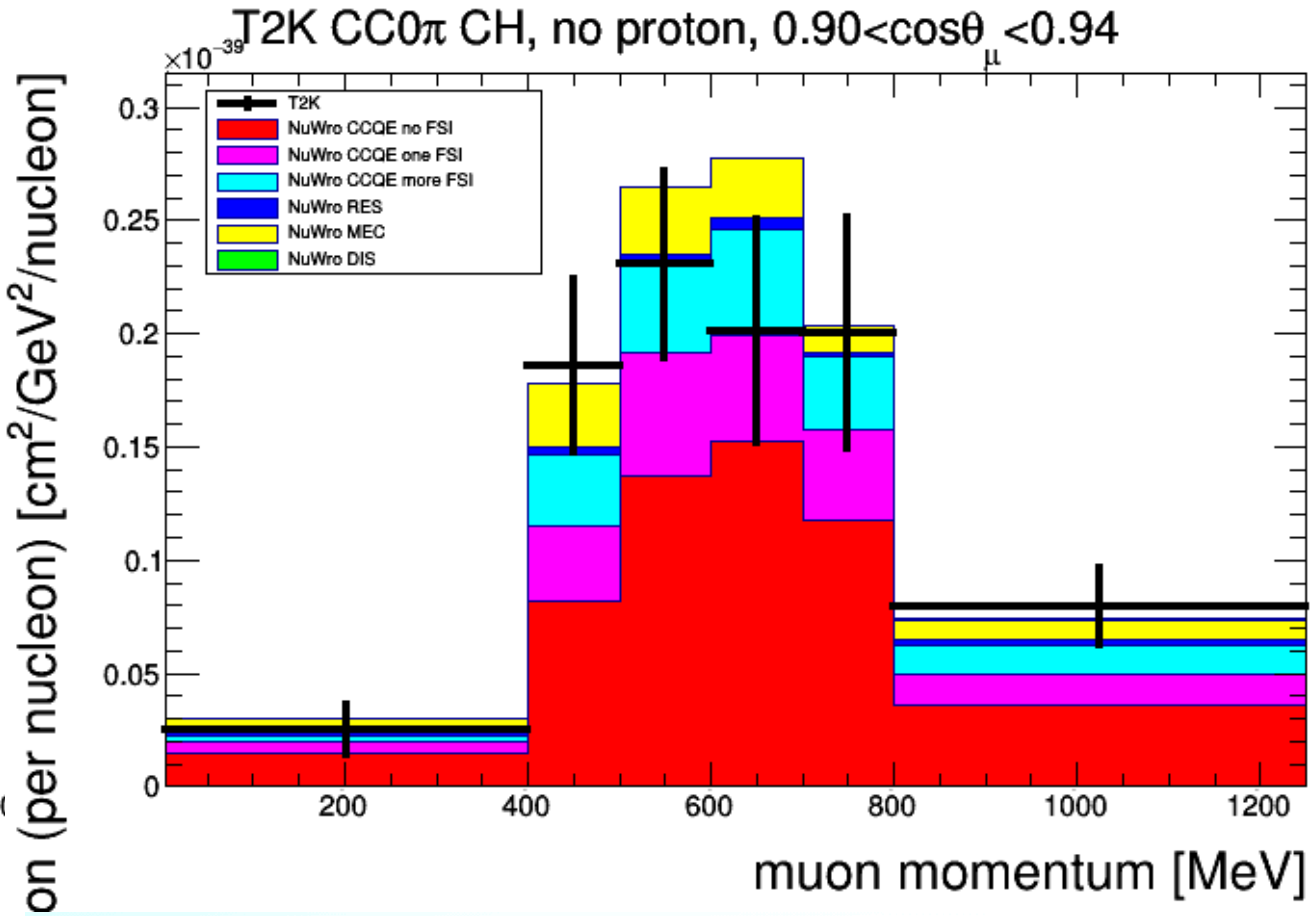
- red: CCQE with no FSI
- magenta: CCQE with one FSI
- cyan: CCQE with more FSI
- blue: RES
- yellow: MEC
- green: DIS

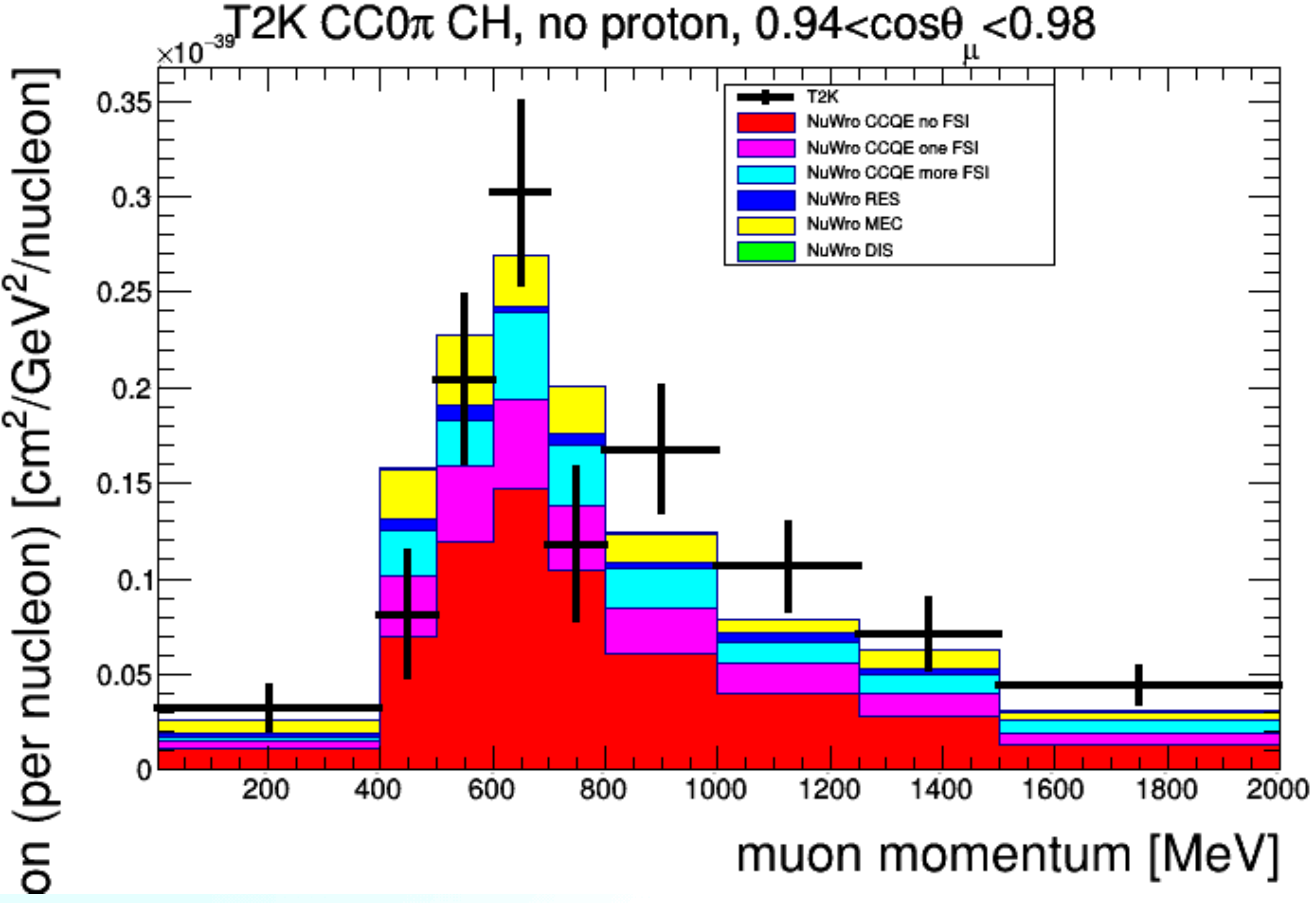


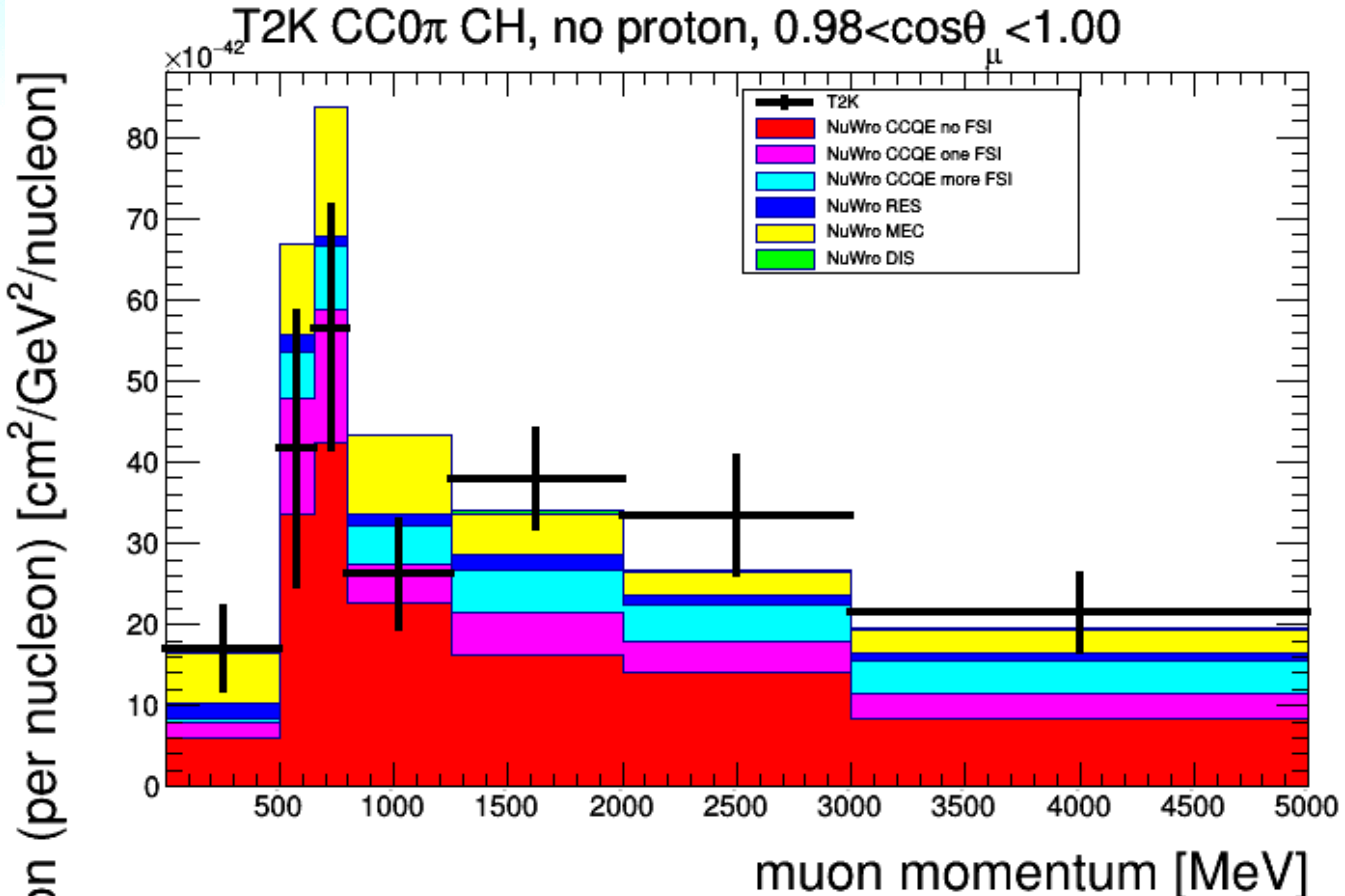


NuWro
Wrocław Neutrino Event Generator


T2K CC0π CH, no proton, 0.85<cosθ_μ<0.90
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
(per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]


T2K CC0π CH, no proton, 0.90<cosθ_μ<0.94
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
(per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]


T2K CC0π CH, no proton, 0.94<cosθ_μ<0.98
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
(per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

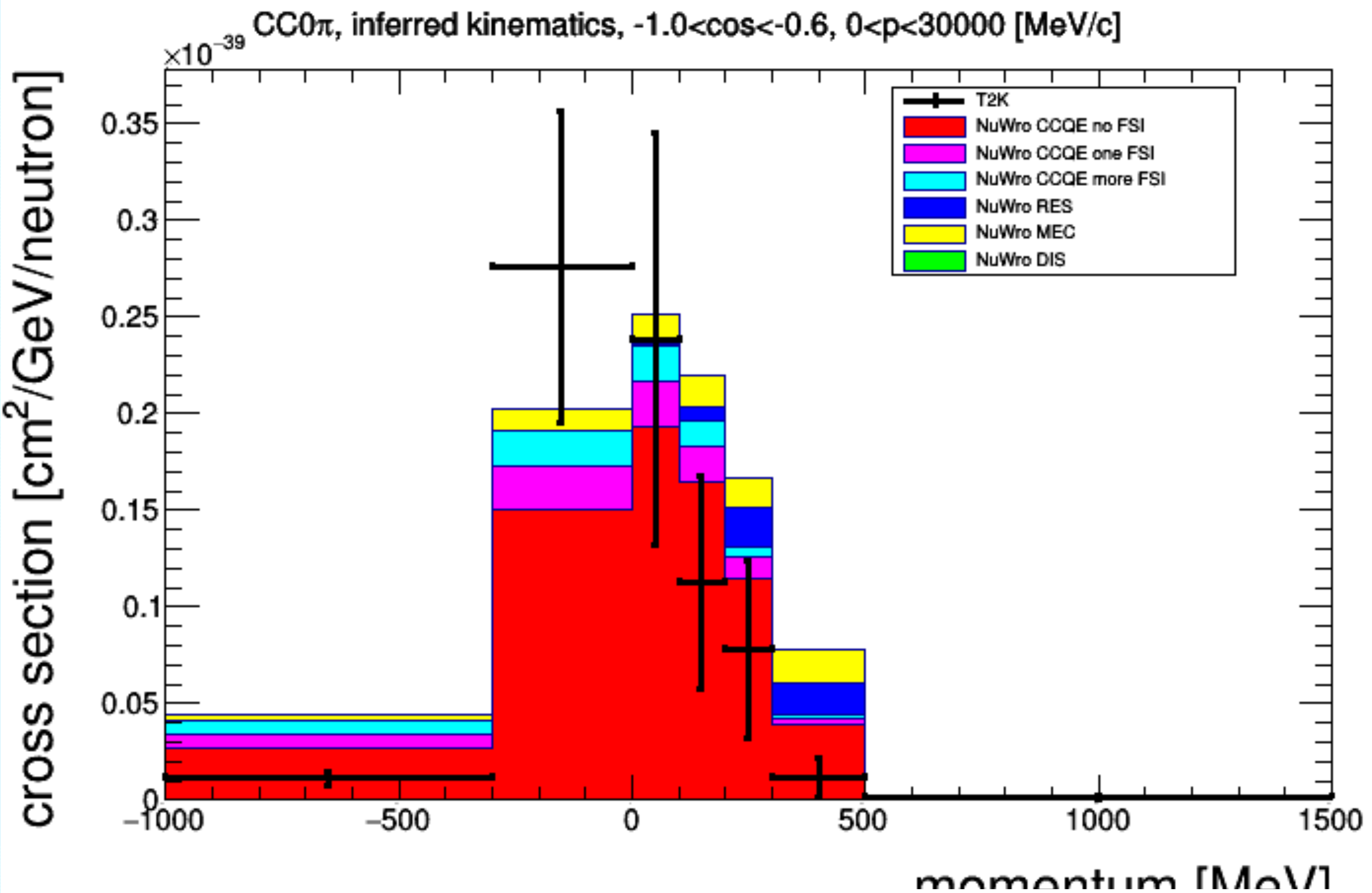

T2K CC0π CH, no proton, 0.98<cosθ_μ<1.00
×10^-42
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
(per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

NuWro - performance

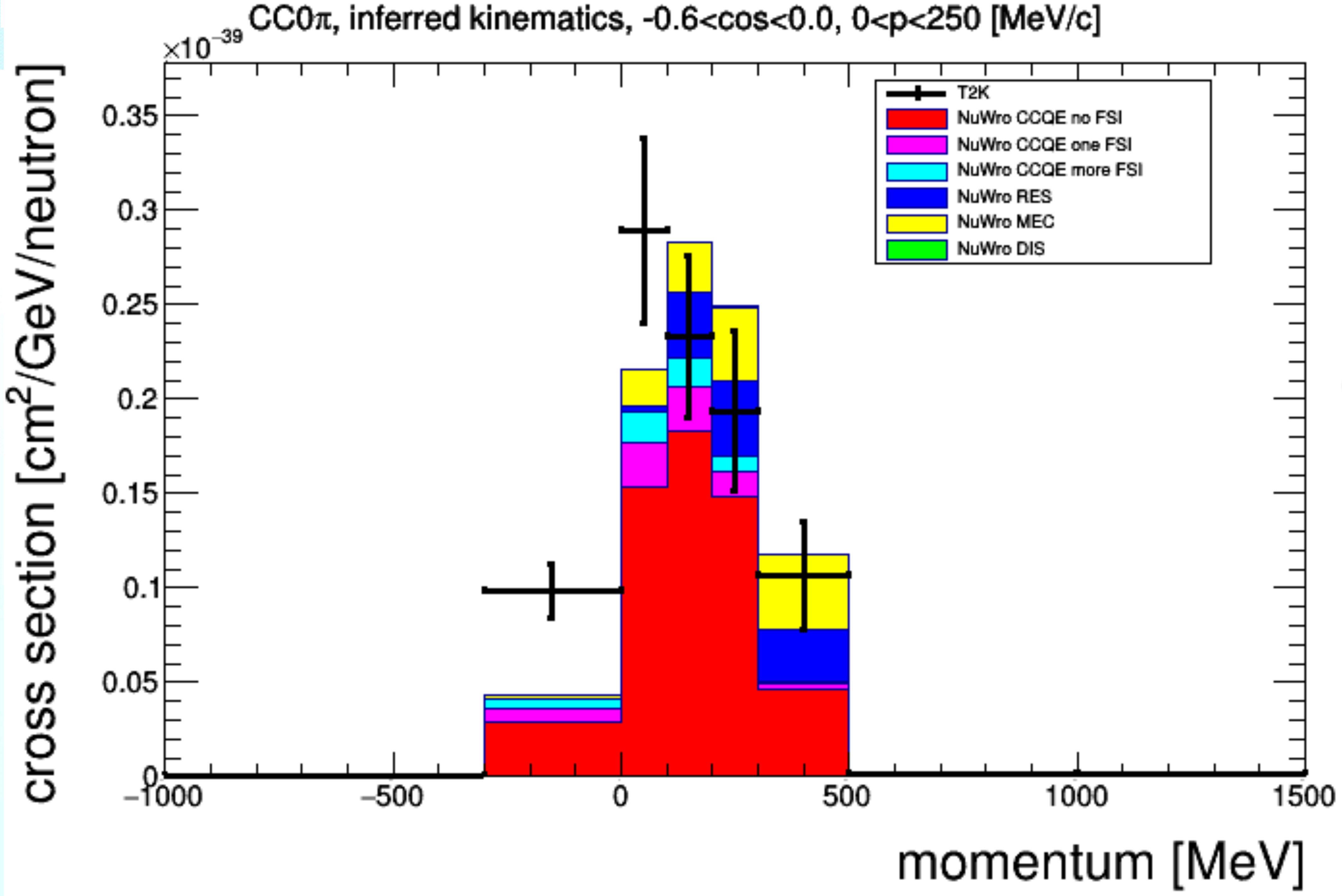
T2K - „inferred kinematics”, *Phys.Rev. D98 (2018) 032003*

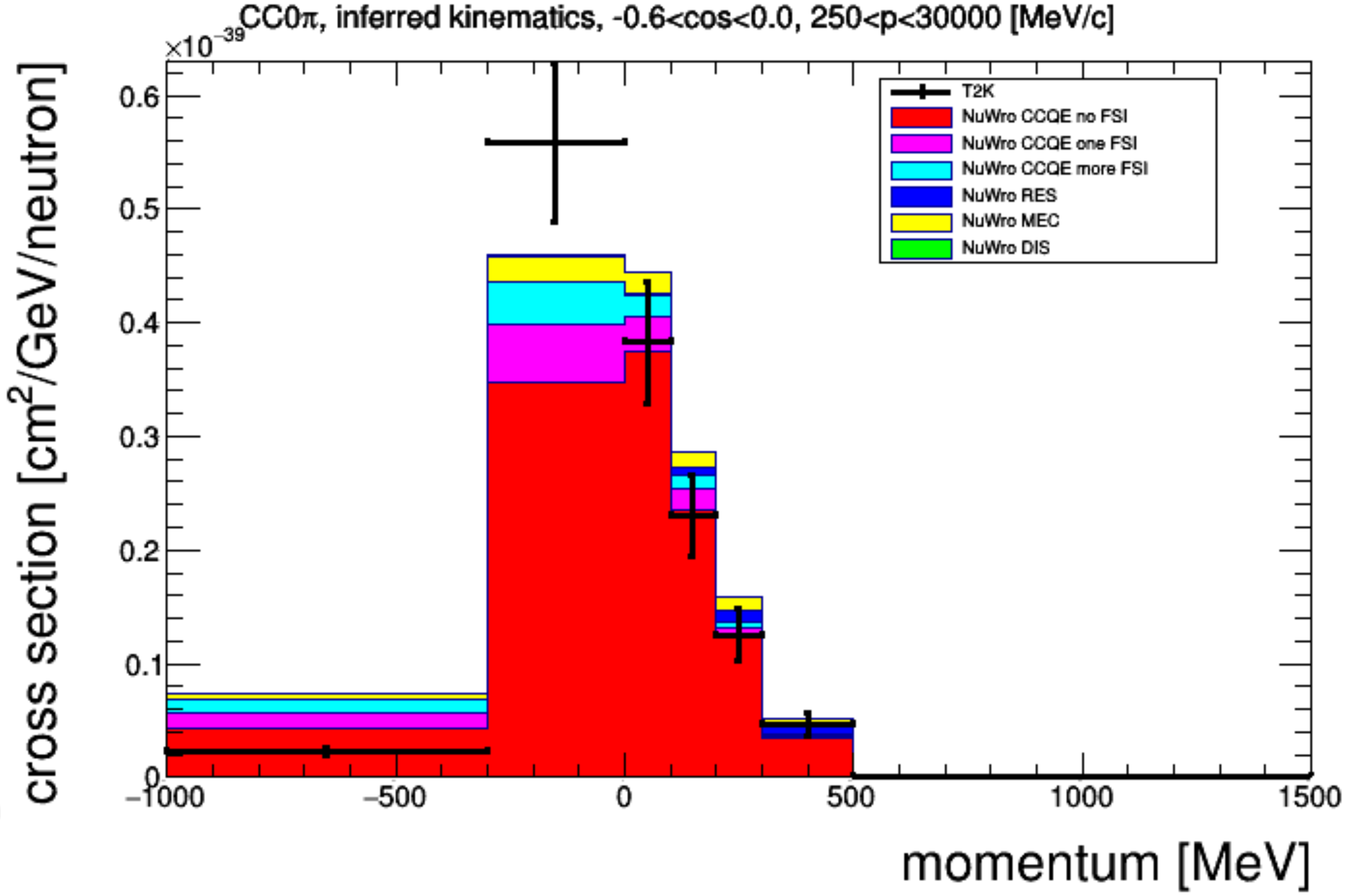
An alternative to better known approach of transverse kinematics imbalance proposed by Xianguo Lu.

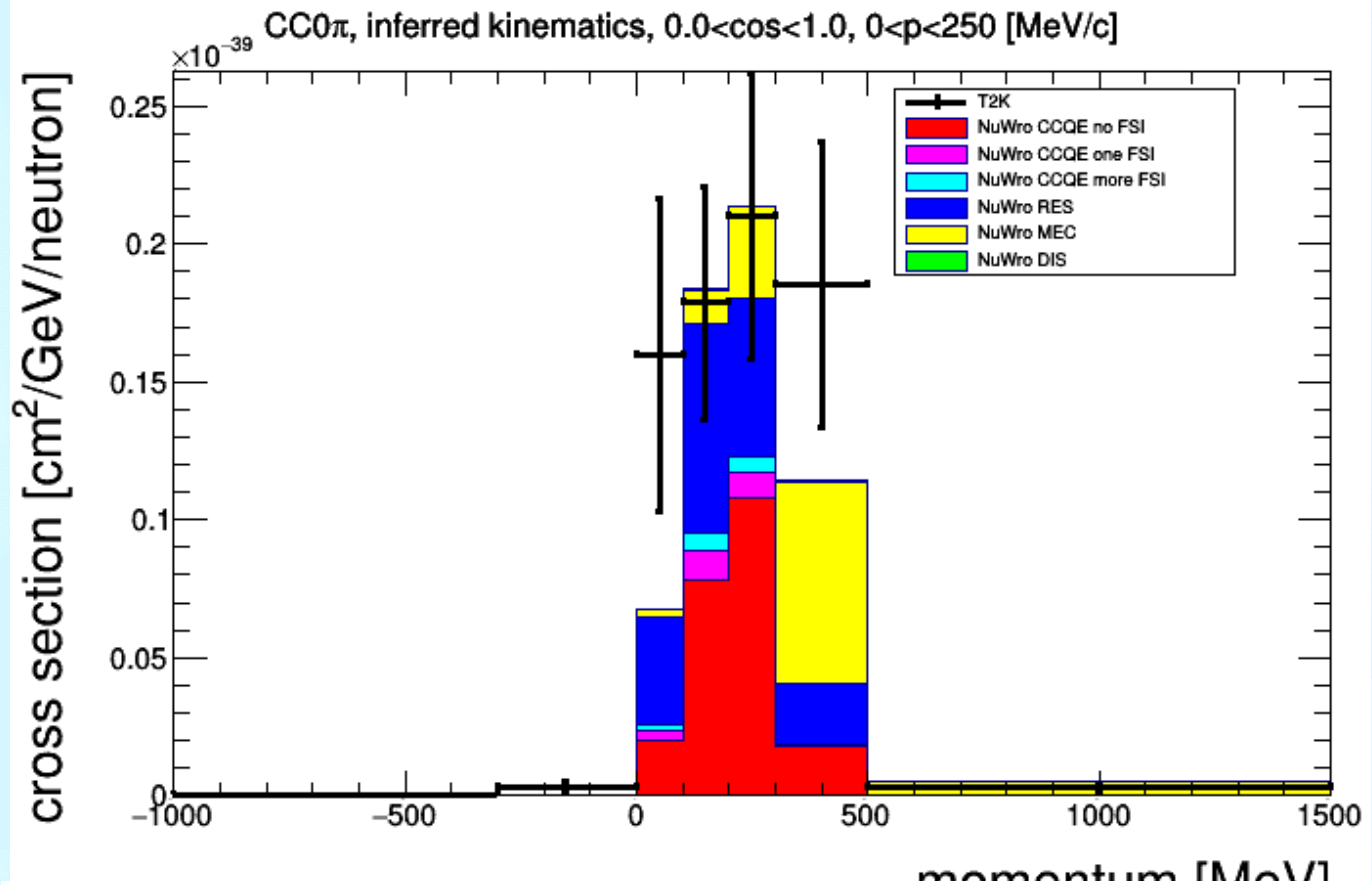
- Starting point: assumption that interaction was CCQE and occured on a bound neutron at rest.
- FSI are neglected.
- From energy and momentum conservation one can calculate expected momentum vector of knocked-out proton $\vec{p}^{inferred}$
- The measured momentum is denoted as $\vec{p}^{observed}$
- A new observable is defined as $|\vec{p}^{observed}| - |\vec{p}^{inferred}|$



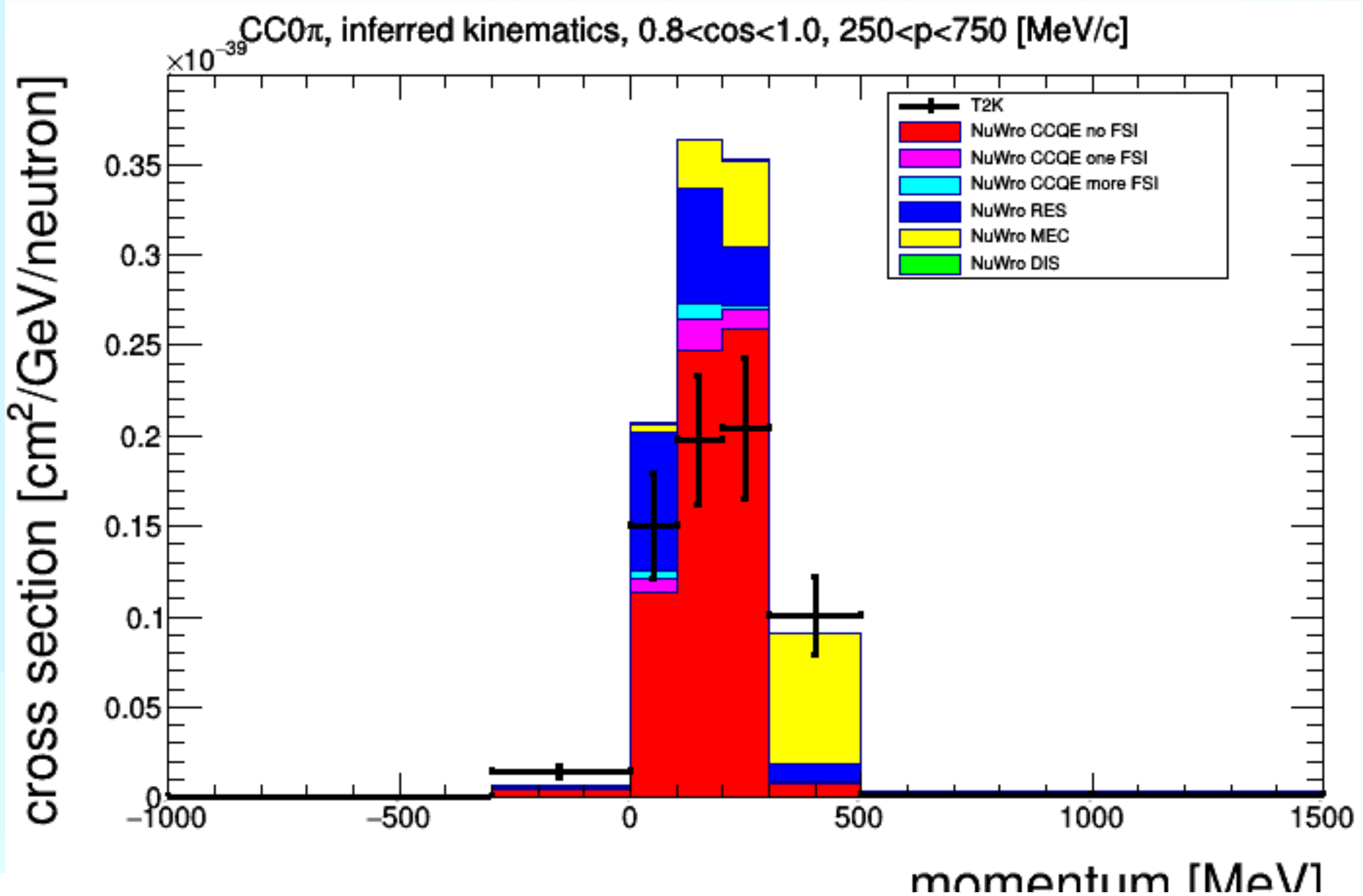
- red: CCQE with no FSI
- magenta: CCQE with one FSI
- cyan: CCQE with more FSI
- blue: RES
- yellow: MEC
- green: DIS



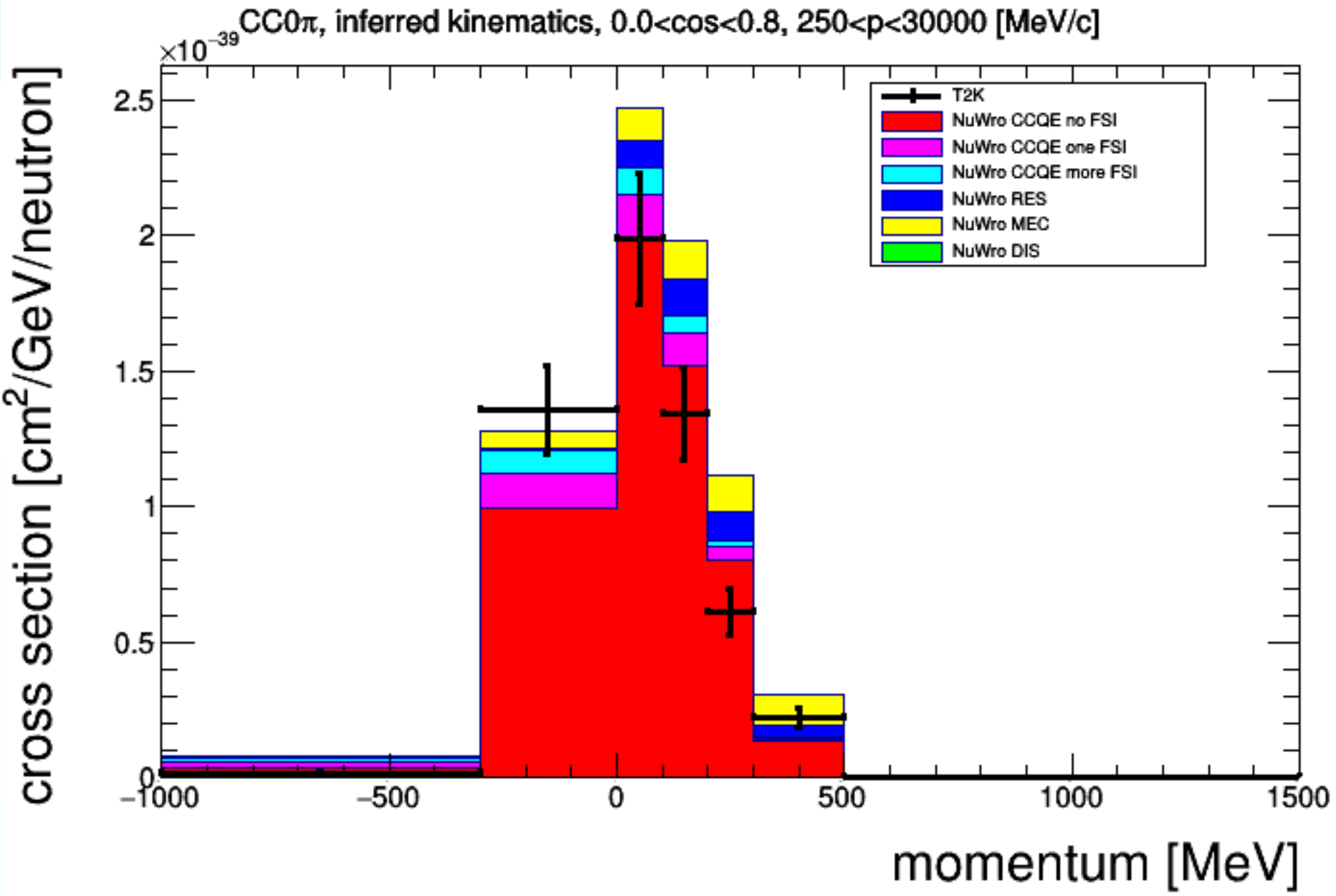




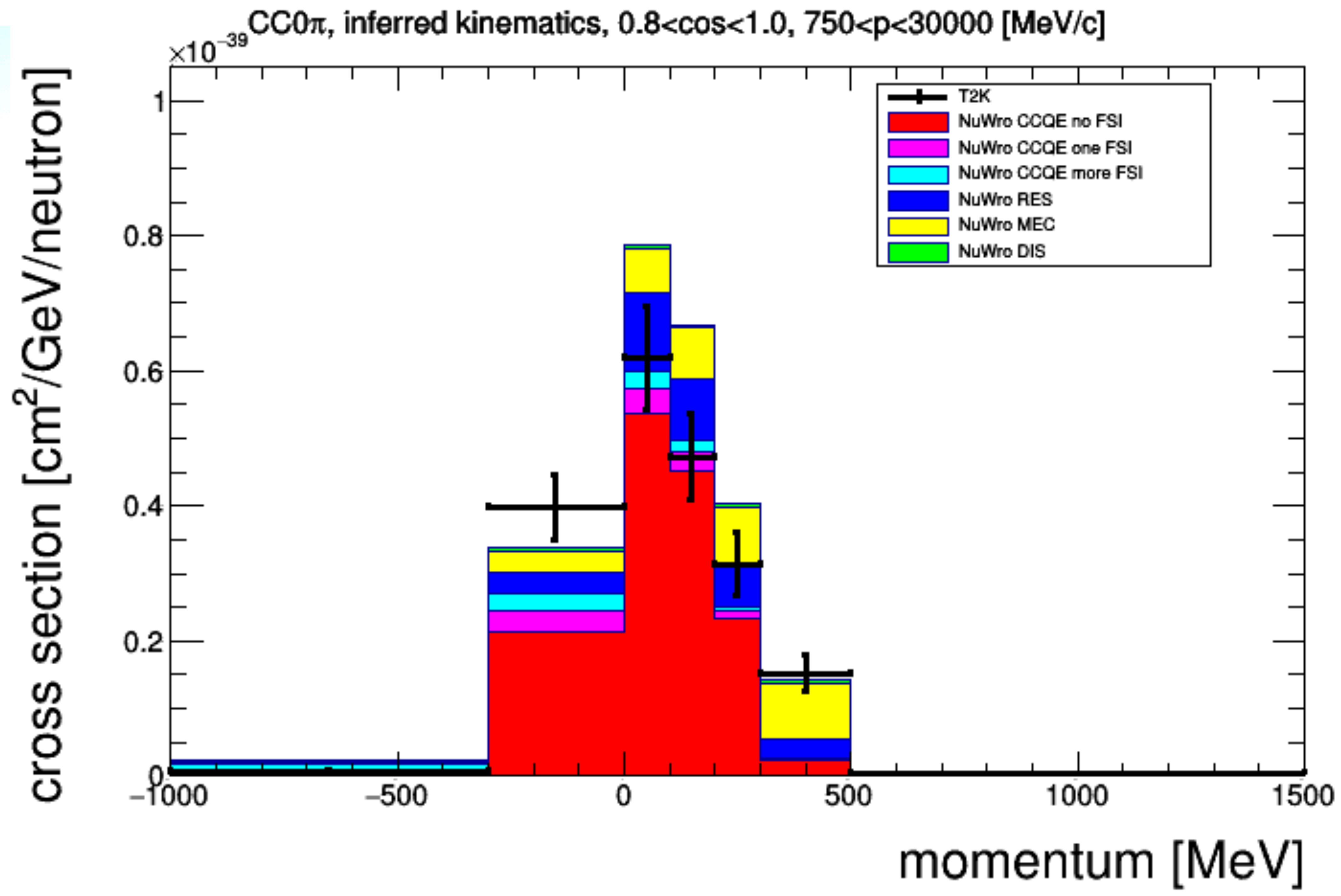
CC0π, inferred kinematics, 0.0<cos<1.0, 0<p<250 [MeV/c]
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
cross section [cm²/GeV/neutron]
momentum [MeV]



CC0π, inferred kinematics, 0.8<cos<1.0, 250<p<750 [MeV/c]
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
cross section [cm²/GeV/neutron]
momentum [MeV]



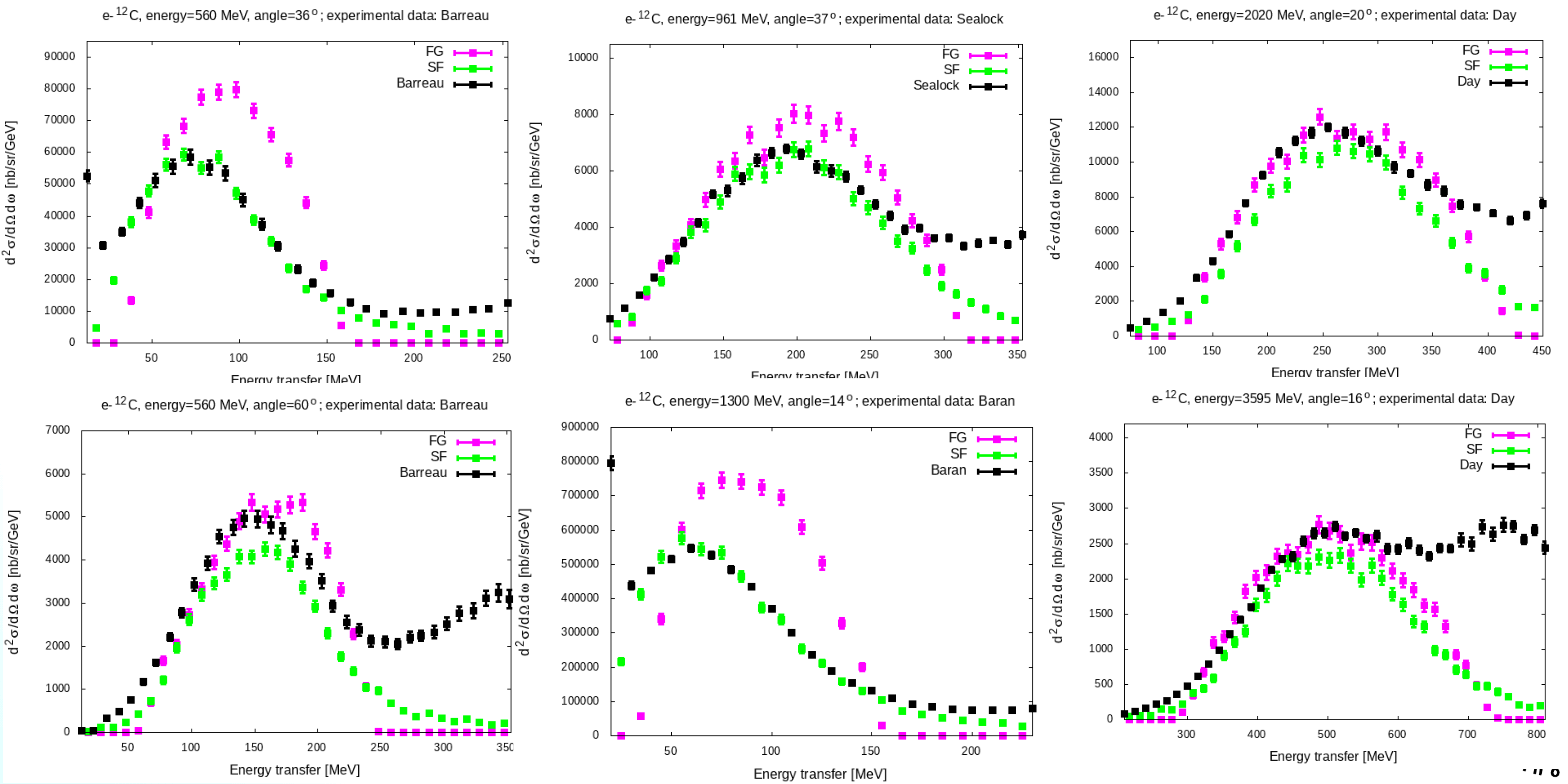
CC0π, inferred kinematics, 0.0<cos<0.8, 250<p<30000 [MeV/c]
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
cross section [cm²/GeV/neutron]
momentum [MeV]



CC0π, inferred kinematics, 0.8<cos<1.0, 750<p<30000 [MeV/c]
×10^-39
T2K
NuWro CCQE no FSI
NuWro CCQE one FSI
NuWro CCQE more FSI
NuWro RES
NuWro MEC
NuWro DIS
cross section [cm²/GeV/neutron]
momentum [MeV]

eWro performance

Magenta - global Fermi gas
Green - hole spectral function



NuWro - new developments

New single pion production model employing theoretical computations of the Ghent group

- poster by Qiyu Yan et al: *Hybrid model for single-pion production incorporated in the NuWro event generator nuclear framework (based on Qiyu Yan, Kajetan Niewczas, Alexis Nikolakopoulos, Raul Gonzalez-Jimenez, Natalie Jachowicz, Xianguo Lu, JTS, Yangheng Zheng, The Ghent Hybrid Model in NuWro …, to be submitted to arXiv)*

Improvements of the MEC model

- Hemant Prasad et al in preparation
- talk by Kajetan Niewczas

Argon spectral function

- poster by Rwik Dharmapal Benerjee and Artur Ankowski *JLab Spectral Functions of Argon in NuWro and their Implications for MicroBooNE (based on Phys. Rev. D109 073004)*

Machine learning methods for event generators

- talk by Krzysztof Graczyk: *Global parametrization of the eC cross section from neural networks*

.

Spectral function approach in NuWro - history

- Hole SF for carbon, oxygen, calcium, iron; information passed as a grid. SF consists of two parts: mean field and correlated (allowing for large nucleon momentum)

O. Benhar et al *NPA579 (1994)493; PRD72 (2005) 053005*

- FSI (affecting lepton) for carbon

A.M. Ankowski, O. Benhar, and M. Sakuda, *PRD91 (2015) 033005*

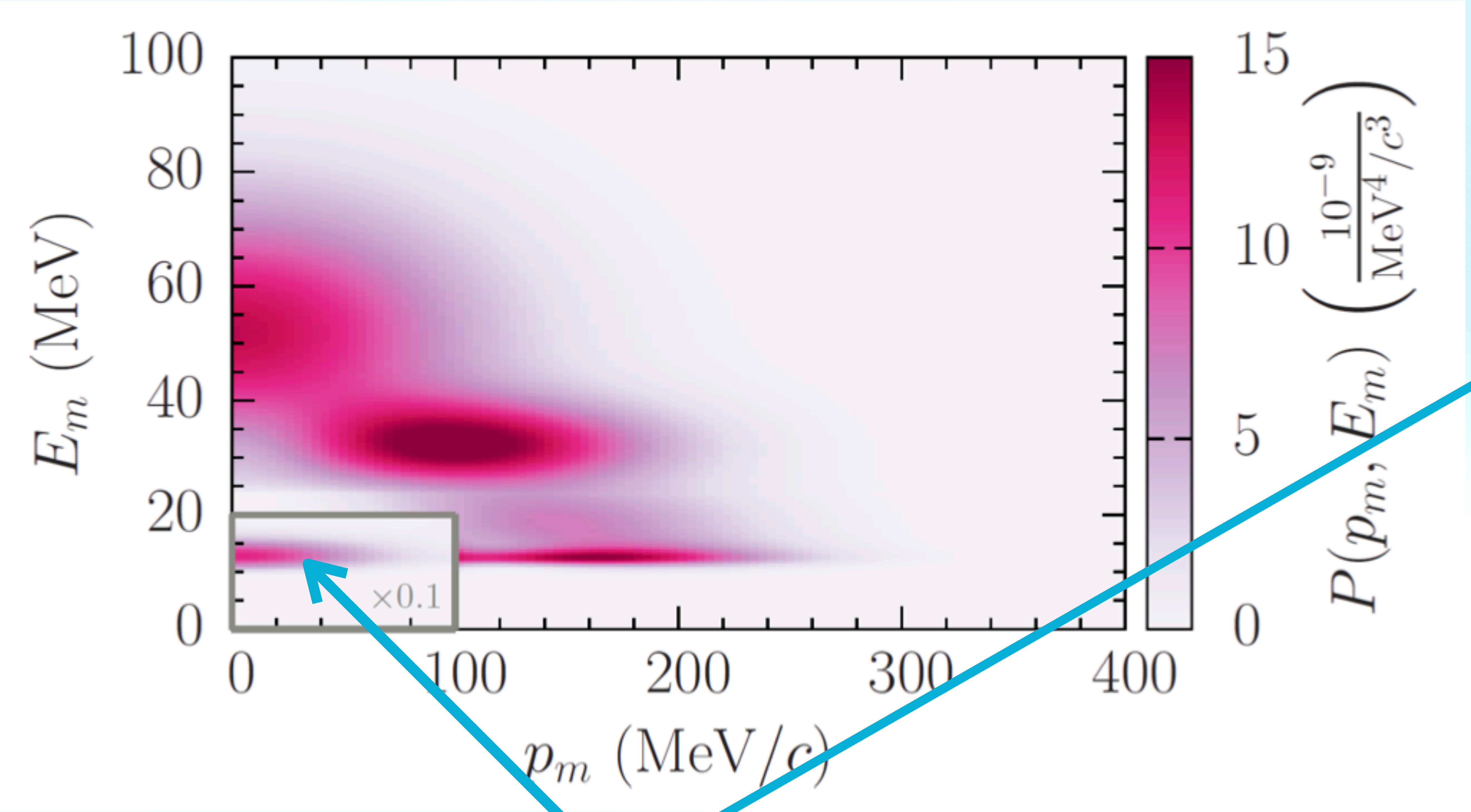
- Obsolete „factorized" SF for argon, calcium, oxygen

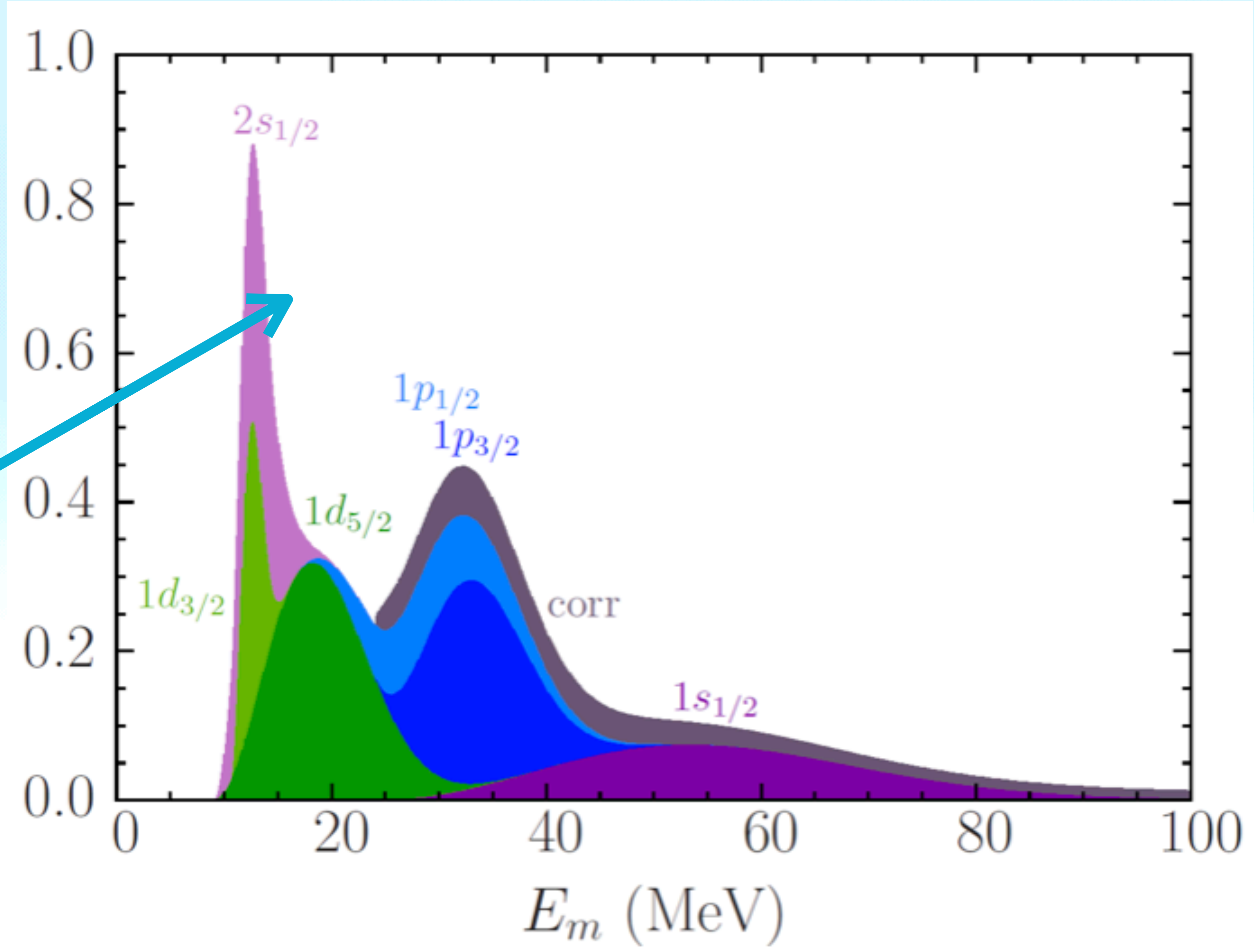
A.M. Ankowski, JTS, *Phys.Rev.C* 74 (2006) 054316, *Phys.Rev.C* 77 (2008) 044311

NuWro implementation done by Cezary Juszczak based on Artur Ankowski code.

Argon spectral function

Below, mean field part of the argon SF is seen





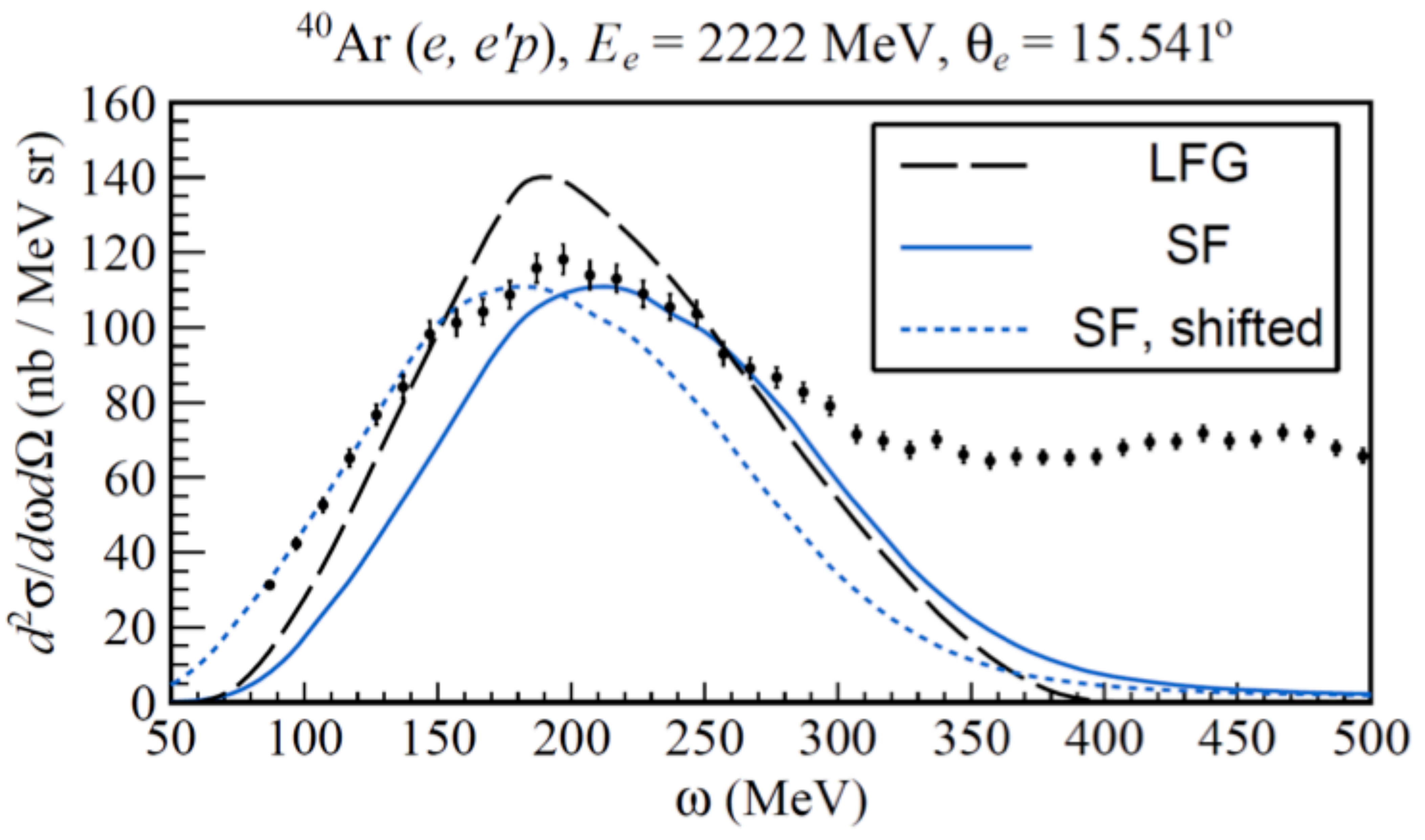
$2s_{1/2}$

Argon SF will soon become a part of a new NuWro release

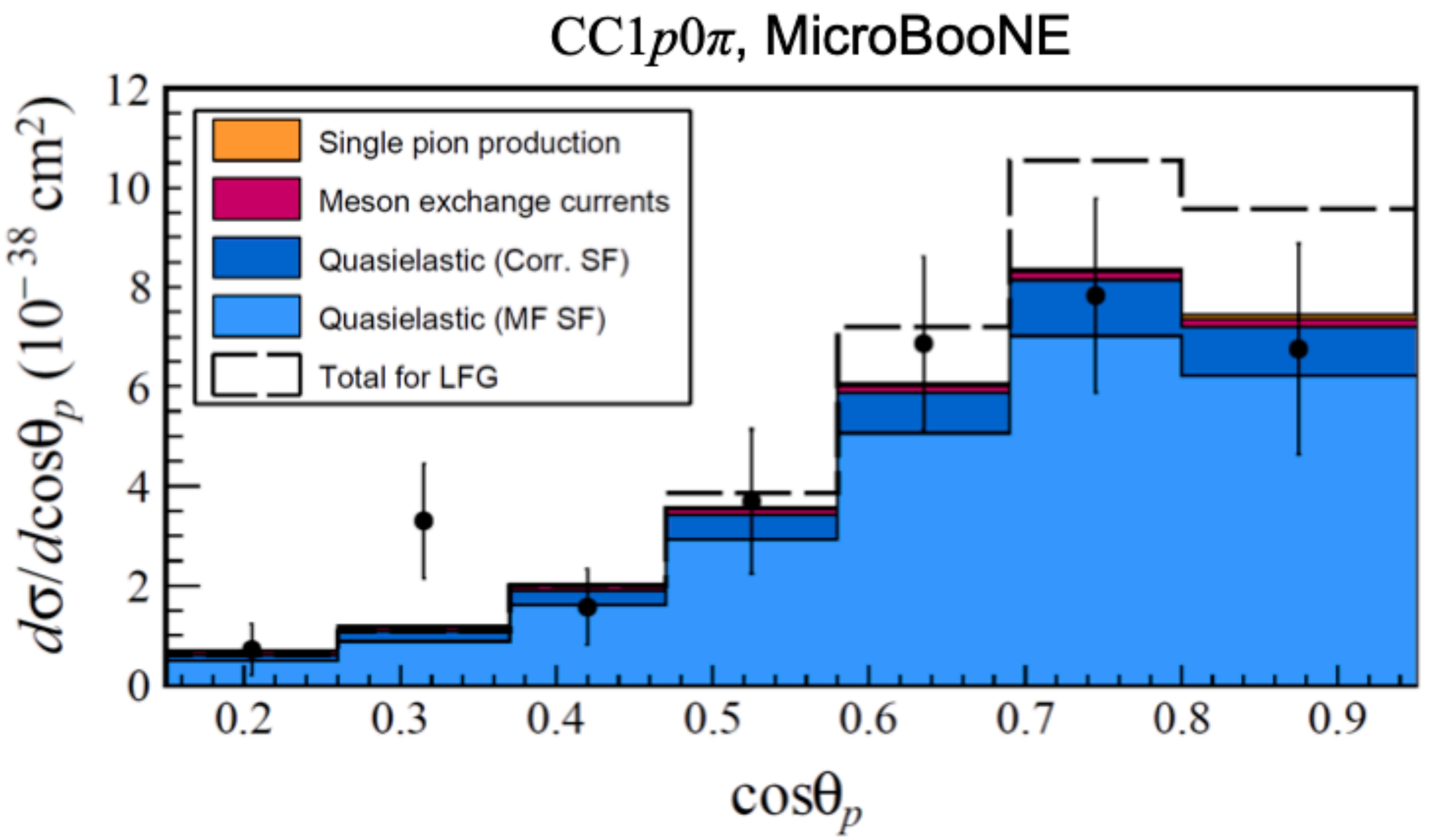
- Mean field and correlation parts are separated
- FSI effects will be added in the next step.

Artur Ankowski based on: L. Jiang *et al.*,
PRD 105, 112002 (2022); PRD 107, 012005 (2023)

Argon spectral function in NuWro



data:Dai *et al.*, PRC 99, 054608 (2019)



data: Abratenko *et al.*, PRL 125, 201803 (2020)

Combined $\chi^2/d.o.f.$ for the MicroBooNE $CC1p0\pi$ data for the restricted phase space $(\cos\theta_\mu < 0.8)$ is 1.0 for the local Fermi gas and 0.7 for the spectral function approach.

Rwik Dharmapal Banerjee, Artur M. Ankowski, Krzysztof M. Graczyk, Beata E. Kowal, Hemant Prasad, and JTS, PRD 109 073004 (2024)

New single pion production (SPP) model (1)

Motivation

- NuWro 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

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

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

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

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

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

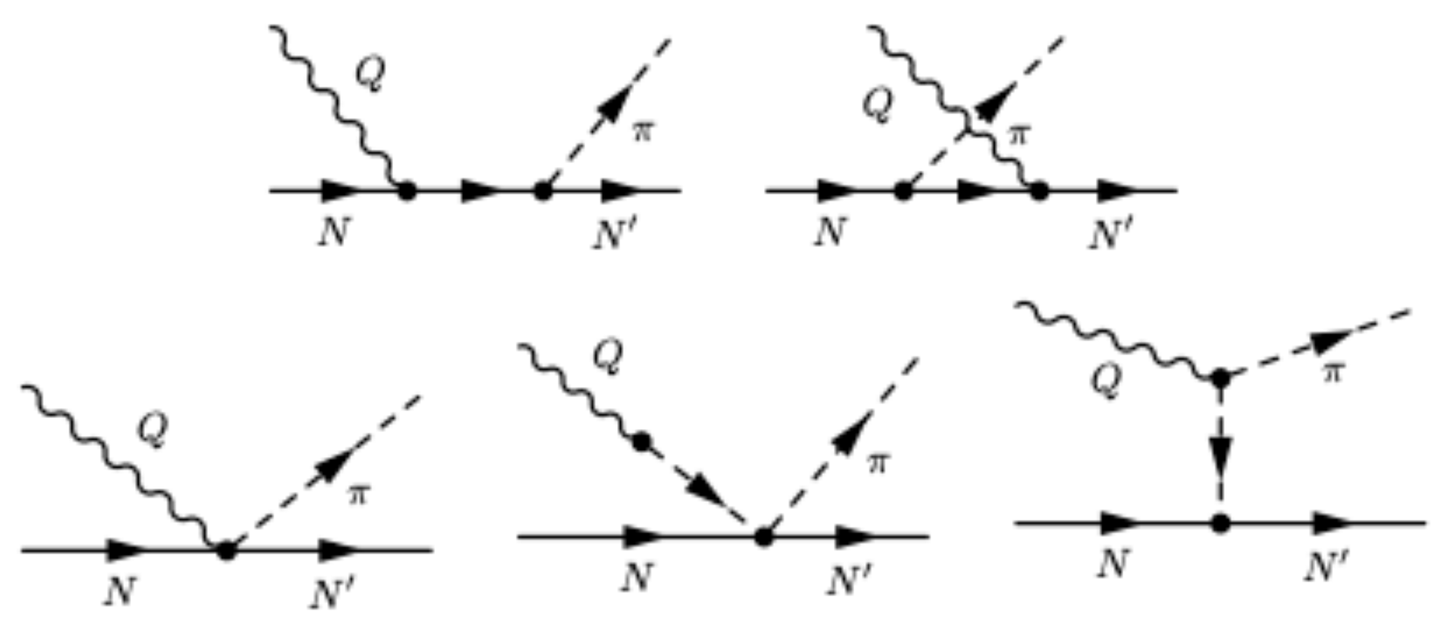
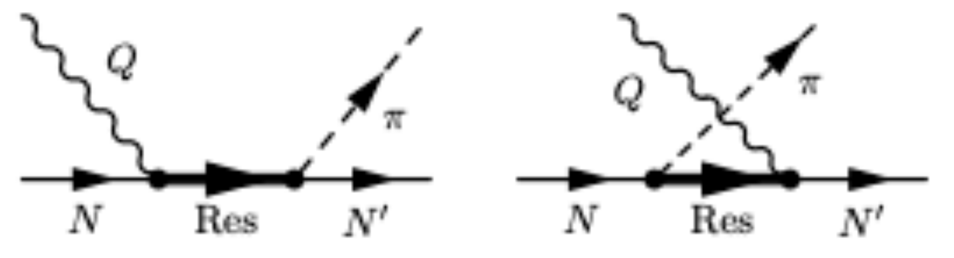


FIG. 5. ChPT-background contributions (from left to right and top to bottom): s channel (nucleon pole, NP), u channel (cross-nucleon pole, CNP), contact term (CT), pion pole (PP), and t channel (pion-in-flight term, PF).



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

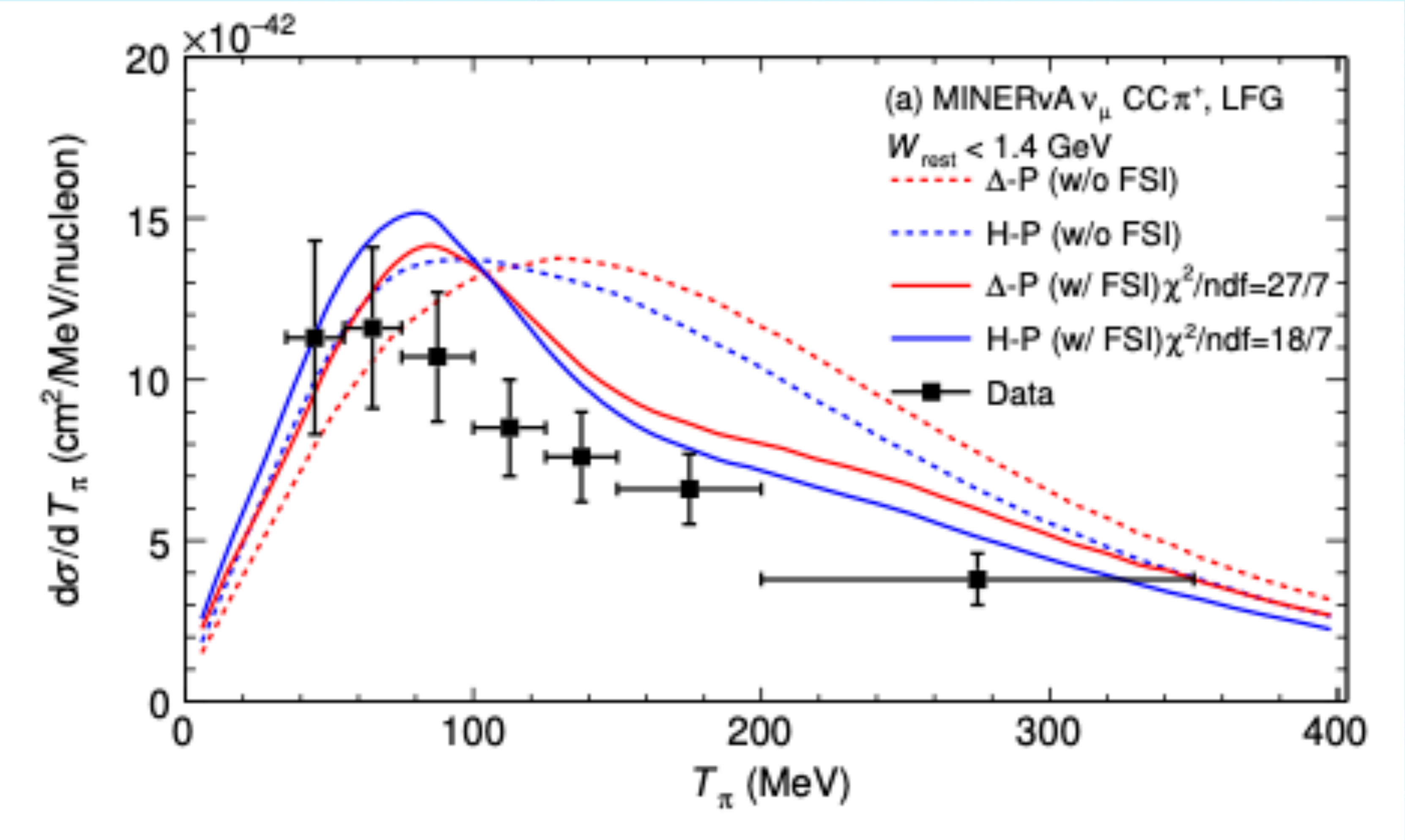
Contributions from resonances $P_{33}(1232)(\Delta)$, $D_{13}(1520)$, $S_{11}(1535)$, $P_{11}(1440)$

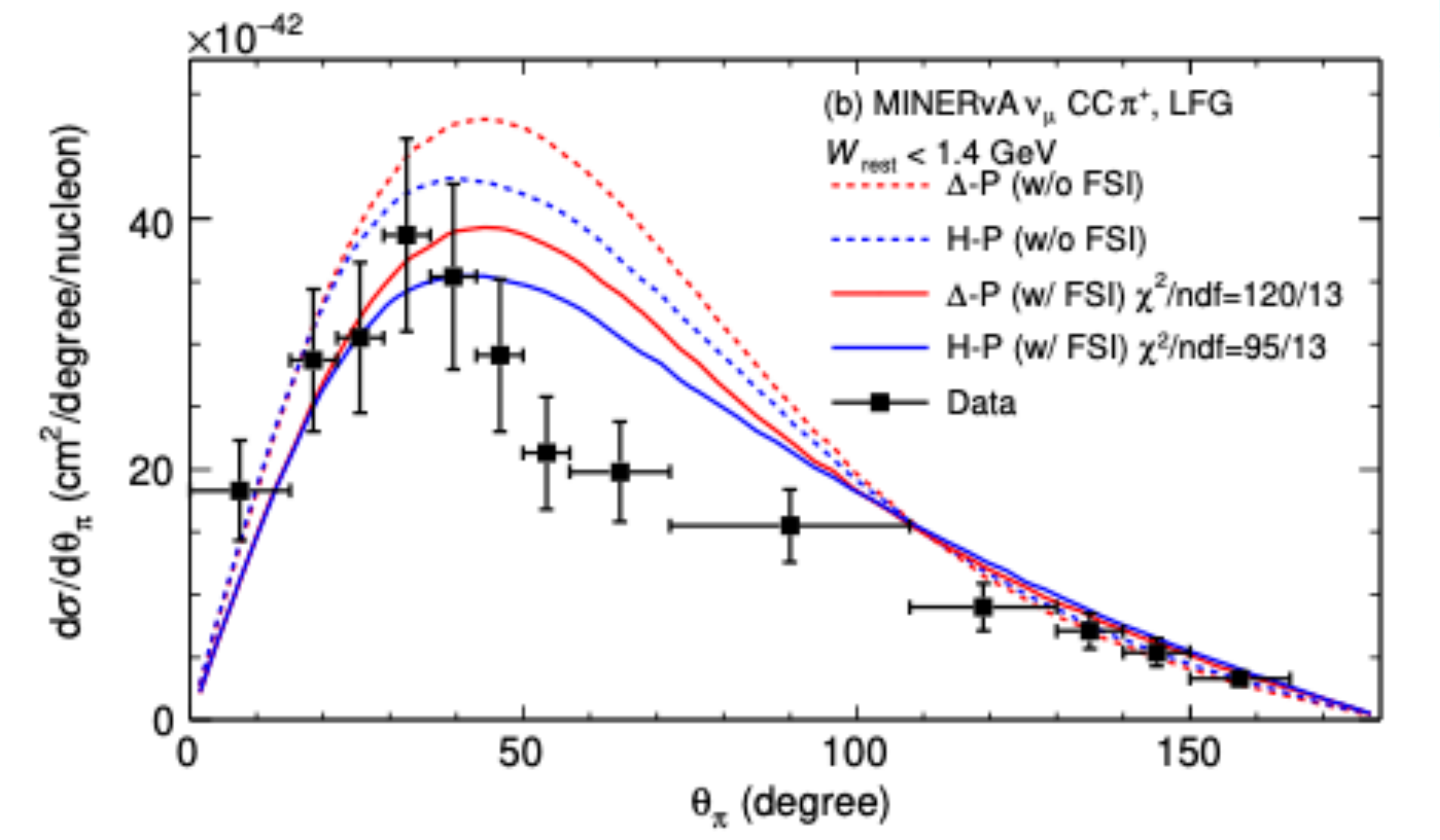
low-energy background, and high-energy background

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

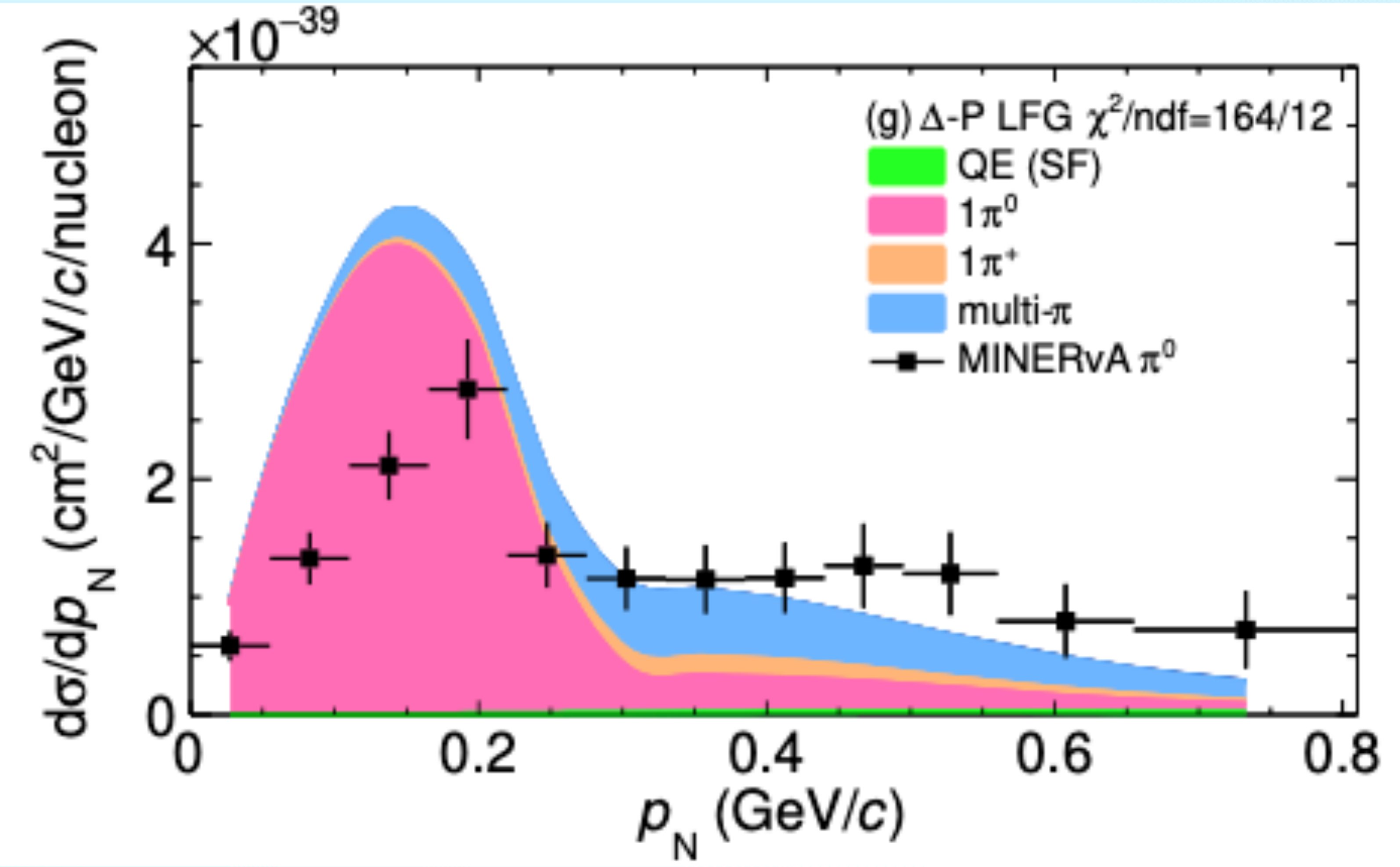
At large W almost entirely ReChi model

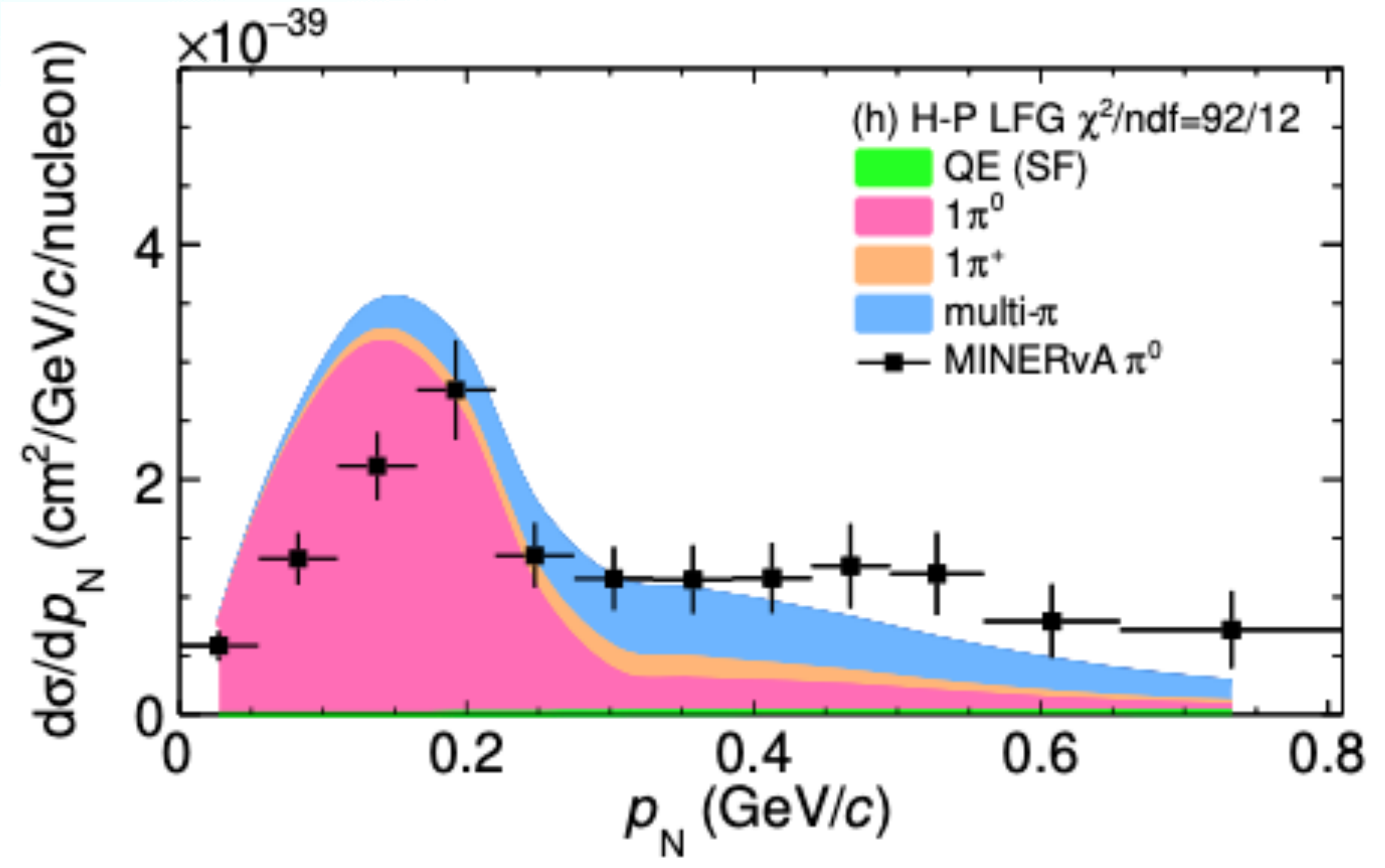
New SPP model (3)



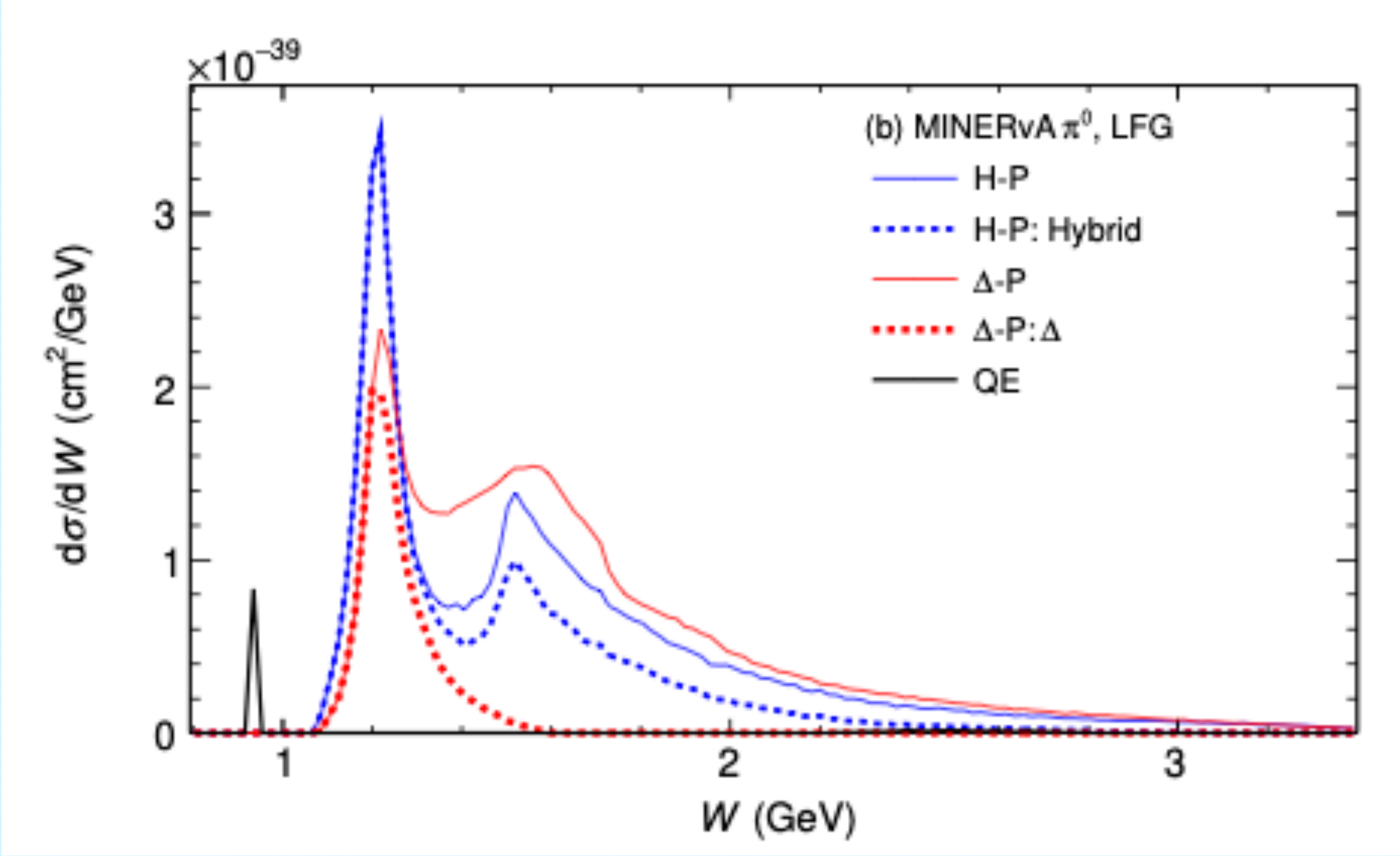


Data from: B. Eberly et al. (MINERvA), Phys. Rev. D92 092008 (2015), arXiv:1406.6415 [hep-ex].





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



Old model Δ-P
New model H-P

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

In preparation

NuWro
Wrocław Neutrino Event Generator

NuWro MEC model

Currently, NuWro relies 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; all the MCs adopt phase space model proposed in JTS, *Phys. Rev.* C86 (2012) 015504

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

A. Includes both 2p2h and 3p3h contributions

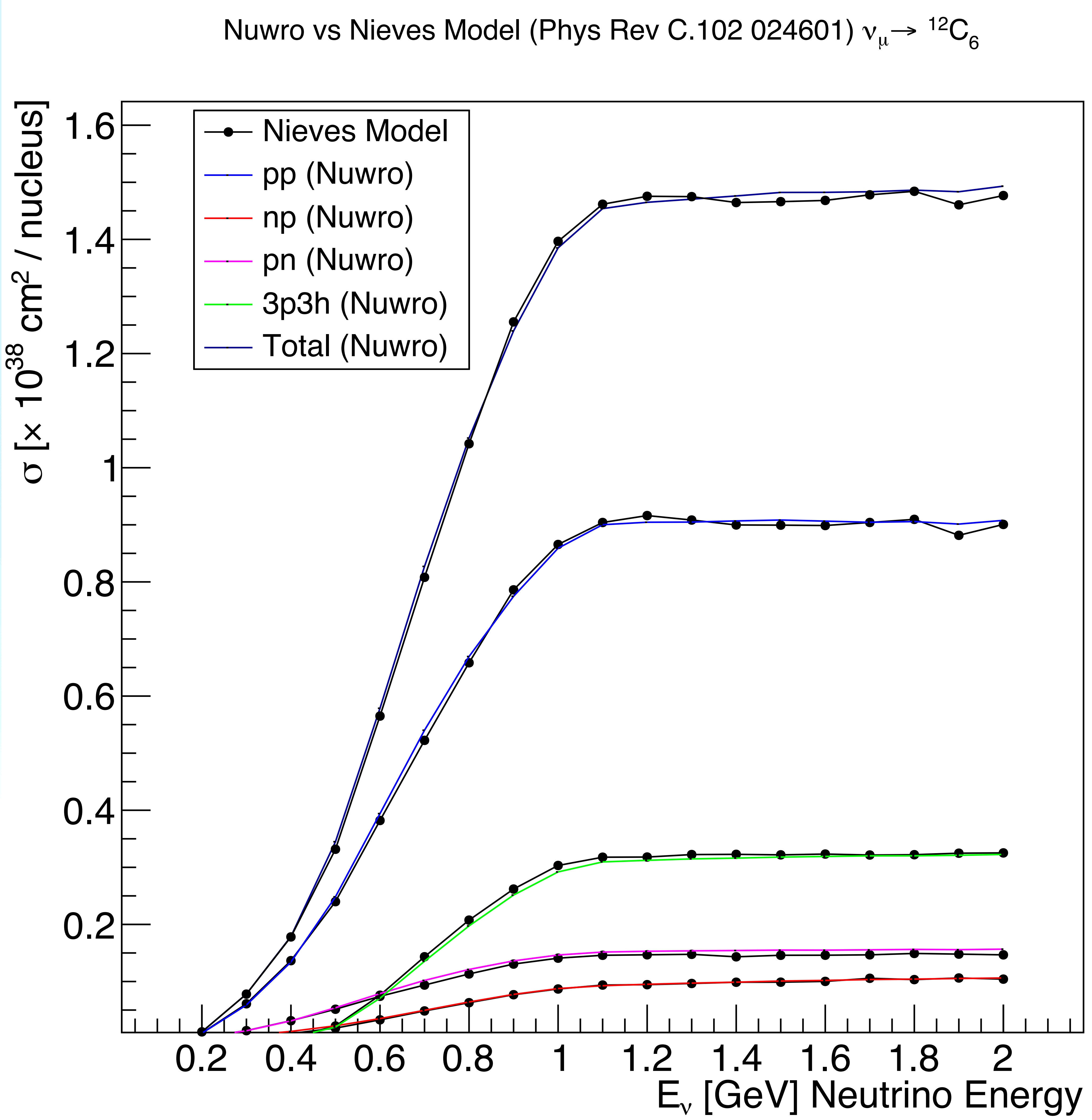
B. DProvides detail predictions for 2p2h including isospin and nucleon momenta

New MEC model

Semi-inclusive cross section

- 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 (an algorithm must be developed)



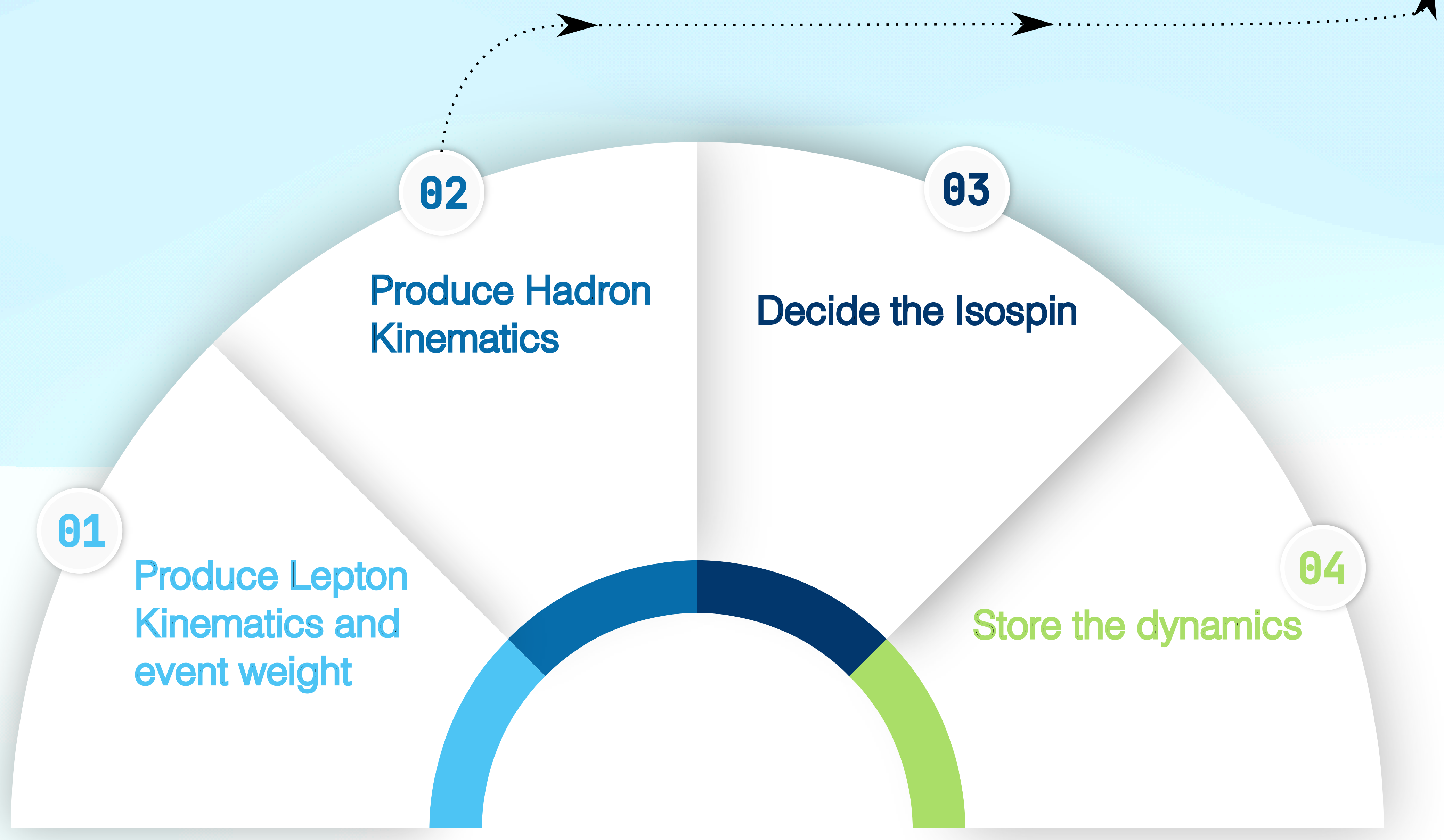
NuWro implementation by Hemant Prasad

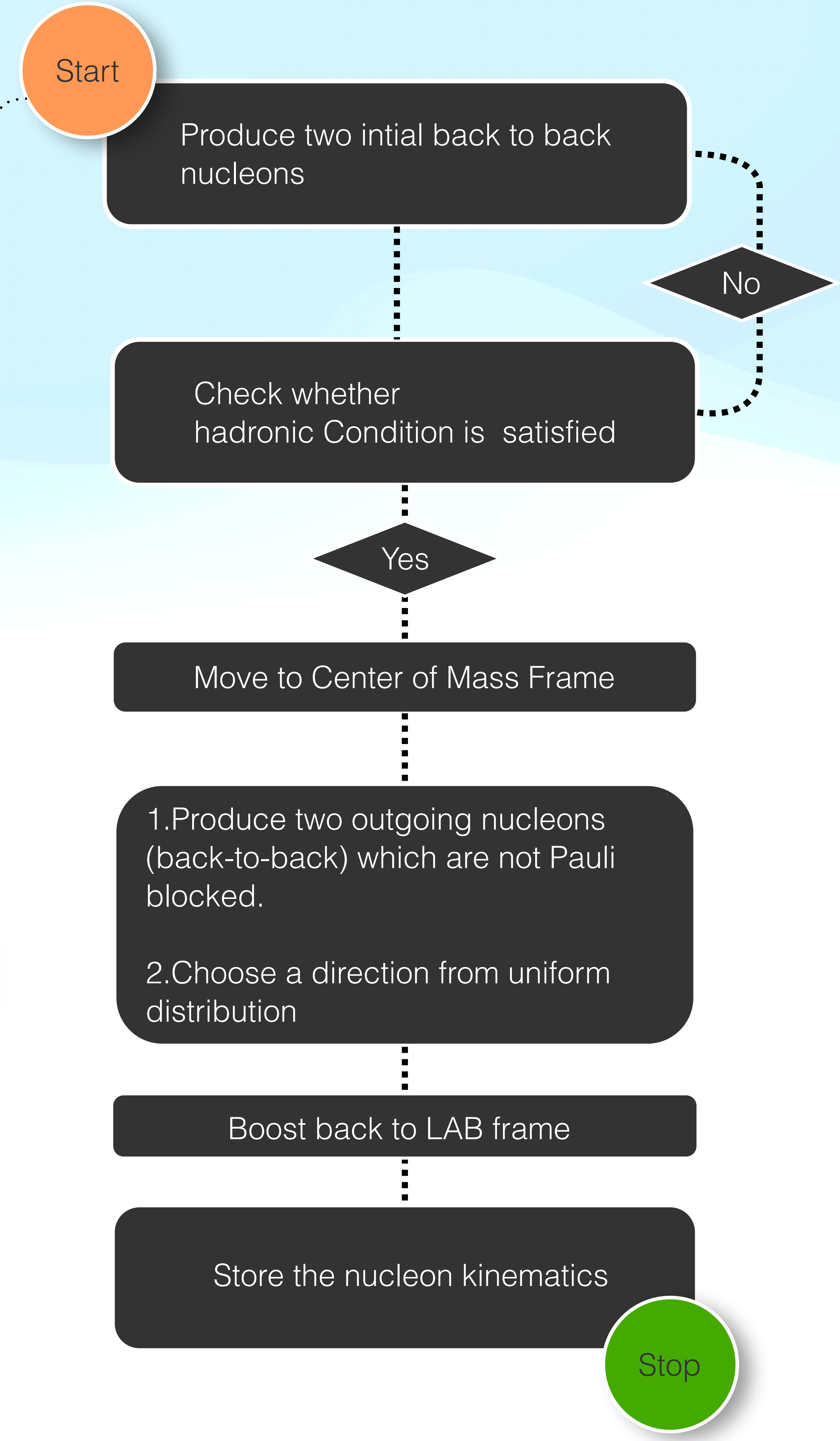
(using code provided by J.E. Sobczyk)

Old MEC hadronic model

Nuwro v21.09.xx

Current MEC scheme



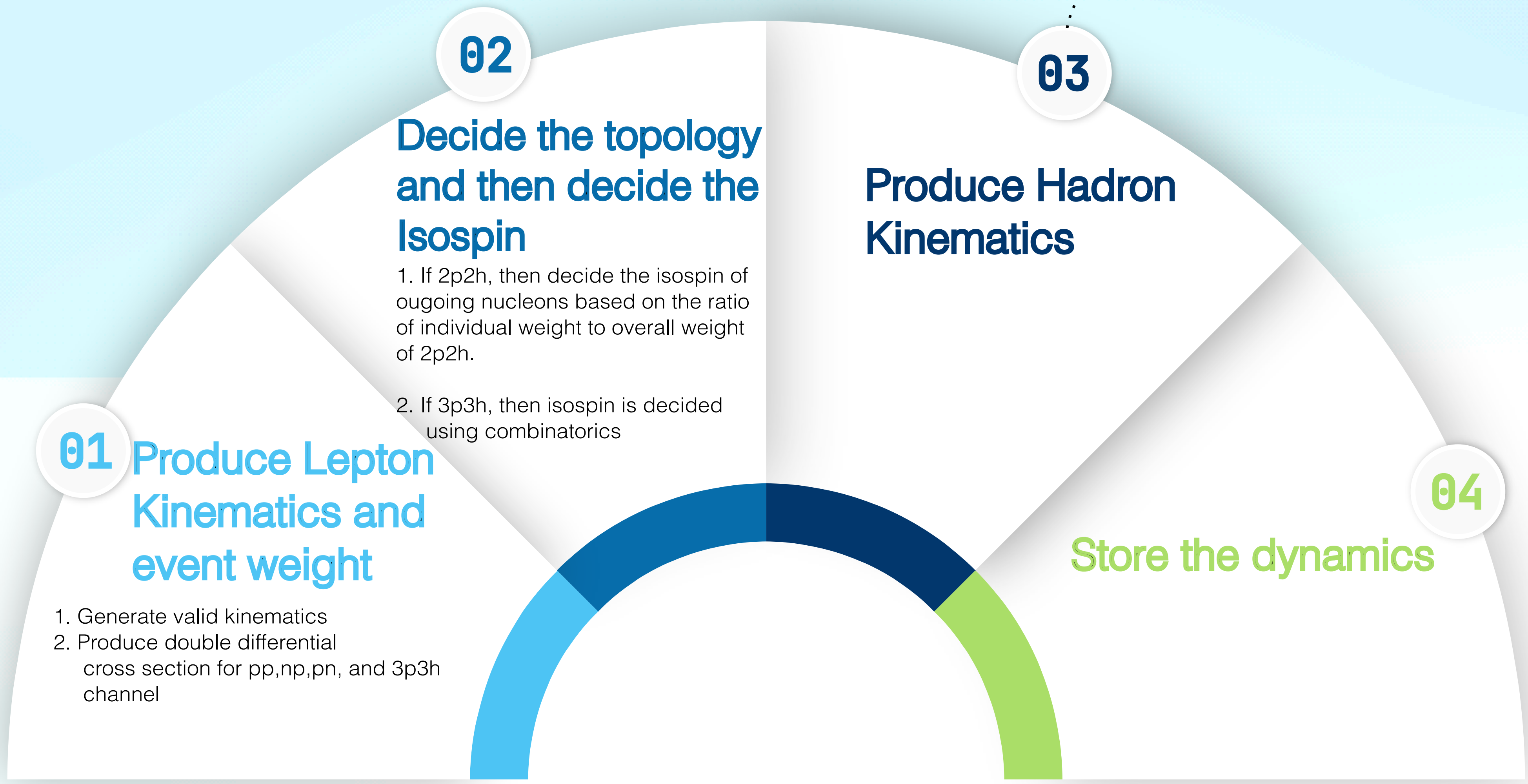


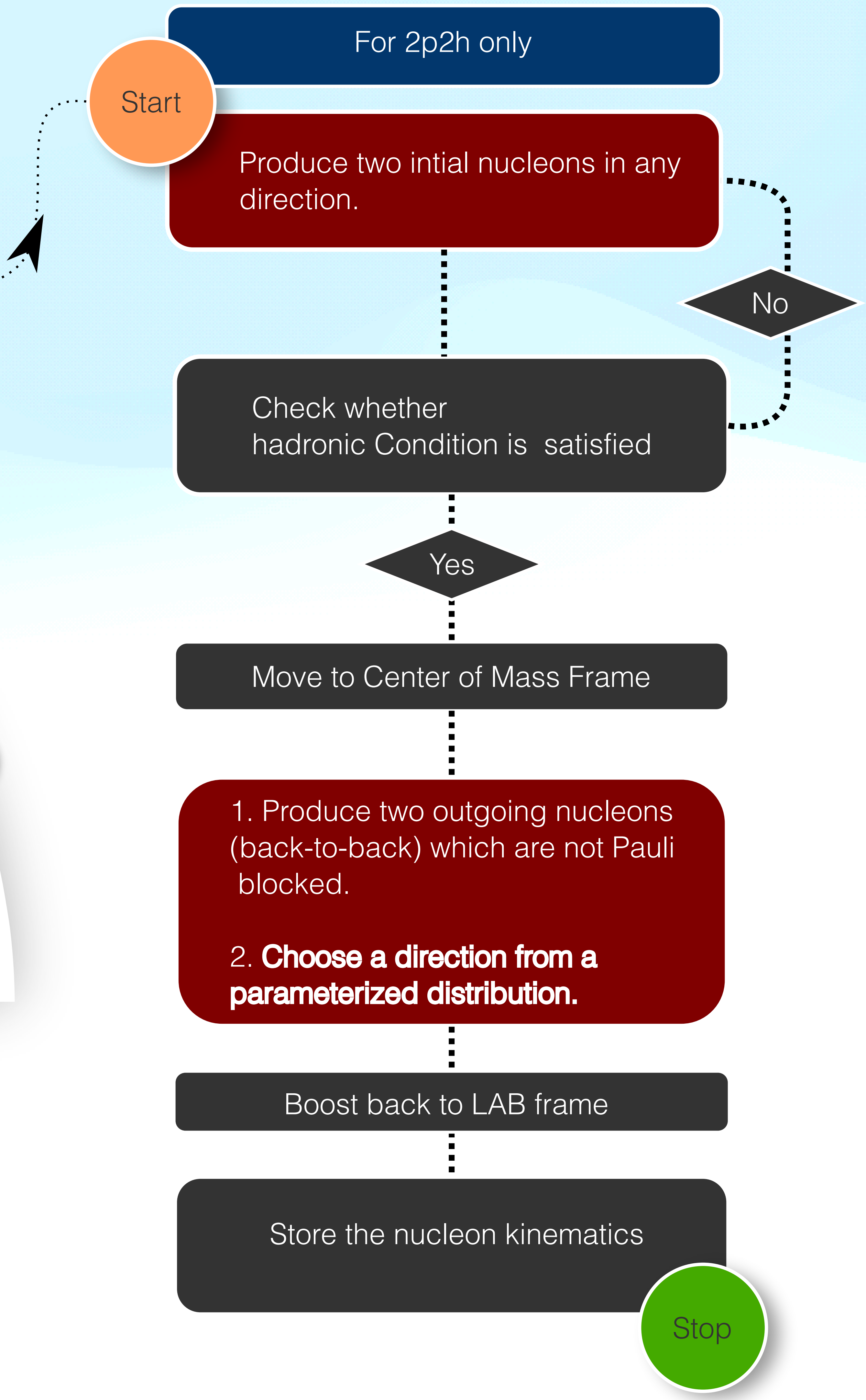
Credit: Hemant Prasad

New MEC hadronic model

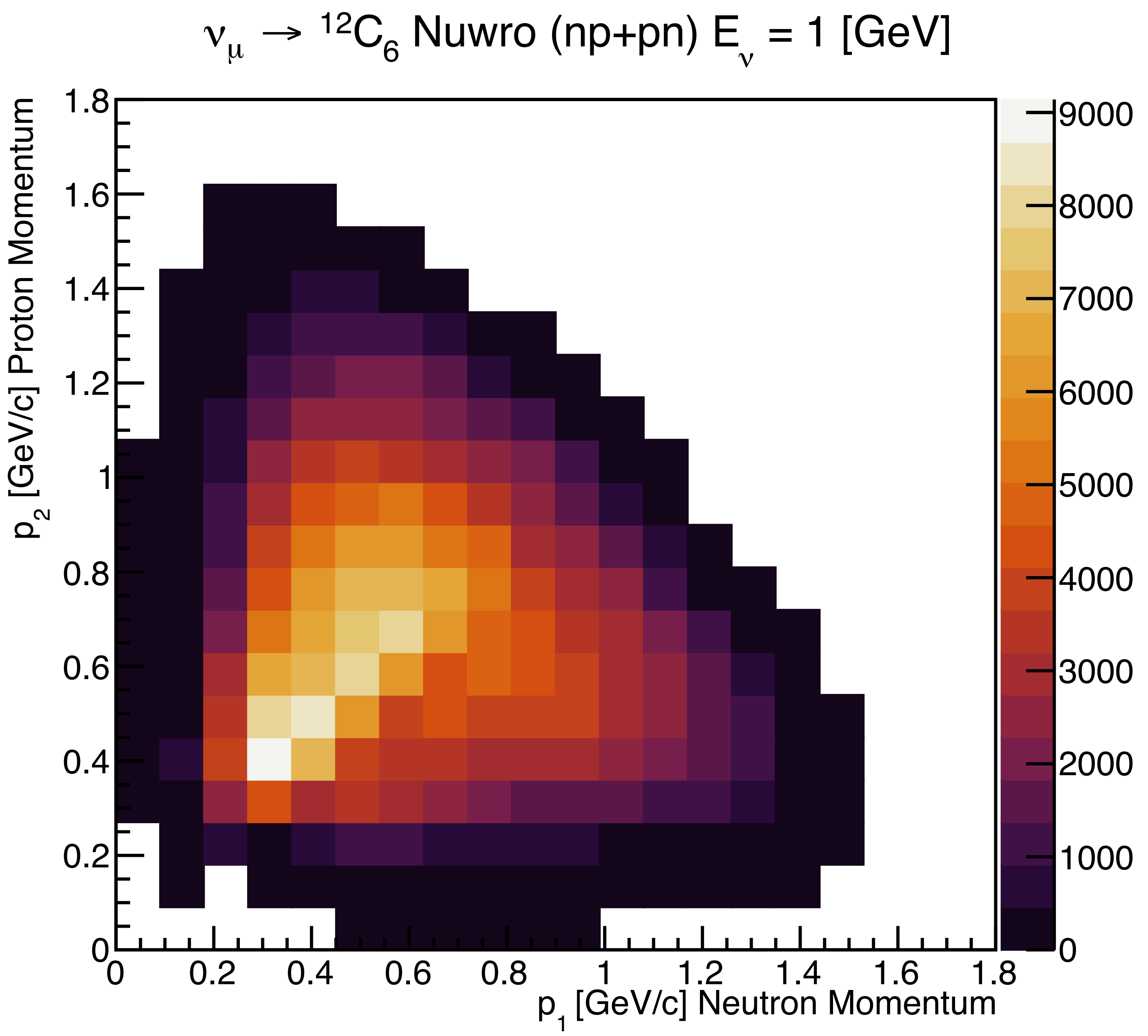
Nuwro v24.xx.?

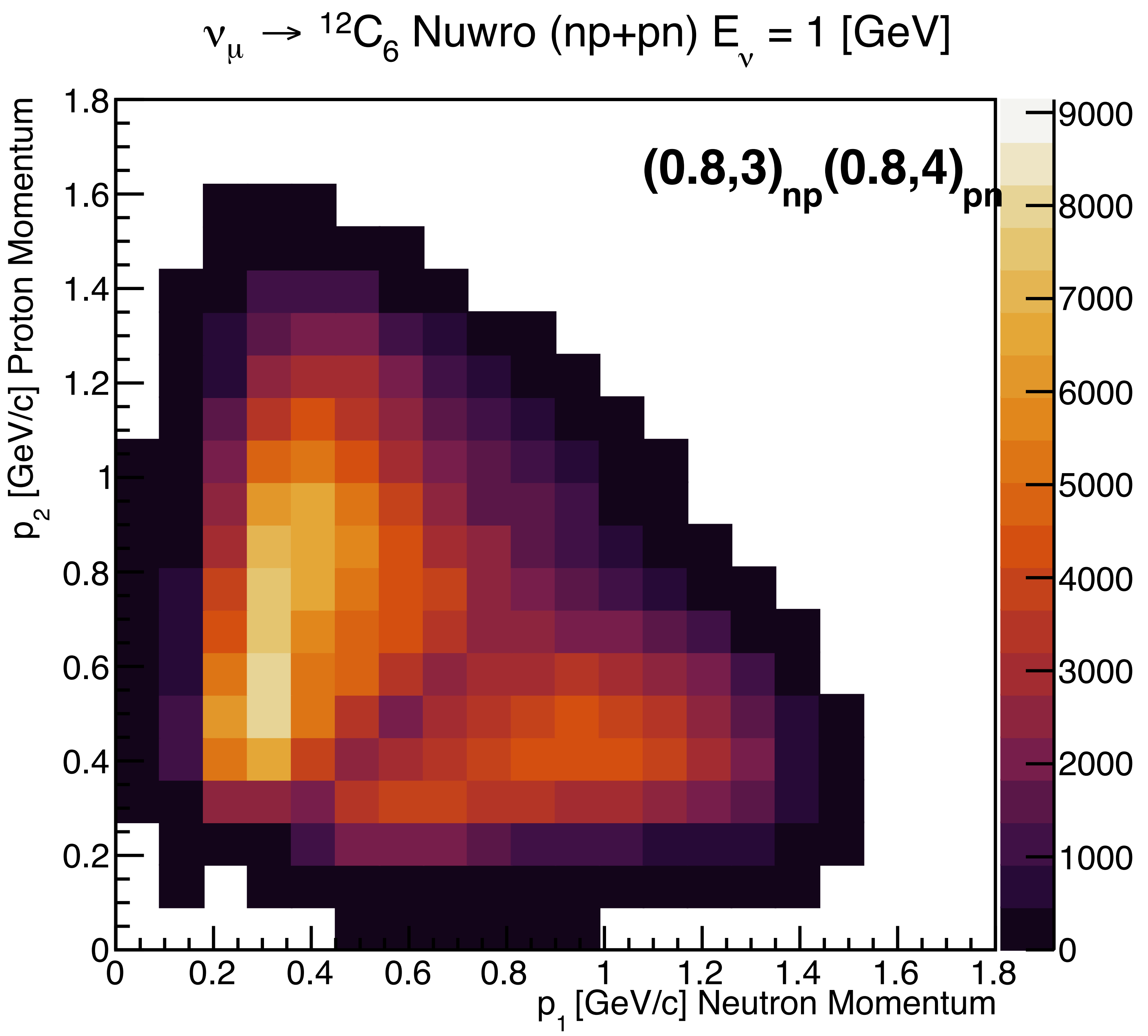
New MEC scheme and Hadronic Model

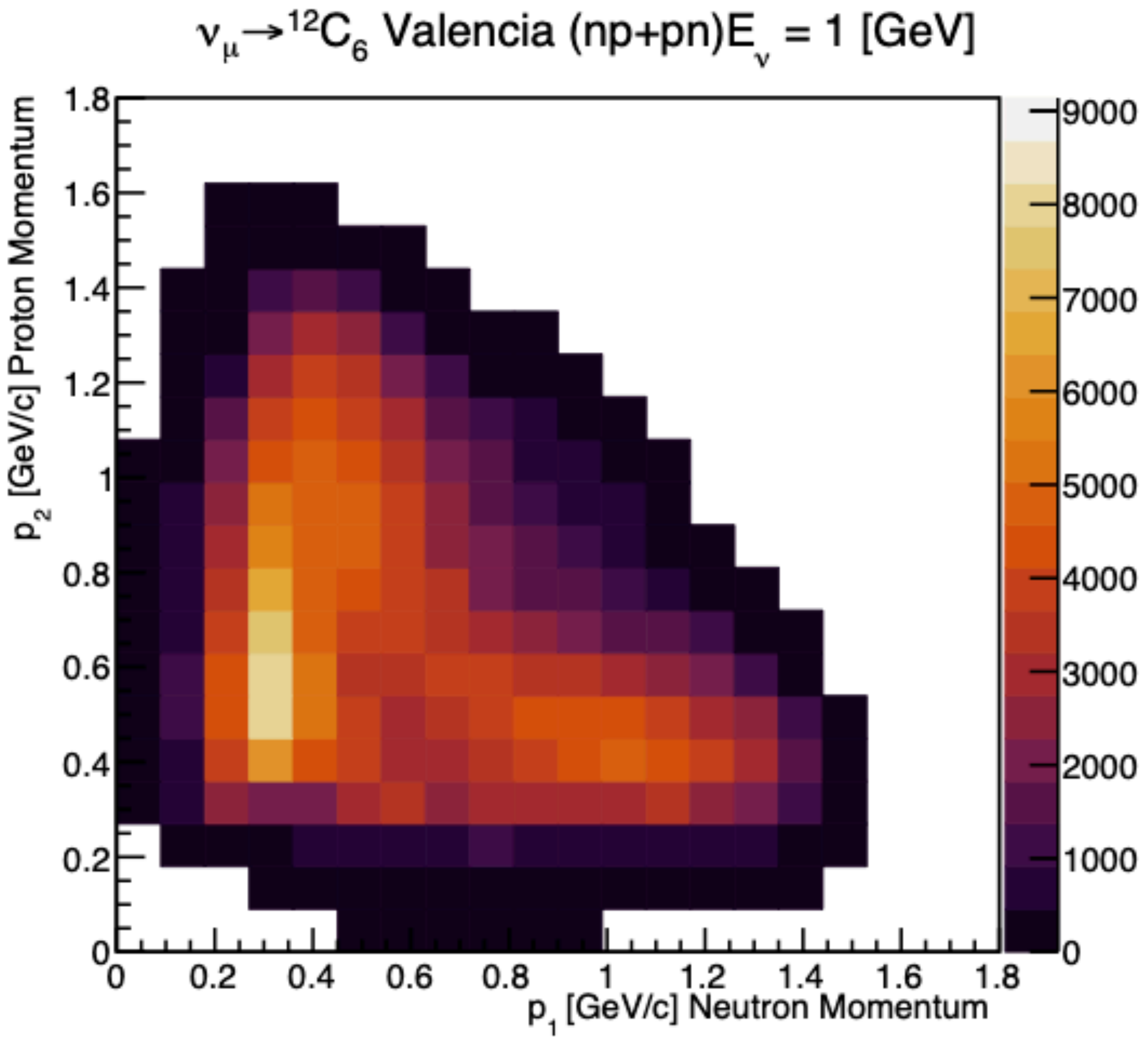




New MEC model - performance

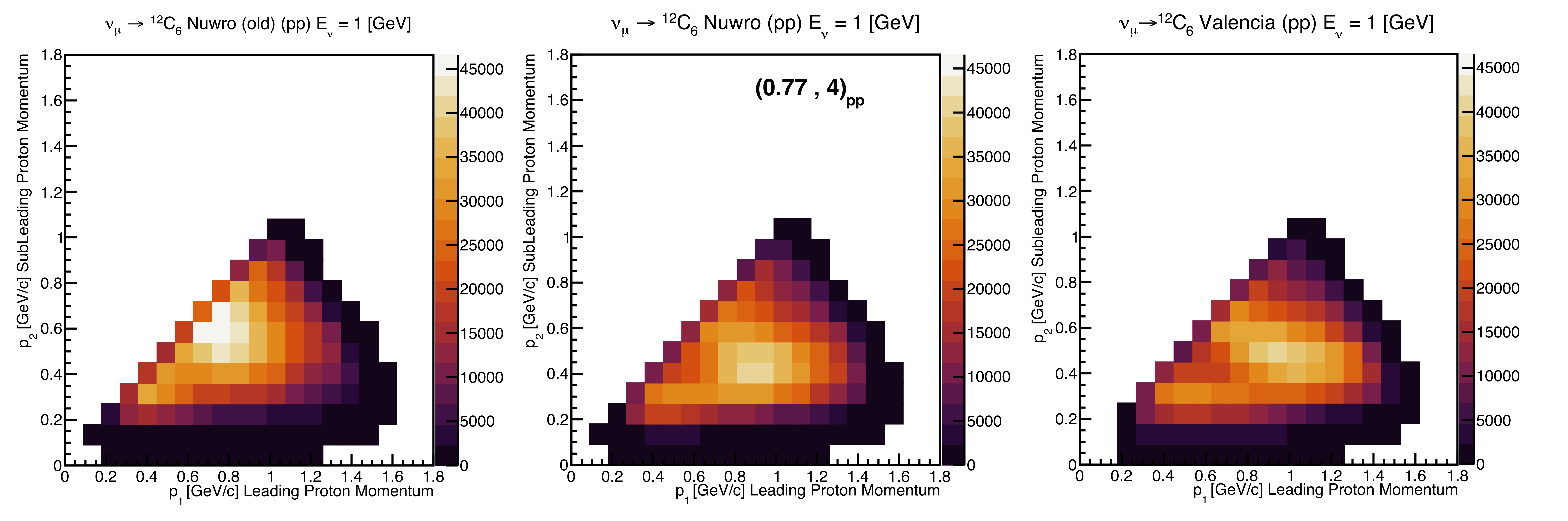






From left to right: old hadronic model, new hadronic model, Valencia model.

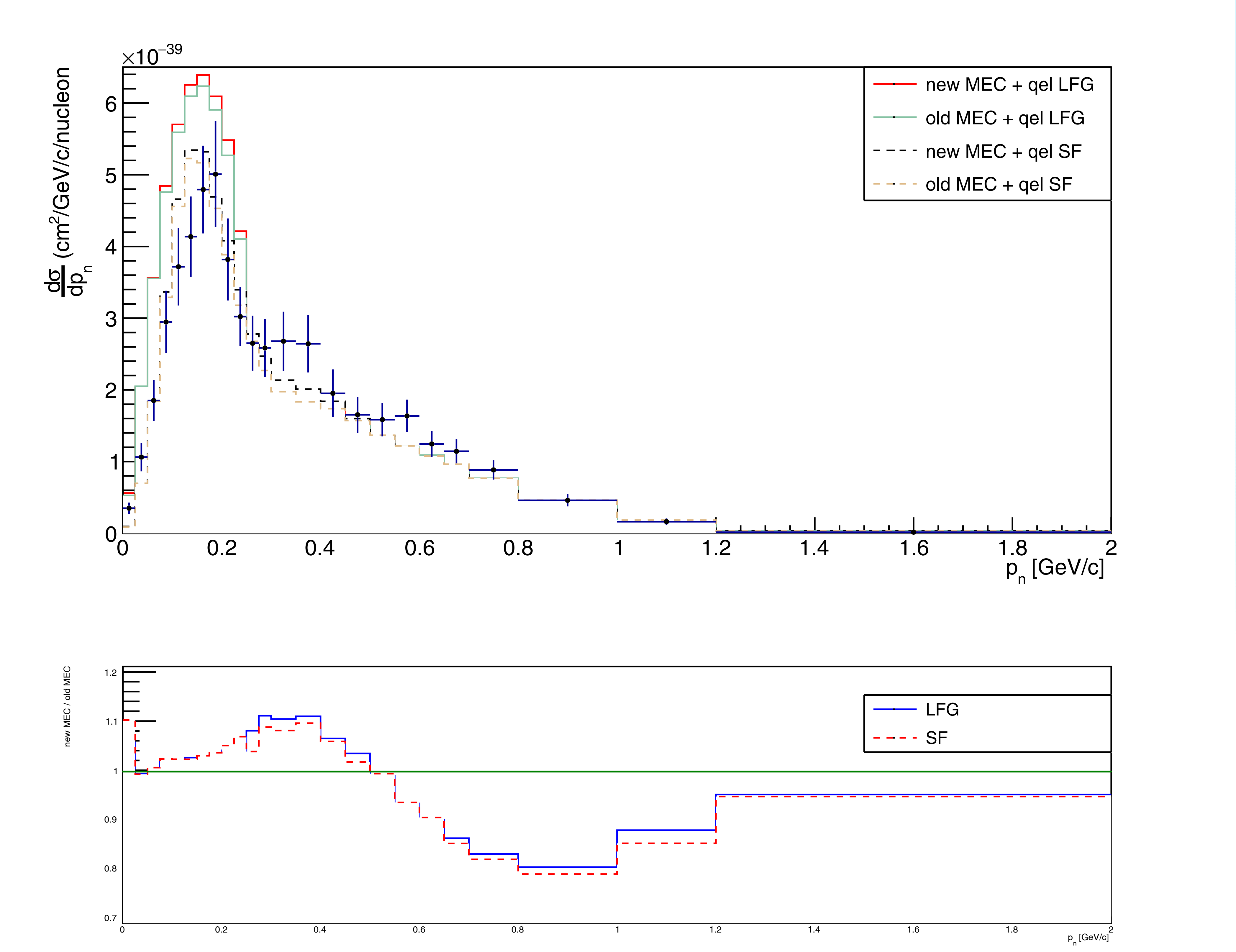
New MEC model - performance

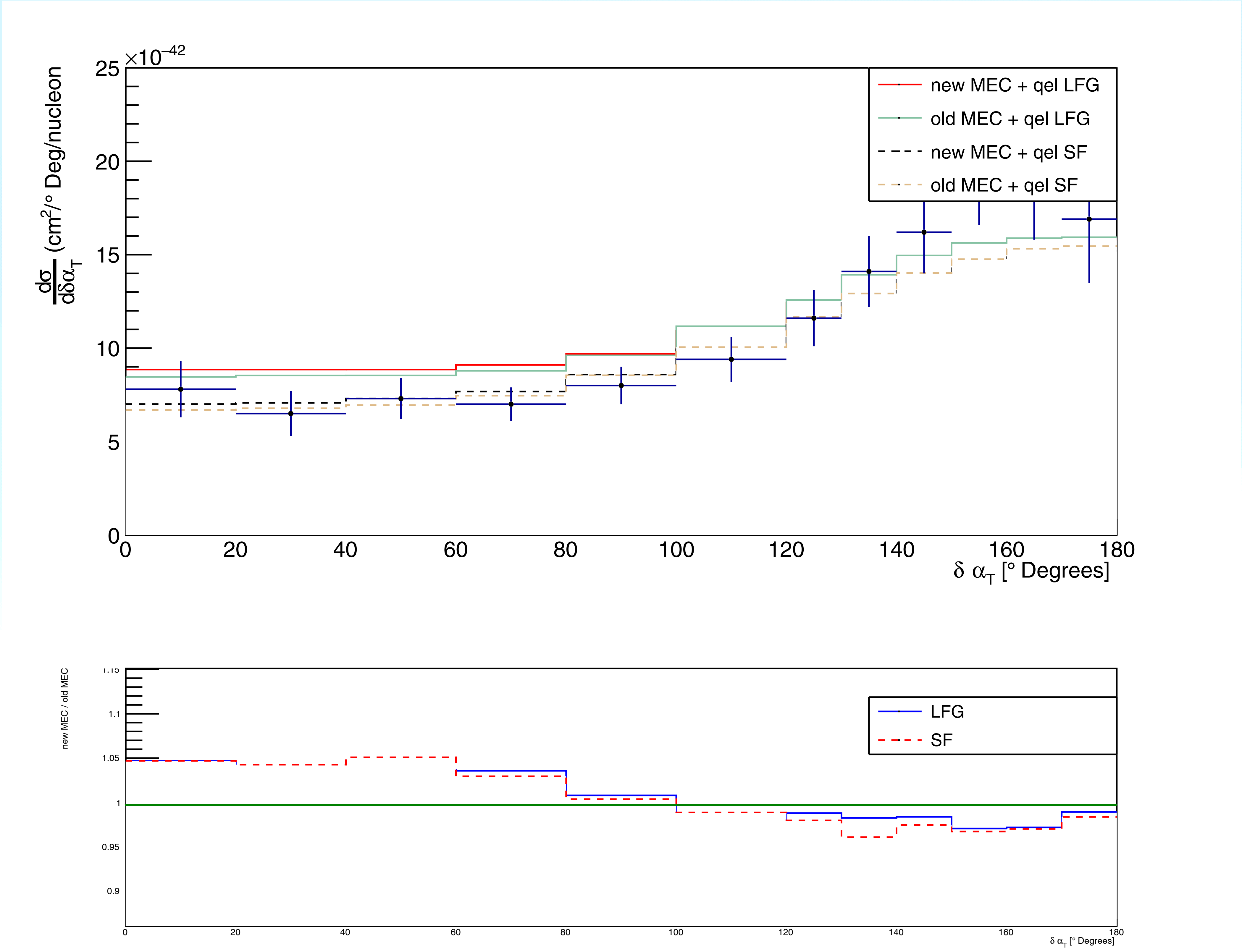


From left to right: old hadronic model, new hadronic model, Valencia model.

NuWro results obtained with a simple but very effective two-parameter fit. If needed can be done much better.

New MEC model performance





Data points: MINERvA Collaboration Phys. Rev. Lett.,121 (2018) 022504

In the lower panels: ratio new vrt old MEC hadronic model.

Outlook

- A new official version of NuWro with significantly improved physics options should be available soon.
- As for eWro there are plans to add single pion production described with the Ghent model.
- Long term plans include employment of ML methods.

Thank you !

Back-up slides

NuWro - basic references

- C. Juszczak, J.A. Nowak, and JTS, *Simulations from a new neutrino event generator*, Nucl. Phys. B Proc.Suppl. 159 (2006) 211.
- T. Golan, C. Juszczak, and JTS, *Final State Interactions Effects in Neutrino-Nucleus Interactions*, Phys. Rev. C86 (2012) 015505.
- PhD thesis of Jarosław Nowak (in Polish), Tomasz Golan and Kajetan Niewczas.
- *NuWro Neutrino Monte Carlo Generator: Physics, Design and Usage* (in preparation).

Event reweighing tools

For some parameters reweight-to reads events from the output root file and re-calculates the cross sections for the new values of parameters, keeping the kinematics and the event topology unchanged

- two options for storing the output of reweighting (a new root file with modified weights, a file containing array with new weights)
- A list of available reweighting includes: C_5^A, M_A and non-resonant background for pion production, M_A for CCQE and NC elastic, z-expansion parameters, overall normalization of individual dynamics.

Nucleon cascade - technicalities (1)

- 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 the top of all that.

Nucleon cascade - technicalities (2)

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.

NuWro: strategies in particular interaction modes

mode	option	cross section formula	remarks
QEL	FG, LFG + RPA	$\frac{d\sigma}{dQ^2}$ $\frac{d^2\sigma}{d\omega dq}$	LLewellyn Smith Eur.Phys.J. C31 (2003) 177
	SF	$\frac{d^2\sigma}{d\omega dq} = \int dE \int d^3p \; P(E,p)\ldots$	targets: ^{12}C, ^{16}O, ^{20}Ca, ^{56}Fe, ^{18}Ar from Omar Benhar and Artur Ankowski; de Forest prescription for off-shell matrix elements; approximate separation $P = P_{MF} + P_{corr}$ and a second nucleon for P_{corr}. FSI effects (A. Ankowski) are included.
	eff SF		Phys.Rev.C 74 (2006) 054316
	$V_{eff}(p,\rho)$		Eur.Phys.J. C39 (2005) 195 $V_{eff}(p, k_F(\rho)) = -\frac{(ak_F)^2(k_F+b)}{f^4+d^3k_F+h^2\frac{p^2}{k_F^2}+p^4}$ from Brieva – Della Fiore

NuWro: strategies in particular interaction modes

mode	option	cross section formula	remarks
MEC	Valencia (Nieves et al)	$\frac{d^2\sigma}{d\omega dq}$ (lepton only)	only CC; hadronic information neglected
	SuSAv2	$\frac{d^2\sigma}{d\omega dq}$ (lepton only)	only CC; wider region in (ω, q),
	TE (Bodek et al)	$\frac{d^2\sigma}{d\omega dq}$ (lepton only)	available for both CC and NC reactions
	Marteau	$\frac{d^2\sigma}{d\omega dq}$ (lepton only)	only CC; a small fraction of 3p3h
			a universal hadronic model PRC86 (2012) 015504 for all the options; targets: ^{12}C, ^{16}O, ^{40}Ca; Rik Gran's like procedures to extrapolate to other targets based on numbers of np and nn/pp pairs (combinatorics)
	mescaling		fit to T2K and MINERvA CC0π data, Phys.Rev.C 102 (2020) 1, 015502.
	MEC_cm_direction		departure from phase space for outgoing nucleons.

NuWro: strategies in particular interaction modes

mode	option	cross section formula	remarks
DIS	Bodek-Yang	$\frac{d^2\sigma}{d\omega d\mathbf{q}}$ (lepton only)	PYTHIA used to produce final states; can be extrapolated down to $W = 1.1$ GeV no nuclear effects beyond Fermi motion.

mode	option	cross section formula	remarks
RES		$\frac{d^2\sigma}{dWdQ^2}$ (lepton only)	incoherent sum of Δ excitation and BKGR BKGR modeled as a fraction of DIS contribution; for SPP Δ/DIS transition region: $W \in (1.3, 1.6)$ GeV; 2π production in $W \in (1.3, 1.6)$ GeV taken from DIS; Δ FFs from a fit to ANL/BNL data (PRD80 (2009) 093001) π angular distribution from ANL/BNL papers; Δ self-energy (Oset et al) - approximation based on PRC87 (2013) 065503.
	bkgrscaling		a change of amount of nonresonant backgroung