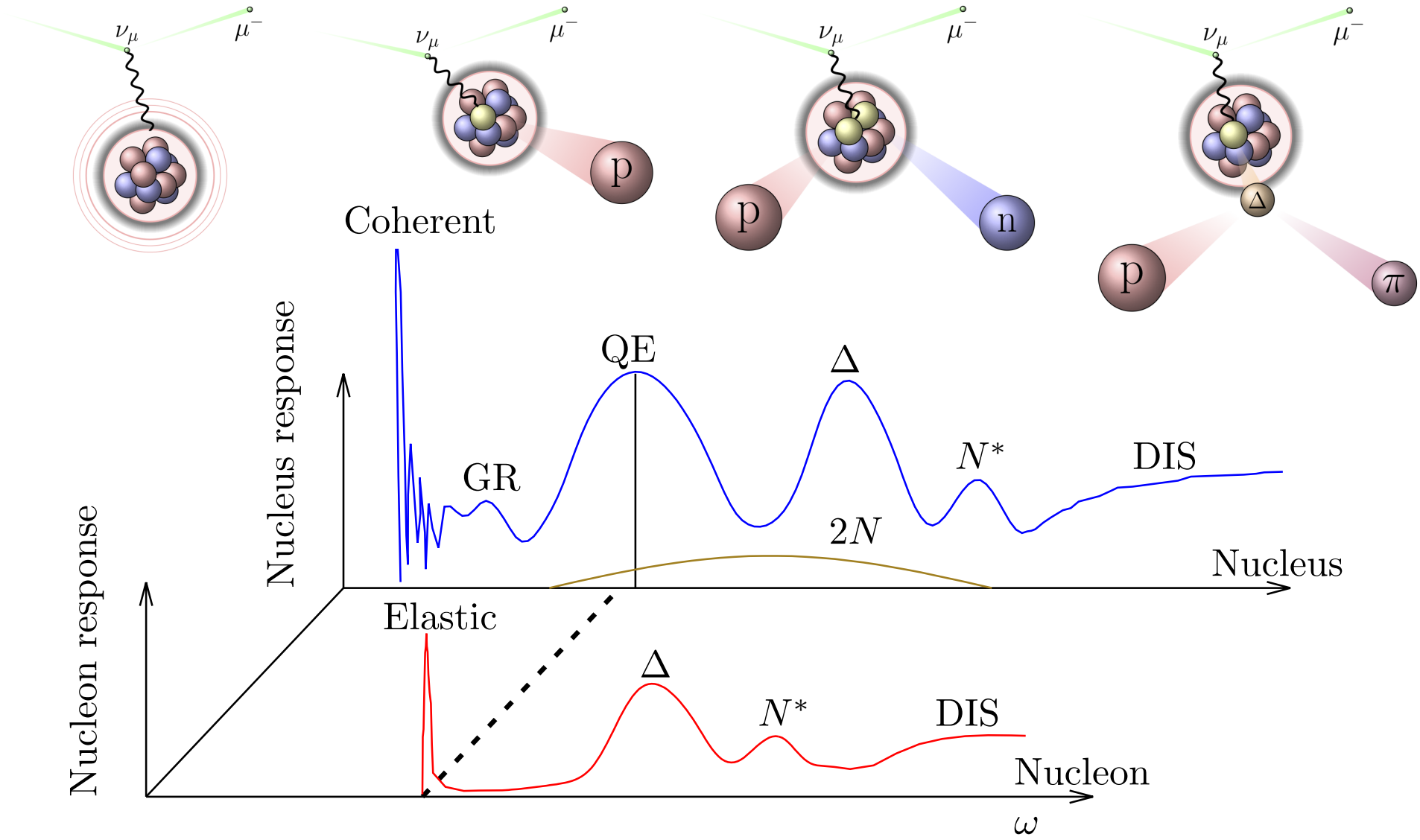
2p2h implementation in NuWro

Kajetan Niewczas

Uniwersytet Wrocławski

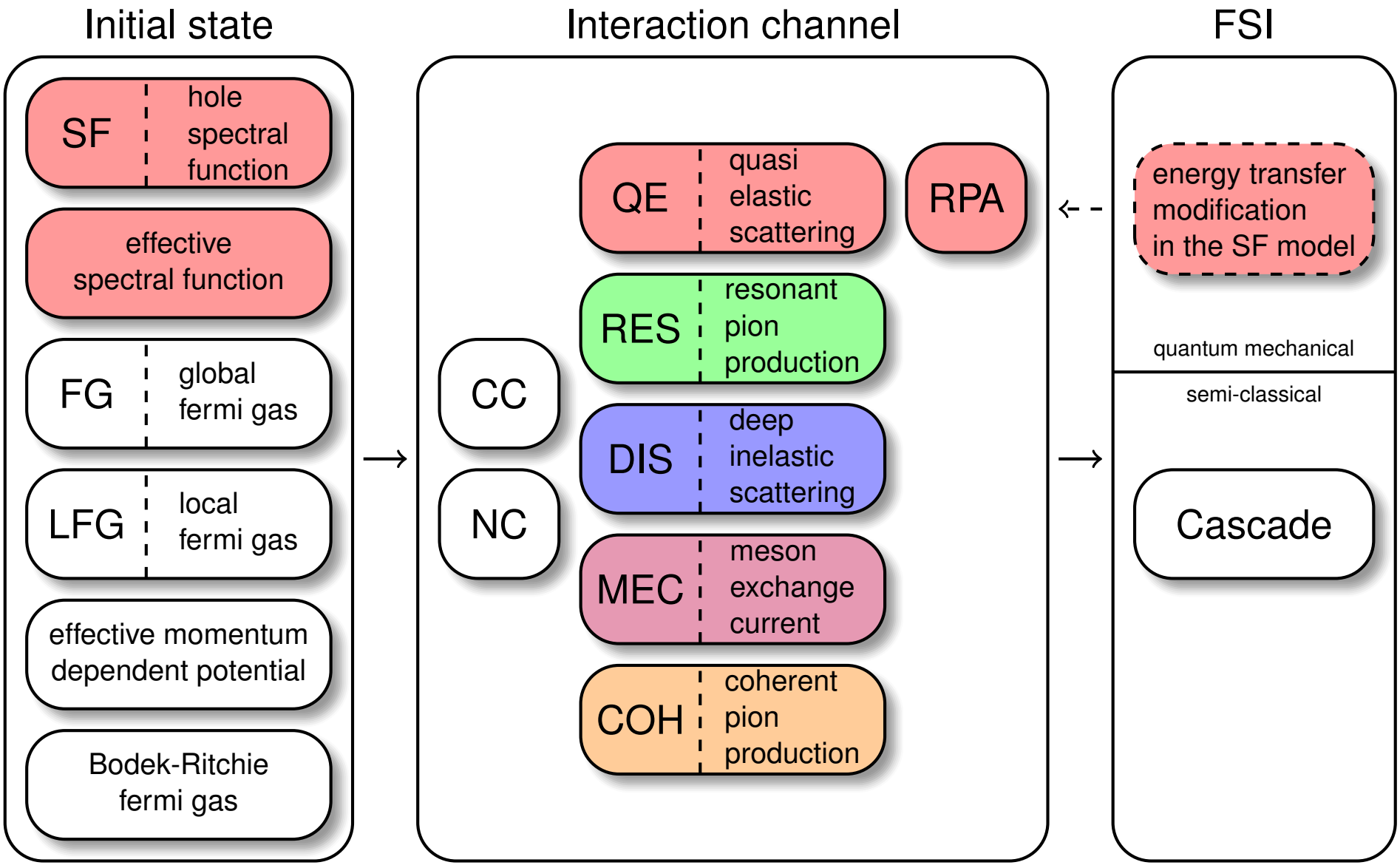
UNIVERSITEIT GENT

Nuclear response

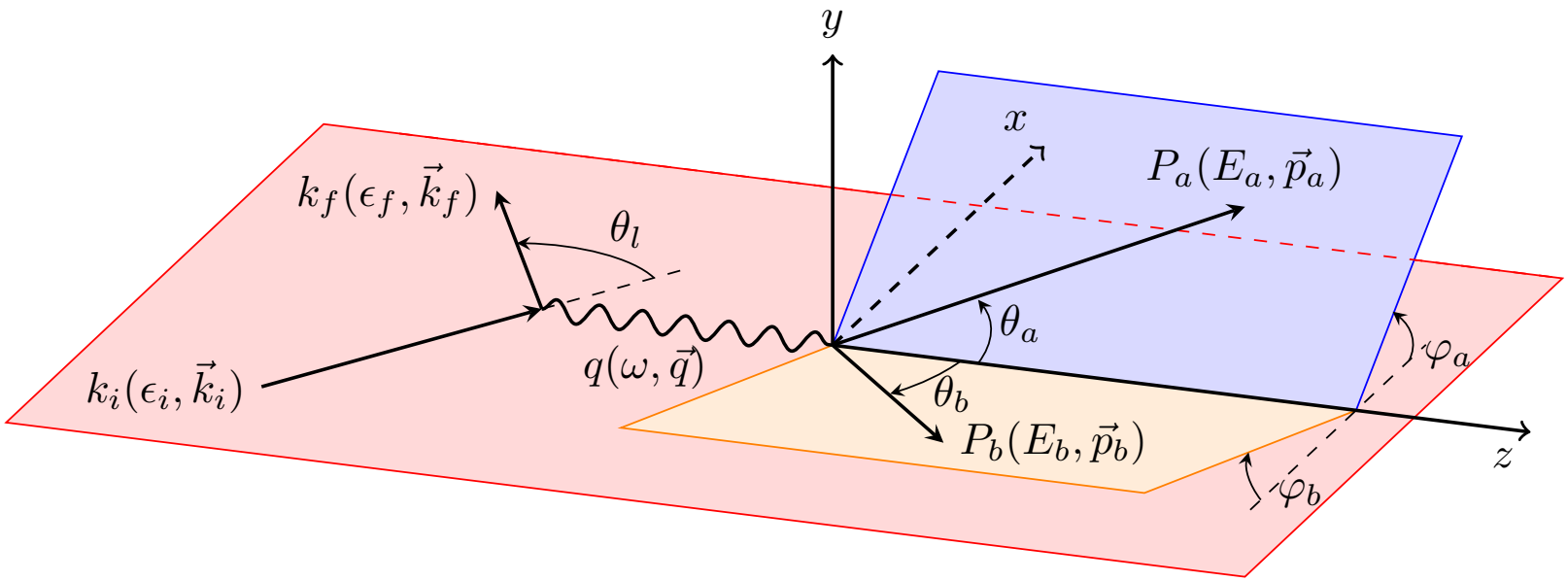


T. Van Cuyck

NuWro blueprint



2p2h cross section



T. Van Cuyck

Exclusive

$$\frac{\mathrm{d}^8\sigma}{\mathrm{d}\epsilon_f \mathrm{d}\Omega_f \mathrm{d}T_a \mathrm{d}\Omega_a \mathrm{d}\Omega_b} \rightarrow$$

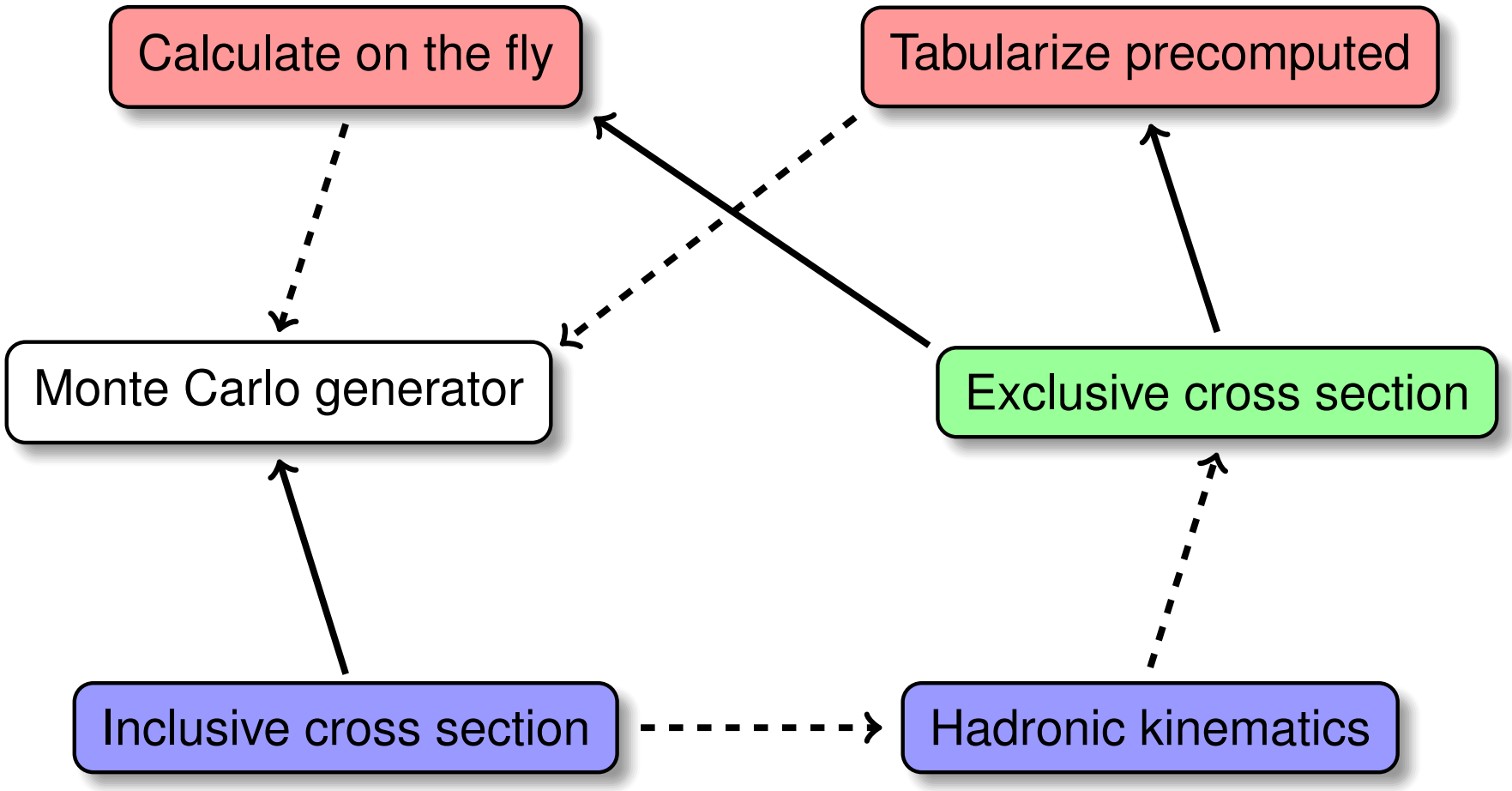
Semi-inclusive

$$\frac{\mathrm{d}^6\sigma}{\mathrm{d}\epsilon_f \mathrm{d}\Omega_f \mathrm{d}T_a \mathrm{d}\Omega_a} \rightarrow$$

Inclusive

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}\epsilon_f \mathrm{d}\Omega_f}$$

Strategy of implementation



MEC: Valencia model

Implemented in terms of 5 hadronic **structure functions** $W_i(\omega, |\vec{q}|)$:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\epsilon_f \mathrm{d}\Omega_f} = \frac{2G_F^2 |\vec{k}_f| \epsilon_f}{\pi} \left\{ 2W_1 \sin^2\frac{\theta_l}{2} + W_2 \cos^2\frac{\theta_l}{2} \mp W_3(\epsilon_i + \epsilon_f)\sin^2\frac{\theta_l}{2} \right.$$
$$+ \frac{m_f^2}{\epsilon_f(\epsilon_f + |\vec{k}_f|)} \left[W_1 \cos\theta_l - \frac{W_2}{2}\cos\theta_l \pm \frac{W_3}{2}\left(\epsilon_f(1-\cos\theta_l) + |\vec{k}_f| - \epsilon_i\right) \right.$$
$$\left. \left. + \frac{W_4}{2}\left(m_f^2\cos\theta_l + 2\epsilon_f(\epsilon_f + |\vec{k}_f|)\sin^2\theta_l\right) - \frac{W_5}{2}(\epsilon_f + |\vec{k}_f|) \right] \right\}$$

Using 5 hadronic **tensor elements**:

$$W_1 = \frac{1}{2}W^{11};\ W_2 = \frac{1}{2}\left(W^{00} + W^{11} + \frac{\omega}{|\vec{q}|^2}(W^{33} - W^{11}) - 2\frac{\omega}{|\vec{q}|}\Re W^{03}\right)$$
$$W_3 = -i\frac{1}{|\vec{q}|}W^{12};\ W_4 = \frac{1}{2|\vec{q}|^2}(W^{33} - W^{11});\ W_5 = \frac{1}{|\vec{q}|}\left(\Re W^{03} - \frac{\omega}{|\vec{q}|}(W^{33} - W^{11})\right)$$

MEC: Valencia model

- Thanks to the courtesy of **Juan Nieves** and **Manuel Vicente Vacas**: **code** producing hadronic **tensor elements** on a **grid** in ω and $|\vec{q}|$

- **Grid size**: 10 MeV steps up to 1.2 GeV in $|\vec{q}|$ ($|\vec{q}_{\mathrm{cut}}|$), same spacing in ω with $\omega \leq |\vec{q}|$ (**triangular physical region**)

- Using $|\vec{q}_{\mathrm{cut}}|$, the original model **extended** up to $E_\nu \simeq 10$ GeV
  R. Gran at al., Phys. Rev. D88 (2013) 113007

- **CC** (anti)neutrinos for two targets: **carbon** and **oxygen** (cross section per nucleon for $Z \leq 6$: carbon grid; for $Z > 6$: oxygen grid)

- For **asymmetric** targets ($A \geq 40$): additional **combinatoric factors**
  R. Gran at al., Phys. Rev. D88 (2013) 113007

J. Nieves, I. Ruiz Simo, and M. Vicente Vacas, Phys. Rev. C83 (2011) 045501

MEC: Transverse Enhancement model

- An **effective approach** based on the analysis of **electron** scattering
- *np-nh* contribution to the **QEL** cross section is introduced by the following **modification** of the **vector magnetic form factor**:

$$G_M^{p/n} \rightarrow \tilde{G}_M^{p/n} = \sqrt{1 + AQ^2 exp(-Q^2/B)}\, G_M^{p/n}$$

where $A = 6\ \mathrm{GeV}^{-2}$, $B = 0.34\ \mathrm{GeV}^2$ and $M_A^{np-nh} = 1013\ \mathrm{MeV}$

- *np-nh* **cross section** is obtained by

$$\left(\frac{\mathrm{d}\sigma^{\nu/\bar{\nu}}}{\mathrm{d}Q^2}\right)_{CC}^{np-nh} \equiv \frac{\mathrm{d}\sigma^{\mathrm{QEL}}}{\mathrm{d}Q^2}(\tilde{G}_M^{p/n}) - \frac{\mathrm{d}\sigma^{\mathrm{QEL}}}{\mathrm{d}Q^2}(G_M^{p/n})$$

$$\left(\frac{\mathrm{d}\sigma^{\nu/\bar{\nu}}}{\mathrm{d}Q^2}\right)_{NC}^{np-nh} \equiv \frac{1}{2}\left[\left(\frac{\mathrm{d}\sigma^{\mathrm{EL}}}{\mathrm{d}Q^2}(\tilde{G}_M^{p}) - \frac{\mathrm{d}\sigma^{\mathrm{EL}}}{\mathrm{d}Q^2}(G_M^{p})\right) + \left(\frac{\mathrm{d}\sigma^{\mathrm{EL}}}{\mathrm{d}Q^2}(\tilde{G}_M^{n}) - \frac{\mathrm{d}\sigma^{\mathrm{EL}}}{\mathrm{d}Q^2}(G_M^{n})\right)\right]$$

- **Lepton kinematics** based on **QEL**, assuming target **nucleon at rest**

A. Bodek, H.S. Budd, and M.E. Christy, Eur. Phys. J. C71 (2011) 1726

MEC: Marteau-like model

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\epsilon_f \mathrm{d}\Omega_f} = \frac{G_F^2 \cos\theta_c |\vec{k}_f|^2}{\pi} \cos^2\frac{\theta_l}{2} \Bigg[G_E^2 \frac{q^4}{|\vec{q}|^4} R_\tau^{NN}$$
$$+ G_A^2 \frac{(M_\Delta - M_N)^2}{2|\vec{q}|^2} R_{\sigma\tau(L)}^{N\Delta} + G_A^2 \frac{(M_\Delta - M_N)^2}{|\vec{q}|^2} R_{\sigma\tau(L)}^{\Delta\Delta}$$
$$+ (G_M^2 \frac{\omega^2}{|\vec{q}|^2} + G_A^2)(-\frac{q^2}{|\vec{q}|^2} + 2\tan^2\frac{\theta_l}{2})(R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta})$$
$$\pm G_A G_M \frac{|\vec{k}_i| + |\vec{k}_f|}{M_N} \tan^2\frac{\theta_l}{2} (R_{\sigma\tau(T)}^{NN} + 2R_{\sigma\tau(T)}^{N\Delta} + R_{\sigma\tau(T)}^{\Delta\Delta}) \Bigg]$$

Responses due to *nucleon-hole* or *delta-hole* excitations:

$$R_\alpha^{PP'} = \sum_n \langle n| \sum_{j=1}^{A} O_\alpha^P(j) e^{i\vec{q}\cdot\vec{x}_j} |0\rangle \langle n| \sum_{k=1}^{A} O_\alpha^{P'}(k) e^{i\vec{q}\cdot\vec{x}_k} |0\rangle^* \delta(\omega - E_n + E_0)$$

where

$$O_{\tau,\sigma\tau(L),\sigma\tau(T)}^N(j) = \tau_j^\pm,\ (\sigma_j\cdot\hat{q})\tau_j^\pm,\ ((\sigma_j\times\hat{q})\times\hat{q})\tau_j^\pm$$
$$O_{\sigma\tau(L),\sigma\tau(T)}^\Delta(j) = (\mathbf{S}_j\cdot\hat{q})T_j^\pm,\ ((\mathbf{S}_j\times\hat{q})\times\hat{q})T_j^\pm$$

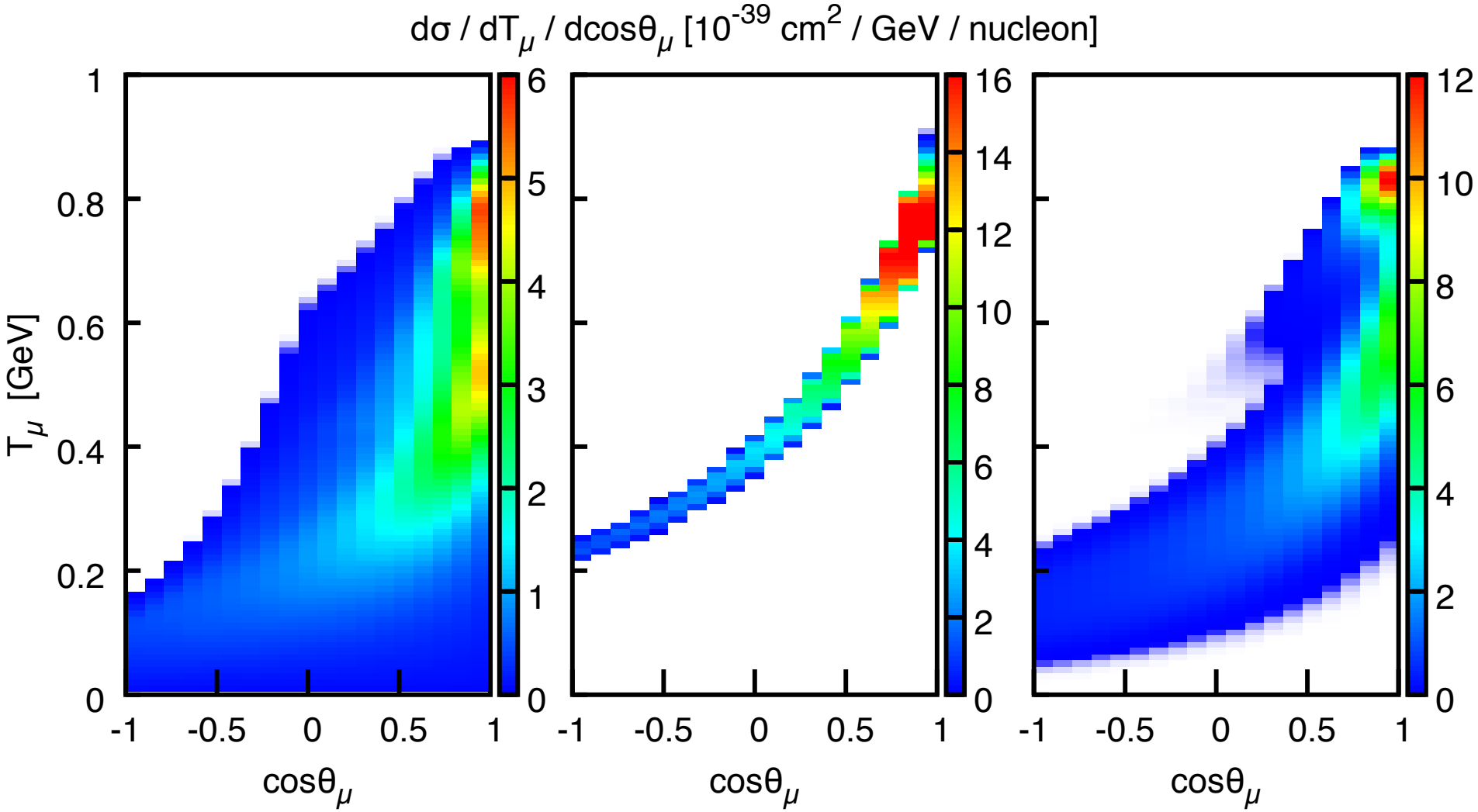
J. Marteau, Eur. Jour. Phys. A5 (1999) 183

MEC: Marteau-like model

- **Custom implementation** with **tabularized responses** up to $\omega < 3\ \mathrm{GeV}$, $|\vec{q}| < 3.6\ \mathrm{GeV}$, then actually **solving integrals**
- The **relativistic kinematics** of nucleons is used
- **Constant** value of **Fermi momentum** is kept
- **Local density effects** are included in the **approximate** way

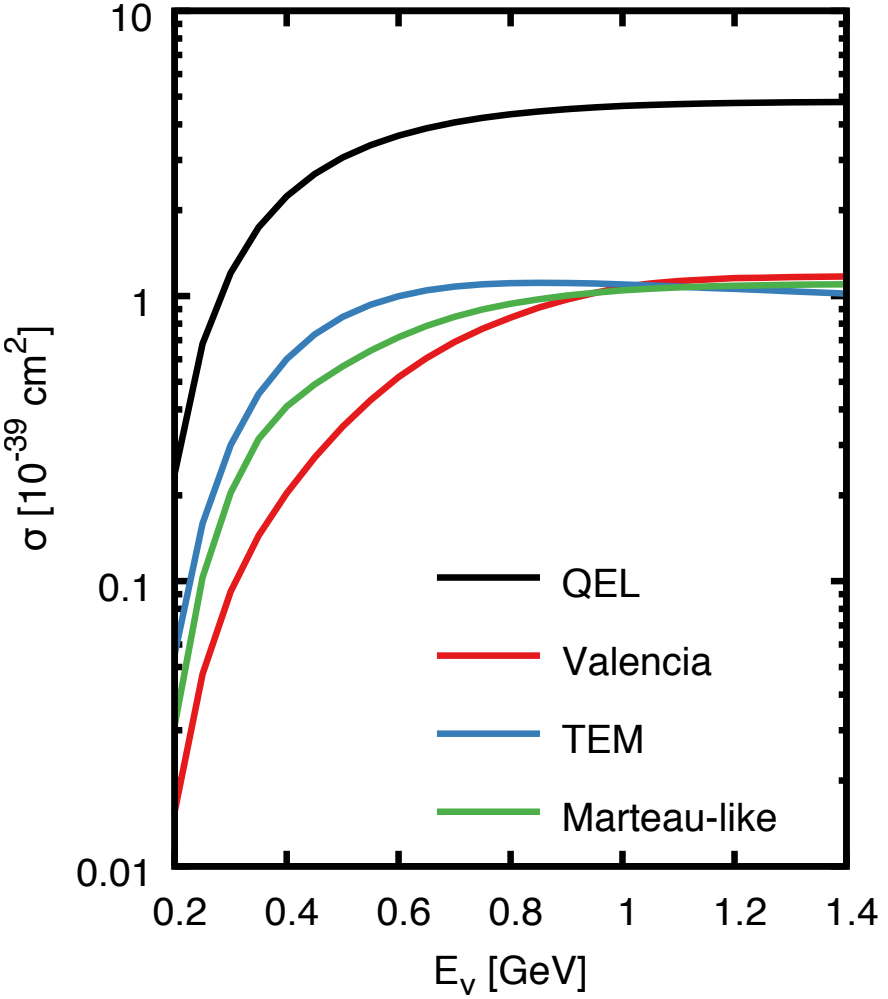
J. Sobczyk, arXiv:nucl-th/0307047 (2003)

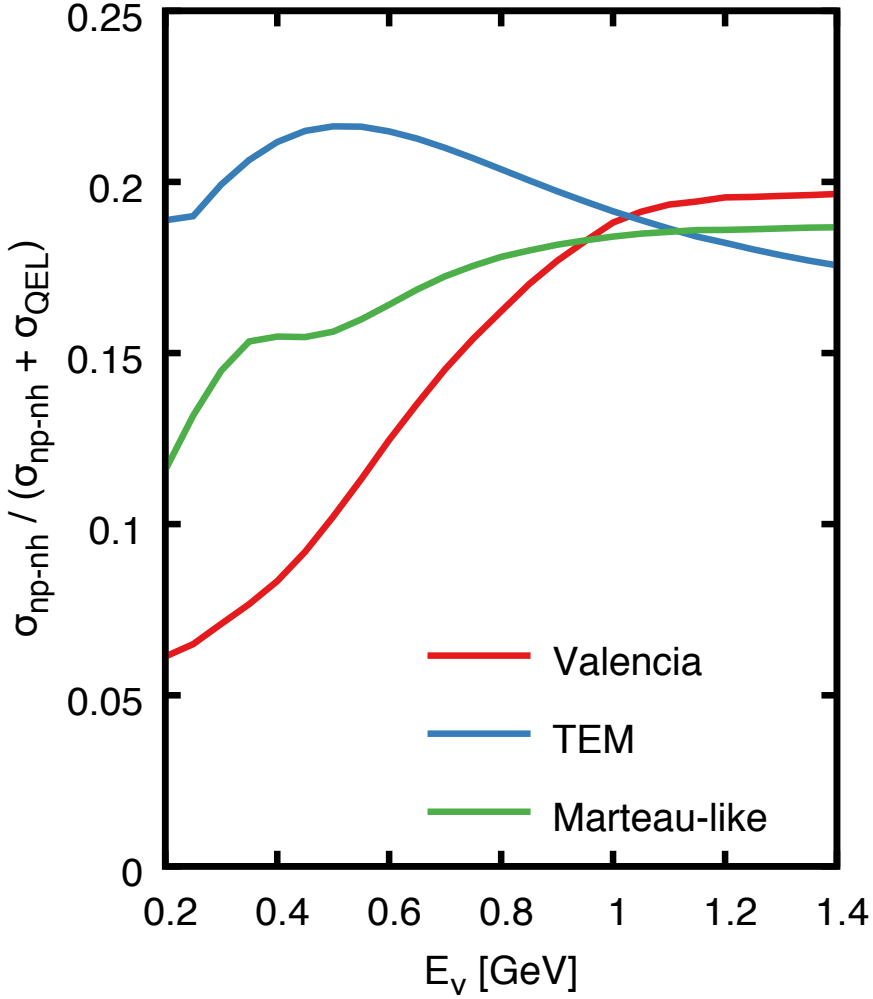
MEC: Inclusive cross section



Scattering of 1 GeV neutrinos on carbon target

MEC: Total cross sections





Scattering of 1 GeV neutrinos on carbon target

A little more exclusive...

- We need to guess the **isospin configuration** of **target nucleons**

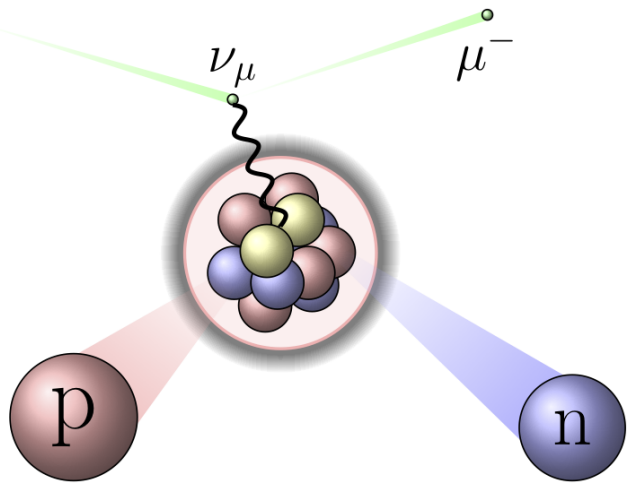
$$\nu_l + p + n \to l^- + p + p \qquad \bar{\nu}_l + p + n \to l^+ + n + n$$

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

$$\nu_l + 2N \to \nu_l + 2N \qquad \bar{\nu}_l + 2N \to \bar{\nu}_l + 2N$$

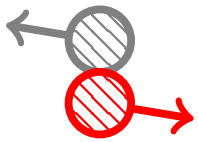
- Fraction of **mixed isospin** pairs for CC is a **free parameter**: p_{CC}
- For NC it is obtained by: $p_{NC} = (2/p_{CC} - 1)^{-1}$

	p_{CC}
Nieves at al.	$\simeq 0.70$
GFMC (SRC)	$\simeq 0.95$
our guess	≈ 0.85



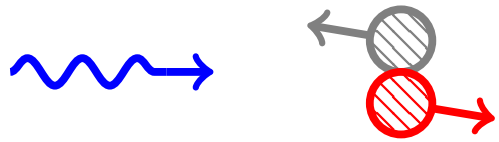
Hadronic phase-space model

1.



Choose p_1, p_2 back-to-back

2.

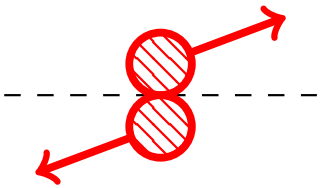


$(p_1 + p_2 + q)^2 > 4M_N^2$

3.

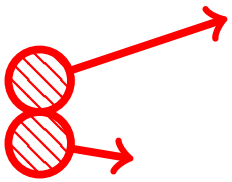
Boost to CMS frame

4.



Decay isotropically

5.



Boost back to LAB frame

6.

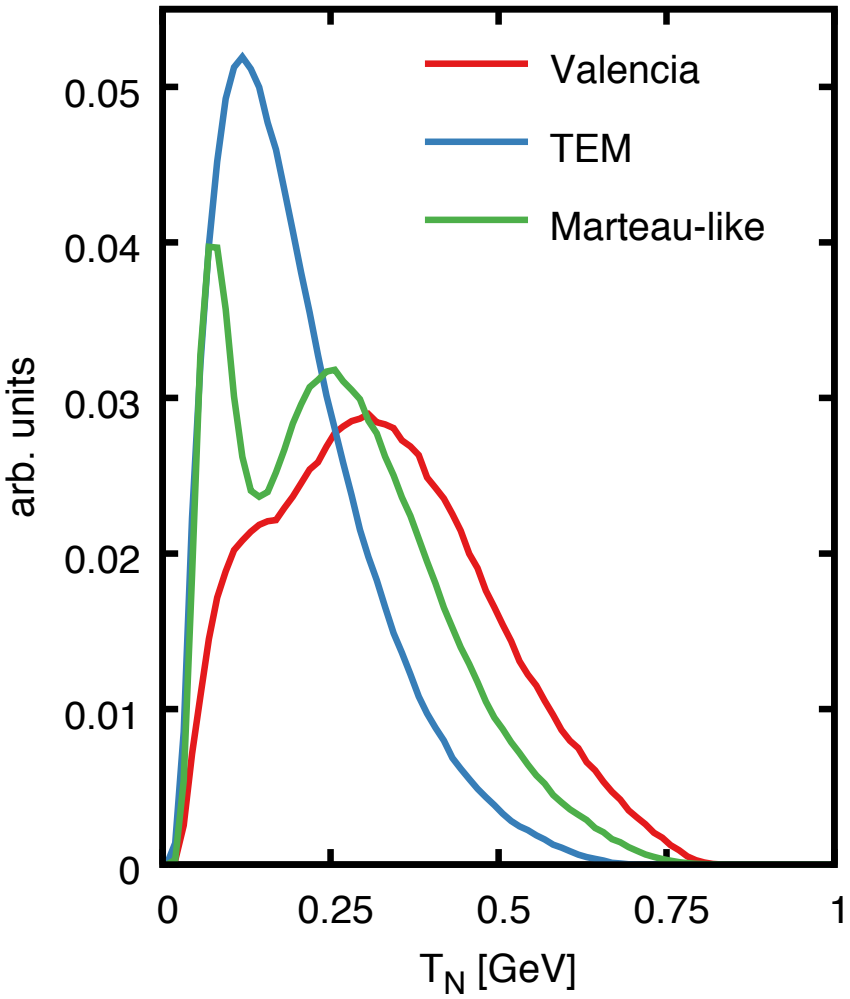
$$\Theta(k_F - |\vec{p}_1'|)\Theta(k_F - |\vec{p}_2'|)$$

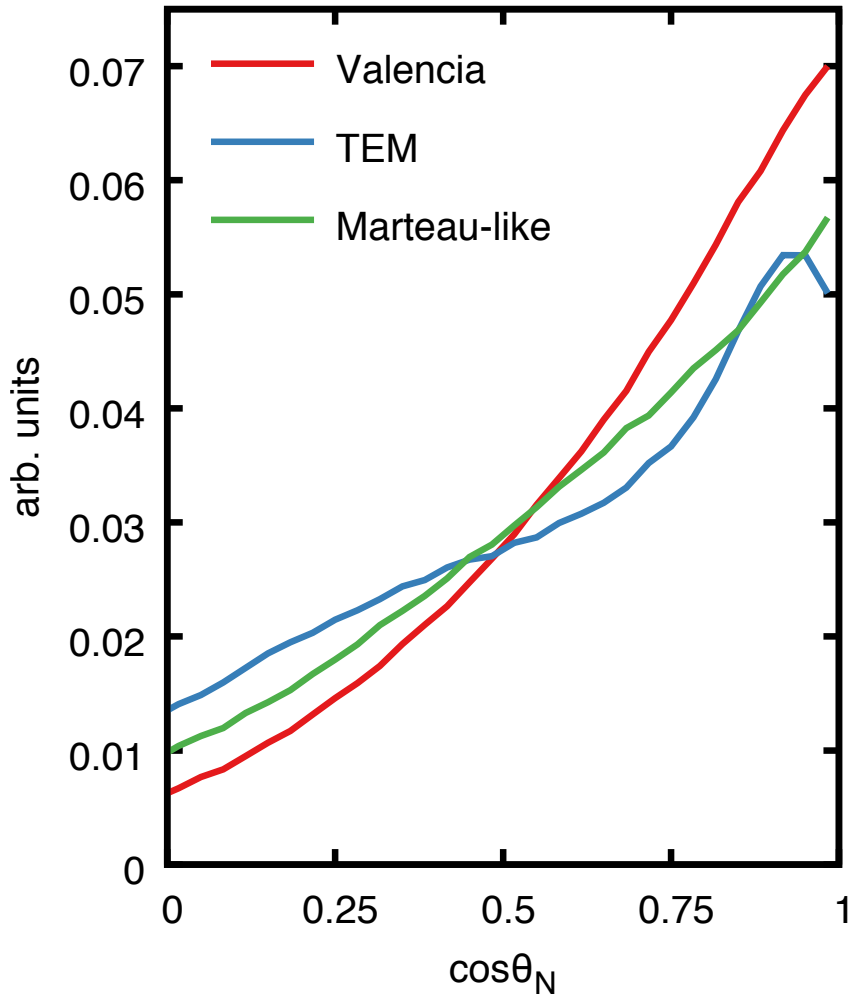
Check Pauli blocking

J.T. Sobczyk, Phys. Rev. C86 (2012) 015504

Hadronic phase-space model

Distributions for the **most energetic nucleon** before FSI





Scattering of 1 GeV neutrinos on carbon target

Enhancing initial hadronic kinematics

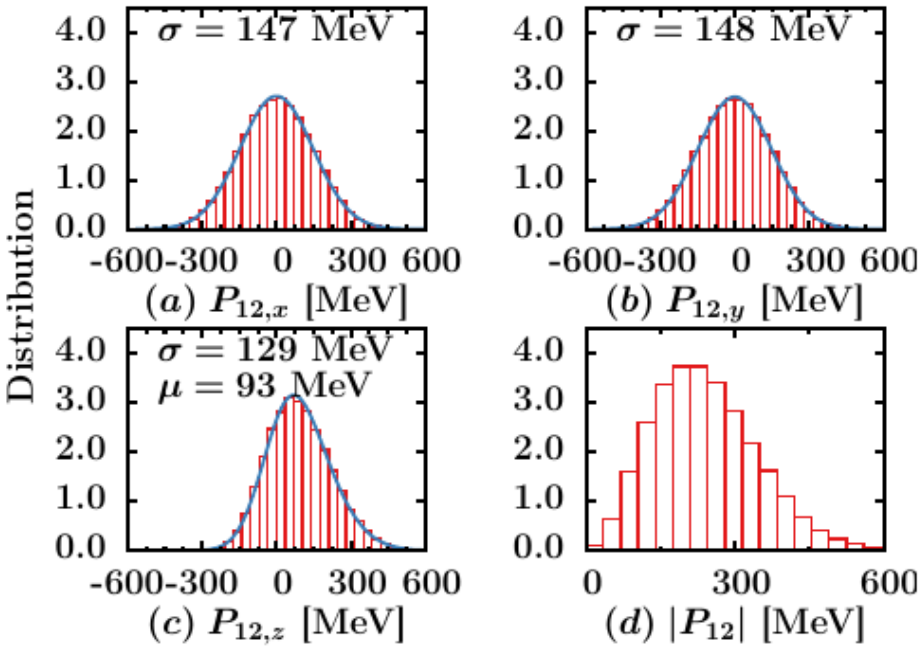
- Add nucleon pair **CM momentum**

  `mec_central_motion` parameterizes the gaussian distribution

- Add **smearing** of the **back-to-back** configuration (when no CM motion)

  `mec_back_to_back_smearing` parameterizes the gaussian distribution

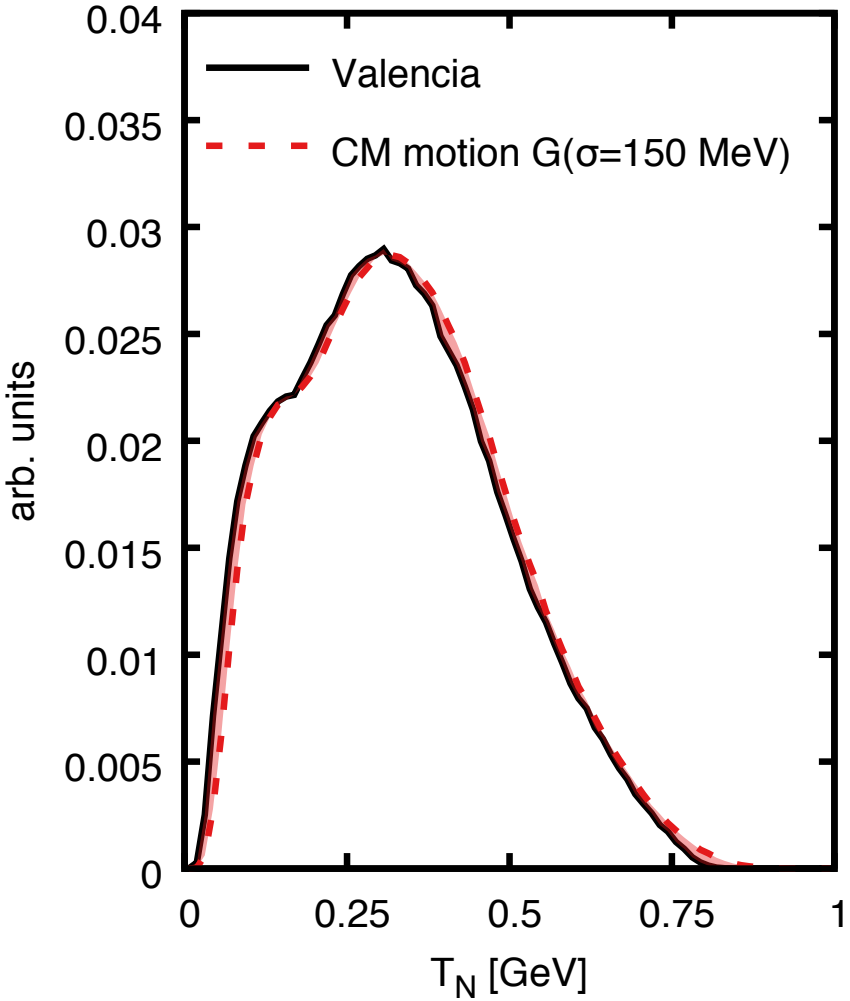
Nucleon pair CM distributions

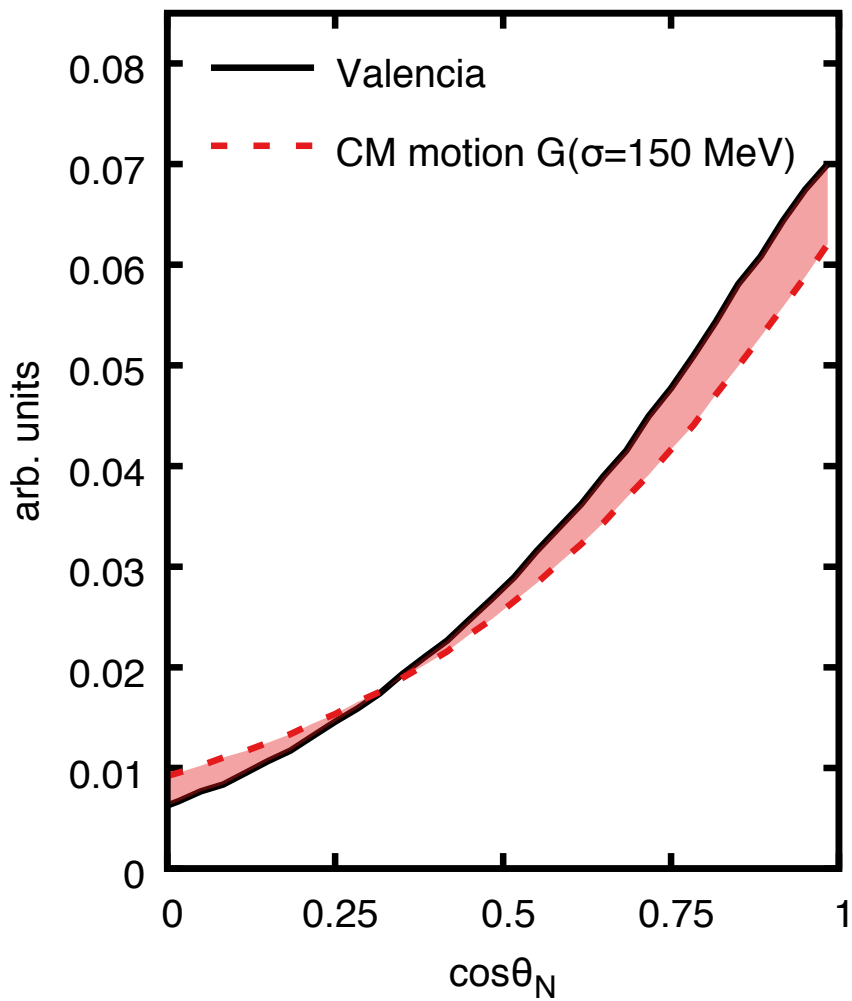


C. Colle et al., Phys.Rev. C89 (2014) 024603

Enhancing initial hadronic kinematics

Distributions for the **most energetic nucleon** before FSI

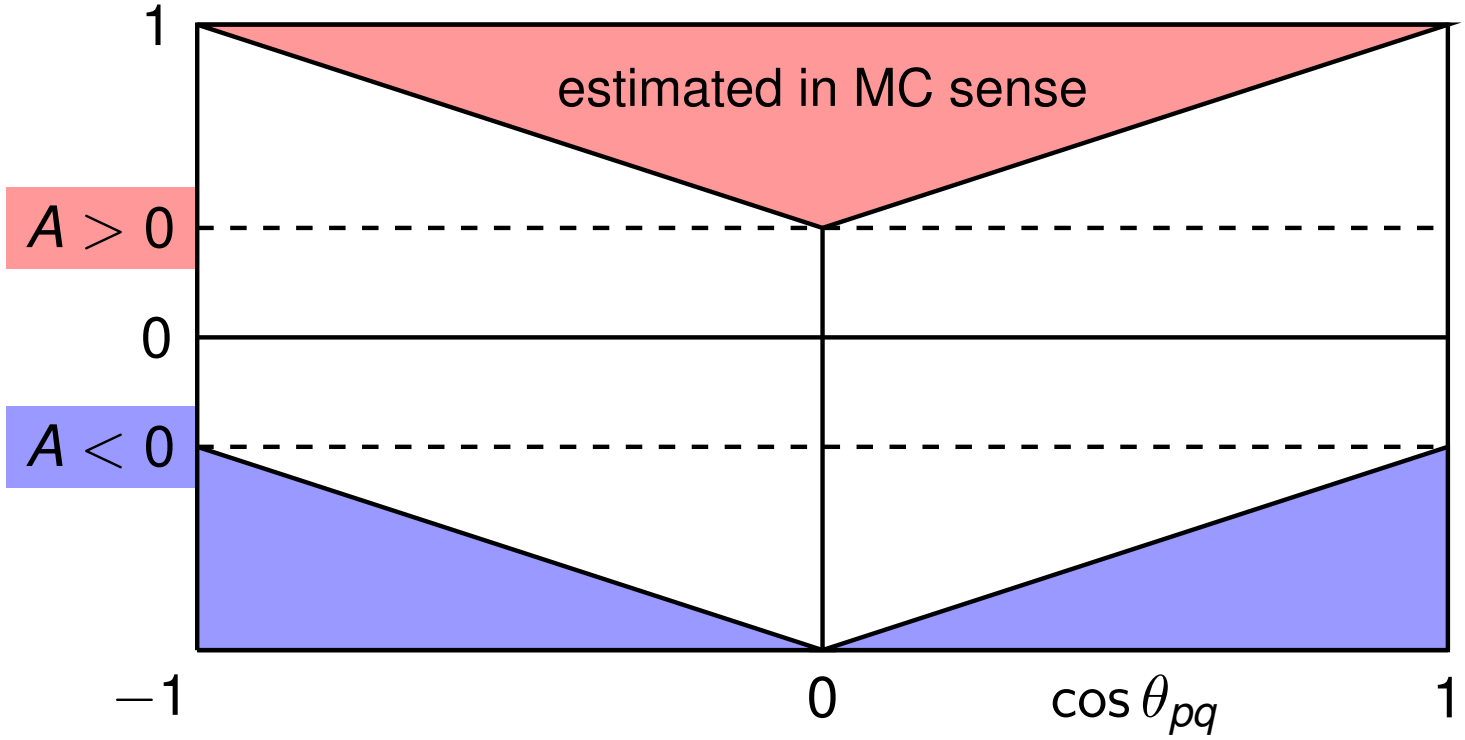




Scattering of 1 GeV neutrinos on carbon target

Enhancing final hadronic kinematics

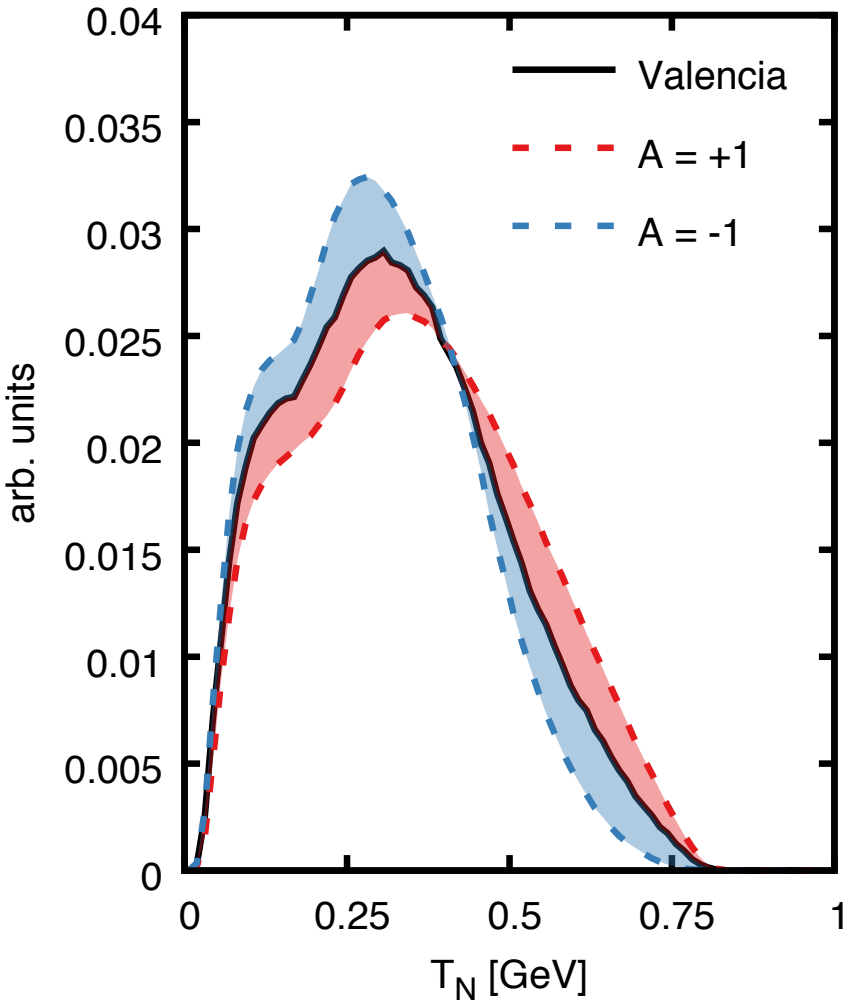
- Nucleon pair **CM distribution** can be **different** than **uniform**
- **Direction** of **momentum transfer** $\vec{q}$ can be distinguished

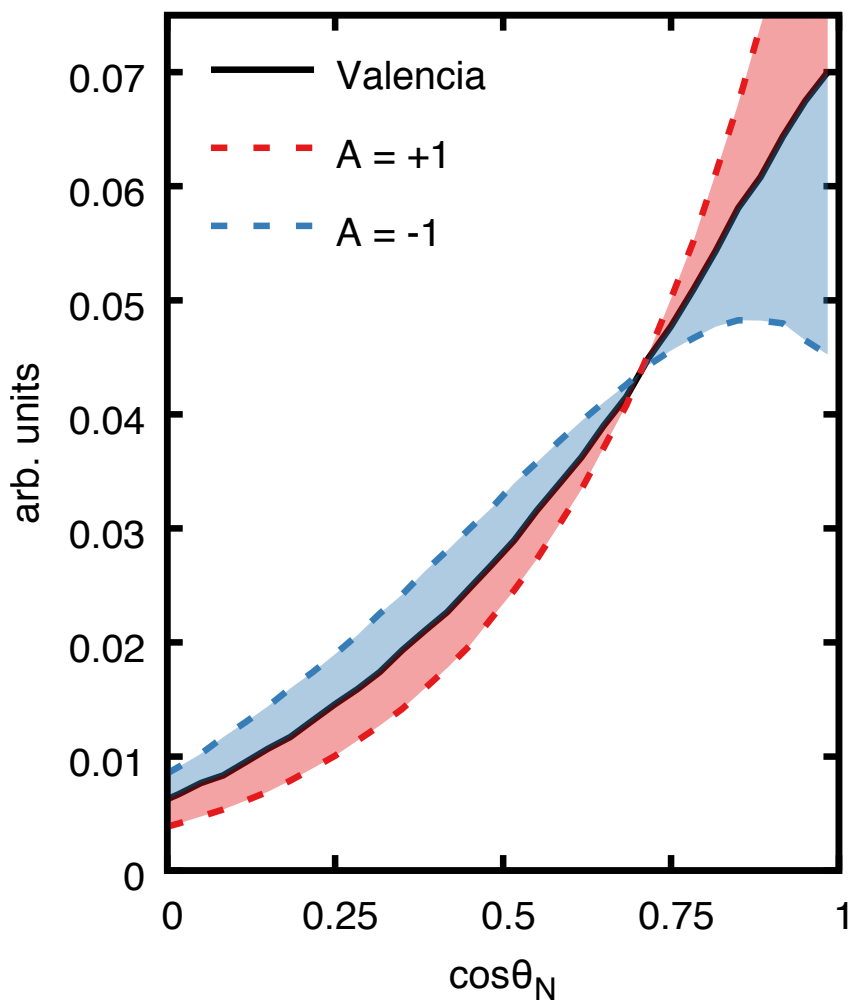


`MEC_cm_direction` (denoted as A)
allows for selecting directions on average more parallel or perpendicular

Enhancing final hadronic kinematics

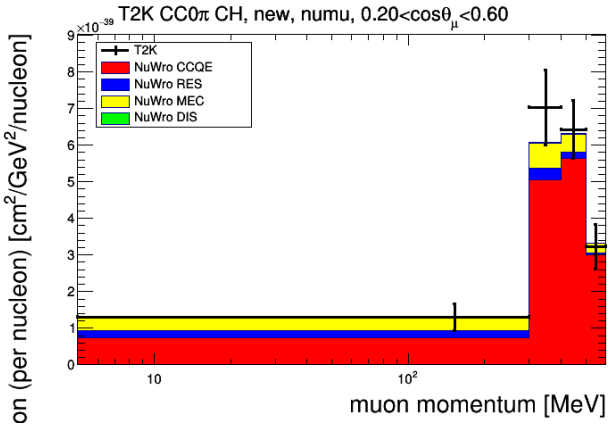
Distributions for the **most energetic nucleon** before FSI

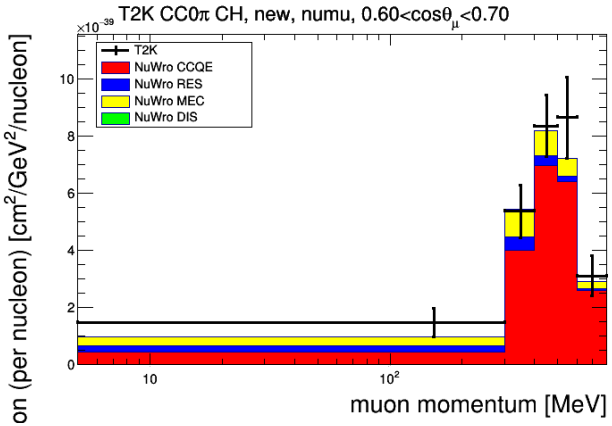


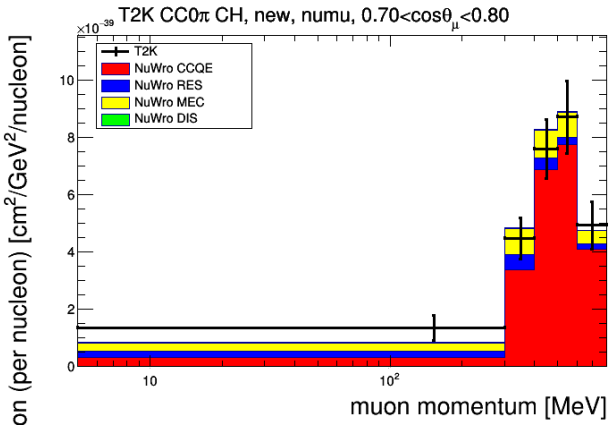


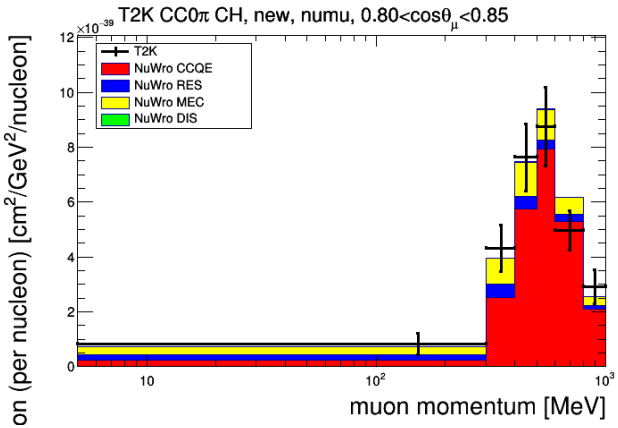
Scattering of 1 GeV neutrinos on carbon target

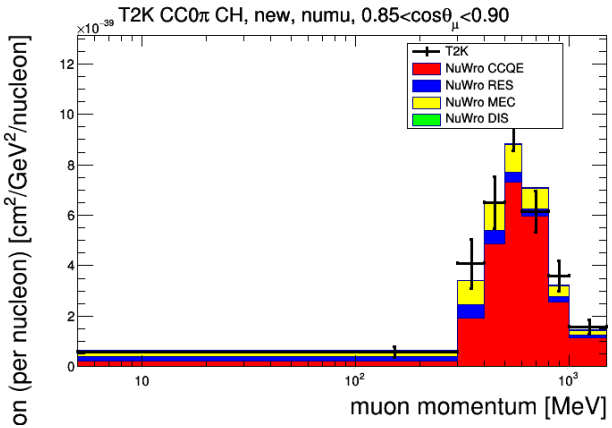
CC 0π ν_μ

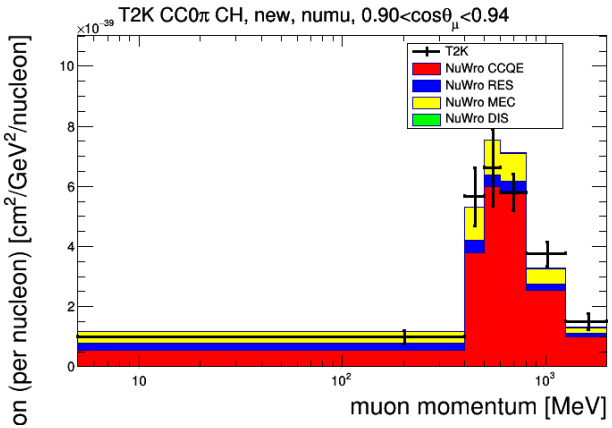

T2K CC0π CH, new, numu, 0.20<cosθ_μ<0.60
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

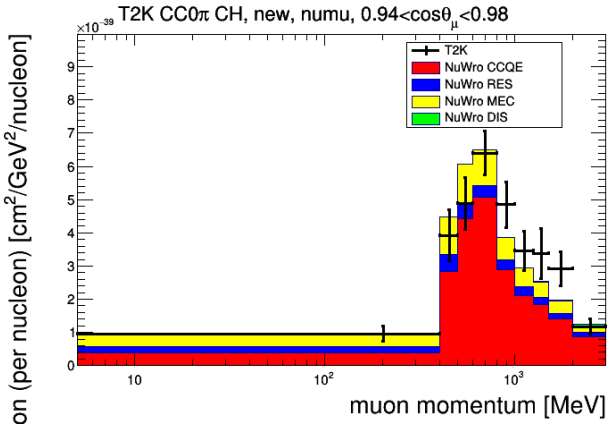

T2K CC0π CH, new, numu, 0.60<cosθ_μ<0.70
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

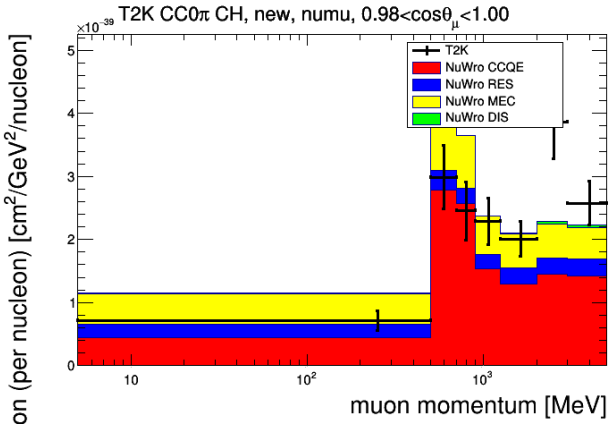

T2K CC0π CH, new, numu, 0.70<cosθ_μ<0.80
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]


T2K CC0π CH, new, numu, 0.80<cosθ_μ<0.85
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

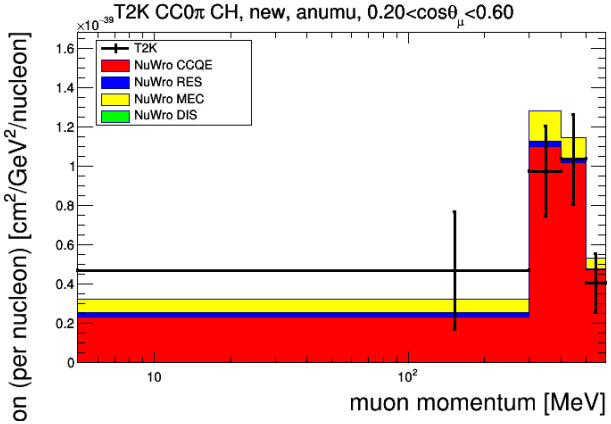

T2K CC0π CH, new, numu, 0.85<cosθ_μ<0.90
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

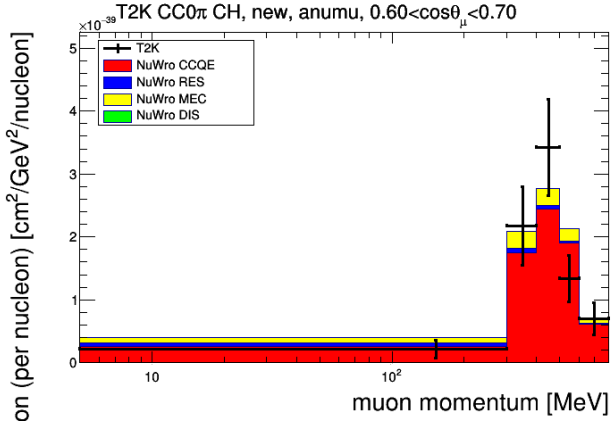

T2K CC0π CH, new, numu, 0.90<cosθ_μ<0.94
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

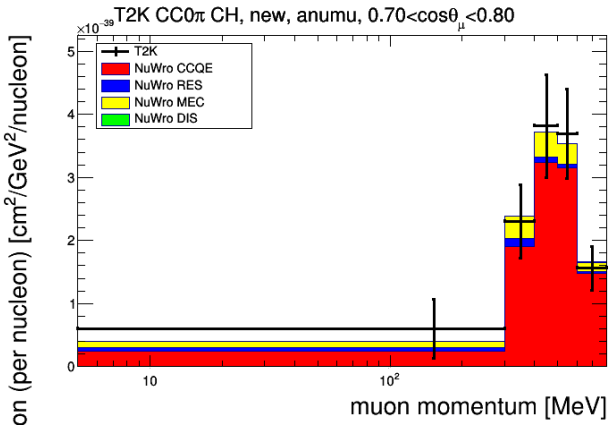

T2K CC0π CH, new, numu, 0.94<cosθ_μ<0.98
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

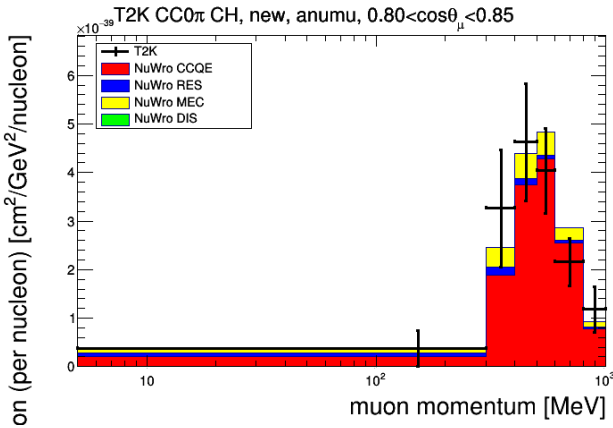

T2K CC0π CH, new, numu, 0.98<cosθ_μ<1.00
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon momentum [MeV]

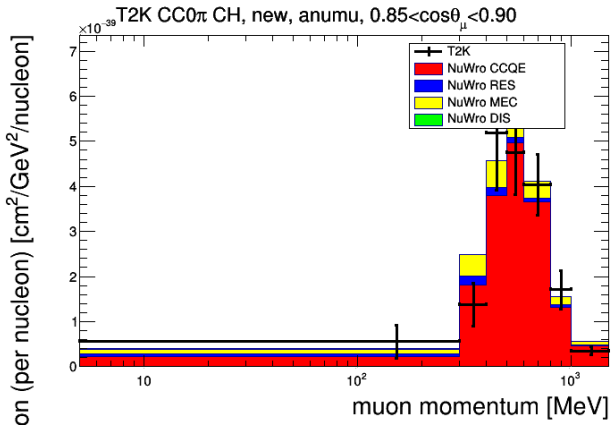
CC 0π $\bar{\nu}_\mu$

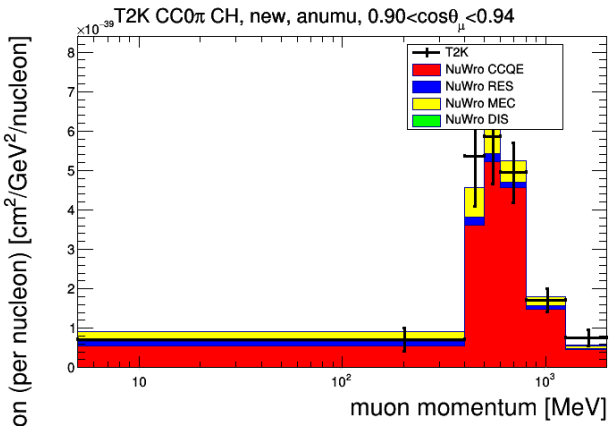


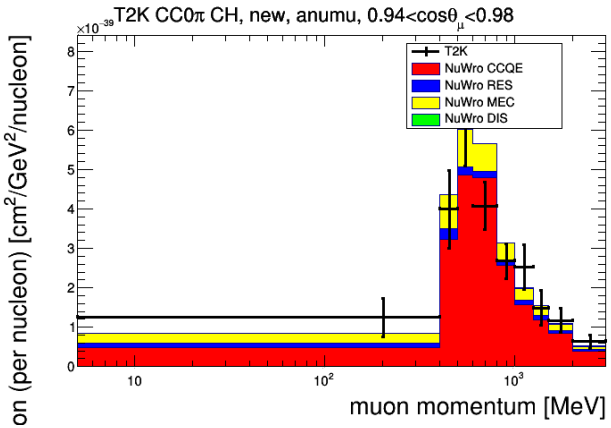


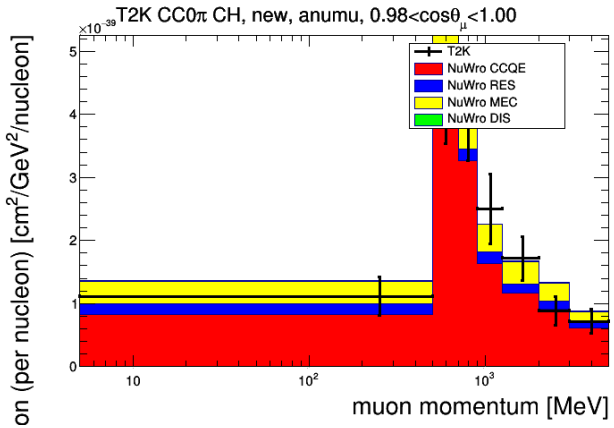


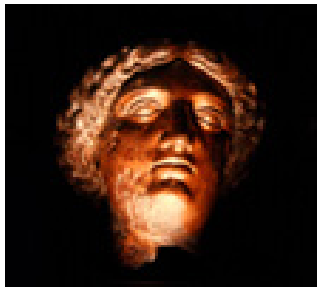




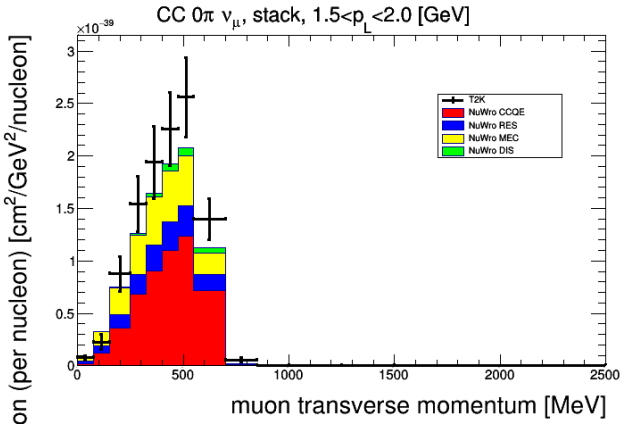


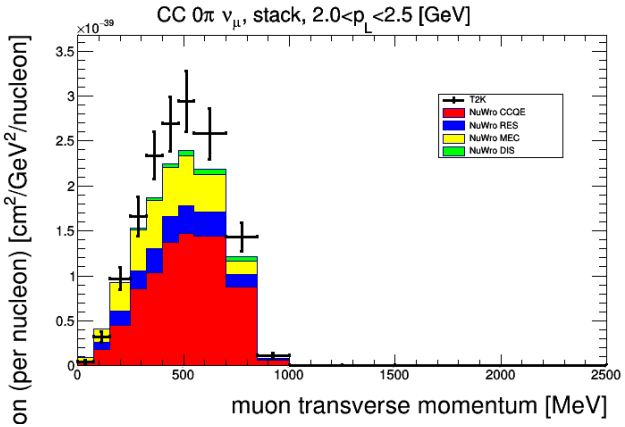


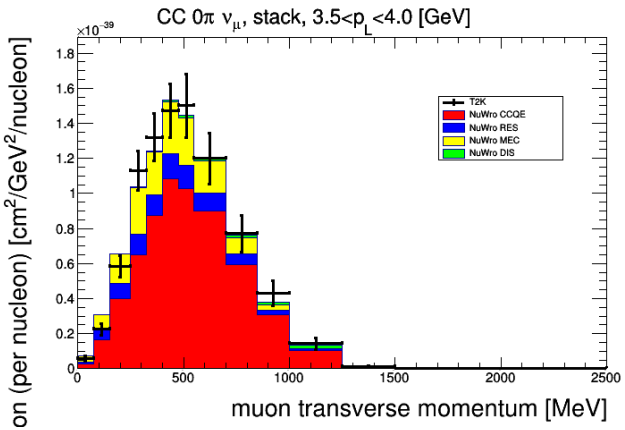


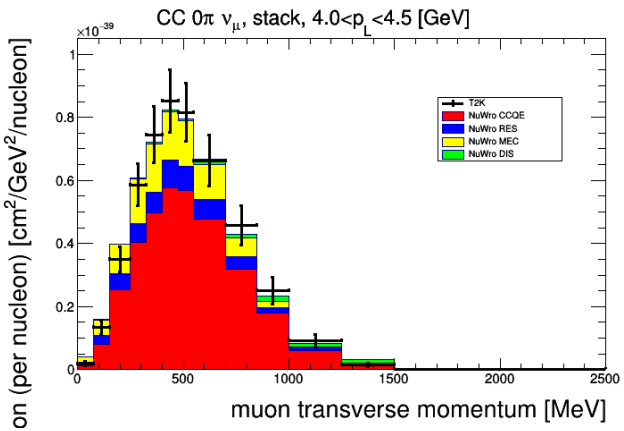


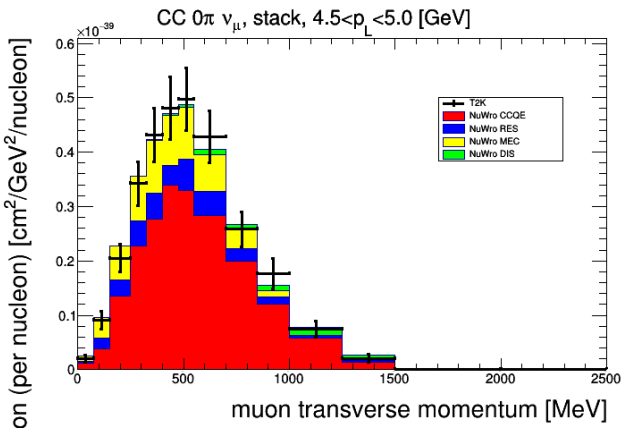
CC 0π ν_μ

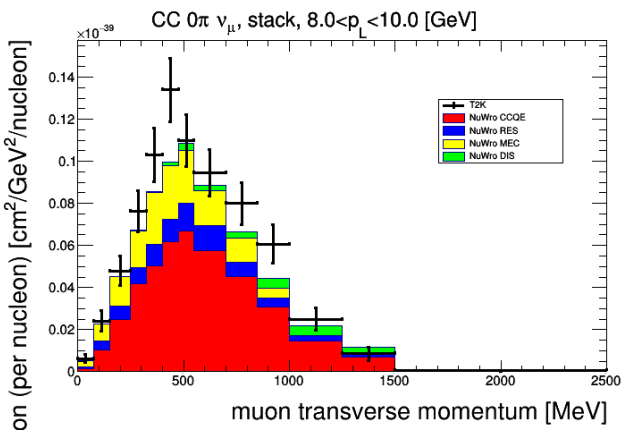

CC 0π ν_μ, stack, 1.5<p_L<2.0 [GeV]
×10^-39
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

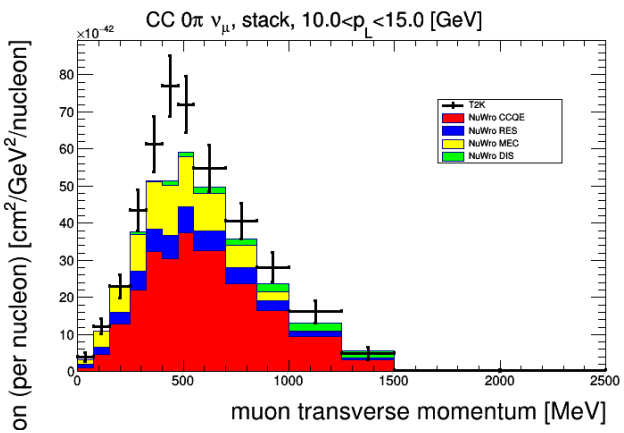

CC 0π ν_μ, stack, 2.0<p_L<2.5 [GeV]
×10^-39
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

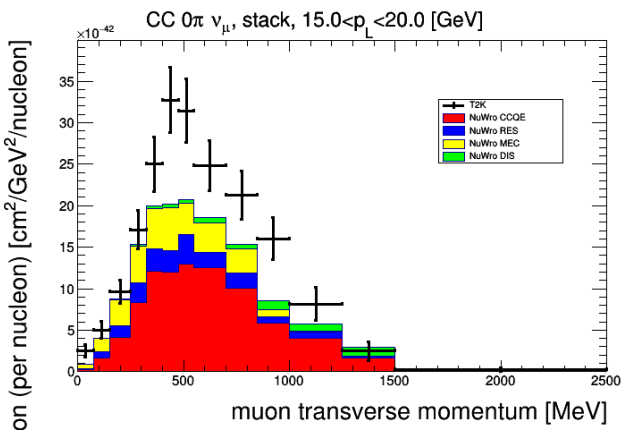

CC 0π ν_μ, stack, 3.5<p_L<4.0 [GeV]
×10^-39
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

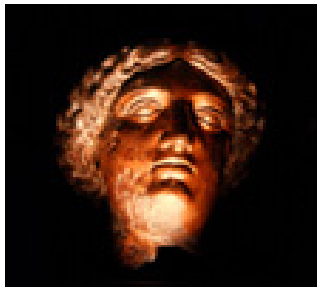

CC 0π ν_μ, stack, 4.0<p_L<4.5 [GeV]
×10^-39
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]


CC 0π ν_μ, stack, 4.5<p_L<5.0 [GeV]
×10^-39
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

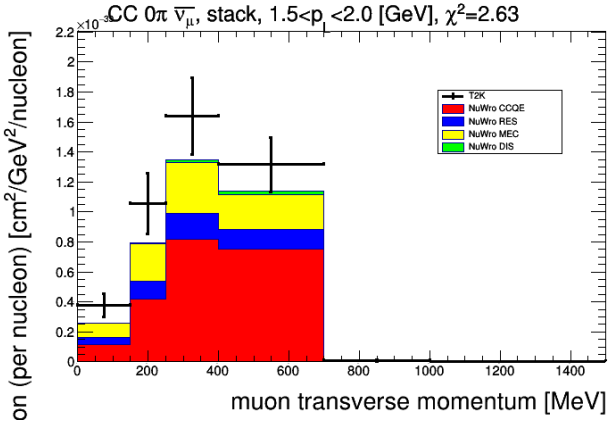

CC 0π ν_μ, stack, 8.0<p_L<10.0 [GeV]
×10^-39
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

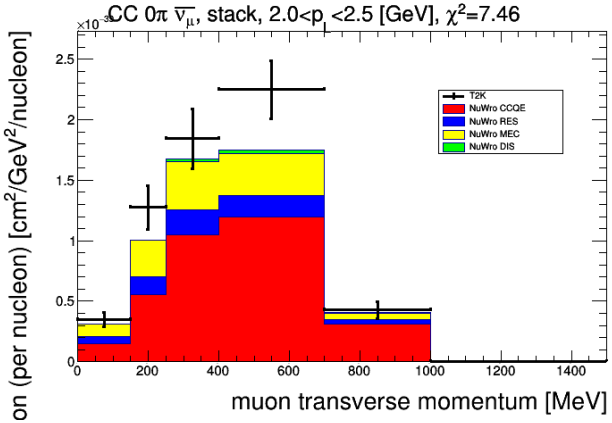

CC 0π ν_μ, stack, 10.0<p_L<15.0 [GeV]
×10^-42
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

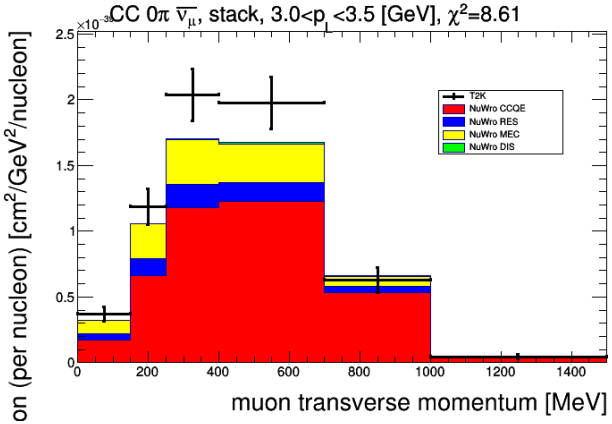

CC 0π ν_μ, stack, 15.0<p_L<20.0 [GeV]
×10^-42
T2K
NuWro CCQE
NuWro RES
NuWro MEC
NuWro DIS
on (per nucleon) [cm²/GeV²/nucleon]
muon transverse momentum [MeV]

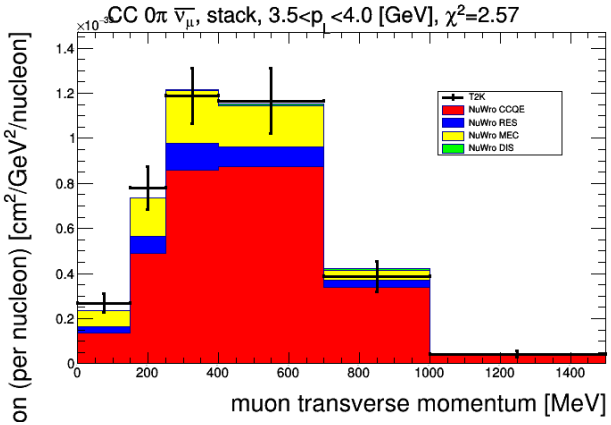


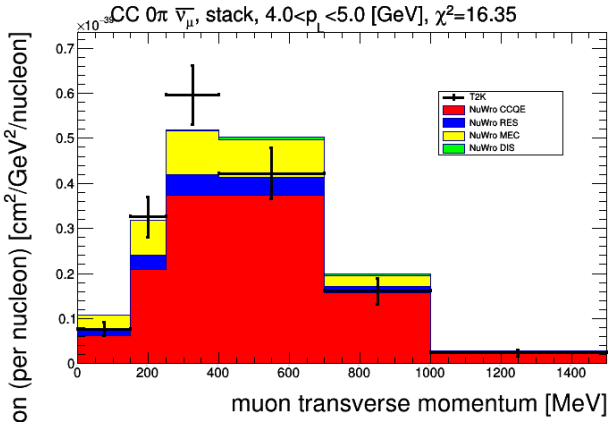
CC 0π $\bar{\nu}_\mu$

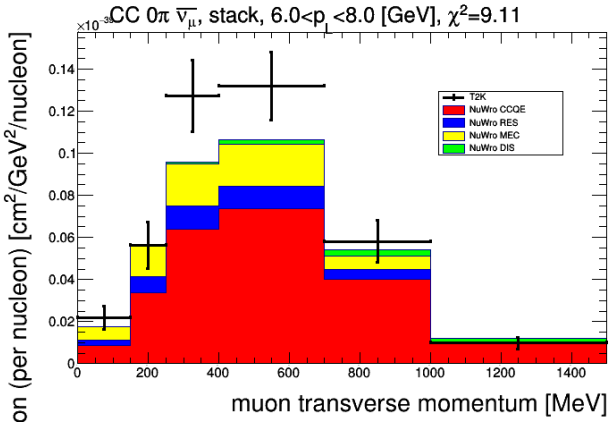


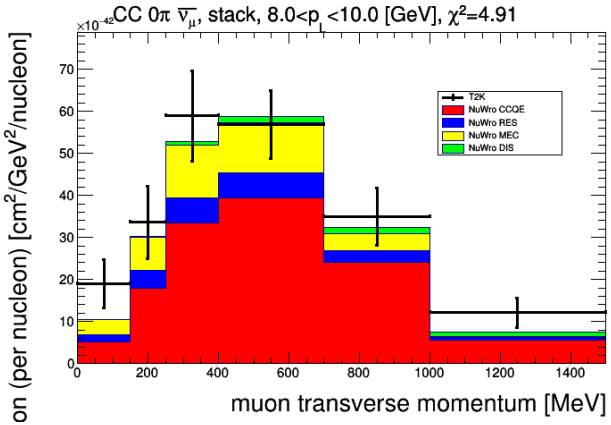


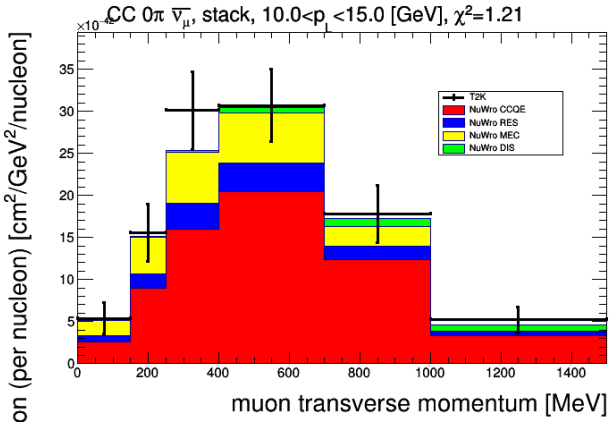












Conclusions

We are working on it!