FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY

PION PRODUCTION IN A HYBRID MODEL

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GHENT UNIVERSITY

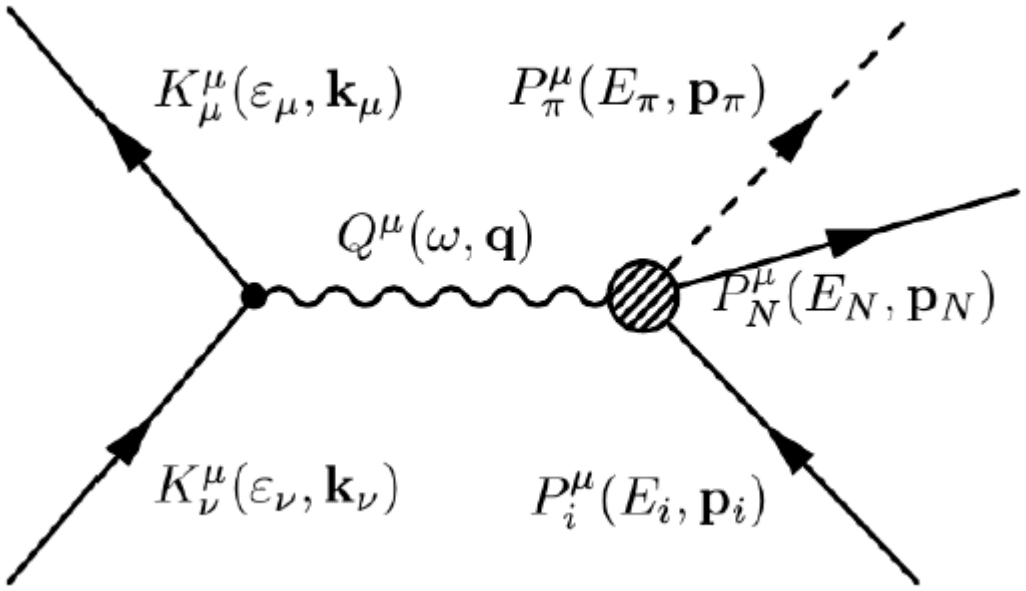
AIM

- Detailed microscopic cross sections calculations for neutrino-induced pion production
- Formalism valid over a broad energy range
- Taking into account as many nuclear physics aspects as feasible

References :

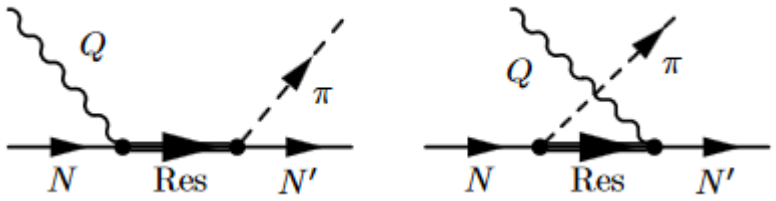
- ‘Neutrino-induced pion production from nuclei at medium energies’, C. Praet, O. Lalakulich, N. Jachowicz, J. Ryckebusch, Phys. Rev. C79, 044603 (2009) ; arXiv:0804.2750.
- Electroweak single-pion production off the nucleon : from threshold to high invariant masses’ R. Gonzalez-Jimenez, N. Jachowicz, K. Niewczas, J. Nys, V. Pandey, T. Van Cuyck, N. Van Dessel, Phys. Rev. D95, 113007 (2017) ; arXiv:1612.05511.
- ‘Pion production within the hybrid-RPWIA model at MiniBooNe and MINERvA kinematics, R. Gonzalez-Jimenez, K. Niewczas, N. Jachowicz, Phys. Rev. D97, 093008 (2018) ; arXiv:1710.08374.
- ‘Modeling neutrino-induced charged pion production on water at T2K kinematics’ A. Nikolakopoulos, R. Gonzalez-Jimenez, K. Niewczas, J. Sobczyk, N. Jachowicz, Phys. Rev. D97, 093008 (2018) ; arXiv:1803.03163.08374.
- ‘Nuclear effects in electron- and neutrino-nucleus scattering within a relativistic quantum mechanical framework’, R. Gonzalez-Jimenez, A. Nikolakopoulos, N. Jachowicz, J.M. Udias,, arXiv1904:10696, accetped for publication PRC

I. Single pion production on the nucleon – low energy model



Cfr. PRC 76, 033005 (2007), PRD87, 113009 (2013)

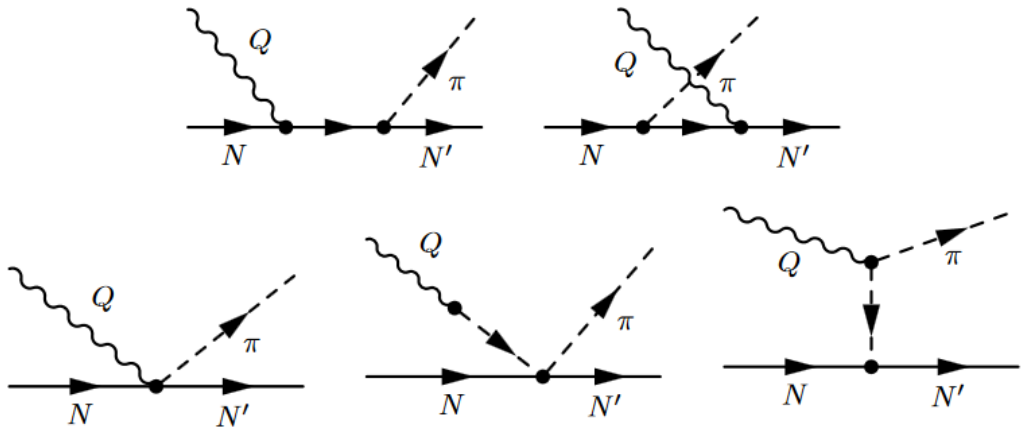
Resonances



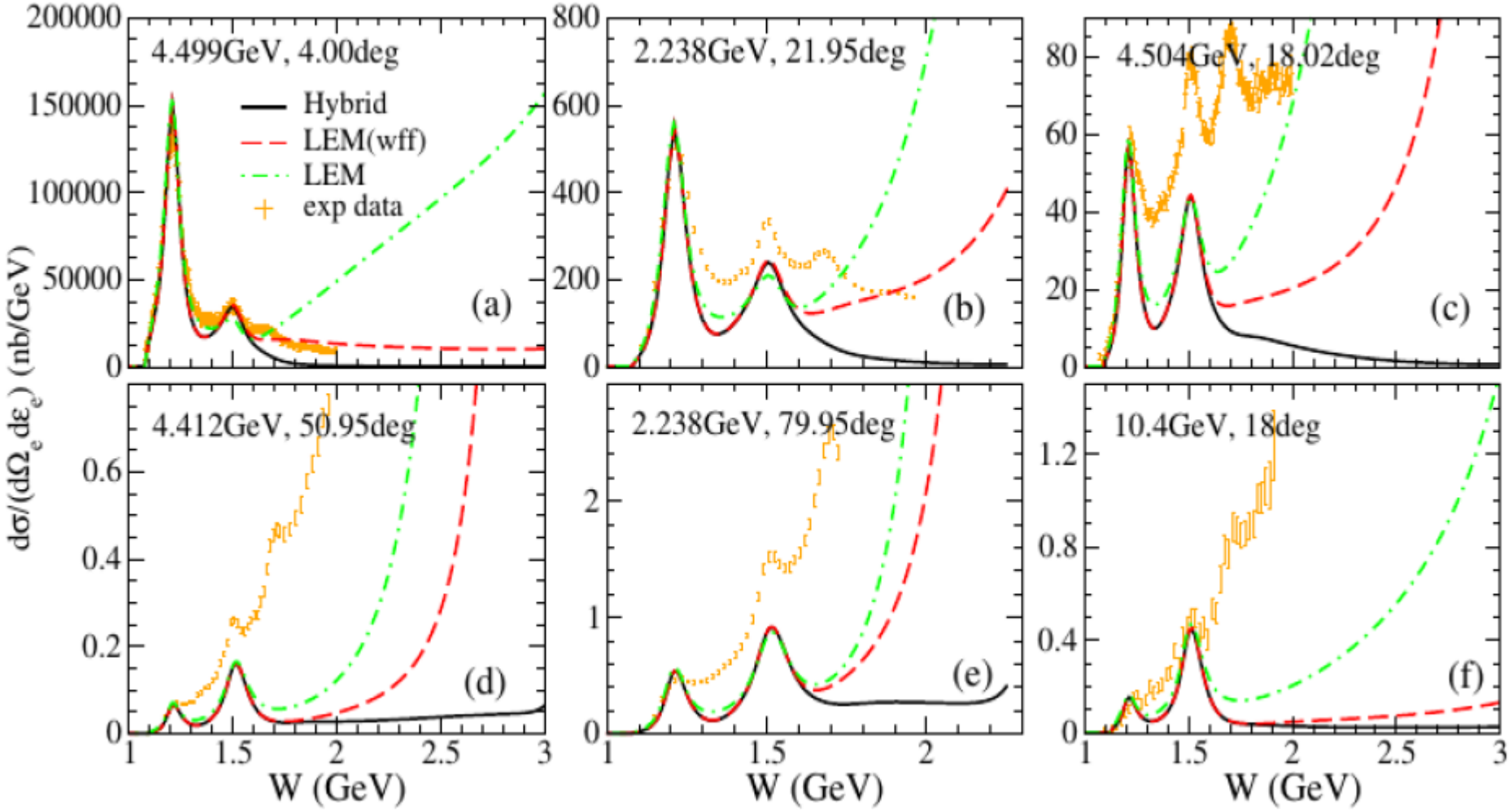
P33 (1232), P11(1440), D13 (1520), S11 (1535)

+

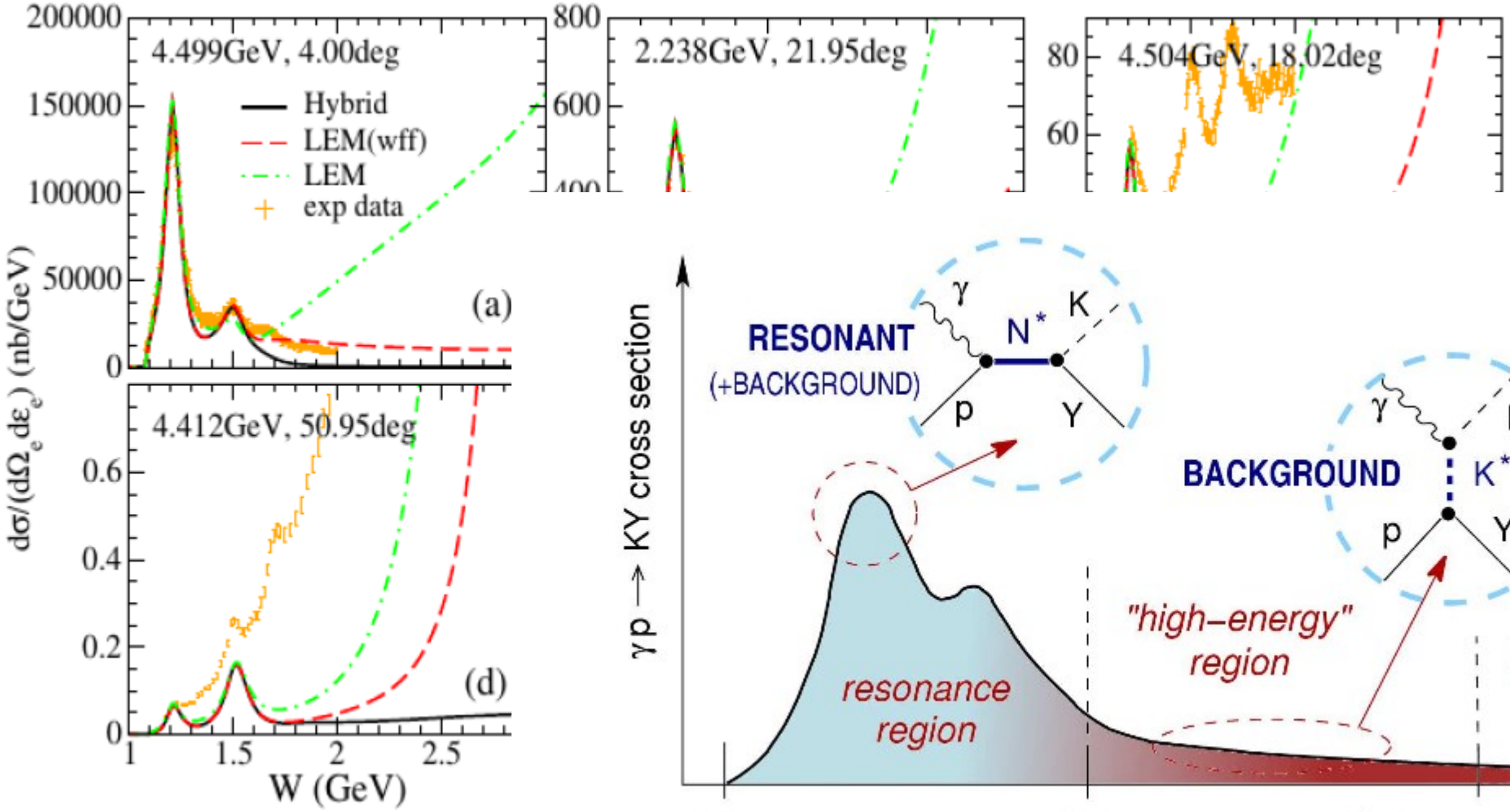
ChPT background



I. Single pion production on the nucleon – some issues of the LEM model …



I. Single pion production on the nucleon – some issues of the LEM model …

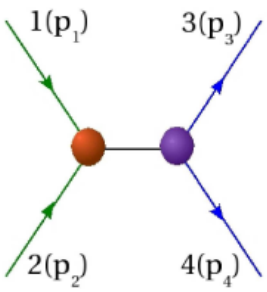


T. Corthals, PhD, UGent 2005

II.High energy model- Regge approach in a nutshell

- Based on crossing symmetry

$$1 + 2 \rightarrow 3 + 4$$

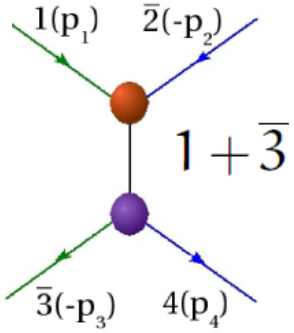


T. Corthals, PhD, UGent 2005

direct
s-channel

$$\mathcal{M}_s(p_1, p_2, p_3, p_4) = \mathcal{M}_t(p_1, -p_3, -p_2, p_4)$$

$$\mathcal{M}_s(s, t, u) \equiv \mathcal{M}_t(t, s, u)$$



$$1 + \bar{3} \rightarrow \bar{2} + 4$$

crossed
t-channel

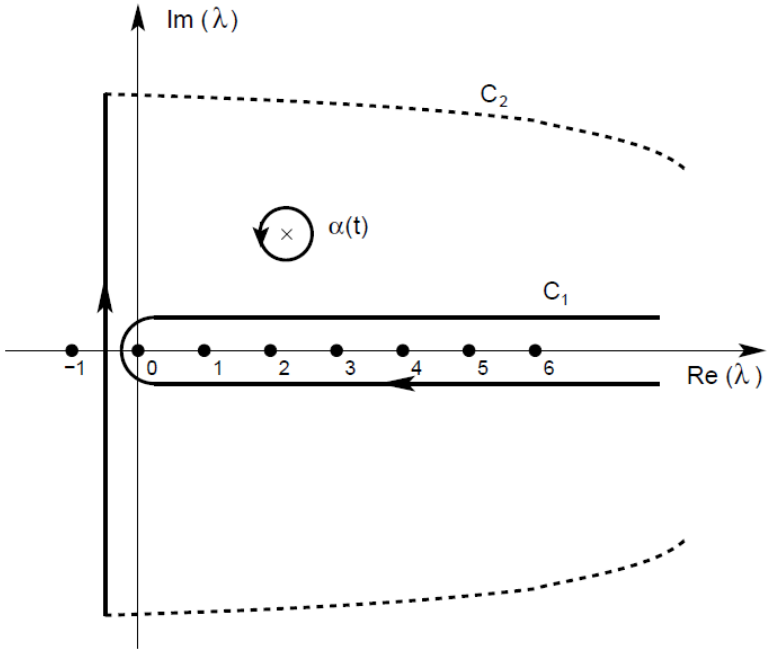
- Amplitude can be expanded in a Legendre series

$$\mathcal{M}_t(t, s) = \sum_{l=0}^{\infty} (2l + 1) \mathcal{M}_l(t) \mathcal{P}_l(\cos\theta_t) = \mathcal{M}_s(s, t)$$

II.High energy model- Regge approach in a nutshell

- The expansion expression can be transformed to a contour integral in the complex angular momentum plane

$$\mathcal{M}(s,t) = -\frac{1}{2i}\oint_{C_1} d\lambda \frac{(2\lambda+1)\,\mathcal{M}_\lambda(t)\,P_\lambda(-\cos\theta_t)}{\sin(\pi\lambda)}$$

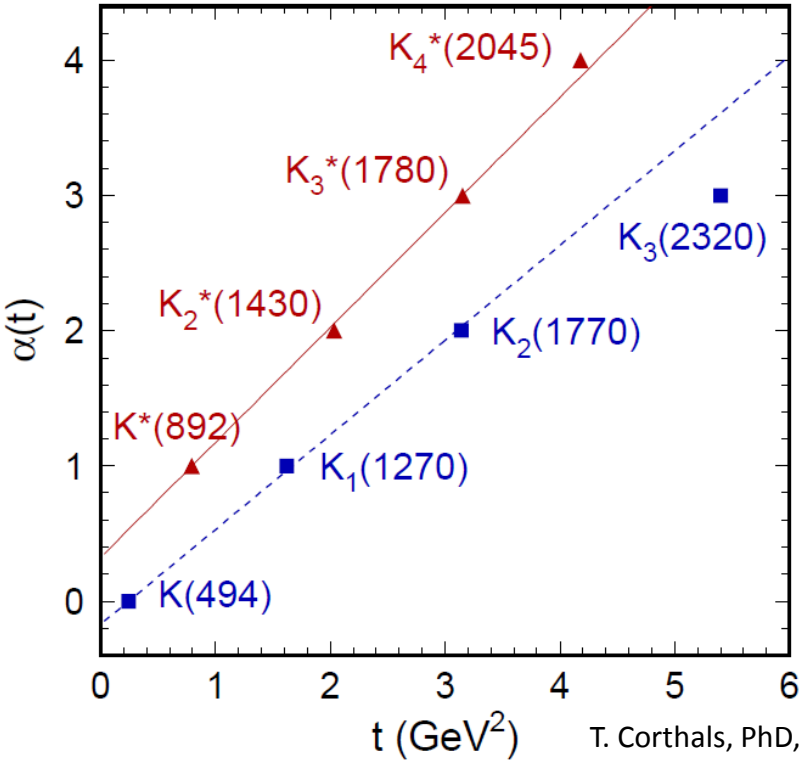


T. Corthals, PhD, UGent 2005

Poles $\lambda = \alpha_i(t)$

$$\alpha_i(t) = n$$

$$m = \sqrt{t}$$



T. Corthals, PhD, UGent 2005

II.High energy model- Regge approach in a nutshell

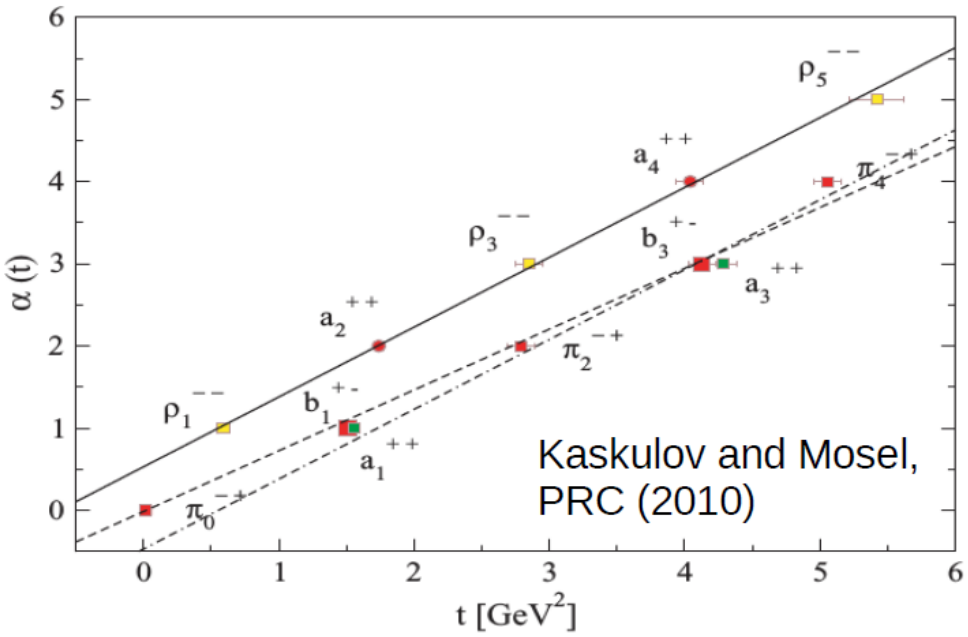
Regge recipe :

- Identify the appropriate Regge trajectories
- Establish t-dependence of amplitude
- Replace propagator by Regge propagator

$$\frac{1}{t - m_\pi^2}$$

$$\downarrow$$

$$\mathcal{P}_\pi(t,s) = -\alpha'_\pi \varphi_\pi(t) \Gamma[-\alpha_\pi(t)](\alpha'_\pi s)^{\alpha_\pi(t)}$$



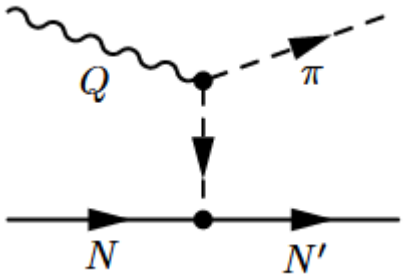
Regge theory provides the s dependence of the amplitude at high energies

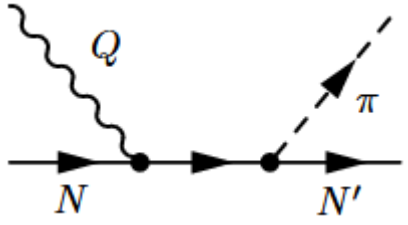
II.High energy model : vector part

Reggeizing the vector current : CVC – based on models for electroproduction of charged pions

- M. Guidal, J.-M. Laget, and M. Vanderhaeghen, Nucl. Phys. A627, 645 (1997).
- M. Kaskulov and U. Mosel, Phys. Rev. C81, 045202 (2010).
- M. Vanderhaeghen, M. Guidal, and J.-M. Laget, Phys. Rev. C57, 1454 (1998).
- T. Vrancx and J. Ryckebusch, Phys. Rev. C89, 025203 (2014).

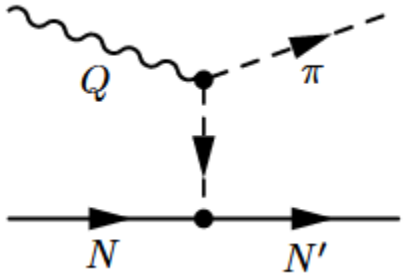
p(e,e' π^+)

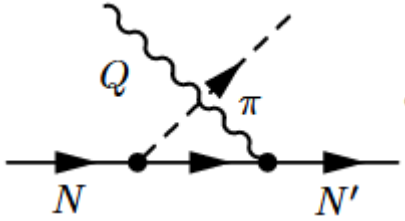




$$J^\mu \sim \overline{u}(\mathbf{p}_N, s_N)\left(\mathcal{O}_{PF} + \mathcal{O}^{ps}_{NPv}\right) u(\mathbf{p}, s)$$

n(e,e' π^-)





$$J^\mu \sim \overline{u}(\mathbf{p}_N, s_N)\left(\mathcal{O}_{PF} + \mathcal{O}^{ps}_{CNPv}\right) u(\mathbf{p}, s)$$

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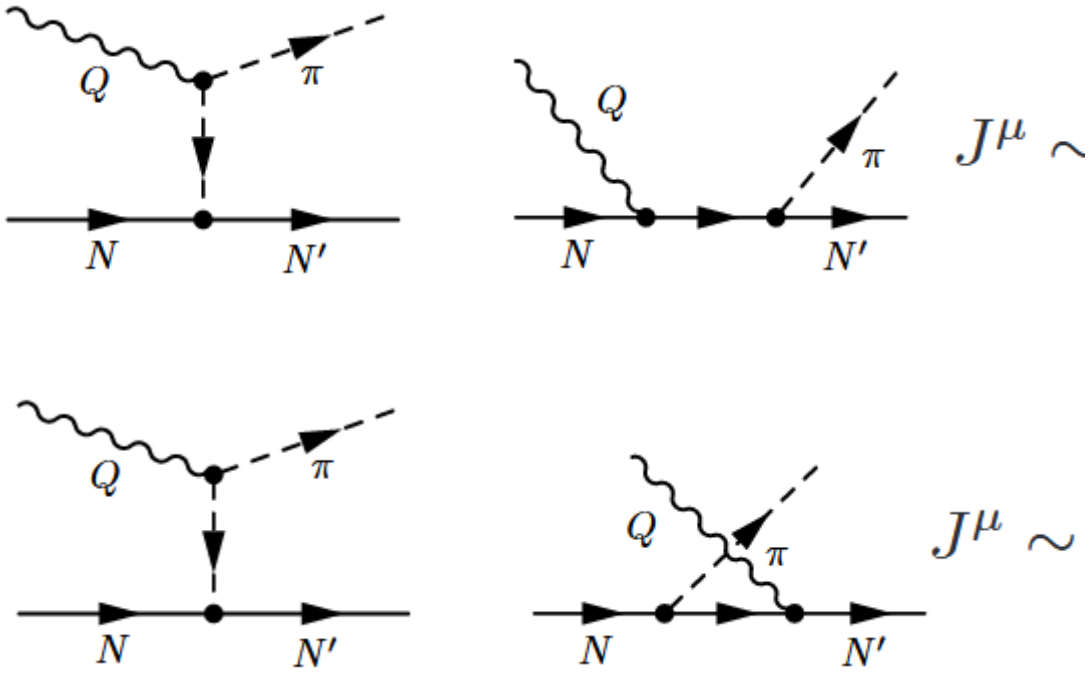
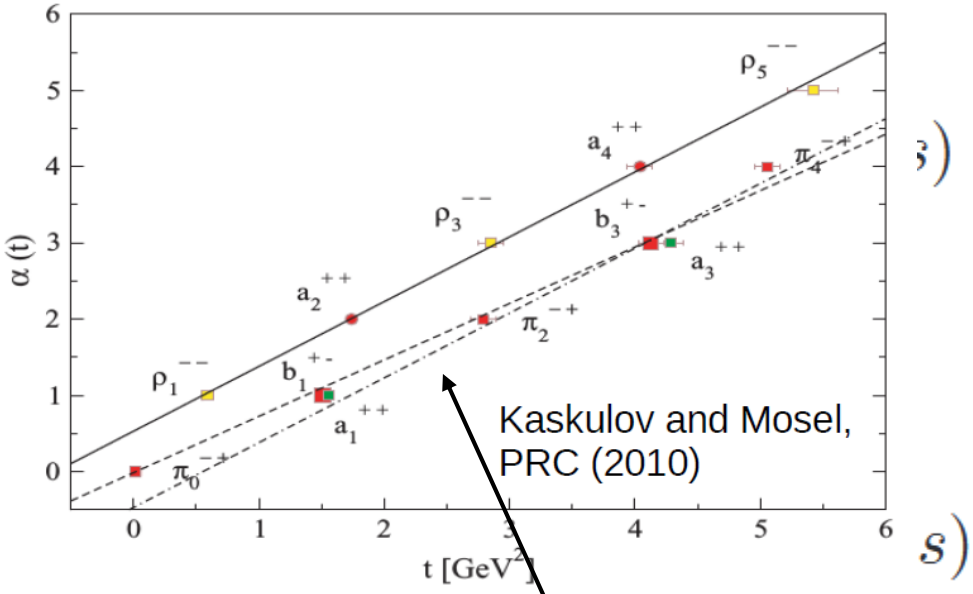
p(e,e' π^+)

n(e,e' π^-)

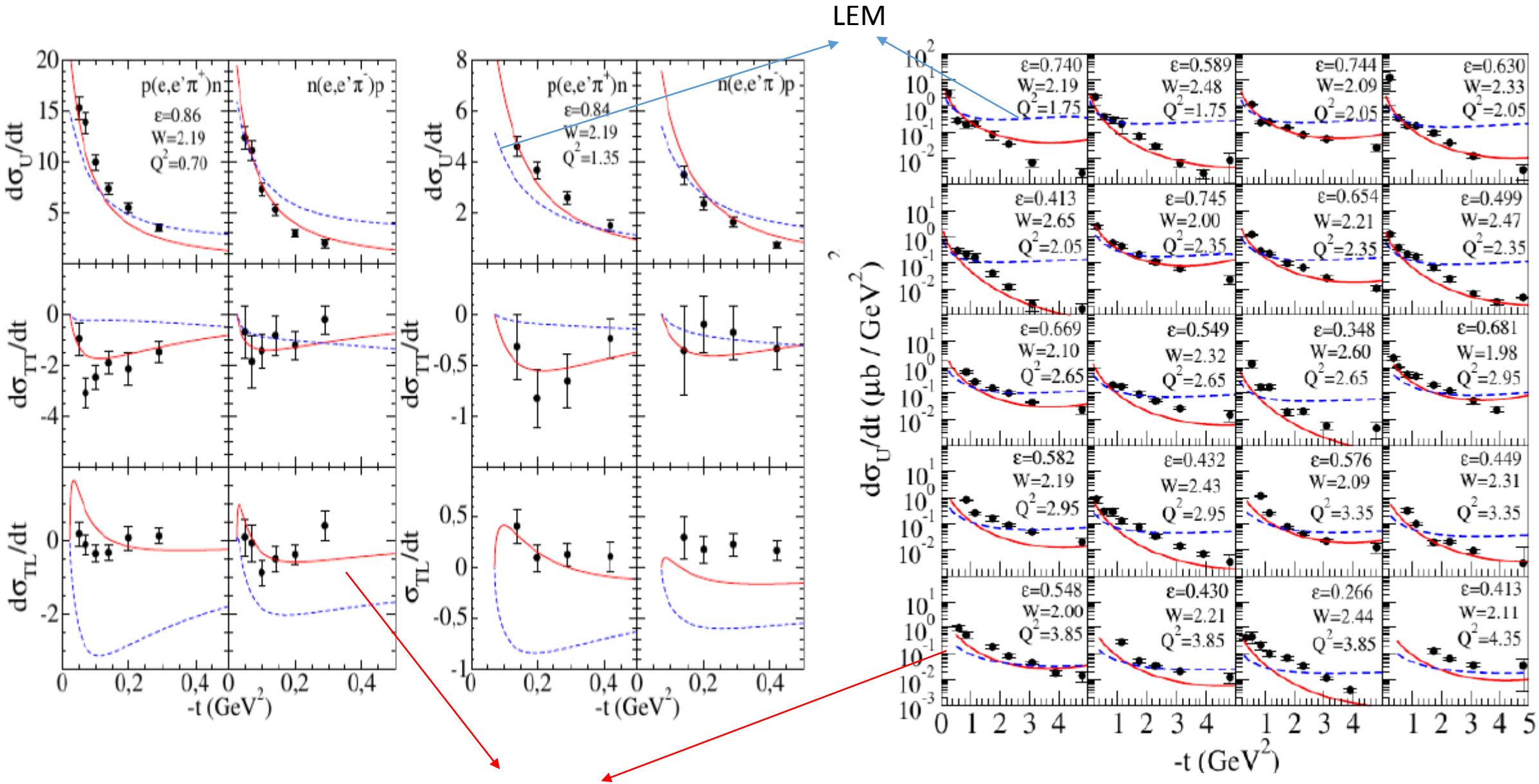




Kaskulov and Mosel, PRC (2010)

$\pi(140)/b_1(1235)$ propagator

II.High energy model – results for electron scattering



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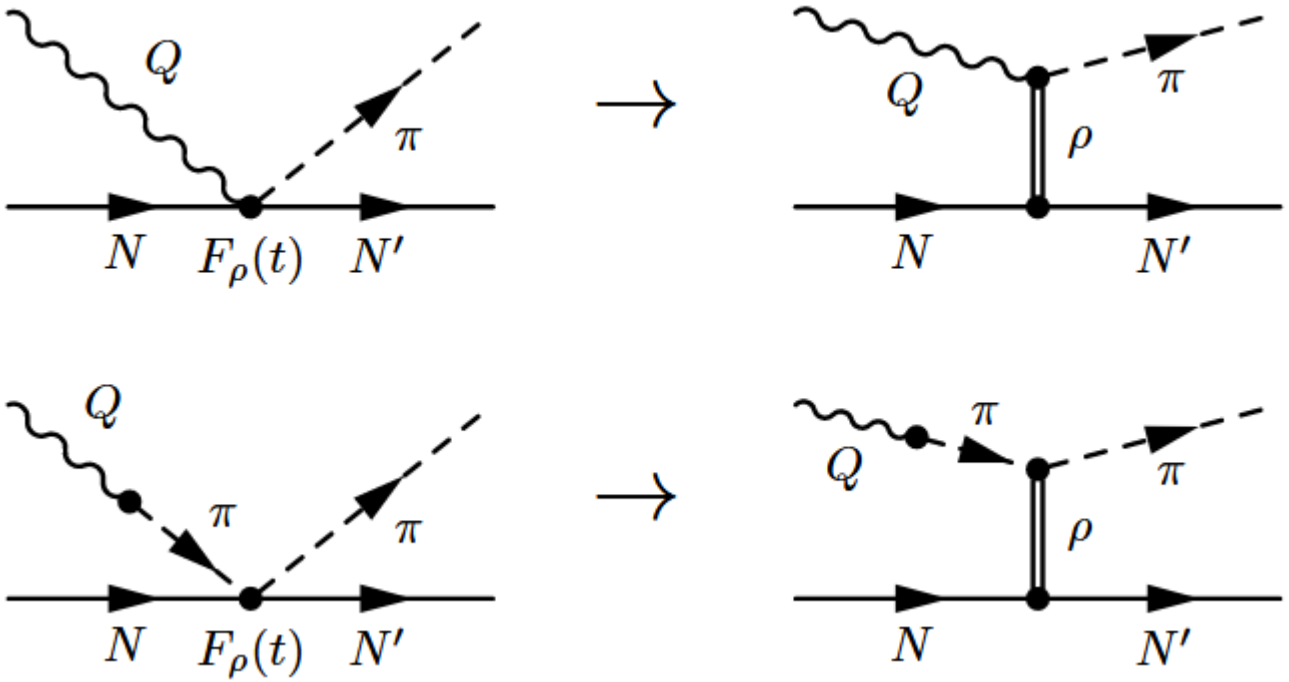
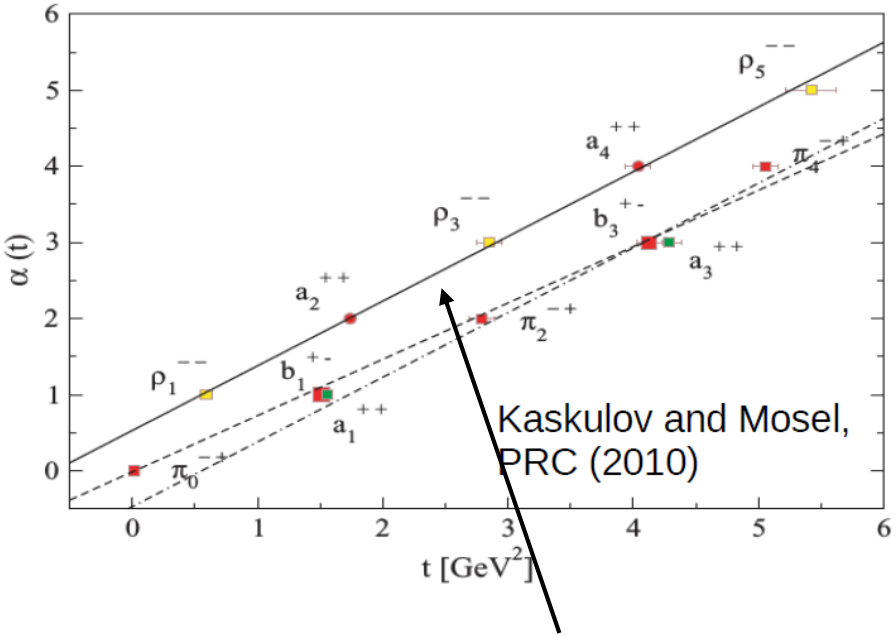
II.High energy model : axial part

Identify the Regge trajectory for the axial current





ρ(770)/a_2(1320) propagator

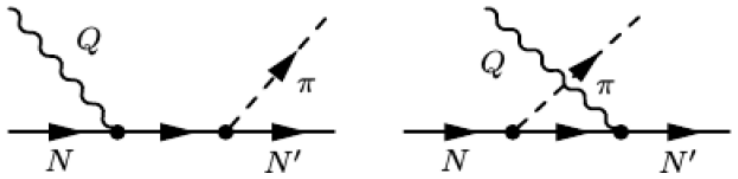
II.High energy model : axial part

Reggeizing the axial current : PCAC –

CTρ + PPρ + Npa + CNPa

Fulfill PCAC

ReChi model: One free parameter in the boson-nucleon-nucleon vertex

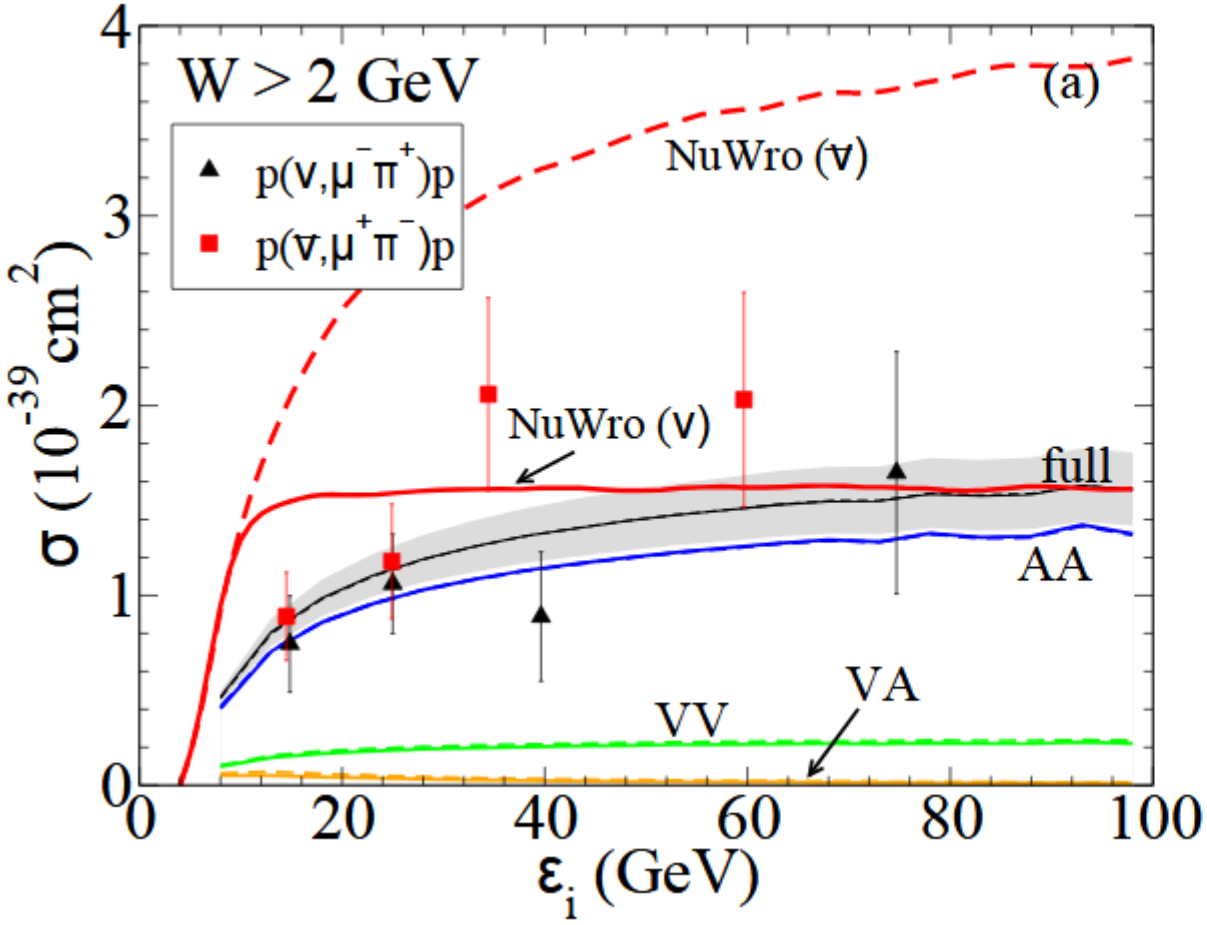


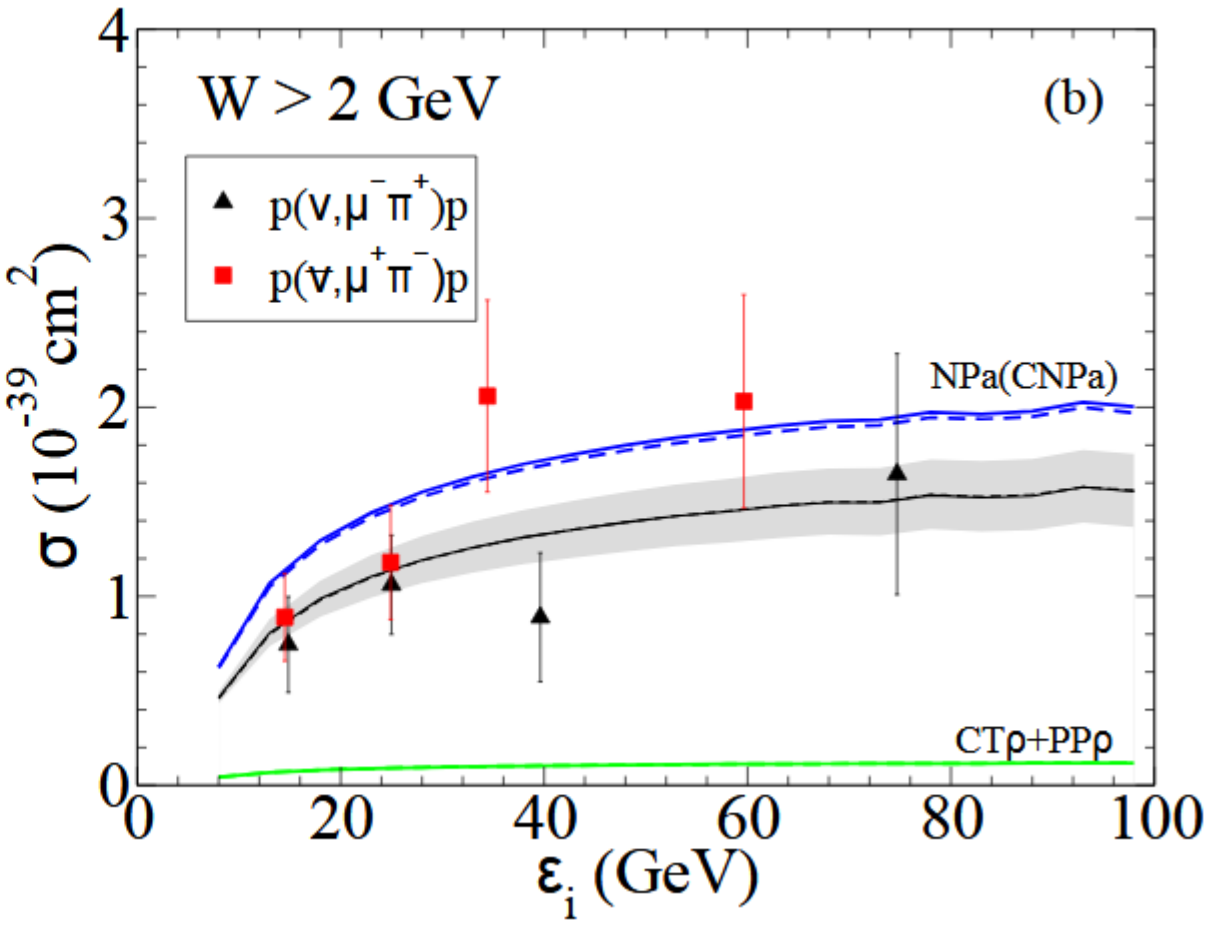
$$G_A[Q^2, s(u)] = g_A \left(1 + \frac{Q^2}{\Lambda_{Apn^*}[s(u)]^2}\right)^{-2}$$

$$\Lambda_{Anp^*}(s) = \Lambda_{Apn} + (\Lambda_\infty^A - \Lambda_{Apn})\left(1 - \frac{M^2}{s}\right)$$

$$\Lambda_\infty^A = \left(7.20 \pm {}^{2.09}_{1.32}\right) \text{GeV}$$

II.High energy model : results





Data :P. Allen et al. Nucl. Phys. B264, 221 (1986).

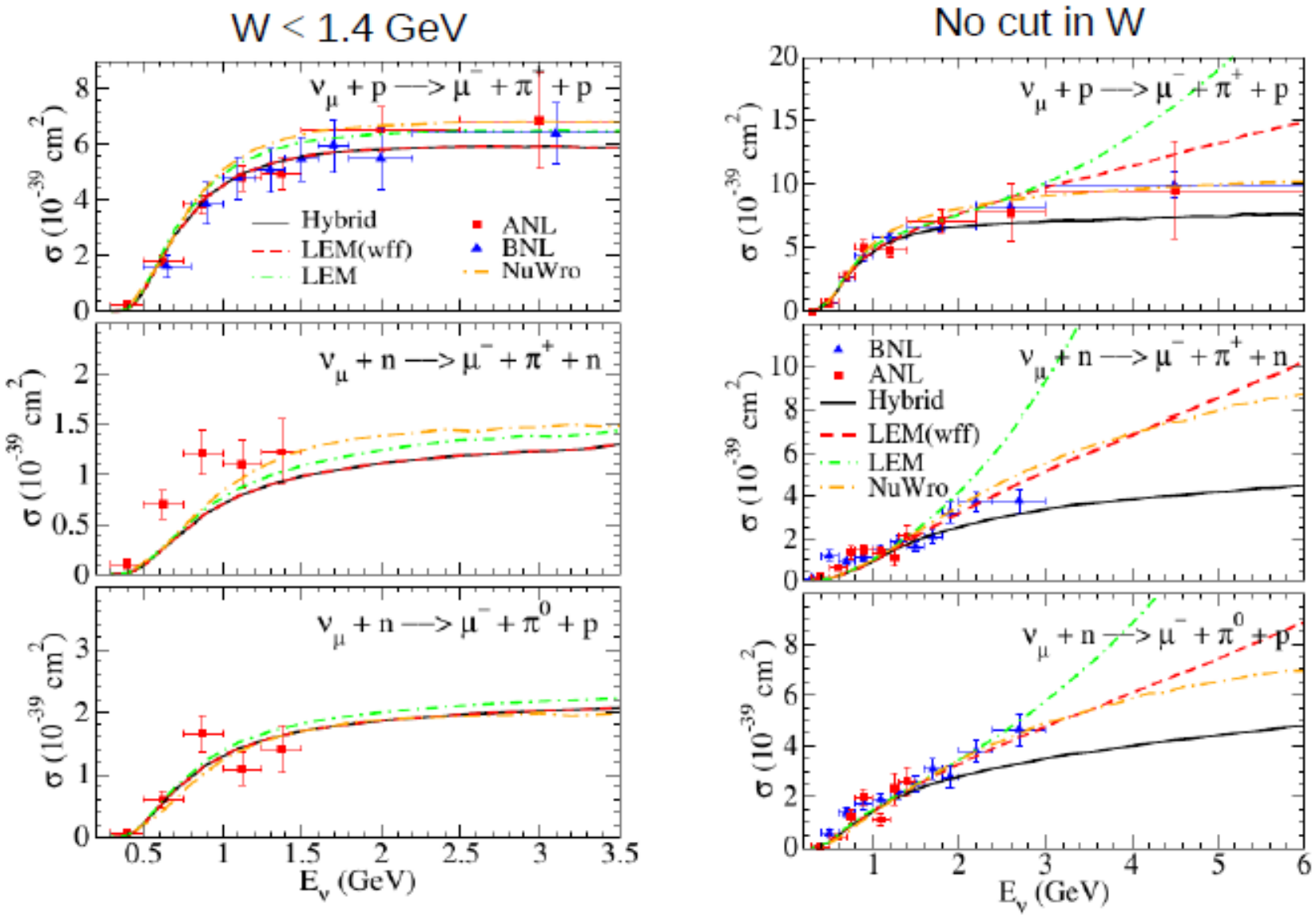
III.Hybrid model : merge both models in a phenomenological way

$$\tilde{\mathcal{O}} = \cos^2\phi(W)\mathcal{O}_{ChPT} + \sin^2\phi(W)\mathcal{O}_{ReChi}$$

$$\phi(W) = \frac{\pi}{2}\left(1 - \frac{1}{1+\exp\left[\frac{W-W_0}{L}\right]}\right)$$

W<1.4 GeV : LEM model : resonances + ChPT background
W>2GeV : Regge background contributions

III.Hybrid model – results



IV.Hybrid model – put the nucleon in a nucleus

Plane waves (for the moment...)

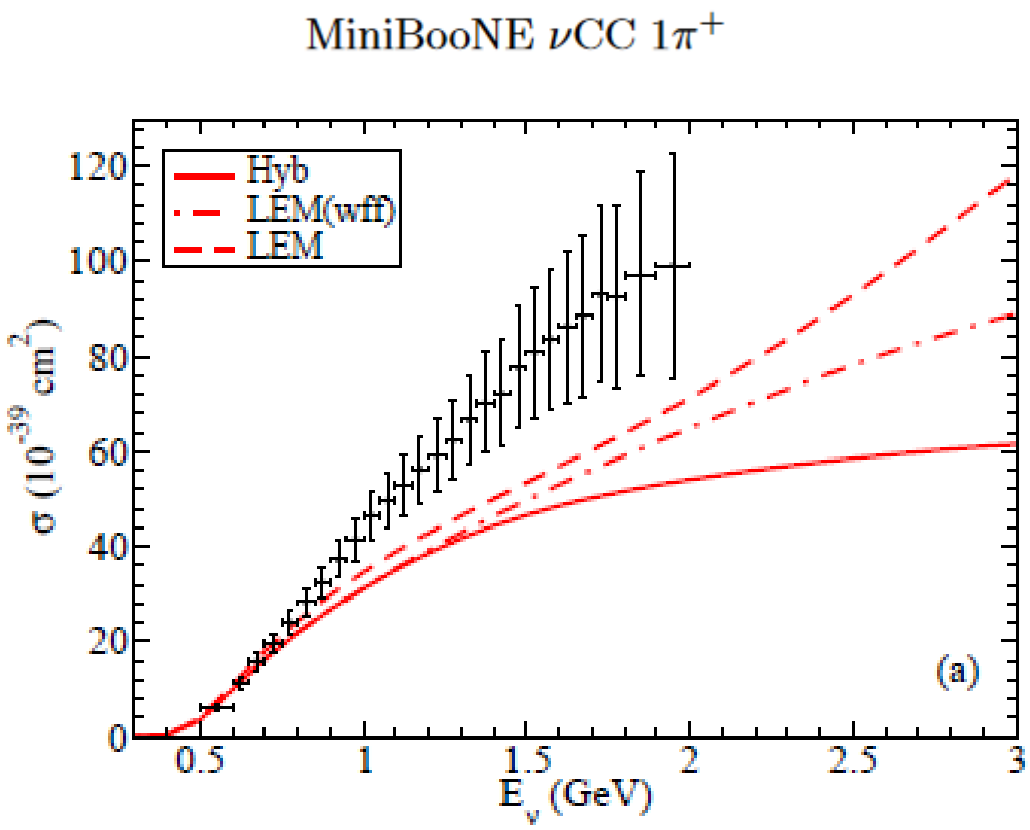
$$J^{\mu}_{had} = \sum_{i}^{A} \int d\mathbf{r}\, \overline{\Psi}_F(\mathbf{r})\, \phi^*(\mathbf{r}) \hat{O}^{\mu}_{one\text{-}body}(\mathbf{r})\, \Psi_B(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$

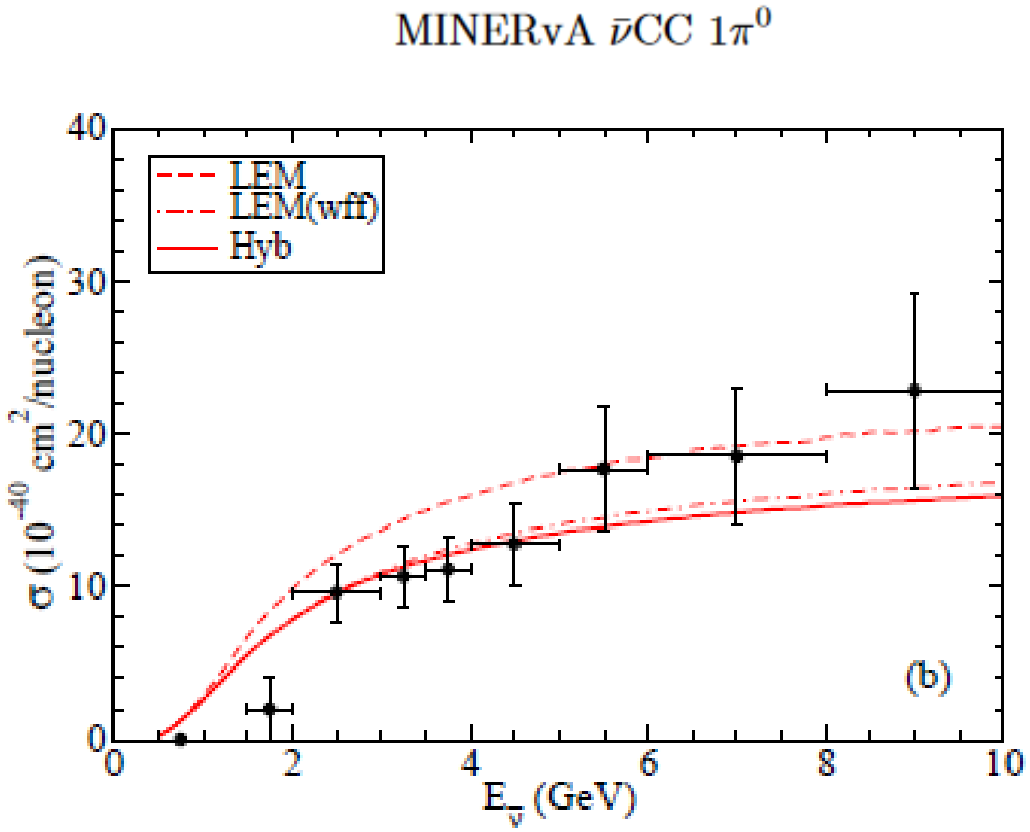
Relativistic mean-field wave functions

+ comparison with NuWro final state

+ investigate effect of medium modifications

IV.Hybrid RPWIA model – results MiniBooNe and MINERvA





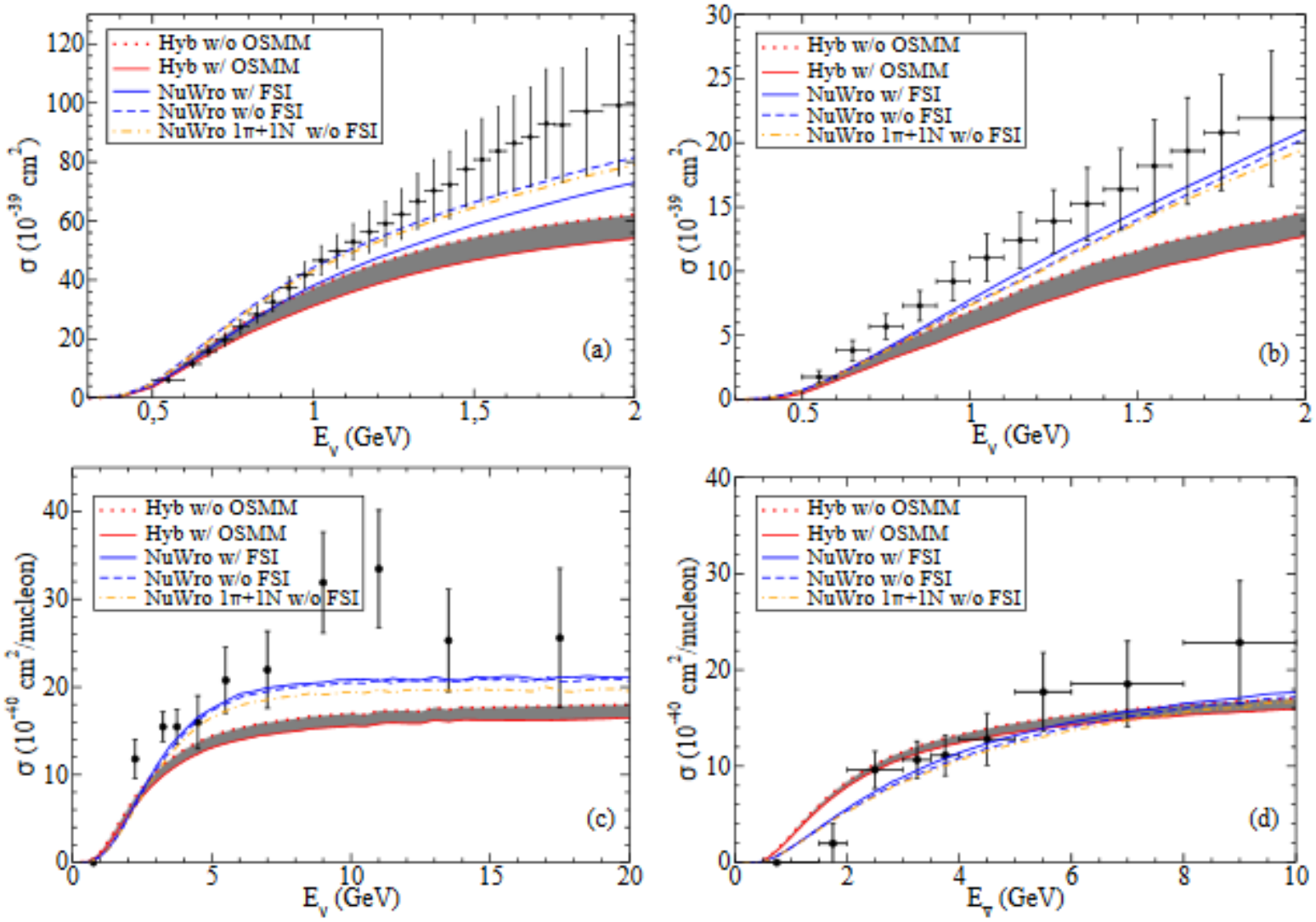
IV.Hybrid RPWIA model – results

MiniBooNE νCC $1\pi^+$

MiniBooNE νCC $1\pi^0$

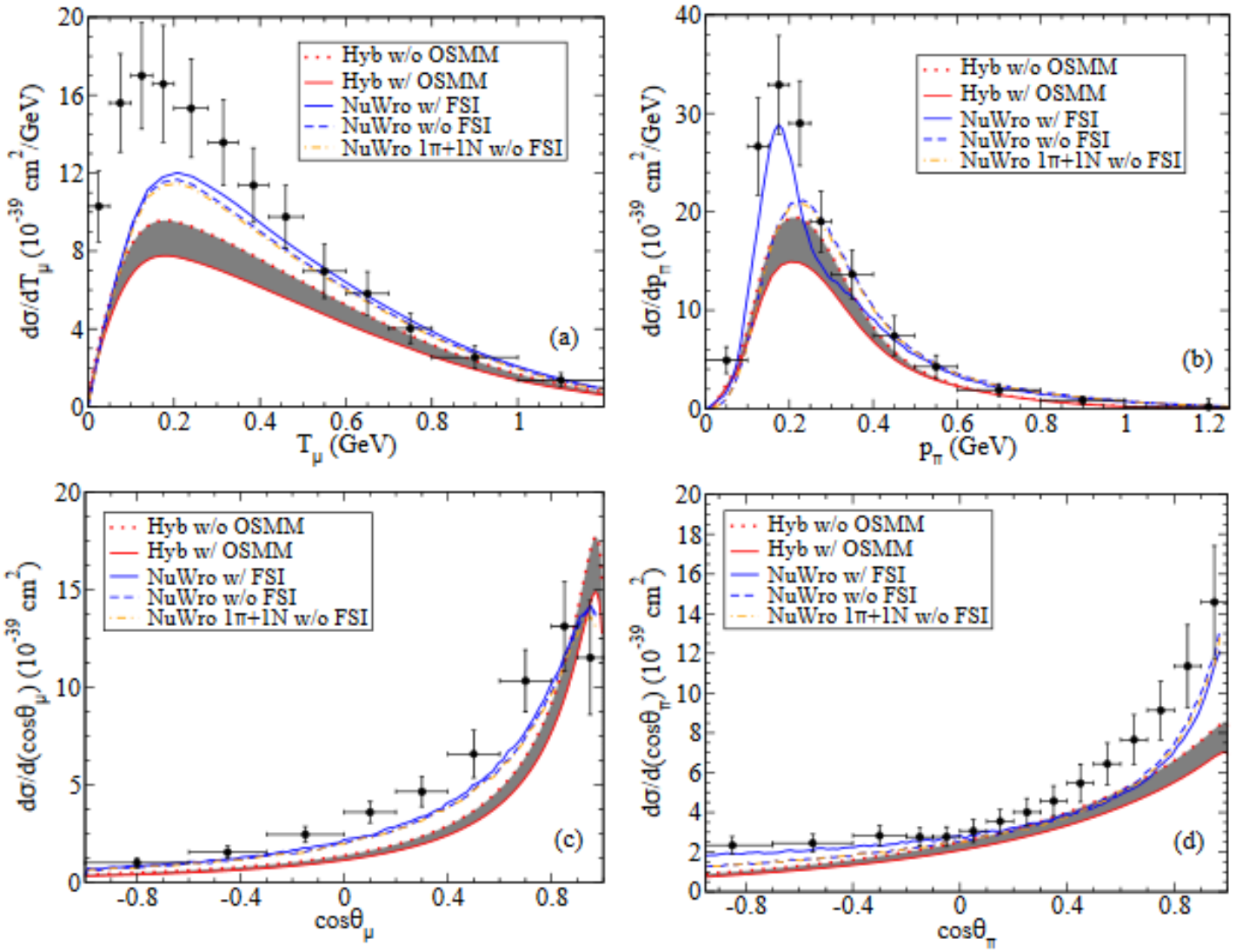
MINERvA νCC $1\pi^0$

MINERvA $\bar{\nu}$CC $1\pi^0$



IV.Hybrid RPWIA model – results and comparison with NuWro

MiniBooNE νCC $1\pi^0$



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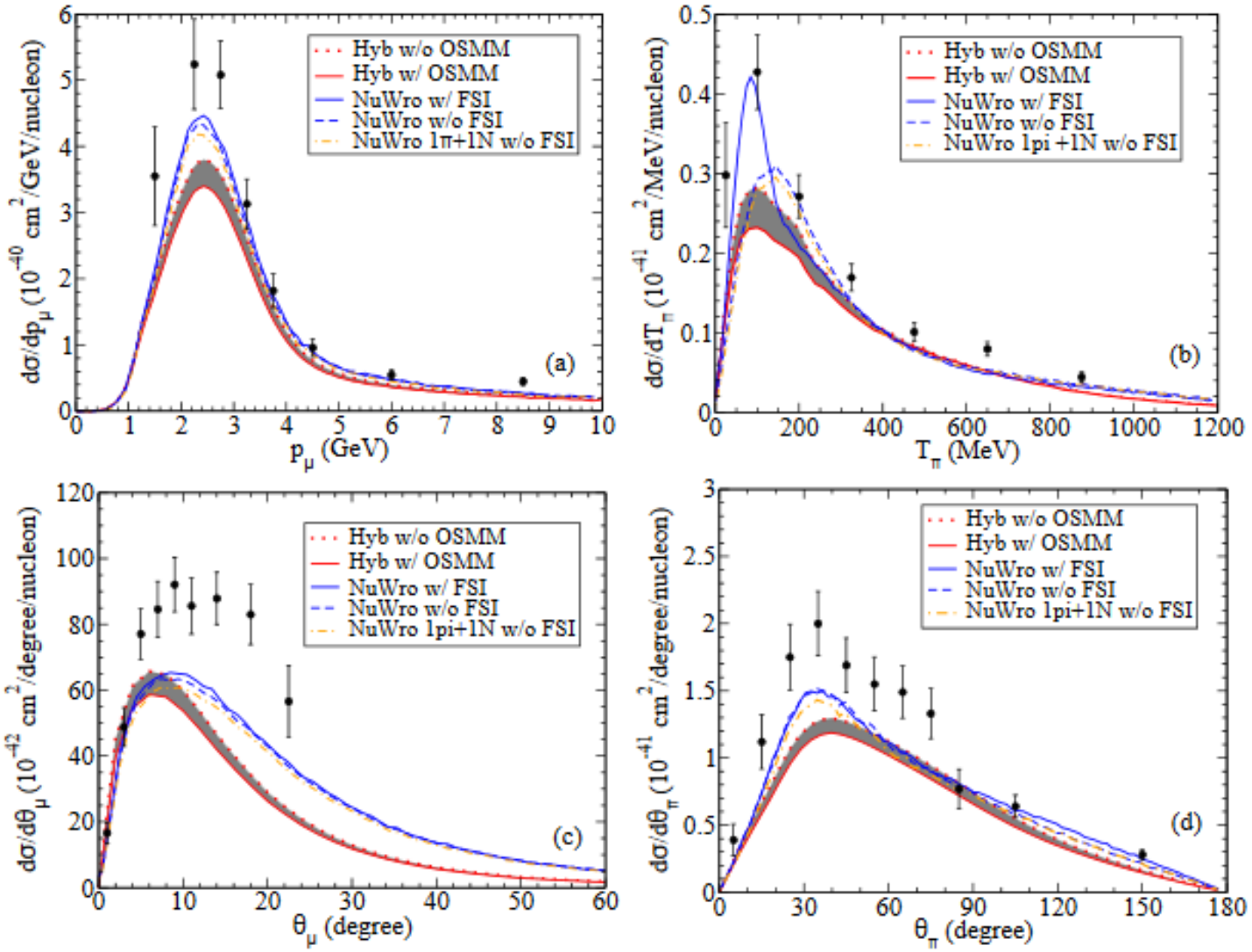
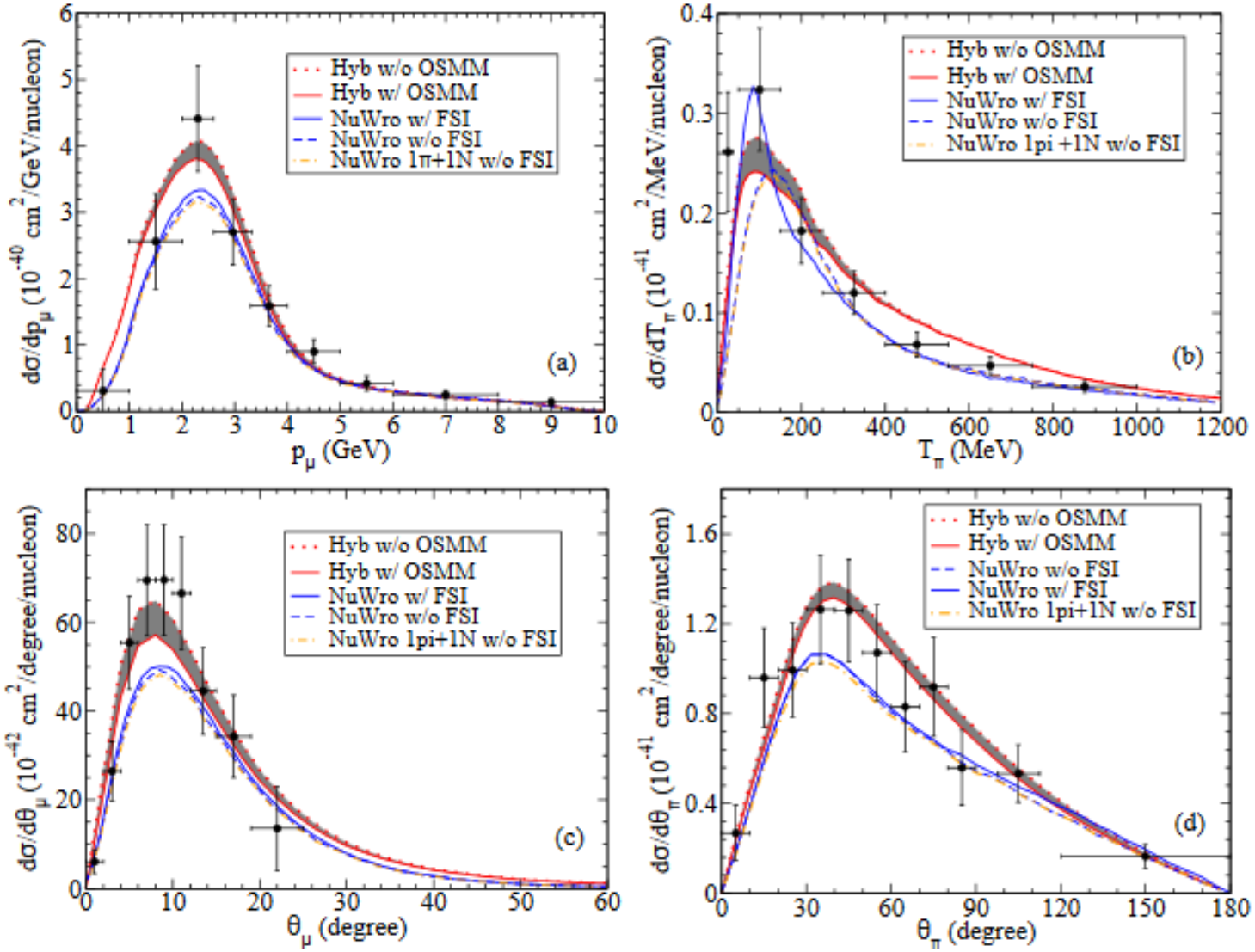


MINERvA νCC $1\pi^0$

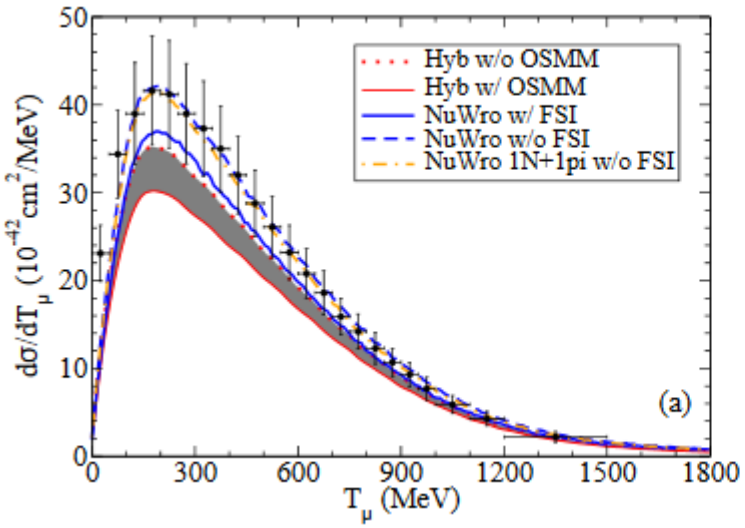
IV.Hybrid RPWIA model – results

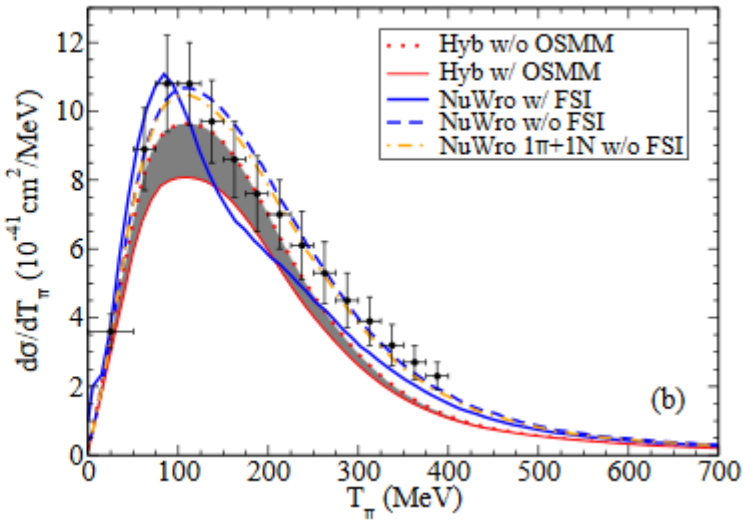


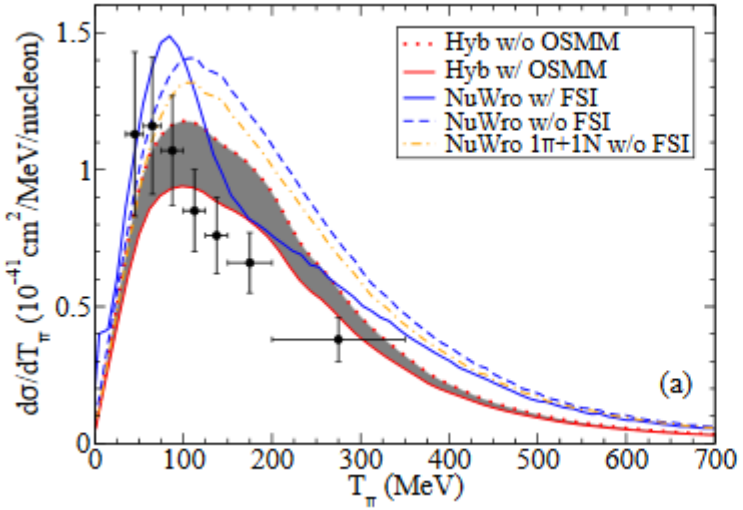
MINERvA $\bar{\nu}$CC $1\pi^0$

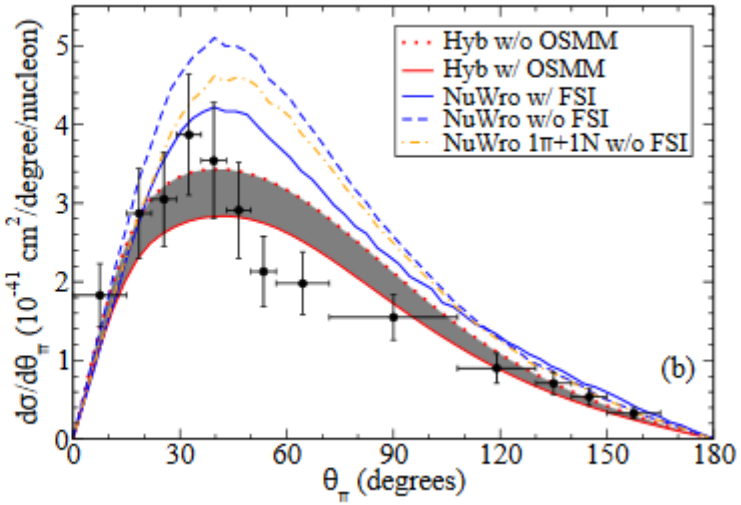
IV.Hybrid RPWIA model – results

MiniBooNE νCC $1\pi^+$





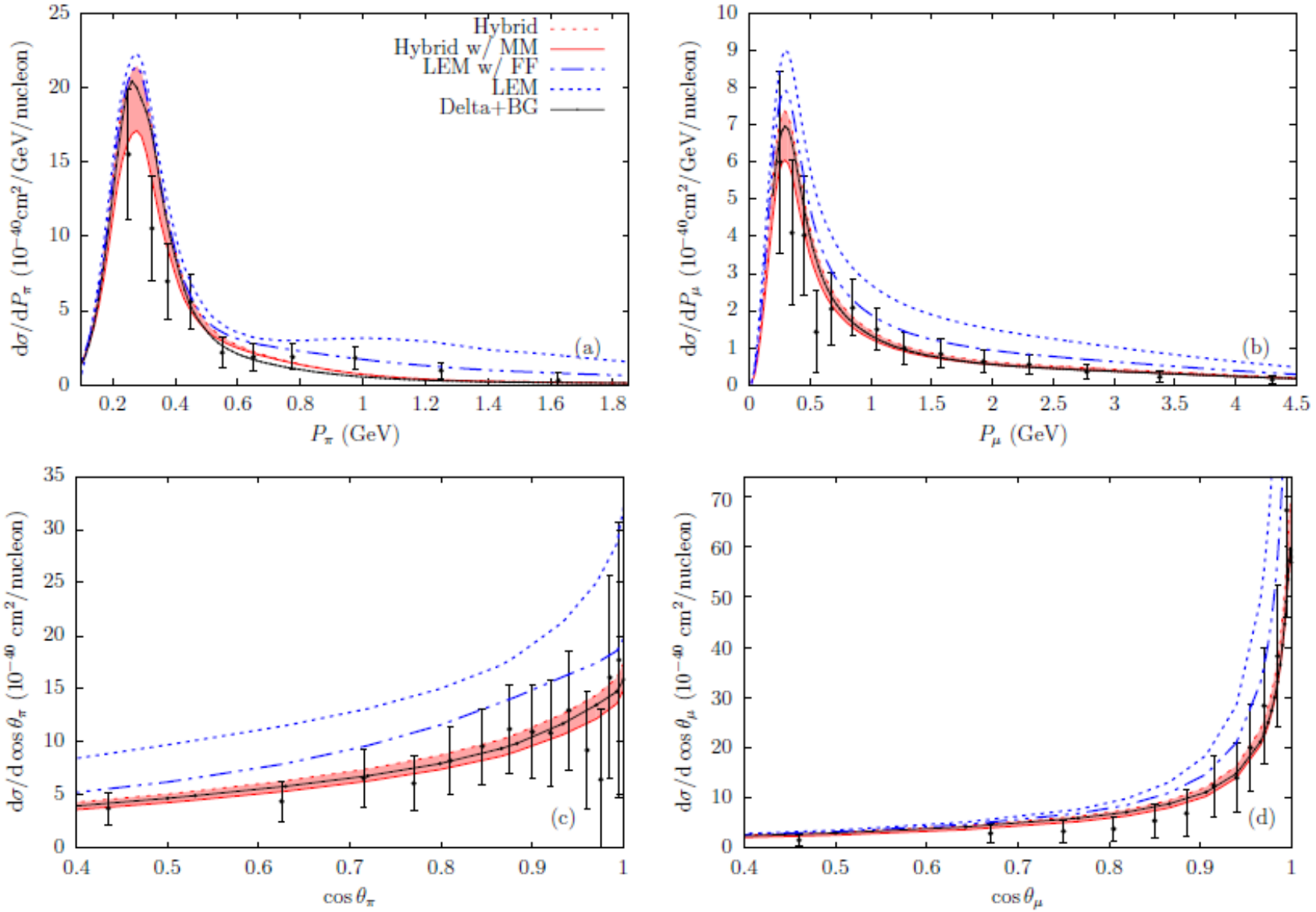




MINERvA νCC $1\pi^+$

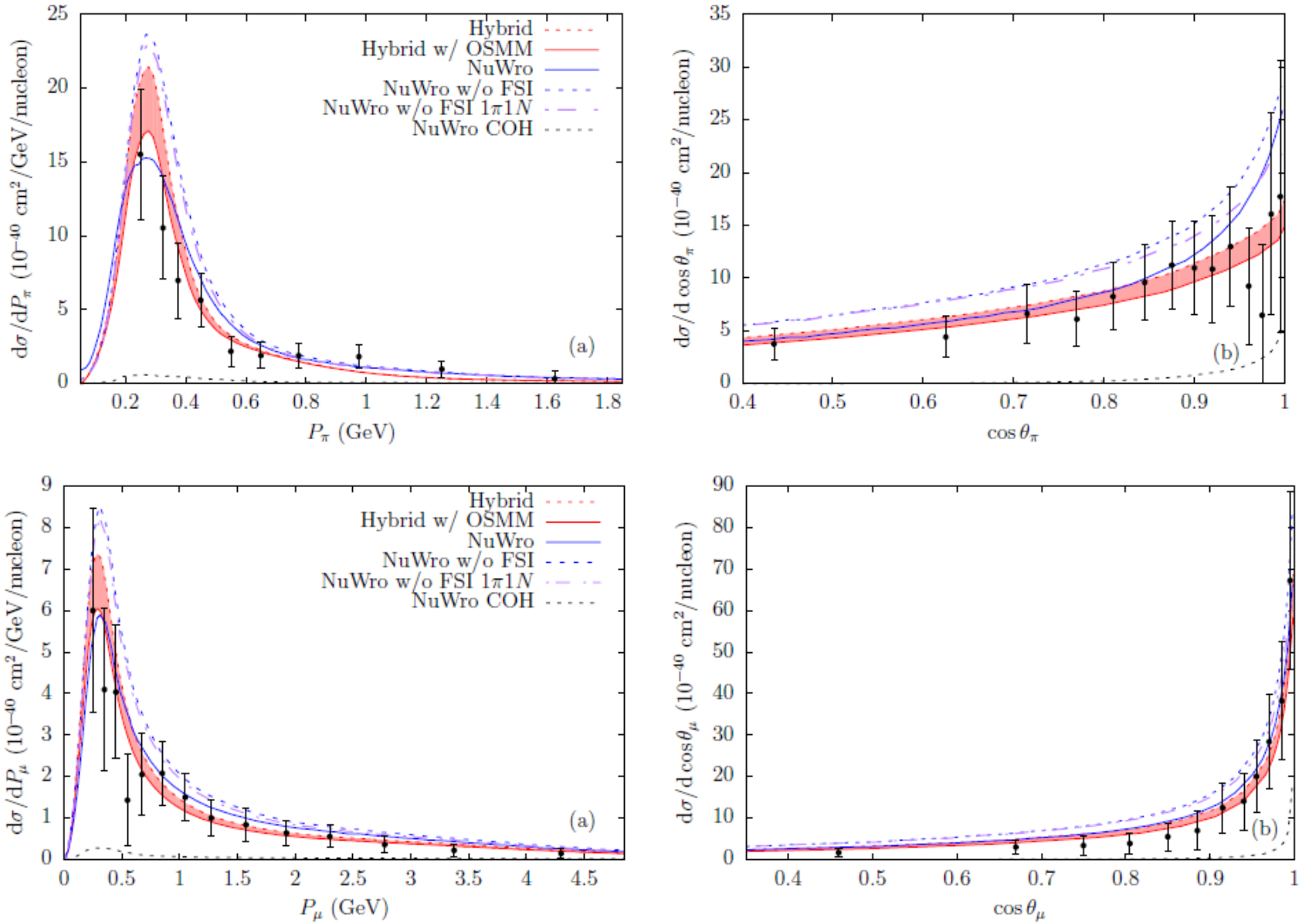
IV.Hybrid RPWIA model – results

T2K CC1π^+



IV.Hybrid RPWIA model – results

T2K CC1π^+



V.Extending the Hybrid model – distorted final state

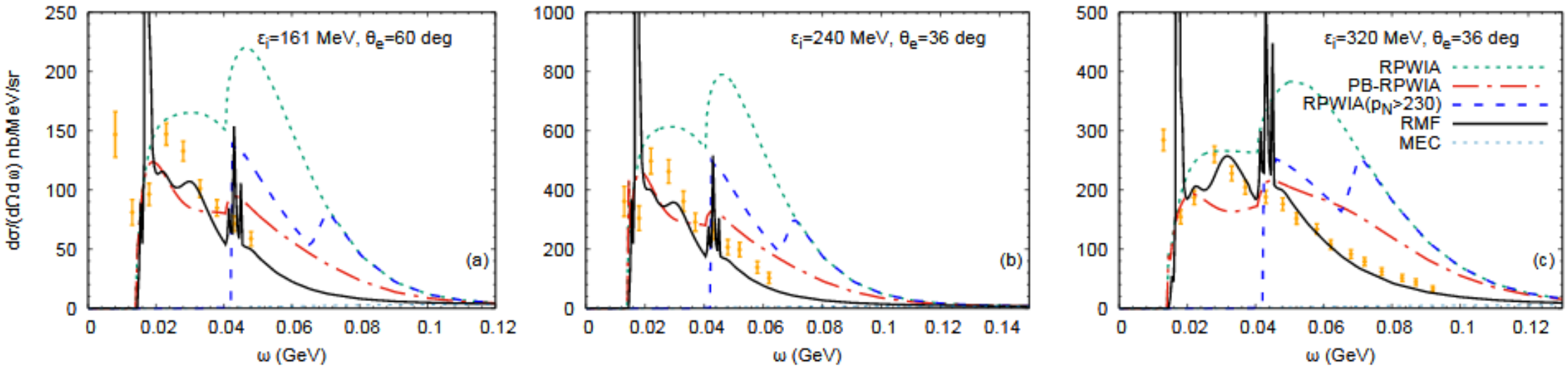
Plane waves

$$J^{\mu}_{had} = \sum_{i}^{A} \int d\mathbf{r}\, \overline{\Psi}_F(\mathbf{r})\, \phi^*(\mathbf{r}) \hat{O}^{\mu}_{one\text{-}body}(\mathbf{r})\, \Psi_B(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$

Relativistic mean-field wave functions

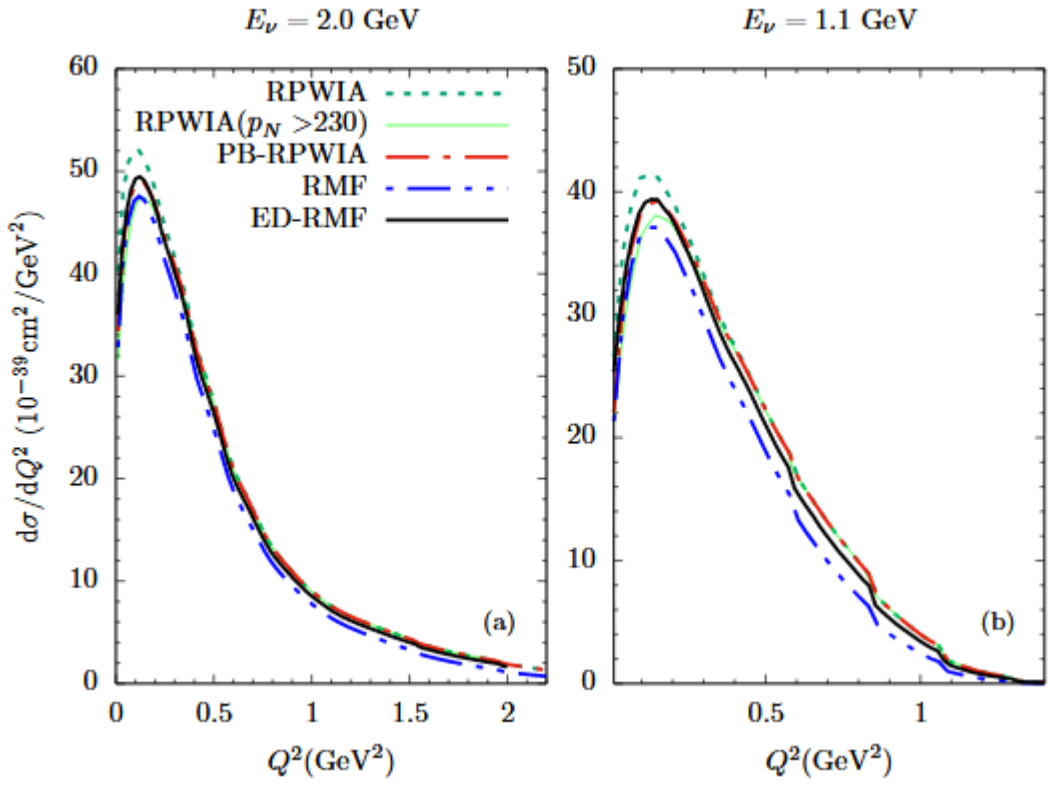
V.Extending the Hybrid model – distorted final state

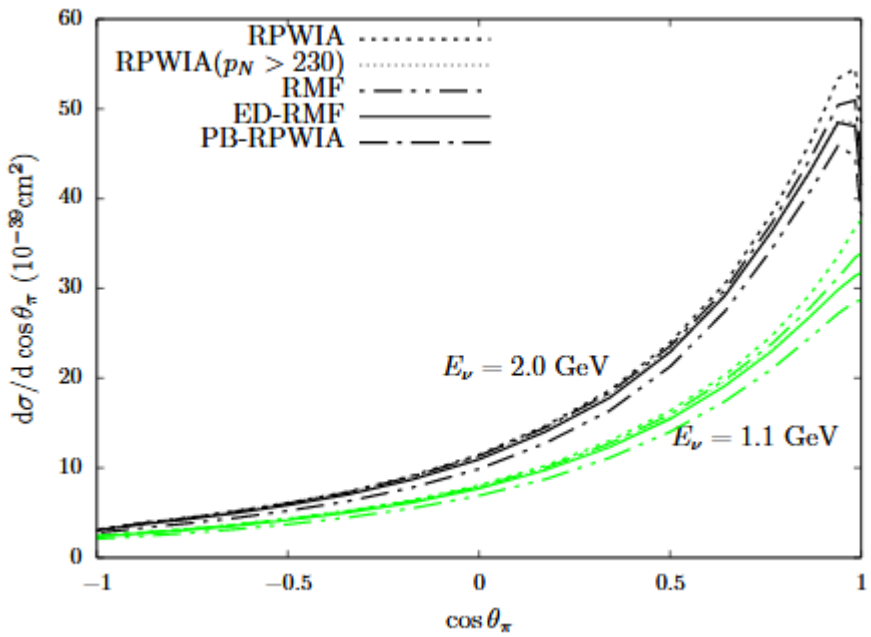
$^{12}C(e,e')$ QE



V.Extending the Hybrid model – distorted final state

$^{12}C(\nu,\nu'\pi)$





Summary

- Detailed microscopic cross sections calculations for neutrino-induced pion production
- Formalism valid over a broad energy range
- Taking into account as many nuclear physics aspects as feasible
- Estimate effect of FSI in comparing with NuWro