

# PION PRODUCTION IN A HYBRID MODEL

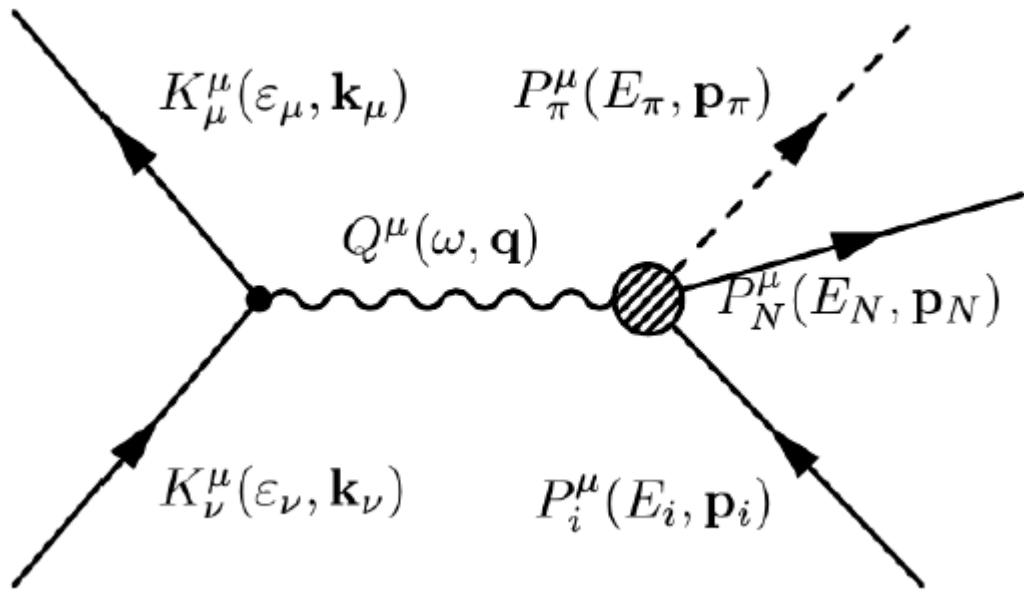
Natalie Jachowicz, A. Nikolakopoulos, R. González-Jímenez, K. Niewczas, J. Nys

- 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 :

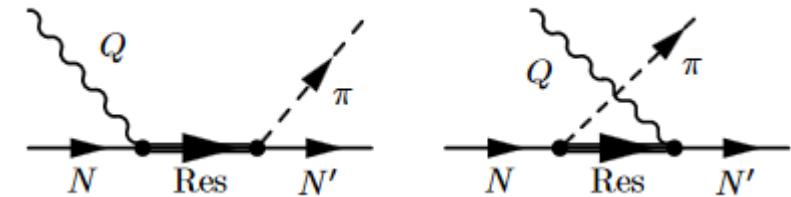
- ‘Neutrino-induced pion production from nuclei at medium energies’, C. Praet, O. Lalakulich, N. Jachowicz, J. Ryckebusch, Phys. Rev. C79, 044603 (2009) ; arXiv:0804.2750.
- ‘Electroweak single-pion production off the nucleon : from threshold to high invariant masses’ R. Gonzalez-Jimenez, N. Jachowicz, 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. Udiás,, arXiv1904:10696, accepted for publication PRC

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



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

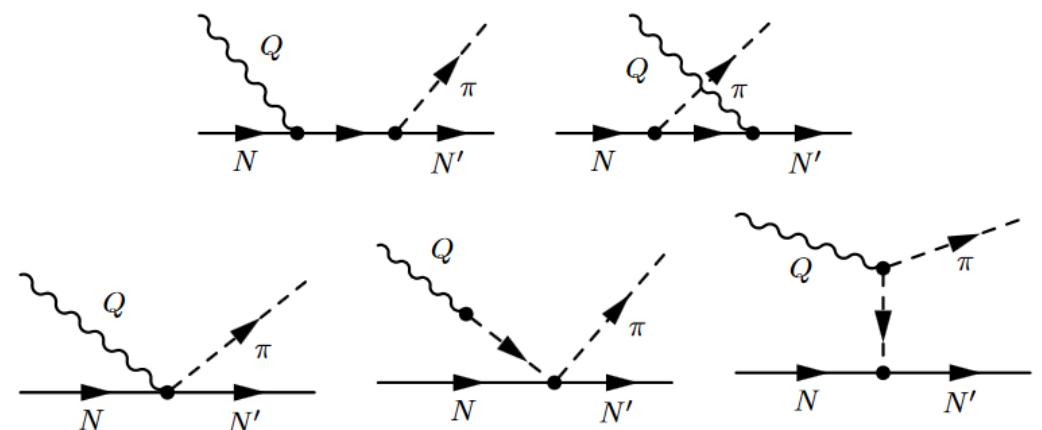
## Resonances



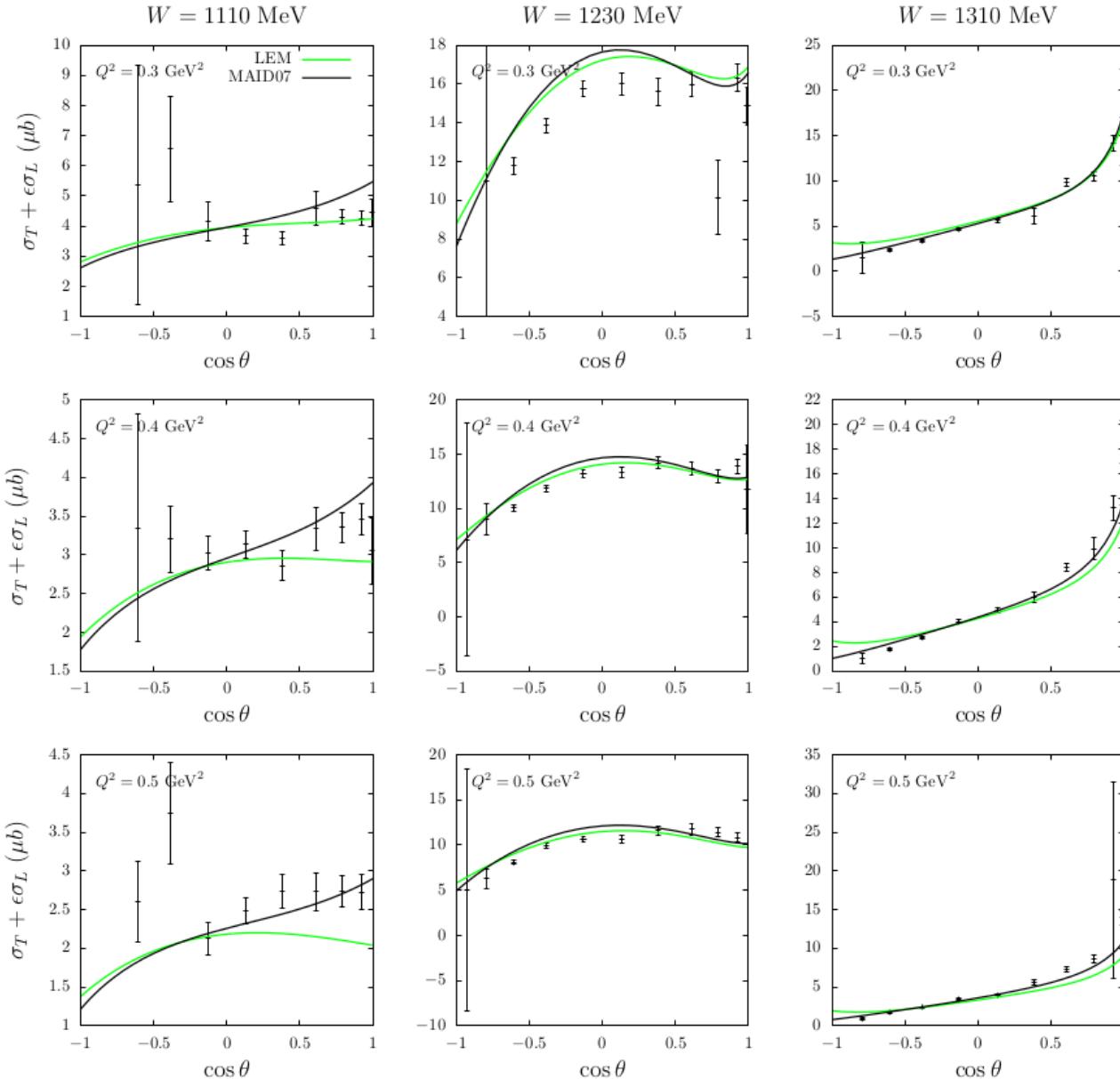
P33 (1232), P11(1440), D13 (1520), S11 (1535)

+

## ChPT background



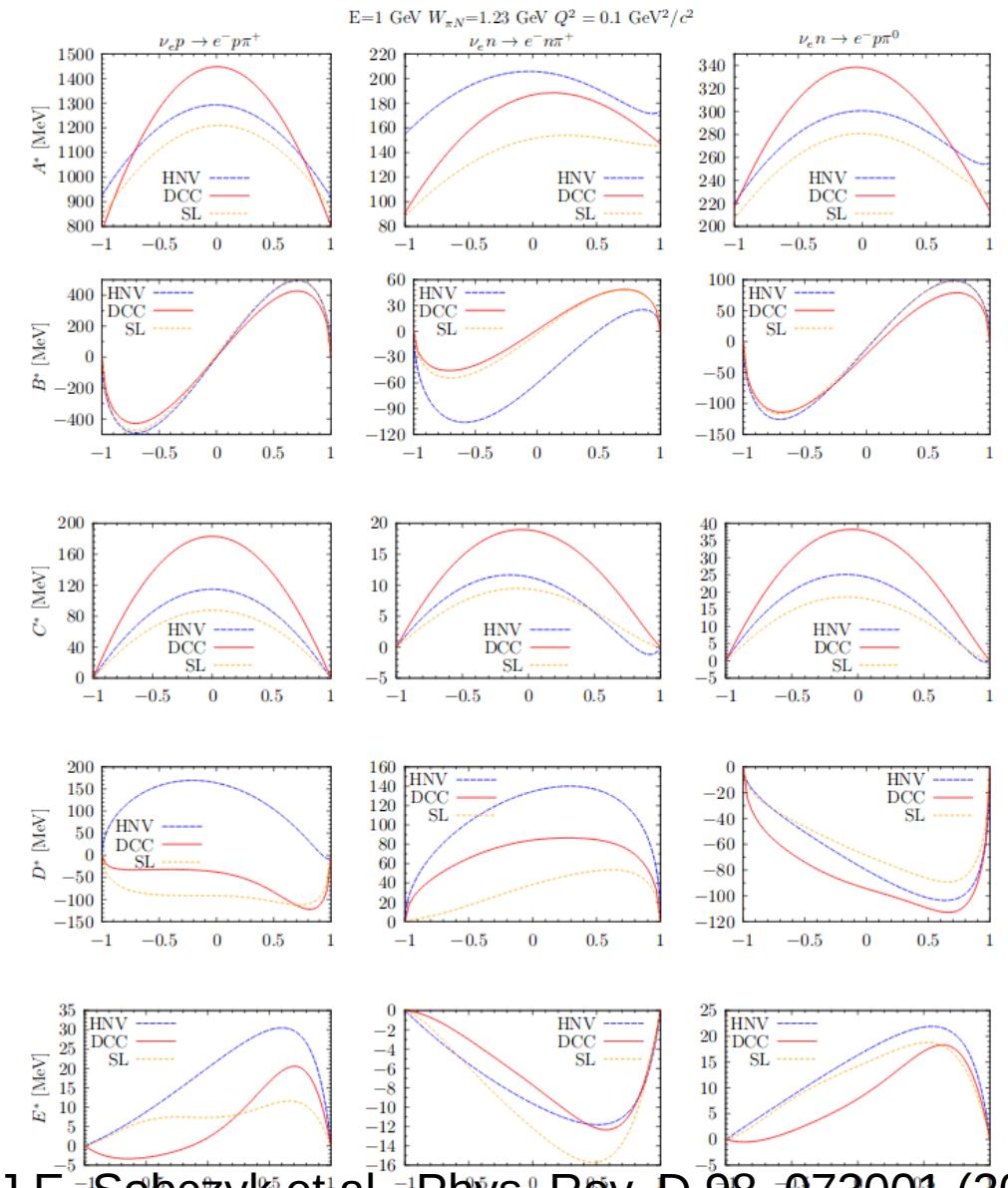
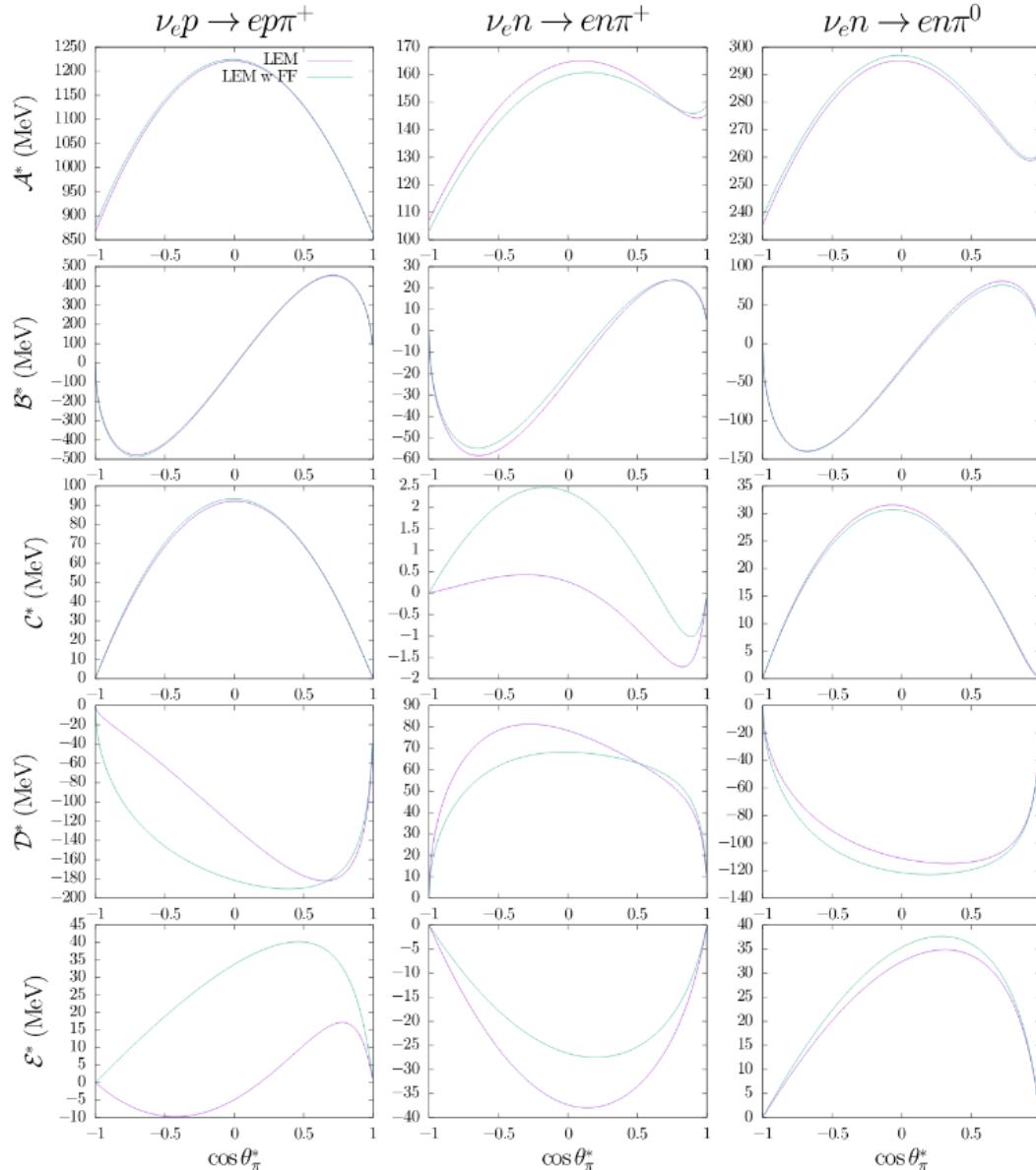
# I. Single pion production on the nucleon – low energy model



## Vector current

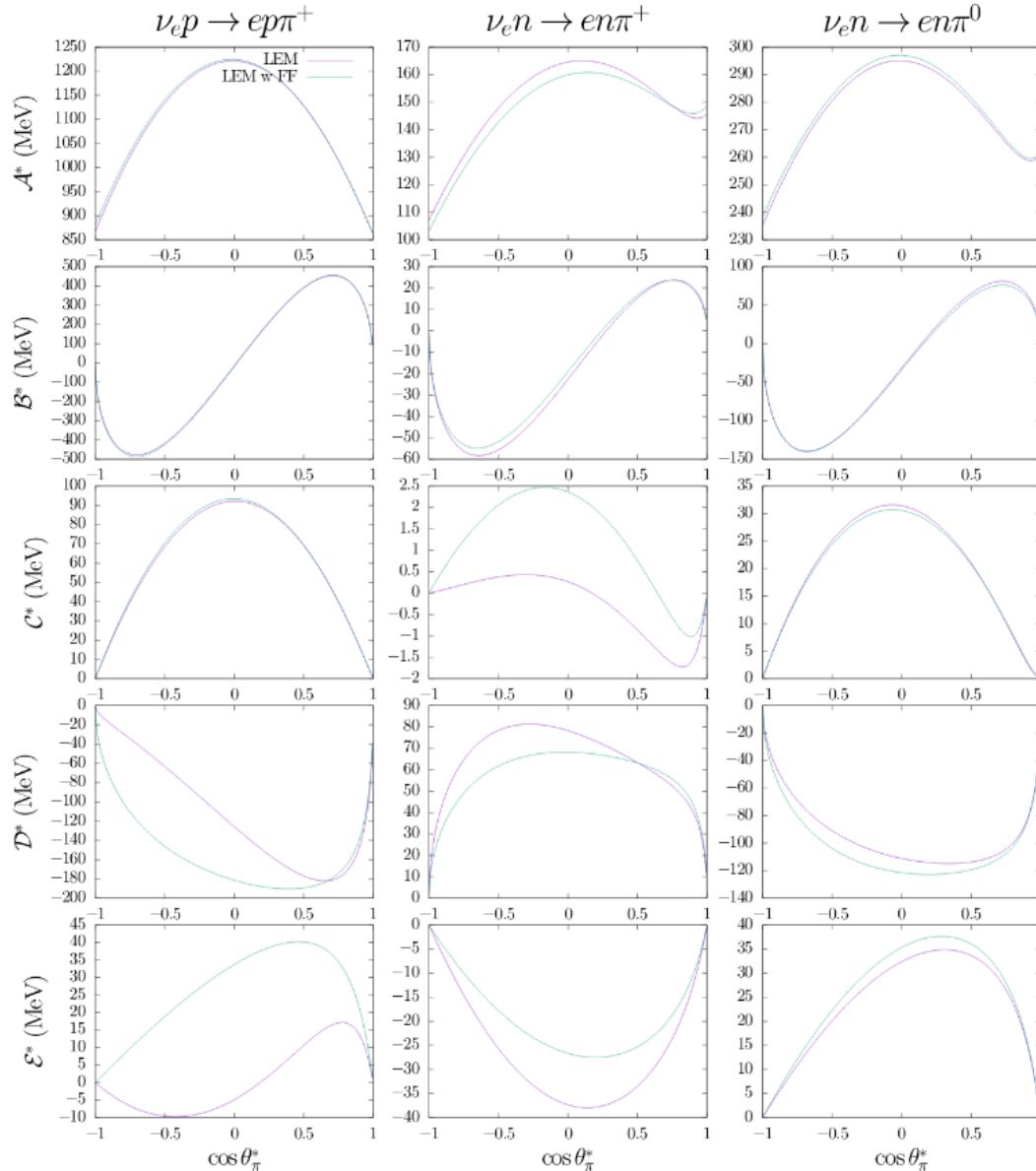
- Comparison to data and MAID07
- Satisfactory description of inclusive structure functions for electroproduction of  $\pi^+$

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



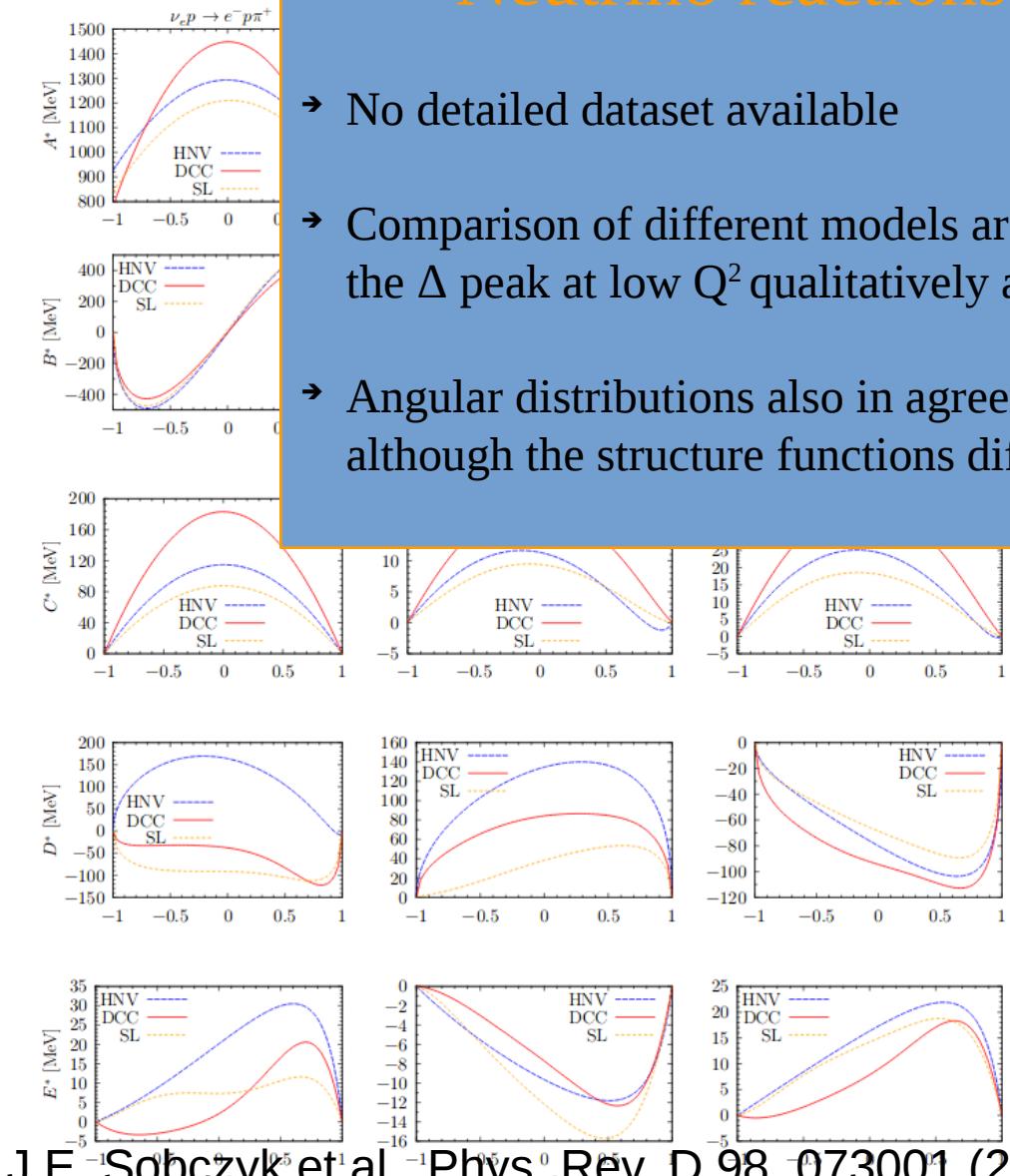
J.E. Sobczyk et al., Phys. Rev. D 98, 073001 (2018)

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

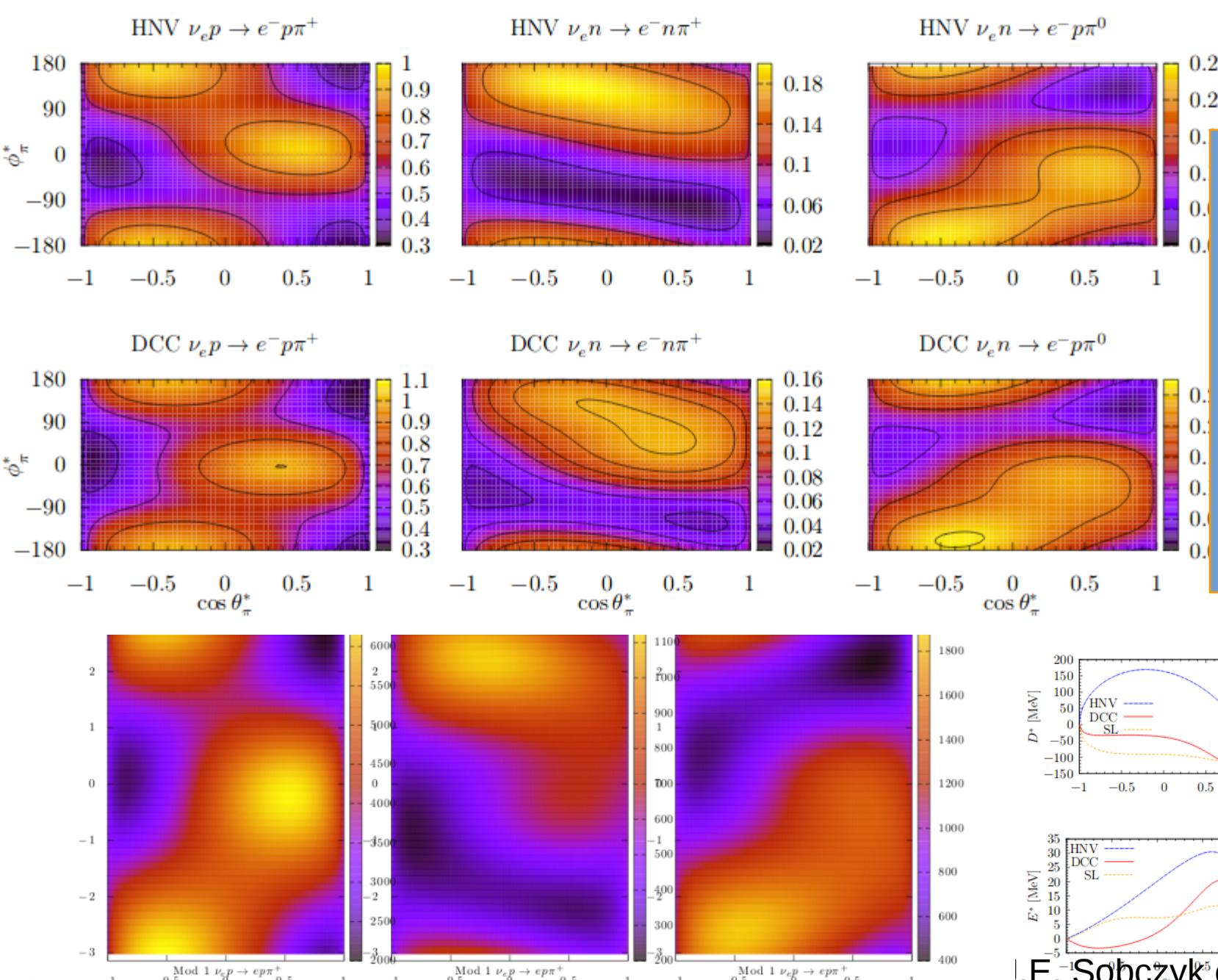


## Neutrino reactions

- No detailed dataset available
- Comparison of different models around the  $\Delta$  peak at low  $Q^2$  qualitatively agree
- Angular distributions also in agreement although the structure functions differ



J.E. Sobczyk et al., Phys. Rev. D 98, 073001 (2018)



model

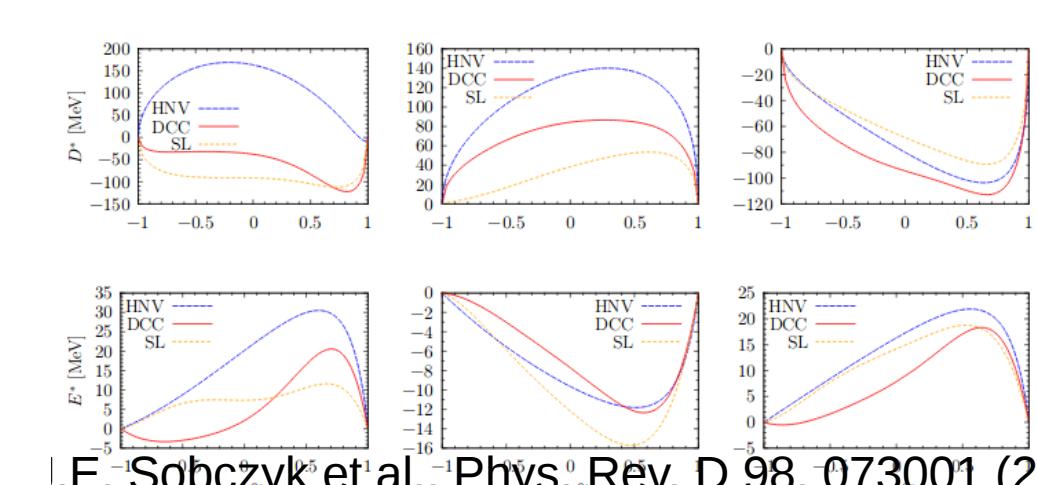
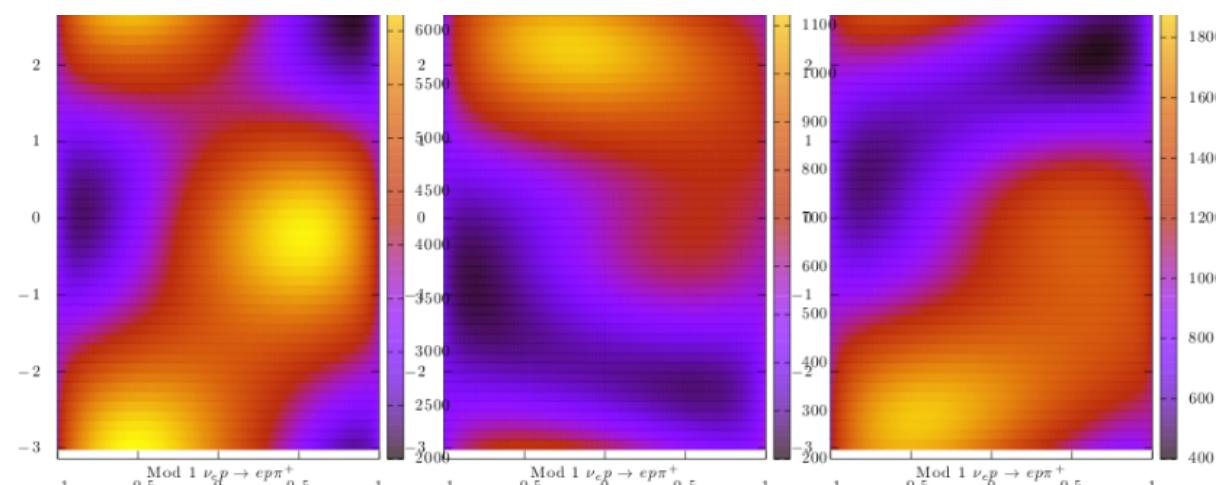
$E=1 \text{ GeV } W_{\pi N}=1.23 \text{ GeV } Q^2 = 0.1 \text{ GeV}^2/c^2$

$\nu_e n \rightarrow e^- n \pi^+$

$\nu_e n \rightarrow e^- p \pi^0$

## Neutrino reactions

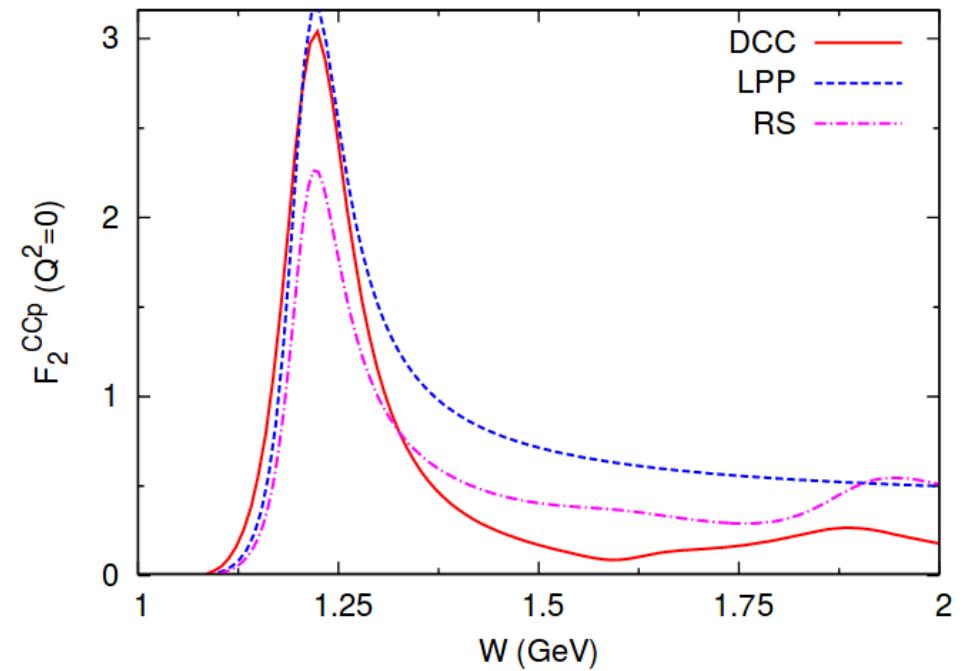
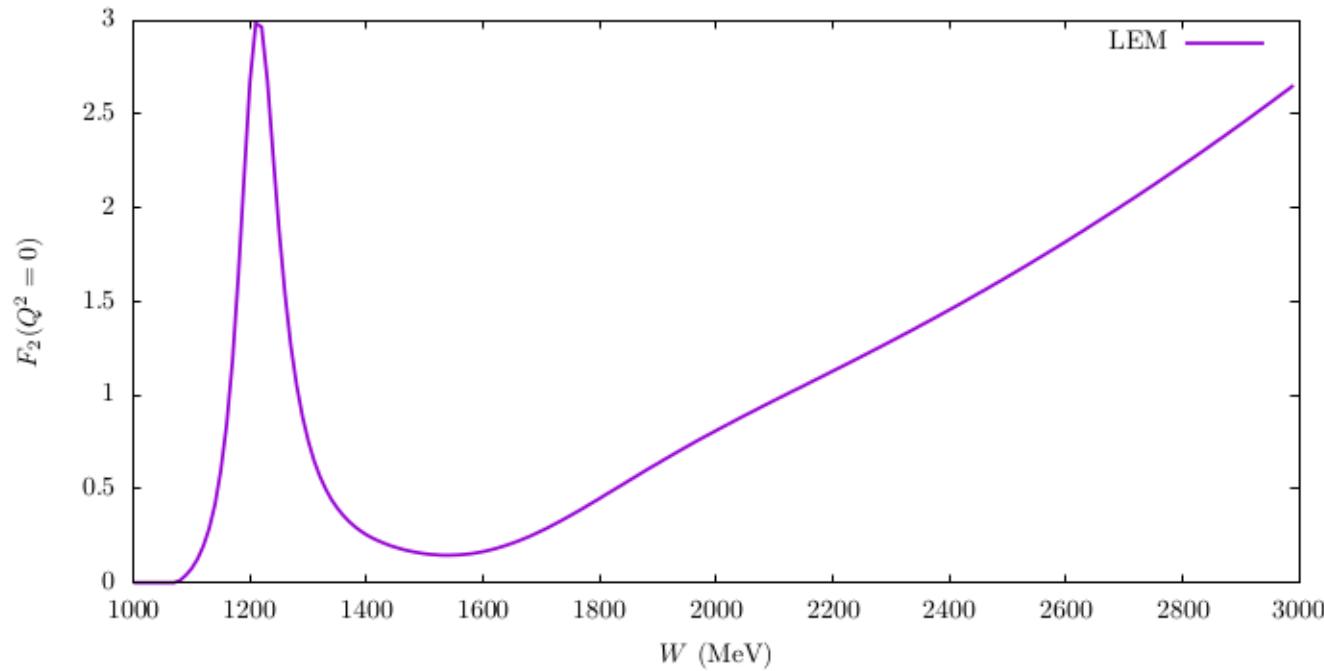
- No detailed dataset available
- Comparison of different models around the  $\Delta$  peak at low  $Q^2$  qualitatively agree
- Angular distributions also in agreement although the structure functions differ



J.E. Sobczyk et al., Phys. Rev. D 98, 073001 (2018)

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

Constraints from  $\pi + N$  scattering at  $Q^2 = m_\pi^2$

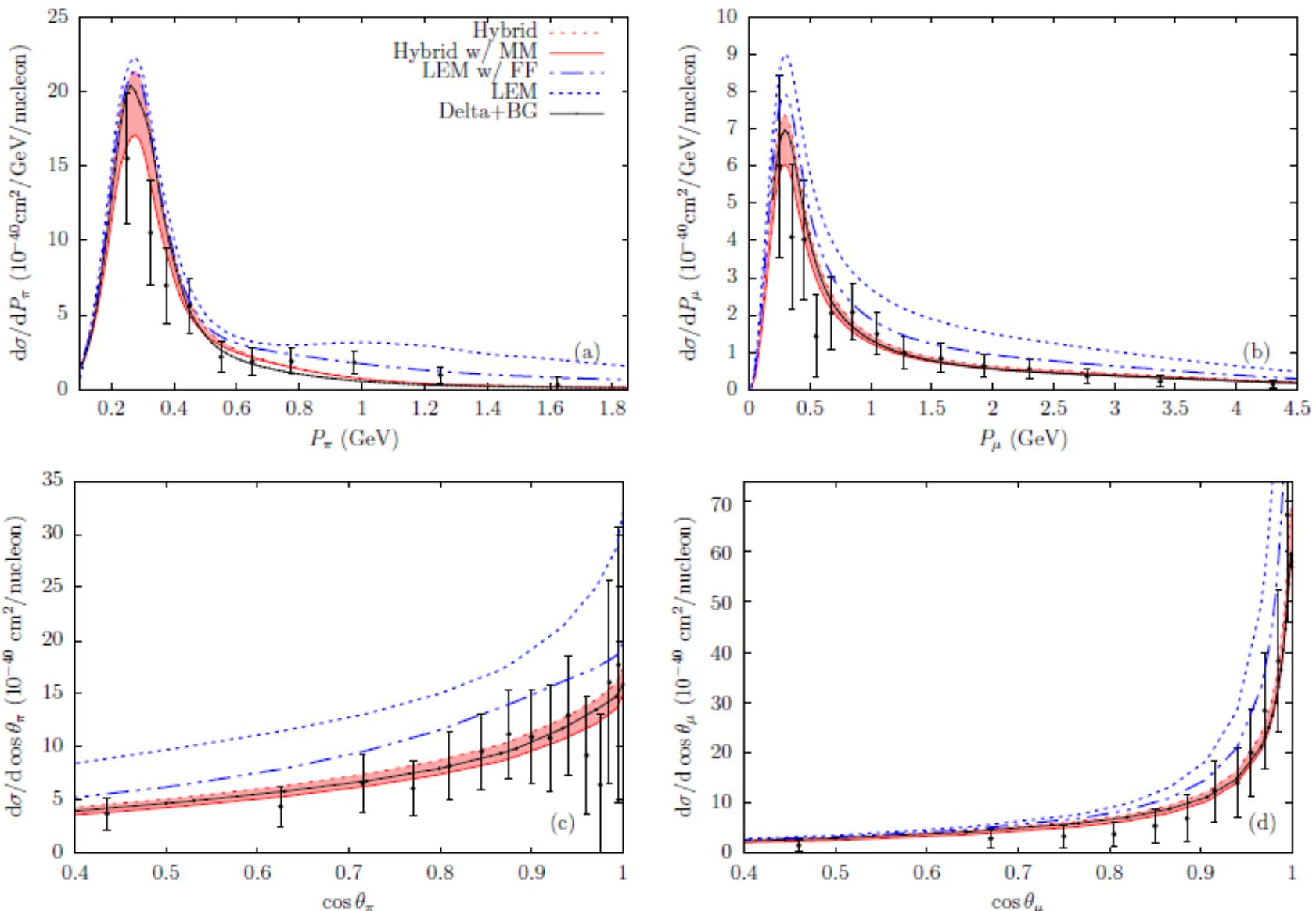


Issues from background diagrams show up at  $W \sim 1.5$  GeV

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

T2K CC1 $\pi^+$

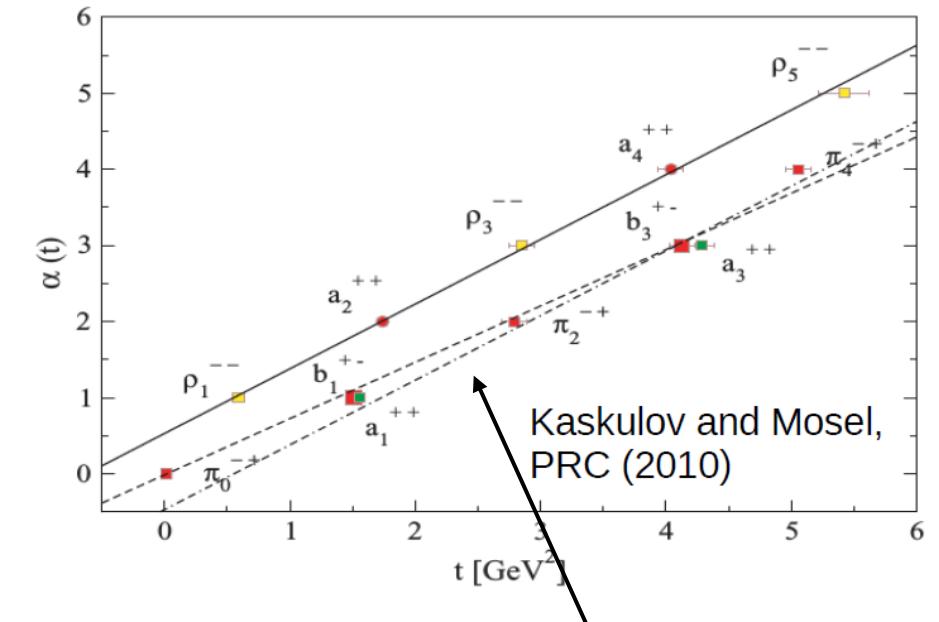
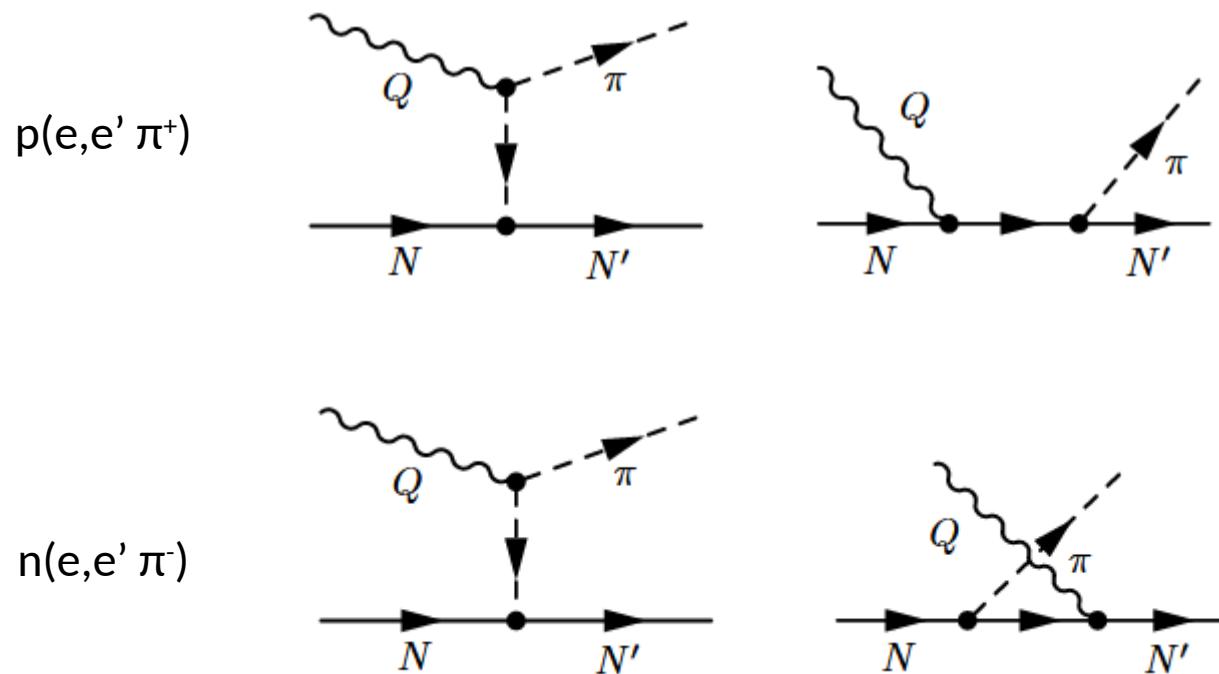
- Comparison of LEM to T2K data shows significant contributions from high W region



## 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).



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

## II.High energy model- Regge approach in a nutshell

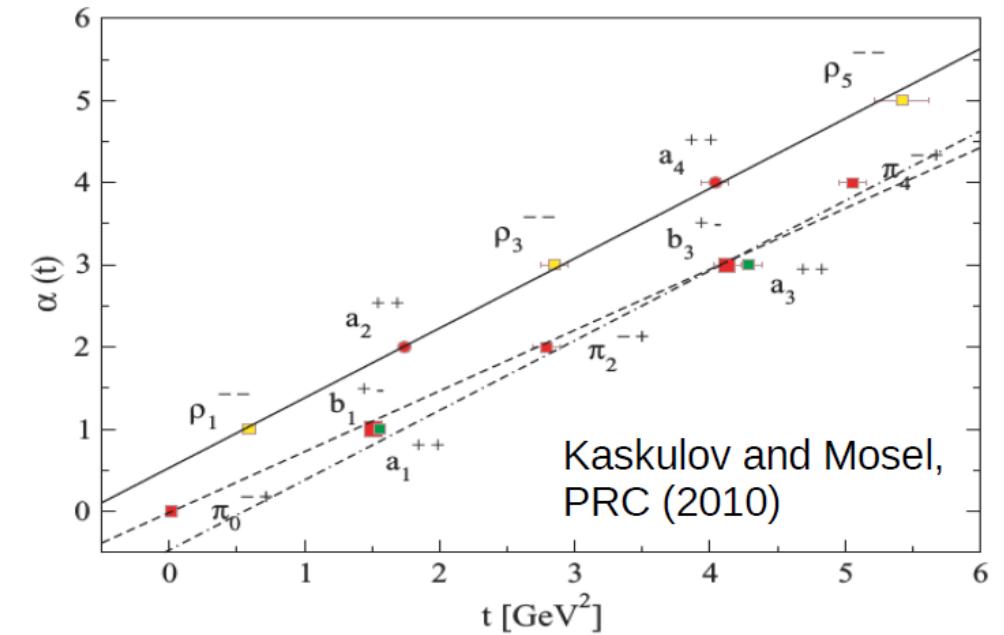
Regge recipe :

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

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

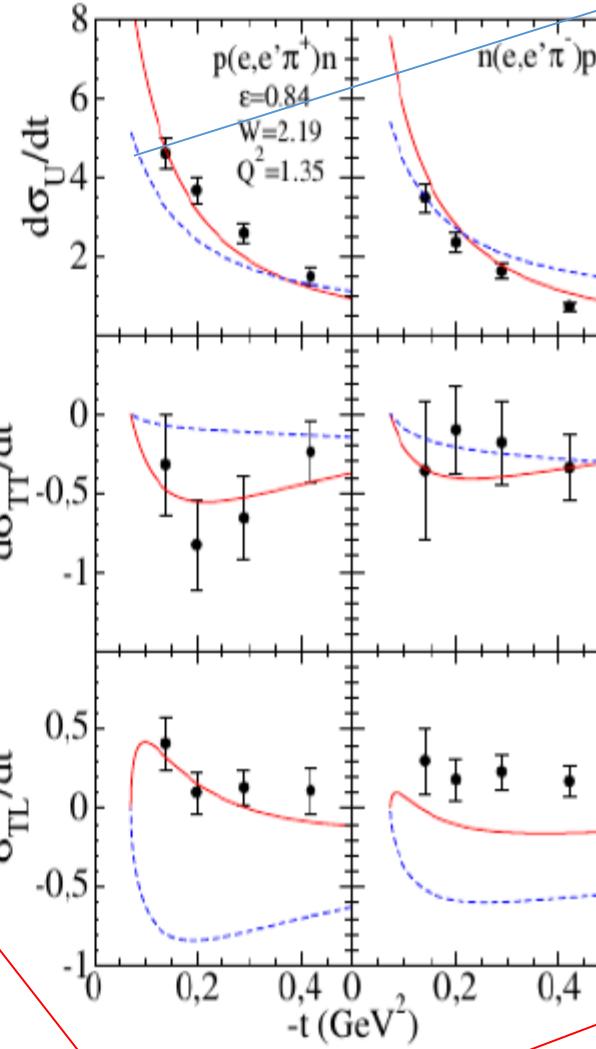
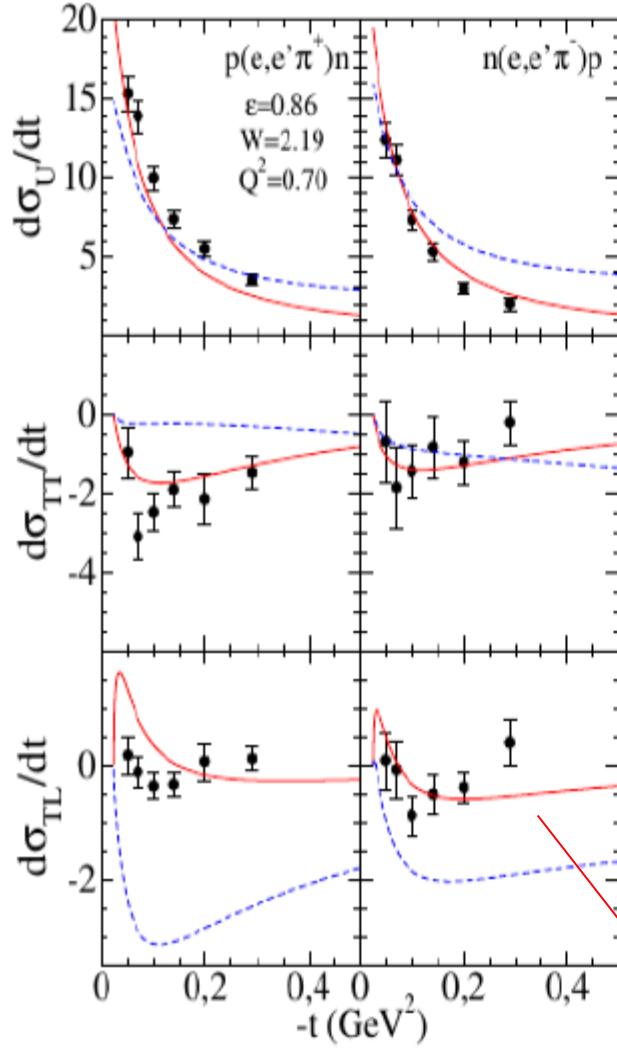
↓

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

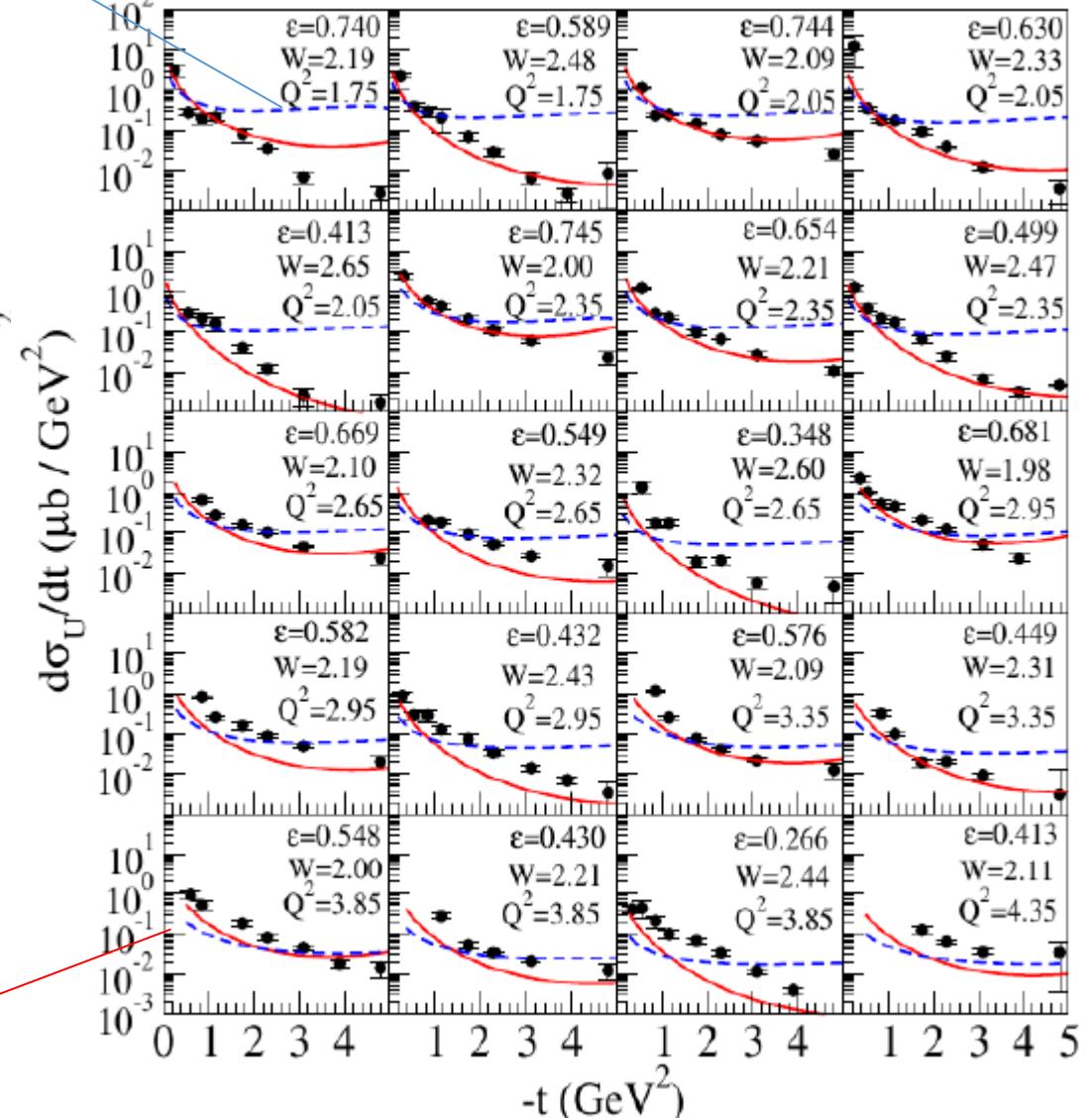


Regge theory provides the s dependence of the amplitude at high energies  
The t-dependence is modeled from the low energy diagrams (GLV approach)

## II.High energy model – results for electron scattering



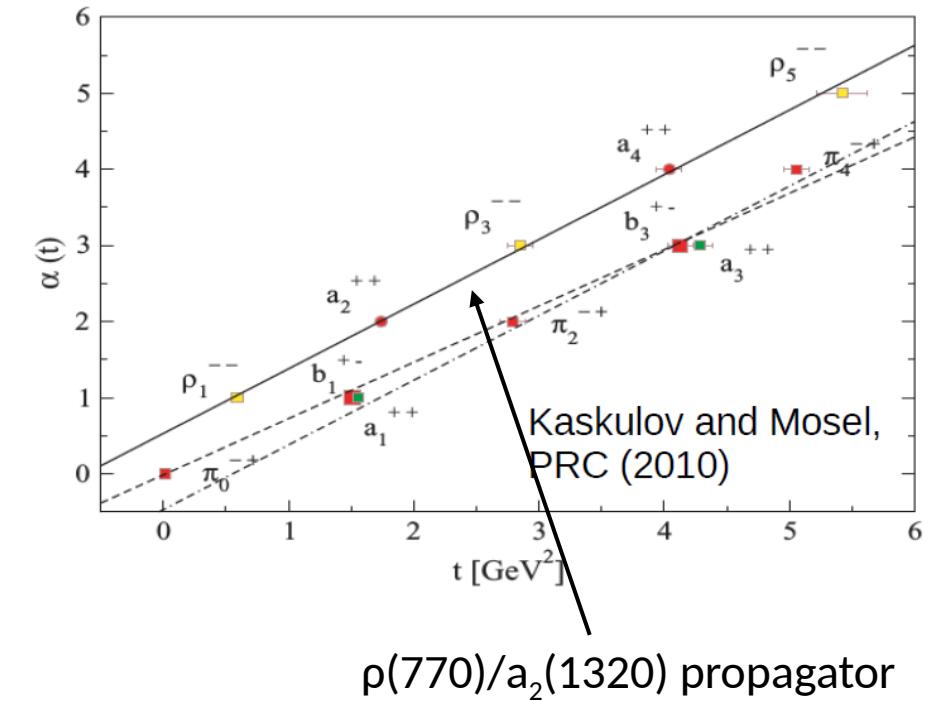
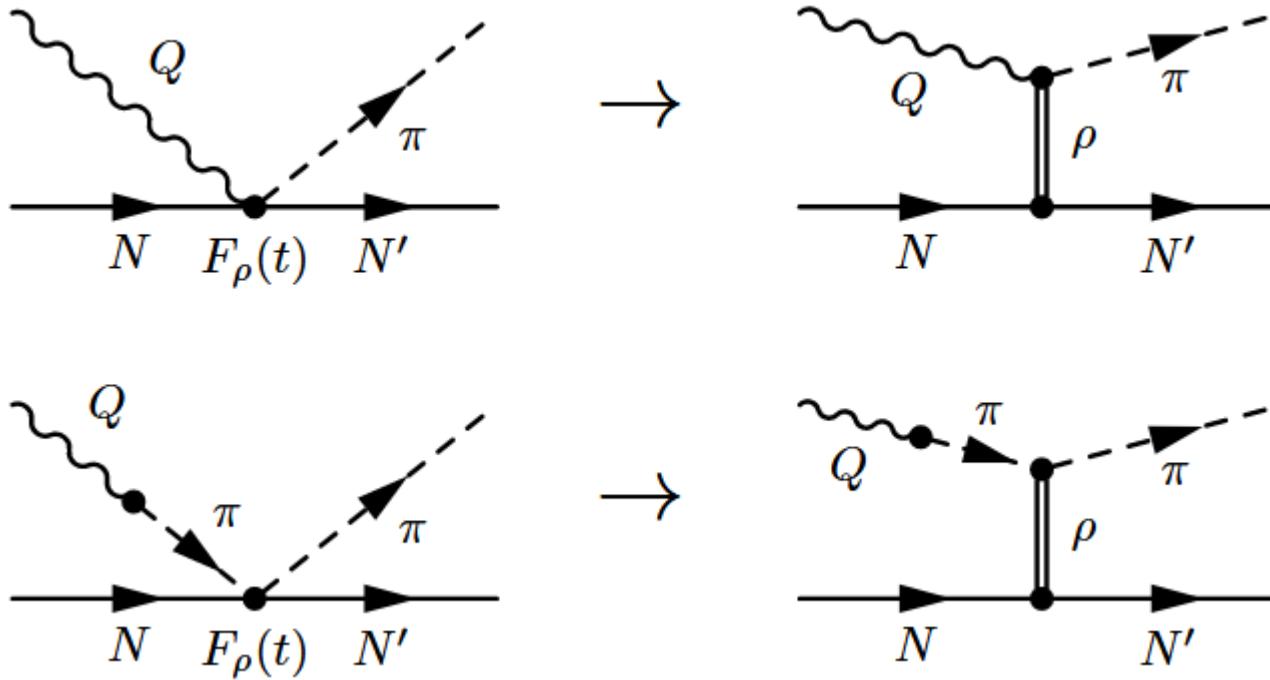
LEM



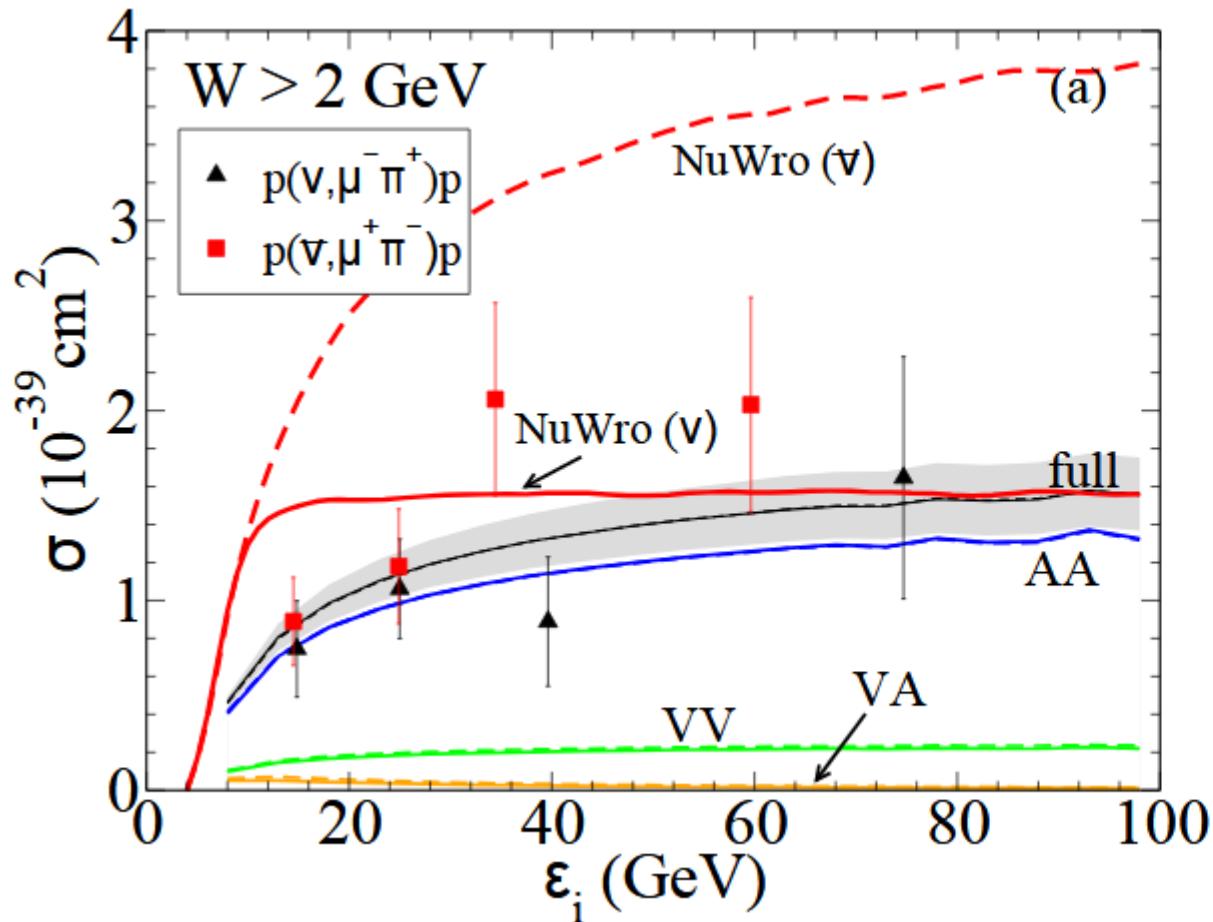
ReChi

## II.High energy model : axial part

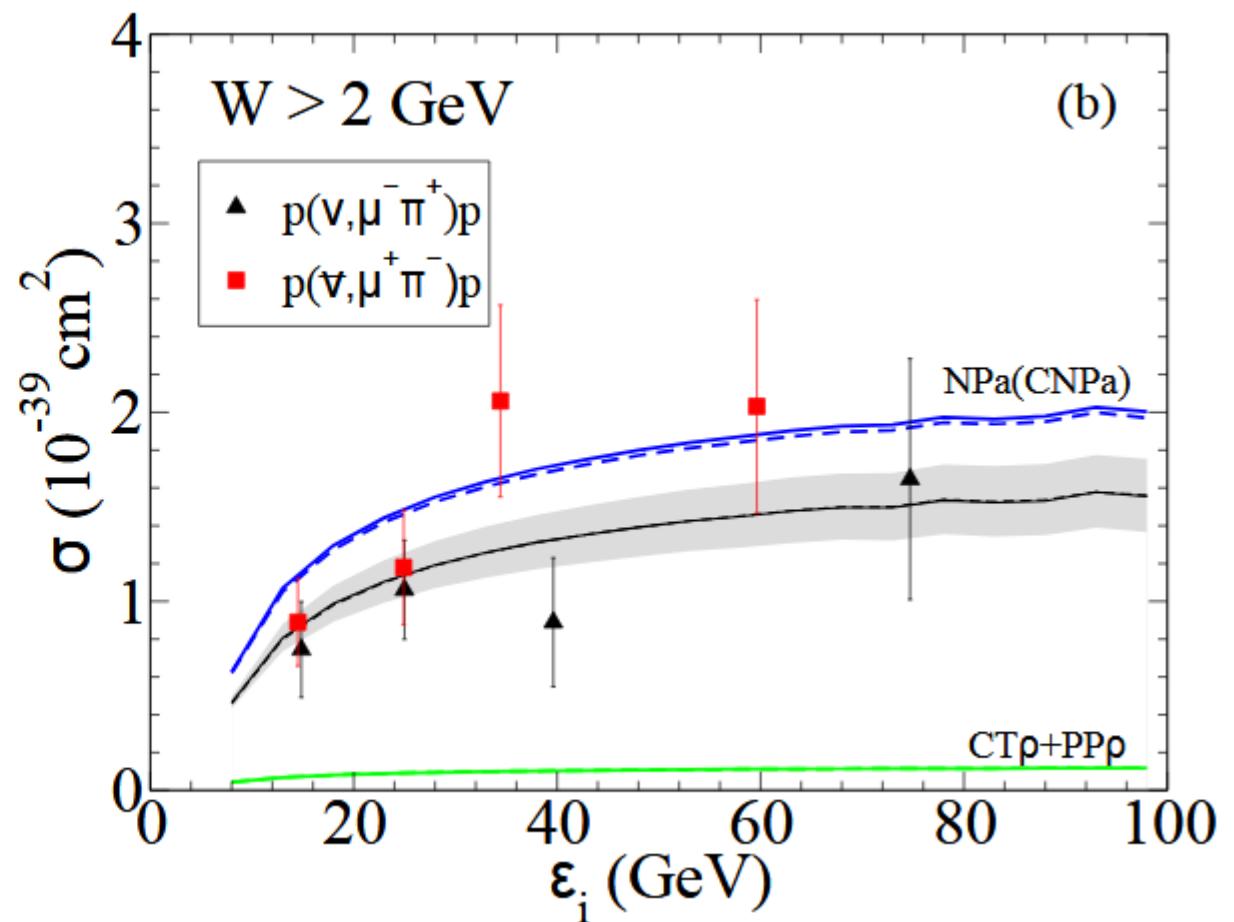
Identify the Regge trajectory for the axial current



## II.High energy model



Fit single parameter to 8 datapoints

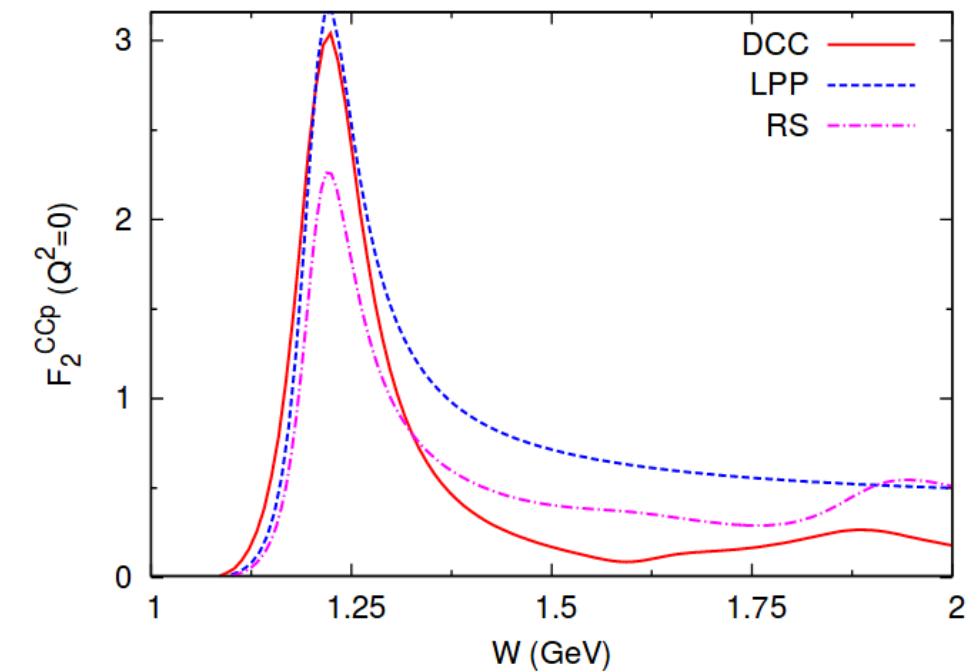
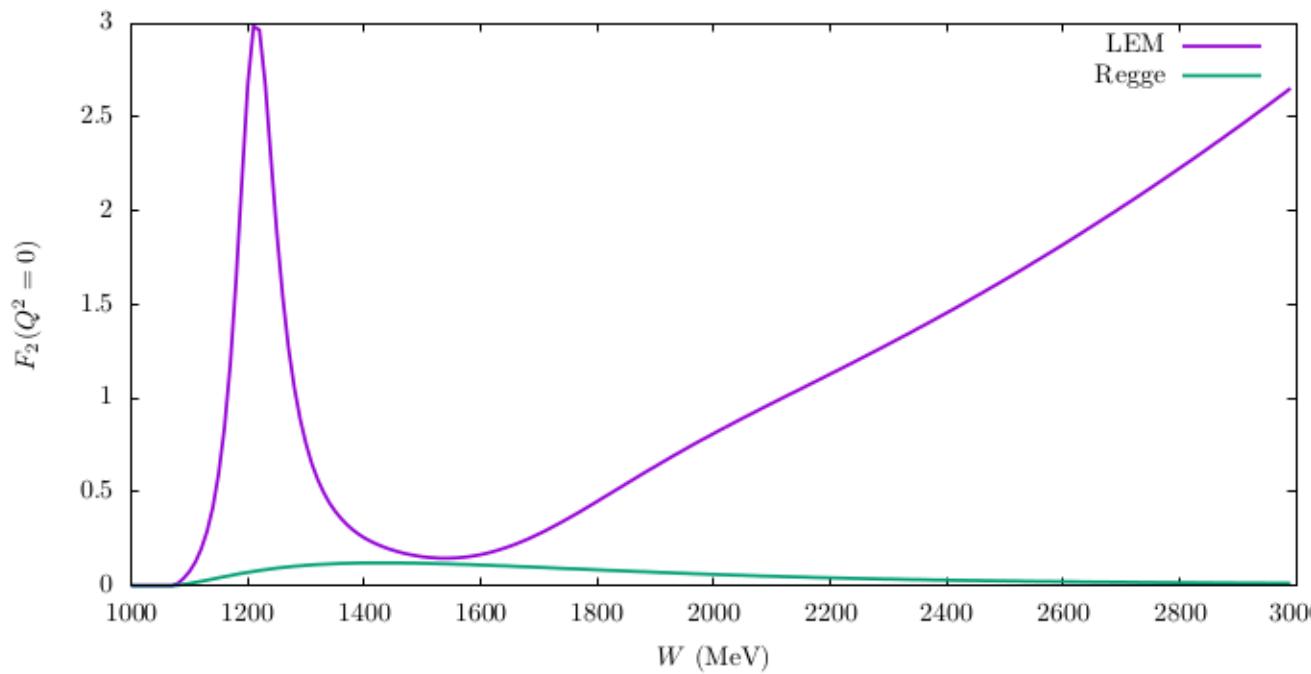


Data :P. Allen et al. Nucl. Phys. B264, 221 (1986).

# I. Single pion production on the nucleon – Hybrid model

Constraints from  $\pi + N$  scattering at  $Q^2 = m_\pi^2$

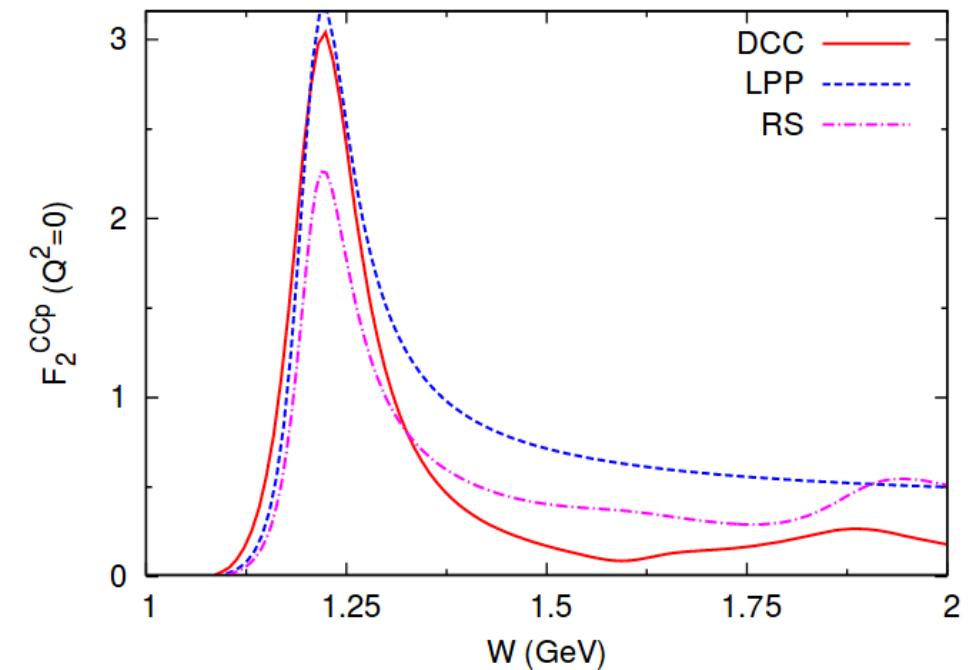
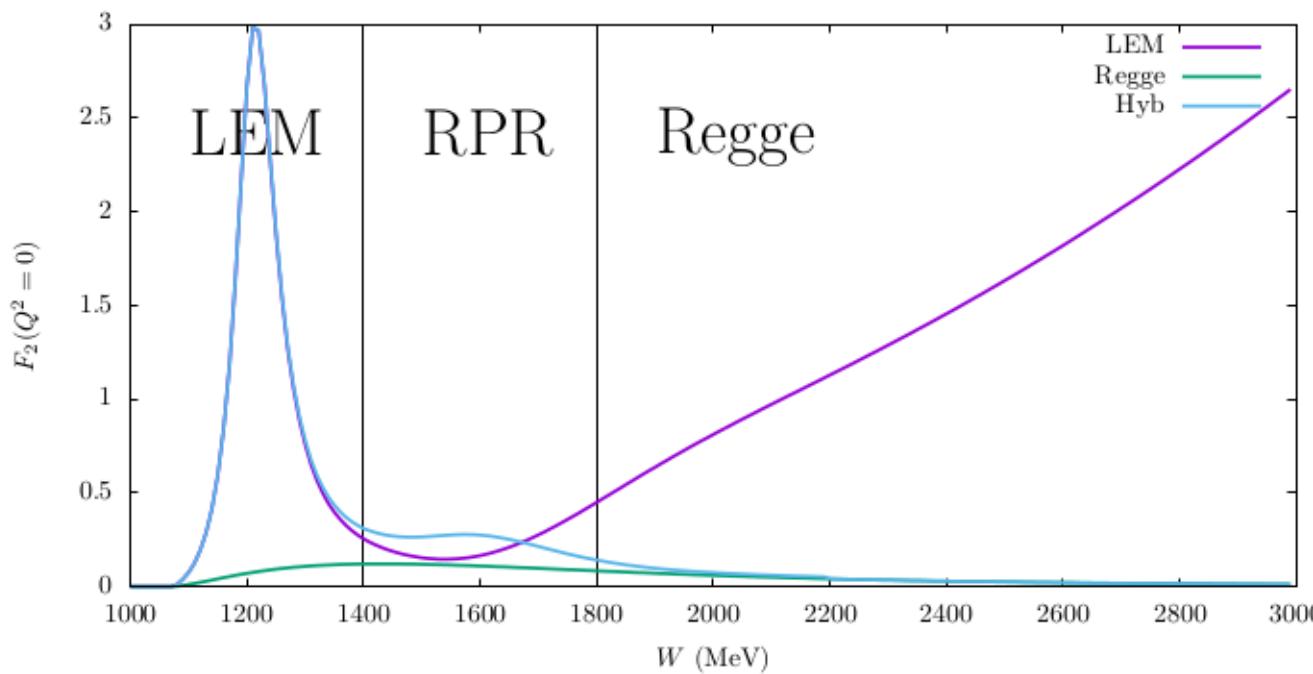
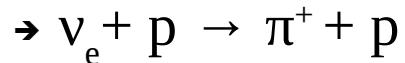
$$\rightarrow v_e + p \rightarrow \pi^+ + p$$



Nakamura et al.  
→ Arxiv:1506.03403v2

# I. Single pion production on the nucleon – Hybrid model

Constraints from  $\pi + N$  scattering at  $Q^2 = m_\pi^2$

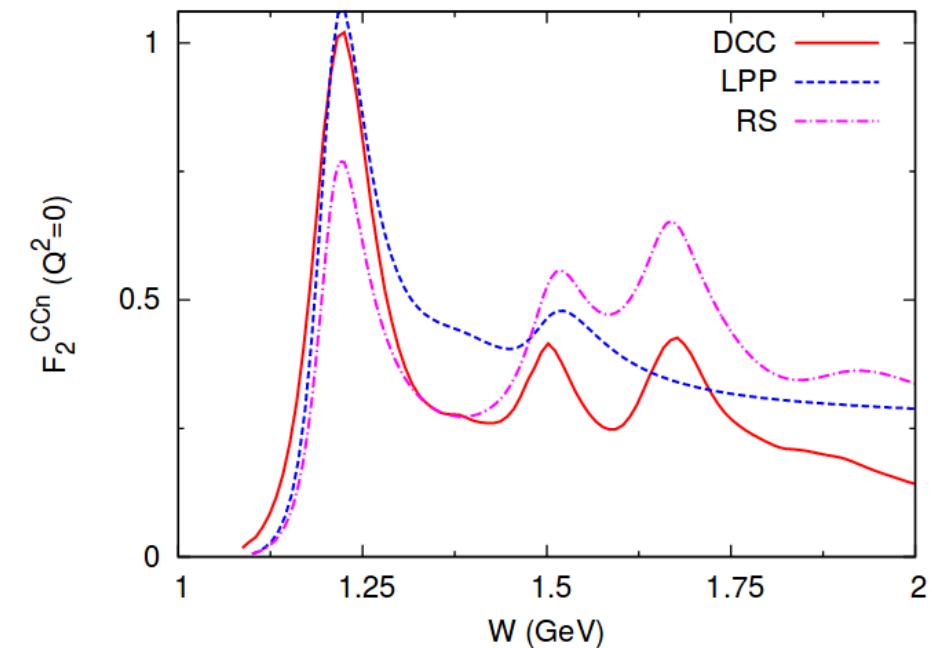
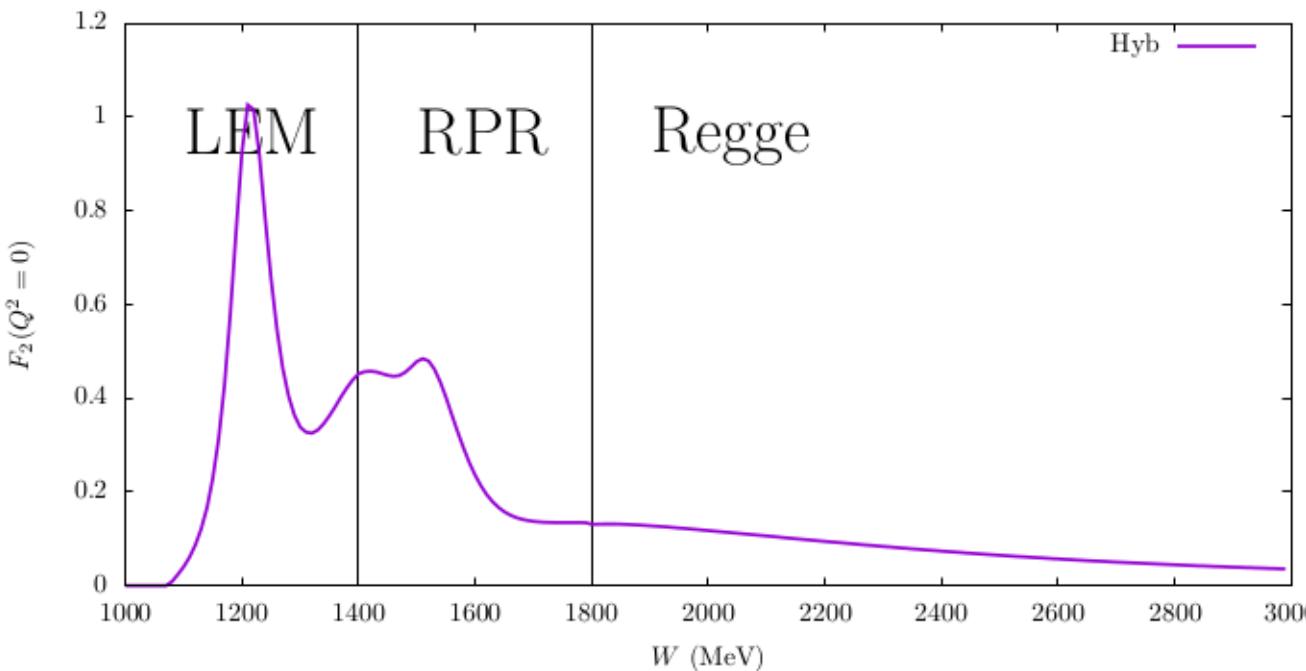


Nakamura et al.  
→ Arxiv:1506.03403v2

# I. Single pion production on the nucleon – Hybrid model

Constraints from  $\pi + N$  scattering at  $Q^2 = m_\pi^2$

$$\rightarrow v_e + n \rightarrow \pi^{+0} + p/n$$



Nakamura et al.  
→ Arxiv:1506.03403v2

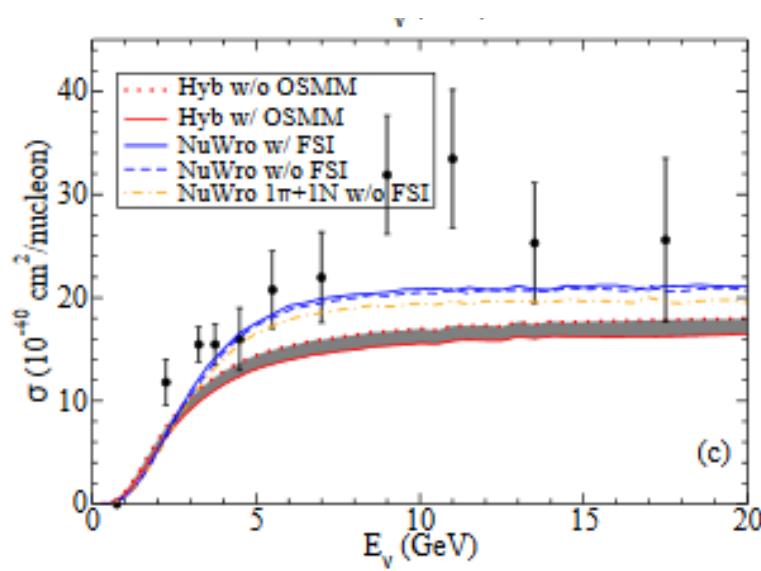
## IV.Hybrid model – put the nucleon in a nucleus

RPWIA approach compared to MiniBooNE Minerva and T2K (arXiv:1803.03163 and arXiv:1710.08374)

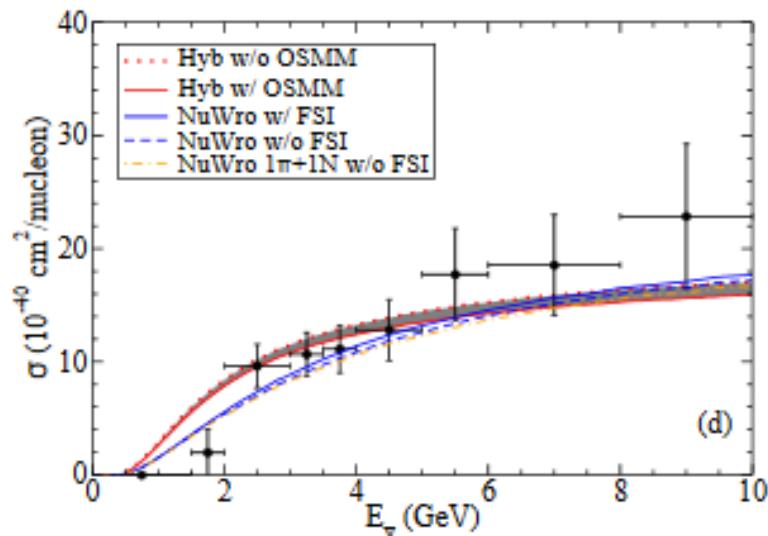
- + comparison with NuWro final state
- + investigate effect of medium modifications

- Consistency between T2K, Minerva and NuWro comparisons, underestimate MiniBooNE always.
- Not always consistent between different channels.

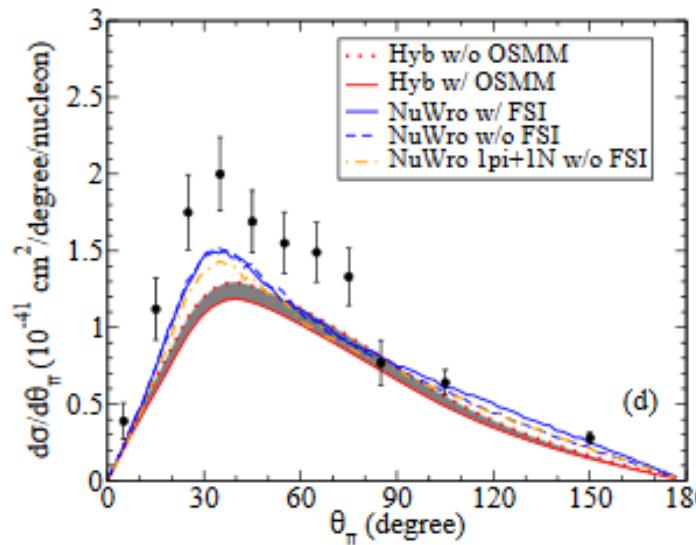
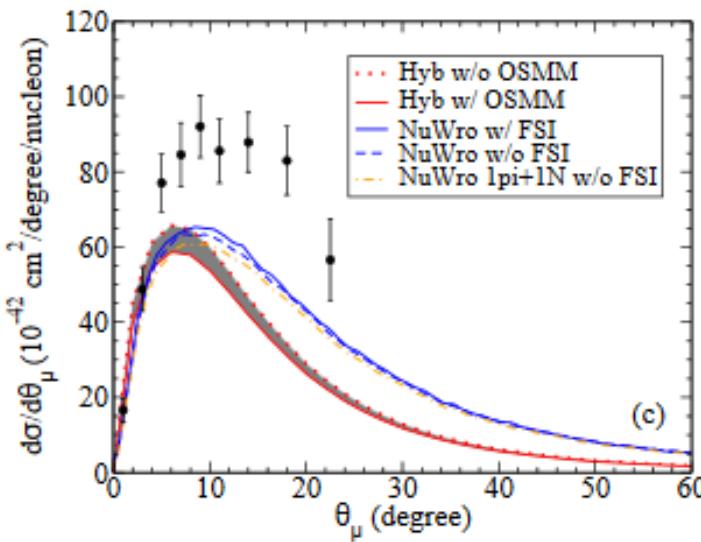
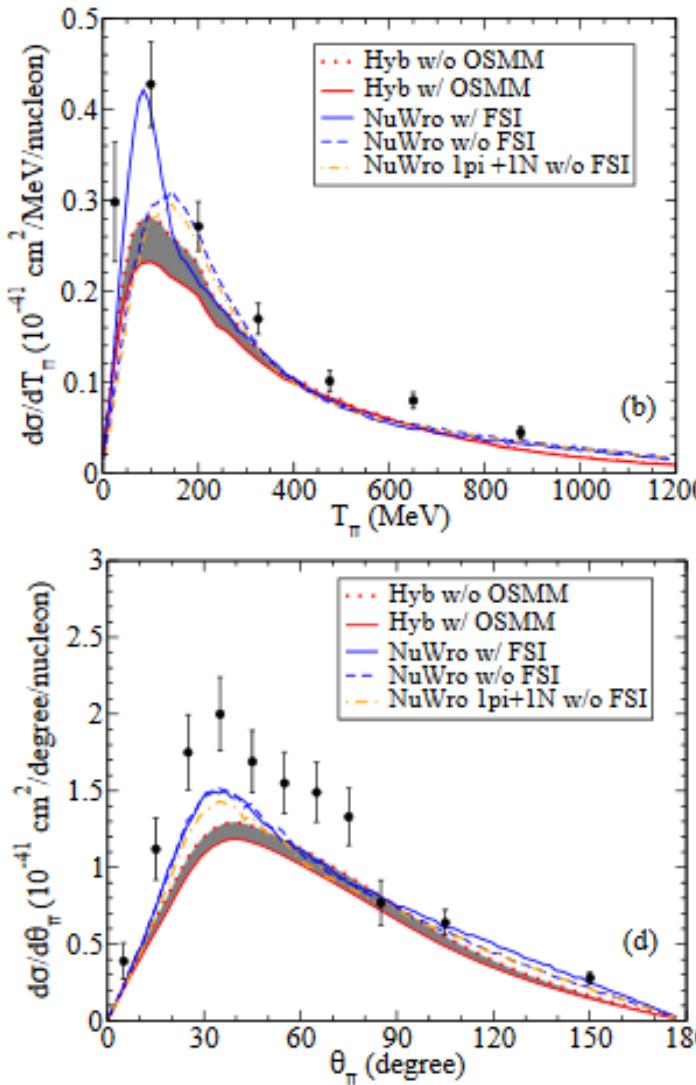
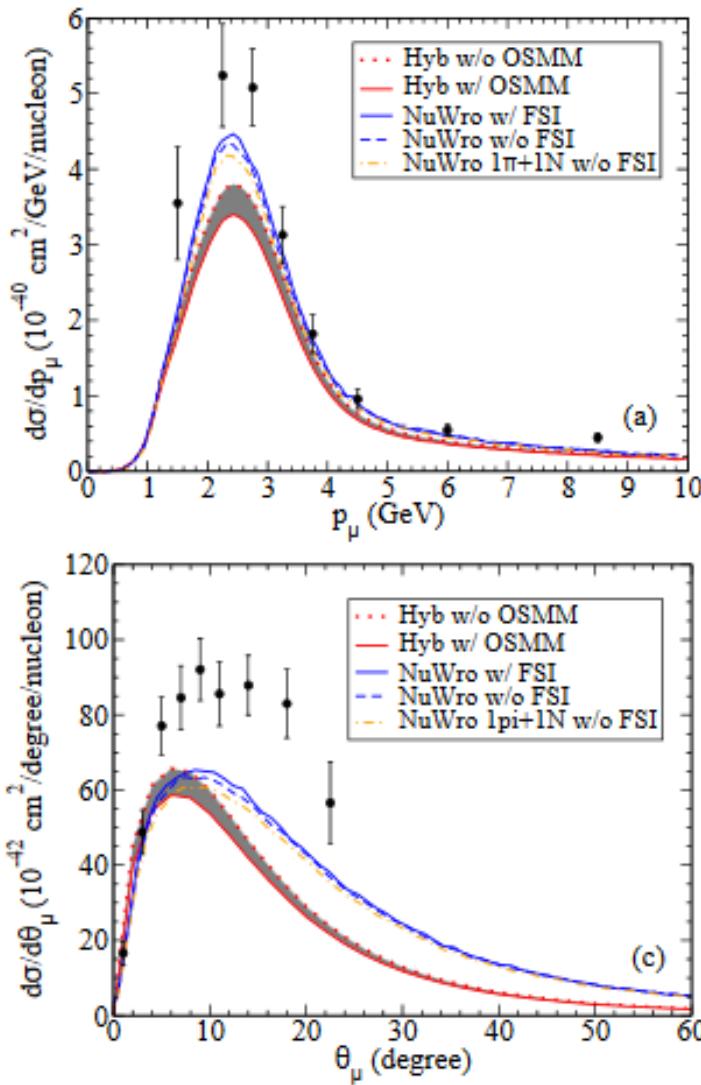
MINERvA  $\nu CC\ 1\pi^0$



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

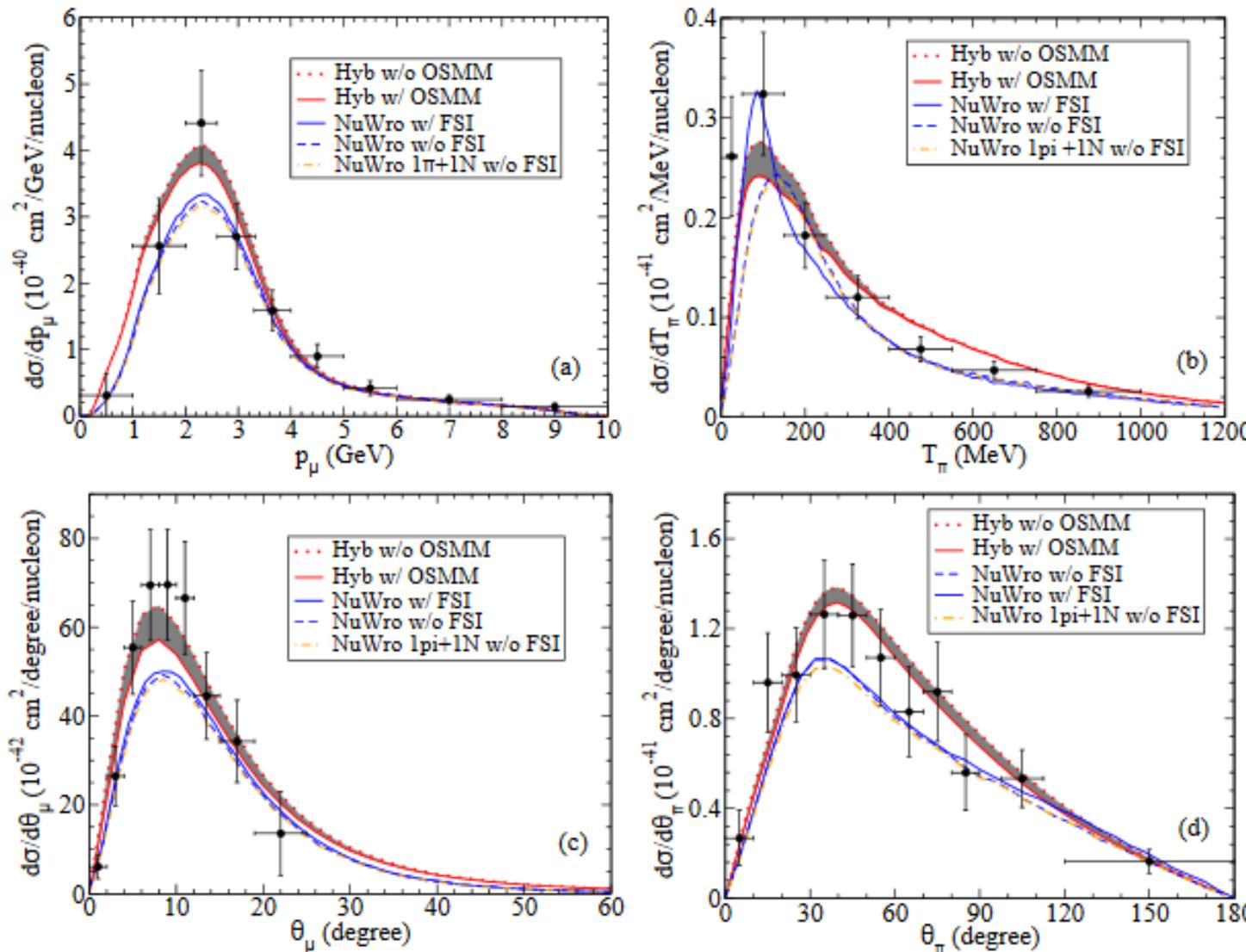


## IV.Hybrid RPWIA model – results



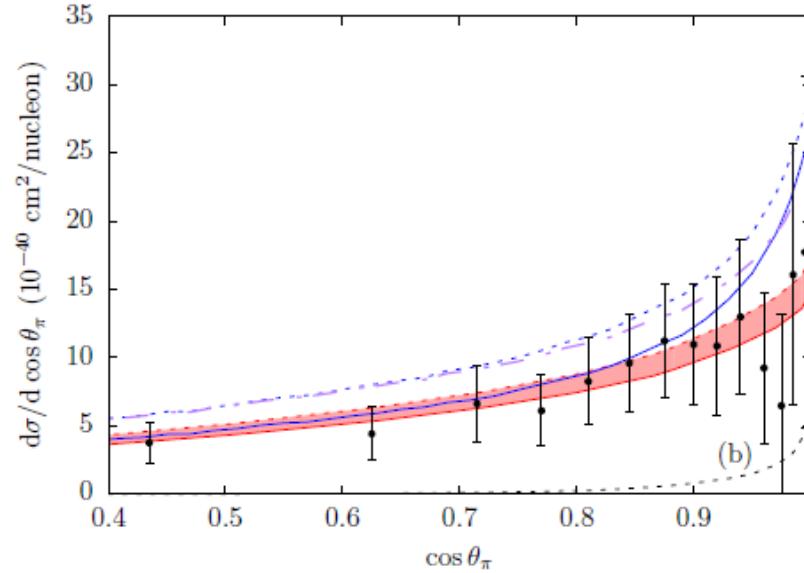
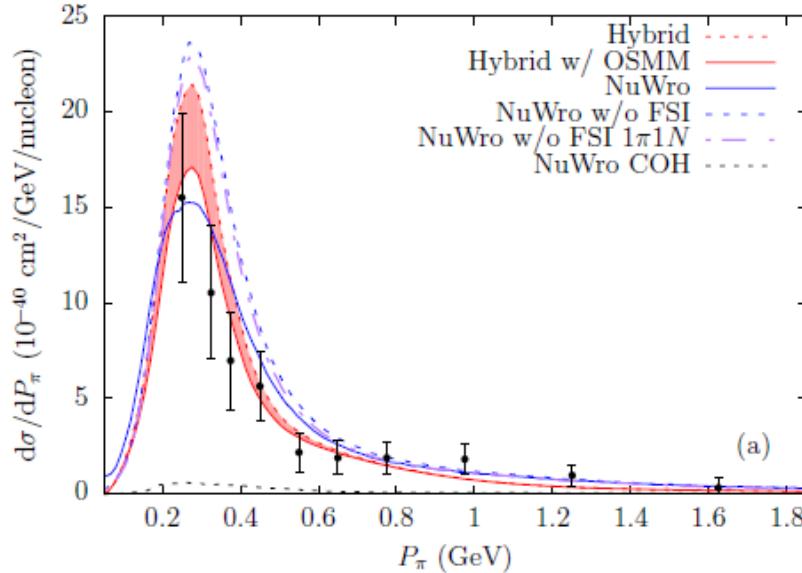
MINERvA  $\nu$ CC  $1\pi^0$

## IV.Hybrid RPWIA model – results

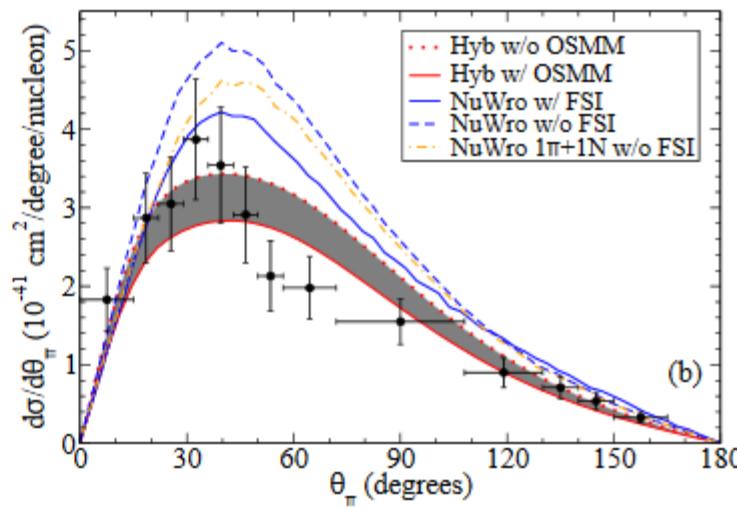
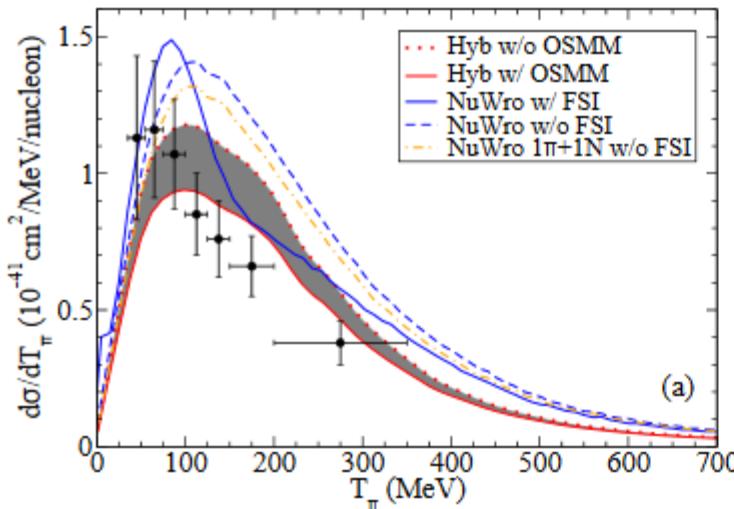


MINERvA  $\bar{\nu}$ CC  $1\pi^0$

## IV.Hybrid RPWIA model – results

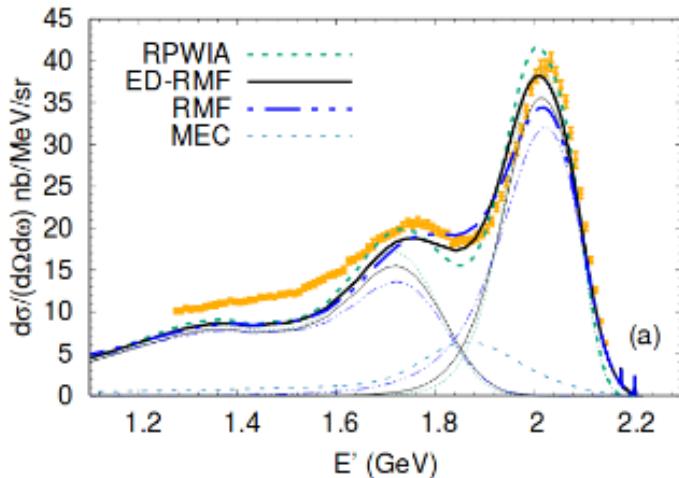


T2K CC1 $\pi^+$



MINERvA νCC 1 $\pi^+$

## V.Nuclear matrix element – distorted final state

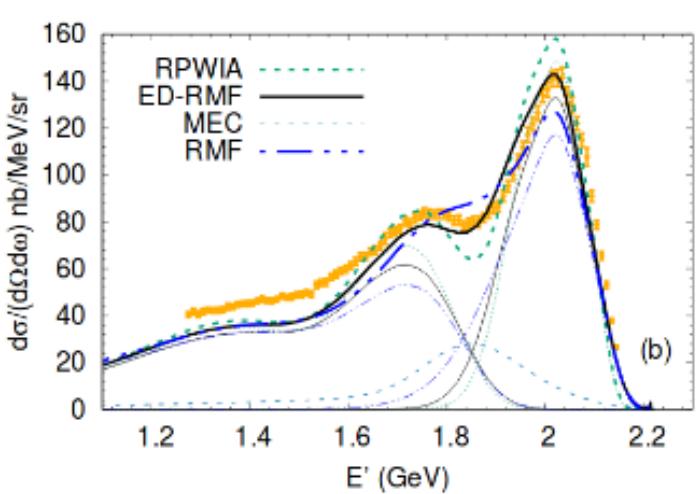


Carbon

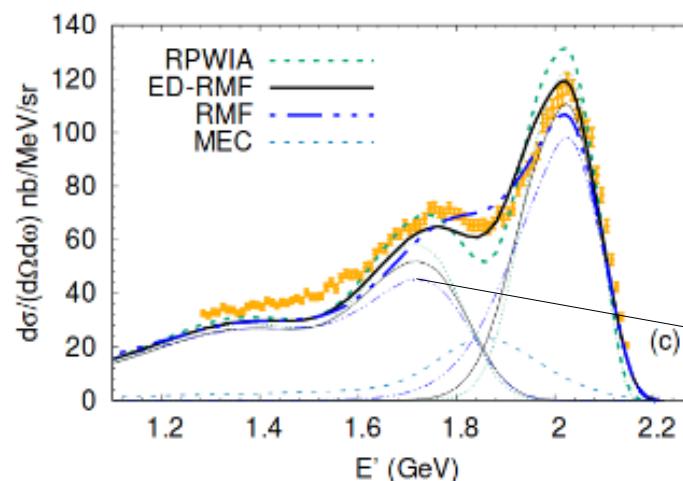
Arxiv:1909.07497

Going beyond the RPWIA:

- Propagate final state nucleon with the RMF self-energy



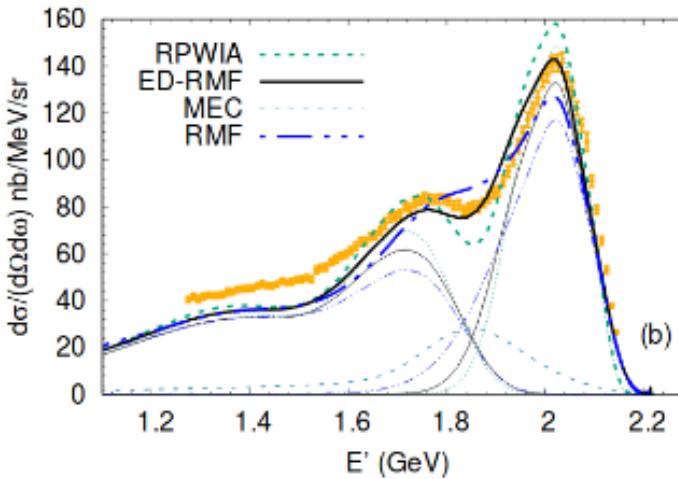
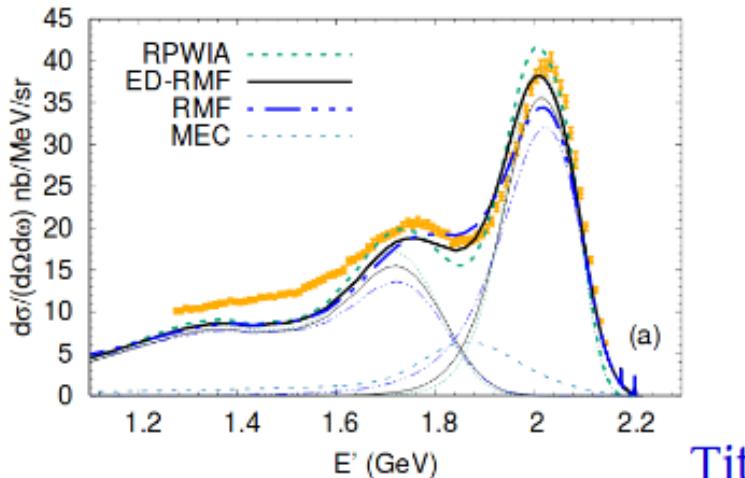
Titanium



Argon

Significant reduction around the Delta

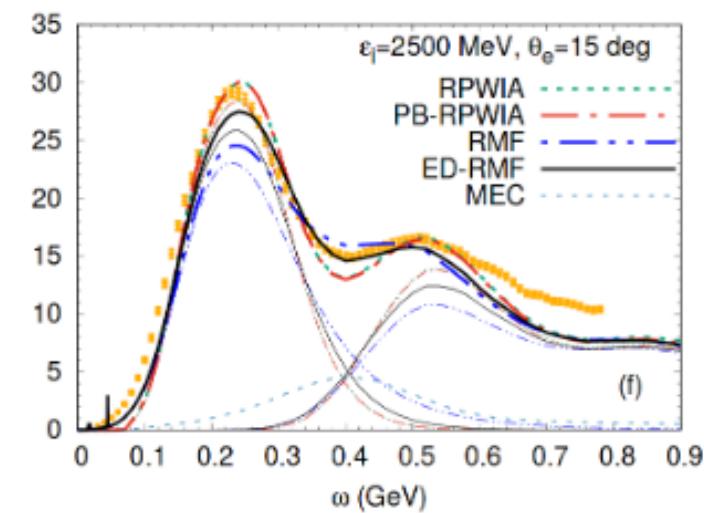
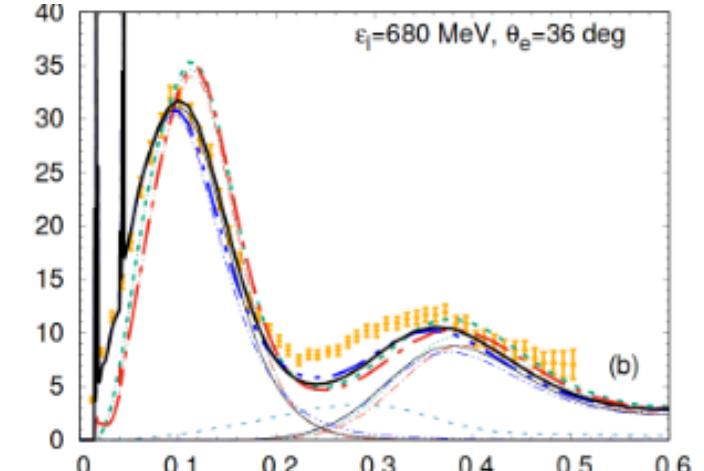
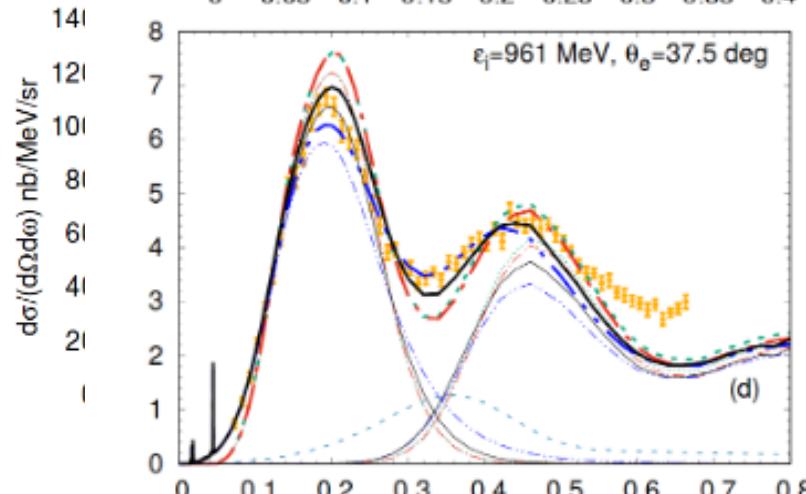
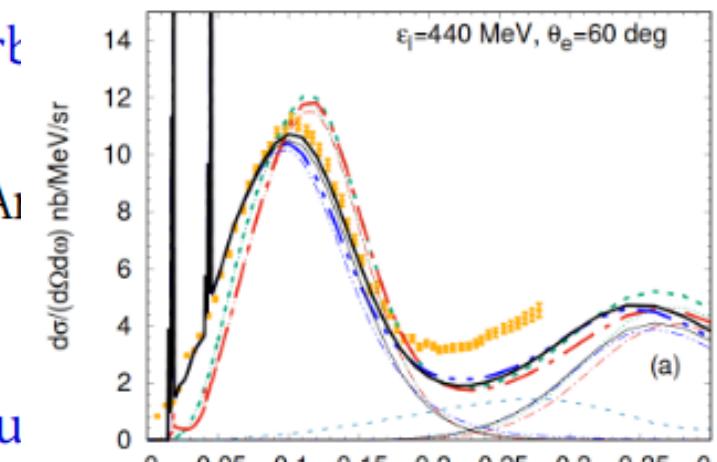
## V.Nuclear matrix element – distorted final state



Carl

Al

Titanium

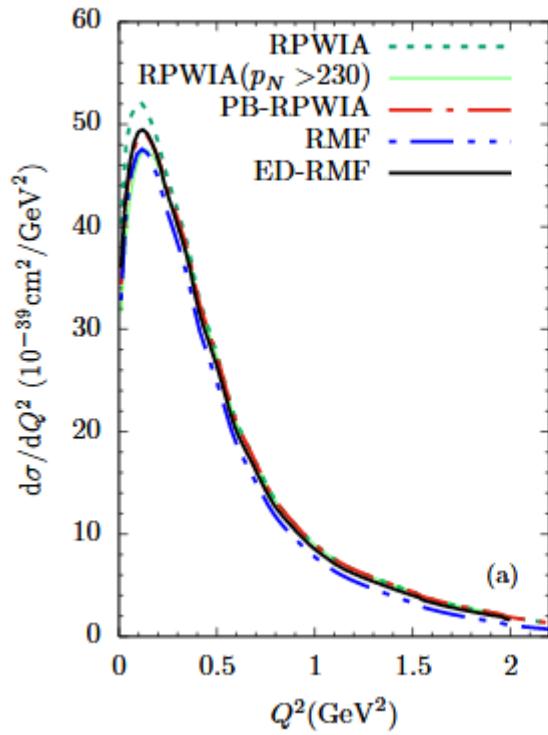


Arxiv: 1904.10696

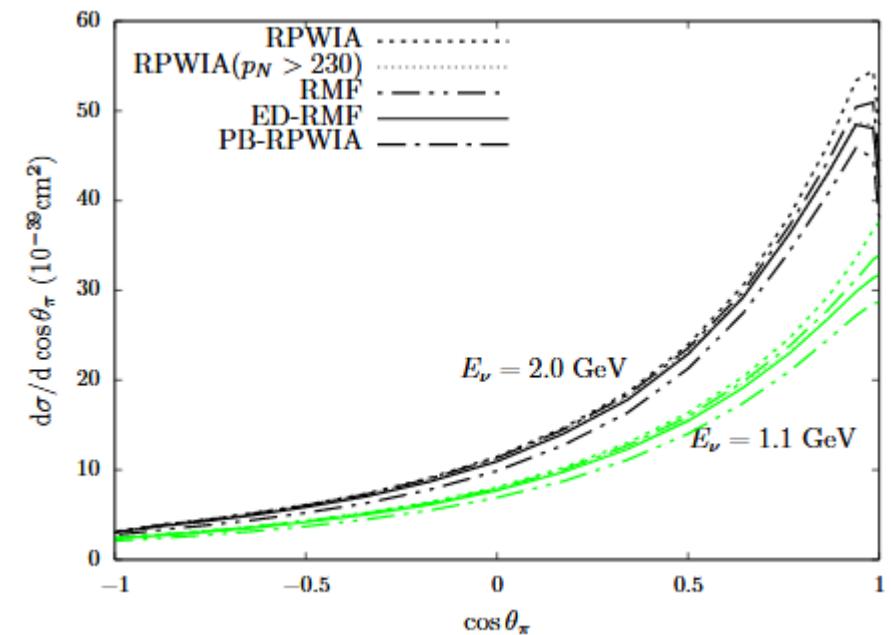
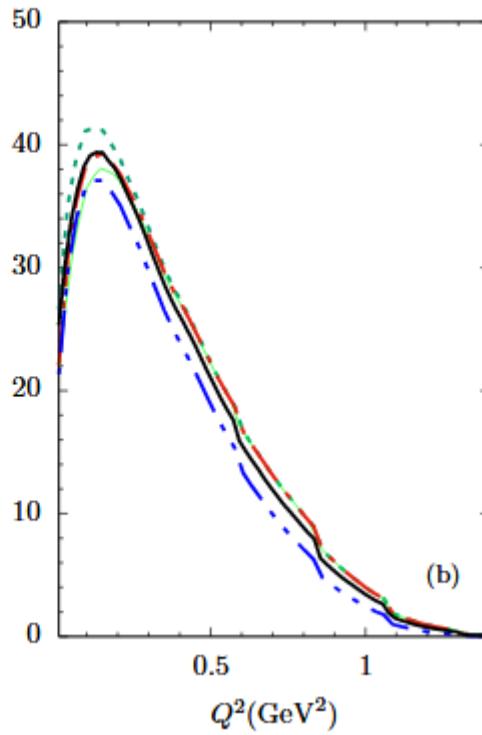
## V.Extending the Hybrid model – distorted final state

$^{12}\text{C}(\nu_{\mu}, \mu\pi^+)$

$E_{\nu} = 2.0 \text{ GeV}$



$E_{\nu} = 1.1 \text{ GeV}$



## Summary & Outlook

- 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
- Further study the effect of nuclear distortion for neutrino data
- Improve and constrain the high-energy model with pion scattering data and by duality