FACULTY OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY

Moving up into the 1pi region

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Overview of non-CC0pi modelling relevant for DUNE and HK

What the organizers first asked me to talk about

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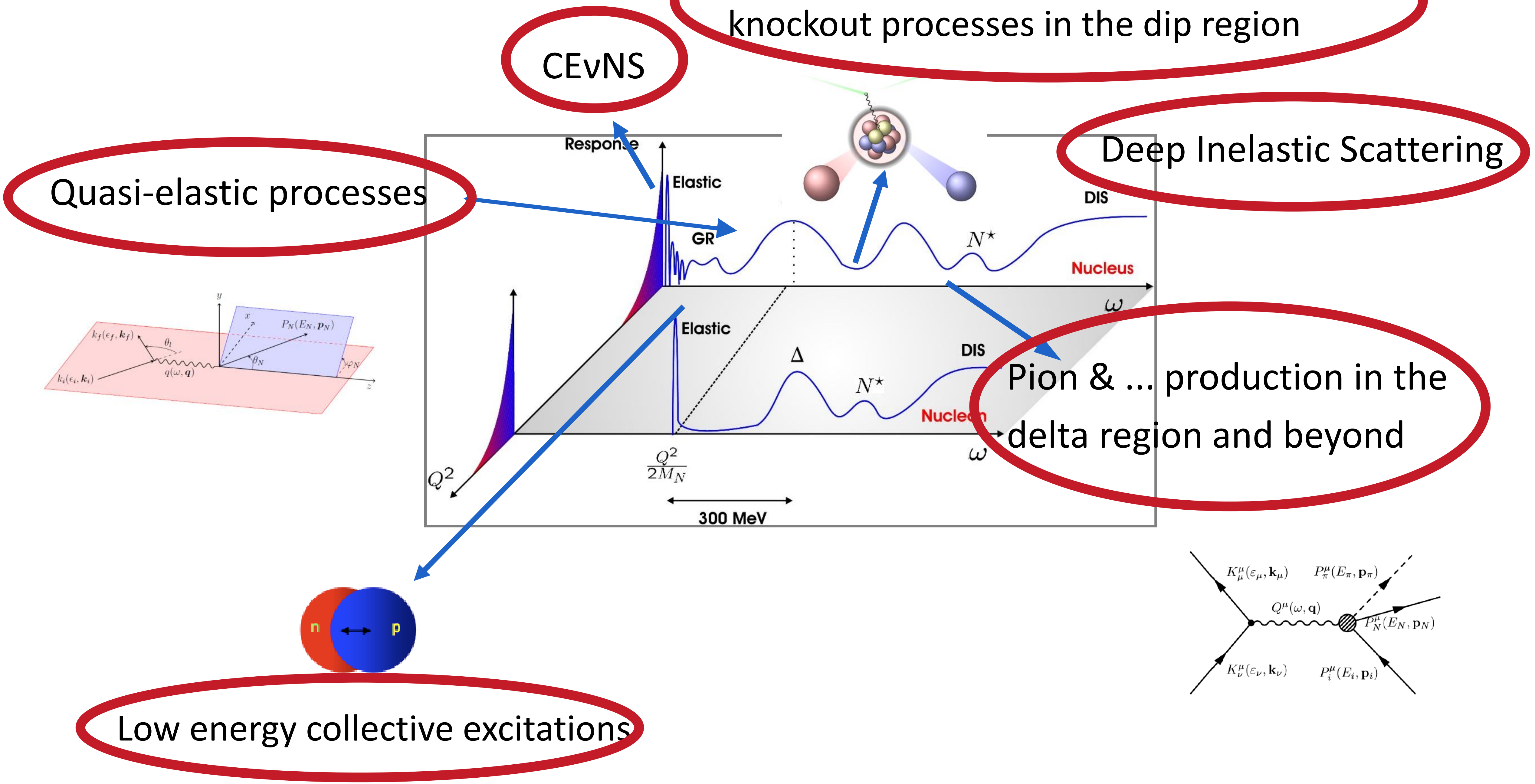
Overview



multinucleon mechanisms and 2-nucleon knockout processes in the dip region
CEvNS
Deep Inelastic Scattering
Quasi-elastic processes
Pion & ... production in the delta region and beyond
Low energy collective excitations
Response
Elastic
GR
DIS
N*
Nucleus
ω
Elastic
Δ
N*
DIS
Nucleon
ω
Q²
Q²/2M_N
300 MeV
n
p

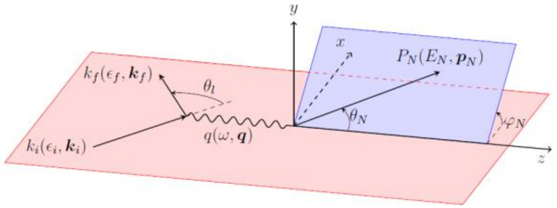
Overview

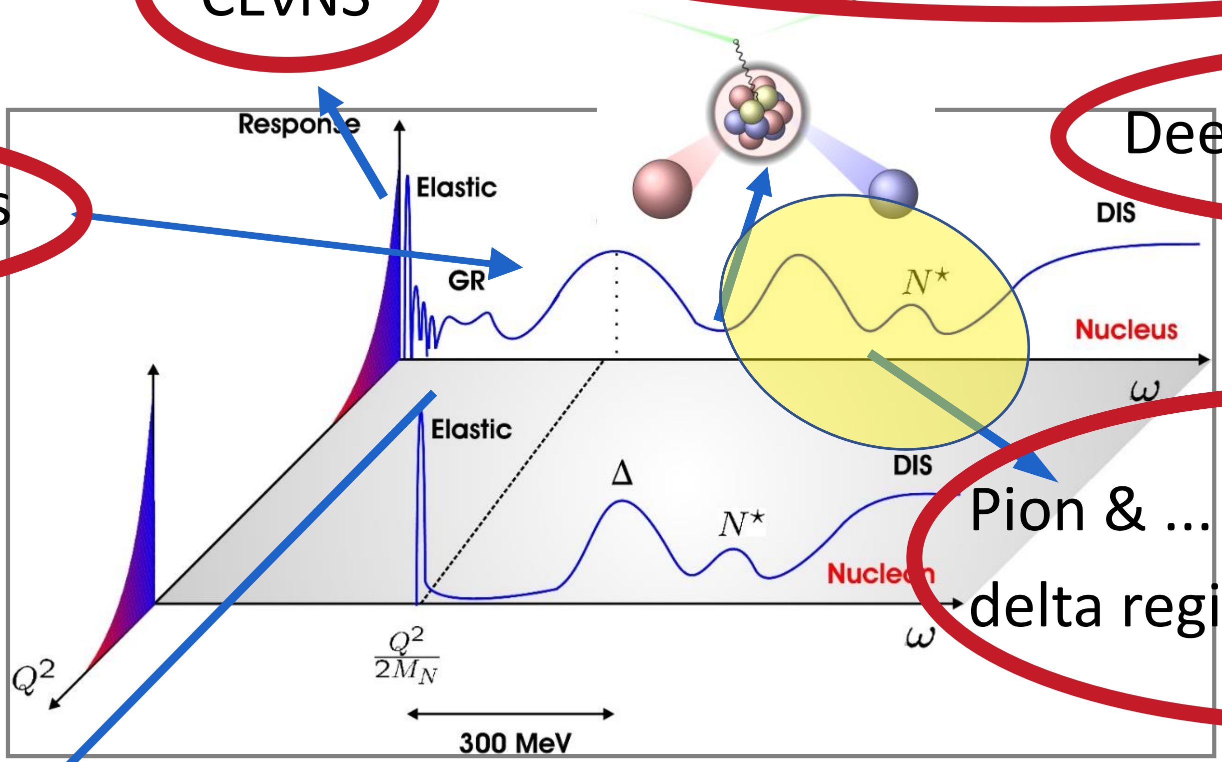
CEvNS

multinucleon mechanisms and 2-nucleon knockout processes in the dip region

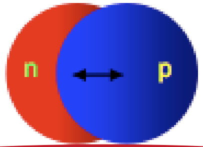
Quasi-elastic processes

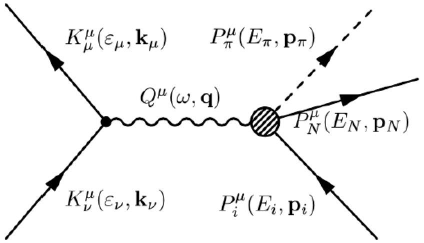
Deep Inelastic Scattering



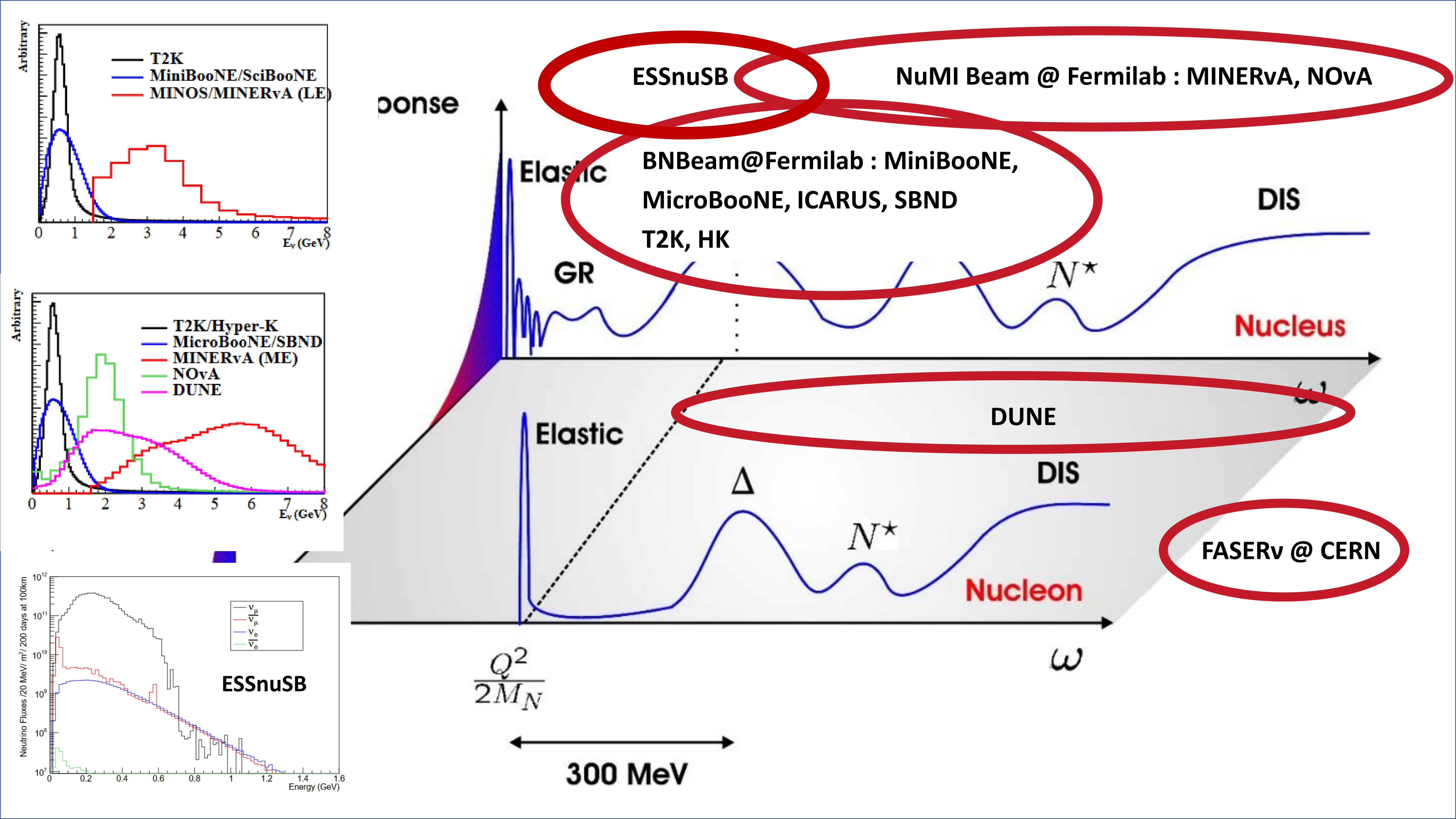


Pion & ... production in the delta region and beyond

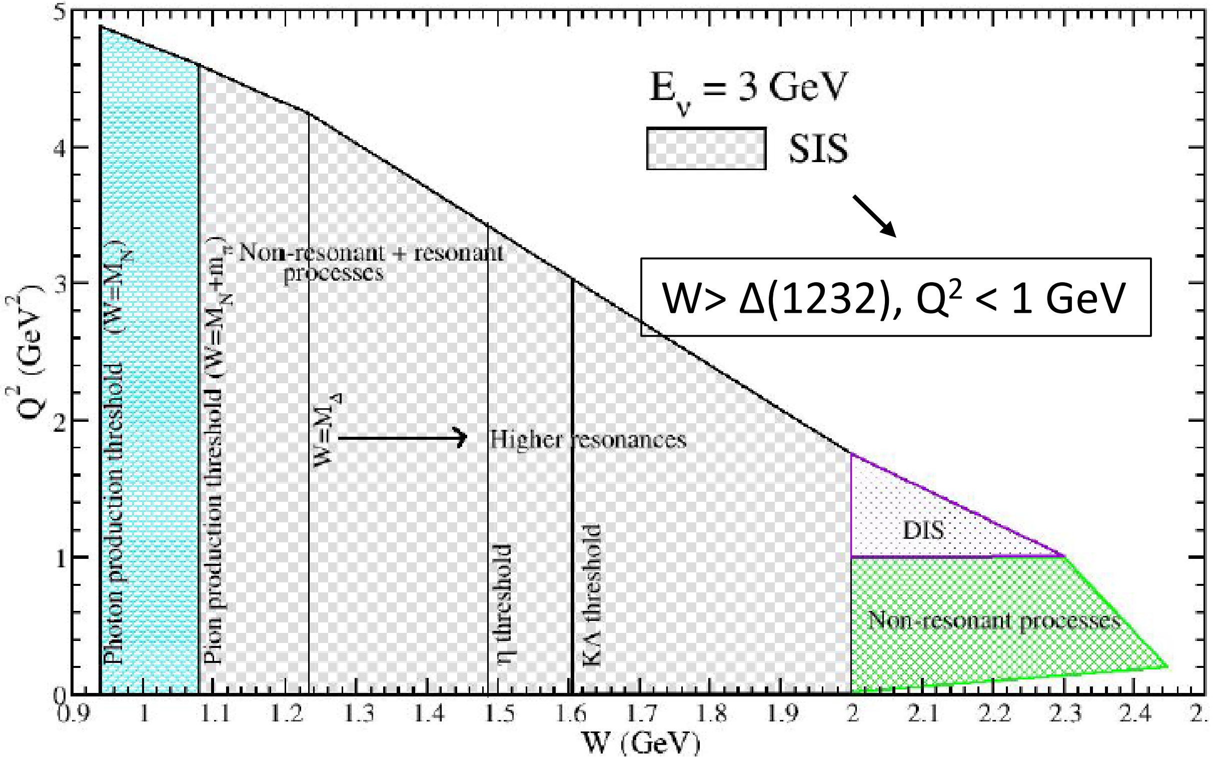


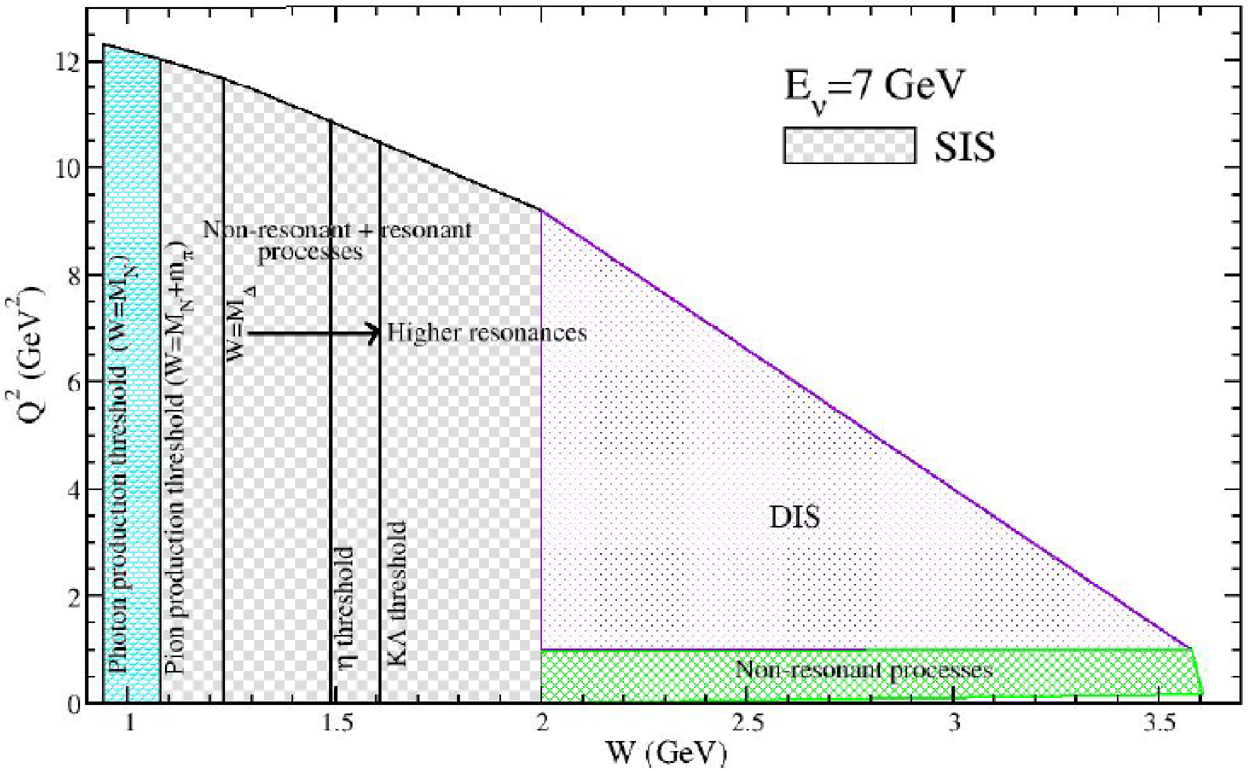


Low energy collective excitations


Arbitrary
T2K
MiniBooNE/SciBooNE
MINOS/MINERvA (LE)
0 1 2 3 4 5 6 7 8
Eν (GeV)
Arbitrary
T2K/Hyper-K
MicroBooNE/SBND
MINERvA (ME)
NOvA
DUNE
0 1 2 3 4 5 6 7 8
Eν (GeV)
Neutrino Fluxes /20 MeV/ m²/ 200 days at 100km
Energy (GeV)
ESSnuSB
ESSnuSB
NuMI Beam @ Fermilab : MINERvA, NOvA
ponse
Elastic
BNBeam@Fermilab : MiniBooNE,
MicroBooNE, ICARUS, SBND
T2K, HK
DIS
GR
N*
Nucleus
ω
DUNE
Elastic
Δ
DIS
N*
Nucleon
FASERν @ CERN
$\frac{Q^2}{2M_N}$
ω
300 MeV

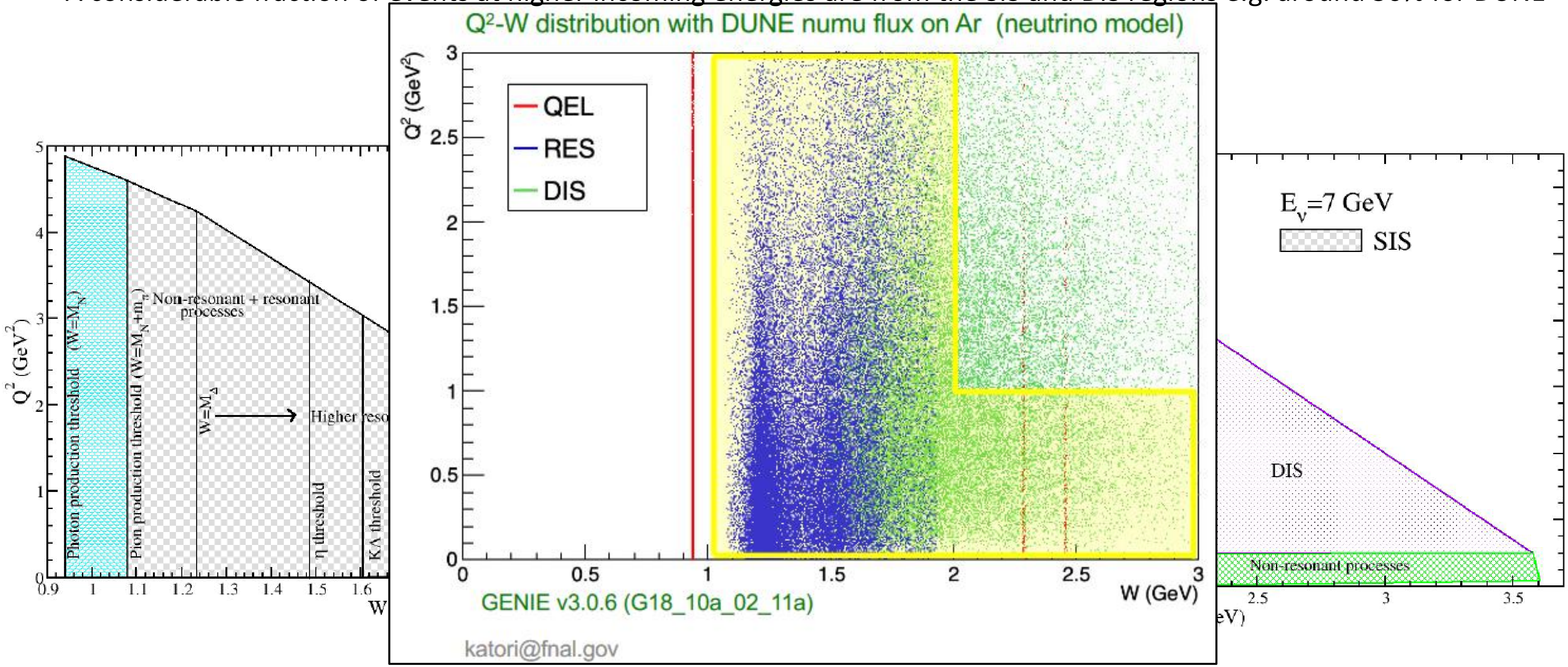
- This kinematic region is not well as well understood as the QE one, both experimentally and theoretically
- A considerable fraction of events at higher incoming energies are from these SIS and DIS regions e.g. around 50% for DUNE





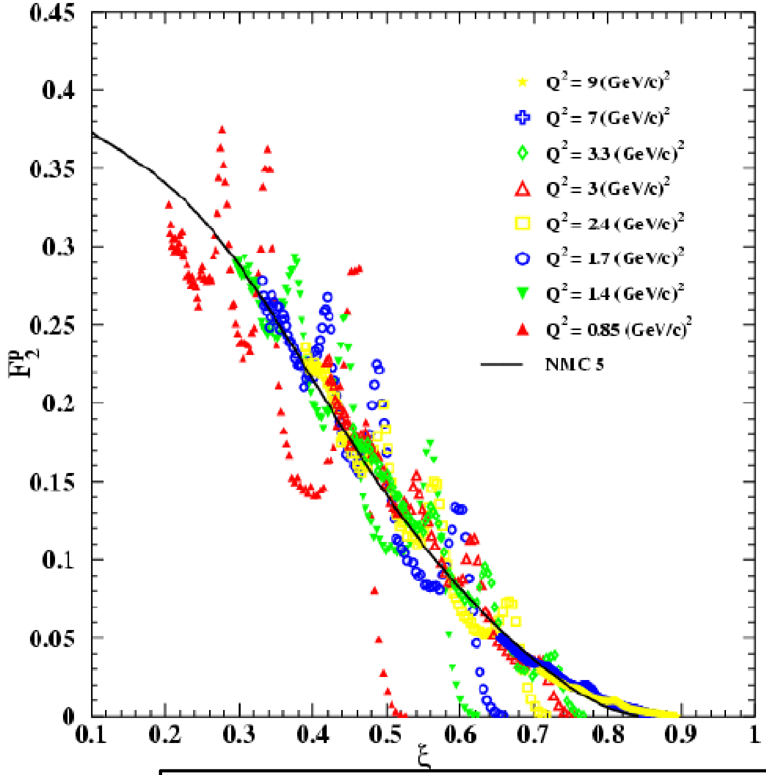
Snowmass WP on theoretical tools for neutrino scattering, L. Alvarez Ruso et al, arXiv:2203.09030

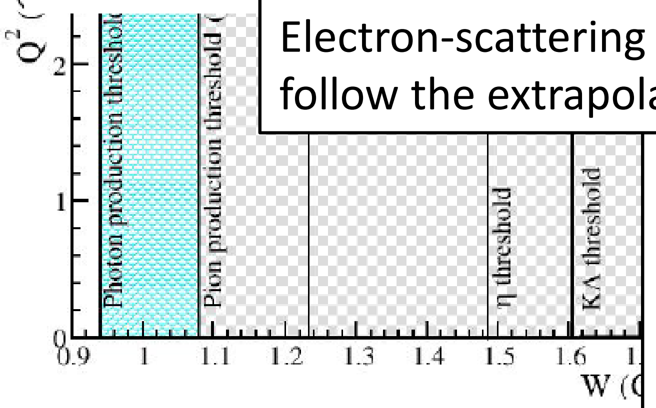
- This kinematic region is not well understood or studied, both experimentally and theoretically
- Important background channel for quasi-elastic cross section measurements as the produced pions may be re-absorbed in the nuclear medium or remain otherwise unobserved, leading to a CC0π topology mimicking a QE event
- A considerable fraction of events at higher incoming energies are from the SIS and DIS regions e.g. around 50% for DUNE

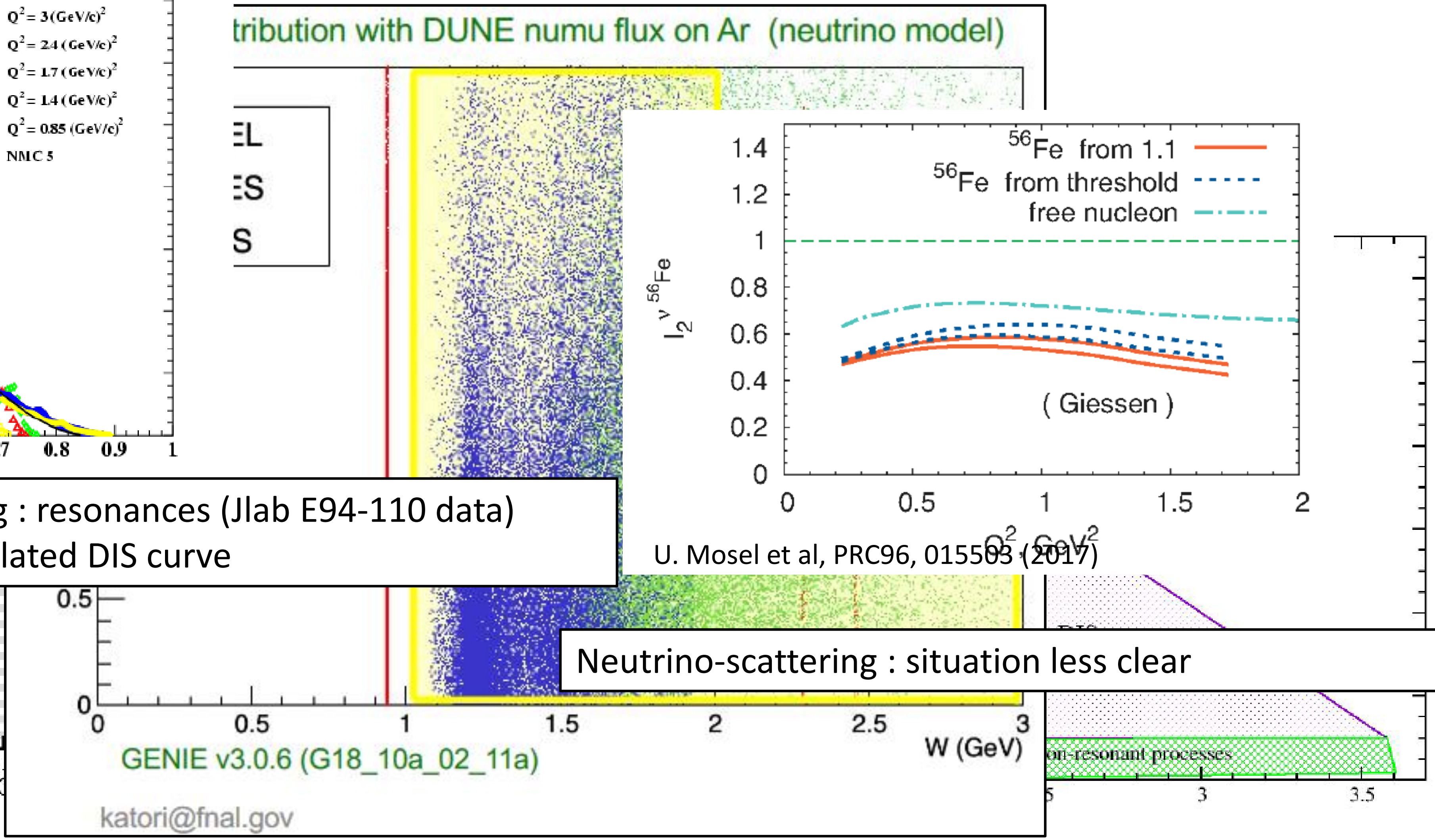


Duality and the transition from nucleon to partonic degrees of freedom

astic cross section measurements as the produced pions may be re-absorbed
e unobserved, leading to a CC0π topology mimicking a QE event
incoming energies are from the SIS and DIS regions e.g. around 50% for DUNE







Electron-scattering : resonances (Jlab E94-110 data) follow the extrapolated DIS curve

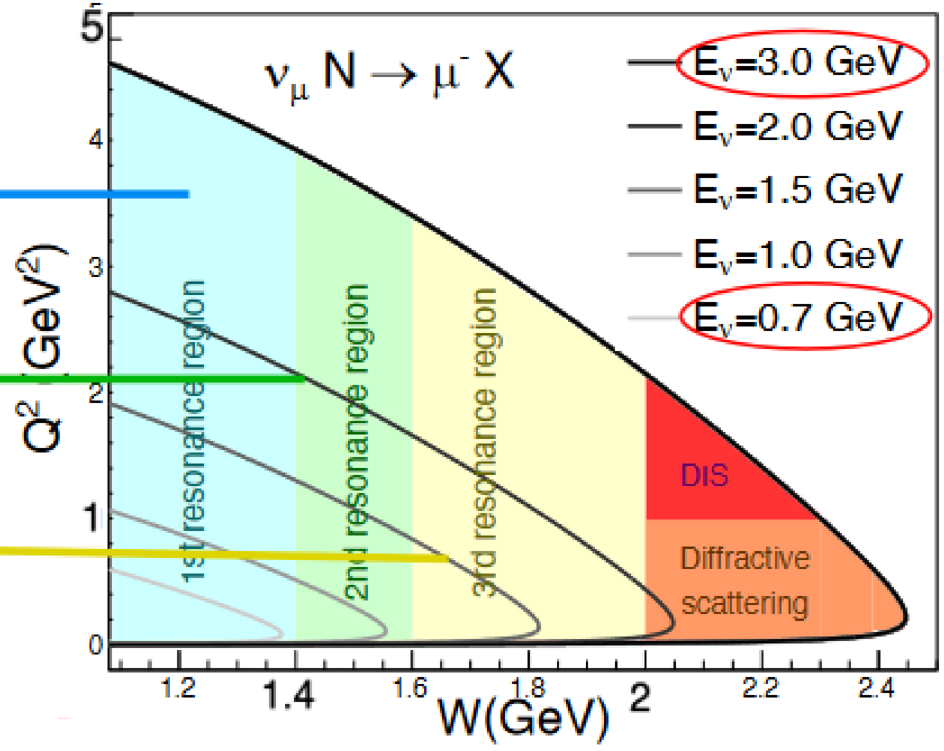
Neutrino-scattering : situation less clear

Basic ingredients for modeling single pion production

Δ resonance 1pi production

Second resonance region :
$P_{11}(1440)$, $D_{13}(1520)$,
$S_{11}(1535)$
2pion, η, ... Production

Third resonance region :
~15 overlapping resonances



MINERvA, DUNE

MiniBooNe, T2K, HK

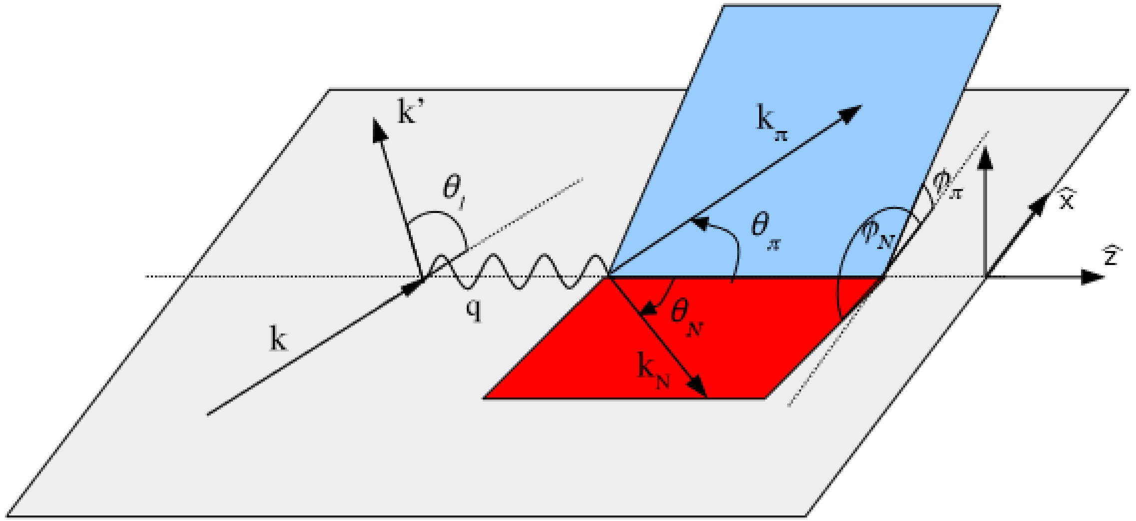
MK arXiv2409.02890

ChPT background

Reggeized background

2

Basic ingredients for modeling single pion production



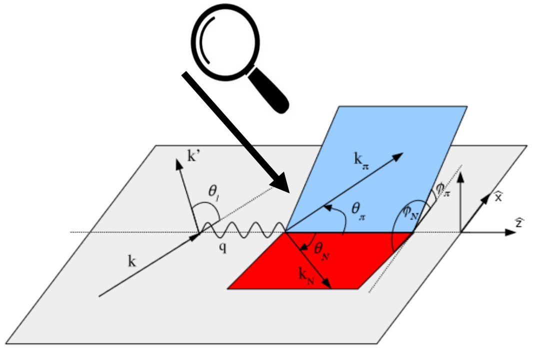
$$d\sigma(E) = \frac{m}{E}\frac{m'}{E'}\frac{d\mathbf{k}'}{(2\pi)^3}\frac{m_N}{E_N}\frac{d\mathbf{p_N}}{(2\pi)^3}\frac{1}{2E_\pi}\frac{d\mathbf{p}_\pi}{(2\pi)^3}\frac{M_B}{E_B}\frac{d\mathbf{p_B}}{(2\pi)^3} \times (2\pi)^4\delta^4(K^\mu + P_A^\mu - K'^\mu - P_N^\mu - P_\pi^\mu - P_B^\mu)|\mathcal{M}|^2,$$

$$d\sigma(E) = \frac{mm'M_N M_B}{2(2\pi)^8 E E' E_N E_\pi E_B} d\mathbf{k}' d\mathbf{p_N} d\mathbf{p}_\pi \, \delta(E + M_A - E' - E_N - E_\pi - E_B)|\mathcal{M}|^2.$$

$$\frac{d^8\sigma(E)}{dE' d\Omega dE_\pi d\Omega_\pi d\Omega_N} = \frac{m_i}{E}\frac{m' k' M_N k_\pi k_N M_B}{2\,(2\pi)^8\, E_B f_{rec}}|\mathcal{M}|^2$$

Basic ingredients for modeling single pion production

$$|\mathcal{M}_W|^2 = \frac{G_F^2 \cos^2\theta_c}{m'm} L^{\mu\nu} H_{\mu\nu}$$



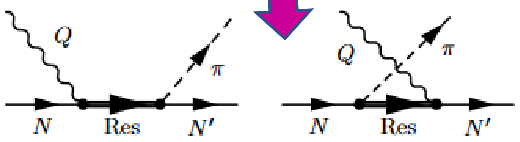
Hadron tensor

$$H^{\mu\nu} = \frac{1}{2}\sum_{s_i,s_f} J^{\mu,*}\left(k_\pi, k_N, Q, s_i, s_f\right) J^{\nu}\left(k_\pi, k_N, Q, s_i, s_f\right)$$

$$J^{\mu}\left(k_\pi, k_N, Q, s_i, s_f\right) = \overline{u}\left(k_N, s_f\right) \mathcal{O}^{\mu}\left(k_\pi, k_N, k\right) u\left(k_i, s_i\right)$$

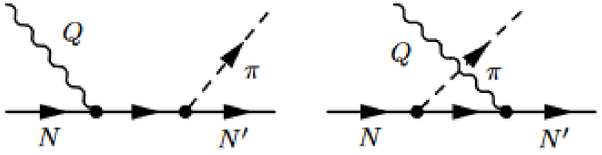
At tree level

Resonances : invariant mass, width Γ, isospin I, spin J, parity P, and for SPP the branching ratio for decay into a pion and nucleon



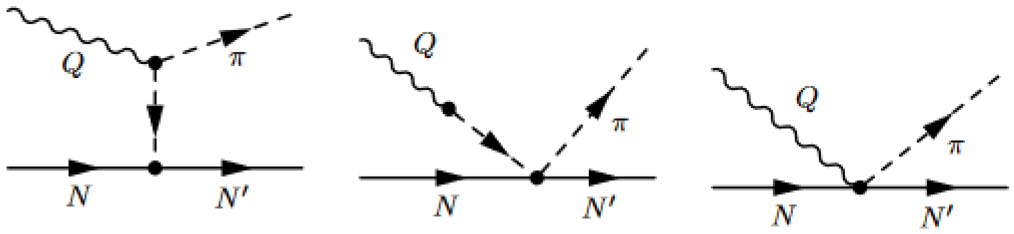
+

Nucleon pole and cross nucleon pole



Non-resonant background

+



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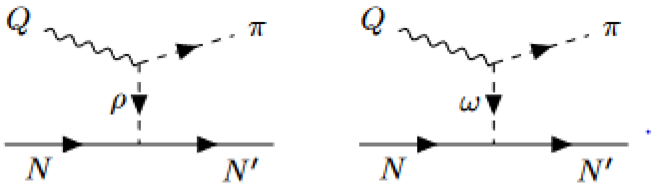


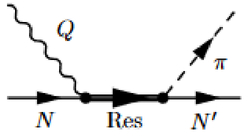
+ interferences

Basic ingredients for modeling single pion production

$$J^\mu = \sum_n \overline{u}(k_N, s_f)\, \mathcal{O}^\mu_n u(k_i, s_i)$$

Let's pick only one contribution ...
spin 3/2 resonance direct contribution

$$\mathcal{O}^\mu_{R_{3/2}} = I_{iso,s} \Gamma^\alpha_{R\pi N}\; S_{R,\alpha,\beta}(k_R)\; \Gamma^{\mu\beta}_{QRN}(K_i, Q)$$



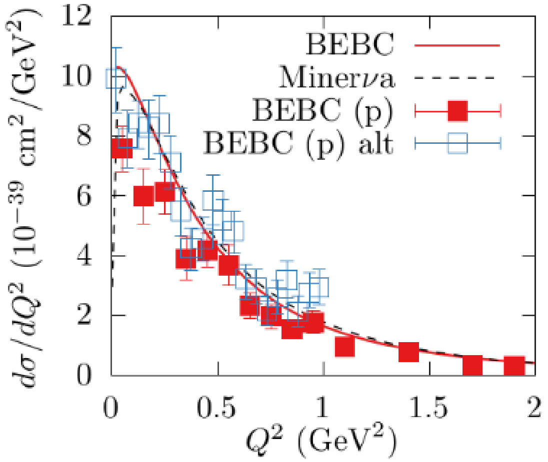
Vertex function for resonance production

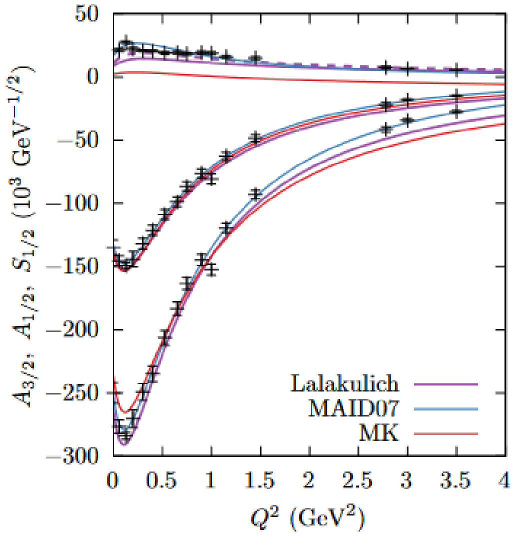
$$\Gamma^{\beta\mu}_{QRN} = \left(\Gamma^{\beta\mu}_{QRN,V} + \Gamma^{\beta\mu}_{QRN,A}\right)\tilde{\gamma}^5$$

$$\Gamma^{\beta\mu}_V = \left[\frac{C_3^V}{M}\left(g^{\beta\mu}\not{Q} - Q^\beta\gamma^\mu\right) + \frac{C_4^V}{M^2}\left(g^{\beta\mu}Q\cdot k_R - Q^\beta k_R^\mu\right) + \frac{C_5^V}{M^2}\left(g^{\beta\mu}Q\cdot k_i - Q^\beta k_i^\mu\right) + C_6^V g^{\beta\mu}\right]\gamma^5,$$

$$\Gamma^{\beta\mu}_A = \frac{C_3^A}{M}\left(g^{\beta\mu}\not{Q} - Q^\beta\gamma^\mu\right) + \frac{C_4^A}{M^2}\left(g^{\beta\mu}Q\cdot k_R - Q^\beta k_R^\mu\right) + C_5^A g^{\beta\mu} + \frac{C_6^A}{M^2}Q^\beta Q^\mu,$$

- Vector and axial contribution
- Constraint through CVC and PCAC
- Axial form factors not well constrained,
- Large uncertainties on neutrino data





e.g. in Lalakulich parametrization

$$C_3 = \frac{2.13/D_V(Q^2)}{1 + Q^2/4M_V^2}$$

$$C_4 = -1.51/2.13 C_3$$

$$C_5 = \frac{0.48/D_V(Q^2)}{1 + Q^2/0.776M_V^2}$$

Basic ingredients for modeling single pion production

Let's pick only one contribution ...
spin 3/2 resonance direct contribution

$$J^{\mu} = \sum_{n} \overline{u}\left(k_N, s_f\right) \mathcal{O}^{\mu}_{n} u\left(k_i, s_i\right)$$

$$\mathcal{O}^{\mu}_{R_{3/2}} = I_{iso,s} \Gamma^{\alpha}_{R\pi N} \; S_{R,\alpha,\beta}\left(k_R\right) \; \Gamma^{\mu\beta}_{QRN}\left(K_i, Q\right)$$

Resonance propagator

$$S_3^{\mu\nu} = \frac{\not{k}_R + M_R}{k_R^2 - M_R^2 + iM_R\Gamma(W)} \left[g^{\mu\nu} - \frac{1}{3}\gamma^{\mu}\gamma^{\nu} - \frac{2}{3}\frac{k_R^{\mu}k_R^{\nu}}{M_R^2} + \frac{k_R^{\mu}\gamma^{\nu} - k_R^{\nu}\gamma^{\mu}}{3M_R} \right]$$

Basic ingredients for modeling single pion production

$$J^\mu = \sum_n \overline{u}(k_N, s_f)\, \mathcal{O}^\mu_n u(k_i, s_i)$$

Let's pick only one contribution ...
Spin 3/2 resonance direct contribution

$$\mathcal{O}^\mu_{R_{3/2}} = I_{iso,s} \Gamma^\alpha_{R\pi N}\, S_{R,\alpha,\beta}(k_R)\ \Gamma^{\mu\beta}_{QRN}(K_i, Q)$$

Vertex function for the decay vertex

$$\Gamma^\mu_{\pi NR} = \frac{\sqrt{2} f_{\pi NR}}{m_\pi} k^\mu_\pi \gamma^5 \tilde{\gamma}^5$$

Depends on

- Coupling constant $f_{\pi NR}$
- Resonance width Γ

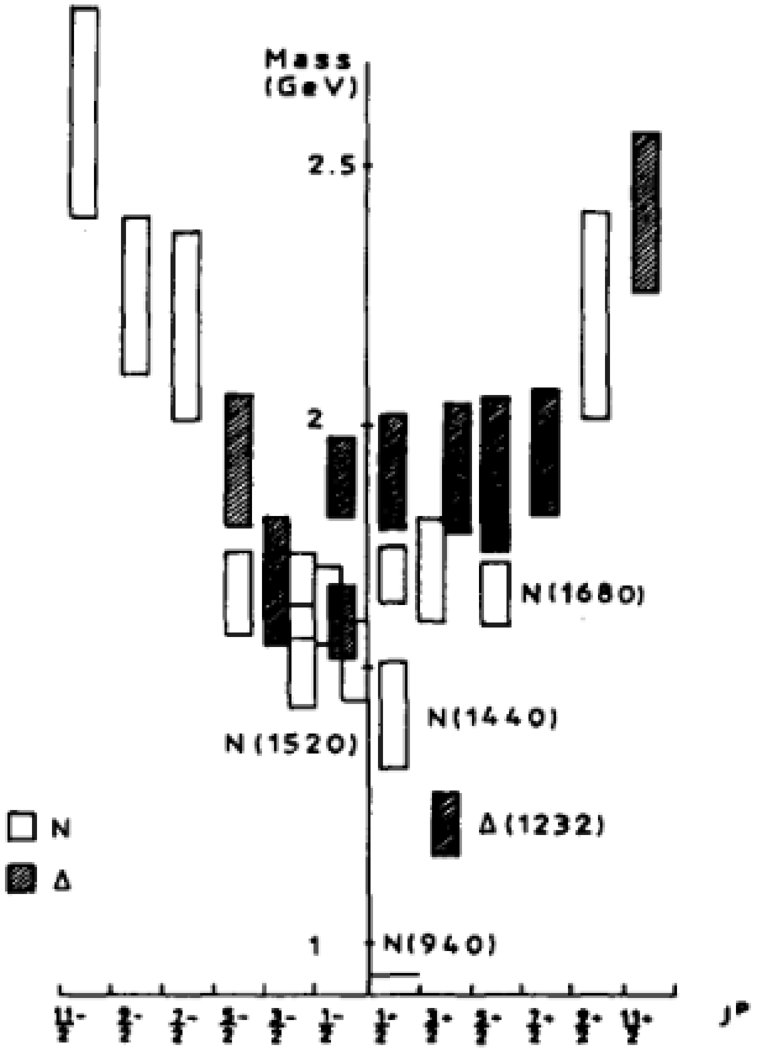
$$\Gamma^{3/2}_{\pi N}(W) = \frac{I_{iso}}{12\pi} \frac{f^2_{\pi NR}}{m^2_\pi} \frac{(k^*_\pi)^3}{W} (E^*_N \pm M_N)$$

	M_R (MeV)	Γ_{exp} (MeV)	$\beta_{\pi N}$	$f_{\pi NR}$
P_{33}	1232	120	1	2.18
S_{11}	1535	150	0.45	0.16
P_{11}	1430	350	0.6	0.49
D_{13}	1515	115	0.6	1.62

$$\Gamma_{\pi N}(M_R) = \beta_{\pi N} \Gamma_{exp}$$

Experimentally determined full width + branching ratio

Basic ingredients for modeling single pion production



M. Giannini, PPNP 24, 253 (1990)

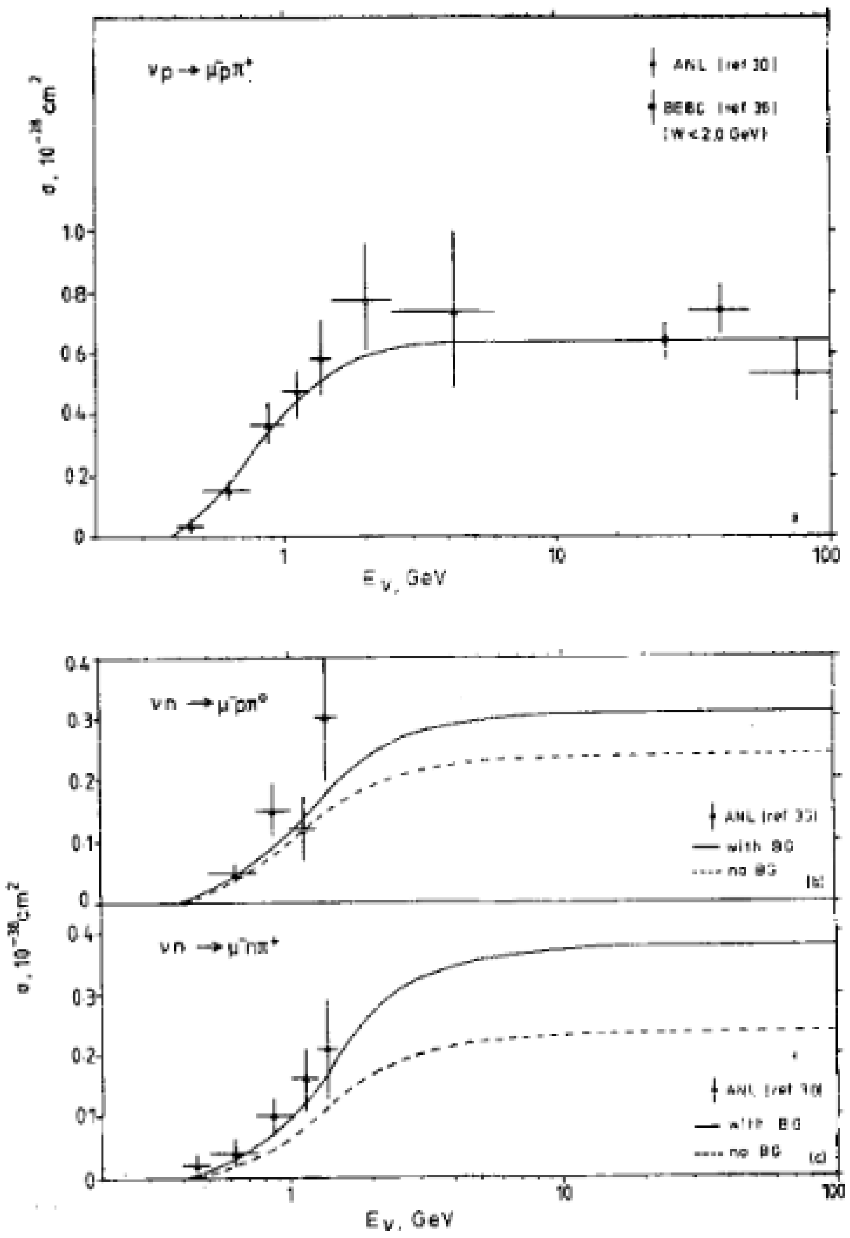
... and these are only resonances ...

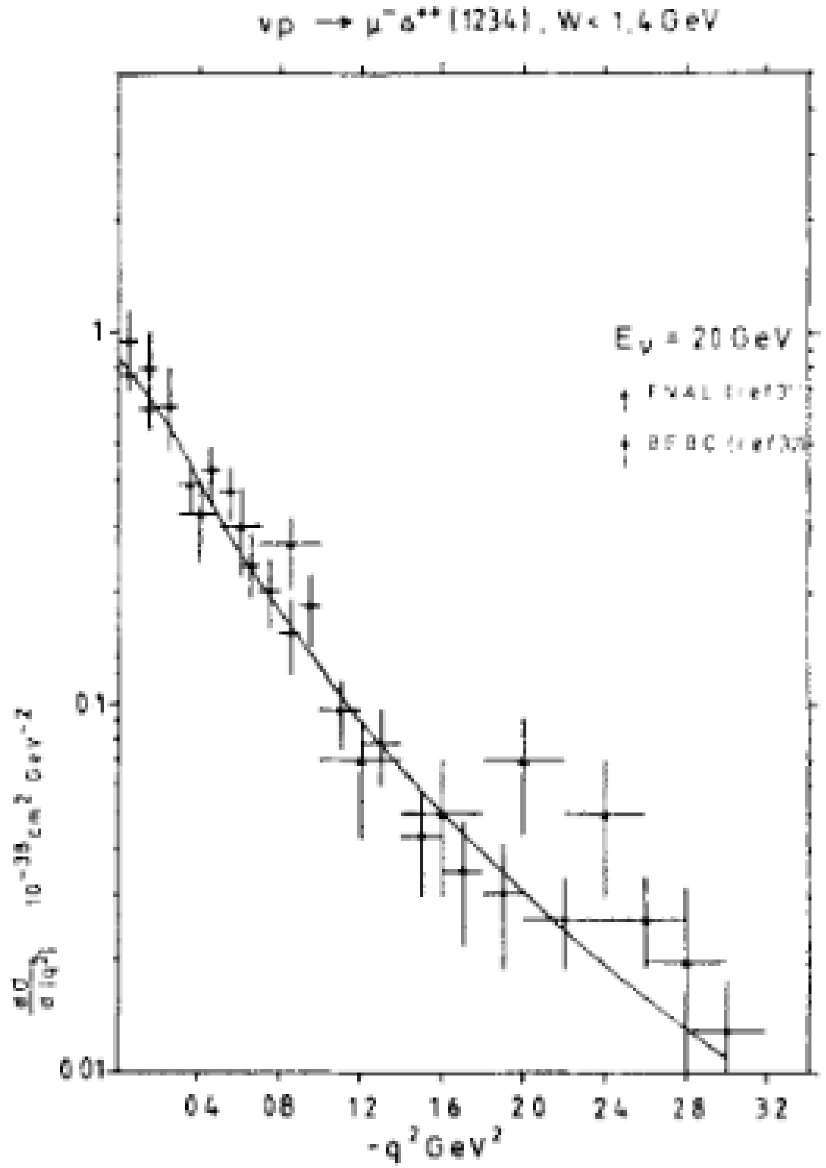
Rein Sehgal model

D. Rein and L.M. Sehgal, Annals of Physics 133, 79 (1981)

This is an attempt to describe all existing data on neutrino production of single pions in the resonance region up to $W = 2$ GeV in terms of the relativistic quark model of Feynman, Kislinger and Ravndal (FKR). We considered single pion production to be mediated by all interfering resonances below 2 GeV. A simple noninterfering, nonresonant background of isospin $\frac{1}{2}$ was added. It improved agreement with experiment, particularly in the ratio of isospin amplitudes in charged current reactions, at the expense of one additional constant. All total cross sections, cross section ratios and W-distributions are well reproduced at low and high energies, with charged and neutral currents (supposing the Salam–Weinberg theory with $\sin^2 \theta_w \approx \frac{1}{4}$ to be correct), and for neutrinos and antineutrinos, giving predictions where data are lacking. New predictions have been made for complex angular distributions in $\mathcal{N}\pi$ channels exhibiting strong interference between neighbouring resonances. These are sensitive (for 1.1 GeV $\lesssim W \lesssim$ 1.5 GeV) to the sign of the Roper resonance $P_{11}(1450)$ which is controversial in photoproduction experiments.

Rein Sehgal model





D. Rein and L.M. Sehgal, Annals of Physics 133, 79 (1981)

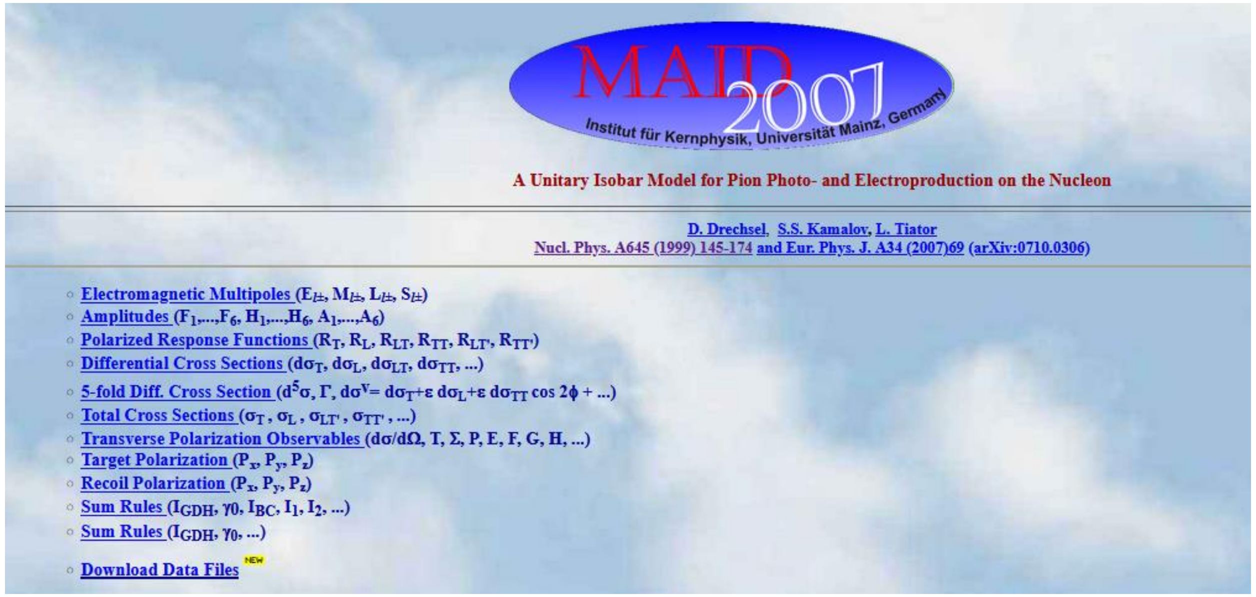
MAID

- Mainz unitary isobar model
- Designed to analyze world data on π photoproduction and (e,e'π)
- Extensions to kaon production, eta production, γππ
- 13 four-star resonances with masses below 2 GeV, unitarized Breit-Wigner shapes
- Background unitarized using K-matrix formalism

https://maid.kph.uni-mainz.de

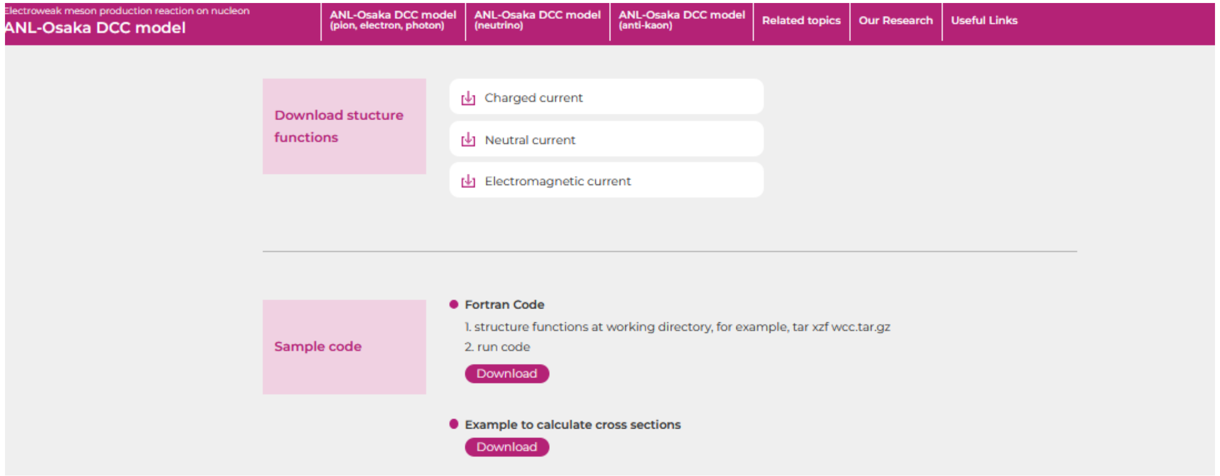
channel	$d\sigma$	Σ	T	P	total
$n\pi^+$	4646	760	645	205	6256
$p\pi^0$	4936	673	353	540	6502
$p\pi^-$	1554	206	94	88	1942

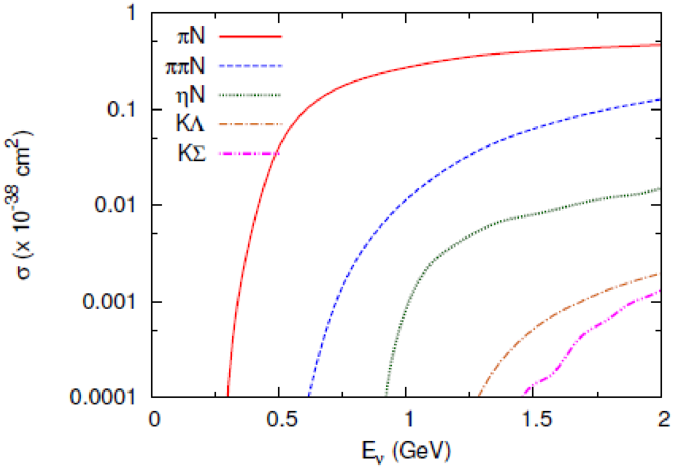
SAID database



ANL-Osaka DCC

- predicts πN, γN partial wave amplitudes used to determine cross sections for πN, ηN, KΛ and KΣ scattering, photoproduction of these channels, 2π production off the nucleon, pion electro- and neutrinoproduction
- Up to W~2 GeV, including ~20 N* states
- Fit to ~30.000 data points for foto pion nucleon, hadron and pion production, and electroproduction for different incoming energies,
- Dynamic coupled channel formalism, different reaction mechanisms contribute in a consistent way to the final state



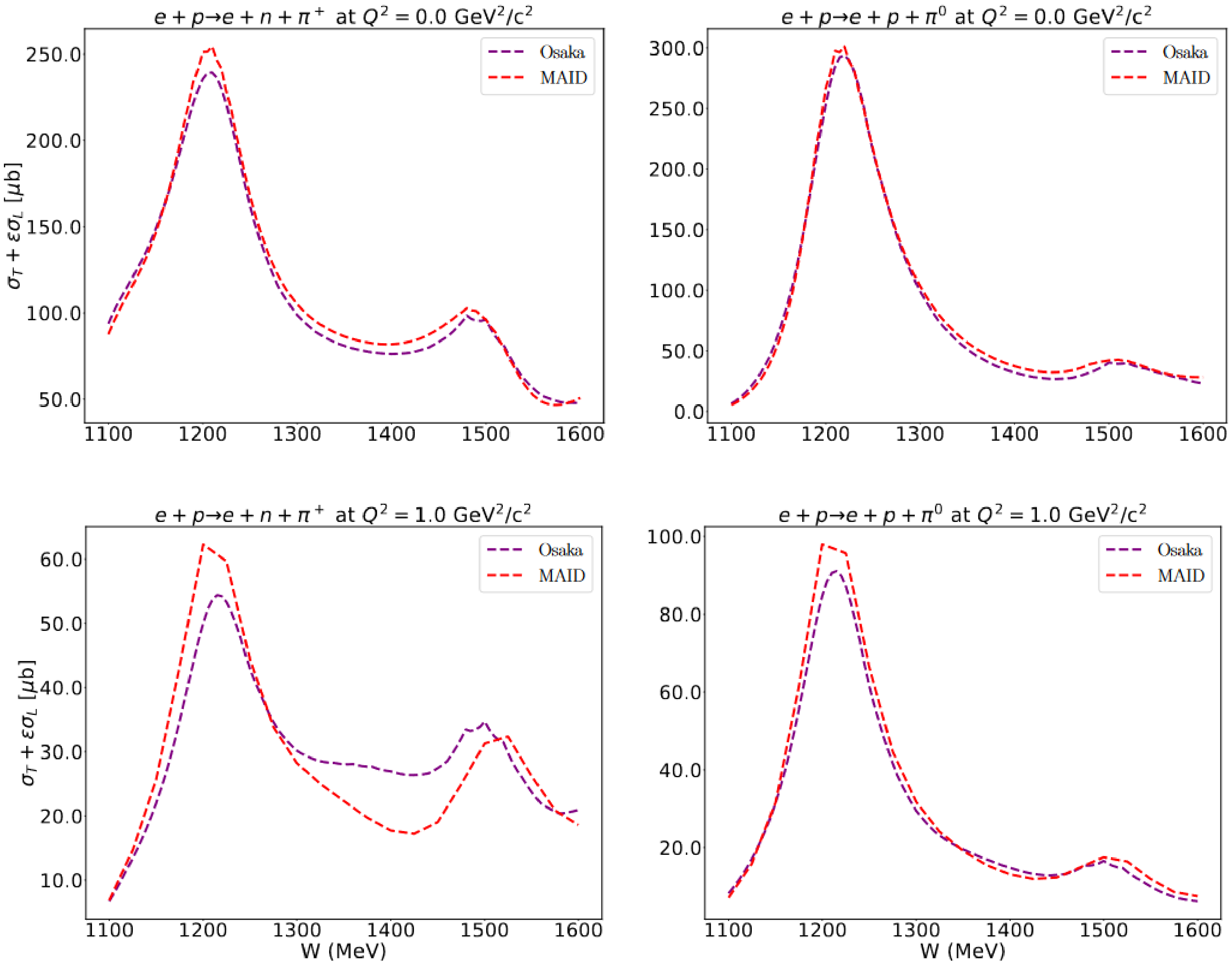


https://www.phy.anl.gov/theory/research/anl-osaka-pwa/

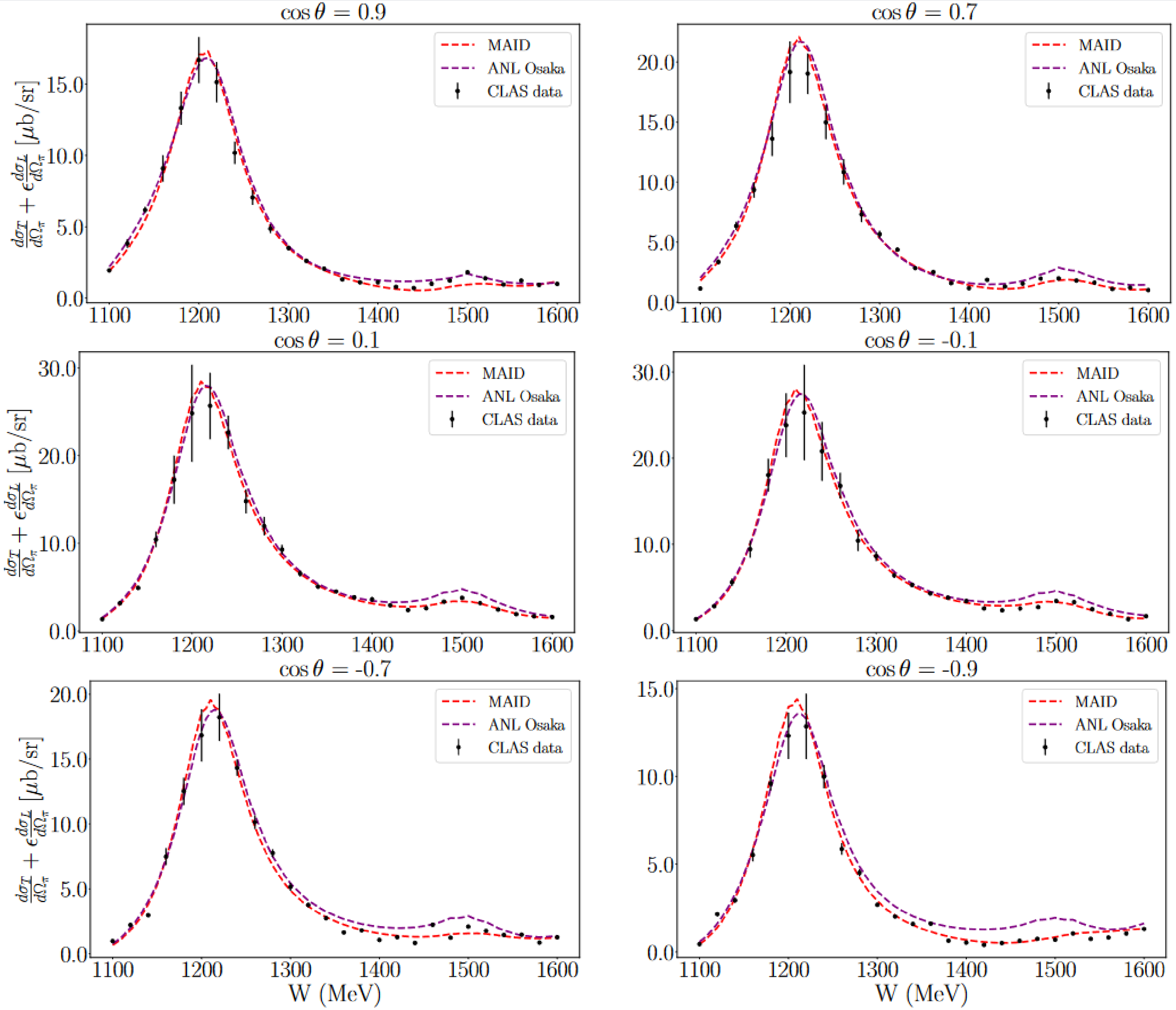
S.X. Nakamura, H. Kamano, T. Sato, PRD92, 074024 (2015)

https://www.rcnp.osaka-u.ac.jp/~anl-osk/neutrino/index.html

MAID vs ANL-Osaka

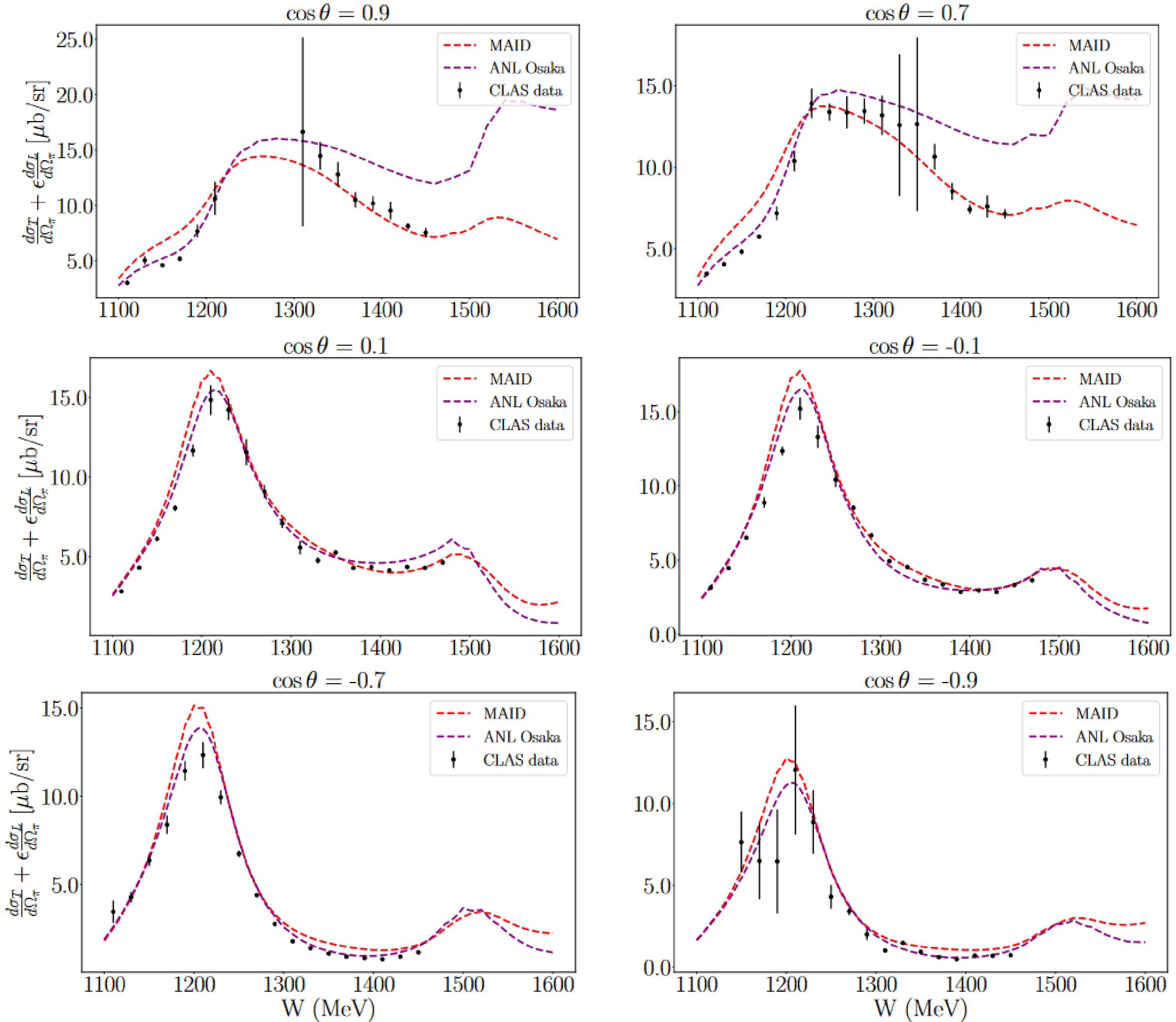


MAID vs ANL-Osaka



$$e + p \rightarrow e + p + \pi^0$$

MAID vs ANL-Osaka



$$e + p \rightarrow e + n + \pi^+$$

MK model

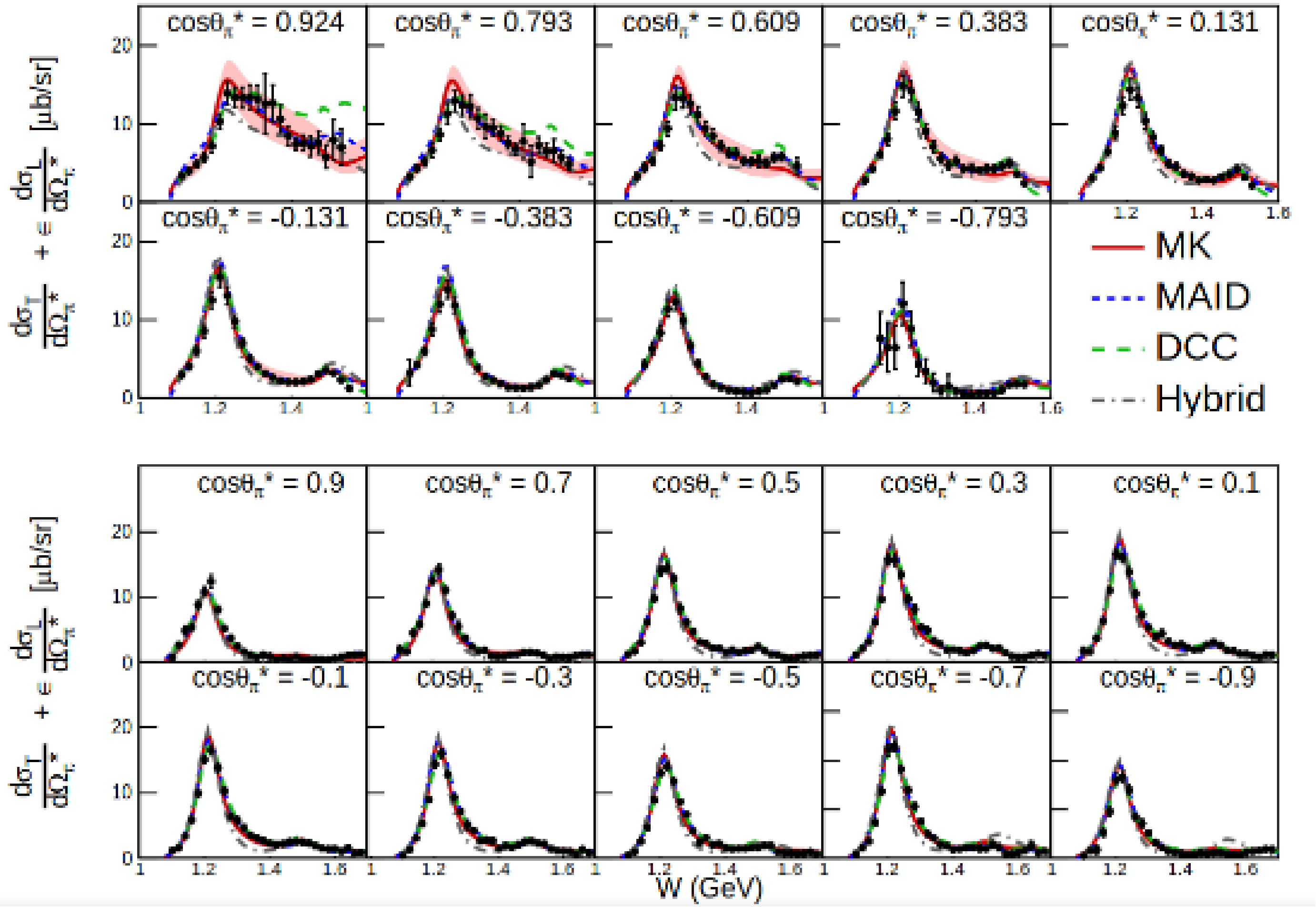
- Single pion production off the nucleon
- developed aiming at describing neutrino induced processes !
- RS with 17 resonances W<2GeV
- Non-resonant background HNV model + Regge
- Fit of a lot of parameters to data
- $d\sigma/dWdQ^2d\Omega_\pi$

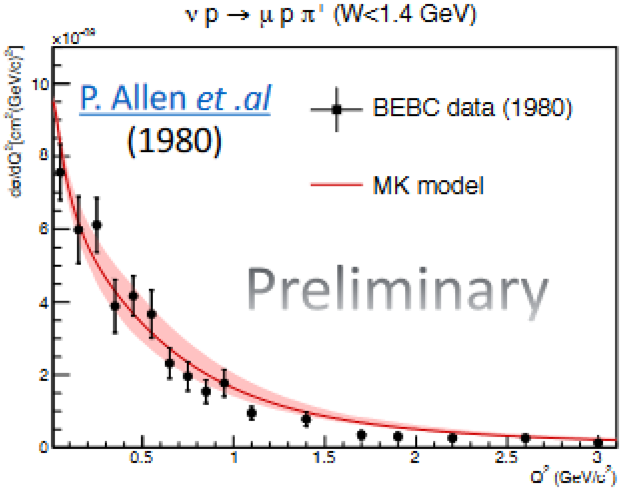
# data point	Photon, electron, pion, Neutrino Channels	Q^2 Range $(GeV/C)^2$	W Range GeV	Form Factors	
≈ 9800	$\gamma p \to n + \pi^+$, $\gamma p \to p + \pi^0$	0	1.08 – 2.0	Proton	Vector
≈ 31000	$ep \to en + \pi^+$, $ep \to ep + \pi^0$	0.16 – 6.0	1.08 – 2.0		
≈ 2500	$\gamma n \to p + \pi^-$	0	1.08 – 2.0	Neutron	
≈ 700	NEW $en \to ep + \pi^-$	0.4 – 1.0	1.08 – 1.8		
≈ 400	$\pi^+ p \to p + \pi^+$, $\pi^- p \to p + \pi^-$	0	1.08 – 2.0	Axial-Vector	
<100	$\nu N \to l^- N + \pi$, $\bar{\nu} N \to l^+ N + \pi$	$Q^2>0$ Integrated	1.08 – 2.0 Integrated		

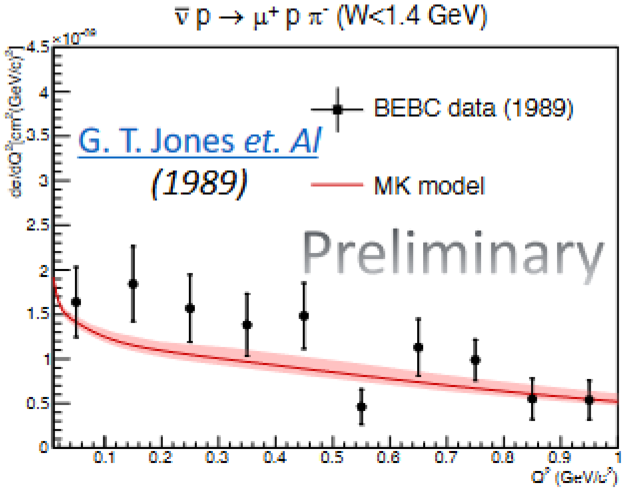
MK model

Electron-induced SPP: high quality proton target data

Figures from M. Kabirnezhad [arxiv:2203.15594]







MK NuInt 2024

Let's talk about .... the nucleus

Models for QE(like) cross sections : Spe… …nction

…gas approaches

:SuSA

Models for QE(like) cross sections

Models for QE(like) cross sections : Ab initio

Models for QE(like…

…els … QE(like) cross sect…

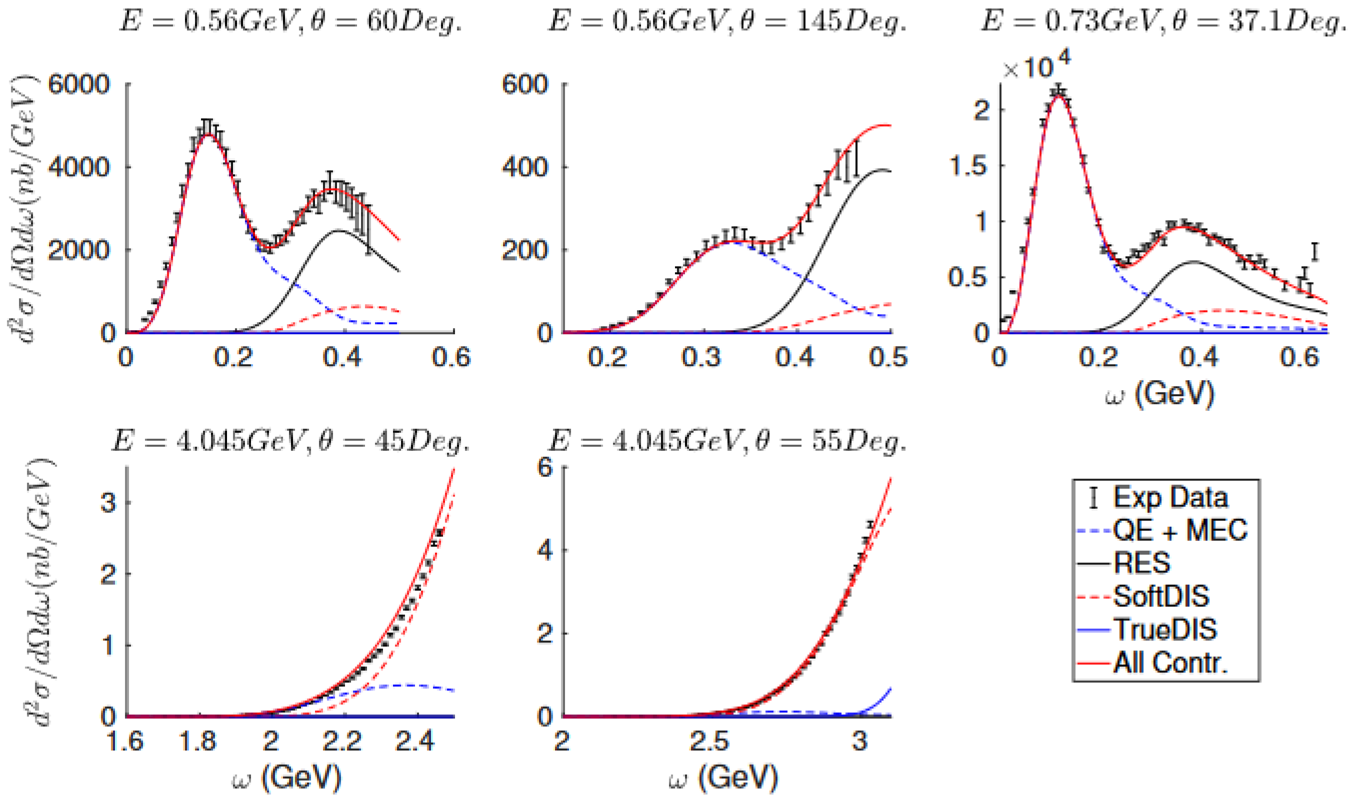
Models for QE(like) cross sections : Coupled cluster

From 0pi to .....

Let's talk about .... the nucleus : DCC implementation in SuSA

Incorporating :

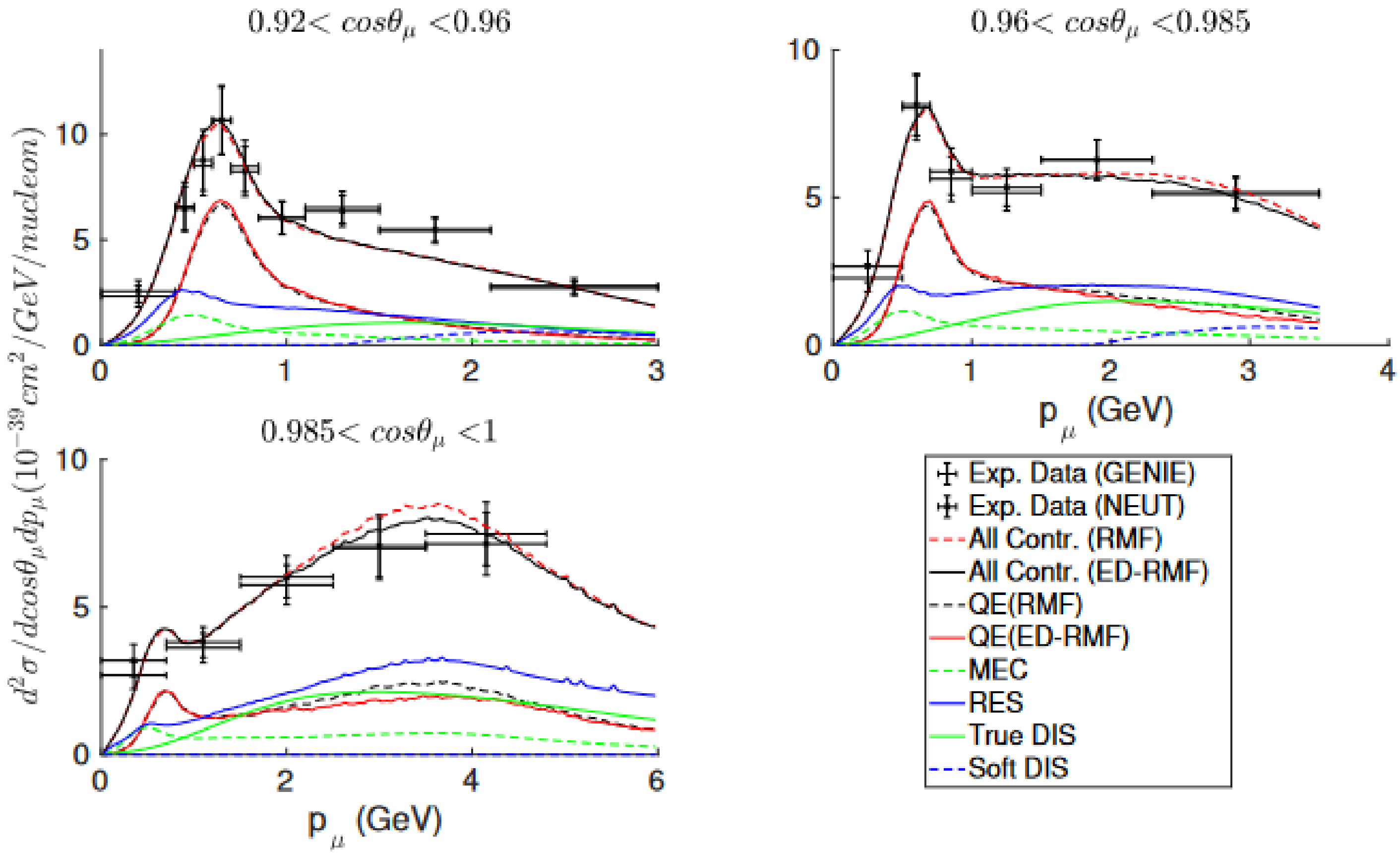
- ANL-Osaka DCC results in SuSAv2
- Inelastic contributions : Bodek-Ritchie, Bosted-Christy or parton distribution functions



Inclusive e-^{12}C

Gonzalez-Rosa et al.PRD 108, 113008 (2023).

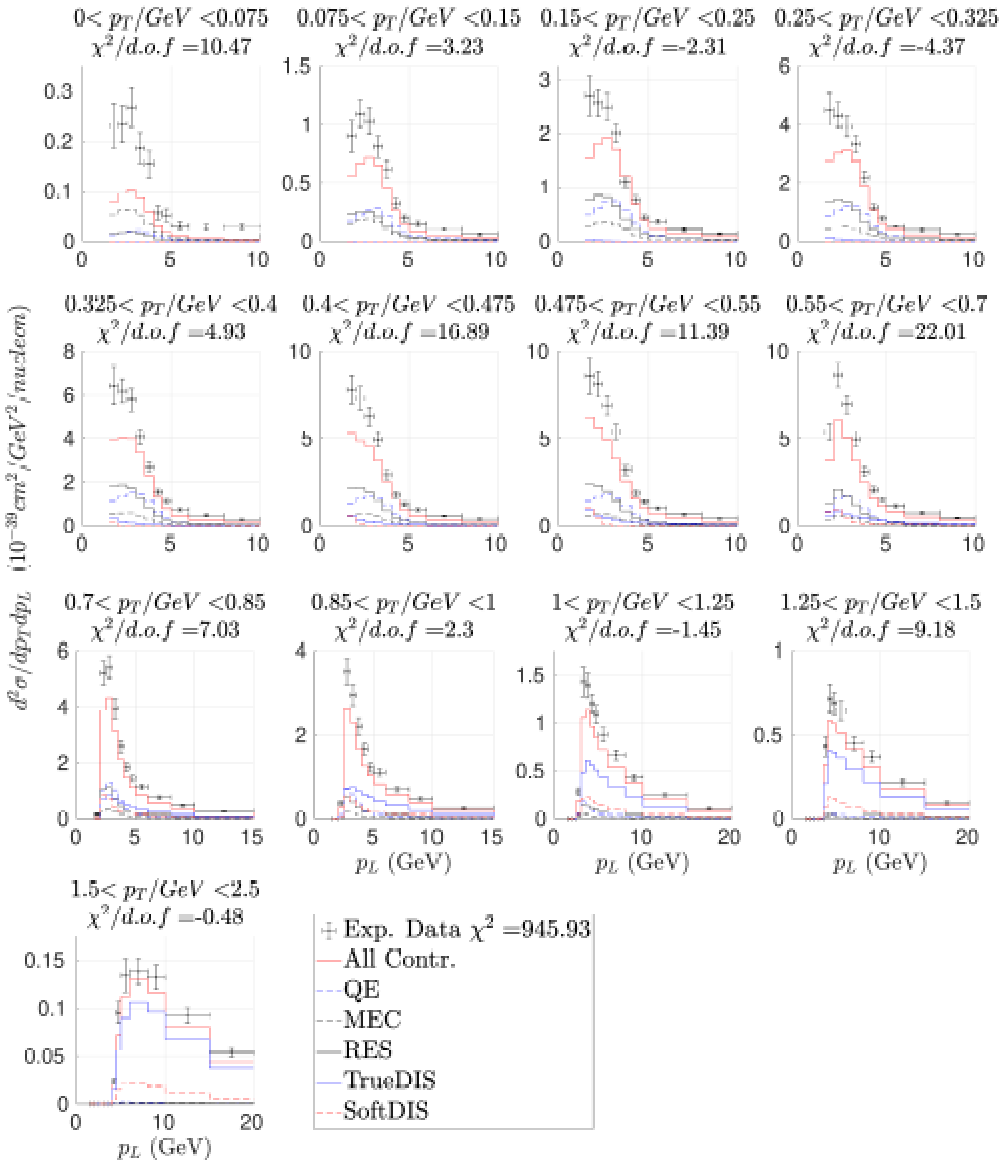
Let's talk about .... the nucleus : DCC implementation in SuSA

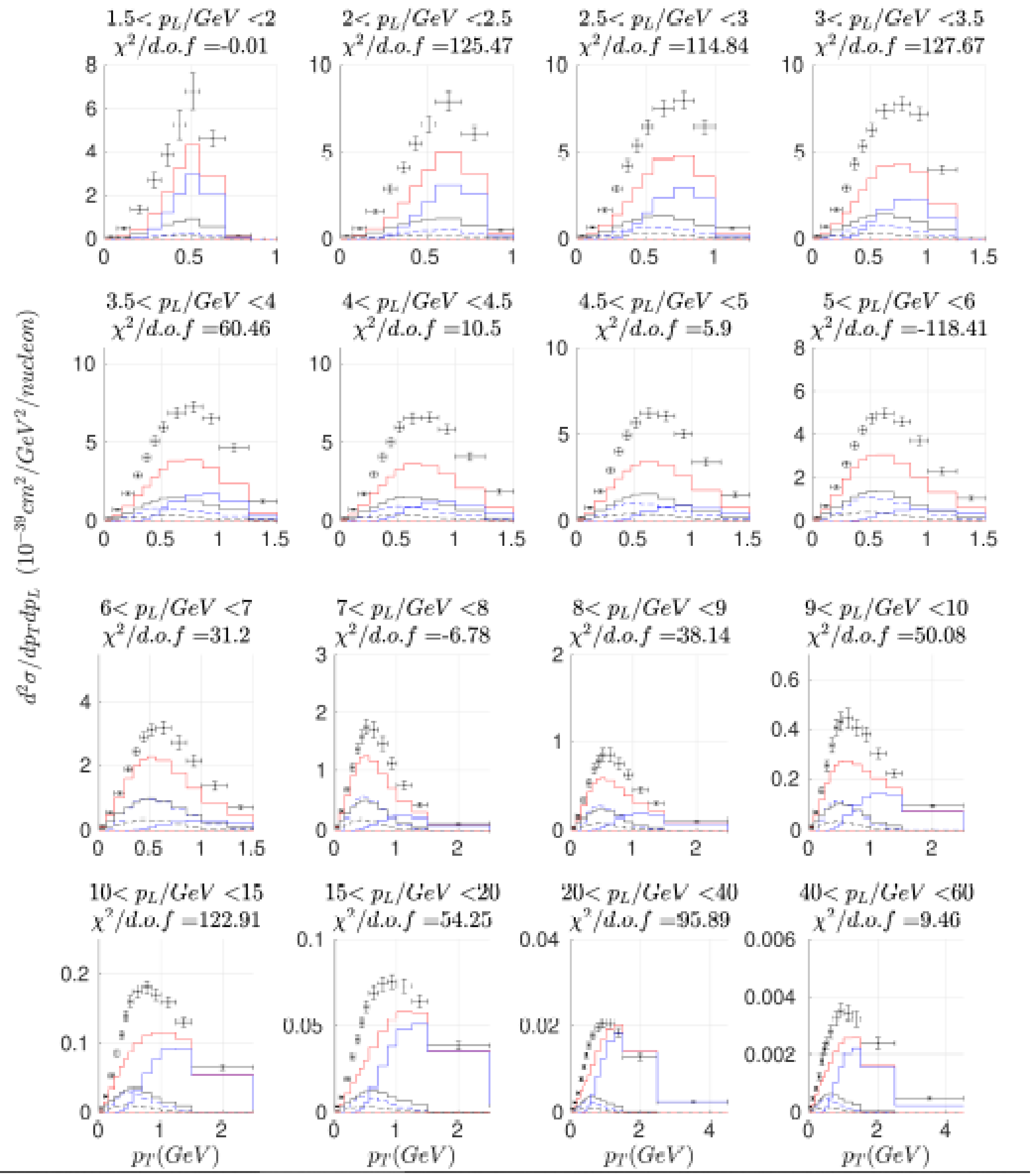


T2K inclusive flux-folded CC

J. Gonzalez-Rosa et al.PRD 108, 113008 (2023).

Let’s talk about .... the nucleus : DCC implementation in SuSA

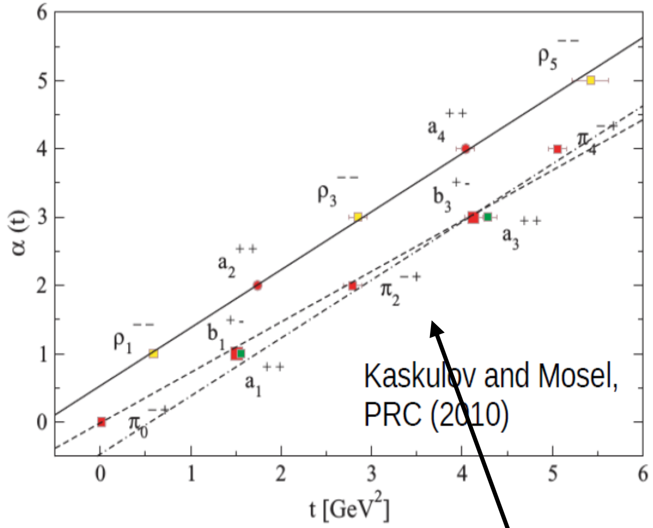




Minerva longitudinal and transverse muon momentum bins

Ghent Hybrid model

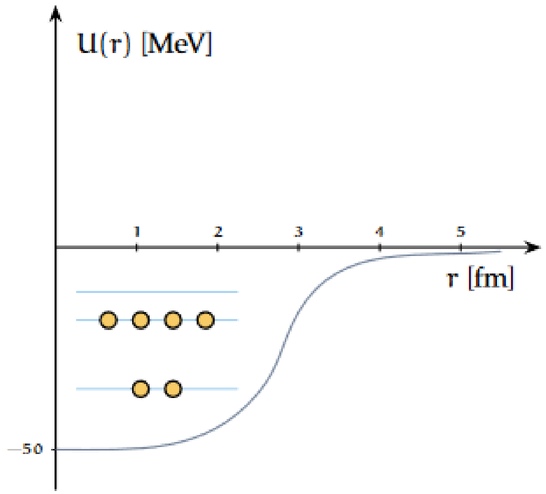
- Designed aiming at the description of pion production off the nucleus
  - Low energy model : resonances + background from ChPT in HNV description
  - High energy model : Reggeized background to overcome shortcomings of the low energy description
- Aiming at fully exclusive description

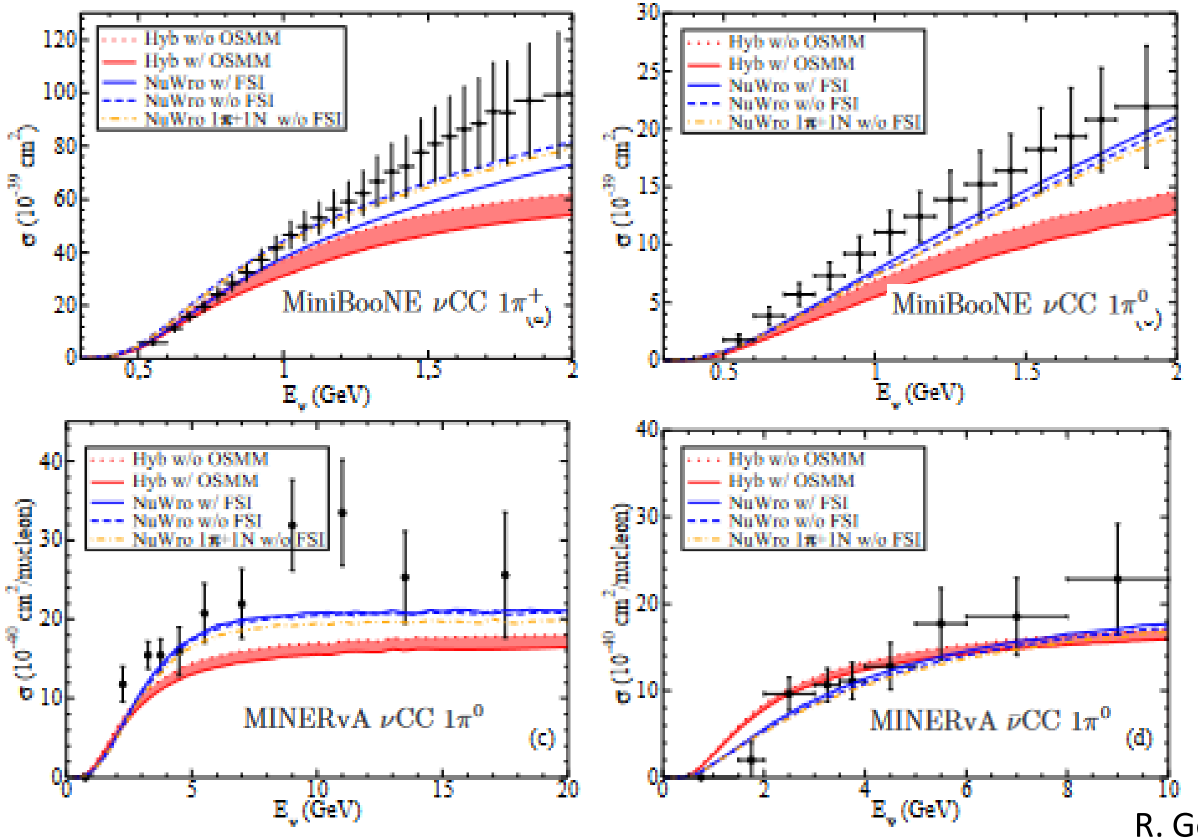


Kaskulov and Mosel, PRC (2010)

π(140)/b_1(1235) propagator

RMF description for the nucleus

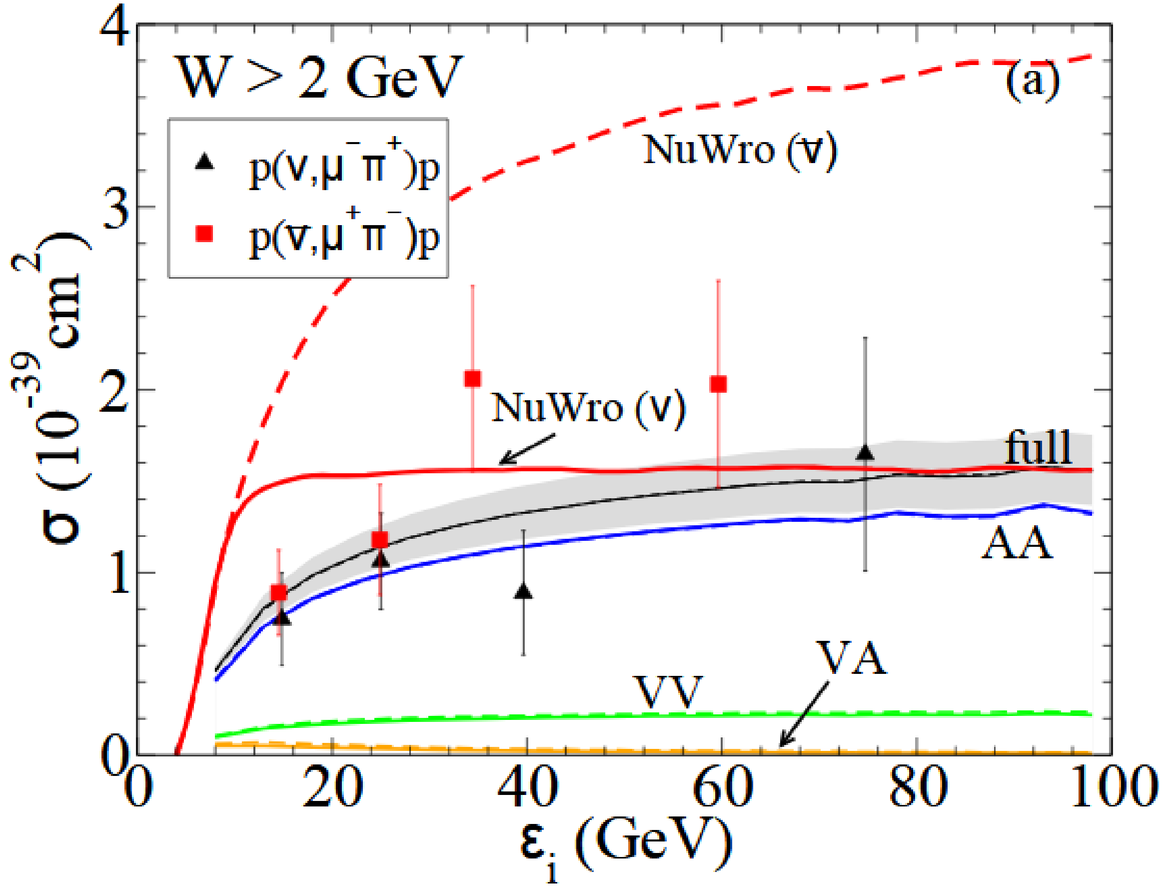


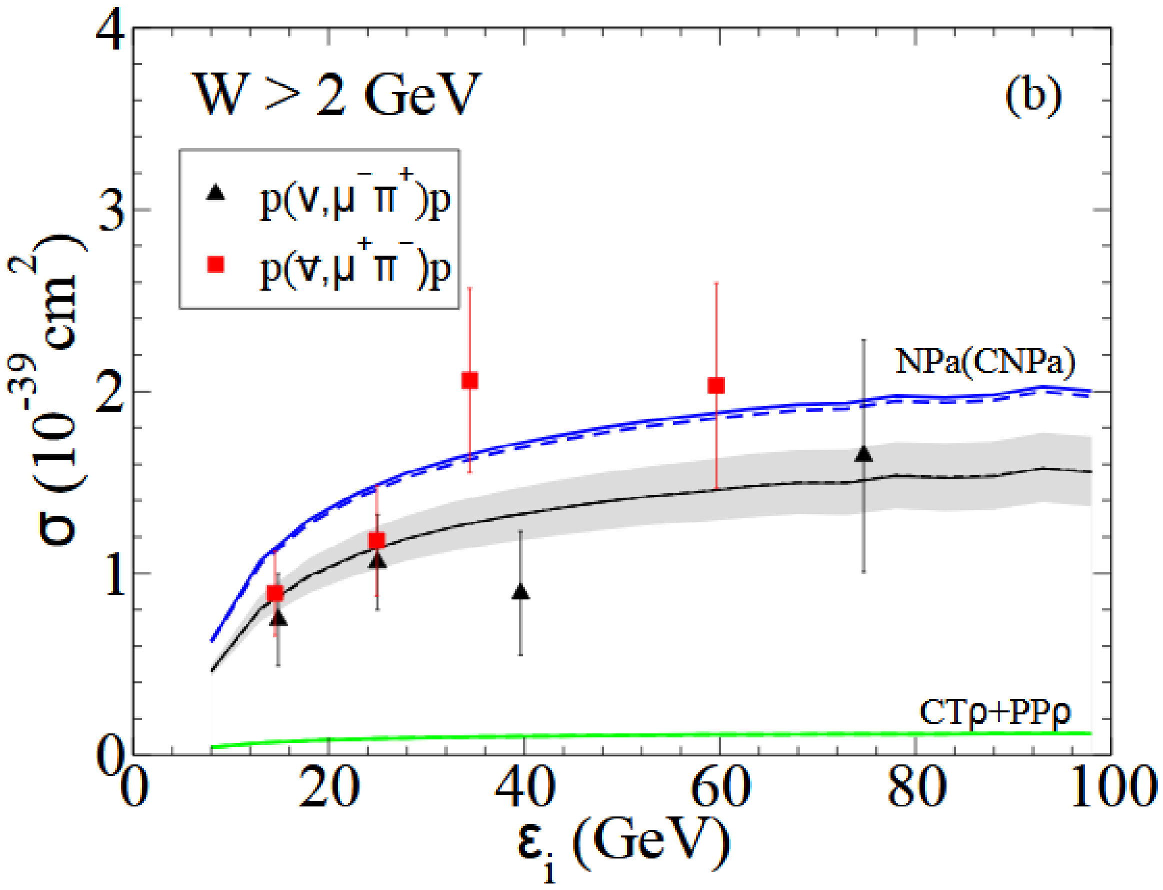


R. Gonzalez-Jimenez et al.,Phys. Rev. D 97

Ghent Hybrid model

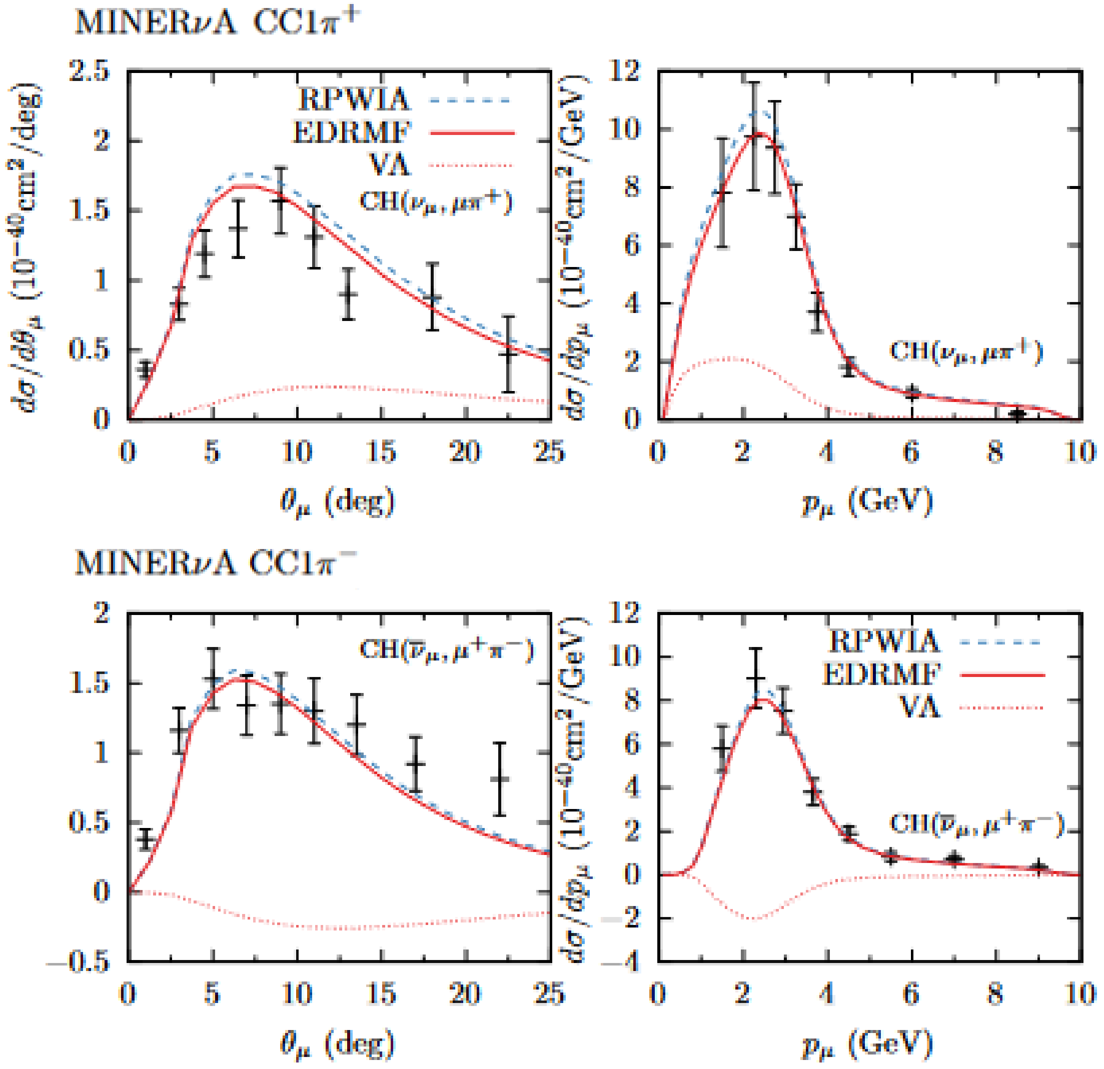
Going beyond W>2 GeV





R. Gonzalez-Jimenez et al.,Phys. Rev. D 97

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



Plane waves

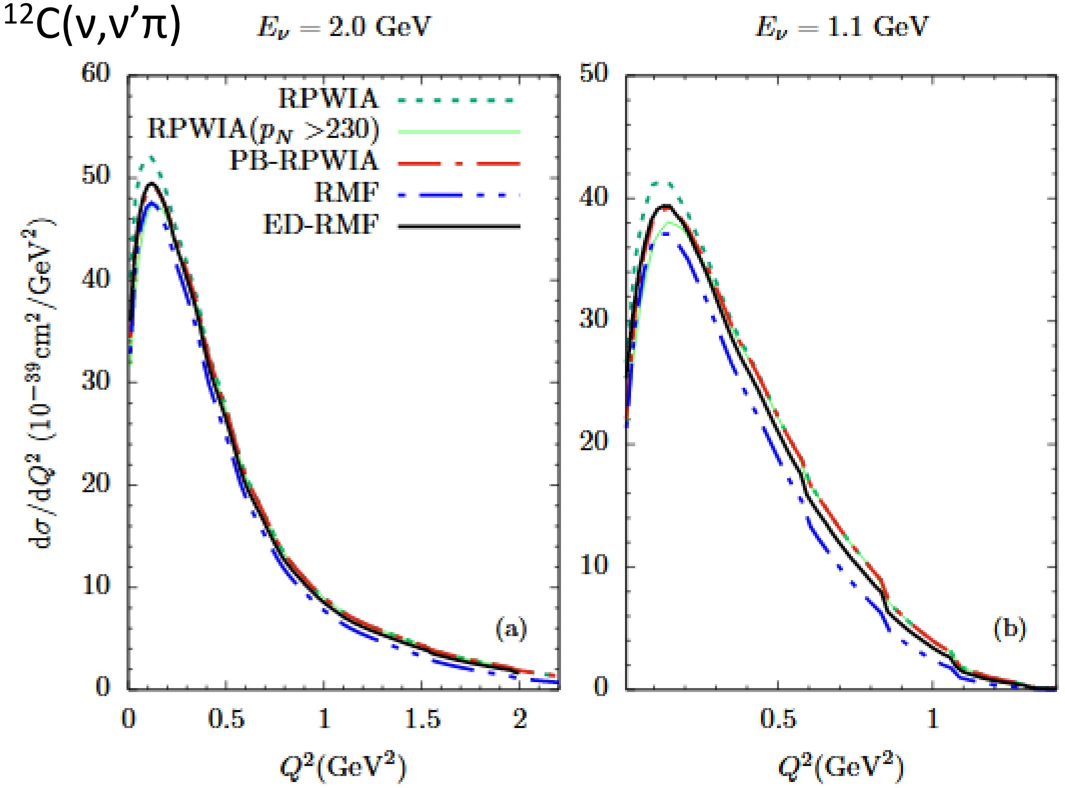
$$J^{\mu}_{had} = \sum_{i}^{A} \int \mathrm{d}\mathbf{r}\, \overline{\Psi}_F(\mathbf{r})\, \phi^*(\mathbf{r}) \hat{O}^{\mu}_{one\text{-}body}(\mathbf{r})\, \Psi_B(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$

Relativistic mean-field wave functions

A. Nikolakopoulos, PhD UGent 2021

Let's talk about .... The nucleus

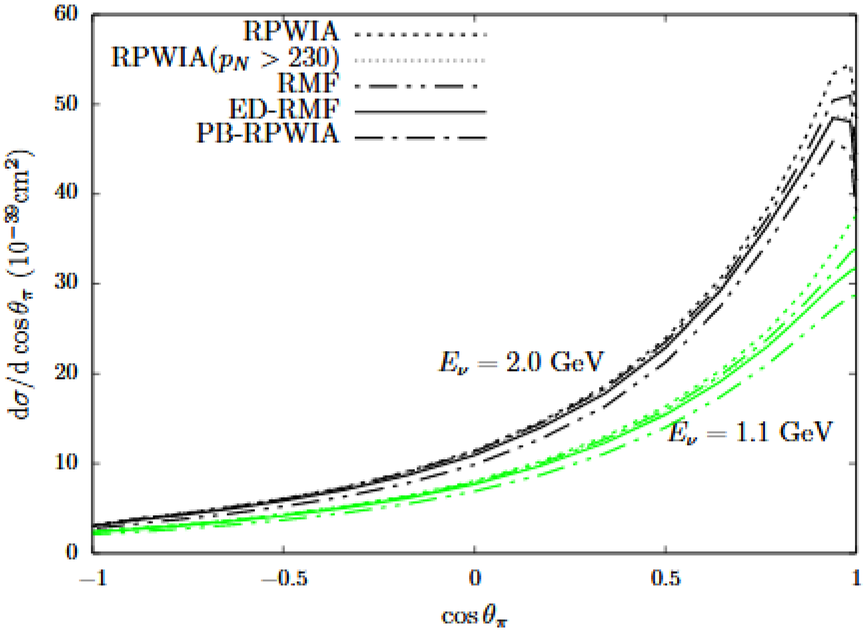
$^{12}C(\nu,\nu'\pi)$



Plane wav

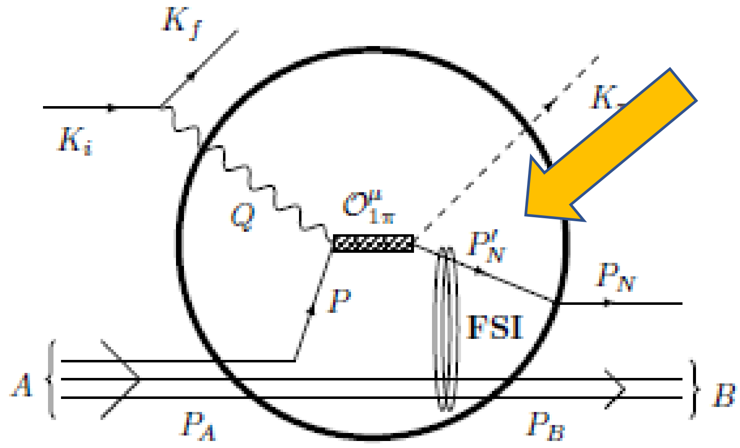
$$J^{\mu}_{had} = \sum_{i}^{A} \int d\mathbf{r}\, \overline{\Psi}_F(\mathbf{r})\, \phi^*(\mathbf{r}) \hat{O}^{\mu}_{one\text{-}body}(\mathbf{r})\, \Psi_B(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$

Relativistic mean-field wave functions

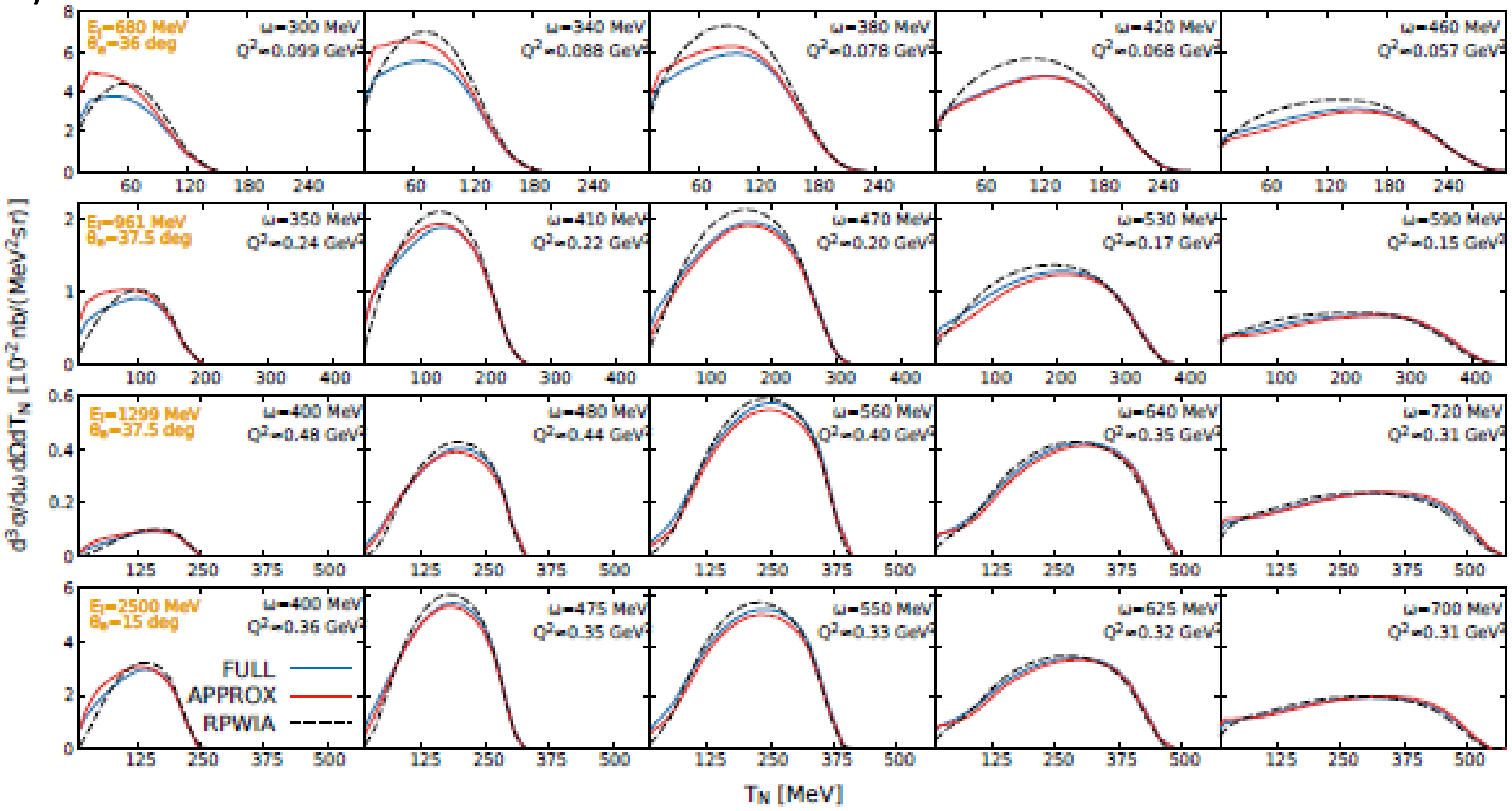


Let’s talk about .... The nucleus

Beyond the asymptotic approximation: fully microscopic calculation of nucleon momentum in the nuclear medium



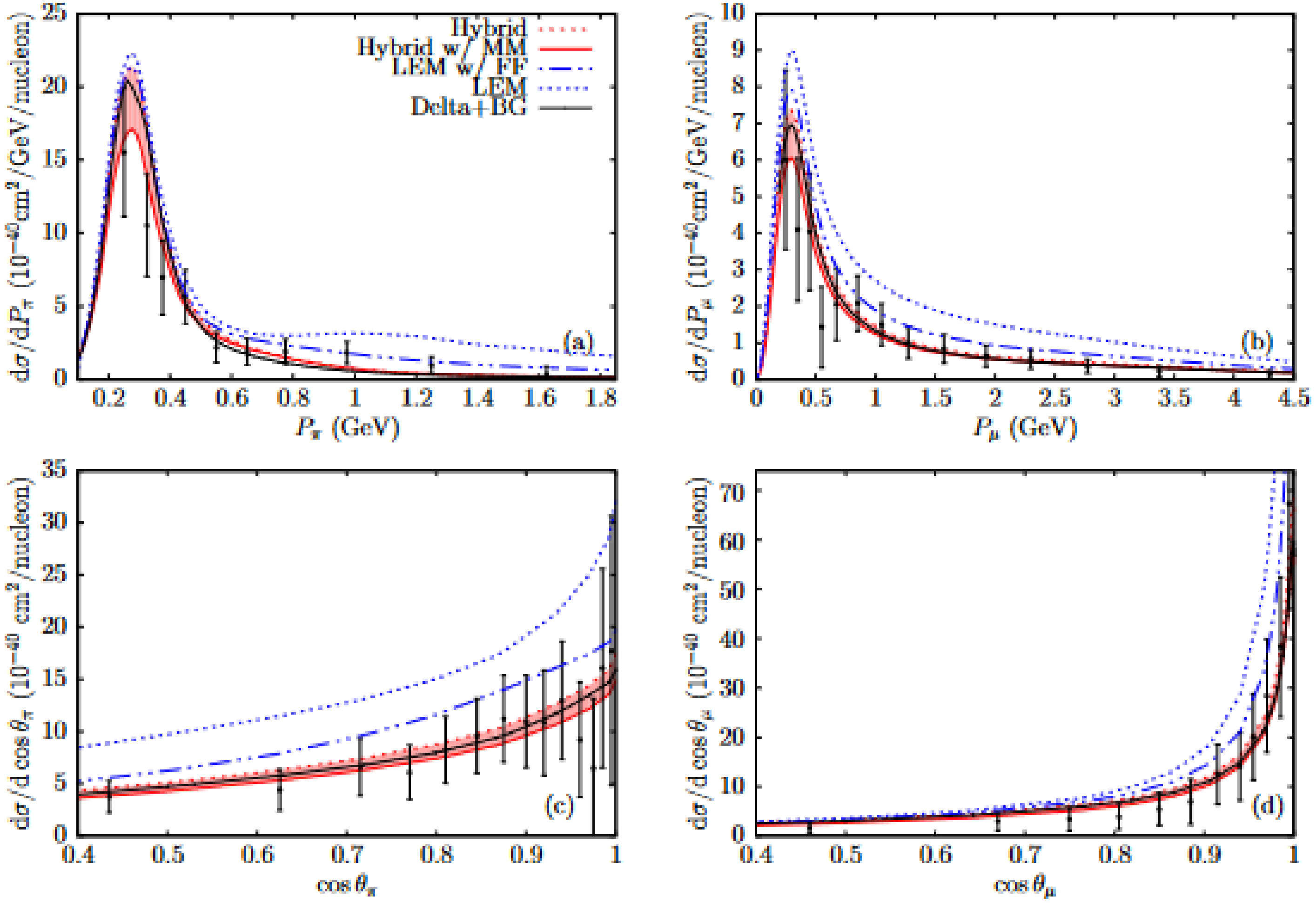
$$J^{\mu}_{had} = \sum_{i}^{A} \int d\mathbf{r}\, \overline{\Psi}_F(\mathbf{r})\, \phi^{*}(\mathbf{r})\, \hat{O}^{\mu}_{one\text{-}body}(\mathbf{r})\, \Psi_B(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$$



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

J. Garcia Marcos et al.PRC109 024608 (2024)

Let's talk about .... the Δ in the medium

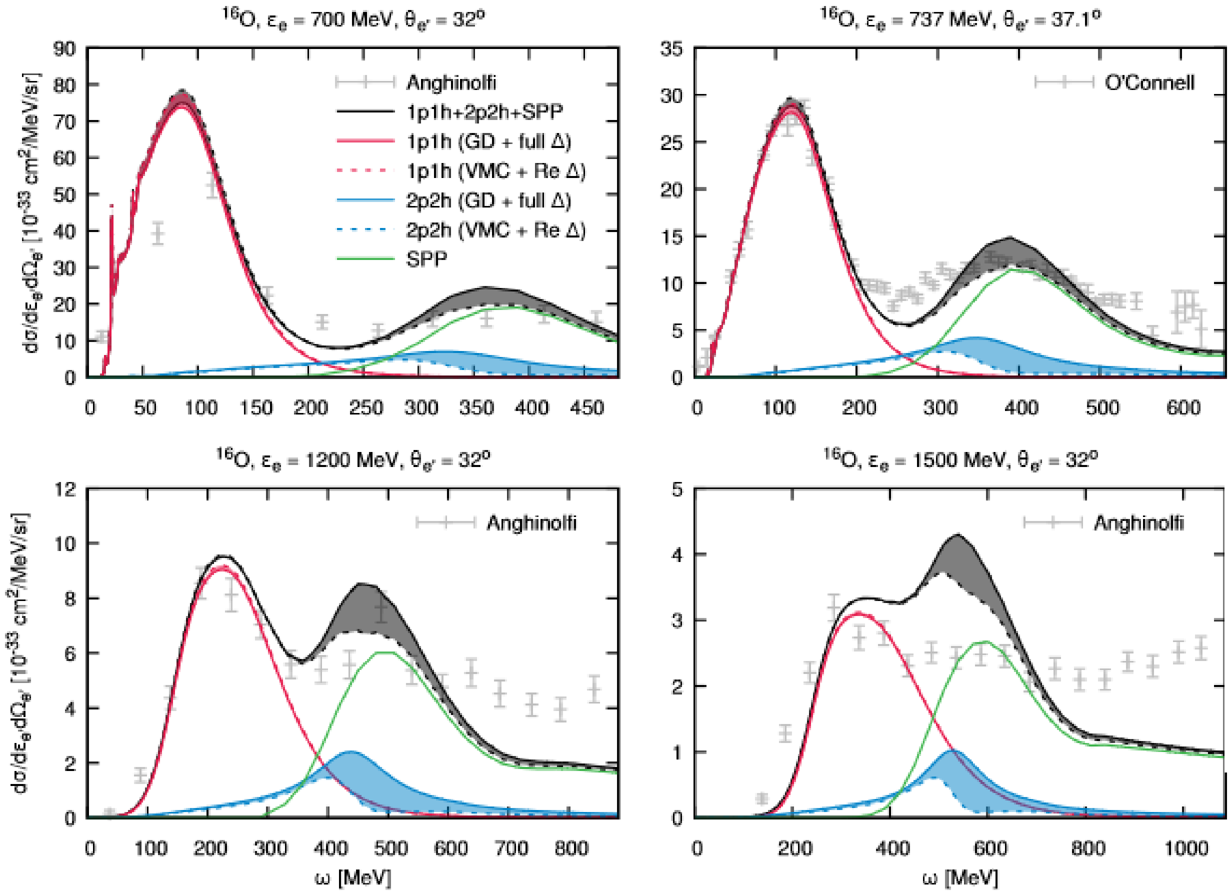


Most commonly used

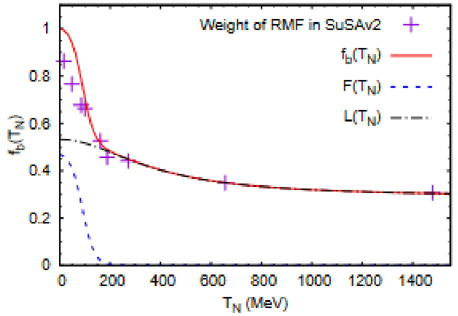
- Oset-Salcedo medium modifications
- Evaluated in FG model

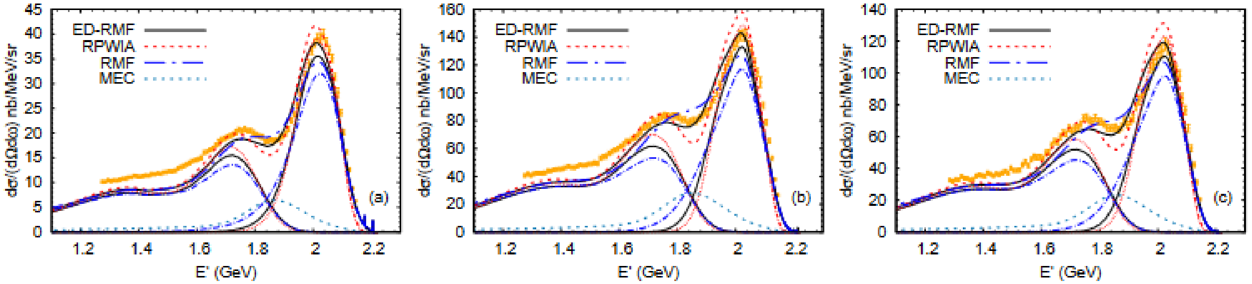
A. Nikolakopoulos, PhD thesis UGent 2021

Let’s talk about .... tails



K. Niewczas PhD Wrocław+UGent 2023

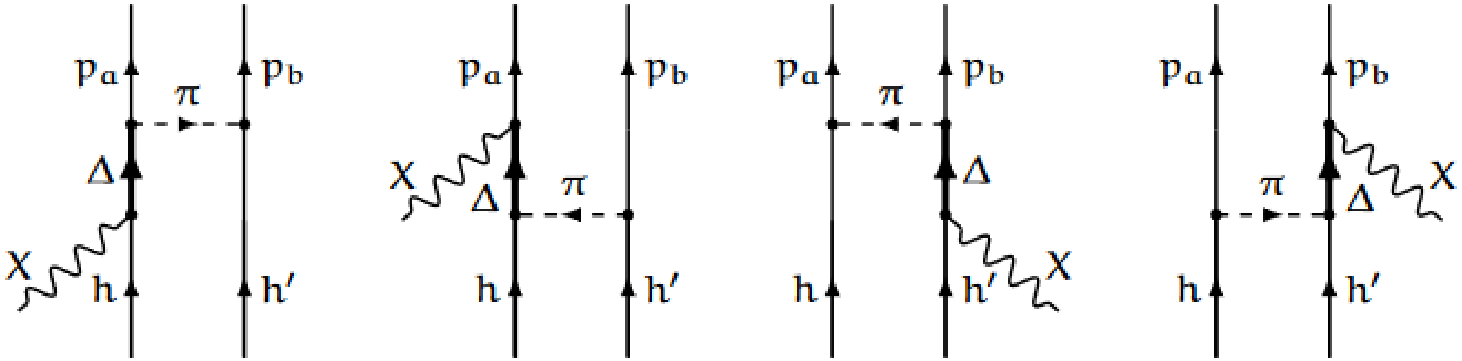




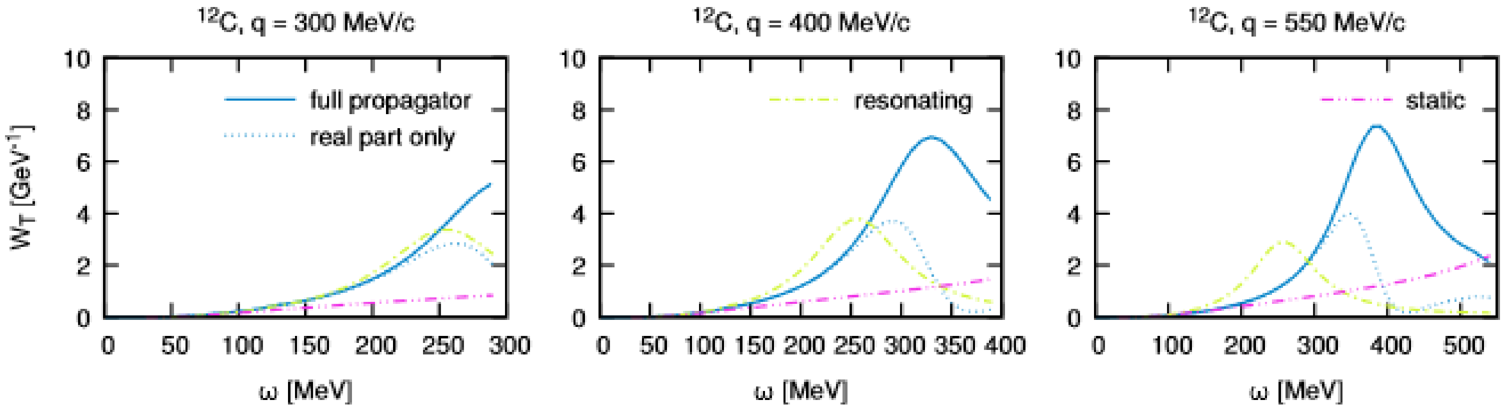
R. Gonzalez-Jimenez Phys. Rev. C 101, 015503 (2020)

Let's talk about .... consistency

Consistency of Delta description with MECs description ?



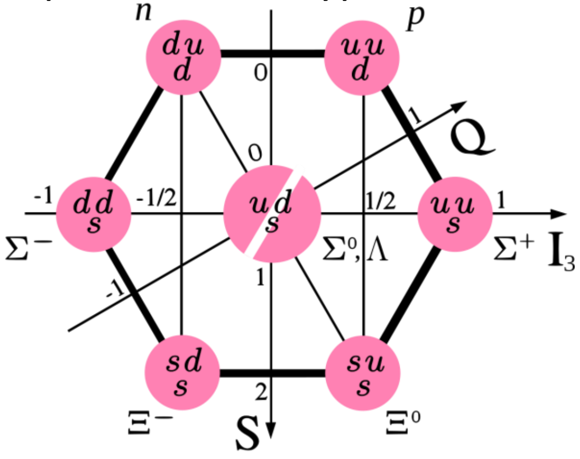
2p2h

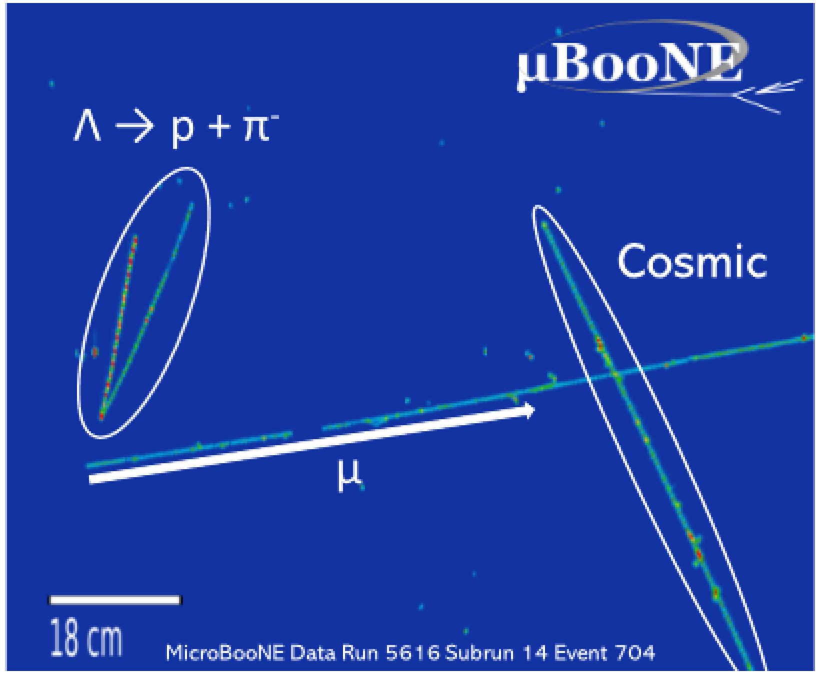


K. Niewczas, PhD thesis 2023

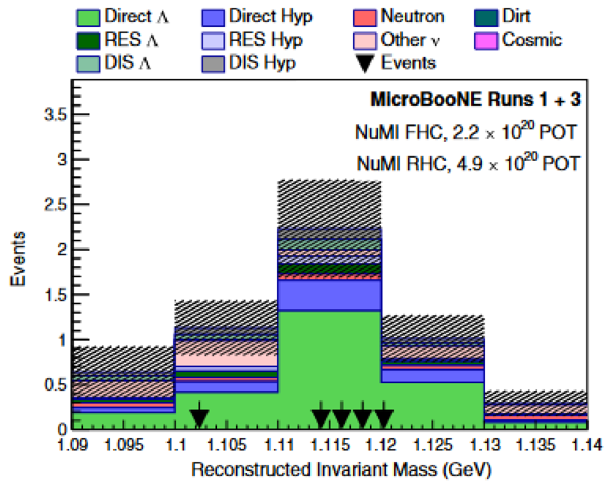
Let's talk about strange things

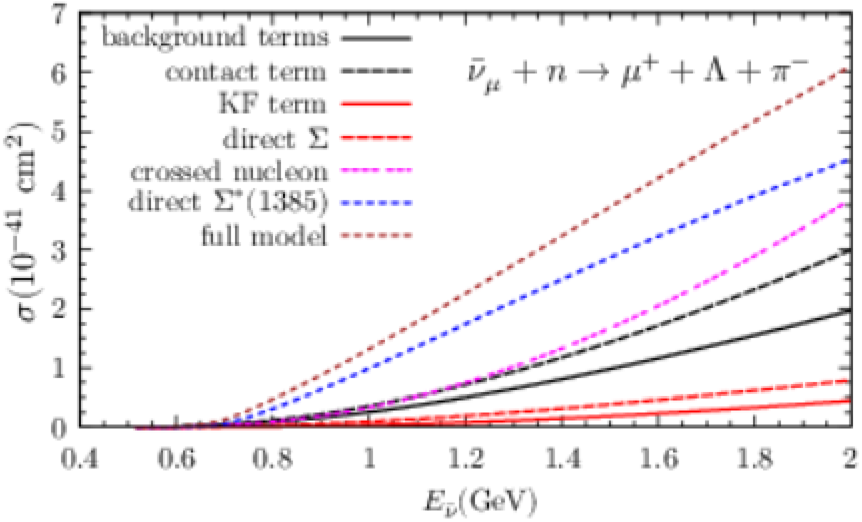
Neutrino strangeness production : hyperons

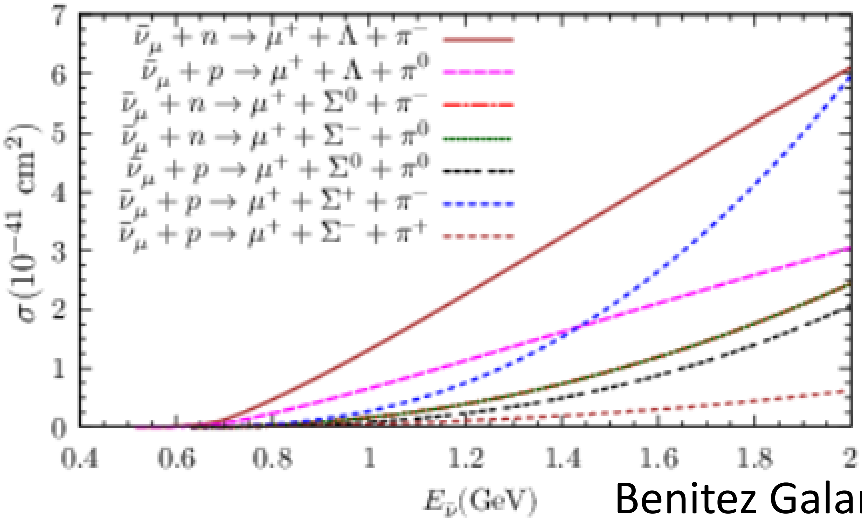




MicroBooNe Phys. Rev. Lett. 130, 231802



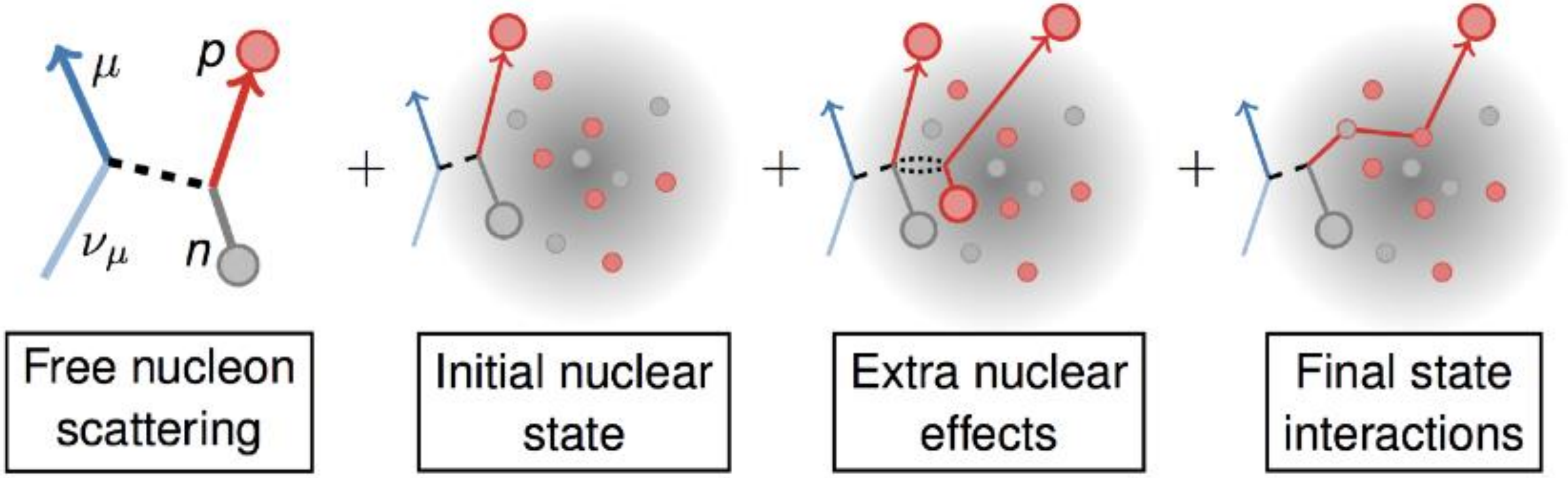




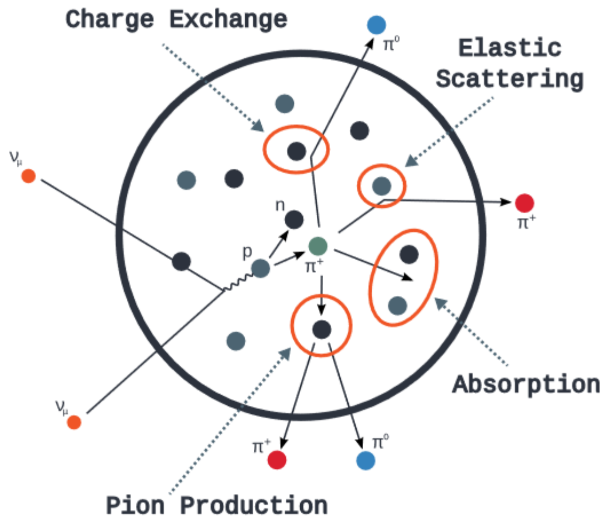
Pion production at low energies !

Benitez Galan, Rafi Alam, Ruiz Simo, PRD104 (2021)

What is going on between initial and final state ... ?



K. Niewczas @ NuFACT2021



T. Golan

- Partially taken into account by some of the nuclear models
- MC Generators used for oscillation analyses tend to rely on efficient but approximate models

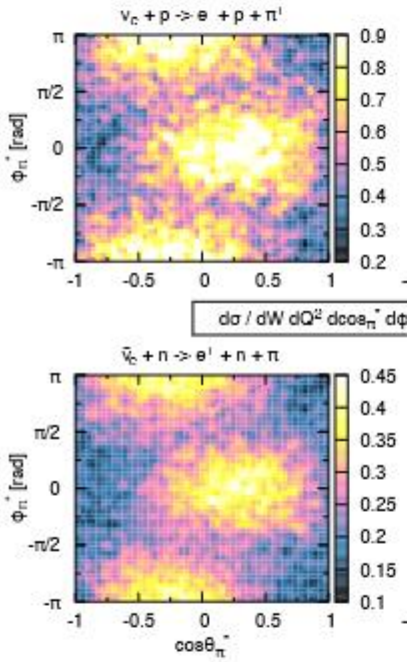
Event generators : bridges between theory and data

Challenges in generator developments :

- Microscopic input for vertex – exclusive description

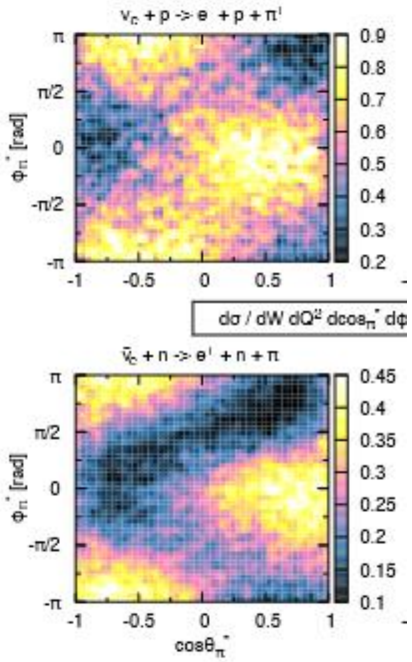
- Default NuWro
- Free nucleon
- Fixed kinematics:

$E = 1$ GeV
$Q^2 = 0.1$ GeV^2
$W = 1230$ MeV



- Ghent LEM
- Free nucleon
- Fixed kinematics:

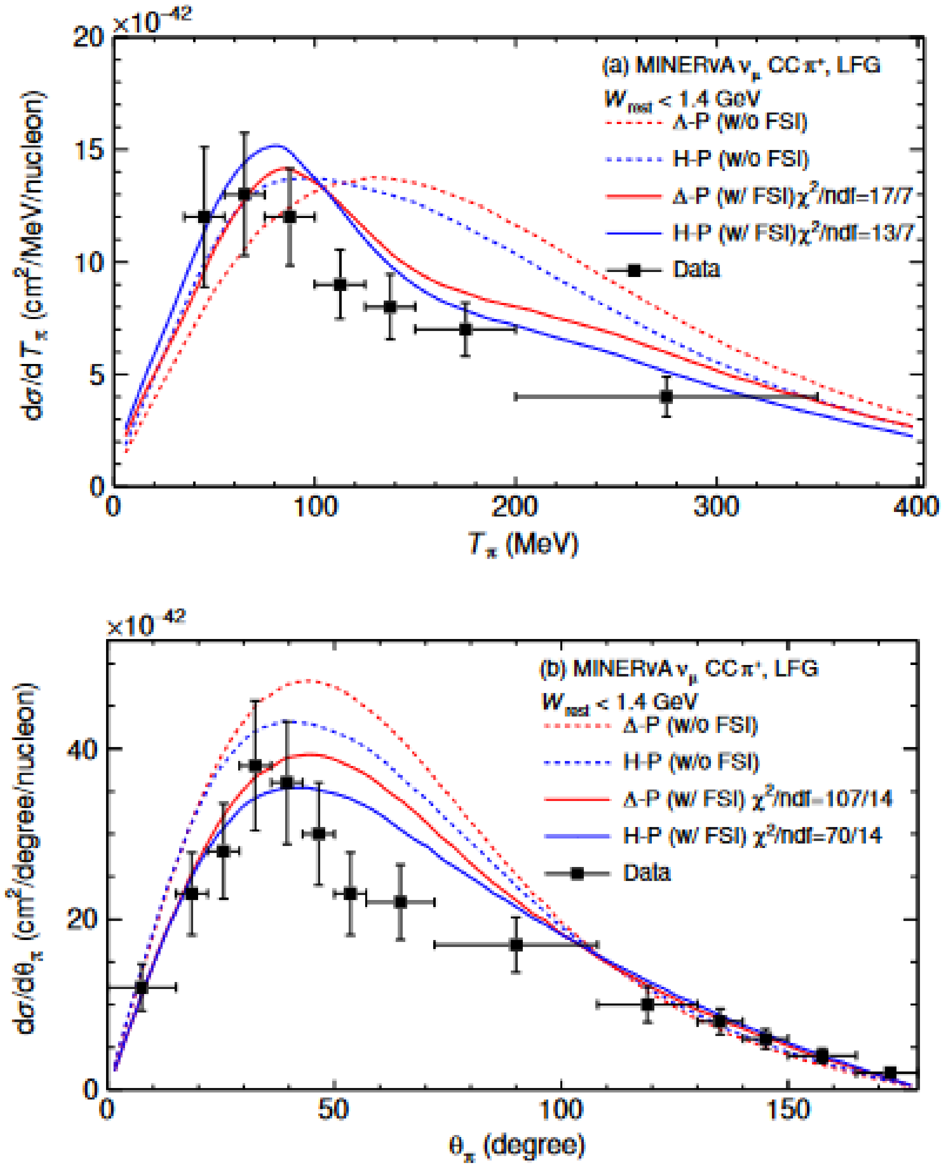
$E = 1$ GeV
$Q^2 = 0.1$ GeV^2
$W = 1230$ MeV



Need to go beyond isotropic approaches in MC generators and include detailed exclusive microscopic calculation results in the simulation

K. Niewczas et al. PRD 103, 053003 (2021)

Event generators : bridges between theory and data

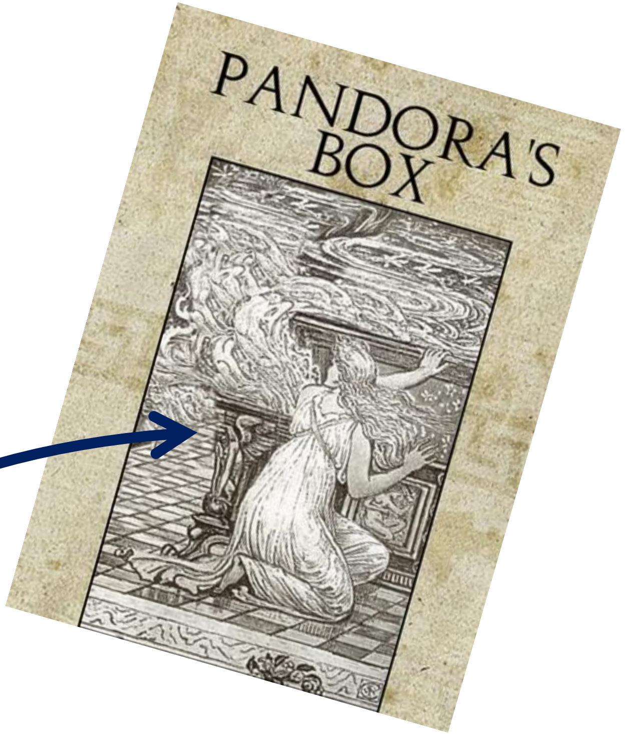


Integration of Ghent hybrid model in NuWro for pion production off the nucleus

Q. Yan et al. arXiv 2405.05212

Summarizing ...

- Single pion production in the Delta region is relatively well understood
- At higher kinematics, for more complex final states and especially for W>2GeV :
  we'll have to go on opening



But ... Hope is still in the box !