The status of neutrino interaction theory and its impact on future neutrino oscillation experiments.

Minoo Kabirnezhad

NOW 2018

Status of neutrino interaction theory

many efforts have been devoted to the **quasielastic peak** and **dip region** but very little attention has been given to the resonance and higher regions.

New CC1π data that can help theory.

Electron-nucleon/nucleus and pion scattering.

Old bubble chamber data with large error.

Verifying the model is difficult with limited data sets!

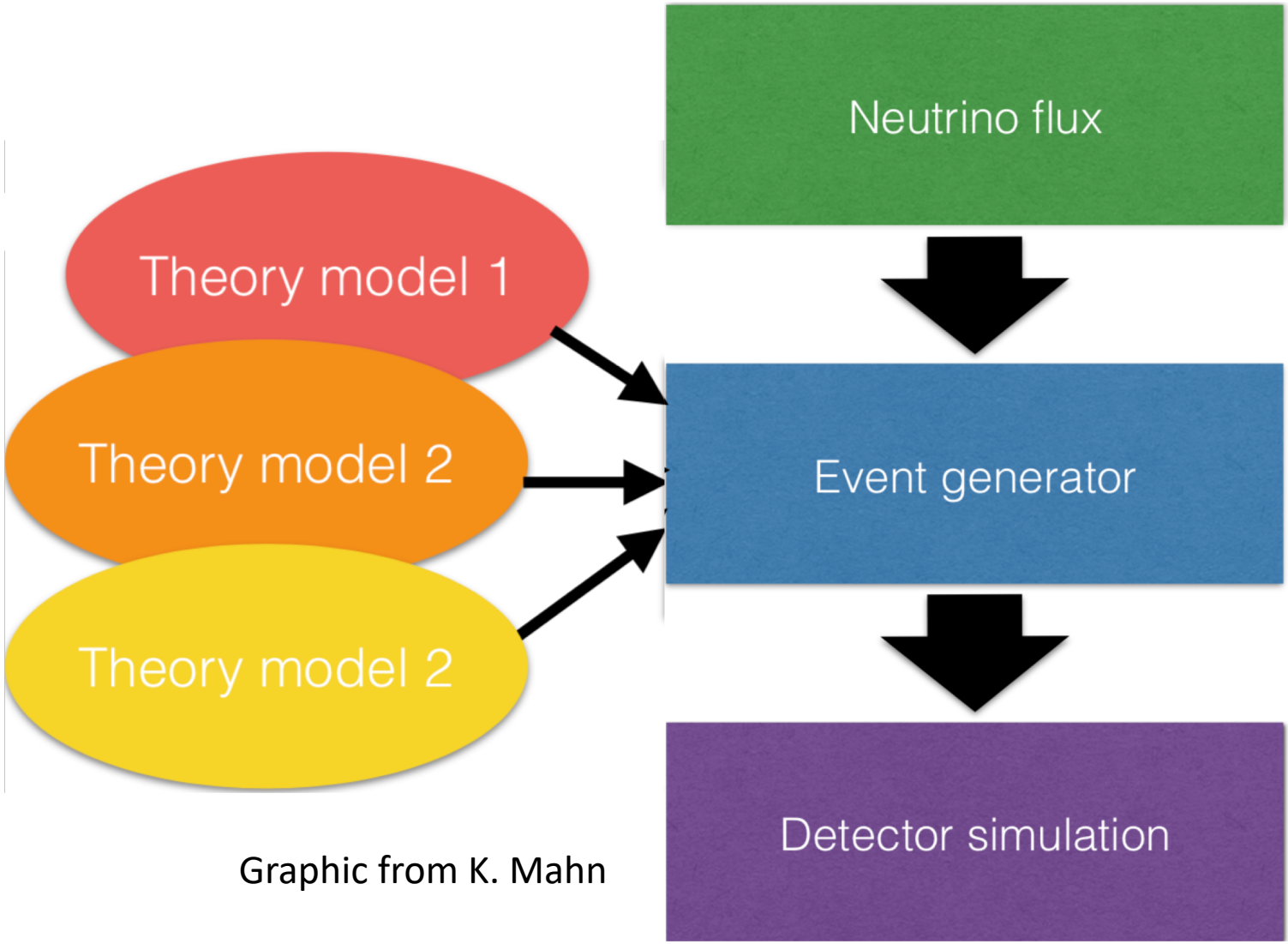
Free parameters in models. data disagree with each other sometimes.

Assumptions in models for simplicity and they are not updated.

Assumptions in model implementation sometimes.

“Generator”? What is that?

- Neutrino interaction models are embedded in software called an “event generator”
- NEUT -> primary generator for T2K, SK, secondary for others.
- GENIE -> widely used by experiments.
- NuWro
- GiBUU
- NUANCE



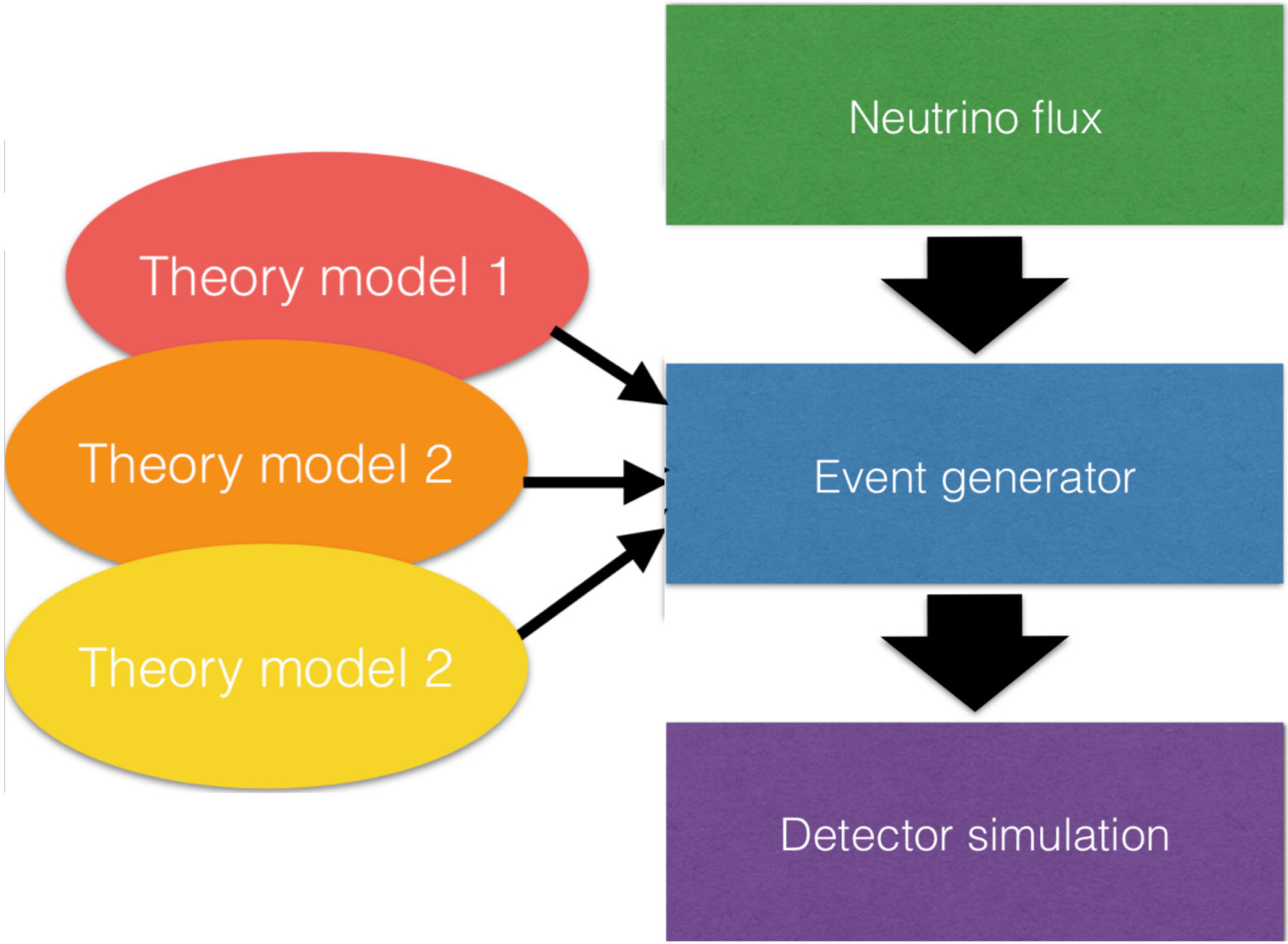
Graphic from K. Mahn

“Generator”? What is that?

- Neutrino interaction models are embedded in software called an “event generator”
- New theory models can be tested in generators.

➢ **Cross Section**

- In any frame
- In any physical region
- With any target
- With any selection
- Wide energy range



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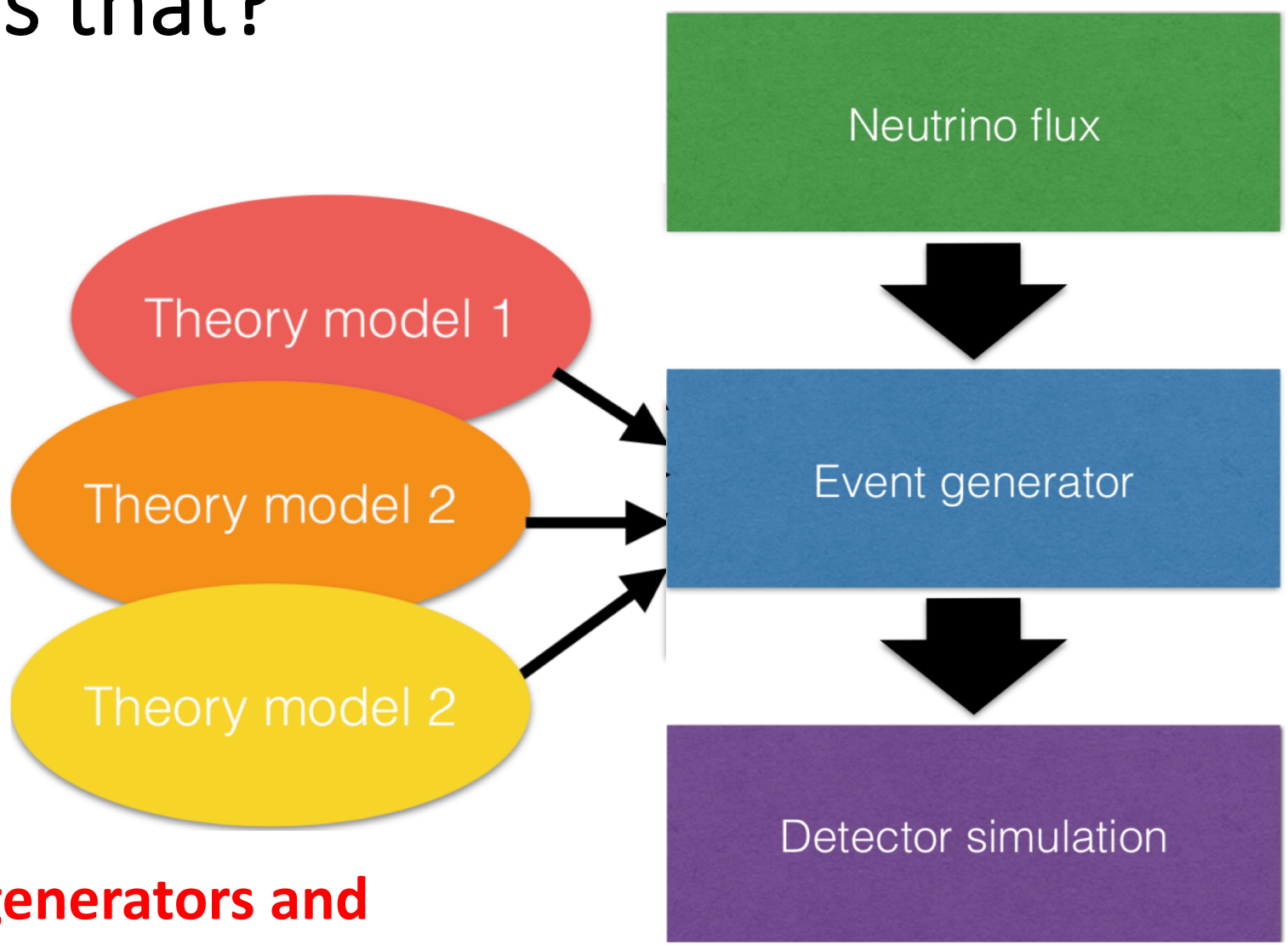


➢ **Cross Section**

➢ **Oscillation analysis**

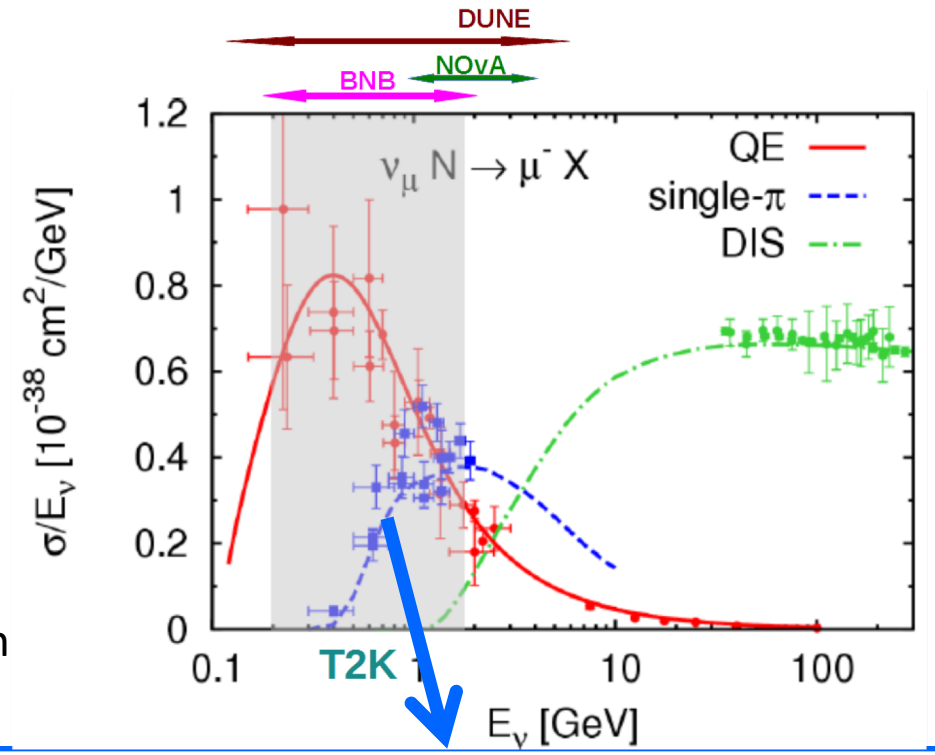
Models should be suitable for generators and be able to predict what is actually measured in experiment.

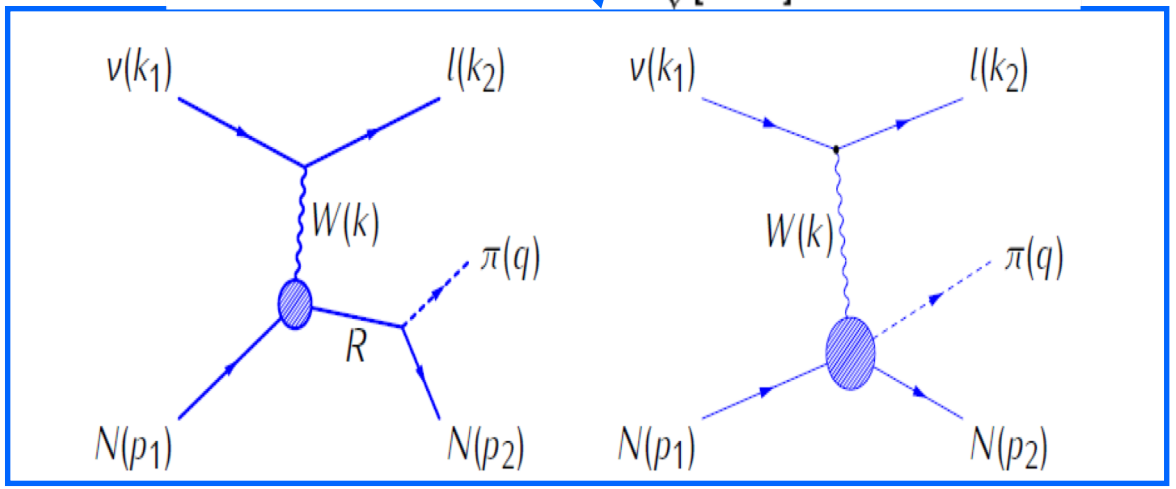
Single pion production in neutrino-nucleon interactions

- Single pion can be produced via decay of resonance excitations or non-resonant interactions.
- It has significant contribution at intermediate energy.

	ν	$\bar{\nu}$
CC	$\nu p \to \mu^- p \pi^+$	$\bar{\nu} n \to \mu^+ n \pi^-$
	$\nu n \to \mu^- p \pi^0$	$\bar{\nu} p \to \mu^+ n \pi^0$
	$\nu n \to \mu^- n \pi^+$	$\bar{\nu} p \to \mu^+ p \pi^-$
NC	$\nu p \to \nu p \pi^0$	$\bar{\nu} p \to \bar{\nu} p \pi^0$
	$\nu p \to \nu n \pi^+$	$\bar{\nu} p \to \bar{\nu} n \pi^+$
	$\nu n \to \nu n \pi^0$	$\bar{\nu} n \to \bar{\nu} n \pi^0$
	$\nu n \to \nu p \pi^-$	$\bar{\nu} n \to \bar{\nu} p \pi^-$

From C. Wilkinson





Rein-Sehgal model (1981)

1. D. Rein and L. M. Sehgal, Annals Phys. 133 (1981) 79.

Rein-Sehgal[1] is default model in the **NEUT** and **GENIE**

- Easy to be implemented in generators.
- It covers all resonances up to 2 GeV.
- It does not cover non-resonant interaction
- Not a full kinematic model. The helicity amplitudes are **not** a function of pion angles $d\sigma/dW\,dQ^2$
- Pion angles is described by density matrix. NEUT and GENIE **only** implemented the Δ resonance.

The RS model is improved by including the pion angles in helicity amplitudes

Output of the modified RS model

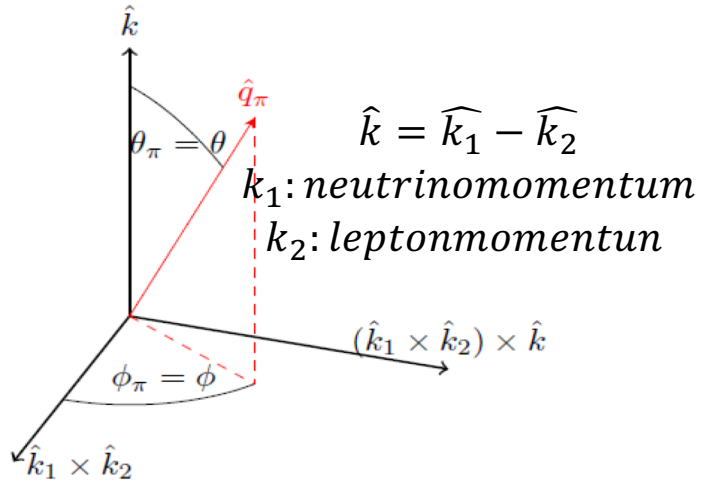
$$d\sigma/dW\,dQ^2 d\Omega_\pi$$

Resonance	M_R	Γ_0	χ_E
$P_{33}(1232)$	1232	117	1
$P_{11}(1440)$	1430	350	0.65
$D_{13}(1520)$	1515	115	0.60
$S_{11}(1535)$	1535	150	0.45
$P_{33}(1600)$	1600	320	0.18
$S_{31}(1620)$	1630	140	0.25
$S_{11}(1650)$	1655	140	0.70
$D_{15}(1675)$	1675	150	0.40
$F_{15}(1680)$	1685	130	0.67
$D_{13}(1700)$	1700	150	0.12
$D_{33}(1700)$	1700	300	0.15
$P_{11}(1710)$	1710	100	0.12
$P_{13}(1720)$	1720	250	0.11
$F_{35}(1905)$	1880	330	0.12
$P_{31}(1910)$	1890	280	0.22
$P_{33}(1920)$	1920	260	0.12
$F_{37}(1950)$	1930	285	0.40

Rein Model (1987)

D. Rein, Z.Phys. C – Particles and Fields 35,43-64 (1987)

- Define a suitable framework; Adler frame
- Calculate both resonant and non-resonant interactions
- Add them coherently to include the interference effects

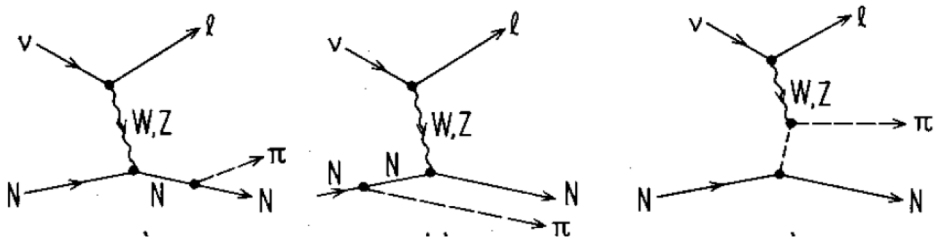


➔Resonant Interaction

- **Rein-Sehgal** model is based on **helicity amplitudes** derived in a relativistic quark mo
- The helicity amplitudes depend on the spin projection of the initial and final particle.

➔Nonresonant Interaction

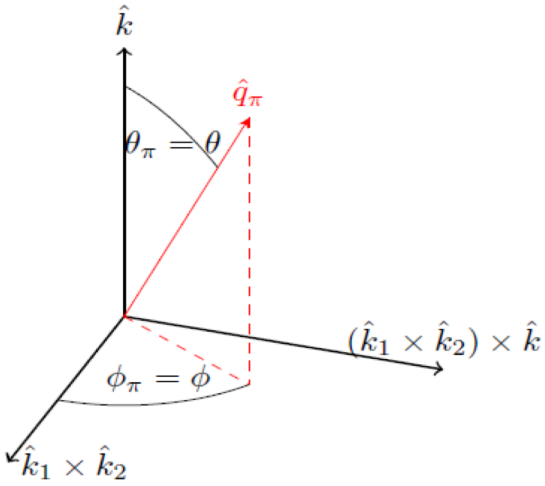
Born graphs based on linear sigma model.



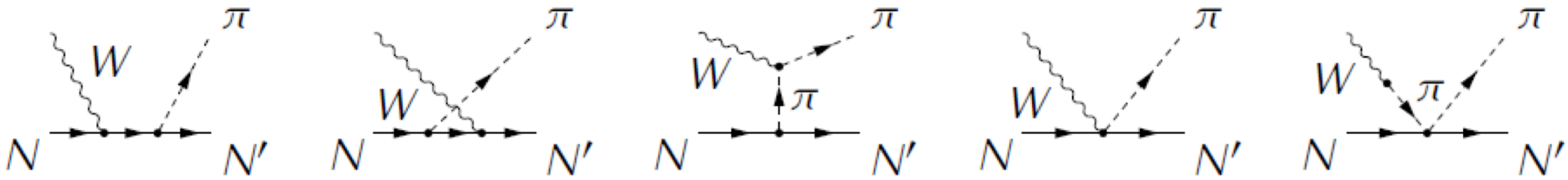
➔The lepton is assumed to be massless

MK-model

M. Kabirnezhad
Phys. Rev. D **97**, 013002

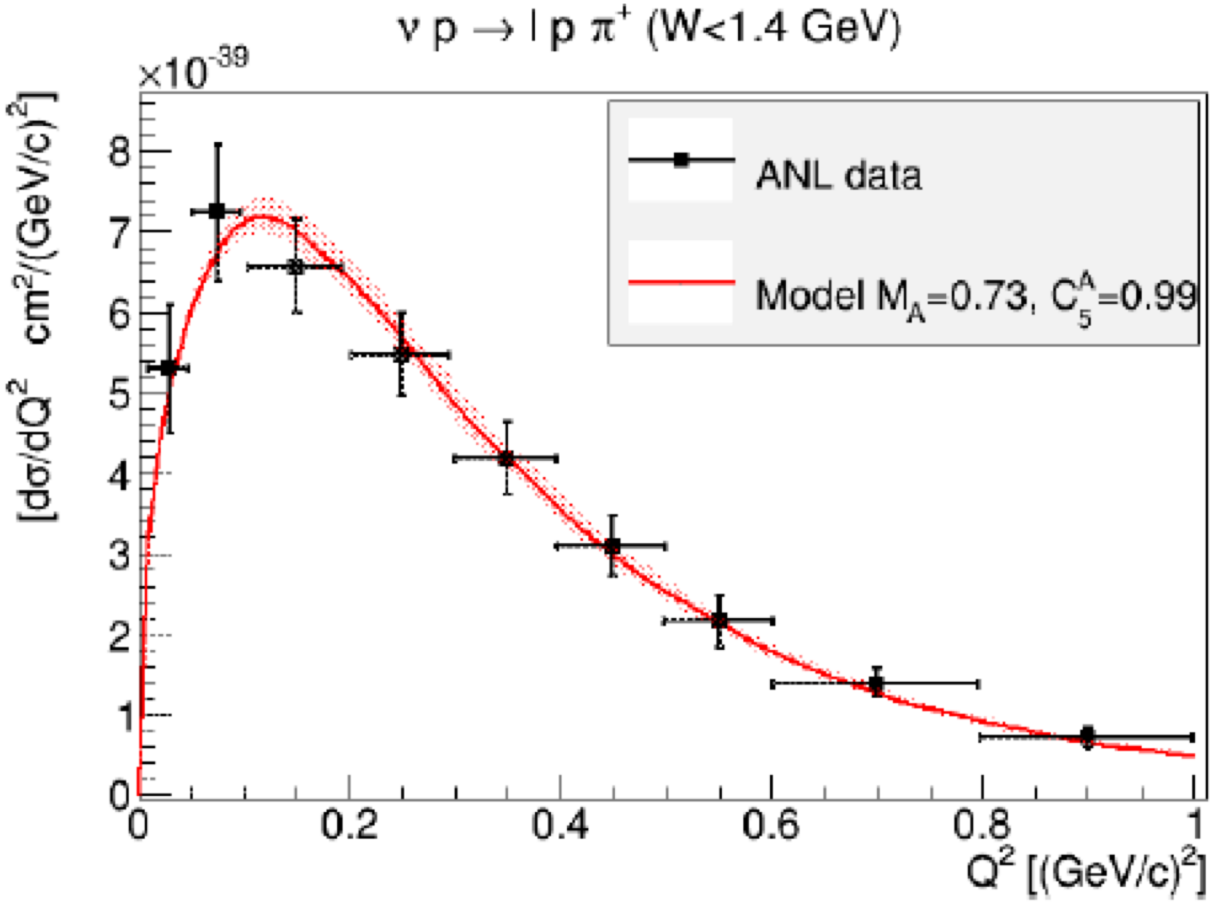


- MK model is a model for single pion production i.e. resonant and nonresonant interactions including **the interference effects**.
- Rein-sehgal model with Graczyk-Sobczyk form-factors predicts resonant interaction (17 resonances) up to W=2 GeV.
- The lepton mass in included.
- non-resonant background is defined by a set of diagrams determined by HNV model.



Verifying the model is difficult with limited data sets!

- Existing bubble chamber data on “free” nucleon are old and with large error and it is very unlikely to be improved :(
- We extract the dipole axial form-factor from the bubble chamber data.

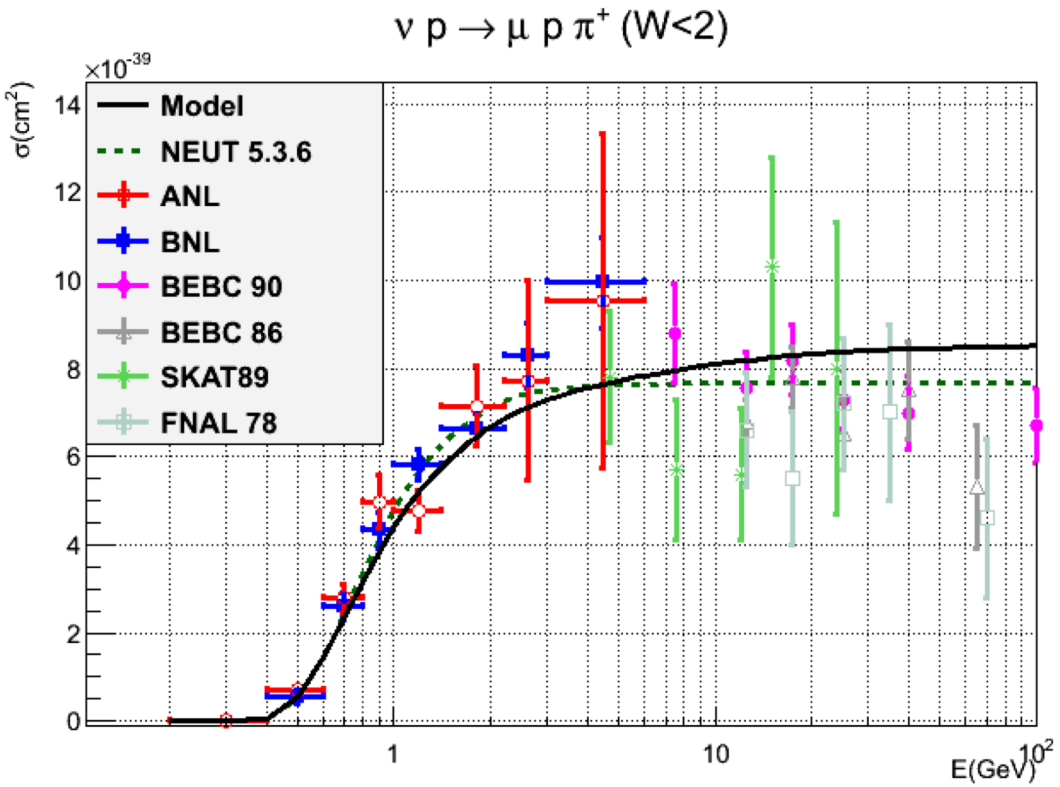


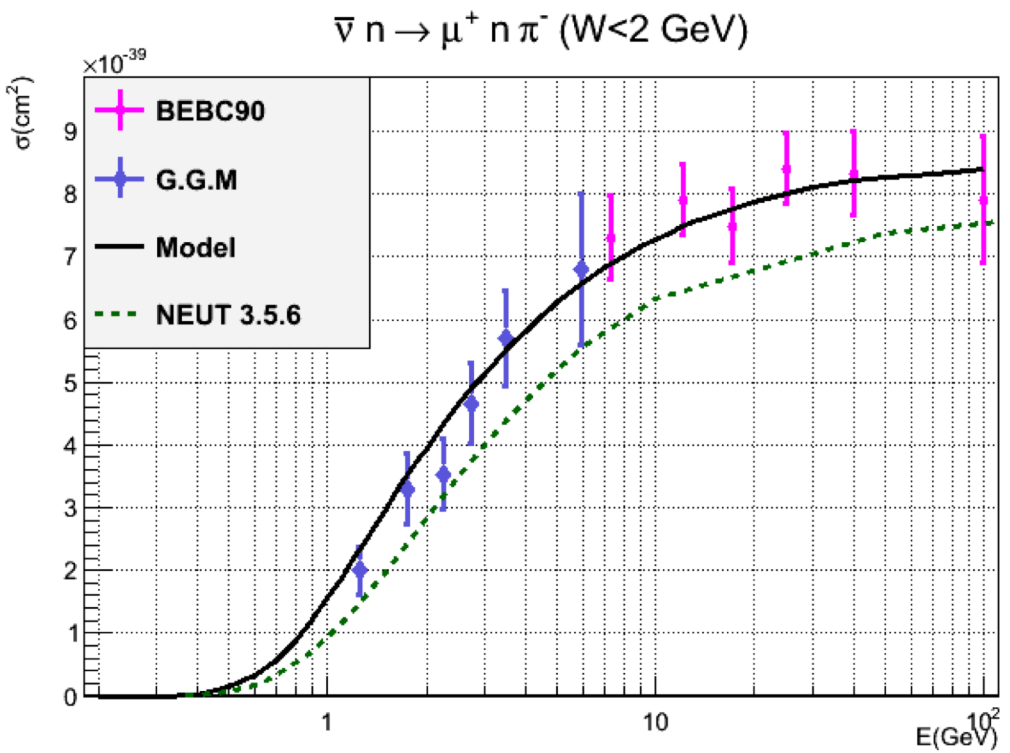
$$C_5^A(k^2) = \frac{C_5^A(0)}{\left(1 - \frac{k^2}{M_A^2}\right)^2}$$

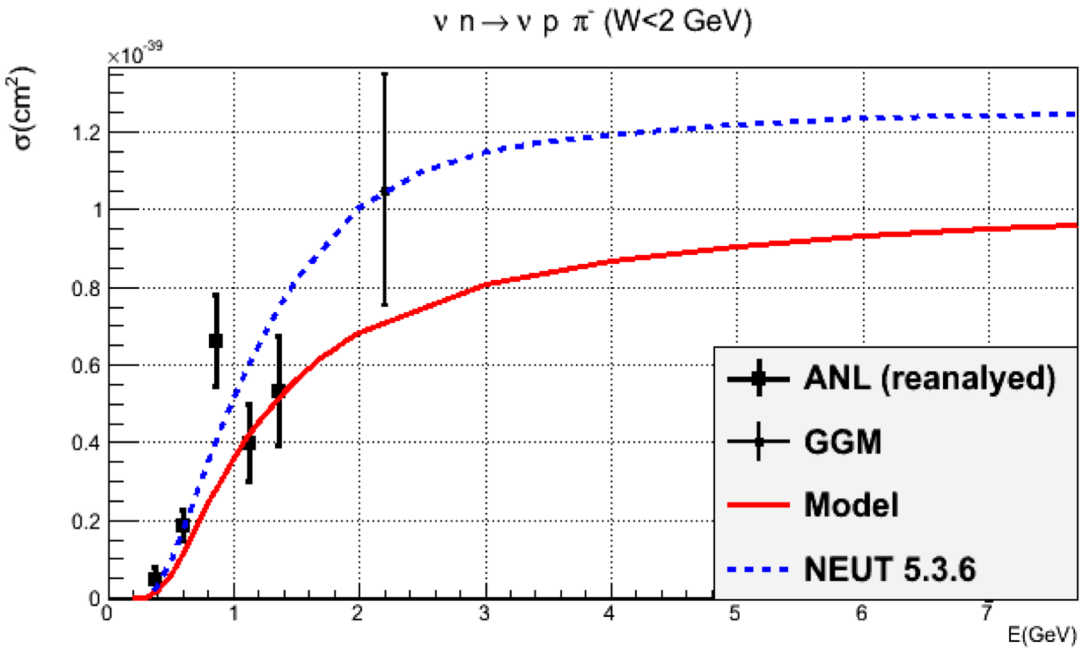
G. M. Radecky et al., Phys. Rev. D 25 (1982) 1161

Total Cross-section

Neutrino-nucleon interactions



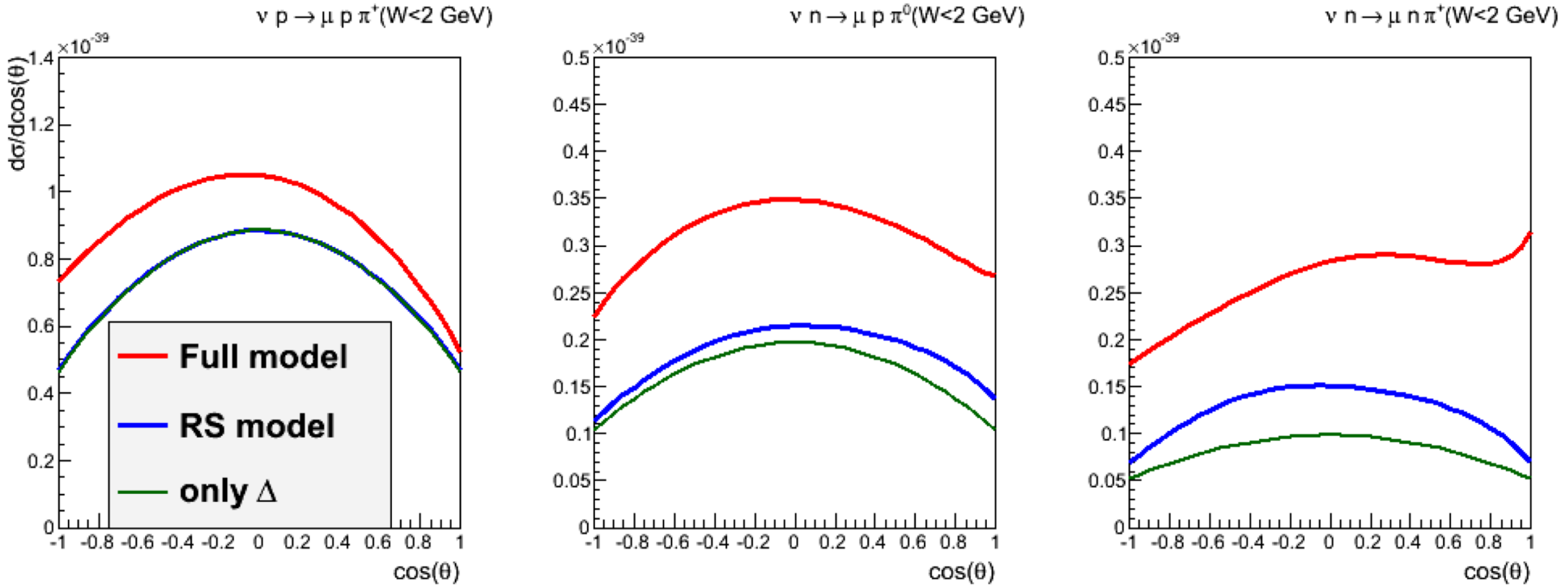




Angular Distribution

In the hadronic rest frame

For T2K energy



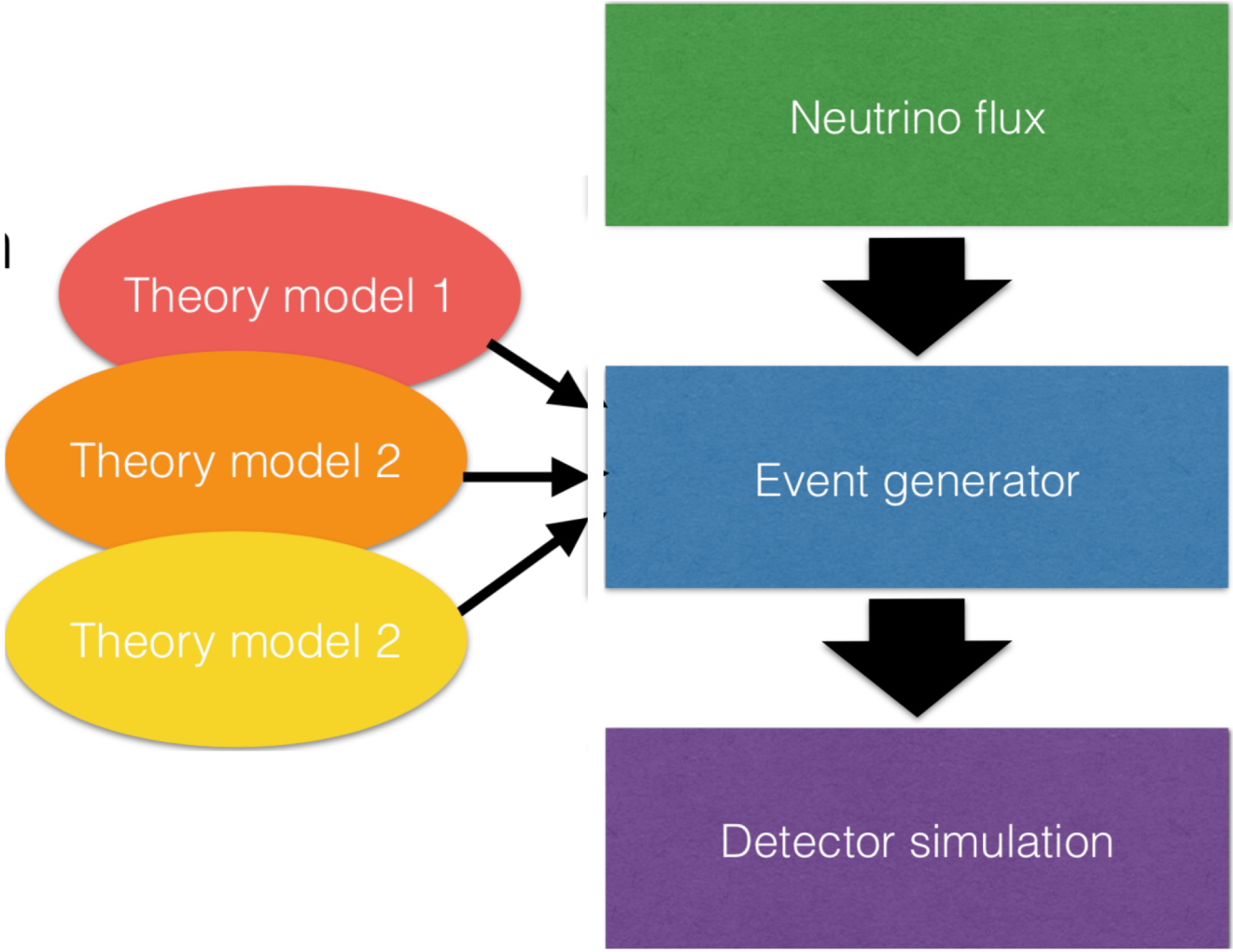
- "Only Δ" has a symmetric distribution.
- Any deviation from the symmetric distribution comes from the interference effects.

The MK-model Implementation in NEUT

NEUT is T2K official event generator.

Data comparison can be done

- In any frame
- In any physical region
- With any target
- With any selection
- Wide energy range

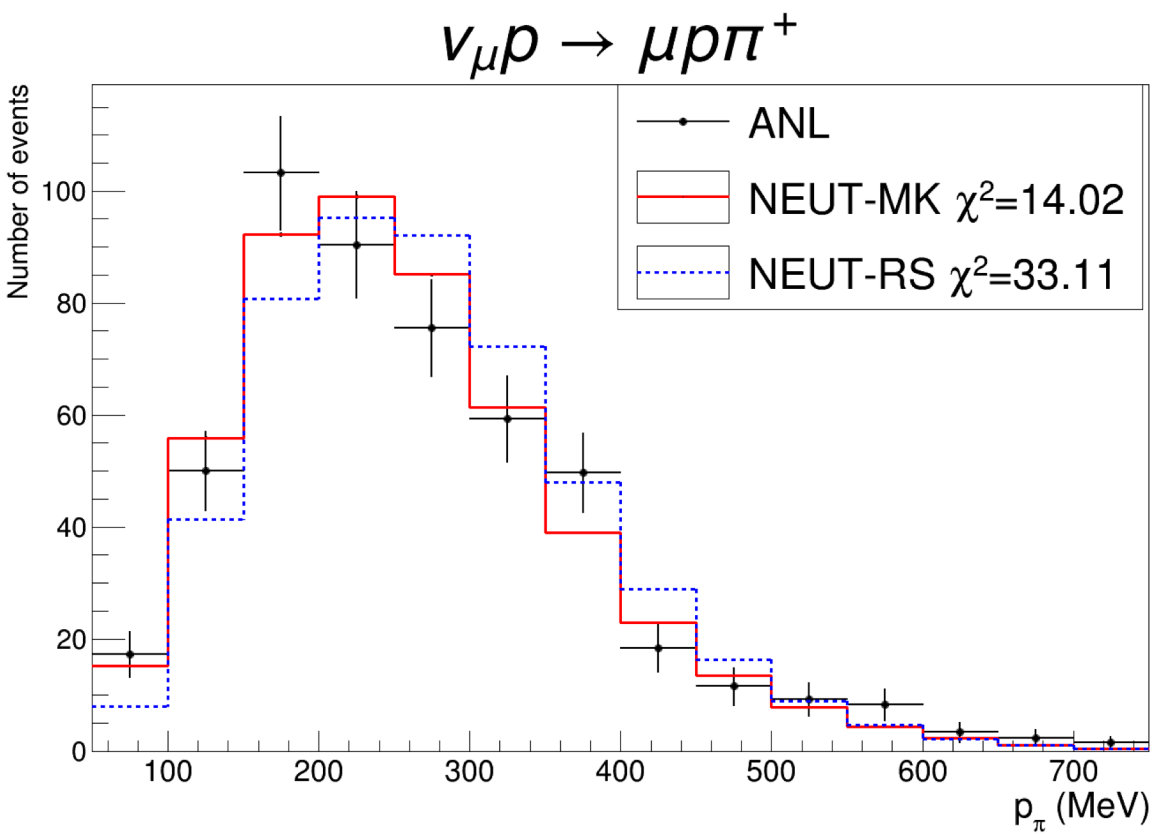


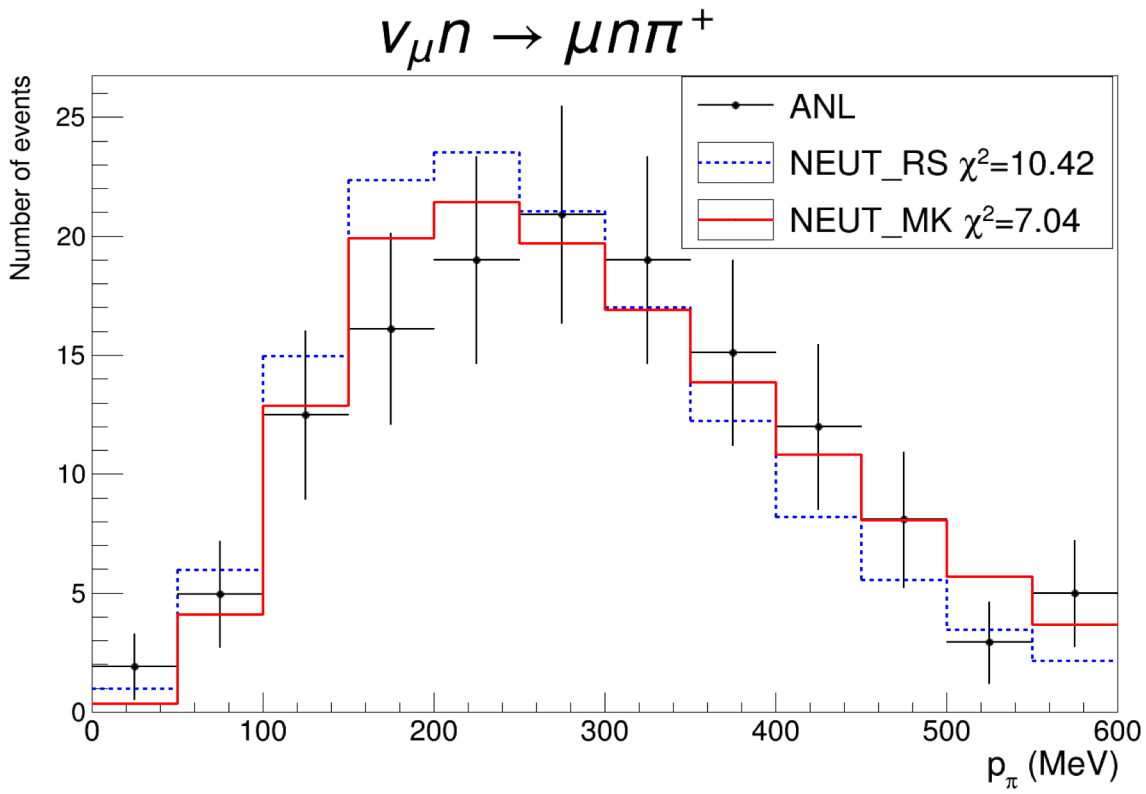
Data comparison with

NUISANCE

P. Stowell et al., JINST 12 (2017) no.01, P01016

Bobble chamber (ANL) data in the lab frame





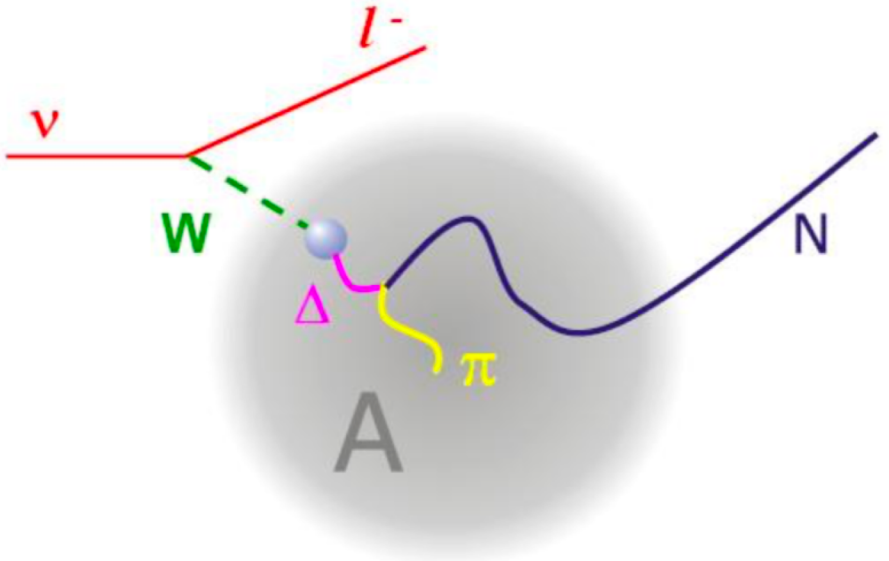
Phys. Rev. D 23, 569 (1981).

Single Pion Production in Neutrino-nucleus interactions

Initially produced hadrons can interact with themselves and with other nucleons in targets on their way out of the nuclear target.

➢ Initial state interaction (ISI)

- Nucleons are bound in the nucleus and we must take into account the nuclear effects such as Fermi motion of the initial nucleons and Pauli blocking of the final ones.
- Medium modify resonances width and therefore νN cross-section (not in NEUT).



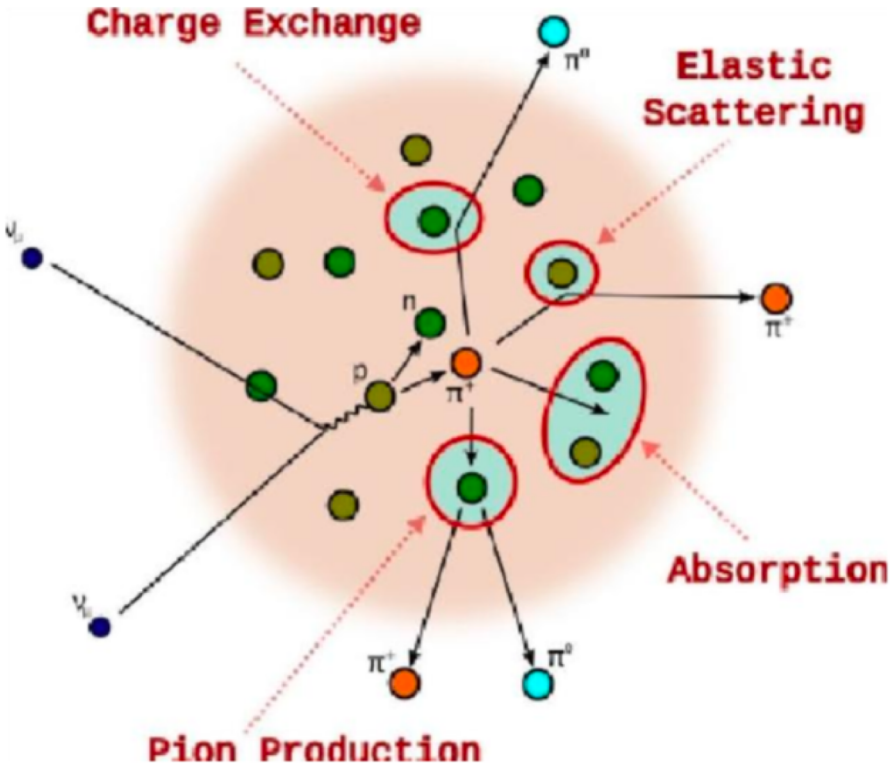
From T. Leitner

Single Pion Production in Neutrino-nucleus interactions

Initially produced hadrons can interact with themselves and with other nucleons in targets on their way out of the nuclear target.

- **Final State Interaction (FSI)**

  - Particles produced in neutrino-nucleon interactions can re-interact before leaving the nucleus and can be absorbed, change their kinematics or even charge before being detected.
  - NEUT use a semi-classical cascade model. (Backup)



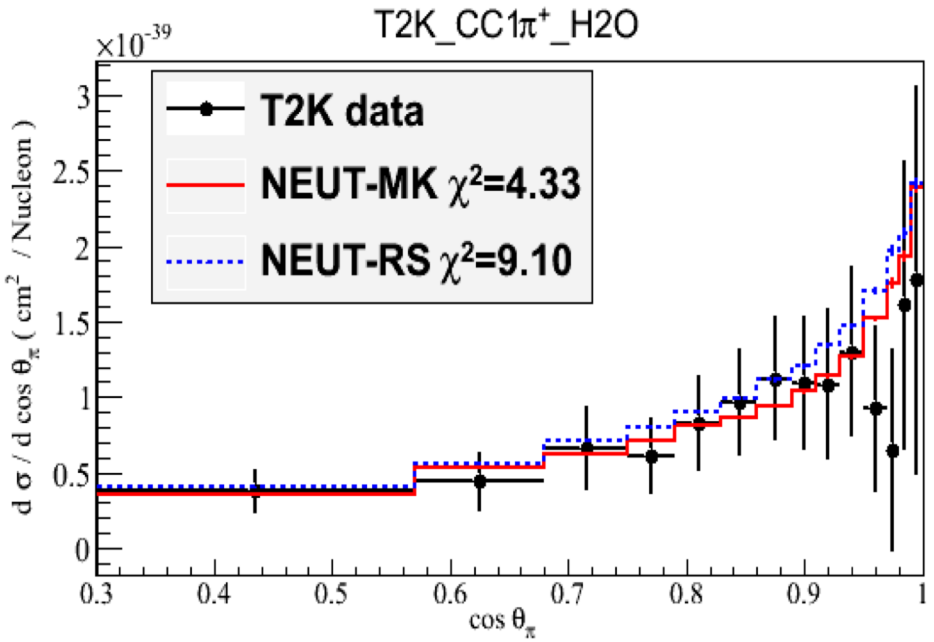
from T. Golan

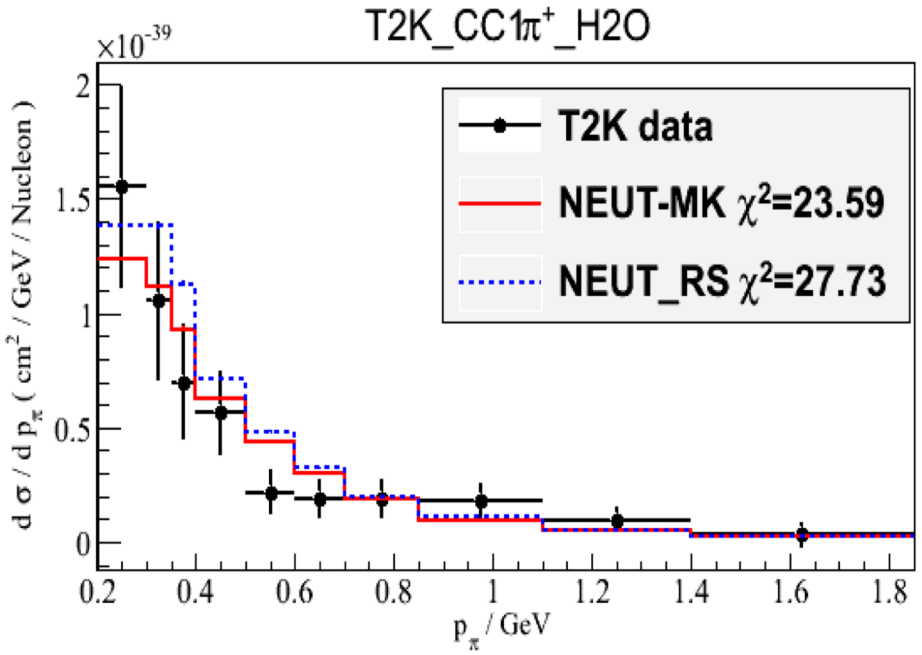
Effects on cross-section

T2K data on Water

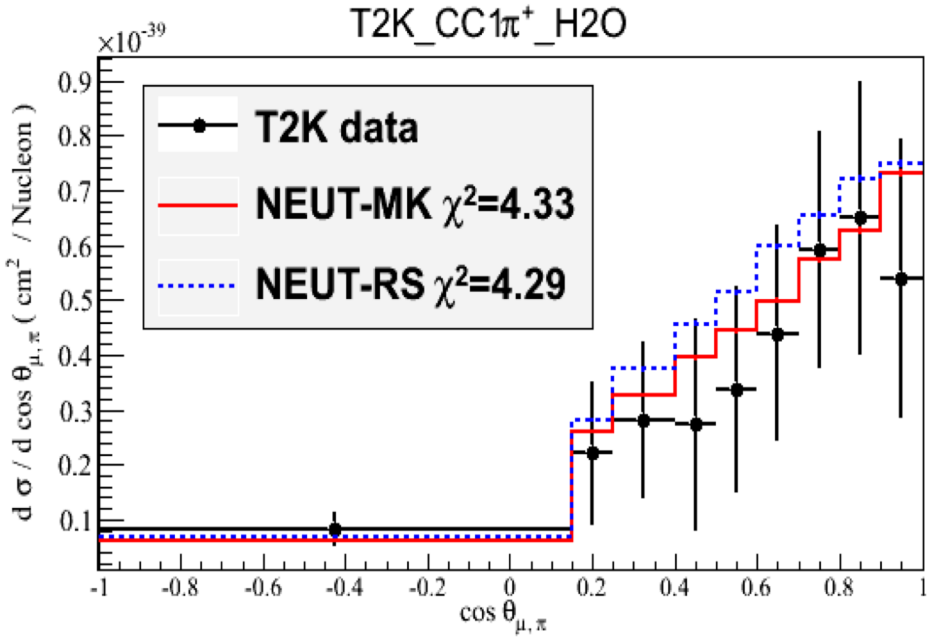
$$\nu_\mu + H_2O \rightarrow \mu^- \pi^+ + X$$

K. Abe et al. [T2K Collaboration], Phys. Rev. D 95 (2017) no.1, 012010.





$p_\mu > 200\, MeV/c$
$p_\pi > 200\, MeV/c$
$\cos\theta_\mu > 0.3$
$\cos\theta_\pi > 0.3$



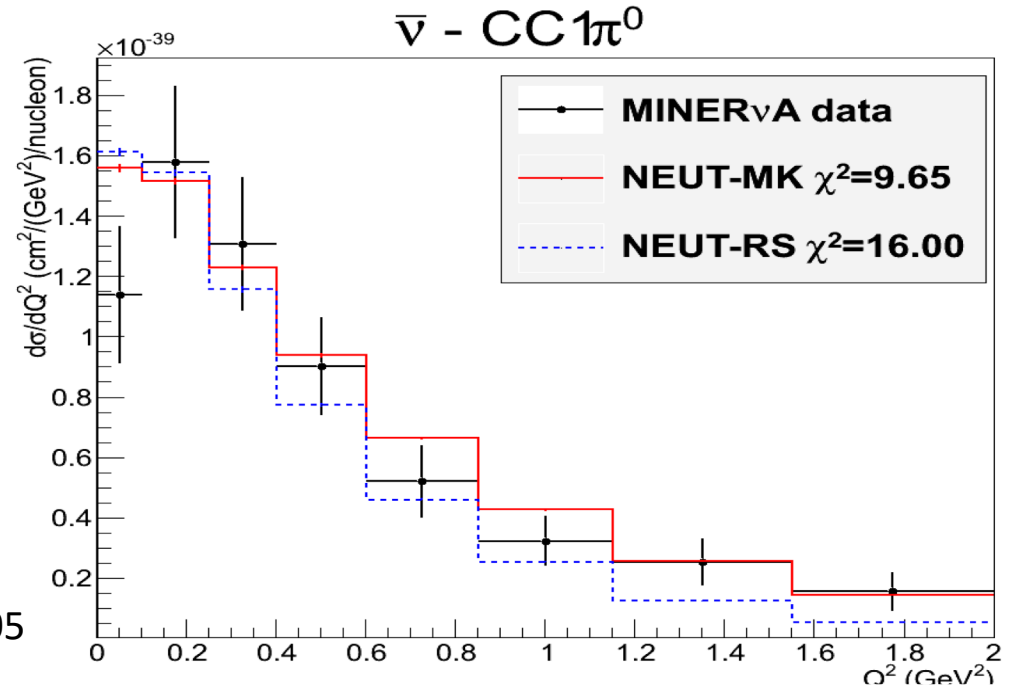
Effects on cross-section

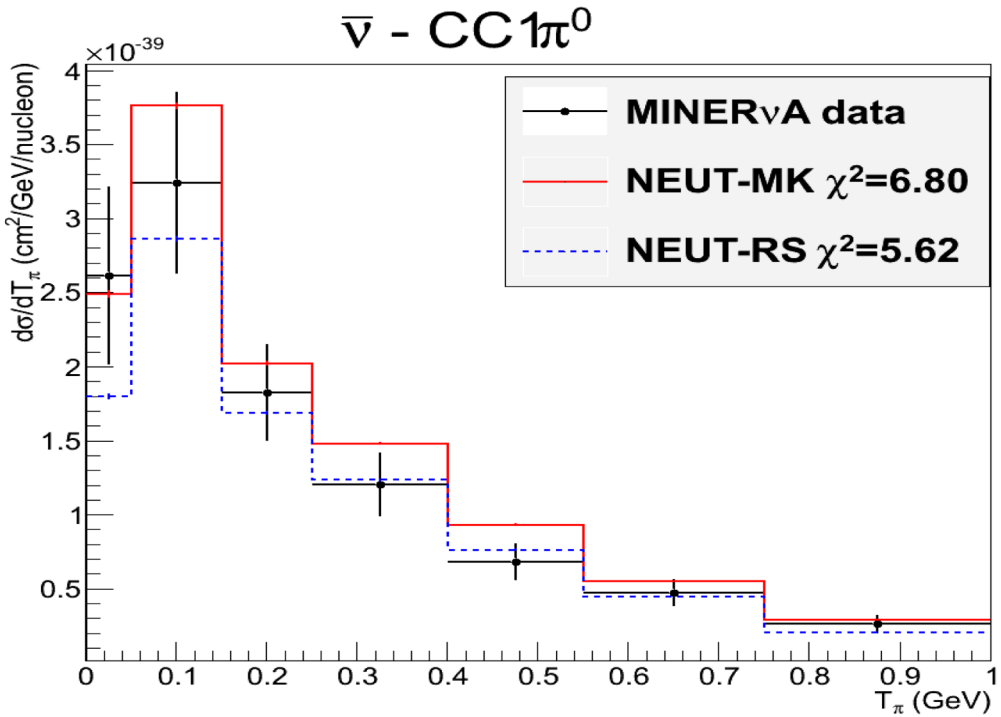
MINERvA data 2016

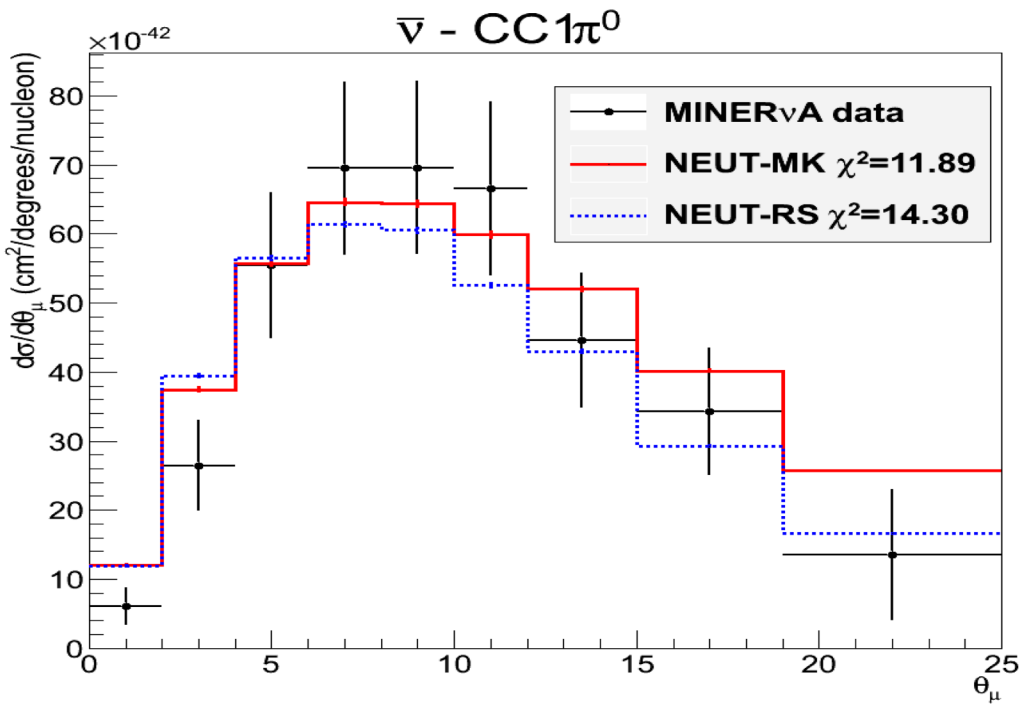
CH target

W<1.8 GeV $\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + \pi^0 + X'$

C. L. McGivern et al. [MINERvA Collaboration], Phys.Rev. D 94 (2016) no.5, 052005

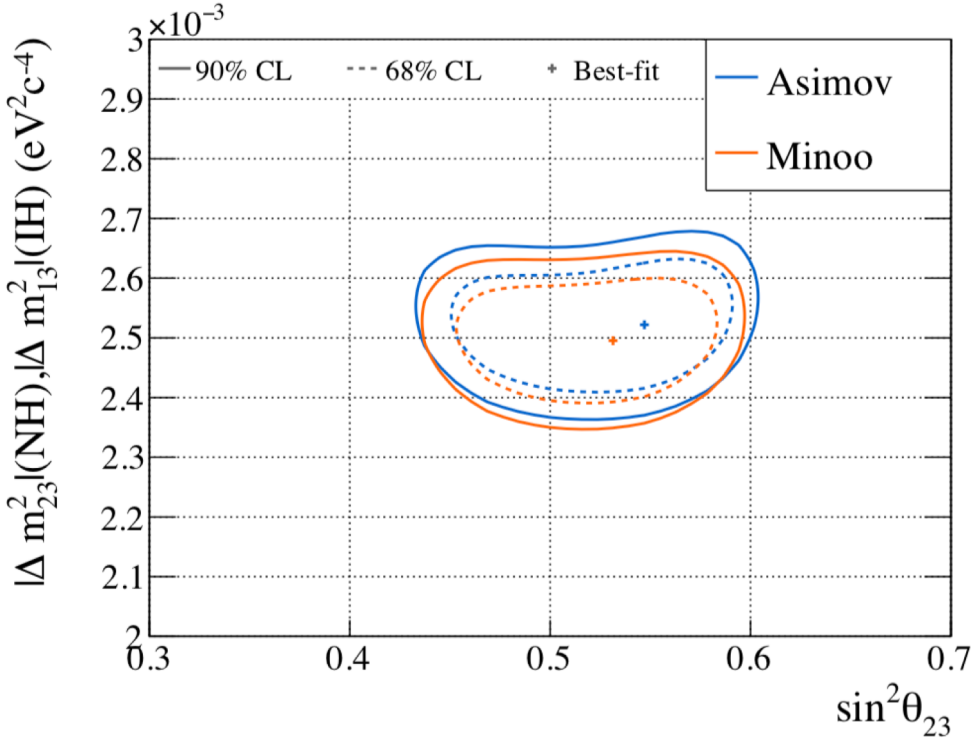


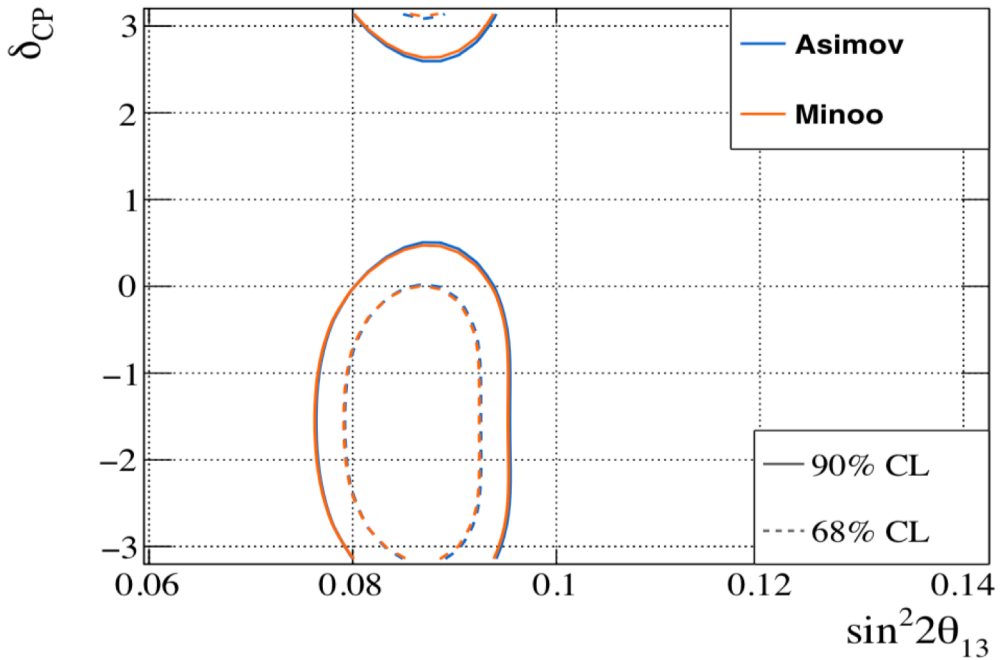




Effects on oscillation analysis (T2K)

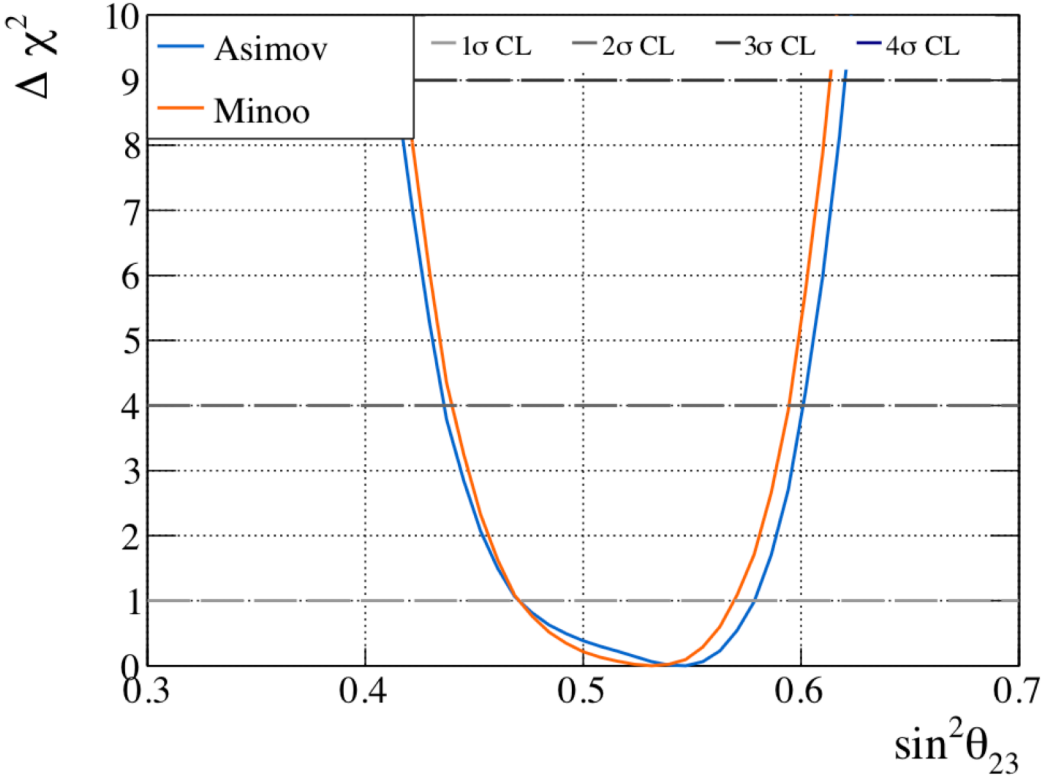
- New modelling effects can be investigated with fake data studies.
- MK-model (Minoo) fake data is generated by NEUT.
- Fit MK-fake data with the nominal model and uncertainties.
- These fake data study gives Δm^2_{23} and Θ_{23} bias for normal hierarchy.
- "Asimov" means fitting the nominal MC with itself.

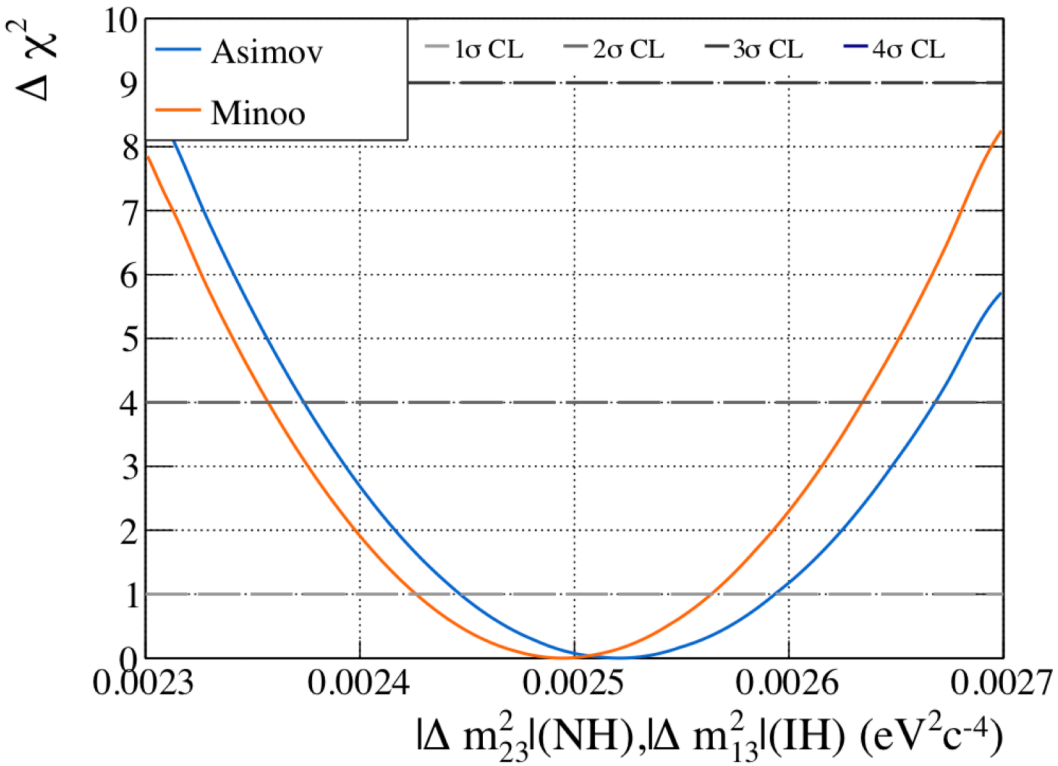




Effects on oscillation analysis (T2K)

1D likelihood, normal hierarchy





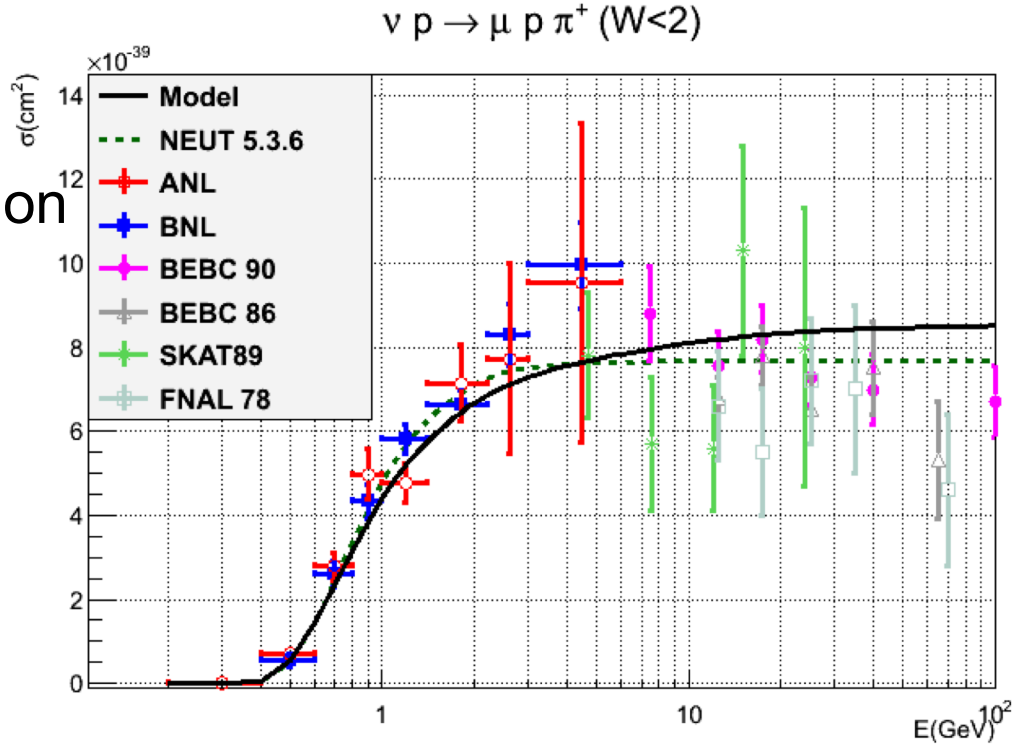
Although bias is small with respect to the uncertainty right now, clearly mis-modelling can produce biased oscillation parameters, and this will be a serious problem for next generation experiments.

Summary

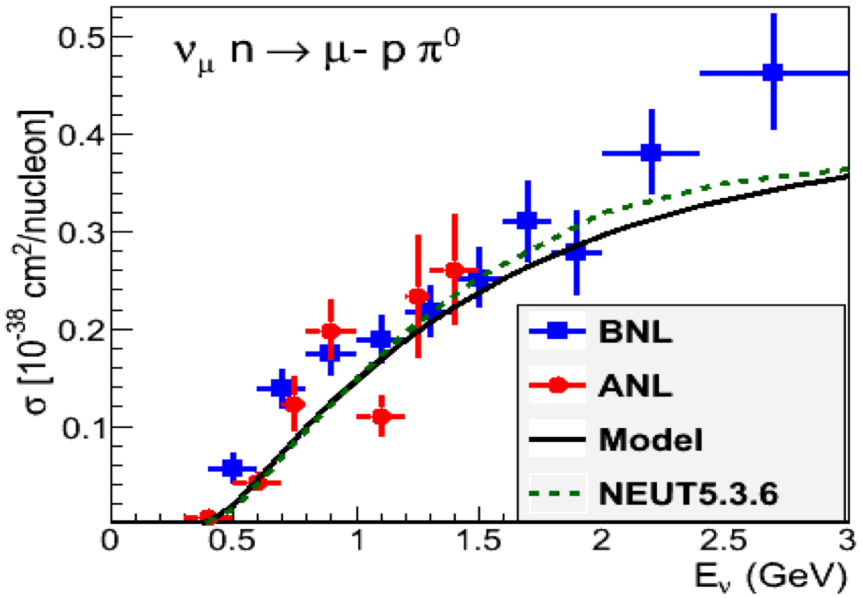
- Good model is very crucial for precision neutrino oscillation measurements especially for high-W region.
- Next generation of neutrino experiments will be operating in few years.
- Main goal is to develop suitable models for Neutrino generators and neutrino measurements.
- Hopefully improved data/MC agreement and reducing systematic uncertainties propagated to the oscillation measurements.

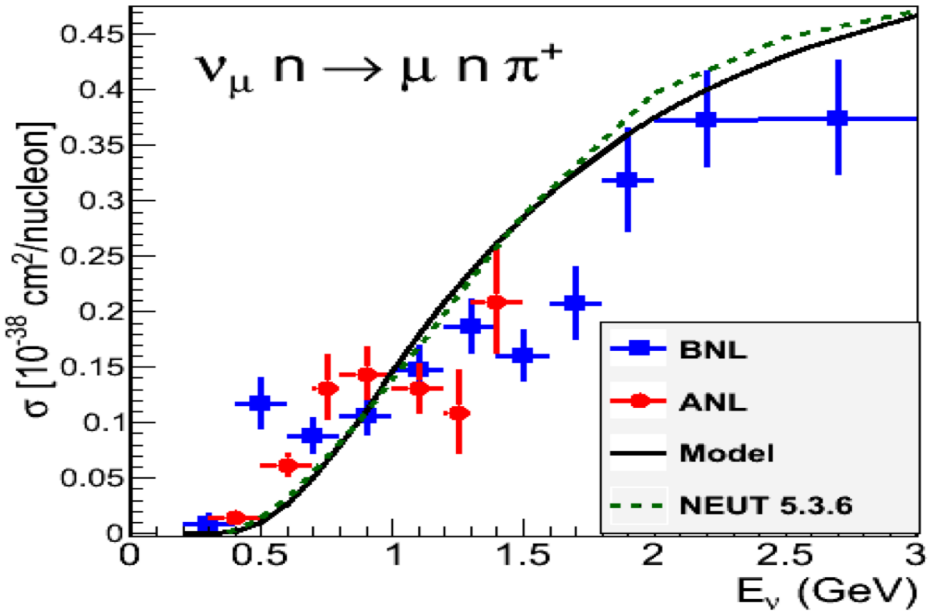
Backup

Total Cross-section for charged current neutrino interaction

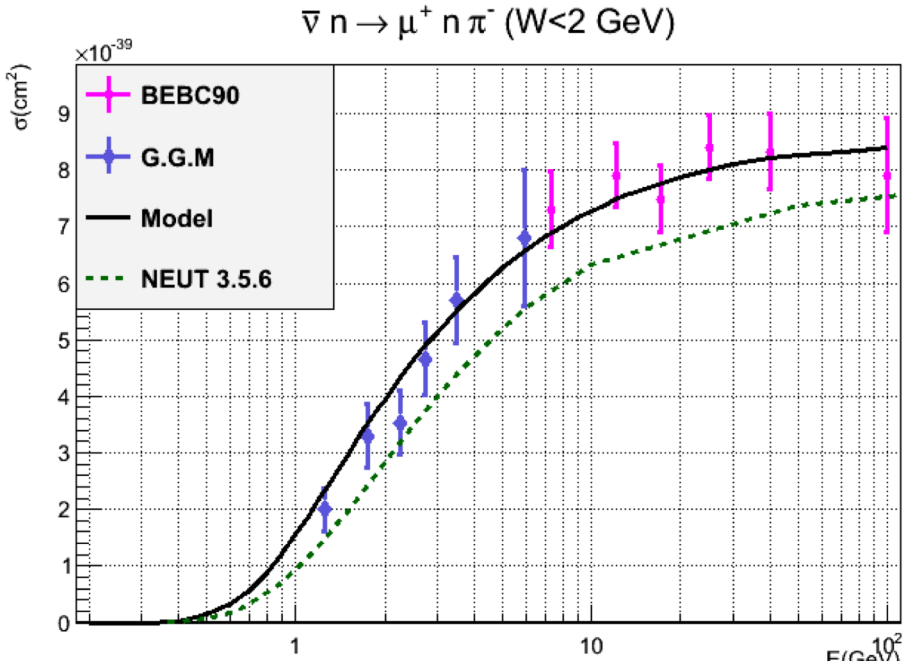


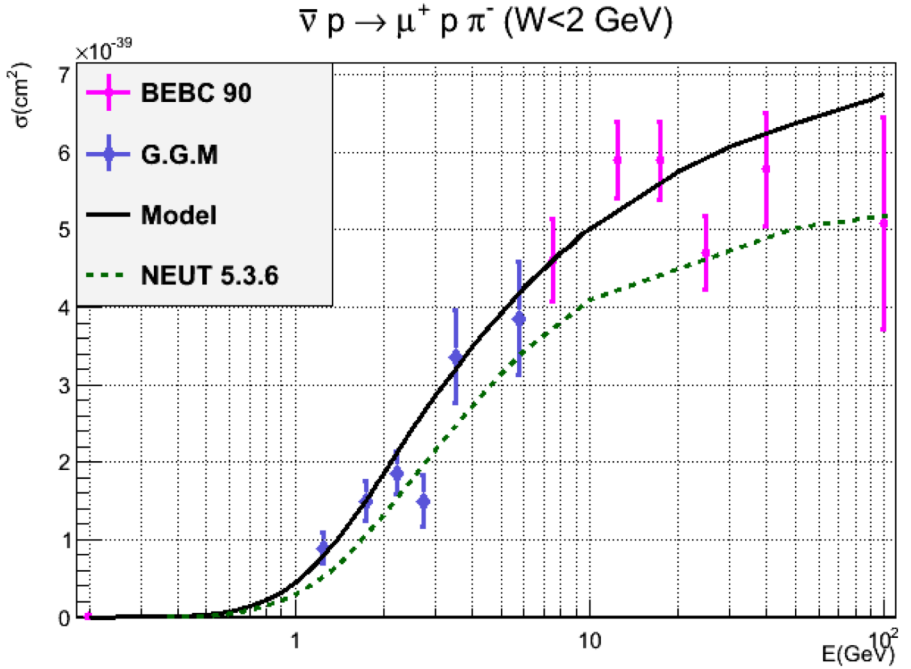
ANL & BNL data is reanalyzed by
C. Wilkinson et al., Phys. Rev. D 90 (2014) 11, 112017





Total Cross-section
for
charged current
anti-neutrino interactions

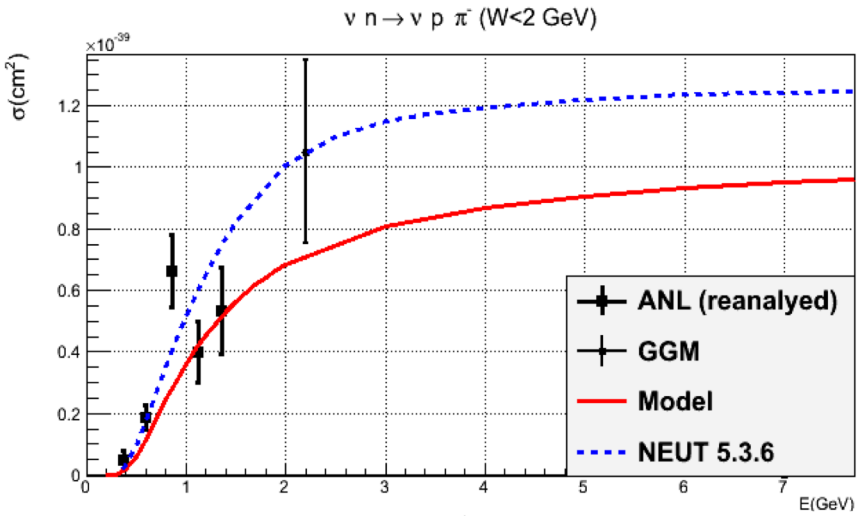


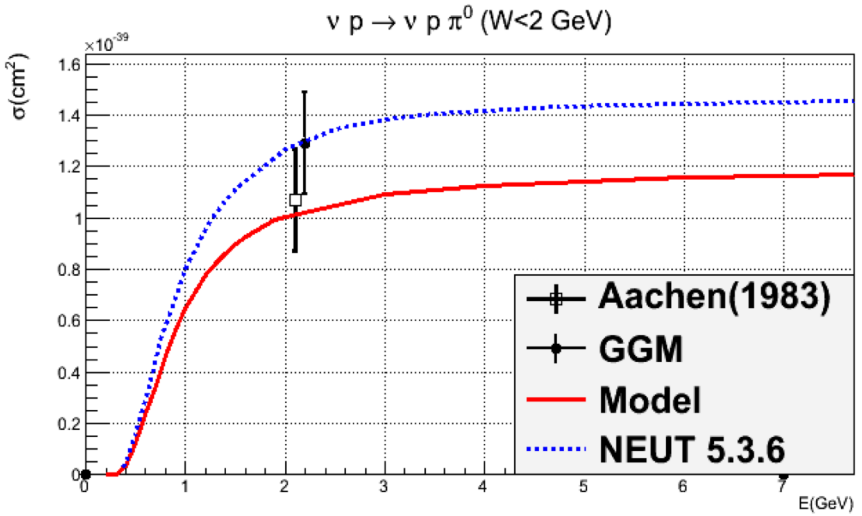


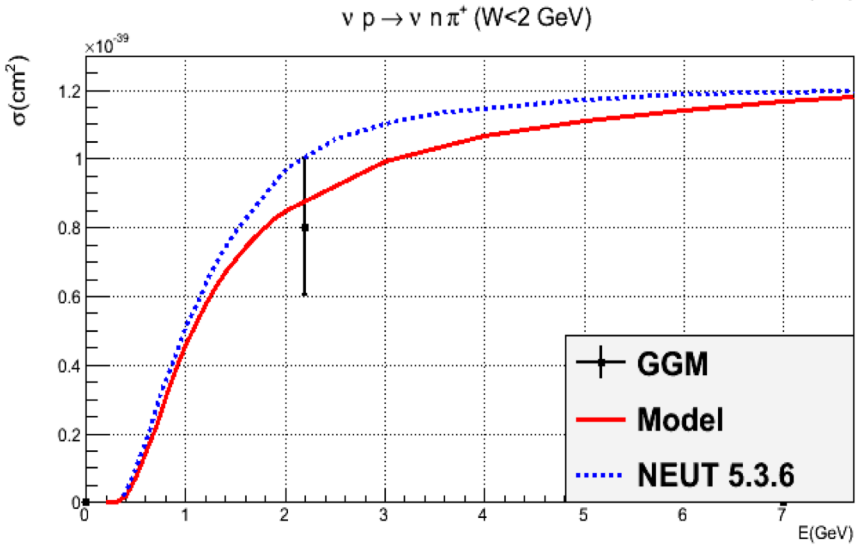
Data from

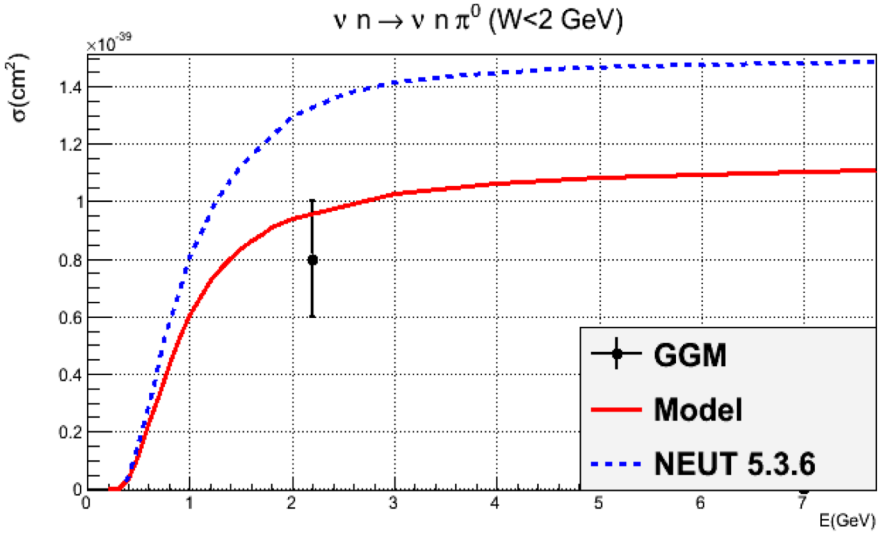
D. Allasia et al., Nucl. Phys. B 343 (1990) 285.
T. Bolognese, J. P. Engel, J. L. Guyonnet and J. L. Riester, Phys. Lett.

Total Cross-section
for neutral current neutrino interactions









Data from J. A. Formaggio and G. P. Zeller, Rev. Mod. Phys. 84 (2012) 1307
ANL data is reanalyzed based on C. Wilkinson et al., Phys. Rev. D 90 (2014) 11, 112017

Monte Carlo cascade models

- particles are classical objects moving on well defiened trajectories in nuclear potential well.
- Collisions are independent
- Collisions preserve energy and momentum.
- free particle-nucleon cross sections are used
- Pauli blocking is the only quantum mechanical effect.
- NEUT cascade for pions is based on the microscopic approach of Salcedo, Oset, Vicente-Vacas, and Garcia-Recio, Nucl. Phys. A484 (1988) 557-592.