# Recent results on neutrino cross sections

## (in the intermediate energy range)

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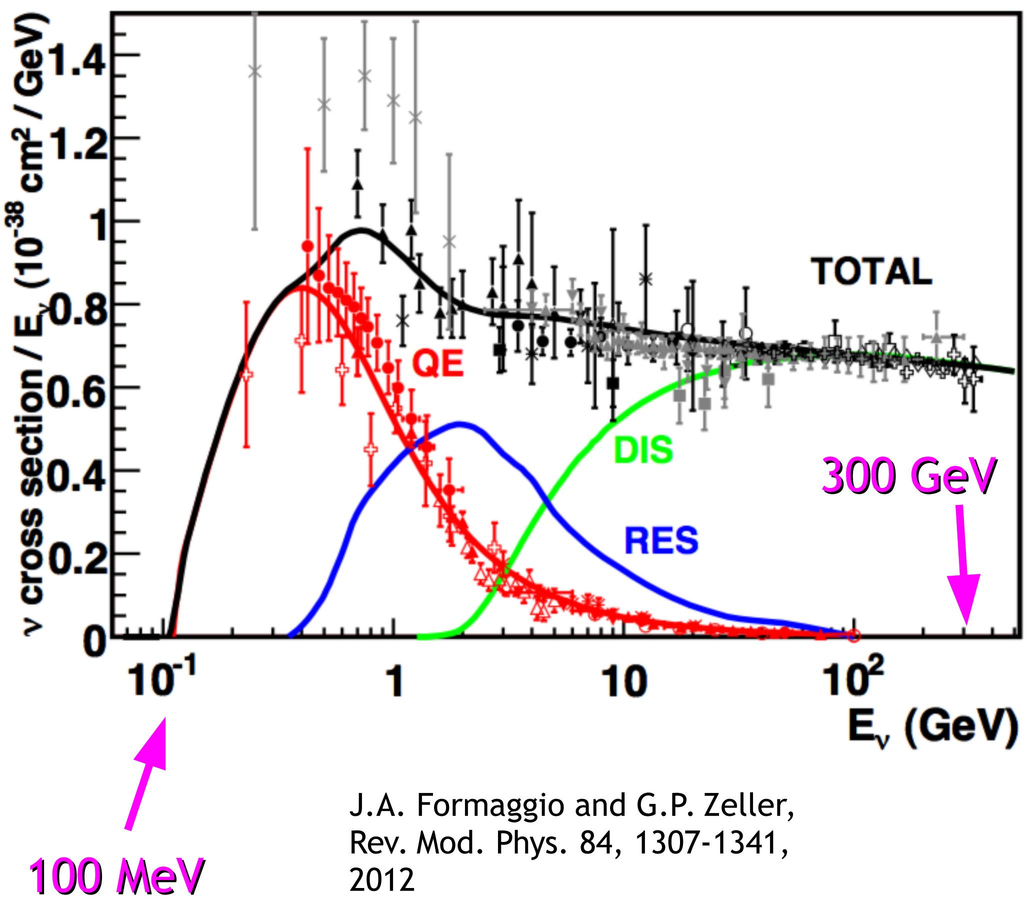
*Matter to the Deepest, Ustroń, 17.09.2015*

# Outline

1. Introduction.
2. Overview of the most important neutrino scattering experiments.
3. Charged current quasi-elastic measurements.
4. Charged current single pion production results.
5. Other results.
6. Summary

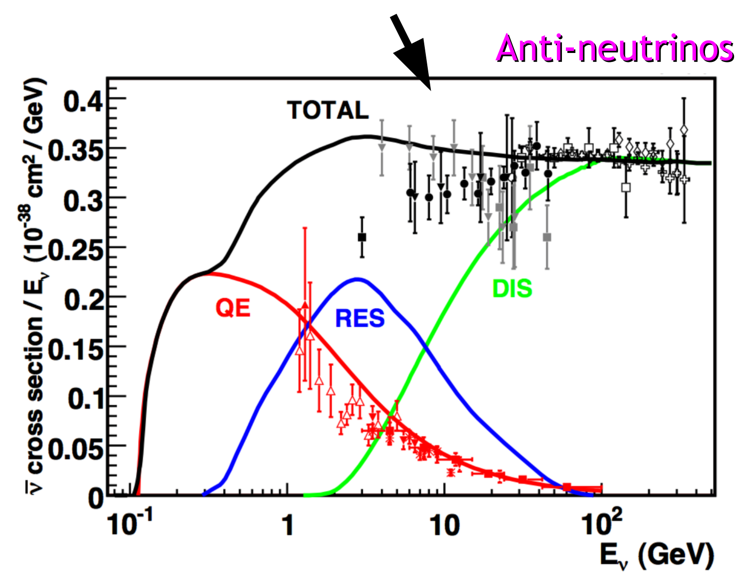
# Introduction

Charged current
neutrino-nucleon cross sections



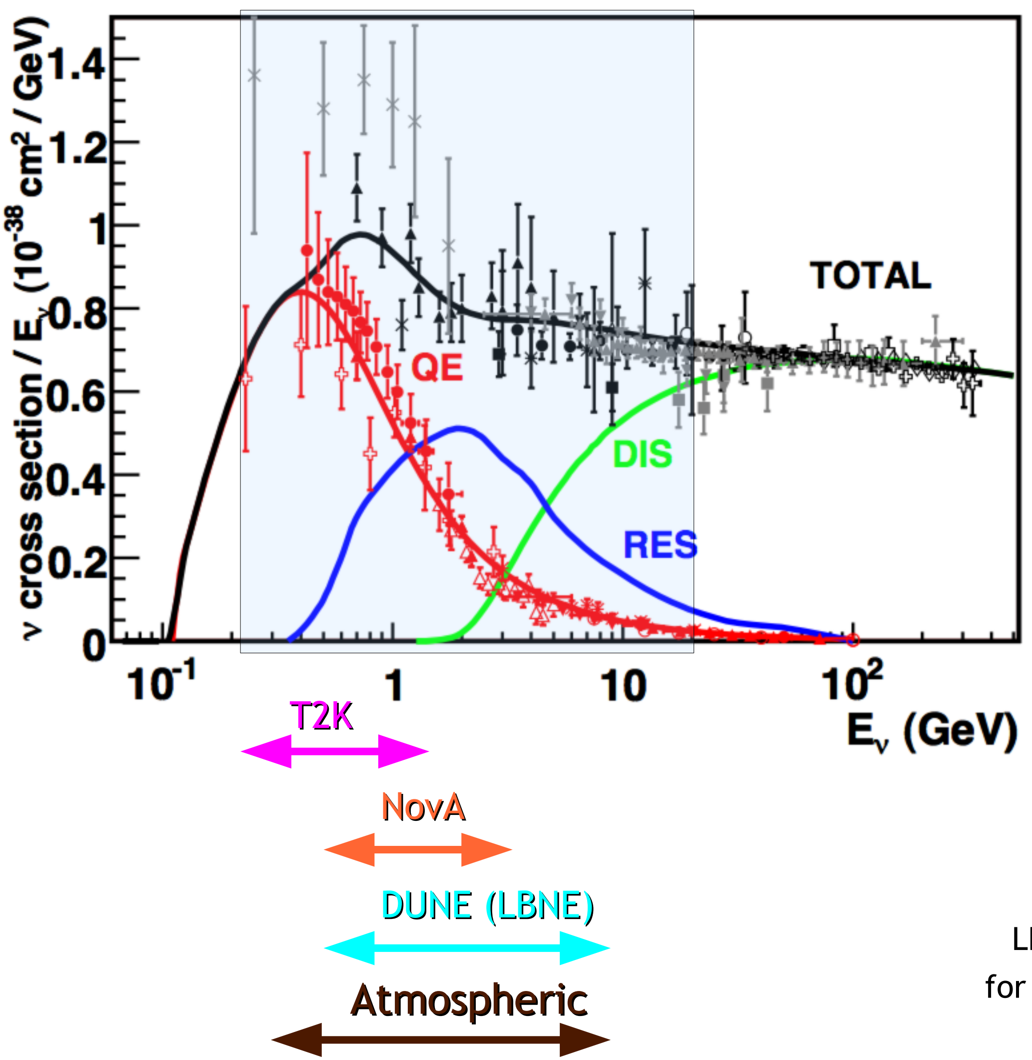

J.A. Formaggio and G.P. Zeller,
Rev. Mod. Phys. 84, 1307-1341,
2012

- Neutrino cross sections are well known at the energies:
  - ~10 MeV (Inverse Beta Decay) – solar neutrinos, reactor neutrinos
  - ~100 GeV (Deep Inelastic Scattering)
- ...but not so well known in the intermediate energy range (10's MeV ~ 10's GeV)
- Situtation is even worse for anti-neutrino interactions.

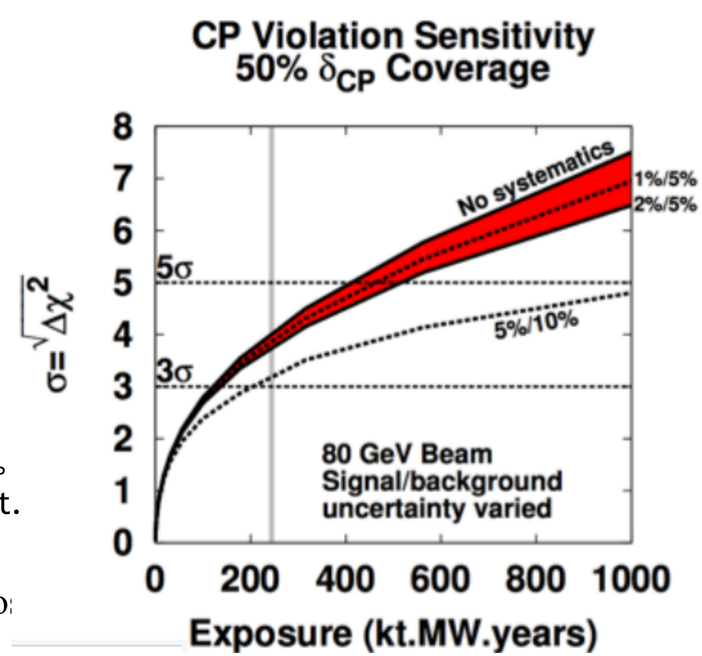


# Introduction

Charged current
neutrino-nucleon cross sections



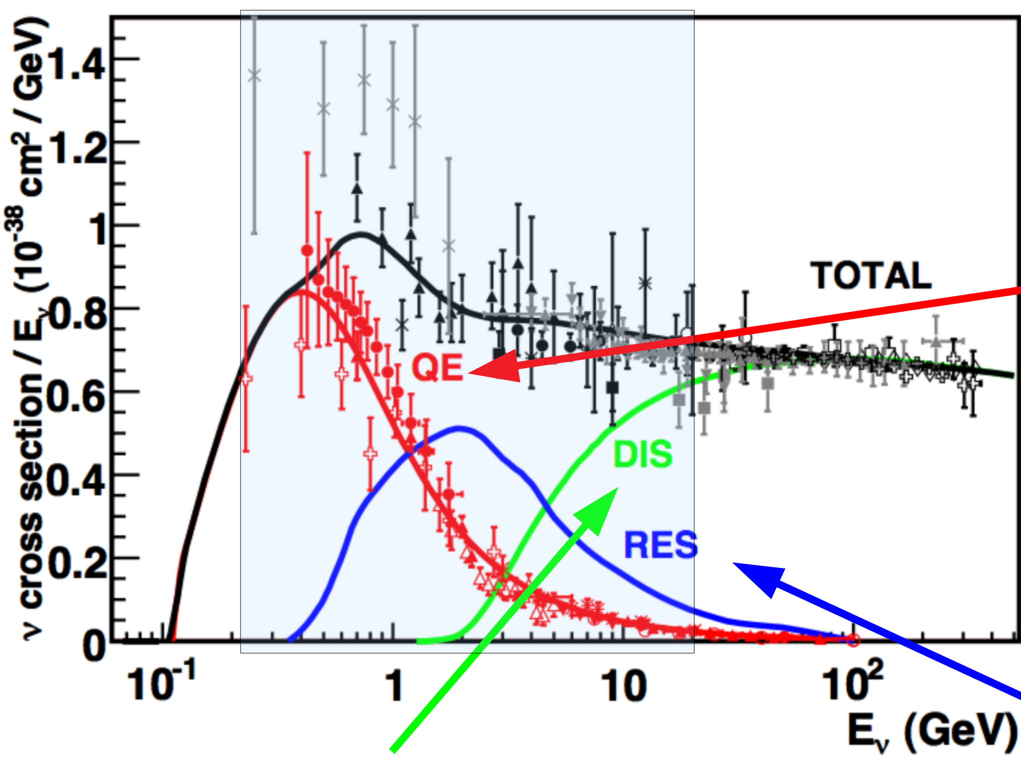

- Why neutrino cross sections in the intermediate energy range are important for us?
  - This is where we do our (long-baseline) neutrino oscillation experiments (CP violation, neutrino mass hierarchy)
  - Requirements for the precise measurements at the future long-baseline neutrino oscillation experiments:
    - **~1% uncertainty on signal normalization (to compare: ~7% T2K today)**




LBNE sensitivity to $\delta_{CP}$
for different sys. uncert.
(M.Bass, NuInt04)

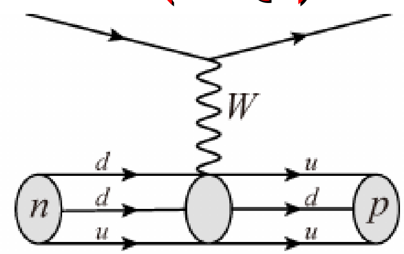
# Introduction

Charged current
neutrino-nucleon cross sections

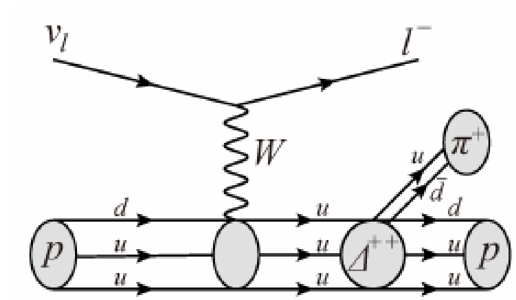


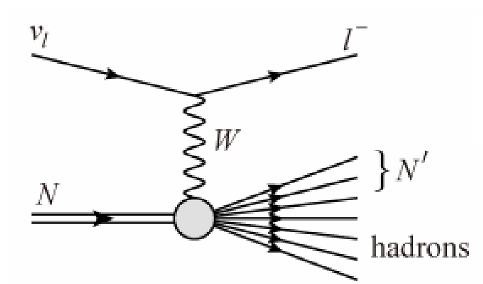

- but the intermediate energy range is complicated...

**Charged current quasi-elastic scattering (CCQE)**




**Resonance pion production (RES)**

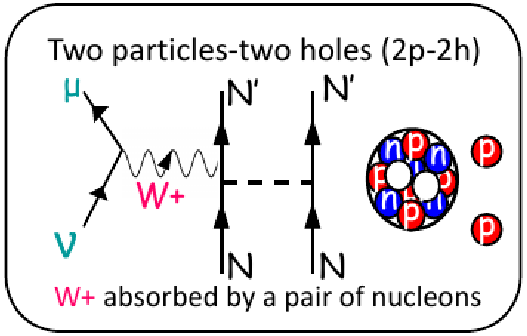



**Deep Inelastic Scattering (DIS)**

Not covered in this talk

# Introduction




- ..even more complications: we use nuclear targets to increase the number of detected neutrino interactions.
- One has to take into account nuclear effects: Fermi motion, Pauli blocking, binding energy, modified nucleon form factors, final state interactions,...
- Some examples of nuclear models used in our neutrino event generators:
  - **Relativistic Fermi Gas (RFG)** – nucleons as independent particles in a potential generated by the rest of the nucleus

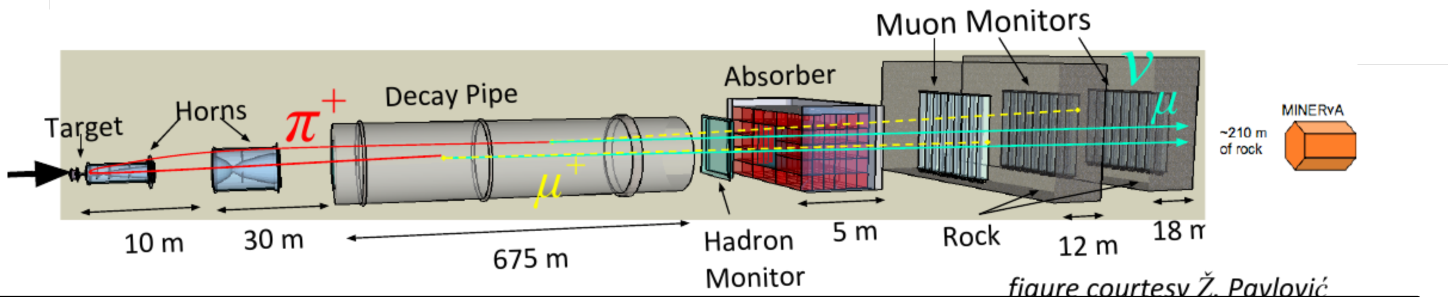
    R. Smith and E. Moniz, Nucl.Phys. B43, 605 (1972); A. Bodek, S. Avvakumov, R. Bradford, and H. S. Budd, J.Phys.Conf.Ser. 110, 082004 (2008); K. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)
  - **Local Fermi Gas (LFG)** – nucleon Fermi momentum and binding energy are a function of the position in the nucleus

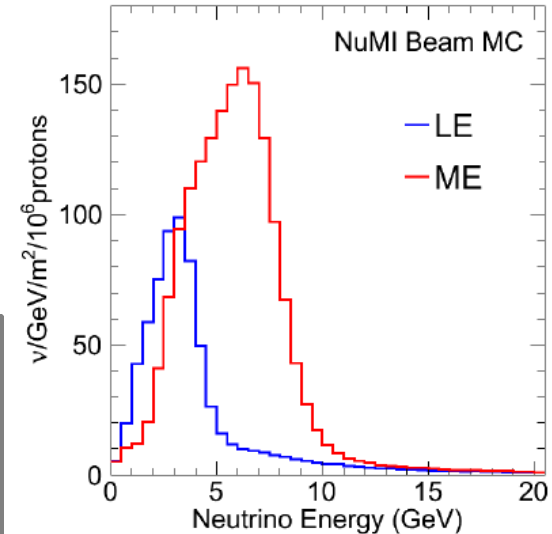
    AK. S. Kuzmin, V. V. Lyubushkin, and V. A. Naumov, Eur.Phys.J. C54, 517 (2008)
  - **Spectral Function (SF)** – correlations between removal energies and initial state momenta of the nucleons, gaussian (not delta-function like in RFG) spectrum of each shell

    O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl.Phys. A579, 493 (1994)
  - **Nucleon-nucleon (NN) correlations, many-body currents: SRC (Short-range correlations) -** A. Bodek, and J. L. Ritchie, Phys. Rev. D23, 1070 (1980), Phys. Rev. D24, 1400 (1981)**,Transverse Enhancement Model (TEM) -** A. Bodek, H. Budd, and M.Christy, Eur.Phys.J. C71, 1726 (2011), **Meson Exchange Currents (MEC, 2p2h) -** J. Nieves, I. Ruiz Simo and M. J. Vicente Vacas, Phys. Rev. C 83 (2011) 045501, **Random Phase Approximation (RPA), ...**

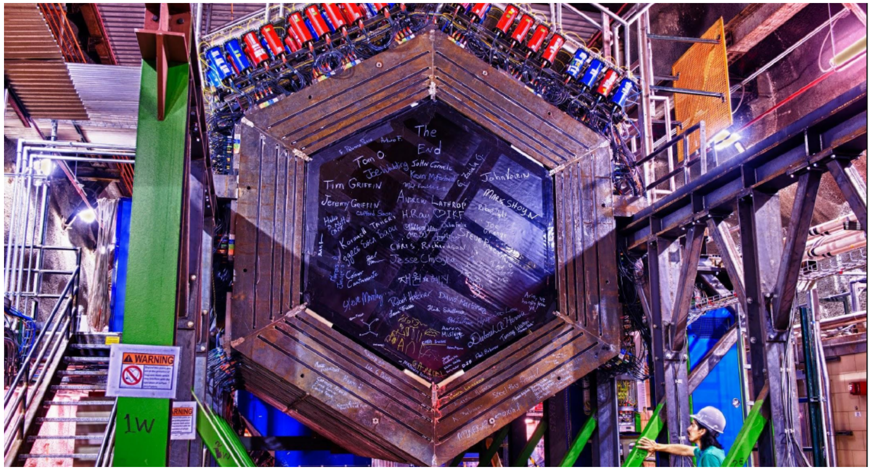
**More details in J. Żmuda talk later today**

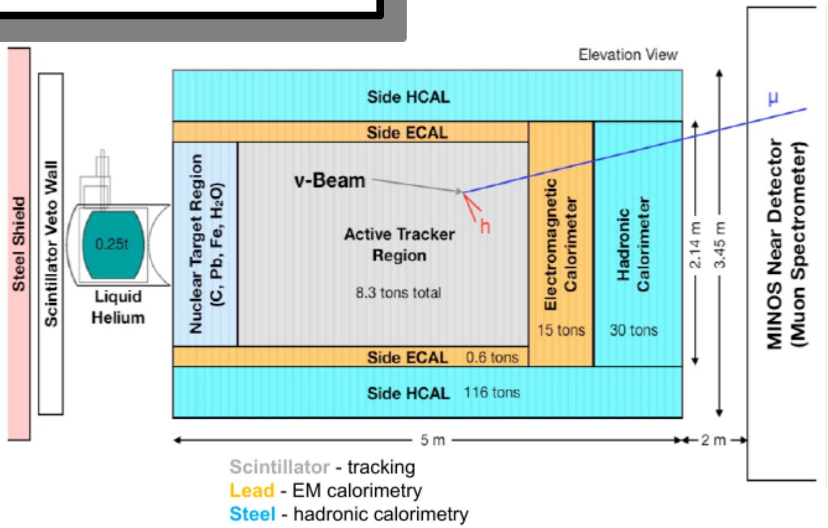
# MINERvA experiment



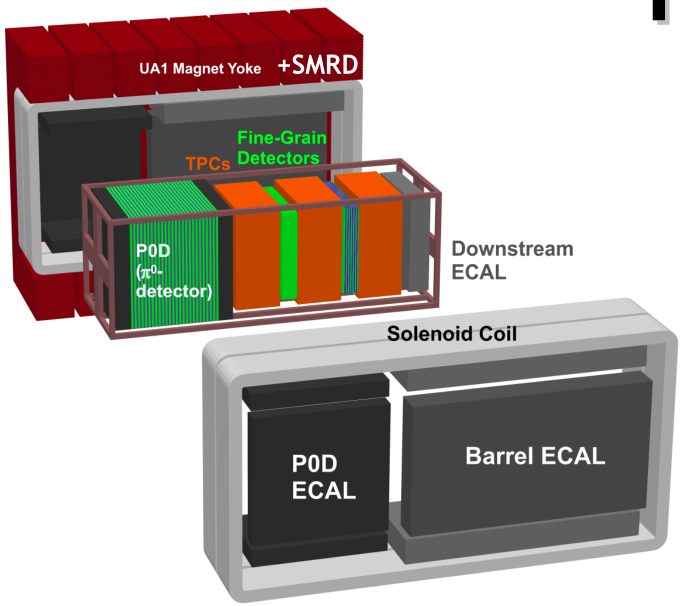



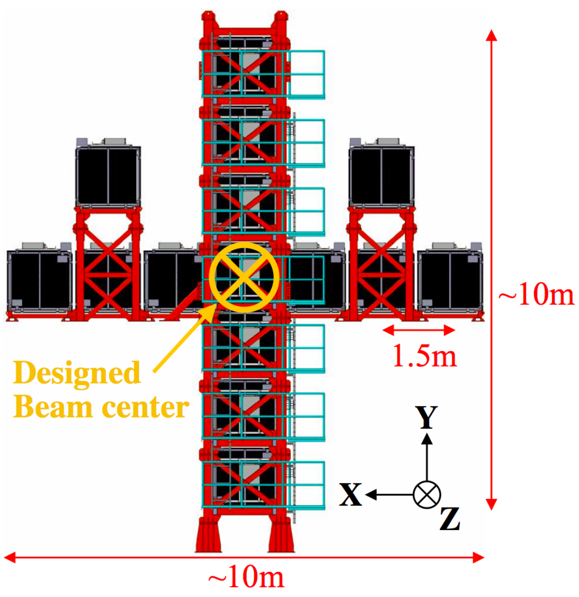

- Accelerator-made neutrino beam (NuMI) with **two energy settings: Low Energy (LE), Medium Energy (ME)**
- Detector:
  - Fine-grained scintillator (**CH**) tracker surrounded by electromagnetic and hadronic calorimeter + MINOS near detector as muon spectrometer
  - 120 modules stacked along the  beam line in three orientations
- Additional nuclear targets upstream of the main detector





# T2K experiment



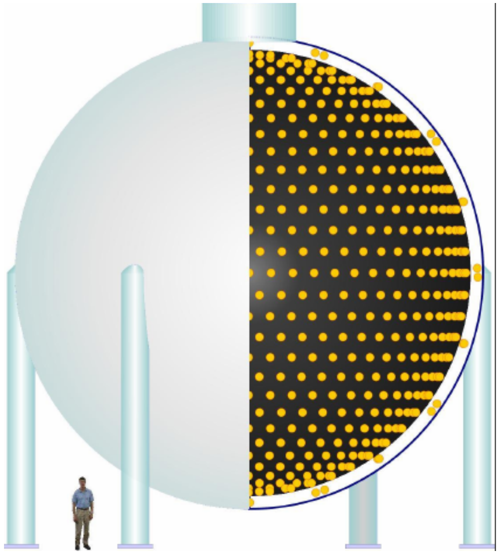

- T2K beam: Accelerator-made neutrino beam from J-PARC center in Japan with **neutrino energy <E$_\nu$>~0.6GeV**

- ND280 off-axis near detector:
  - Several sub-detectors in 0.2 T magnetic field:
    - Tracker (TPCs & Fine Grained Detectors), Pizero Detector (P0D), Electromagnetic Calorimeter (ECAL), Side Muon Range Detector (SMRD)
  - FGD targets: **hydrocarbon (CH) + water ($H_2O$)**
  - TPC: good particle tracking efficiency, resolution and particle identification via dE/dx

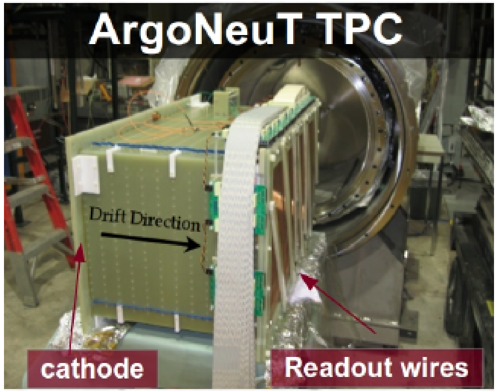
- INGRID on-axis near detector:
  - 16 modules: iron/scintillator sandwich + additional scintillator-only module (proton module)
  - Not magnetized, less precise but larger mass than off-axis: **iron (Fe) + hydrocarbon (CH)**

# MiniBooNE & ArgoNeuT

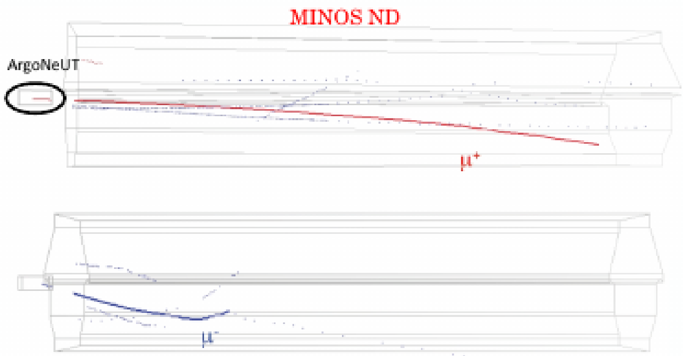
- Using accelerator-made neutrino beam from FermiLab's Booster accelerator: $\mathbf{E_\nu = 0.5 - 1}$ **GeV**
- Detector located 541m downstream of neutrino target
  - Filled with 800 tons of pure **mineral oil ($CH_2$)**, 450t fiducial volume
  - 12m diameter sphere (10m fiducial volume)
  - 1280 inner phototubes
  - 240 veto phototubes
  - 3m overburden



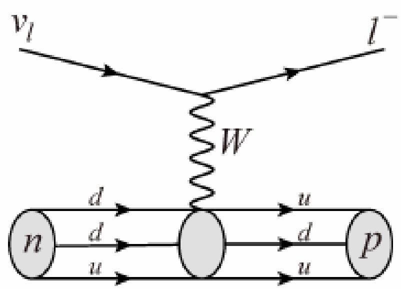
- Small-scale **liquid argon time projection chamber (LArTPC)** to the NuMI neutrino beam.



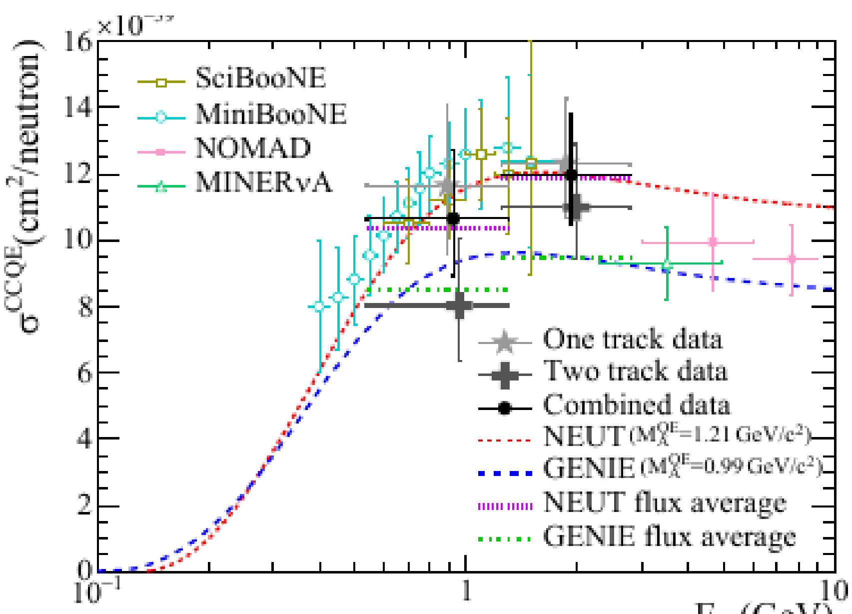

- Upstream of the MINOS near detector (used as a muon spectrometer). First LAr TPC in a **medium (1-10 GeV) energy** neutrino beam.
- TPC: 47 x 40 x 90 cm$^3$, 240 kg active mass
- Data-taking concluded in March 2010 (from 09/2009), and analysis is ongoing.



# Charged current quasi-elastic scattering



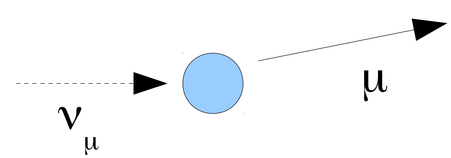

$$E_\nu^{QE} = \frac{m_p^2 - {m'}_n^2 - m_\mu^2 + 2{m'}_n E_\mu}{2({m'}_n - E_\mu + p_\mu \cos\theta_\mu)}$$



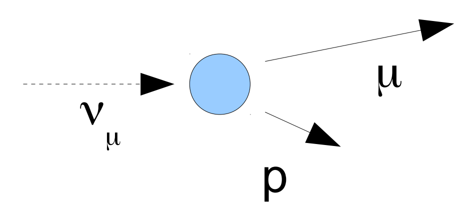

Phys. Rev. D 91 112002 (2015)

- Charged current quasi-elastic scattering (CCQE) is dominant contribution at the sub-GeV energies. Gives the largest contribution to the signal samples in oscillation experiments.
- Quasi-elastic (QE) approximation (target nucleon at rest) is used in the oscillation experiments (eg. T2K) to reconstruct neutrino energy ($E_\nu$) from muon kinematics → wrong modelling can lead to bias in oscillation parameters

**1-track CCQE**



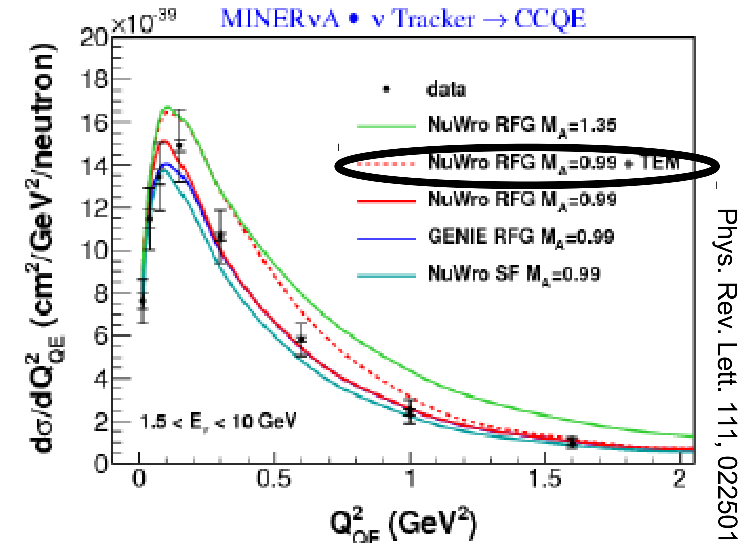

**2-track CCQE**



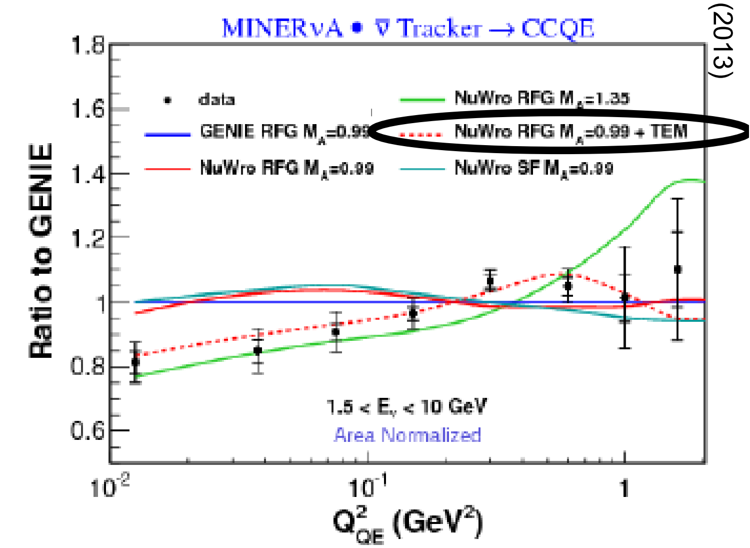

- T2K CCQE result: model describing one track (grey star, red dashed line) data is not sufficient to also describe two track (black cross) topology.

# CCQE in MINERvA

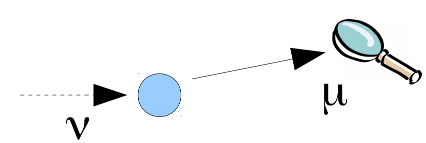
- Models which describe well CCQE in terms of the outgoing muon kinematics do not work well in the case of outgoing proton kinematics
- Muon kinematics result ($Q^2$ estimated using muon kinematics) favors RFG + TEM model and suggests the presence of the initial state NN correlations
- In contrast: Proton kinematics result ($Q^2$ estimated using proton kinematics) favors straightforward GENIE RFG model



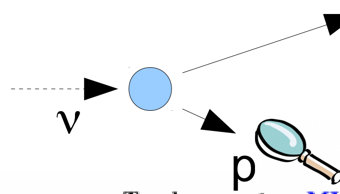

Phys. Rev. Lett. 111, 022501 (2013)

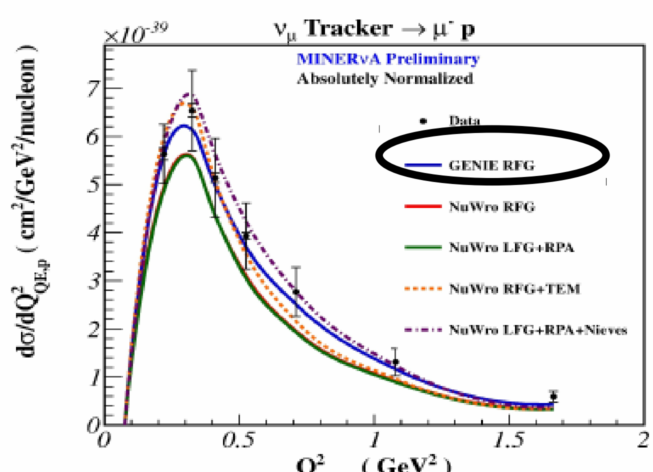


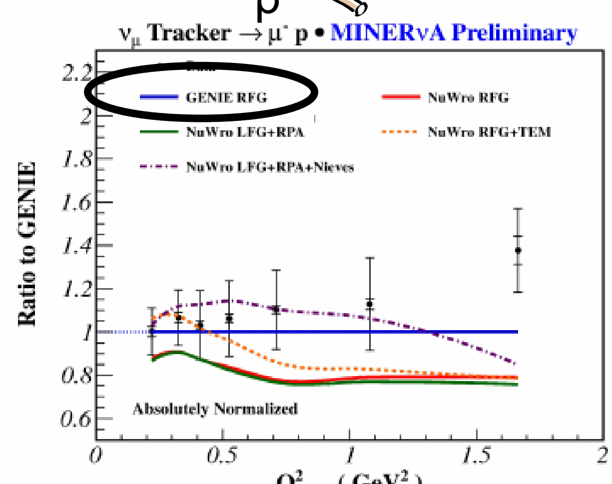

**Muon kinematics**




**Proton kinematics**



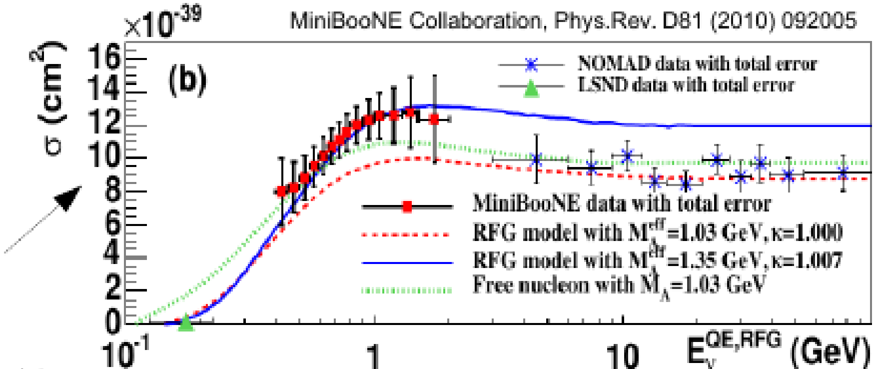

Phys. Rev. D 91, 071301 (2015)

sections

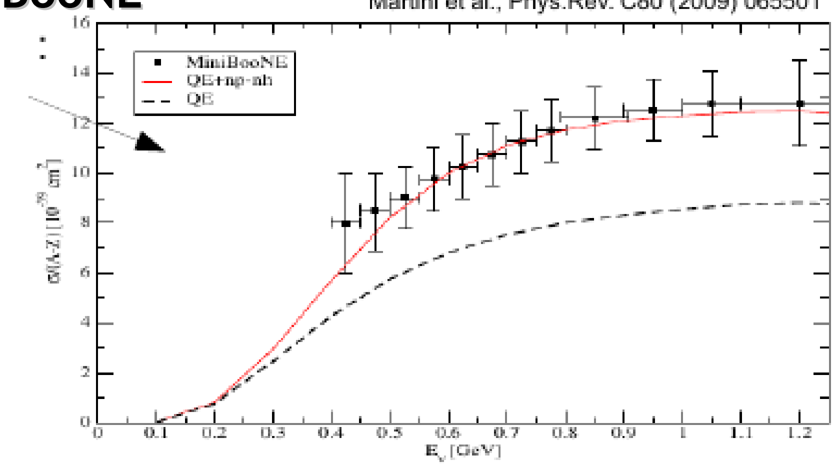
ss

# ArgoNeuT: Observation of 1μ+2p events

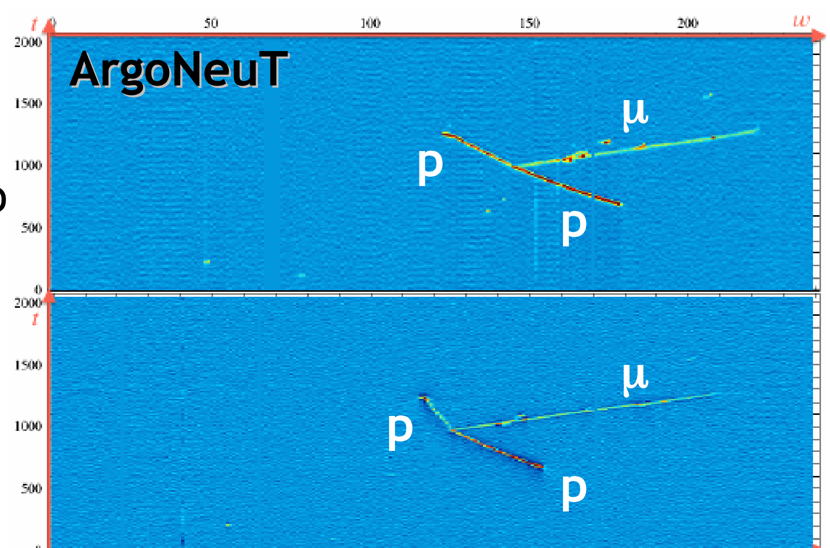
- Current (common) CCQE model in Monte Carlo:
  - Form factors tuned from e-p scattering and bubble chamber experiments
  - Nuclear effects: RFG + Pauli blocking
- MiniBooNE experiment shows large discrepancy wrt this model
- New models include:
  - Possibility of interactions with NN pairs (2p2h, MEC)
  - Long range correlations between nucleons (RPA)




MiniBooNE




Neutrino beam

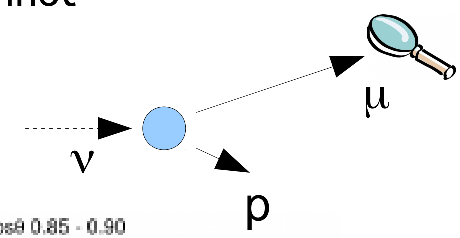


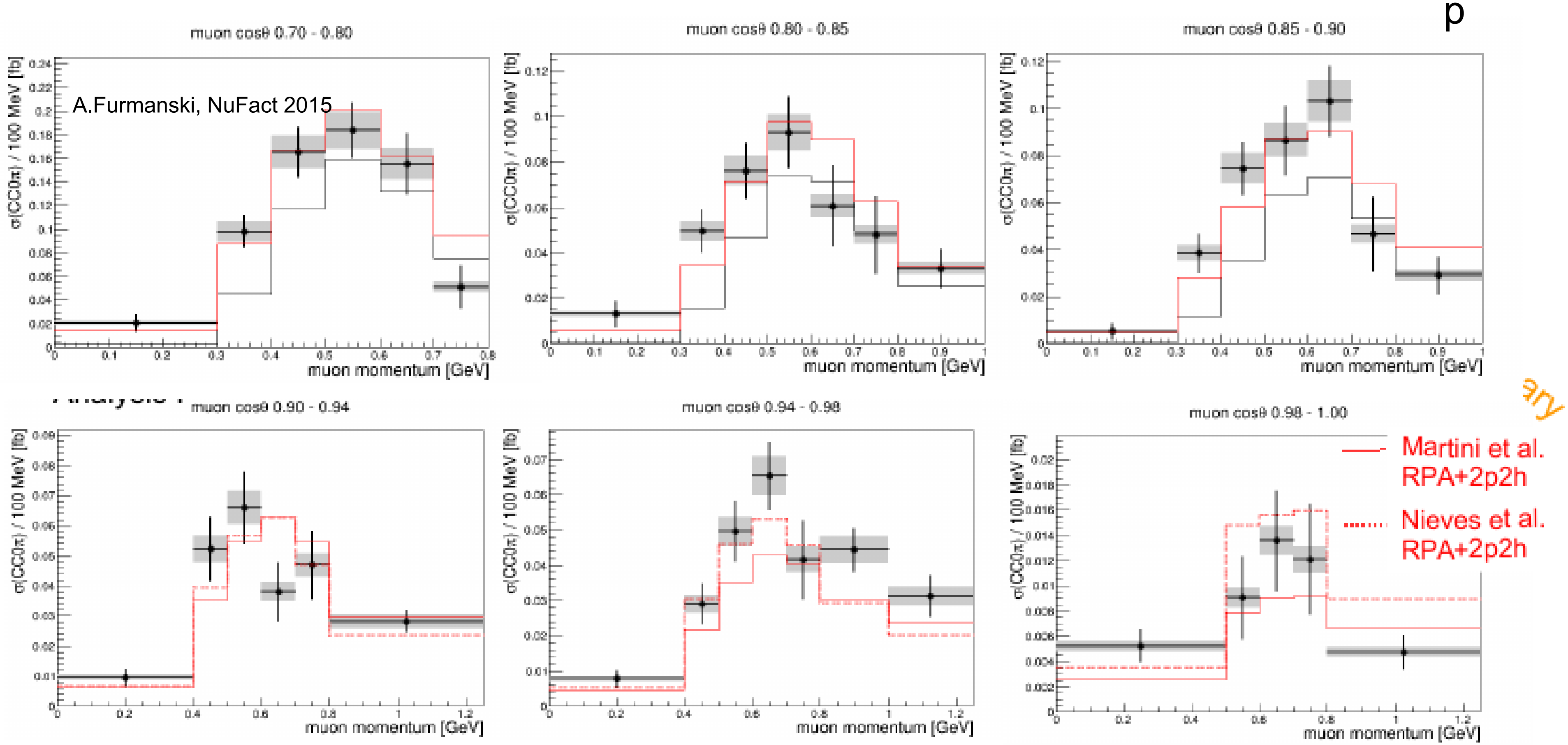

Phys. Rev. D 90, 012008 (2014)

- ArgoNeut experiment sees events with muon and two protons <u>suggesting presence of NN correlations and/or two-body currents (MEC, 2p2h)</u>
- 4 back-to-back proton pair events ("hammer") observed: $\cos\gamma < -0.95$, $P_{p1} \sim P_{p2}$ – most probably effect of initial state NN short-range correlations (SRC)

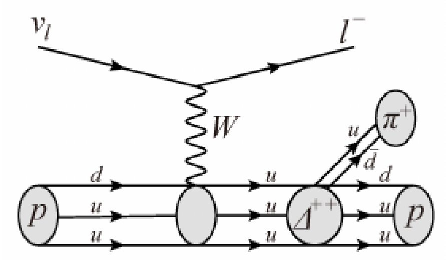
# T2K: CC0π (CCQE) measurement

- T2K shows that also new models which include NN correlations (RPA + 2p2h) cannot describe the full phase-space (eg. forward region).
- Lack of statistical power to discriminate between models.
- It is crucial to estimate the uncertainties of the new models.

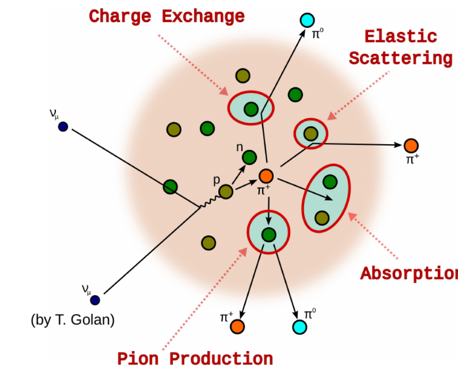


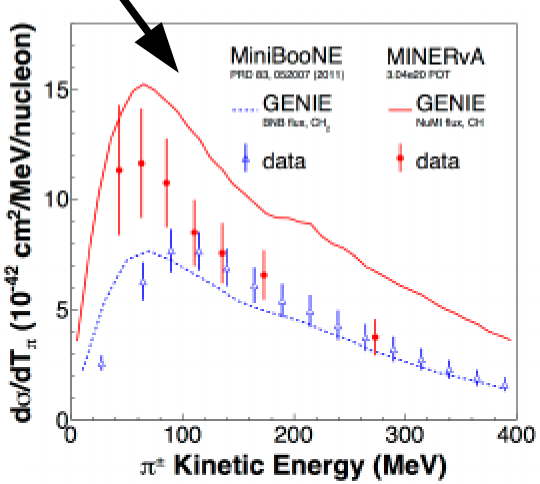
# MINERvA: Single pion production

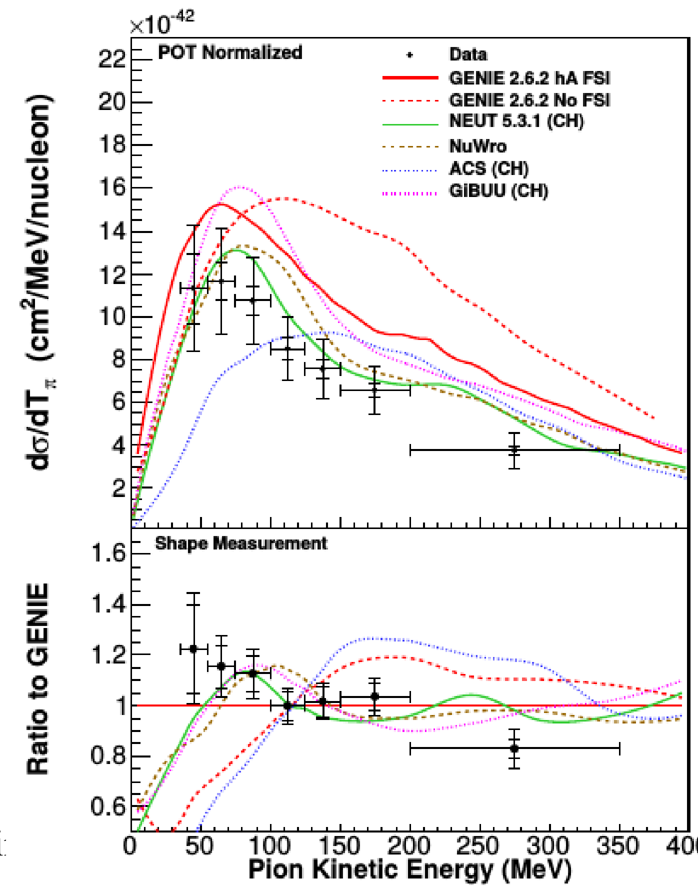



- Neutrino induced single pion production is one of the main backgrounds for neutrino oscillation experiments.
- Large effects from final state interactions (FSI): pion absorption, scattering, charge exchange in the nucleus




- MINERvA data favors presence of FSI in neutrino event generators.
- MiniBooNE sees harder momenta, more events and less FSI than MINERvA. MINERvA – MiniBooNE discrepancy in neutral pion production.

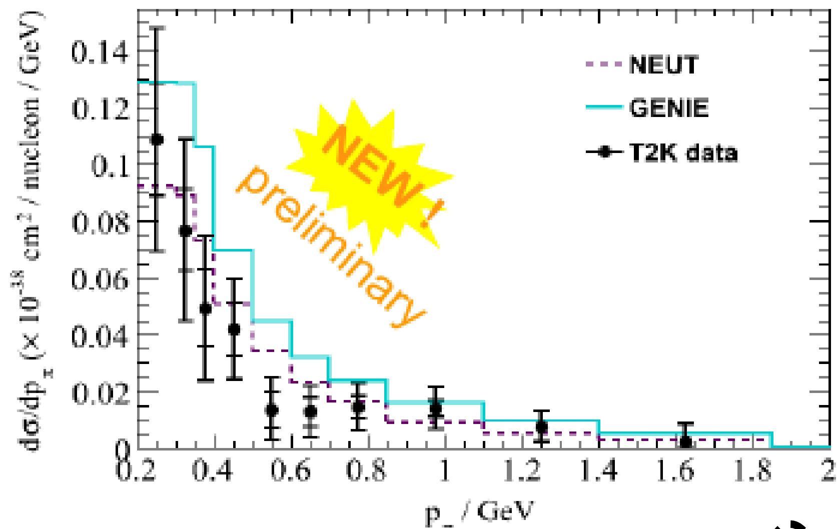


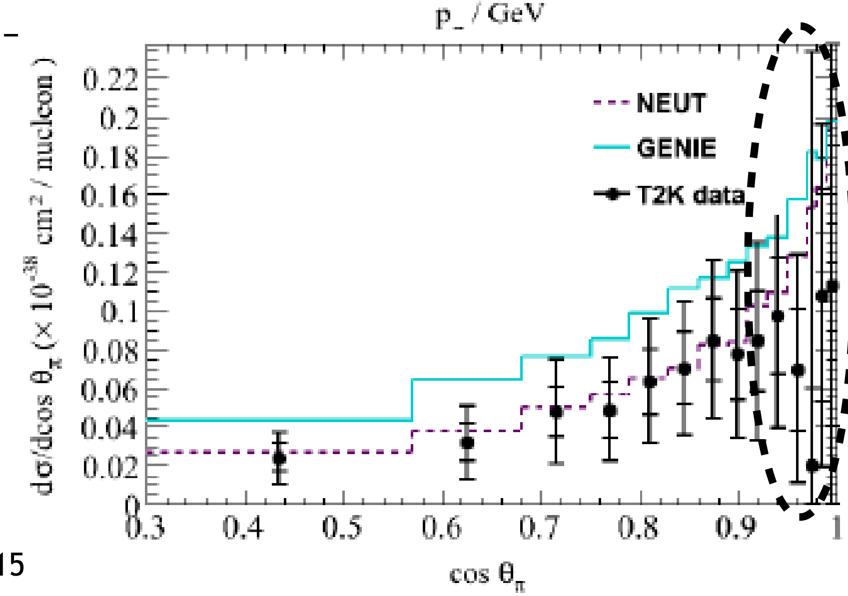




arXiv:1406.6415 [hep-ex]

# T2K: Charged pion production on water

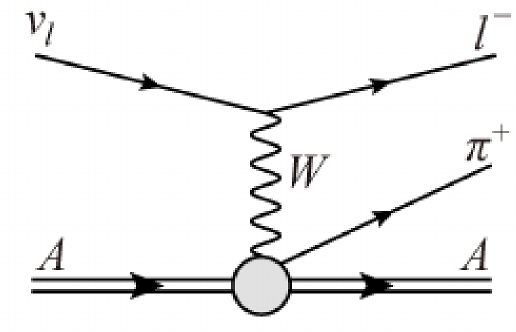
- Will be able to constrain FSI on different nuclei (Carbon and Oxygen targets in T2K)
- Current T2K result is below GENIE MC prediction → similar to the MiniBooNE result
- At low pion angles ($\cos\theta_{\pi}$~1) – "suppression" effect - large contribution from coherent pion production



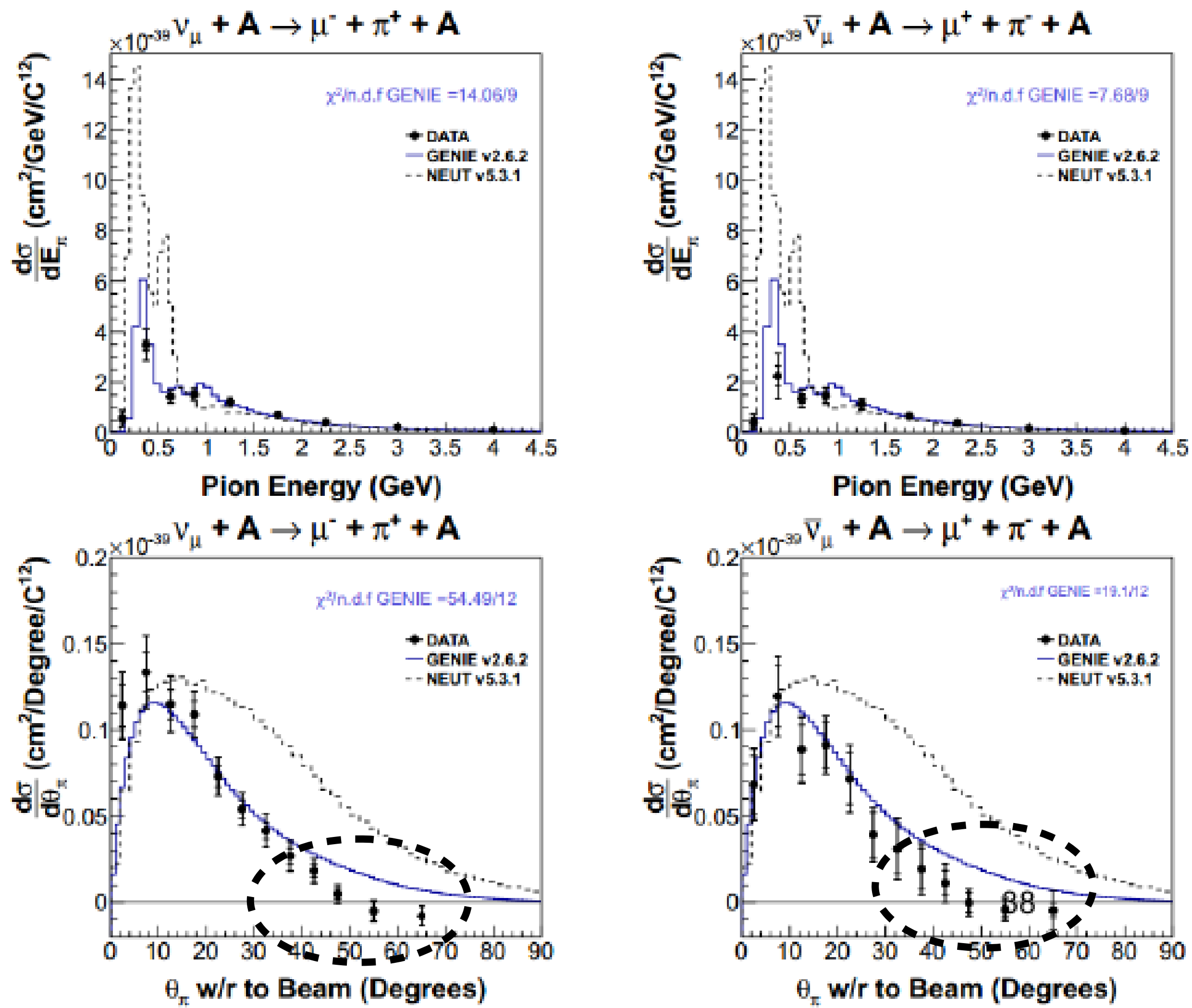




M. Nikko, NuFact 2015

# MINERvA: coherent pion production




- Characteristic feature: low 4-momentum transfer to the nucleus ($|t| < 0.125$ GeV$^2$)
- MINERvA observes coherent pion production for neutrinos and anti-neutrinos
- NEUT model used in this analysis is out-of-date and is currently being improved.
- Disagreement at the high angles for GENIE.
- This result is a benchmark to test new coherent pion production models in GENIE

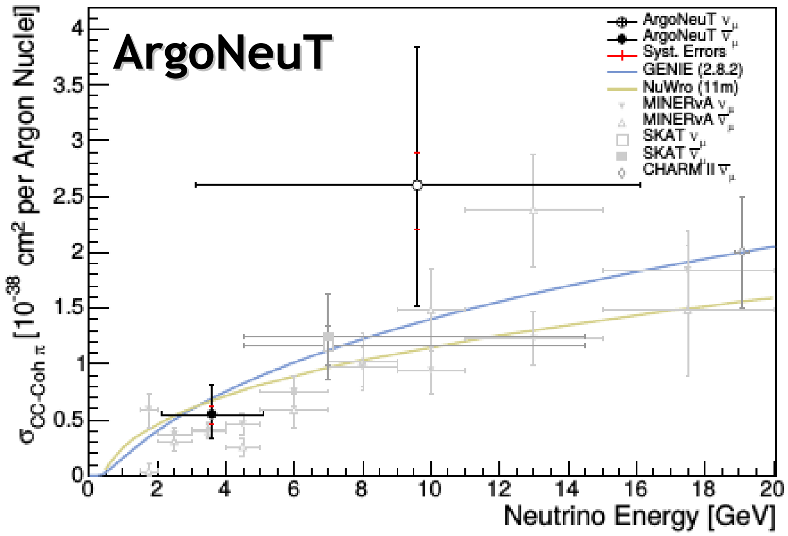



Phys. Rev. Lett. 113, 261802 (2014)

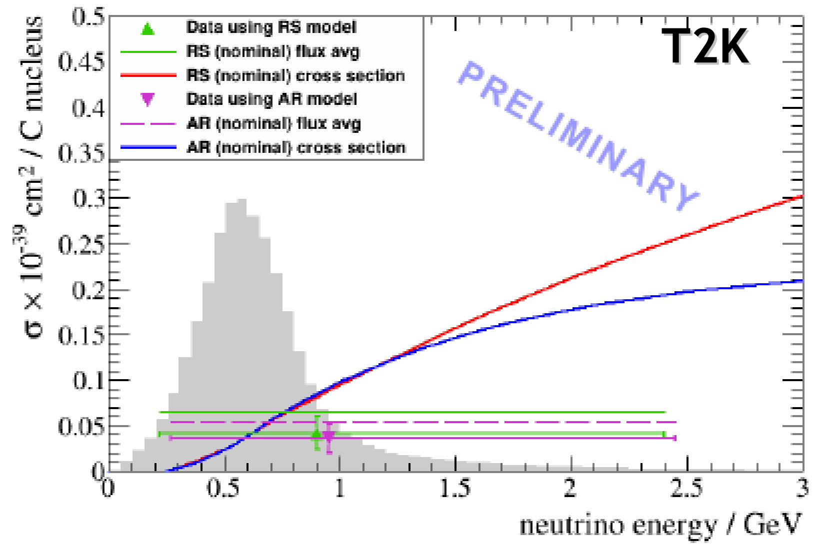
# Coherent pion production

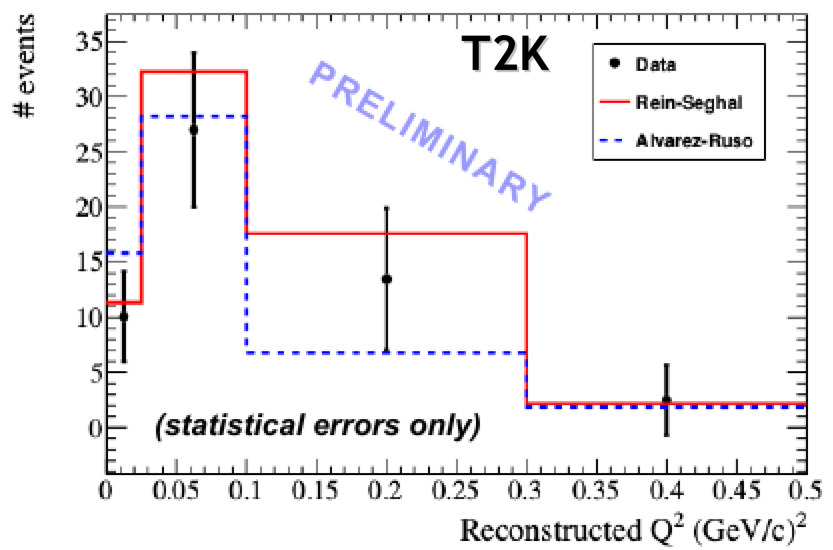
- First charge current coherent pion cross section measurement on argon reported by ArgoNeuT – important result for future experiments.
- T2K result:
  - Excess of 55±20 events observed at 2.7 σ → first experimental indication of coherent pion production below 1.5 GeV
  - Cross section calculated using two coherent production models in GENIE: Rein-Seghal, Alvarez-Ruso
  - Currently lack of statistics to distinguish between those two models

Phys. Rev. Lett. 113, 261801 (2014)



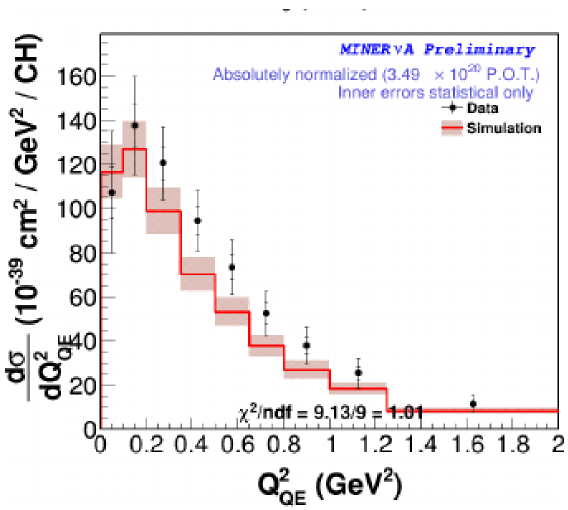

M. Nikko, NuFact 2015



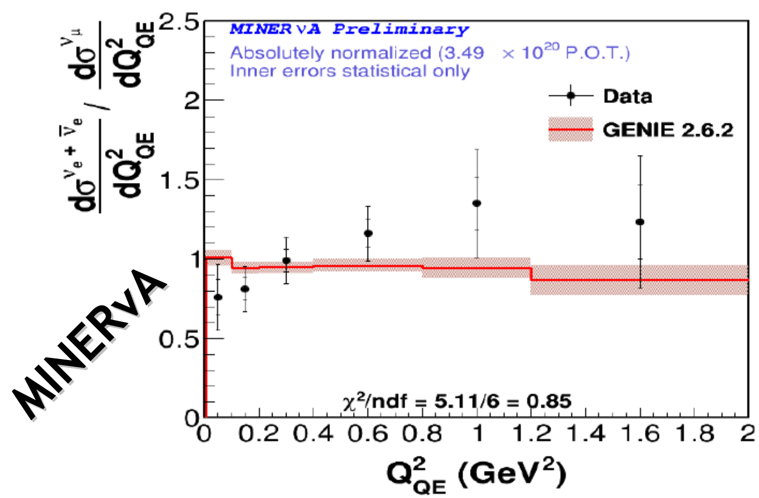



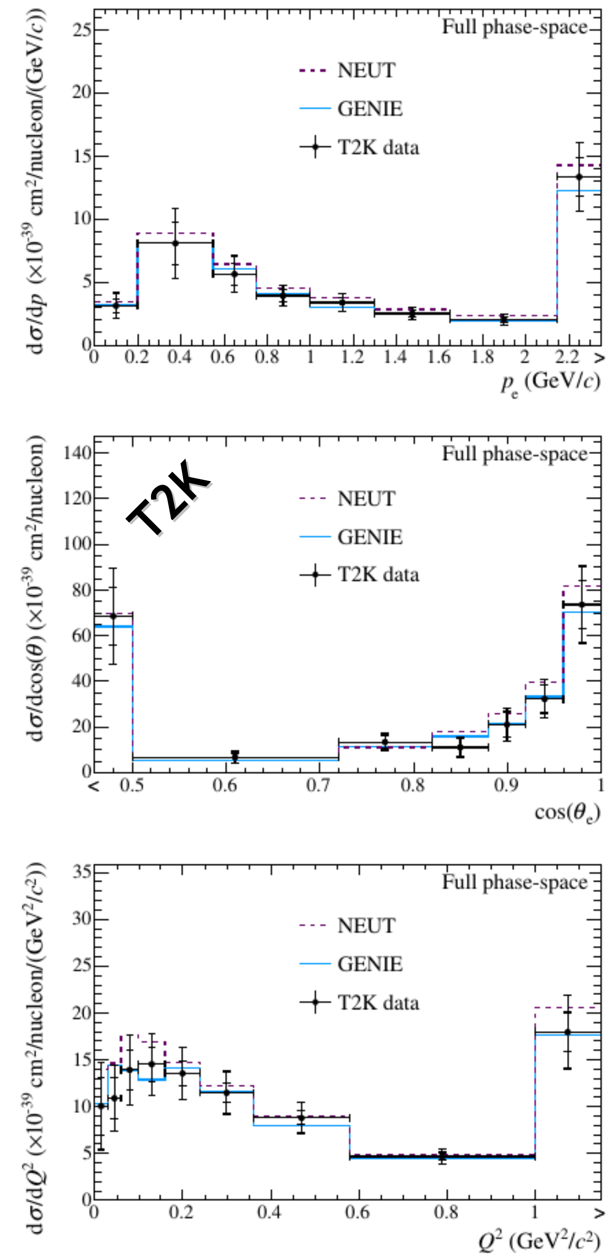
# $\nu_e$ charged current cross section

- T2K reported in July 2014 the first measurement of the differential electron neutrino cross section at the energies ~1GeV
  - Results agree with the predictions from NEUT generator
- MINERvA result showed at the NuFact 2015 conference:
  - Consistent with predictions from GENIE neutrino event generator
  - Ratio of electron neutrino and muon neutrino cross sections agrees between data and GENIE predictions




A. Ghosh, NuFact 2015



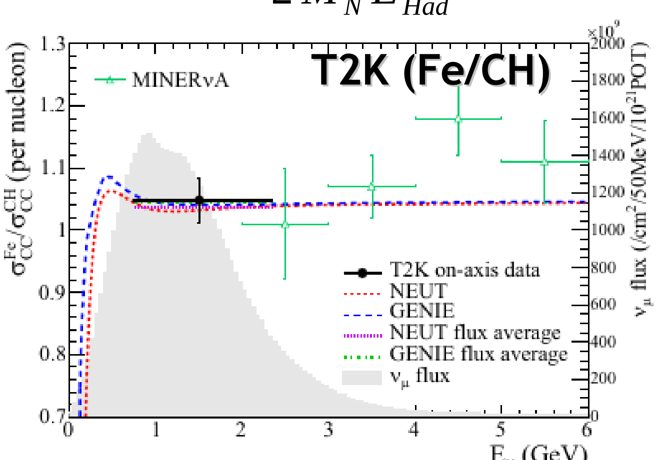




Phys. Rev. Lett. 113, 241803 (2014)

# Cross section ratios on various nuclear targets

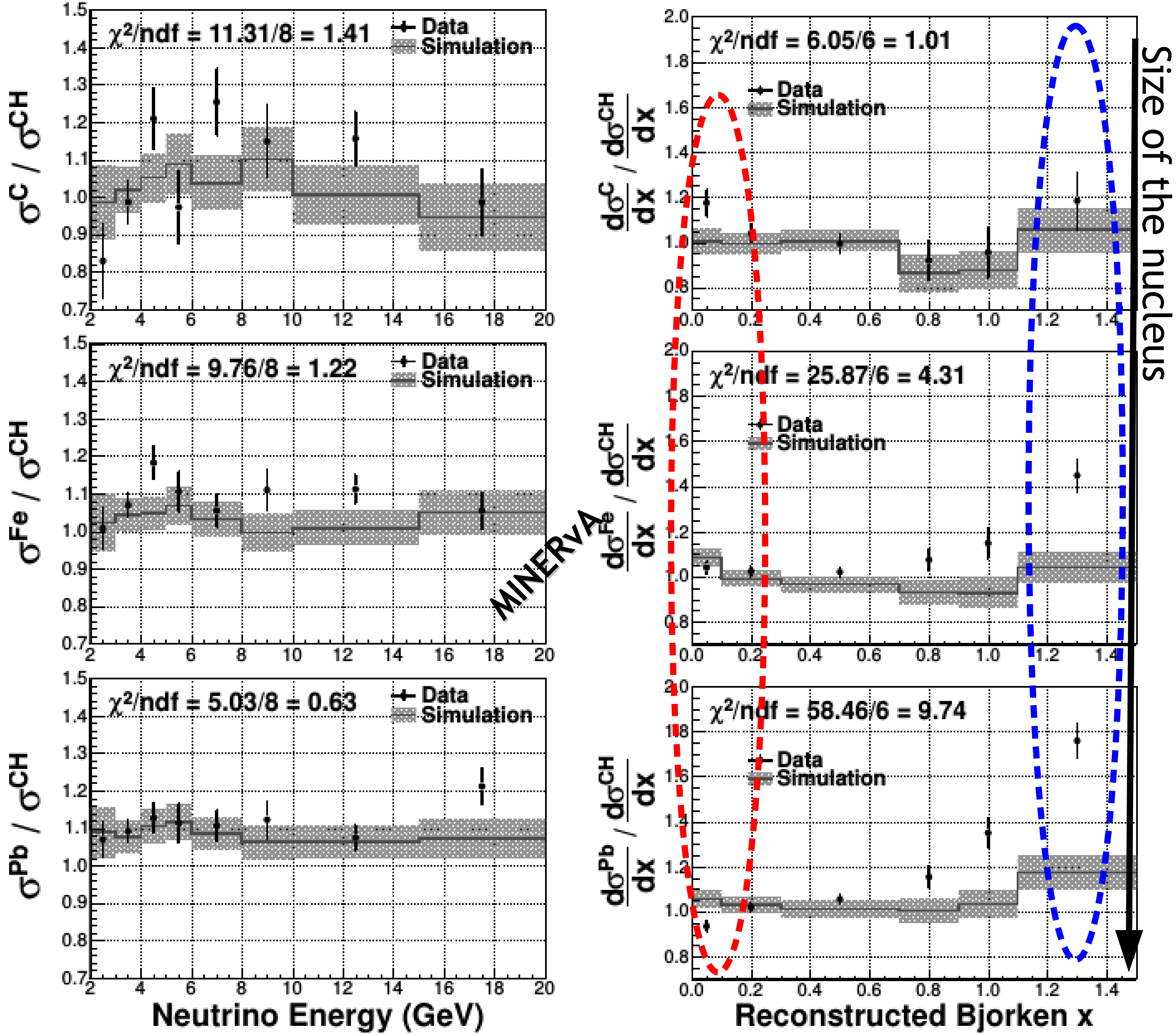
- Data/MC: good agreement vs $E_\nu$ also at T2K
- At low x, MINERvA observes a deficit that increases with the size of the nucleus.
- At high x, they observe an excess that increases with the size of the nucleus.
- These effects are not reproduced by current neutrino interaction models.

$$x = \frac{Q^2}{2 M_N E_{Had}}$$




Phys. Rev. D. 91, 112002 (2015)

Phys. Rev. Lett. 112, 231801 (2014)



# Summary

- Neutrino cross section measurements are important for neutrino oscillation measurements and to understand the nature of neutrino-nucleus scattering.
- Large number of interesting cross section results appeared during the last two years (2013-2015).
- Charge current quasi-elastic scattering **(CCQE) is currently under change of paradigm: studying new models (MEC/2p2h).** Theoretical convergence is needed to predict the impact of multi-nucleon process in CCQE with sufficient accuracy.
- Pion production (CC1$\pi$) channel has proven to be an excellent probe for the final state interactions.
- **There are many models on the market but currently no model is able to explain all CCQE and CC1$\pi$ data sets** → Data reveals many clues and certainly **we need more sophisticated models** to be implemented into generators.
- Interesting $\nu_e$ cross section results appeared → consistent with Monte Carlo predictions.
- **Dependency of charge current cross section ratios on the size of the nucleus needs to be confirmed →** waiting for medium energy MINERvA data (much larger statistics)
- We also **need more measurements with large statistics** (more power to discriminate between various models) and lowered systematic errors → far from 1% normalization uncertainty needed for CP violation measurements

# Thank you for your attention!

# References

- Covered:
  - https://indico.fnal.gov/conferenceDisplay.py?confId=8903 - NuFact 2015 conference slides
  - http://arxiv.org/abs/1503.07452 - T2K on-axis CCQE
  - http://arxiv.org/abs/1409.3835 - MINERvA CC coherent pion production measurement
  - http://arxiv.org/abs/1409.4497 - MINERvA CCQE muon+proton sample
  - http://arxiv.org/abs/1408.0598 - ArgoNeuT CC coherent pion production cross section on argon
  - http://arxiv.org/abs/1407.7389 – T2K inclusive nue CC differential cross section
  - http://arxiv.org/abs/1407.4256 - T2K on-axis cross section measurement
  - http://arxiv.org/abs/1406.6415 - MINERvA pion production differential cross section
  - http://arxiv.org/abs/1405.4261 - ArgoNeuT 1mu+2p events
  - http://arxiv.org/abs/1403.2103 - MINERvA cross section ratio with different targets
  - http://arxiv.org/abs/1305.2243, http://arxiv.org/abs/1305.2234 - MINERvA CCQE measurements

- Not covered:
  - http://arxiv.org/abs/1503.02107 – MINERvA CCpi0
  - http://arxiv.org/abs/1404.4809 - ArgoNeuT CC-inclusive differential cross section on Ar
  - http://arxiv.org/abs/1309.7257 - MiniBooNE NCEL cross section
  - http://arxiv.org/abs/1302.4908 - T2K first CC inclusive cross section result