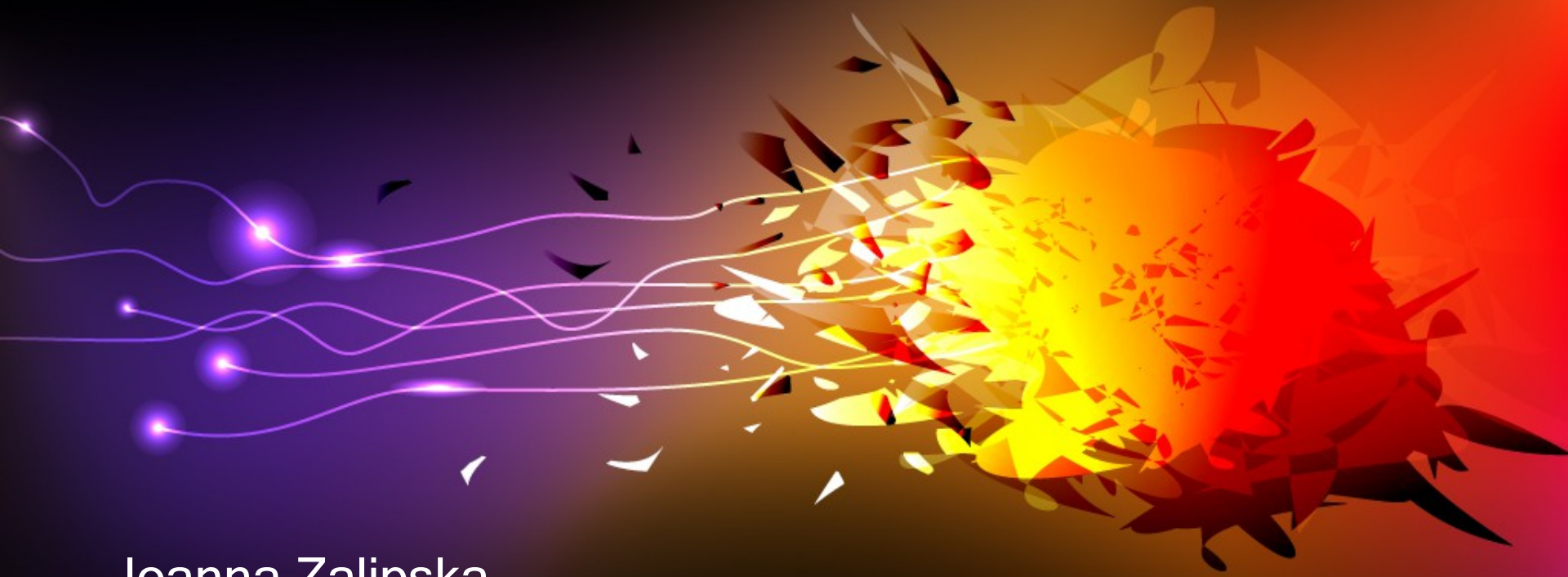
Studies of Neutrino Physics in the T2K Experiment



Joanna Zalipska

National Centre for Nuclear Research

Annual Seminar of NCBJ, 9th January 2018

Polish Neutrino Group

- NCBJ:
  Full **Professors:** E. Rondio, M. H. Szeptycka
  Associate Prof.: J. Łagoda
  Assistant Prof.: K. Kowalik, P. Przewłocki, D. Stefan, R. Sulej, J. Zalipska
  PhD Students:
  M. Kabirnezhad, G. Żarnecki

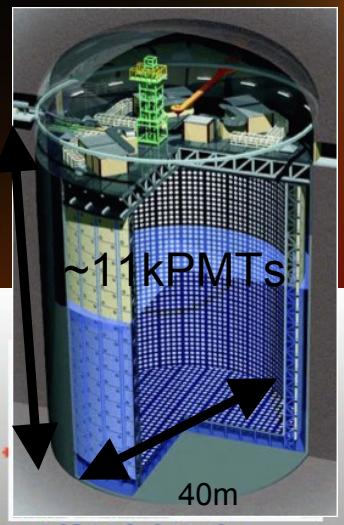
- University of Warsaw
- Warsaw Institute of Technology
- University of Wrocław
- Silesian University, Katowice
- The Henryk Niewidoczański Institute of Nuclear Physics Polish Academy of Science, Kraków

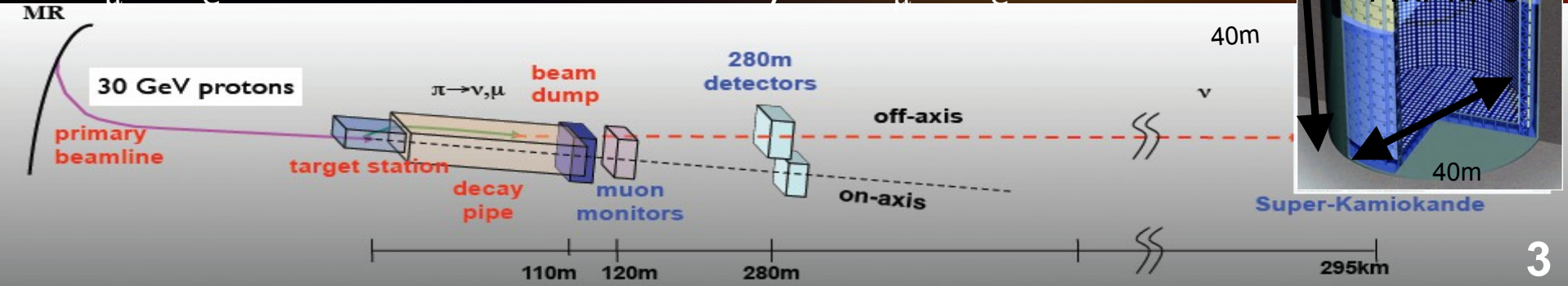
The T2K Experiment

- ν_μ beam produced at JPARC laboratory when 30GeV protons hit graphite target
- Near detector – ND280 – measures un-oscillated ν_μ beam
- Far detector – Super-Kamiokande - measures oscillations of ν_μ beam

- Precise measurement of θ_{23} by studying disappearance of ν_μ-> ν_μ
- First measurement of θ_{13} in appearance of ν_μ->ν_e
- Search for CP violation in ν sector, does $\bar{\nu}_\mu$->$\bar{\nu}_e$ oscillate in the same way as ν_μ->ν_e

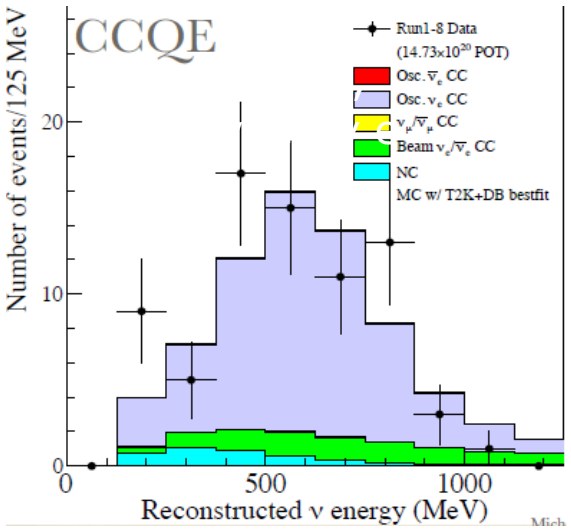
Tokai 2 Kamioka



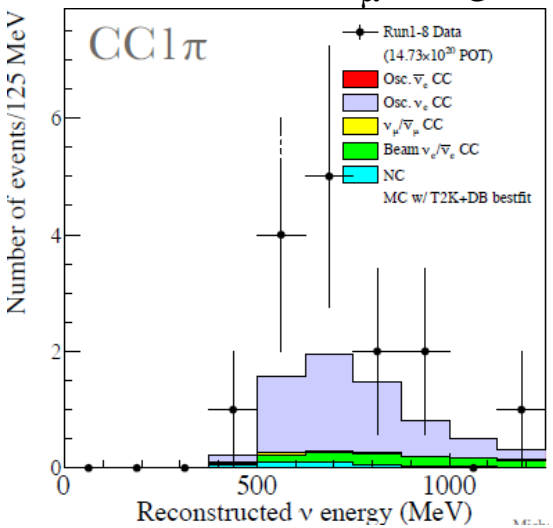


Observed T2K Appearance Events

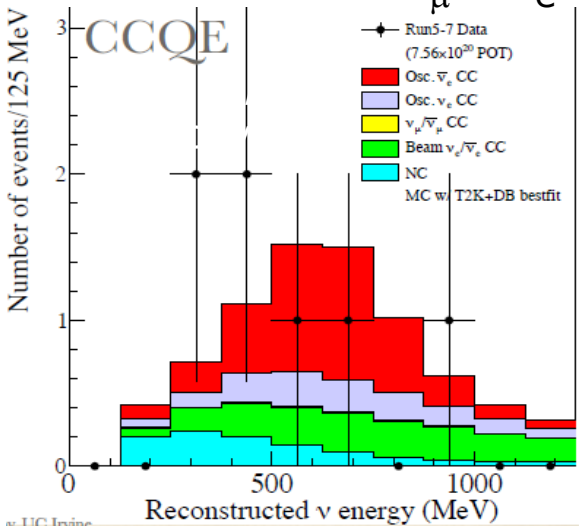
Neutrino $\nu_\mu \rightarrow \nu_e$



Neutrino $\nu_\mu \rightarrow \nu_e$



Anti-neutrino $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



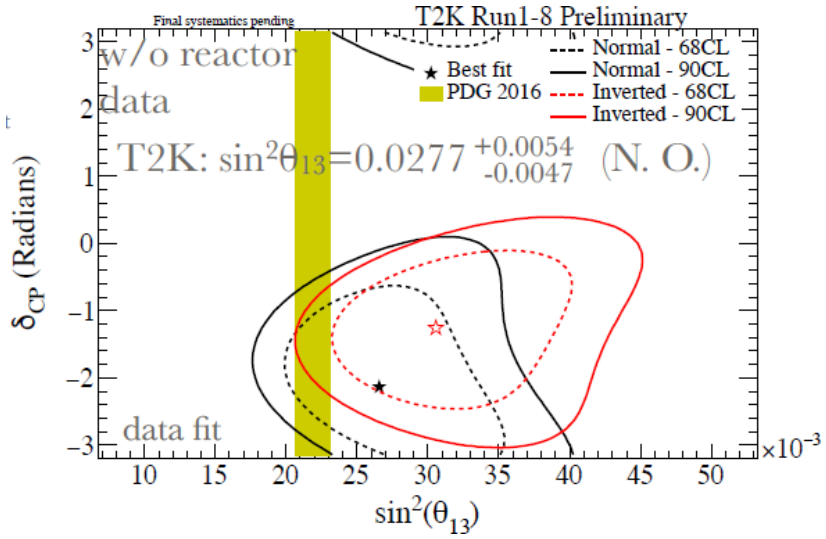
1.49×10^{21} POT ν-mode, 0.76×10^{21} POT $\bar{\nu}$-mode

	$\delta=-0.5\pi$	$\delta=0\pi$	$\delta=0.5\pi$	$\delta=\pi$	**observed**
ν_e CCQE	73.5	61.5	49.9	62.0	**74**
ν_e CC1π	6.92	6.01	4.87	5.78	**15**
$\bar{\nu}_e$ CCQE	7.93	9.04	10.04	8.93	**7**

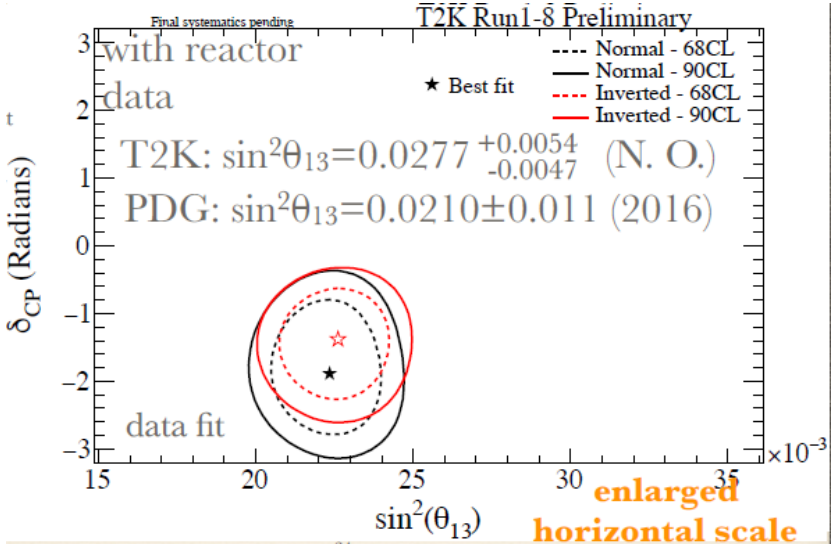
More ν_e appearance and less $\bar{\nu}_e$ appearance than expected for $\delta=0,\pi$

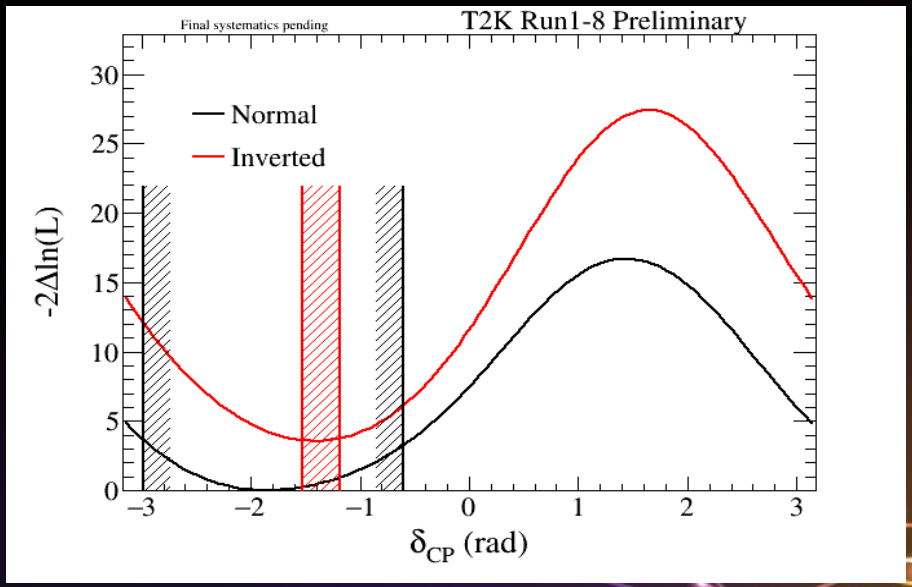
ν_μ->ν_e Oscillations and δ Constraint

Closed contours at 90% C.L.



Better δ constraint with reactors



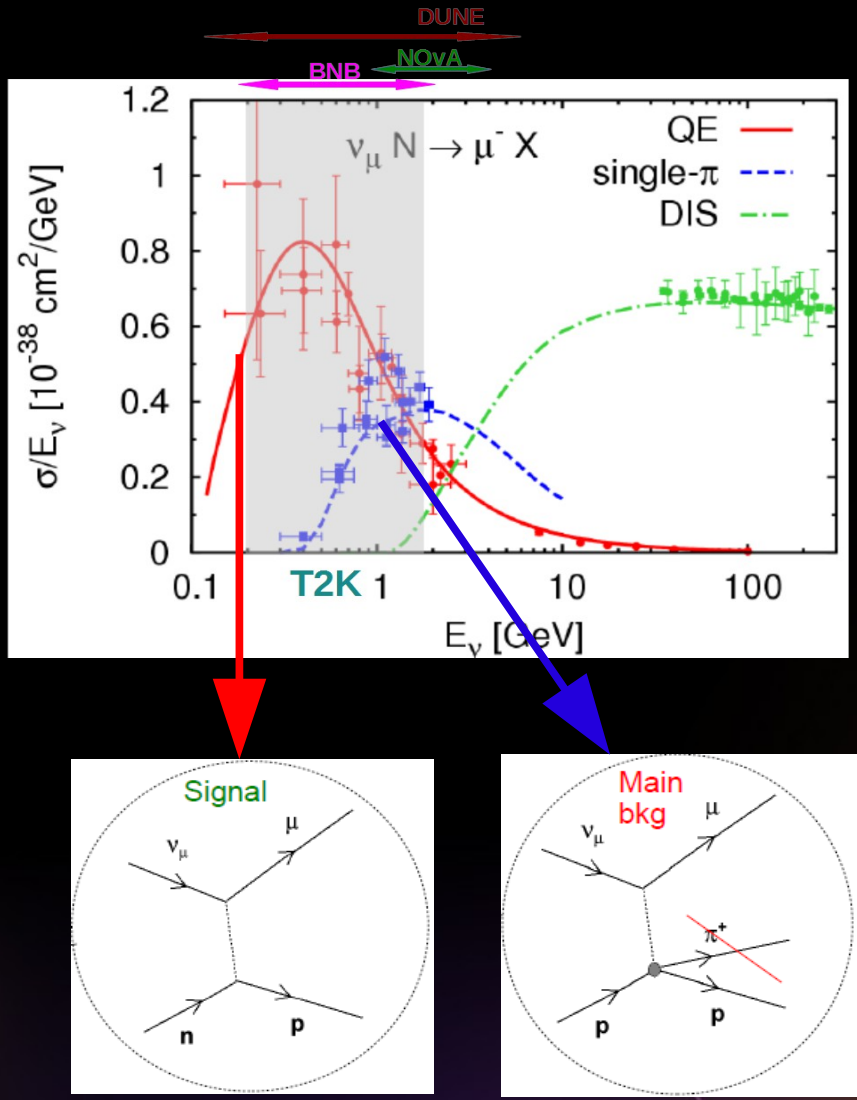


- Critical $\Delta[-2\ln(L_{marg})]$ values using the Feldman-Cousins prescription
- 2σ confidence intervals:
  Normal Hierarchy [-2.98,-0.60] rad.
  Inverted Hierarchy [-1.54,-1.19] rad.
- CP conserving values are outside of the 2σ intervals

Our activities are targeted mostly towards improvement of measurement of CP violation in T2K

- Single pion production model in generator of neutrino interactions with matter – M. Kabirnezhad (We propose as achievement in 2017)
- Antineutrino CC1π^- cross section measurement – G. Żarnecki, J. Łagoda
- Search for 2p2h interactions in the Near Detector neutrino data – J. Zalipska
- K^+ production cross section – K. Kowalik

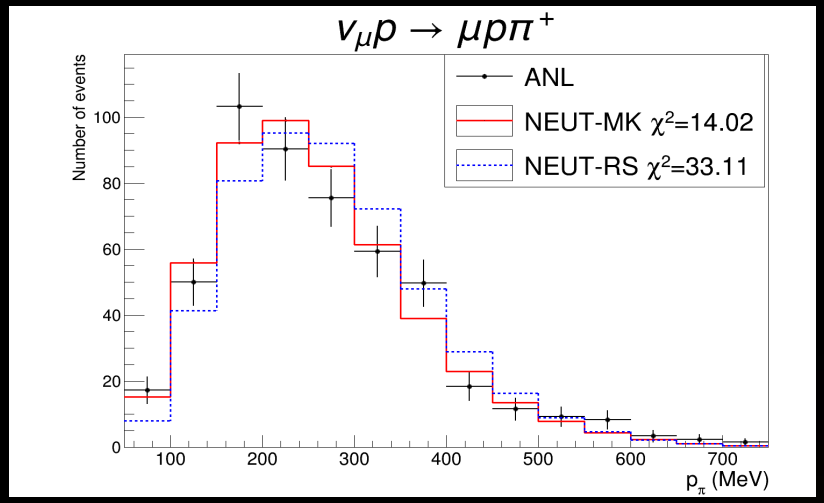
Single Pion Production Model

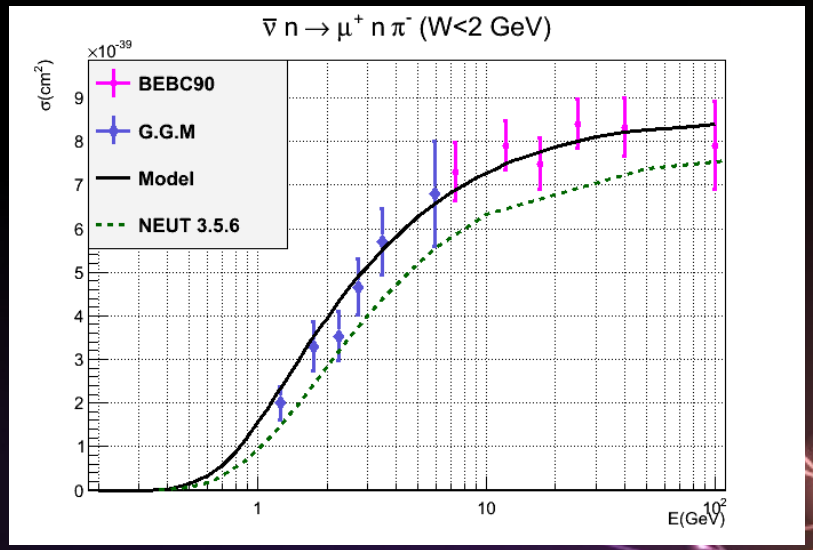


- Single pion production has significant contribution at inter-mediate energy.
- Good model is very crucial for precise neutrino oscillation measurements.
- Model has beed developped which consists of resonant and nonresonant interactions, including the interference effect. The lepton mass is included.
- The model is implemented in NEUT – the official neutrino event generator used by the T2K collaboration.

Single Pion Production Model

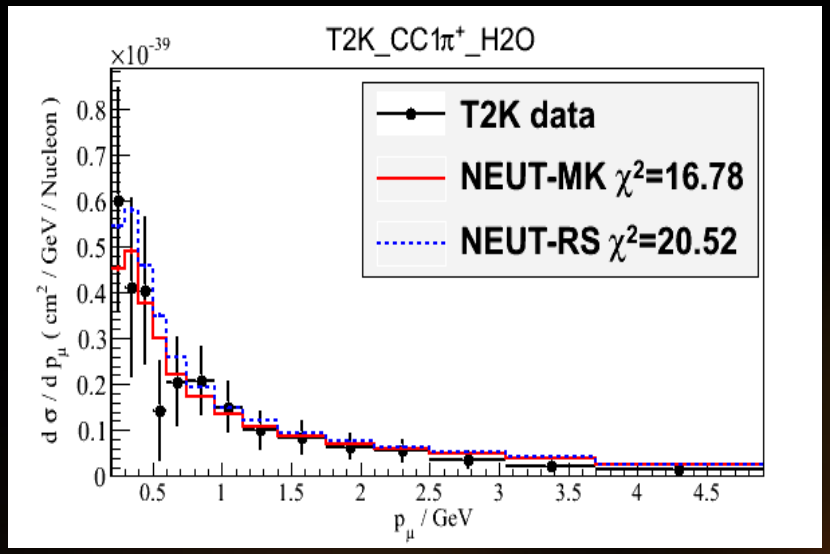
Good agreement with Bubble chamber data





T2K data on water

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



Publication “Single Pion Production in Neutrino-Nucleon Interactions” accepted by Phys. Rev. D.

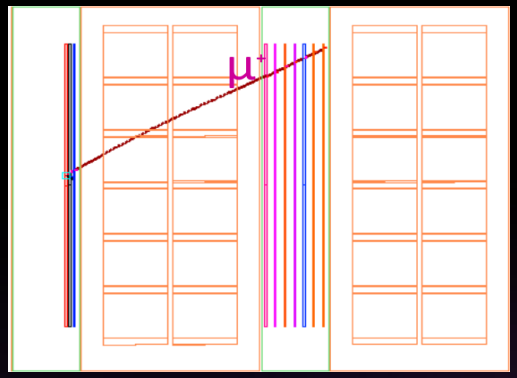
Subject of PhD thesis which has already obtained positive reviews

G. Żarnecki

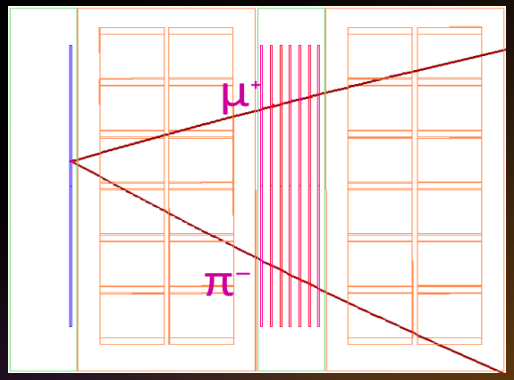
$\bar{\nu}$ CC1π^- cross section measurement and study of the μ^+ selection

- PhD student G. Żarnecki joined the T2K collaboration on March 2017 (supervised by dr hab. J. Łagoda). The main goal of his analysis is measuring x-section for ν_μ CC interactions with single π^- production on carbon target.

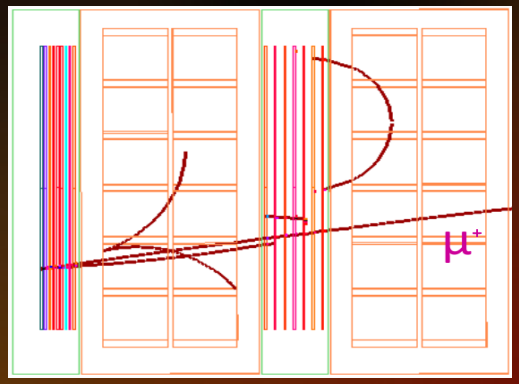
- CC interactions are often divided into three topologies: CC0π – without pions produced in the final state, CC1π – with single π^- in final state and CCOther – with reconstructed π^+ or π^0 or more than one π^-.



CC0π



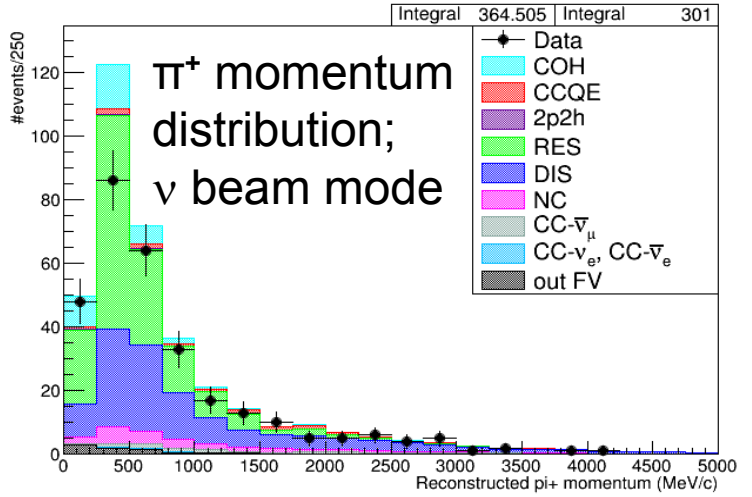
CC1π

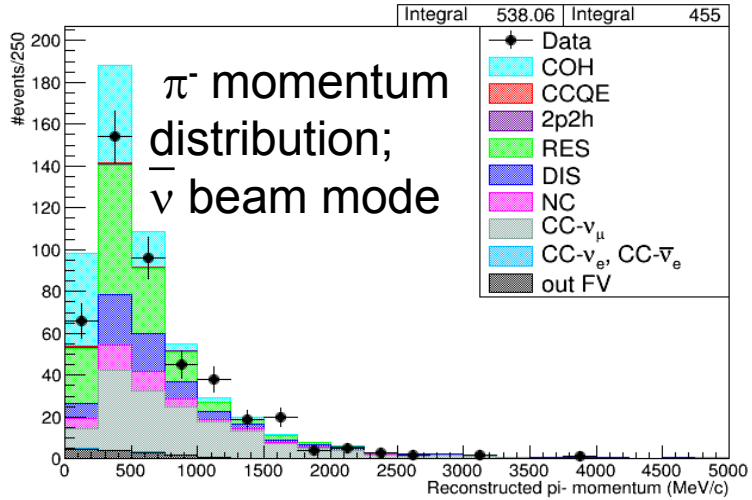


CCother

- Currently the components of the background for CC1π^- interaction is studied to improve the selection and find appropiate background subtraction methods.

Pion Kinematics Study

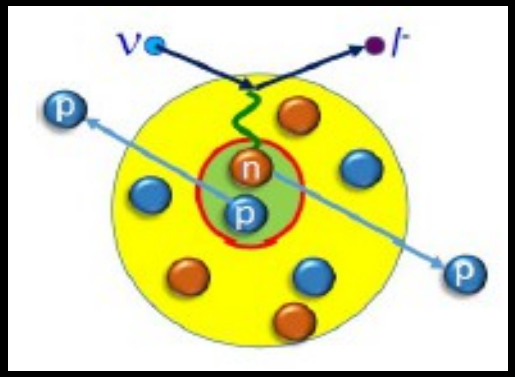




- Pion kinematics were studied for ν ($\bar{\nu}$) CC interaction with single π^+ (π^-) production
- Comparison between data and MC is important for setting systematic uncertainties and potential revision of the models and parameters.
- This results were used by one of the collaboration groups to set the uncertainty of the non resonant part of the CC1π^- cross-section for low momenta.

J. Zalipska

2p2h neutrino interactions



- Search for 2 particle 2 hole (2p2h) or Meson Exchange Current (MEC) Neutrino Interactions. Energy of inte-Racting n is transferred to 2 nucleons (*nn* or *np*)

- Events with 2 or more protons. Low energy protons are important. Unerstanding of Final State interactions are important.

- 2p2h are the backgrund for E_ν reconstruction of quasi-elastic events. Knowledge of 2p2h x-sec will improve precision of oscillation analysis.

- Study realized under OPUS grant together with group of theoretical physicists from University of Wrocław (NuWro)

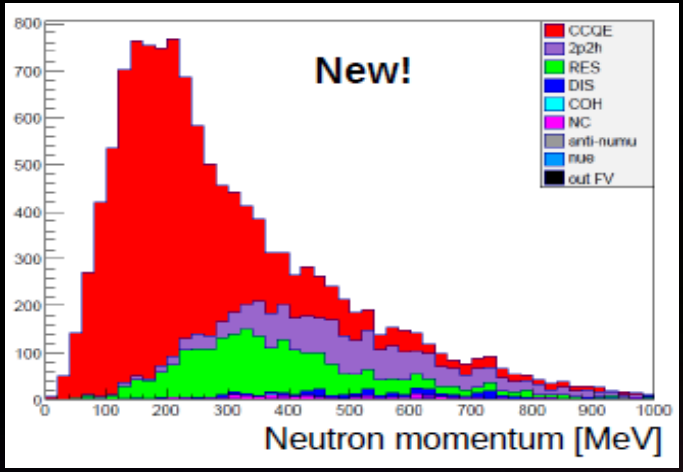
- One Master student from University of Warsaw working with NCBJ on that project. Free space for PhD student.

J. Zalipska

Measurement of 2p2h interactions in Near Detector ν data

Kinematic variables

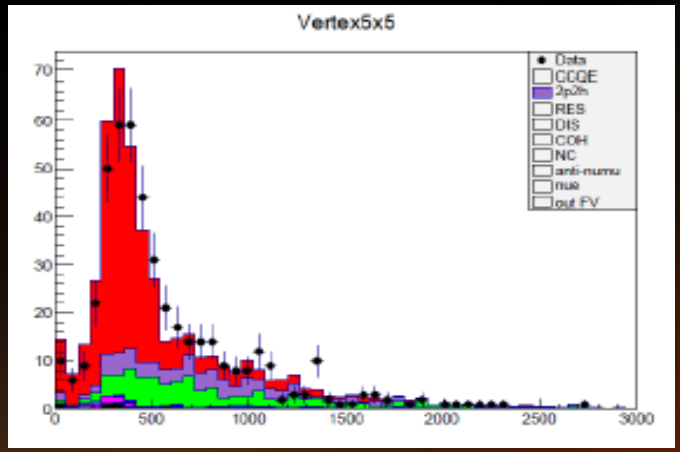
- Select 2p2h signal region using variouse variables such as: $\cos\theta_\mu$-p, transverse variables, p_n



- Determine fraction of 2p2h events in the model in generator of ν interactions comparing against ν data

Energy deposit near the vertex

- Check energy deposited by not reconstructed tracks in areas close to vertex of ν interaction

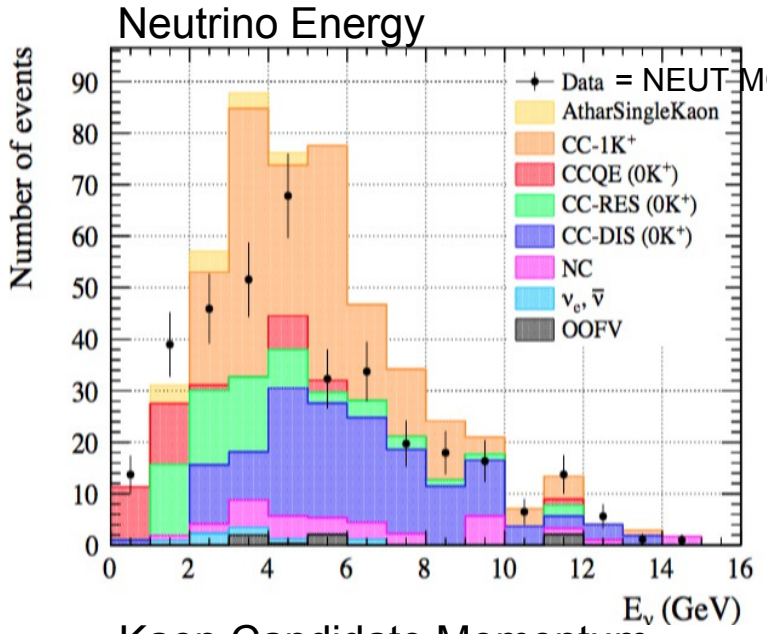


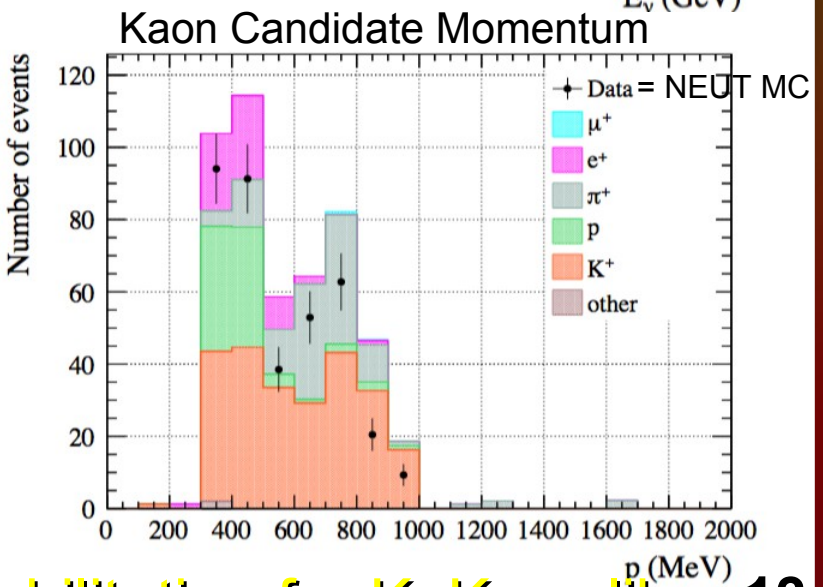
- Check if low mementum protons are modelled correctly by ν event generators such as NuWro or NEUT

K+ Production Cross-Section

K. Kowalik

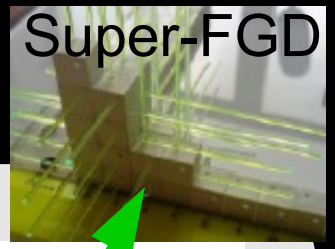
- Strange particles production x-sections are small and not well known in (anti-)ν interactions
- The first measurement in T2K is the inclusive K^+ x-section in n interactions
- Production processes:
  Associated Production $\nu_\mu + n \to \mu^- K^+ \Lambda$
  Single Kaon $\nu_\mu + p \to \mu^- K^+ p$
- Charged K is identified in TPC with PID likelihood cuts (47% pure, 13% efficiency)
- Backgrounds from misid: π^+(25%), p(18%), e^+(10%)
- Analysis in advanced stage, technical note documenting analysis under internal review
- Publication is forseen





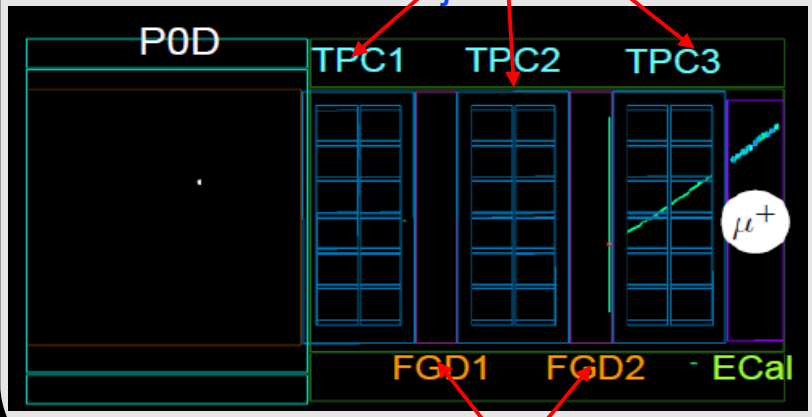
Subject of habilitation for K. Kowalik

Upgrade of the Near Detector



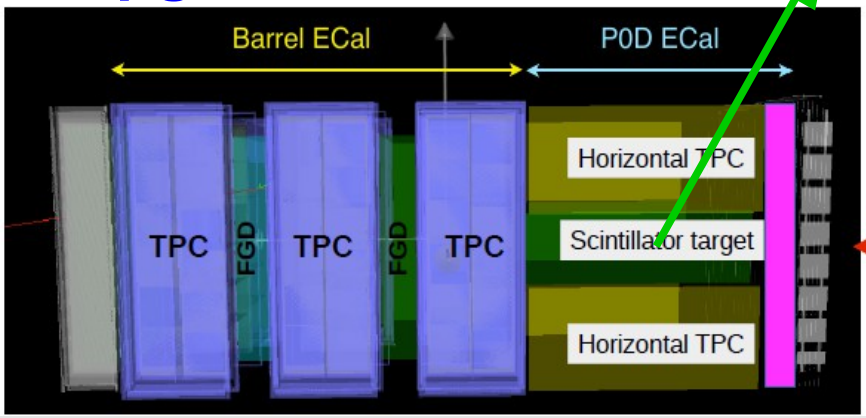
Current Near Detector

Time Projection Chambers



Target:Scintillator detectors

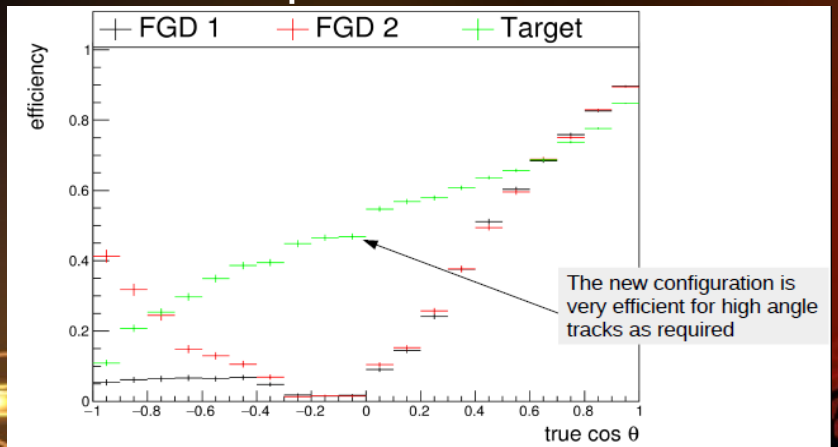
Upgraded ND



New Horizontal TPCs and Scintillator target

- 2017: detector optimization
- 2018: building of the TPC prototype + beam tests we will participate
- 2019-2020: production and integration at CERN, test on cosmic muons
- 2021: transportation and instalation of the detectors in Japan

New configuration efficient for high angle μ tracks. Lower threshold for *protons* and pions.



Future Long Baseline Experiments

Measurement of CP violation, precise determination of θ_{23} and mass hierarchy

Hyper-Kamiokande

- Located in Japan
- Baseline 295km, NBB ~600MeV
- Beam power 1.3MW
- 2x260kT Water Cherenkov det.

- Simulation of neutron background
- Electronics design by Warsaw Inst. Of Technology

DUNE

- Located in USA
- Baseline 1300km, WBB few GeV
- Beam power 1.2MW up to 2.4MW
- 40kT LArTPC

- Development of reconstruction for LArTPC
- Work on proto-DUNE prototype at CERN (R. Sulej, D. Stefan)

Our Activities

- **K. Kowalik**
  - convener of the NuMu analysis group at T2K
  - member of review committee of T2K internal note

- **J. Łagoda**
  - chair of internal review and paper committees (ν_μCC x-sec)
  - member of Executive Committee and Analysis Steering Group
  - convener of the Near Detector
  - co-supervisor of Bachelors Thesis at University of Warsaw
  - reviewer of Bachelors Thesis at University of Warsaw
  - head of Horizon 2020 grant for T2K and HyperK at NCBJ

- **P. Przewłocki**
  - member of paper committee (interactions of CC1π^+ on C)
  - audycja w radiu TokFm

- **E. Rondio**
  - member of Institutional Board in T2K
  - country representative in T2K and HyperK board
  - head of T2K grant (6 Polish institutions) of Ministry of Science and Higher Education

- **J. Zalipska**
  - member of paper committee (x-sec measur. with protons, 2p2h)
  - review of article from Advances in High Energy Physics
  - public lecture during Festival of Science
  - head of OPUS grant at NCBJ for 2p2h search

Summary

- The last year allowed to improve the oscillation results of T2K and obtain better δ constrain
- More data are desired. In 2018 Super-Kamiokande tank will be opened for maintenance. Beam power is also expected to be improved in the future.
- We actively participate in the collaboration work:
  - performing various analysis
  - joining various committees
  - presenting results on conferences
  - Polish group is taking over responsibility on operation of FGD detector
- A new activities start to be more and more important as Upgrade of the Near Detector or Hyper-Kamiokande
- More manpower needed! PhD students and post-docs.

Backup Slides

Our Presentations

- **M. Kabirnezhad**
  - talk about pion production at NuInt conference, Toronto

- **K. Kowalik**
  - talk about T2K flux prediction at NuInt conference, Toronto

- **J. Łagoda**
  - neutrino overview talk at Zjazd Fizyków Polskich
  - neutrino overview talk at Astrofizyka Cząstek w Polsce
  - talk about HyperK at Flavor Physics & CP Violation conference, Prague

- **J. Zalipska**
  - neutrino overview talk at Matter to the Deepest conference, Podlesice

- **G. Żarnecki**
  - poster at Pntecorvo Neutrino School, Prague