Recent neutrino cross-section measurements at T2K

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GDR Neutrino – November 2015 - Saclay

A hot topic...

- **Oscillation measurements in far detector constrained from near detector (xsec x flux)**

  ND→FD extrapolation :
  - different acceptance and target
  - different E_ν spectrum
  - $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu$

  → **rely on models to extrapolate**

Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

T2K Phys. Rev. D 91, 072010 (2015)

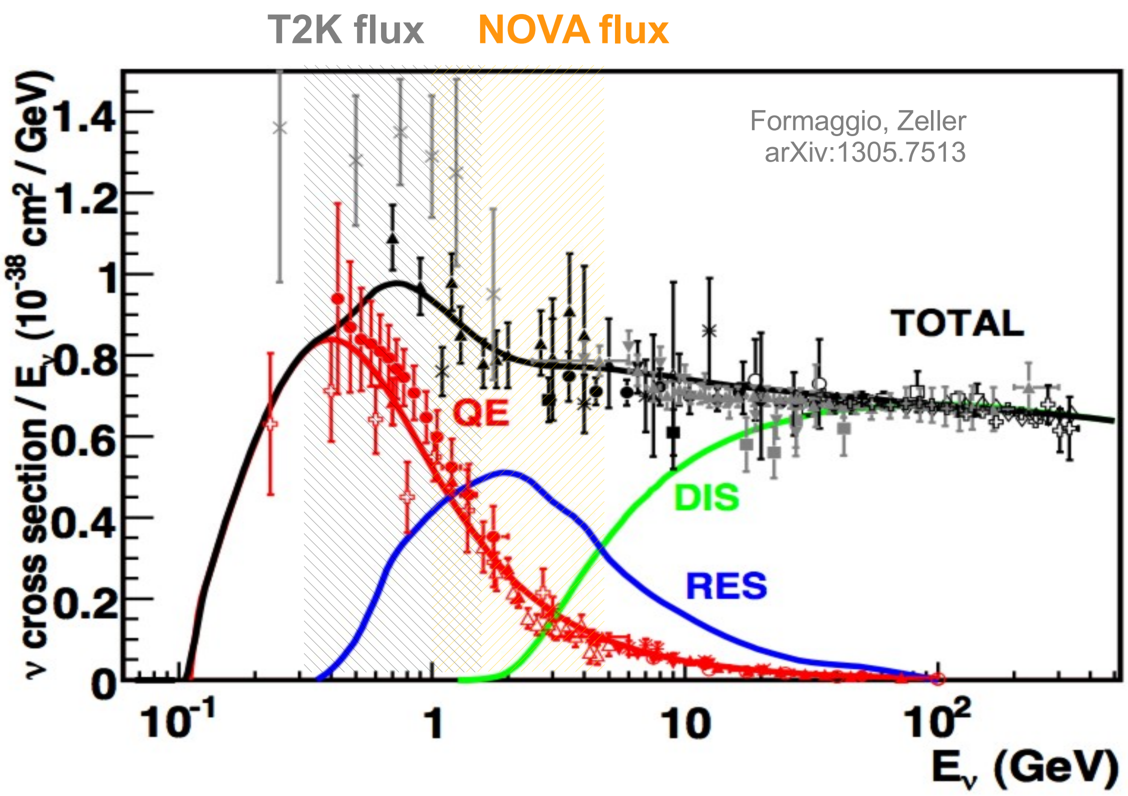
- Measurement of ν xsec at ND is **experimentally complicated:**
  - E_ν not known: xsec measurement always convoluted with flux → importance of minimization of uncertainties in flux modeling (and/or ratio measurements)
  - E_ν inferred from final state leptons/hadrons which have limited angular acceptance, threshold on low energy particles, very small info on recoiling nucleus...

large model uncertainties convoluted with unfolding of detector effects
→ measurements also quoted in limited phase space, x-checks btw different selections

large model uncertainties on background
→ control regions and sidebands to constrain background from data

Outline

- Neutrino xsec as a nuclear physics problem



- **CC0π dominant at T2K**

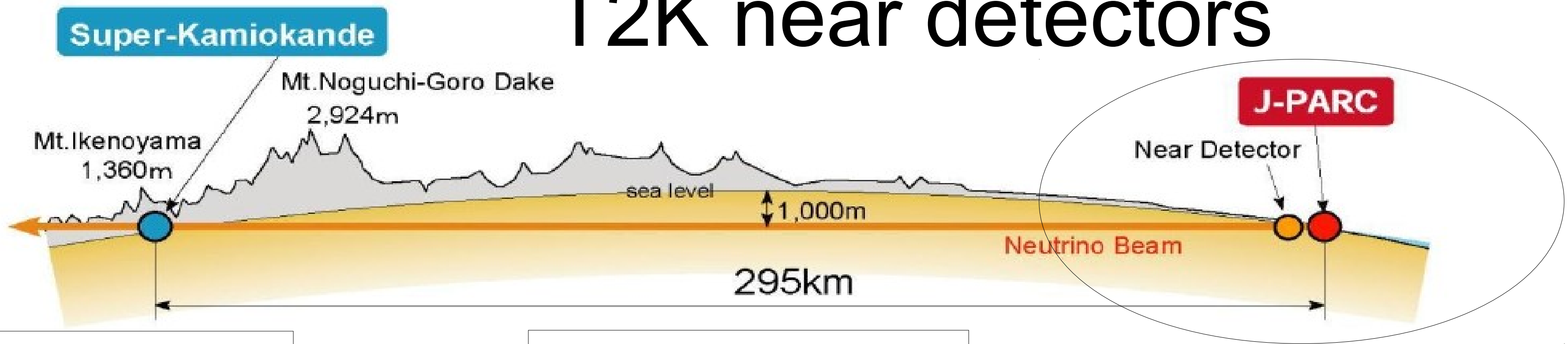
  → from the detector measurement (muon+proton) to the incoming neutrino energy

- **CC1π (+ DIS) dominant at NOVA**

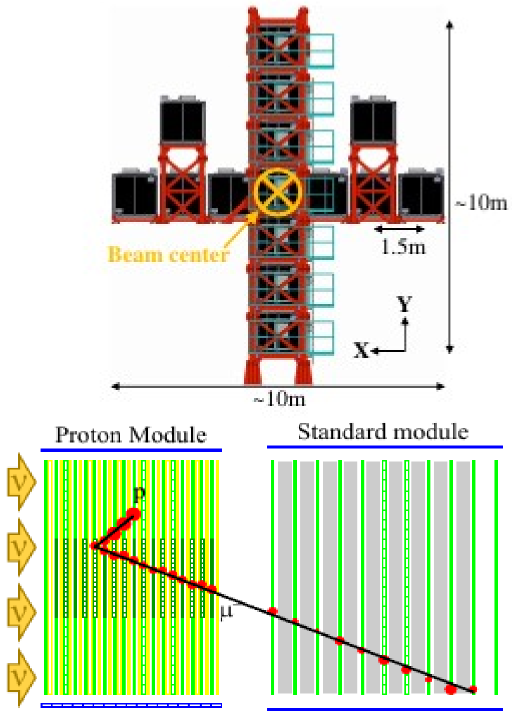
  → how to disentangle Final State Interaction effects

- Impact on present and future oscillation measurements (δ_{CP}) : $\nu_\mu \longrightarrow \nu_e, \bar{\nu}_{\mu/e}$

T2K near detectors

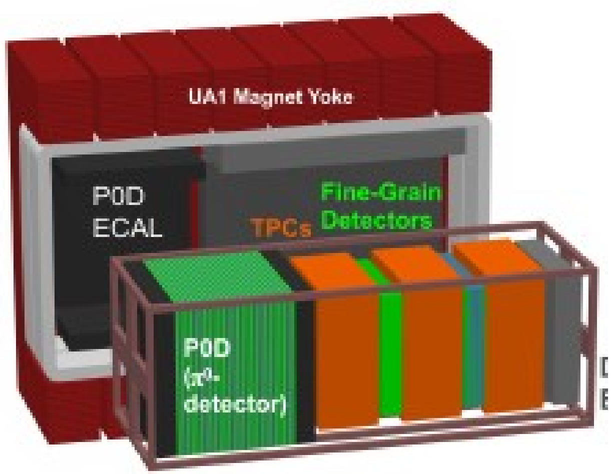


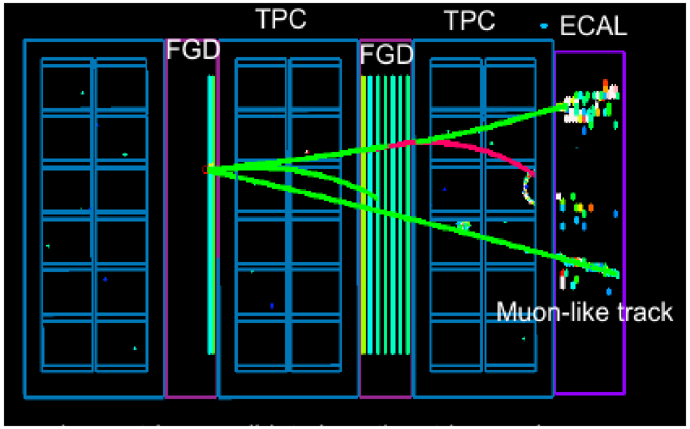
INGRID : on-axis



- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass**

ND280 : off-axis (2.5°)





- fully magnetized (0.2 T)
- FGD: CH scintillators alternated with H2O
- TPC → **good tracking efficiency, resolution** (6% p_T<1GeV) **and particle ID**
- P0D scintillator with water target

Nuclear physics is the name of the game

- **CCQE model tuned from bubble chambers νH data: M_A^{QE}~1GeV**
  → modern experiments (K2K) include nuclear effects on heavy target (C,O): Fermi Gas

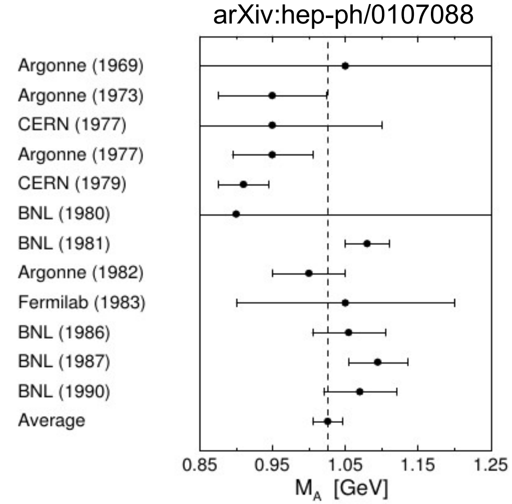
- **MiniBoone measurement shows large discrepancy wrt to this model** (large M_A^{QE})
  → explication from theoretical models including :
  - long range **correlation between nucleons** (aka RPA)
  - possibility of **interactions with NN pairs** (aka 2p2h and MEC effects)

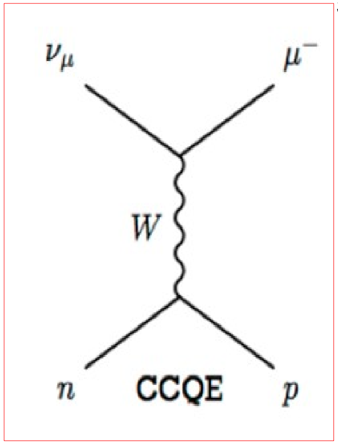
ν_μ n p → μ^- p p
$\bar{\nu}_\mu$ n p → μ^+ n n

(well known in ep scattering but not definitive model)

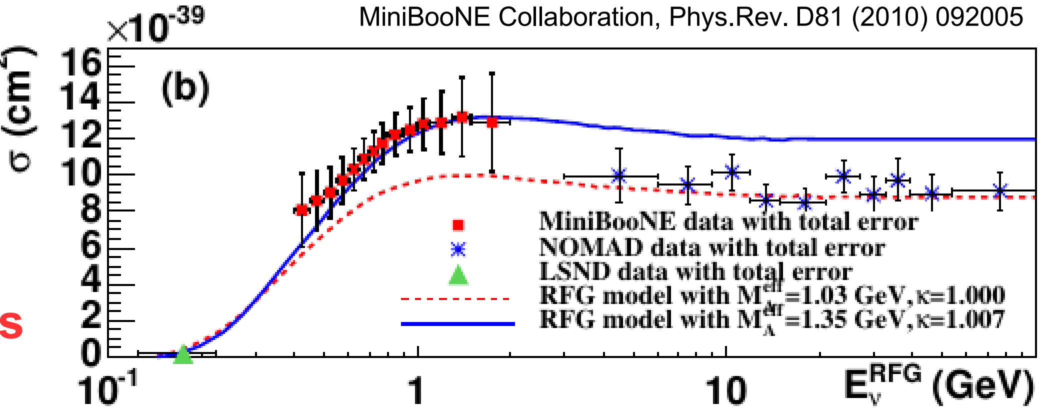
- **Final State Interaction only included in MC models**: CC1π with pion re-absorption included in signal (CC0π)

arXiv:hep-ph/0107088

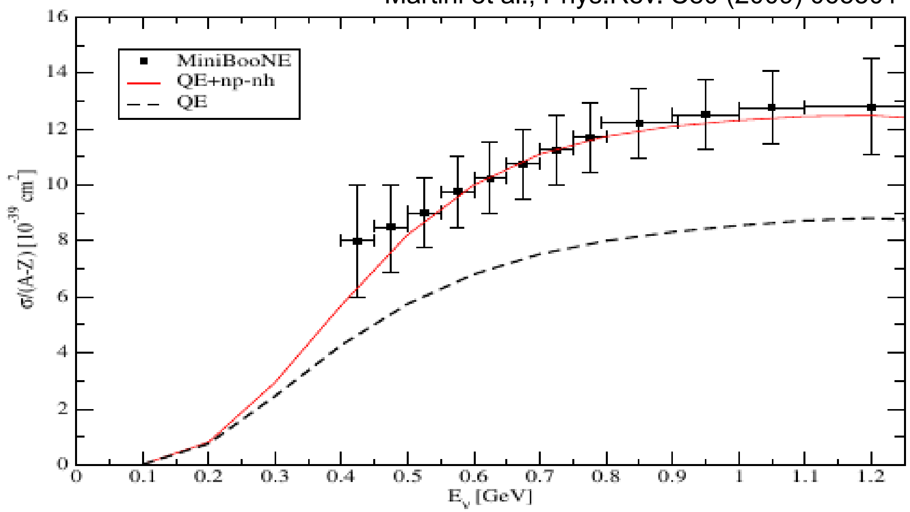




MiniBooNE Collaboration, Phys.Rev. D81 (2010) 092005



Martini et al., Phys.Rev. C80 (2009) 065501

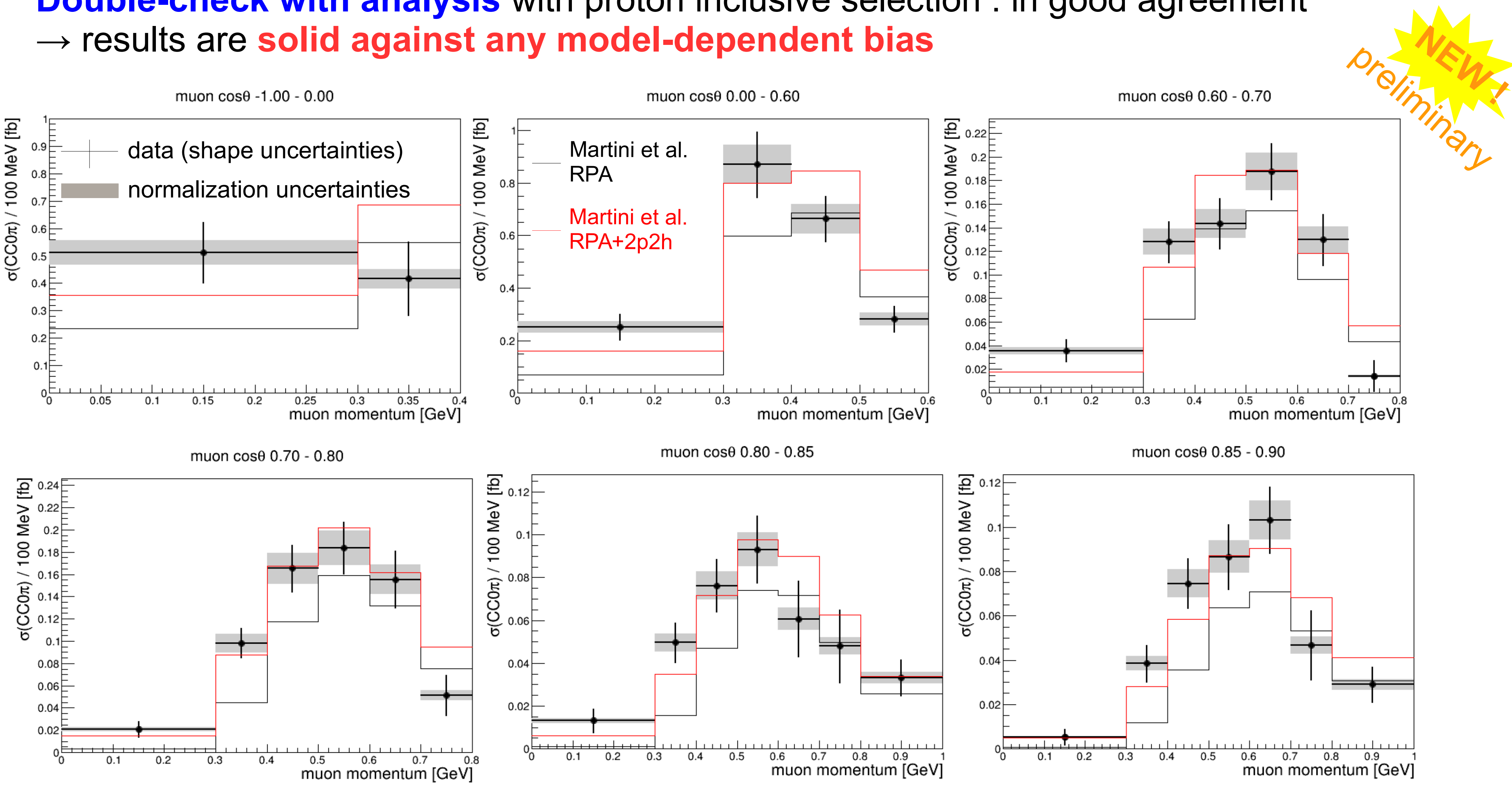


CC0π: T2K new result

New analysis : **mu, mu+p** → increased acceptance at high angle
background from control regions
differential in muon kinematics

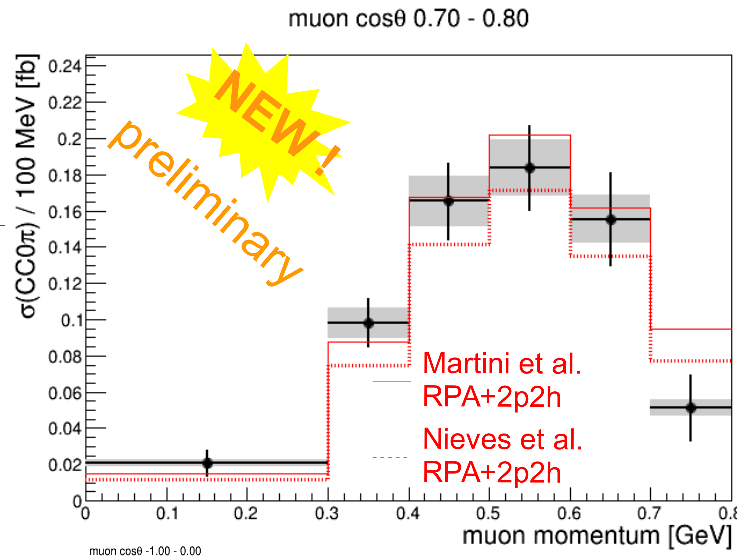
minimize model-dependence

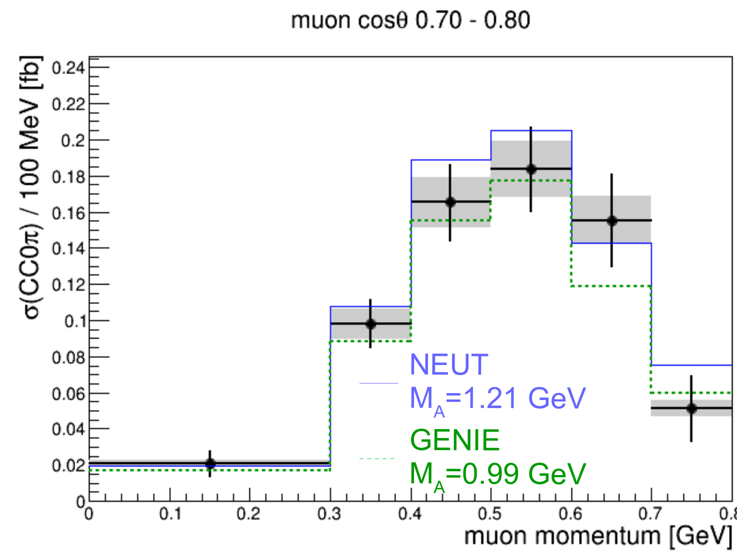
Double-check with analysis with proton inclusive selection : in good agreement
→ results are **solid against any model-dependent bias**



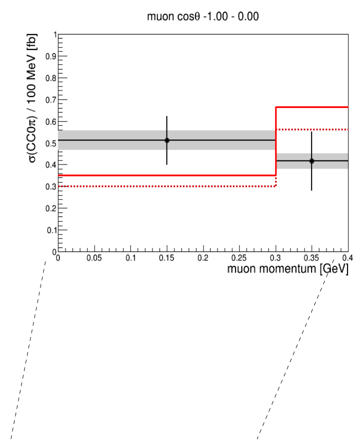
Work ongoing ...

- Degeneracies between models and between parameters inside each model

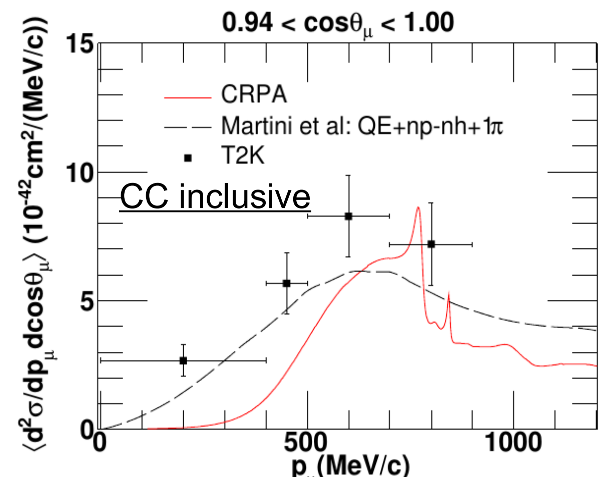




- Difficult to cover full phase space



low efficiency for backward muons: large systematics and low statistics



large theoretical uncertainties for very forward muons (small $|Q^2|$)

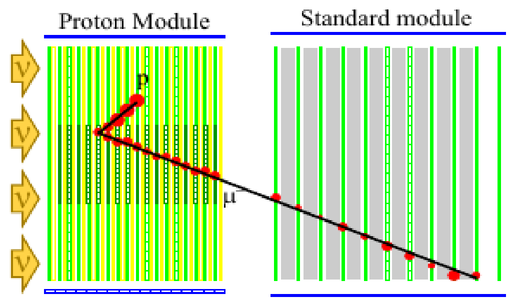
- Difficult to make quantitative statement about “preferred” model → difficult to interpret statistically the model uncertainties for oscillation analysis

→ The only way out: **increase/improve the experimental data**

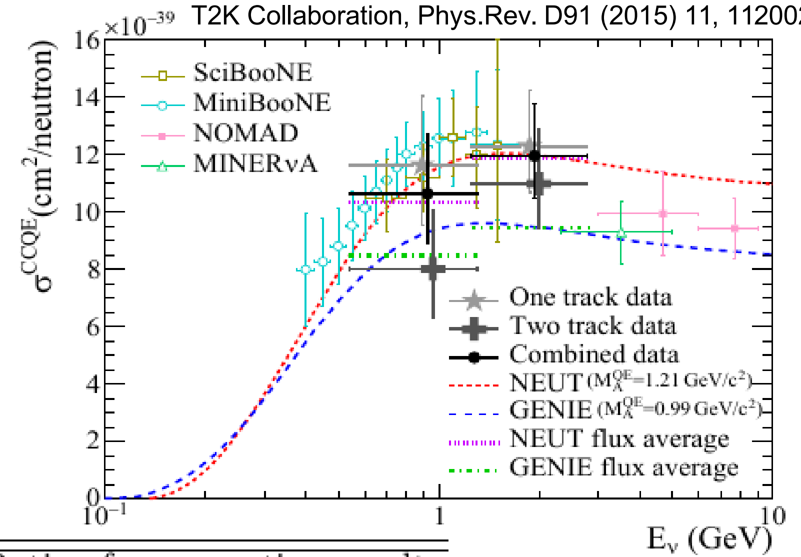
CC0π: proton kinematics

- **T2K on-axis INGRID**: limited acceptance and strong kinematics cuts (against FSI, and 2p2h)

large model dependence : discrepancy btw mu only and mu+p samples



T2K Collaboration, Phys.Rev. D91 (2015) 11, 112002

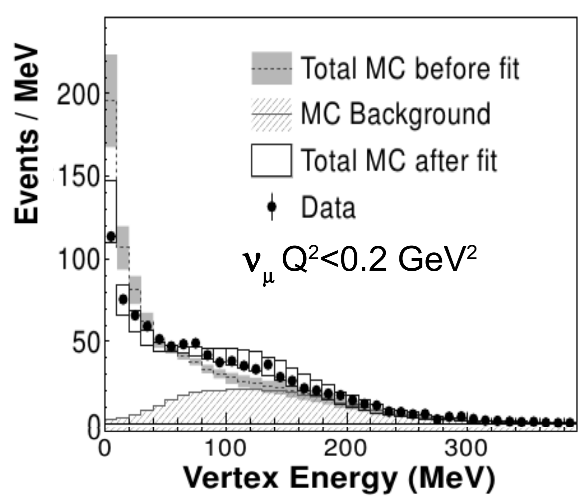


Nuclear model in MC	Ratio of cross-section results
Relativistic Fermi gas model	$1.45 \pm 0.09(stat.)^{+0.24}_{-0.29}(syst.)$
Spectral function	$1.25 \pm 0.08(stat.)^{+0.22}_{-0.26}(syst.)$

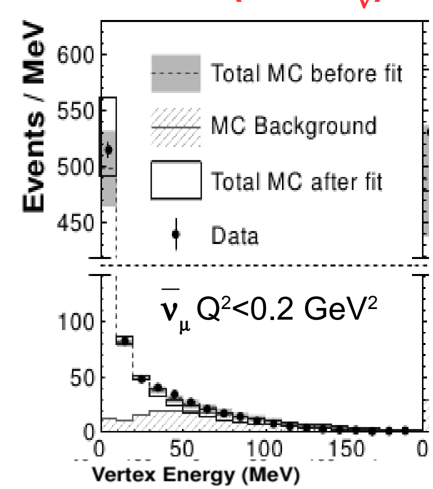
- **Models do not describe well the proton kinematics → analyses should have largest possible acceptance and avoid to unfold on model dependent variables (Q^2, E_ν)**

  - More inclusive proton-related variable: **vertex activity**
    → difficult to compare with models (need folding of detector effects)

  - Model-independent full **4D** analysis: ongoing at T2K by LPNHE-CEA



excess: ν_μ n p → μ^- p p



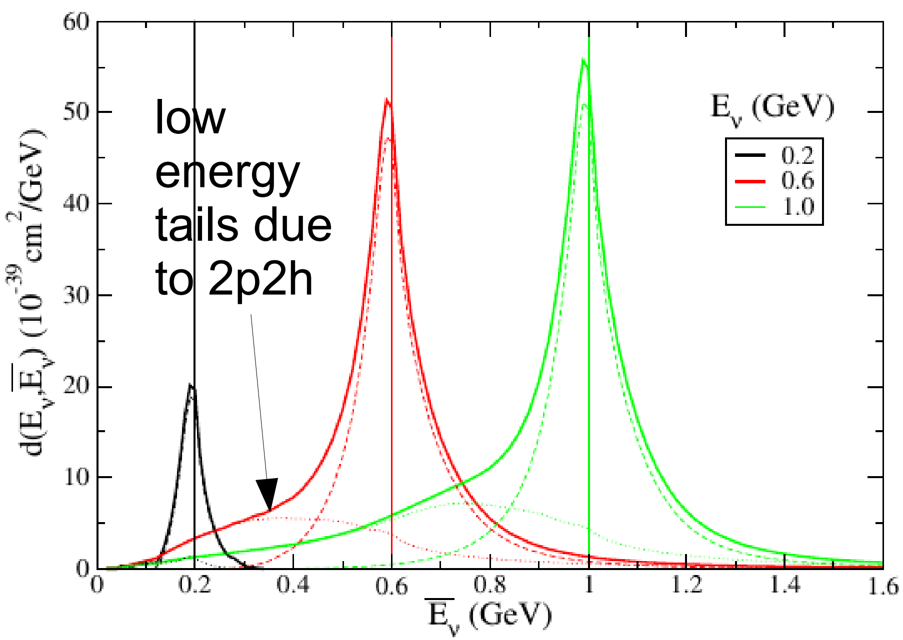
no excess: $\bar{\nu}_\mu$ n p → μ^+ n n

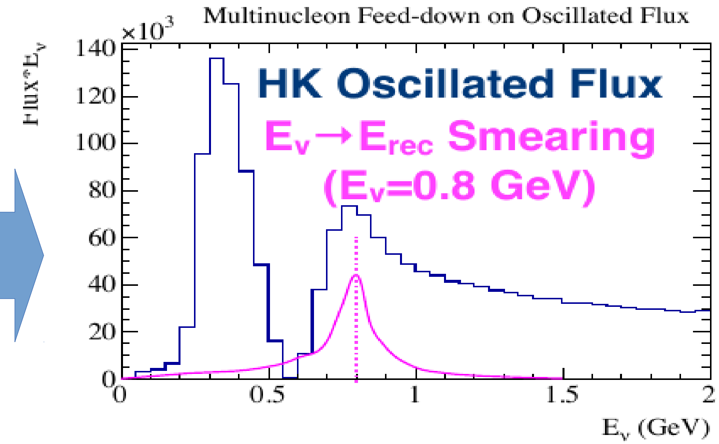
Minerva Collaboration, Phys.Rev.Lett. 111 (2013) 022502, Phys.Rev.Lett. 111 (2013) 2, 022501

Why is that a problem?

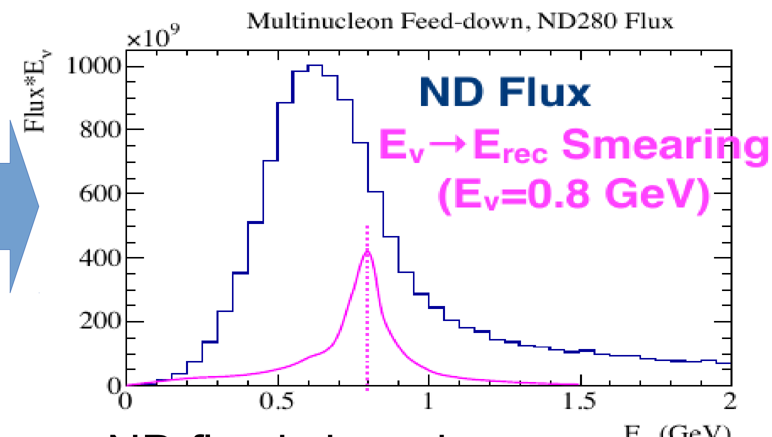
Why we need to know the CC0π xsec is such details (not just norm but shape) to perform the ND → FD extrapolation? ND and FD have different E_ν spectra

- We do not measure E_ν ! We measure the outgoing muon (and possibly the proton) and we infer the neutrino energy on the base of available models





2p2h events fill the "dip" region sensitive to $\sin\theta_{13}$ → **wrong modelling would cause bias on oscillation parameters**

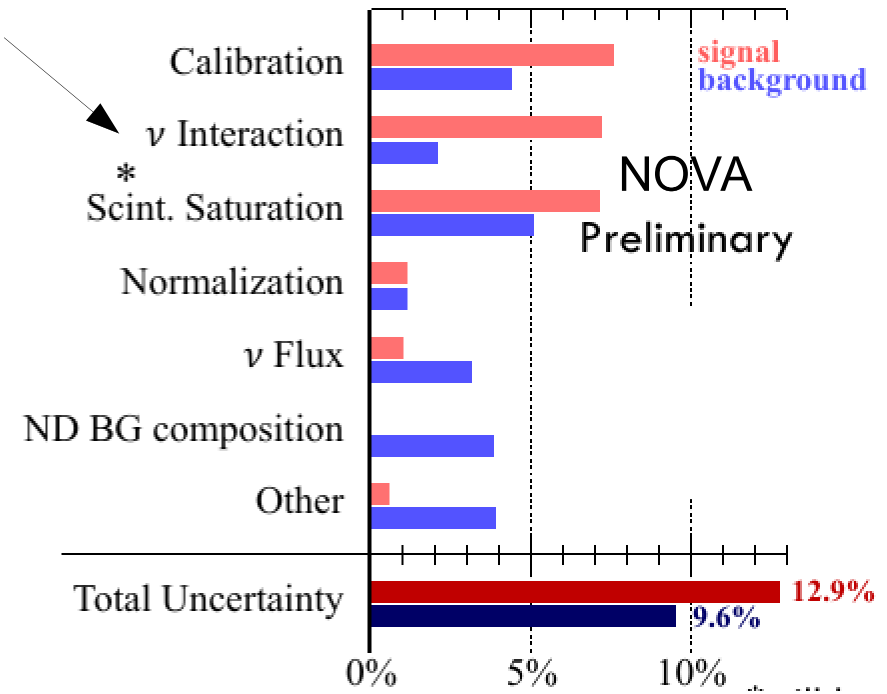


ND flux is broad: difficult to constrain E_ν smearing effects

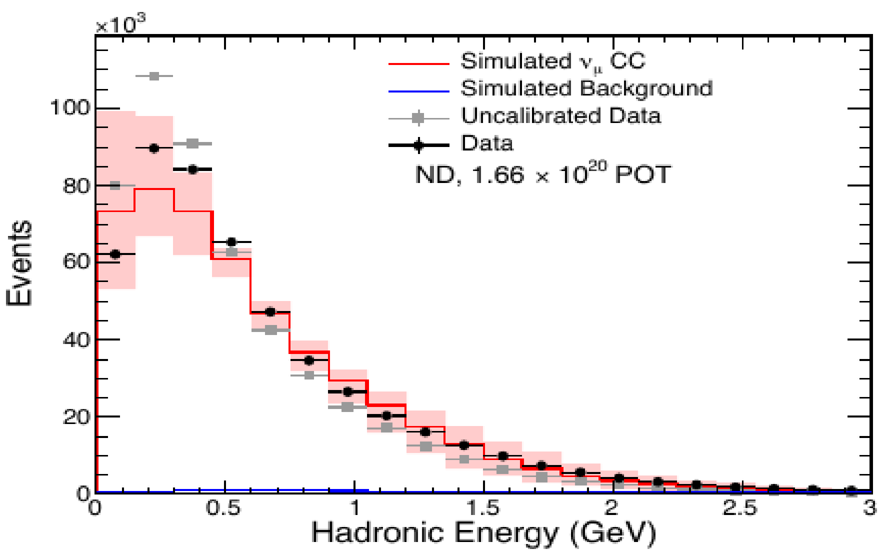
Effect on DUNE?
Relying on Eν shape more heavily than SK or HK (use 1st and 2nd oscillation maxima)
Better E_ν reco from calorimetry?

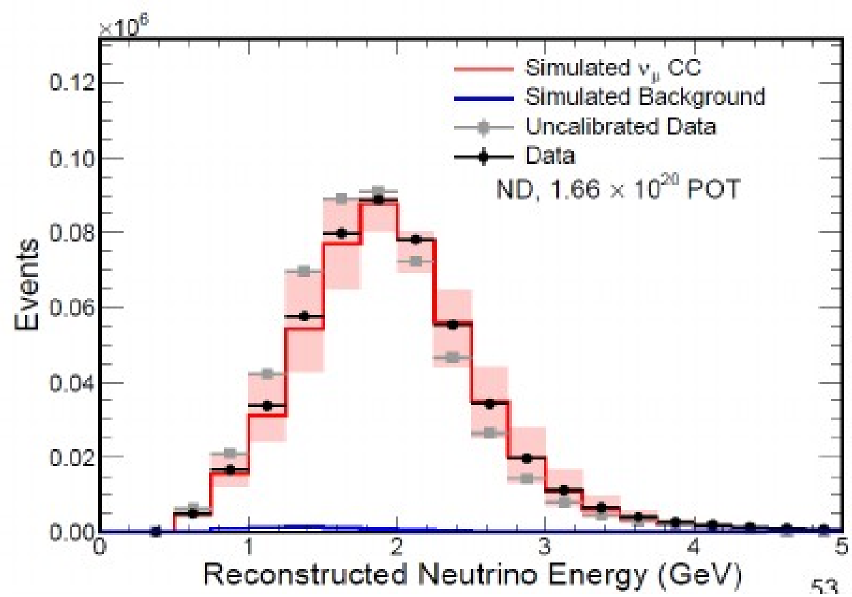
Possible shortcuts (1)

We know better the flux than the cross-section
(and we know how to improve further the flux uncertainty)



- NOVA uses the flux peak position to correct for hadronic energy bias in data-MC
  - actually part (most?) of the data-MC discrepancy may be due to ν interaction models
  - taste of the future (DUNE): calorimetry calibration precision tightly convoluted with shape effects in interaction models





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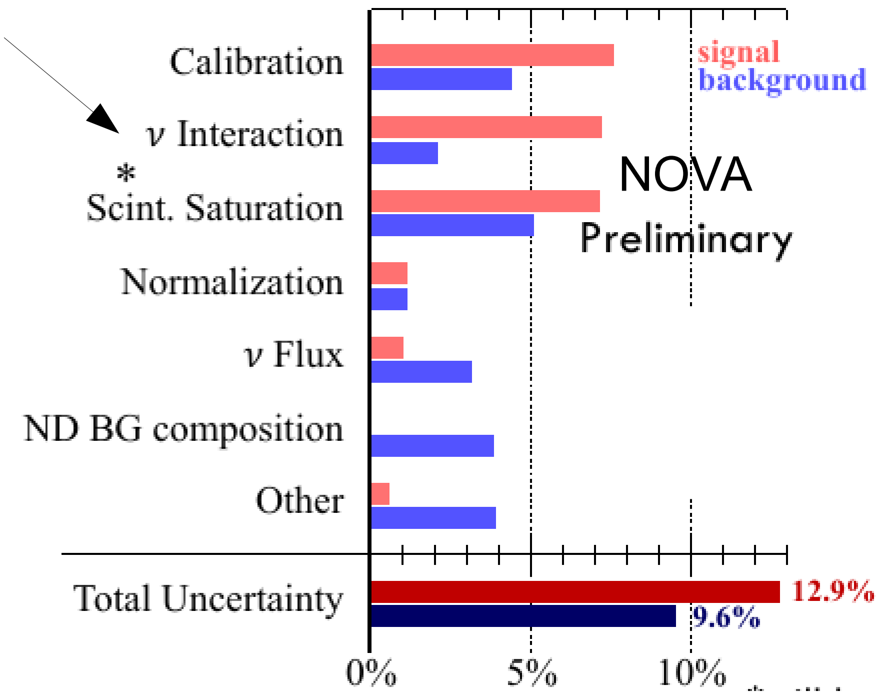

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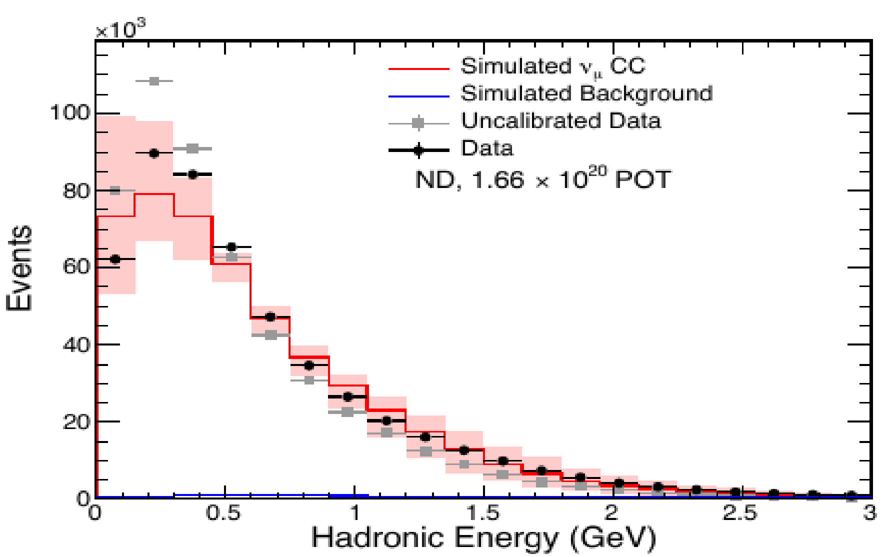
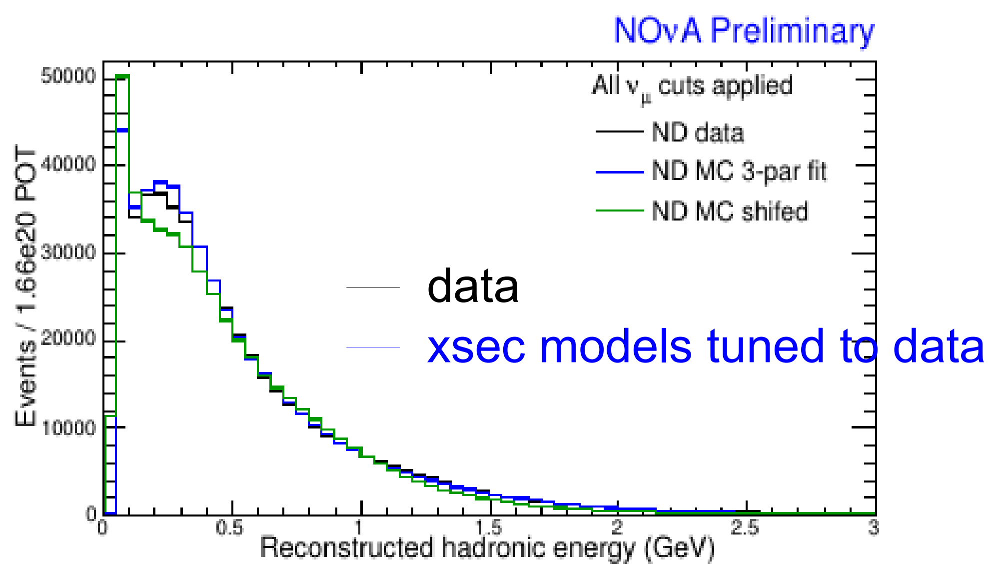
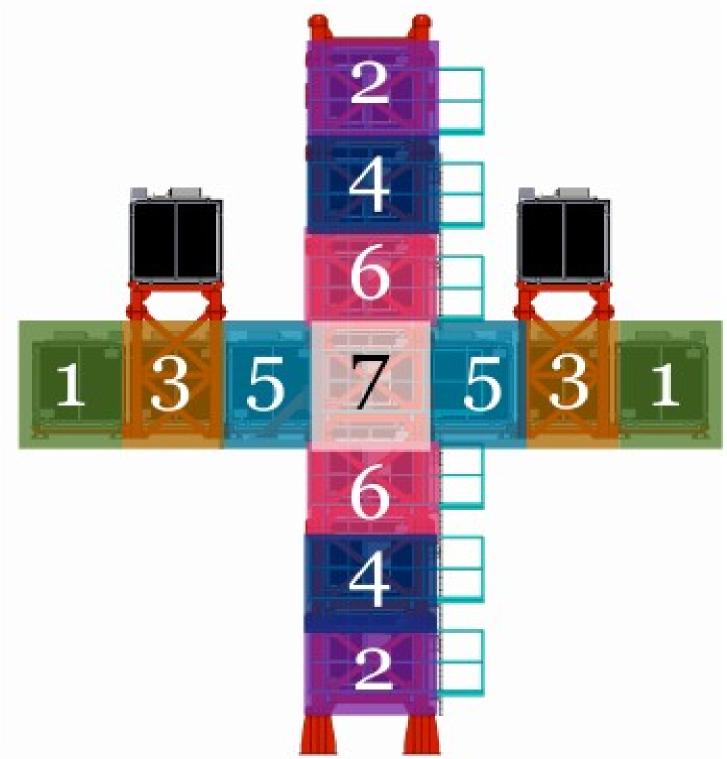


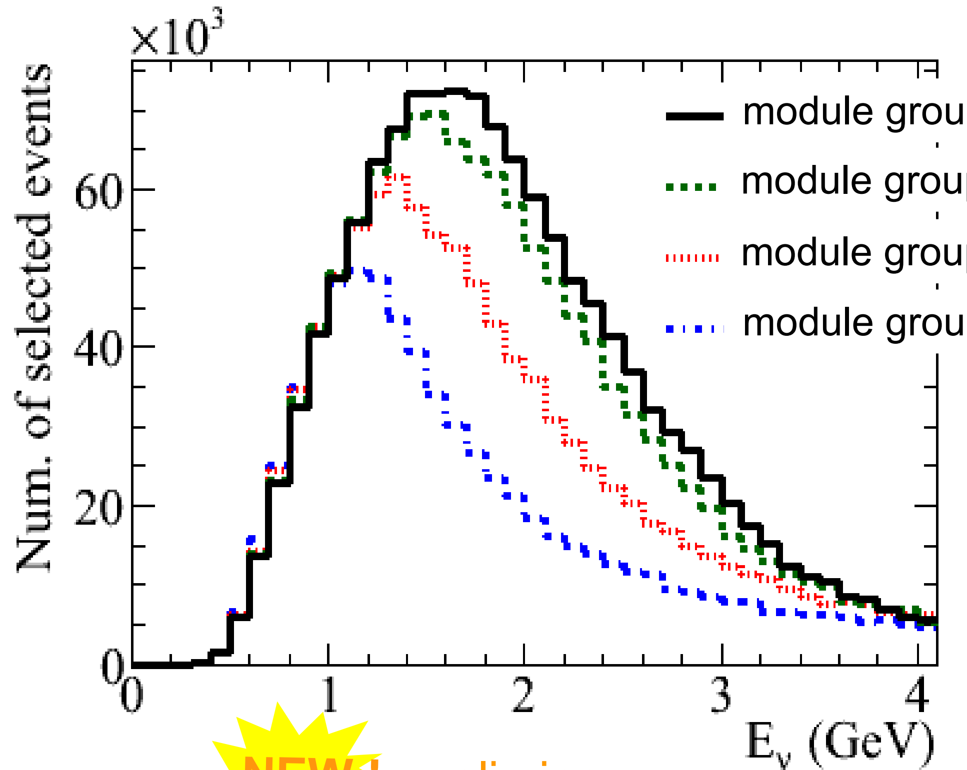


Possible shortcuts (2)

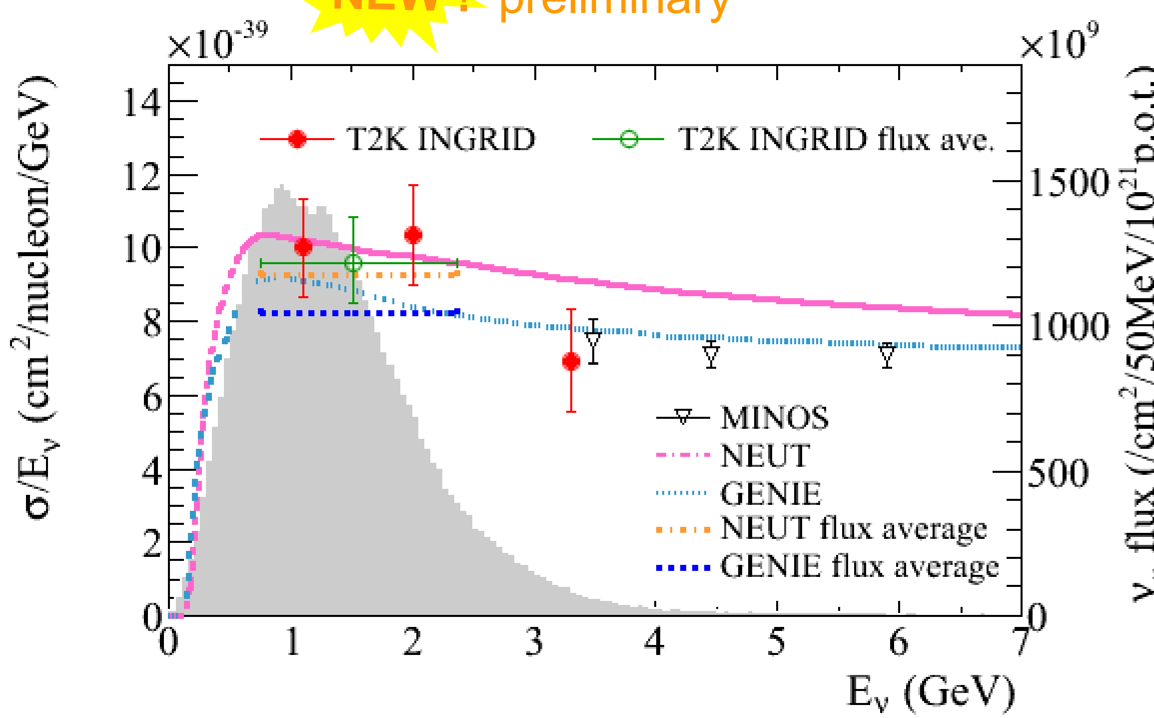
Flux at different off-axis angle = different E_ν spectra → direct measurement of σ vs E_ν
(NuPRISM concept)

T2K INGRID: CC inclusive

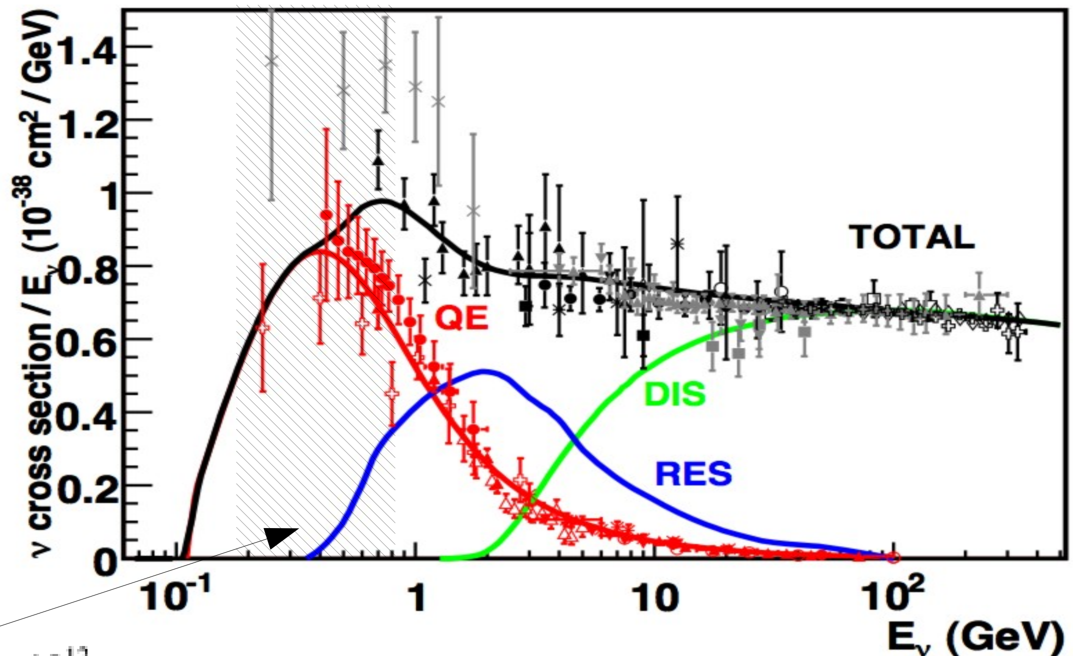


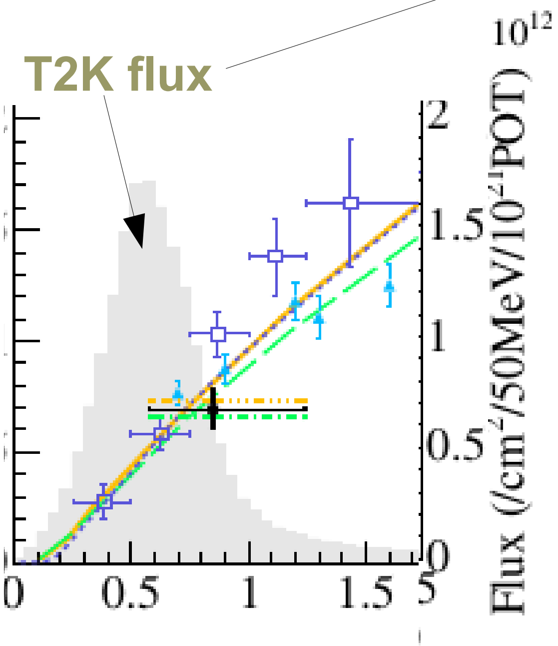


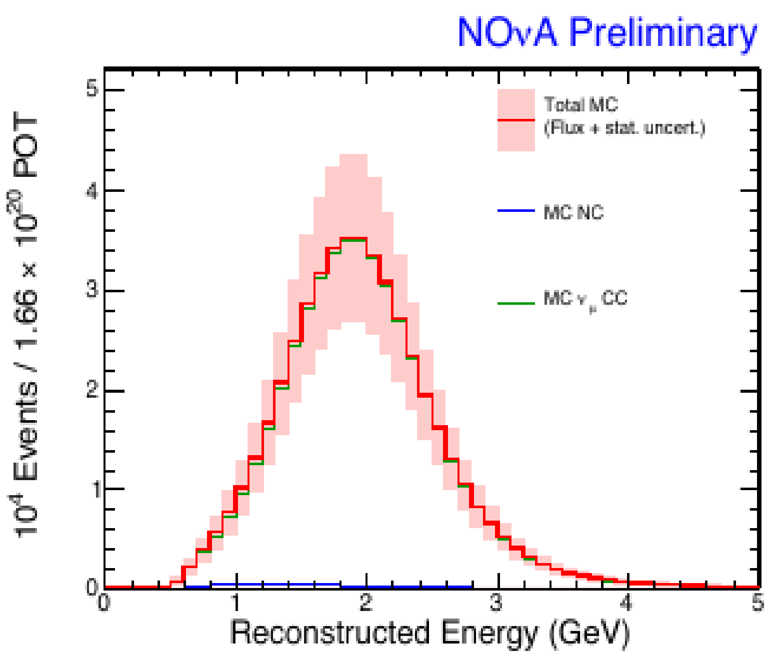
NEW ! preliminary

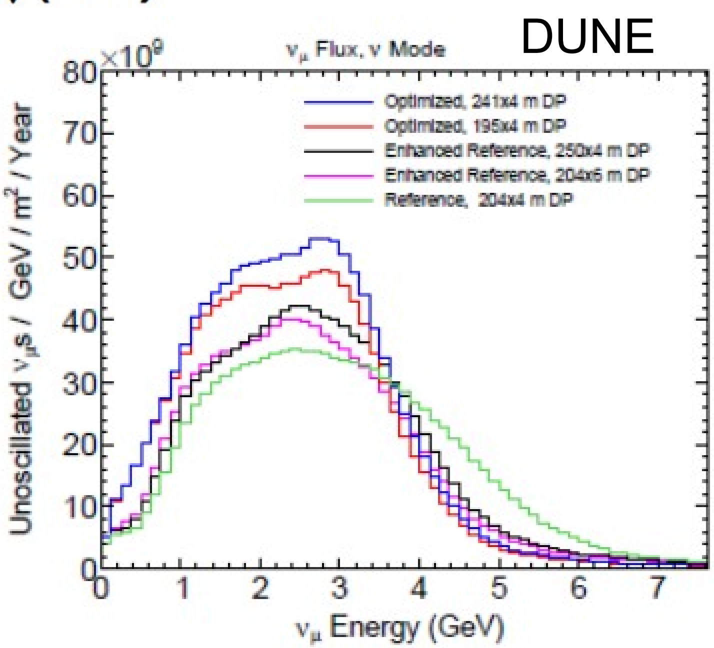


Moving to larger energies ...









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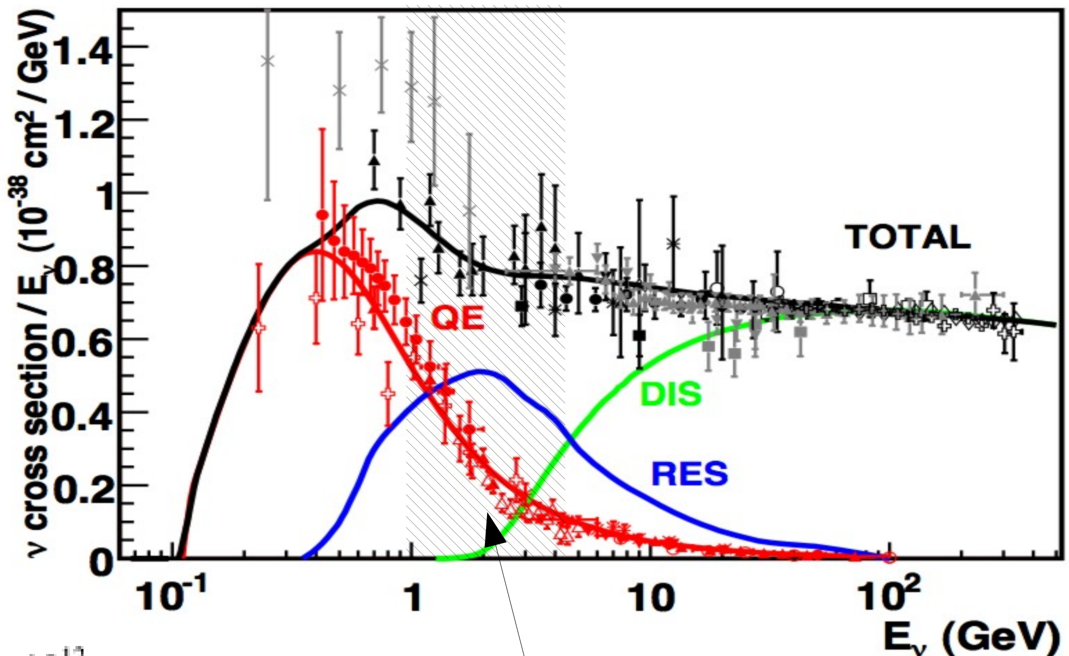

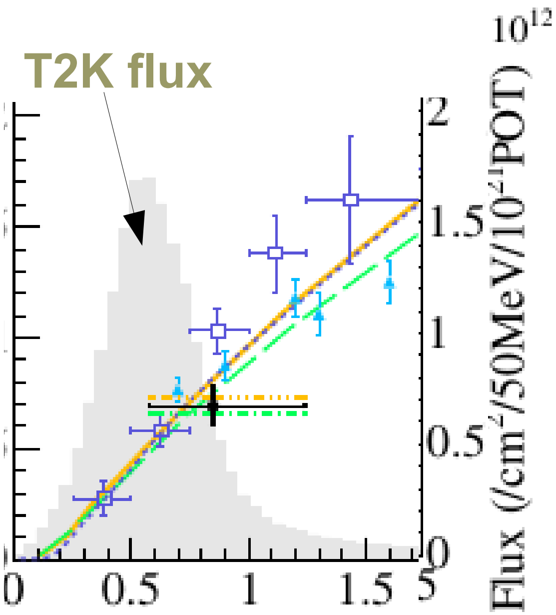

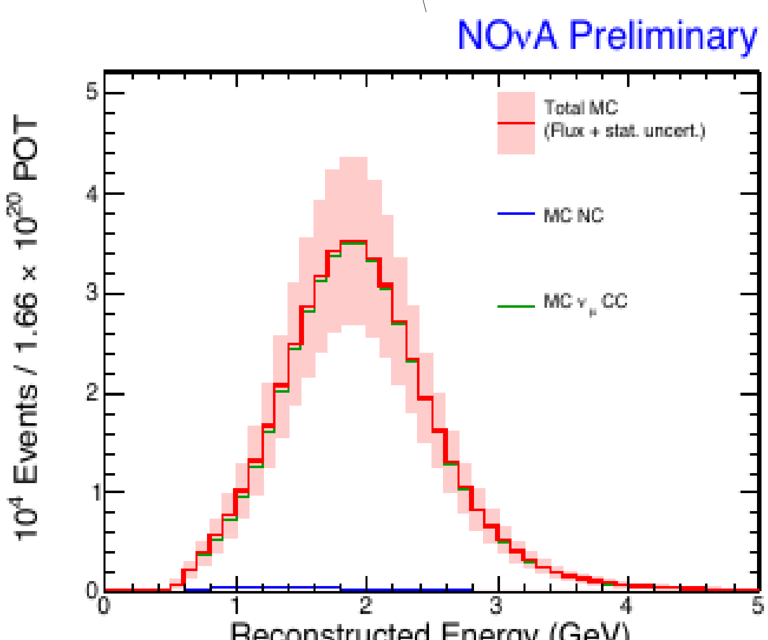

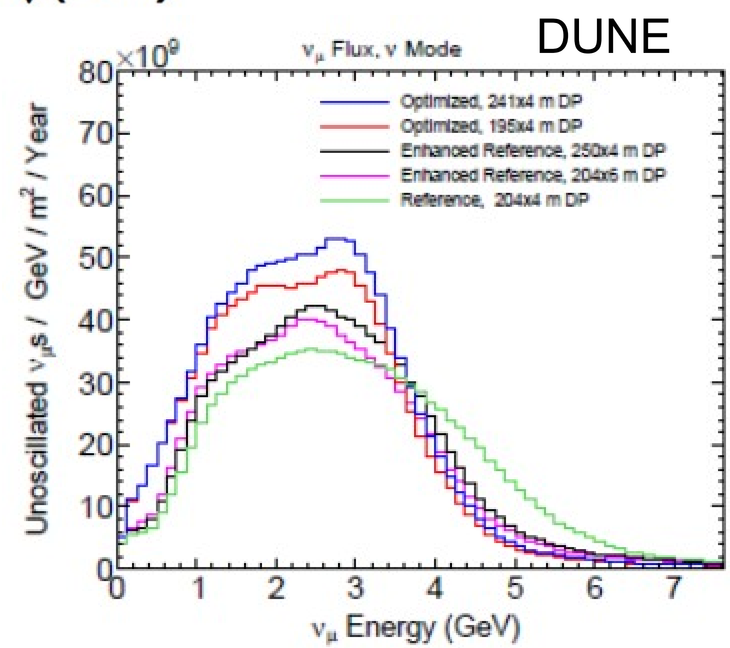

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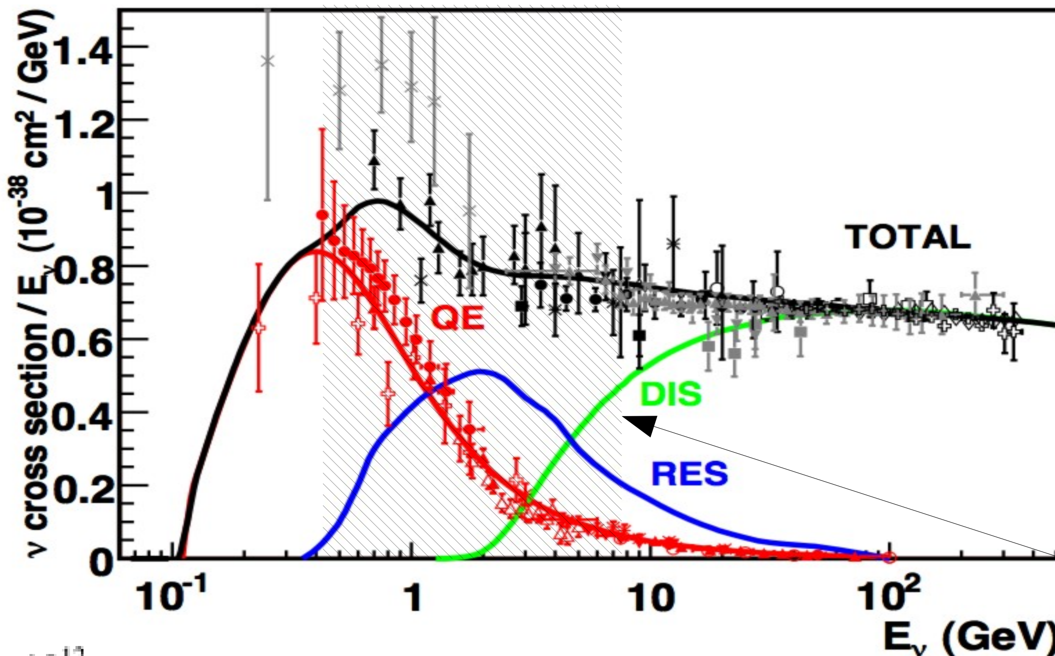
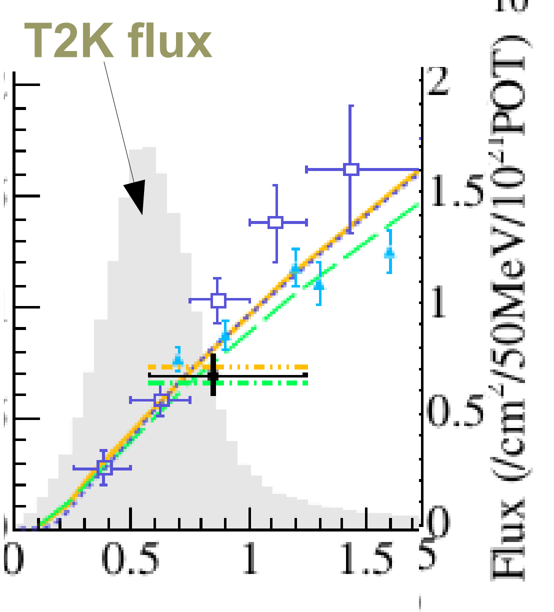
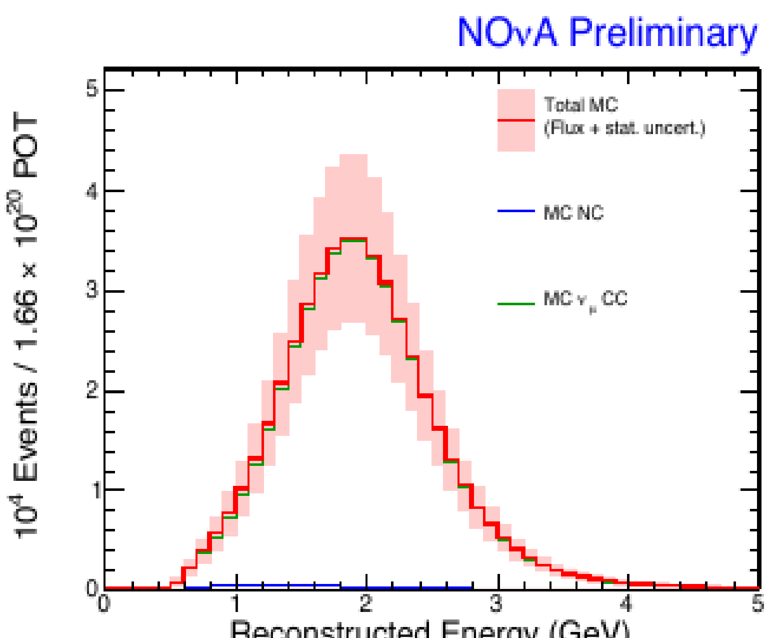
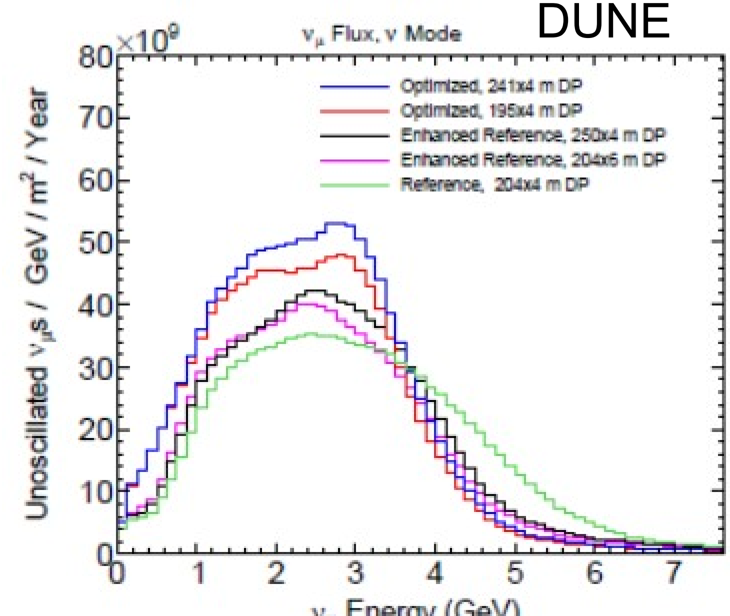


Need to control well all different xsec, each process has very different detector acceptance

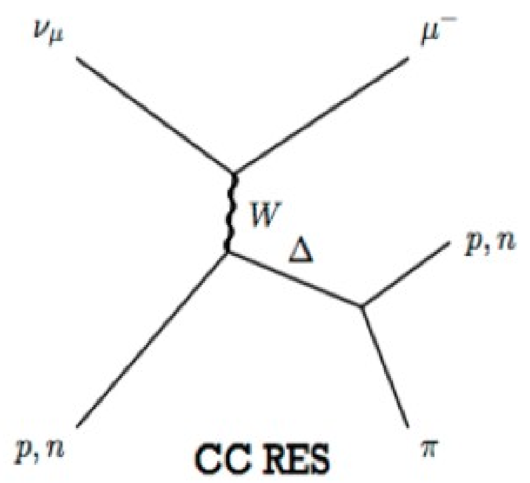
DUNE



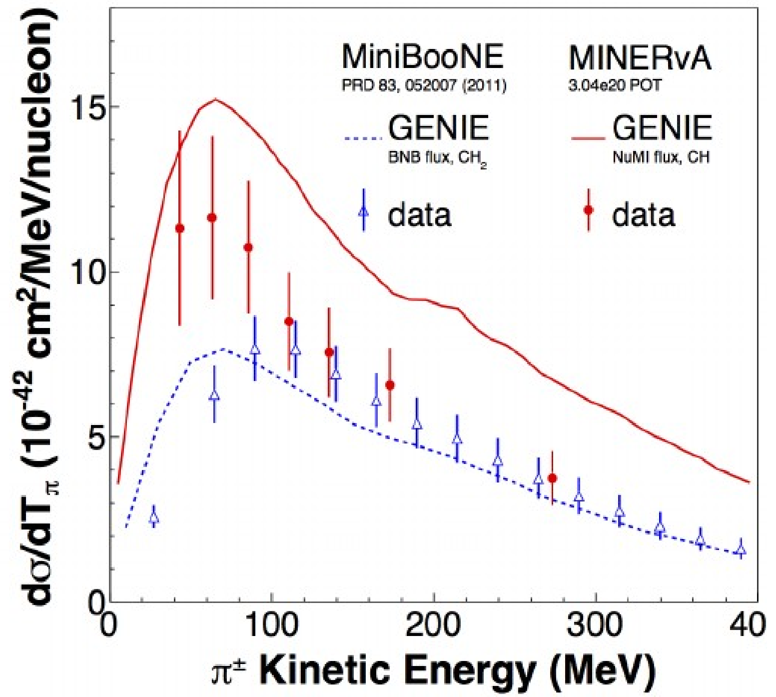




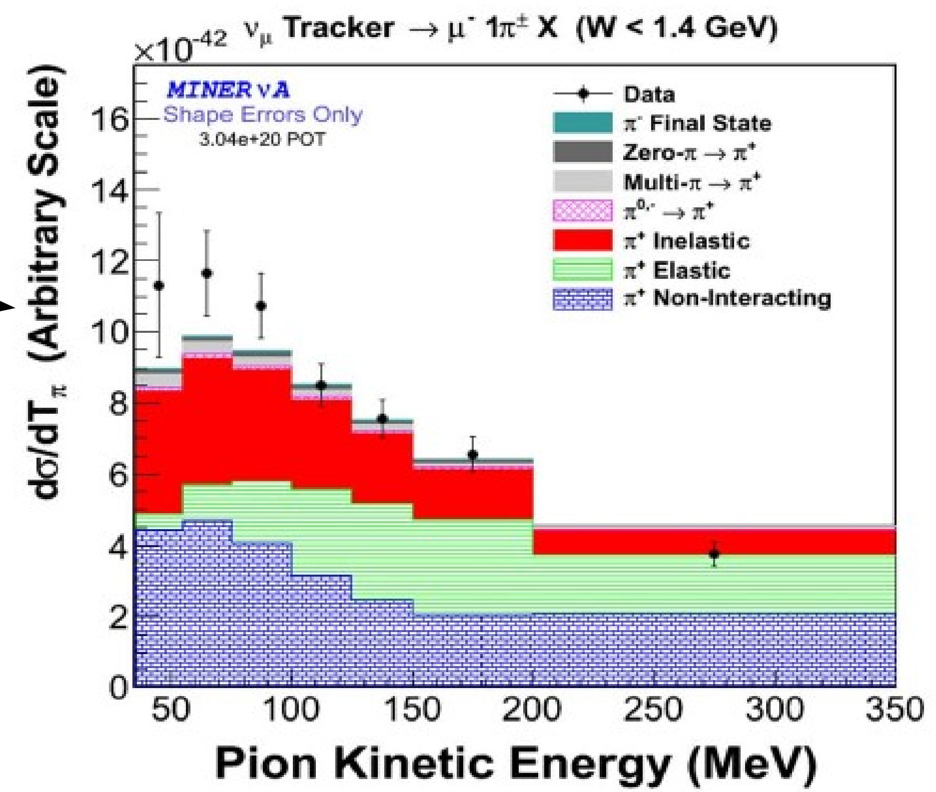
CC1π



MiniBooNE – MINERvA discrepancy?



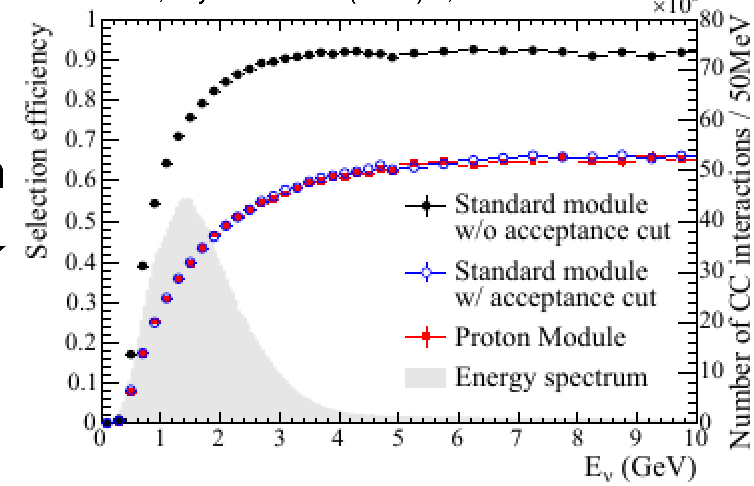
Large effects from Final State Interaction:
re-scattering of the π inside the nucleus
(nuclear physics again!)



Cross-section and FSI have different A-dependence → important effect when extrapolation **from ND and FD with different material**

Measuring A-scaling

T2K,Phys.Rev. D90 (2014) 5, 052010

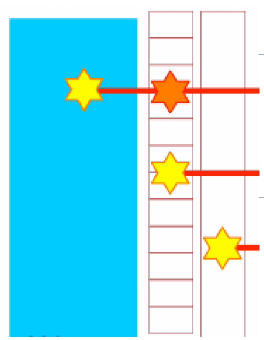


- **T2K INGRID CC inclusive**: standard modules(Fe) / proton module(CH)
  → impose same acceptance to cancel systematics on xsec modelling and flux

$$\frac{\sigma^{Fe}_{CC}}{\sigma^{CH}_{CC}} = 1.047 \pm 0.007(stat.) \pm 0.035(syst.),$$

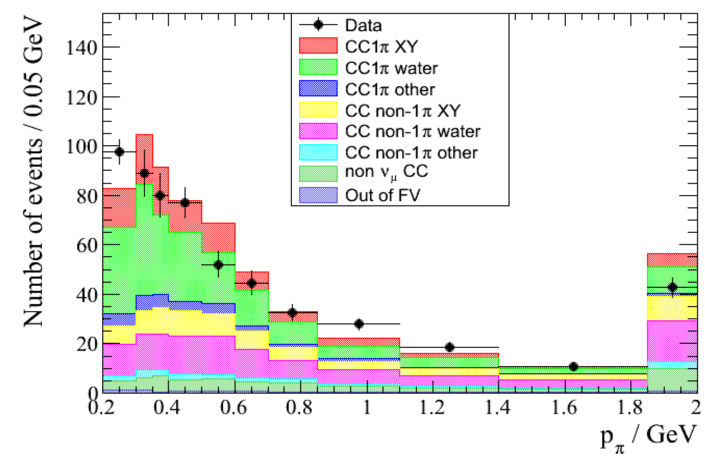
NEUT 1.037,
GENIE 1.044

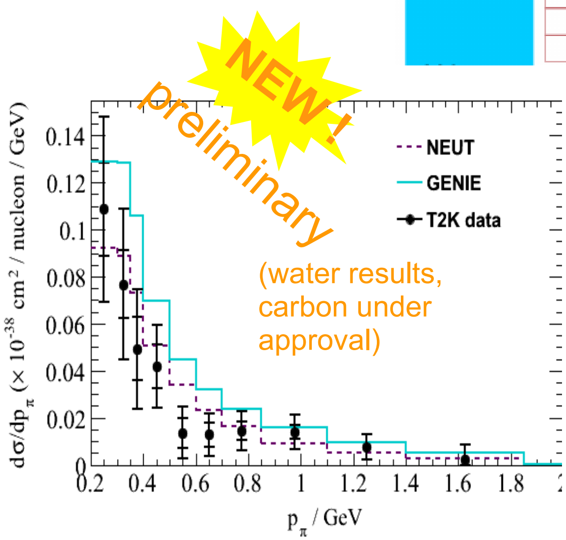
- **T2K FGD2 CC1pi**: water and carbon
  - passive water interleaved with CH scintillator modules

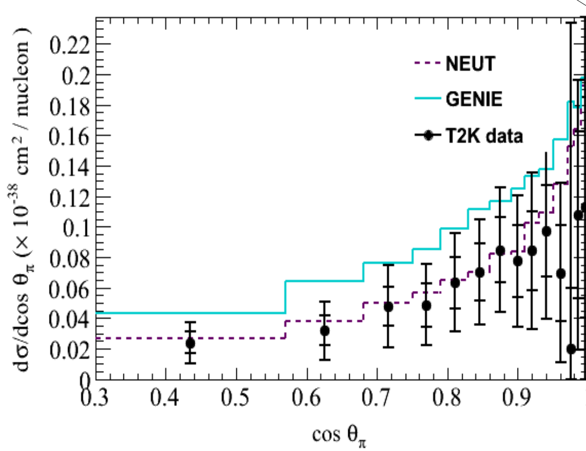


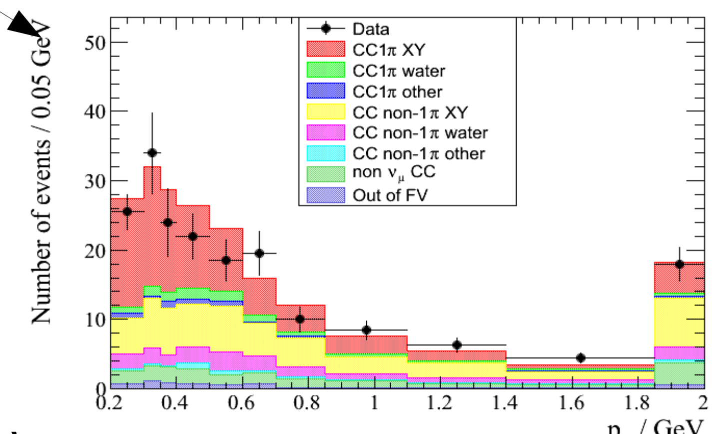
upstream modules $CH+H_2O$

downstream modules CH only









- **T2K CC0pi on Carbon and Water on-going (LLR-CEA)**

Future experiments: ν_e and $\bar{\nu}$ xsec

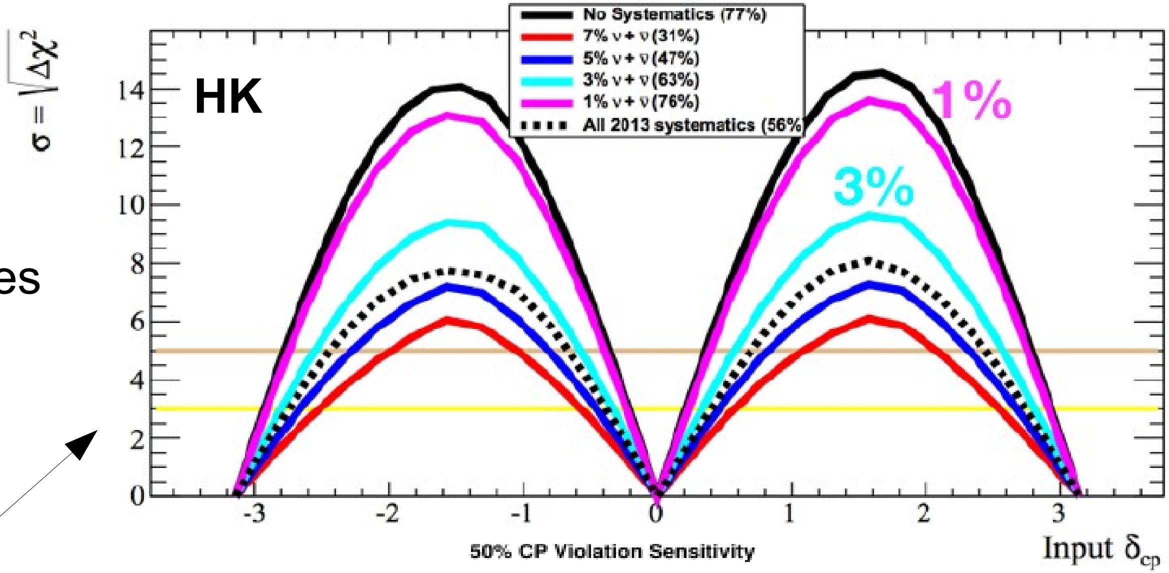
- We are interested to ν_e **appeareance and δ_{CP} from $\nu - \bar{\nu}$ comparison** but in ND we mostly measure ν_μ cross-sections.

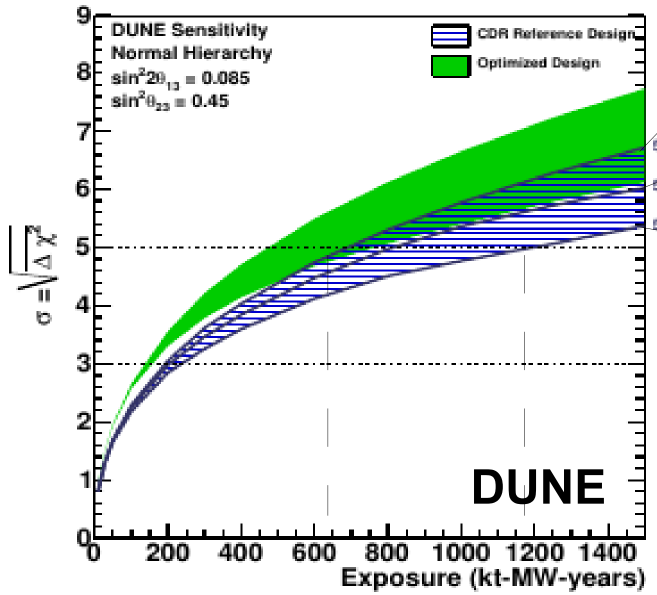
T2K:

ν_μ sample	ν_e sample	$\bar{\nu}_\mu$ sample	$\bar{\nu}_e$ sample
7.7%	6.8%	11.6%	11.0%

- In future (HK, DUNE) large samples of 4 ν species → the uncorrelated uncertainties are relevant
  - **HK** needed uncertainty to have negligible impact on dCP: **ν_e-$\bar{\nu}_e$ uncorrelated 1-2%**
  - For **DUNE** assumed: **uncorrelated ν_μ - $\bar{\nu}_\mu$ 5%** and **ν_e - $\bar{\nu}_e$ 2%**

(shape of ν_μ itself may be more important for DUNE: shape analysis and spanning over different xsec)





5% ± 1%

5% ± 2%

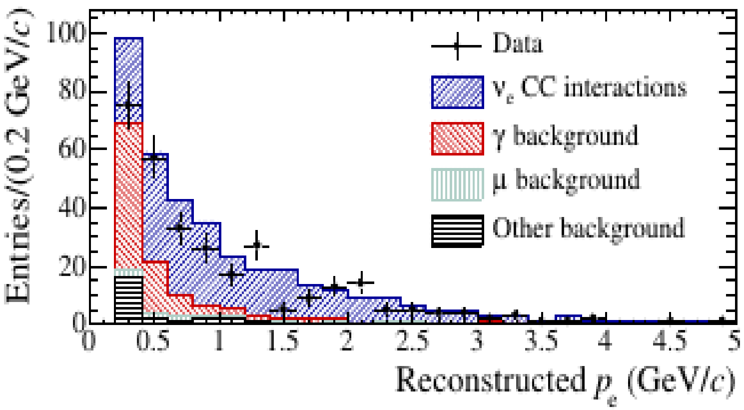
5% ± 3%

→ equivalent to factor 2 in exposure!

DUNE and HK talks @ NuFact 2015

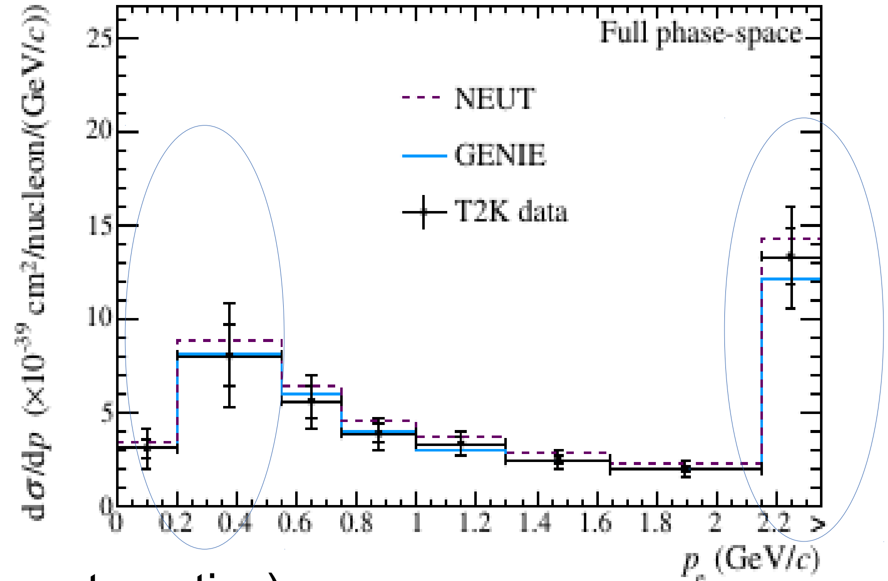
T2K ν_e and $\bar{\nu}_\mu$ xsec

- **ν_e on C**: flux ~1 %



unfolding

T2K Collaboration, Phys.Rev.Lett. 113 (2014) 24, 241803



- $\pi^0 \to \gamma$ background constrained from data (2.1 % systematics)
- large model-dependence where very small efficiency (otherwise stat. limited)

- **ν_e on water with T2K P0D filled with water or emptied (air)**

$$R_{water\ runs} = data_{water} / MC_{water} = 0.89 \pm 0.08 (stat.) \pm 0.11 (syst)$$

$$R_{water\ runs} = data_{air} / MC_{air} = 0.90 \pm 0.09 (stat.) \pm 0.13 (syst)$$

$$R_{on\ water} = (water - air)_{data} / (water - air)_{MC} = 0.87 \pm 0.33 (stat.) \pm 0.21 (syst)$$

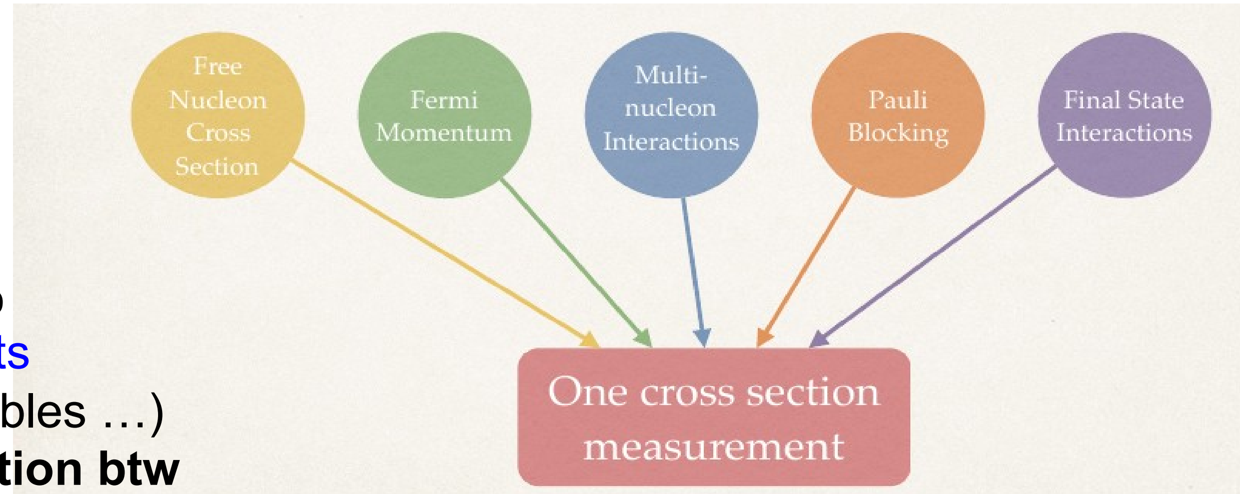
- $\bar{\nu}_\mu$ xsec measurment (CC inclusive and CC0π) ongoing at T2K (CEA):

$$\frac{\sigma^{\nu} - \sigma^{\bar{\nu}}}{\sigma^{\nu} + \sigma^{\bar{\nu}}} \longrightarrow \delta_{CP}$$

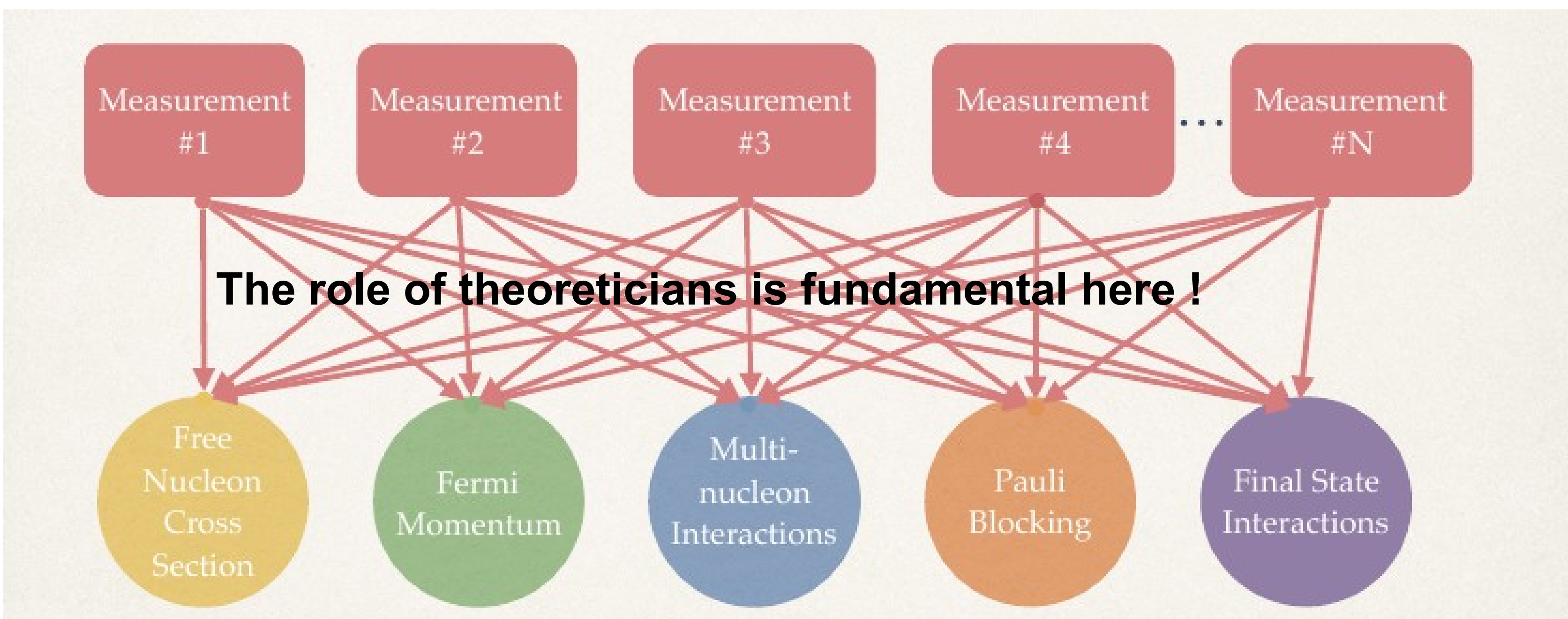
T2K Collaboration, Phys.Rev. D91 (2015) 11, 112010

The way out?

- A given cross-section measurement is affected by many different effects



- To disentangle them we need to compare different measurements (C, O, ν species, different variables …)
→ **long term plan & collaboration btw experiments at different flux**



The role of theoreticians is fundamental here !

Importance of theoreticians

- **Quite rare (today) nuclear-physics know-how**
  (same expertise needed for 0νββ matrix elements: collaboration?)

- **Neutrino community should push for a better funding/visibility of this theoretical/nuclear physics**
  → will be fundamental for the success of present/future neutrino long baseline experiments

ENSTN workshop at Saclay (April 2015)

by M.Martini (CEA, SPhN)

Two-body current contributions in neutrino-nucleus scattering

Marco Martini*
Ghent University, Ghent, Belgium and IRFU/SPhN, CEA-Saclay, France

Maria Barbaro*
University of Turin and INFN, Turin, Italy

Sara Bolognesi*
IRFU/SPP, CEA-Saclay, France

Magda Ericson*
IPNL, Lyon, France and CERN, Geneva, Switzerland

Natalie Jachowicz*
Ghent University, Ghent, Belgium

Project of the Espace de Structure et de réactions Nucléaires Théorique

http://esnt.cea.fr

Spring 2016

CEA Saclay, SPhN, Orme des Merisiers, b. 703, room 135, F-91191 Gif-sur-Yvette

BACKUP

Recent **neutrino cross-section** measurements at **T2K**

S.Bolognesi
(IRFU, CEA Saclay)

GDR Neutrino – November 2015 - Saclay

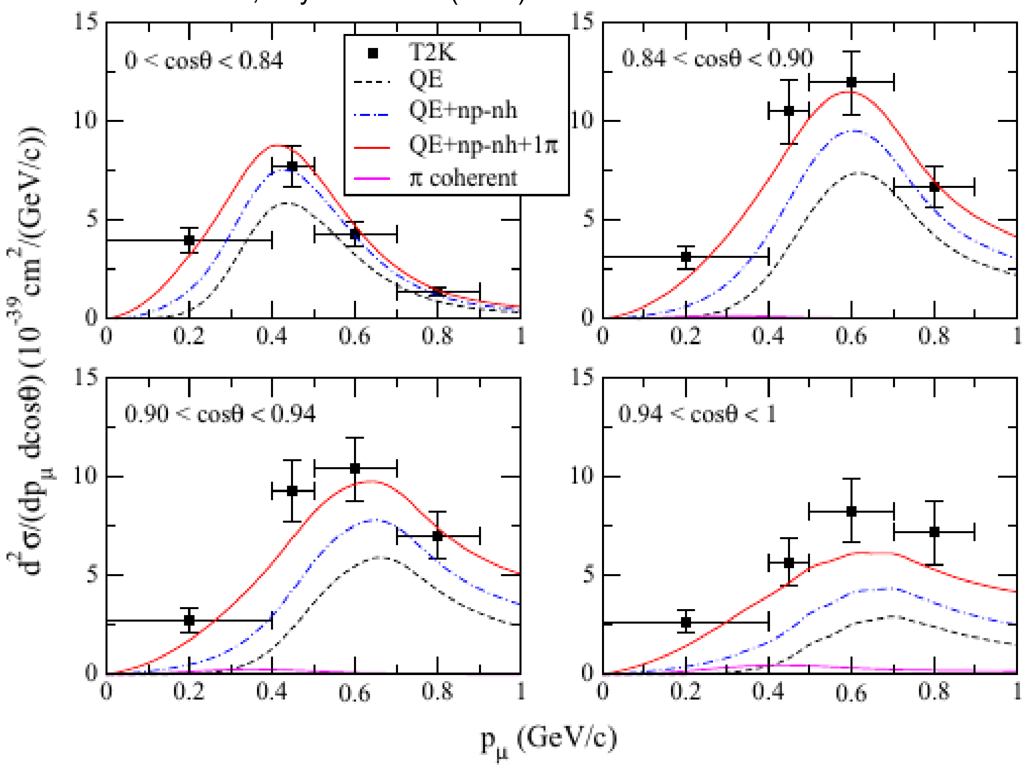
CC inclusive: T2K

- Simple analysis: require at least one muon (small background from NC and flux pollution ν_μ)
- **Dominated by CCQE at T2K E_ν energy:**

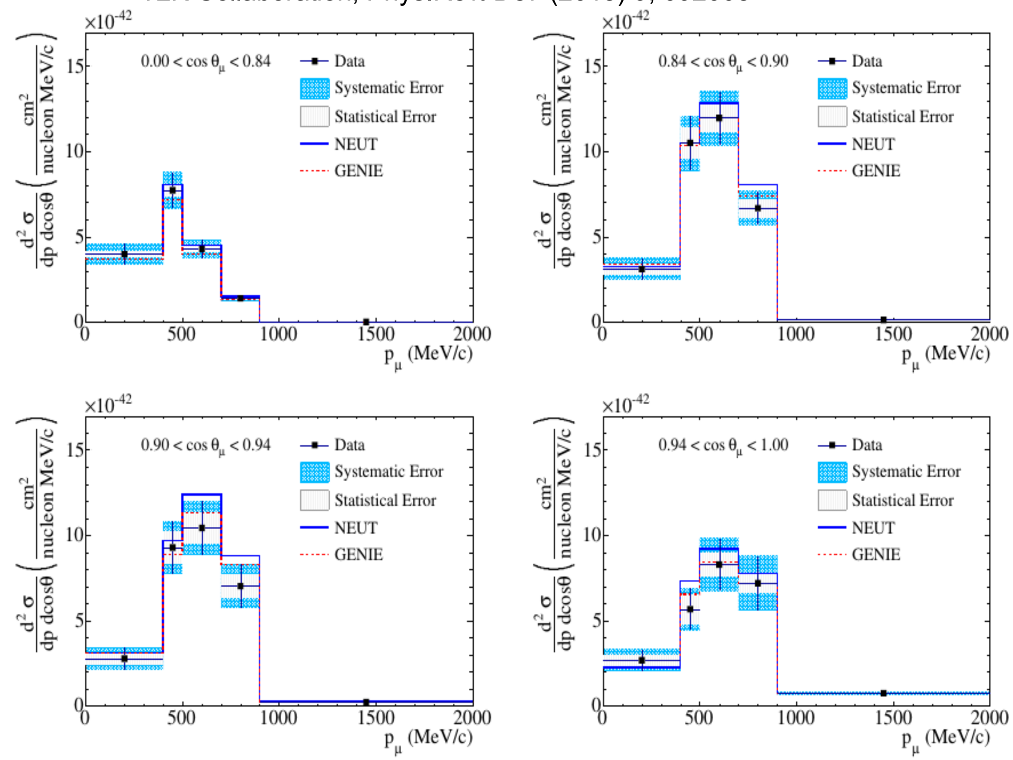
→ indications in favour of new models with 2p2h

→ agreement also with old tuned models

Martini et al, Phys.Rev. C90 (2014) 025501



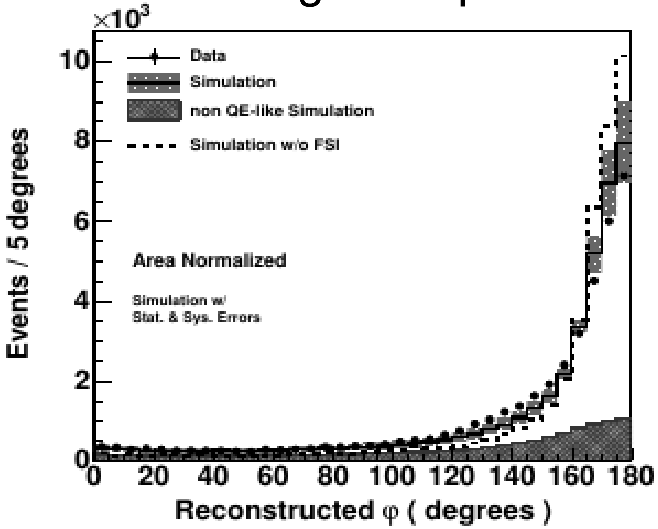
T2K Collaboration, Phys.Rev. D87 (2013) 9, 092003



CC0π: proton kinematics

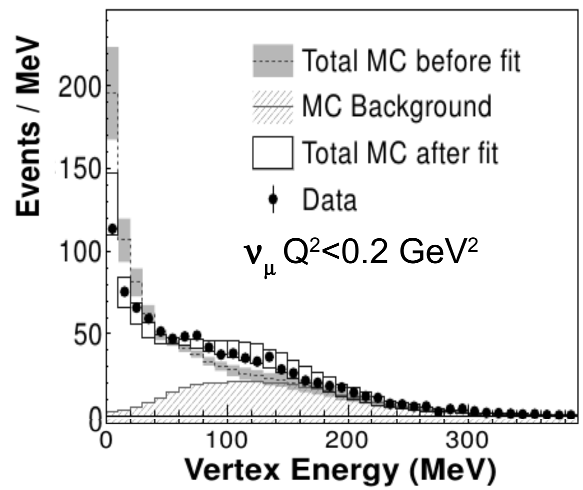
- **MINERvA**

angle mu-p

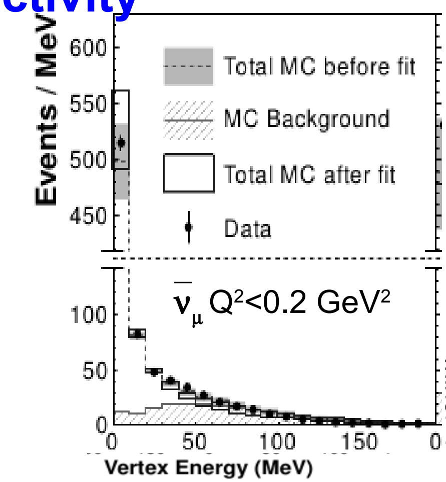


QE peak (180°) smeared by Fermi motion, inelastic scatt. and FSI
(+ NN correlations)

- more inclusive proton-related variable: **vertex activity**



excess $\nu_\mu\, n\, p \to \mu^-\, p\, p$

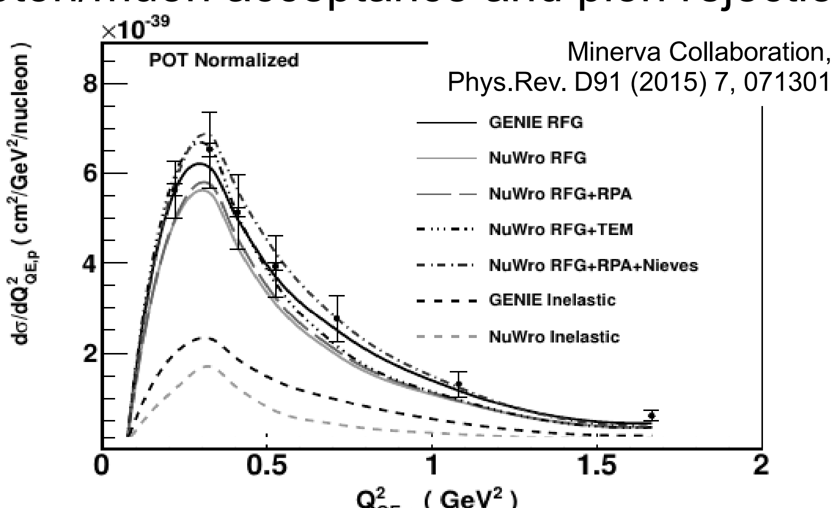


no excess

$\bar{\nu}_\mu\, n\, p \to \mu^+\, n\, n$

Minerva Collaboration, Phys.Rev.Lett. 111 (2013) 022502, Phys.Rev.Lett. 111 (2013) 2, 022501

Converting to Q2 ➡ still dominated by model uncertainties through proton/muon acceptance and pion rejection

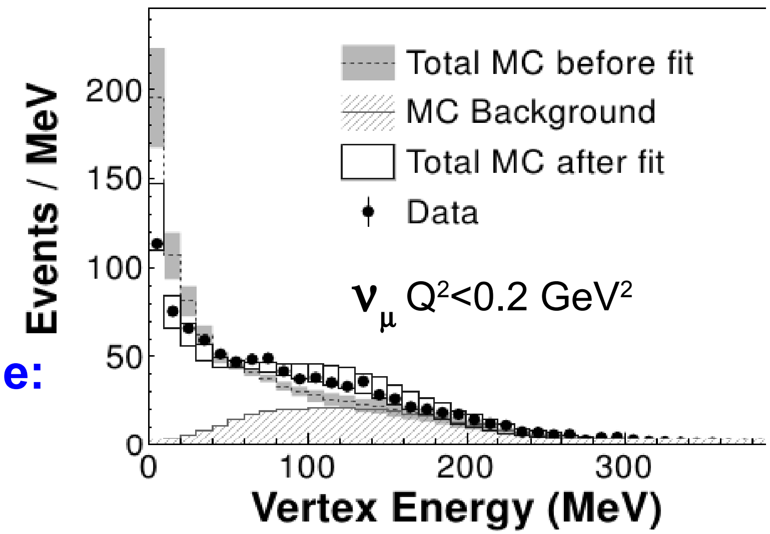


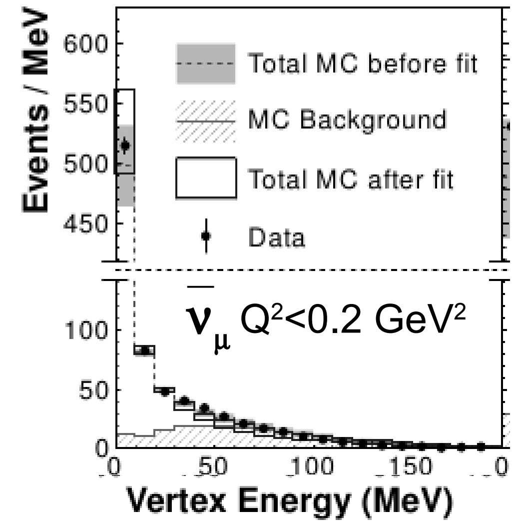
Minerva Collaboration, Phys.Rev. D91 (2015) 7, 071301

CC0π MINERvA: vertex activity

Minerva Collaboration, Phys.Rev.Lett. 111 (2013) 022502, Phys.Rev.Lett. 111 (2013) 2, 022501

- **MINERvA :**
  - muon + minimal hadronic activity far from vertex
  - **more inclusive proton-related variable: vertex activity**





2p2h interactions :

ν_μ **n p → μ^- p p** ;

$\bar{\nu}_\mu$ **n p → μ^+ n n**

ν_μ **data** suggest additional proton with E<225MeV in 25 ± 1(stat) ± 9(syst) % of events

$\bar{\nu}_\mu$ **data**: no additional proton (low sensitivity of Minerva to low E neutrons)

unlikely to be due to systematics (eg, FSI): highly correlated (0.7) btw ν_μ and $\bar{\nu}_\mu$

- **In the pipeline for T2K:**
  - proton counting (but modelling of proton kinematics basically unknown...)
  - water vs carbon → disentangle FSI from MEC
  - comparison of ν and $\bar{\nu}$ CC0π : MEC/2p2h effects partially suppressed in $\bar{\nu}$

ArgoNeuT: 2p2h observation

Proof of principle of LAr technology: full 3D imaging, very low proton threshold (21 MeV)

- **Short Range Correlation NN pair** typically above Fermi level

→ final state with μ + 2 high-momentum protons (no experimental sensitivity to neutrons)

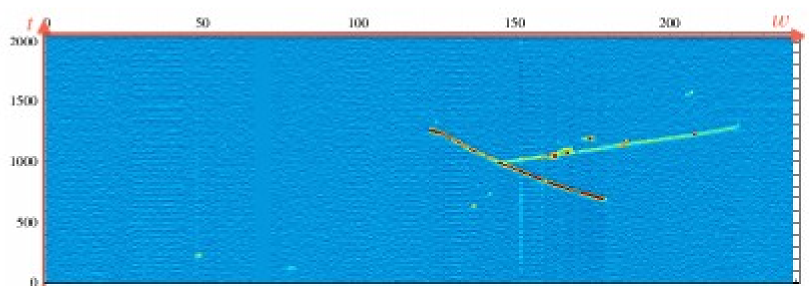
- **back-to-back protons before FSI:**

  CC Δ pionless decay and meson exchange current with low momentum transfer to the pair

- **back-to-back protons in Lab. reference frame:**

  CCQE interaction on a nucleon in SRC pair → correlated n ejected as well due to high relative momentum of the pair

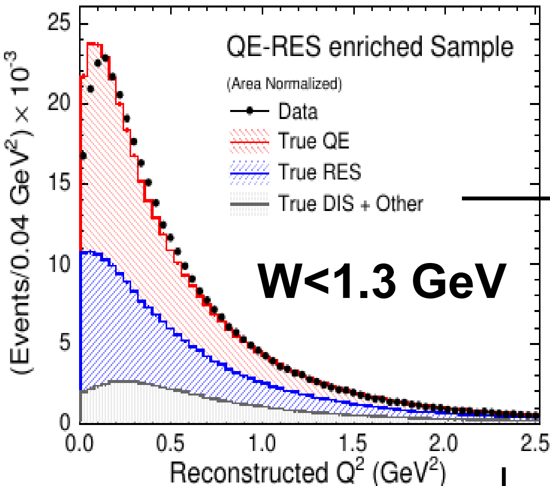
from analogy to electron-N and hadron-N scattering

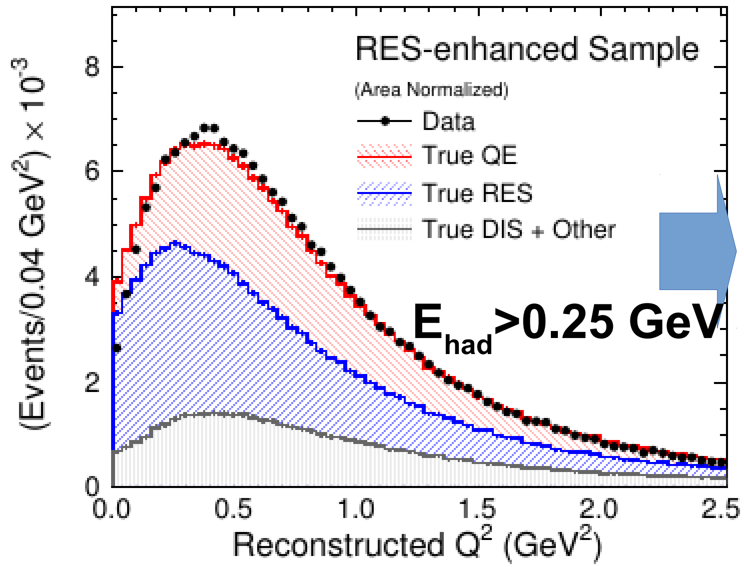


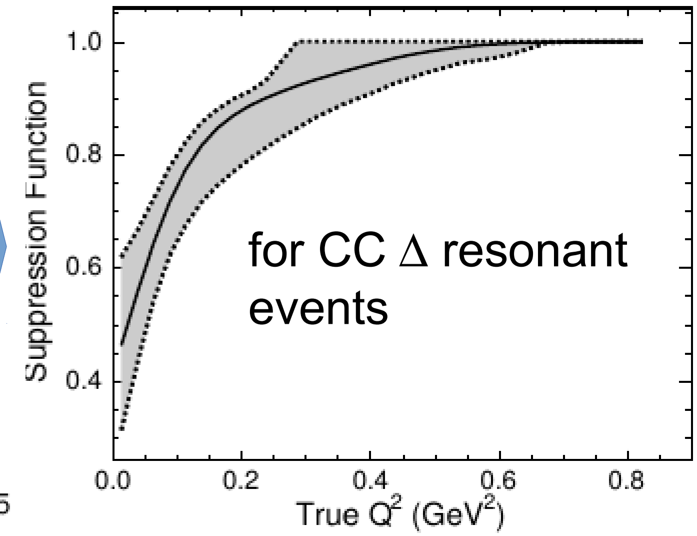
<u>More precise quantitative analysis need improved models for interpretation of experimental data (including FSI!)</u>

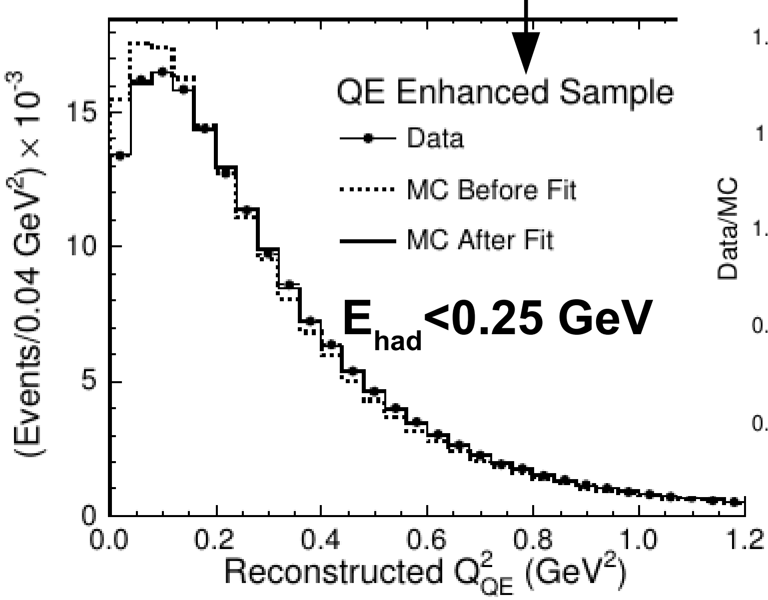
MINOS: CCQE

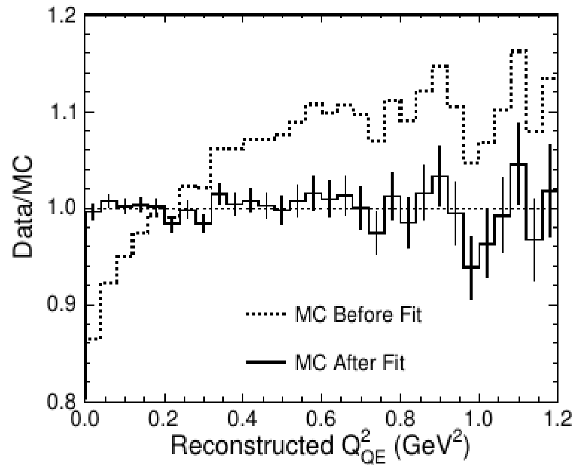
Effective parametrization for background constraint and signal (M_A^{QE})











Q^2_{QE} Range (GeV^2)	M_A (GeV)	E_μ scale	M_A^{RES} (GeV)	k_{Fermi} scale
0.0 - 1.2	$1.23^{+0.13}_{-0.09}$	1.00 ± 0.01	$1.09^{+0.14}_{-0.15}$	1.06 ± 0.02
0.3 - 1.2	$1.22^{+0.18}_{-0.11}$	$1.00^{+0.01}_{-0.02}$	$1.09^{+0.15}_{-0.16}$	N.A.

nuisances

$$\boxed{M_A = 1.23^{+0.13}_{-0.09}(\text{fit})^{+0.12}_{-0.15}(\text{syst.})\ \text{GeV}}$$

M_A^{QE} well above measurement from bubble chamber

→ modern explication: 2p2h contribution

CC1$\pi^{\pm}$ coherent: MINERvA

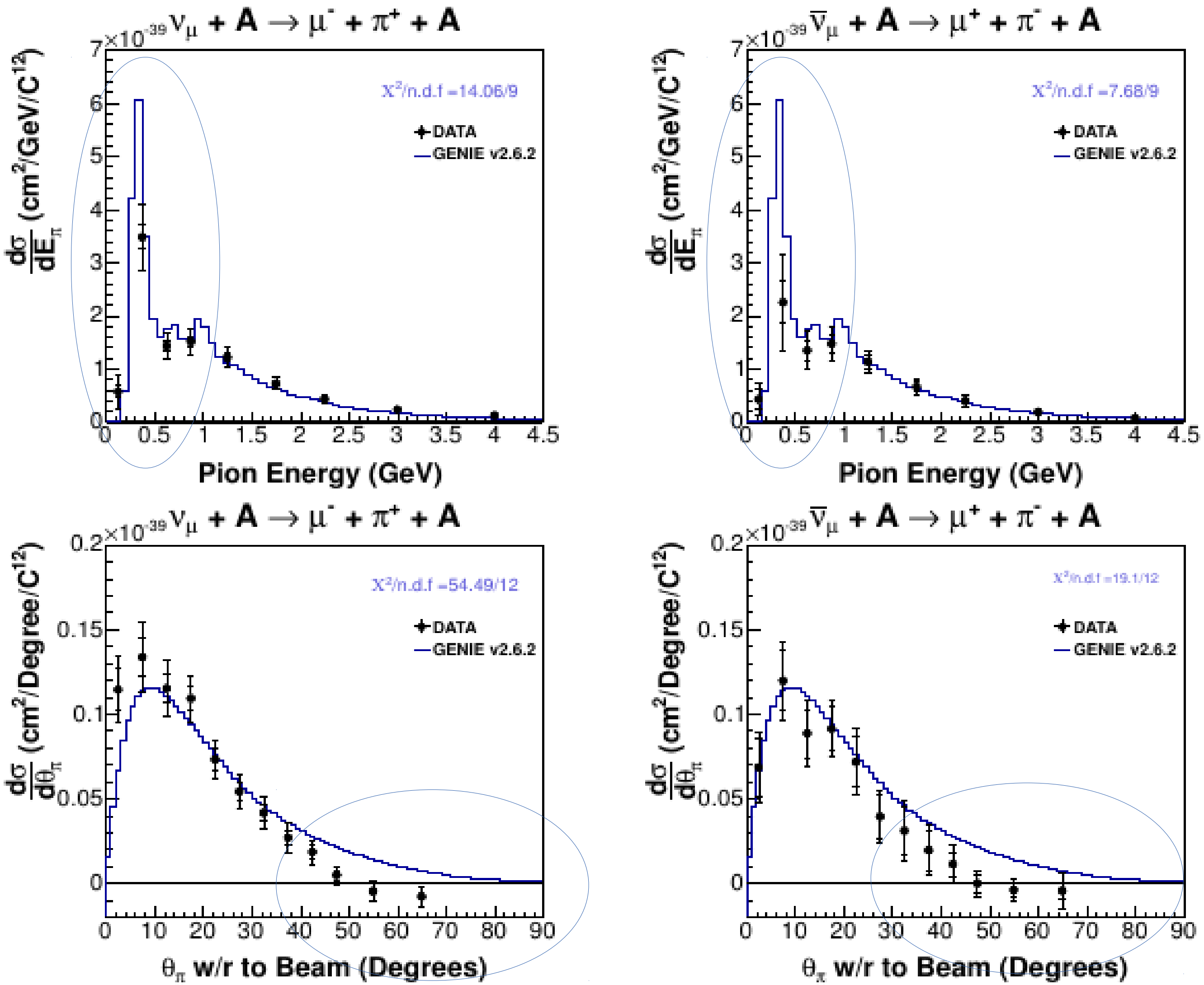
- Similar selection and background constraints applied to ν and $\bar{\nu}$ beams

→ large suppression of backgrounds wrt to MC predictions (60-70 %)

- Enough statistics for a differential measurement

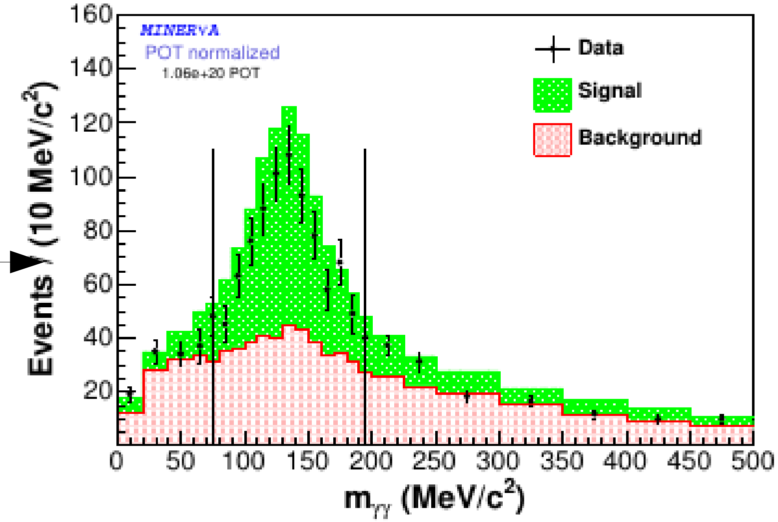
→ indication of **suppression at low π energy and large π angle wrt to Rein-Seghal model**

- systematics dominated by model uncertainties

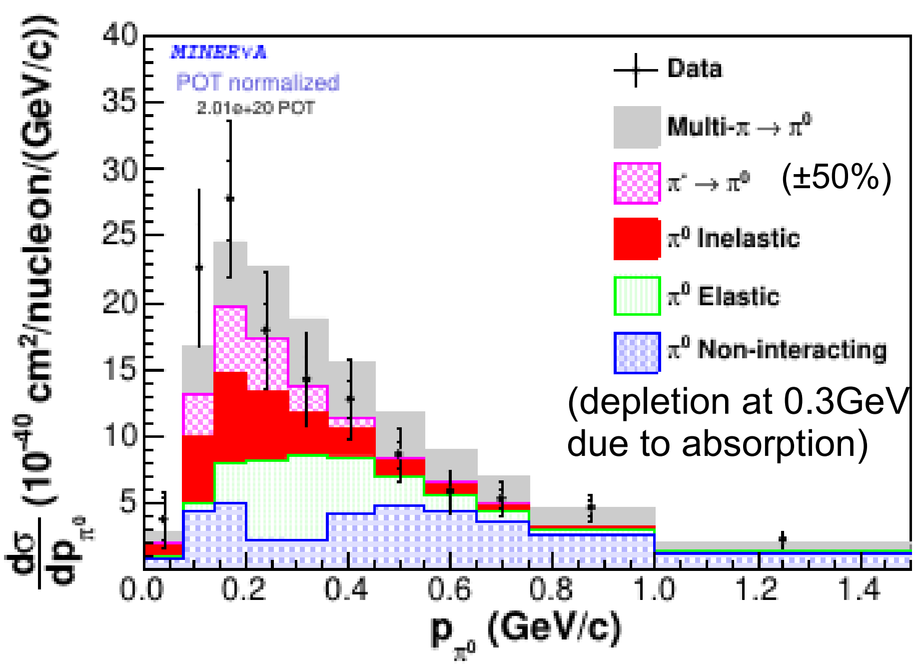


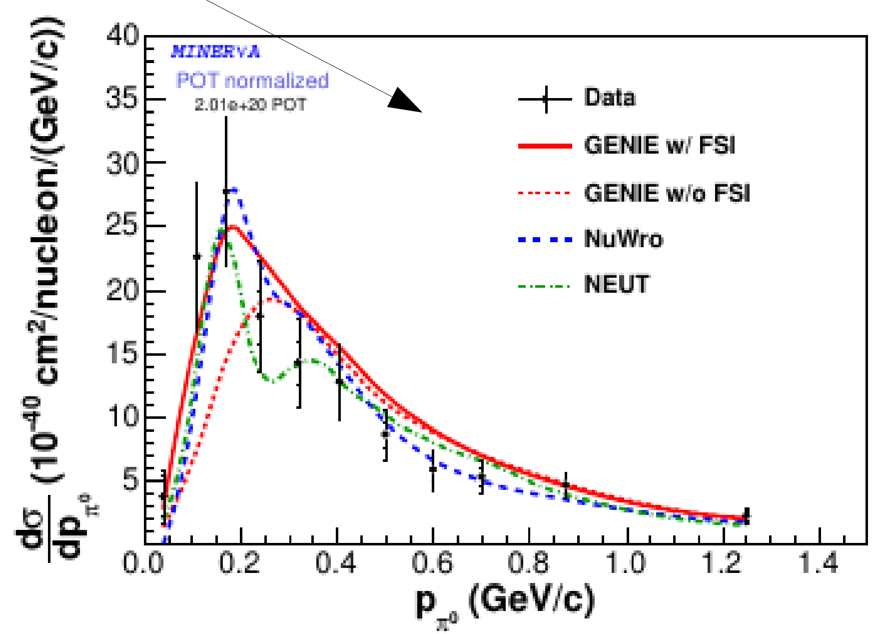
MINERvA : π^0 from CC in $\bar{\nu}$ beam

- Interesting channel $\bar{\nu}\, p \rightarrow \mu^+\, n\, \pi^0$:
  - **NC π^0 production is dominant background for ν_e appearance**
  - **provide constraints on FSI for π^0**: no π^0 beam → FSI model based only on isospin relations $\pi^\pm \rightarrow \pi^0$
- Analysis:
  - require μ+ (MINOS) π0 (from energy deposited by $\gamma\gamma$)
  - background normalized from data: 70 % from multi-π with π^0 and missing $\pi^\pm$



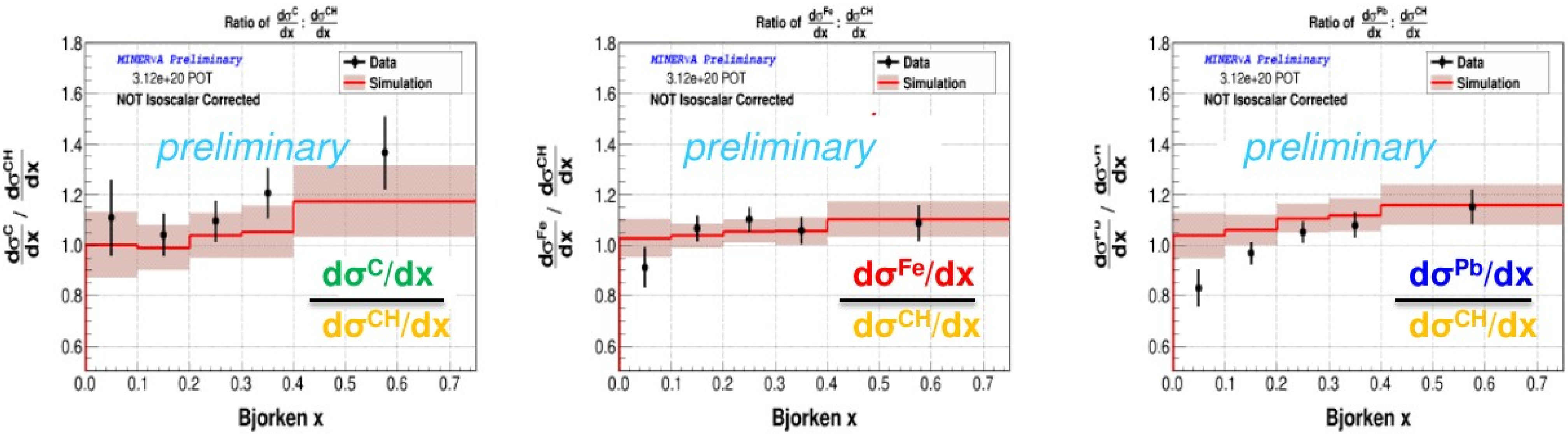
- Results: only 20% signal has no FSI
  → results indicate preference for presence of FSI





A.Bravar
EPS 2015

DIS Cross Section Ratios – $d\sigma$ / dx_{Bj}



Select DIS sample by requiring $Q^2 > 1$ GeV^2 and $W > 2$ GeV
(these cuts remove the quasi-elastic and resonant background)

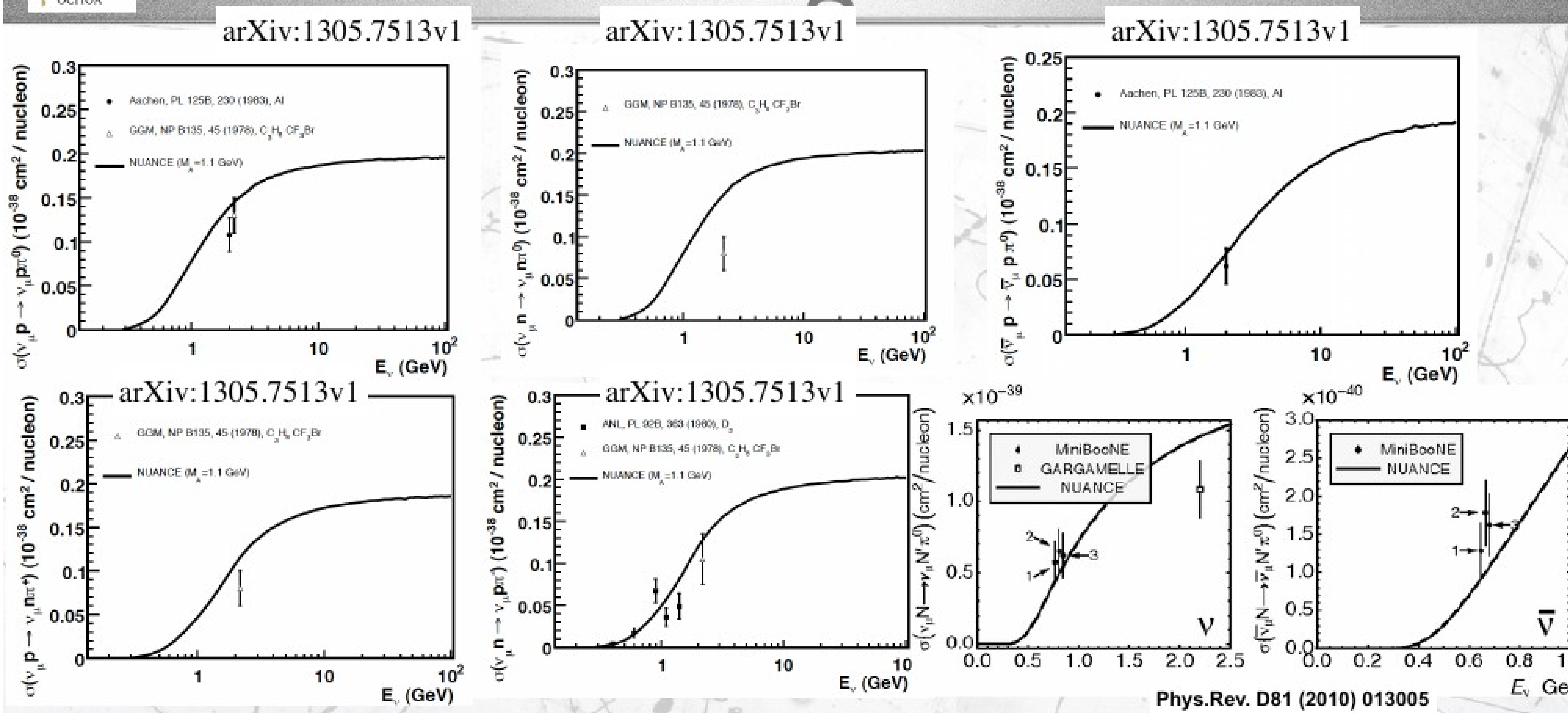
x dependent ratios directly translates to *x* dependent nuclear effects
(interpret data at partonic level)
cannot reach the high-*x* with current beam energy (LE data sample)

MINERνA data suggests additional nuclear shadowing in the lowest *x* bin
($\langle x \rangle = 0.07$, $\langle Q^2 \rangle = 2$ GeV^2)

In EMC region ($0.3 < x < 0.7$) good agreement between data and models
(GENIE assumes an *x* dependent effect from charged lepton scattering on nuclei)

Existing data

F.Sanchez
Neutrino 2014

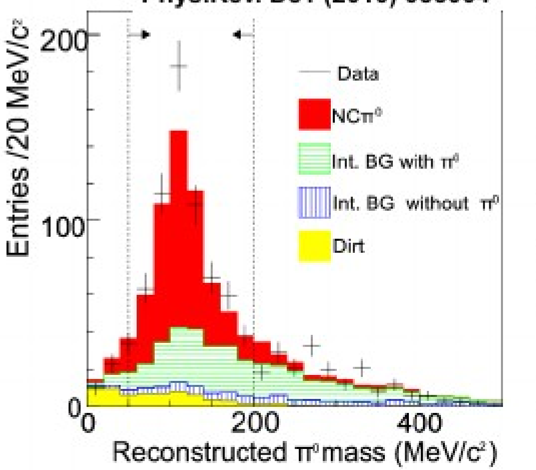


- 30 years old and sparse data && MiniBoone (2009).
- No new results in Nuint'14.
- Important background for ν_μ disappearance ($NC\pi^+$) νe appearance. ($NC\pi^0$)
- ν sterile searches!

Recent results

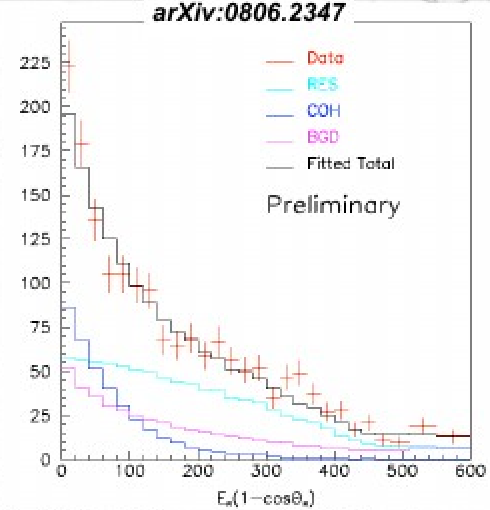
F.Sanchez
Neutrino 2014

Phys.Rev. D81 (2010) 033004



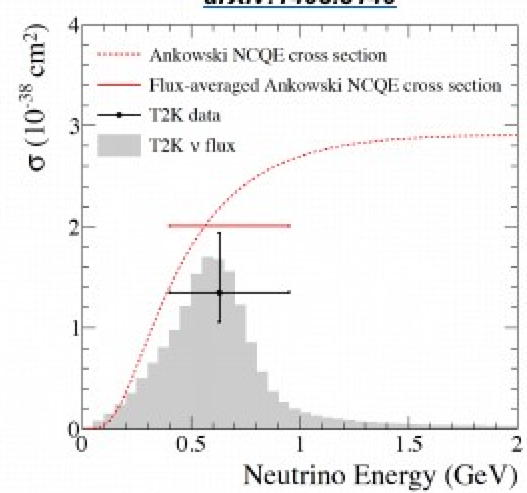
2010 SciBoone NCπ⁰/CC

arXiv:0806.2347



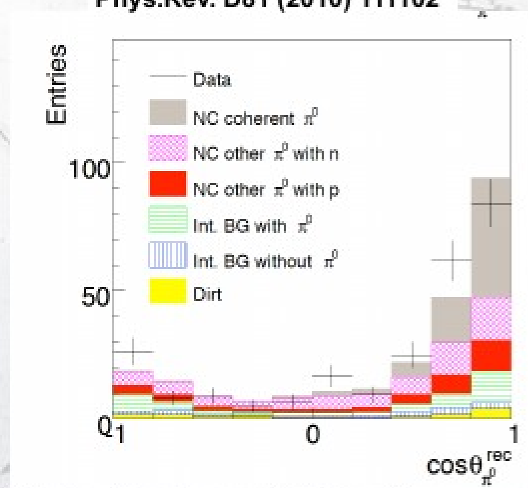
2008 MiniBoone NCπ⁰ Coherent.

arXiv:1403.3140



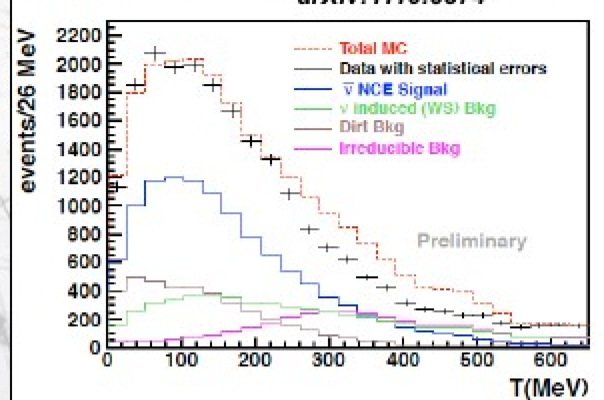
2014 T2K NC-QE from nuclear de-excitation γ rays.

Phys.Rev. D81 (2010) 111102



2010 SciBoone NCπ⁰ coh.

arXiv:1110.6574



2011 MiniBoone NC elastic.

2014 T2K NC π⁰ (poster)

Beyond oscillation analysis

- Inelastic: $\nu + {}^{16}O \rightarrow \nu + {}^{16}O^* \rightarrow$ de-excitation γ
  used to detect SN neutrinos (10-20 MeV)

NCQE: $\boxed{\nu + {}^{16}O \rightarrow \nu + p + {}^{15}N^*}$

→ primary deexcitation γ + secondary γ from p scattering

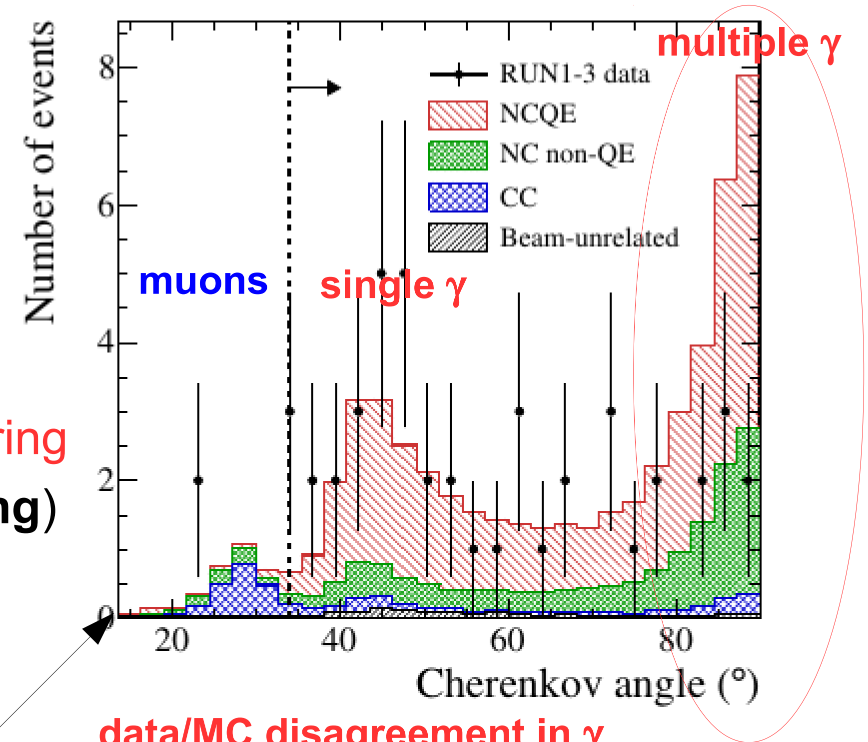
(overwhelming at ~500 MeV → **bkg for SN ν counting**)

- Measurement at Super-Kamiokande

- very low PMT trigger threshold
  (radioactive bkg removed with beam timing cut)
- primary background from non-QE interaction
  with pion reabsorption by FSI
- γ spectrum depend on details of O nuclear
  structure (primary) and the n/p multiplicity
  (secondary)

↓

efficiency 70%
(+25% NCQE w/o γ)



data/MC disagreement in γ multiplicity but good agreement in total γ energy