NUFACT 15 RIO DE JANEIRO BRAZIL AUGUST 10-15

Experimental status of neutrino scattering

S.Bolognesi
(T2K, CEA Saclay)

A hot topic...

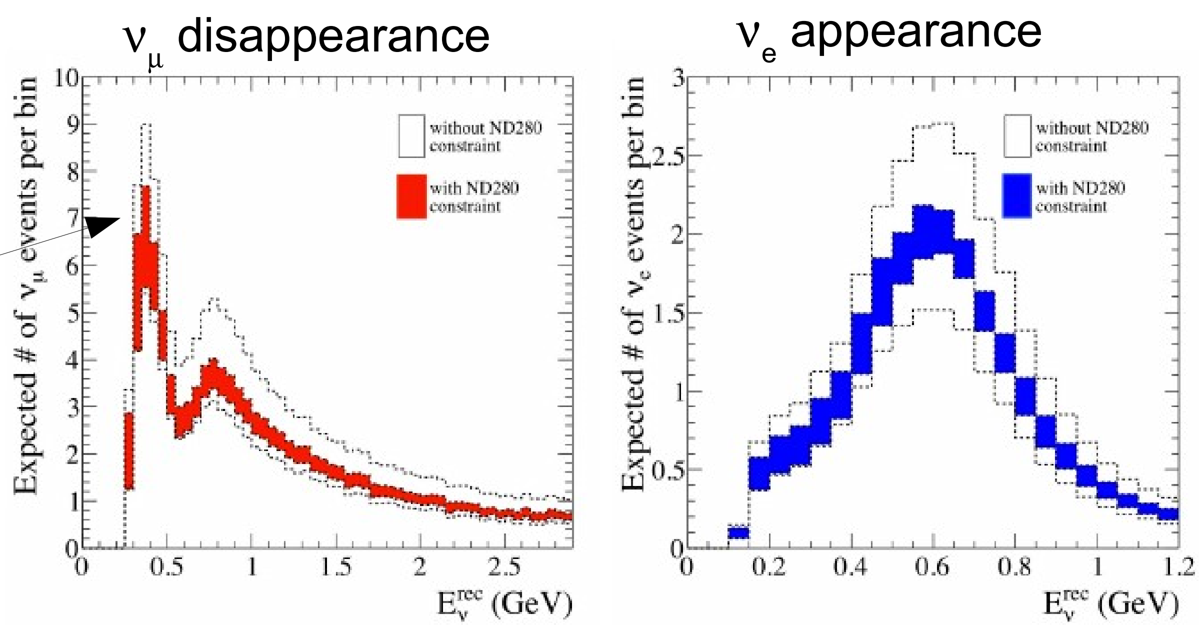
T2K Collaboration, Phys.Rev. D91 (2015) 7, 072010

- **Oscillation measurements in far detector constrained from near detector (xsec x flux)** : aim to ~1% uncertainty on signal normalization at future long baseline **(T2K today ~8 %) !**

ND→FD extrapolation :

- different acceptance and target
- different E_ν distribution
- $\nu_\mu \rightarrow \nu_e, \bar{\nu}_\mu$

→ **rely on models to extrapolate** : many different ν interaction models + convolution of xsec with final state interaction effects



- 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

- Brief description of experiments:
  - **T2K**
    - off-axis near detector **(ND280)**
    - on-axis near detector **(INGRID)**
  - **MINERvA**

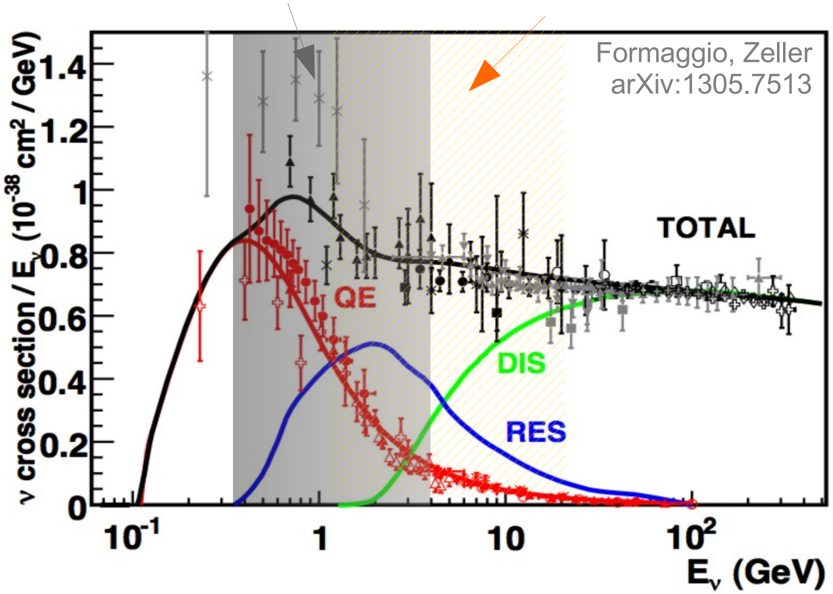
  (not covered: NOMAD, MiniBooNE, ArgoNeut,...)

ArgoNeut see back-up

CAPTAIN talk from A. Higuera

- Overview of recent measurements

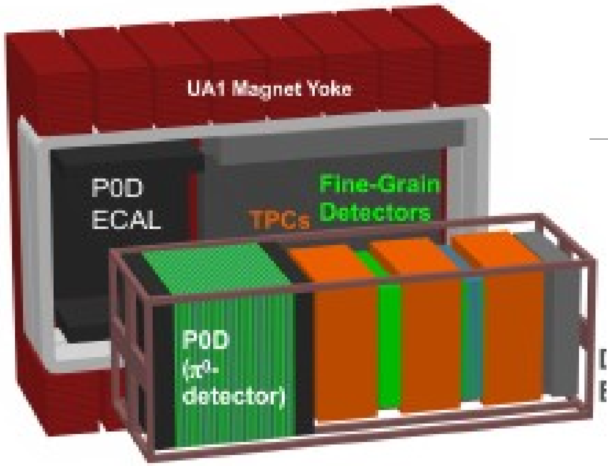
T2K flux : ND280→INGRID **MINERvA flux**



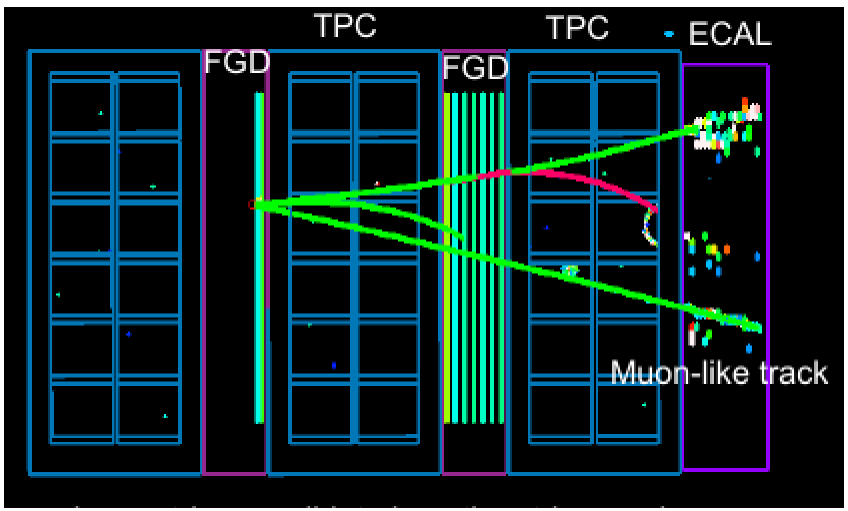
- **CC0π**
  (talks from A. Furmanski, A.Ghosh)
- **CC1π , coherent CC1π**
  (talks from M.Nirkko, M.Carneiro)
- **CC inclusive in different targets, and for ν_e**
- (**DIS**: talk from A.Bravar)

- Theoretical review of models in talks from H.Gallagher, M.Martini, T.Feusels

T2K near detectors

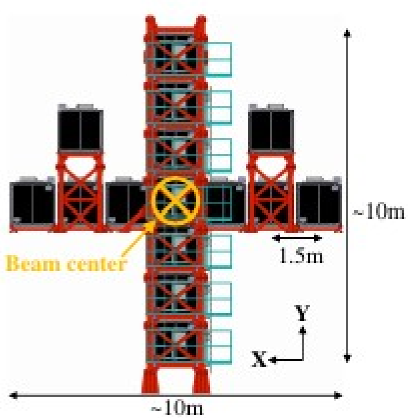


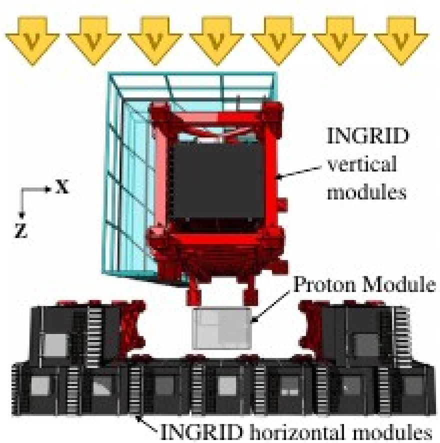
- **Oscillation experiment** on **J-PARC beam** with Super-Kamiokande as FD (POT : ~$6x10^{20}$ ν_μ + ~$4x10^{20}$ $\bar{\nu}_\mu$)
  - flux measurement from dedicated experiment **NA61/SHINE with T2K replica target**



ND280 : off-axis (2.5°)

- fully magnetized (0.2 T)
- FGD scintillators : ~$8x10^{29}$ nucleons (CH) + $2.2x10^{28}$ (H_2O)
- TPC → **good tracking efficiency** (acceptance enlarged to backward tracks), **resolution** (6% p_T<1GeV) **and particle identification**
- P0D scintillator with water target

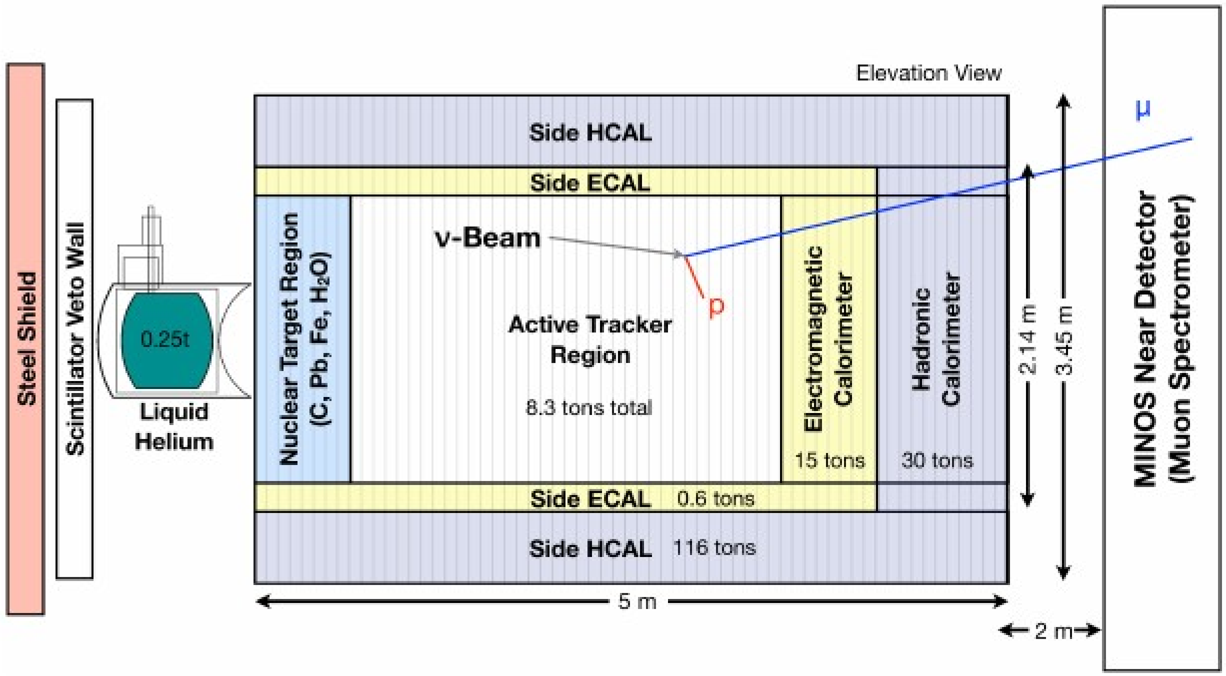




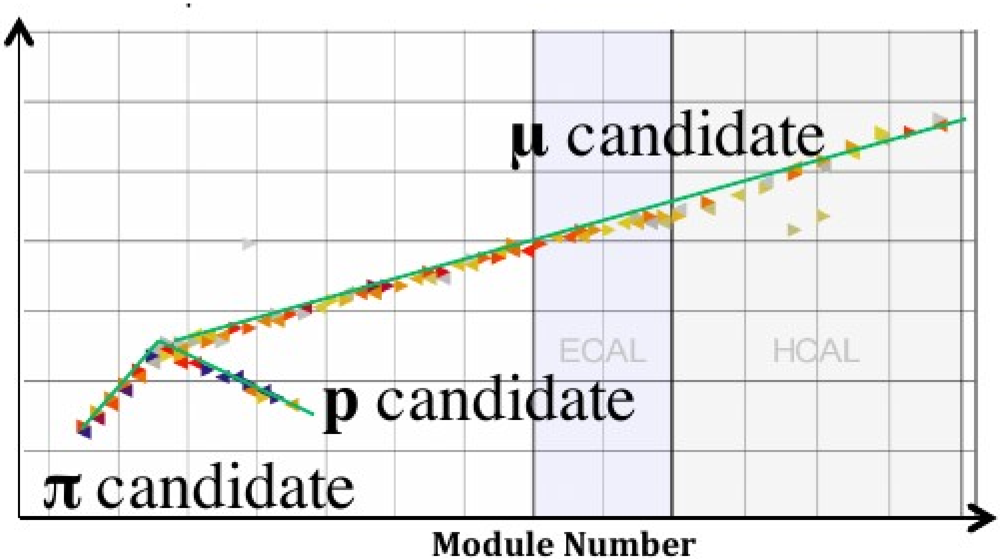
INGRID : on-axis

- iron plates alternated with CH scintillator (+ proton module : fully active scintillator)
- **coarser granularity, not magnetized but larger mass :** $2.5x10^{30}$ nucleons (Fe) + $1.8x10^{29}$ nucleons (CH)

MINERvA

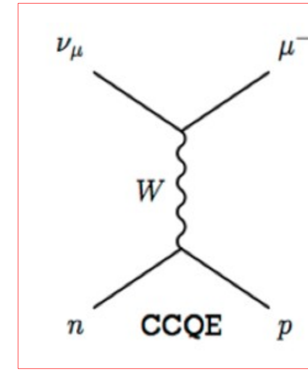


- **Dedicated xsec experiment on the NuMi beam**
  POT : $3\mathrm{x}10^{20}\ \nu_\mu + 2\mathrm{x}10^{20}\ \bar{\nu}_\mu$
  - flux constrained from NA49 on C and π/K ratio from MIPP (replica NuMi target)



- **large active mass composed of scintillator** (~$3.5\mathrm{x}10^{30}$ nucleons CH)
- **muon → MINOS : strong dependence of efficiency on muon kinematics**
  (0 eff for p_μ<1GeV and θ_μ>20º)
  momentum resolution 11 %
- upstream inactive targets (C, Pb, Fe, H_2O) alternated with scintillator

Charged Current Quasi-Elastic



- **Dominant contribution at T2K flux** : QE approximation assumed to compute E_ν (from E_μ) for all selected events in SuperKamiokande
  → **wrong modelling would cause bias on oscillation parameters**

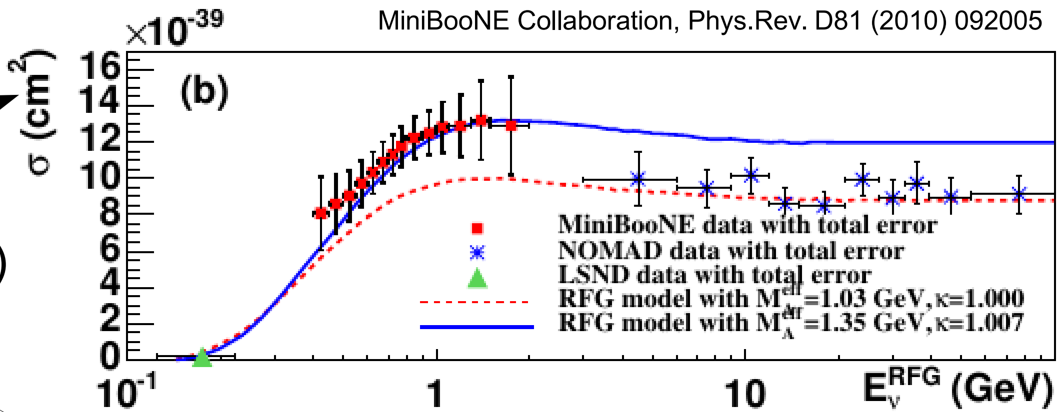
- **MC description tuned from bubble chambers νH data**

- **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)

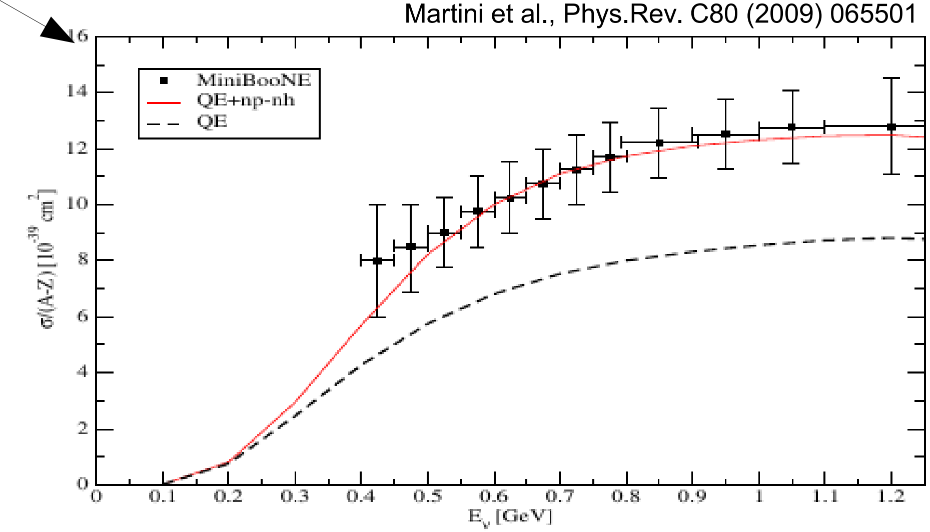
  Effort ongoing to include them in MC

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

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



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

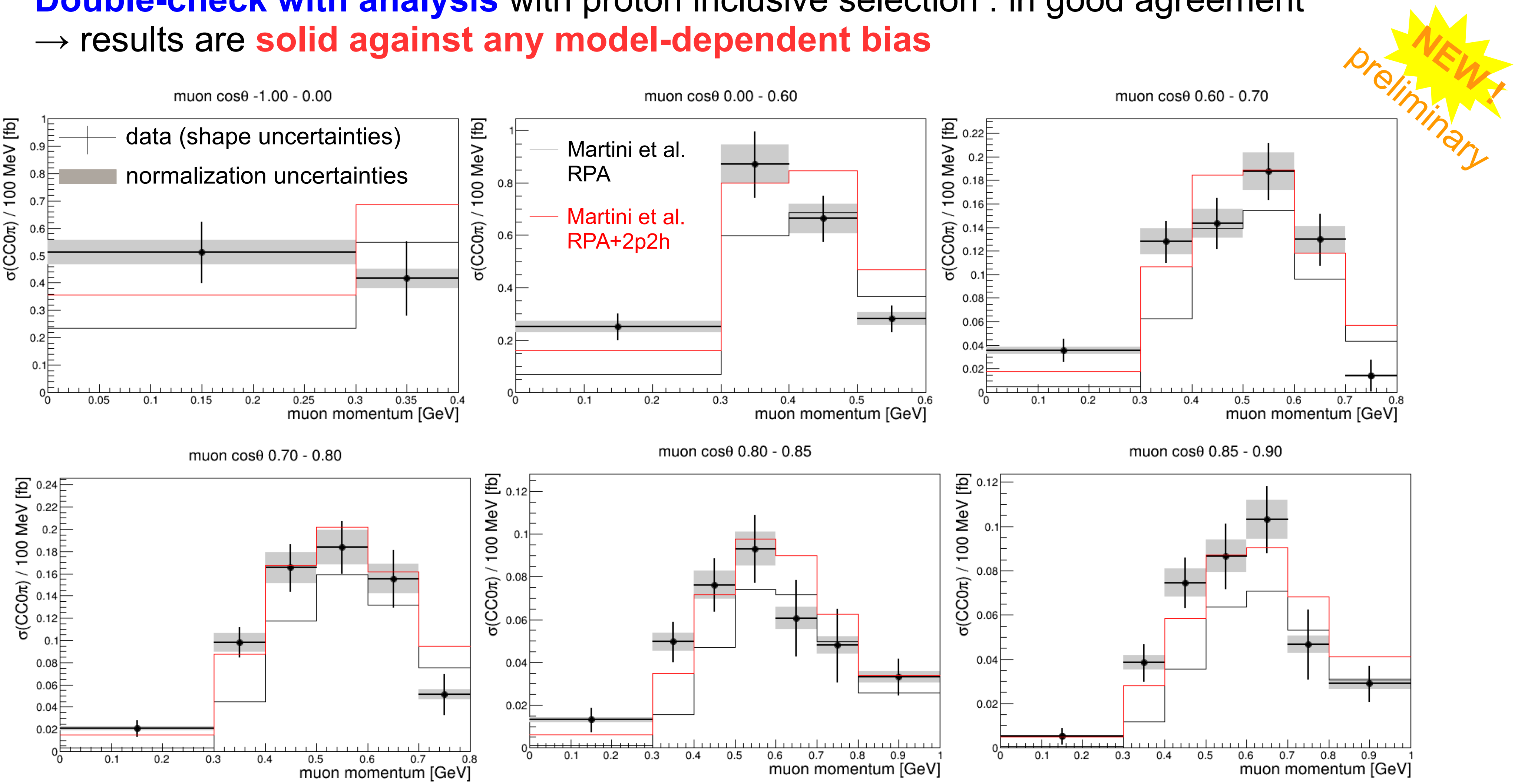


CC0π: T2K new result

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**

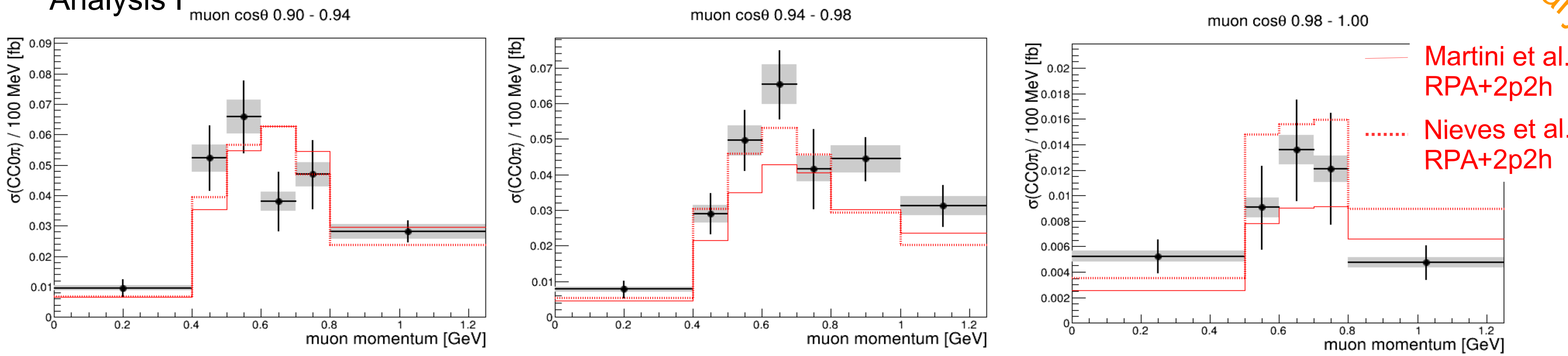


CC0π: open issues

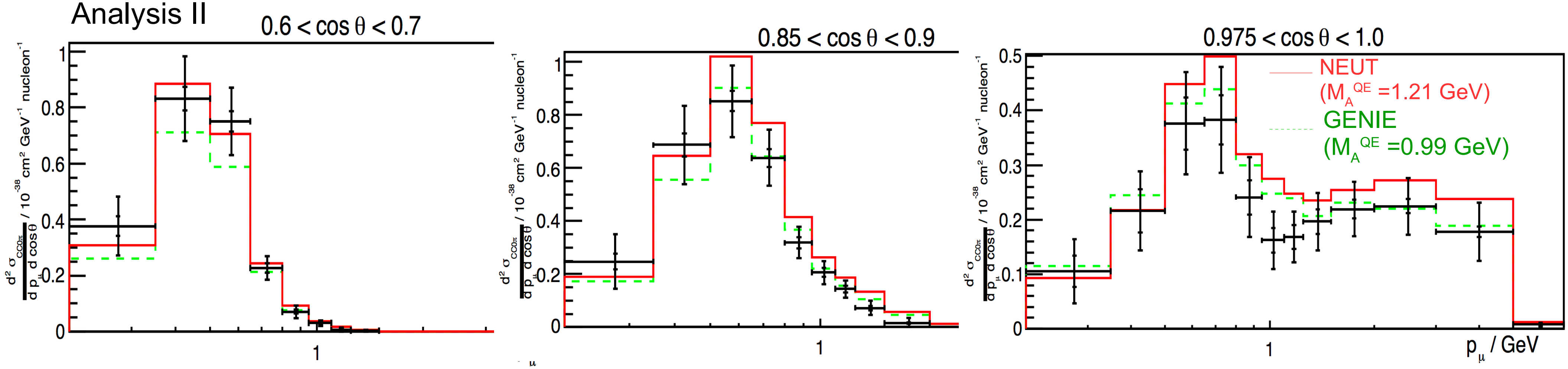
- New models with RPA+2p2h **cannot describe full phase space** (eg forward region has pollution from CC1π + π absorption FSI)
- need to properly quantify **new model uncertainties** (eg comparisons btw models)
- **'old' models implemented in MC** contain handles to tune to data

NEW! preliminary

Analysis I

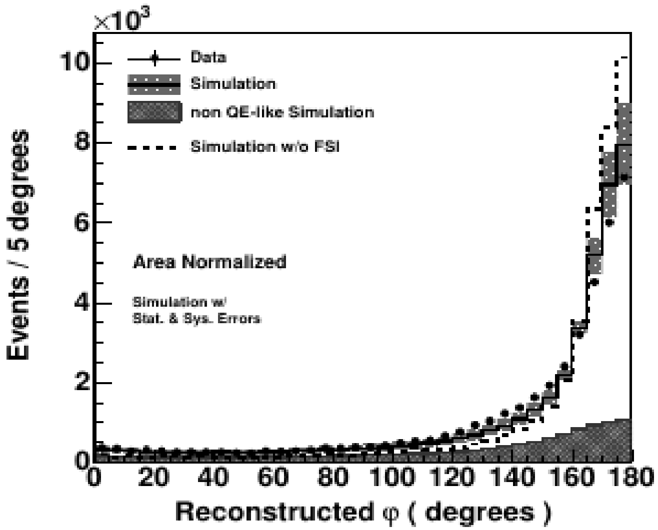


Analysis II

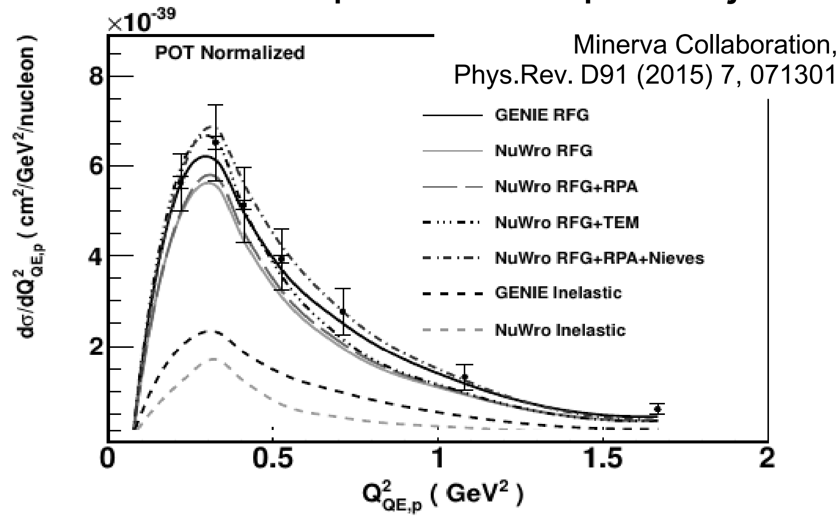


CC0π: proton kinematics

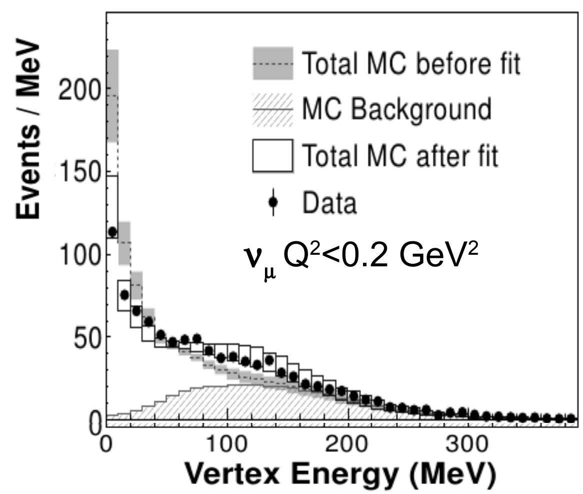
- **MINERvA** more inclusive : mu + at least 1p (no pions) and no cuts against FSI ➡ still dominated by model uncertainties through proton/muon acceptance and pion rejection

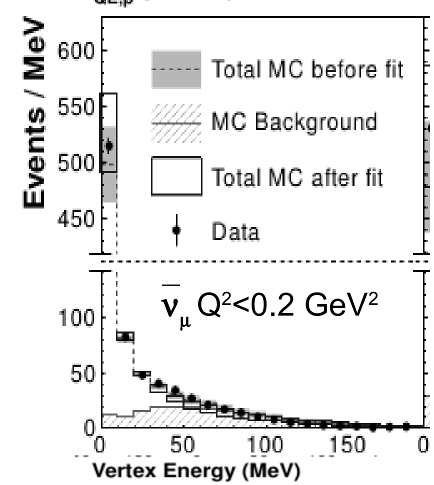


QE peak (180°) smeared by Fermi motion, inelastic scatt. and FSI **(+ NN correlations)**



- **MINERvA :**
  - more inclusive proton-related variable: **vertex activity**
  - **comparison $\nu - \bar{\nu}$** : systematics highly correlated (70%)





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

2p2h interactions :

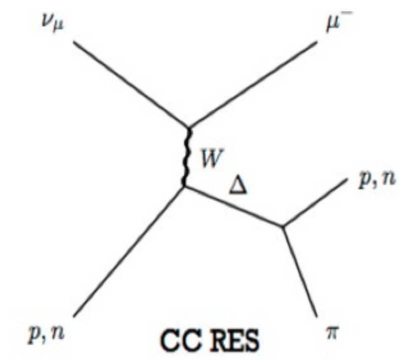
ν_μ **n p → μ^- p p**

$\bar{\nu}_\mu$ **n p → μ^+ n n**

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

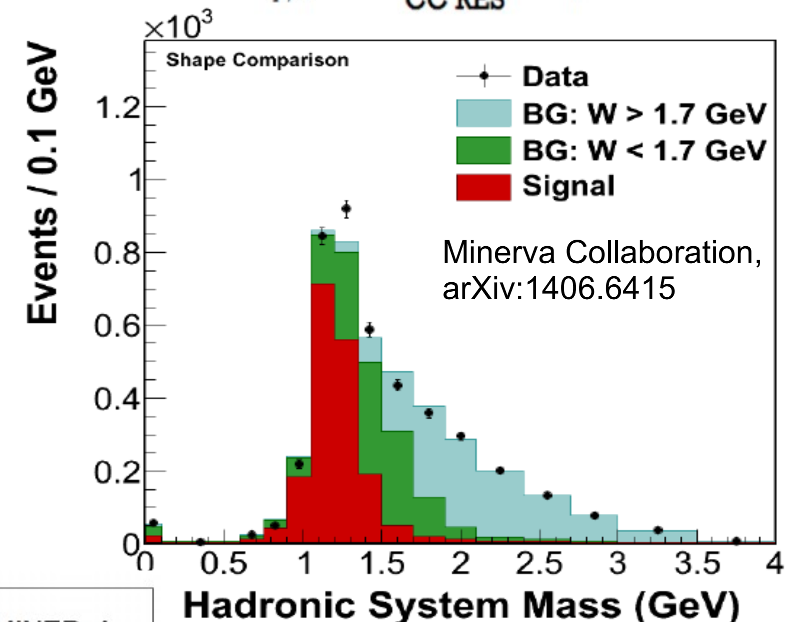
$\bar{\nu}_\mu$ **data**: no additional proton (low sensitivity of Minerva to low E neutrons)

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

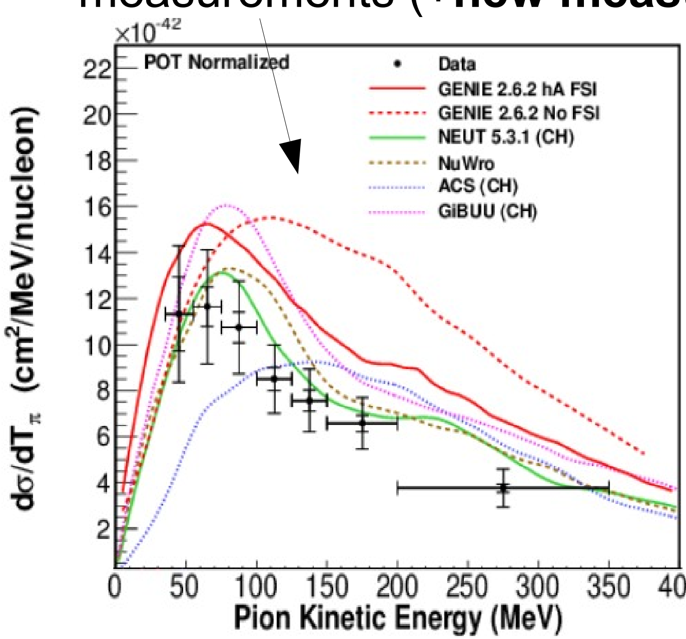


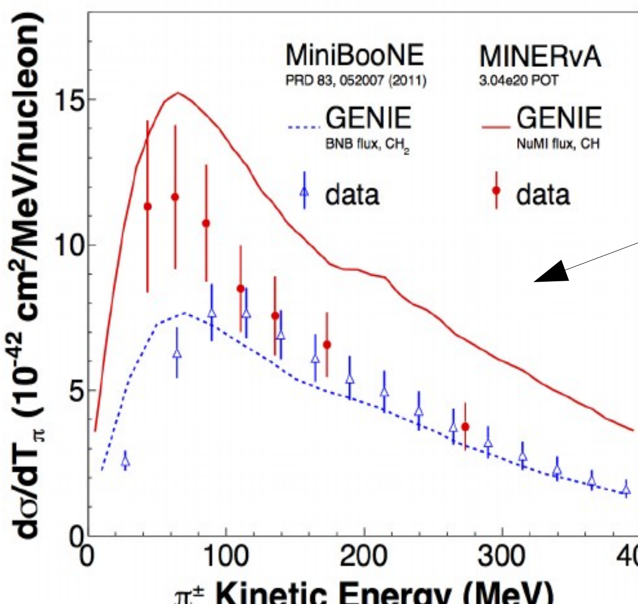
- Mainly from Δ **resonance**
  Large effects from FSI: pion absorption, production or charge exchange

- Signal defined as $\nu_\mu + N \rightarrow \mu^- + \pi^\pm + X$
  with no other pions and W_{true}<1.4 GeV
  (background normalized from fit to W_{reco} in data)



- FSI effects larger than difference in xsec models :
  FSI from MC cascade models tuned with π-N measurements (+**new measurement** by DUET)

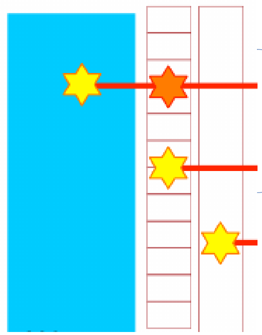


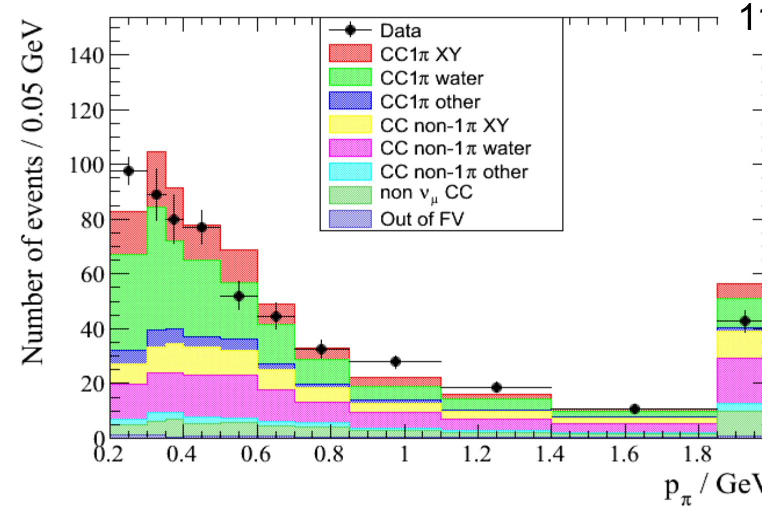


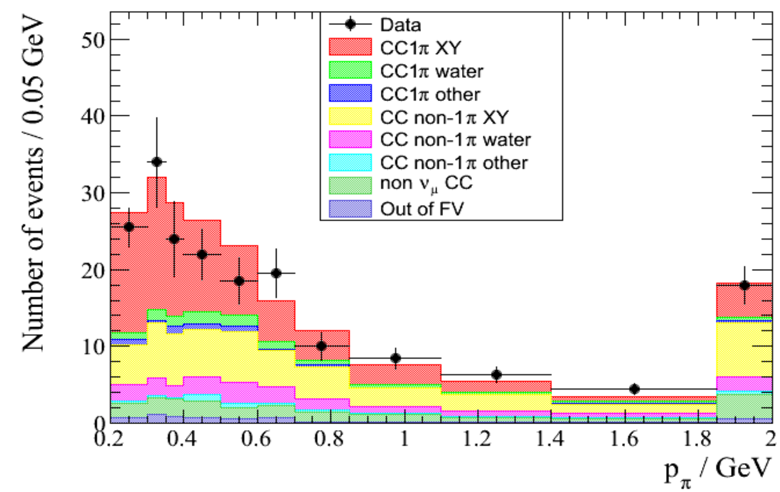
- **MiniBooNE – MINERvA discrepancy?**

CC1π^+ in water : T2K

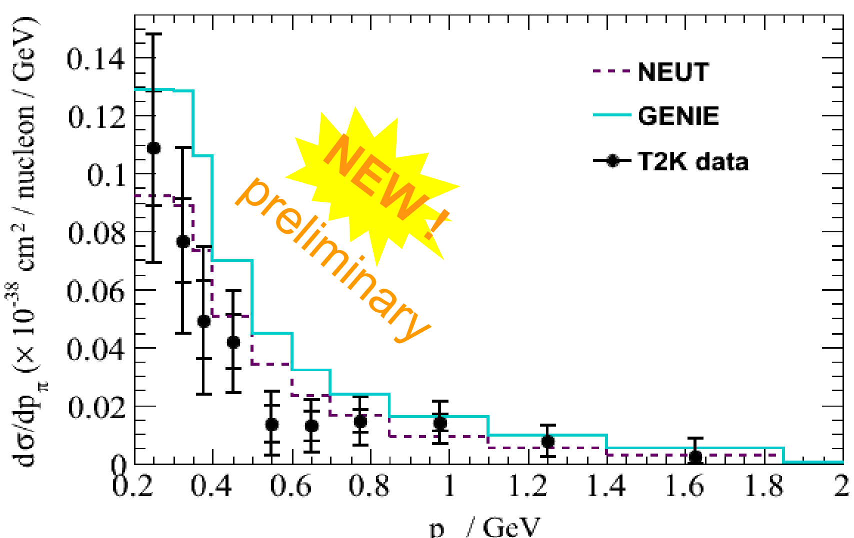
- **Constrain FSI on different nuclei (C vs O)**
- FGD2 :
  - passive water interleaved with CH scintillator modules

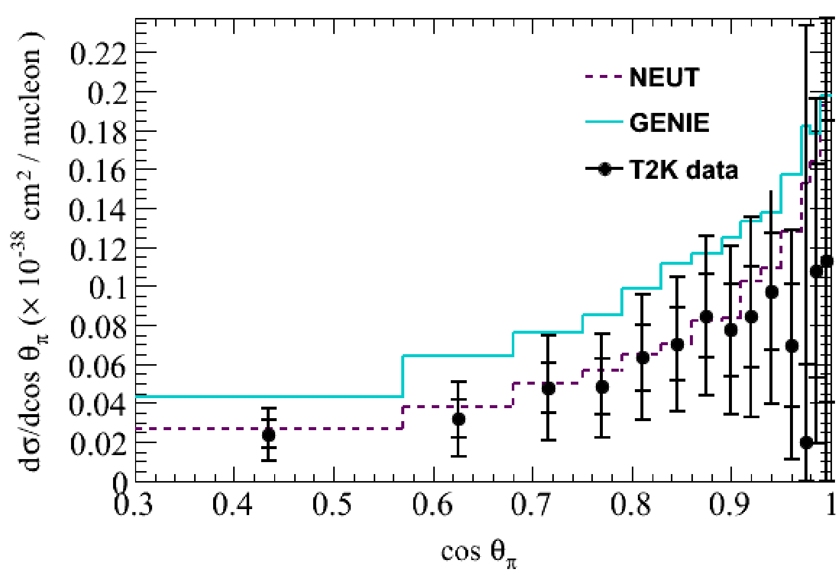






  - backgr. of carbon interactions constrained from data (also control regions for other CC interactions)
- Results :
  - data below GENIE as in MINERvA
  - suppression at π small angle (contribution from coherent CC1π)

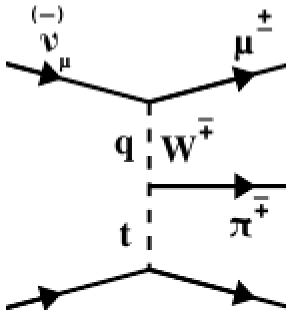




coming soon : T2K CC1π in Carbon with interesting angular studies...

CC1π coherent

- Small component (~1% of **CC**) :



- very small momentum transferred to the nucleus (**|t|**) which remains intact and unaffected

- may be a background to oscillation experiment when $\pi^{\pm}$ (NC π^0) mistagged as proton (electron)

- very large model uncertainties

  Rein-Seghal model: Adler theorem to relate pion-nucleus xsec to CC1π coherent at Q^2=0 and then approximation to go away from Q^2=0

  Alvarez-Ruso model is a microscopic model which computes diagrams with Δ resonance

- difficult to isolate → maturity of our experiments !

selection based on presence of only μ and π, **no energy released around the vertex (low vertex activity) and small |t|**

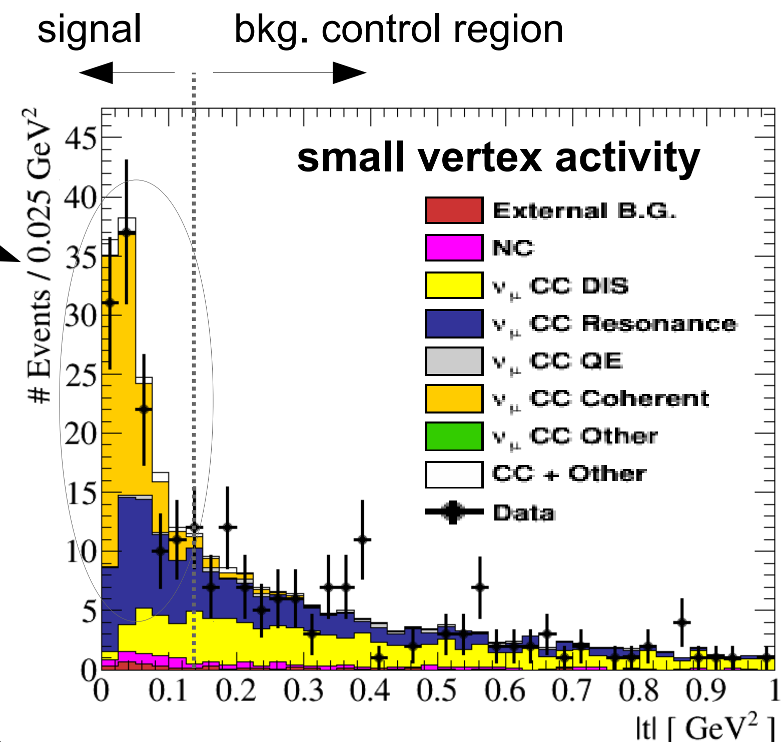
→ still model-dependence in acceptance corrections

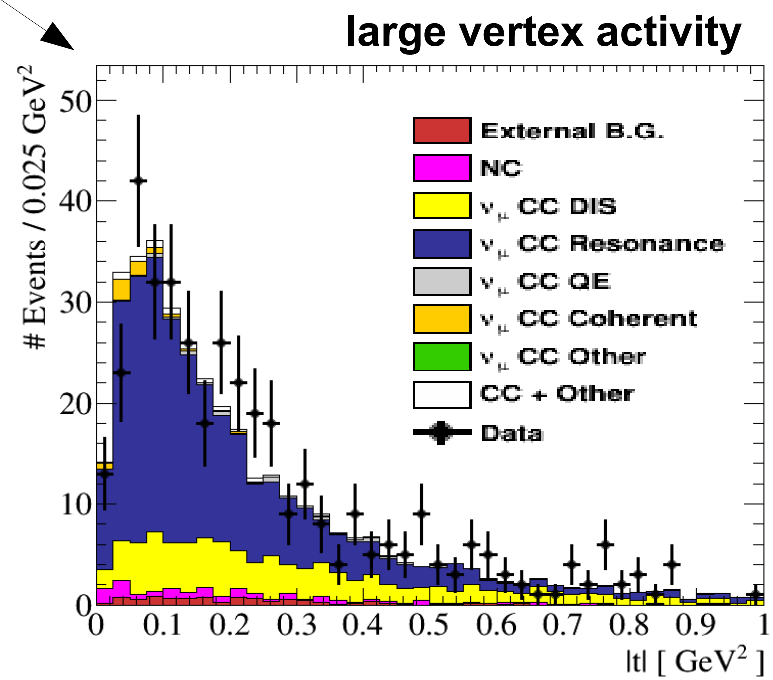
→ contamination of diffractive xsec on H : 5% T2K, 7% MINERvA

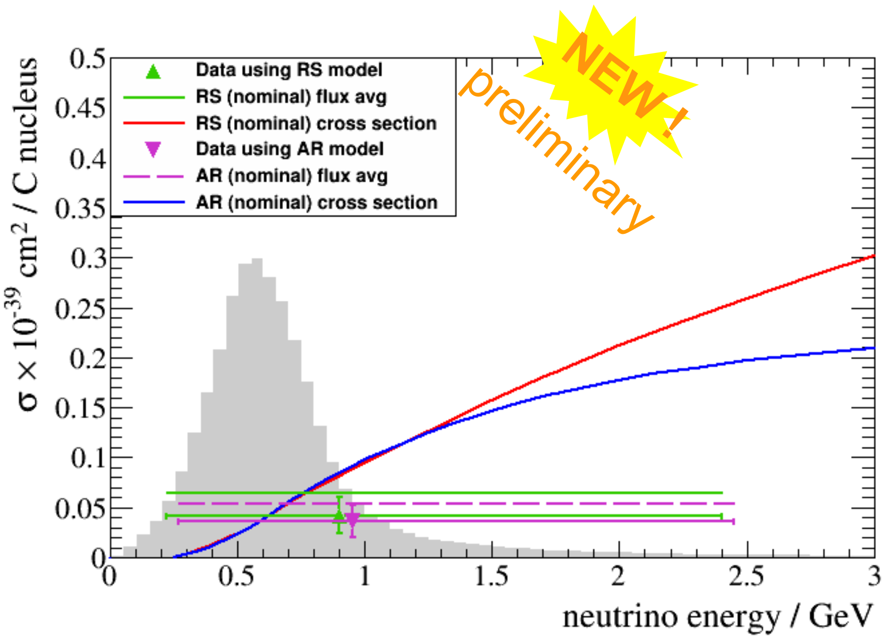
CC1π^+ coherent: T2K

- Signal region with small vertex activity and low |t| → **2.5σ indication of CC1π coherent**
- 2 control regions (large vtx activity and |t|) to fit background vs pion momentum and hadronic mass (MC suppressed by ~85%)

  → very good agreement of background tuned from data but still large backg. model uncertainties







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

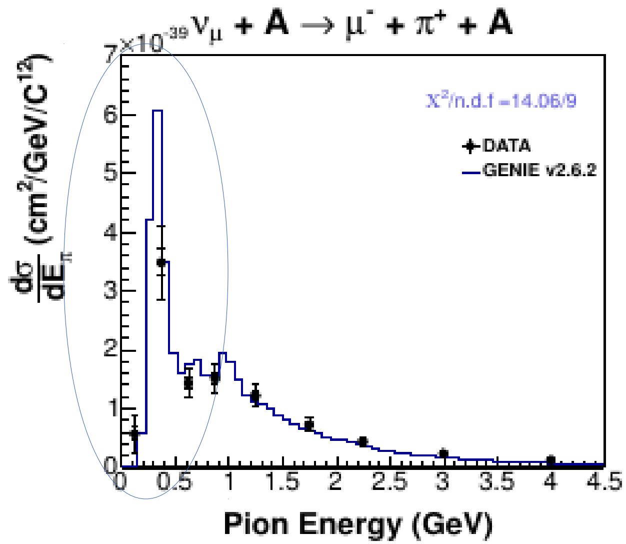
Minerva Collaboration,
Phys.Rev.Lett. 113 (2014) 26, 261802

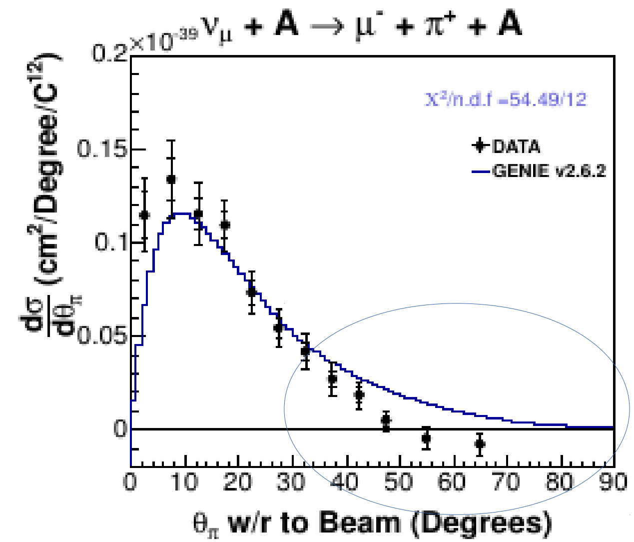
- Similar selection and background constraints in ν and $\bar{\nu}$ beams

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

- Enough statistics for a differential measurement

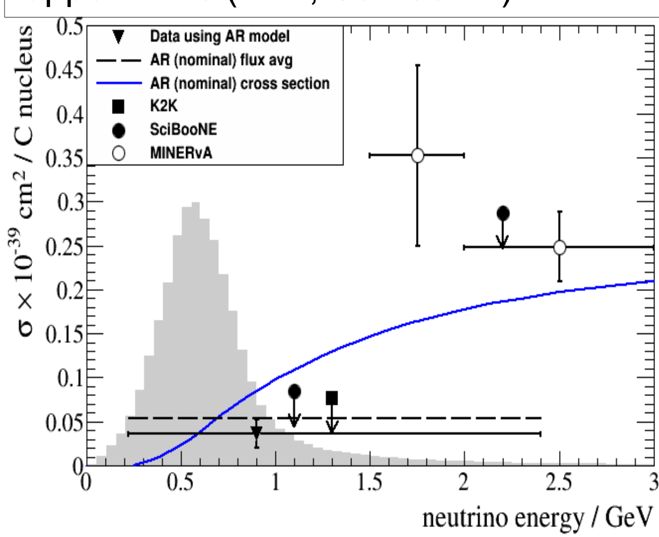
→ indication of **suppression at low π energy and large π angle wrt to Rein-Seghal model**



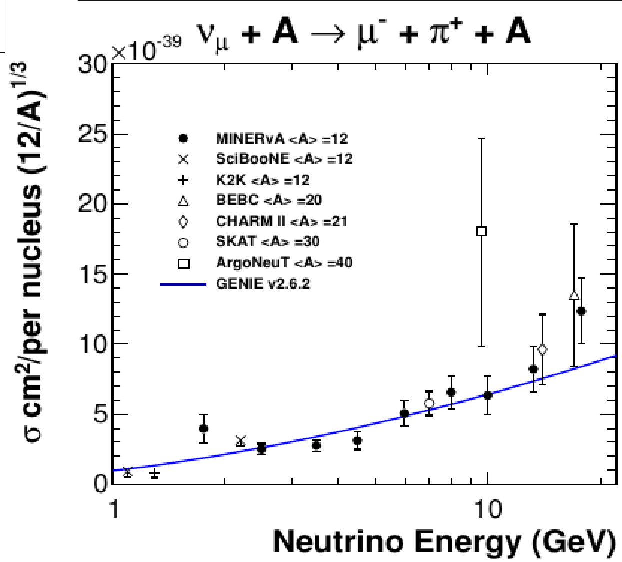


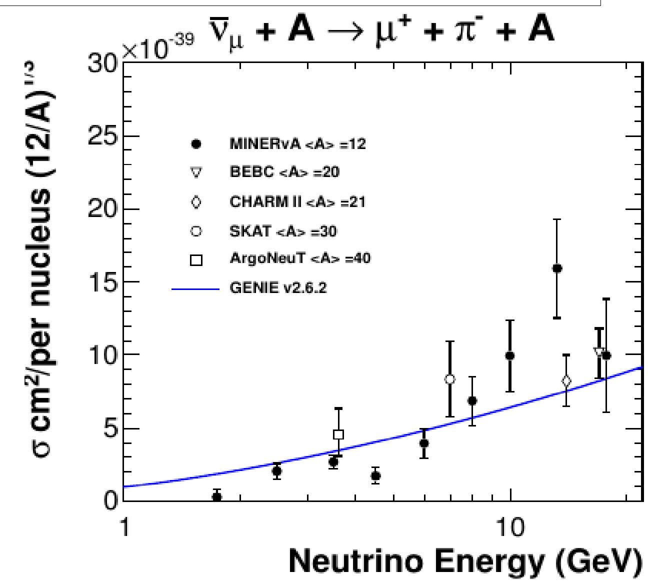
Total xsec:

at low energy first measurement from T2K: in agreement with previous upper limits (K2K, SciBooNE)



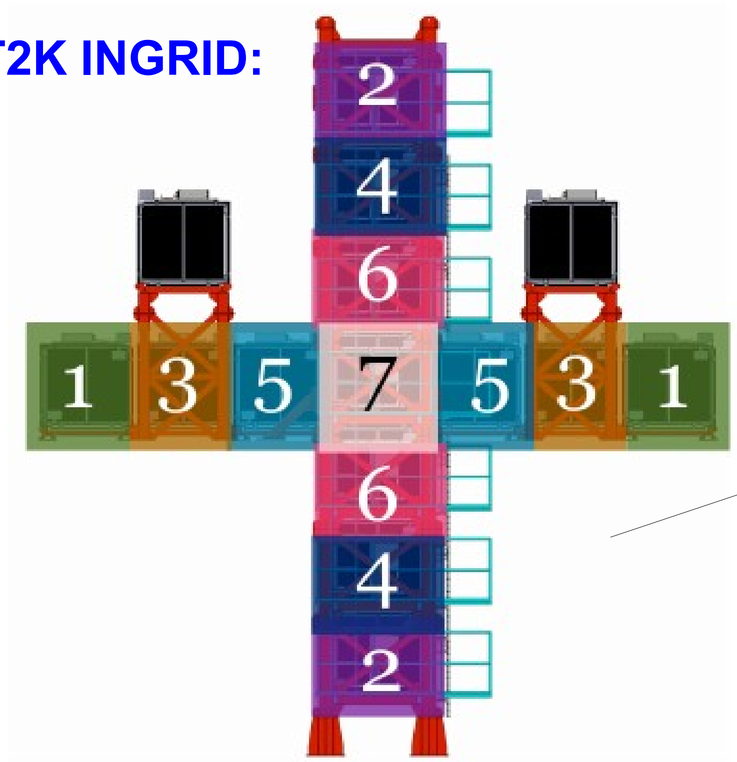
higher energy MINERvA agrees with previous measurements on different targets (eg ArgoNeut)

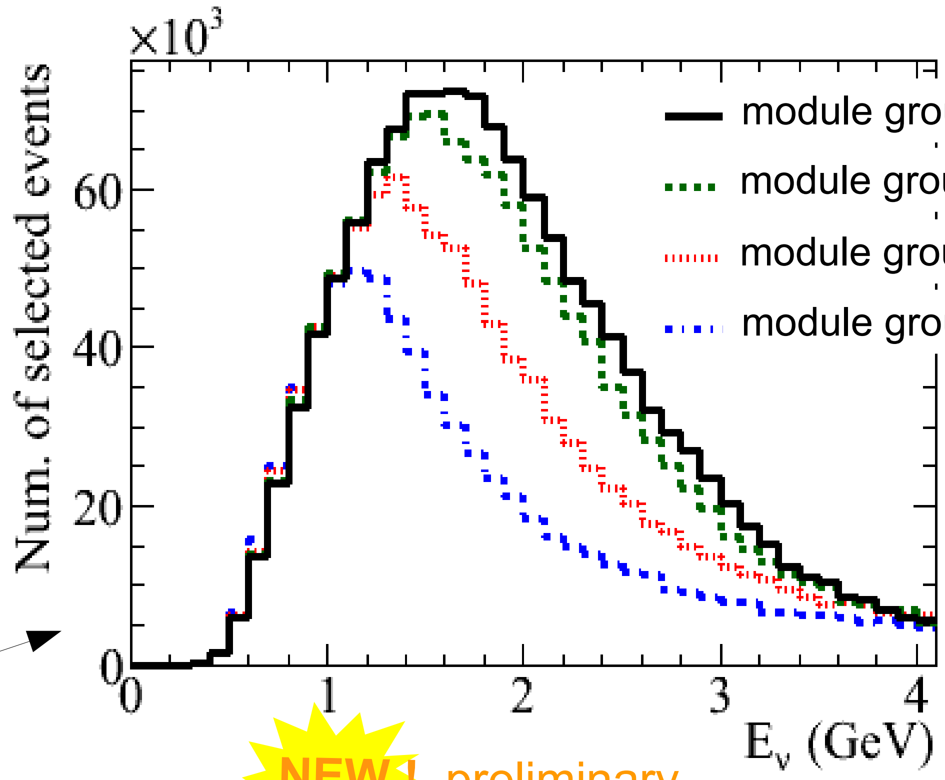




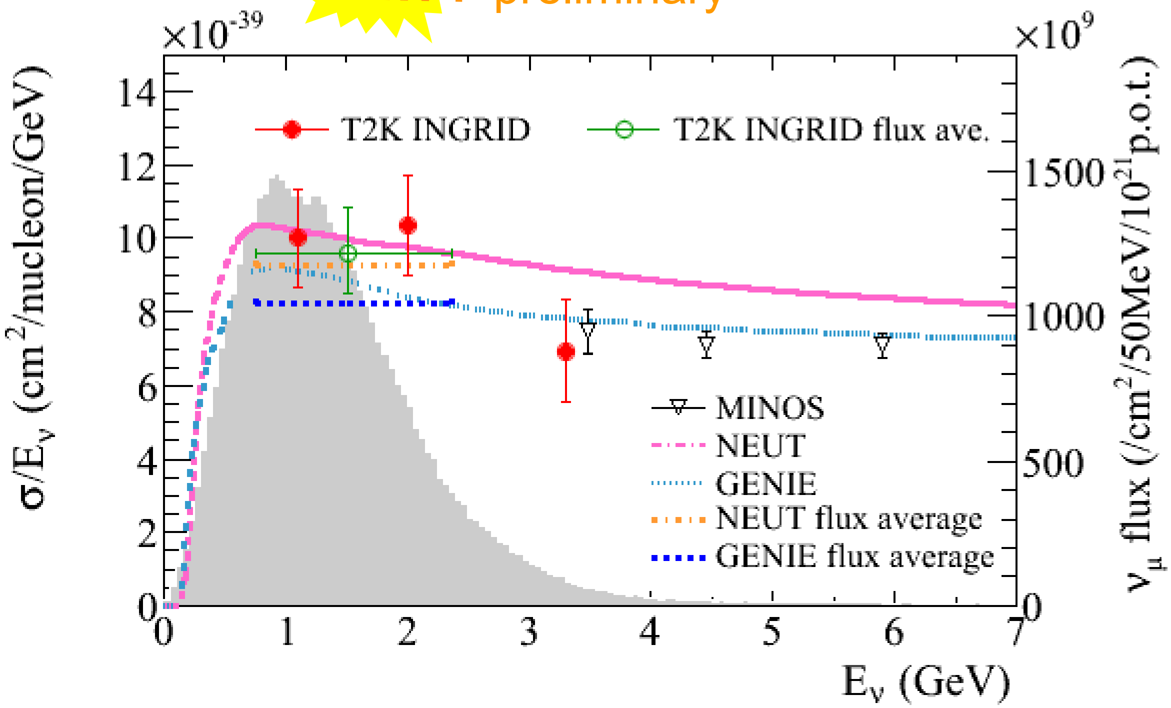
CC inclusive vs E_ν

T2K INGRID:





NEW ! preliminary



- Different off-axis angles correspond to different E_ν flux → **extract E_ν in a model independent way** (same concept of NuPrism)
- **Importance of good flux modelling**

Ratio between targets (CC inclusive)

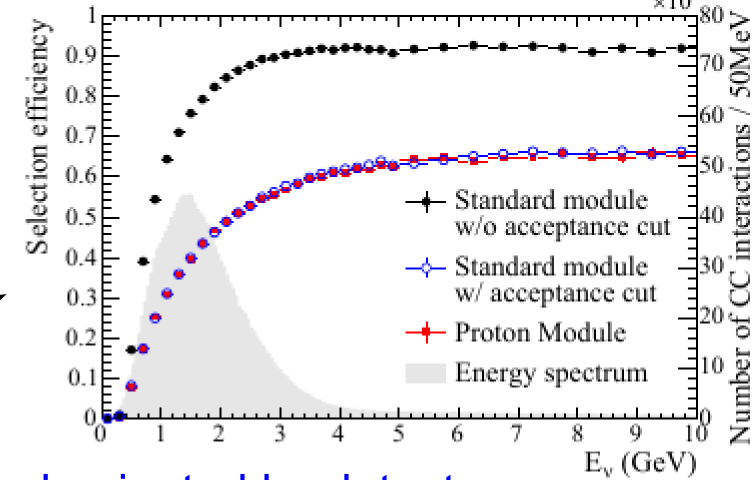
Useful to constrain nuclear effects (scaling with A)

- **T2K INGRID**: standard modules(Fe) / proton module(CH)

  → impose same acceptance to cancel systematics on xsec modelling and flux

$$\frac{\sigma_{CC}^{Fe}}{\sigma_{CC}^{CH}} = 1.047 \pm 0.007(stat.) \pm 0.035(syst.),$$ NEUT 1.037, GENIE 1.044

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



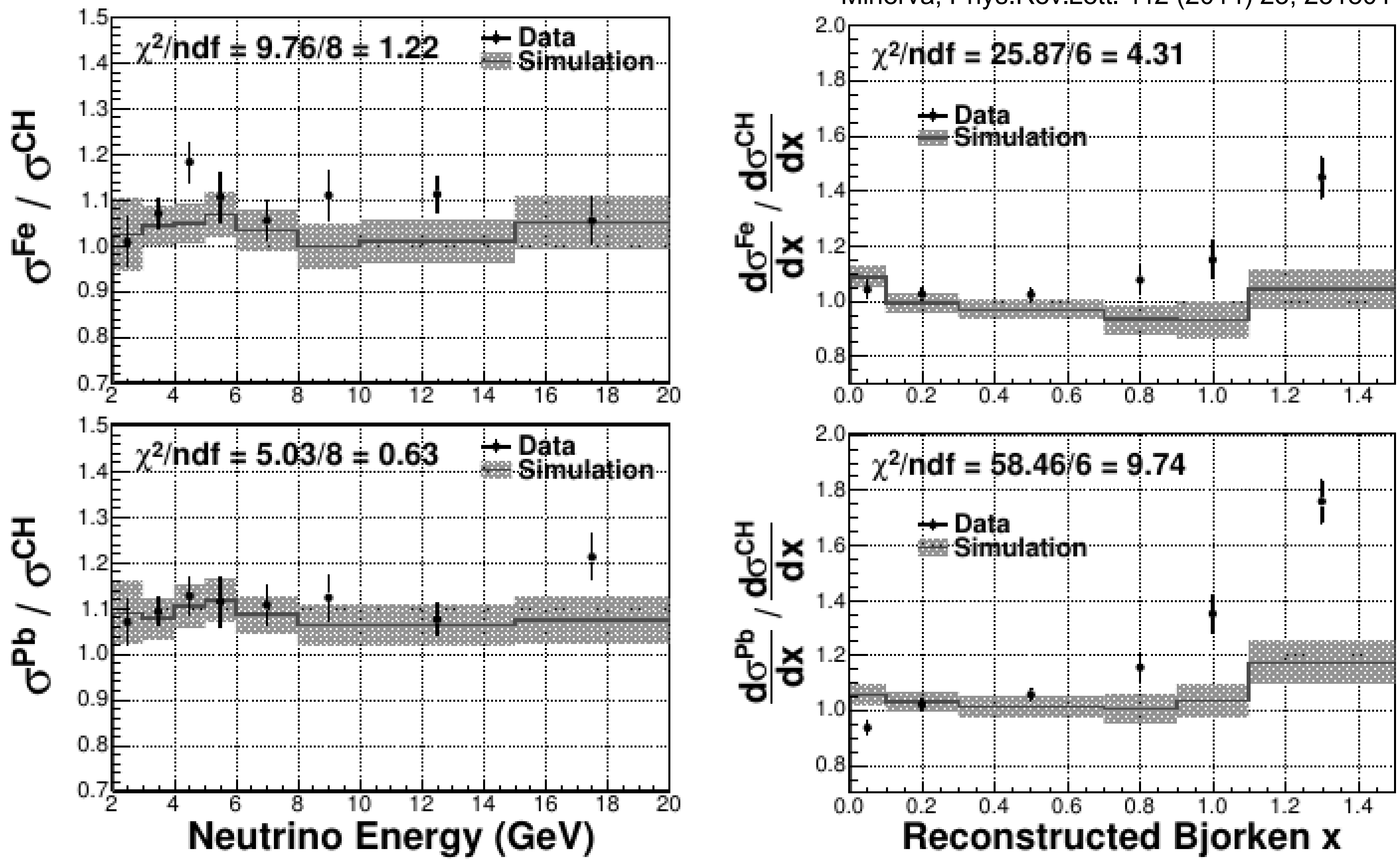
dominated by detector systematics (!)

- **MINERvA** : using upstream inactive targets
  - CH contamination (20-40%) constrained from data (2-8% uncertainty)
  - E_{had} from calorimetric energy deposited
    → Bjorken x

    $$x = Q^2 / (2 M_N E_{had})$$

  - **data/MC good agreement vs E_ν but not vs Bjorken x**

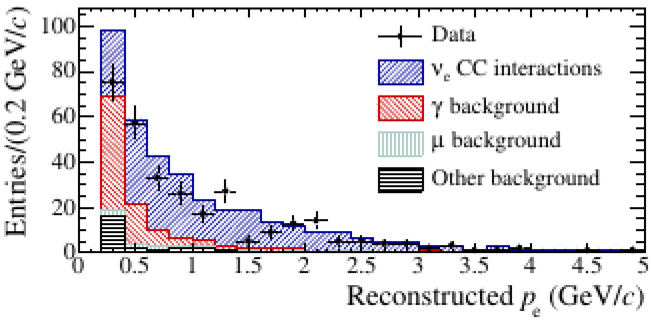
Minerva, Phys.Rev.Lett. 112 (2014) 23, 231801



T2K ν_e xsec

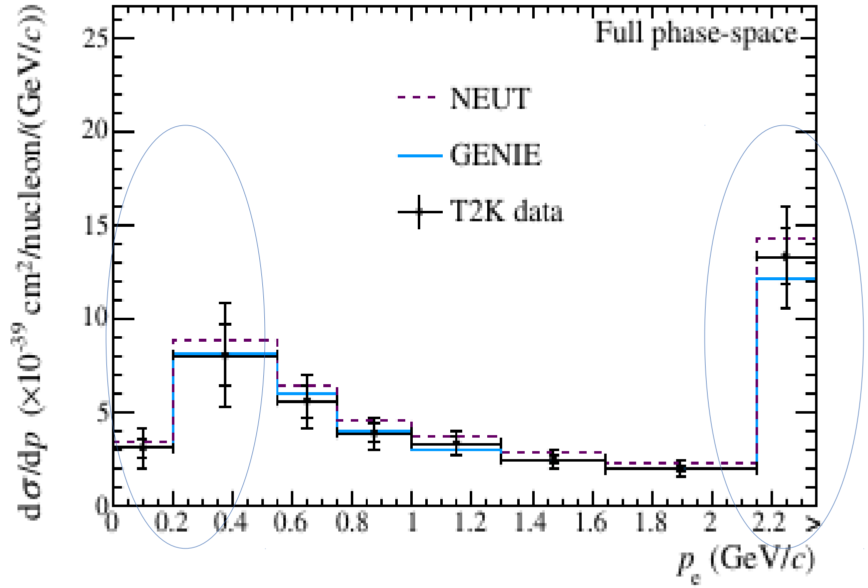
Important for oscillation : $\nu_\mu \rightarrow \nu_e$ appearance

- **ν_e on C**: flux ~1 % → stringent selection



unfolding

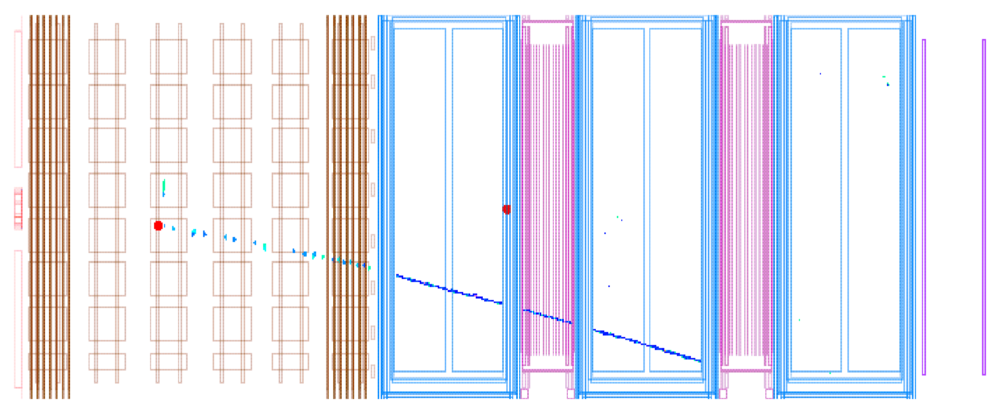
T2K Collaboration, Phys.Rev.Lett. 113 (2014) 24, 241803



- $\pi^0 \rightarrow \gamma$ background 70 % from out-of-fiducial-volume 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)**

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



- requires forward electrons (θ<45°) + shower/track variable to remove μ and π^0

	MC Signal	MC Background	MC Total	Data
Water	196.1 ± 4.8	56.7 ± 2.7	252.8 ± 5.5	230
On-Water	60.2 ± 2.6	14.5 ± 1.3	74.7 ± 2.9	
Not-Water	135.9 ± 4.0	42.2 ± 2.3	178.2 ± 4.6	
Air	173.6 ± 4.6	97.4 ± 3.6	271.0 ± 5.8	257

- subtraction of air data from water data
→ large statistical uncertainties (syst dominated by detector)

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

Conclusions and prospects

NEW CC0π measurement in T2K

- **CC0π under change of paradigm: study of MEC and 2p2h effects**
  - estimation of proper uncertainties for these new models and implementation in MC
  - need to gain control (both experimentally and in models) on hadronic part of final state (proton after FSI)

NEW CC1π on water T2K

- **CC1π:**
  - how to disentangle xsec uncertainties and large FSI effects
  - first measurements on coherent CC1π to constrain very large uncertainties for low |t|

NEW CC1π coherent in T2K

NEW CC vs E_ν in T2K

More measurements needed: hadronic (inclusive) variables, angular distributions (with large statistics), comparison of different targets, ν vs $\bar{\nu}$, ...

[many results shown today are the first measurements for that energy or target nuclei !!]

- Far from 1% normalization uncertainty **needed for δ_{CP} measurements** at DUNE and HK

  → crucial to keep investment on long term effort on neutrino xsec measurement

  complementarity of T2K and MINERvA (MicroBooNE...): measurements with different flux, acceptance, systematics, ...

BACKUP slides

Experimental status of neutrino scattering

S.Bolognesi (T2K, CEA Saclay)

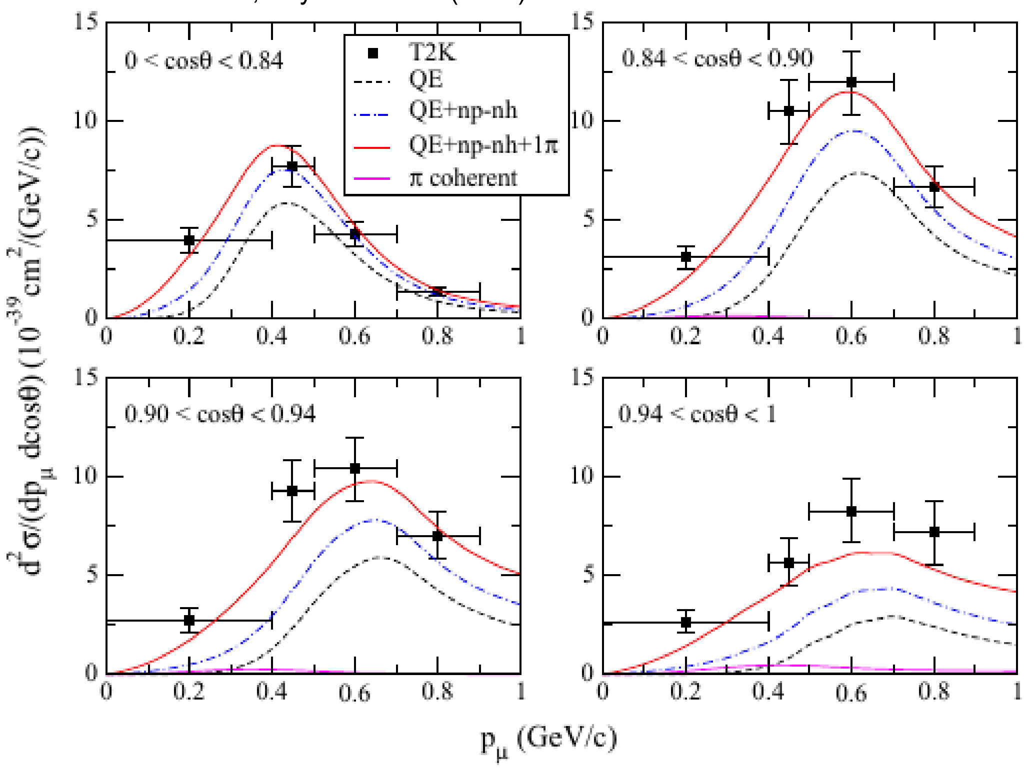
CC inclusive: T2K

- Simple analysis: require at least one muon (small background from NC and flux pollution $\bar{\nu}_\mu$)
- **Dominated by CCQE at T2K E_ν energy:**

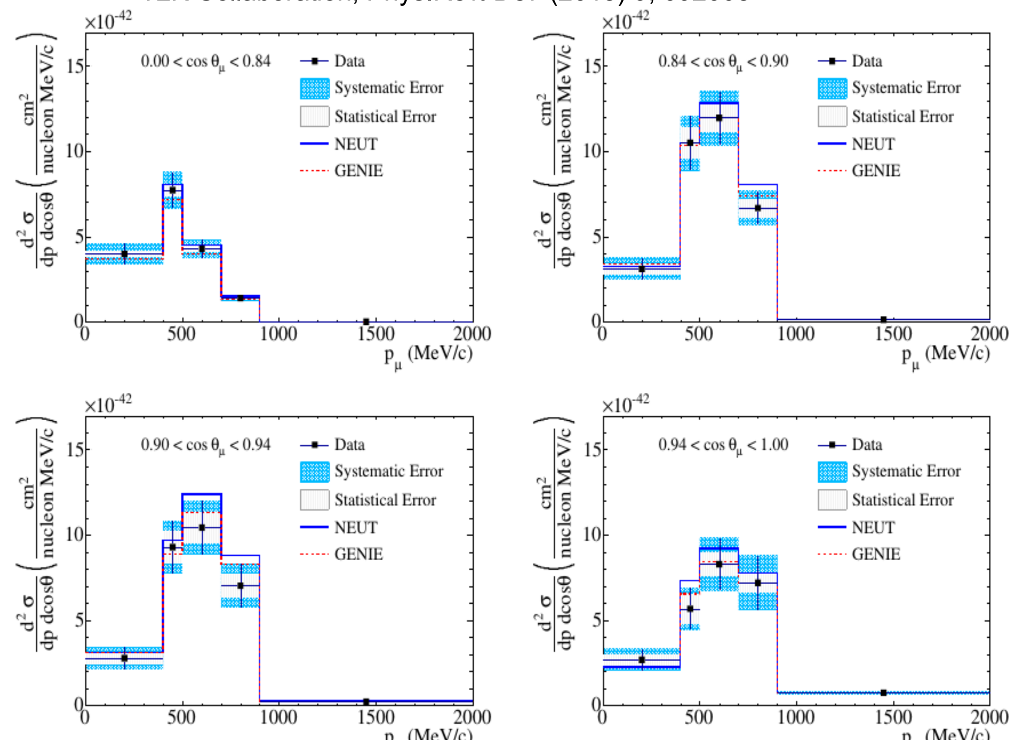
→ indications in favour of new models with 2p2h

→ agreement also with old tuned models

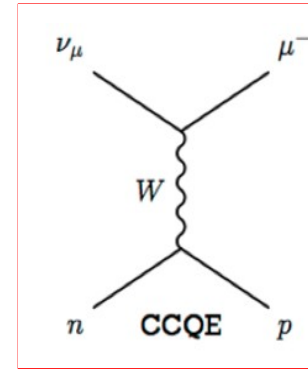
Martini et al, Phys.Rev. C90 (2014) 025501



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



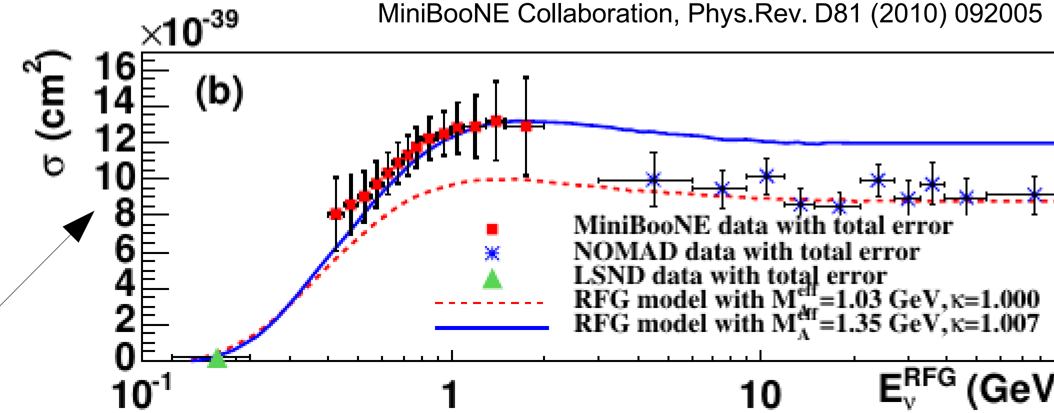
Charged Current Quasi-Elastic



- **Dominant contribution at T2K flux** : QE approximation assumed to compute E_ν (from E_μ) for all selected events in Super-Kamiokande
  → **wrong modelling would cause bias on oscillation parameters**

- **MC description based on**
  - form factors tuned from ep scattering (M_V) and νH xsec in bubble chamber (M_A, deuterium)
  - nuclear effects : Relativistic Fermi Gas with Pauli blocking
  (+ FSI in MC cascade models)

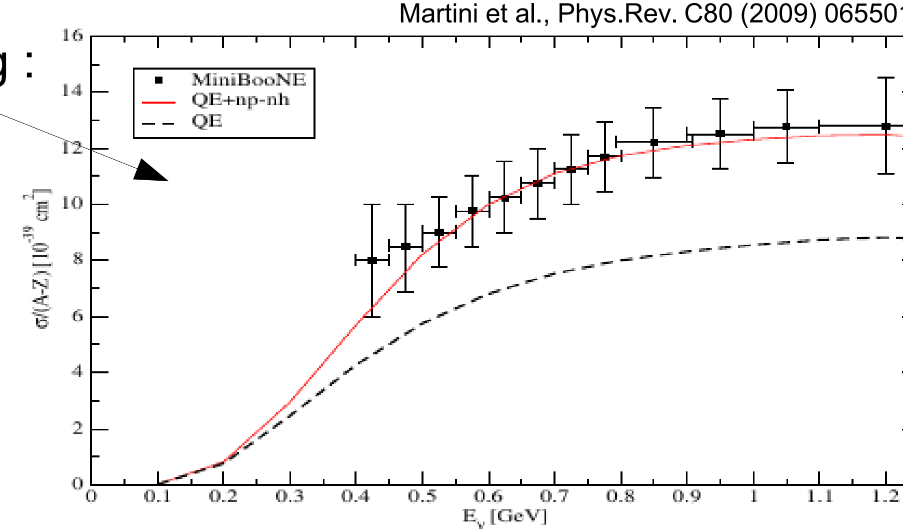
MiniBooNE Collaboration, Phys.Rev. D81 (2010) 092005



- **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)

  Effort ongoing to include them in MC

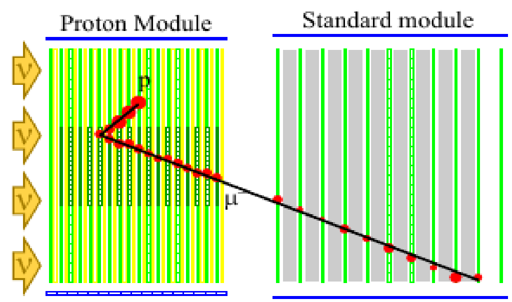
Martini et al., Phys.Rev. C80 (2009) 065501



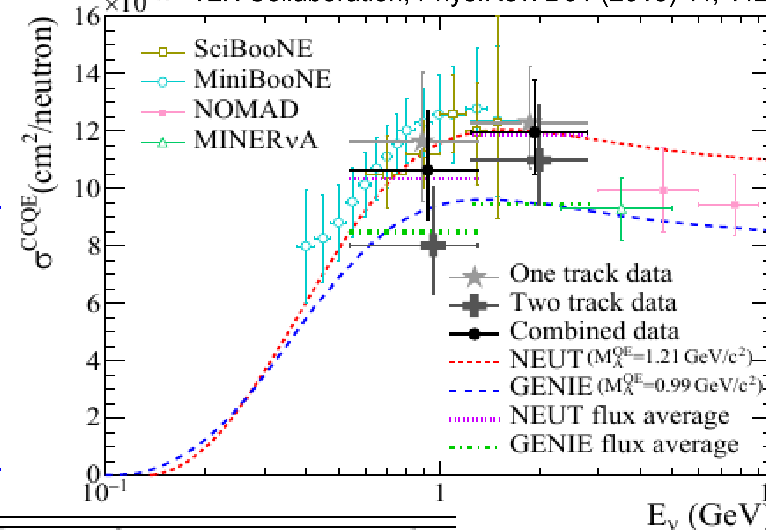
- **Final State Interaction only included in MC models**: CC1π with pion re-absorption included in signal (CC0π)

CC0π: proton kinematics

- **T2K on-axis INGRID**: separate only pure CCQE (kinematics cuts against FSI, and 2p2h) → large model dependence : discrepancy btw mu only and mu+p → **models do not describe well the proton kinematics**

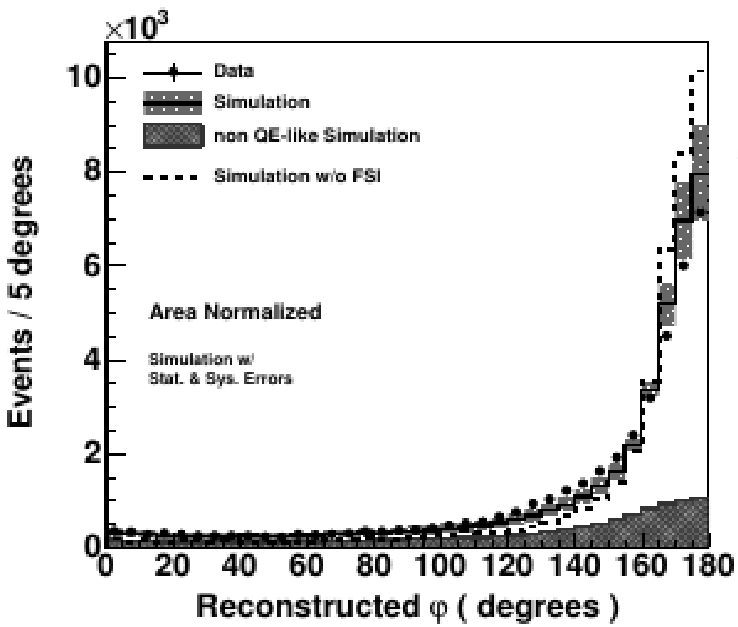


T2K Collaboration, Phys.Rev. D91 (2015) 11, 112002

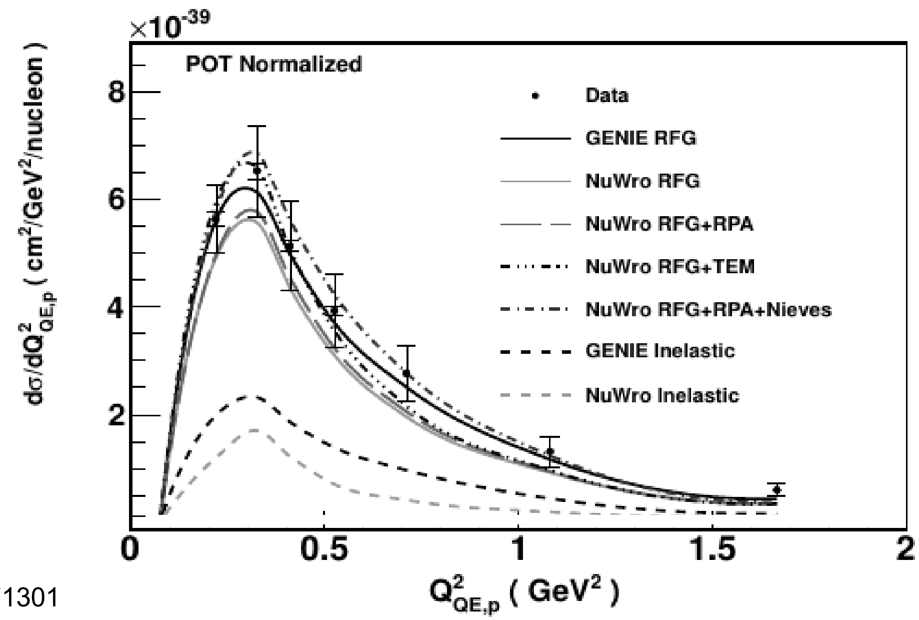


Nuclear model in MC	Ratio of cross-section results
Relativistic Fermi gas model	$1.45 \pm 0.09(stat.)^{+0.24}_{-0.29}(syst.)$
Spectral function	$1.25 \pm 0.08(stat.)^{+0.22}_{-0.26}(syst.)$

- **MINERvA** more inclusive : mu + at least 1p (no pions) and no cuts against FSI → still dominated by model uncertainties through proton/muon acceptance and pion rejection



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

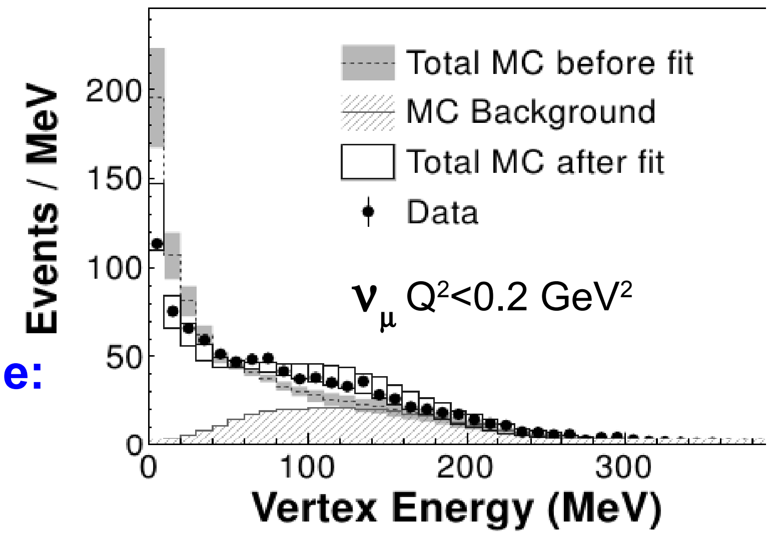


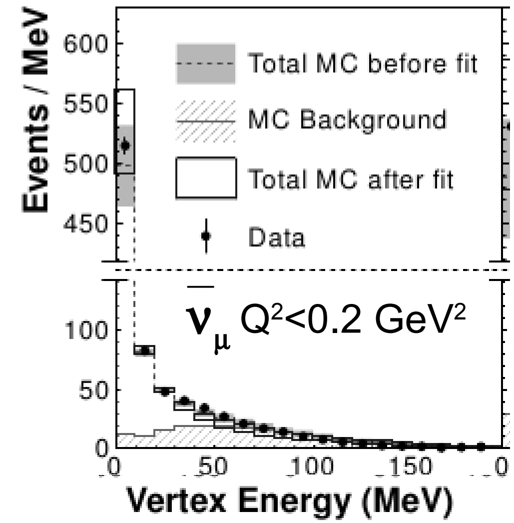
Minerva Collaboration, Phys.Rev. D91 (2015) 7, 071301

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)

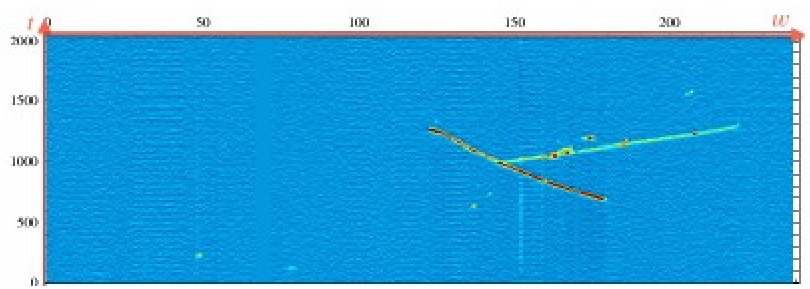
- **back-to-back protons before FSI:**

  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

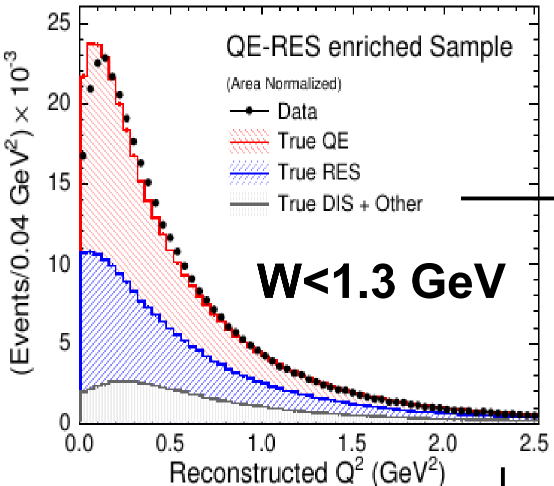
from analogy to electron-N and hadron-N scattering

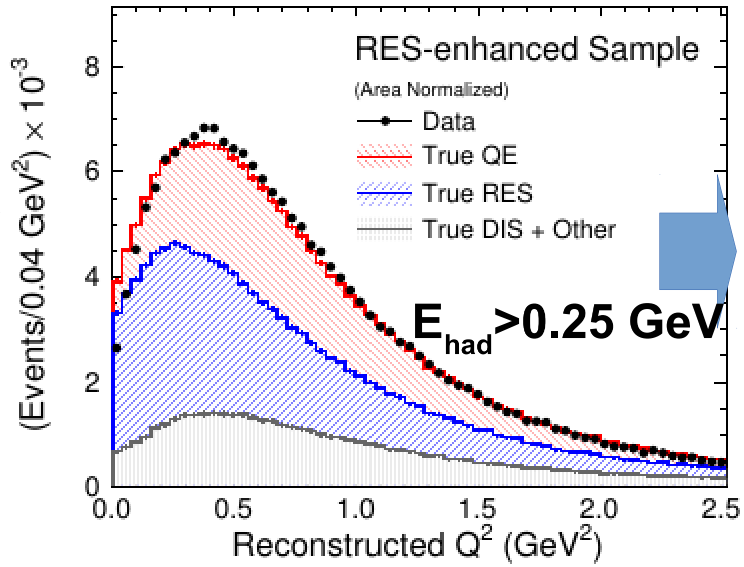


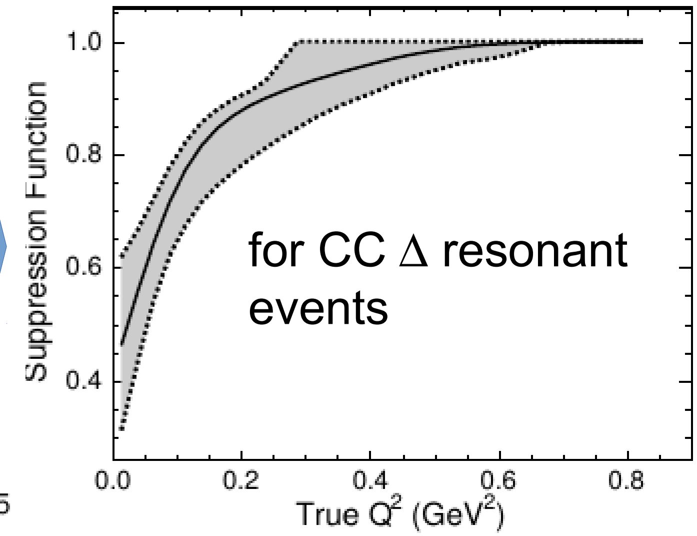
More precise quantitative analysis need improved models for interpretation of experimental data (including FSI!)

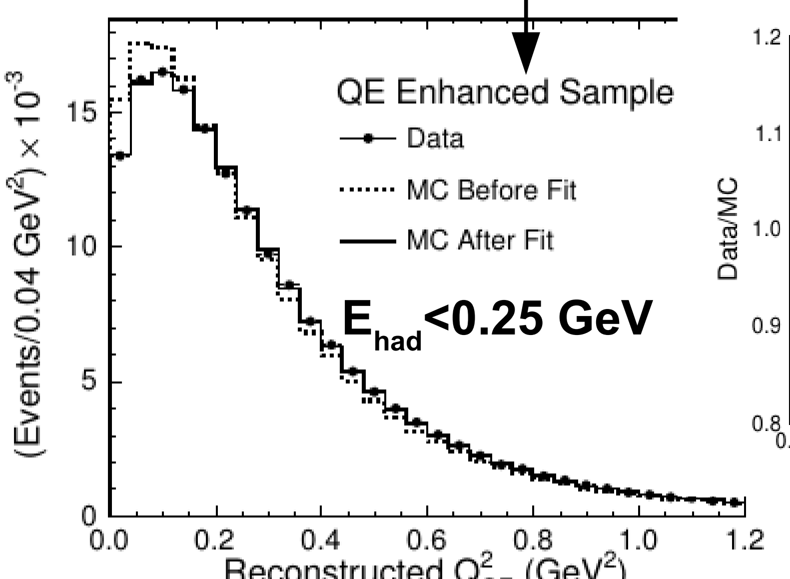
MINOS: CCQE

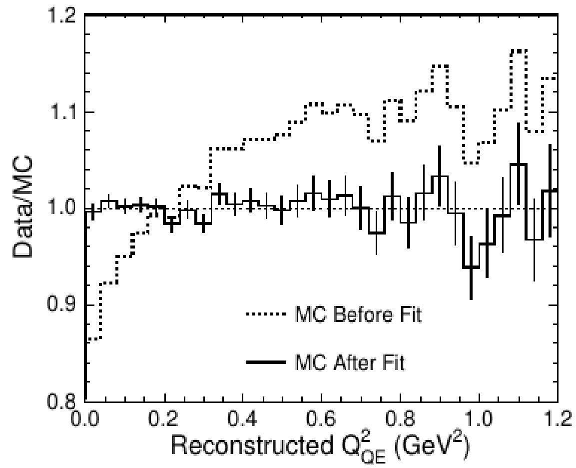
Effective parametrization for background constraint and signal (M_A^{QE})











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

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

M_A^{QE} well above measurement from bubble chamber

→ modern explication: 2p2h contribution

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

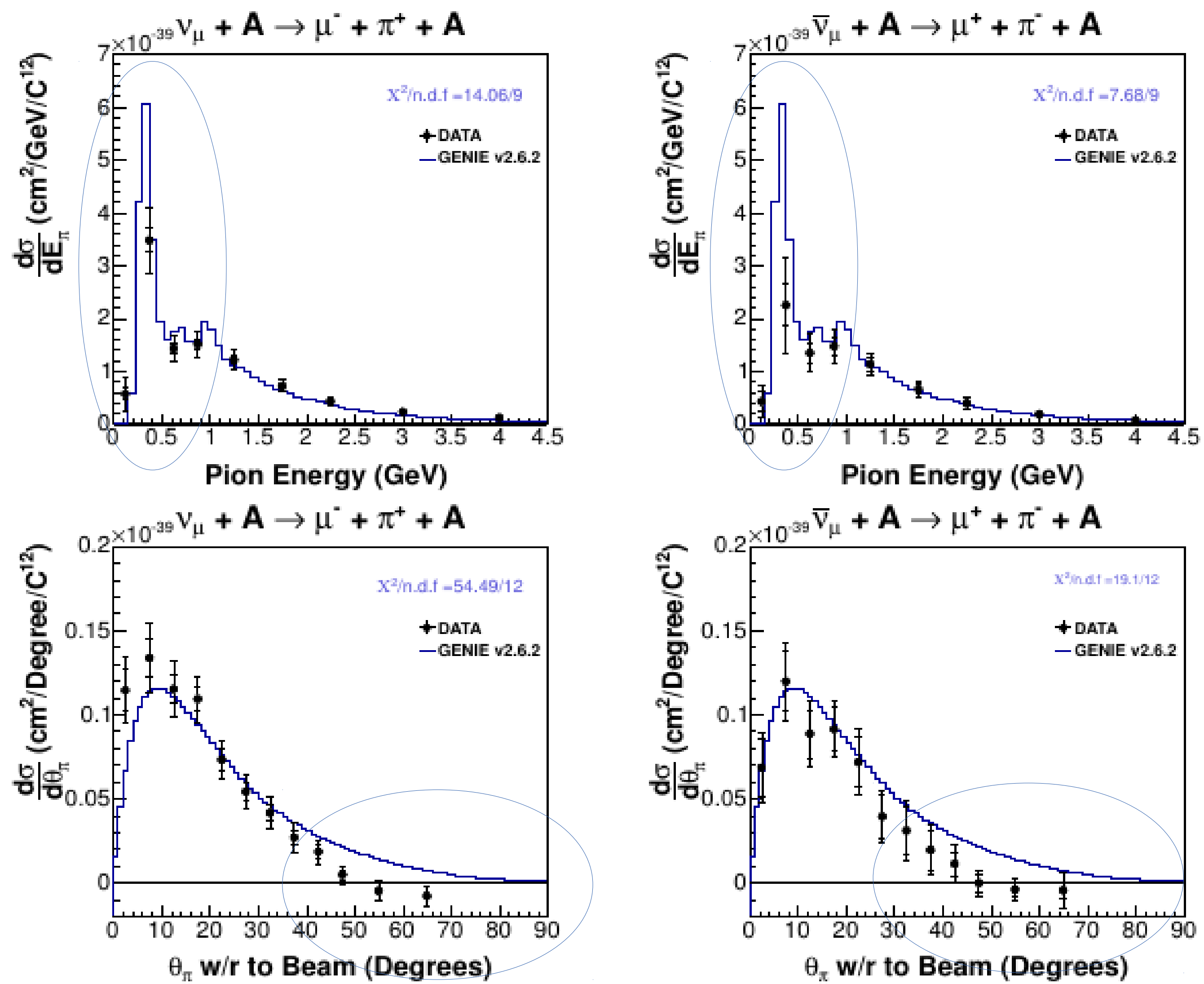
- Similar selection and background constraints applied to ν and $\bar{\nu}$ beams

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

- Enough statistics for a differential measurement

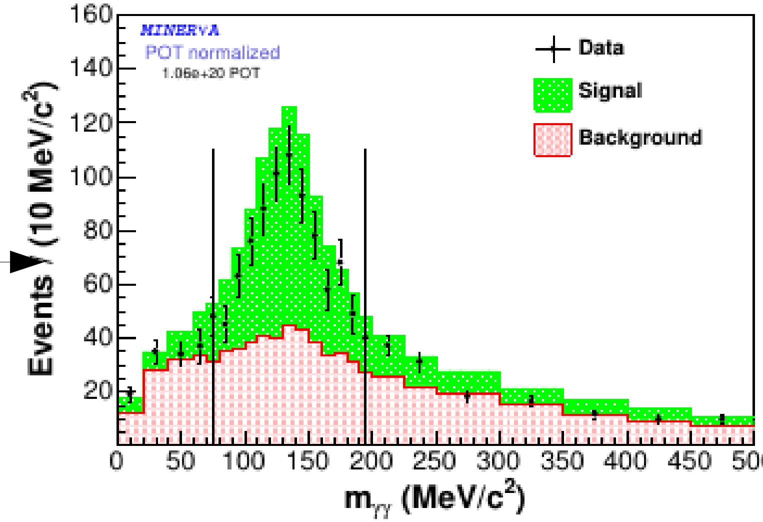
→ indication of **suppression at low π energy and large π angle wrt to Rein-Seghal model**

- systematics dominated by model uncertainties

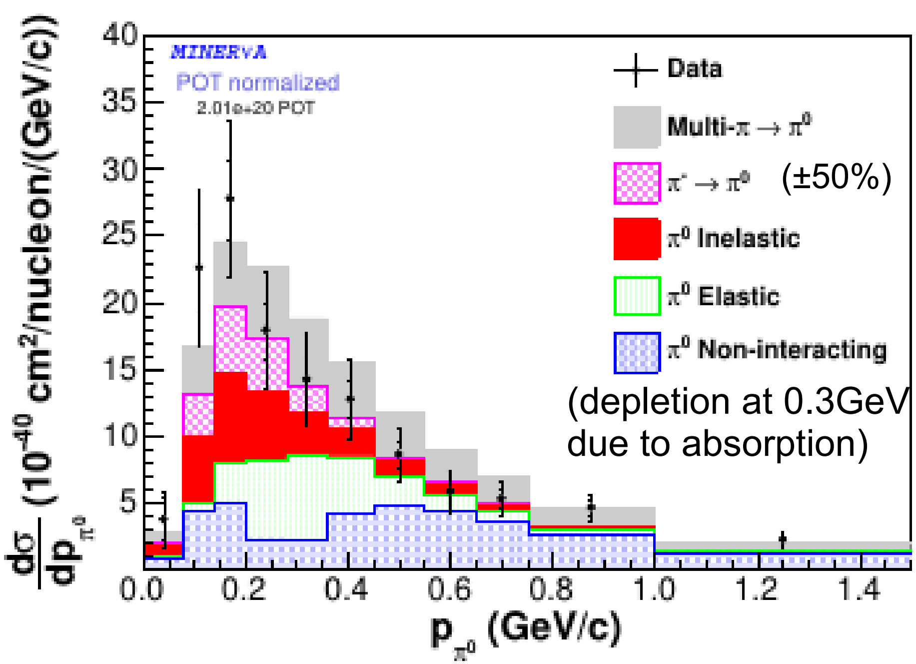


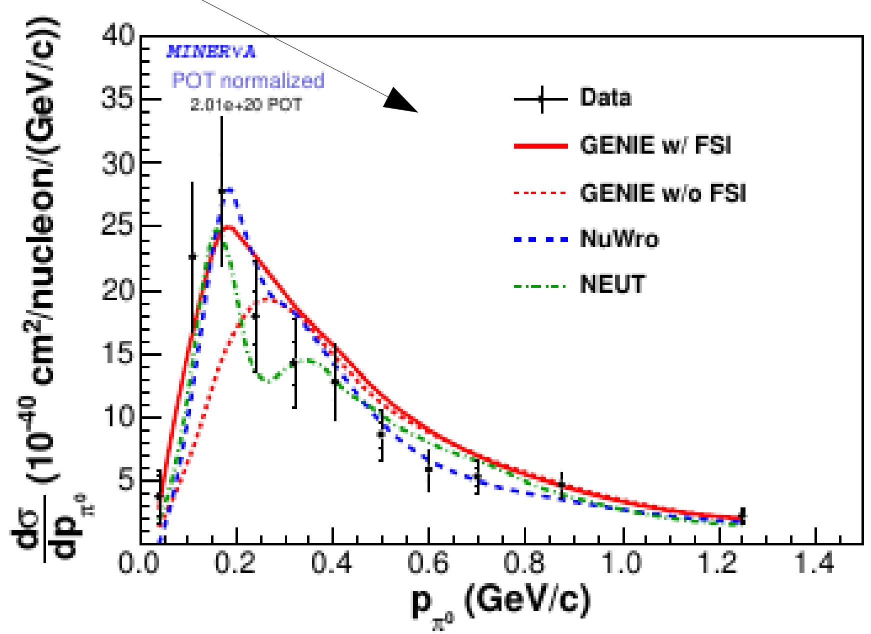
MINERvA : π^0 from CC in $\bar{\nu}$ beam

- 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 $\pi^\pm$



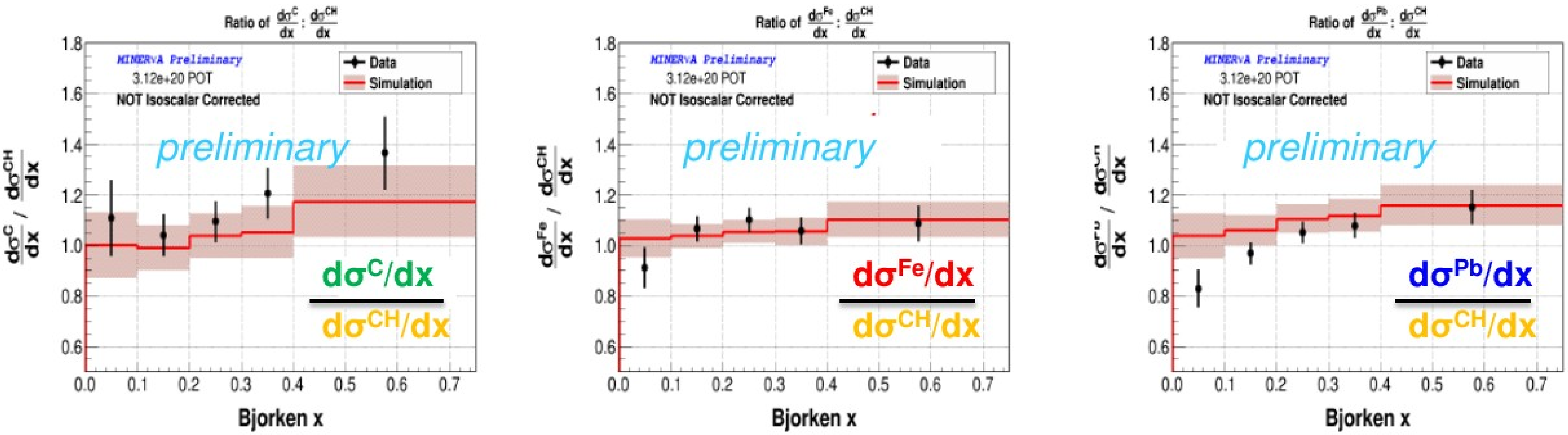
- Results: only 20% signal has no FSI
  → results indicate preference for presence of FSI





A.Bravar
EPS 2015

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



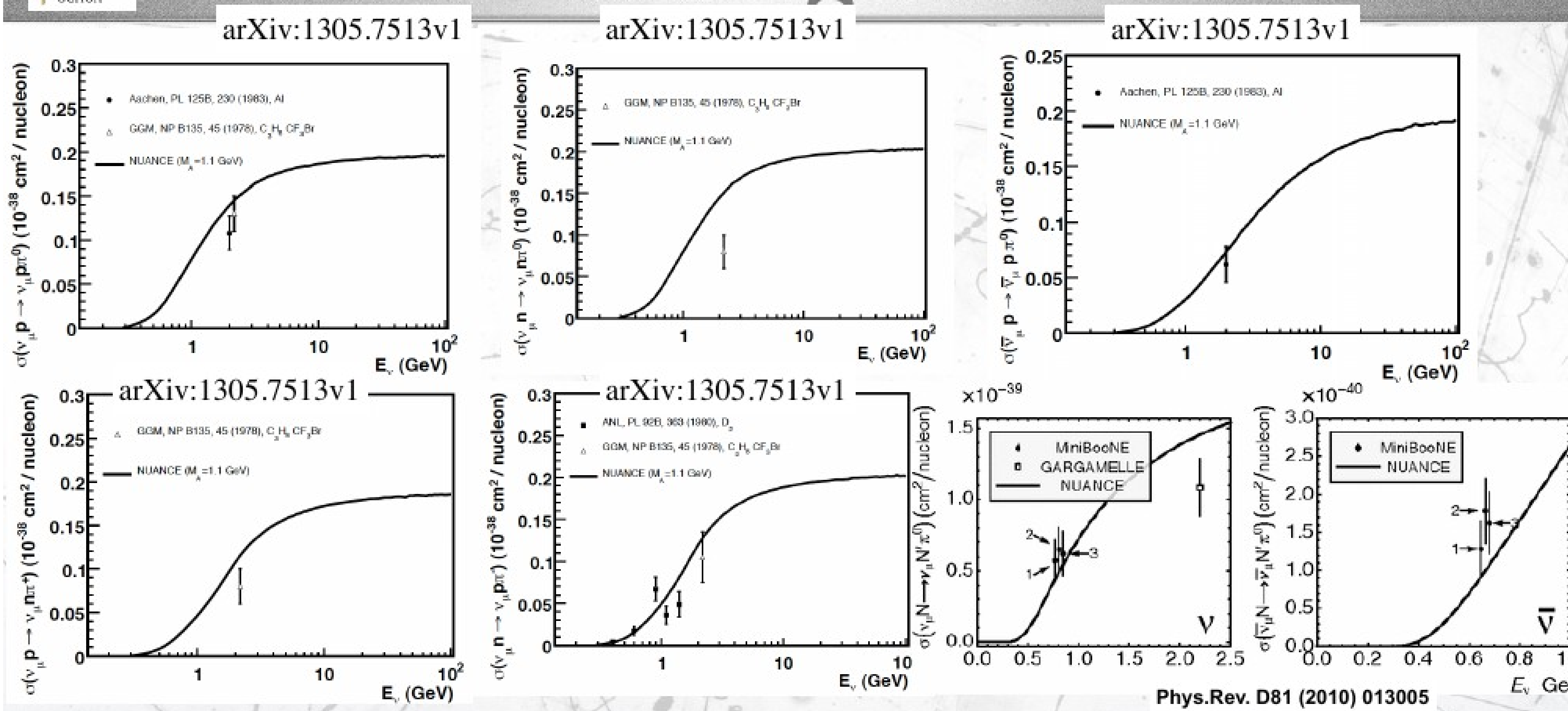
Select DIS sample by requiring $Q^2 > 1$ GeV^2 and $W > 2$ GeV
(these cuts remove the quasi-elastic and resonant background)

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

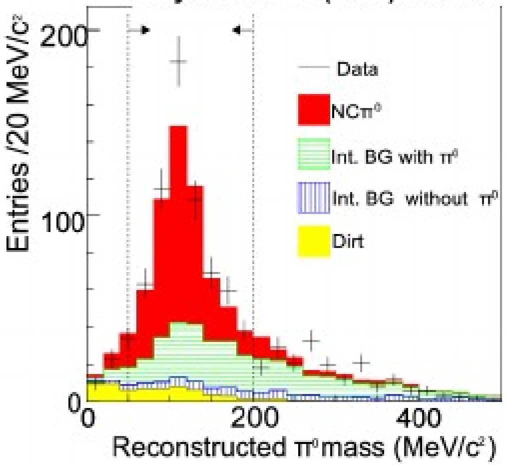


- 30 years old and sparse data && MiniBoone (2009).
- No new results in Nuint'14.
- Important background for ν_μ disappearance ($NC\pi^+$) νe appearance. ($NC\pi^0$)
- ν sterile searches!

F.Sanchez
Neutrino 2014

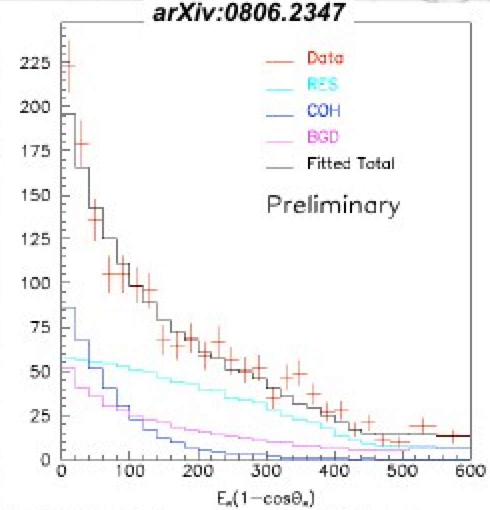
Recent results

Phys.Rev. D81 (2010) 033004



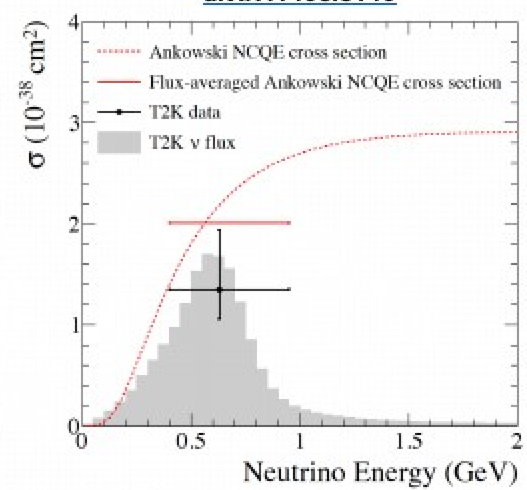
2010 SciBoone NCπ^0/CC

arXiv:0806.2347



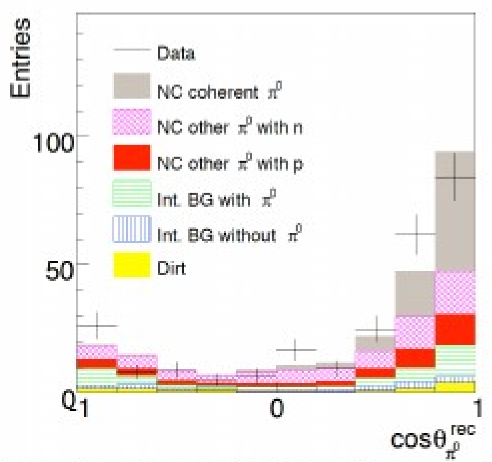
2008 MiniBoone NCπ^0 Coherent.

arXiv:1403.3140



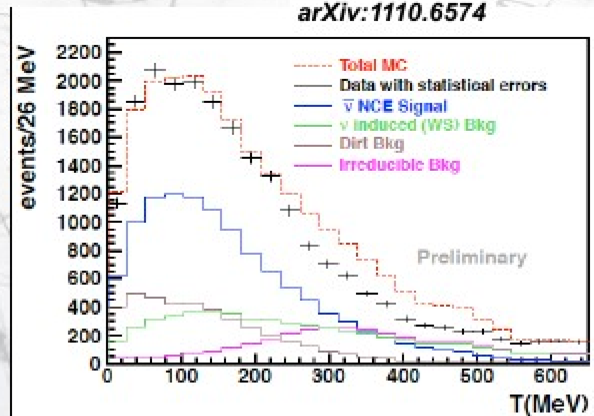
2014 T2K NC-QE from nuclear de-excitation γ rays.

Phys.Rev. D81 (2010) 111102



2010 SciBoone NCπ^0 coh.

arXiv:1110.6574



2011 MiniBoone NC elastic.

2014 T2K NC π^0 (poster)

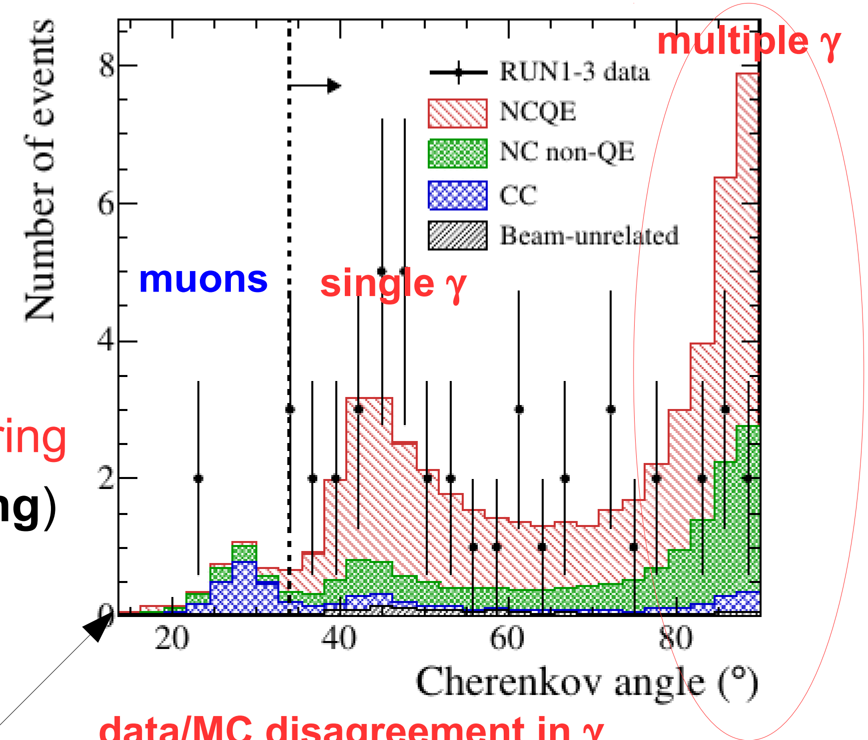
Beyond oscillation analysis

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

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

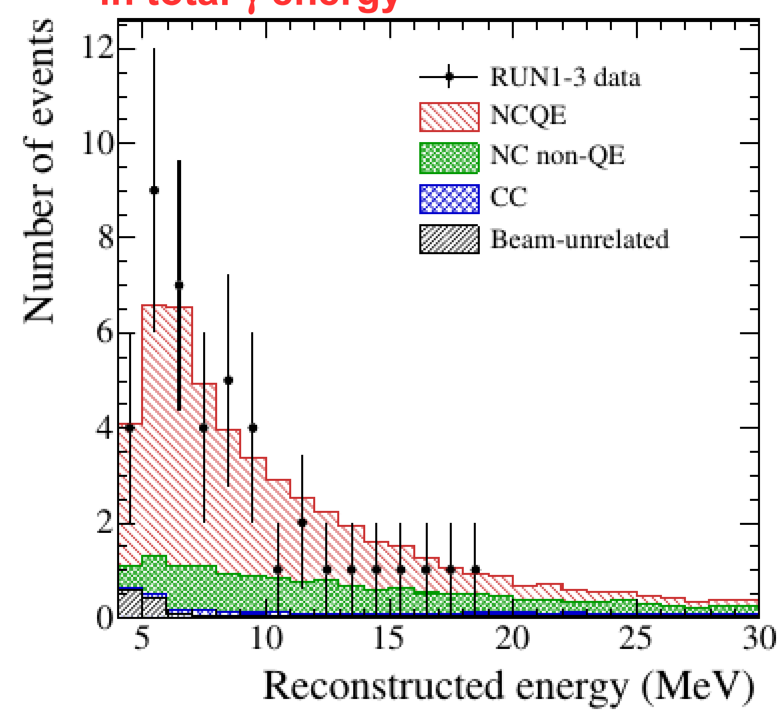
→ primary deexcitation γ + secondary γ from p scattering

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



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

- 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)