NEUTRINO INTERACTIONS AND XSECTS IN THE NEXT DECADE

i.e.

what will and will-not have been measured after MicroBooNE era?

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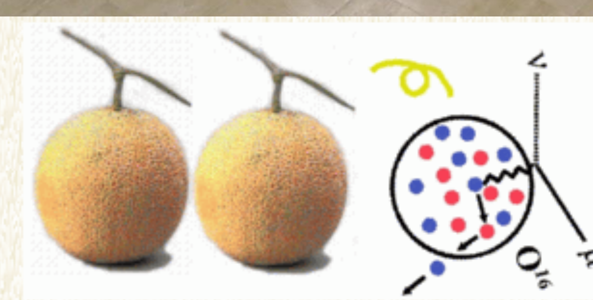
Nov. 21, '13

... the risk of slipping into trite remarks is extremely high

to project in time by 10-12 yrs from now,
it could be helpful to first go back in time by 10-12 yrs
and
evaluate achievements and pace of progress since then.

This may give some support for projections and guesses

WHERE WERE WE 12 YRS AGO?



NuInt01 : The First International Workshop on Neutrino-Nucleus Interactions in the Few GeV Region

December 13-16, 2001, KEK, Tsukuba, Japan

Available at that time

M. Sakuda (summary talk)

1. Data

- Most of the experimental data of ν–interactions were taken with bubble chambers.

1. CERN Heavy Liquid BC (Freon, Propane)
2. Gargamelle (Freon, Propane)
3. BNL 7 – foot H_2/D_2 BC
4. ANL 12 – foot H_2/D_2 BC
5. CERN BEBC
6. BNL E734 fine-grain detector
7. SKAT BC →Ammosov
8. IHEP-JINR → Vovenko

Summary

- Past experimental data are still very valuable.
- Ask old experiments to make data tables and reanalalyse/estimate (ratio of) the cross sections.
  →PDG listing (Currently no reaction tables)
  This will certainty help us reduce our systematic errors.
- Future near detectors with narrow-band beam will Update the cross sections. Or HARP will measure π/K

(collected from 1979 to1995)

+ NOMAD Data (already collected)

- from Preface of the NuInt01 Proceedings -

The NuMI / MINOS project at Fermilab and the CNGS project at CERN are under construction and expecting to begin taking data within the next 2 - 4 years. These experiments are designed to improve the precision of the measurements of neutrino oscillation parameters. In addition, the short-baseline MiniBooNe experiment at Fermilab is on-schedule to begin data-taking this summer.

As these experiments accumulate increasingly-large data sets, the contribution of systematic errors will become more significant in the oscillation analysis. Important sources of these systematic errors are the uncertainty in the neutrino-nucleus cross sections and subsequent nuclear effects in the few GeV energy region such as Fermi motion, Pauli blocking, nucleon binding, nuclear correlation, shadowing, the "EMC" effect and final-state interactions. To better understand these sources as they apply to neutrino scattering will be essential for the K2K, MiniBooNe, MINOS and CNGS experiments as well as the planned neutrino oscillation experiments at JHF-Kamioka, future atmospheric neutrino experiments and next generation proton-decay experiments. Considering the above situation, the organizers believed it was a propitious time to organize an international workshop on this subject.

CC-Inclusive XSECT

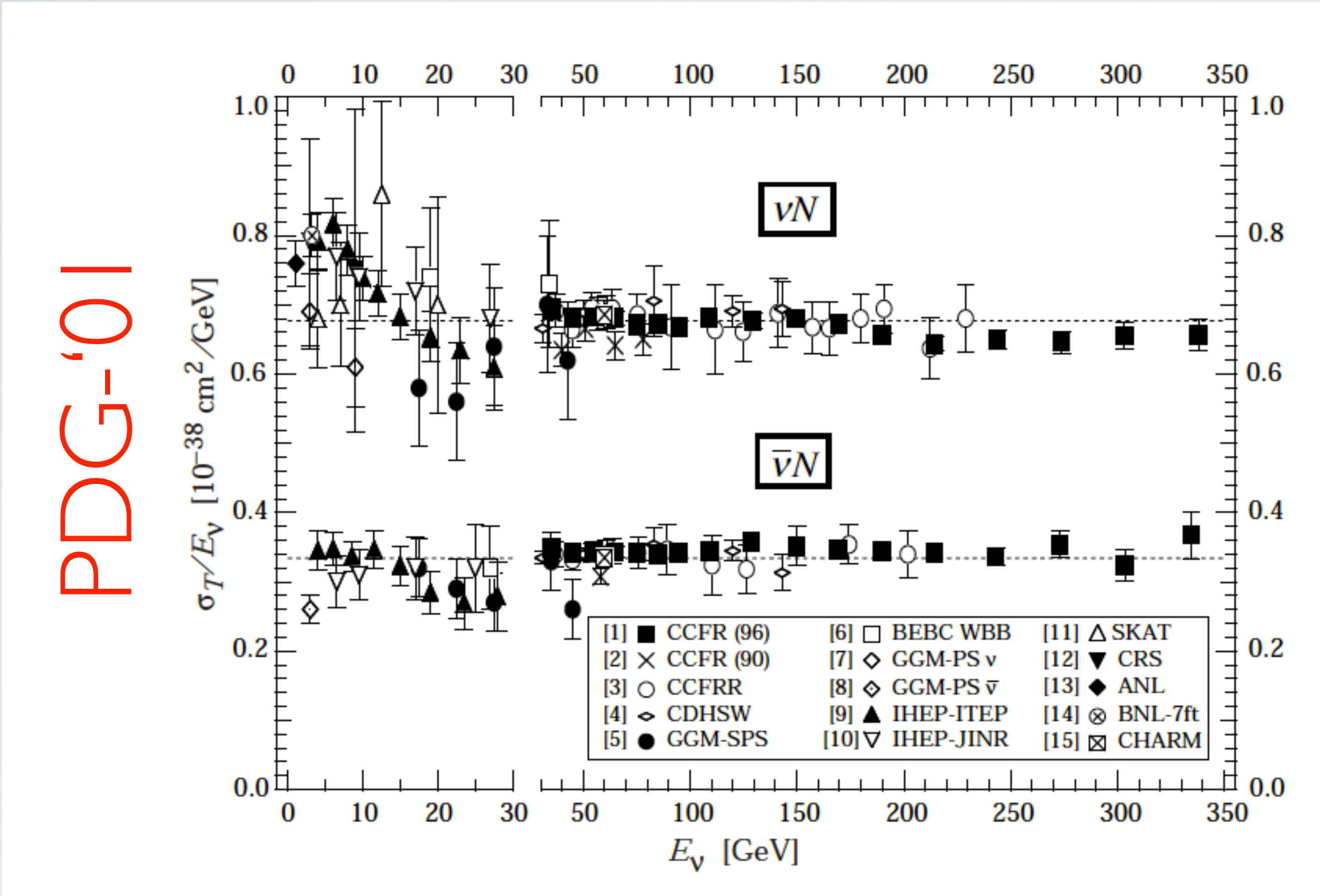
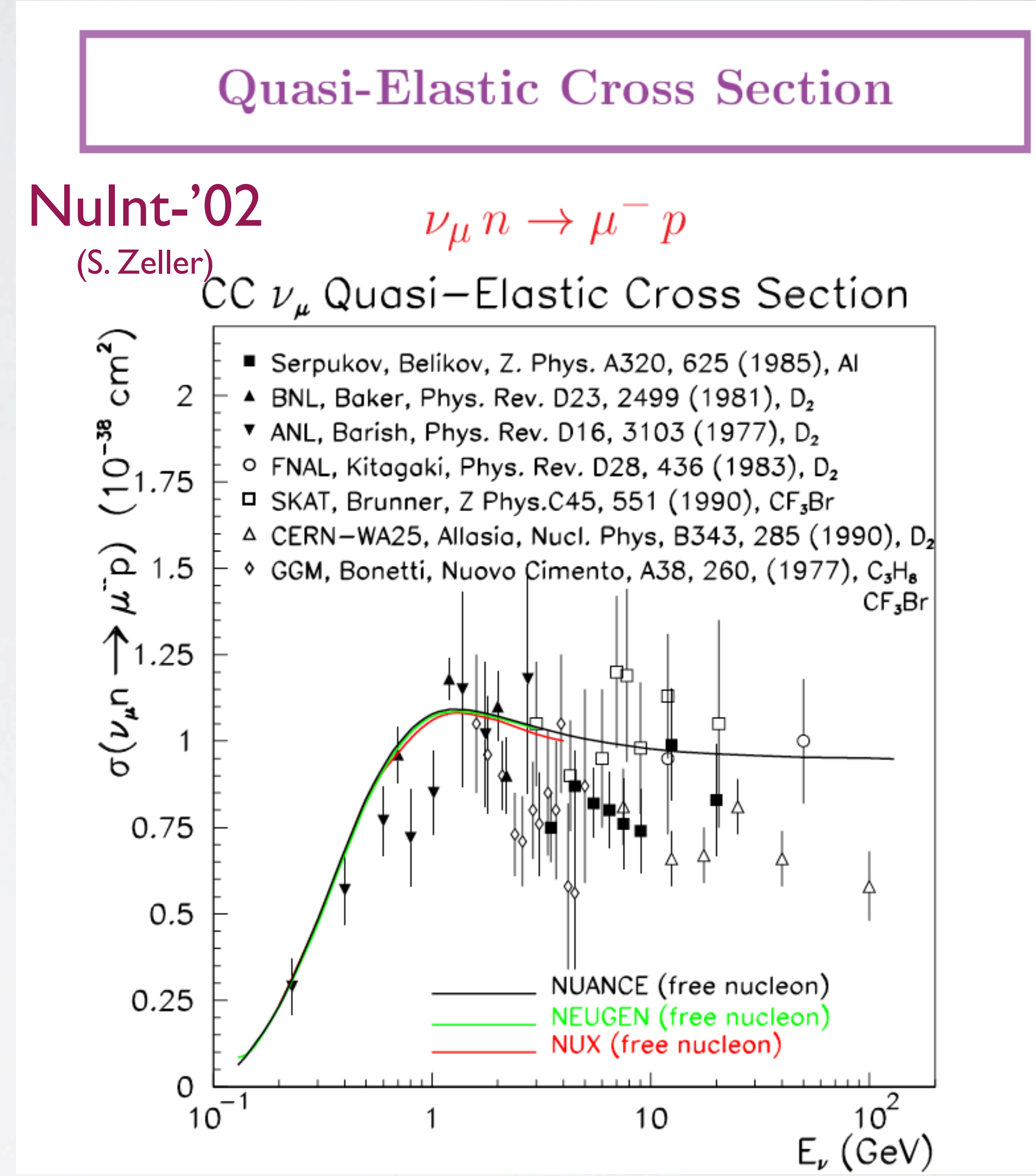


Figure 38.7: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy.



XSect data looked scattered, and errors were large

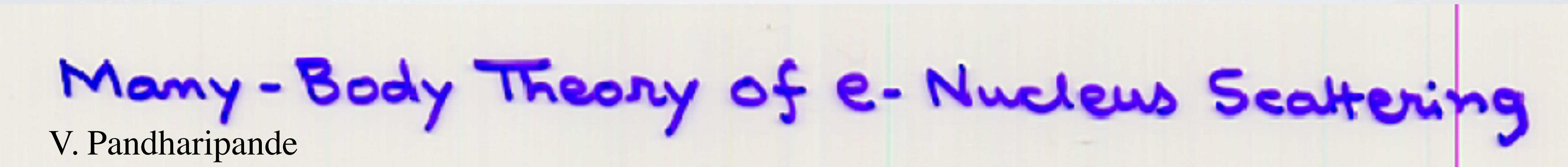
Cross section

$$\sigma(E_\nu)=\frac{N(E_\nu)}{\Phi(E_\nu)n_T\varepsilon(E_\nu)}$$

but (general opinion), statistics was low, flux affected by large uncertainties, detector systematics (possibly) non fully understood/controlled

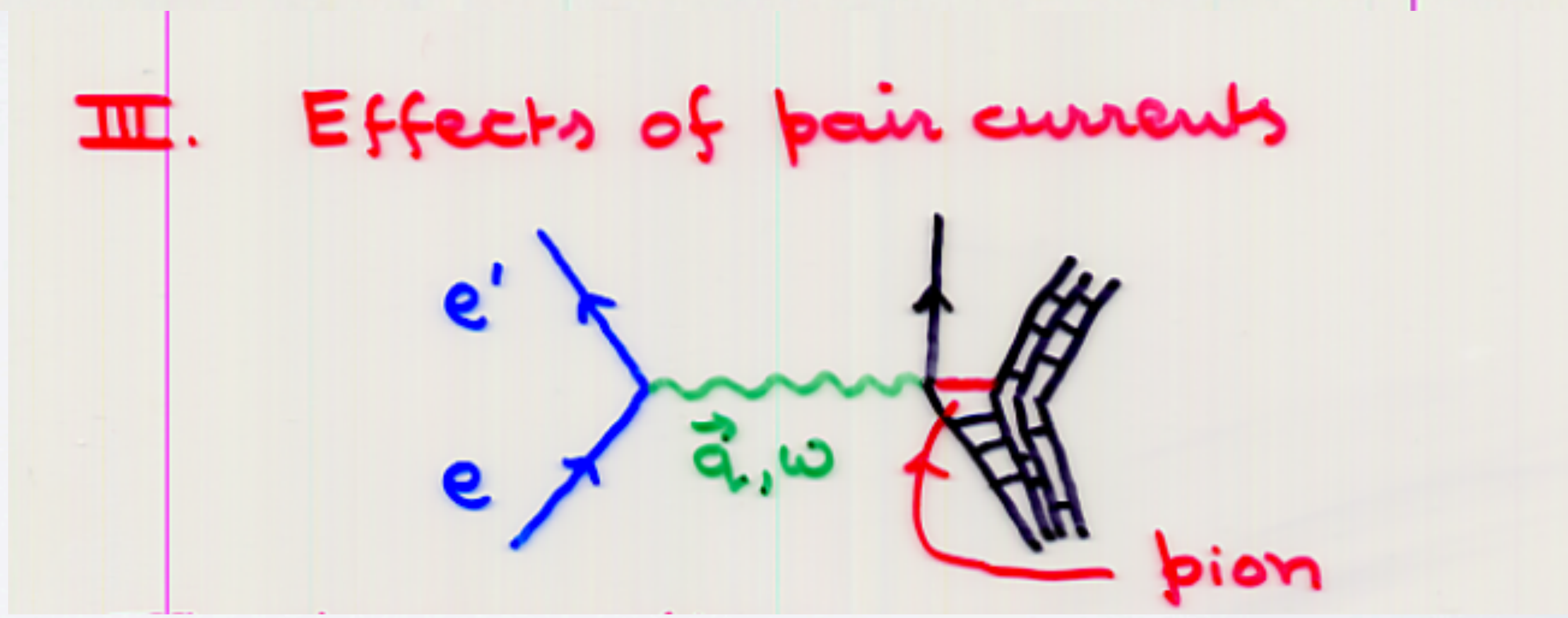
However, the real (scary) message the (e,e') community from the (e,e')-community was:

NUCLEAR EFFECTS ARE IMPORTANT AND FAR MORE COMPLEX AND OVERWHELMING THAN USUALLY ASSUMED

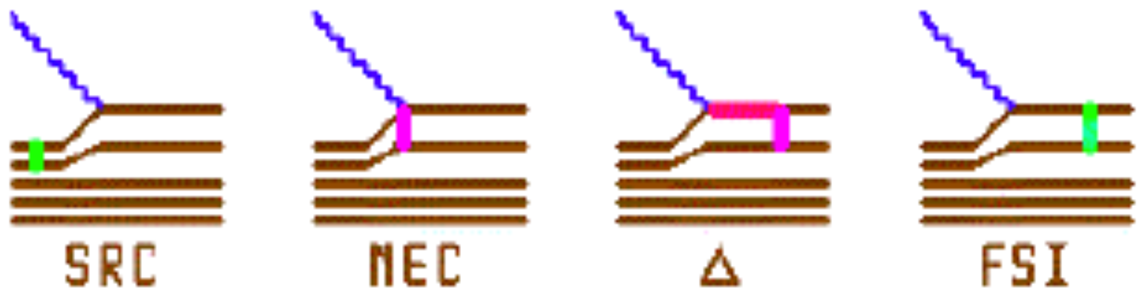


V. Pandharipande

NuInt'01



This was for many of us (neutrino community) the start of an exhausting effort into nuclear physics (mediated through the e,e'-experience)



- we know (now) that about 20% Nucleons in Nuclei are in SRC (np) pairs

- long range correlations (MEC) are very relevant and may change significantly XSECT measurements

- Pion absorption (two-body) is relevant

- FSI's are always a big pain

- all these effects are combined and interfere w/ each other - (e.g. MEC can involve SRC pairs !)

* **today a consistent picture is far to be available yet**

- Fermi Gas model for nucleons in Nuclei is no longer a considered a satisfactory model

- MC's need truly major upgrades in the treatment of nuclear effects
  [but again, coherent/comprehensive theoretical models are not yet available - i.e. universally accepted - and MC coding is very difficult (if not impossible) at this stage]

Additional (BIG) complications wrt (e,e')experiments are intrinsically connected to:

* Neutrino Experimental Approach
and
* Neutrino Detectors

* the big, main difference btw. el-scattering & ν-scattering experiments is the incident energy, not fixed, but broadly distributed in the beam spectrum

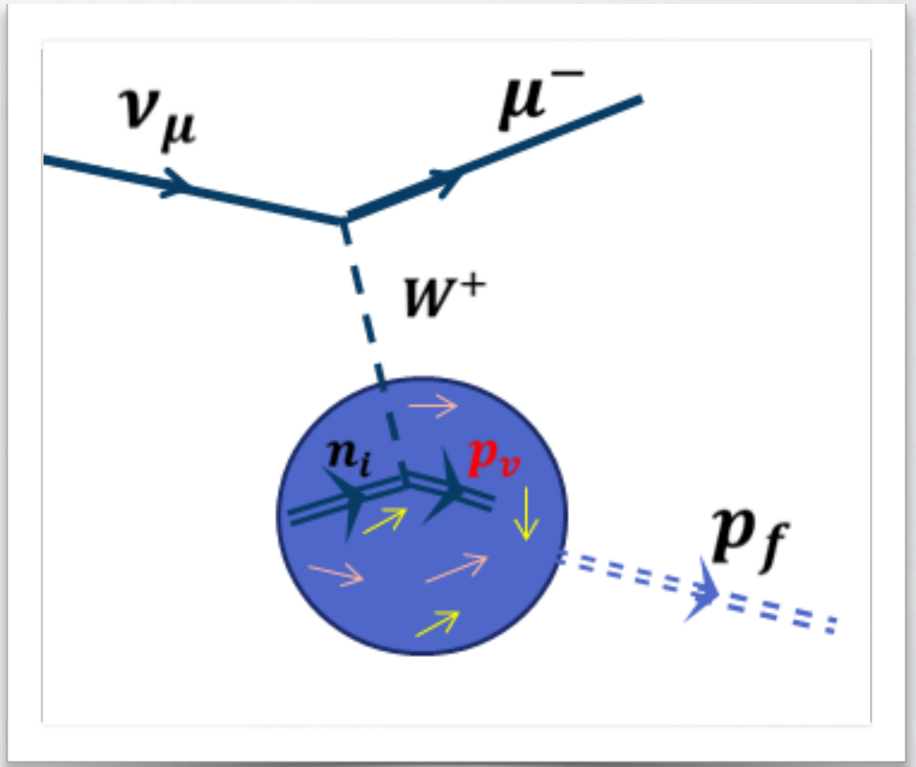
* as a consequence, also the 4-Momentum Transfer components (ω,**q**) are not directly determined by final lepton kinematics

⇒ the study of Nuclear Effects

that heavily affect neutrino interactions

- all currently used targets are Medium/Heavy Nuclei -

is hampered to some extent by the limited accuracy in (ω,**q**)



Neutrino Energy Reconstruction and the Detector Technology

Cross section

from NuInt-'01

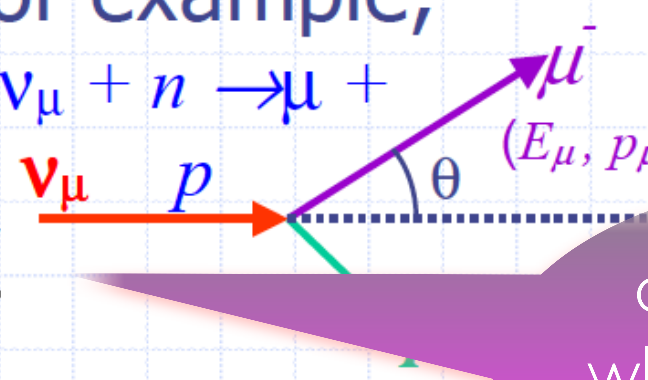
M. Sakuda (summary talk)

$$\sigma(E_\nu) = \frac{N(E_\nu)}{\Phi(E_\nu) n_T \varepsilon(E_\nu)}$$

1) How to calculate E_ν

- Measure all the particles in the final state and sum up the energy
- Measure lepton energy and angle, and use kinematics for quasi-elastics, for example,

$\nu_\mu + n \to \mu + $



$$E_\nu = \frac{(m_N - B)E_\mu + (2m_N B - B^2 - m_\mu^2)/2}{m_N - B - E_\mu + p_\mu \cos\theta_\mu}$$

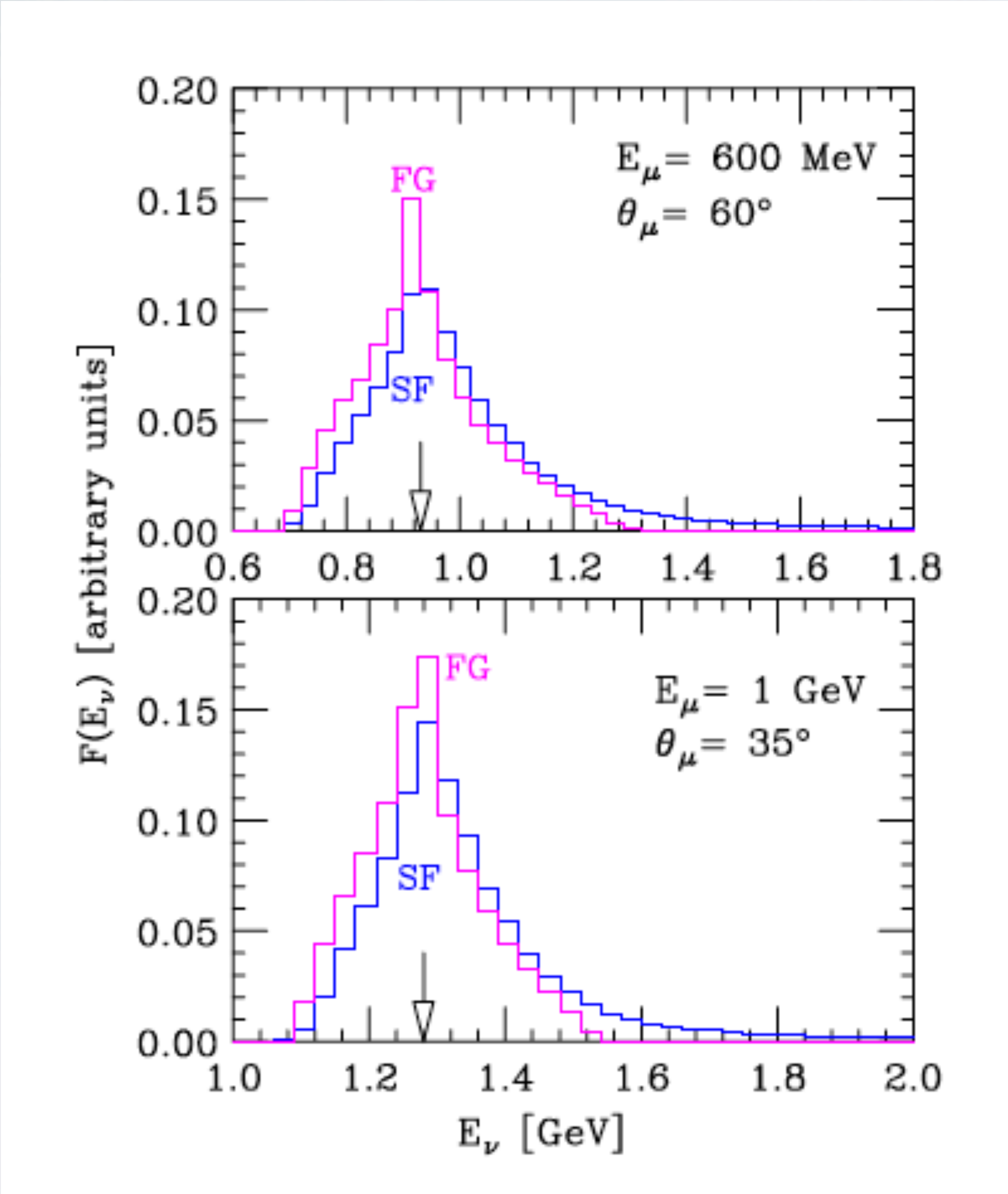
B=Binding energ[y]

possible (only) if your detector allows for it !!

....this, however, was just a wish at that time

otherwise this is what one could do: use only muon

Cherenkov detectors



O. Benhar and N. Rocco
arXiv:1310.3869

Neutrino energy distribution at E_μ = 600 MeV and θ_μ= 60 deg (upper panel) and E_μ= 1 GeV and θ_μ= 35deg (lower panel), reconstructed from previous slide Eq. using random target nucleon (p;E) values sampled from the probability distributions associated with spectral function (SF) and the RFGM, with Fermi momentum p_F = 225 MeV and removal energy = 27 MeV (FG). The arrows point to the values of $\mathbf{E^{\nu}_{rec}}$ obtained from Eq. in (previous slide).

This also reflects on
(ω,**q**)
transfer momentum determination

THE NEED OF DETECTORS WITH ENHANCED DETECTION CAPABILITY FOR EMITTED PROTONS AND LOW ENERGY PIONS FROM NEUTRINO INTERACTIONS IS QUITE EVIDENT

WHERE ARE WE NOW ??
(A DECADE AFTER NUINT'01)

Non-XSECT-dedicated ν exp's
(NOMAD, MiniBooNE, MINOS-ND, T2K-ND)
provided high statistics nu-XSECT measurements,
but (!):
- run at high energy (DIS dominated)
or
- with no/limited sensitivity to Nucl.Effects

New Generation - *XSECT-dedicated* ν*-experiments*
(MINERvA, SciBooNE, ArgoNeuT)

New Experimental Results:

2012-13

CC-Inclusive:
- MiniBooNE
- MINERvA
- T2K
- ArgoNeuT

Ch.π production:
- MINERvA
- T2K

Neutr. π production:
- MINERvA
- T2K

CC QE:
- MiniBooNE
- MINERvA
- (prospects from T2K)

CC-0π (=1μ+N*p* topology)
- ArgoNeuT

Nuclear Effects:
- ArgoNeuT

MonteCarlo:

Comparisons (GENIE, NEUT, NUANCE, NUWRO)

Features of GiBUU generator

MEC implementation in GENIE, NUWRO, GiBUU

Theory (a limited selection):

Anti-ν to ν Xsect systematics

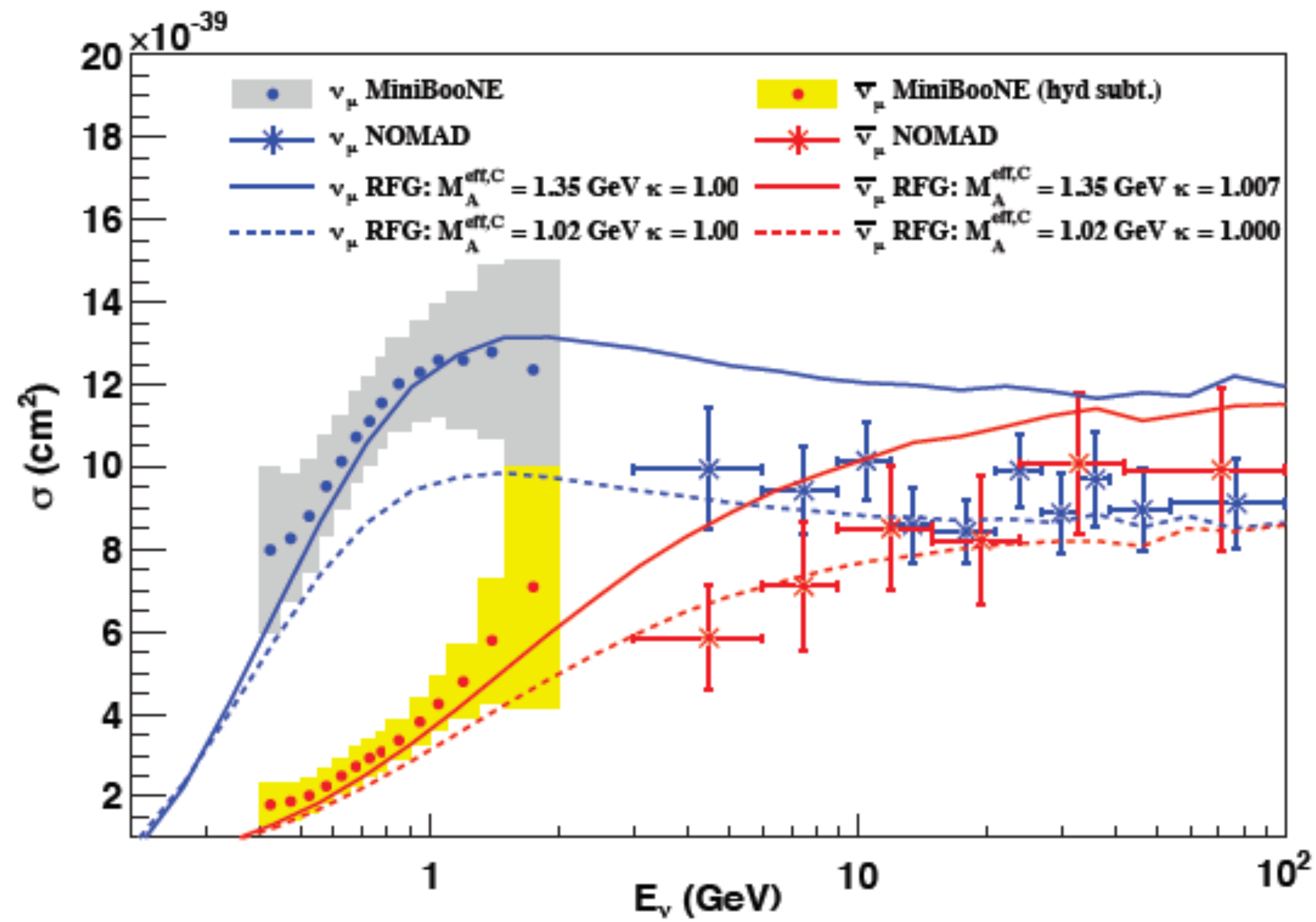
Strange Particle productions

CCQE, 2p2h excitations and ν energy reconstruction

Photon emission in (anti)ν NC interactions with nucleons and nuclei

High Stat. (non-XSECT-dedicated) ν-Exp's

MiniBooNE and NOMAD ν_μ and anti-ν_μ CCQE



- New anti-neutrino CCQE data favor high normalization and harder momentum transfer spectrum compared to expectation associated with M_A = 1.0 GeV. NCE data favors higher normalization.

XSECT-dedicated ν-Exp's

PRL 111, 022502 (2013) PHYSICAL REVIEW LETTERS week ending 12 JULY 2013

MINERvA

Measurement of Muon Neutrino Quasielastic Scattering on a Hydrocarbon Target at $E_\nu \sim 3.5$ GeV

state. Deviations are found between the measured $d\sigma/dQ^2$ and the expectations of a model of independent nucleons in a relativistic Fermi gas. We also observe an excess of energy near the vertex consistent with multiple protons in the final state.

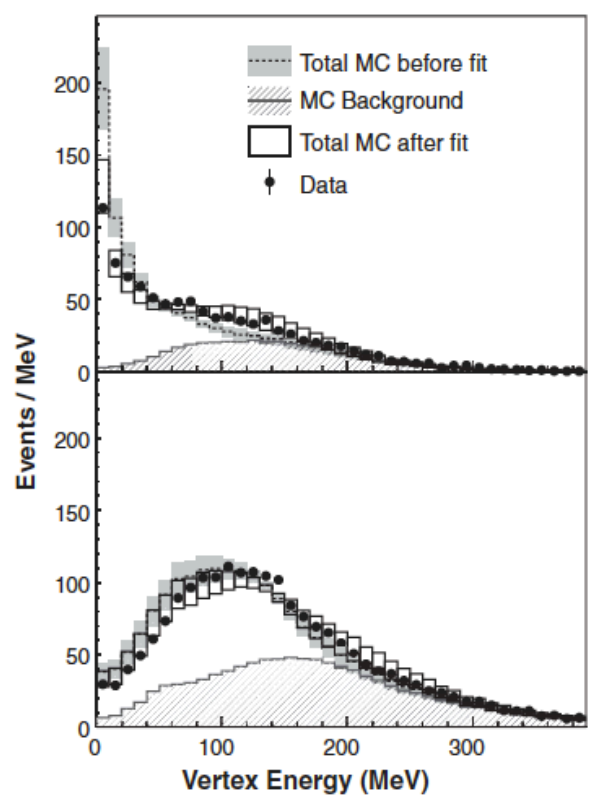


FIG. 5. Reconstructed vertex energy of events passing the selection criteria in the data (points with statistical errors) compared to the GENIE RFG model (shown with systematic errors) for $Q^2_{QE} < 0.2$ GeV$^2/c^2$ (top) and for $Q^2_{QE} > 0.2$ GeV$^2/c^2$ (bottom).

Experience from electron quasielastic scattering on carbon suggests that multibody final states are dominated by initial-state np pairs [24,43,44]. This could lead to an expectation of final state pp pairs in neutrino quasielastic scattering and nn pairs in the analogous antineutrino channel. The vertex energy measurement, shown in Fig. 5, is sensitive to these effects. These data prefer the addition of a final state proton with less than 225 MeV kinetic energy in 25 ± 1(stat) ± 9(syst)% of the events. The corresponding result in the antineutrino mode [35], in contrast, prefers the removal of a final state proton in 10 ± 1(stat) ± 7(syst)% of the events. The systematic uncertainties for

Nuclear Effects definitively play a key-role. For a quantitative investigation, a more sensitive detector technology is necessary

ArgoNeuT

Imaging LAr-TPC detector:

- *exclusive topologies* can be fully reconstructed

the high PID capability allows:

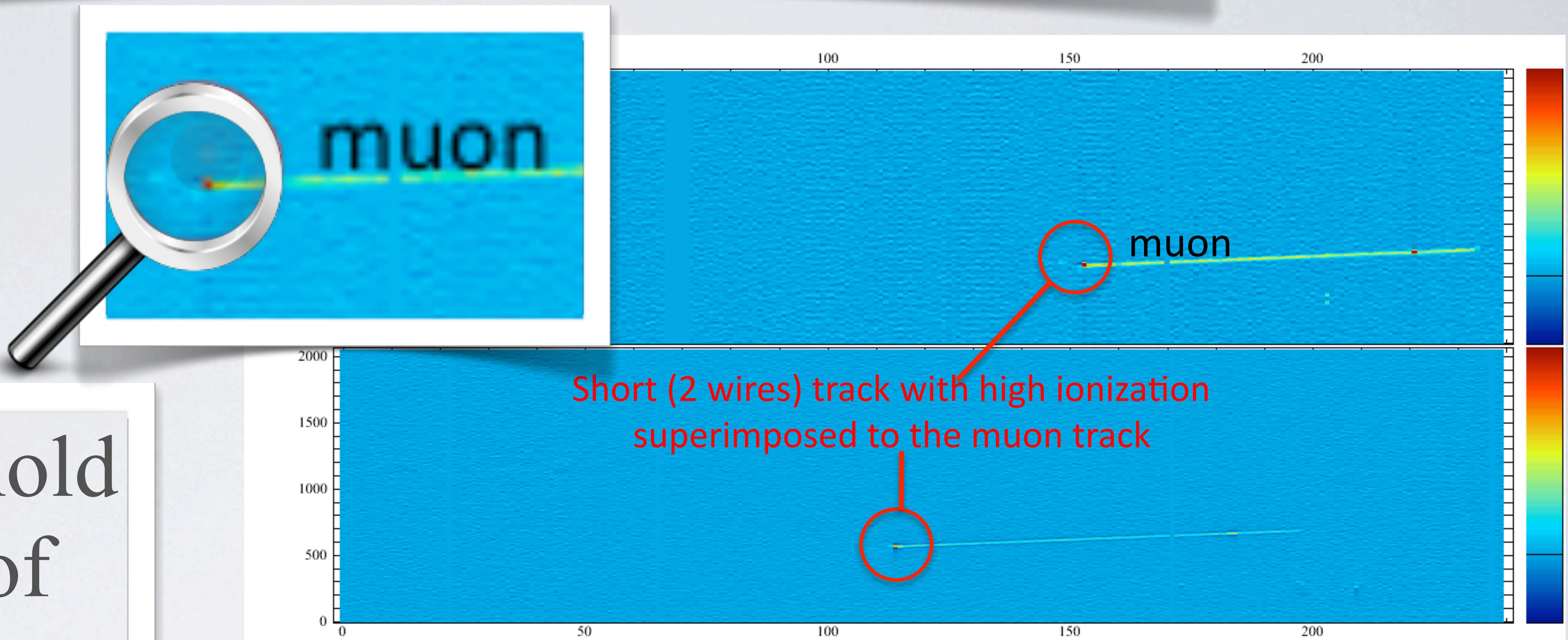
- *proton* detection and determination of *proton multiplicity* at the neutrino interaction vertex down to ***very low proton energy threshold -***

(*in ArgoNeuT: T_{thr} = 21 MeV, i.e. below Fermi level*)

- *soft pion* detection and discrimination from proton

- ***reconstruction of** proton(s) kinematics* ultimately allow for most precise ***reconstruction of the incoming neutrino energy*** (from its ***excellent Energy and Spacial resolutions***).

Low energy proton reconstruction



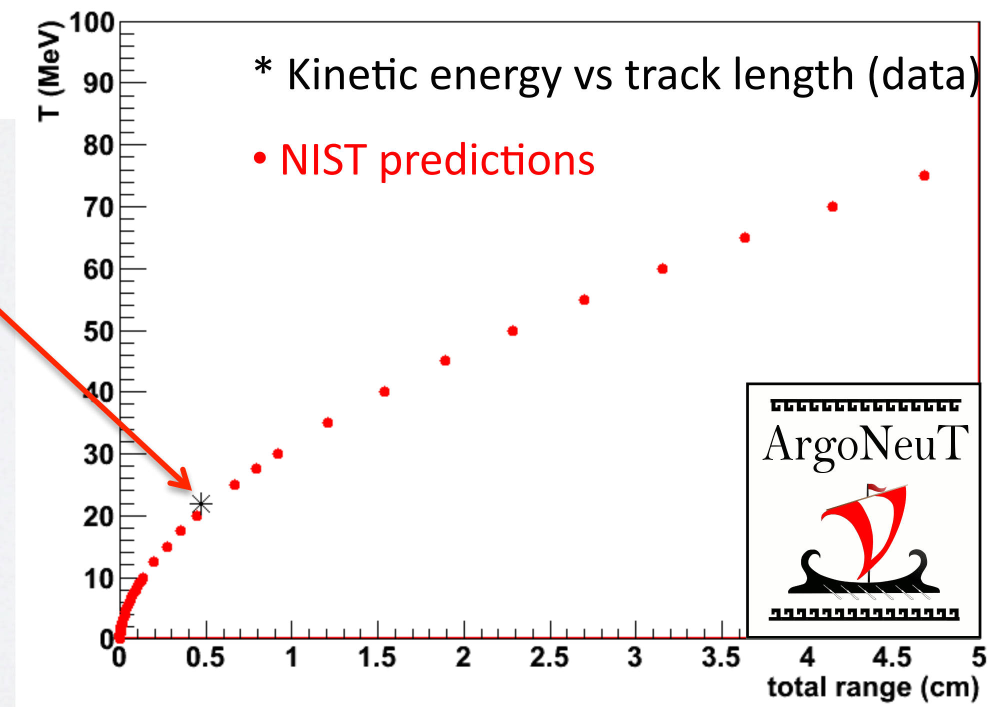
proton threshold is 21 MeV of Kinetic Energy (ArgoNeuT)

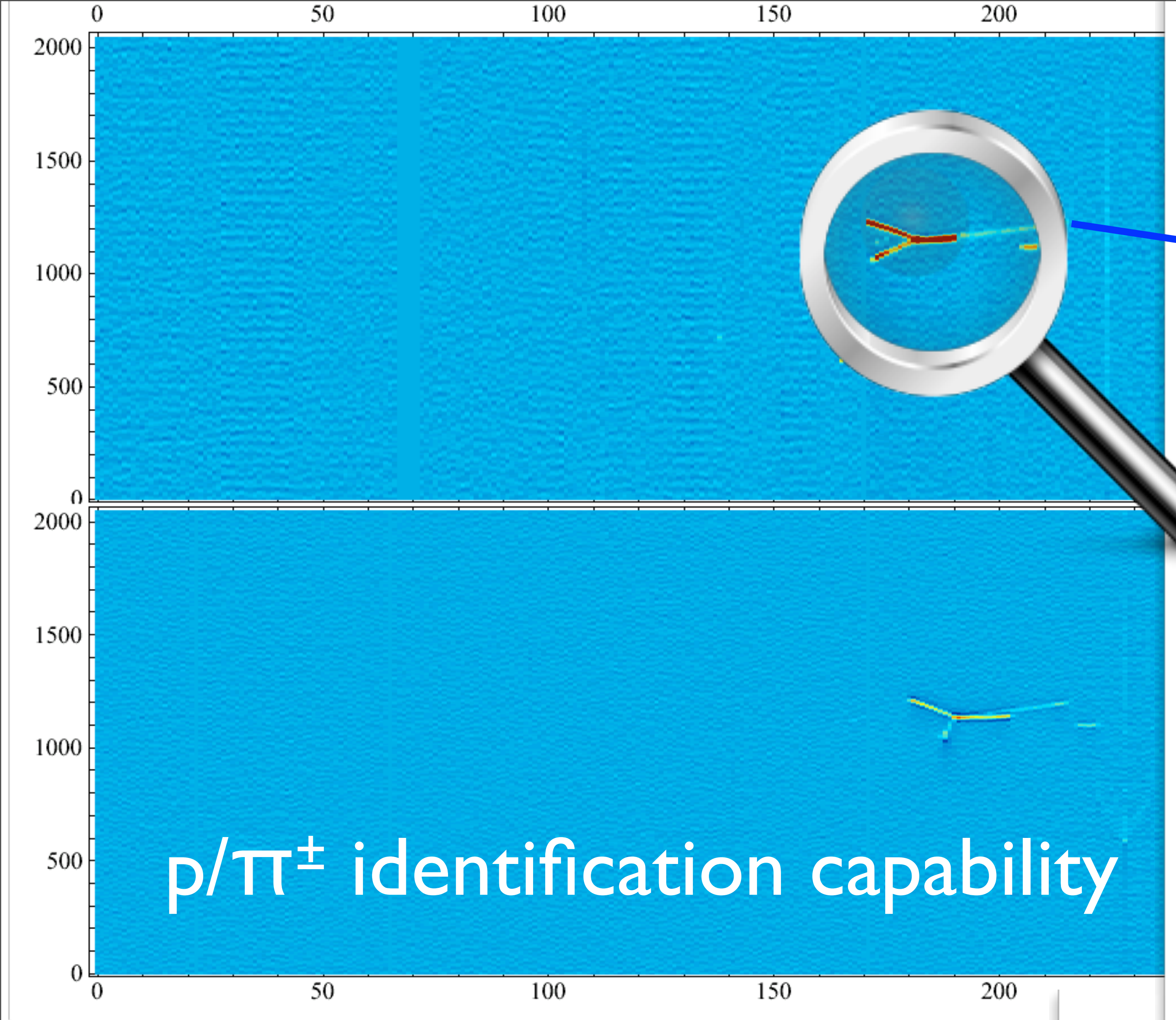
The short track behaves like proton

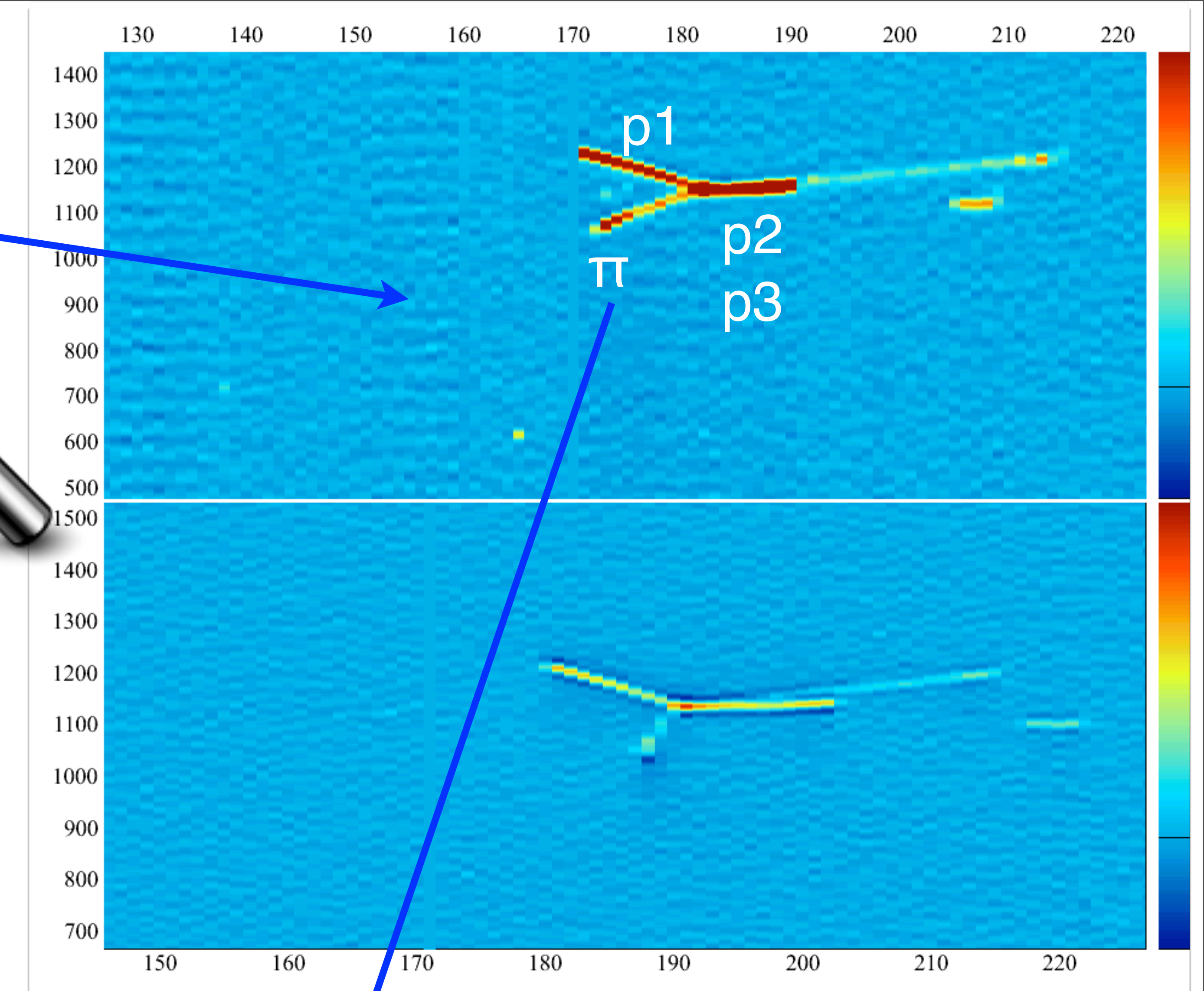
The event is (CCQE) 1p – 1 μ−

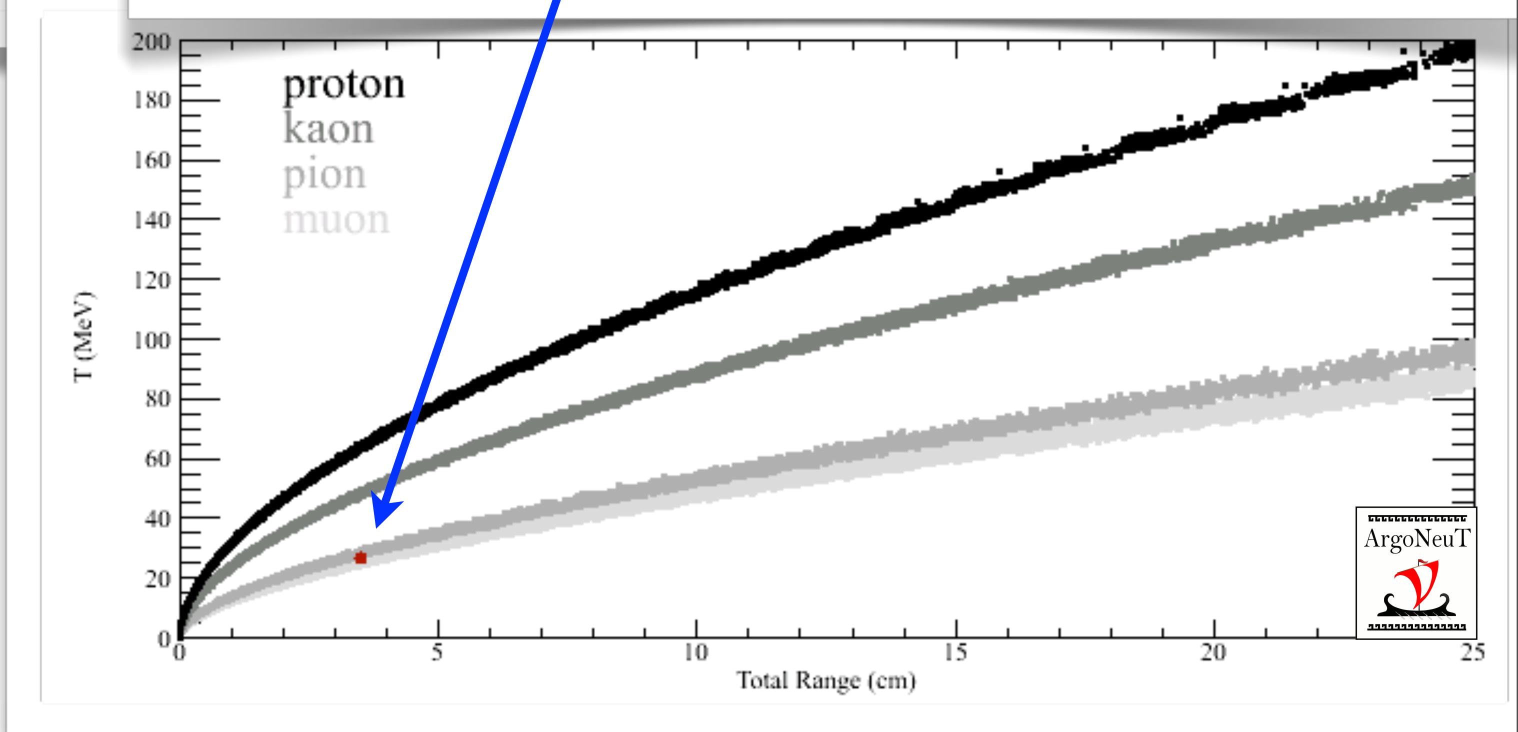
KE=22±3 MeV

Length=0.5 cm









- *p1*: 4.9 cm ----> T=83±5 MeV
- *p2*: 5 cm ----> T=134±7 MeV
- *p3*: 5 cm ----> T=134±7 MeV
- **π**: 3.5 cm ----> T=26±3 MeV

1μ 3p 1π

⇒ Event not in the muon+Np sample

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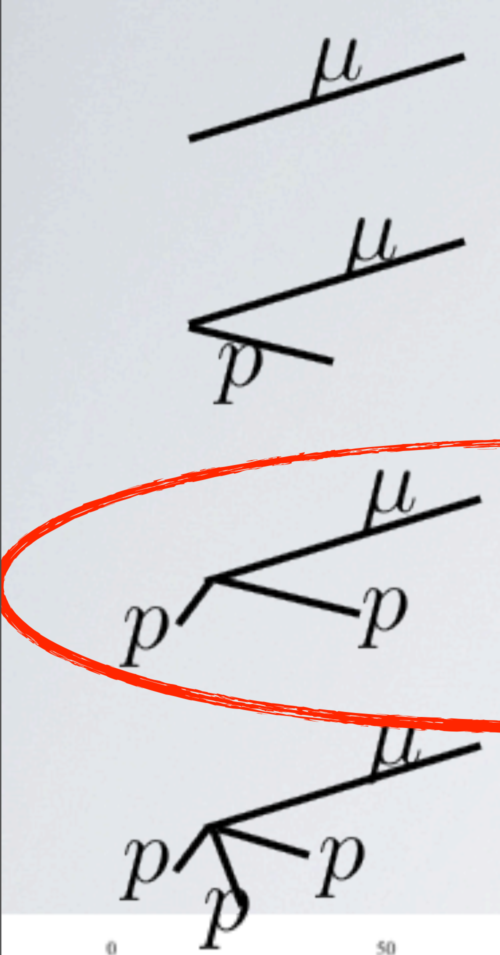
EXCLUSIVE EVENT TOPOLOGY



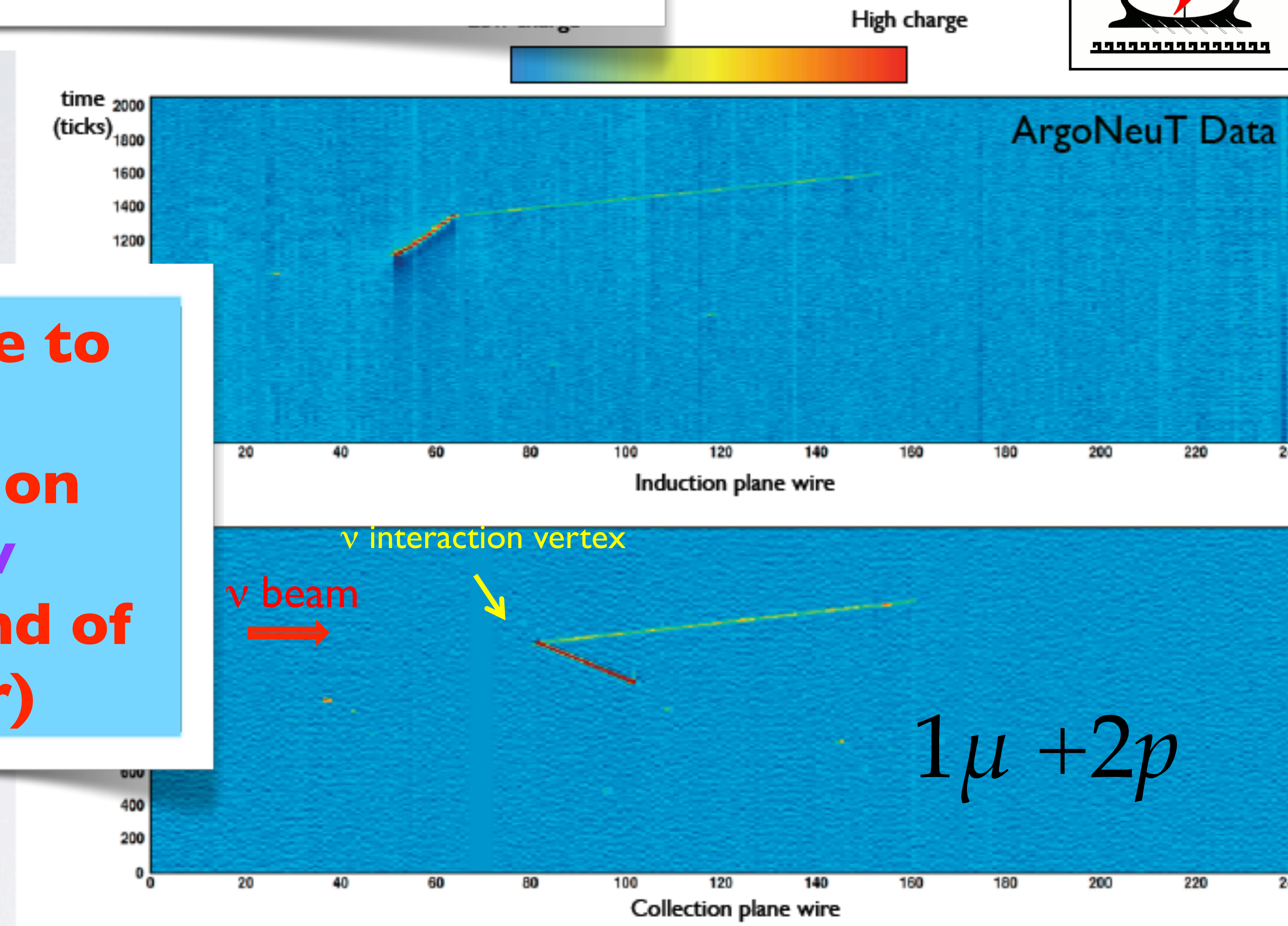
$1\mu + 0p$

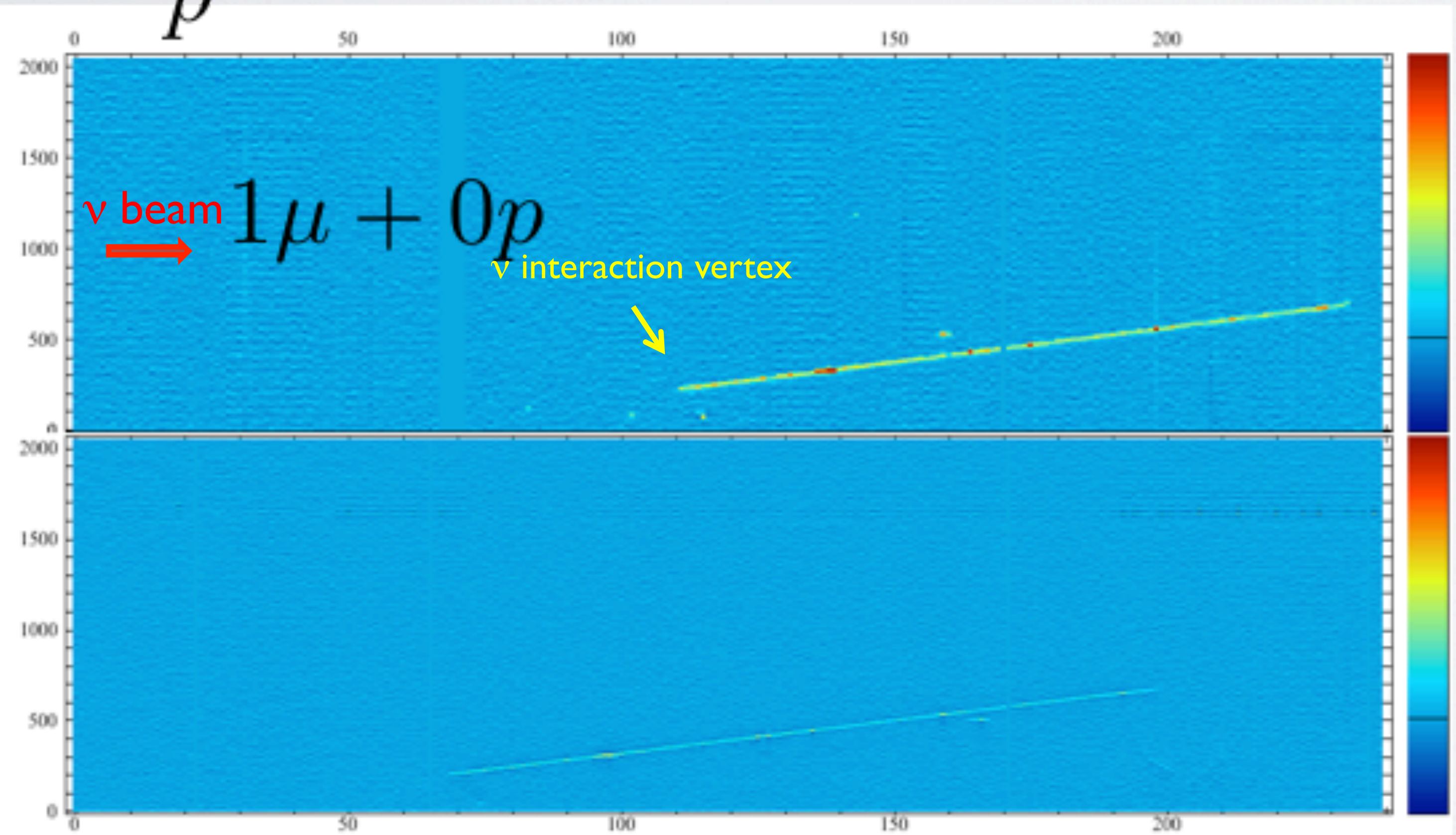
$1\mu + 1p$

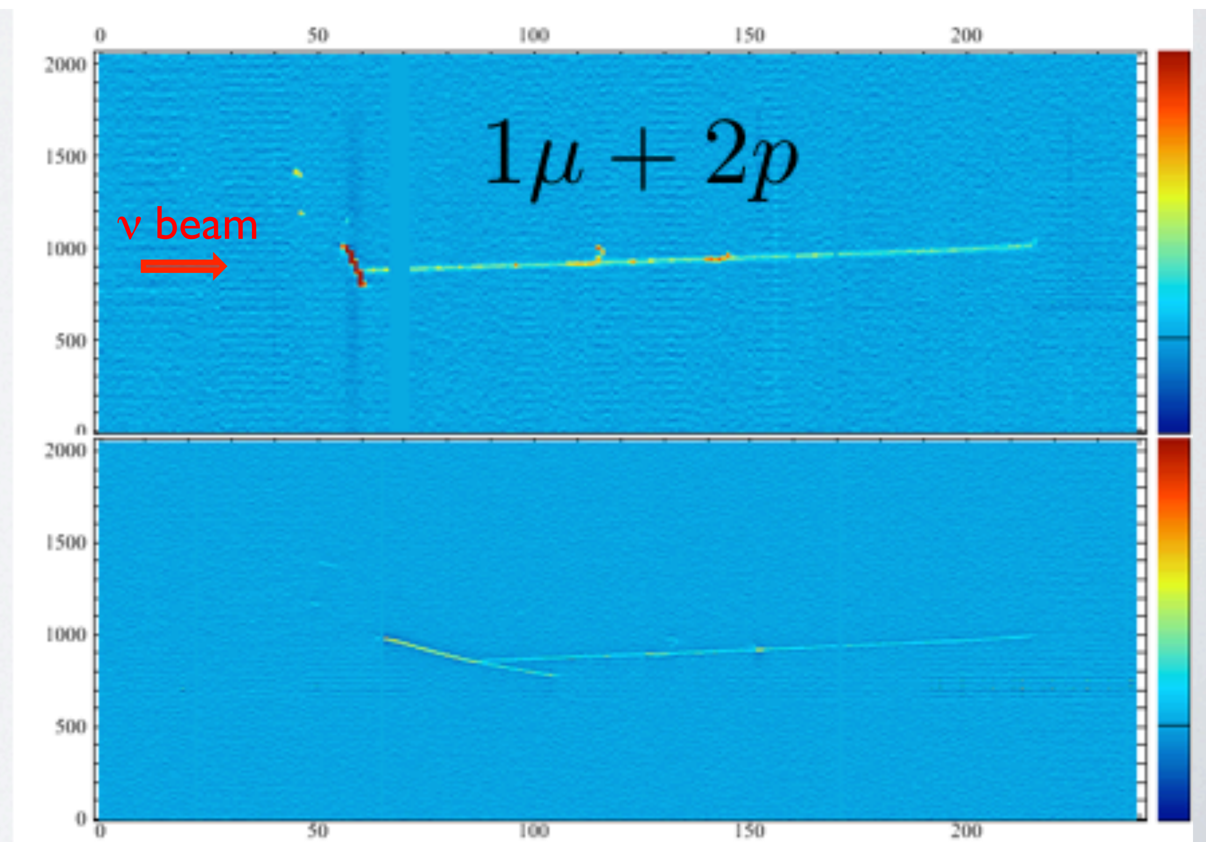
$1\mu + 2p$

$1\mu + 3p$

Sensitive to SRC (paper on arXiv by the end of the yr)







WHERE WILL WE BE IN 5YRS FROM NOW ??

MINERvA era - continued

NOvA - started

MicroBooNE - about to start

IN THE FOLLOWING:
THE MICROBOONE PERSPECTIVE/VIEW

MicroBooNE:

- **most sensitive detector to study Nuclear Effects and ν-Energy reconstruction**
- simultaneously exposed to BNB (~0.8 GeV) and NuMI-offaxis (2-3 GeV)
- XSECT is (one of the two) major physics goal of its program

Booster ν-Beam

Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		88,098
CC 0 π	$\nu_\mu N \to \mu + Np$	56,580
	$\cdot\ \nu_\mu N \to \mu + 0\text{p}$	12,680
	$\cdot\ \nu_\mu N \to \mu + 1\text{p}$	31,670
	$\cdot\ \nu_\mu N \to \mu + 2\text{p}$	5,803
	$\cdot\ \nu_\mu N \to \mu + \geq 3\text{p}$	6,427
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + 1\pi^\pm$	21,887
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	1,953
CC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	9,678
NC Inclusive		33,000
NC 0 π	$\nu_\mu N \to \text{nucleons}$	21,509
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	4,886
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	635
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	6,657
	ν_e *Events*	
CC Inclusive		567
NC Inclusive		207
Total ν_μ and ν_e Events		121,099
	ν_μ *Events (By Physical Process)*	
CC QE	$\nu_\mu n \to \mu^- \text{p}$	48,626
CC RES	$\nu_\mu N \to \mu^- N$	26,852
CC DIS	$\nu_\mu N \to \mu^- X$	10,527
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	376

Table 1: Estimated event rates using GENIE in a 6.6e20 POT exposure of MicroBooNE. In enumerating proton multiplicity, we assume an energy threshold on protons of 21 MeV. The 0π topologies include any number of neutrons in the event.

MicroBooNE

Instead of MC based classification of the events in the interaction channels *(QE, RES, DIS etc)*, *CC* neutrino events in *LAr* can be classified in terms of **Final State Topology** based on Particle Multiplicity:

0 *pion* (*i.e.* μ+Np, *where* N=0,1,2...),

1 *pion* (i.e. μ+Np+1π),

etc..

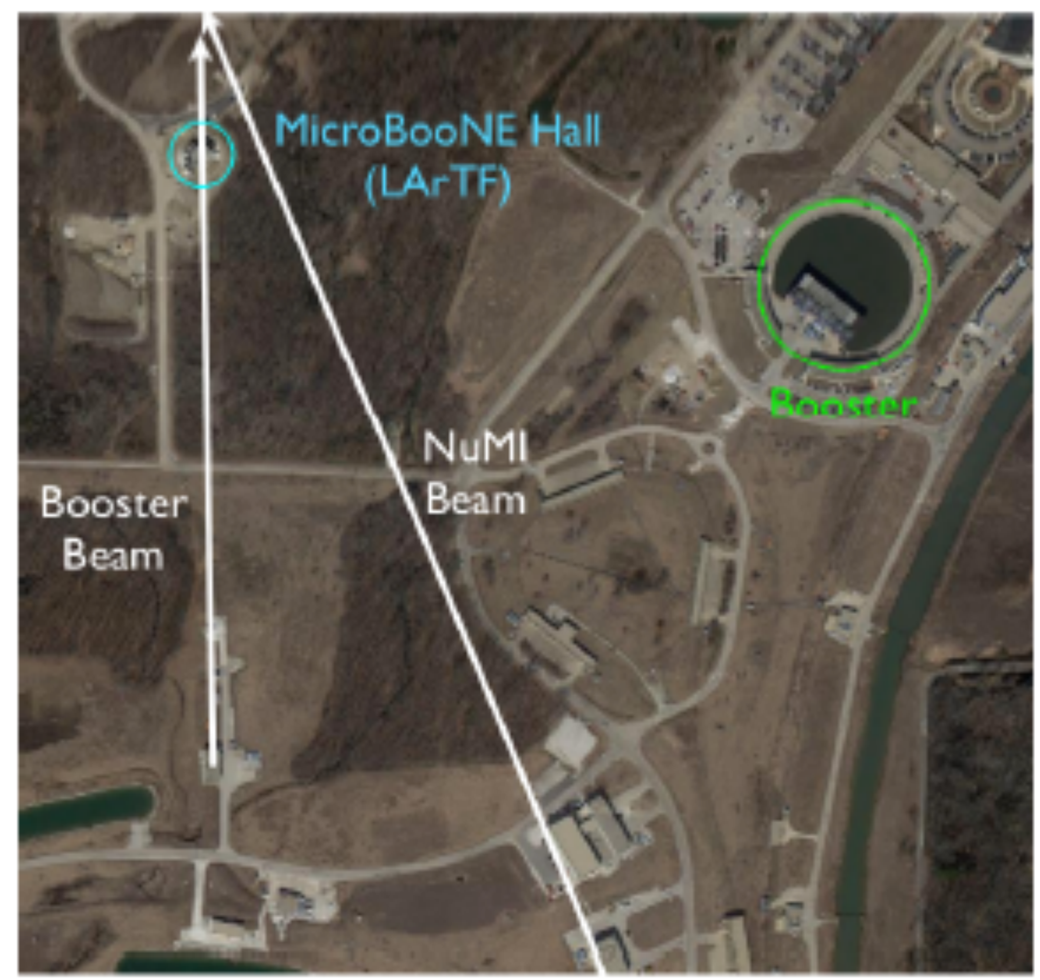
- *High Stat.* study of Nuclear Correlations and their impact on ν_μ-CC QE / RES reactions (in quasi-DIS-free conditions)

Data from BNB

What about NuMI-off axis data ? (I)

- assuming 9e20 POT per 3 years for NuMI, about equivalent Stat. is being collected (> 100k evts) [C. Adams - Yale]

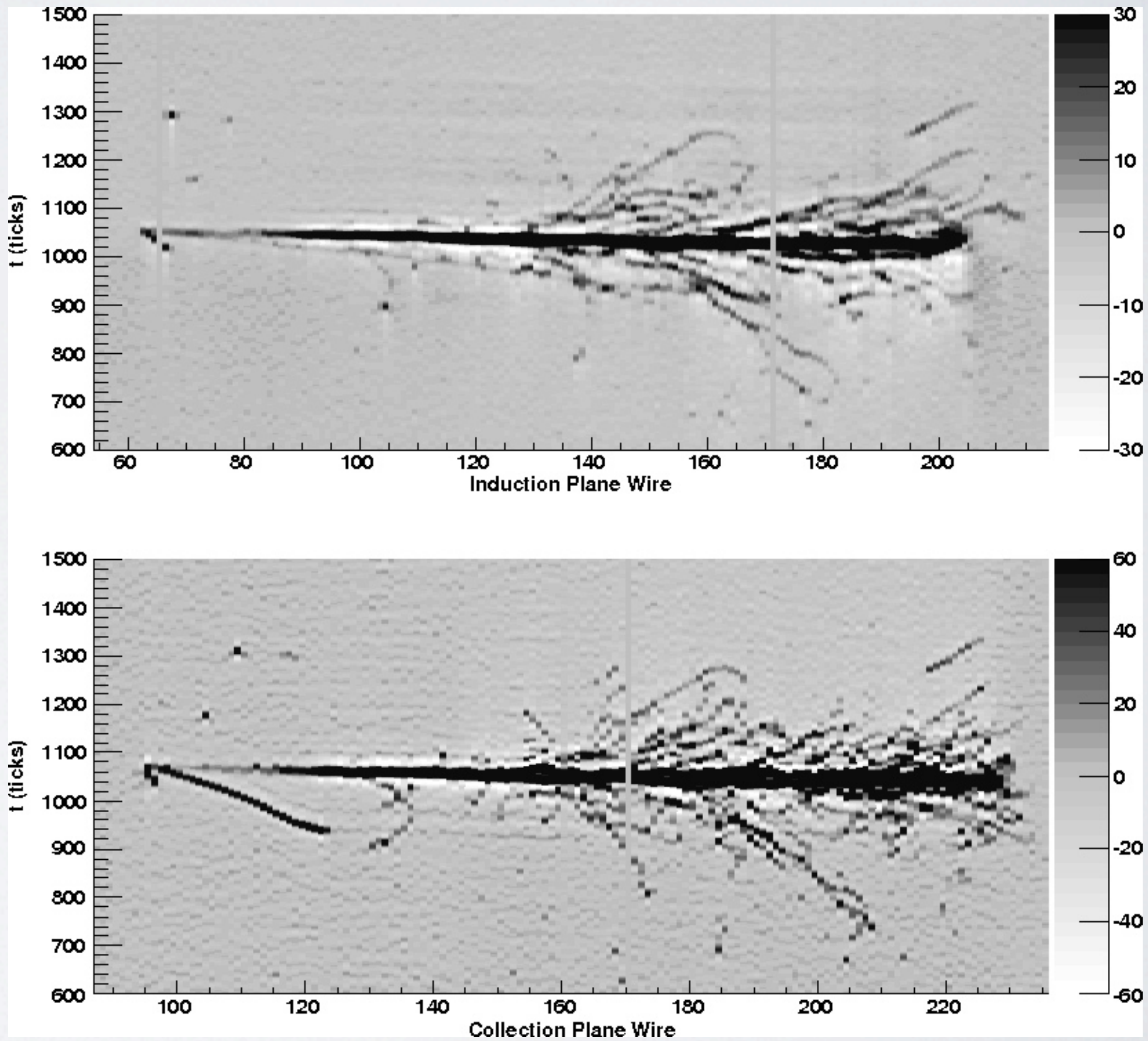
- extension of precise neutrino energy reconstruction/nuclear effects in the LBNE energy range



What about NuMI-off axis data ? (II)

- a first considerably large sample of ν_e **CC events (~4k)** is available (intrinsic NuMI beam) [C. Adams - Yale] [similar to current ArgoNeuT ν_μ CC Statistics]

This sample will provide opportunity to step into the so far unexplored ν_e **CC** territory



ArgoNeuT ν_e **CC event**: (**1e** + **2p**) Event

WHERE WILL WE BE SOMETIME BY THE END OF THE DECADE ??

view from a crystal ball (...full of LAr)

after MicroBooNE,
a "precision era" in XSECT
measurement could start
as soon as
a high-resolution detector
be operated
as Near-Detector in a
high-intensity ν -beam

for next generation oscillation
studies

STRANGE Particle production in ν-N interactions search for rare processes: a new page in neutrino interaction physics

ν and $\bar{\nu}$ induced single kaon production

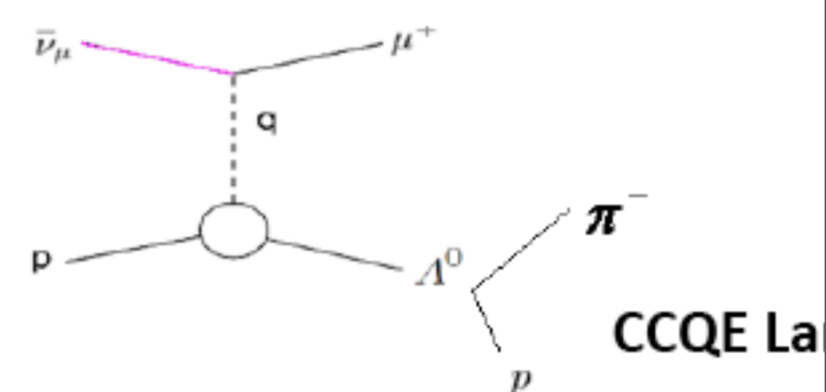
CC $\Delta S = 1$ processes

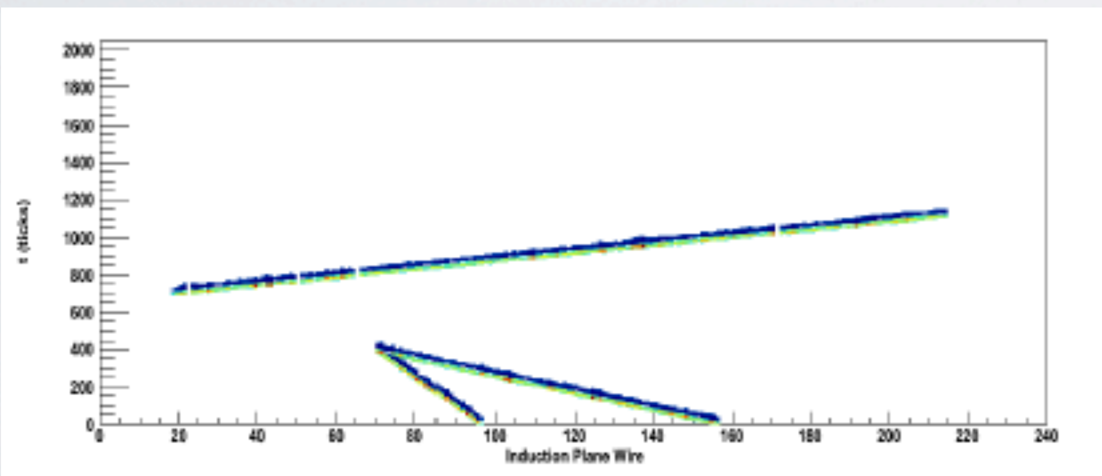
$$\nu_l n \to l^- K^+ n \qquad \bar{\nu}_l n \to l^+ K^- n$$
$$\nu_l p \to l^- K^+ p \qquad \bar{\nu}_l p \to l^+ K^+ p$$
$$\nu_l n \to l^- K^0 p \qquad \bar{\nu}_l p \to l^+ \bar{K}^0 n$$

Cabibbo suppressed

Single Strange Baryon production

$$\bar{\nu}_l + p \to l^+ + \Lambda$$
$$\bar{\nu}_l + p \to l^+ + \Sigma^0$$
$$\bar{\nu}_l + n \to l^+ + \Sigma^-$$





CC $\Delta S = 0$ processes

$$\nu_l n \to l^- K^0 \Sigma^+ \qquad \bar{\nu}_l p \to l^+ K^+ \Sigma^-$$
$$\nu_l n \to l^- K^+ \Lambda^0 \qquad \bar{\nu}_l p \to l^+ K^0 \Lambda^0$$
$$\nu_l n \to l^- K^+ \Sigma^0 \qquad \bar{\nu}_l p \to l^+ K^0 \Sigma^0$$
$$\nu_l p \to l^- K^+ \Sigma^+ \qquad \bar{\nu}_l n \to l^+ K^0 \Sigma^-$$

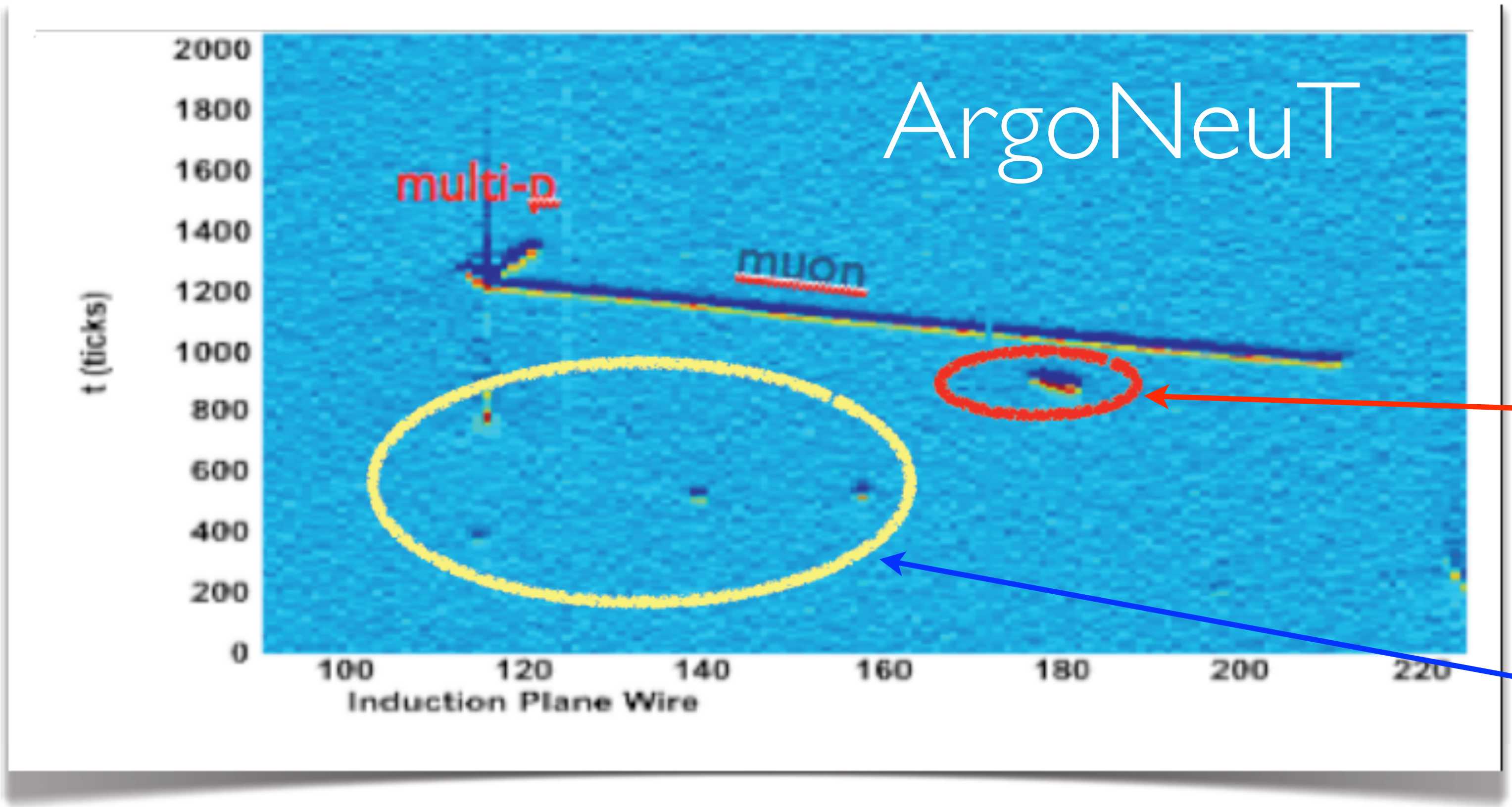
require Bubble Chamber-like detector capabilities: detached vtx's detection and excellent PId

high-resolution detector

Direct access to nuclear effects requires:

e.g VERTEX ACTIVITY

Measurement of γ activity around the vertex and neutron → proton can also help to tune MC generators



- *low threshold for proton detection (well below Fermi level)*

- *neutron detection capability (p conversion via CEX)*

- *sensitivity to low energy de-excitation γ's (via Compton Sc.)*

Near-Detector in a

high-intensity ν-beam

arXiv:1309.7987 [physics.ins-det]

LAr1-ND: Testing Neutrino Anomalies with Multiple LArTPC Detectors at Fermilab

C. Adams[1], C. Andreopoulos[2], J. Asaadi[3], B. Baller[4], M. Bishai[5], L. Camilleri[6], F. Cavanna[1], H. Chen[5], E. Church[1], D. Cianci[7], G. Collin[8], J. Conrad[8], A. Ereditato[9], B. Fleming*[1], W.M. Foreman[7], G. Garvey[10], R. Guenette[11], C. Ignarra[8], B. Jones[8], G. Karagiorgi[6], W. Ketchum[10], I. Kreslo[9], D. Lissauer[5], W.C. Louis[10], K. Mavrokoridis[2], N. McCauley[2], G.B. Mills[10], O. Palamara*[1], Z. Pavlovic[10], X. Qian[5], L. Qiuguang[10], R. Rameika[4], D.W. Schmitz*[7], M. Shaevitz[6], M. Soderberg[3], J. Spitz[8], A.M. Szelc[1], C.E. Taylor[10], K. Terao[6], M. Thomson[12], C. Thorn[5], M. Toups[8], C. Touramanis[2], T. Strauss[9], R.G. Van De Water[10], C.R. von Rohr[9], M. Weber[9], B. Yu[5], G. Zeller[4], and J. Zennamo[7]

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November 6, 2013

*Contact persons

"precision era"

for Exclusive Topologies XSECT determination

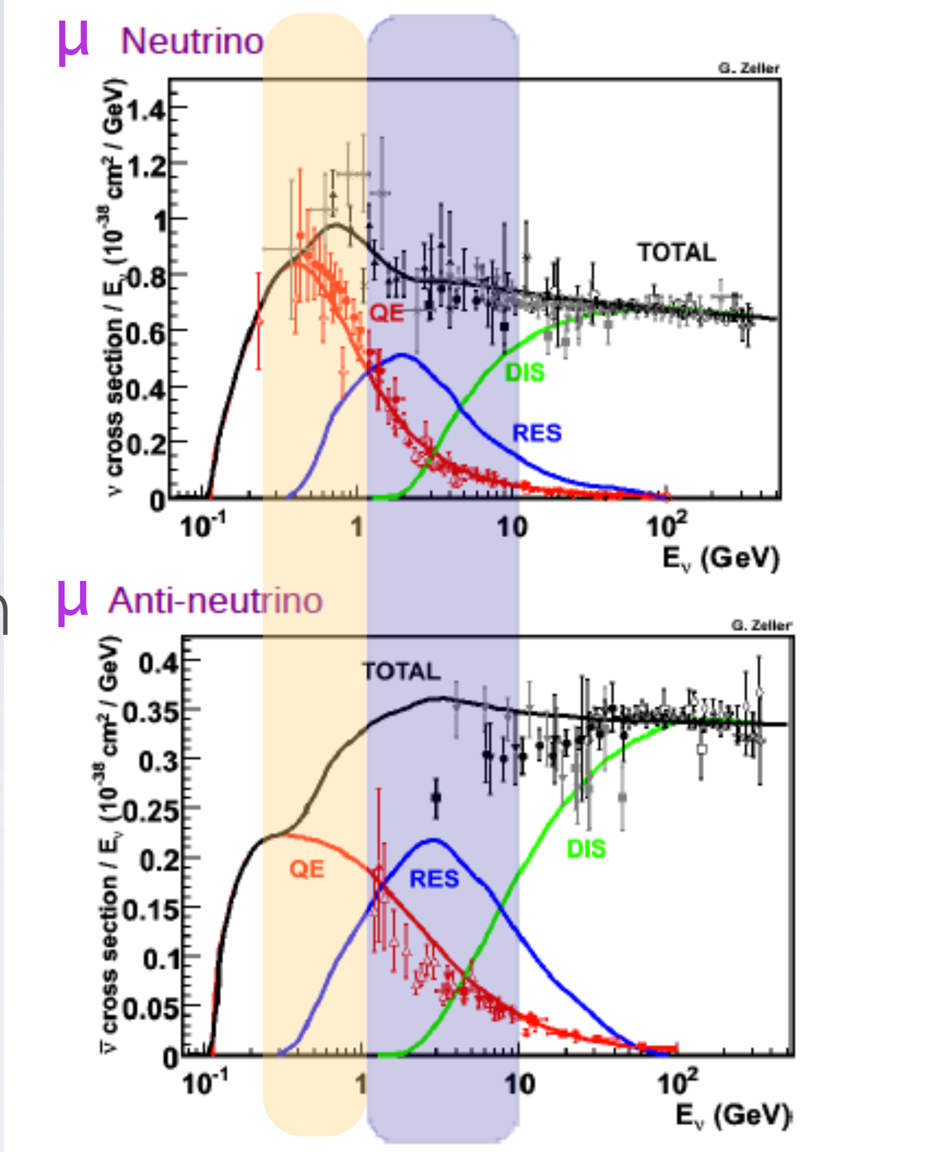
Process		No. Events
	ν_μ *Events (By Final State Topology)*	
CC Inclusive		449,959
CC 0 π	$\nu_\mu N \to \mu + Np$	307,441
	· $\nu_\mu N \to \mu + 0p$	73,863
	· $\nu_\mu N \to \mu + 1p$	173,830
	· $\nu_\mu N \to \mu + 2p$	29,894
	· $\nu_\mu N \to \mu + \geq 3p$	29,854
CC 1 $\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + 1\pi^\pm$	99,446
CC $\geq 2\pi^\pm$	$\nu_\mu N \to \mu + \text{nucleons} + \geq 2\pi^\pm$	8,433
CC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	43,048
NC Inclusive		171,869
NC 0 π	$\nu_\mu N \to \text{nucleons}$	118,787
NC 1 $\pi^\pm$	$\nu_\mu N \to \text{nucleons} + 1\pi^\pm$	22,407
NC $\geq 2\pi^\pm$	$\nu_\mu N \to \text{nucleons} + \geq 2\pi^\pm$	2,788
NC $\geq 1\pi^0$	$\nu_\mu N \to \text{nucleons} + \geq 1\pi^0$	30,910
	ν_e *Events*	
CC Inclusive		3,465
NC Inclusive		1,195
Total ν_μ and ν_e Events		626,488
	ν_μ *Events (By Physical Process)*	
CC QE	$\nu_\mu n \to \mu^- p$	270,623
CC RES	$\nu_\mu N \to \mu^- N$	124,417
CC DIS	$\nu_\mu N \to \mu^- X$	46,563
CC Coherent	$\nu_\mu Ar \to \mu Ar + \pi$	1,664

Table 4: Estimated event rates using GENIE in a 2.2×10^{20} POT exposure of LAr1-ND. In enumerating proton multiplicity, we assume an energy threshold on protons of 21 MeV. The 0π topologies include any number of neutrons in the event.

LAr1-ND: a new ~50t fid. LArTPC on the BNB - *(SciBooNE Site)*

SUMMARY

- present generation ν-Exp's (MINERvA, MicroBooNE):
  - in-depth study of Nuclear Effects and their impact on ν-Interaction reconstruction
  - first hints about ν_e-XSECT



J.A. Formaggio and G.P. Zeller,
'From eV to EeV: Neutrino Cross Sections Across Energy Scales'
Rev. Mod. Phys., 2012.

- **NEXT generation**

high-resolution detectors operated as Near-Detector in high-intensity ν-beams:

The Rare Process&Precision era in exclusive XESECT measurements for both muon and electron neutrino