Neutral Current Resonant Pion Production ~Experimental Results~

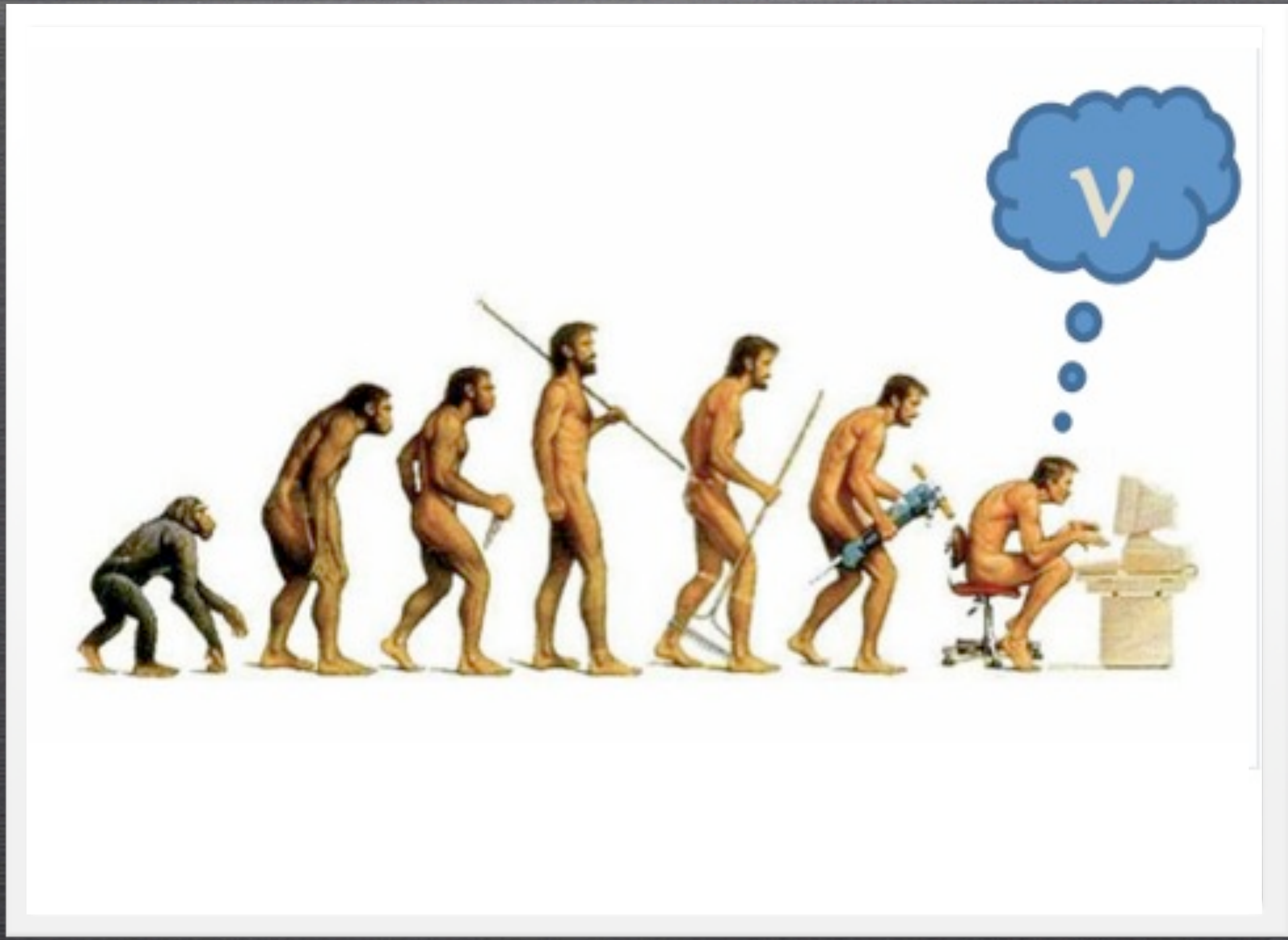
Hide-Kazu TANAKA

BNL

BROOKHAVEN NATIONAL LABORATORY

NuFact2010 at Mumbai, October 24, 2010

Contents



Introduction

Neutral Current Resonant π Production

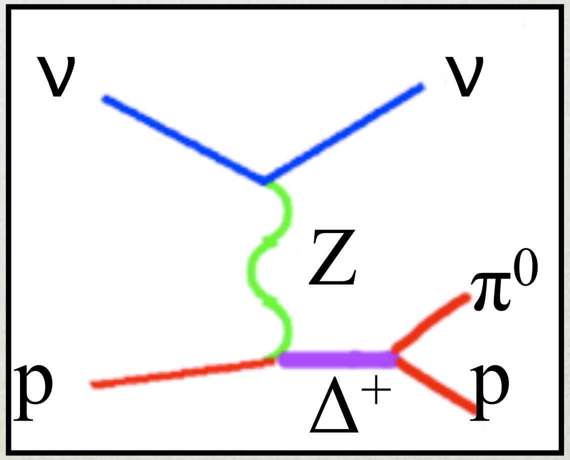
- Among several resonances, Δ(1232) resonance is the main contribution to the “resonant pion production”.
- Δ(1232) decays to single pion final state. In neutral current mode, four possible processes:

$$\nu\ p \to \nu\Delta^+ \to \nu\ p\ \pi^0$$

$$\nu\ n \to \nu\Delta^0 \to \nu\ n\ \pi^0$$

$$\nu\ p \to \nu\Delta^+ \to \nu\ n\ \pi^+$$

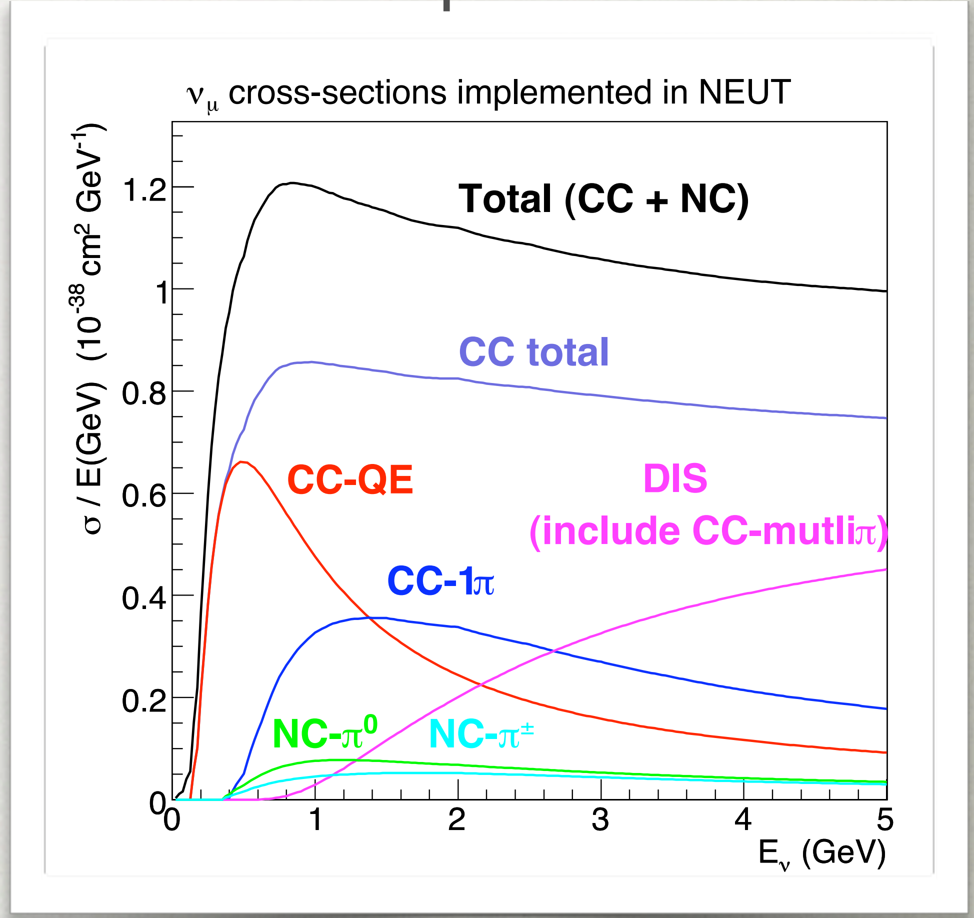
$$\nu\ n \to \nu\Delta^0 \to \nu\ p\ \pi^-$$



Measurement of NC pion production

- In experiments, extracting resonant pion production cross section is non-trivial because of Bkg contributions:
  - Non-resonant processes: DIS, coherent-π
  - Nuclear effect: absorption, inelastic, charge exchange (mimic resonant-π event)
- σ(NC res-π) extraction depends on modeling of the background processes

NEUT prediction



- ➜ Experimental observable: σ(NC-1π)
  - NC-1π ≡ NC event with a pion exiting target nucleus
    - all the FSI effects included (e.g. Multi-π/DIS can be part of signal events)
  - NC-1π cross section often more important to modern-day neutrino oscillation experiment (later slide)

Past NC-1π Measurements

- Several measurements in past
  - Most of results in the form of cross section ratio, e.g. ratio to CC-1π
  - Few results in form of absolute cross section

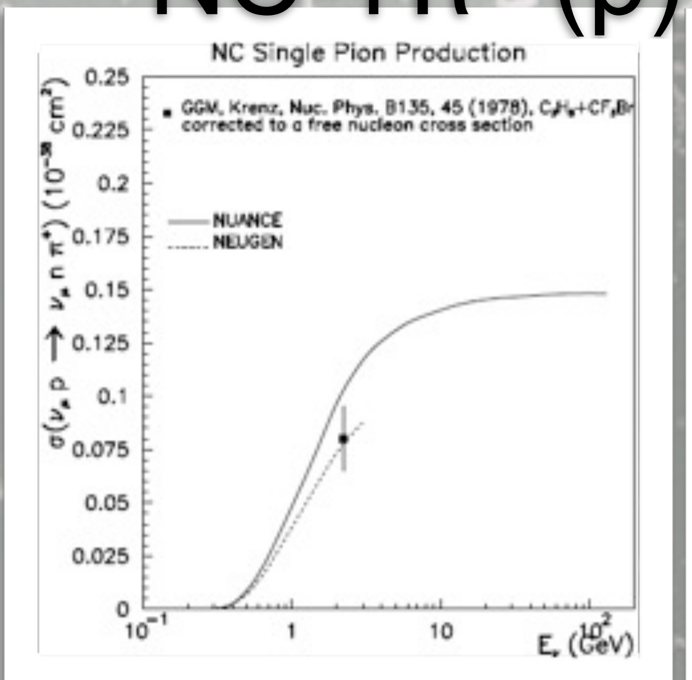
Source	Target	NC/CC Ratio	Value
ANL	H_2	$\sigma(\nu_\mu\, p \to \nu_\mu\, p\, \pi^0)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	$0.51 \pm 0.25^*$
ANL	H_2	$\sigma(\nu_\mu\, p \to \nu_\mu\, p\, \pi^0)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	$0.09 \pm 0.05^*$
NUANCE	free nucleon	$\sigma(\nu_\mu\, p \to \nu_\mu\, p\, \pi^0)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	0.20
ANL	H_2	$\sigma(\nu_\mu\, p \to \nu_\mu\, n\, \pi^+)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	0.17 ± 0.08
ANL	H_2	$\sigma(\nu_\mu\, p \to \nu_\mu\, n\, \pi^+)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	0.12 ± 0.04
NUANCE	free nucleon	$\sigma(\nu_\mu\, p \to \nu_\mu\, n\, \pi^+)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	0.17
ANL	D_2	$\sigma(\nu_\mu\, n \to \nu_\mu\, p\, \pi^-)/\sigma(\nu_\mu n \to \mu^-\, n\, \pi^+)$	0.38 ± 0.11
NUANCE	free nucleon	$\sigma(\nu_\mu\, n \to \nu_\mu\, p\, \pi^-)/\sigma(\nu_\mu n \to \mu^-\, n\, \pi^+)$	0.27
Gargamelle	$C_3H_8\ CF_3Br$	$\Sigma_{N=n,p}\, \sigma(\nu_\mu\, N \to \nu_\mu\, N\, \pi^0)/2\, \sigma(\nu_\mu n \to \mu^-\, p\, \pi^0)$	0.45 ± 0.08
CERN PS	Al	$\Sigma_{N=n,p}\, \sigma(\nu_\mu\, N \to \nu_\mu\, N\, \pi^0)/2\, \sigma(\nu_\mu n \to \mu^-\, p\, \pi^0)$	0.40 ± 0.06
BNL	Al	$\Sigma_{N=n,p}\, \sigma(\nu_\mu\, N \to \nu_\mu\, N\, \pi^0)/2\, \sigma(\nu_\mu n \to \mu^-\, p\, \pi^0)$	$0.17 \pm 0.04^{**}$
BNL	Al	$\Sigma_{N=n,p}\, \sigma(\nu_\mu\, N \to \nu_\mu\, N\, \pi^0)/2\, \sigma(\nu_\mu n \to \mu^-\, p\, \pi^0)$	$0.248 \pm 0.085^{**}$
NUANCE	free nucleon	$\Sigma_{N=n,p}\, \sigma(\nu_\mu\, N \to \nu_\mu\, N\, \pi^0)/2\, \sigma(\nu_\mu n \to \mu^-\, p\, \pi^0)$	0.41
ANL	D_2	$\sigma(\nu_\mu\, n \to \nu_\mu\, p\, \pi^-)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	0.11 ± 0.022
NUANCE	free nucleon	$\sigma(\nu_\mu\, n \to \nu_\mu\, p\, \pi^-)/\sigma(\nu_\mu p \to \mu^-\, p\, \pi^+)$	0.19

Table and figures form G. Zeller, hep-ex/0312061

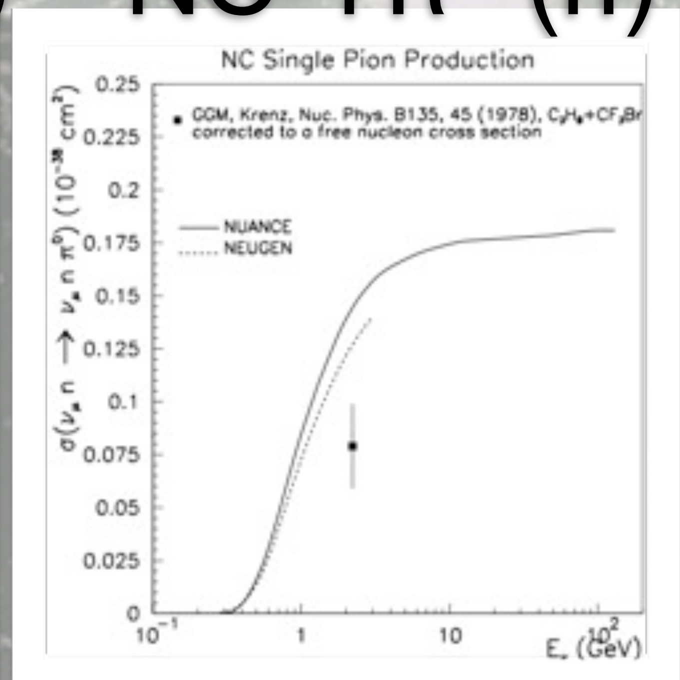
Past NC-1π Measurements

- Several measurements in past
  - Most of results in the form of cross section ratio, e.g. ratio to CC-1π
  - Few results in form of absolute cross section

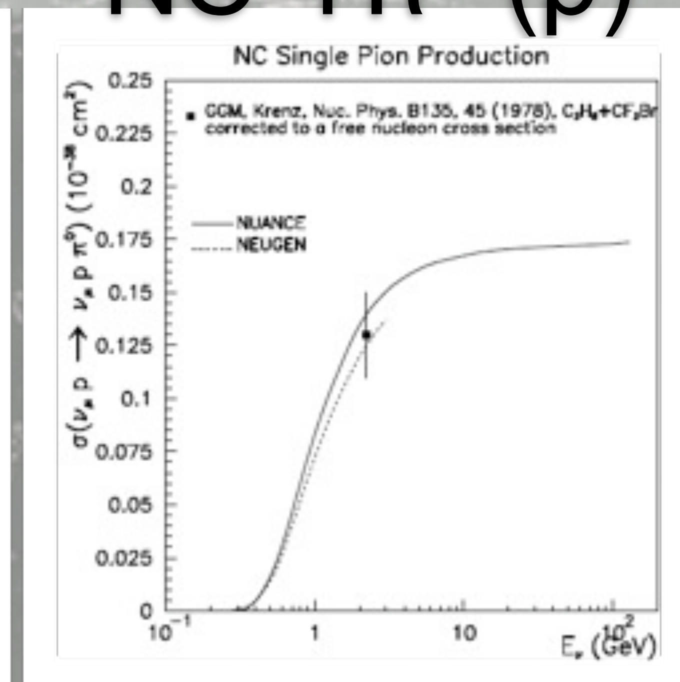
NC-$1\pi^+$ (p)



NC-$1\pi^0$ (n)



NC-$1\pi^0$ (p)



NC-$1\pi^-$ (n)

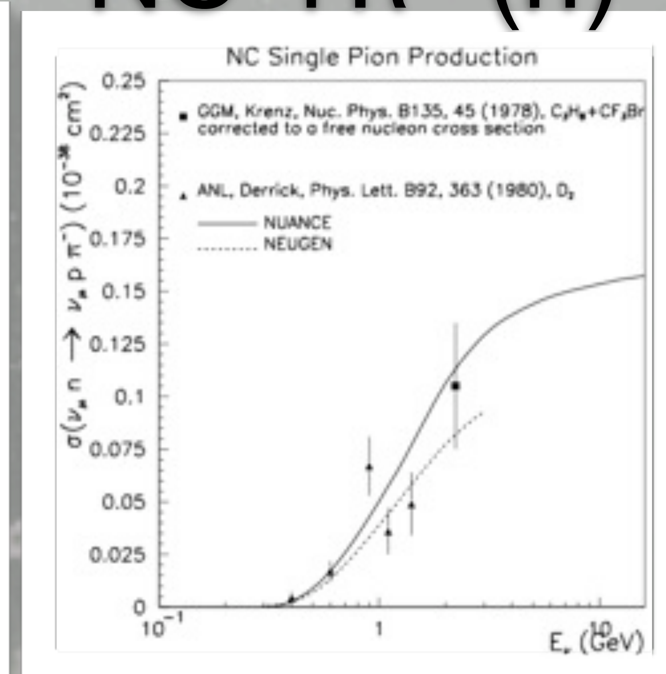
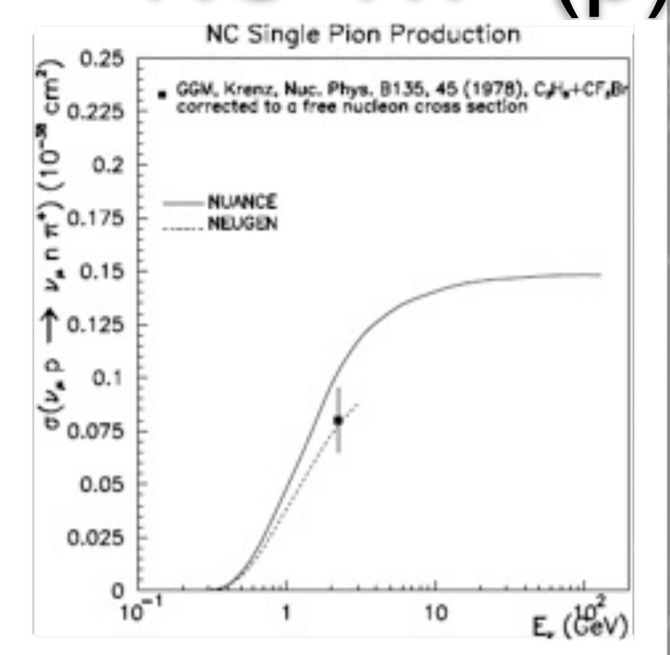


Table and figures form G. Zeller, hep-ex/0312061

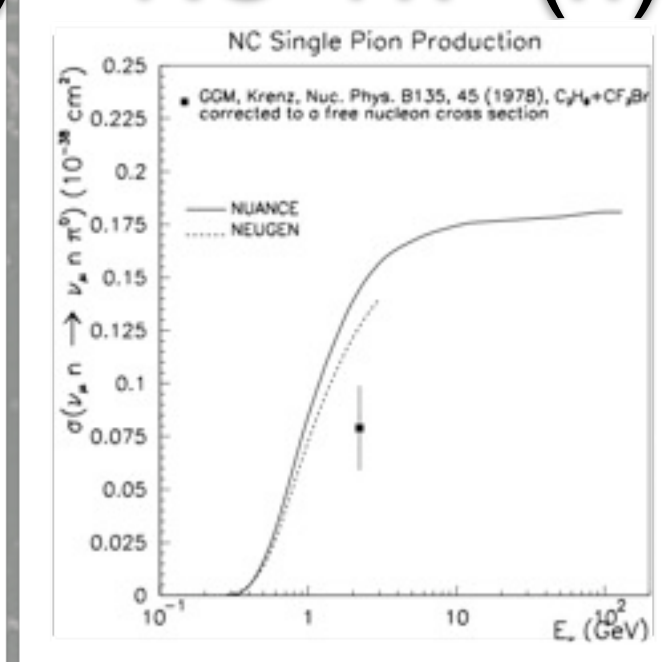
Past NC-1π Measurements

- Several measurements in past
  - Most of results in the form of cross section ratio, e.g. ratio to CC-1π
  - Few results in form of absolute cross section

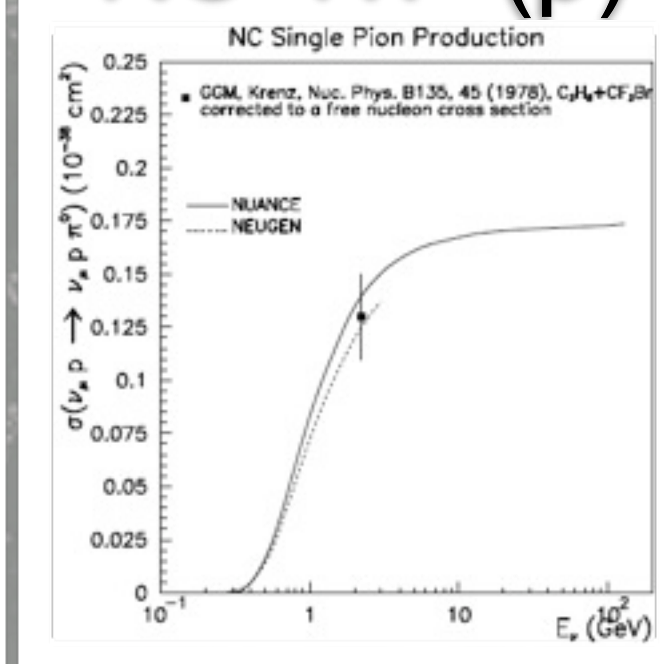
NC-1π+ (p)



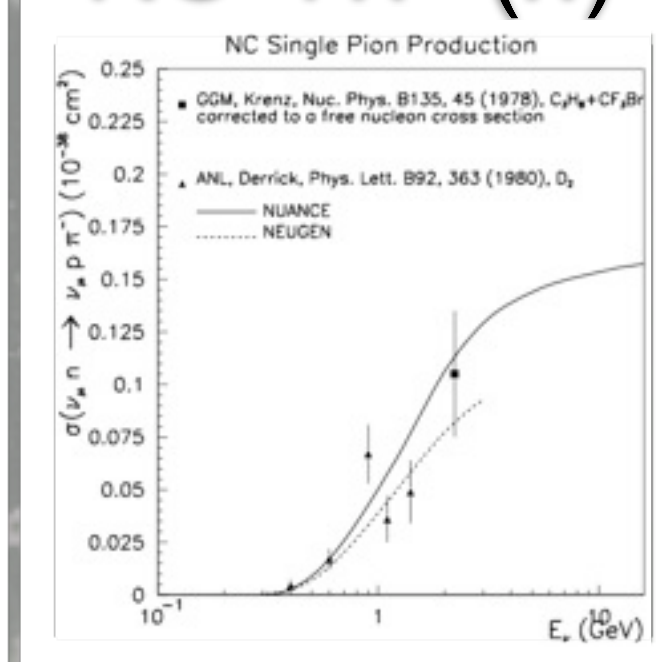
NC-1π0 (n)



NC-1π0 (p)



NC-1π− (n)



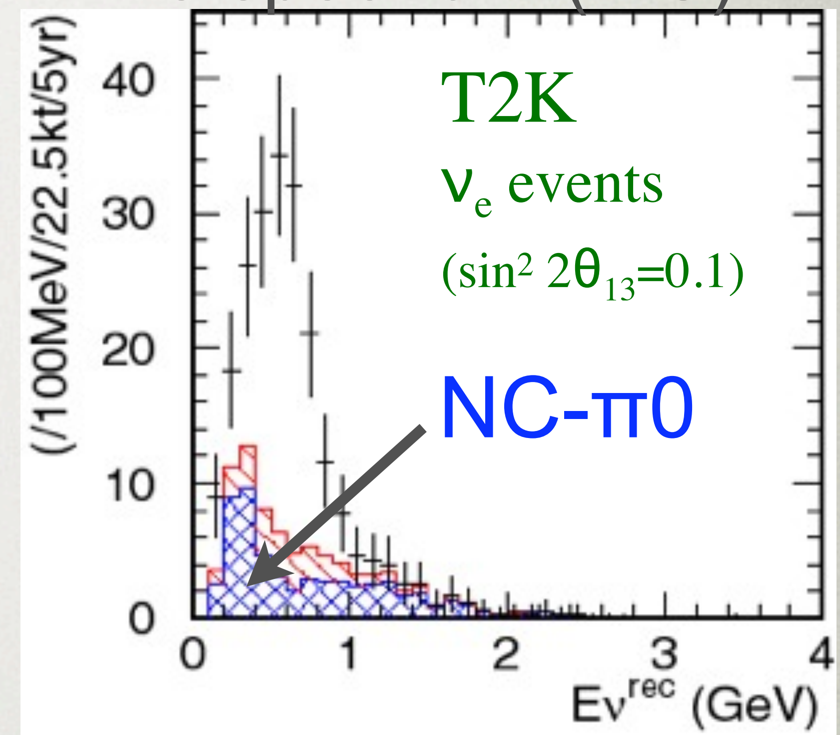
NC-1π cross sections are extremely sparse, compared to CC-1π modes.

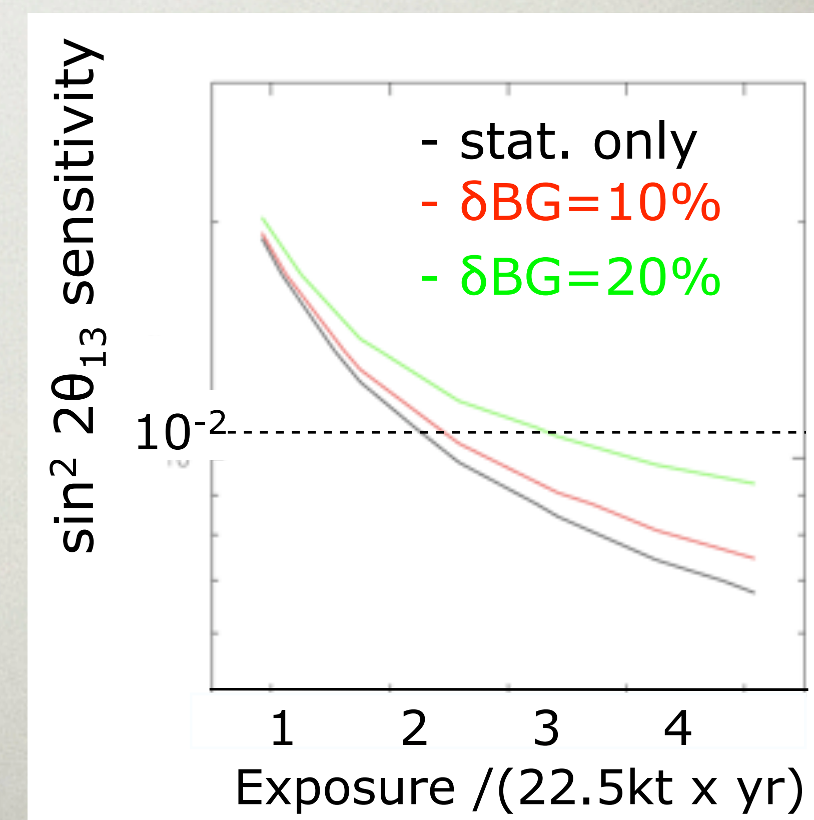
Table and figures form G. Zeller, hep-ex/0312061

Need NC-1π measurement?

- Neutrino oscillation experiments need precise knowledge on NC-1π^0
- NC-1π^0 is the major background for $\nu_\mu \rightarrow \nu_e$ oscillation search
  - Gamma-rays (from π^0) mimic electron signal in Cherenkov detector, e.g. overlapping two rings
- ➜ π^0 kinematics is also important to determine misidentification rate in ν_e search as well as cross section.

ve spectrum (MC)

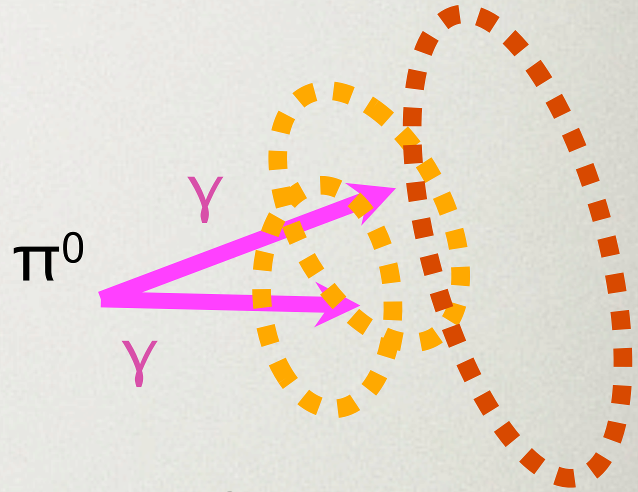




Need NC-1π measurement?

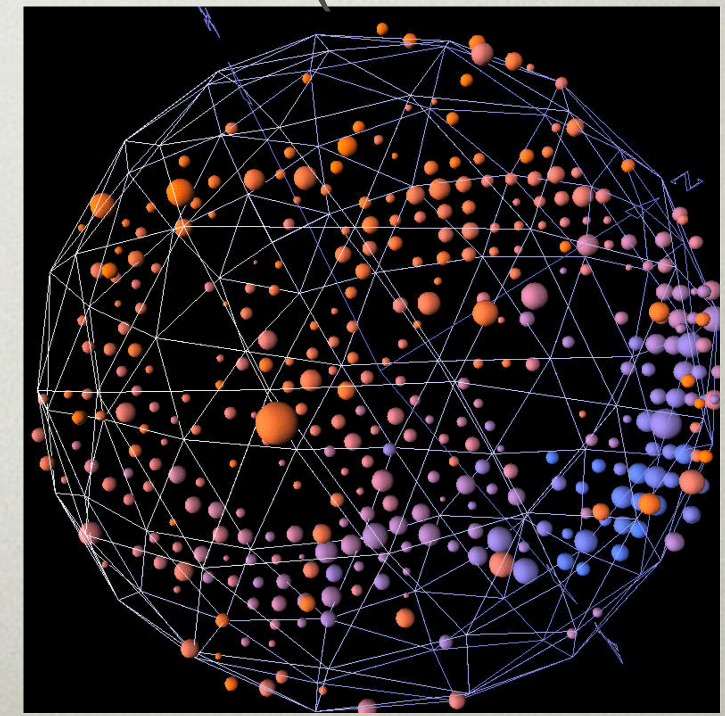
- Neutrino oscillation experiments need precise knowledge on NC-1π^0
- NC-1π^0 is the major background for $\nu_\mu \rightarrow \nu_e$ oscillation search
    - Gamma-rays (from π^0) mimic electron signal in Cherenkov detector, e.g. overlapping two rings
- ➜ π^0 kinematics is also important to determine misidentification rate in ν_e search as well as cross section.

Two rings merged to 1 ring in Cherenkov detector



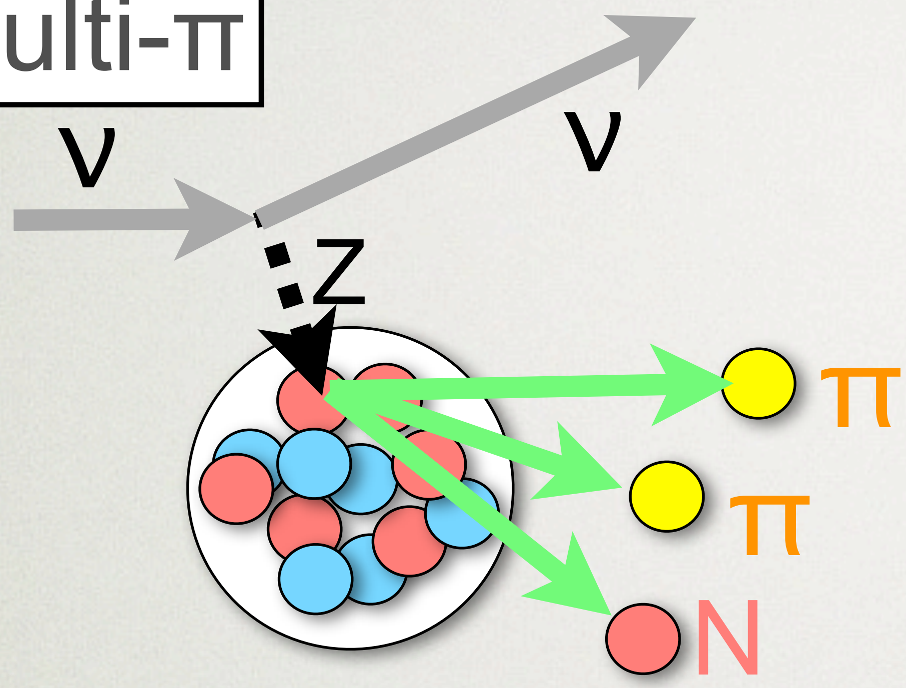
Overlapping rings

π^0 event (MiniBooNE)

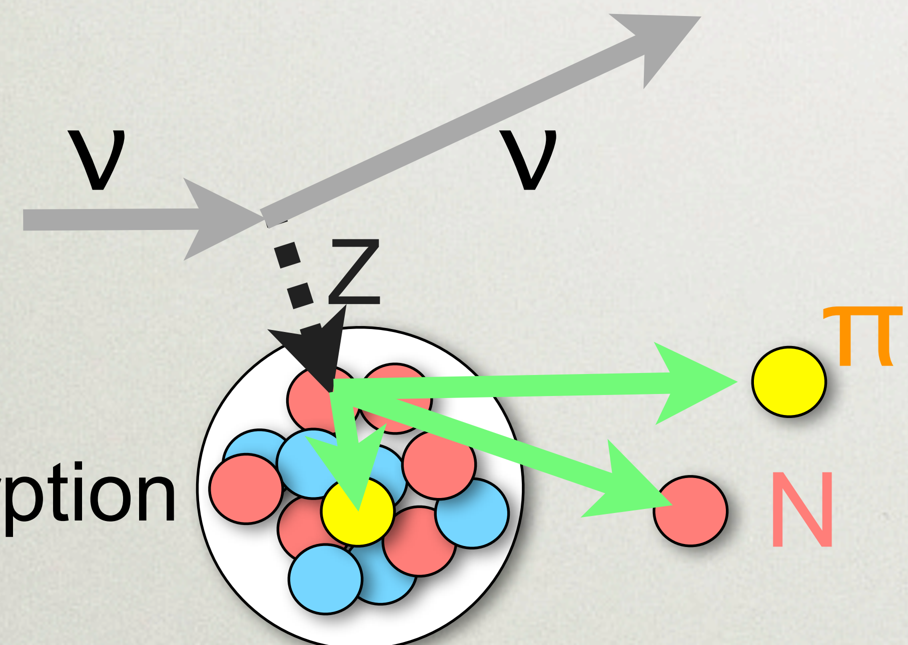


Challenge

NC multi-π



π absorption



π is often absorbed in target nucleus → NC multi-π events indistinguishable from NC-1π.

- Nuclear target
  - Oscillation experiment use nuclear target (C, O, Fe, Ar)
- ➜ “Nuclear effect”
  - Final state interaction
  - Modify kinematics/charge of final state particles (π, p)
  - Vanish particles (absorption)
  - e.g. ~40% of π^0s interact in the target nucleus (NEUT, Carbon target, average over SciBooNE flux (Eν~0.7GeV))
  - Nuclear effect is not well modeled yet

▶ Important to understand ν int. with nuclear effect

Recent Measurements

Recent measurement

- Four recent measurements of NCπ0:

Exp	Mode	Target	ν/ν̄	Ev (GeV)	Publication
K2K-1KT	NC-1π0	H_2O	ν	1.3	PLB619, 255 (2005)
MiniBooNE	NC-1π0	CH_2	ν and ν̄	0.8(ν) 0.7(ν̄)	PRD81, 013005 (2010)
SciBooNE	NC-π0	CH	ν	0.8	PRD81, 033004 (2010)

Note: NC coh-π measurements are not included in the list.
See H. Tanaka (my) talk for coh-π measurements.

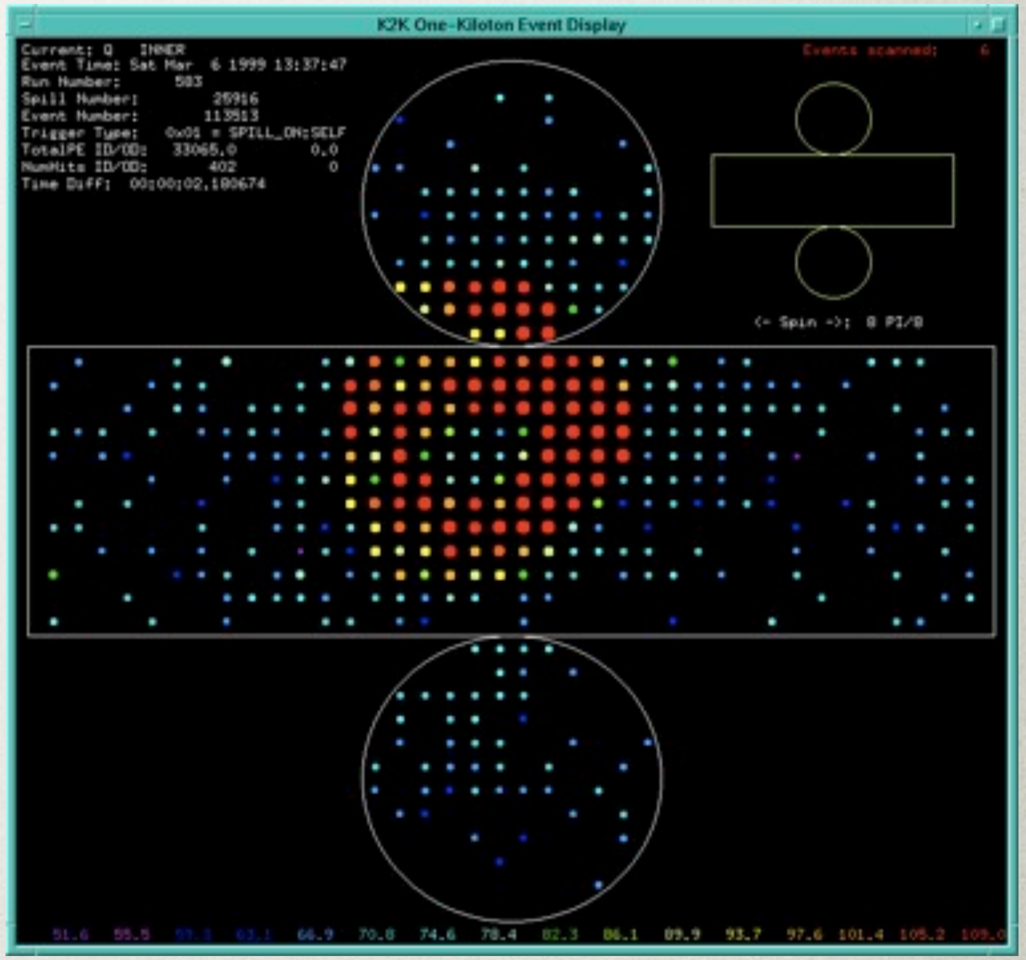
Measuring cross sections

- Measured quantity:
  - Cross section ratio: many systematics are canceled, especially beam related.
  - Absolute cross section: require good understanding of flux and control of flux uncertainties.
- Signal definition
  - Slightly different definition in each experiment:
    - **NC-1π^0** ≡ NC int. resulting in one π^0 exiting the target nucleus & no other mesons
    - **NC-π^0** ≡ NC int. in which at least one π^0 in the final state

K2K-1KT $\sigma(NC\text{-}1\pi^0)/\sigma(CC)$

Phys. Lett. B619, 255 (2005)

- Water Cherenkov detector
- Signal definition: NC-1π^0
- 1st meas. of NC-1π^0 in H_2O
- Identify event using hit topology
  - Two e-like rings
- NC-1π^0 purity: 71%
  - Resonant: 52%
  - Coherent: 10%
  - DIS: 4%, FSI(CC/NC-1$\pi^\pm$): 3%
- $\sigma(NC\text{-}1\pi^0) / \sigma(CC) = (6.4 \pm 0.1 \pm 0.7)\%$
  <Ev>=1.3 GeV
  - In agreement with expectation (NEUT, R-S): 6.5%
- Momentum distribution disagrees

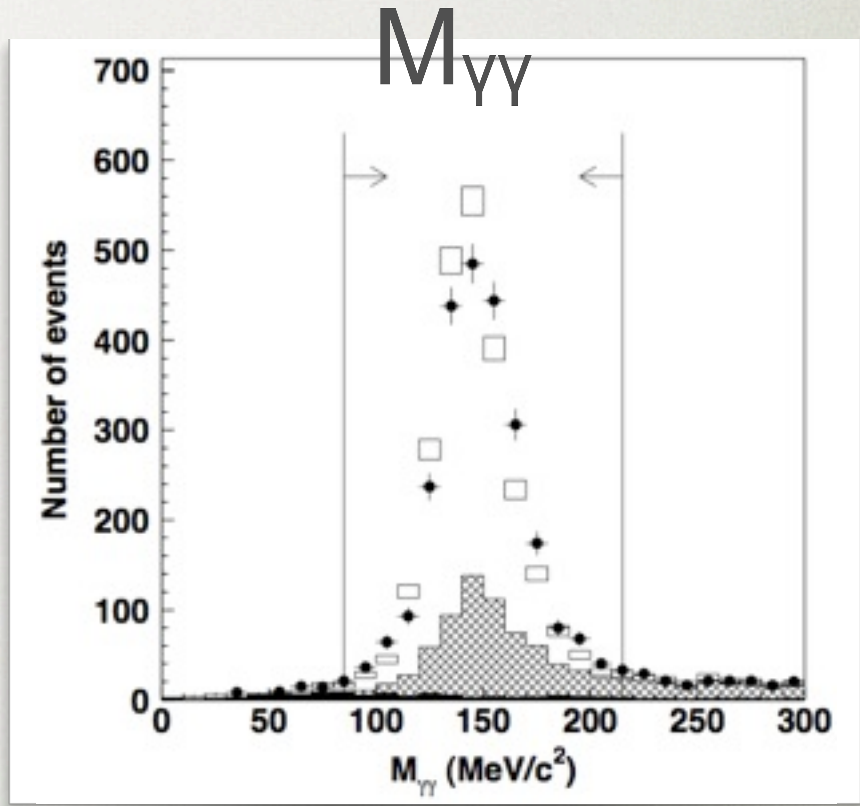


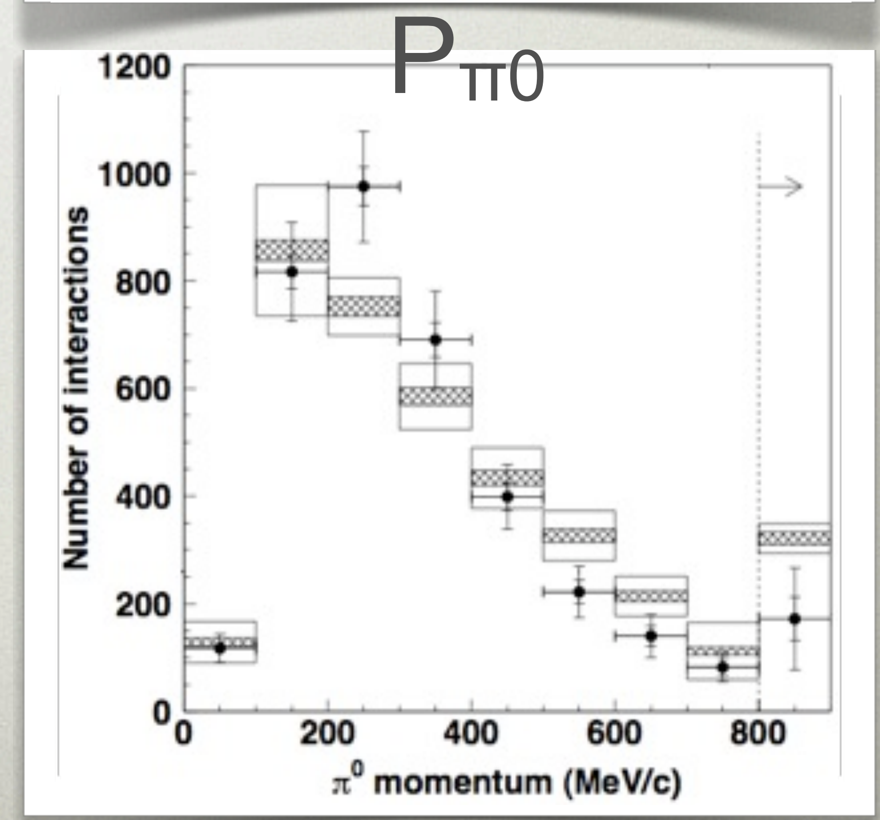
K2K-1KT event display

K2K-1KT σ(NC-1π⁰)/σ(CC)

Phys. Lett. B619, 255 (2005)

- Water Cherenkov detector
- Signal definition: NC-1π^0
- 1st meas. of NC-1π^0 in H_2O
- Identify event using hit topology
    - Two e-like rings
- NC-1π^0 purity: 71%
    - Resonant: 52%
    - Coherent: 10%
    - DIS: 4%, FSI(CC/NC-1$\pi^\pm$): 3%
- σ(NC-1π^0) / σ(CC) = (6.4±0.1±0.7)%
  <Ev>=1.3 GeV
    - In agreement with expectation (NEUT, R-S): 6.5%
- Momentum distribution disagrees

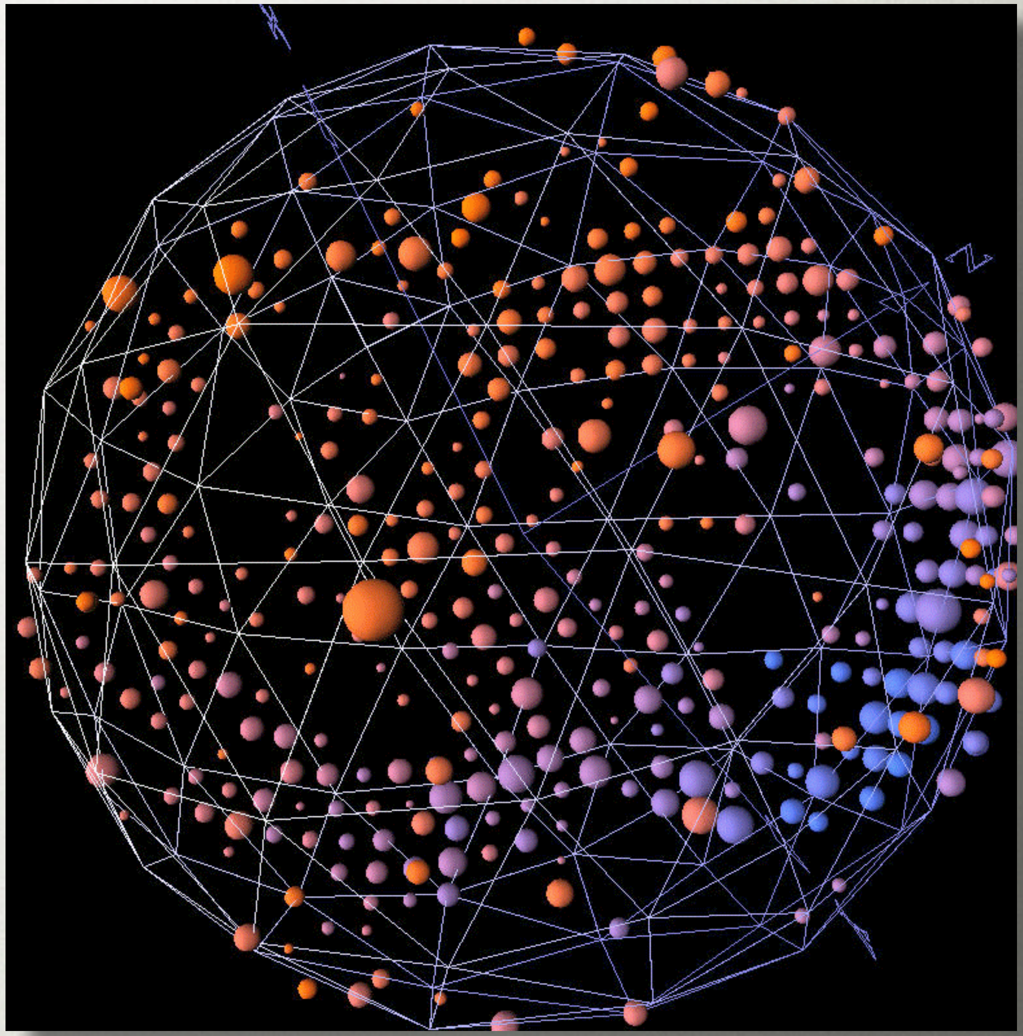




MiniBooNE σ(NC-1π^0)

Phys. Rev. D81, 013005 (2010)

- Mineral oil Cherenkov detector
- Signal definition: NC-1π^0
- 1st **absolute** NC-1π^0 diff'l cross section
    - ν and $\bar{\nu}$ modes
- Identify event using hit topology
    - Two e-like rings
- NC-1π^0 purity: 73% (ν), 58% ($\bar{\nu}$)
    - Major Bkg components:
        - ν mode: NC$\pi^{\pm}$(23%), CC$\pi^{\pm,0}$(25%)
        - $\bar{\nu}$ mode: NC$\pi^{\pm}$(13%), WS(56%)
          [$\pi^{\pm}$ produce π^0 outside the target nucleus]
- Discrepancies in normalization and shape



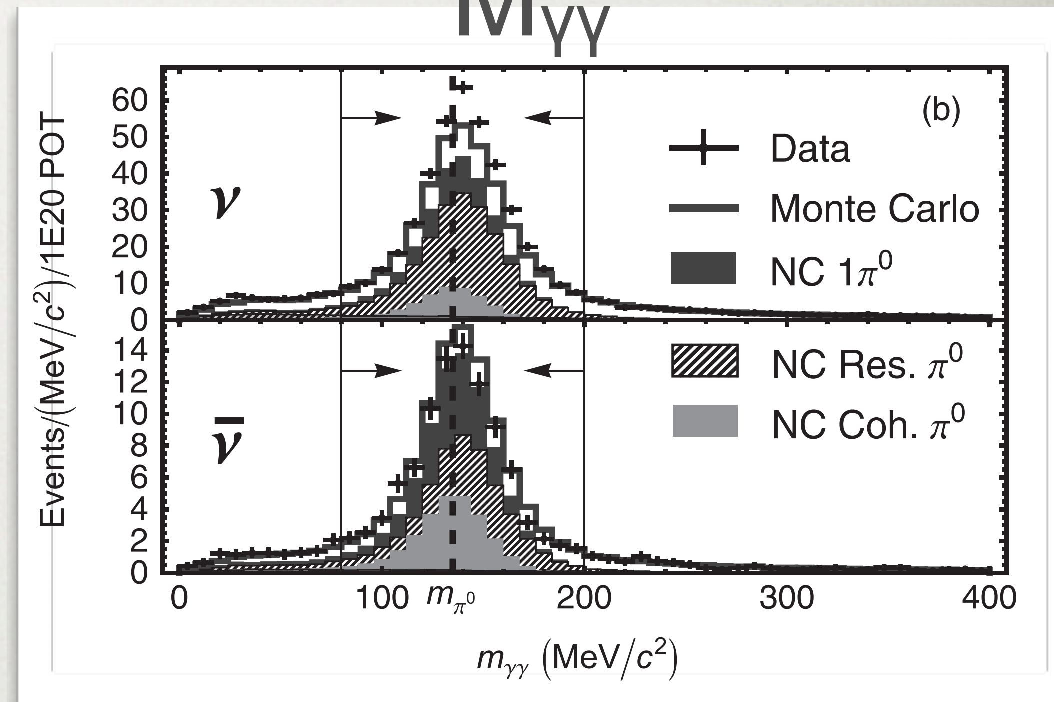
MiniBooNE Event Display
(π^0 event)

MiniBooNE σ(NC-1π^0)

Phys. Rev. D81, 013005 (2010)

- Mineral oil Cherenkov detector
- Signal definition: NC-1π^0
- 1st **absolute** NC-1π^0 diff'l cross section
  - ν and $\bar{\nu}$ modes
- Identify event using hit topology
  - Two e-like rings
- NC-1π^0 purity: 73% (ν), 58% ($\bar{\nu}$)
  - Major Bkg components:
    - ν mode: NC$\pi^{\pm}$(23%), CC$\pi^{\pm,0}$(25%)
    - $\bar{\nu}$ mode: NC$\pi^{\pm}$(13%), WS(56%)
      [$\pi^{\pm}$ produce π^0 outside the target nucleus]
- Discrepancies in normalization and shape

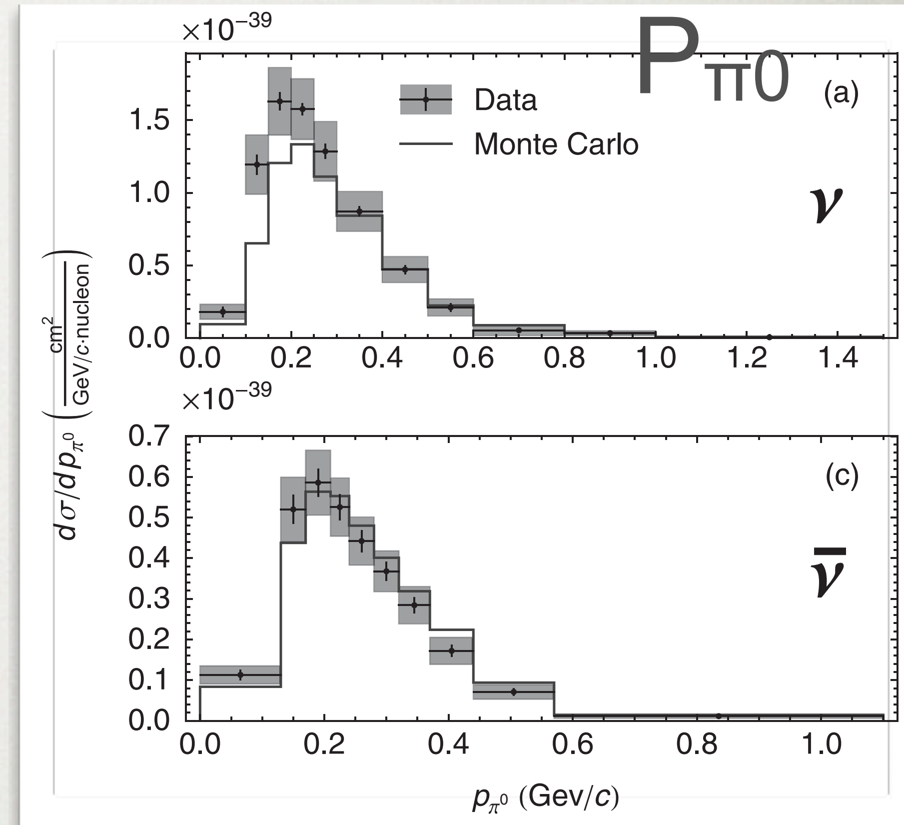
$M_{\gamma\gamma}$

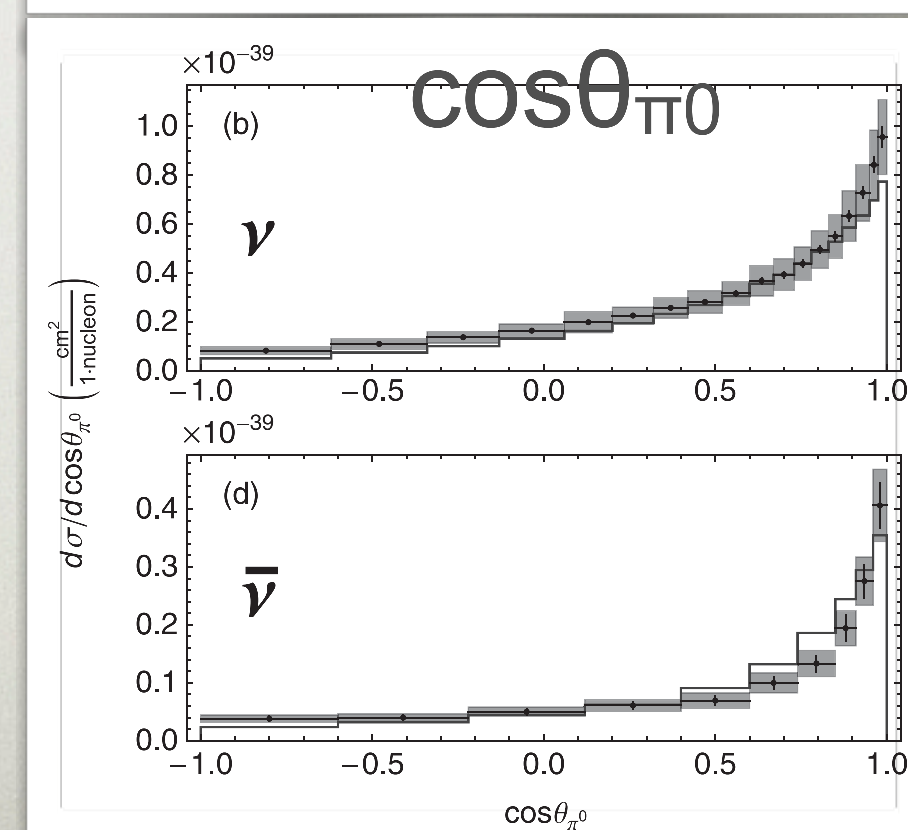


MiniBooNE σ(NC-1π^0)

Phys. Rev. D81, 013005 (2010)

- Mineral oil Cherenkov detector
- Signal definition: NC-1π^0
- 1st **absolute** NC-1π^0 diff'l cross section
  - ν and ν̄ modes
- Identify event using hit topology
  - Two e-like rings
- NC-1π^0 purity: 73% (ν), 58% (ν̄)
  - Major Bkg components:
  - ν mode: NC$\pi^\pm$(23%), CC$\pi^{\pm,0}$(25%)
  - ν̄ mode: NC$\pi^\pm$(13%), WS(56%)
    [$\pi^\pm$ produce π^0 outside the target nucleus]
- Discrepancies in normalization and shape

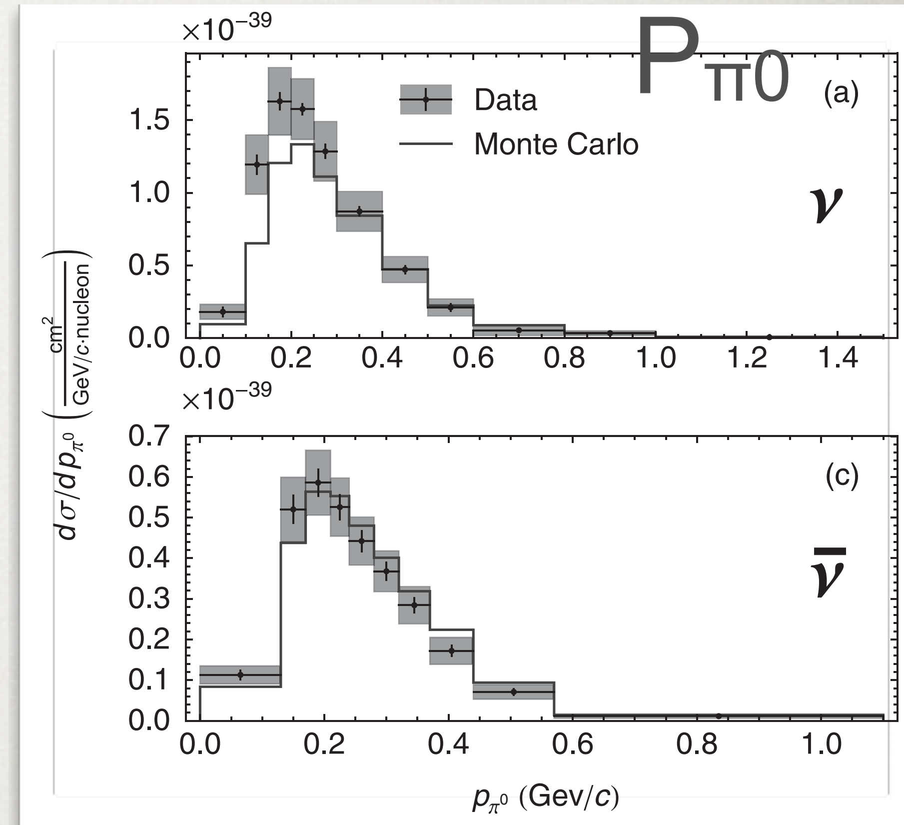


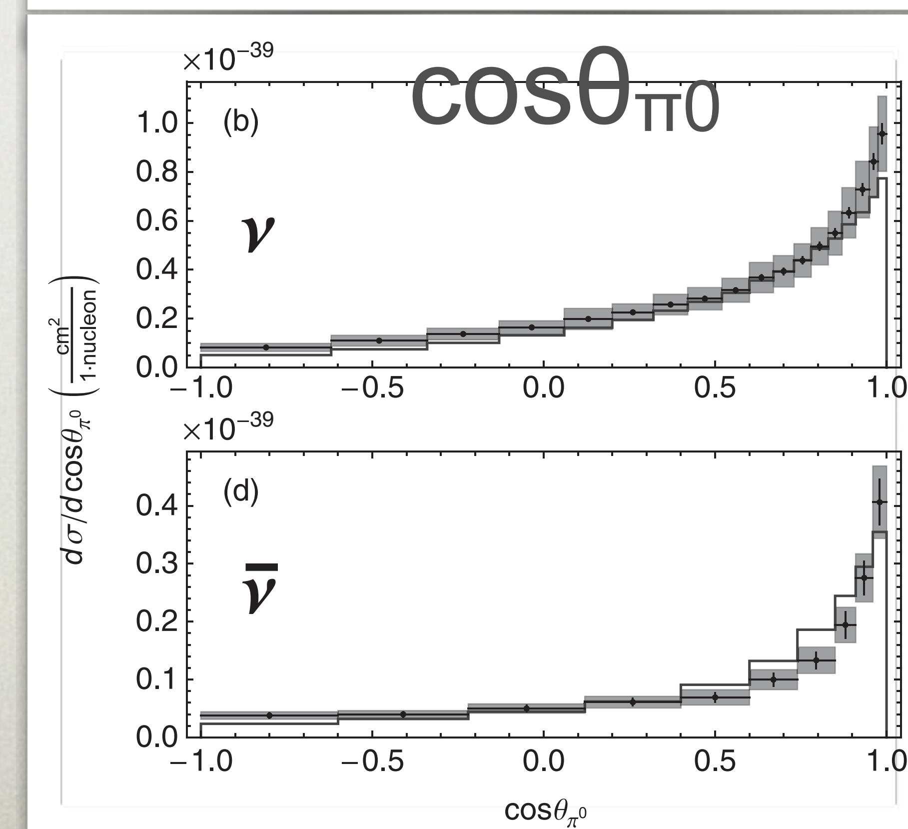


MiniBooNE $\sigma(NC\text{-}1\pi^0)$

Phys. Rev. D81, 013005 (2010)

- Mineral oil Cherenkov detector
- Signal definition: NC-1π^0
- 1st **absolute** NC-1π^0 diff'l cross section
  - ν and $\bar{\nu}$ modes



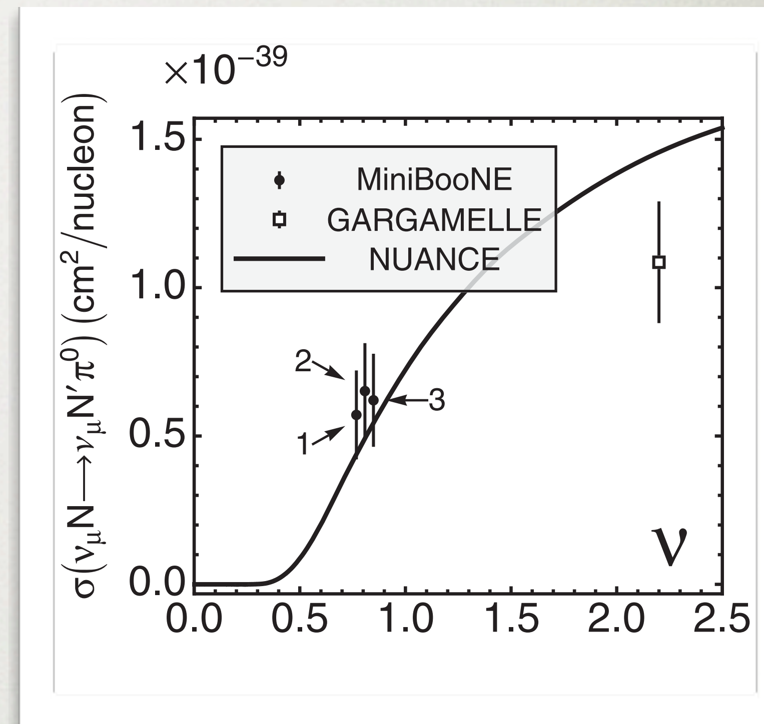


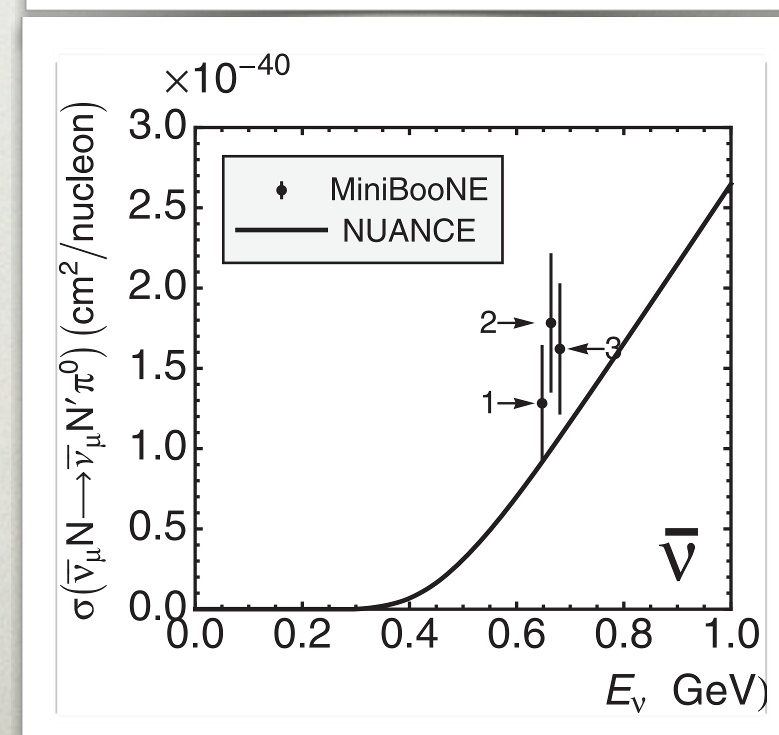
- Inclusive NC-1π^0 cross sections
  - least model dependence on coh-π and FSI
- $\sigma(\nu\ NC\text{-}1\pi^0)$ =
  $(4.76 \pm 0.05 \pm 0.76) \times 10^{-40}$ cm^2/nucleon
  <Ev>=808MeV
- $\sigma(\bar{\nu}\ NC\text{-}1\pi^0)$ =
  $(1.48 \pm 0.05 \pm 0.23) \times 10^{-40}$ cm^2/nucleon
  <Ev>=664MeV

MiniBooNE "incoherent" cross section

- Extract exclusive "incoherent" NC-1π0 cross section
  - Subtract NC coherent-π process as a background & Efficiency correction at initial interaction vertex
- $\sigma(\nu\ \text{NC-}1\pi^0) =$ $(5.71 \pm 0.08_{stat} \pm 1.45_{sys}) \times 10^{-40}$ cm^2/nucleon
- $\sigma(\bar{\nu}\ \text{NC-}1\pi^0) =$ $(1.28 \pm 0.07_{stat} \pm 0.35_{sys}) \times 10^{-40}$ cm^2/nucleon
- Found a significant effect of FSI
- Demonstrate coh-π model dependence using three different models:
  - 1: MiniBooNE NUANCE (65% of R-S model)
  - 2: J. E. Amaro et al, PRD79, 013002 (2009)
  - 3: L. Alvarez-Ruso et al, PRC76, 068501 (2007)

Phys. Rev. D81, 013005 (2010)

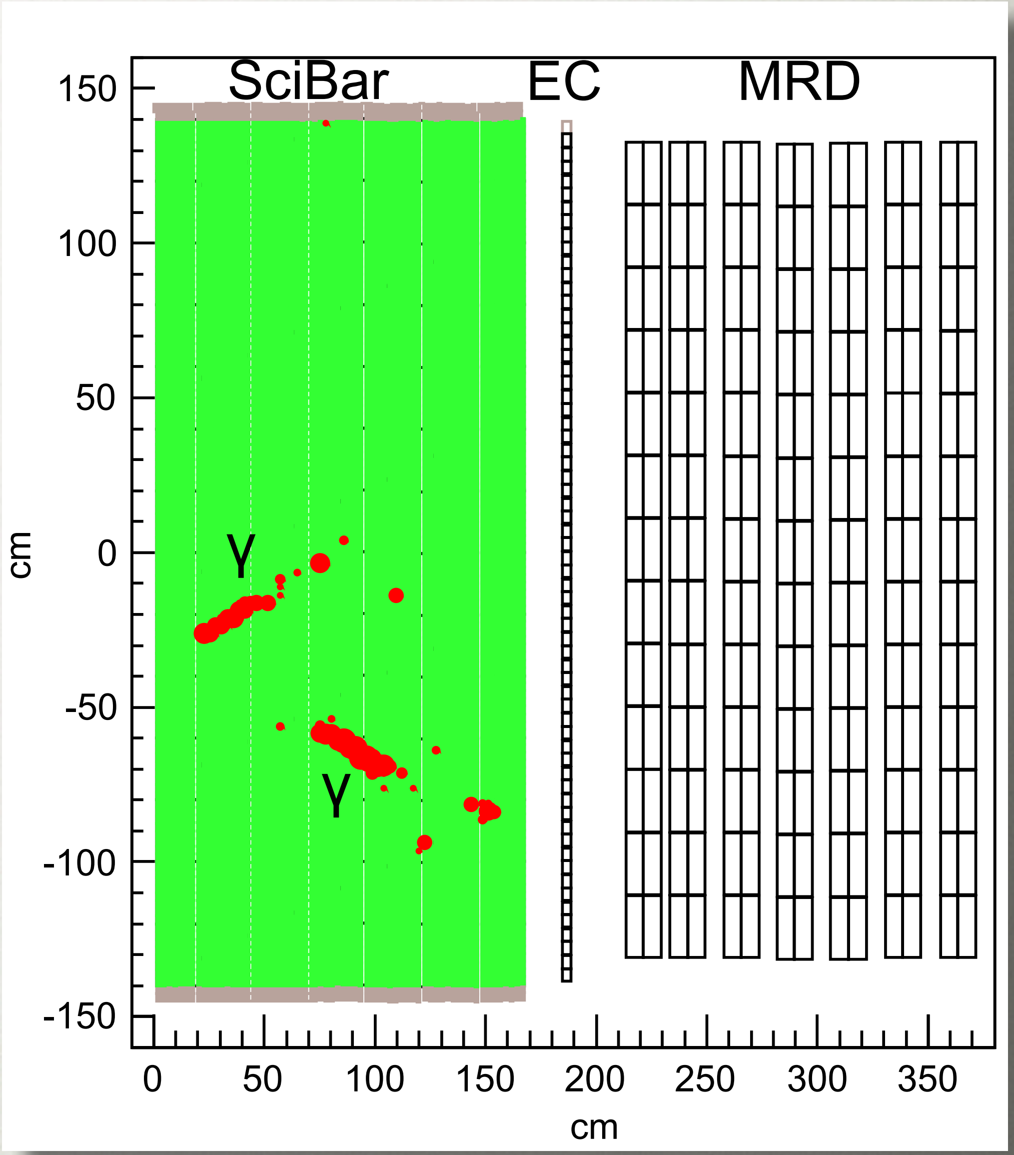




SciBooNE σ(NC-π⁰)/σ(CC)

Phys. Rev. D81, 033004 (2010)

- Tracking (SciBar) + EM-Cal (EC)
- Signal definition: NC-π^0
- Identify "shower-like" tracks in SciBar
- NC-π^0 purity: 61% (resonant: 40%, coherent: 15%, DIS/Multi-π: 5%)
- $\sigma(\text{NC-}\pi^0)/\sigma(\text{CC}) = (7.7\pm0.5\pm0.5)\text{x}10^{-2}$
  <Eν>=1.14 GeV
  - In agreement with expectation (NEUT, R-S): $6.8\text{x}10^{-2}$
    - Cross check with NUANCE
      - $\sigma(\text{NC-}\pi^0)/\sigma(\text{CC}) = 7.9\text{x}10^{-2}$
        (NUANCE expectation: 7.1E-2)
- π^0 kinematics of expectation (NEUT) in good agreement with data within error.

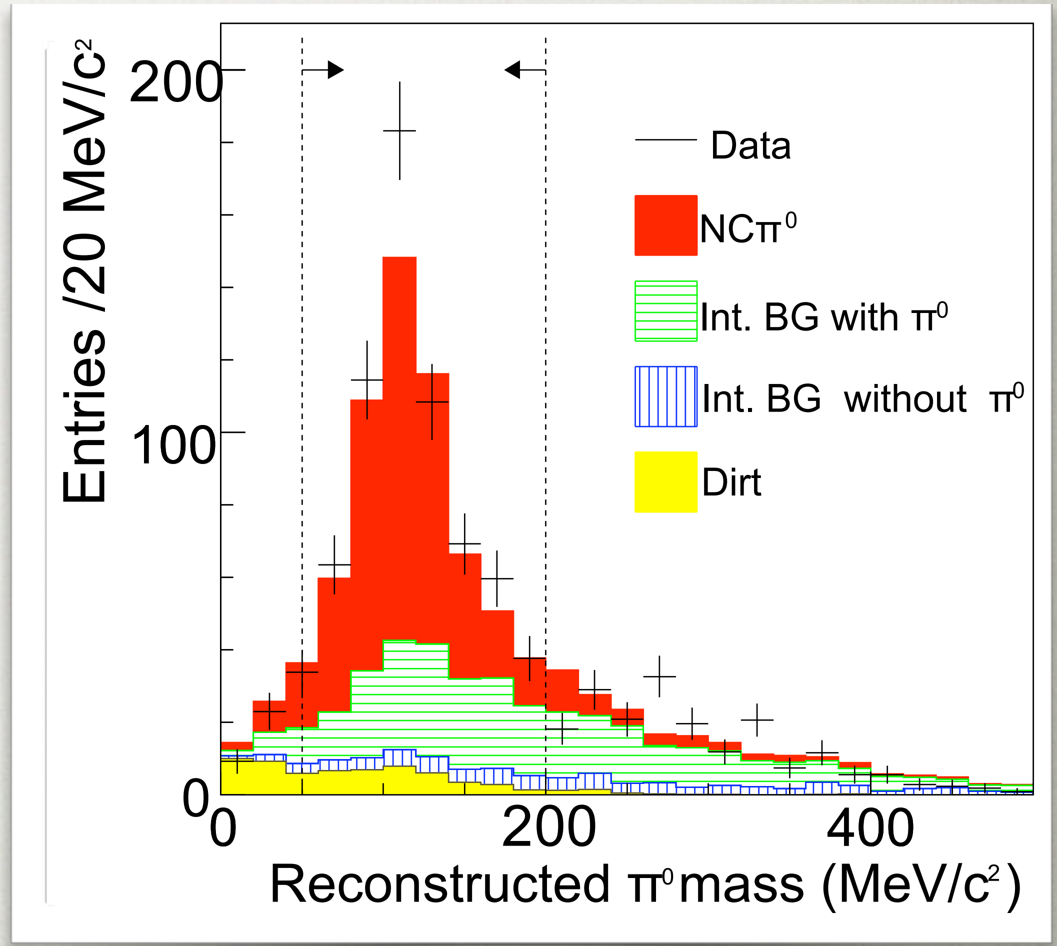


SciBooNE Event Display (NC-π0 candidate)

SciBooNE $\sigma(NC\text{-}\pi^0)/\sigma(CC)$

Phys. Rev. D81, 033004 (2010)

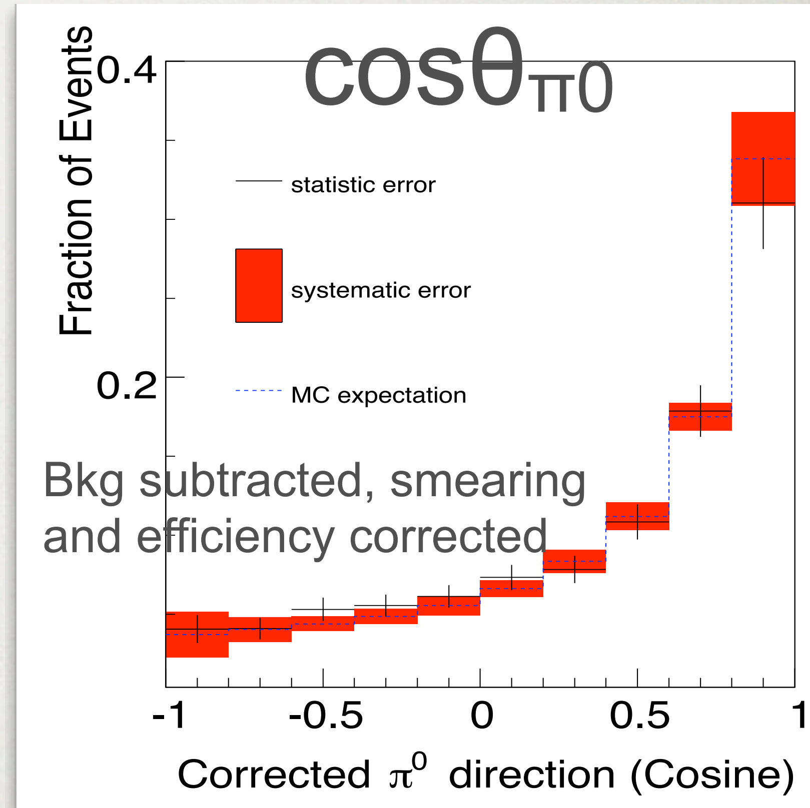
- Tracking (SciBar) + EM-Cal (EC)
- Signal definition: NC-π^0
- Identify "shower-like" tracks in SciBar
- NC-π^0 purity: 61% (resonant: 40%, coherent: 15%, DIS/Multi-π: 5%)
- $\sigma(NC\text{-}\pi^0)/\sigma(CC) = (7.7\pm0.5\pm0.5)\times10^{-2}$
  <Ev>=1.14 GeV
  - In agreement with expectation (NEUT, R-S): 6.8×10^{-2}
    - Cross check with NUANCE
      - $\sigma(NC\text{-}\pi^0)/\sigma(CC) = 7.9\times10^{-2}$
        (NUANCE expectation: 7.1E-2)
- π^0 kinematics of expectation (NEUT) in good agreement with data within error.

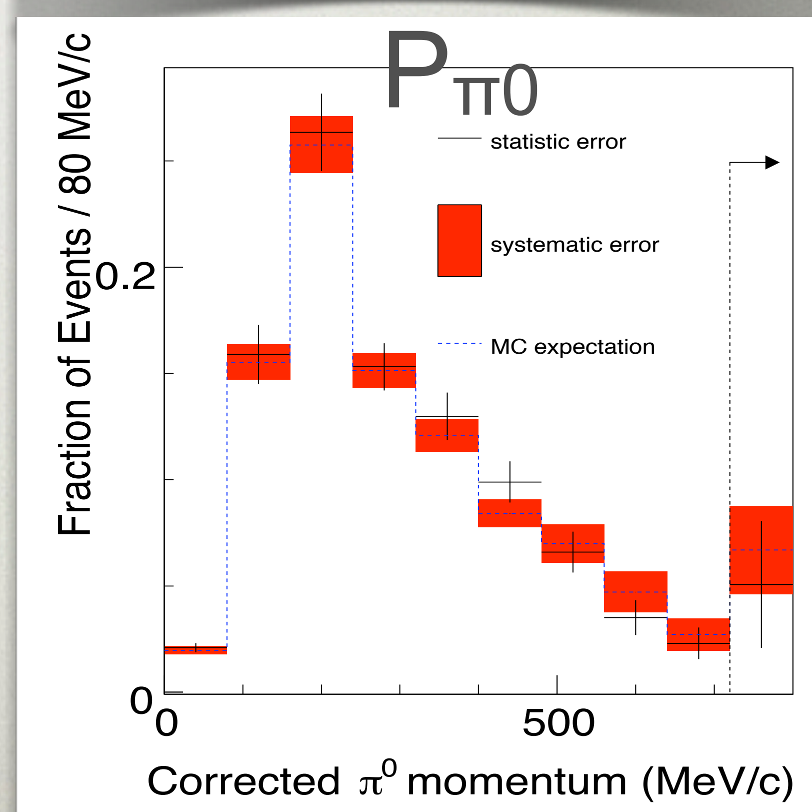


SciBooNE $\sigma(NC\text{-}\pi^0)/\sigma(CC)$

Phys. Rev. D81, 033004 (2010)

- Tracking (SciBar) + EM-Cal (EC)
- Signal definition: NC-π^0
- Identify "shower-like" tracks in SciBar
- NC-π^0 purity: 61% (resonant: 40%, coherent: 15%, DIS/Multi-π: 5%)
- $\sigma(NC\text{-}\pi^0)/\sigma(CC) = (7.7 \pm 0.5 \pm 0.5) \times 10^{-2}$
  <Ev>=1.14 GeV
  - In agreement with expectation (NEUT, R-S): 6.8×10^{-2}
    - Cross check with NUANCE
      - $\sigma(NC\text{-}\pi^0)/\sigma(CC) = 7.9 \times 10^{-2}$
        (NUANCE expectation: 7.1E-2)
- π^0 kinematics of expectation (NEUT) in good agreement with data within error.





Remarks from recent measurements

- High statistics, systematic error dominating
- K2K-1KT and MiniBooNE saw a Data/MC discrepancies in π^0 kinematics.
- Exclusive incoherent NC-1π^0 cross section [MiniBooNE]
    - Significant effect of FSI
    - Coh-π model dependence can be covered by existing systematic error.
- Results of cross section ratio using different event-generators (NEUT, NUANCE) are in agreement within error [SciBooNE].

Looking forward

- Recent results on NC-π^0 satisfy the requirements (~10% precision) from current ν oscillation experiments, T2K (and NOvA).
- Next generation experiments, CP violation & mass hierarchy measurements require
  - σ_ν error should be (much) smaller than 10% ($\leq$5%?)

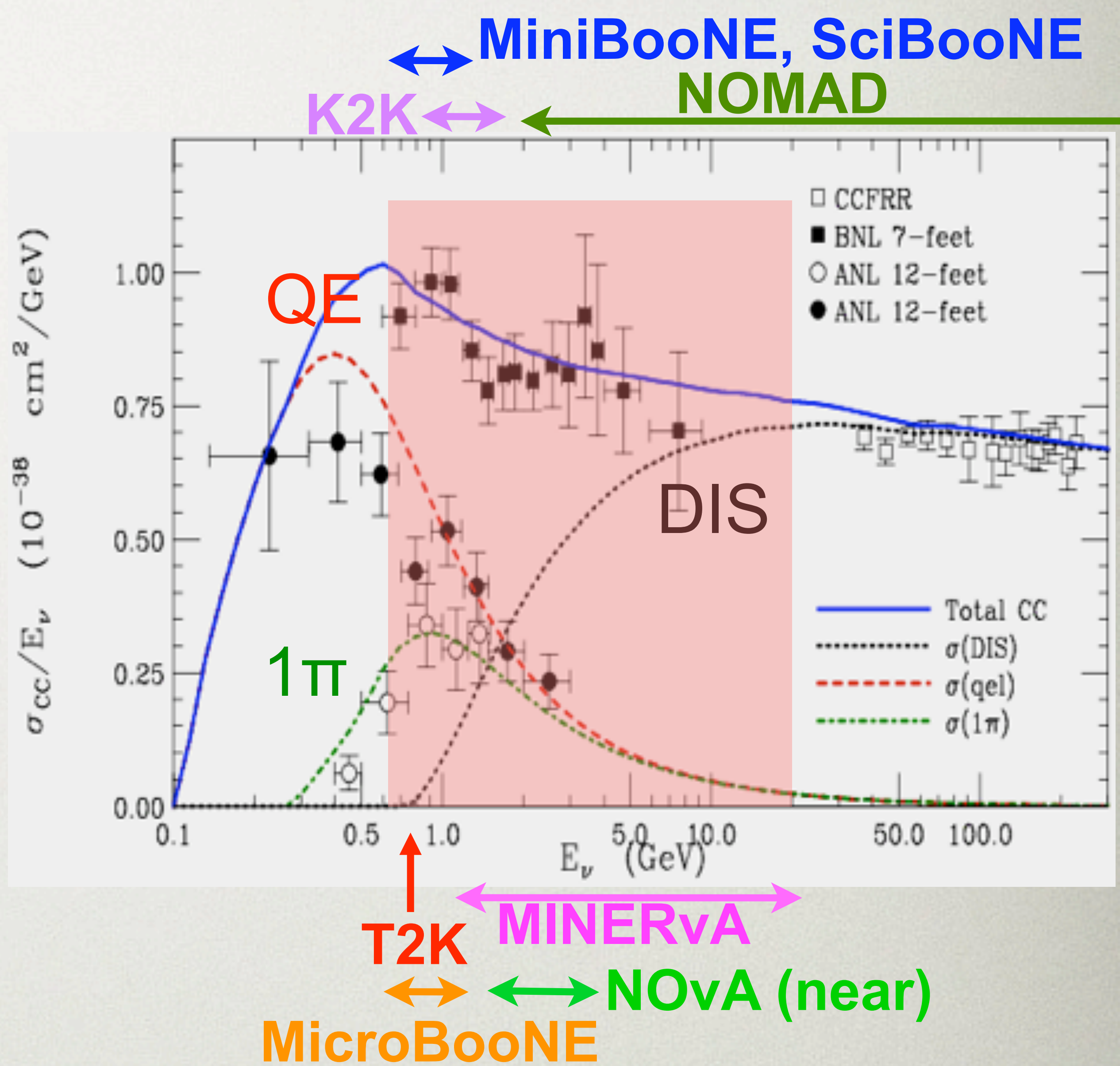
    ➜ Need σ_ν measurement with more precise control of systematic errors on flux and Bkg processes, including FSI.

    ➜ Need reliable predictions/models of multiple processes (resonant-π, multi-π, DIS, FSI)
  - σ_ν in a wide energy range: 0.5~20 GeV

    ➜ New experiment!

New Experiments

- **MINERvA:** Fine-grained scintillator, FNAL-NuMI, He, C, H_2O, Fe, Pb, Ev=1~20GeV
- **T2K Near Detector:** Fine-grained scintillator, TPC in Magnet, J-PARC, C, H_2O, Pb, Ev~0.7GeV
- **NOvA Near Detector:** Liquid scintillator tracker, FNAL-NuMI, C, Ev~2 GeV
- **MicroBooNE:** Liquid Argon TPC, FNAL-BNB, Ar, Ev~0.7GeV



They compliment each other; cover wide energy range, several nuclear targets, several detection techniques.

Summary

- Precise knowledge of NC-1π^0 is vital in the hunt for θ_{13}, δ_{cp} and mass hierarchy
- Recent measurements on NC-π0
  - K2K, MiniBooNE, SciBooNE
    - High statistics, systematics error dominating
    - Satisfying the requirements from current generation θ_{13} experiments, T2K, NOvA.
- New experiments can go further!
  - MINERvA, T2K near, NOvA near, MicroBooNE
  - Important for next generation ν oscillation experiment: δ_{cp}, mass hierarchy.