Measurements of Neutral Current Neutral Pion Production by Neutrinos at SciBooNE

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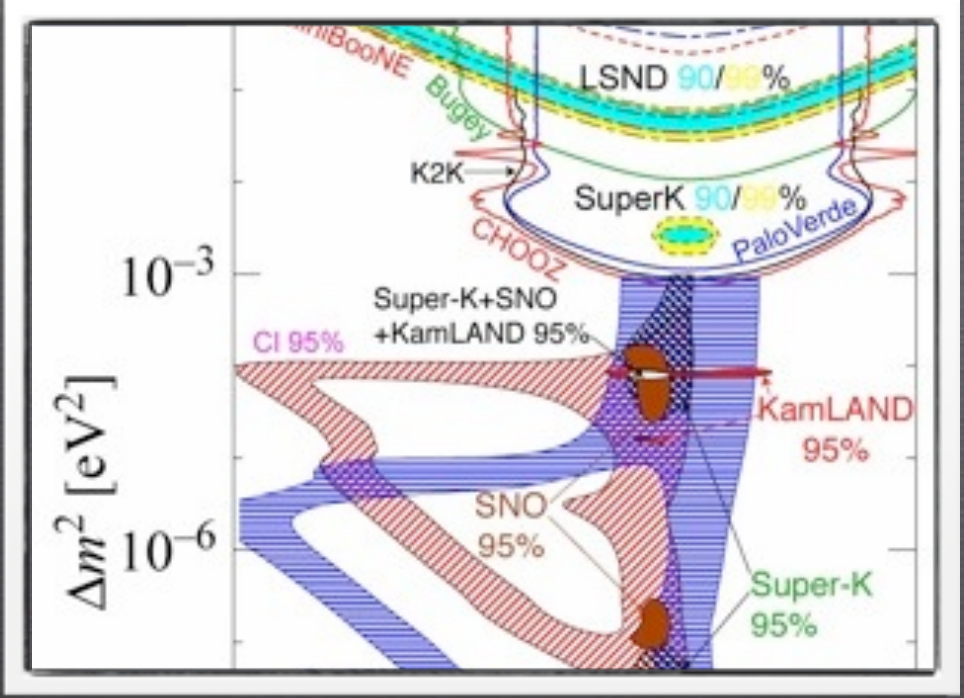
Imperial College London

9 June, 2010
Imperial HEP Seminar

Contents



INTRODUCTION

Motivation

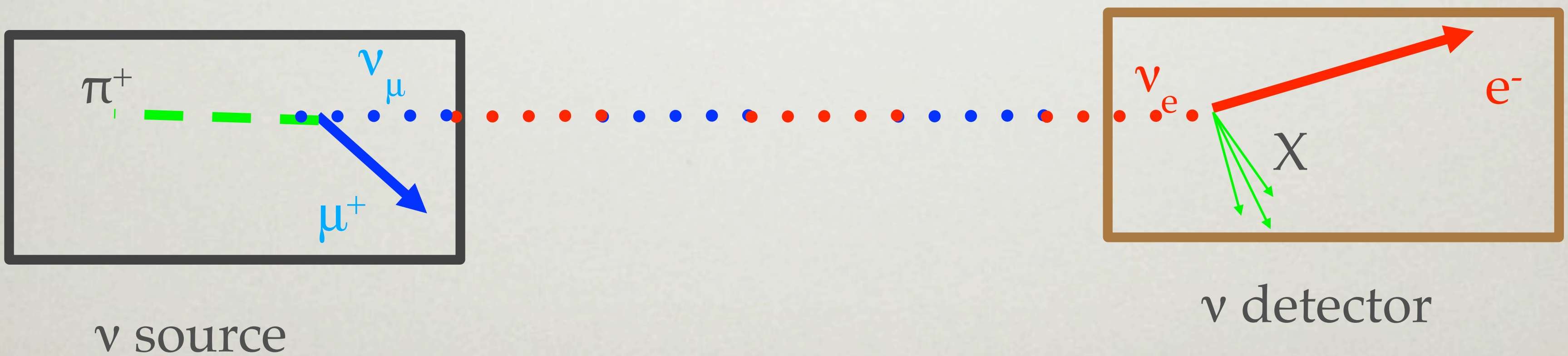
if neutrinos have mass...

a neutrino that is produced as a ν_μ

- (e.g. $\pi^+ \rightarrow \mu^+ \nu_\mu$)

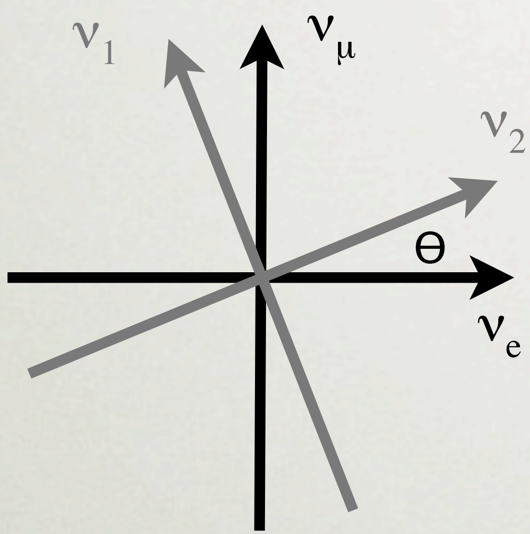
might some time later be observed as a ν_e

- (e.g. $\nu_e\, n \rightarrow e^- p$)



Neutrino Oscillation

$$\begin{pmatrix} \nu_\mu \\ \nu_e \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- Consider only two types of neutrinos
- If weak states differ from mass states
  - i.e. $(\nu_\mu\ \nu_e) \neq (\nu_1\ \nu_2)$
- Then weak states are mixtures of mass states

$$|\nu_\mu(t)\rangle = -\sin\theta\,|\nu_1\rangle\, e^{-iE_1 t} + \cos\theta\,|\nu_2\rangle\, e^{-iE_2 t}$$

$$P_{osc}(\nu_\mu \to \nu_e) = |\langle \nu_e | \nu_\mu(t)\rangle|^2$$

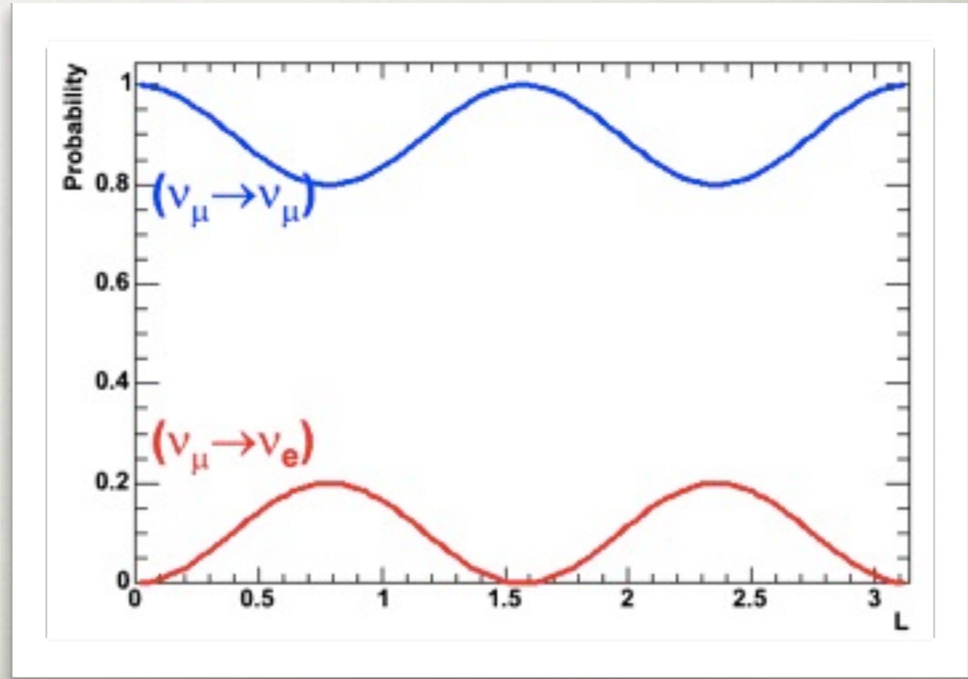
- Probability to find ν_e when you started with ν_μ

Neutrino Oscillation

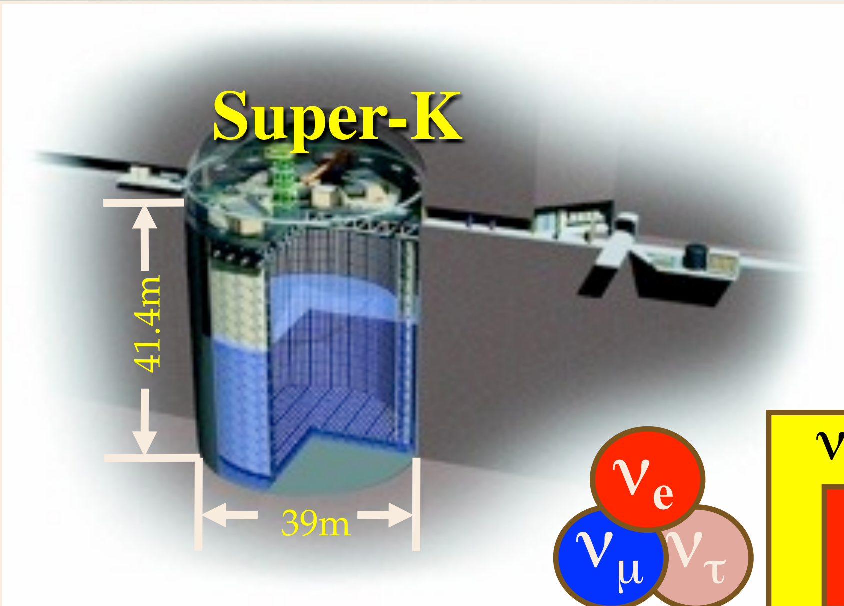
- In units that experimentalists like:

$$P_{osc}(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2(\mathrm{eV}^2)L(\mathrm{km})}{E_\nu(\mathrm{GeV})}\right)$$

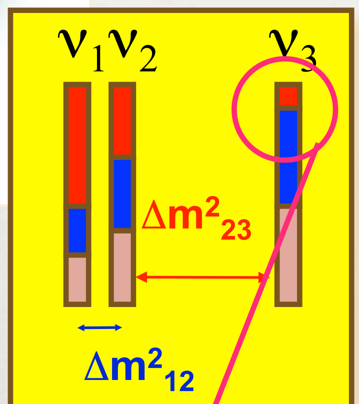
- Fundamental Parameters
  - mass squared differences
  - mixing angle
- Experimental Parameters
  - L = distance from source to detector
  - E = neutrino energy



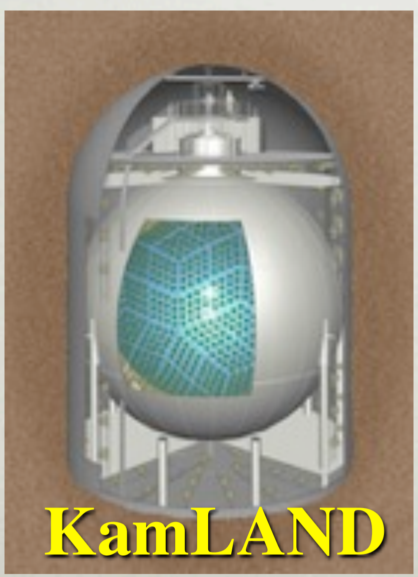
Neutrino Oscillation Observations

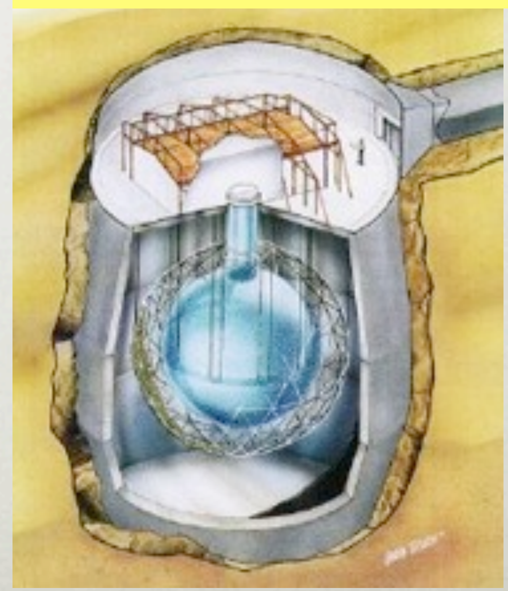


Neutrino masses (Δm_{12}^2, Δm_{23}^2)
Mixing Angles (θ_{12}, θ_{23})

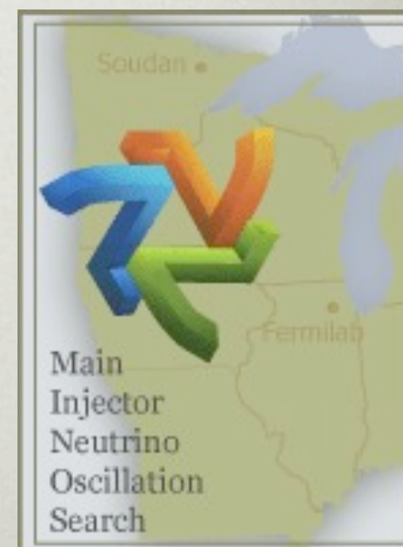


$\theta_{13} \rightarrow \delta$





SNO



MINOS

Next Steps

ν_e ν_μ ν_τ

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

ν_1 ν_2 ν_3

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

U

atmospheric | **Cross Mixing** | solar

- Discover the last oscillation channel
  → θ_{13}
- CP violation in the lepton sector (ν, $\bar{\nu}$)
  → δ **non-zero?** (Matter/antimatter asymmetry)
- Test of the standard ν oscillation scenario (U_{MNS})
  → Precise measurements of ν oscillations ($\pm\Delta m_{23}^2$, θ_{23})

Next Steps

ν_e ν_μ ν_τ

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

ν_1 ν_2 ν_3

$$c_{ij} = \cos\theta_{ij}$$
$$s_{ij} = \sin\theta_{ij}$$

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{Cross Mixing}} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

atmospheric **Cross Mixing** solar

- Discover the last oscillation channel
  → θ_{13}
- CP violation in the lepton sector (ν, $\bar{\nu}$)
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- Test of the standard ν oscillation scenario (U_{MNS})
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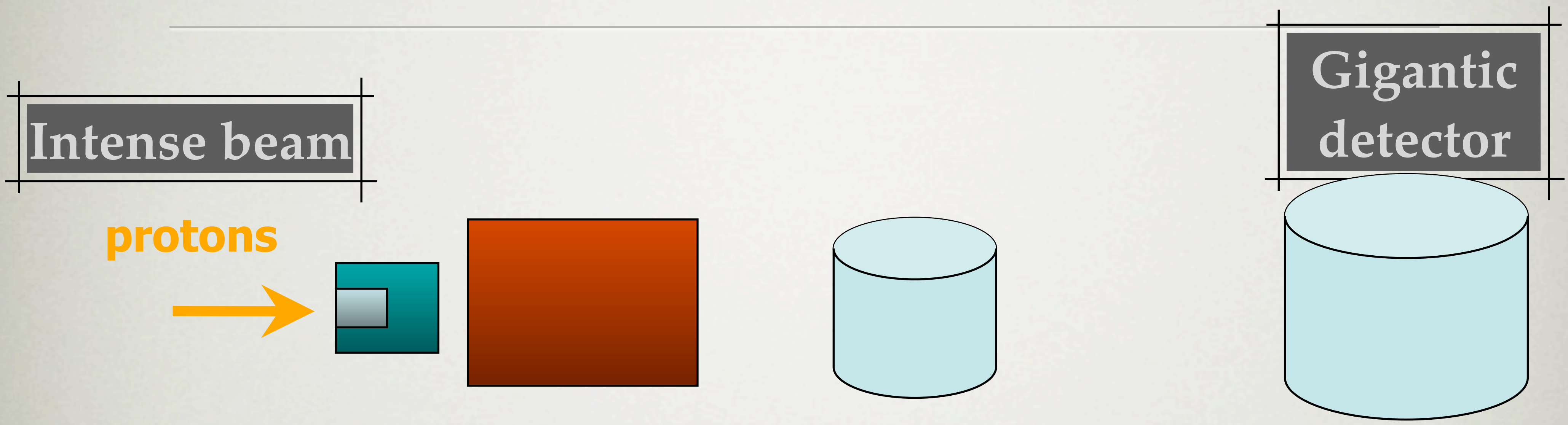
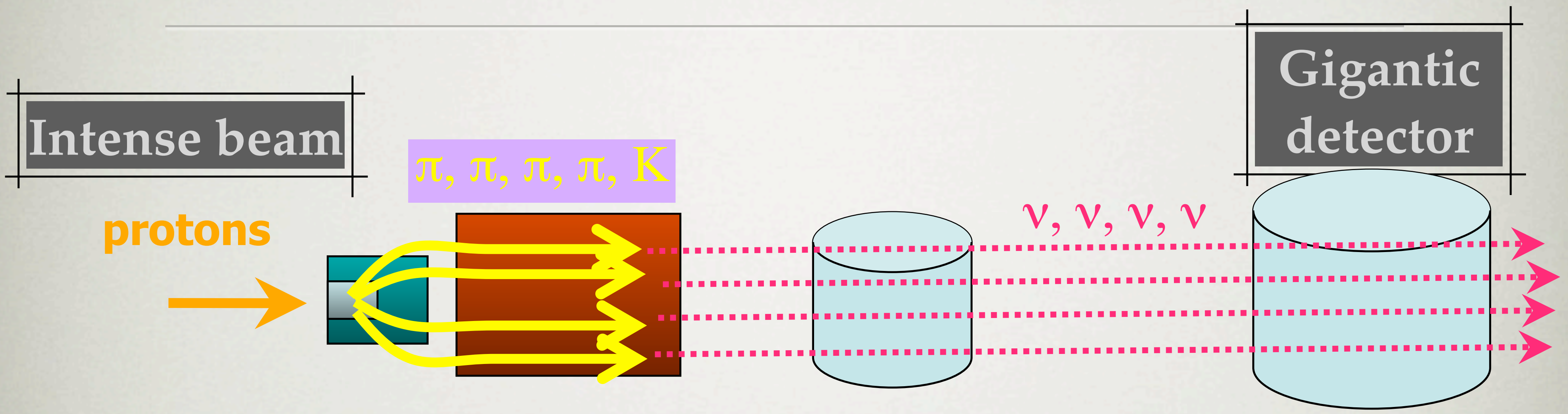
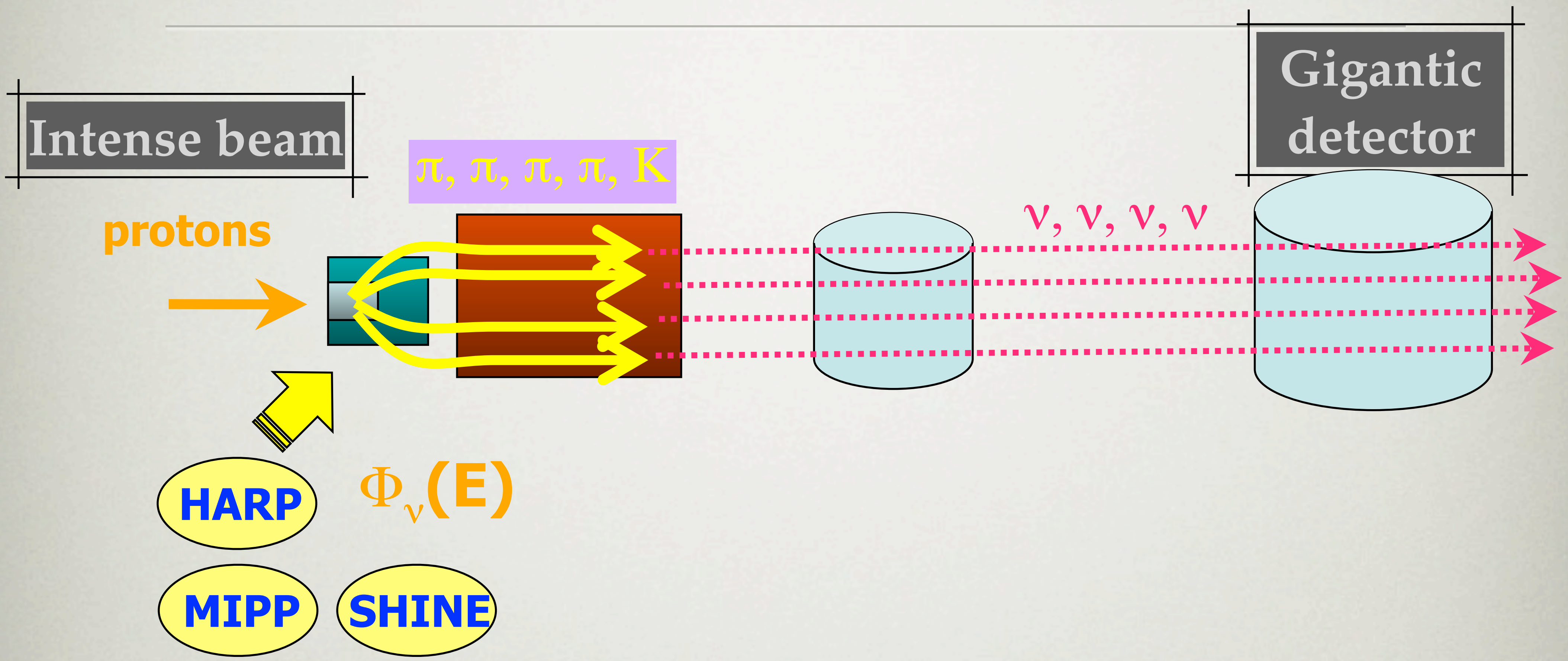
accelerator Oscillation Experiments



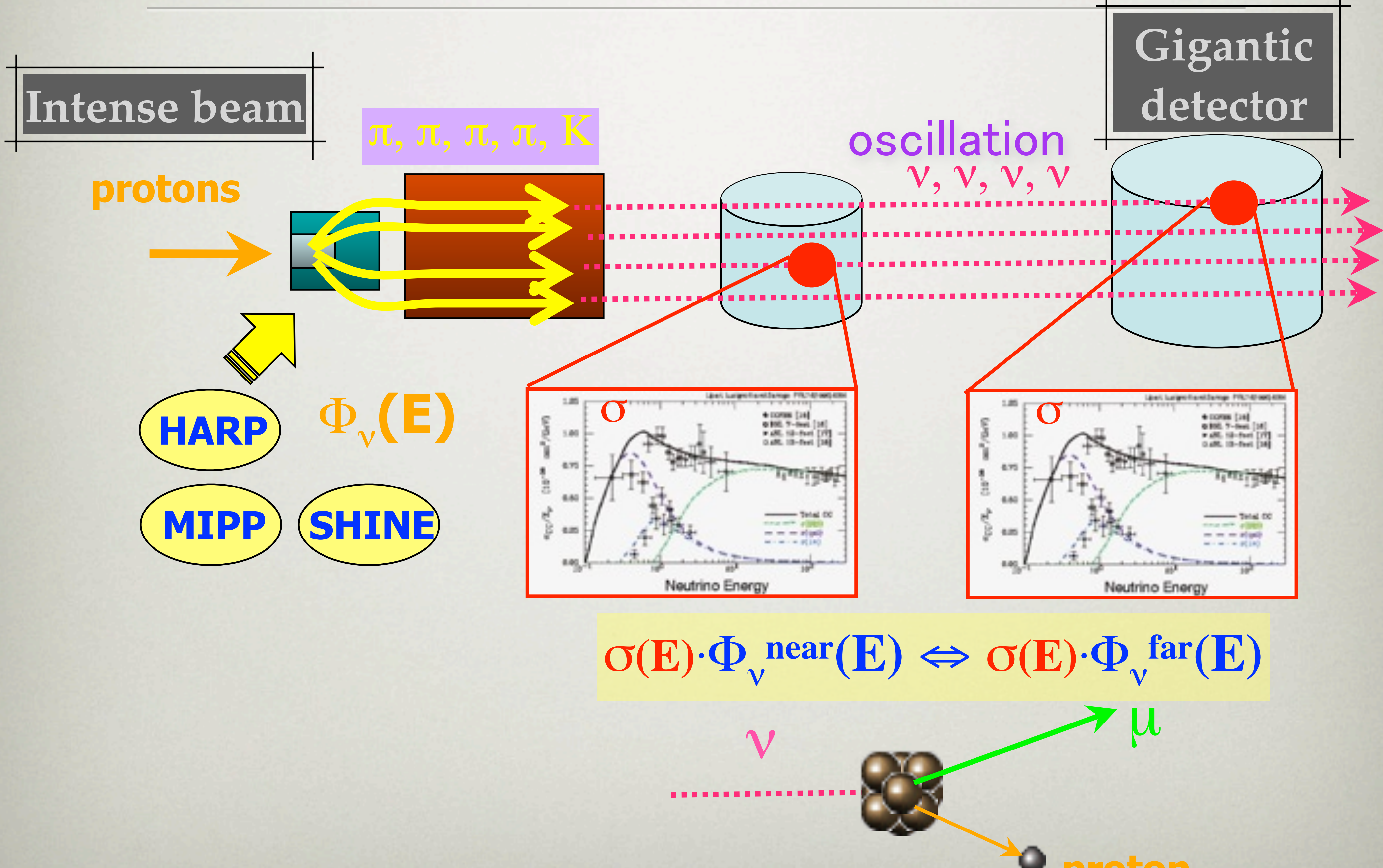
accelerator Oscillation Experiments



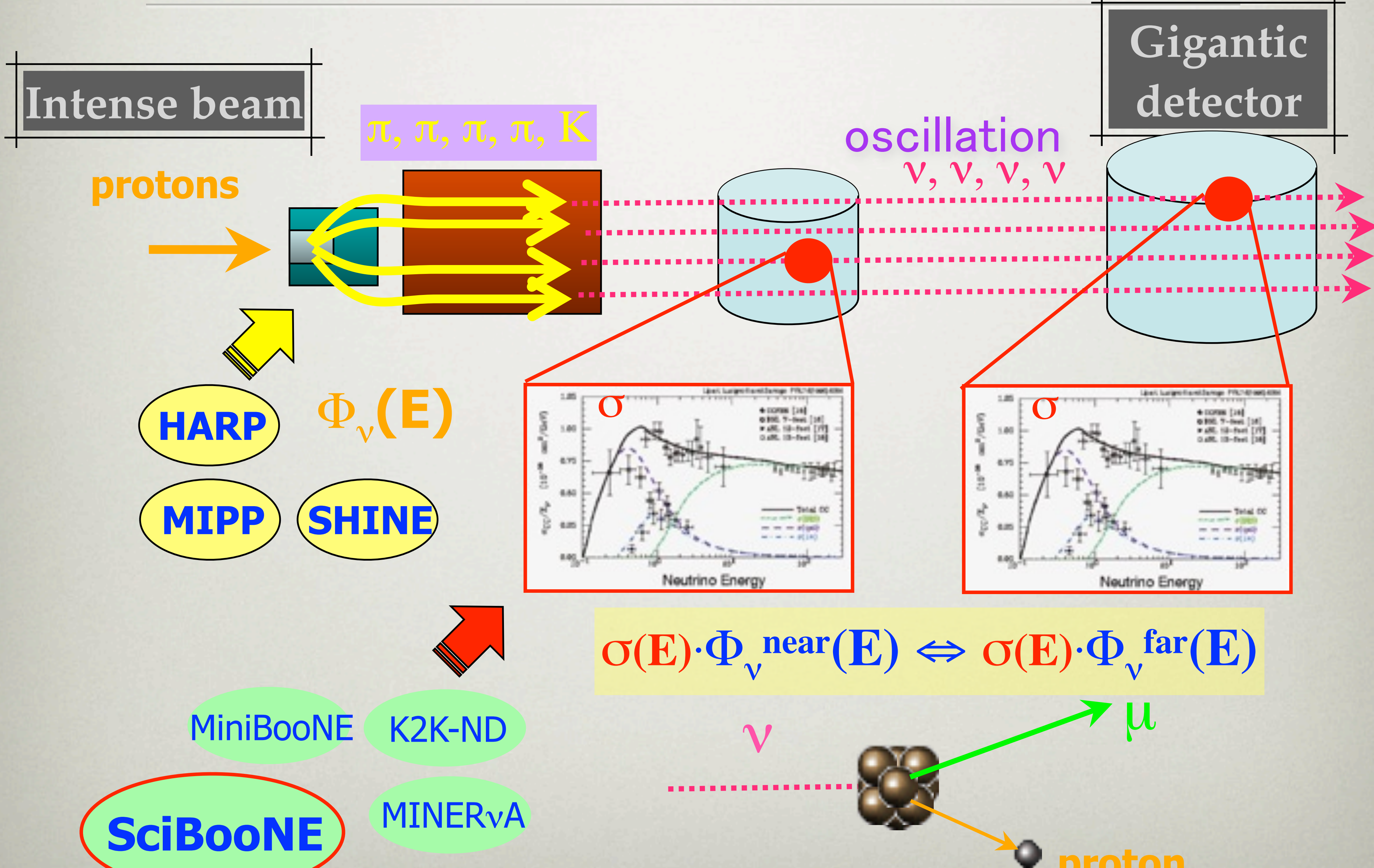
accelerator Oscillation Experiments



accelerator Oscillation Experiments



ACCELERATOR OSCILLATION EXPERIMENTS

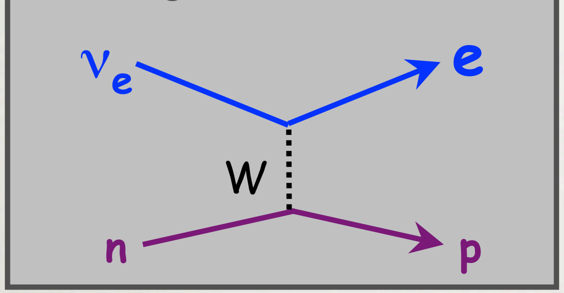


Background Processes

ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

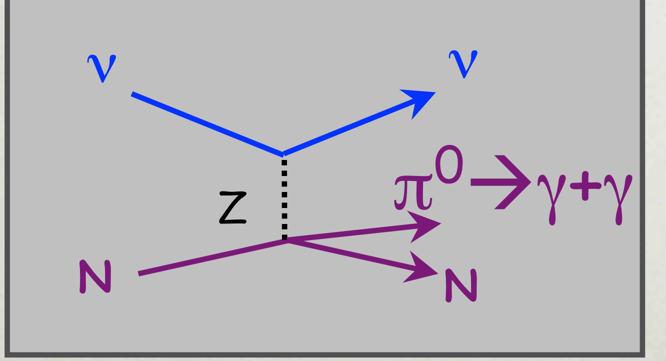
Signal

ν_e CC-QE



Background

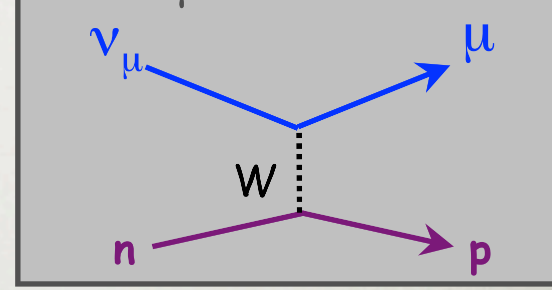
NC-1π^0



ν_μ disappearance ($\nu_\mu \rightarrow \nu_x$)

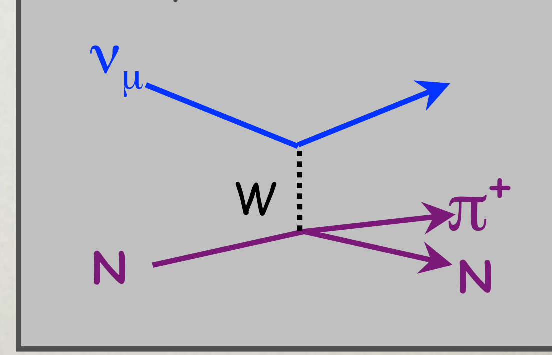
Signal

ν_μ CC-QE



Background

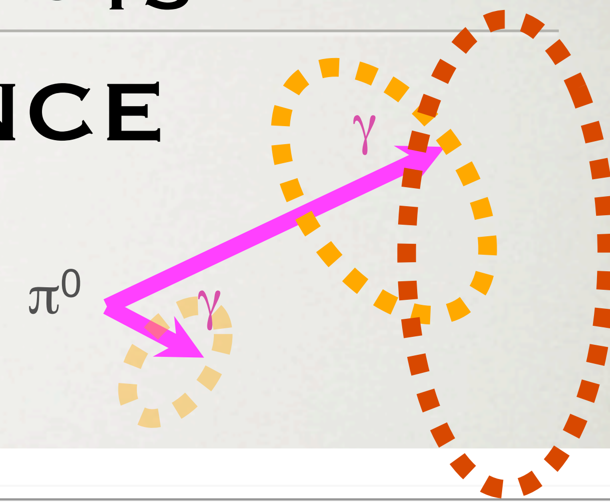
ν_μ CC-1π^+



Need to understand these processes well

Search for θ_{13}

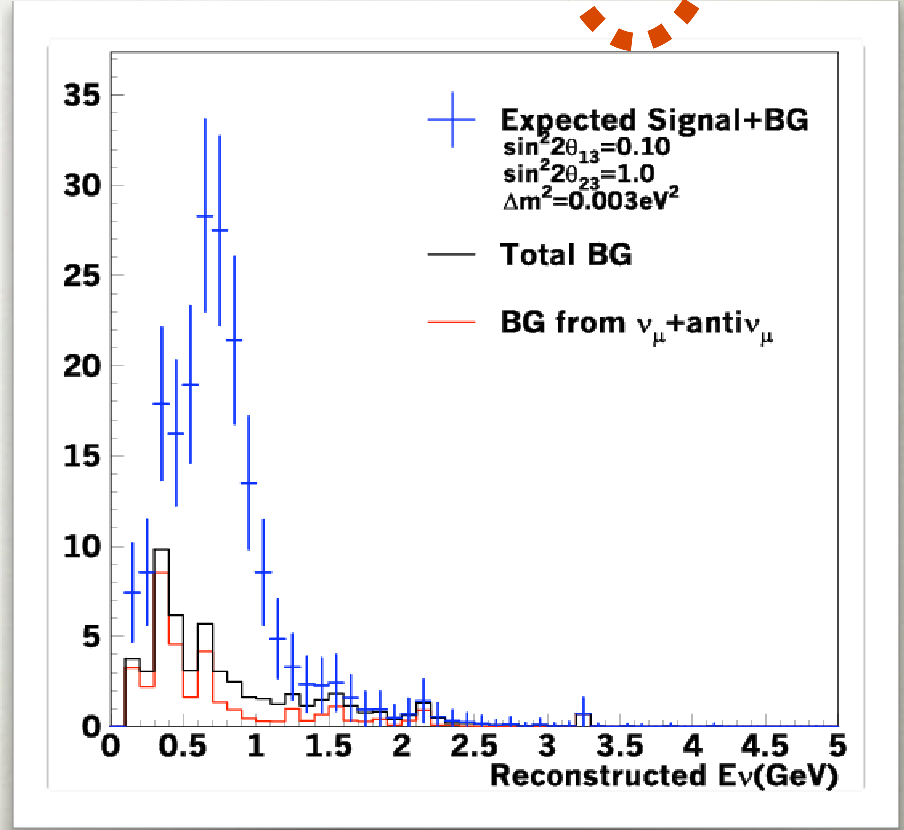
ν_e appearance

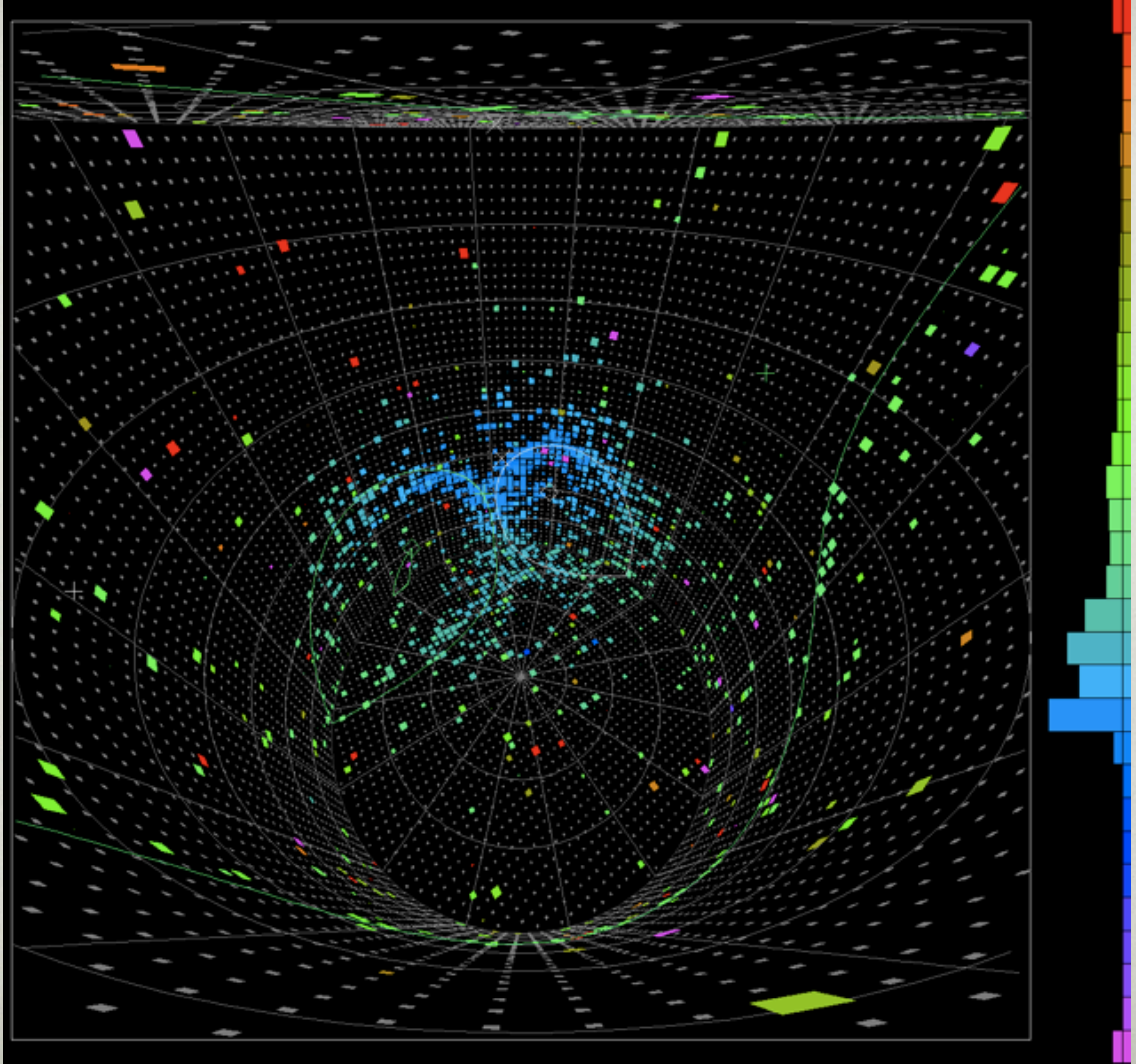


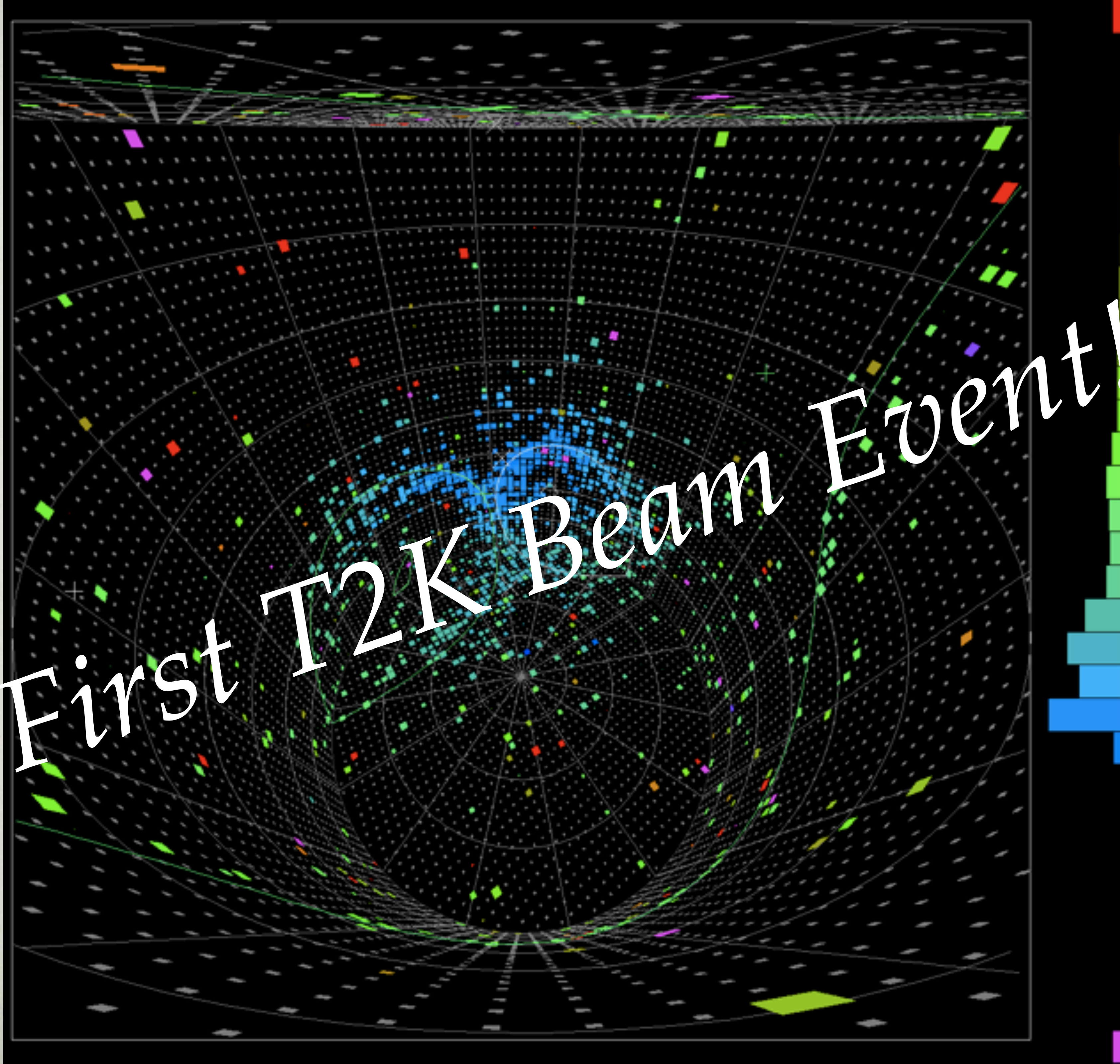
- Subdominant oscillation

  $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2 2\theta_{13}$

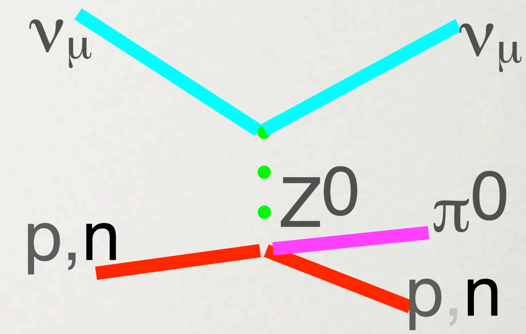
- Major background from NCπ^0 events
  - γ rings mimic e rings in Super-K
- Must reduce uncertainty on NCπ^0 cross section

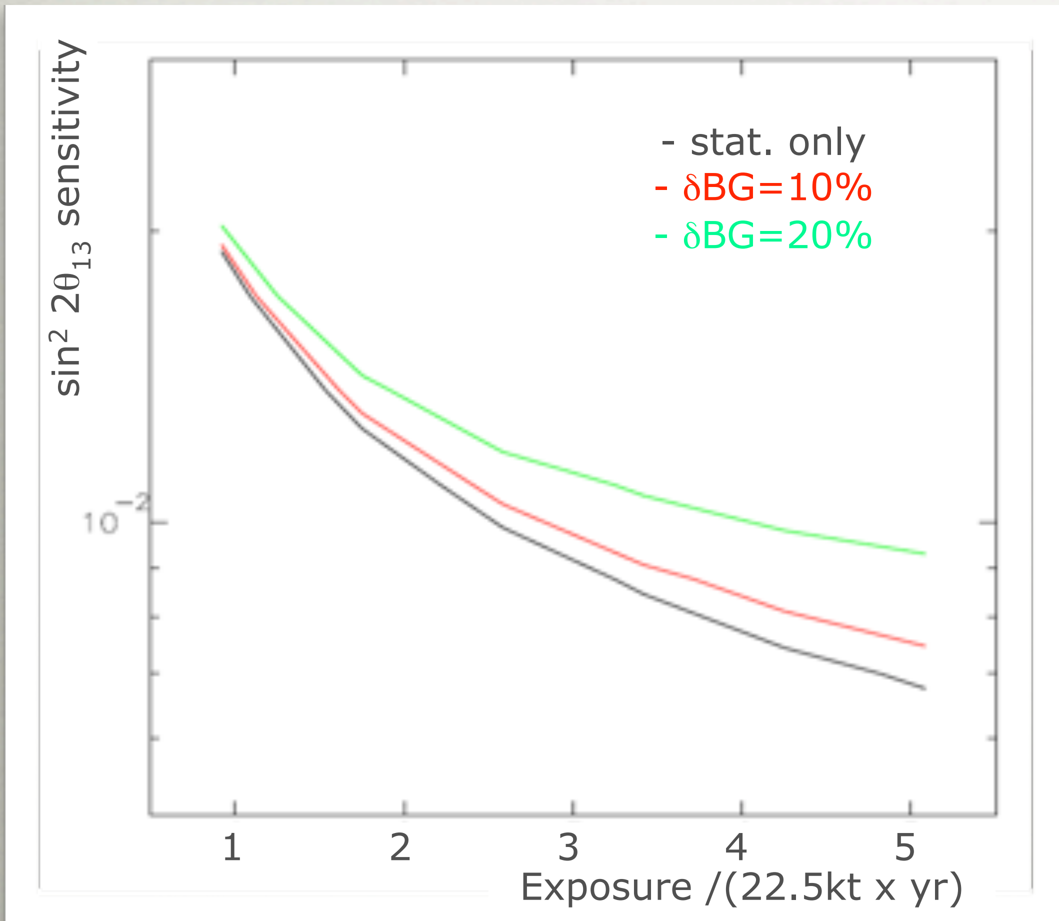





First T2K Beam Event!

Effect of NCπ^o





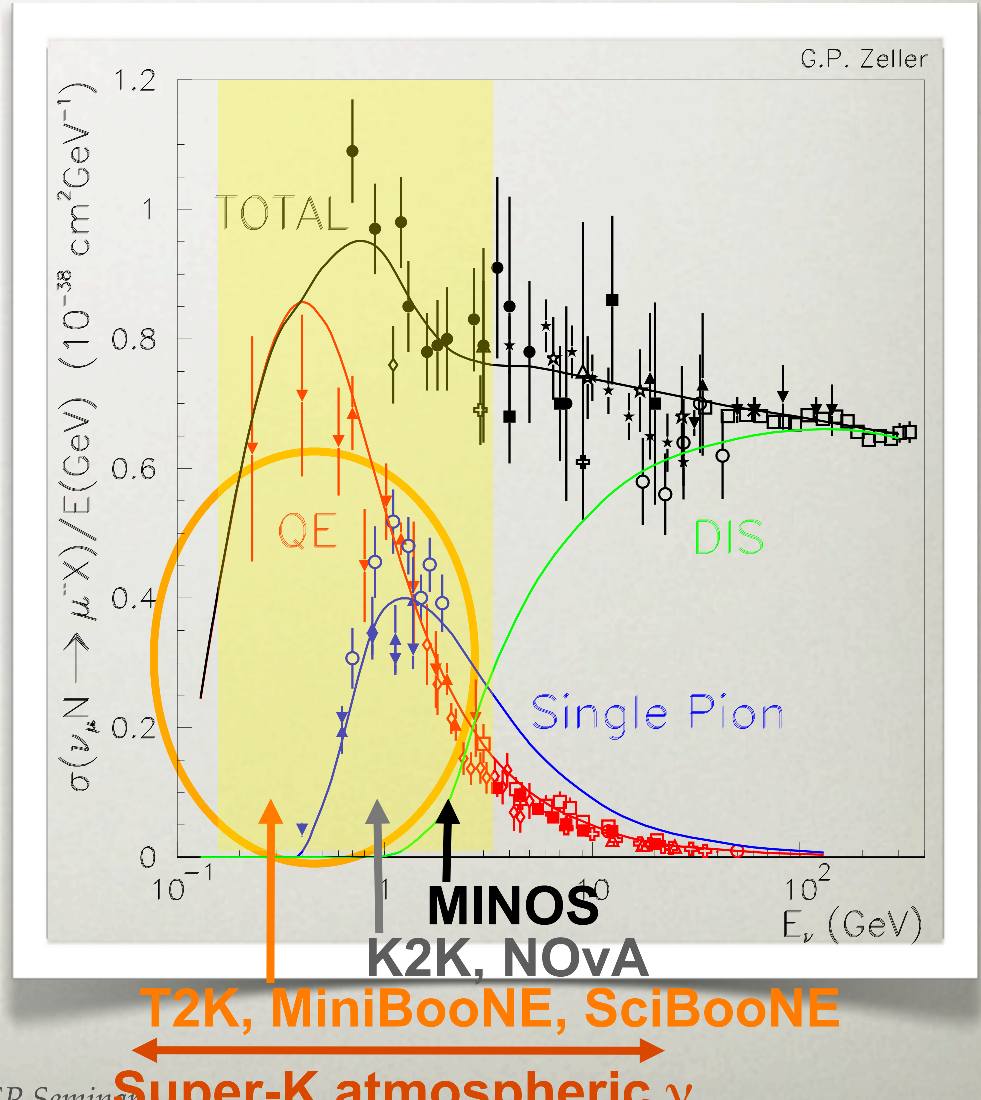
- Want to reduce uncertainty in σ (NCπ^0) from 20% to 10%
  - improvement of factor of 2 in ultimate T2K sensitivity to θ_{13}
  - or 2.5 years vs. 4 years to 10^{-2}

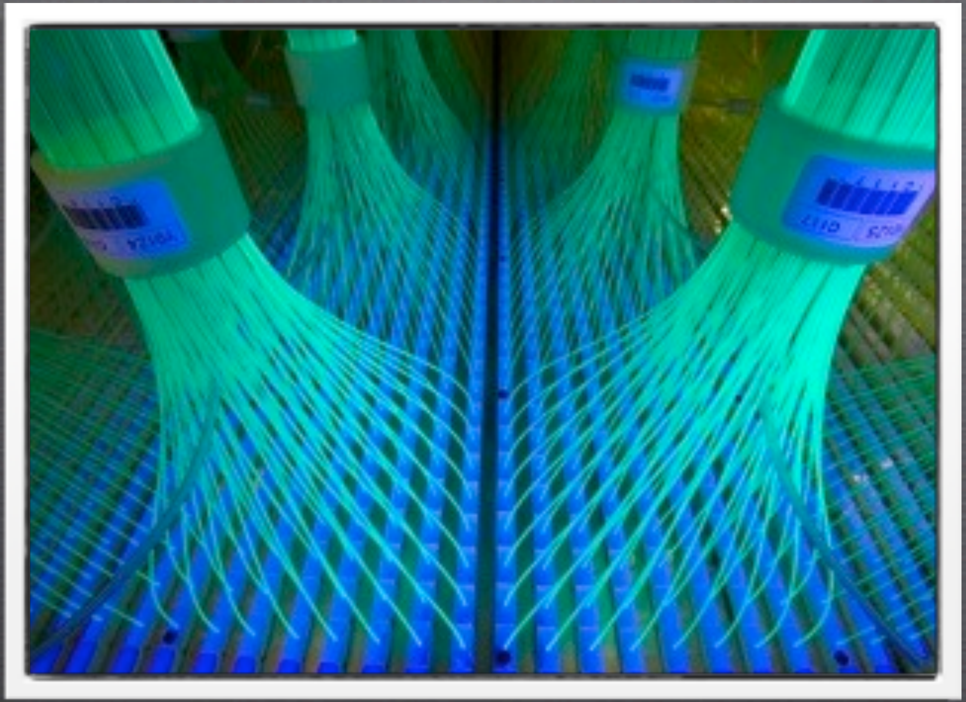
ν-NUCLEUS CROSS SECTIONS

Future neutrino oscillation experiments need precise knowledge of neutrino cross sections near 1 GeV

Data from old experiments
(1970~1980)
Low statistics
Systematic Uncertainties

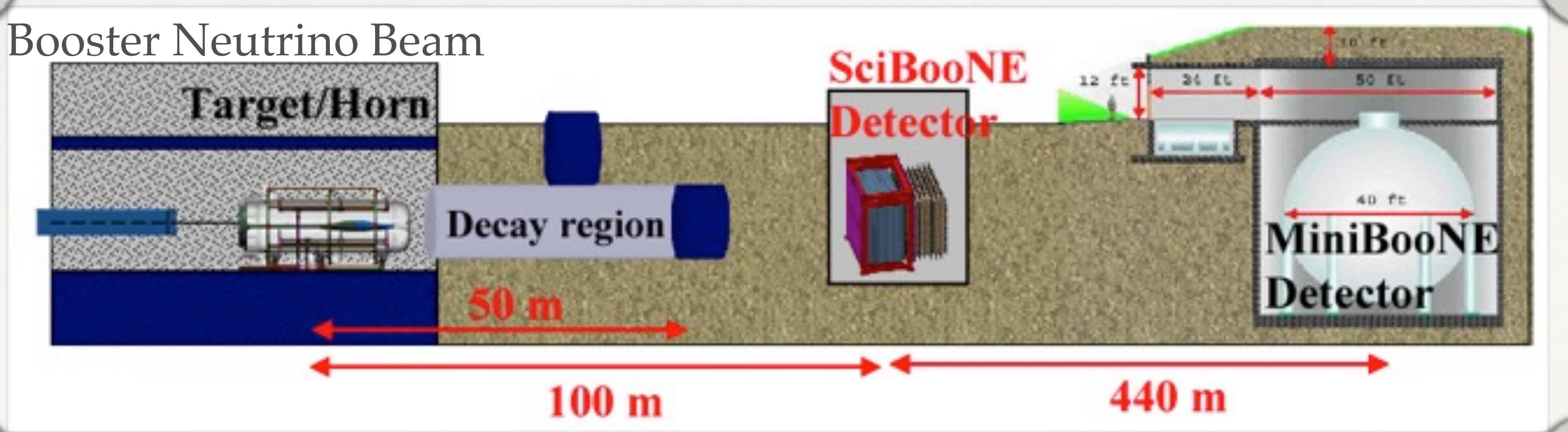
New data from
K2K, MiniBooNE, SciBooNE
revealing surprises





SciBooNE Description

SciBooNE Experiment (FNAL E954)



- Precise measurements of ν- and $\bar{\nu}$-nucleus σs near 1 GeV
  - Essential for future neutrino oscillation experiments
- Neutrino energy spectrum measurements
  - MiniBooNE/SciBooNE joint ν_μ disappearance
  - ν_e & $\bar{\nu}_e$ constraint for MiniBooNE

SciBooNE Collaboration

Universitat Autonoma de Barcelona
University of Colorado, Boulder
Columbia University
Fermi National Accelerator Laboratory
High Energy Accelerator Research Organization (KEK)
Imperial College London
Indiana University
Institute for Cosmic Ray Research (ICRR)
Kyoto University
Los Alamos National Laboratory
Louisiana State University
Massachusetts Institute of Technology
Purdue University Calumet
Università di Roma "La Sapienza“ and INFN
Saint Mary's University of Minnesota
Tokyo Institute of Technology
Unversidad de Valencia

~60 physicists
5 countries 17 institutions

Spokespersons:
M.O. Wascko (Imperial), T. Nakaya (Kyoto)

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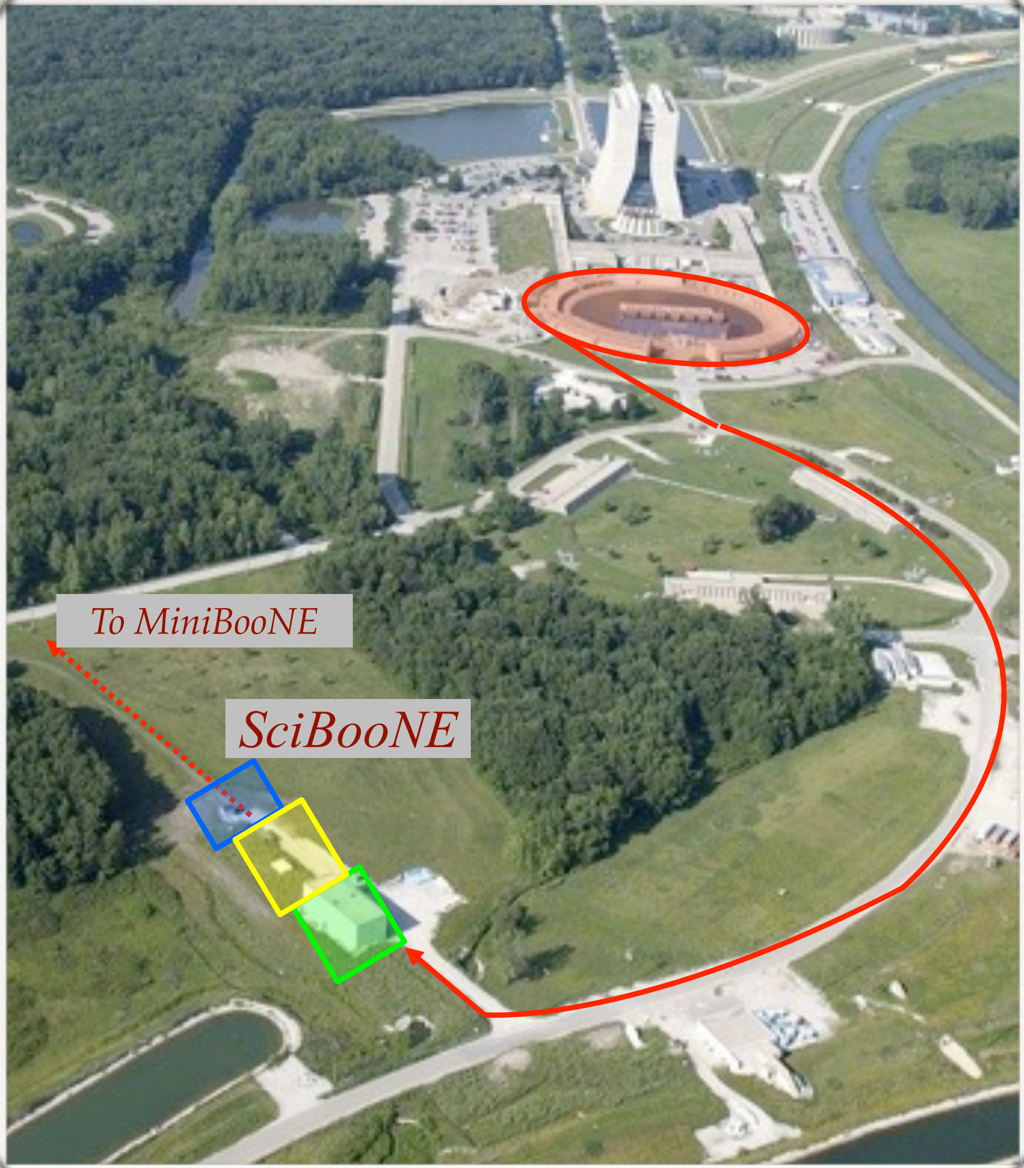


Booster Proton accelerator

- 8 GeV protons sent to target

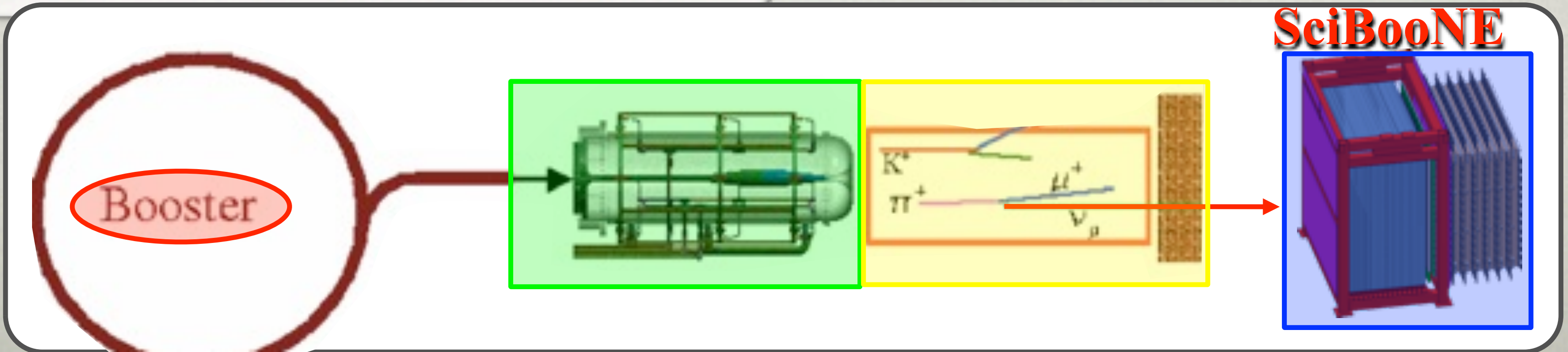
Target Hall

- Beryllium target:
  71cm long 1cm diameter
- Resultant mesons focused with magnetic horn
- Reversible horn polarity

50m decay volume

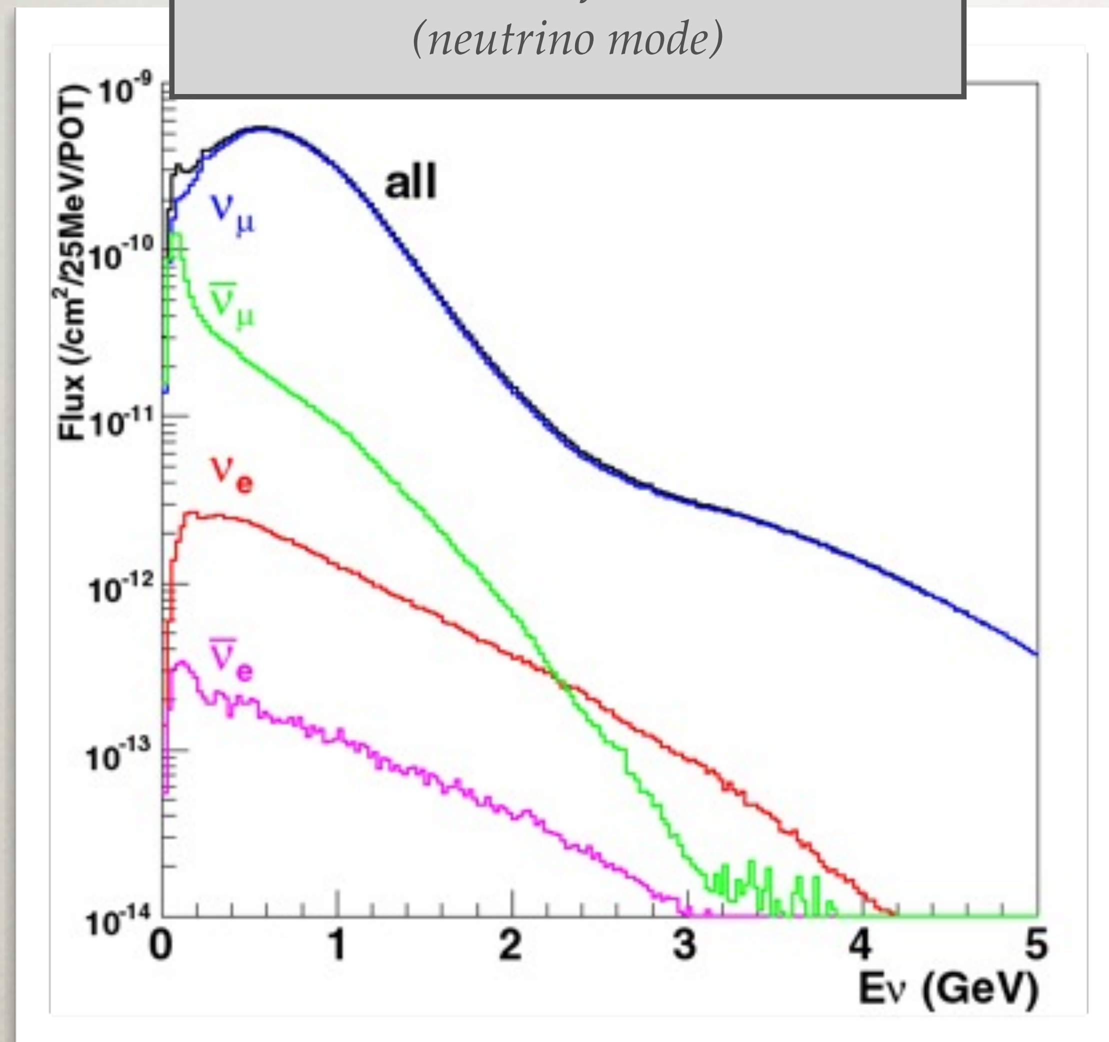
- Mesons decay to μ & ν_μ
- Short decay pipe minimizes $\mu \rightarrow \nu_e$ decay

SciBooNE located 100m from the beryllium target



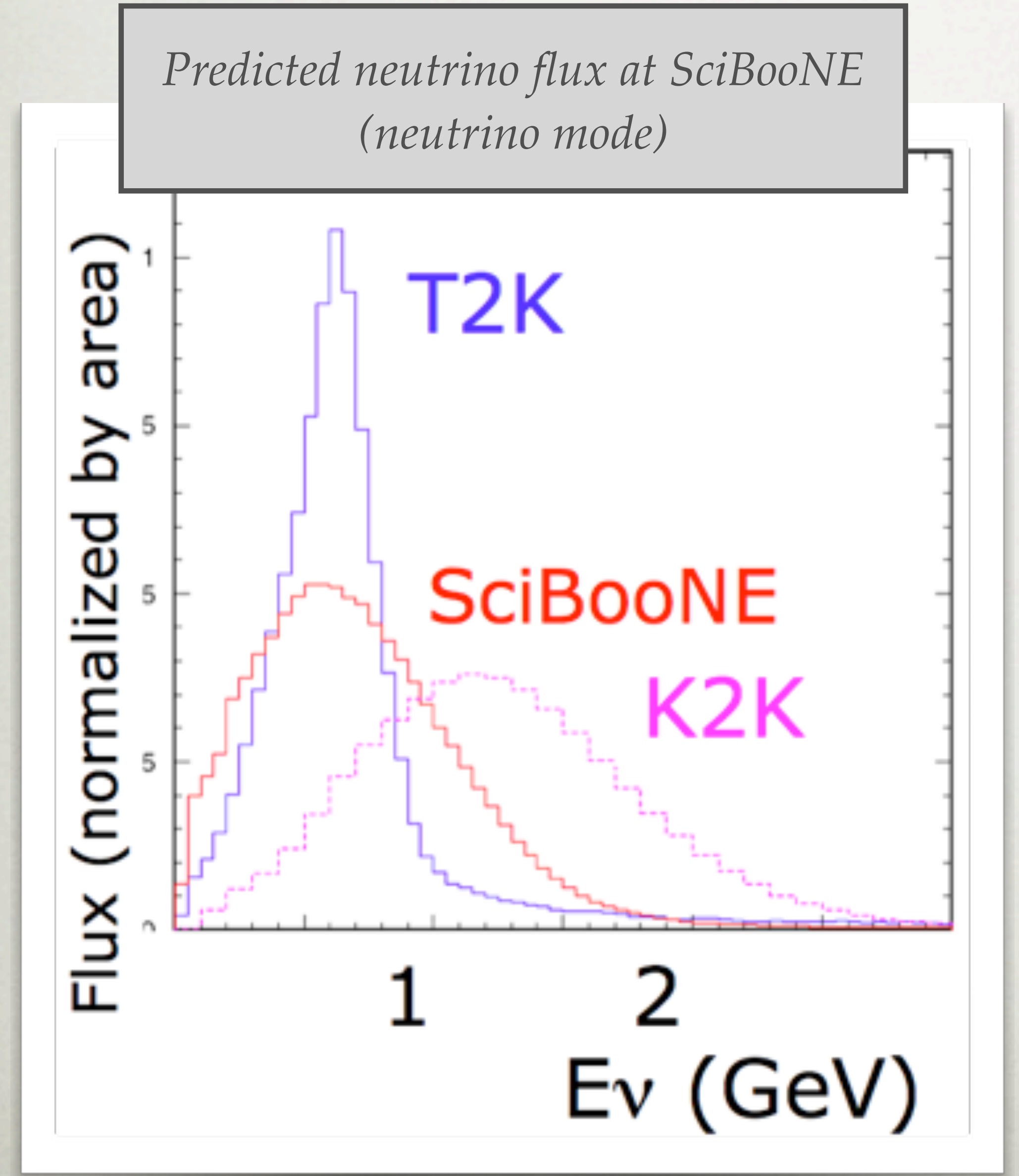
Booster Neutrino Beam

Predicted neutrino flux at SciBooNE (neutrino mode)



- mean neutrino energy ~0.7 GeV
  - 93% pure ν_μ beam
  - $\bar{\nu}_\mu$ (6.4%)
  - ν_e + $\bar{\nu}_e$ (0.6%)
- Good match to T2K
- antineutrino beam obtained by reversing horn polarity

Booster Neutrino Beam



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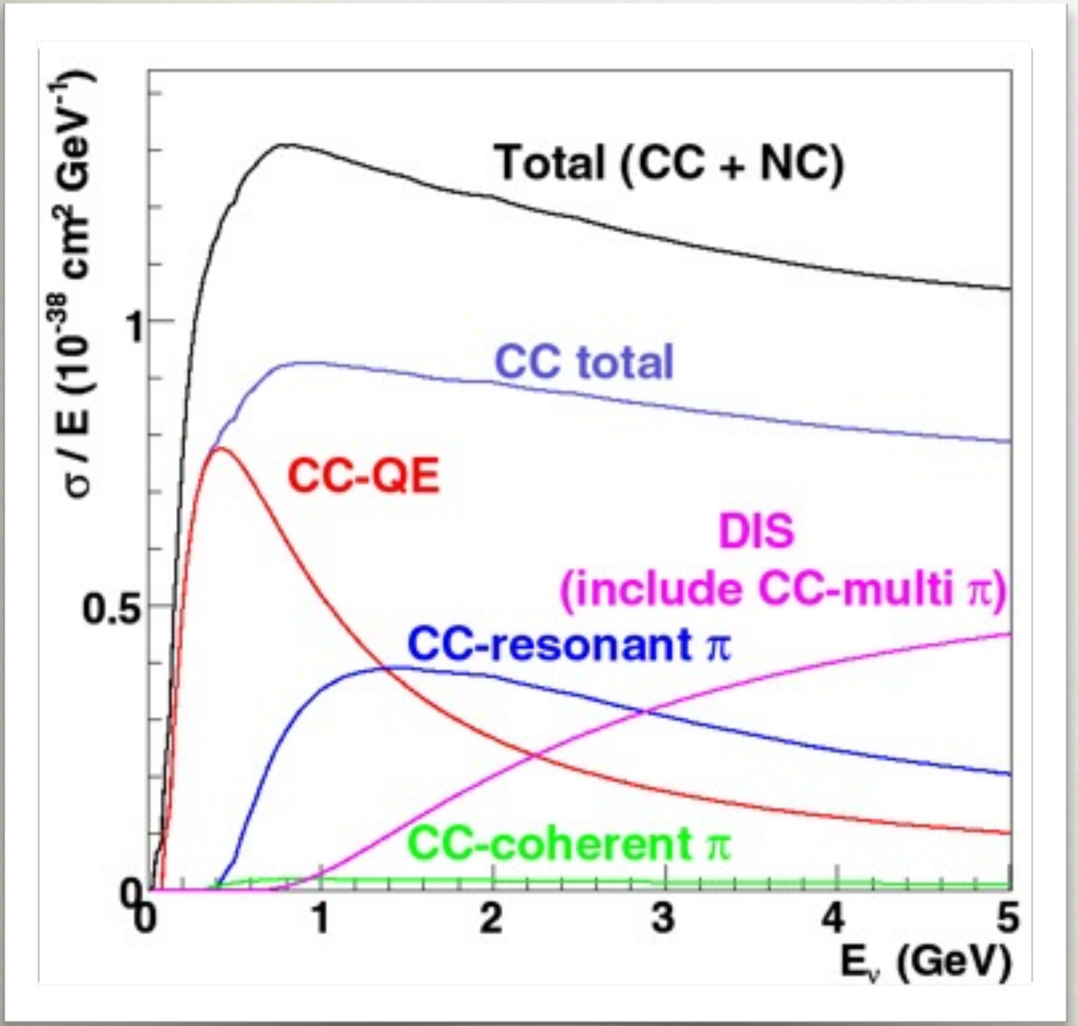
Neutrino Event Generator (NEUT)



- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2 (GeV/c)^2
  - P_F=217 MeV/c, E_B=27 MeV (for Carbon)
- Resonant π
  - Rein-Sehgal (2007)
  - M_A=1.2 (GeV/c)^2
- Coherent π
  - Rein-Sehgal (2006)
  - M_A=1.0 (GeV/c)^2

CC/NC-1π

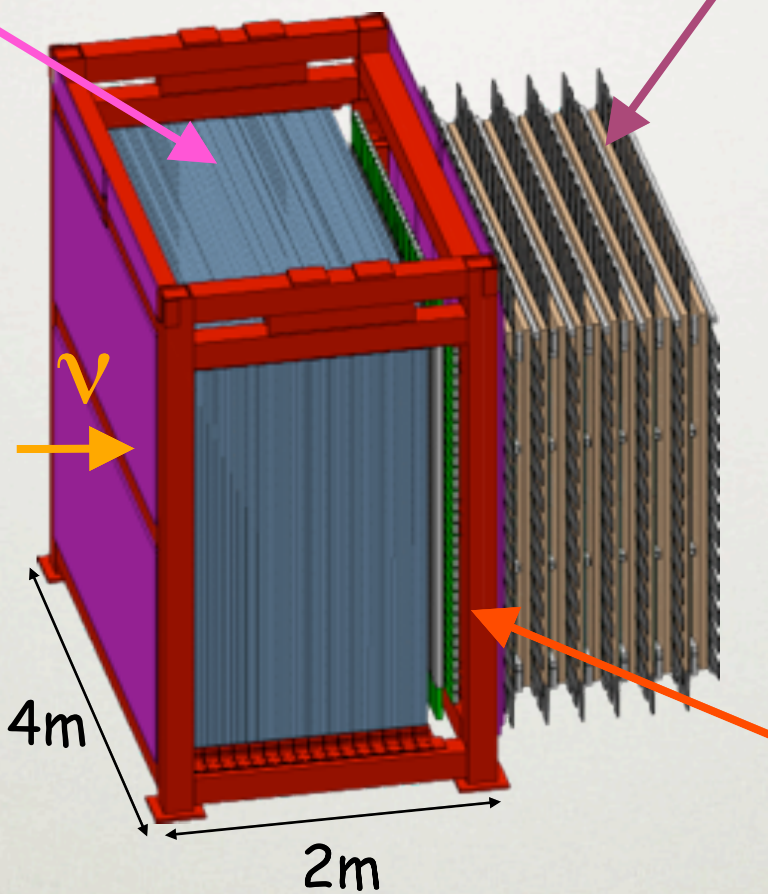
- Deep Inelastic Scattering
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

SciBooNE detector

SciBar

- scintillator tracking detector
- 14,336 scintillator bars (15 tons)
- Neutrino target
- detect all charged particles
- p/π separation using dE/dx

Used in K2K experiment



Muon Range Detector (MRD)

- 12 2”-thick steel + scintillator planes
- measure muon momentum with range up to 1.2 GeV/c

Parts recycled from past experiments

Electron Catcher (EC)

- spaghetti calorimeter
- 2 planes (11 X_0)
- identify π^0 and ν_e

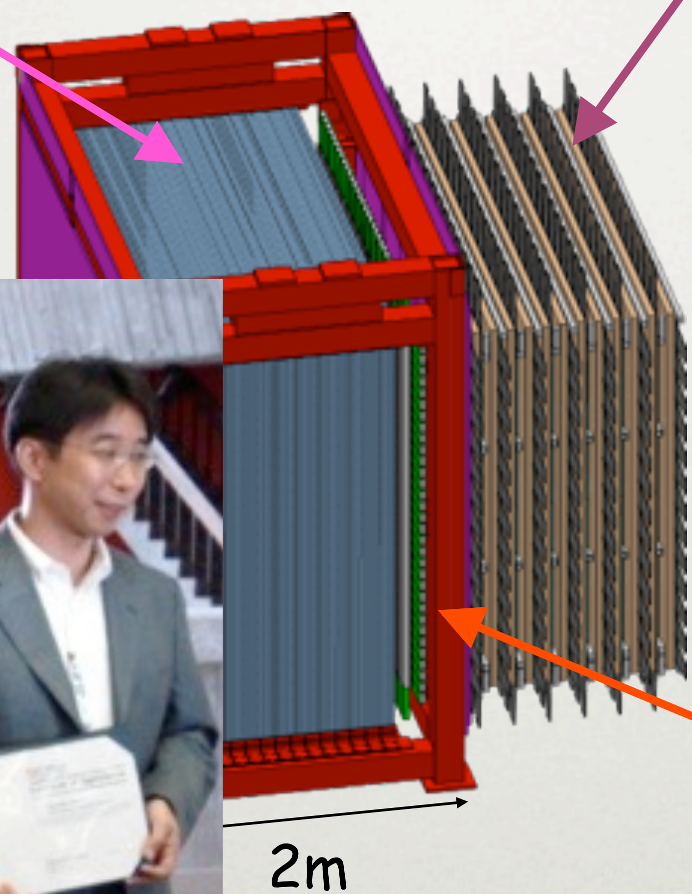
Used in CHORUS, HARP and K2K

DOE-wide Pollution Prevention Star (P2 Star) Award

SciBooNE detector

SciBar

- scintillator tracking detector
- 14,336 scintillator



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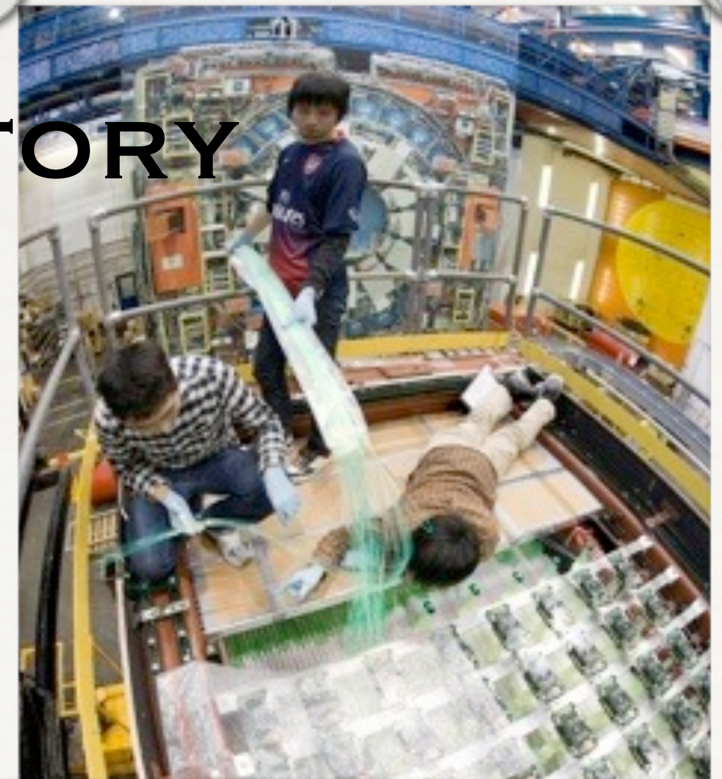
SciBooNE History

Groundbreaking ceremony
(Sep. 2006)

Detector
Assembly
(Nov. 2006
-Mar.2007)



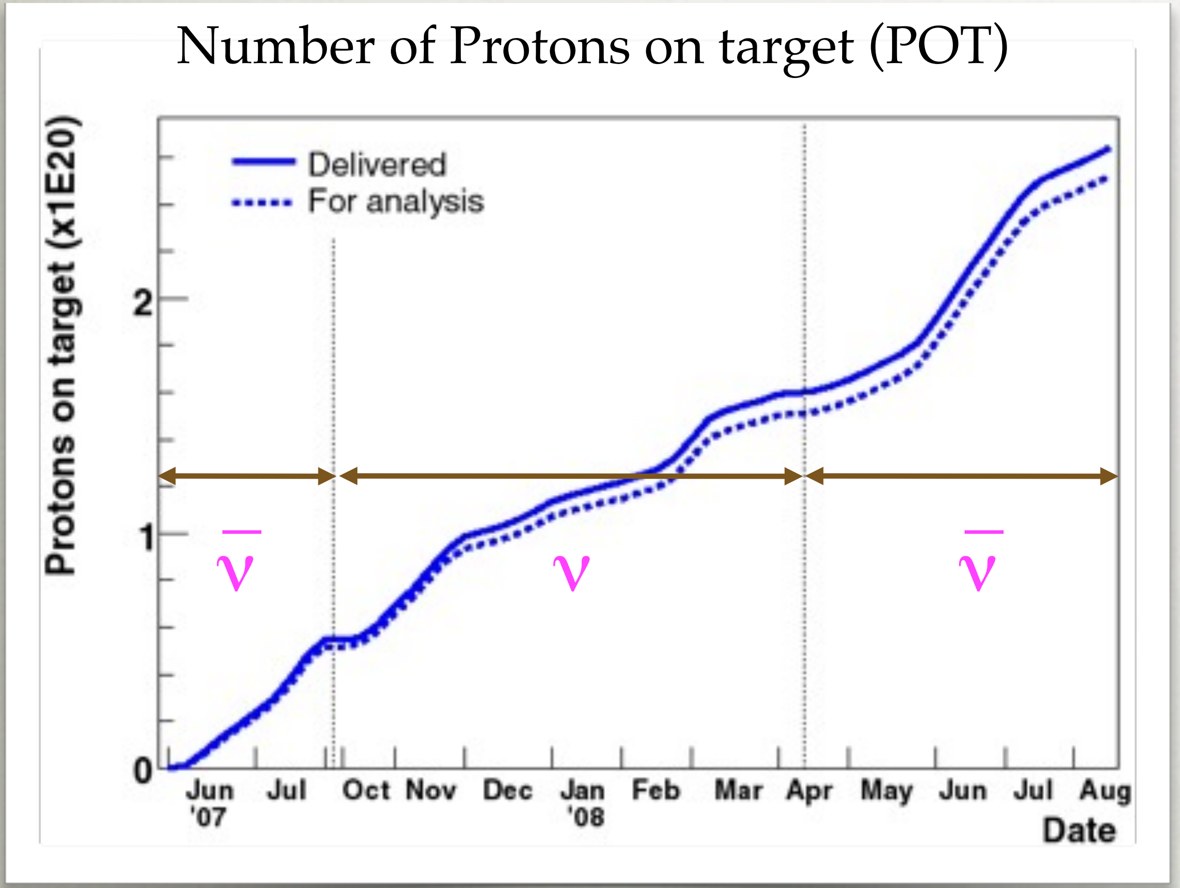
SciBooNE History

Students contributed significantly

Detector installation (Apr. 2007)

End-of-run party (Aug. 2008)

SciBooNE Data-Taking



- Jun. 2007 – Aug. 2008
- 95% data efficiency
- 2.52x10^{20} POT in total
  - neutrino : 0.99x10^{20} POT
  - antineutrino: 1.53x10^{20} POT

Results from full neutrino data set presented today

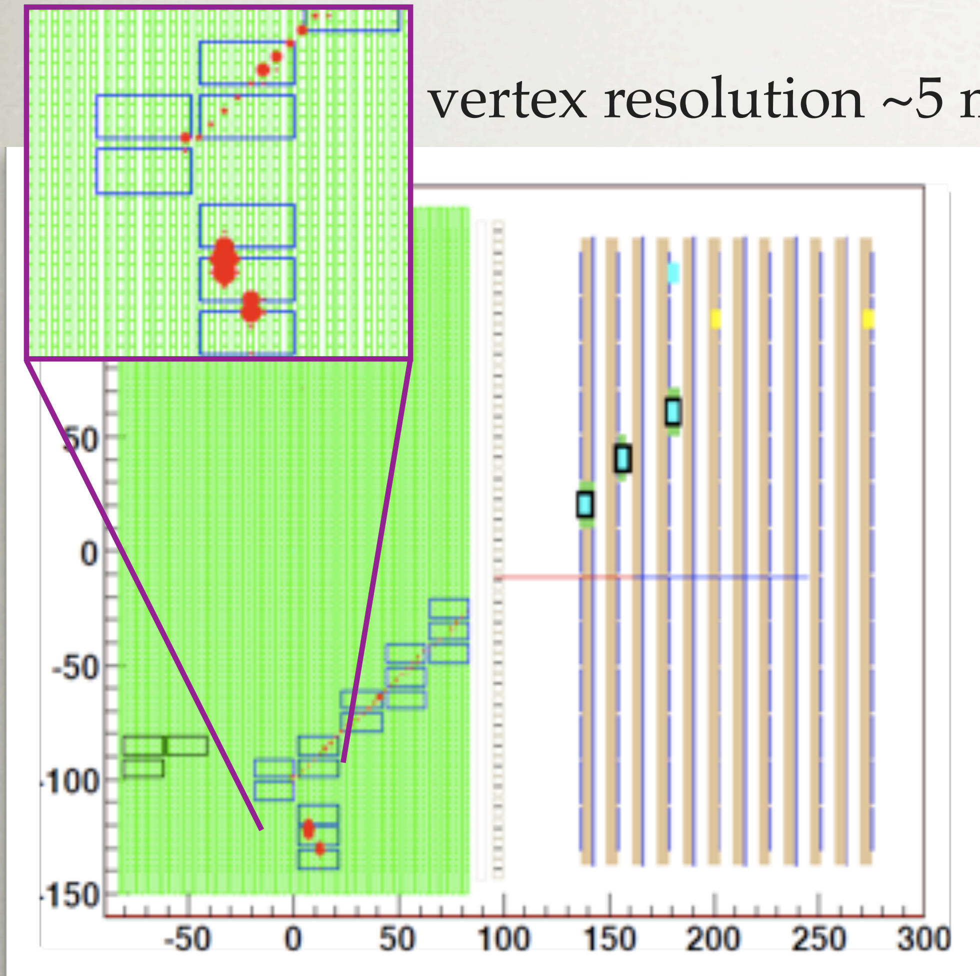
Neutrino event displays

Real SciBooNE Data

ADC hits (area ∝ charge)

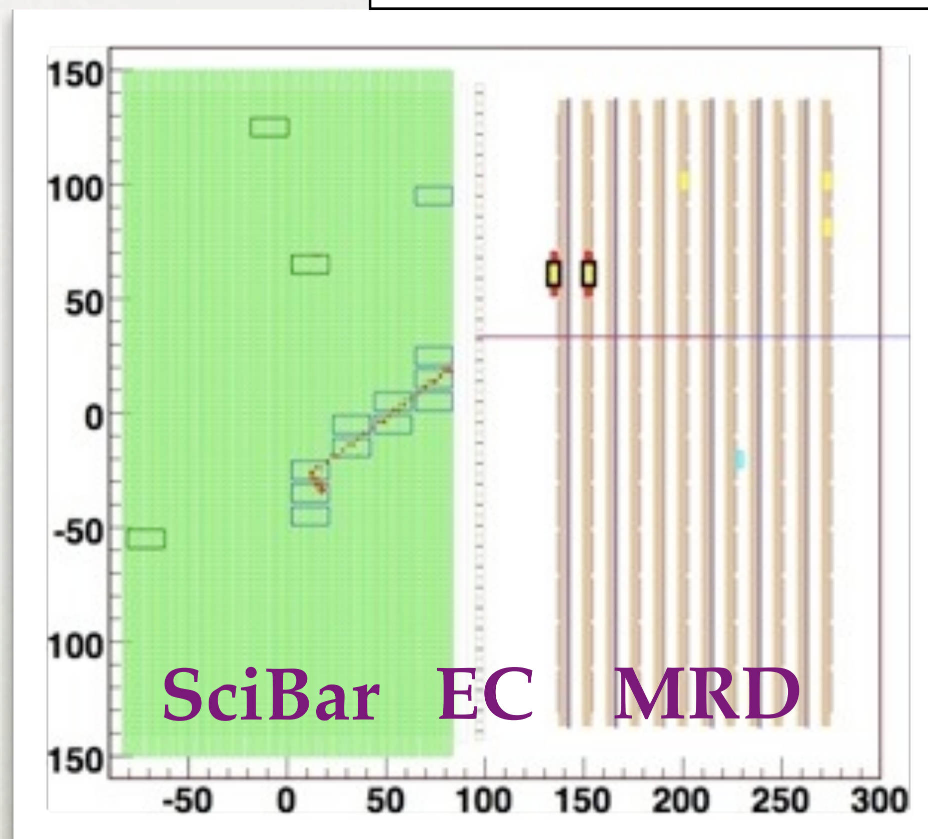
TDC hits (32ch "OR")

vertex resolution ~5 mm



anti-ν_μ CC-QE candidate

$(\bar{\nu}_\mu + p \rightarrow \mu + n)$



ν_μ CC-QE candidate

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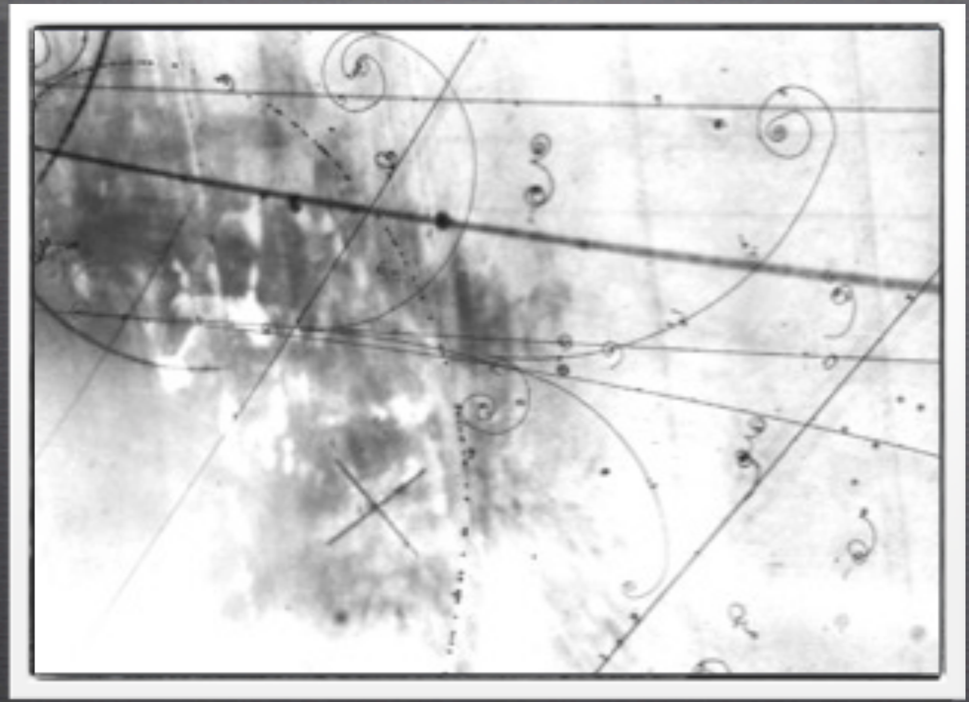
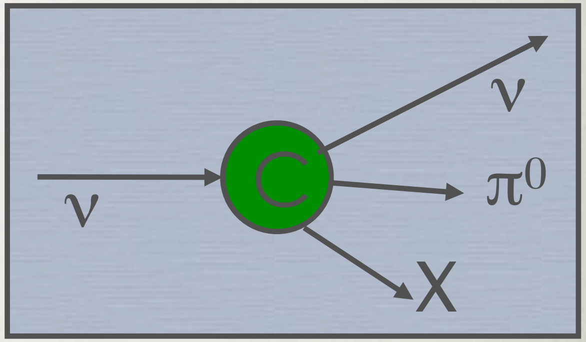


Neutral Current Pion Production

Neutral pion production

The signal for today's search

- Neutrino interacts with carbon nucleus, producing a pion
- Inclusive signal definition
  - Require a π^0 and no μ in final state



Resonant: $\nu_\mu + C \rightarrow \nu_\mu + \Delta + X \rightarrow \nu_\mu + X + \pi^0$

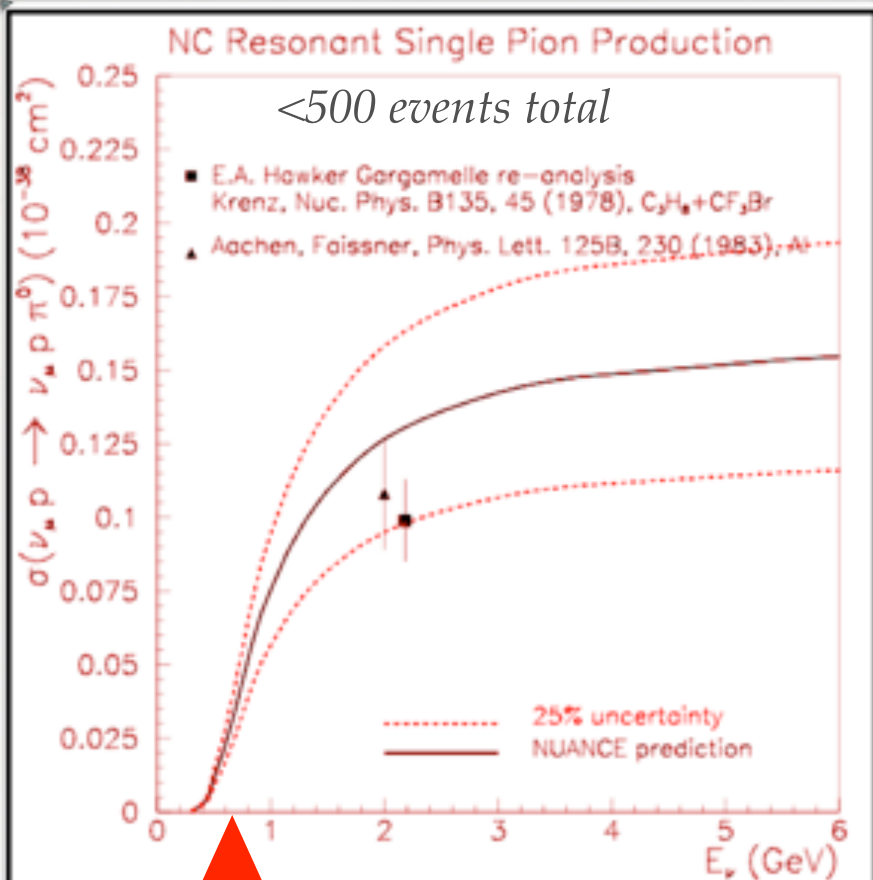
Coherent: $\nu_\mu + C \rightarrow \nu_\mu + C + \pi^0$

Few measurements (before K2K and MiniBooNE)

- only neutrino, no antineutrino
- low statistics
- >2 GeV, up to ~100 GeV

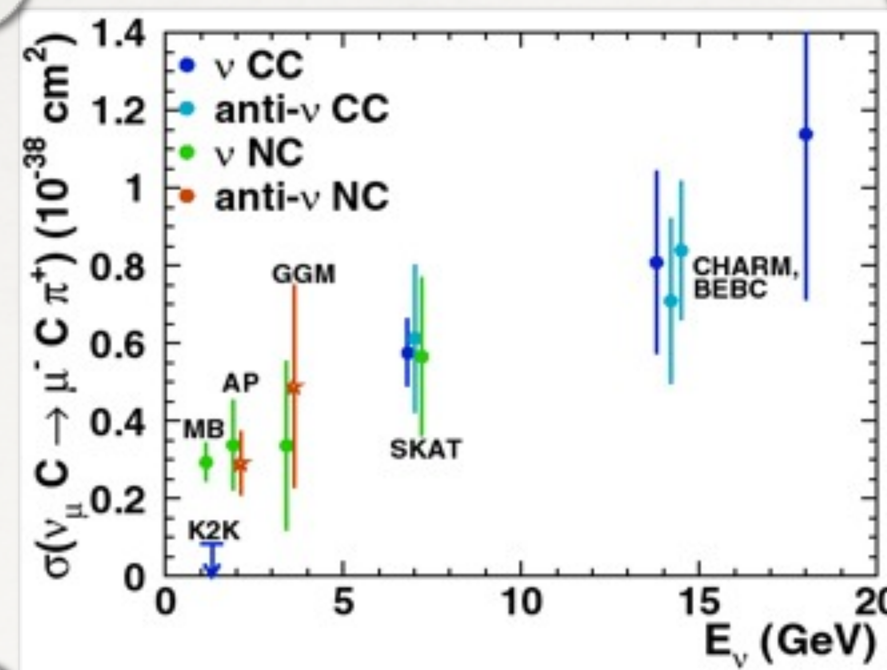
Past Measurements

Resonant



SciBooNE mean energy

Coherent

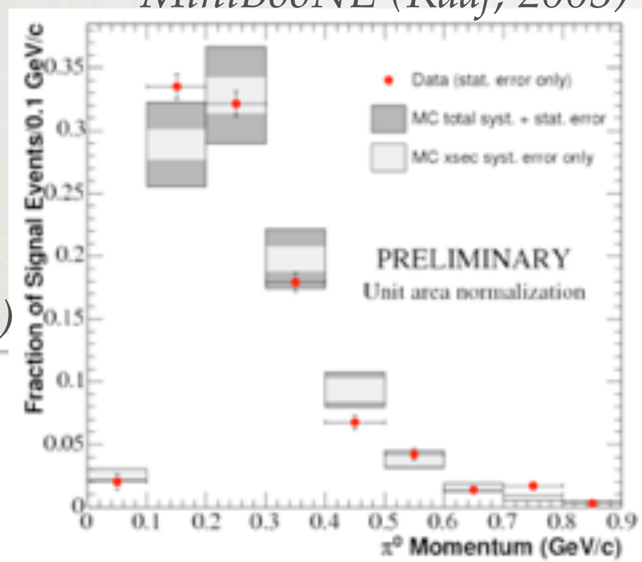


There are also recent K2K results and a new MiniBooNE result.

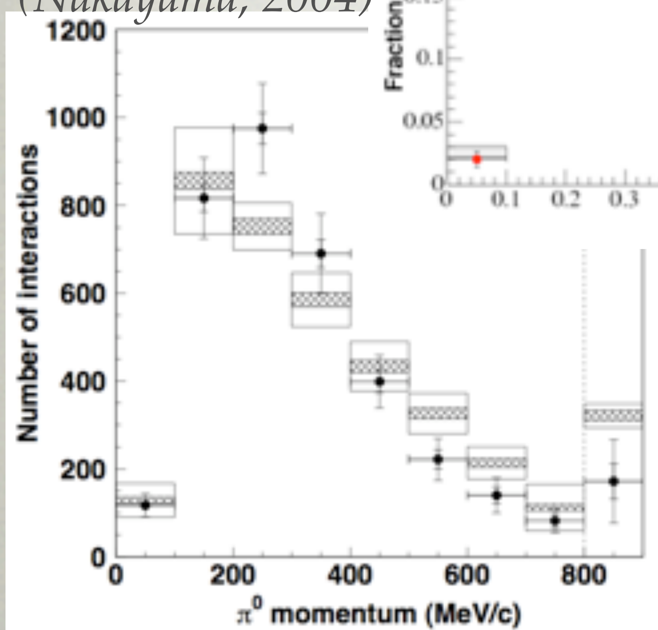
Past Measurements

Resonant

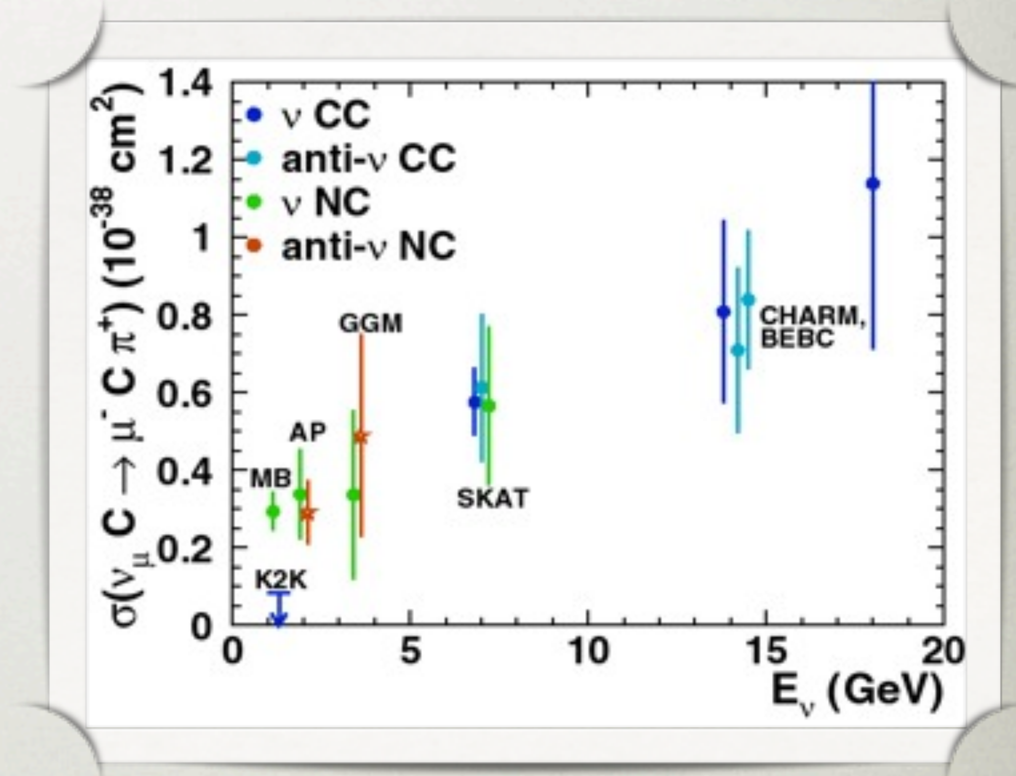
MiniBooNE (Raaf, 2005)



K2K (Nakayama, 2004)



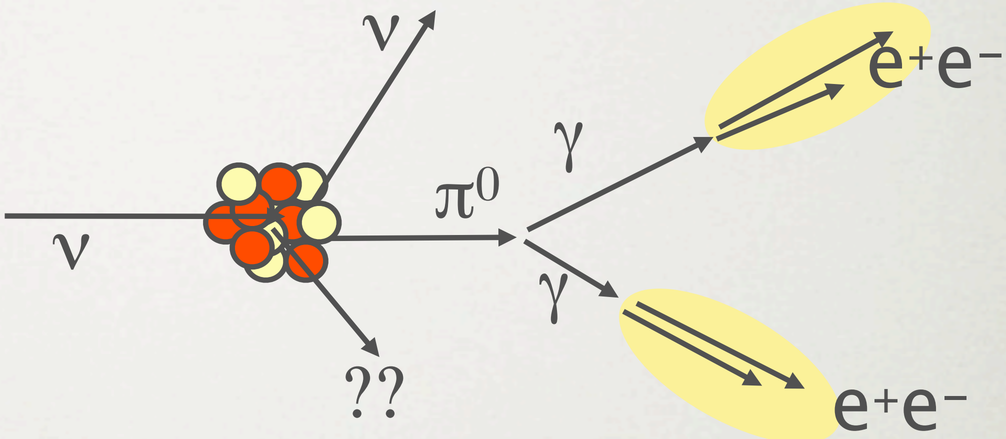
Coherent



There are also recent K2K results and a new MiniBooNE result.

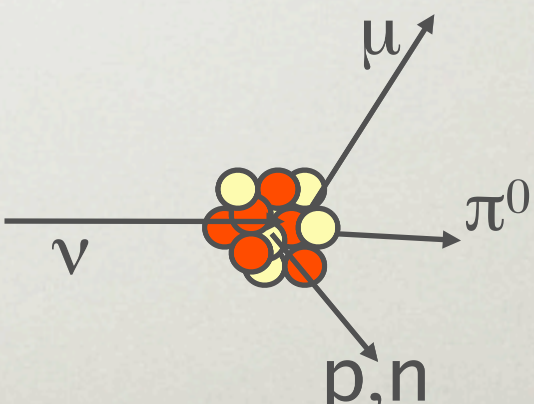
Neutral Pion Production

Signal
NC1π^0 production
$\nu + C \rightarrow \nu + X + \pi^0$



- 2 "shower-like" tracks (from π^0 decay)
- ~6% of total ν interactions based on Rein-Sehgal model

Background
CC1π^0 production
Secondary π^0 production
External particles ("dirt" neutrinos)

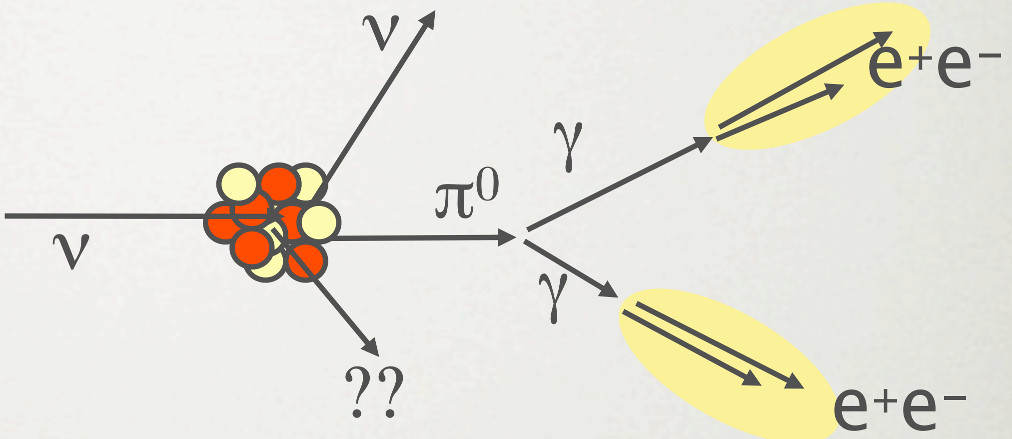


Neutral Pion Production

Signal

NC1π^0 production

$\nu + C \rightarrow \nu + X + \pi^0$



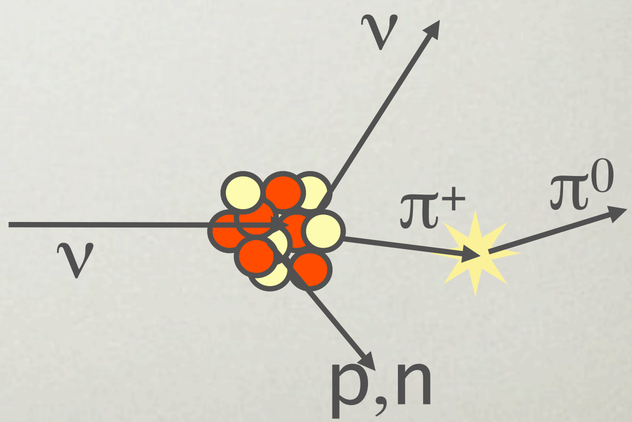
- 2 "shower-like" tracks (from π^0 decay)
- ~6% of total ν interactions based on Rein-Sehgal model

Background

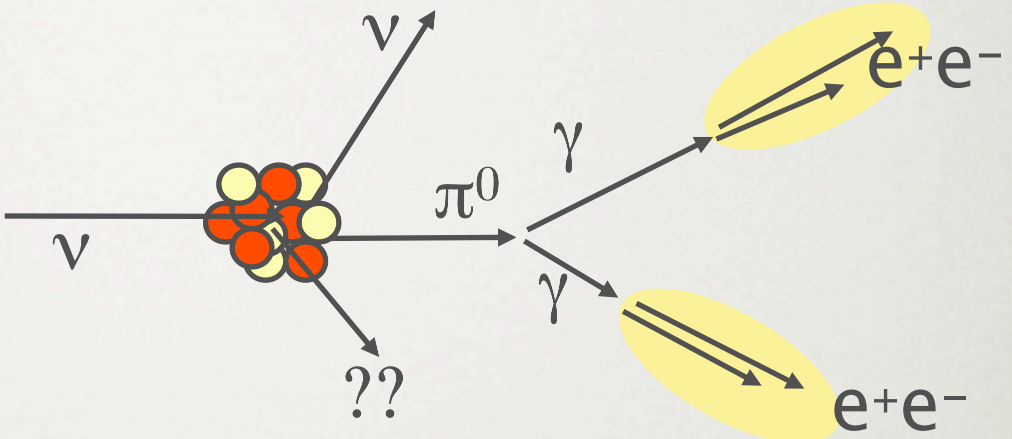
CC1π^0 production

Secondary π^0 production

External particles ("dirt" neutrinos)



Neutral Pion Production



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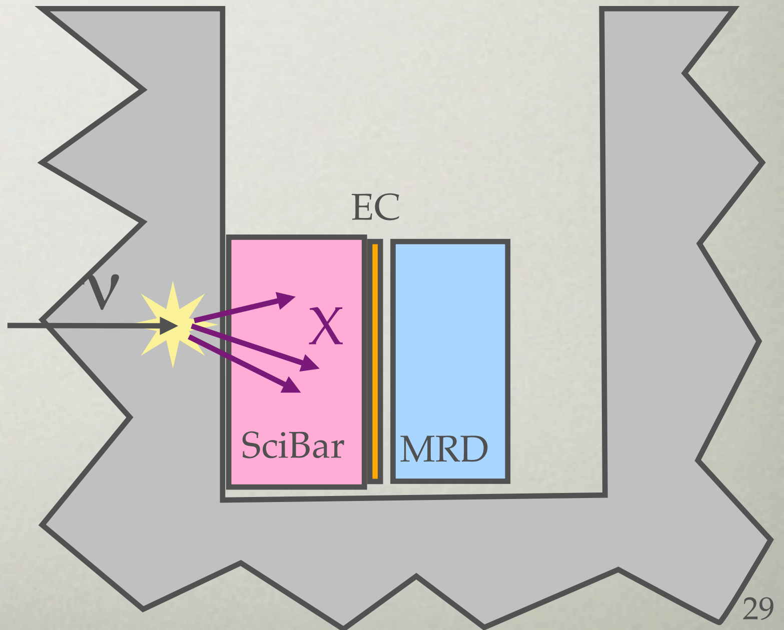


Background

CC1π^0 production

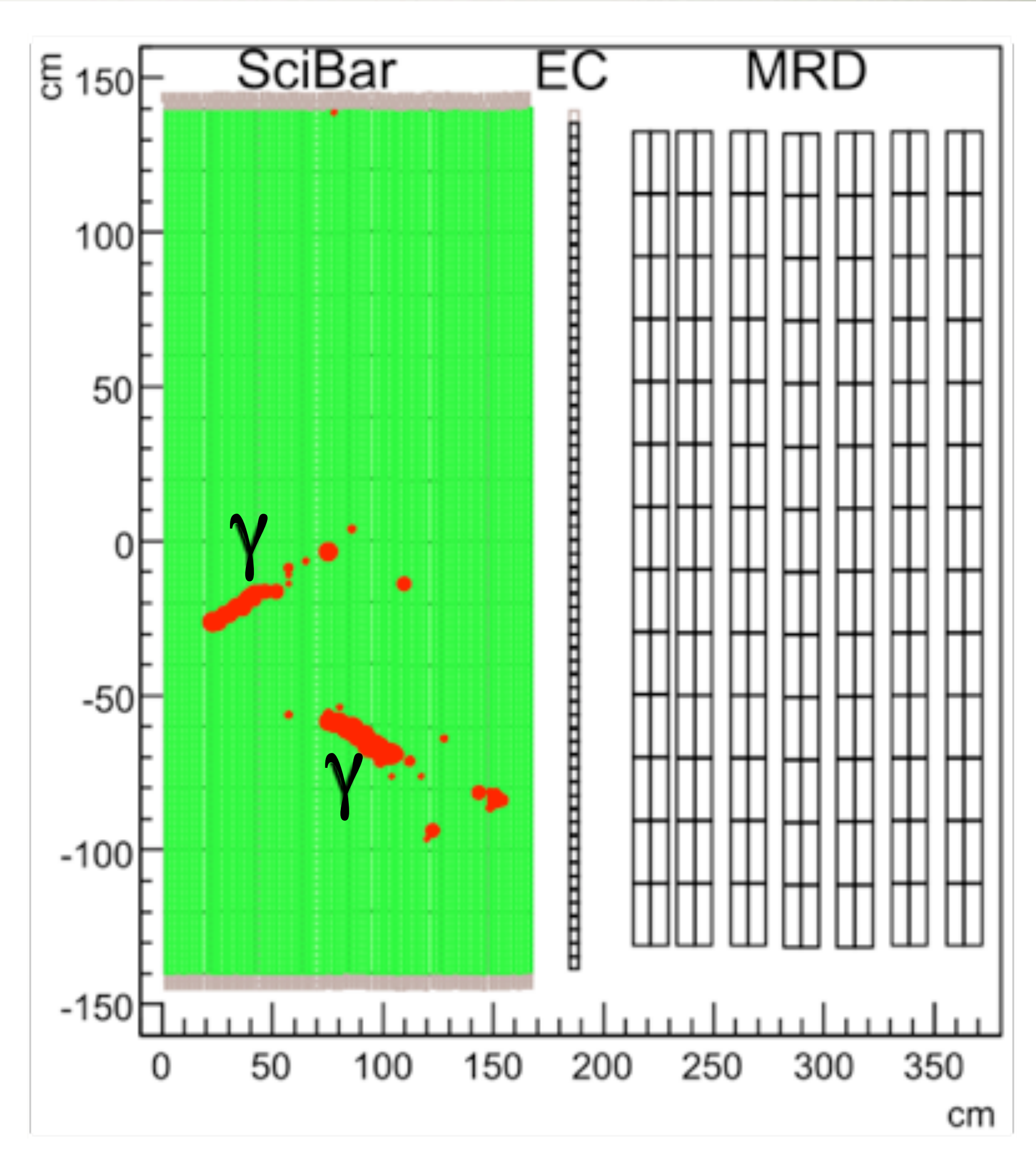
Secondary π^0 production

External particles ("dirt" neutrinos)

NC1π^0 candidate

- Event selection cuts designed to find pairs of converted photons with invariant mass of π^0

1. Pre-Selection
2. Internal BG rejection (muons)
3. External BG rejection (particles from upstream)



Three Results

- $\sigma(NC\pi^0) / \sigma(CC)$ ratio
- π^0 kinematics
- NC Coherent π^0 fraction

Published results

New result

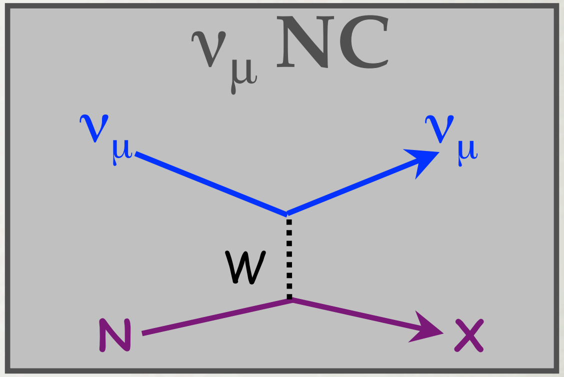
Y. Kurimoto, *et al*., "Measurements of Neutral Current π^0 Production on Carbon in a Few GeV ν Beam"; Phys.Rev.D. **81** 033004 (2010), arXiv:0910.5768 [hep-ex].

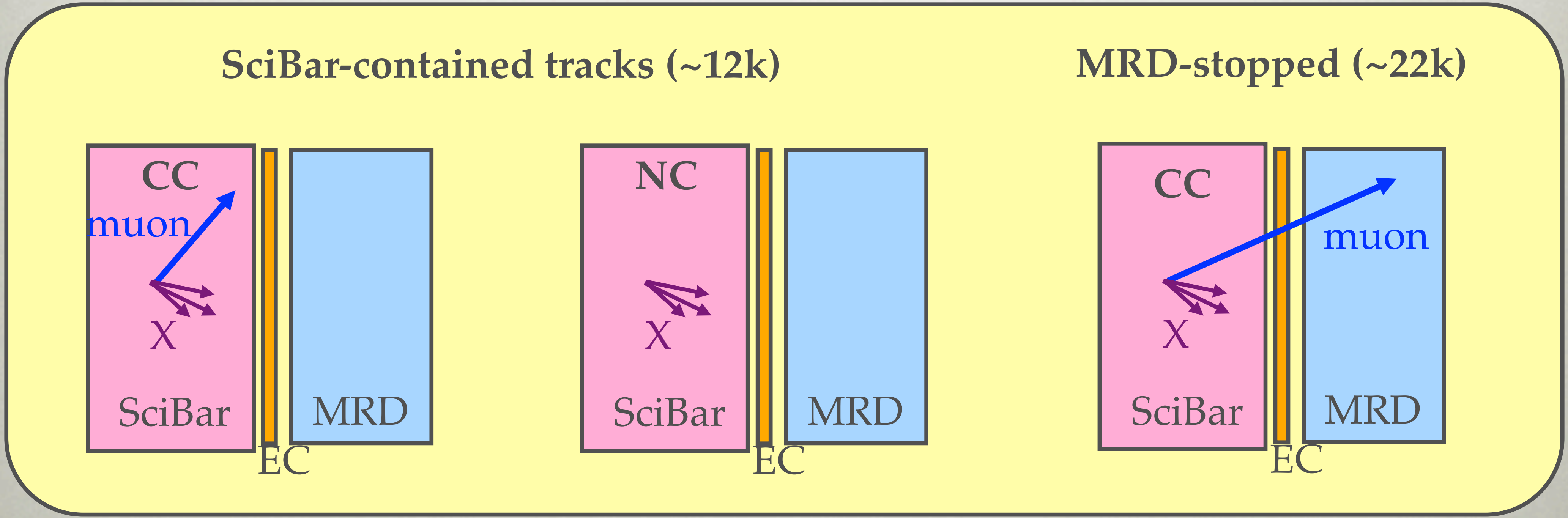
Y. Kurimoto, *et al*., "Improved Measurement of Neutral Current Coherent π^0 Production on Carbon in a Few GeV ν Beam"; submitted to PRDRC, arXiv:1005.0059 [hep-ex].

NCπ^0 Event Selection

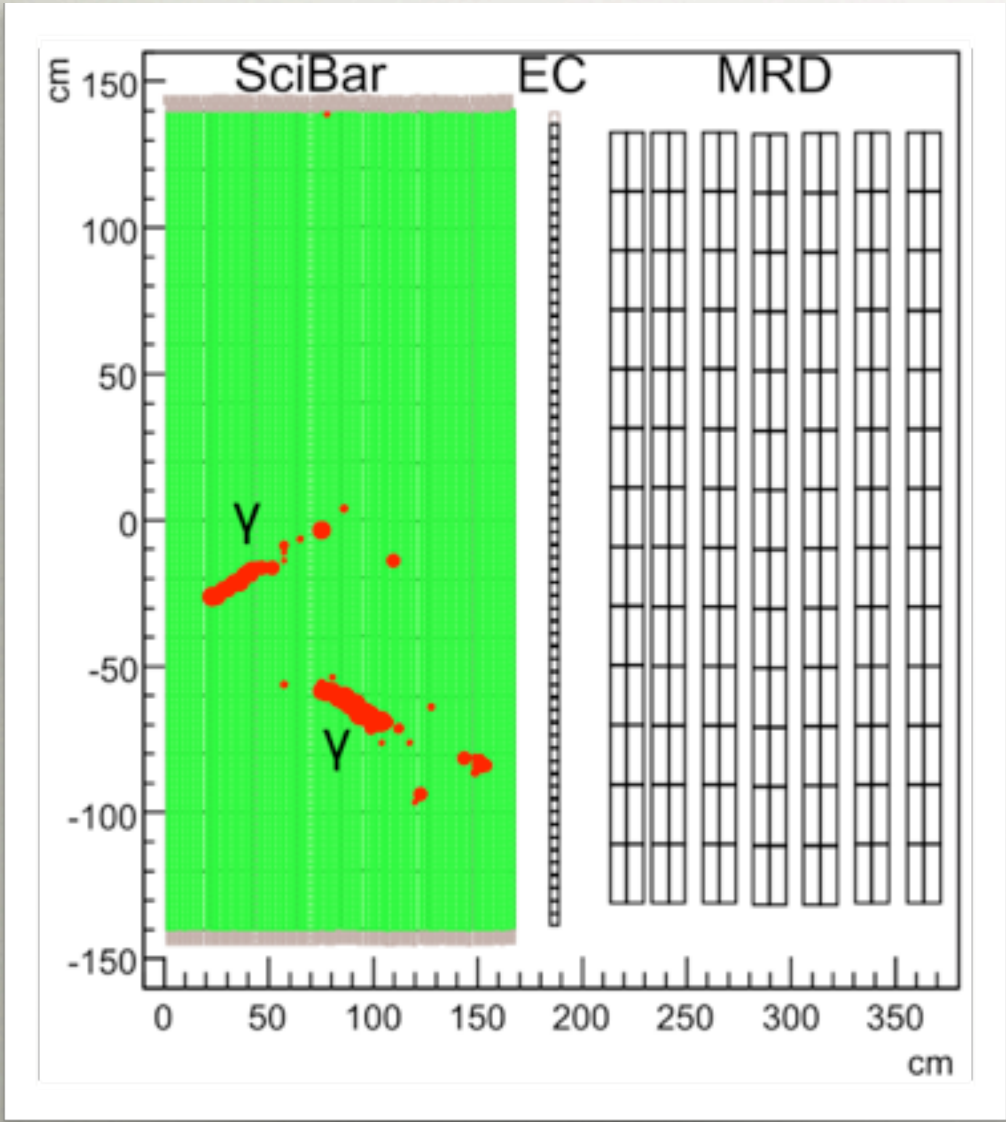
Neutral Current (NC) event selection

- Require tracks contained in SciBar
  - Need further cuts to remove contained muons
- MRD-matched events used as normalisation sample



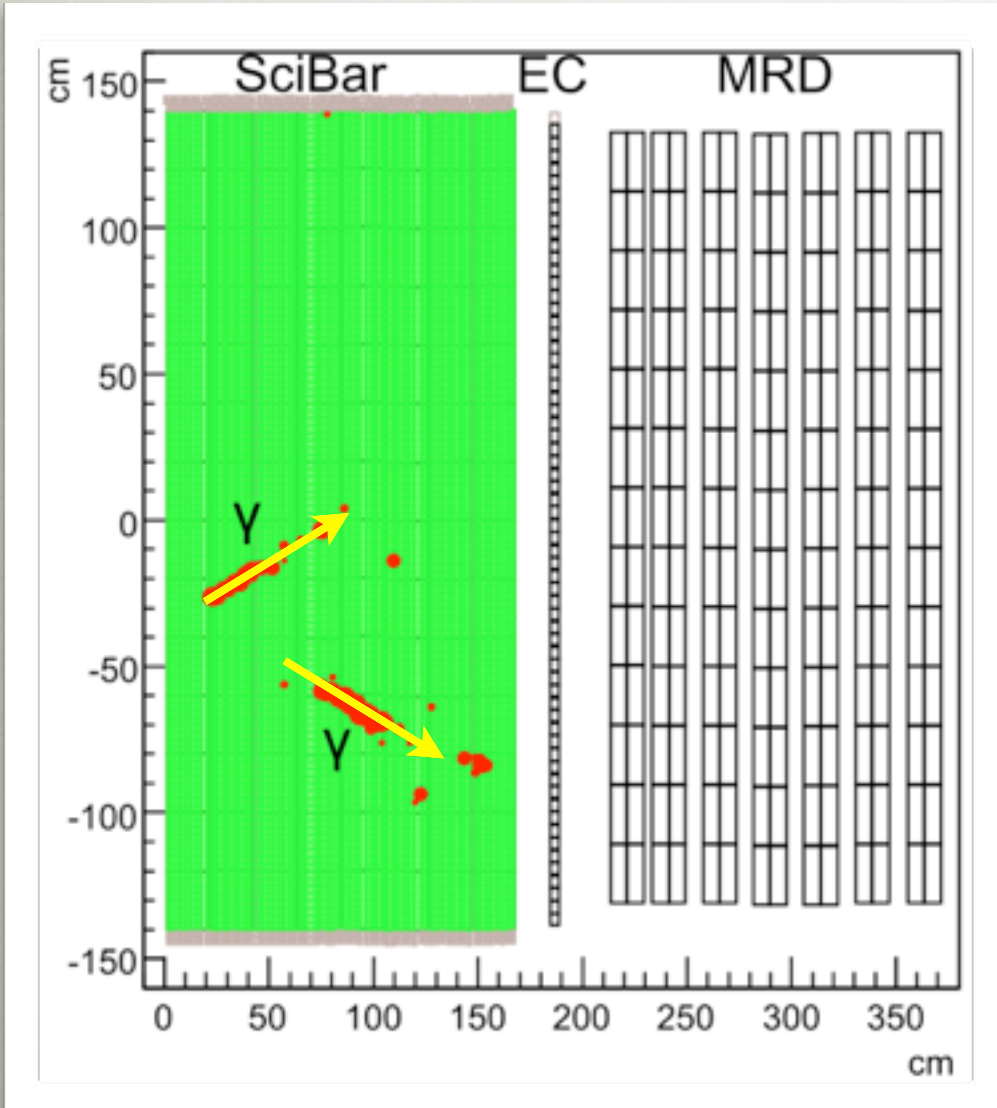


Pre-Selection Cuts



- Require at least 2 tracks
  - Cellular automaton algorithm
  - No hits in first layer (rejects dirt)
  - Tracks contained in SciBar
  - Tracks must be in beam window
- ~12k events, 15% purity

Pre-Selection Cuts



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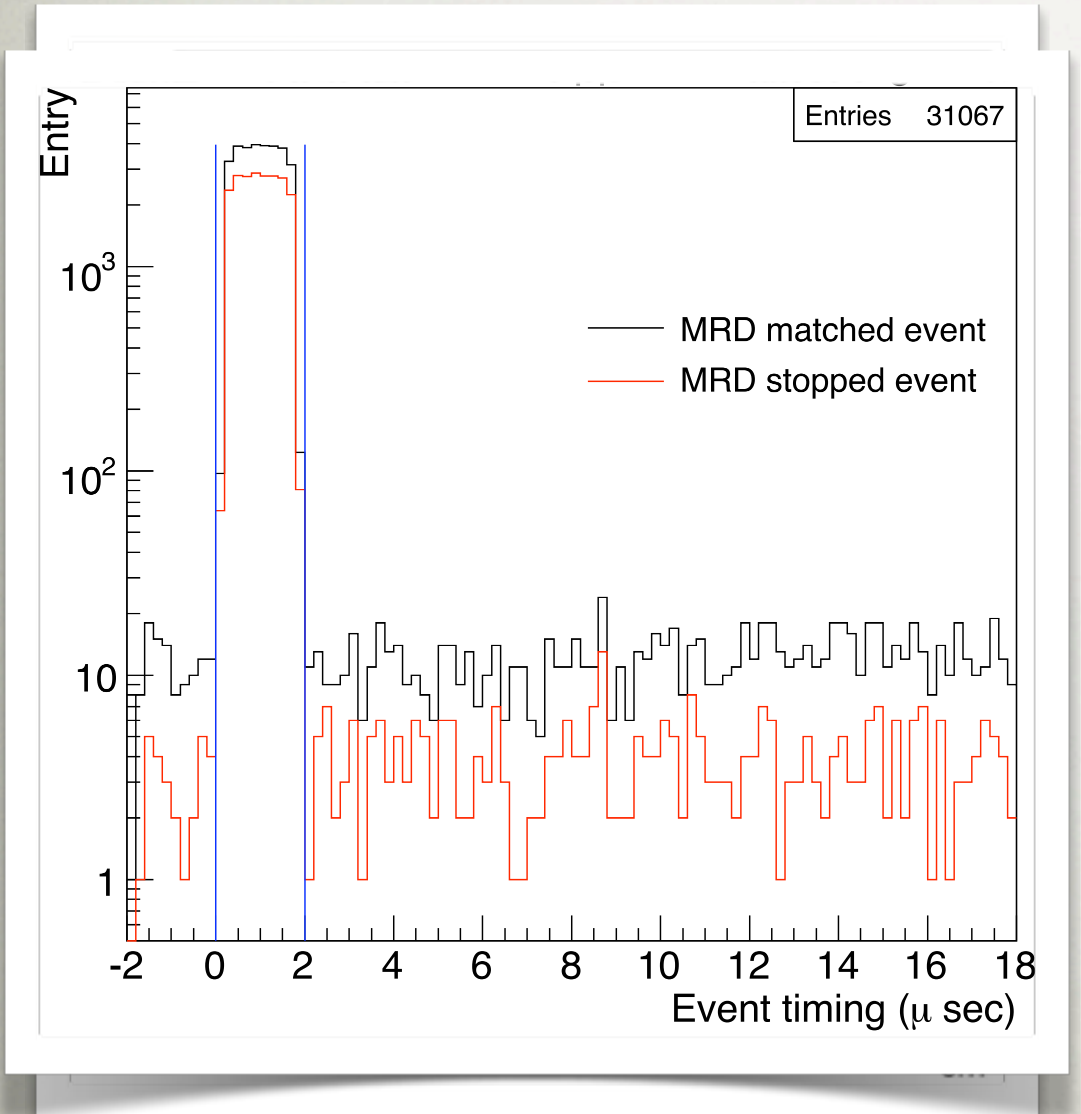
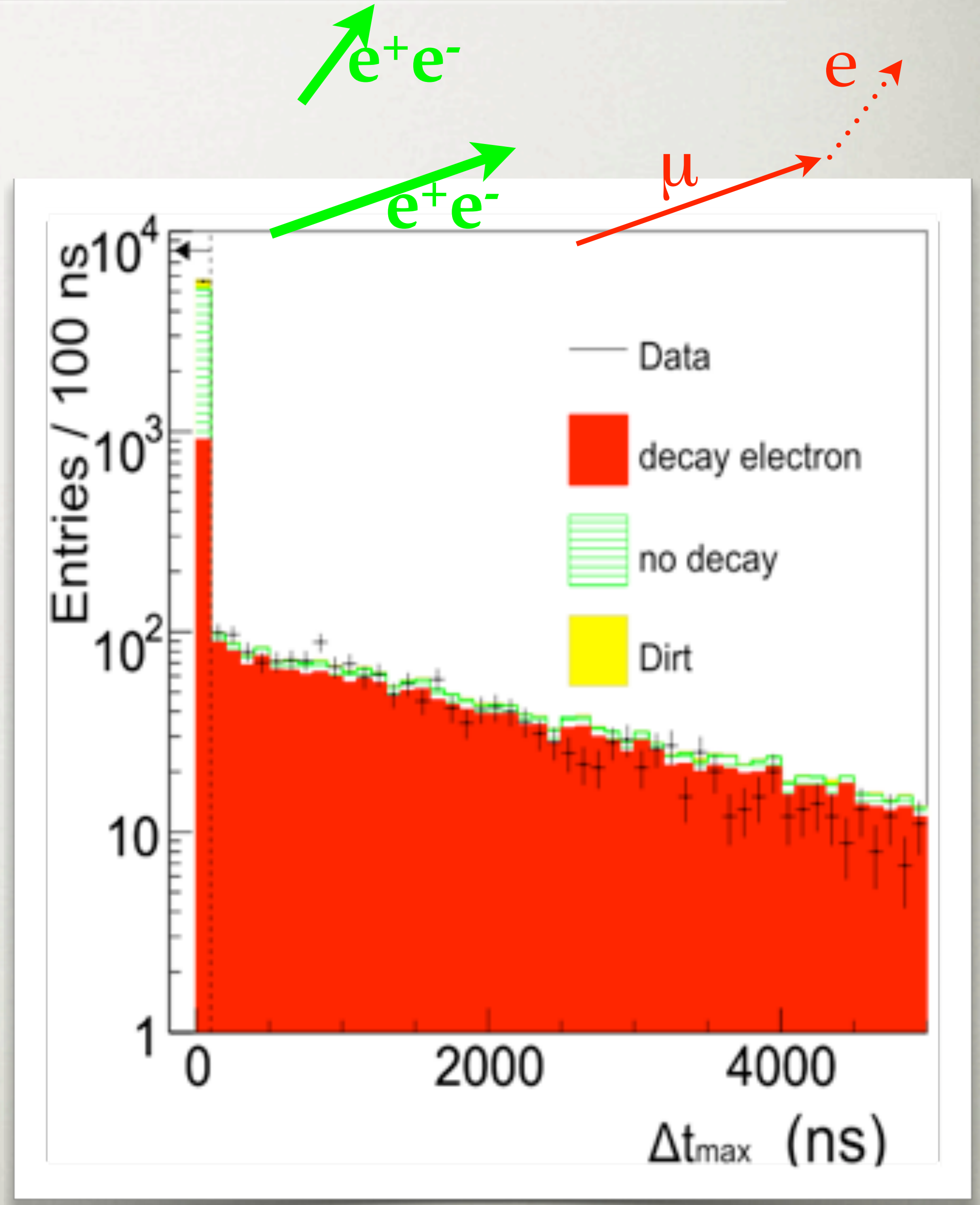


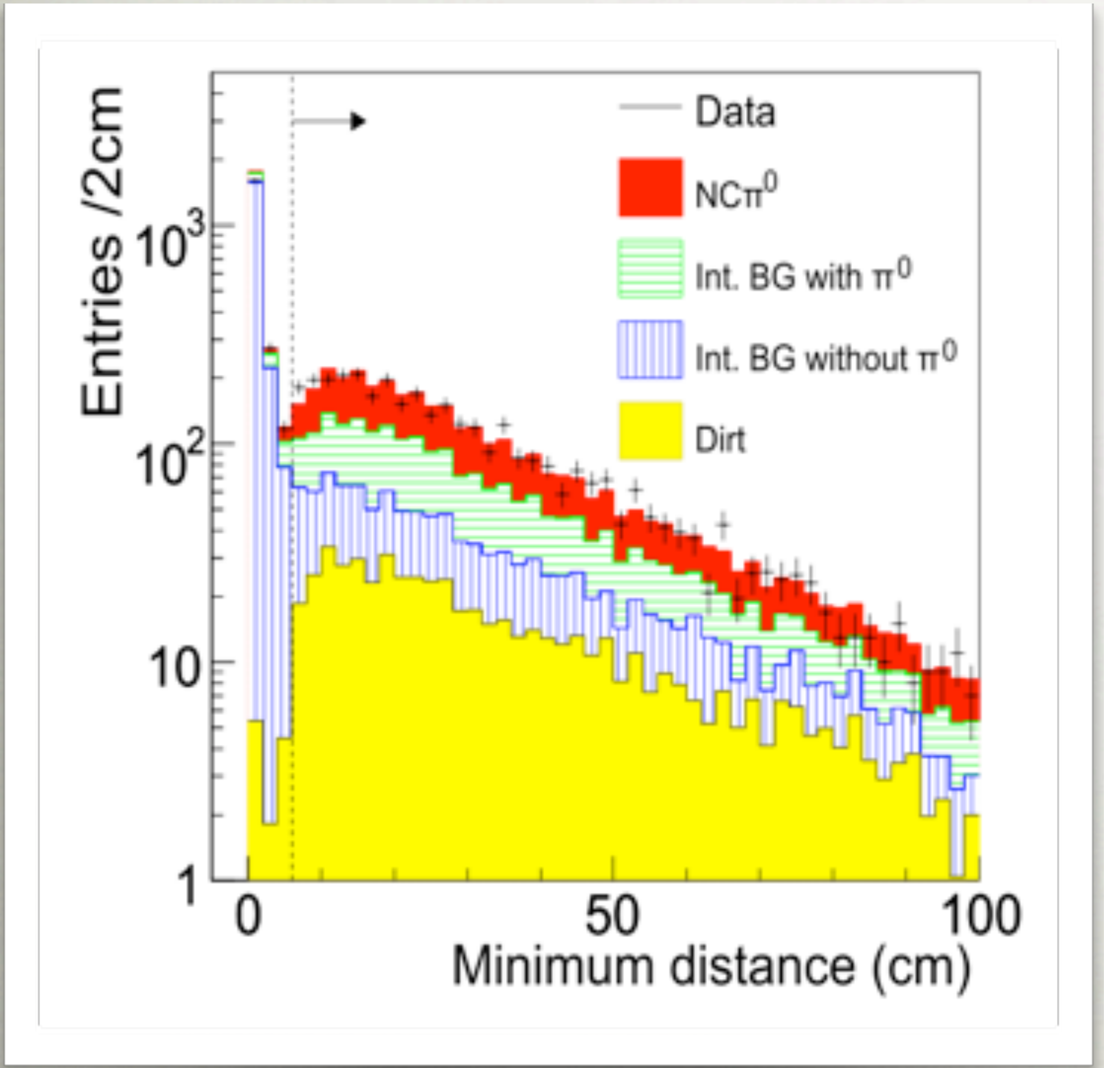
- Require at least 2 tracks
  - Cellular automaton algorithm
  - No hits in first layer (rejects dirt)
  - Tracks contained in SciBar
  - Tracks must be in beam window
- ~12k events, 15% purity

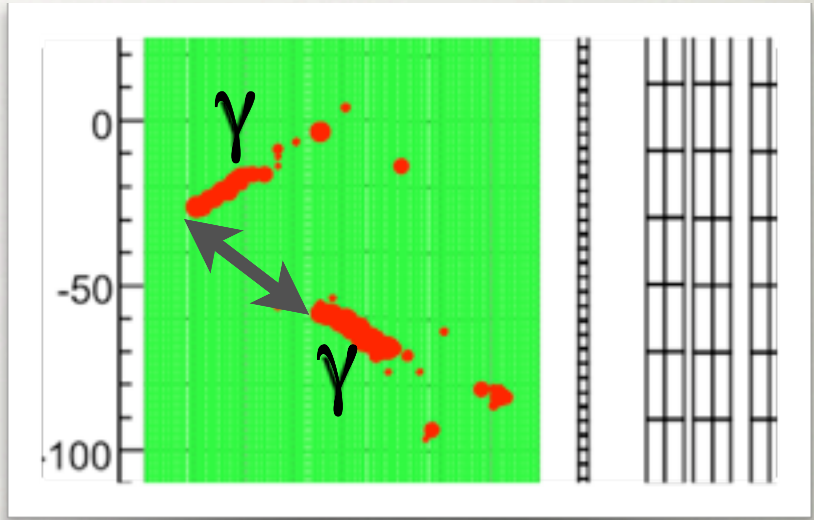
Muon Track Rejection

- Reject tracks escaping from side
- Calculate time difference between track edges and late TDC hits
- Require $\Delta t<100$ ns
- ~6k events, 24% purity



Track Separation

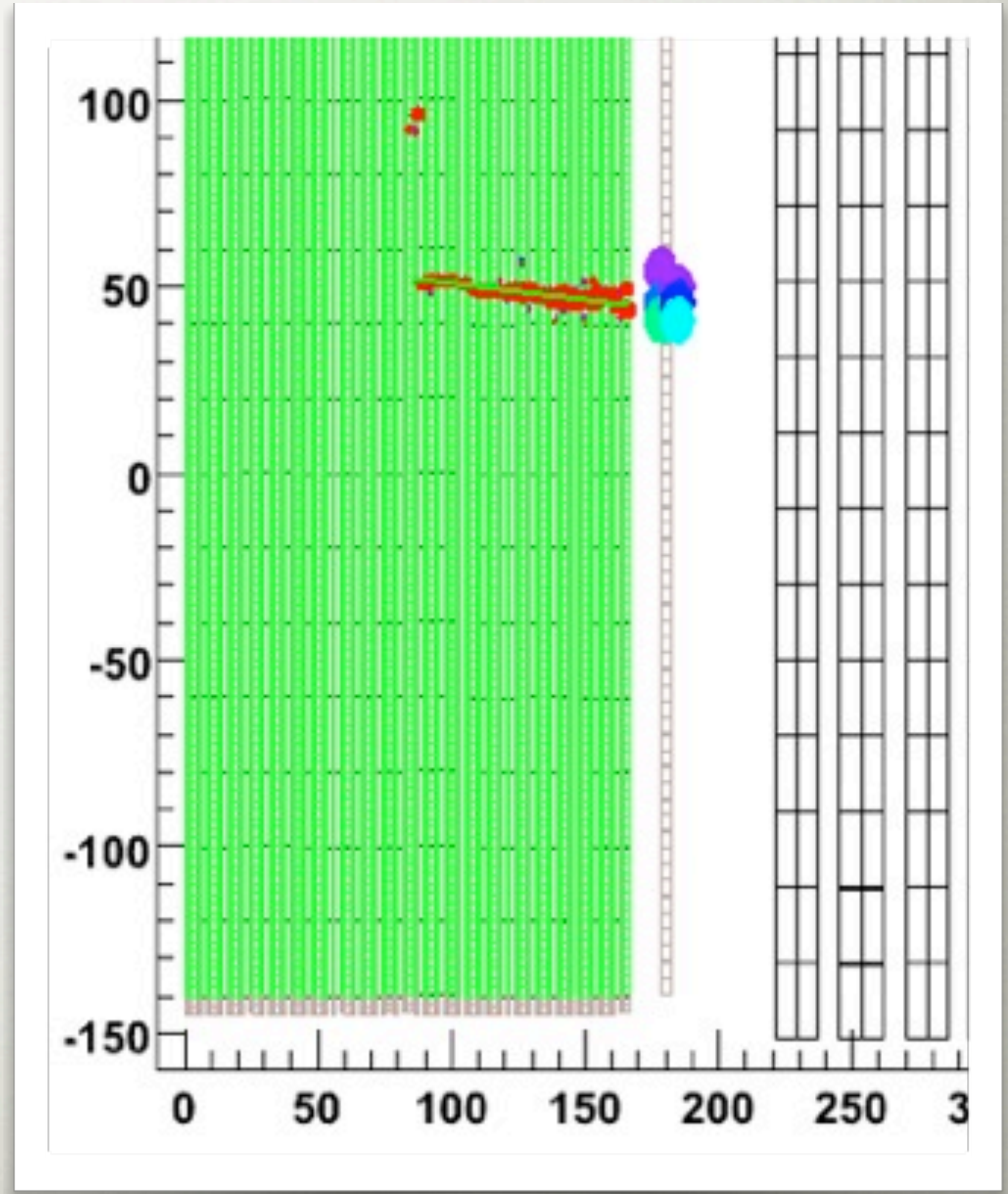




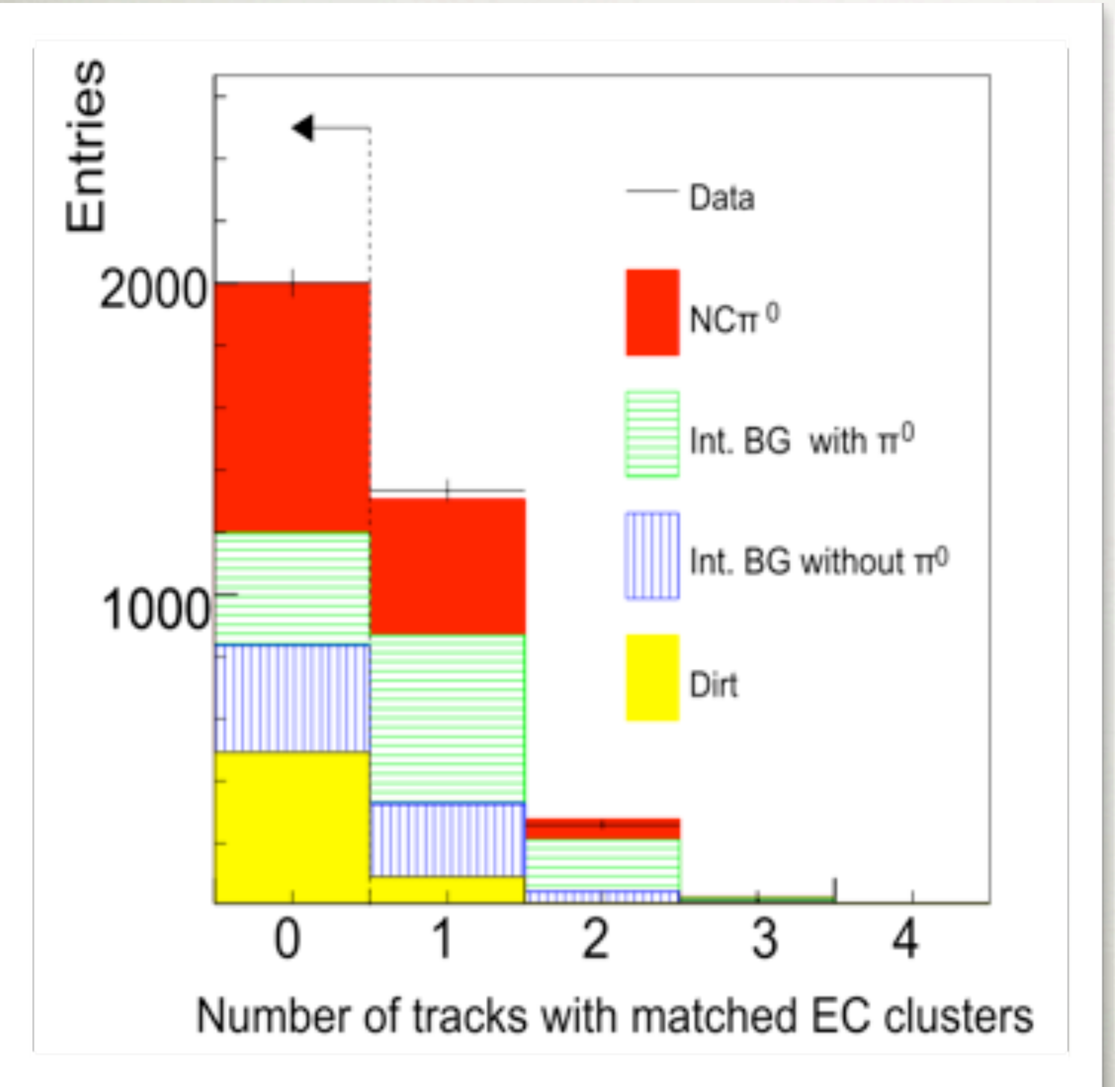
- Photons have finite conversion distance
- Require tracks be at least 6 cm apart
- ~4k events, 36% purity

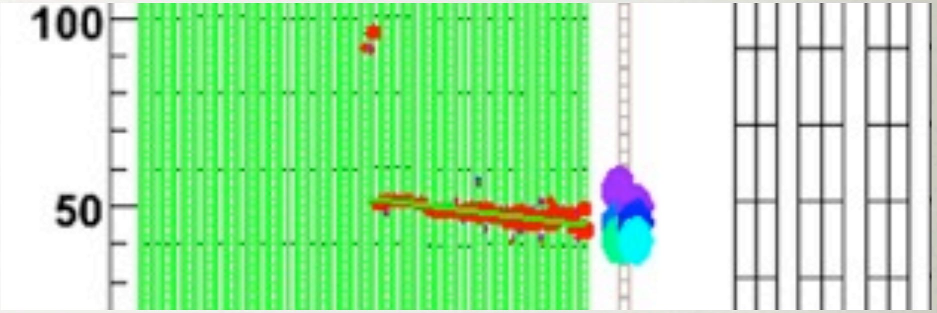
Electron Catcher Cuts

- Tracks might penetrate into the EC
- Three cuts
    - Matching SciBar tracks with EC clusters
    - Energy deposit in upstream EC layer
    - Ratio of energy deposited in two EC layers



SciBar-EC Matching



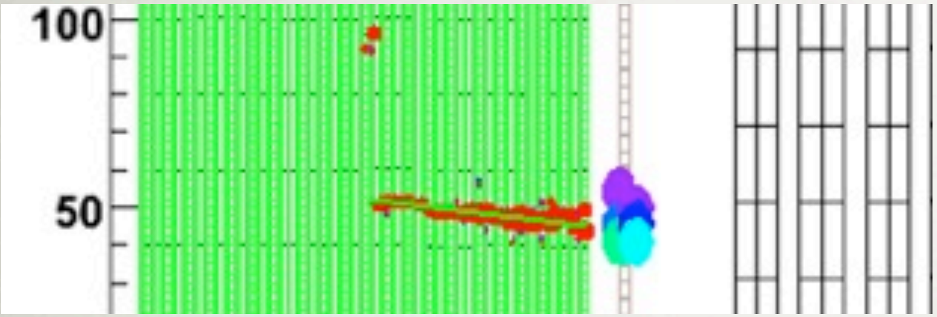


- EC clusters are contiguous calorimeter modules with energy deposited

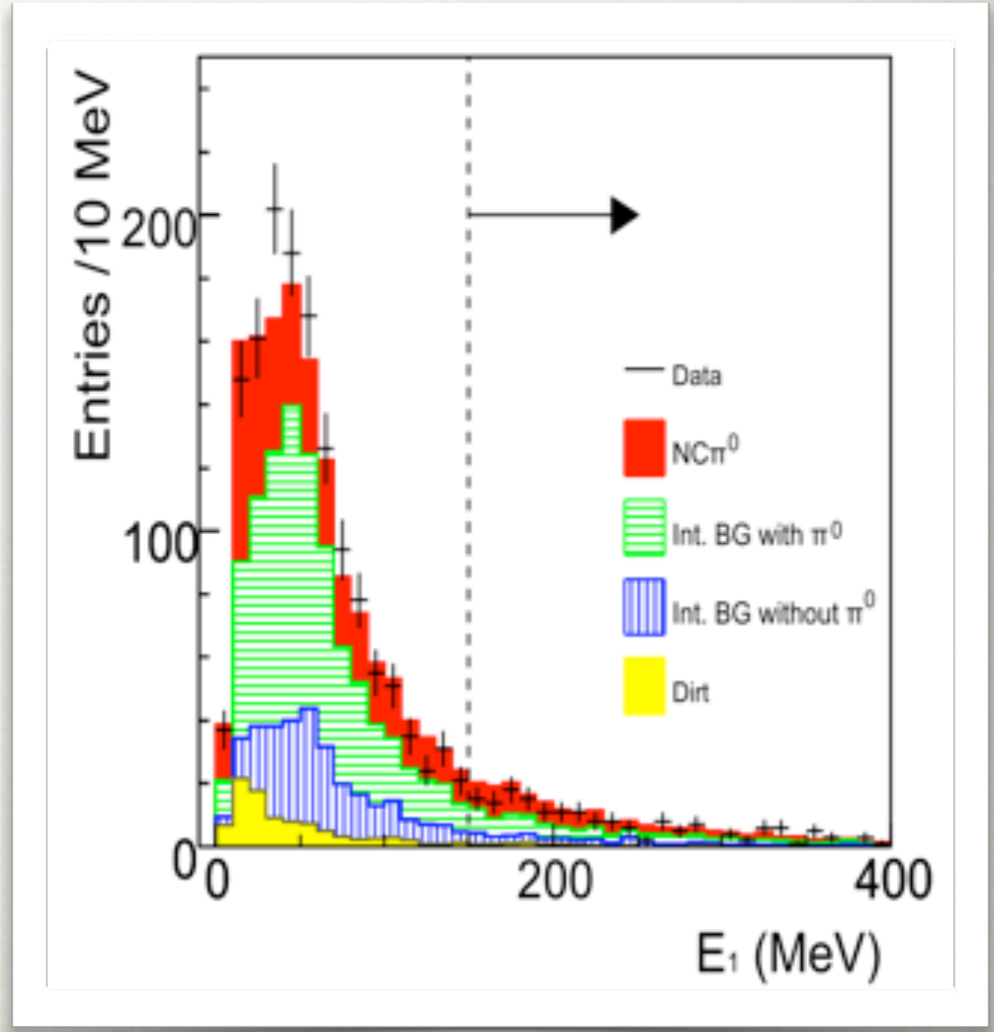
✓ If no SciBar track matches an EC cluster - accept

➡ If there are matches, must pass one of the next cuts

EC Energy Deposit

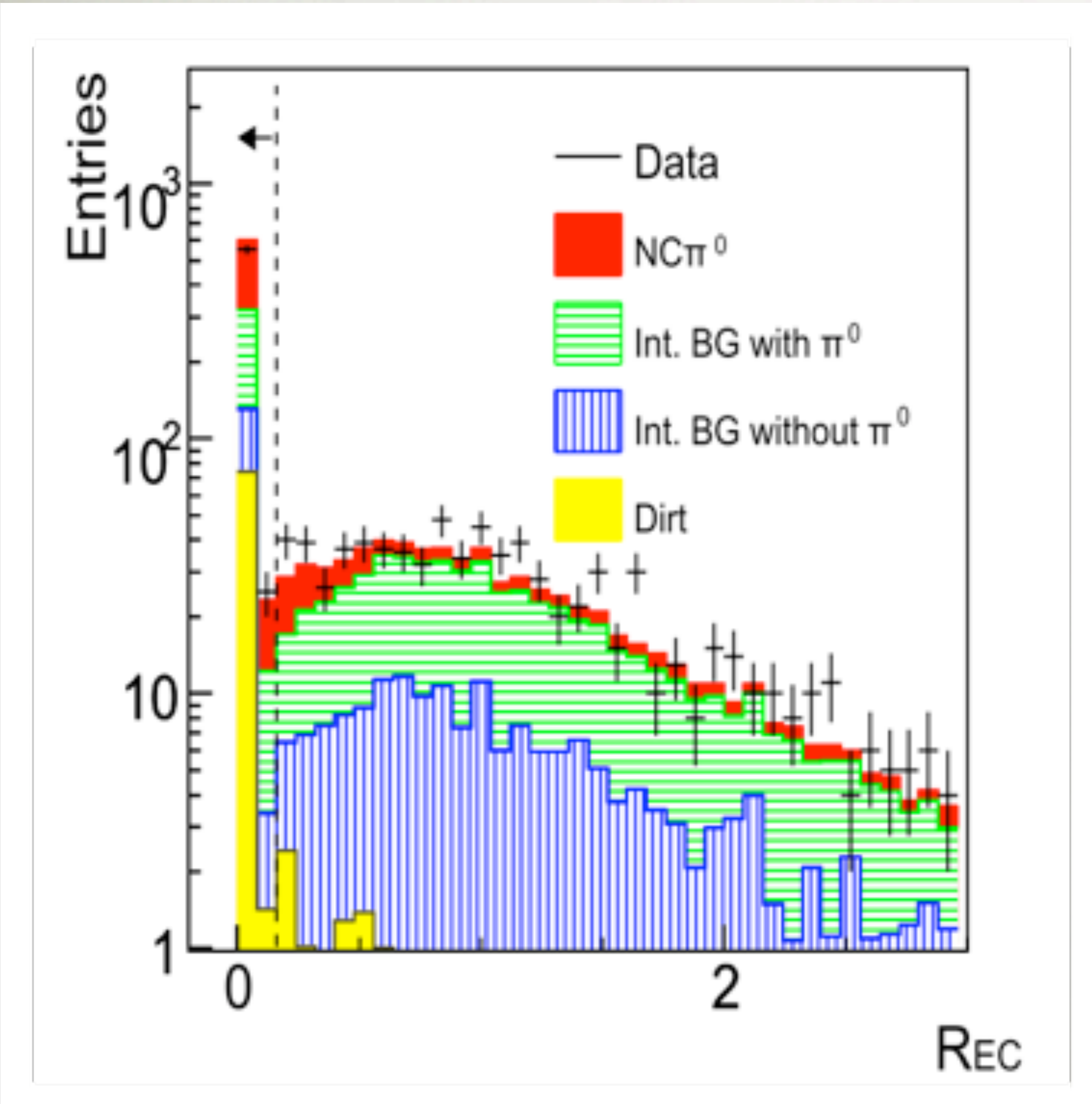


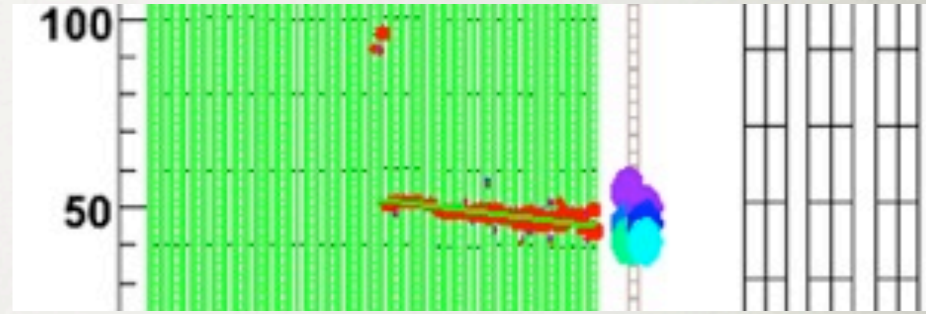
- Look for high energy deposited in upstream EC layer
  - Require $E_{dep} > 150$ MeV
  - removes MIP tracks



Events that failed first EC cut

EC Layer Energy Ratio



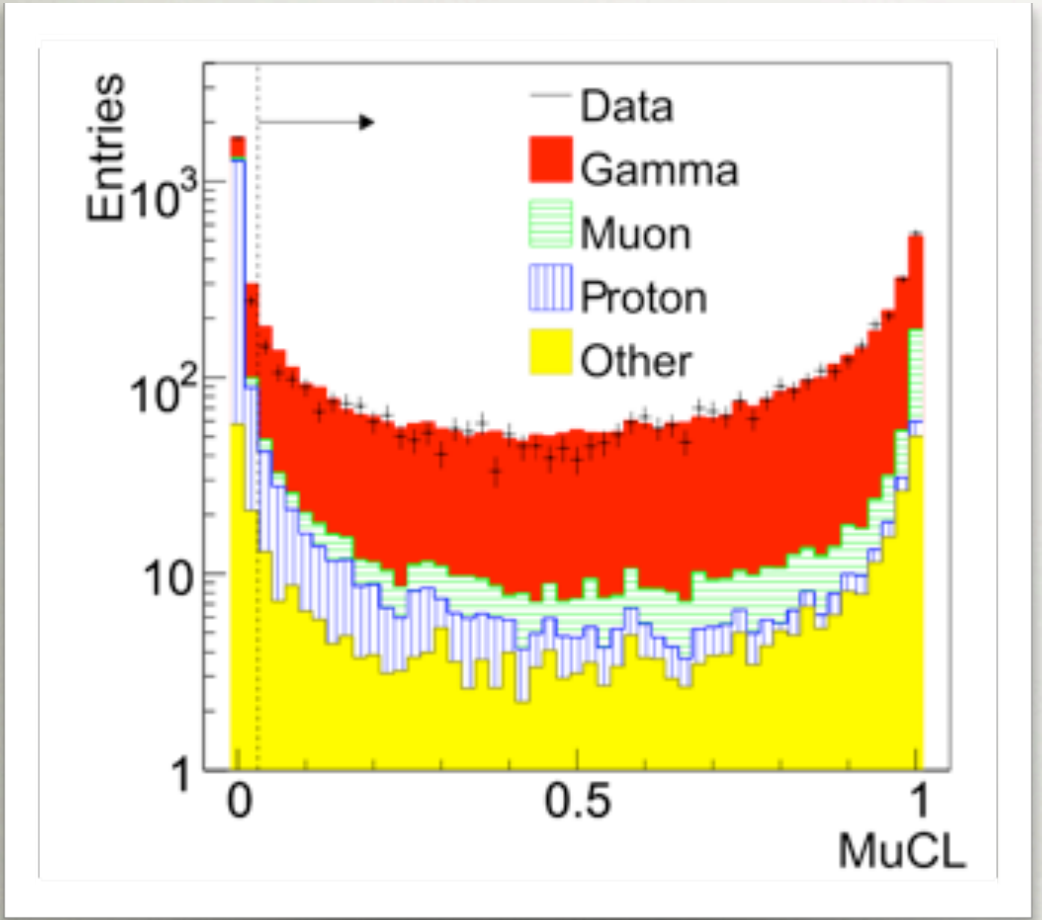


- EM showers from π^0 decays tend to deposit most energy in upstream layer
- Require :

$$R_{EC} = EC2/EC1 < 0.2$$

- ~3k events, 42% purity

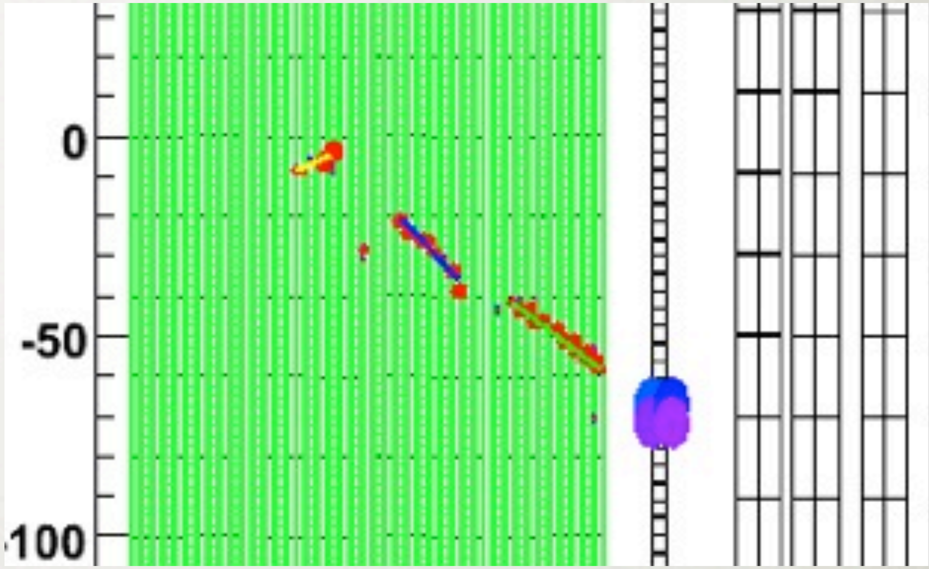
Proton Track Rejection

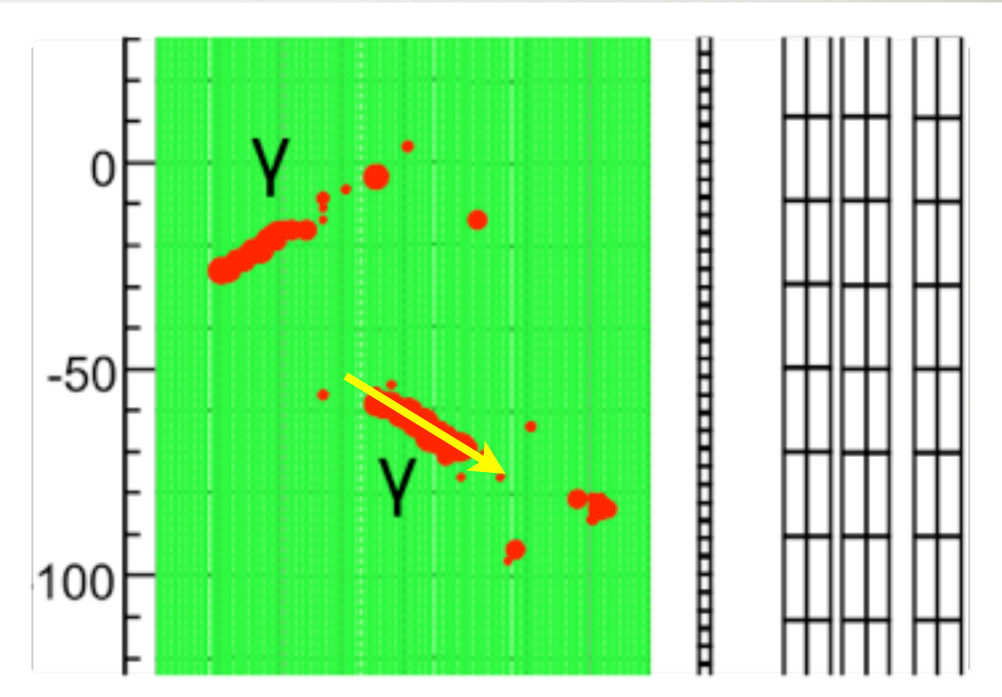


- Remove highly ionising tracks, which tend to come from protons
  - MuCL is PID parameter based on energy deposit
- photon efficiency 87%, photon purity 81%
- NCπ^0 purity ~44%

Extended Tracks

- Start from simple tracks reconstruction
- Now extend to simple cluster reconstruction
  - Join colinear tracks together
  - Collect hits within 20 cm of reconstructed tracks
- *Further cuts based on extended tracks...*





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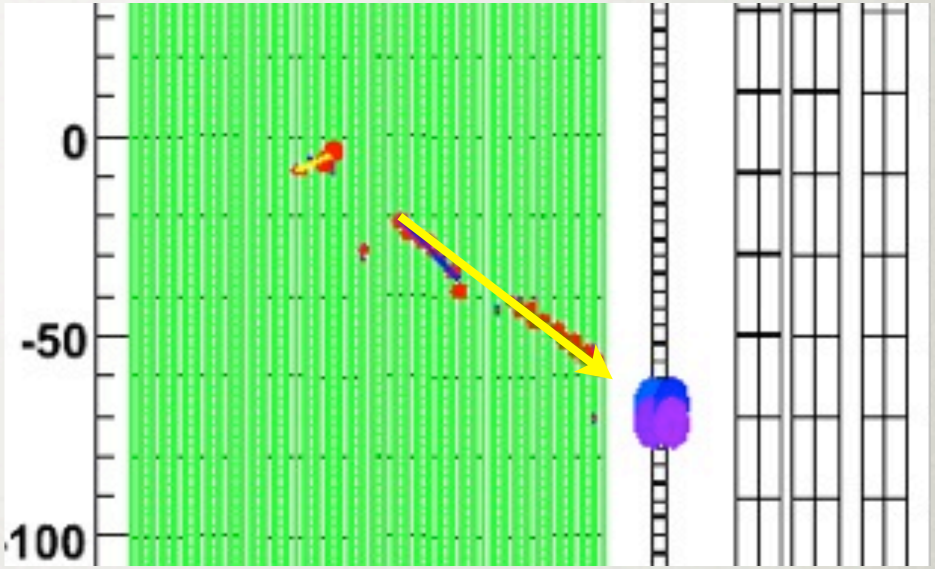

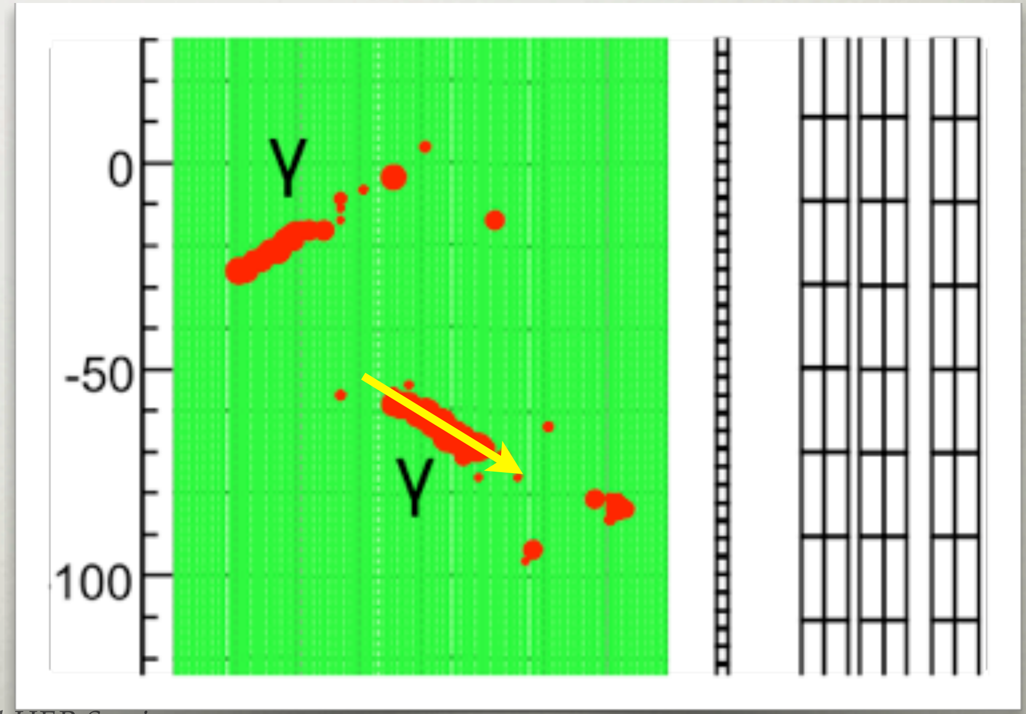

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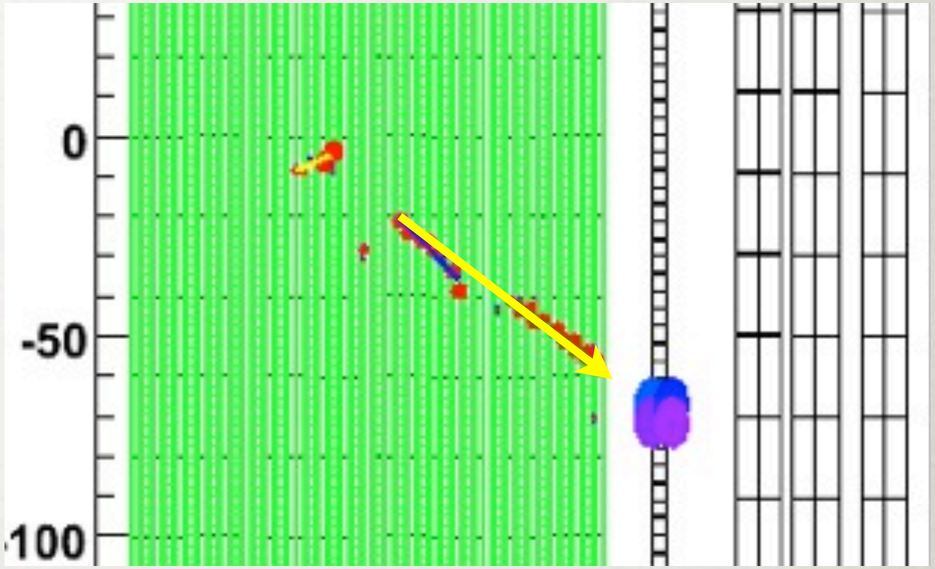
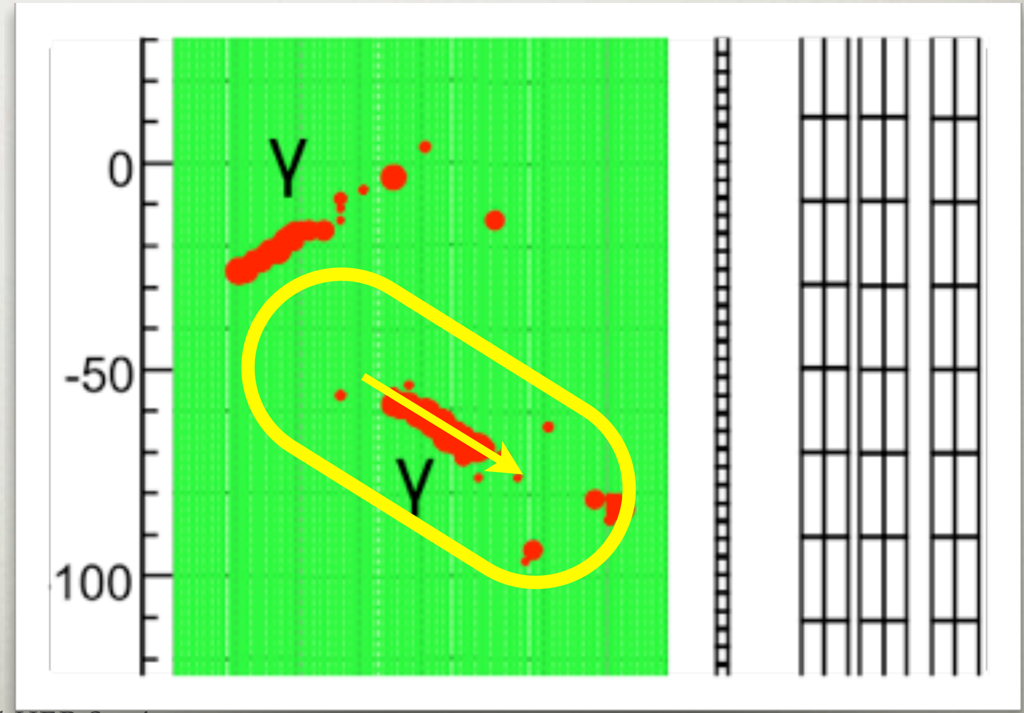
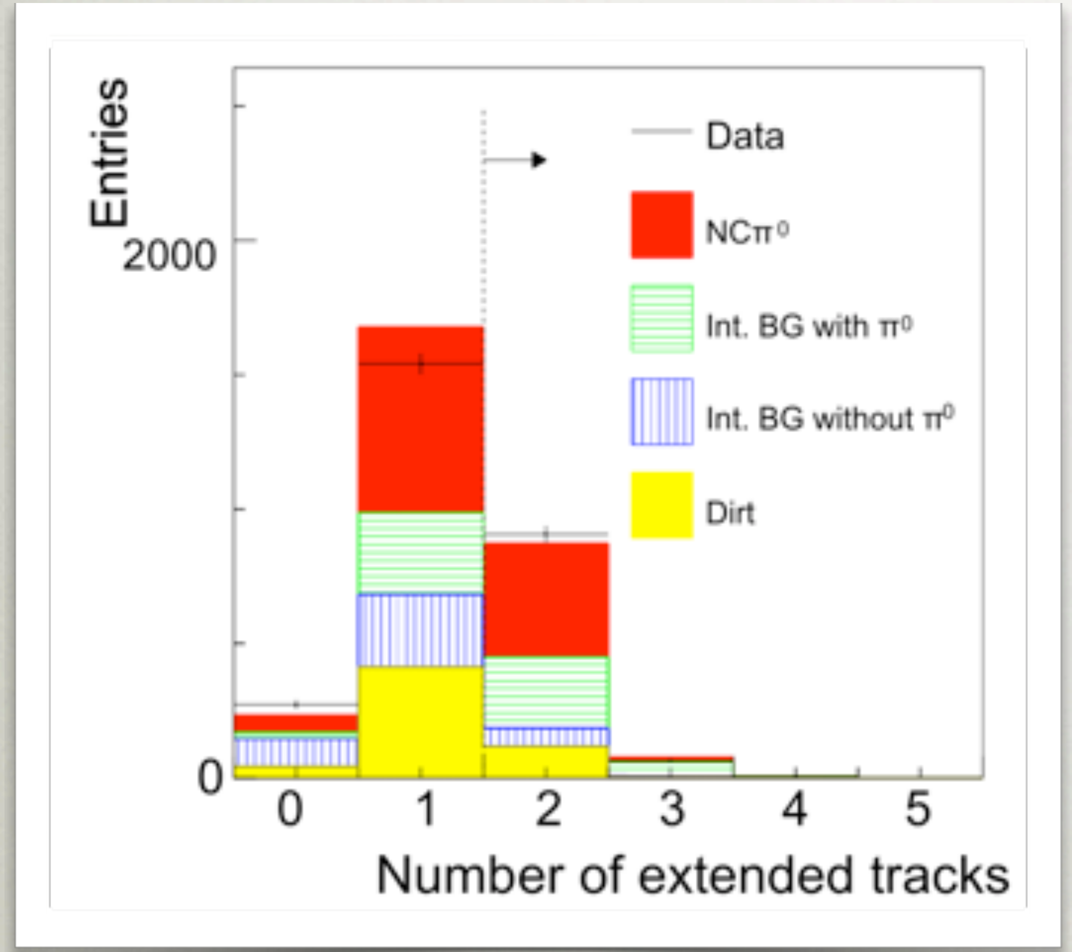




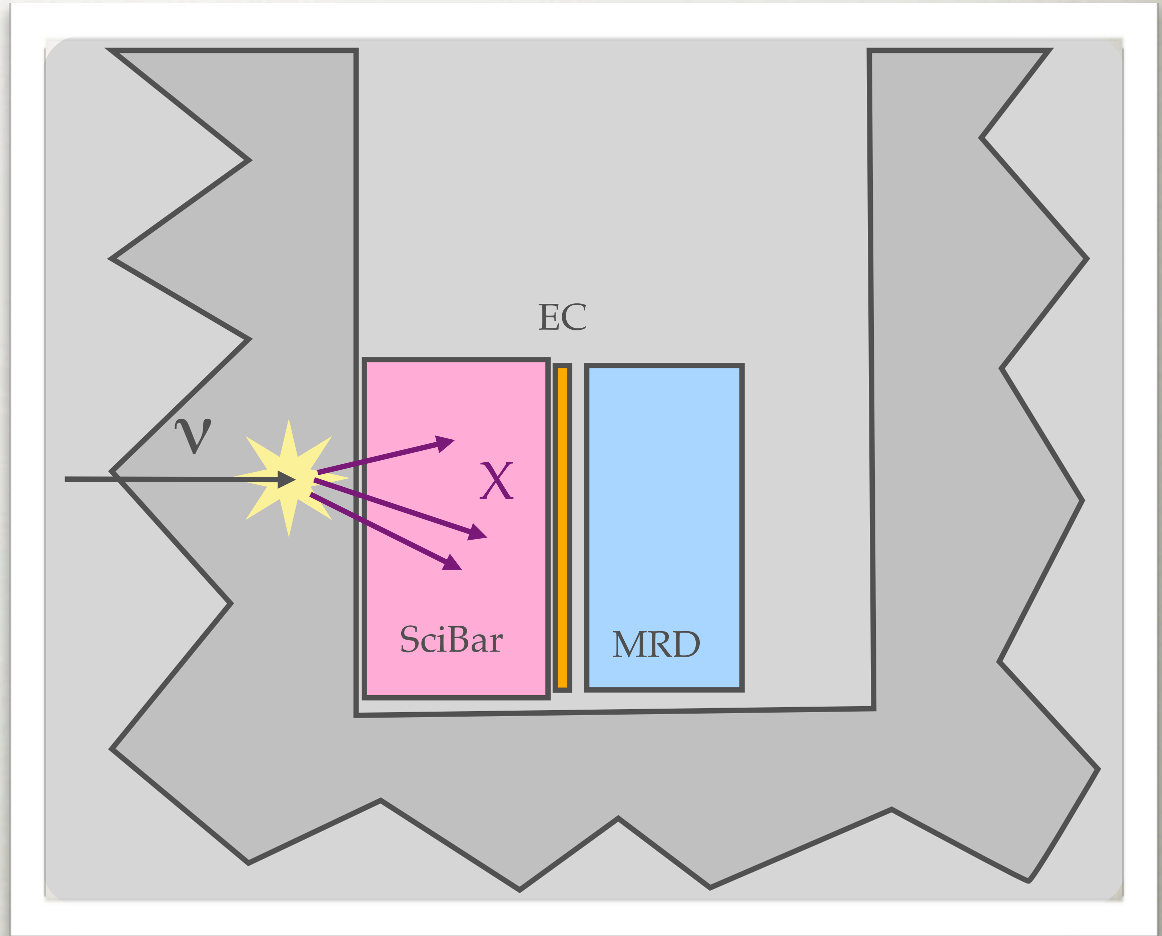
Number of Photons



- Need to reconstruct pion invariant mass
- Require at least two reconstructed photons
  - Rejects ~58% of signal events
    - These can't be reconstructed anyway
  - effective for dirt BG
- 973 signal events, 46% signal purity

Vertex position Cut

- Significant backgrounds from upstream of detector
- Require photon tracks to point to a common vertex within SciBar
- Removes significant fraction of “dirt” events
- 905 events, 49% signal purity



$$z_{vtx} = \frac{\frac{z_{top}}{\delta z_{top}^2} + \frac{z_{sid}}{\delta z_{sid}^2}}{\frac{1}{\delta z_{top}^2} + \frac{1}{\delta z_{sid}^2}}$$

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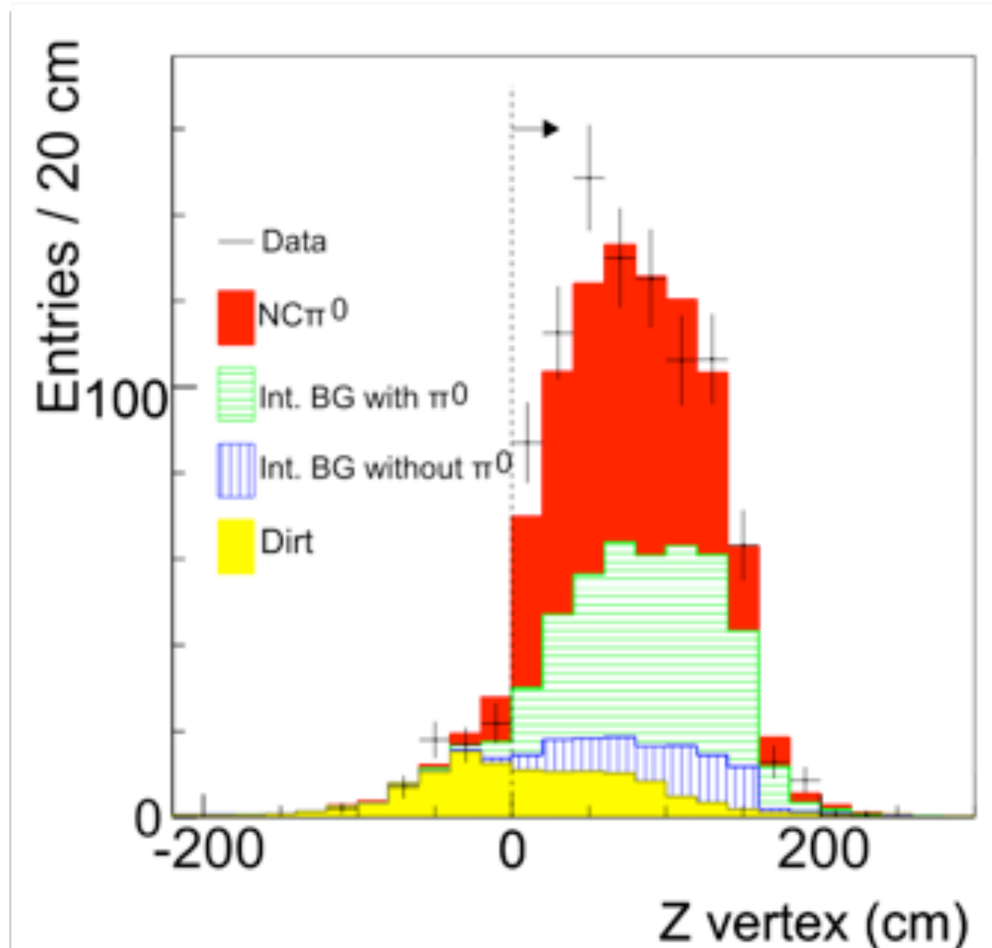
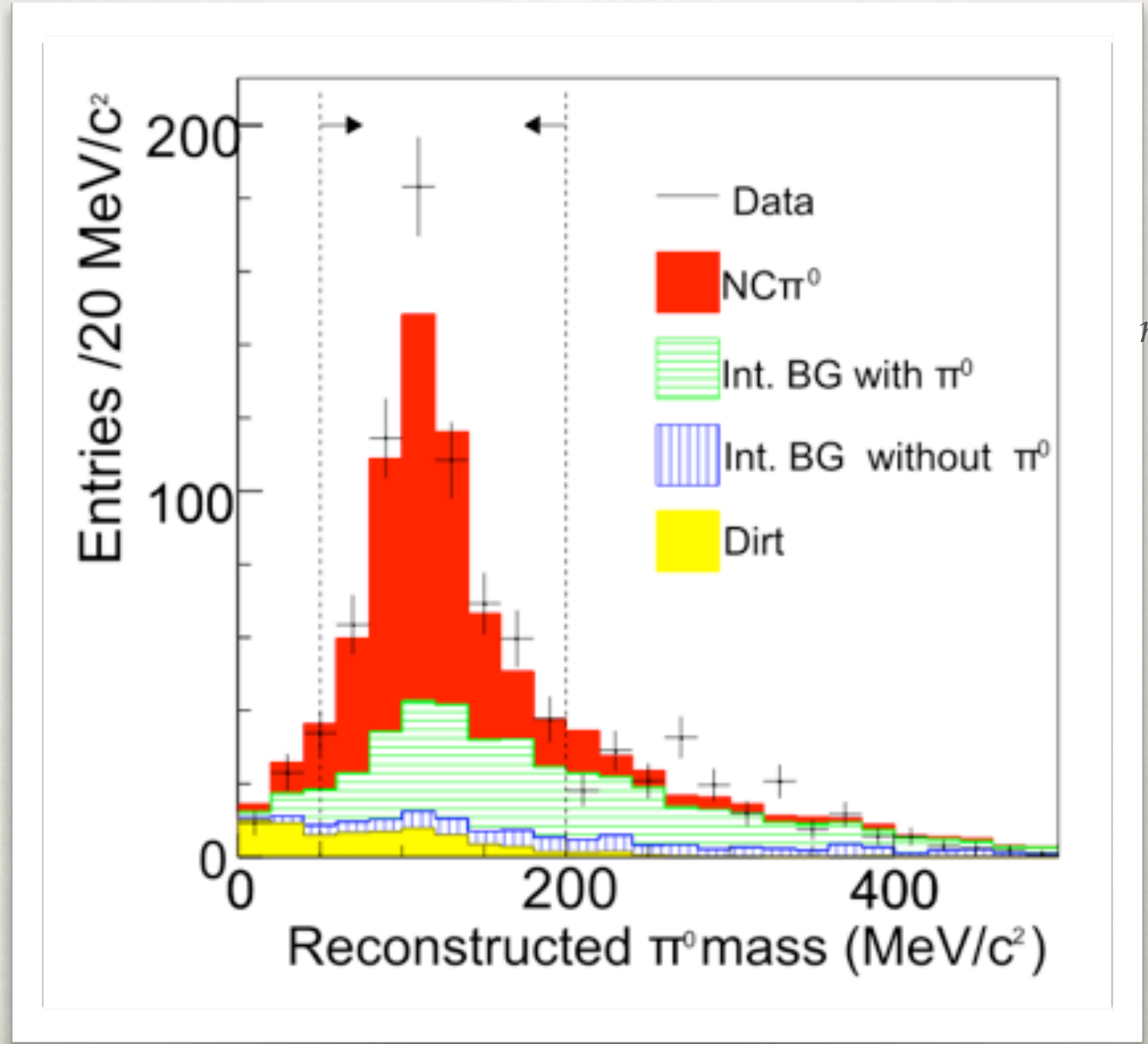


vertex resolution ~12cm

$$z_{vtx} = \frac{\frac{z_{top}}{\delta z_{top}^2} + \frac{z_{sid}}{\delta z_{sid}^2}}{\frac{1}{\delta z_{top}^2} + \frac{1}{\delta z_{sid}^2}}$$

π^0 MASS CUT



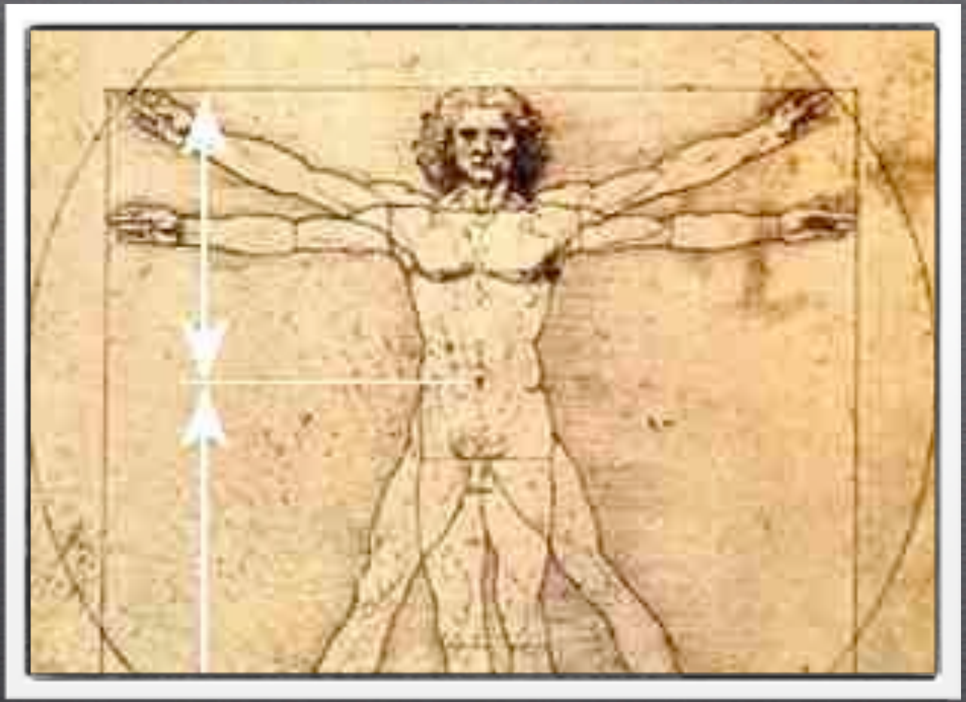
$m_{\pi 0}{}^{rec}$ slightly low due to energy leakage

$$m_{\gamma\gamma}^{rec} = \sqrt{2E_{\gamma 1}^{rec} E_{\gamma 2}^{rec}(1 - \cos\theta_{\gamma\gamma}^{rec})}$$

Event Selection Summary

Event selection	DATA	$NC\pi^0$ Efficiency	$NC\pi^0$ Purity
Pre-selection Cuts	11,926	27.3%	15%
Muon Track Rejection Cuts	5,609	19.8%	24%
Track Disconnection Cuts	3,614	18.9%	36%
Electron Catcher cut	2791	17.3%	42%
Number of Photon Tracks	973	6.5%	46%
π^0 Reconstructed π^0 Position Cut	905	6.2%	49%
Reconstructed π^0 mass	657	5.3%	61%

N.B.: SciBar is only four radiation lengths deep
Maximum efficiency (two photons conversions) is 30%

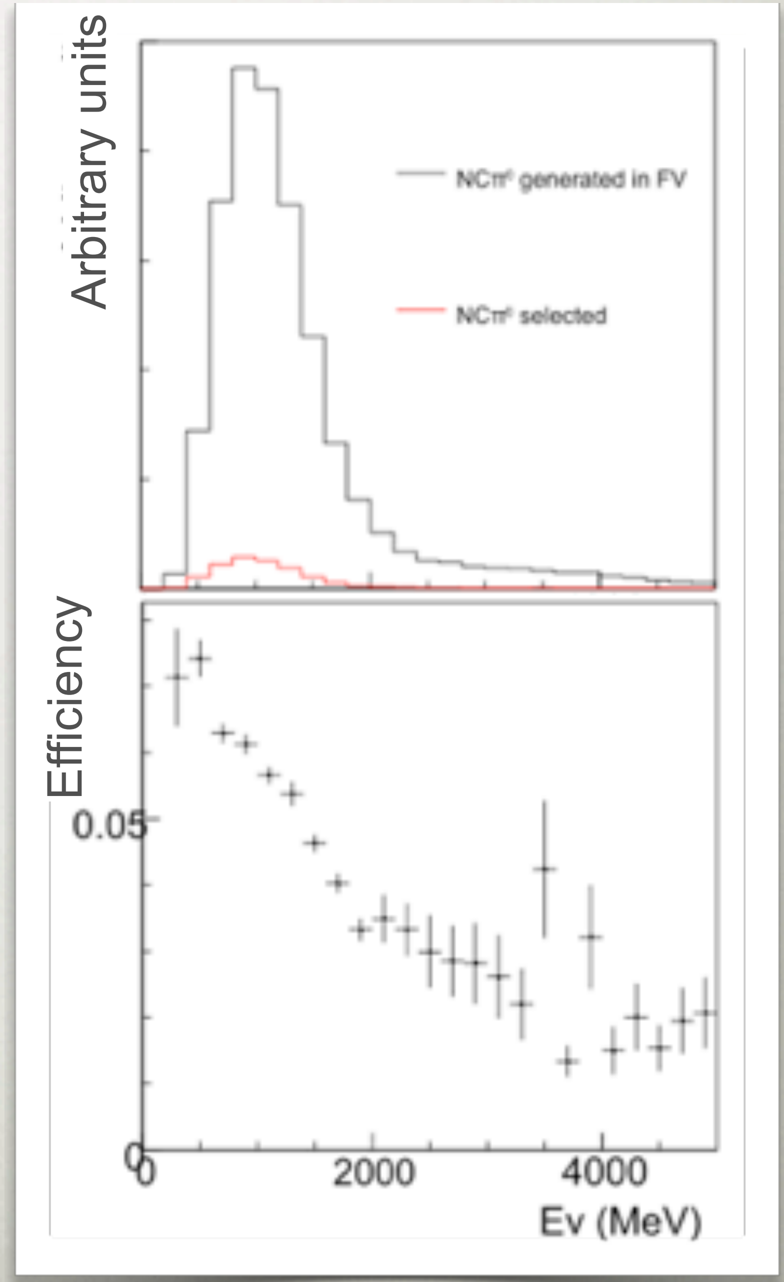


Cross Section Ratio

NCπ^0 Event Numbers

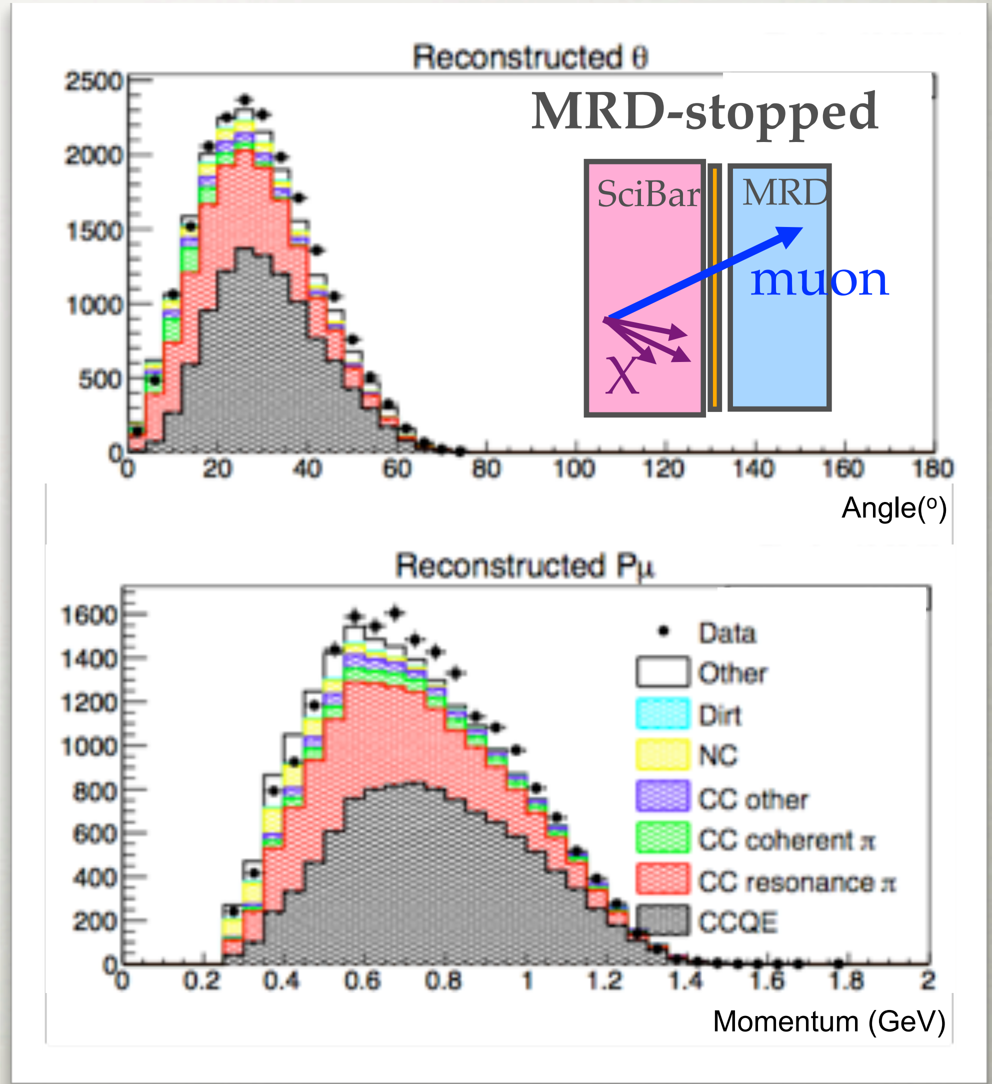
$$N(NC\pi^0) = \frac{N_{obs}^{NC\pi^0} - N_{BG}^{NC\pi^0}}{\epsilon_{NC\pi^0}}$$

- 657 observed events in data
- 240 expected BG events (from MC, relatively normalised)
- efficiency 5.3% (MC)
- Total = [7.8±0.5 (stat)]x10^3
- $\langle E_\nu \rangle$ = 1.1 GeV

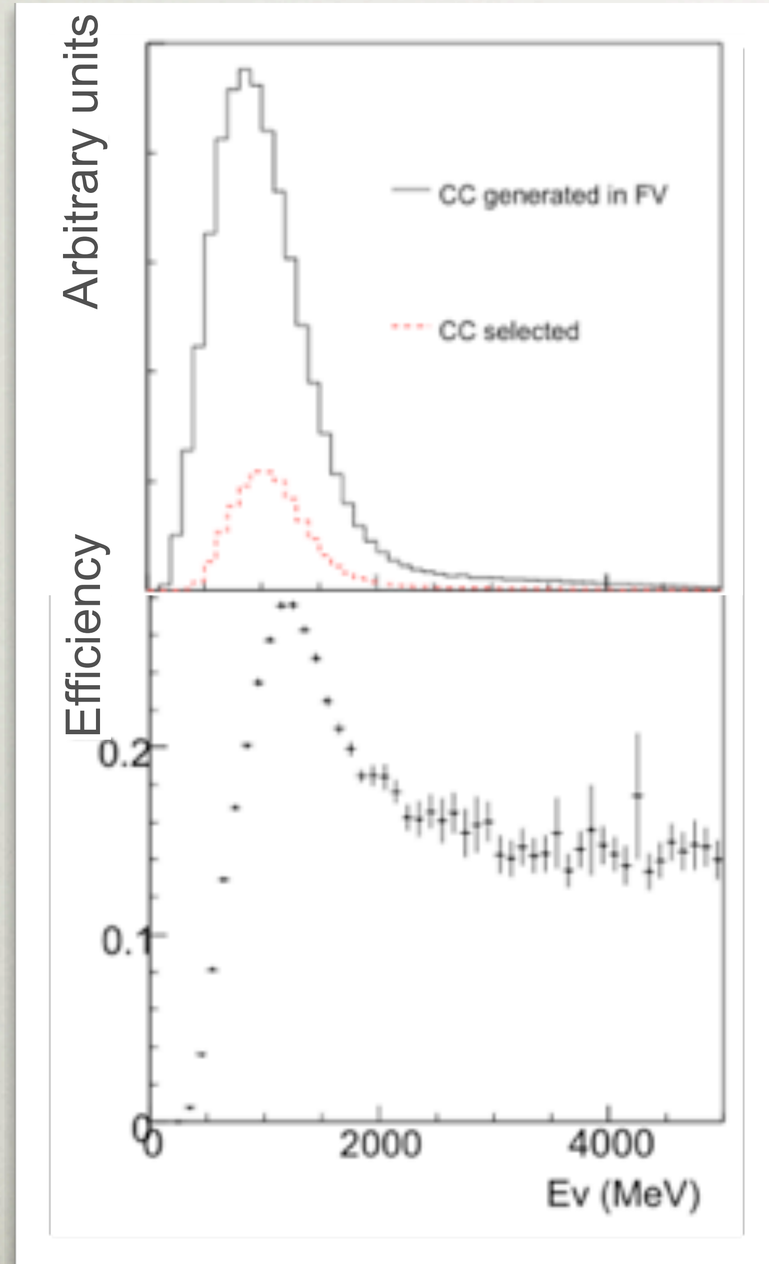


CC Sample Selection

- Use CC inclusive sample to normalise cross section ratio
- Choose MRD-stopped sample
  - Similar energy to NCπ^0 sample
  - Best characterised due to contained tracks in MRD
  - Lowest systematics



CC Sample



$$N(CC) = \frac{N_{obs}^{CC} - N_{BG}^{CC}}{\epsilon_{CC}}$$

- 21,702 events in total sample
- 2348 BG events
  - (from MC)
- efficiency 19%
  - (from MC)
- $[1.02 \pm 0.01(\text{stat})] \times 10^5$

NCπ^0/CC Ratio

$$\frac{\sigma(NC\pi^0)}{\sigma(CC)} = \frac{N(NC\pi^0)}{N(CC)}$$

$$\frac{\sigma(NC\pi^0)}{\sigma(CC)} = (7.7 \pm 0.5 \pm 0.5) \times 10^{-2}$$

MC expectation is $6.8\text{x}10^{-2}$
based on the Rein-Sehgal model (NEUT)

Measurement is 11% higher that expectation,
but only 1.3 σ higher

Systematic Uncertainties

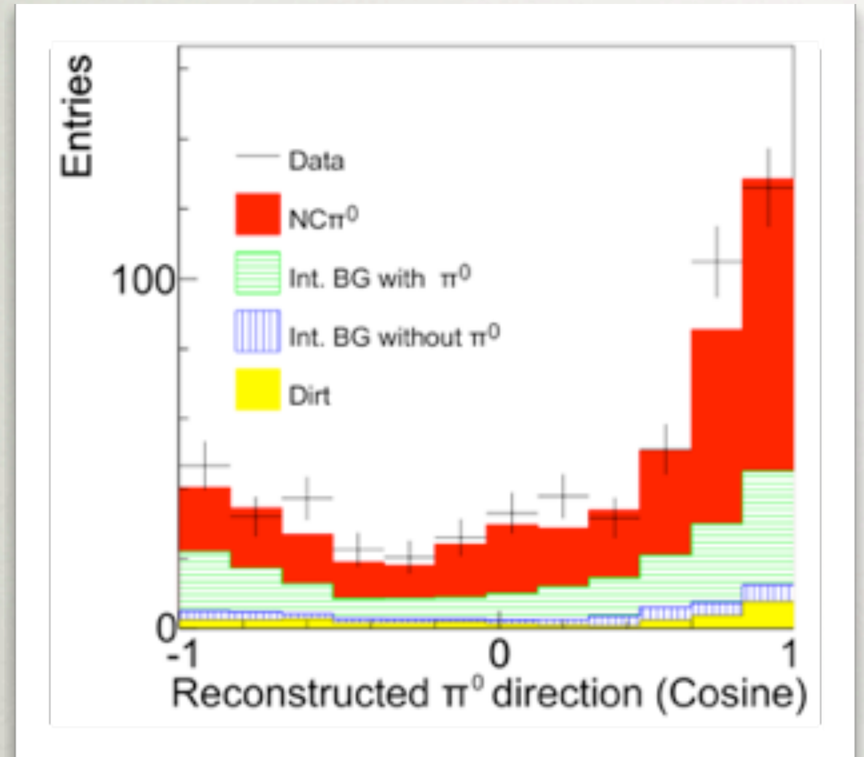
Source	error ($\times 10^{-2}$)	
Detector response	-0.39	0.38
ν interaction	-0.25	0.30
Dirt background	-0.10	0.10
ν beam	-0.11	0.22
Total	-0.48	0.54

- Use MC to estimate systematic uncertainties
  - Tested 14 sources
  - 4 categories
- Dominant systematic uncertainties:
  - MAPMT crosstalk and single PE hit threshold
  - CC1π cross section and pion absorption
- Cross-check: use NUANCE generator and repeat analysis
  - Result changes by only 3%

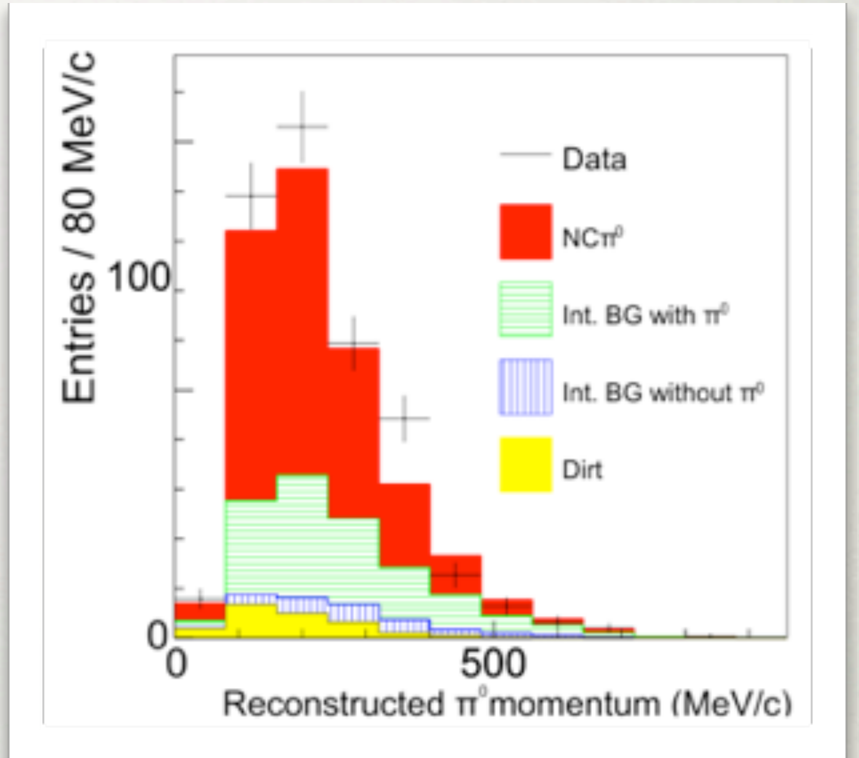
Reconstructed π^0 Kinematics

π^0 Reconstructed Variables

Kinematics determine misidentification rate in ν_e searches



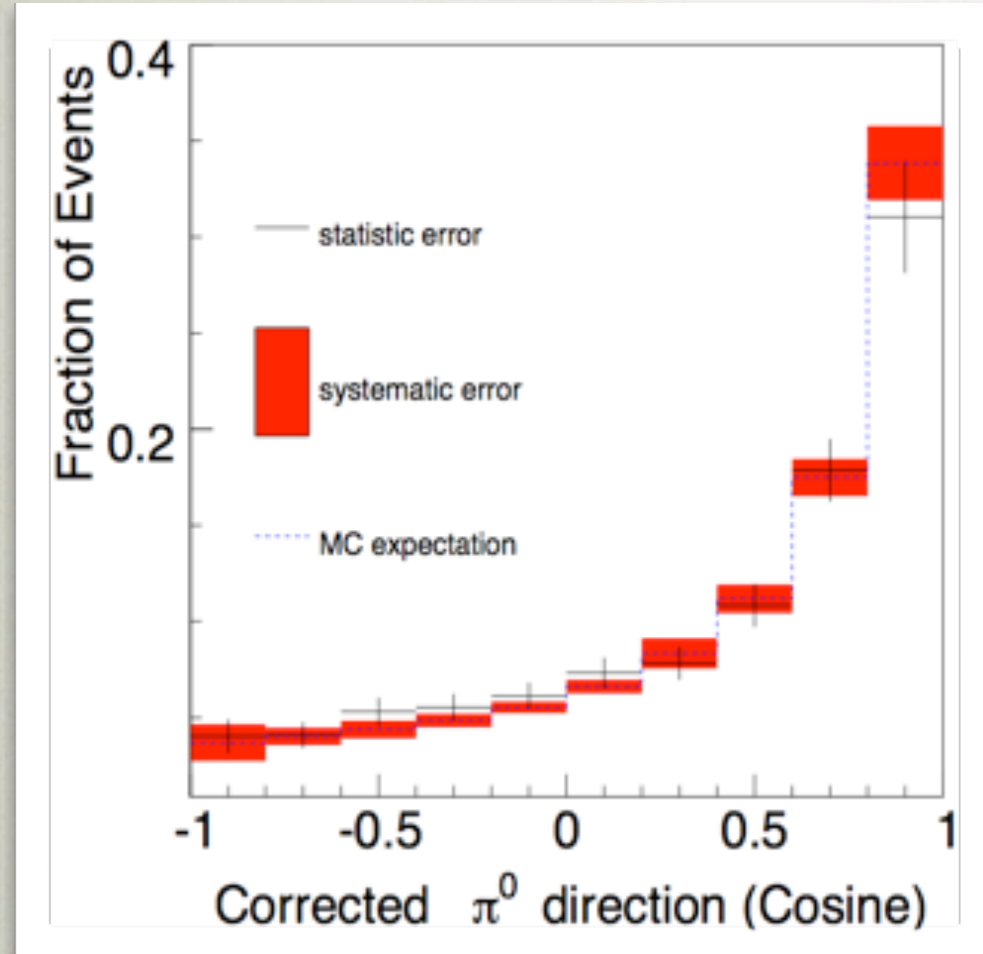
θ_{π° resolution ~ 6°

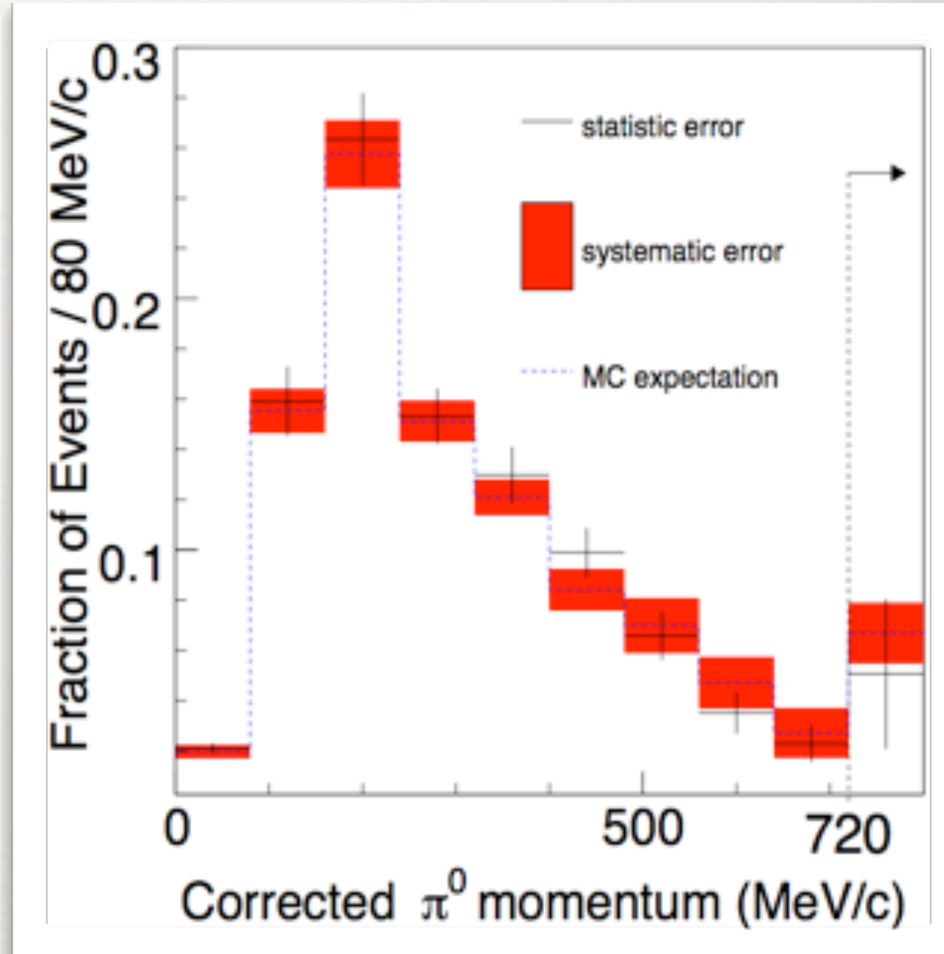


p_{π° resolution ~ 23%

Subtract backgrounds; use MC to remove resolution/ smearing effects (unfolding); apply efficiency corrections.

π^0 Kinematic Variables

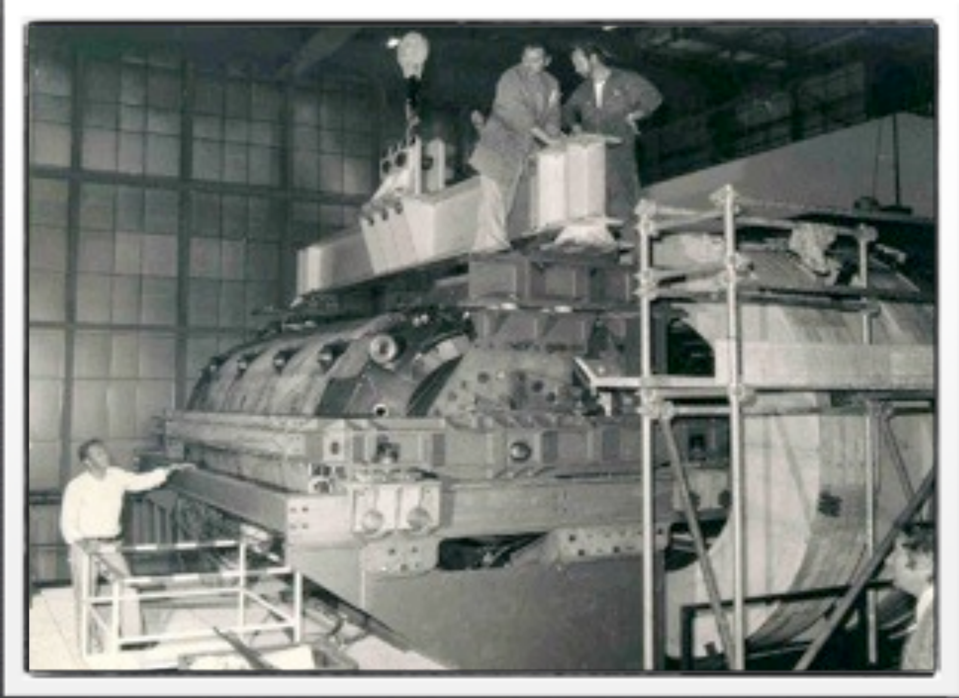




Final results

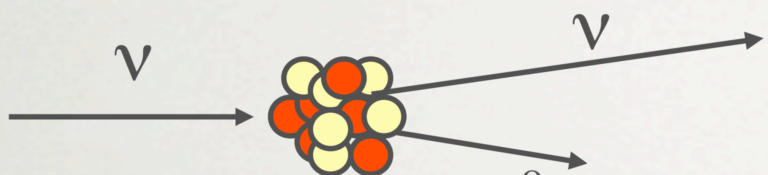
Systematics from same sources, estimated in same way, as ratio

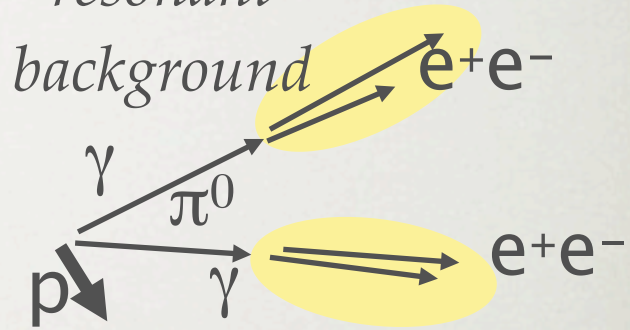
Already being used by theorists and model builders!



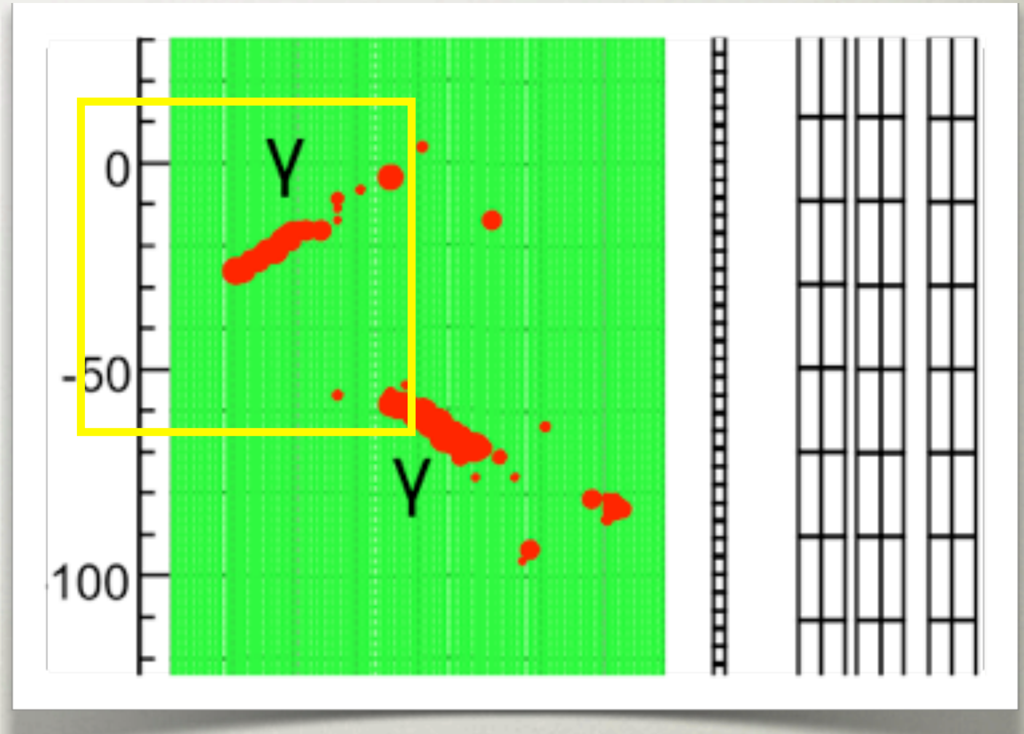
Coherent Production

Coherent Pion Production

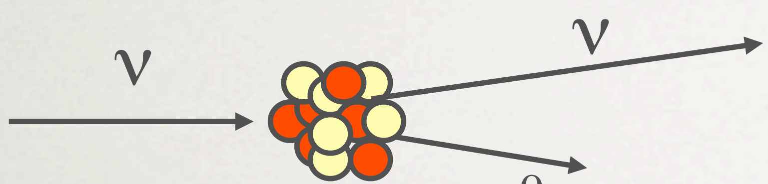




- Boson interacts with entire nucleus
  - No recoil nucleon
  - Search for recoil nucleon near vertex in each view
    - *Vertex activity:* highest single scintillator ±40 cm of vertex (not associated with tracks)
  - Split into 2 samples
    - Coherent enhanced and resonant enhanced



Coherent Pion Production



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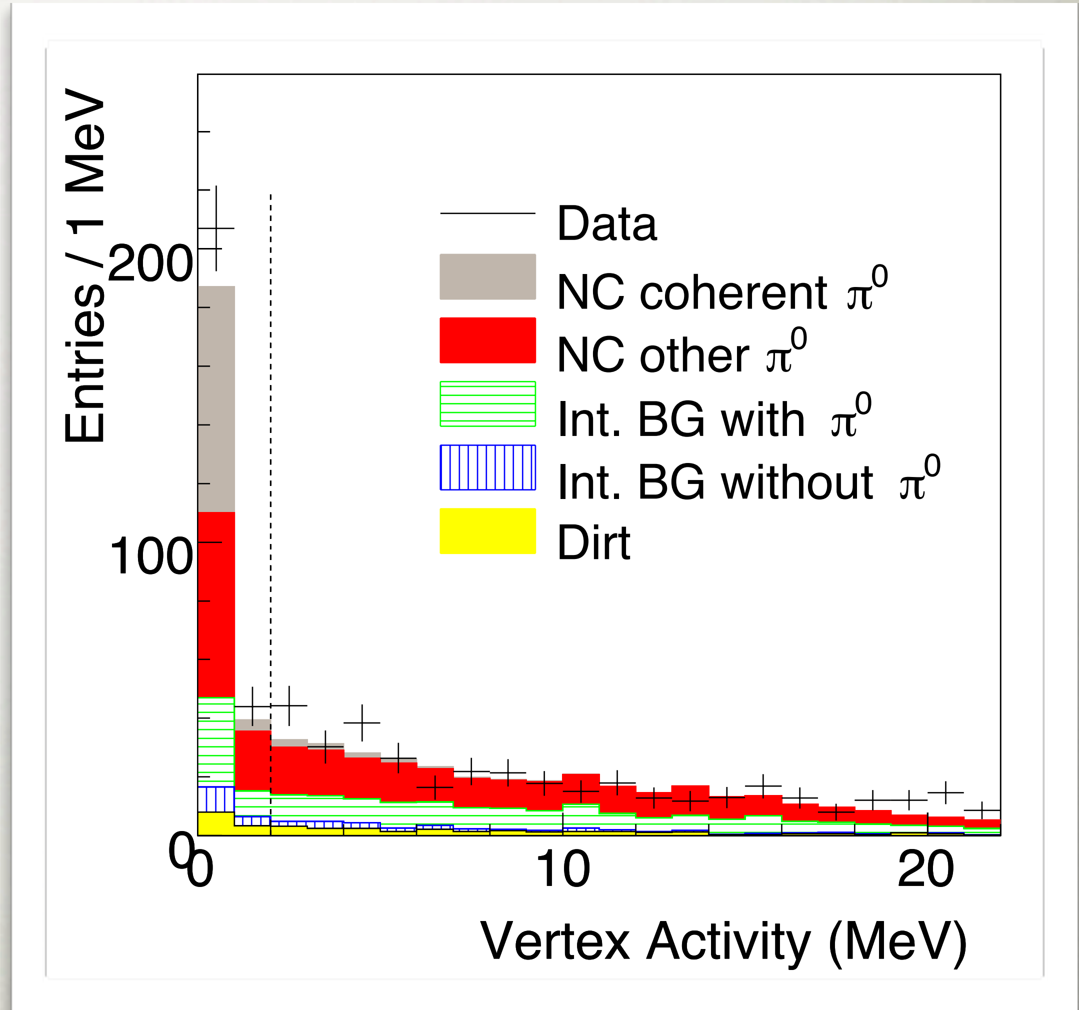
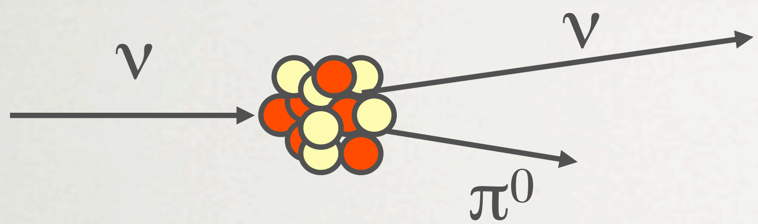
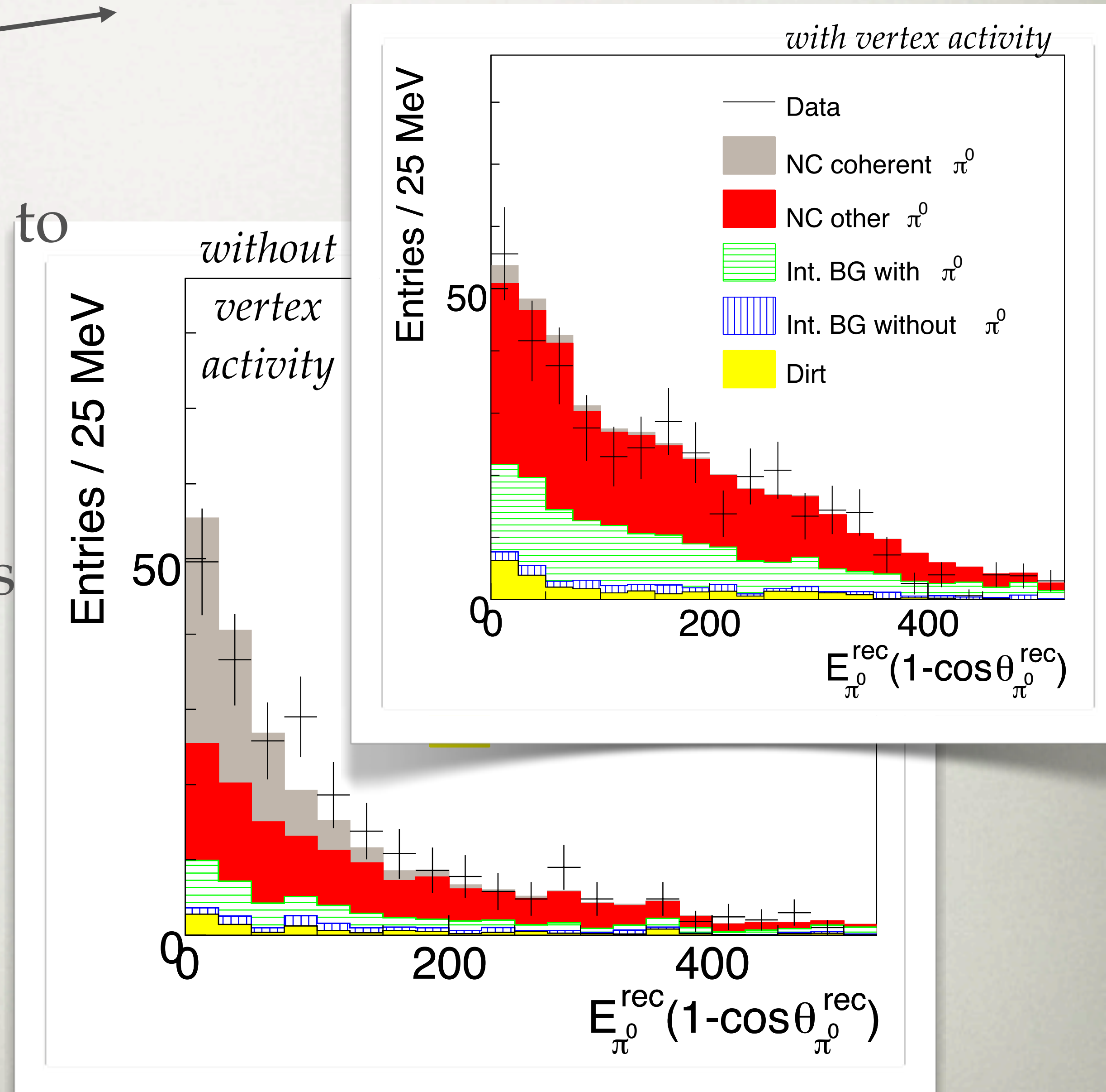


Coherent Pion Production



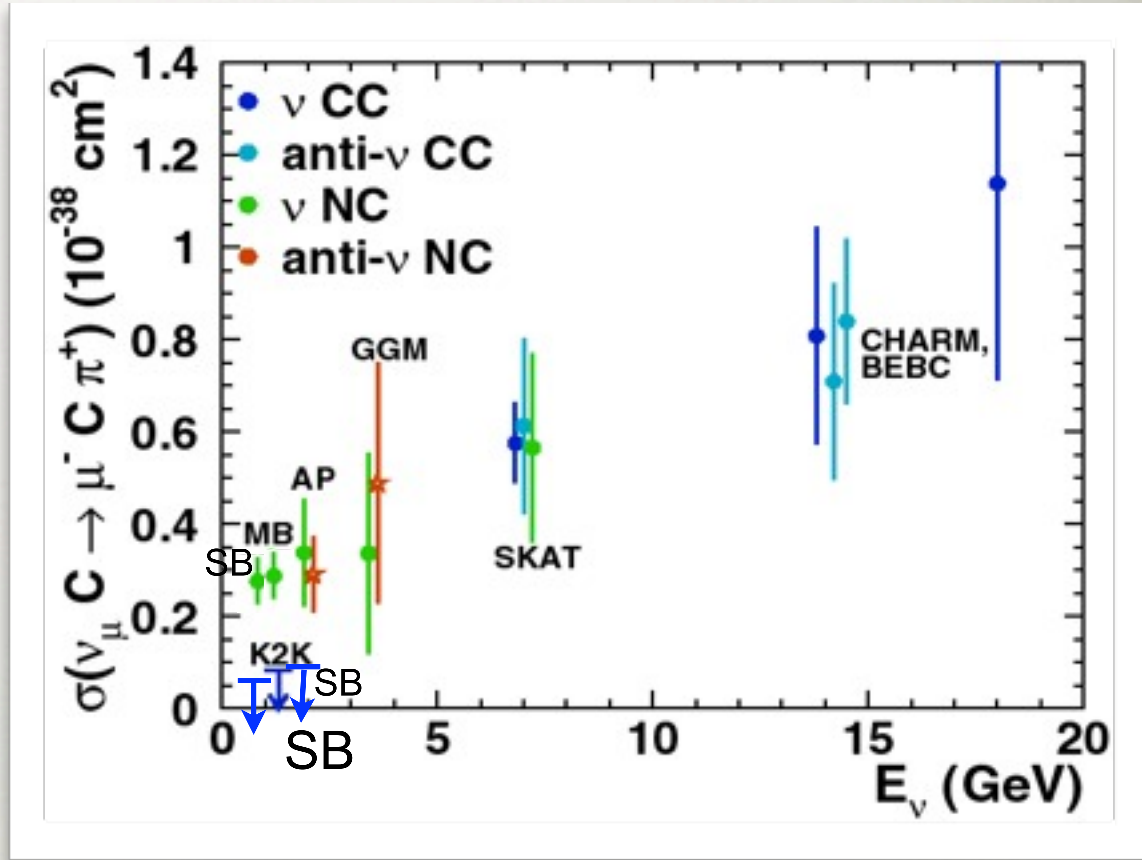
- Low momentum transfer to nucleus
  - ➡ Hard to measure!
- Fit E(1-cosθ) distributions
- Split MC into three templates:
  - NC*coh*π^0
  - NC*other*π^0
  - BG



Coherent Fraction

$$\frac{\sigma(NCcoh\pi^0)}{\sigma(CC)} = (1.17 \pm 0.23) \times 10^{-2}$$

- $<E_\nu>$ 0.8 GeV
- MC expectation is 1.21×10^{-2}



- Rein-Sehgal model predicts CC/NC ratio=2

$$\frac{\sigma(CCcoh\pi^+)}{\sigma(NCcoh\pi^0)} = (0.14^{+0.30}_{-0.28}) \times 10^{-2}$$

Coherent Fraction

$$\frac{\sigma(NCcoh\pi^0)}{\sigma(CC)} = (1.17 \pm 0.23) \times 10^{-2}$$

- $\langle E_\nu \rangle$ 0.8 GeV
- MC expectation is 1.21×10^{-2}
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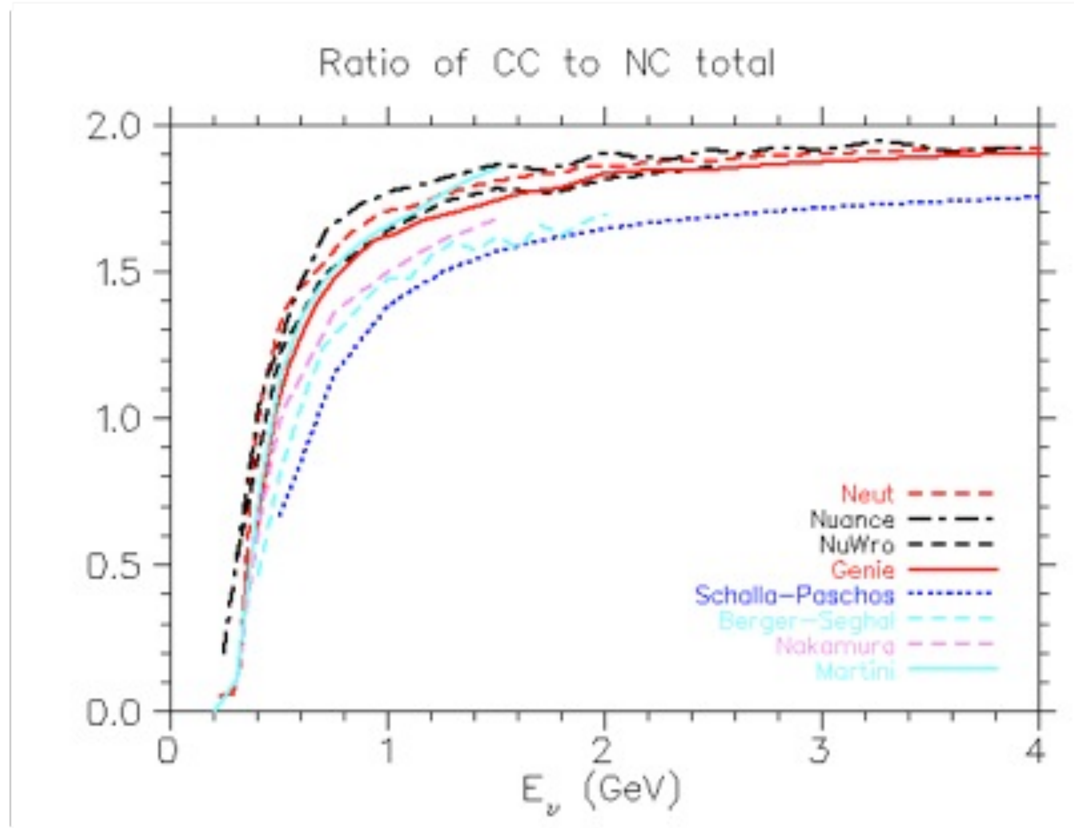


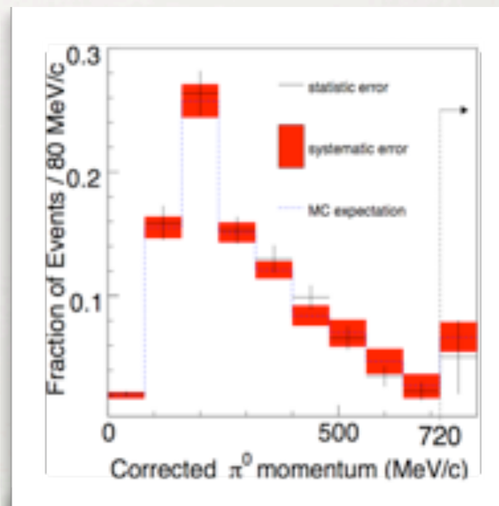
S. Boyd, et al., AIP Conf. Proc. 1189, 60 (2009)

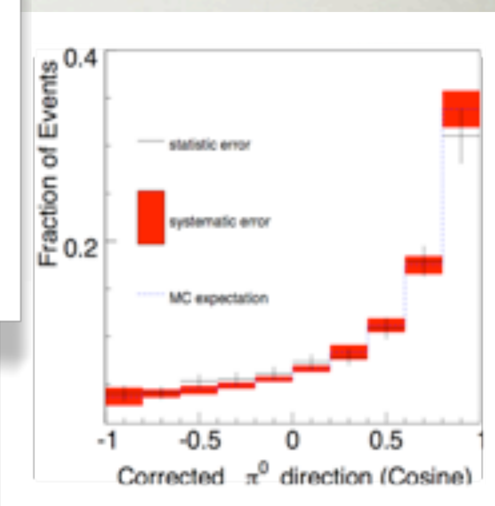
$$\frac{\sigma(CCcoh\pi^+)}{\sigma(NCcoh\pi^0)} = (0.14^{+0.30}_{-0.28}) \times 10^{-2}$$

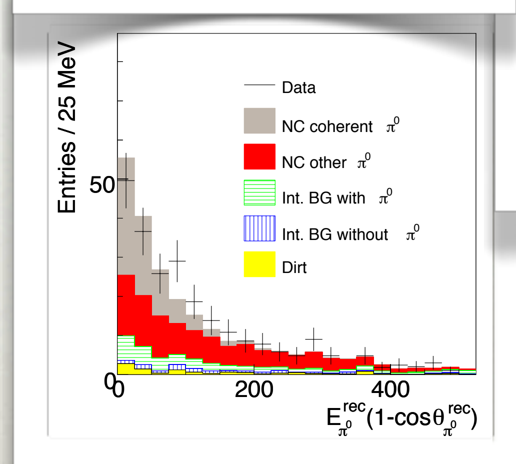
Analysis Summary

$$\frac{\sigma(NC\pi^0)}{\sigma(CC)} = (7.7 \pm 0.5 \pm 0.5) \times 10^{-2}$$

- Measured NC π^0/CC cross section ratio
  - Goal 10%
    Measured 9%
- Measured π^0 kinematics
- Extracted coherent π^0 production fraction
  - CC/NC ratio disagrees with models!







Many more analyses!

- Oscillation searches with MiniBooNE
  - Flux studies (absolute cross sections)
- Cross Sections
  - CCQE cross sections
    - Two separate data samples
  - Incoherent (resonant) $CC1\pi^+$
  - Neutral current elastic
    - Δs
  - $CC1\pi^0$ cross section
  - A-dependence
  - Modern nuclear models
  - Antineutrino analyses!
- "Exotic" analyses
  - Short range nuclear correlations

11 PhD students

Expect 20+ publications total

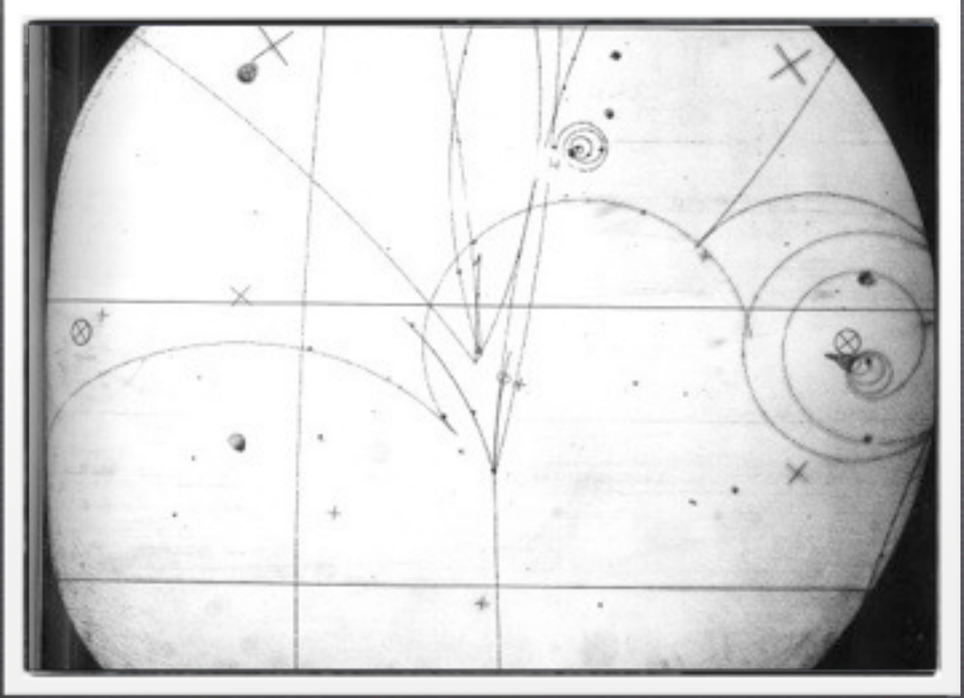
Many more analyses!

- Oscillation searches with MiniBooNE
  - Flux studies (absolute cross sections)
- Cross Sections
  - CCQE cross sections
    - Two separate data samples
  - Incoherent (resonant) C
  - Neutral current elastic
    - Δs
  - CC1π^0 cross section
  - A-dependence
  - Modern nuclear model
  - Antineutrino analyses!
- "Exotic" analyses
  - Short range nuclear correlations

Conclusion

- To search for CP violation neutrino physics must enter a precision era
    - Including ν-nucleus scattering!
- T2K beginning this year
    - θ_{13} next important step in CP violation search
- SciBooNE ran successfully at Fermilab in 2007-8
    - Publishing high quality data needed by future experiments

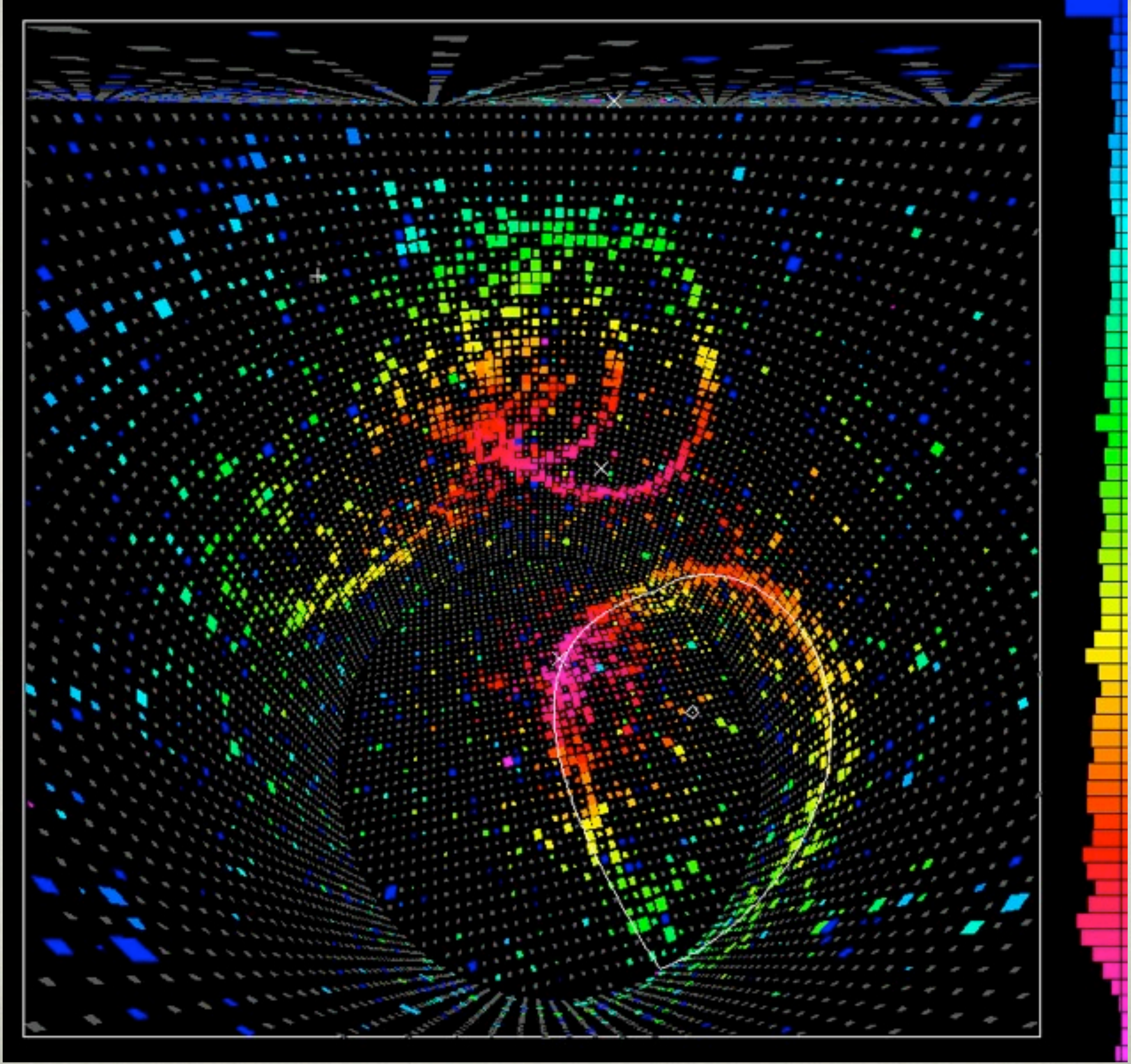
There's never been a better time for neutrino physics!



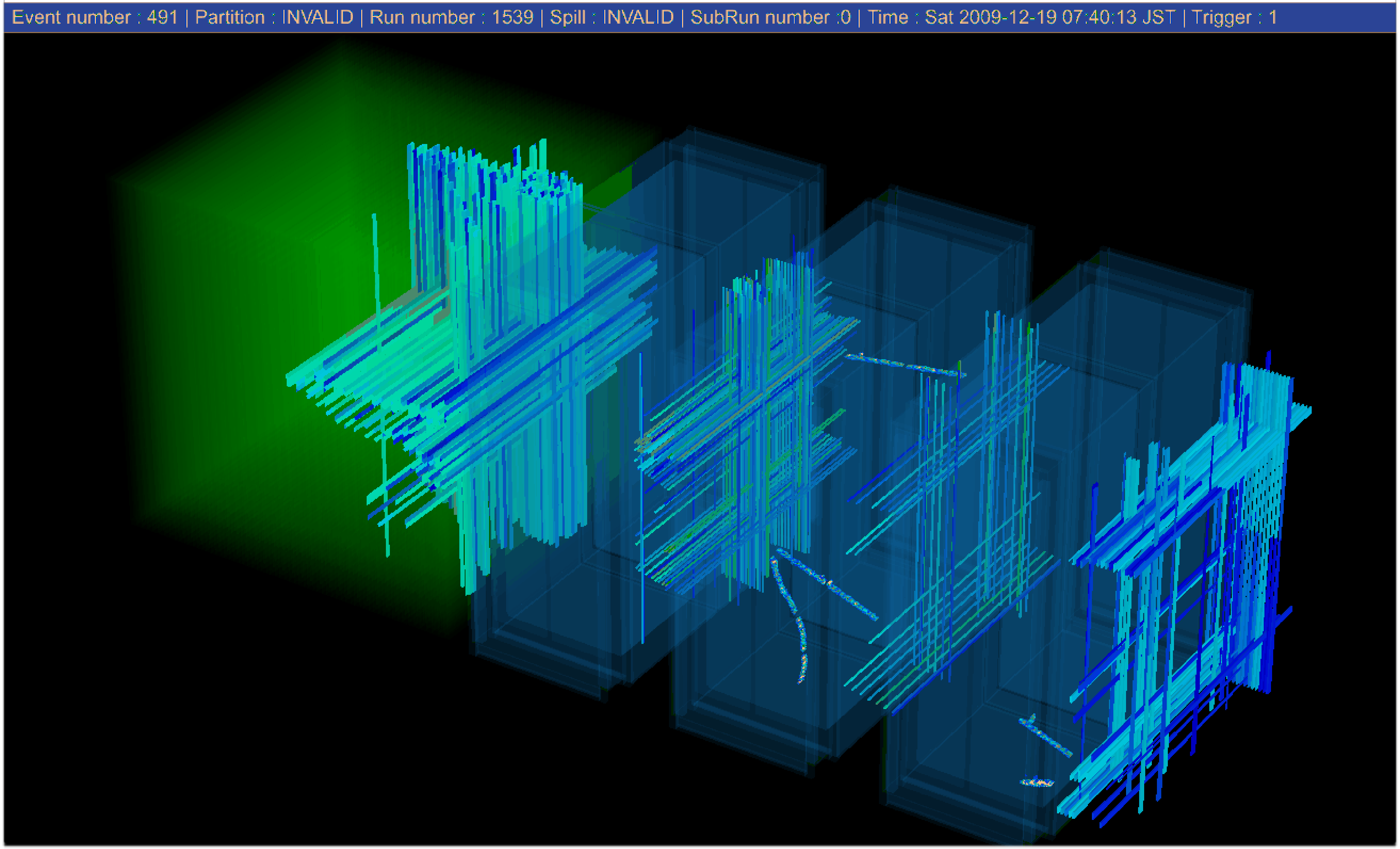
Thank you!

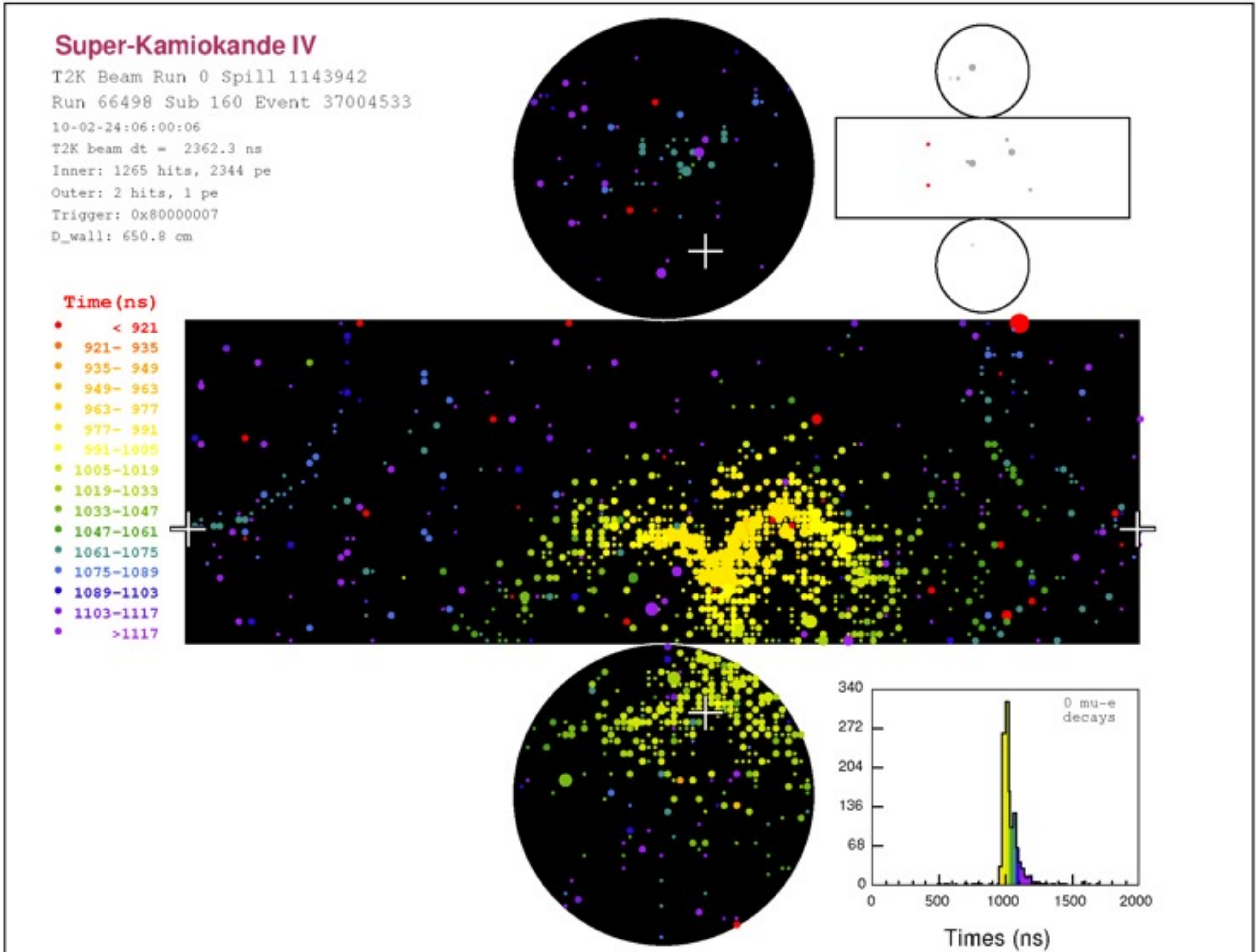
SciBooNE

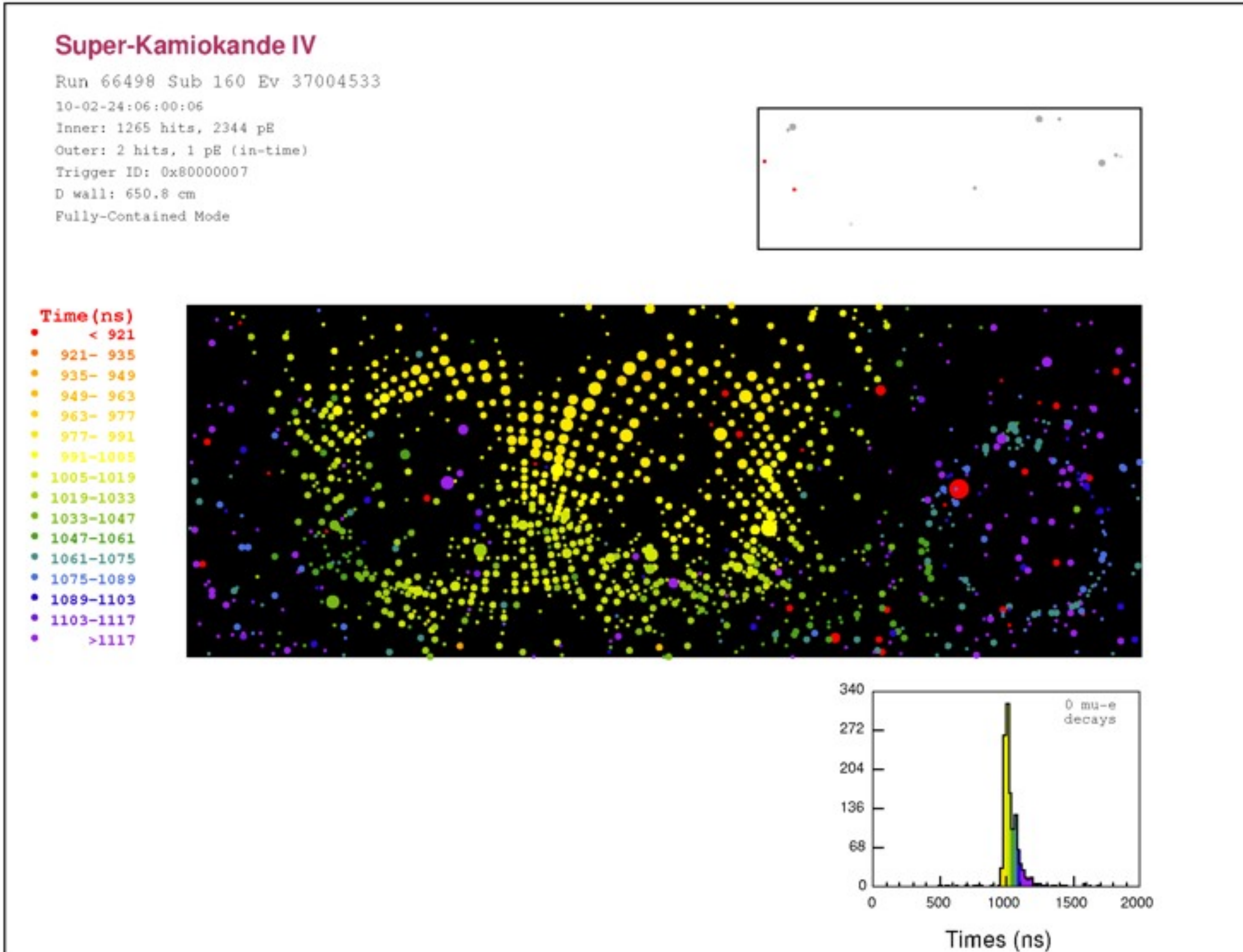
Backup slides



First neutrino interaction in ND280 off axis detector December 19, 2009




Super-Kamiokande IV
T2K Beam Run 0 Spill 1143942
Run 66498 Sub 160 Event 37004533
10-02-24:06:00:06
T2K beam dt = 2362.3 ns
Inner: 1265 hits, 2344 pe
Outer: 2 hits, 1 pe
Trigger: 0x80000007
D_wall: 650.8 cm
Time (ns)
< 921
921- 935
935- 949
949- 963
963- 977
977- 991
991-1005
1005-1019
1019-1033
1033-1047
1047-1061
1061-1075
1075-1089
1089-1103
1103-1117
>1117
0 mu-e decays
340
272
204
136
68
0
0
500
1000
1500
2000
Times (ns)

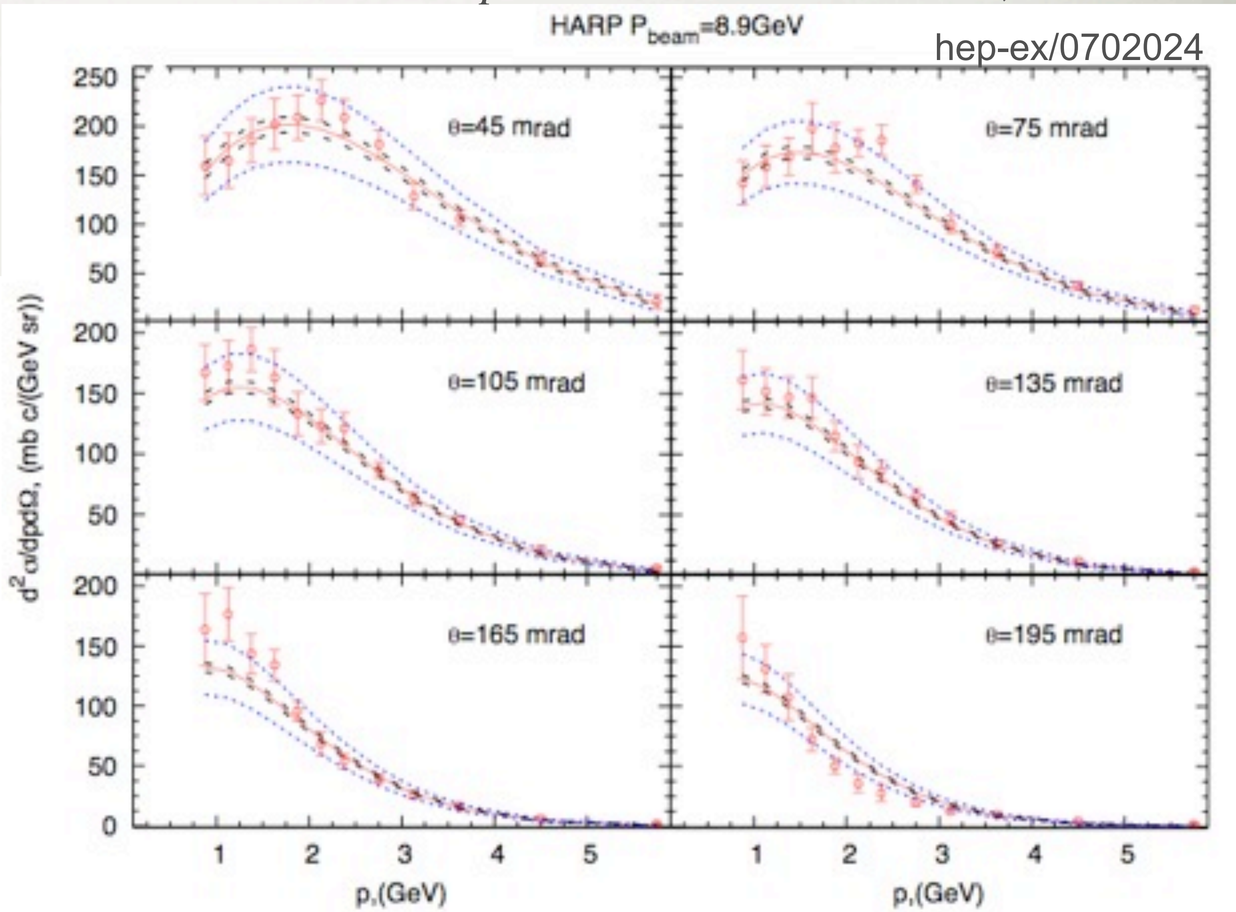


Super-Kamiokande IV
Run 66498 Sub 160 Ev 37004533
10-02-24:06:00:06
Inner: 1265 hits, 2344 pE
Outer: 2 hits, 1 pE (in-time)
Trigger ID: 0x80000007
D wall: 650.8 cm
Fully-Contained Mode
Time(ns)
< 921
921- 935
935- 949
949- 963
963- 977
977- 991
991-1005
1005-1019
1019-1033
1033-1047
1047-1061
1061-1075
1075-1089
1089-1103
1103-1117
>1117
340
272
204
136
68
0
0
500
1000
1500
2000
0 mu-e decays
Times (ns)

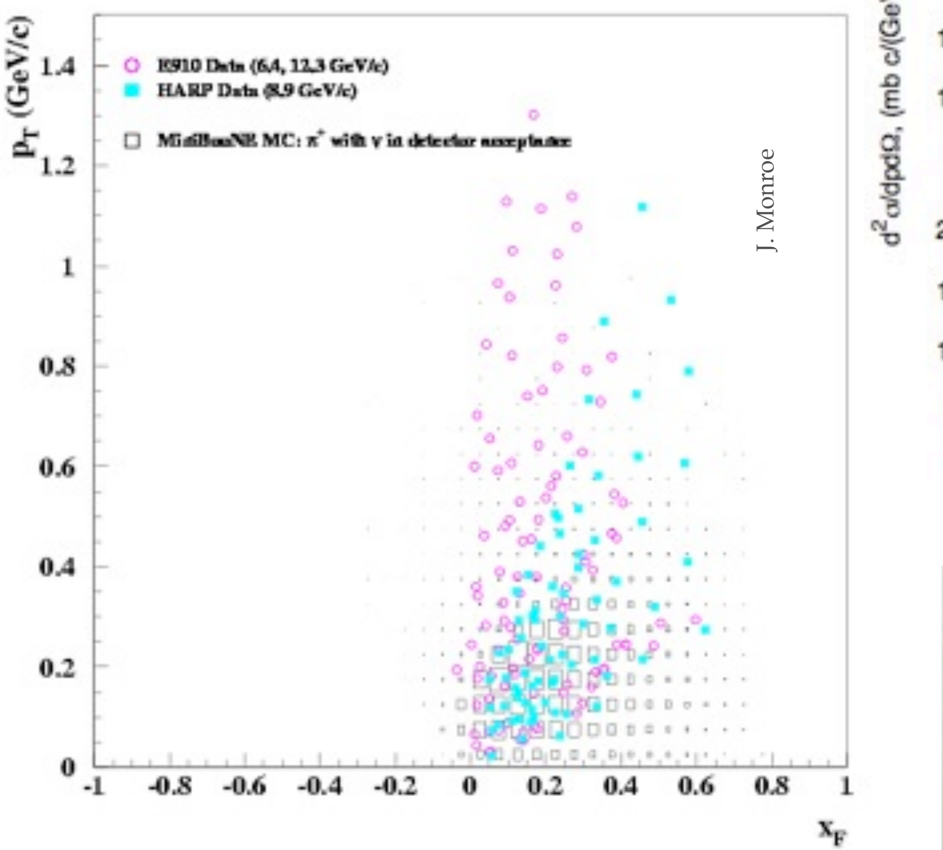
Booster Beam: Modeling Meson Production

***Prediction** from a fit to p Be → π^+ X production data form HARP experiment (p_p = 6-12 GeV/c, θ_p = 0 - 330 mrad.)*

Fit (shown at right) uses Sanford-Wang parametrisation



HARP has excellent phase space coverage for MiniBooNE



π^- similarly parametrised

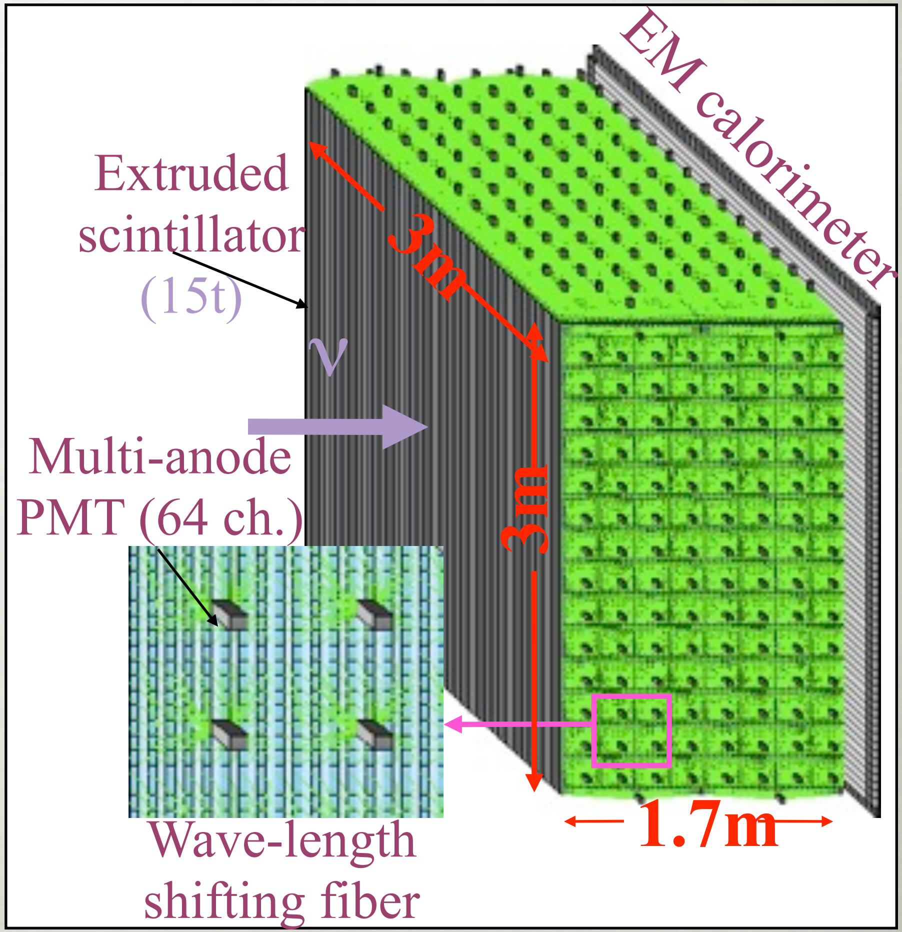
Kaons flux predictions use a Feynman Scaling parametrisation (no HARP data)

*PRD **79** 072002 (2009)*

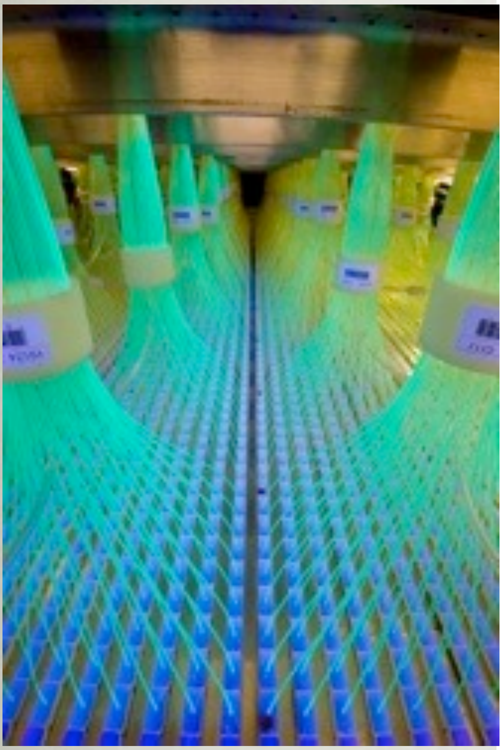
SciBar detector

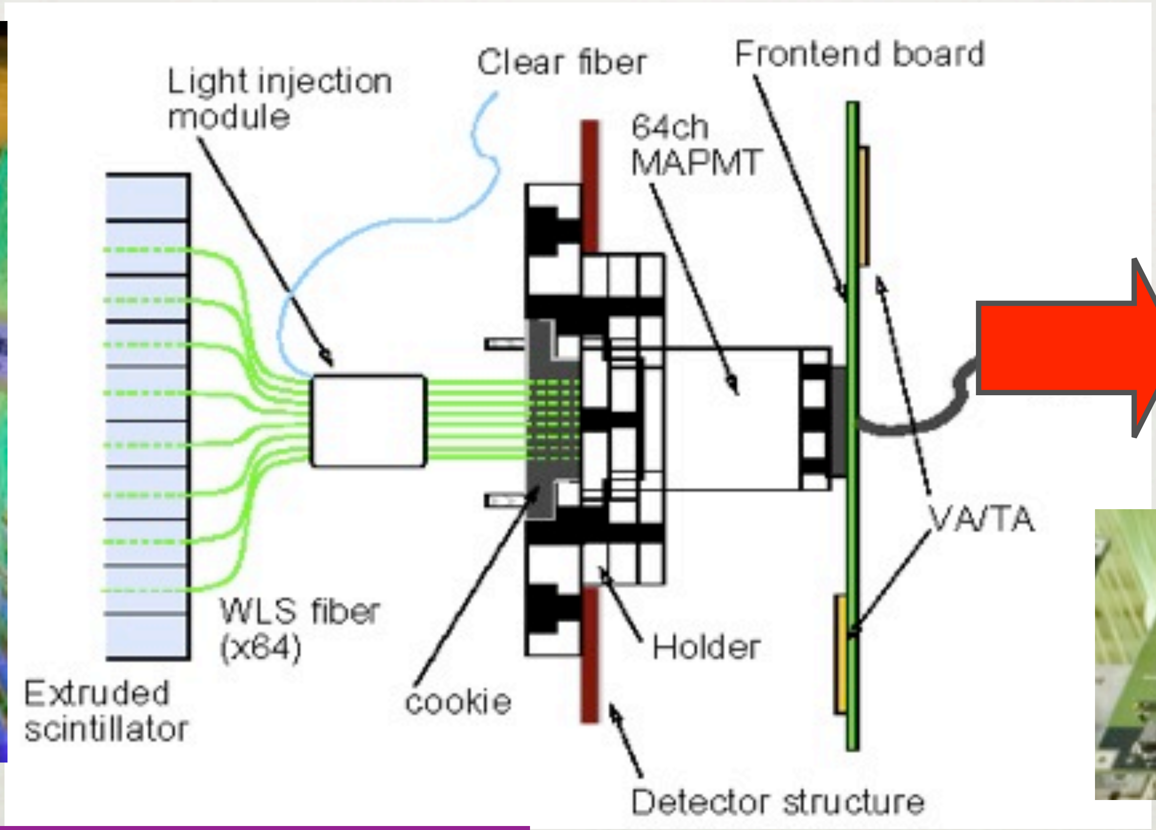
- Extruded scintillators with WLS fiber readout
- Scintillators are the neutrino target
- 3m x 3m x 1.7m (Total: 15 tons)
- 14,336 channels
- Detect short tracks (>8cm)
- Distinguish a proton from a pion by dE/dx

→Clear identification of ν interaction process



SciBar readout





64 charge info.
2 timing info.

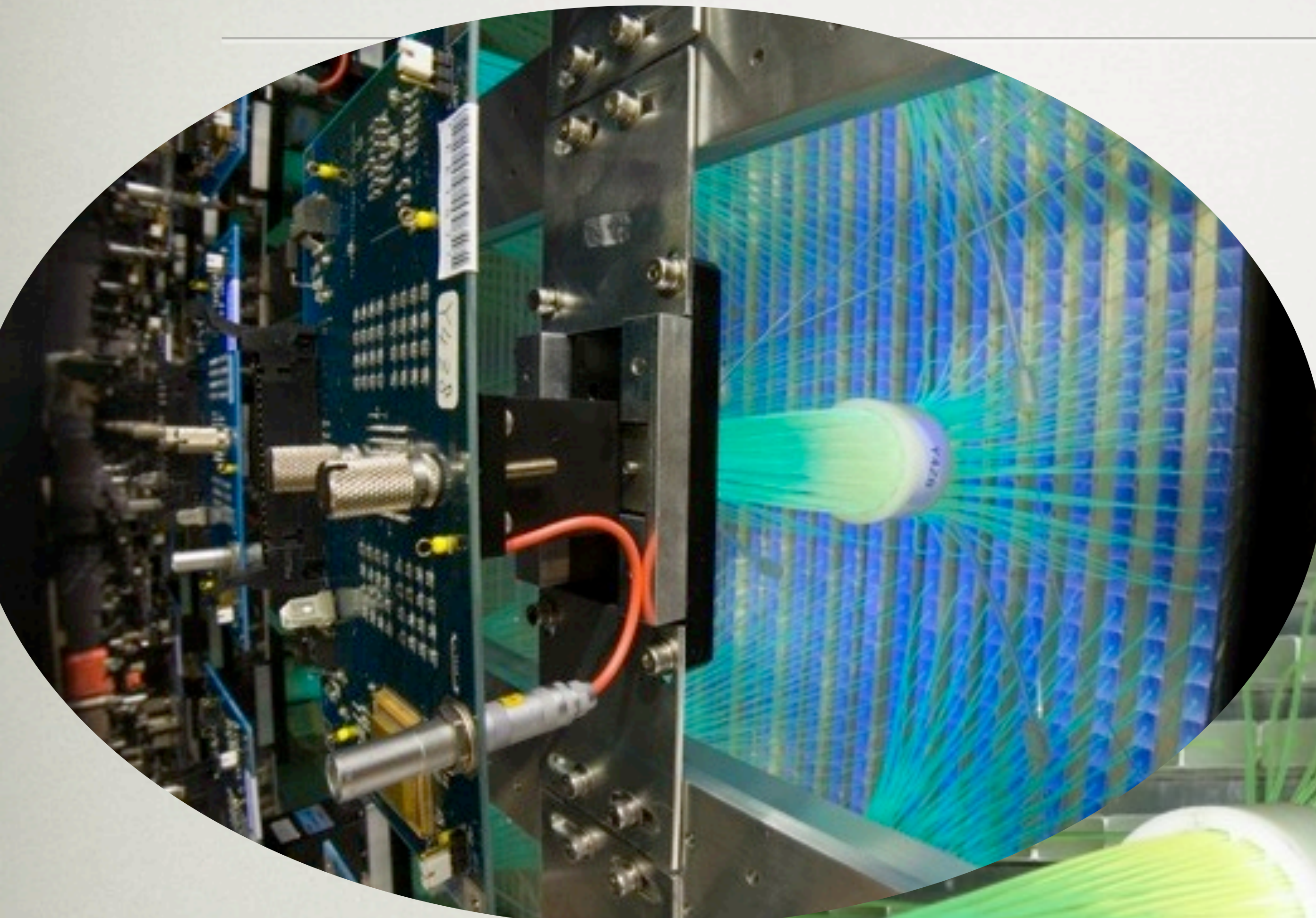
Extruded Scintillator ($1.3 \times 2.5 \times 300 cm^3$)
- made by FNAL (same as MINOS)

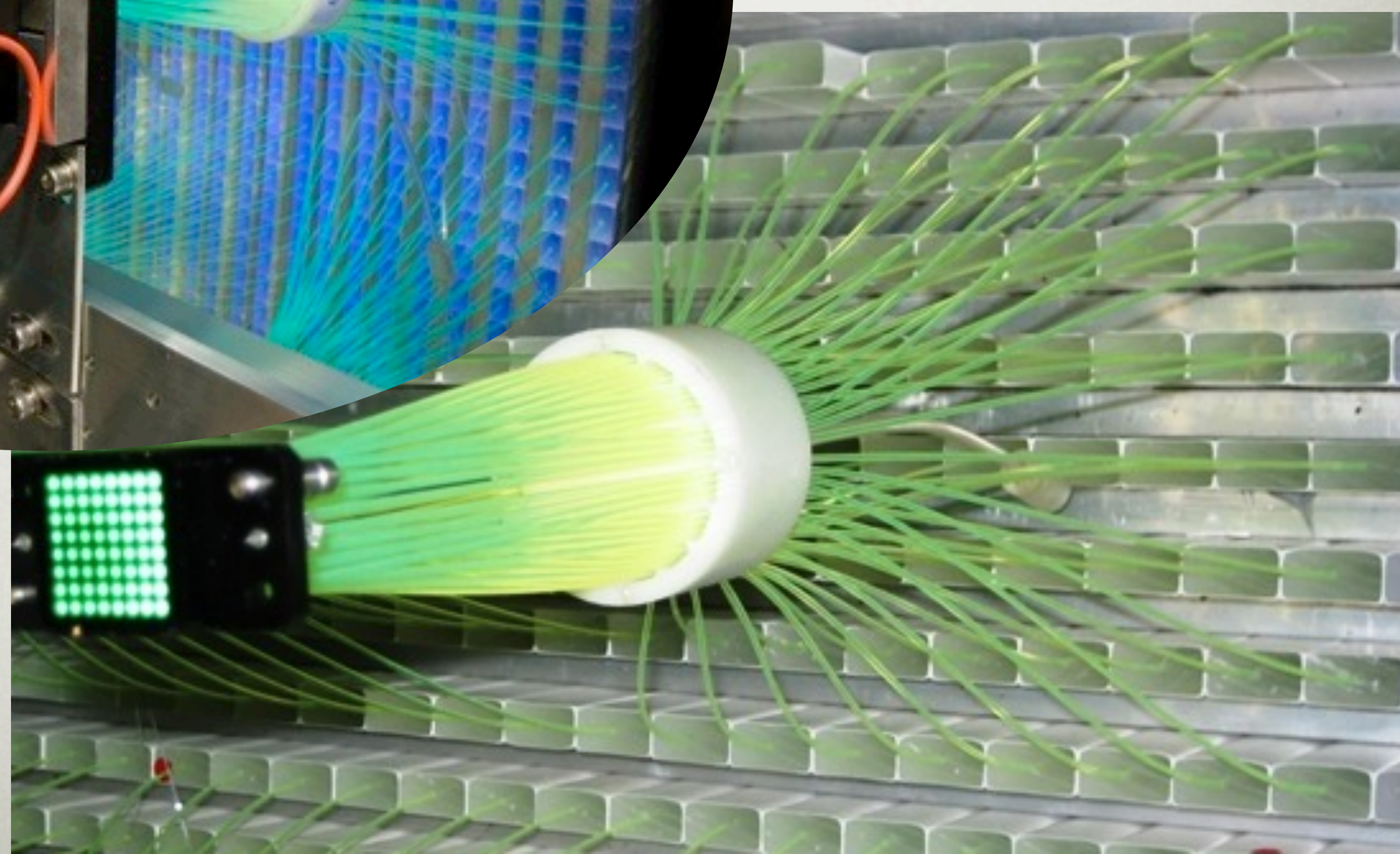
Wave length shifting fiber (1.5mmΦ)
- Long attenuation length (~350cm)
→ Light Yield : ~20p.e./1.3cm/MIP

64-channel Multi-Anode PMT
- $2x2mm^2$ pixel (3% cross talk@1.5mmΦ)
- Gain Uniformity (20% RMS)
- Good linearity (~200p.e. @6×10^5)

Readout electronics with VA/TA
- ADC for all 14,336 channels
- TDC for 448 sets (32 channels-OR)

SciBar Photos

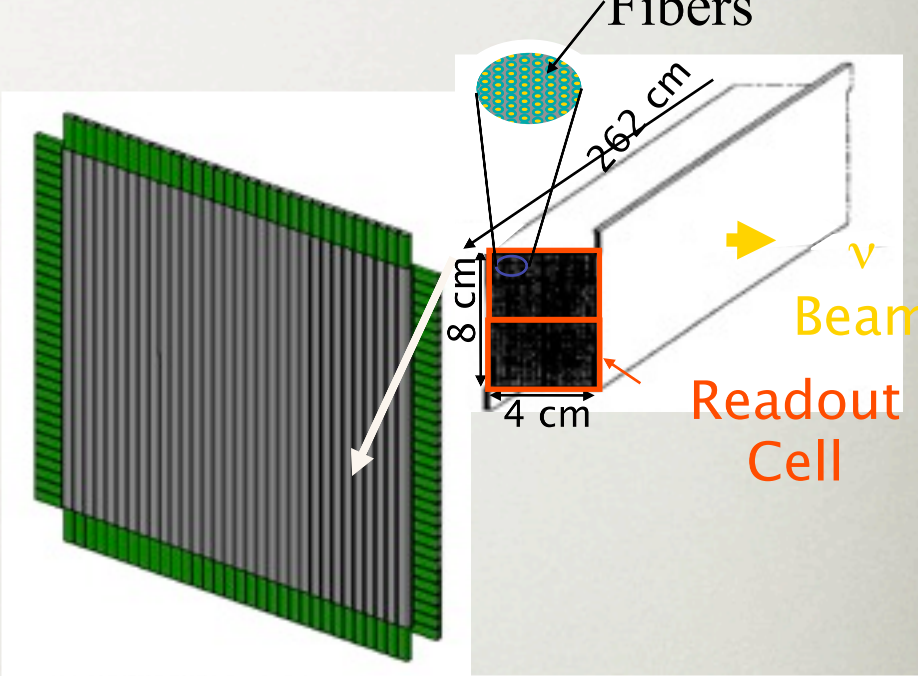


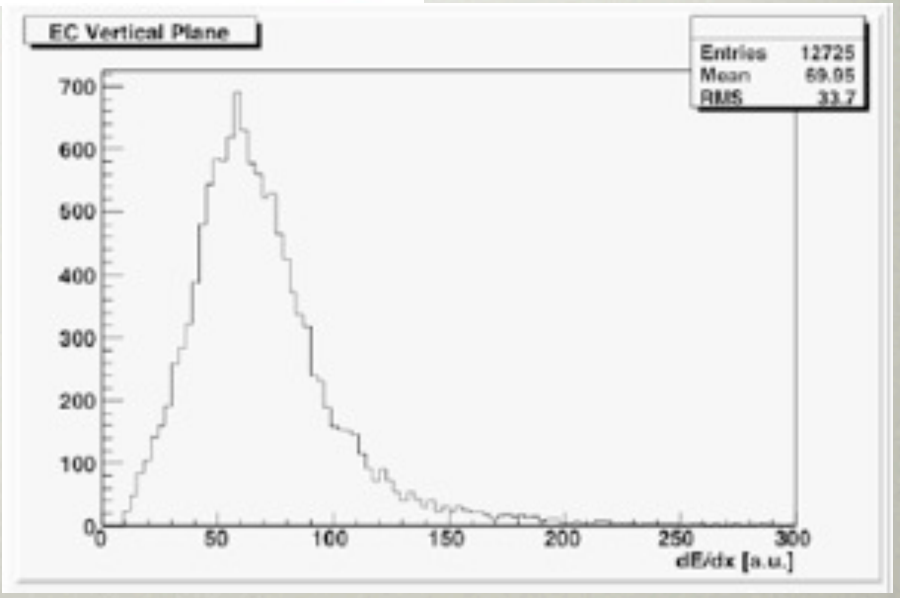


Electron Catcher (EC)

- "spaghetti" calorimeter
- 1mm diameter fibers in the grooves of lead foils
- $4x4cm^2$ cell read out from both ends
- 2 planes **(11X_0)**

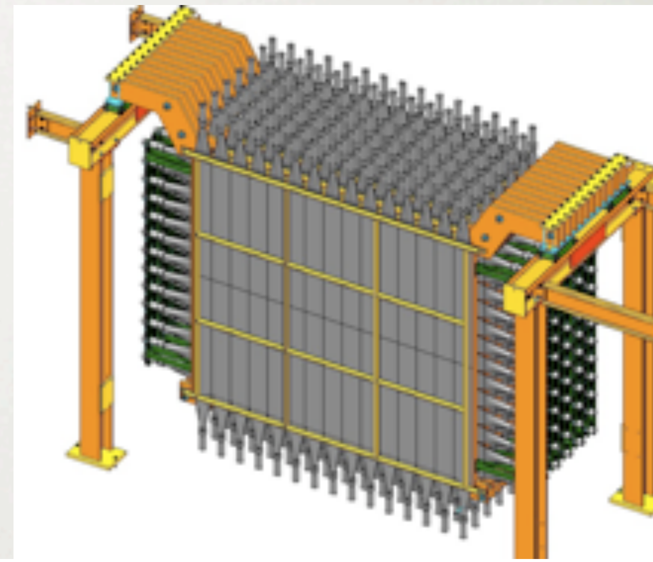
  Horizontal: 32 modules
  Vertical : 32 modules
- Total 256 readout channels
- Expected resolution **14%/√E (GeV)**
- Linearity: **better than 10%**





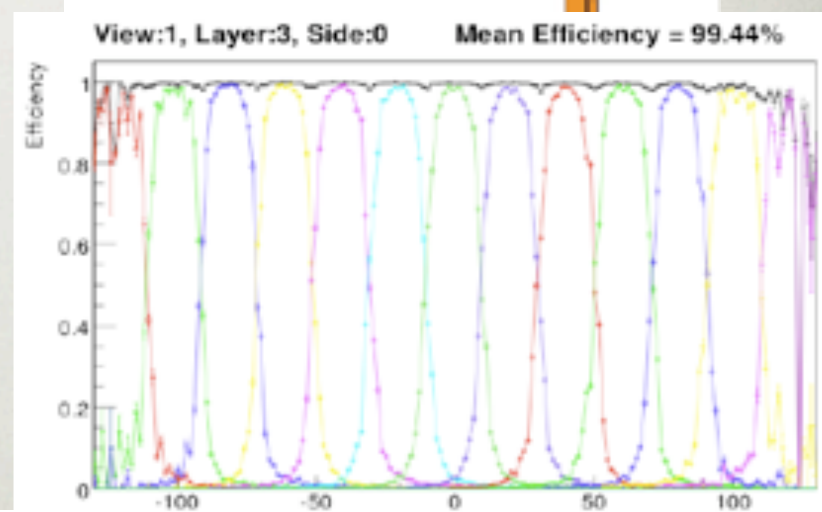
dE/dx distribution of vertical plane for cosmic ray muons

Muon Range Detector (MRD)



A new detector built with the used scintillators, iron plates and PMTs to measure the muon momentum up to 1.2 GeV/c.

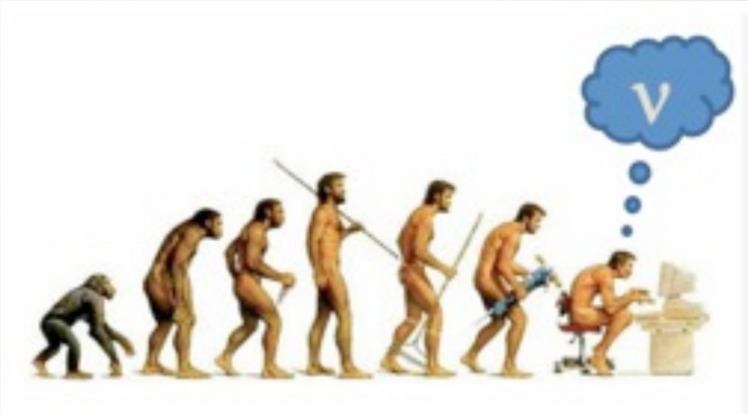
- Iron Plate
  - $305 \times 274 \times 5 cm^3$
  - Total 12 layers
- Scintillator Plane
  - Alternating horizontal and vertical planes
  - Total 362 channels



Hit efficiency of a typical horizontal plane

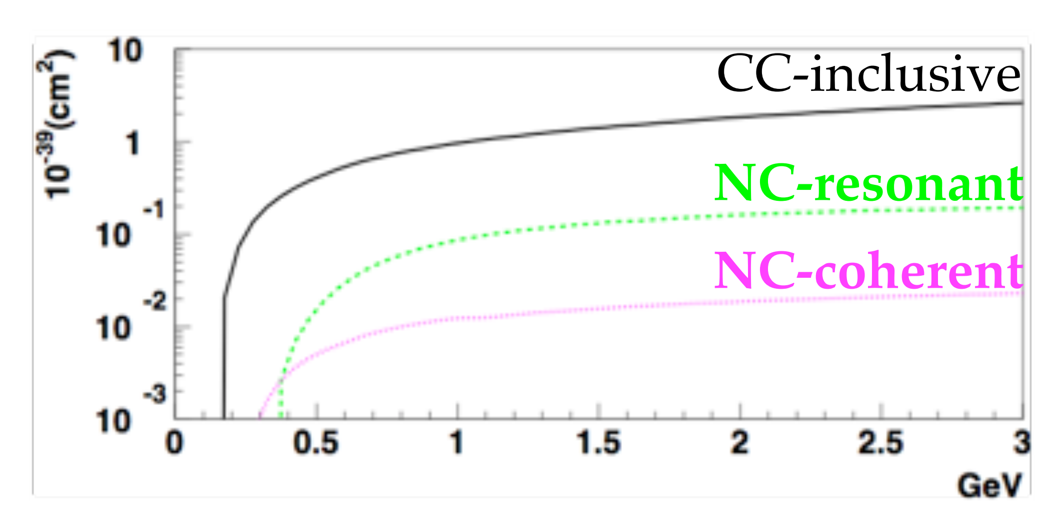
SciBooNE Timeline

- 2005, Summer - Collaboration formed
- 2005, Dec - Proposal
- 2006, Jul - Detectors move to FNAL
- 2006, Sep - Groundbreaking
- 2006, Nov - Sub-detectors Assembly
- 2007, Apr - Detector Installation
- 2007, May - Commissioning
- 2007, Jun – Started Data-taking
- 2008, Aug – Completed data-taking
- 2008, Nov – 1st physics result



Only 3 years from formation to 1st physics result

Cross Section Predictions



Interaction Type	# Events	Fraction(%)
CC quasi-elastic	53,363	41.4
CC single π via resonances	29,688	23.1
CC coherent π	1,771	1.4
CC single meson except π	839	0.7
CC DIS	6,074	4.7
NC elastic	22,521	17.5
NC single π^0 via resonances	6,939	5.4
NC coherent π^0	1,109	0.9
NC single meson except π^0	4,716	3.7
NC DIS	1,768	1.4

- NEUT cross sections vs energy
- NEUT event breakdown for 0.99E20 POT

Particle Identification

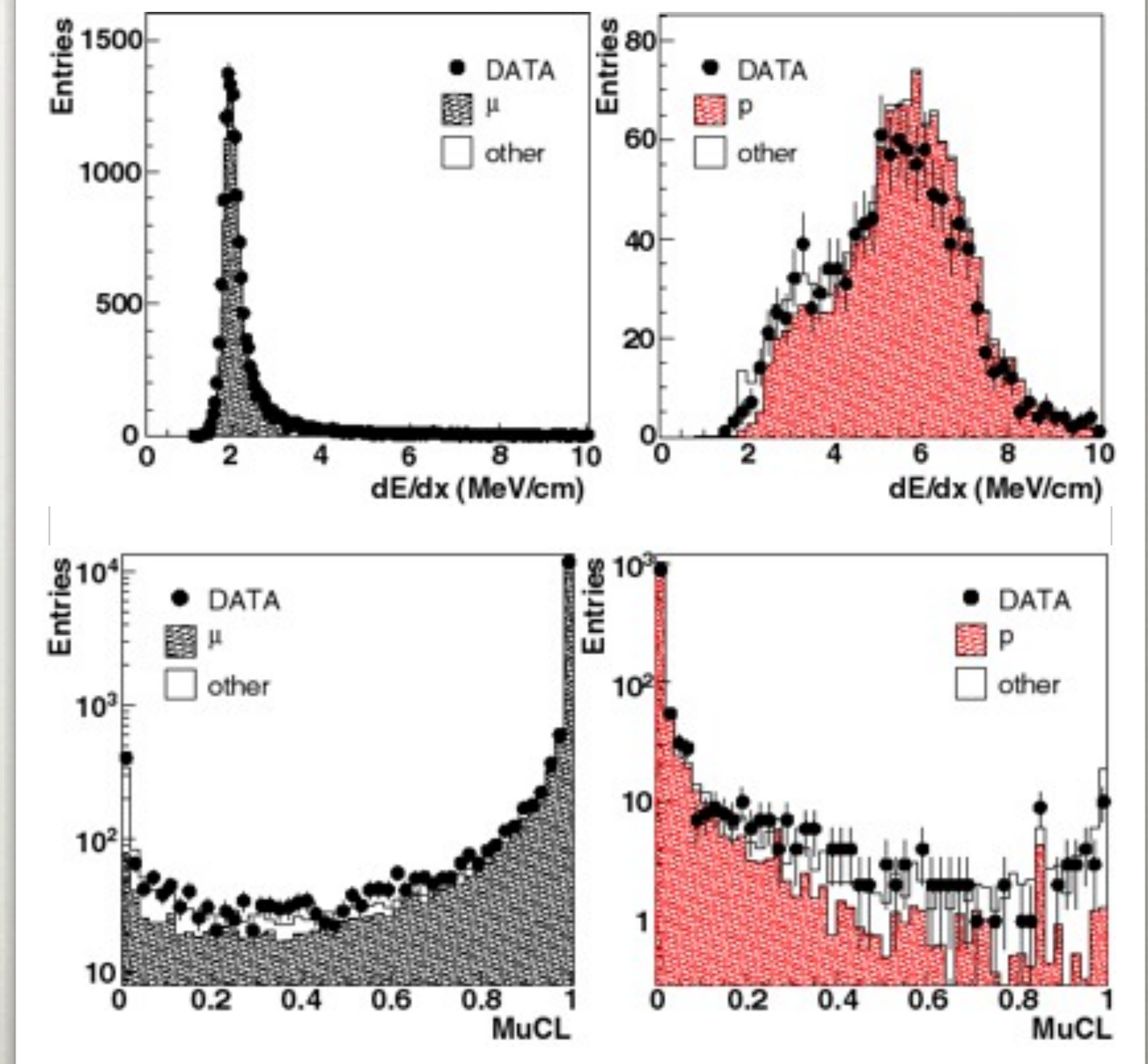
Particle ID using dE/dx in SciBar

Muon confidence level (MuCL)

MuCL >0.05 → muon-like
<0.05 → proton-like

Test mis-ID probability with CC sample
Muon: 1.1%
Proton: 12%

Muon enriched *Proton enriched*



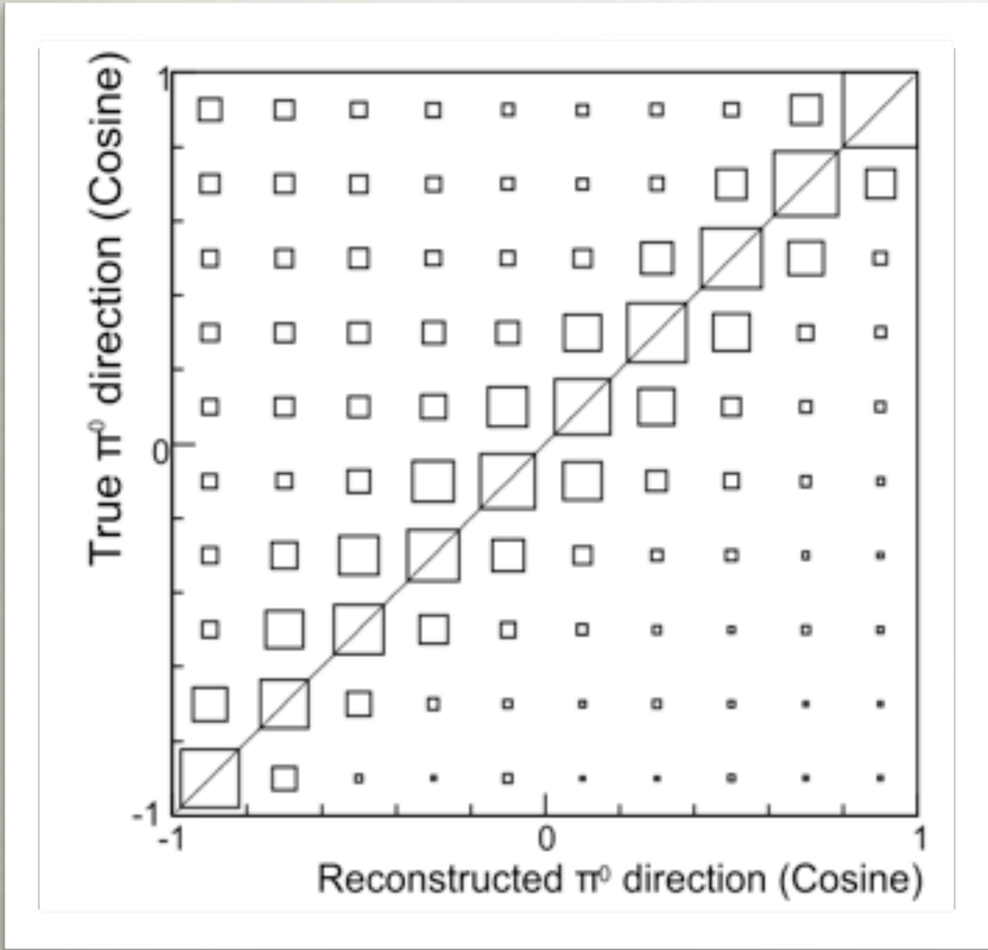
Photon Leakage

- Some gamma ray energy escapes detection - Leakage
- L_{act} = 1-(E_γ in ext-track)/(total E_γ) = 24%
  - 11% from loss in passive regions
  - 13% from energy deposited but not assigned to ext-track
- L_{eff} - 1-(E_{rec} of ext-track)/(true E_{rec}) = 15%
  - (sort of a purity measure….)

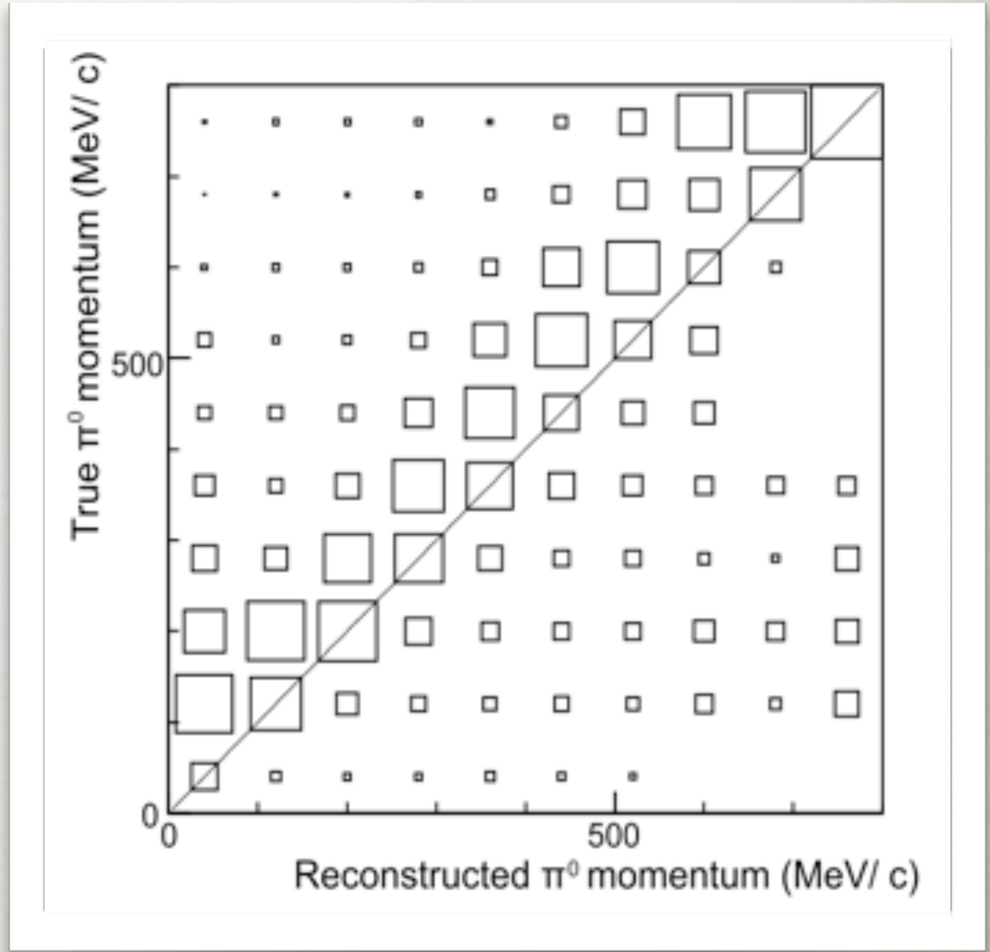
Systematic Uncertainties

- Detector response and reconstruction
  - MAPMT cross talk, 3.15%±0.0.4%
  - Single PE resolution, 50%±20%
  - Birk's constant, .0208±.0023 cm/MeV
  - Hit threshold, ±20%
  - π-C scattering, ±10%
  - gamma energy scale, ±3%
  - cross-check: alternate gamma reconstruction algorithms
- Neutrino interactions
  - CC1 π rate ±20%
  - M_A^{QE}, $M_A^{1\pi}$ ±0.1 (GeV/c)2
  - NC/CC ratio ±20%
  - pion absorption, ±30%
  - pion charge exchange, ±30%
  - cross-check: NUANCE
- Dirt BG
  - alter dirt density in MC
  - scale rate by ±15%
- Neutrino flux
  - PRD **79**, 072002 (2009)
  - pion production cross sections varied within error bands from AHRP analysis
  - kaon production varied by errors from global fits
  - secondary hadronic interactions
  - horn current

Unfolding Matrices



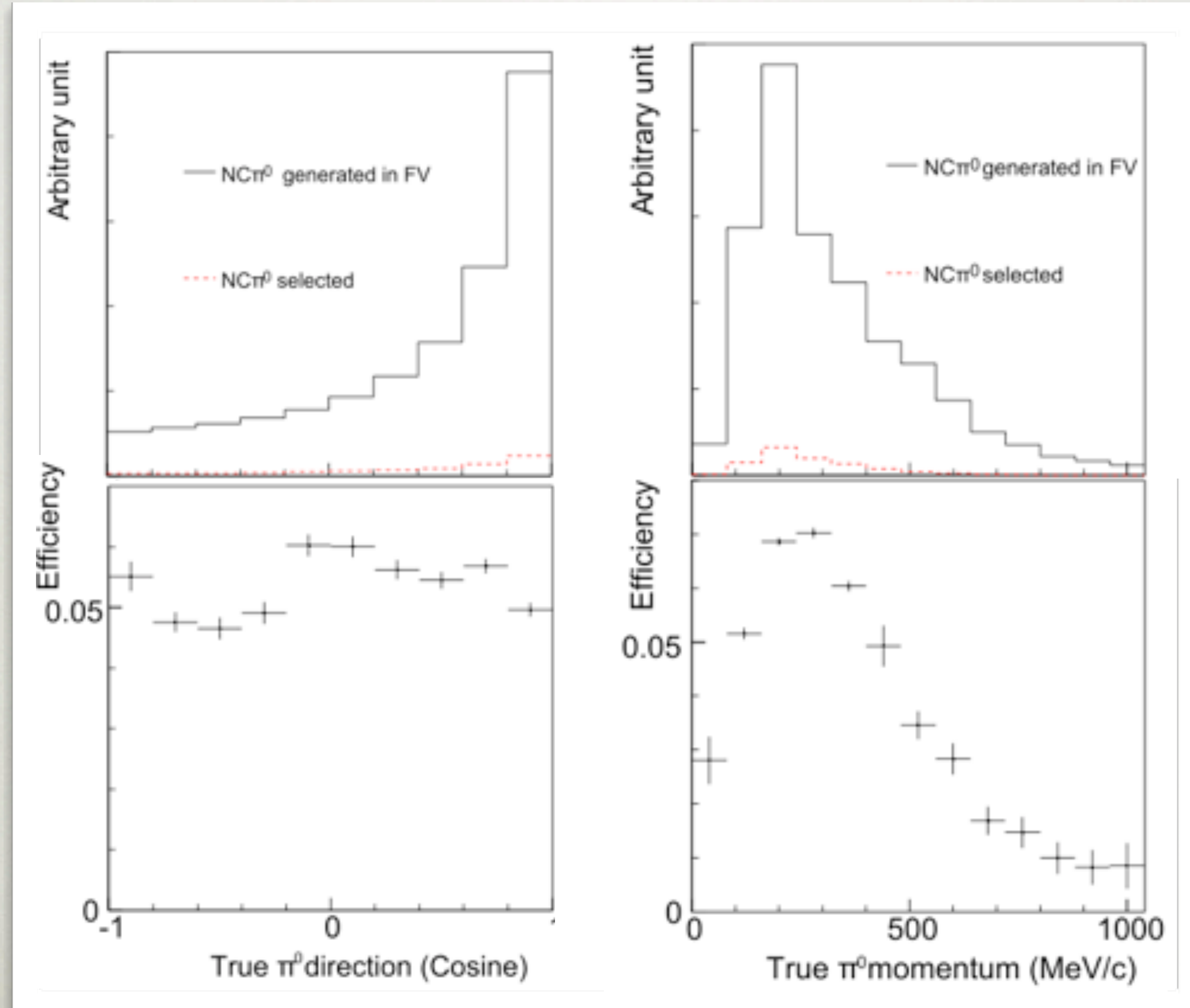
θ_{π° resolution ~ 6°



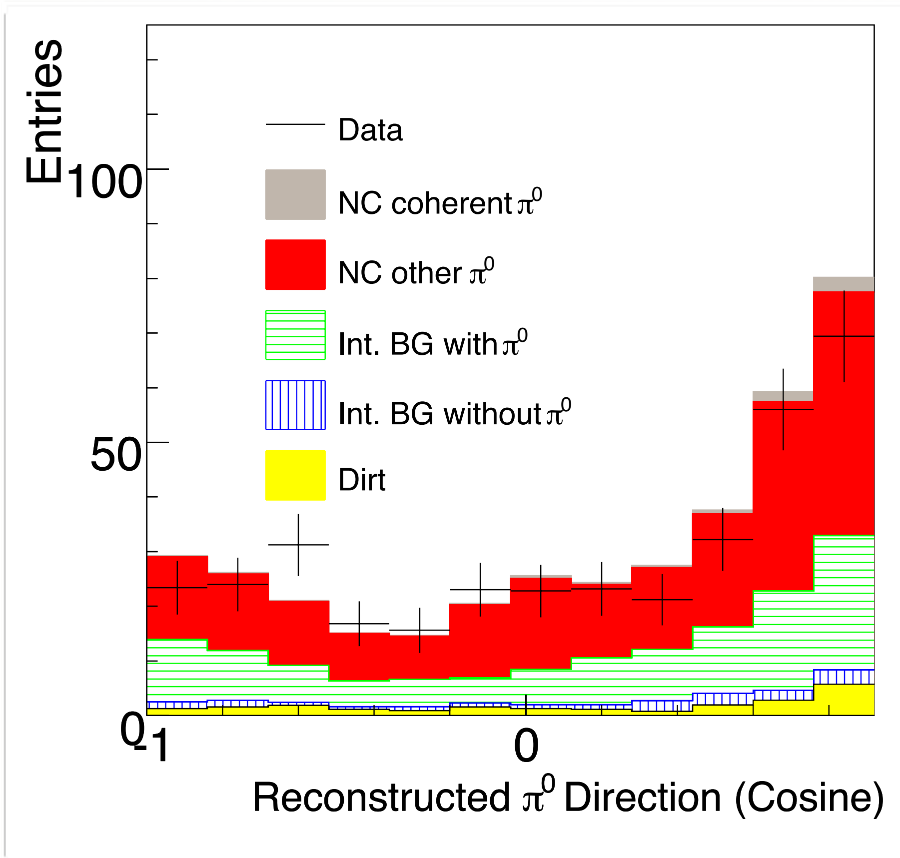
p_{π° resolution ~ 23%

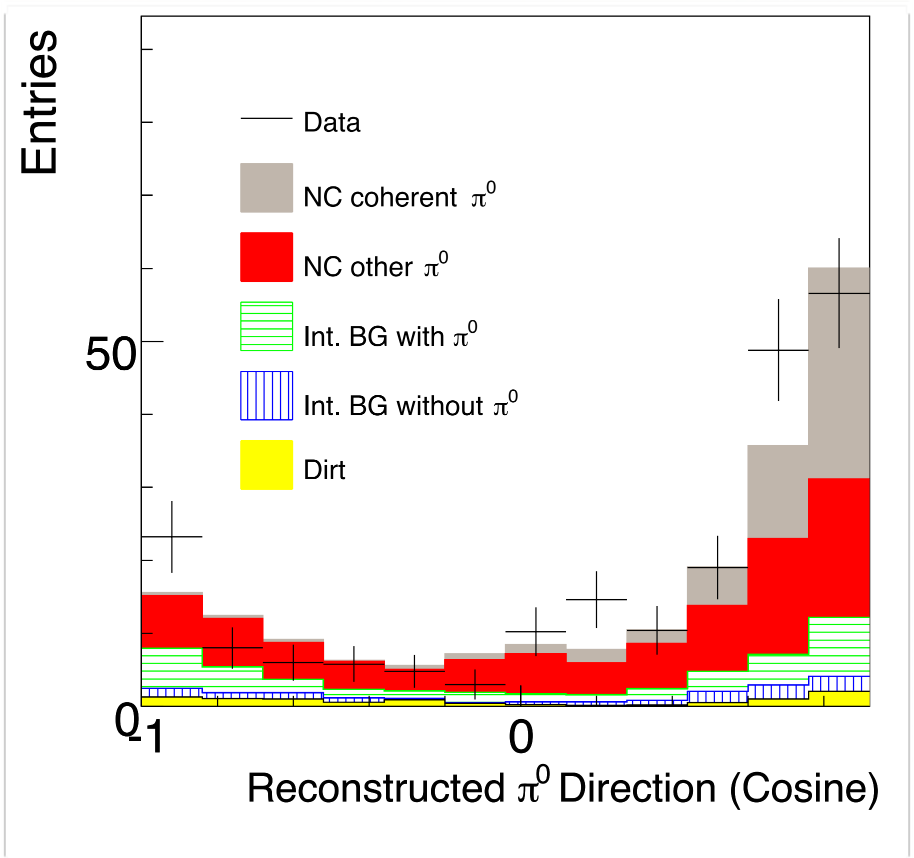
Subtract backgrounds then use MC to remove resolution/smearing effects (Unfolding)

Efficiency Corrections

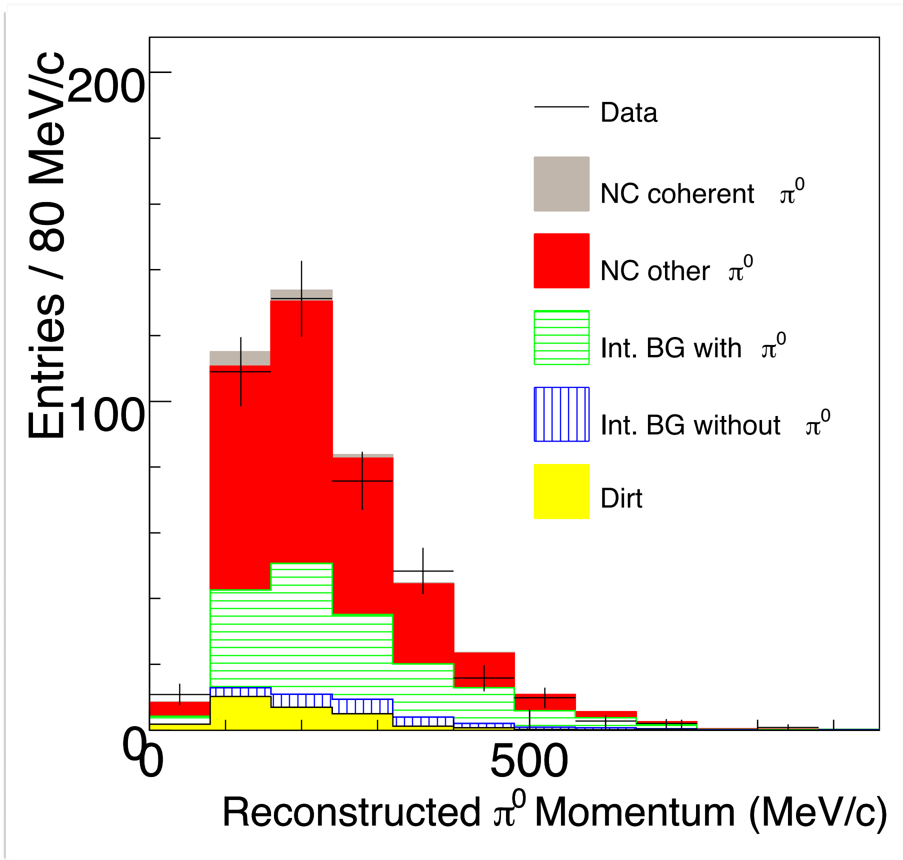


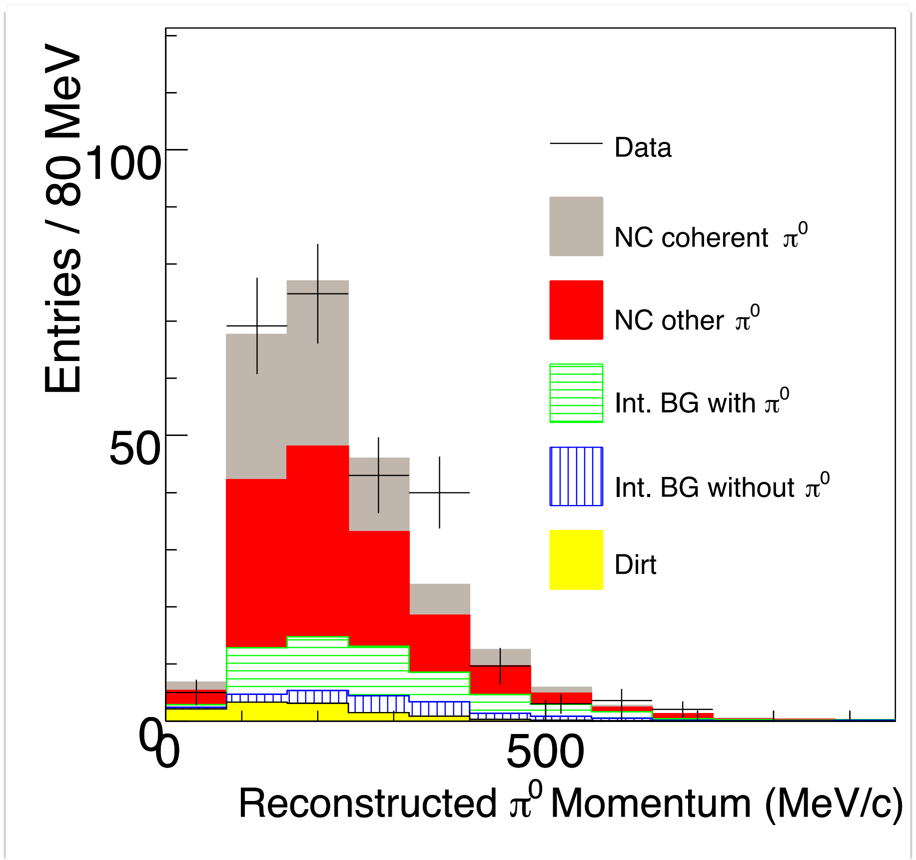
After Coherent Fits





After Coherent Fits

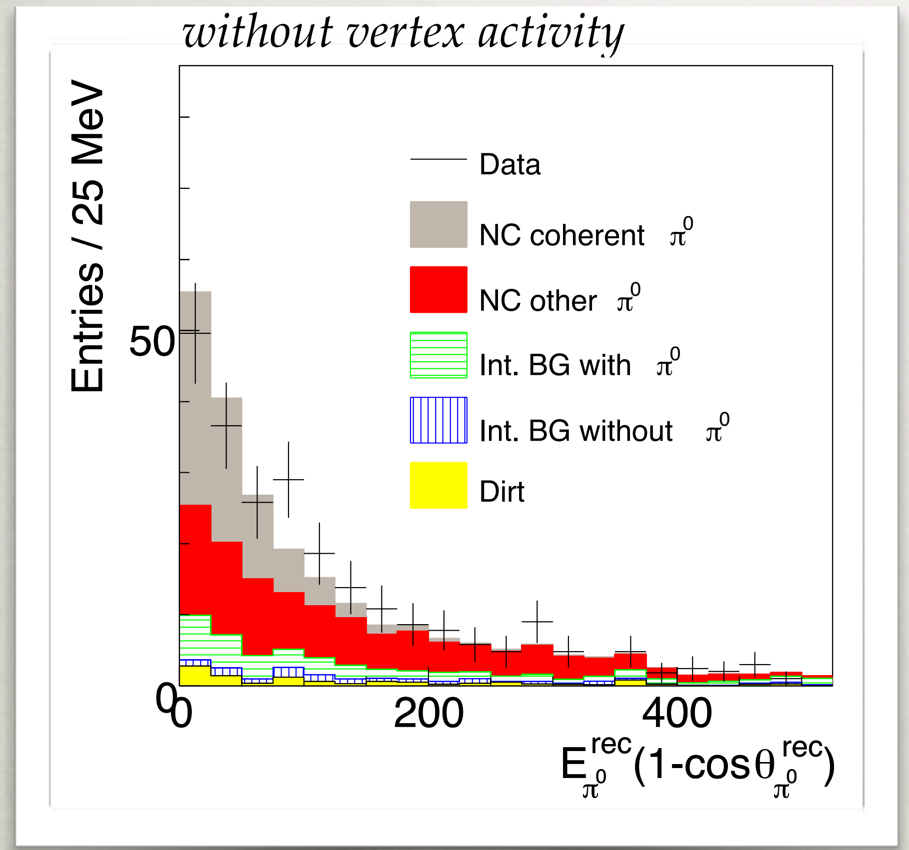




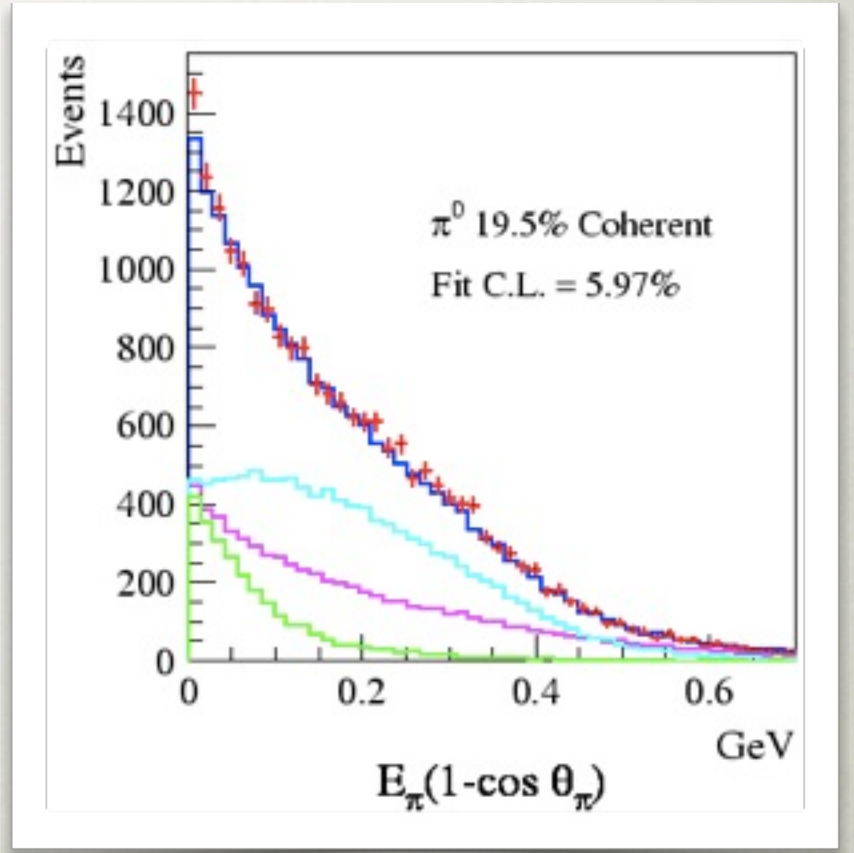
Comparison with MiniBooNE

$$\frac{\sigma(NCcoh\pi^0)}{\sigma(NCcoh\pi^0)+\sigma(NCres\pi^0)}$$

without vertex activity



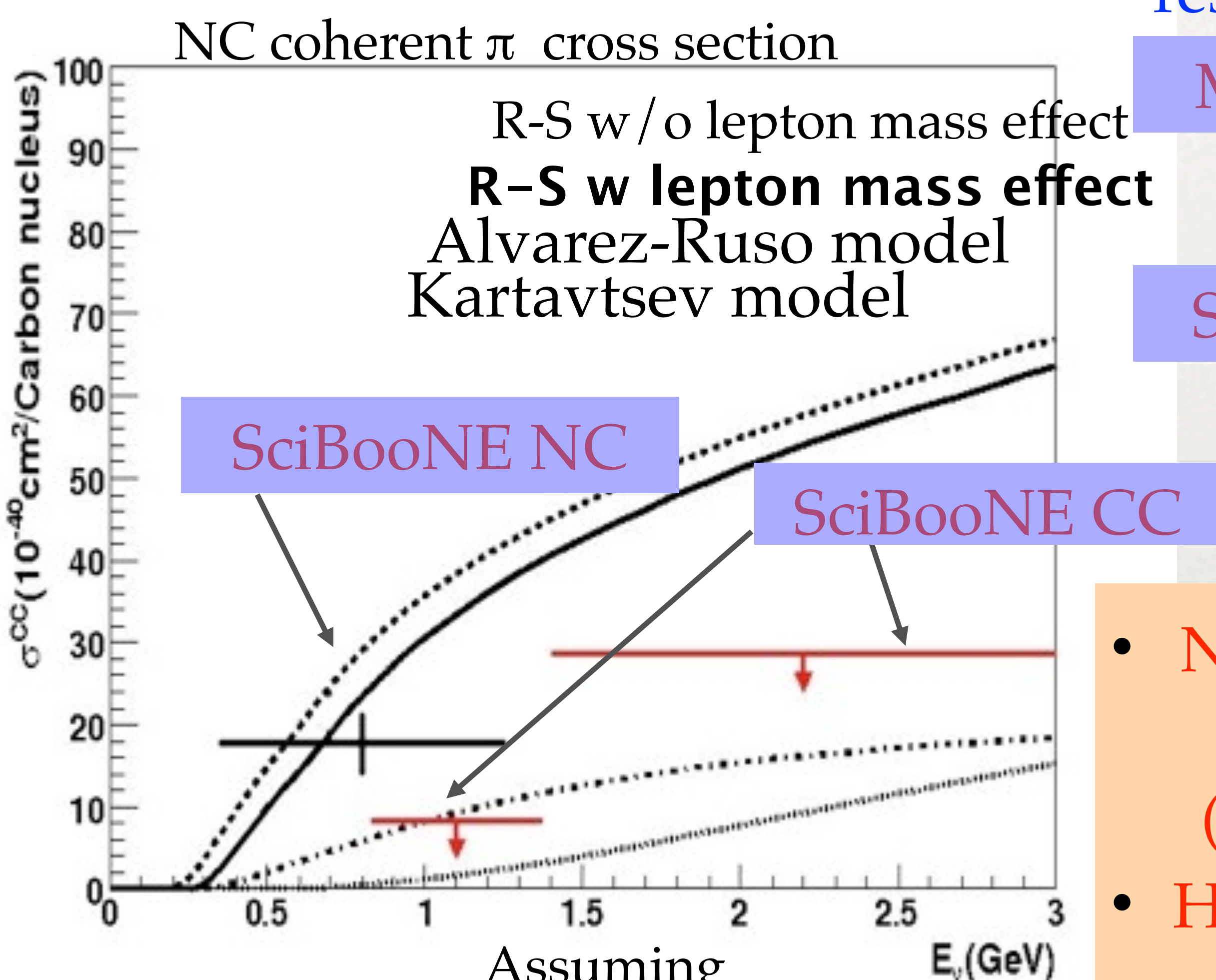
17.9±3.9 %



$19.5\pm1.1_{stat}\pm2.5_{sys}$ %

Discussion

Comparison with CC measurement



Assuming

$\sigma(CC) = 7.6 \times 10^{-39}$ cm^2 at 0.8 GeV by NEUT

$\sigma(CCcoh)=2\sigma(NCcoh)$

Comparison with MiniBooNE NC result ($\sigma(NCcoh\pi)/(\sigma(NC1\pi^0))$)

MiniBooNE NC

$19.5\pm1.1_{stat}\pm2.5_{sys}$ %

SciBooNE NC

17.9 ± 3.9 %

Preliminary

Good Agreement

- No contradiction among recent Measurements (SciBooNE,K2K,MiniBooNE)
- However , the RS model can not explain all of measurements

→ Further study is ongoing