# Neutral Pion Production Measurements at SciBooNE

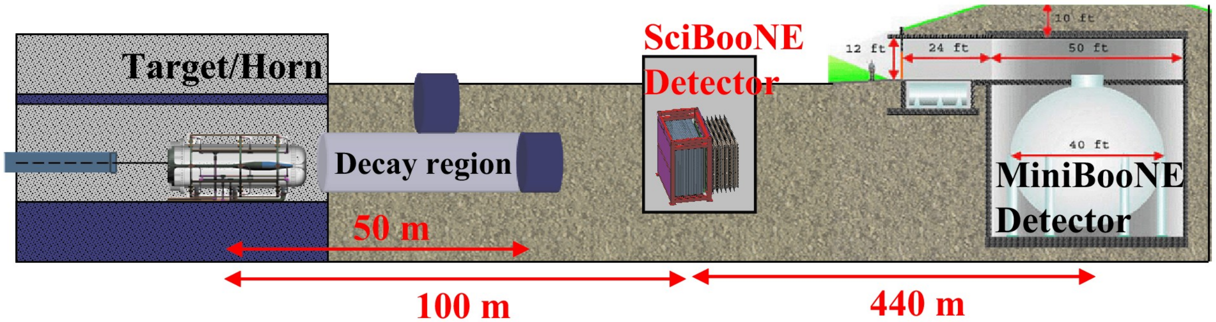
NOW 2010

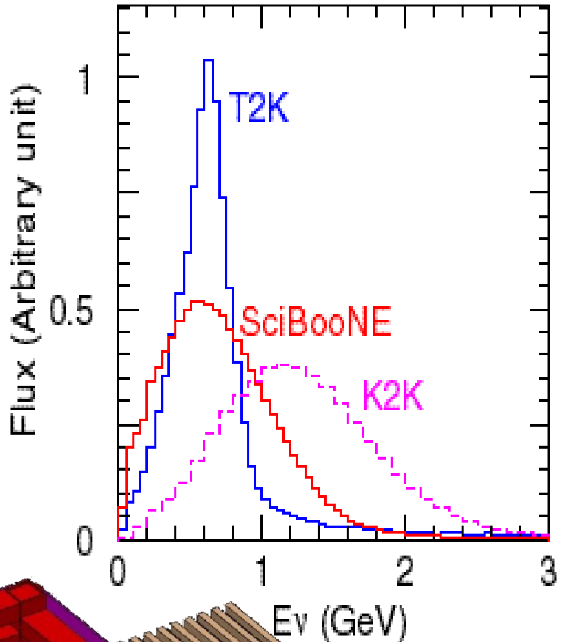
Joan Catala - IFIC(U.Valencia/CSIC)

# SciBooNE Experimental setup

# SciBooNE

## Booster Neutrino Beam

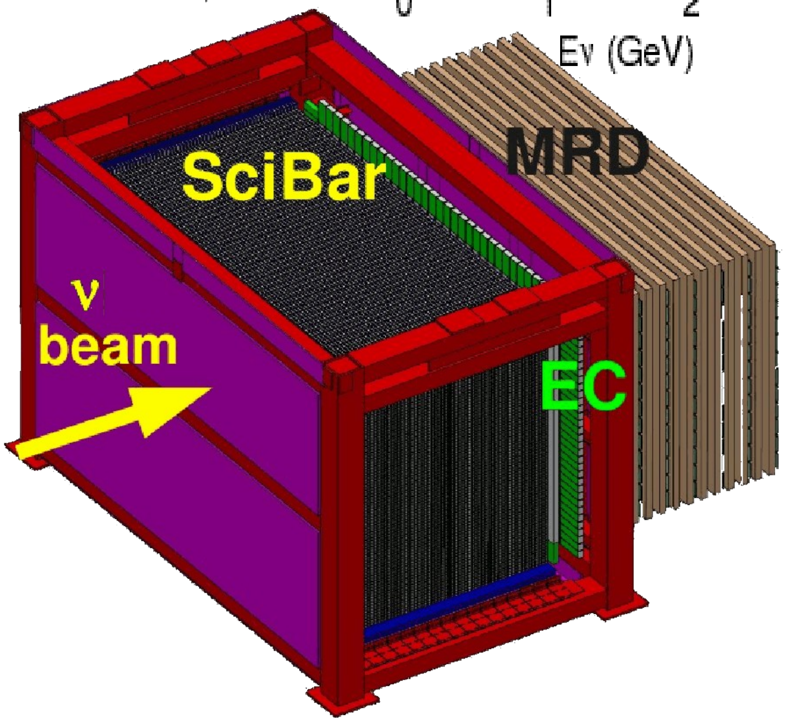



Beamline: 0.8 GeV mean energy neutrino/anti-neutrino beam produced by 8 GeV protons on Beryllium.

Detector setup:

- SciBar
  - Fully-active fine-grained scintillator detector.
  - 14336 bars (~15 tons)
  - dE/dx particle identification
- EC
  - Scintillator-Lead spaghetti calorimeter.
  - 2 layers with a total of $11X_0$
  - Identifies $e^-$ and pi0
- MRD
  - Used for muon tagging.
  - Muon momentum measurement via range.



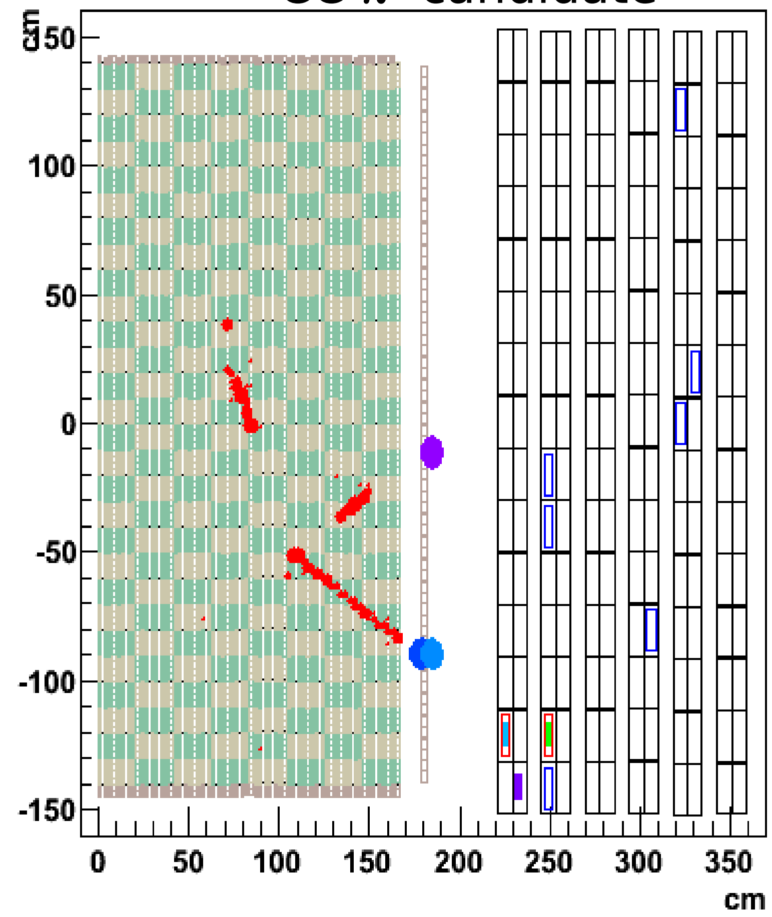
# SciBooNE Motivations and capabilities

Measurement of σ(ν-nucleus) at 1 GeV needed for the future neutrino oscillation experiments.
As a near detector of MiniBooNE for Short baseline neutrino oscillation search

SciBooNE neutral pion reconstruction capabilities:

- SciBar
  - Fine grained
    - allows to detect disconnected tracks.
    - helps with complicated topologies
    - good angular resolution
  - Fully active
    - Helps with energy reconstruction.
    - Allows vertex activity detection
  - dE/dx capability
    - reject protons from gamma candidates.
  - timing capability
    - reject beam muons stopping in scibar
    - reject cosmic ray muons
- EC
  - recovery of energy leakage
  - Gamma conversions in EC

CC $\pi^0$ candidate



# Neutral Current

# Motivation

$\nu_\mu$ induced NC$\pi^0$: One of the largest background for $\nu_\mu \to \nu_e$ search.

- NC$\pi^0$ can mimic a $\nu_e$ quasi-elastic event if one of the gammas produced by the $\pi^0$ is not detected. For T2K, the goal is to obtain a NC$\pi^0$ / CCinc cross section ratio with error below 10%
- Theoretical models differ in the prediction of pion kinematics distribution after Final State Interactions. Interest in measuring $\pi^0$ kinematics as well as total cross-section.
- K2K and SciBooNE found CC coherent $\pi$ production much lower than Rein & Sehgal model prediction (results compatible with no coherent production). On the other hand, MiniBooNE observed NC coherent $\pi^0$ production. Interest to check MiniBooNE results by SciBooNE.

# Signal Definition and Selection

At least one $\pi^0$ emitted from the interaction nucleus after Final State Interactions.

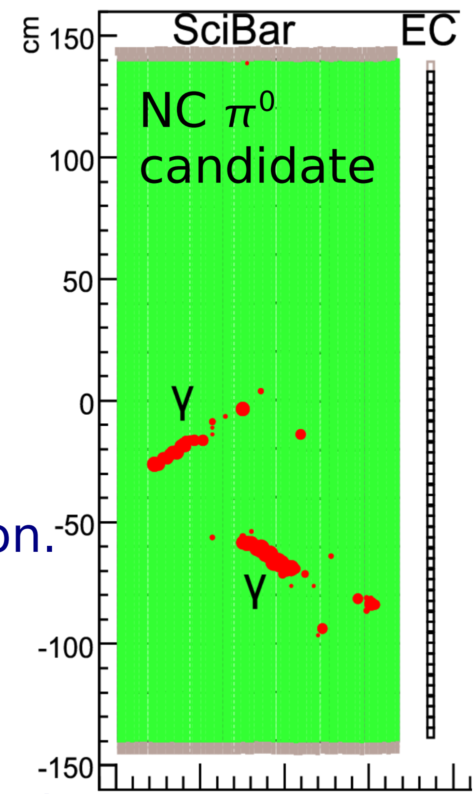
$$\nu_\mu + A \rightarrow \nu_\mu + \pi^0 + X + A'$$

Event selection:

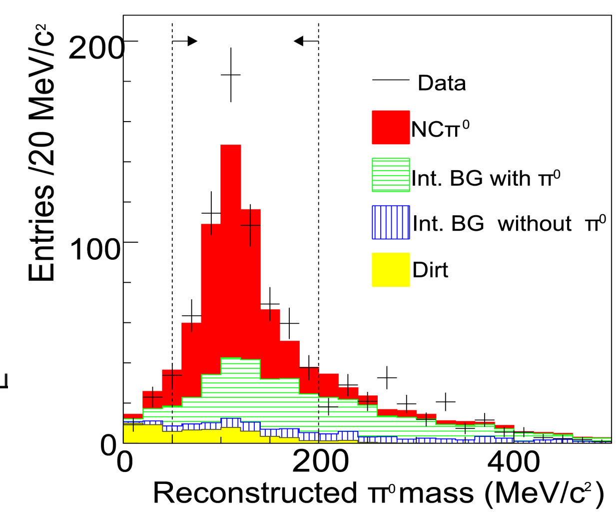
•Event containment and external background removal:
- 2 or more tracks in SciBar FV.
- No hits in the 1st layer
- No side escaping track

•Charged Current rejection:
- Using muon tagging:
  - No tracks with Michel electron.
  - No tracks reaching the MRD.
- Using event topology:
  - No common vertex

•Neutral pion and gamma reconstruction:
- 2 or more extended tracks
- $\pi^0$ vertex inside SciBar
- $M_{\gamma\gamma} = \pi^0$ mass cut




$$M^{rec}_{\pi^0} = \sqrt{2E^{rec}_{\gamma 1} E^{rec}_{\gamma 2}(1 - \cos\theta^{rec})}$$



# $\sigma(NC\pi^0)/\sigma(CC)$

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

Cross section ratio to CC events to reduce the systematic error of ν flux

$$\boxed{(7.7 \pm 0.5(\mathrm{stat.}) \pm 0.5(\mathrm{sys.})) \times 10^{-2}}$$

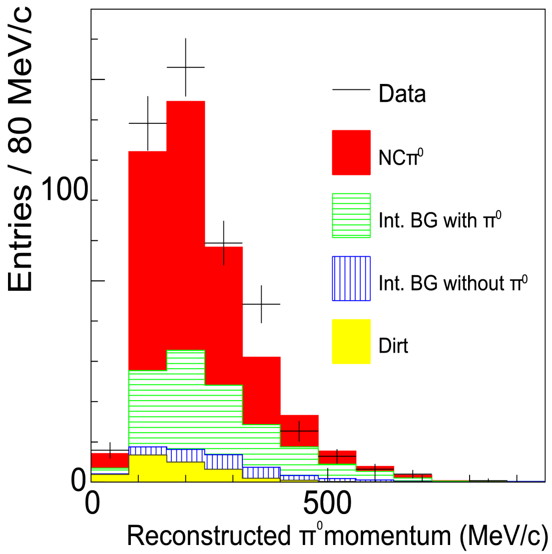
*PRD81, 033004 (2010)*

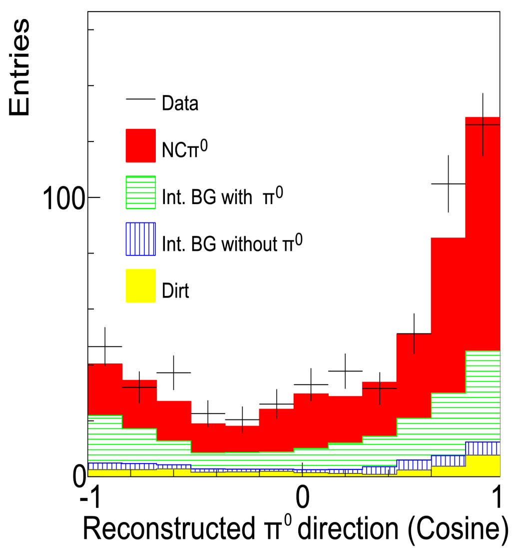
| Source of systematic | Error (x $10^{-2}$) | |
|---|---|---|
| Detector response | -0.39 | +0.38 |
| ν interaction, nuclear model | -0.25 | +0.30 |
| Dirt background | -0.10 | +0.10 |
| ν beam | -0.11 | +0.22 |
| **Total** | **-0.48** | **+0.54** |

Evaluated at $<E_\nu>$=1.14 GeV
Total error : ±0.7 x $10^{-2}$
NEUT expectation: 6.8 x $10^{-2}$

- Achieved less than 10% error

# $\pi^0$ kinematics

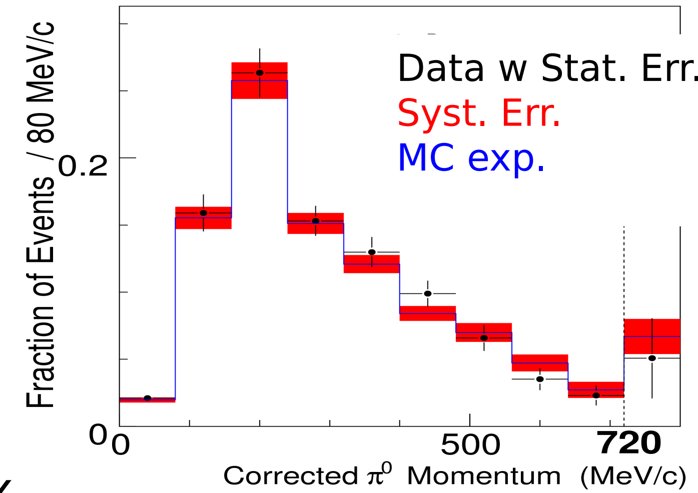


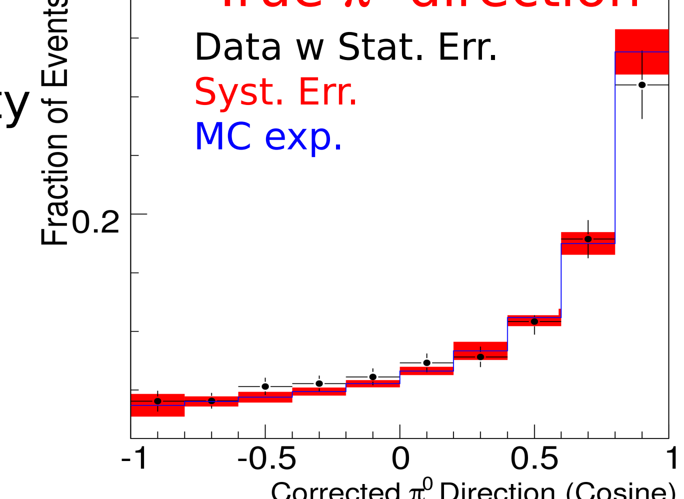

True $\pi^0$ momentum and direction obtained as follows

1. BG subtraction using MC
2. Reconstructed → True using unfolding matrix obtained by MC
3. Efficiency correction
4. Normalized to be unity for both MC and Data (shape comparison)

True $\pi^0$ momentum




True $\pi^0$ direction




Good agreement between data and MC
Can trust on the nuclear model in NEUT at this level of uncertainty (10 %)

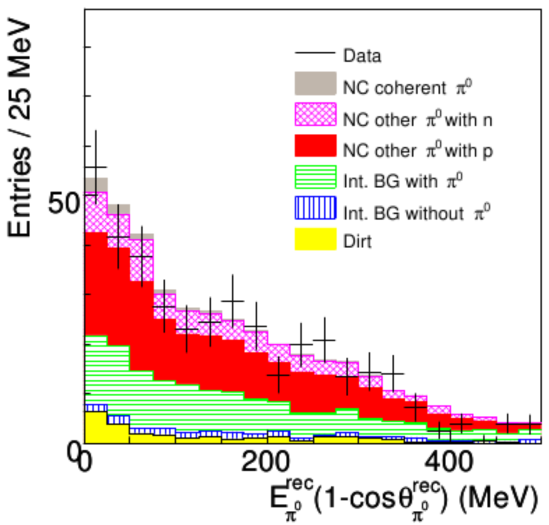
# NC coherent $\pi^0$ cross section

•Using absence of vertex activity and the forward peak of $\pi^0$ for coherent selection.

•Extracting the coherent fraction by performing a simultaneous fit over two $E_{\pi 0}$ $(1\text{-}\cos\theta_{\pi 0})$ distributions, with and without vertex activity, using 3 MC templates and 2 parameters:

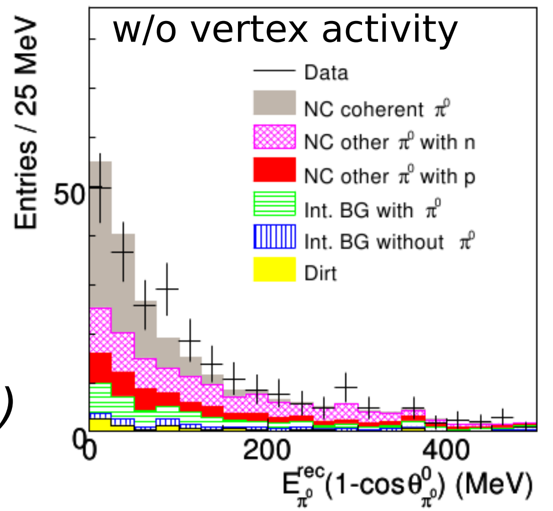
$$N_i^{\mathrm{exp}} = \mathrm{R_{coh}} \times N_i^{\mathrm{coh}} + \mathrm{R_{inc}} \times N_i^{\mathrm{inc}} + N_i^{\mathrm{BG}}$$

w/ vertex activity




MC ratio prediction [$\sigma(\mathrm{NCcoh}\pi^0)/\sigma(\mathrm{CC})$] = 1.21 x $10^{-2}$
Hence:

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = (1.16 \pm 0.24) \times 10^{-2}$$




*PRD81, 111102(R) (2010)*

Evaluated at $<E_\nu>=0.8$ GeV

NC coherent $\pi^0$ measurement agrees with the Rein and Sehgal prediction while CC coherent $\pi$ from K2K and SciBooNE disagrees with the model.

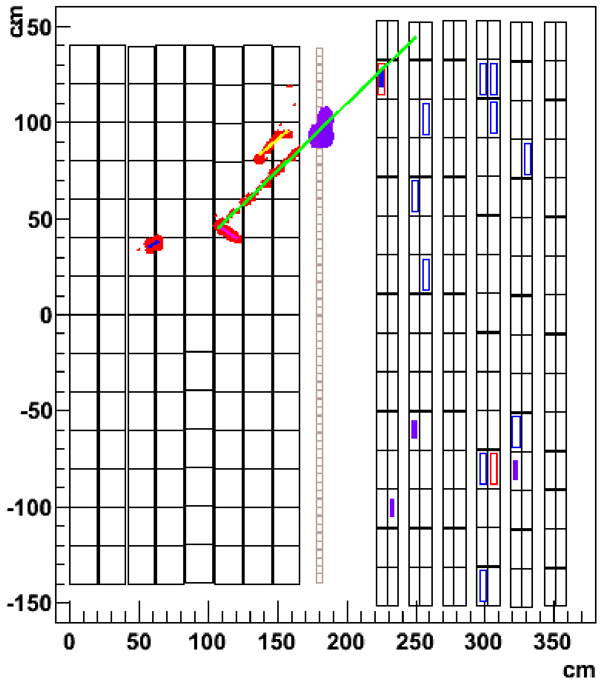
# Charged Current

# Motivation & challenges

$\pi^0$ production is an important fraction of CC inelastic interactions and its knowledge is important for $\nu_\mu$ disappearance measurements.

Only incoherent channels contribute.
Sensitive to resonant and deep inelastic processes.

TOP VIEW CC $\pi^0$ candidate




Challenges:

The SciBar track finding efficiency drops with the number of tracks on the event mostly due to track overlapping.
Given the typical topology of a CC$\pi^0$, we are facing high track multiplicity events in this analysis and so relatively small fraction of reconstructed events.

We aim for obtaining both a cross-section ratio CC$\pi^0$/CCinc and an absolute CC$\pi^0$ cross section. Those measurements will be statistically limited.

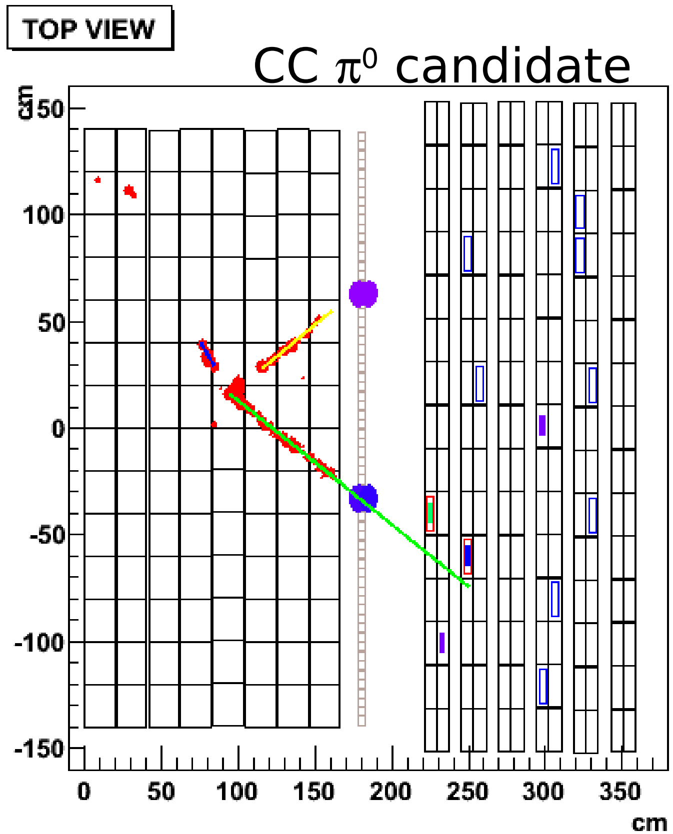
# Event sample selection

**Signal definition:**
**One muon and One neutral pion coming out from the interaction vertex.**

**Event selection:**

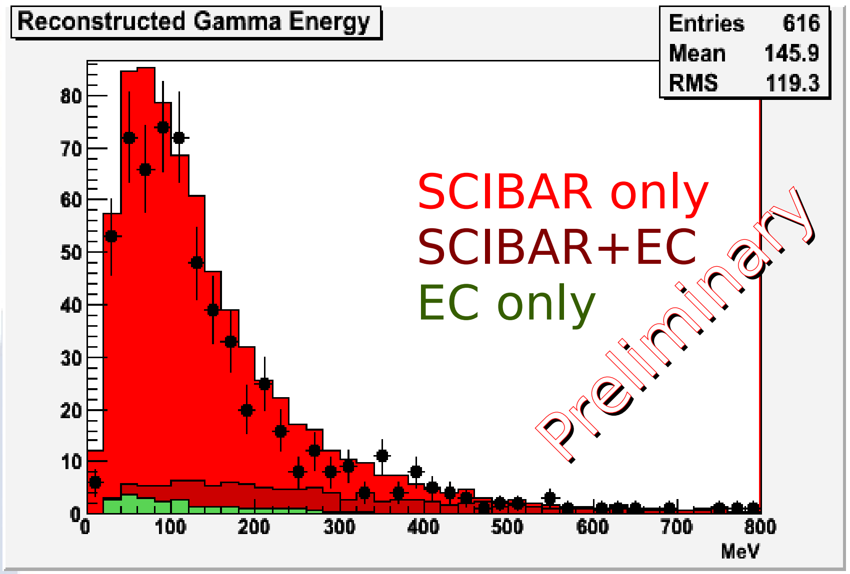
- **1Muon (and only one) hitting the MRD**
- **non-muon tracks should be in 20 ns around muon time.**

- **Making Gamma Candidates:**
  - **No tracks escaping/entering from the front or sides of SciBar.**
  - **No proton-like tracks (dE/dx)**
  - **Tracks disconnected from the vertex**
- **>=2 GammaCandidates**
- **Cosine of opening angle between gammas <.96**
- **1 Pi0Candidate**



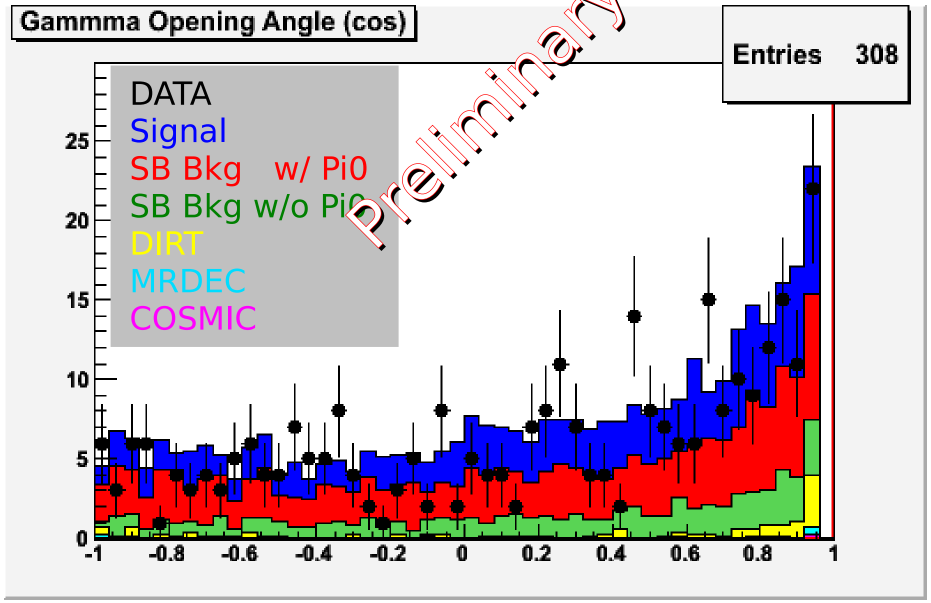

| Cut \ sample | Data | Total MC | Signal | SB bkg w/pi | SB bkg w/o | MRD/EC | DIRT | COSMIC | Purity | Efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| Muon hitting MRD | 30271 | 30271.0 | 1863.0 | 1768.7 | 25499.3 | 787.0 | 177.7 | 175.3 | 6.15% | 25.37% |
| 1 Muon | 29069 | 28803.2 | 1573.8 | 1469.0 | 24647.1 | 778.7 | 166.5 | 168.2 | 5.46% | 21.43% |
| Trk on muon time | 28118 | 28572.8 | 1559.3 | 1457.1 | 24482.3 | 756.6 | 165.4 | 152.0 | 5.46% | 21.23% |
| GC>=2 | 428 | 564.0 | 205.2 | 240.2 | 88.4 | 2.5 | 25.6 | 2.2 | 36.38% | 2.79% |
| 1pi0c | 308.0 | 370.6 | 141.6 | 150.6 | 62.9 | 2.1 | 13.0 | 0.2 | 38.23% | 1.93% |

# Photon reconstruction



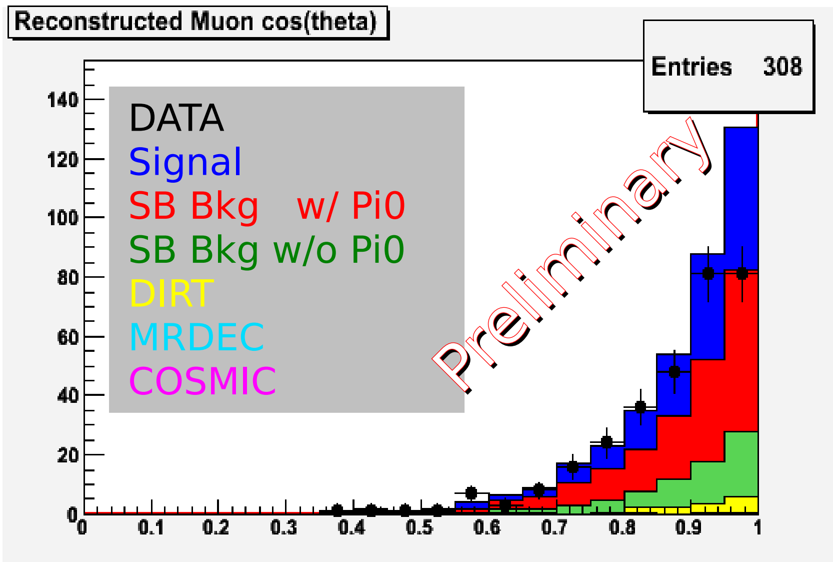

In addition to gamma candidates in SciBar only and SciBar+EC, we also reconstruct gamma candidates using EC only.

**CCinc normalized**




Events with small opening angle between gammas are rejected. Typically are the same photon reconstructed as 2 different GC.

# Muon reconstruction

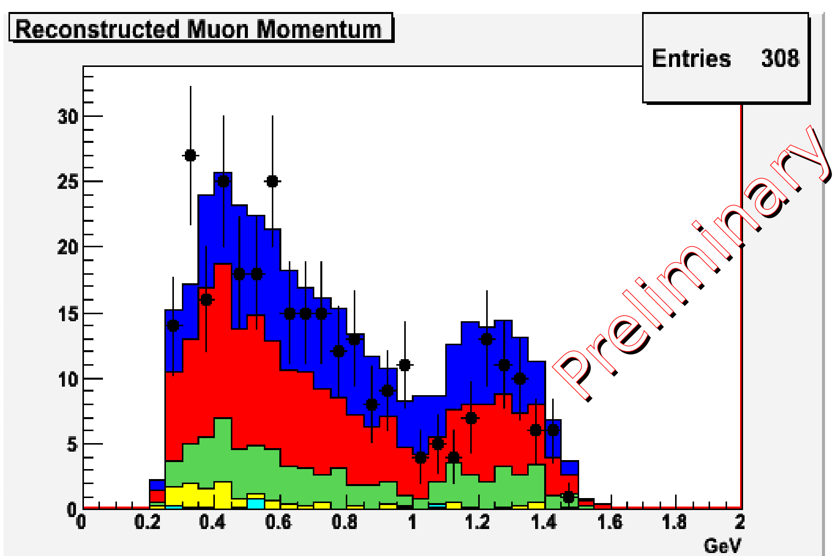


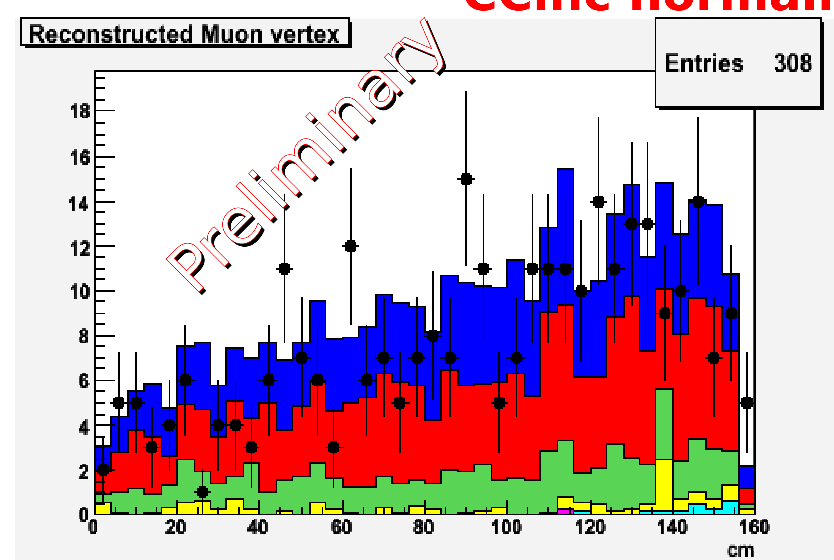

- Small External background contribution.

- DATA/MC deficit concentrated in forward muon direction.

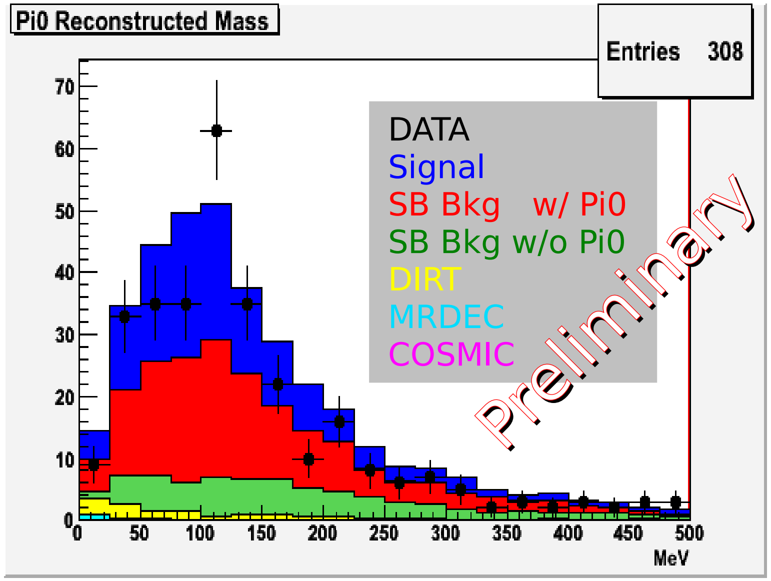
- Momentum bump at 1.2GeV due to muons escaping from MRD.
- Shape agreement for muon momentum and vertex position distributions.

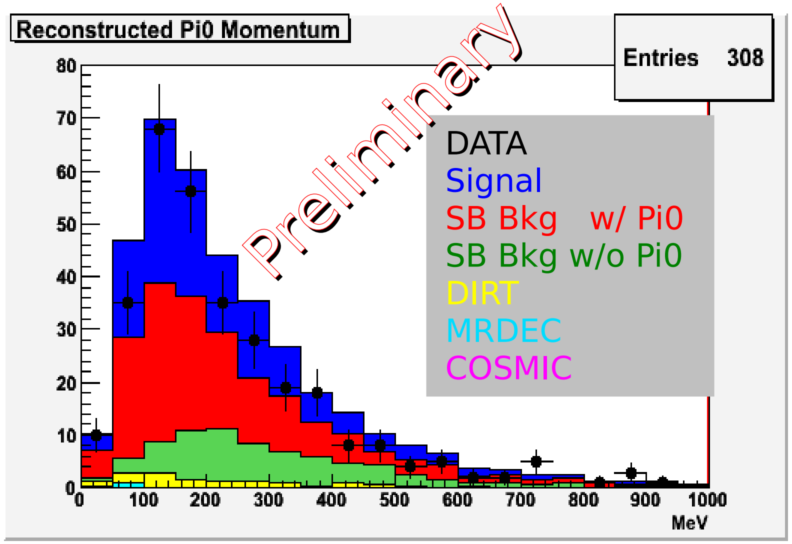
**CCinc normalized**



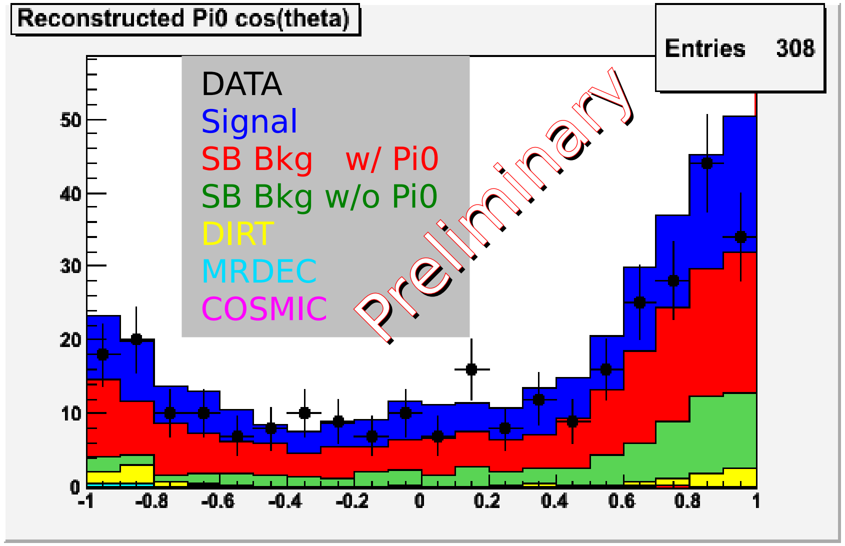



# $\pi^0$ reconstruction




**CCinc normalized**




Despite the observed DATA deficit, we find a good agreement in shape between DATA and MC for the reconstructed quantities.

Notice main background comes from events that contains $\pi^0$.
NC$\pi^0$, CC with secondary $\pi^0$ and multi-$\pi^0$ contributes to this background

# NC Summary

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

Evaluated at $<E_\nu>$=1.14 GeV

Achieved less than 10% error as required by T2K $\nu_e$ appearance search

$\pi^0$ kinematics (momentum and direction) measurements agree with the MC prediction:

We can trust the nuclear model in NEUT at this level of uncertainty (10%)

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\mathrm{CC})} = (1.16 \pm 0.24) \times 10^{-2},$$

Evaluated at $<E_\nu>$=0.8 GeV

NC coherent $\pi^0$ production agrees with Rein-Sehgal model in NC

# CC Summary

Despite the low statistics we are able to reconstruct $\pi^0$ kinematics that agrees in shape with the MC prediction.

Given that the MC is normalized to total CC events, the data deficit on the CC$\pi^0$ selection give us a hint for the CC$\pi^0$ /CCinc cross section ratio, we expect it to be lower than the MC prediction.

Future prospects:

We aim to obtain a measurement on the CC$\pi^0$ /CCinc cross section ratio as well as a value for the CC$\pi^0$ absolute cross section.

We are working now in the way to perform an evaluation of the composition of the backgrounds of the analysis by fitting the data.

Despite the low statistics, coarse measurement of cross section neutrino energy dependence may be possible.

# SciBooNE Collaboration

Mar 18, 2008

- Universitat Autonoma de Barcelona
- University of Cincinnati
- 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
- Purdue University Calumet
- Universita degli Studi di Roma "La Sapienza" and INFN
- Saint Mary's University of Minnesota
- Tokyo Institute of Technology
- Unversitat de Valencia

~70 physicists
5 countries 17 institutions

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

# Bakcup

# Summary of NC Event Selections

| | DATA | MC | | | $NC\pi^0$ |
|---|---|---|---|---|---|
| | | $NC\pi^0$ signal | Internal BG (CC) | Dirt BG | Efficiency |
| Pre selection | 11,926 | 1,893 | 9,808 (9050) | 895 | 27.3% |
| μ rejection (SB) | 5,609 | 1,377 | 3,785 (3326) | 606 | 19.8% |
| Isolated tracks | 3,614 | 1,314 | 1,706 (1306) | 595 | 18.9% |
| μ rejection (EC) | 2791 | 1202 | 1088 (714) | 579 | 17.3% |
| 2γ selections | 973 | 443 | 389 (294) | 121 | 6.5% |
| $\pi^0$ vertex | 905 | 428 | 382 (288) | 65 | 6.2% |
| $\pi^0$ mass | 657 | 368 | 202 (140) | 38 | 5.3% |

CC rejections

Dirt background rejections