Coherent-π production experiments review

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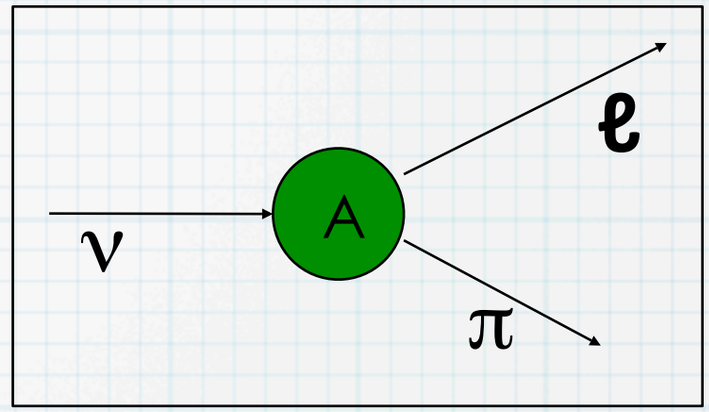
Outline

- Introduction
- Measurements in past
- Recent results at low energy
  - K2K, MiniBooNE, SciBooNE
- Future prospect
- Summary

Coherent pion production

- Neutrino interacts with nucleons *coherently*, producing a pion
- No nuclear breakup occurs



Charged Current (CC): $\nu_\mu + A \rightarrow \mu + A + \pi^+$

Neutral Current (NC): $\nu_\mu + A \rightarrow \nu_\mu + A + \pi^0$

Coherence requires:

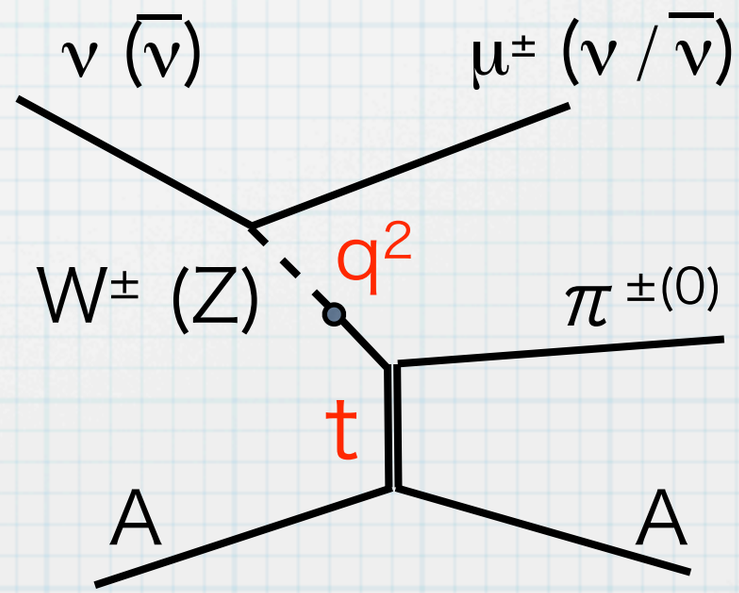
$t = (q - p_\pi)^2 < 1/R^2$

where R is the size of the nucleus.

From the Rein-Sehgal model:

1) $\sigma(CC) = 2\,\sigma(NC)$
2) $\sigma(A) \sim A^{1/3}$
3) $\sigma(\nu) \sim \sigma(\bar{\nu})$

Characterized by a small momentum transfer to the nucleus, forward going π.

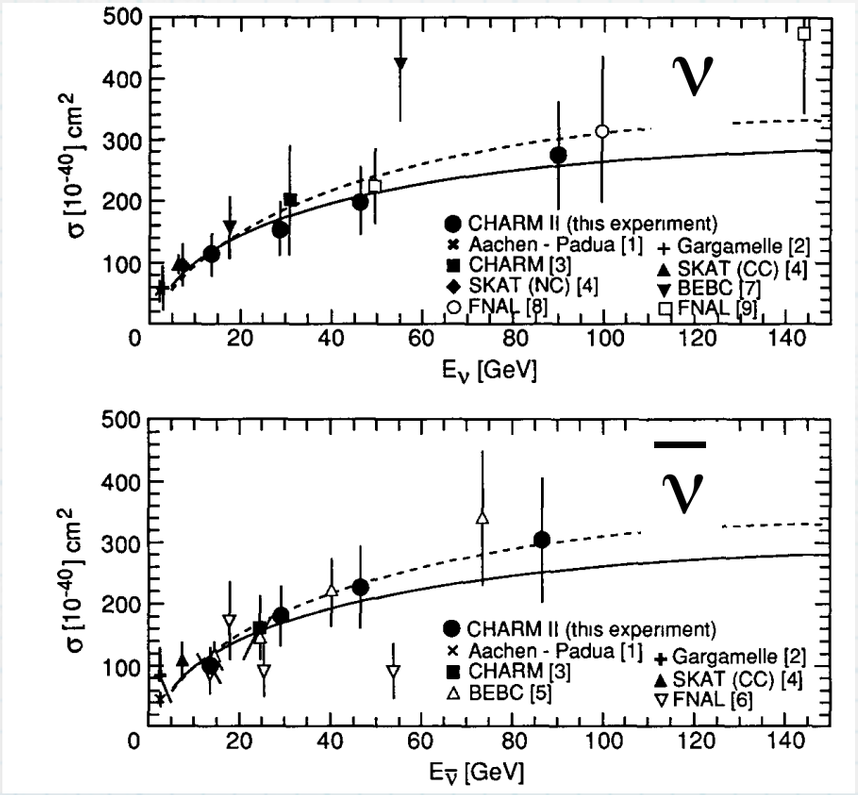


Measurements in past

- Measurements for ν, $\bar{\nu}$ CC and NC modes
  - for various nuclear targets
- High energy region: >7GeV (CC), >2GeV (NC)
- R&S model agrees with the high energy results.

Assume:

- $A^{1/3}$ dependence
- σ(CC coherent)=2*σ(NC coherent)



Plots from Phys.Lett. B313, 267-275 (1993)

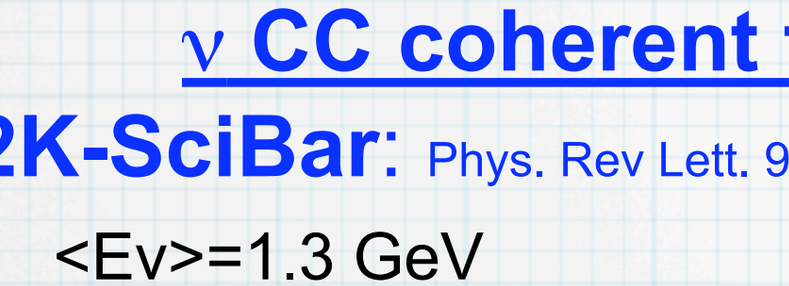
Experiments	CC/NC	ν / $\bar{\nu}$	E (GeV)	Target <A>
Aachen-Padova	NC	ν, $\bar{\nu}$	2	Al <27>
Gargamelle	NC	ν, $\bar{\nu}$	2	Freon <30>
CHARM	NC	ν, $\bar{\nu}$	20-30	Glass <20.7>
CHARM II	CC	ν, $\bar{\nu}$	20-30	Glass <20.7>
BEBC	CC	$\bar{\nu}$	5-100	Ne/H_2 <20>
SKAT	CC, NC	ν, $\bar{\nu}$	3-20	Freon <30>
FNAL 15-ft	NC	ν	2-100	Ne/H_2 <20>
FNAL 15-ft E632	CC	ν, $\bar{\nu}$	10-100	Ne/H_2 <20>

Recent results
at low energy (~1GeV)

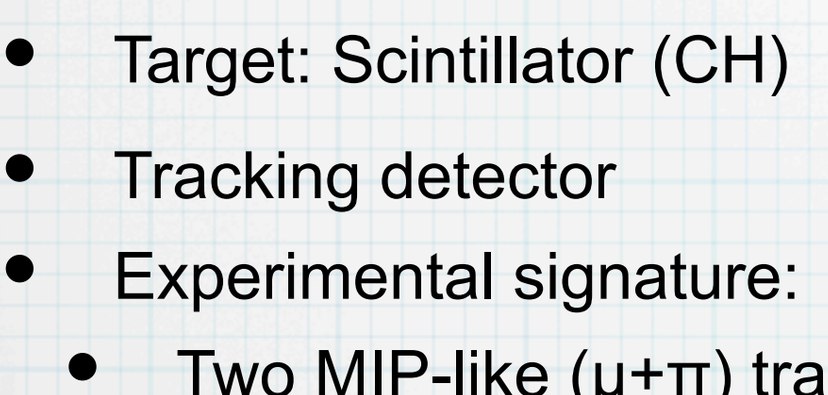
ν CC coherent π^+

K2K-SciBar: Phys. Rev Lett. 95, 252301 (2005)

- <Ev>=1.3 GeV
- Target: Scintillator (CH)
- Tracking detector
- Experimental signature:
  - Two MIP-like (μ+π) tracks
  - By looking at recoil proton (vertex activity) isolate coh-π



Coherent π (MC)



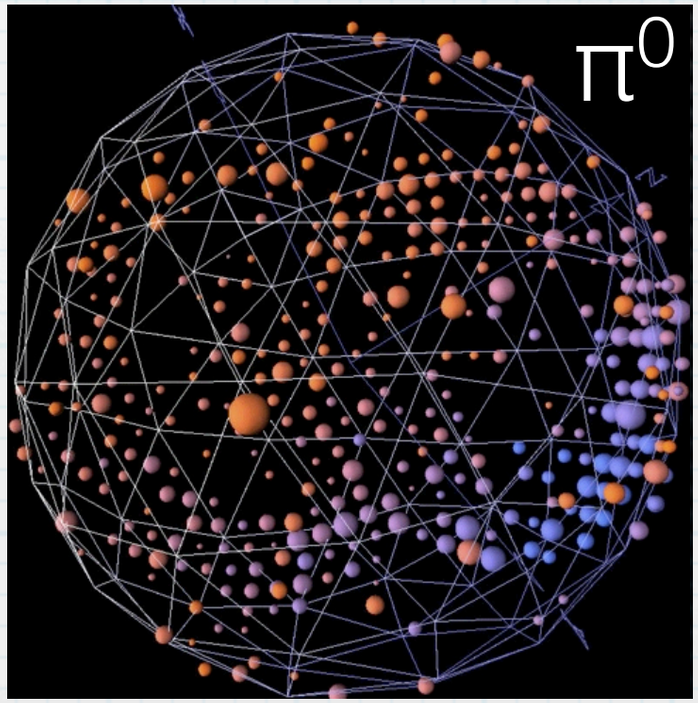
Resonant π (MC)

Vertex activity
(recoil proton)

ν NC coherent π^0

MiniBooNE: Phys. Lett. B664, 41 (2008)

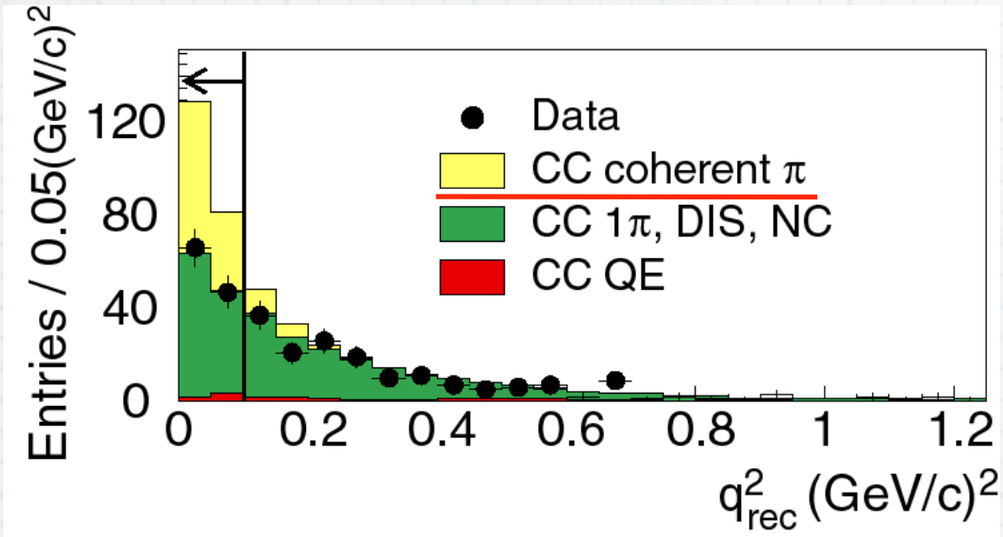
- <Ev>=1.1GeV
- Target: Mineral oil (CH_2)
- Cherenkov detector
- Experimental signature:
  - Two e-like ring ($\pi^0 \rightarrow \gamma\gamma$) events
  - With pion in forward direction



Recent results
at low energy (~1GeV)

ν CC coherent π^+

K2K-SciBar: Phys. Rev Lett. 95, 252301 (2005)



Cross section ratio:

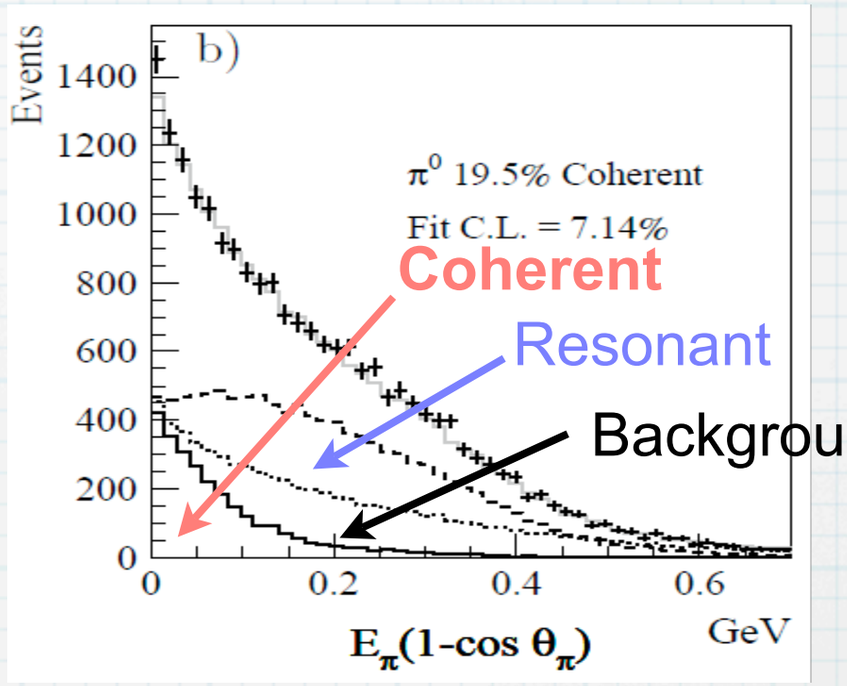
σ(CC coh-π) / σ (CC)

$= (0.04 \pm 0.29\ (\text{stat.})\ ^{+0.32}_{-0.35}\ (\text{sys.})) \times 10^{-2}$

No evidence of CC coherent π prod.

ν NC coherent π^0

MiniBooNE: Phys. Lett. B664, 41 (2008)



Coherent fraction in NC-1π^0:

$N_{coh}/(N_{coh} + N_{res})$

$= (19.5 \pm 1.1\ (\text{stat.}) \pm 2.5\ (\text{sys.}))\%$

Clear evidence of NC coherent π prod.

More NC-π^0 from MiniBooNE

C.E. Anderson at NuInt09

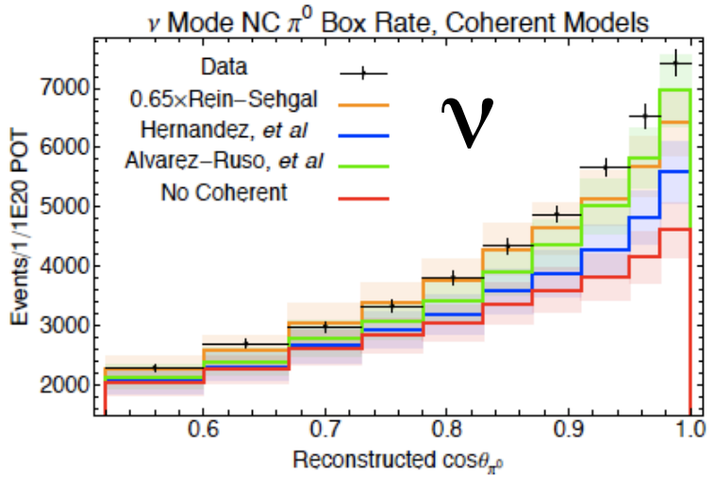
Coherent Production Models

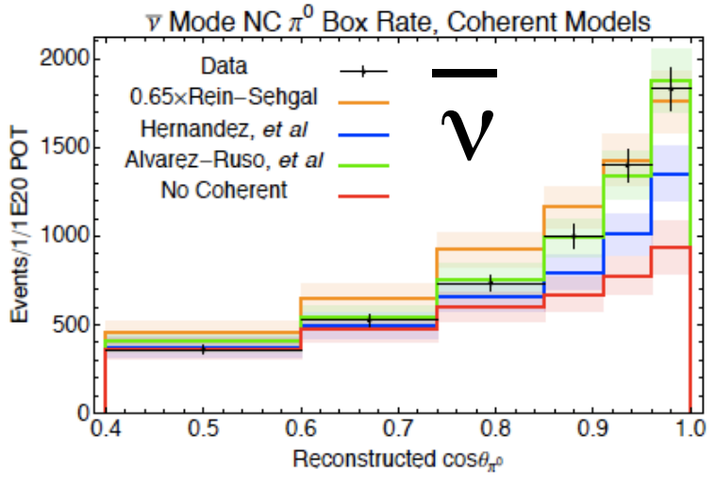
- Models for NC coherent π^0 production demonstrate wide variabilities in their predictions
- Forward angular distribution (particularly for antineutrino mode) is very sensitive to predictions
- MiniBooNE uses the Rein–Sehgal[a] prediction scaled by 0.65 by default in MC; also incorporated predictions from Hernandez, *et al*[b], and Alvarez-Ruso, *et al*[c]

[a] Nucl. Phys. B**223**, 29, (1983)

[b] arXiv:0903.5285v1; thanks to Juan Nieves for predictions

[c] Phys. Rev. C **76**, 068501 (2007); thanks to Luis Alvarez-Ruso for predictions





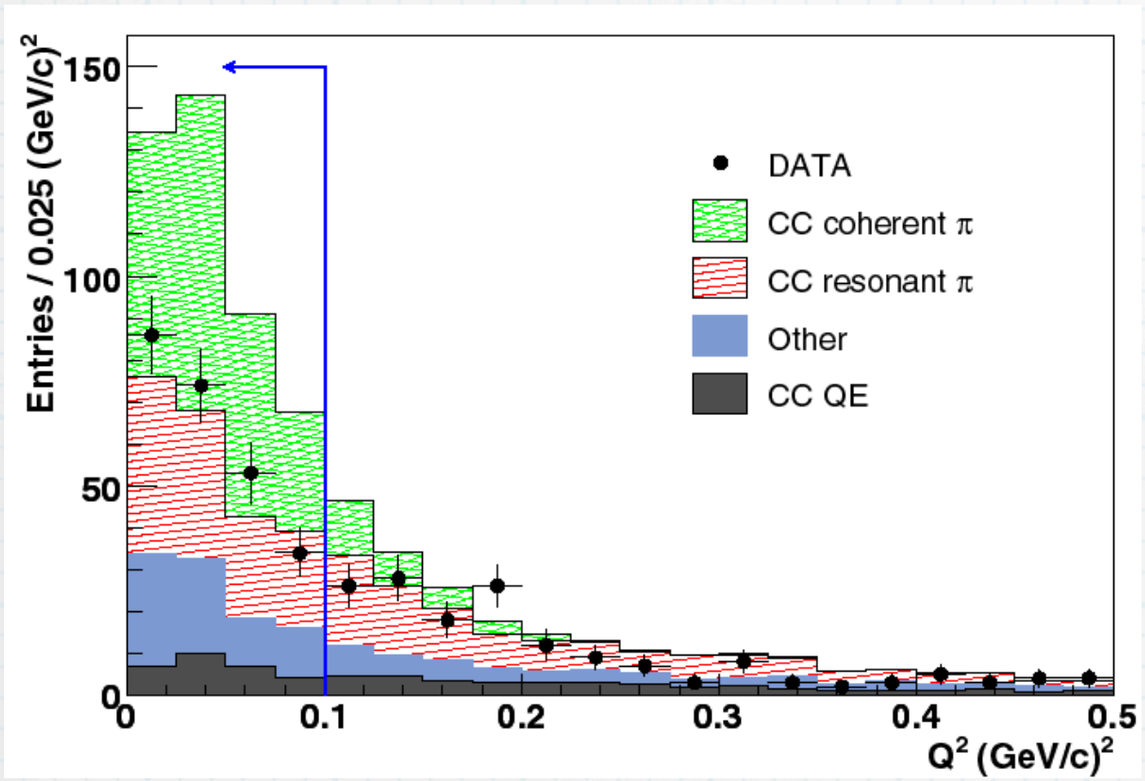
NOTE: MC distributions are absolutely normalized

- New NC-π^0 results for both ν and $\bar{\nu}$ beam modes.
- Demonstrated comparison between data and models
- ν and $\bar{\nu}$ data suggest:
- Clear evidence of non-zero NC coh-π
- Forward angular distribution is sensitive to model predictions

CC coh-π results from SciBooNE

Phys . Rev. D78 112004, 2008

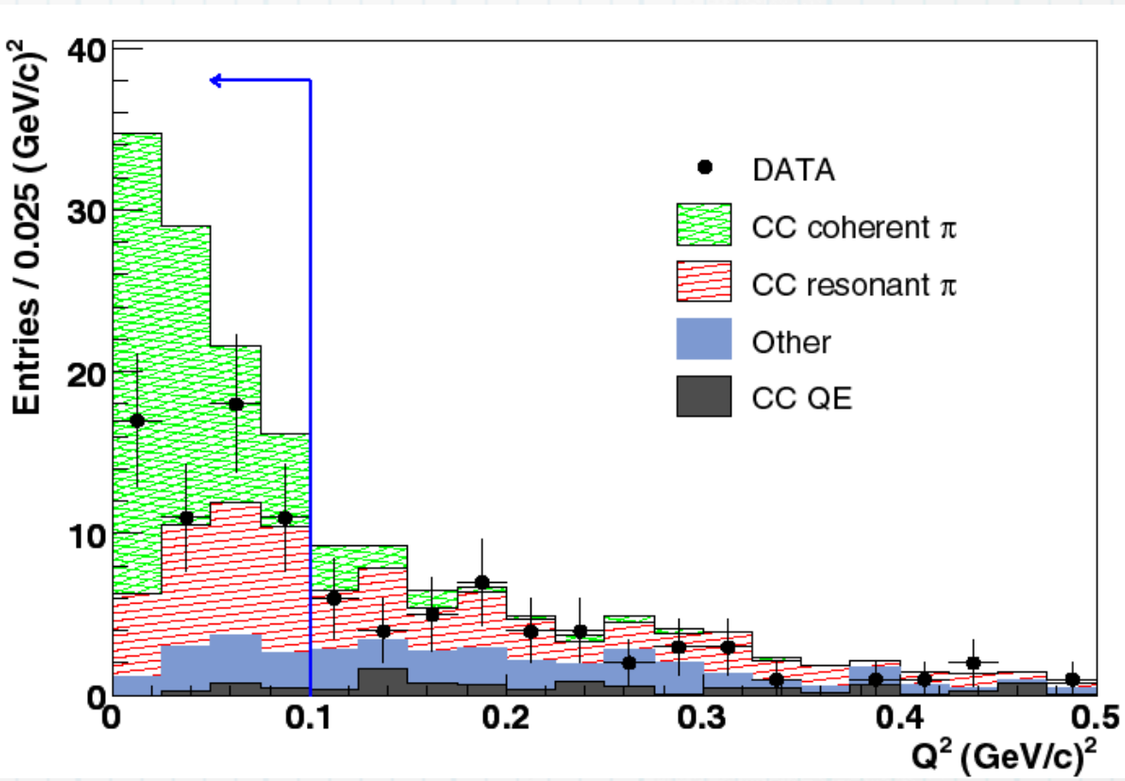
MRD stopped sample
<Eν>= 1.1 GeV



$$\sigma(\text{CC coherent}\,\pi)/\sigma(\text{CC})$$

$$= (0.16 \pm 0.17(stat)^{+0.30}_{-0.27}(sys)) \times 10^{-2}$$

MRD penetrated sample
<Eν>= 2.2 GeV



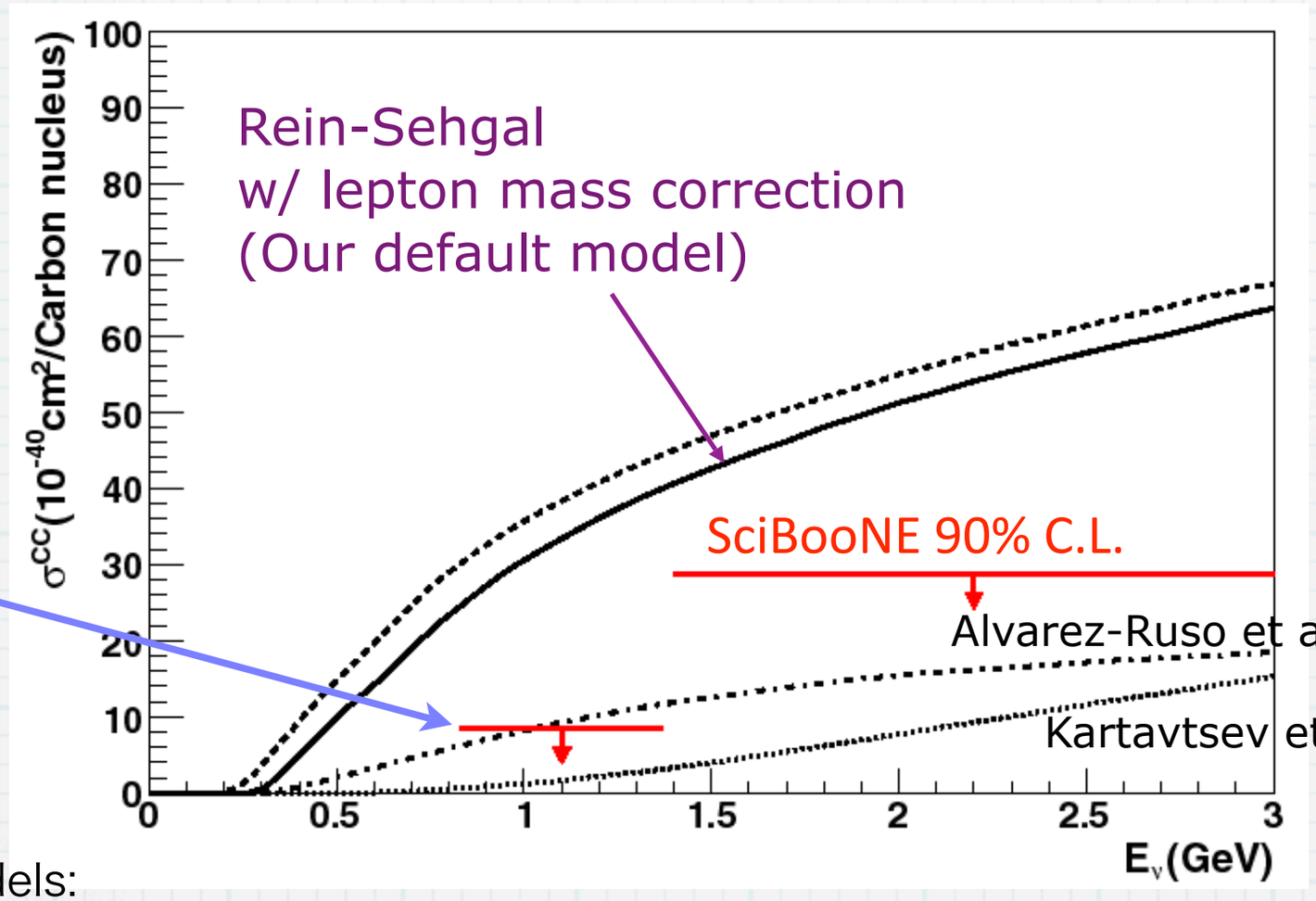
$$\sigma(\text{CC coherent}\,\pi)/\sigma(\text{CC})$$

$$= (0.68 \pm 0.32(stat)^{+0.39}_{-0.25}(sys)) \times 10^{-2}$$

No evidence of CC coherent pion production was found.

➜ Confirmed K2K results

Upper limit on cross section



Upper limit: 33% of the prediction

Measured upper limits on σ(CC coherent π)/σ(CC) ratios are converted to upper limits on absolute cross sections by using σ(CC) predicted by MC simulation.

New coherent π models:

- Singh et al., Phys Rev. Lett. 96:241801 (2006).
- Paschos and Kartavtsev, Phys. Rev D74:054007 (2006).
- Alvarez-Ruso et al., Phys. Rev C75:05501 (2007).
- Nakamura et al. arXiv:0901.2366
- Hernandez et al. Phys. ReV D76, 033005 (2007), D79, 013002 (2009)
- ...

Recently proposed CC coherent π models predict production of CC coherent π events just below our upper limit.

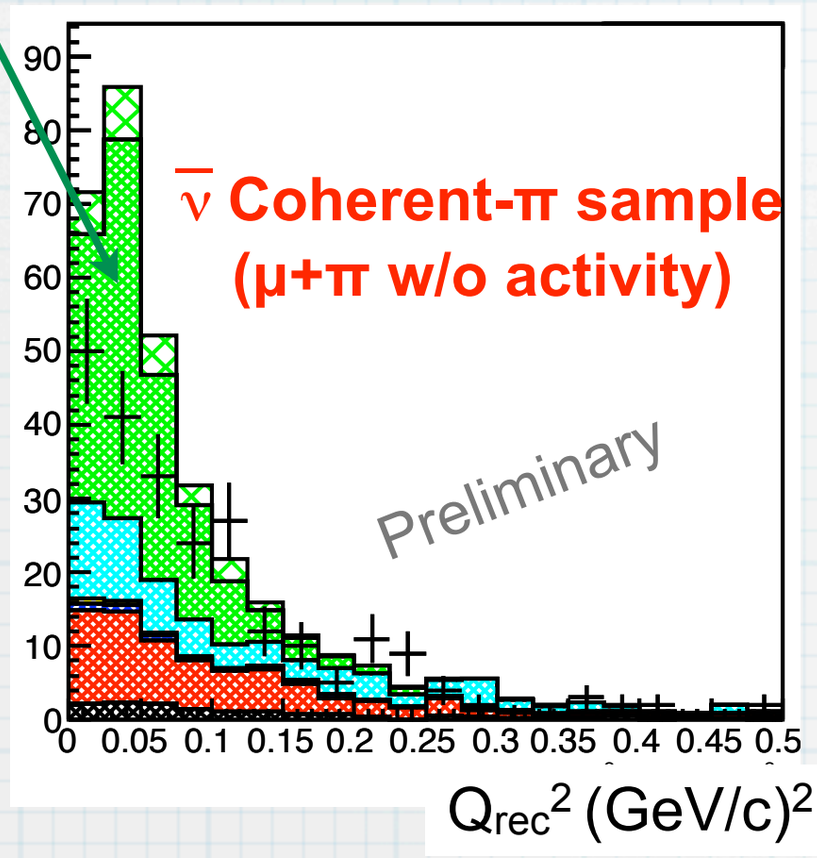
➜ Search for $\bar{\nu}$ CC coherent pion production, since $\bar{\nu}$ data is expected to be more sensitive to look at CC coherent π production than ν data.

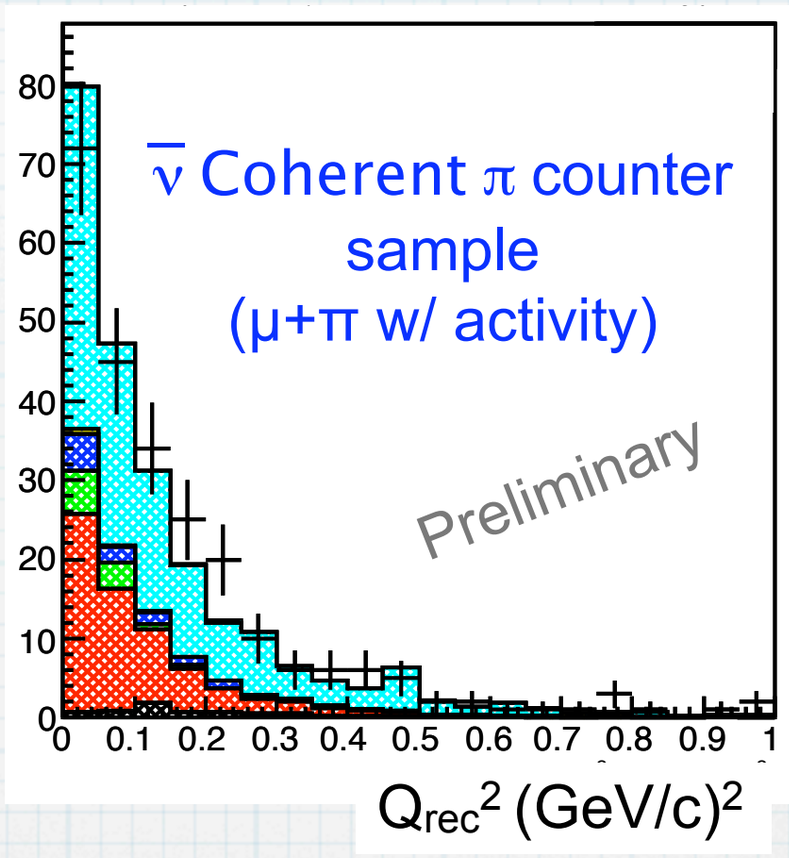
Search for $\bar{\nu}$ CC coherent π at SciBooNE

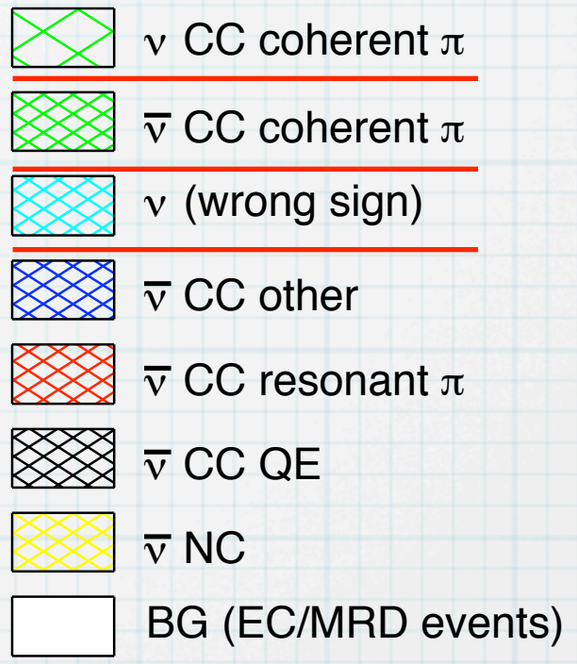
Used the same selection criteria as ν coherent π

(NOTE: no syst. error included, no MC tuning yet)

coherent-π



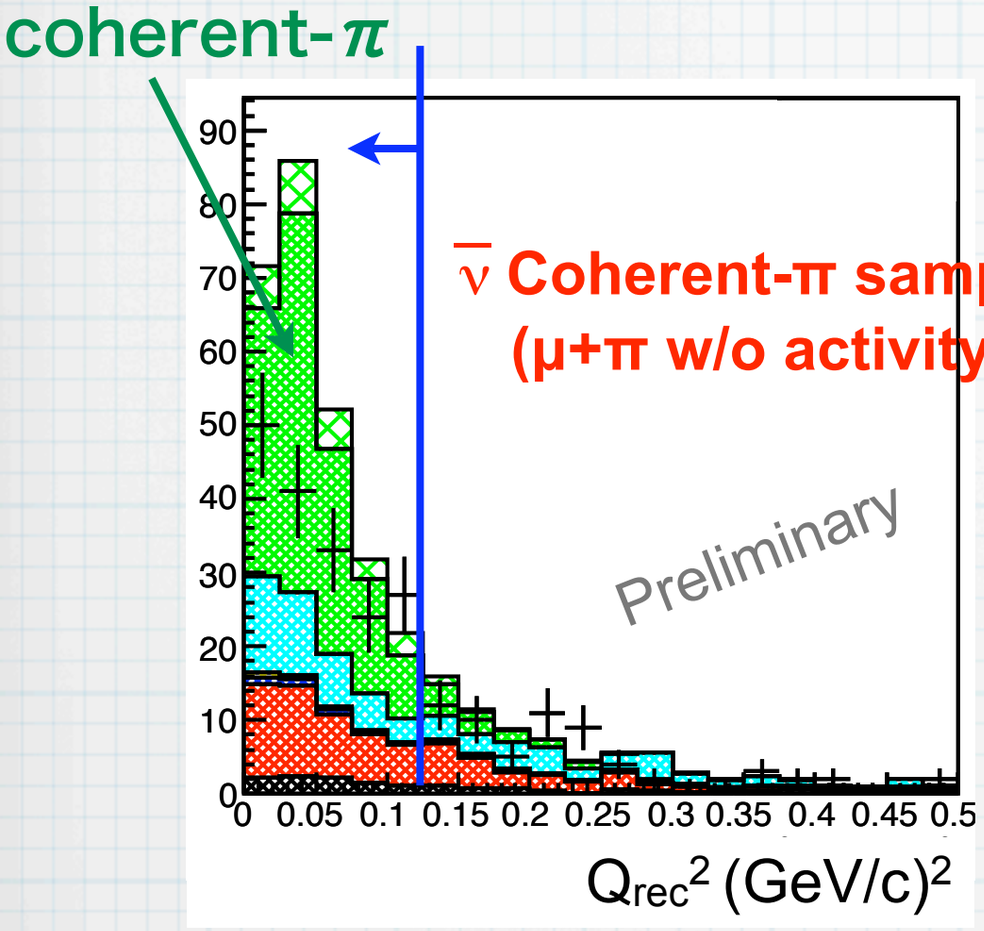




$\bar{\nu}$ coherent π sample also show data deficit at low Q^2 region.

But data suggest non-zero CC coherent π component.

Search for $\bar{\nu}$ CC coherent π at SciBooNE



Preliminary & stat. error only

Define signal region: $Q^2<0.1$ (GeV/c)^2

- 139 events observed
- 80 non-coherent π events (BG)

➜ Data - BG: 59±14 (stat)

NEUT (R&S) prediction: 151 ($\bar{\nu}$:130 ν:21)

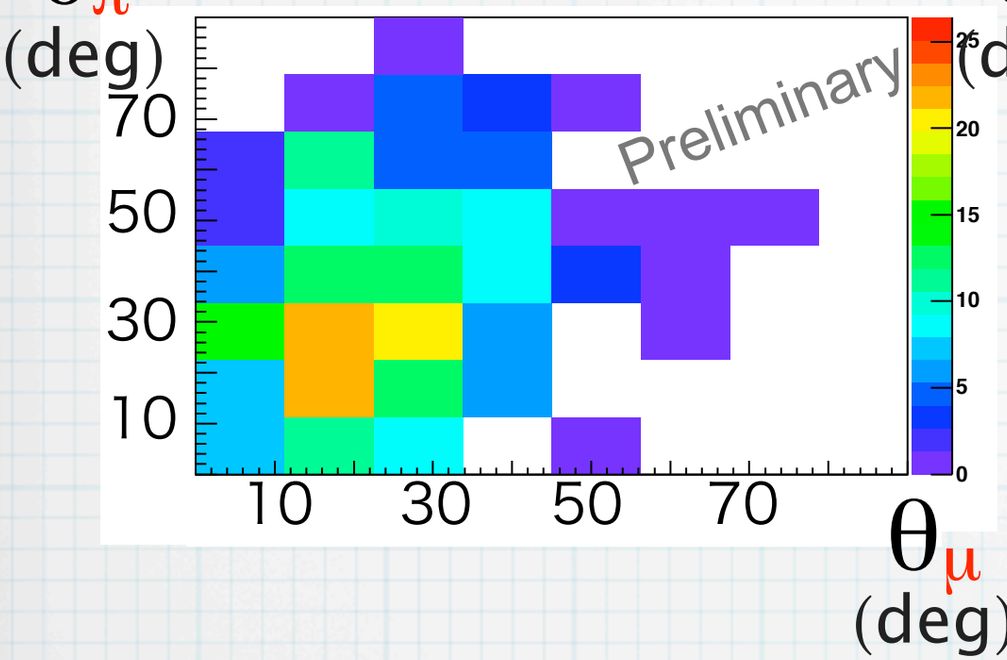
➜ Upper limit of ν results 33% of the prediction: 50 ($\nu+\bar{\nu}$)

4σ level "data excess".

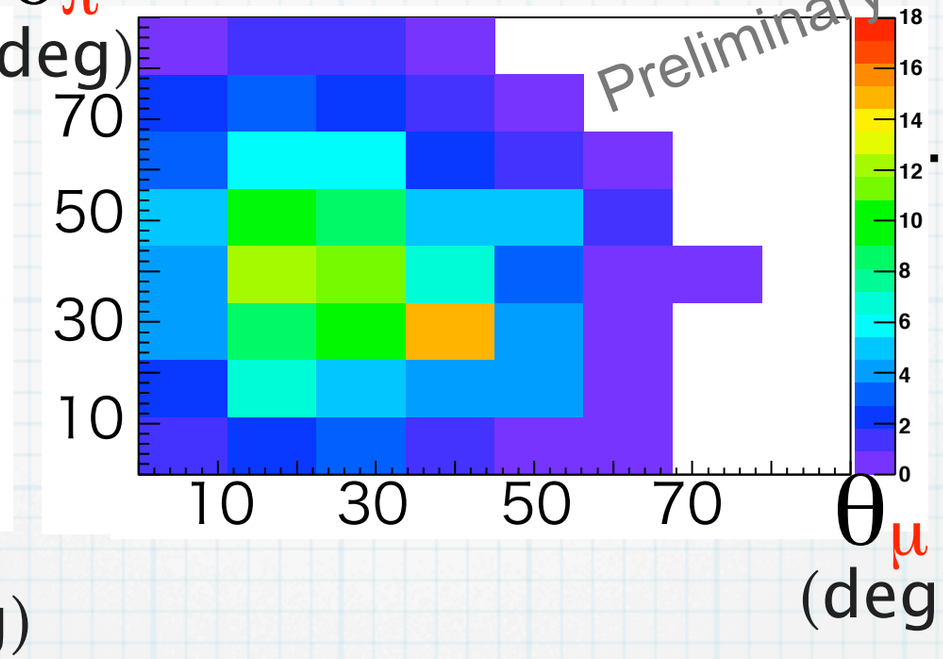
And consistent with ν CC coh-π upper limit within stat error.

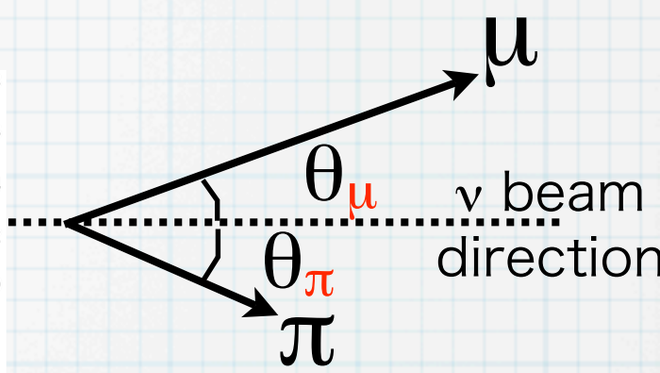
$\bar{\nu}$ CC coherent π sample in θ_π vs θ_μ

Data

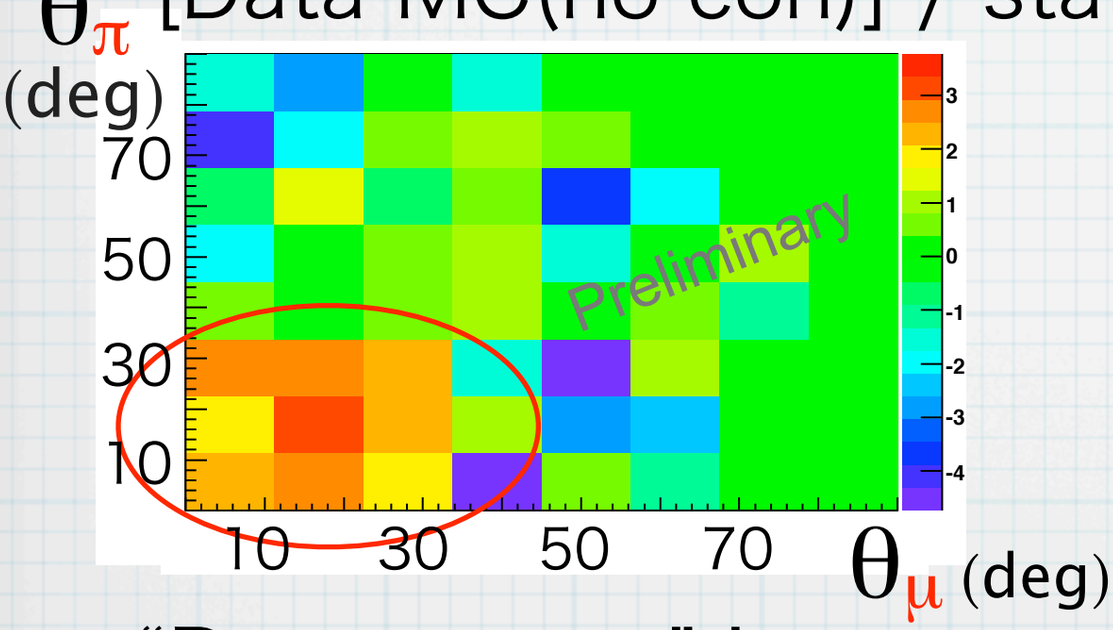


MC (no coh-π)





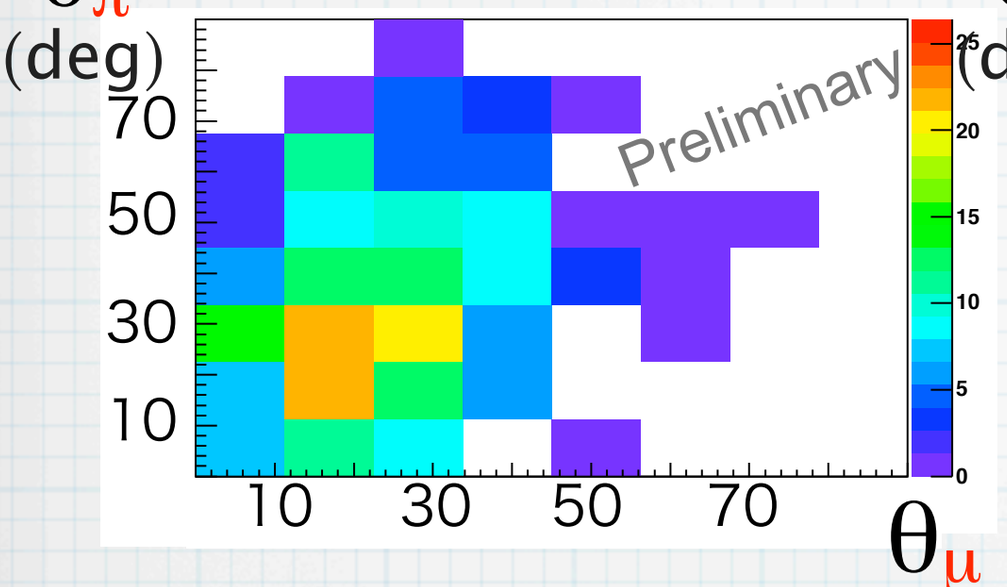
[Data-MC(no coh)] / stat. err



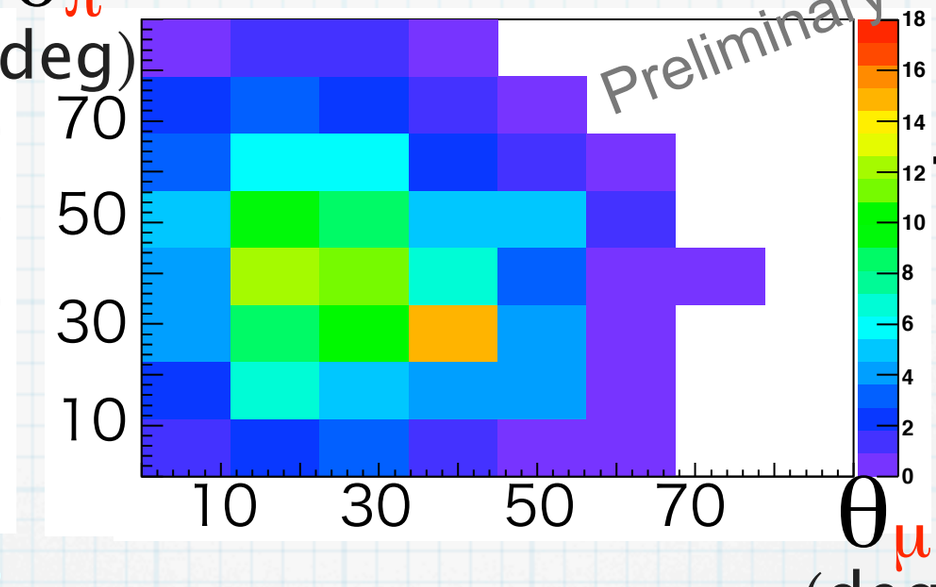
"Data excess" in
small θπ && small θμ

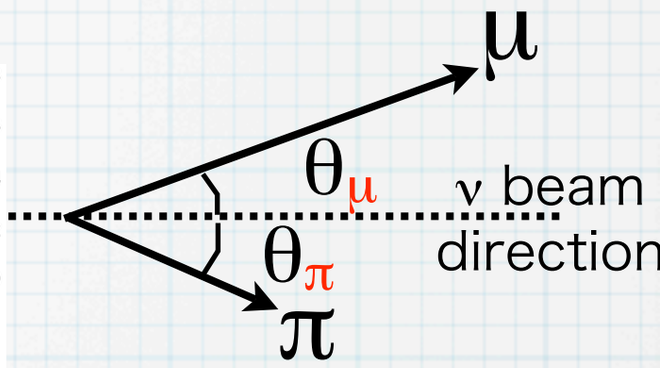
$\bar{\nu}$ CC coherent π sample in θ_π vs θ_μ

Data

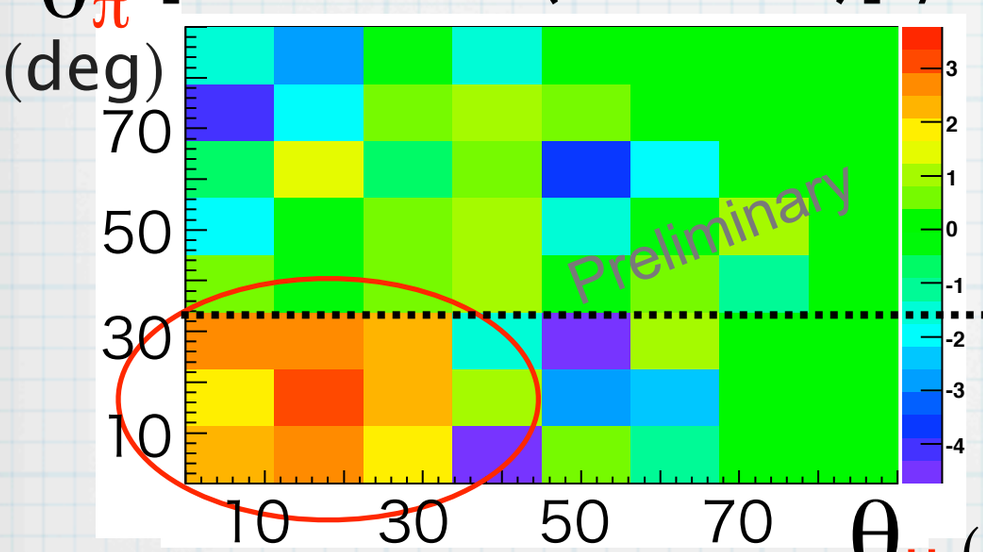


MC (no coh-π)

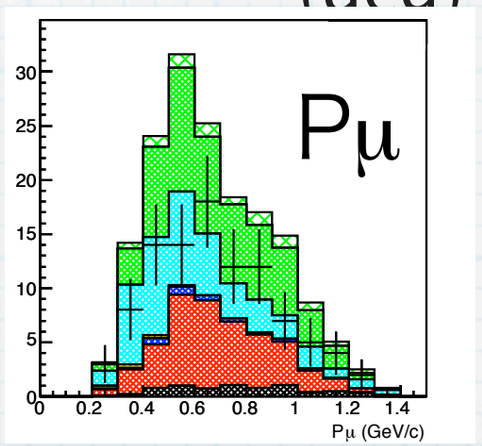


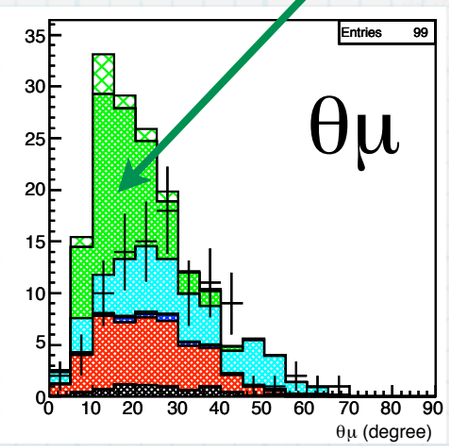


θ_π [Data-MC(no coh)] / stat. err



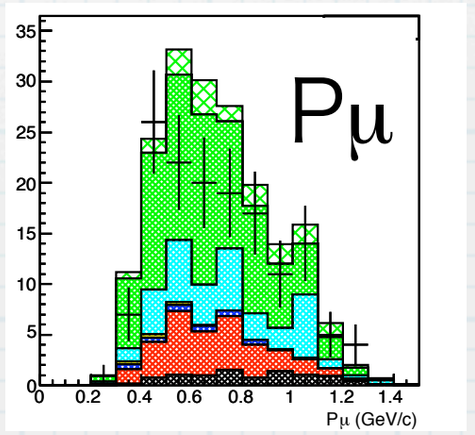
$\theta\pi$ >35°

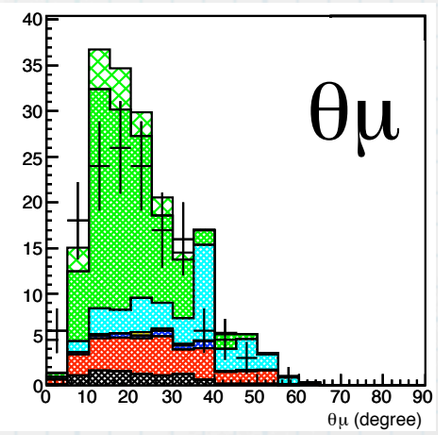




coherent-π

$\theta\pi$ <35°

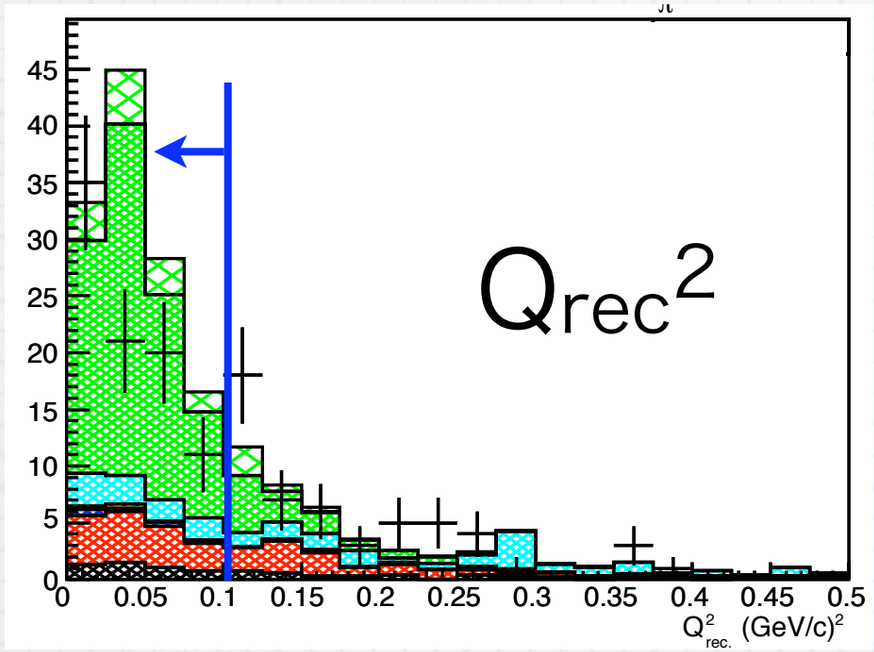




"Data excess" in
small $\theta\pi$ && small $\theta\mu$

$\bar{\nu}$ CC coherent π

$\bar{\nu}$ coh-π, $\theta\pi < 35^{o}$



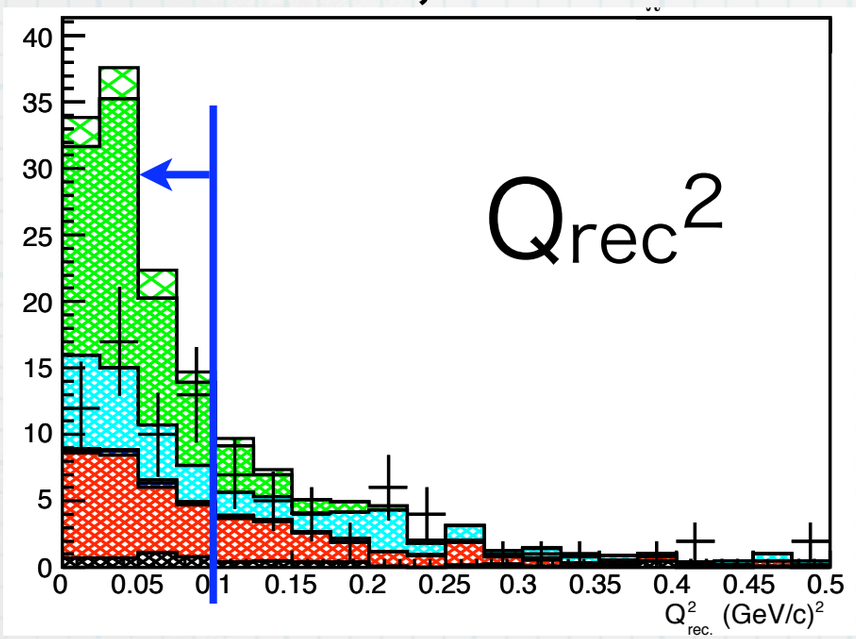
Preliminary & stat. error only

Signal region: $Q^2<0.1$
- 87 events observed
- 31 non-coherent π events (BG)

➜ Data - BG: 56±11 (stat)

NEUT (R&S) prediction: 92 ($\nu+\bar{\nu}$)

$\bar{\nu}$ coh-π, $\theta\pi > 35^{o}$



Signal region: $Q^2<0.1$
- 52 events observed
- 49 non-coherent π events (BG)

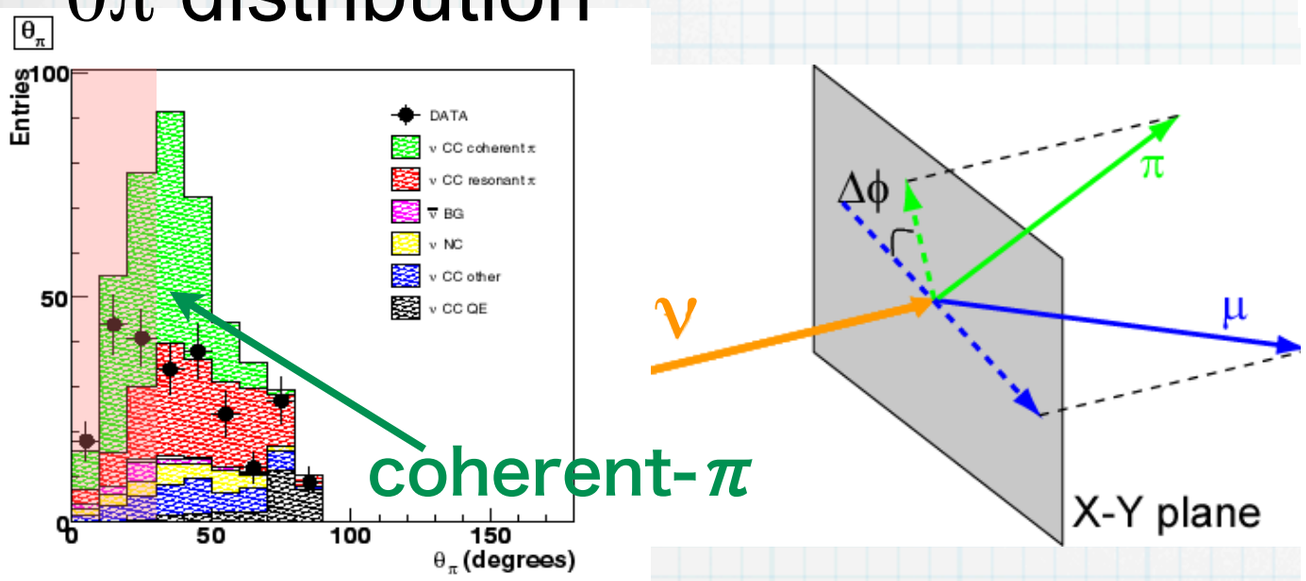
➜ Data - BG: 2.6±8.5 (stat)

NEUT (R&S) prediction: 59 ($\nu+\bar{\nu}$)

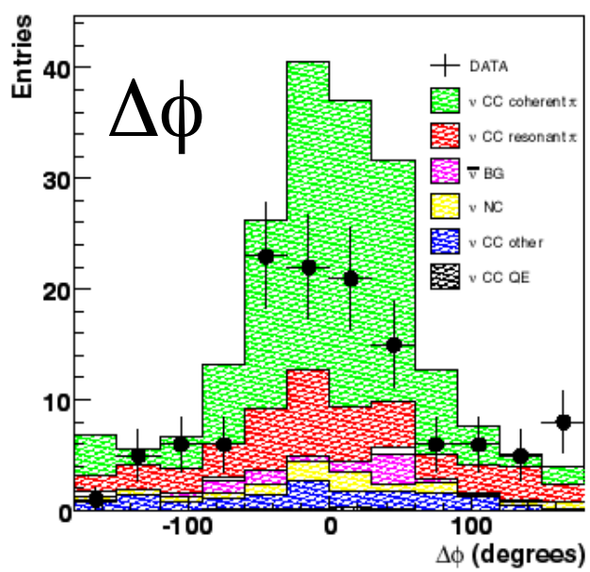
CC coherent π component at small θ_π region.

ν CC coherent π

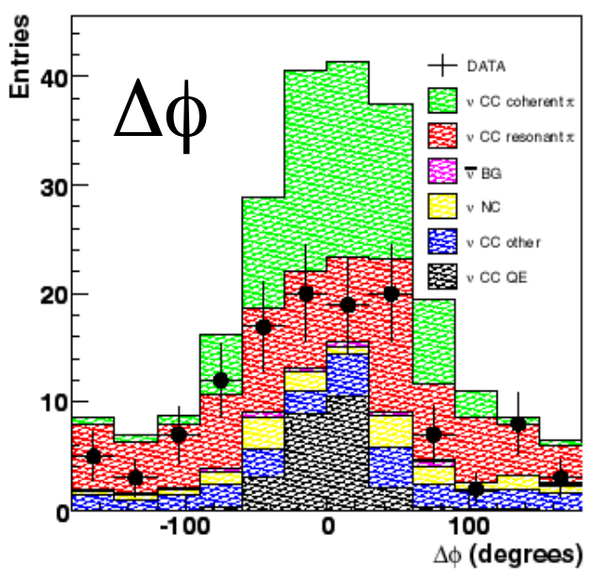
θπ distribution



θπ < 35 deg



θπ > 35 deg

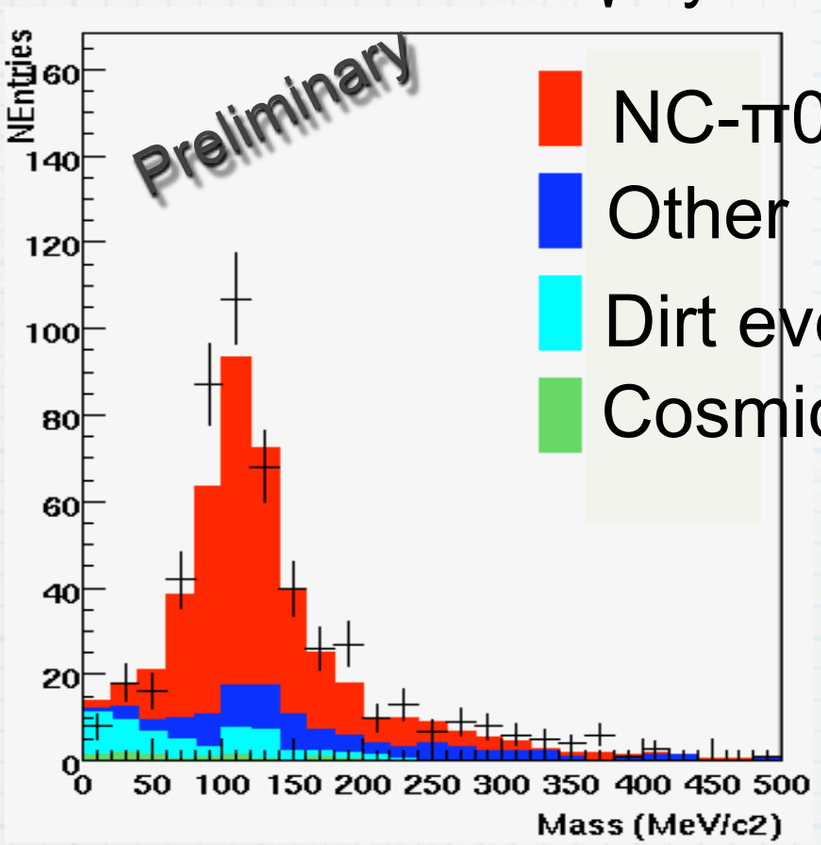


K. Hiraide at NuInt09

- Similar enhancement in ν data
  - ➜ Pions from CC coh-π production tend to be produced more forward than prediction.
- Important to measure π kinematics.
- In order to describe data, pion kinematics description needs to be improved.

NC-π^0 from SciBooNE

Reconstructed invariant mass in 2γ system

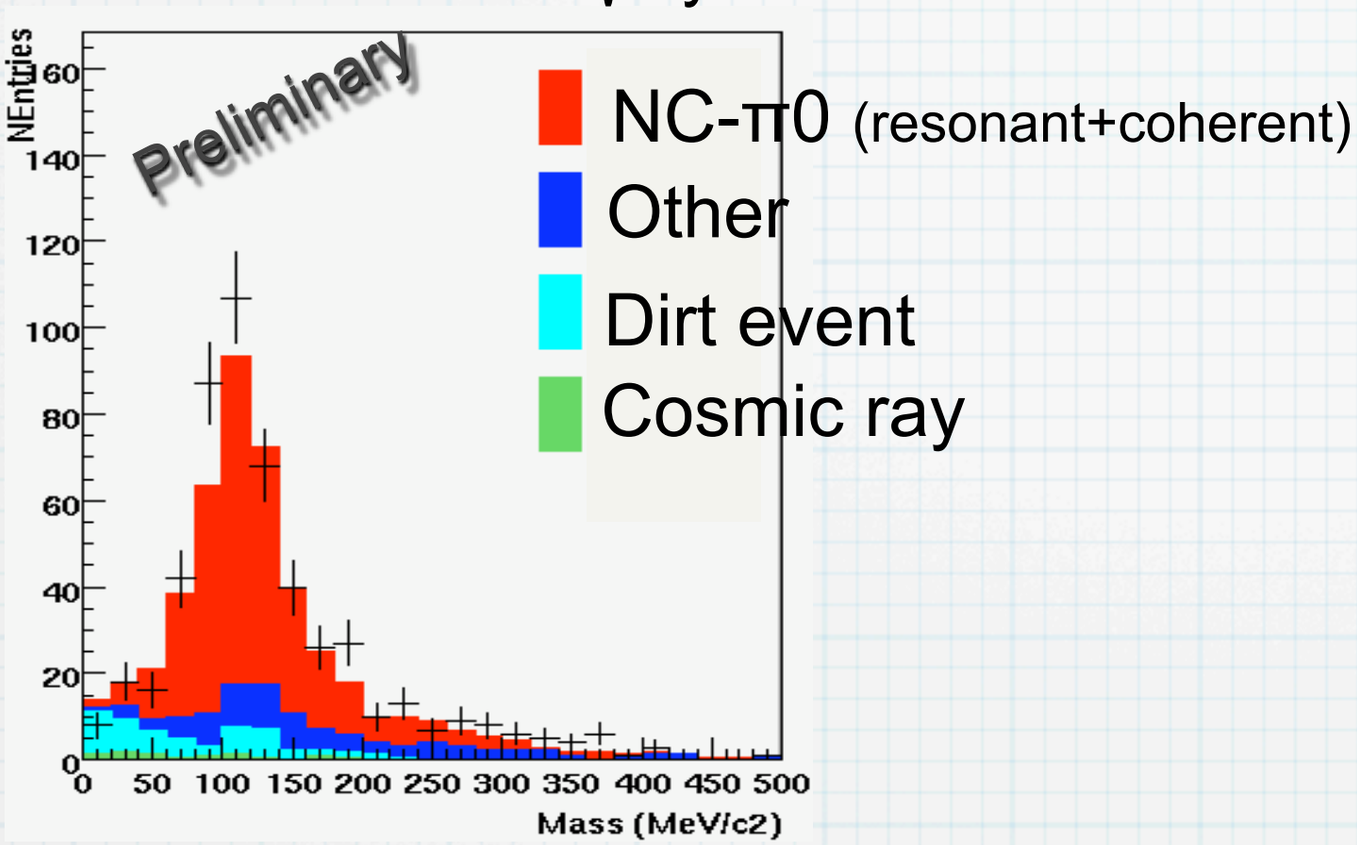


$$\frac{\sigma(\text{NC-}\pi^0)}{\sigma(\text{CC})} = 7.5 \pm 0.6(\text{stat.})\ ^{+0.76}_{-0.90}\ (\text{sys.}) \times 10^{-2}$$

cf. MC prediction: $\frac{\sigma(\text{NC-}\pi^0)}{\sigma(\text{CC})} = 6.8 \times 10^{-2}$

NC-π^0 from SciBooNE

Reconstructed invariant mass in 2γ system



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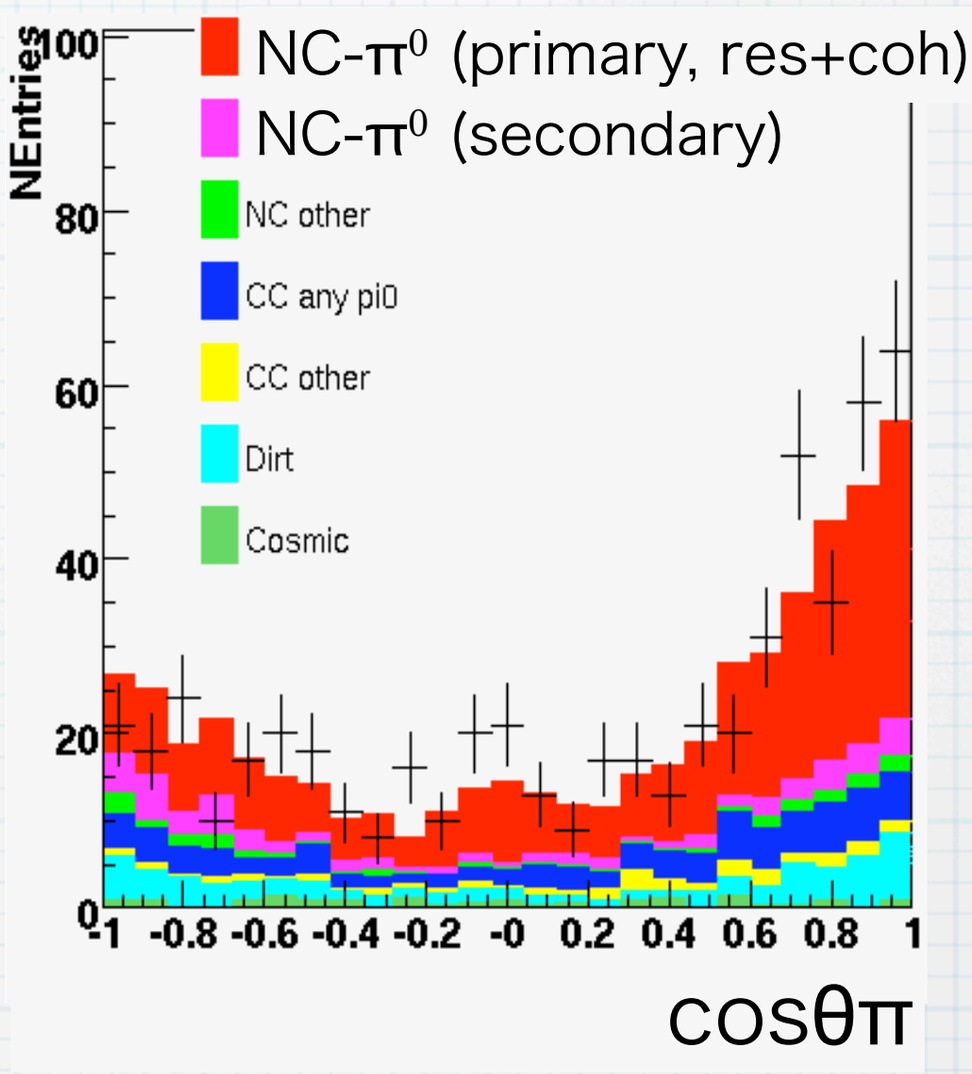
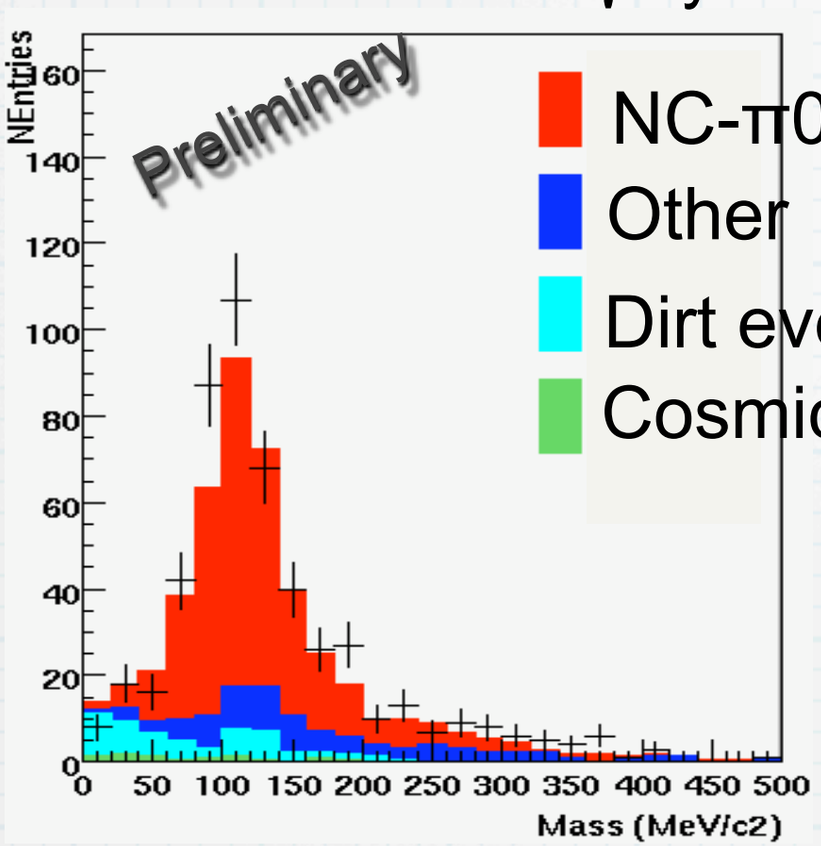


Data/MC prediction are in fairy good agreement.

NC-π^0 from SciBooNE

Reconstructed invariant mass in 2γ system



$$\frac{\sigma(\text{NC-}\pi^0)}{\sigma(\text{CC})} = 7.5 \pm 0.6(\text{stat.})\ ^{+0.76}_{-0.90}\ (\text{sys.}) \times 10^{-2}$$

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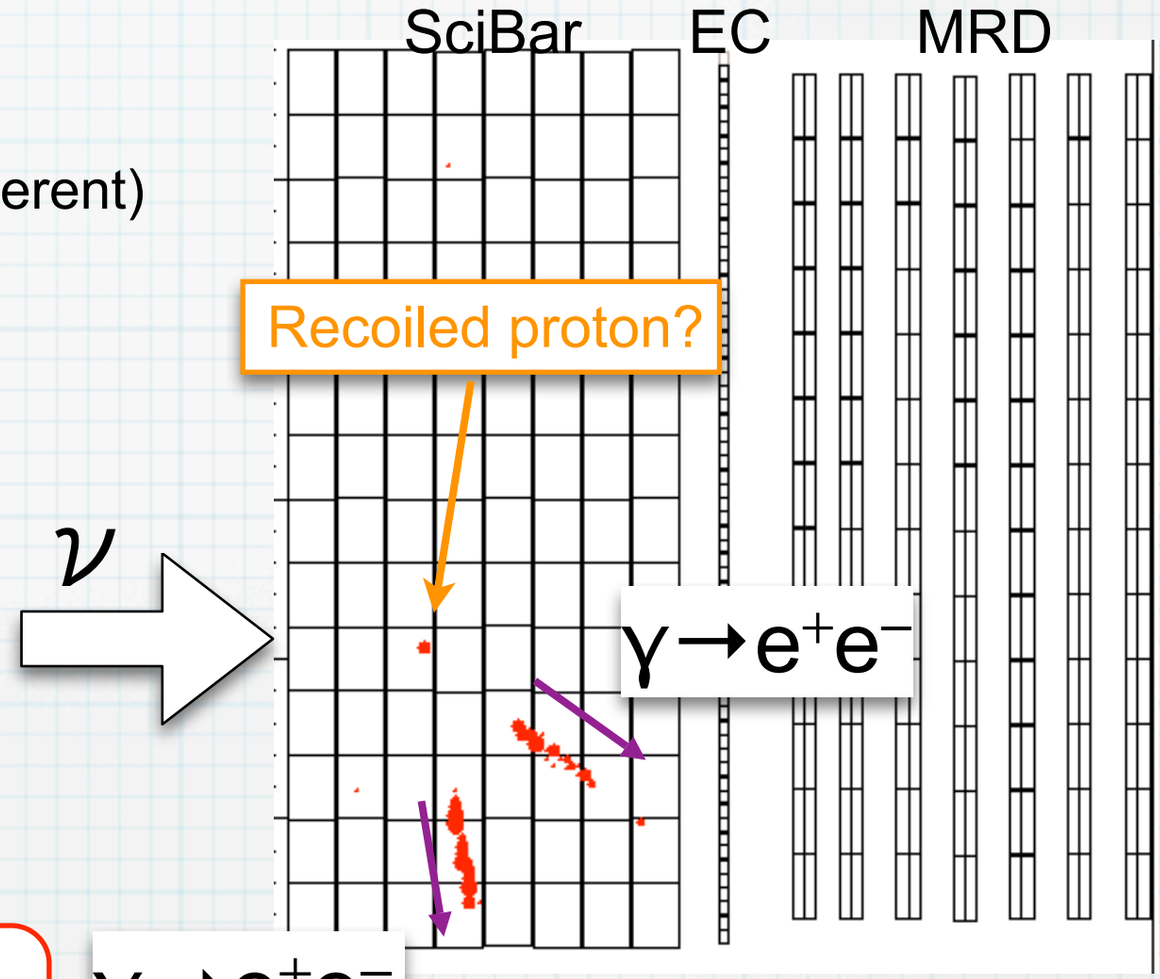


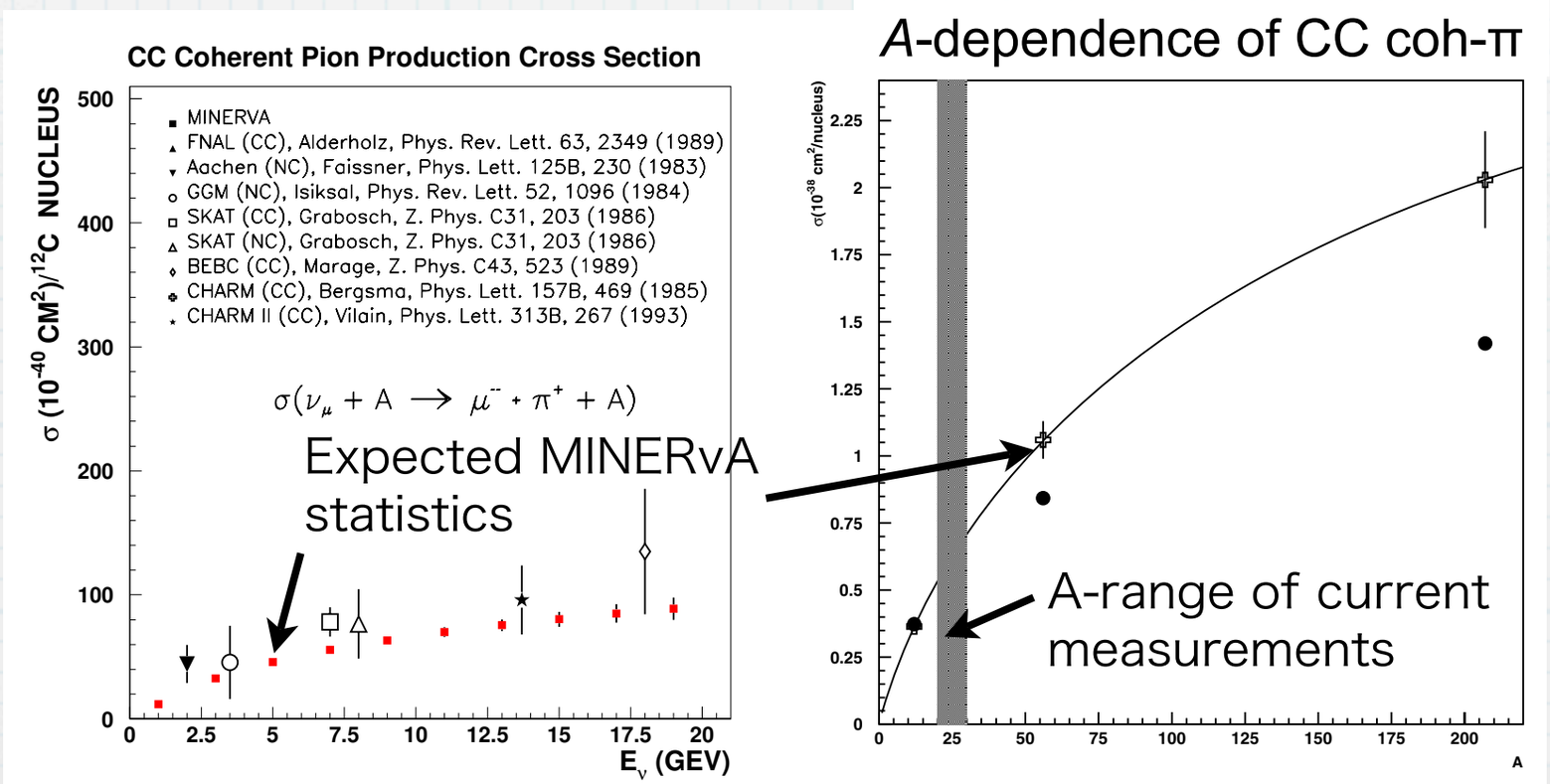
● : SciBar hit, area∝energy deposit

SciBar has a capability to distinguish NC resonant-π0 and coherent-π0 event-by-event.

Future prospect

- MINERvA (NuMI at Fermilab) has an excellent capability for CC and NC coherent π productions
  - Wide energy range: Ev ~2-20 GeV
  - Several nuclear targets: He, C (and CH), Fe, Pb
  - Reconstruct energy of final state hadronic system.
  - Data taking starts soon.
- Have been running with the full Tracking Prototype in the ν beam since mid April 2009!

Plots from MINERvA proposal



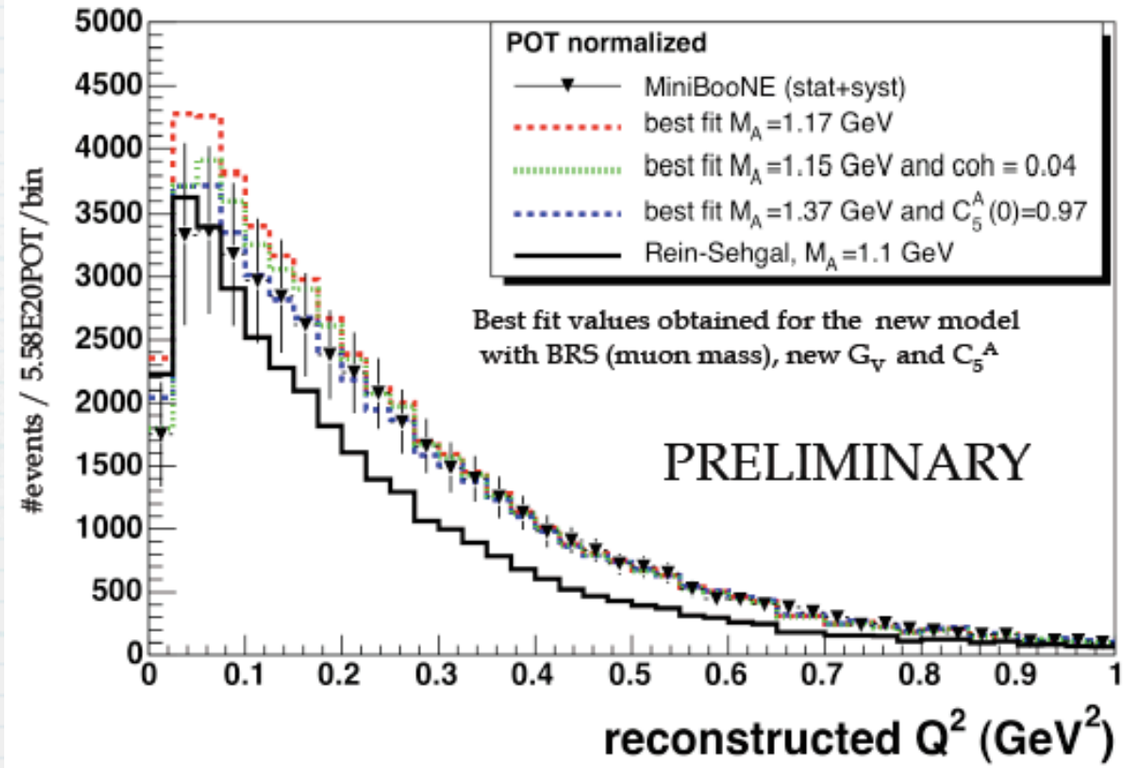
Summary

- Several measurements on coherent pion production.
  - ν, $\bar{\nu}$, CC and NC modes
- Recent results on CC/NC coherent π at low energy, ~1GeV.
  - Although good agreement between high energy results and R&S model, not so for low energy results.
- Data suggest: pions from CC coherent π tend to be produced more forward than R&S model prediction.
- A variety of models has been proposed.
- New experimental results will be published shortly.
- Experimental & theoretical studies are in progress.

Backup

CC-π^+ at MiniBooNE

J. Nowak at NuInt09



- The new model of charged Current pion production Improved agreement with data
- We performed fits for three models

1. The fit result for $M_A^{1\pi}$ for $Q^2>0.2GeV^2$

$M_A^{1\pi}$=1.17±0.13 GeV.

2a. Coherent contribution and $M_A^{1\pi}$

$M_A^{1\pi}$=1.15 GeV
Coherent<0.04

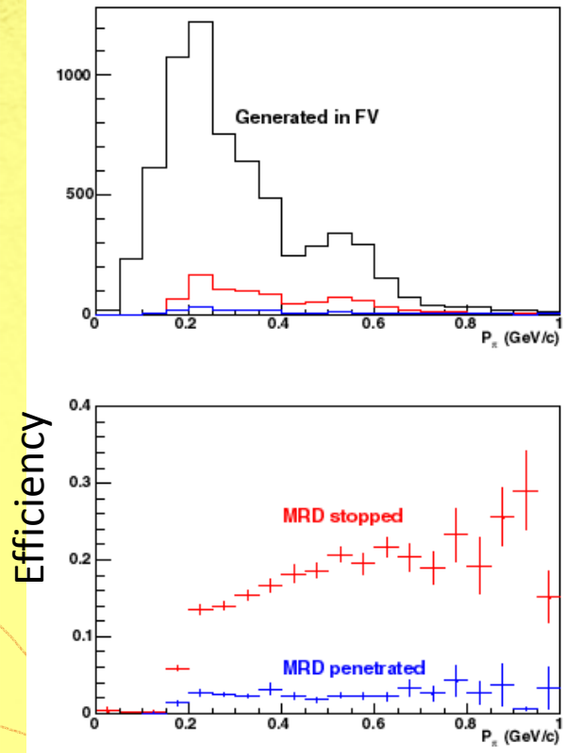
2b. $M_A^{1\pi}$ and $C_5^A(0)$

$M_A^{1\pi}$=1.37 GeV
$C_5^A(0)$=0.97

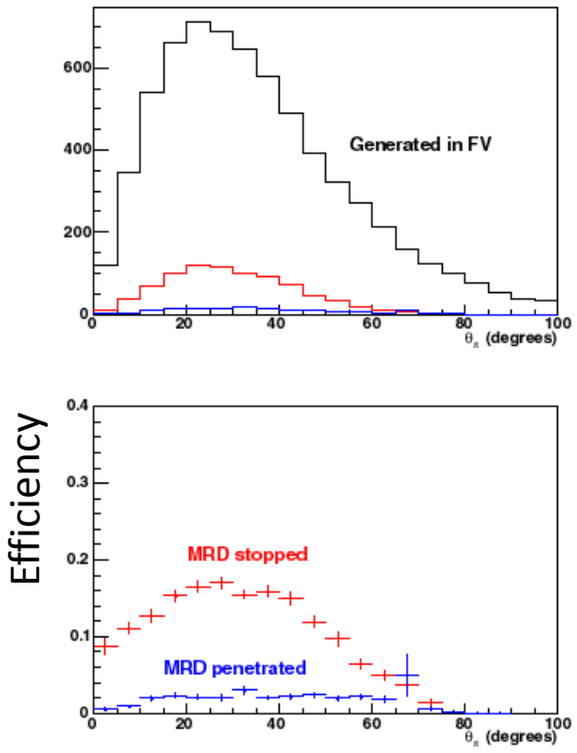
SciBooNE efficiency

CC coherent pi efficiency vs Pπ, θπ, and θμπ

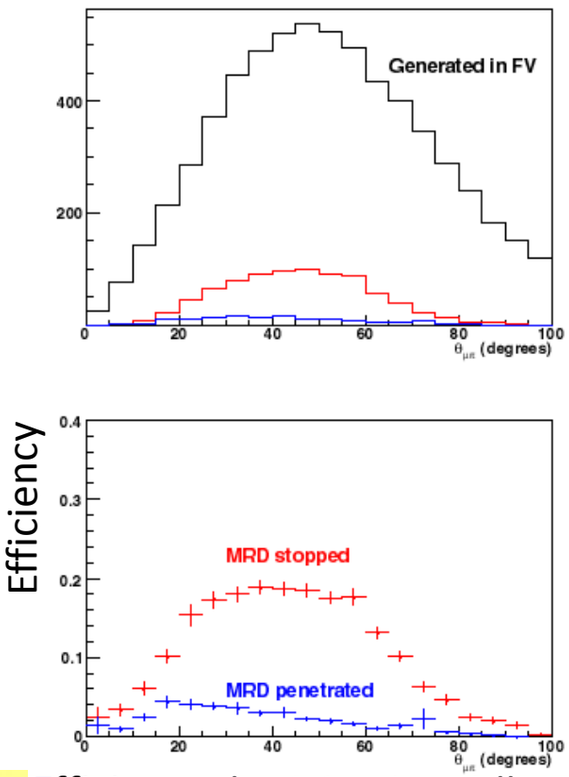
Pion momentum



Pion angle



Opening angle



No efficiency for pion momentum below 0.15 GeV/c

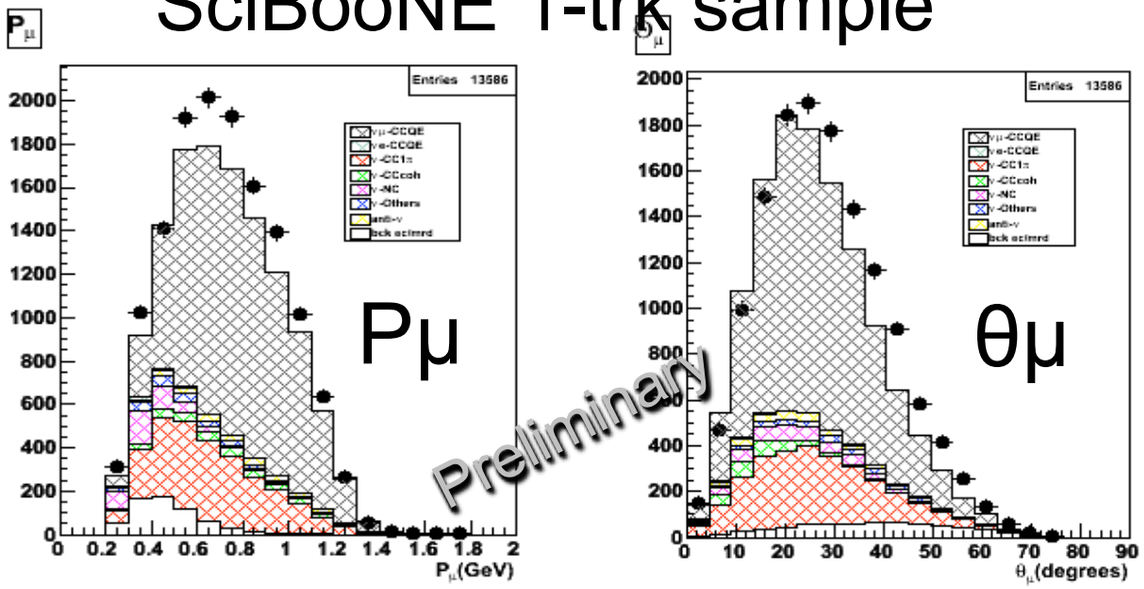
Efficiency drops at a small (<20 degrees) opening angle between muon and pion

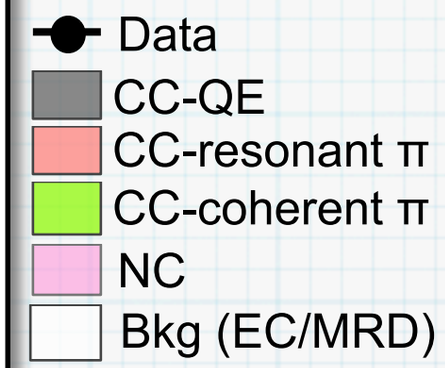
The efficiency calculation depends on the model prediction of kinematics

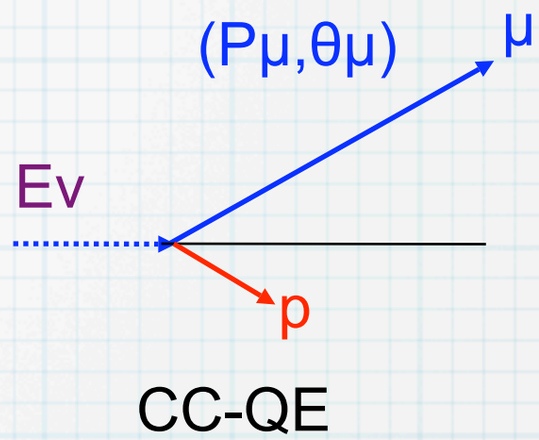
K. Hiraide at NuInt09

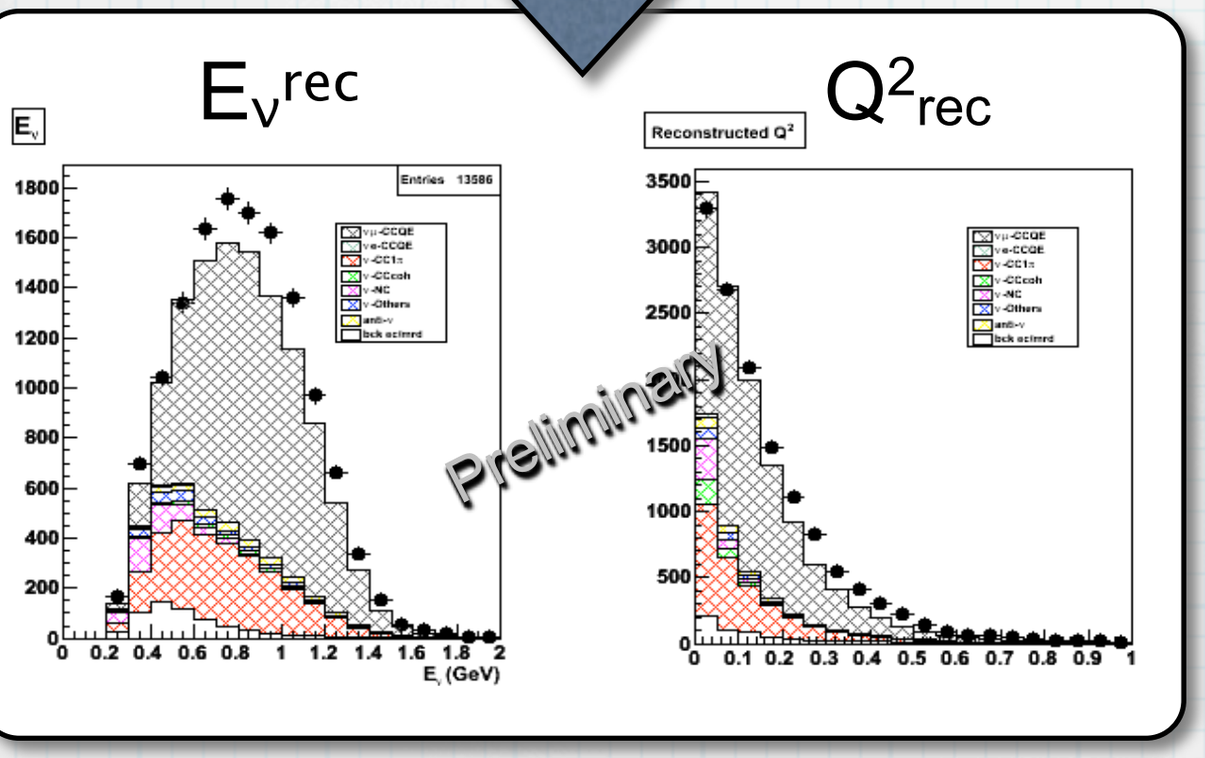
Ev, Q^2 reconstruction

SciBooNE 1-trk sample









Ev, Q^2 reconstruction assuming CC-QE (v+n→μ+p)

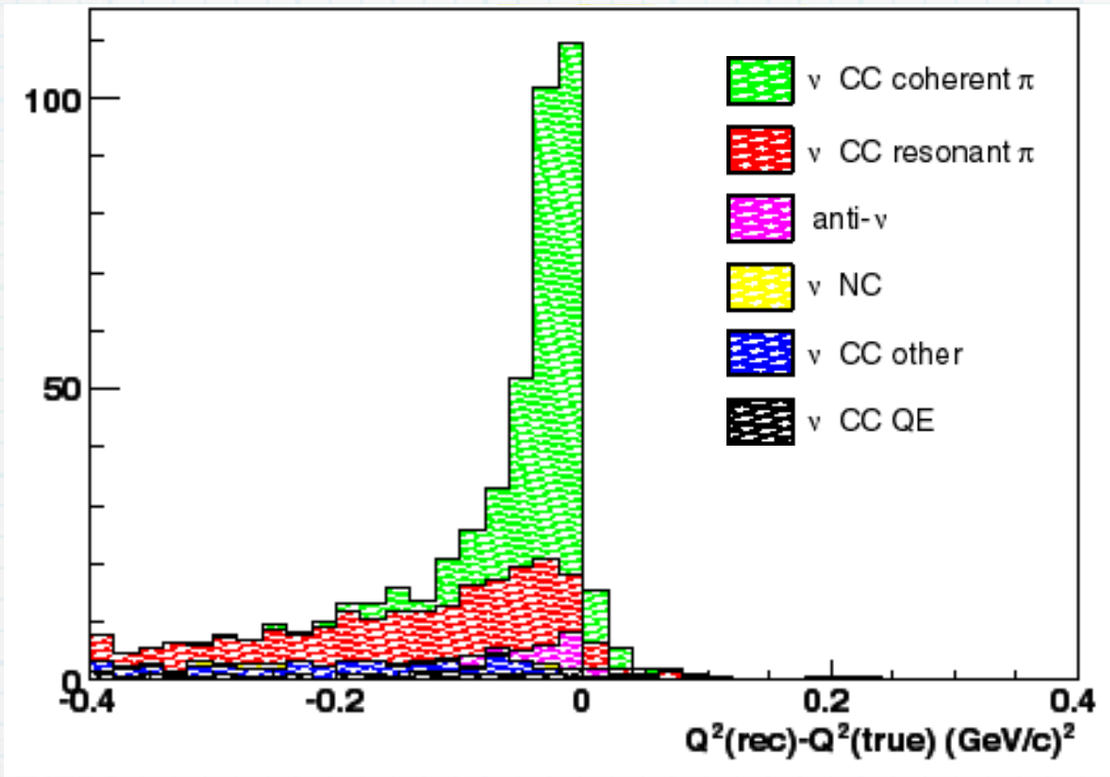
Uses only muon kinematics

$$E_\nu^{rec} = \frac{1}{2}\frac{(M_p^2 - m_\mu^2) - (M_n - V)^2 + 2E_\mu(M_n - V)}{(M_n - V) - E_\mu + p_\mu \cos\theta_\mu}$$

V: nuclear potential (27MeV)

$$Q^2_{\text{rec}} = 2E_\nu^{rec}(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$$

Q2 resolution for CC coherent π



Q2 resolution of CC-coherent πevents

Mean: -0.024 $(GeV/c)^2$

Sigma: 0.016 $(GeV/c)^2$

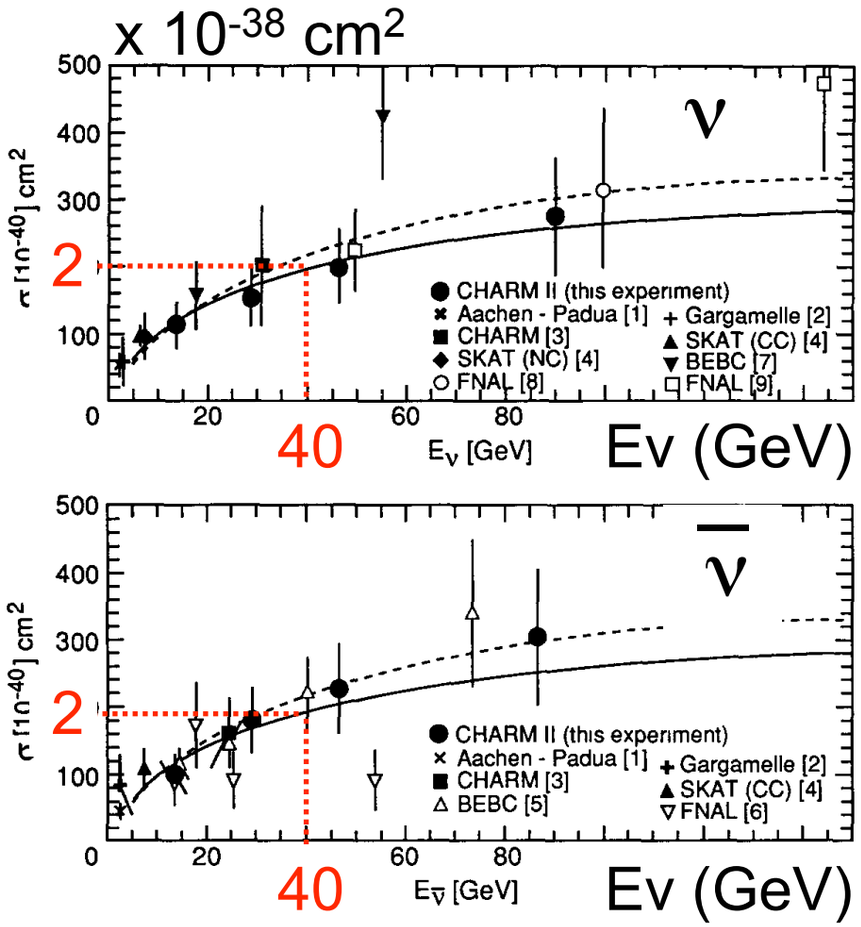
$\bar{\nu}$ Coherent pion production

Several measurements in past (‘80-’90).

Measurements are at high energy region.
Rein-Sehgal model well describes the data.

High energy results and the model suggest: cross sections of coherent π prod. for ν and $\bar{\nu}$ are similar size.

$\sigma(\nu CC\text{-coh}) \sim \sigma(\bar{\nu}\ CC\text{-coh})$



Plots from Phys.Lett. B313, 267-275 (1993)

Solid line: Rein-Sehgal model

Dotted line: Bel’kov-Kopeliovich

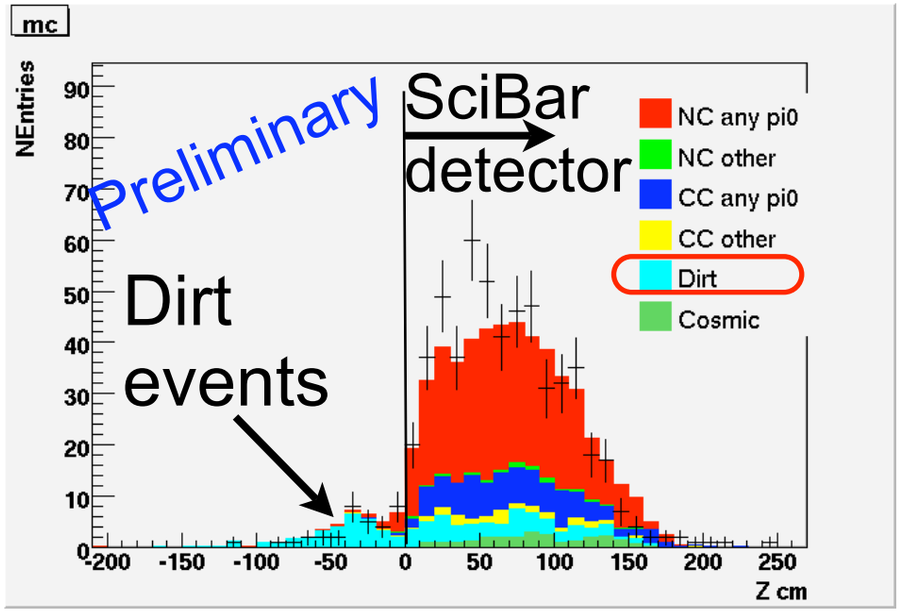
➜ $\bar{\nu}$ data is expected to be more sensitive to look at CC coherent π production than ν data.

∵ $\sigma(\nu\ CC) > \sigma(\bar{\nu}\ CC)$

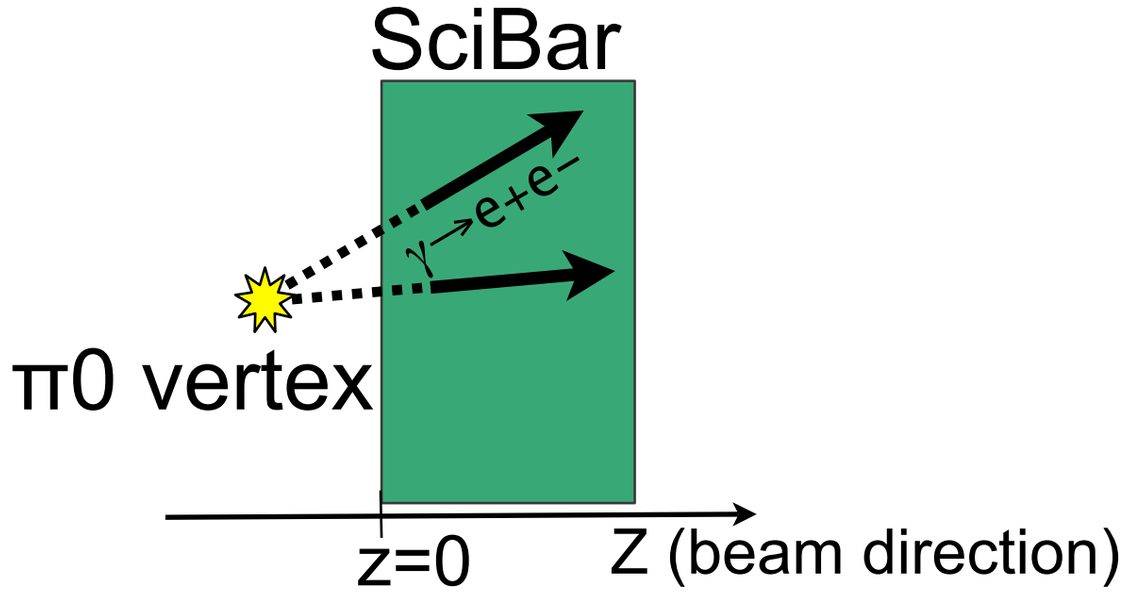
Reconstructing π0

Y. Kurimoto

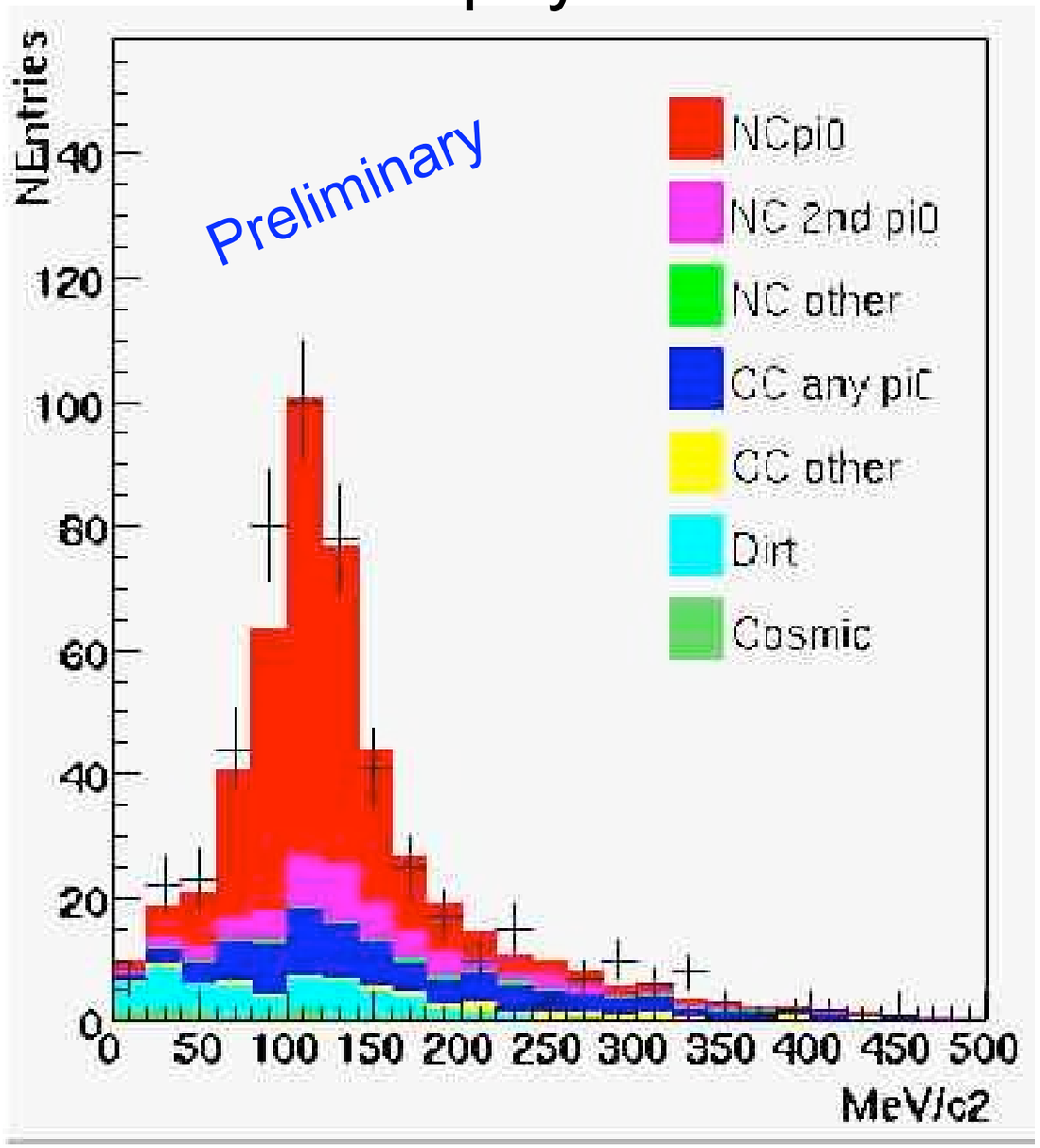
Reconstructed π0 vertex position



ex. Dirt event



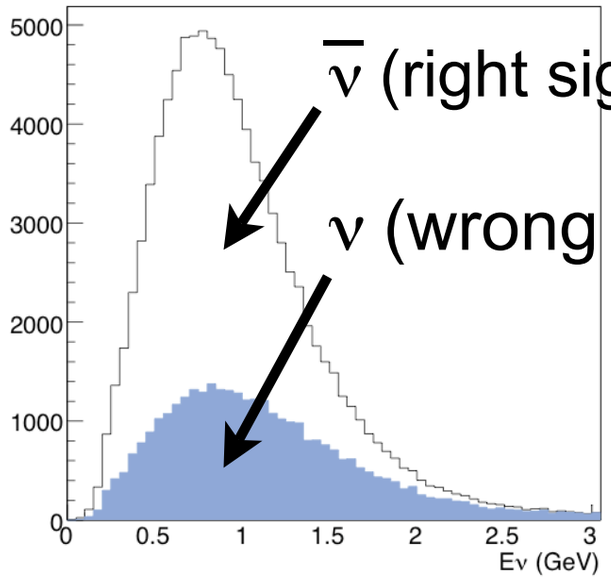
Reconstructed invariant mass for 2γ system



Data: ~550 events
MC: ~60% NCπ0 purity

ν contamination in $\bar{\nu}$ beam mode

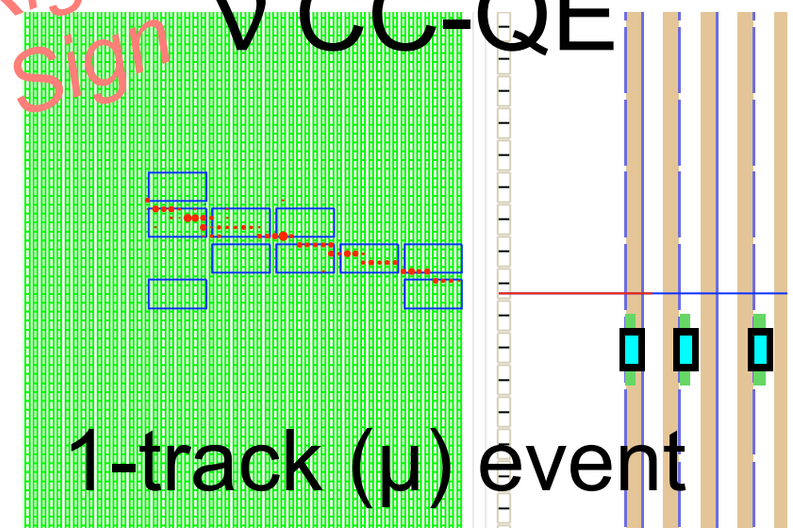
SciBooNE



ν (wrong sign) ~30% background in MRD stopped sample

Right sign

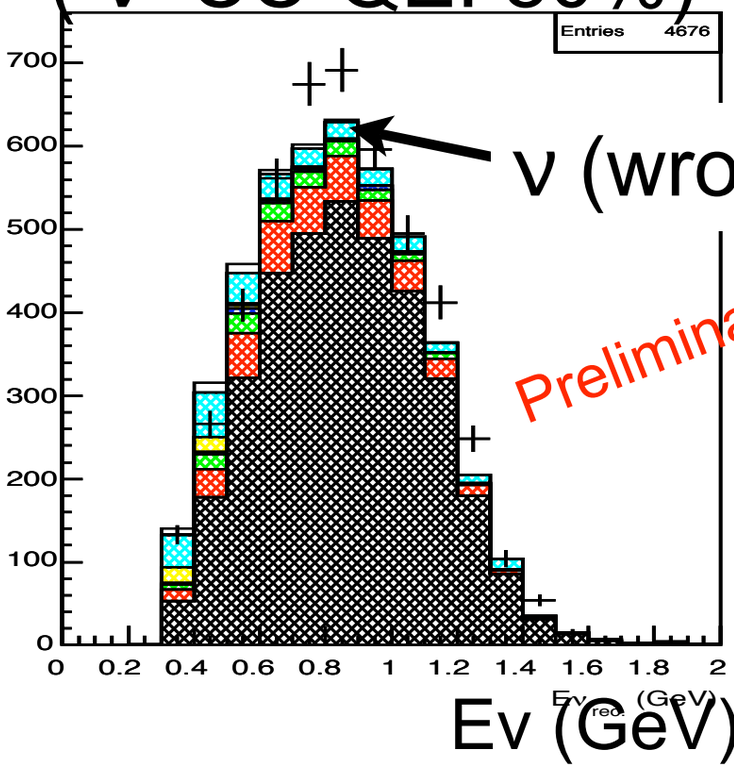
$\bar{\nu}$ CC-QE



1-track (μ) event

~90% $\bar{\nu}$ purity

($\bar{\nu}$ CC-QE: 80%)

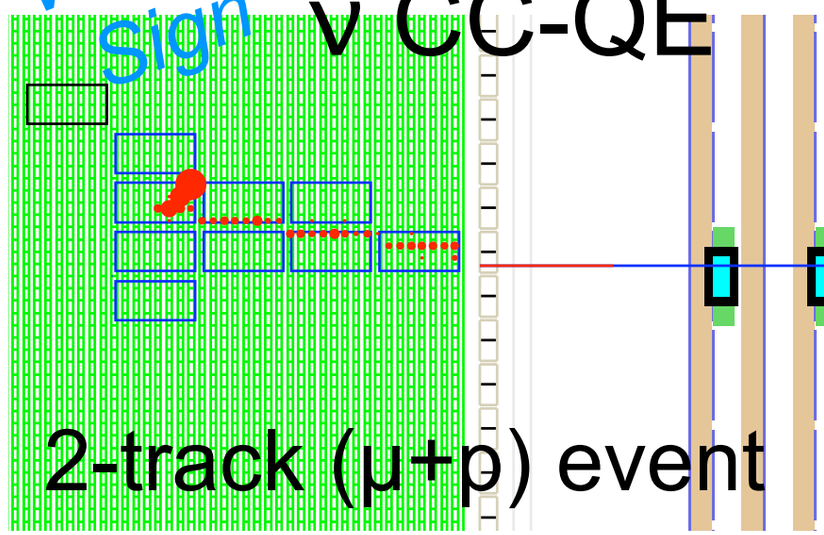


Ev (GeV)

1-track w/o activity sample

Wrong sign

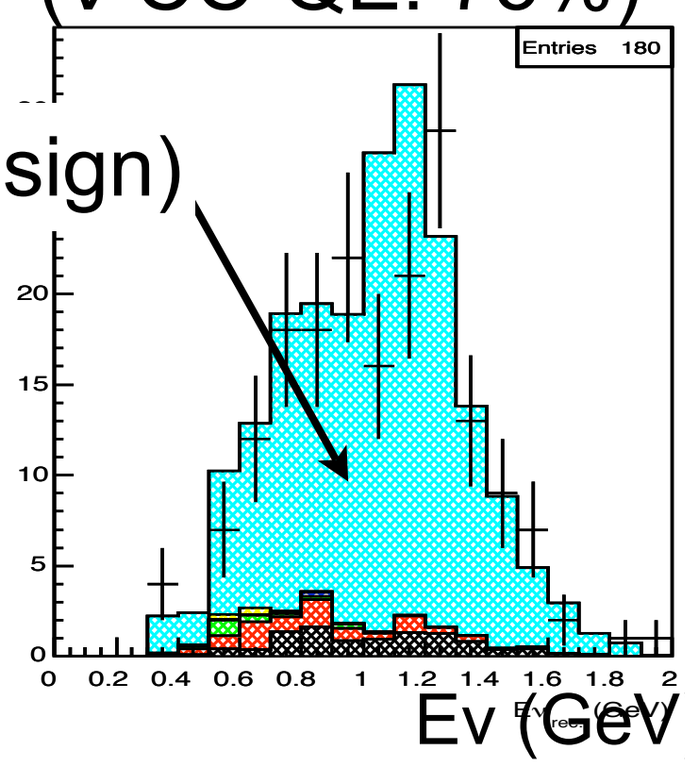
ν CC-QE



2-track (μ+p) event

~90% ν purity

(ν CC-QE: 75%)



Ev (GeV)

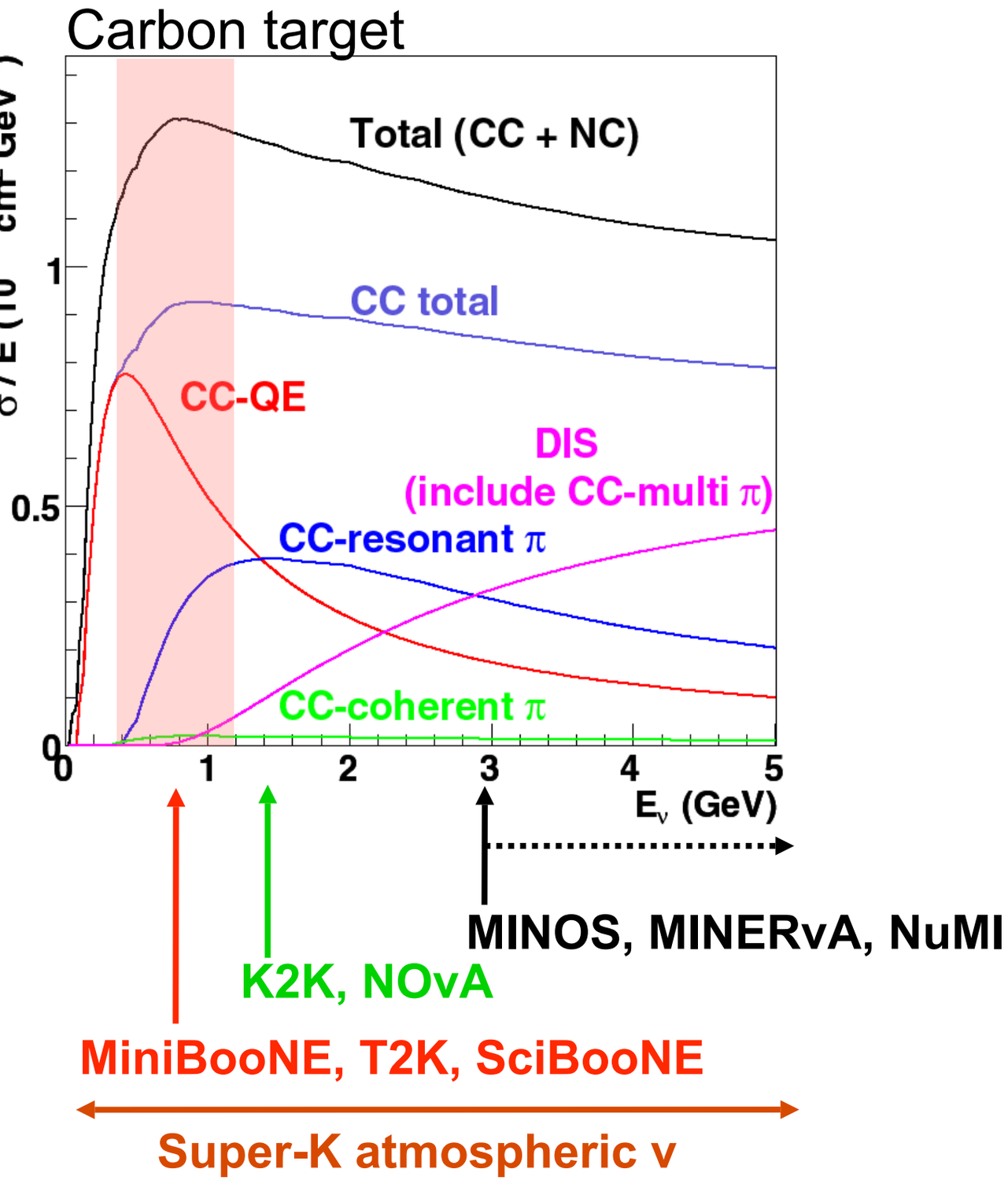
2-track QE-like sample

ν (wrong sign)

Preliminary

$\bar{\nu}$ CC QE
$\bar{\nu}$ CC resonant π
$\bar{\nu}$ CC coherent π
$\bar{\nu}$ CC other
$\bar{\nu}$ NC
ν (wrong sign)
BG (EC/MRD events)

Neutrino cross section (NEUT prediction)



- QE
  - Llewellyn Smith, Smith-Moniz
  - M_A=1.2GeV/c^2
  - P_F=217MeV/c, E_B=27MeV (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
- DIS
  - GRV98 PDF
  - Bodek-Yang correction
- Intra-nucleus interactions

Normalization for MC sample
at SciBooNE

- Use “fractional” normalization for MC sample, which is defined by CC event selection.
- For example...

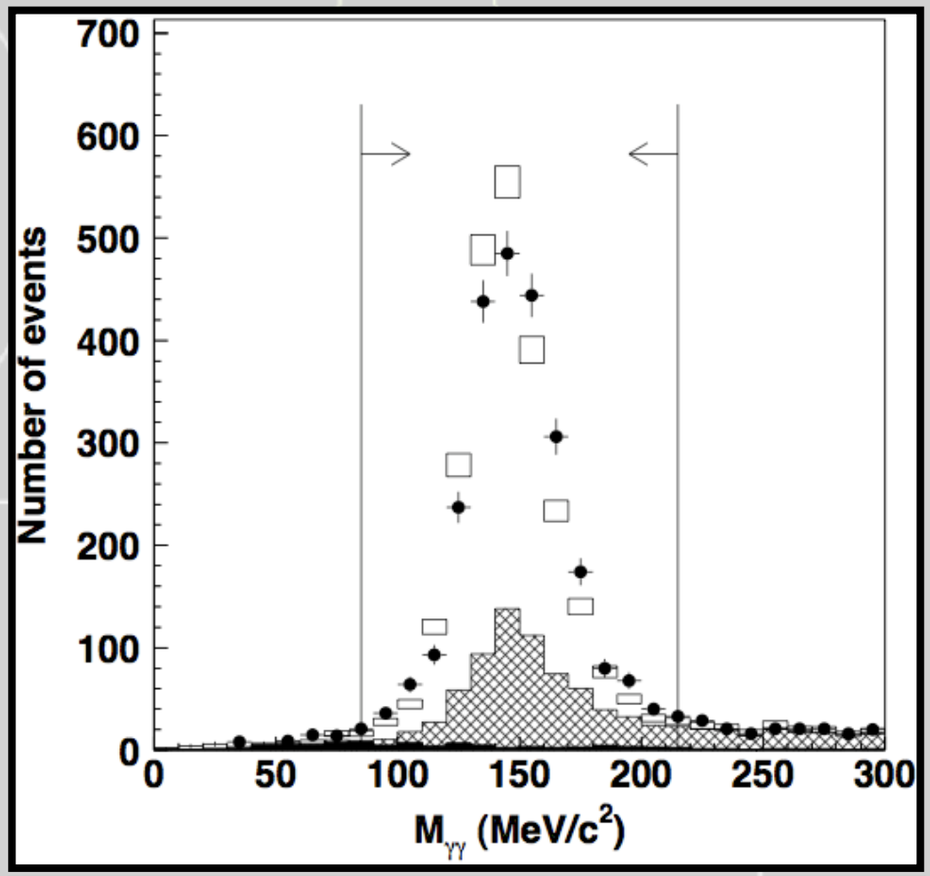
	Data	MC
CC selection (SciBar-MRD matching)	30,337	30,337
# of track (2-track selection)	5,939	5898
PID (μ+π selection)	2,255	2,388
Vertex activity (isolate coh-π)	425	661

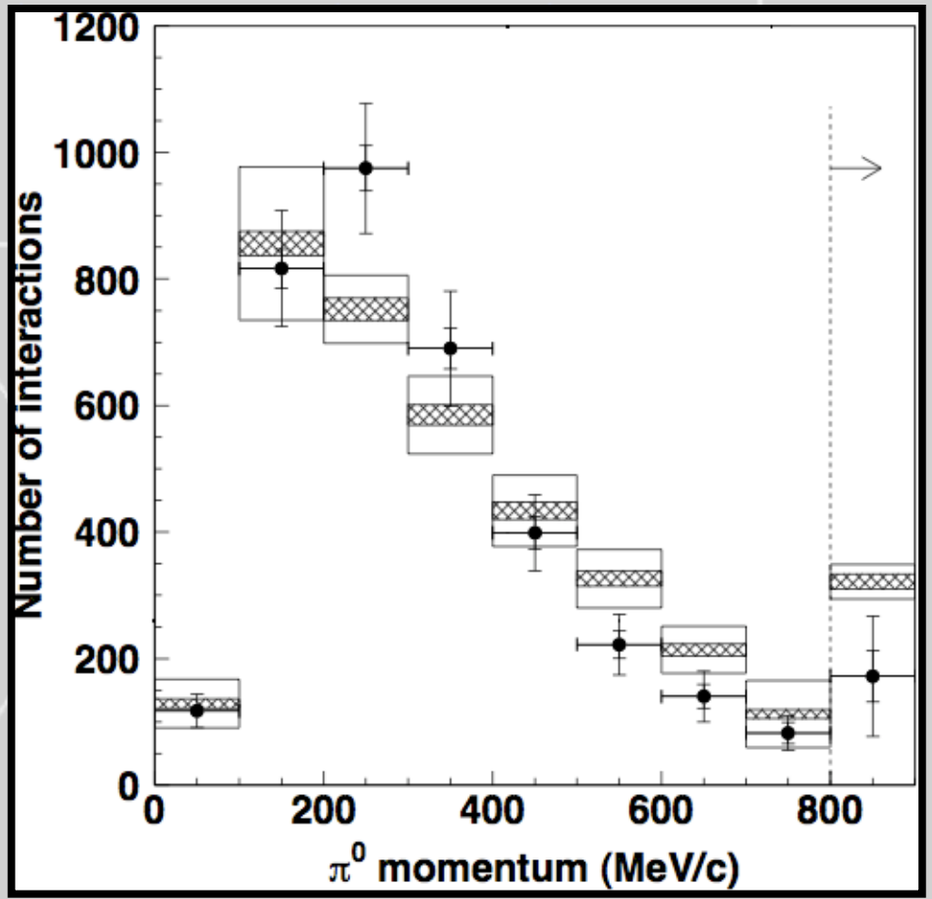
← Define normalization: Start with the same # of events

NC-1π^0 meas. by K2K-1KT

- 1KT detector: K2K near detector
  - 1,000 ton water Cherenkov
- Neutrino energy: 1.3 GeV
- 1st meas. of NC-1π^0 prod. in H_2O

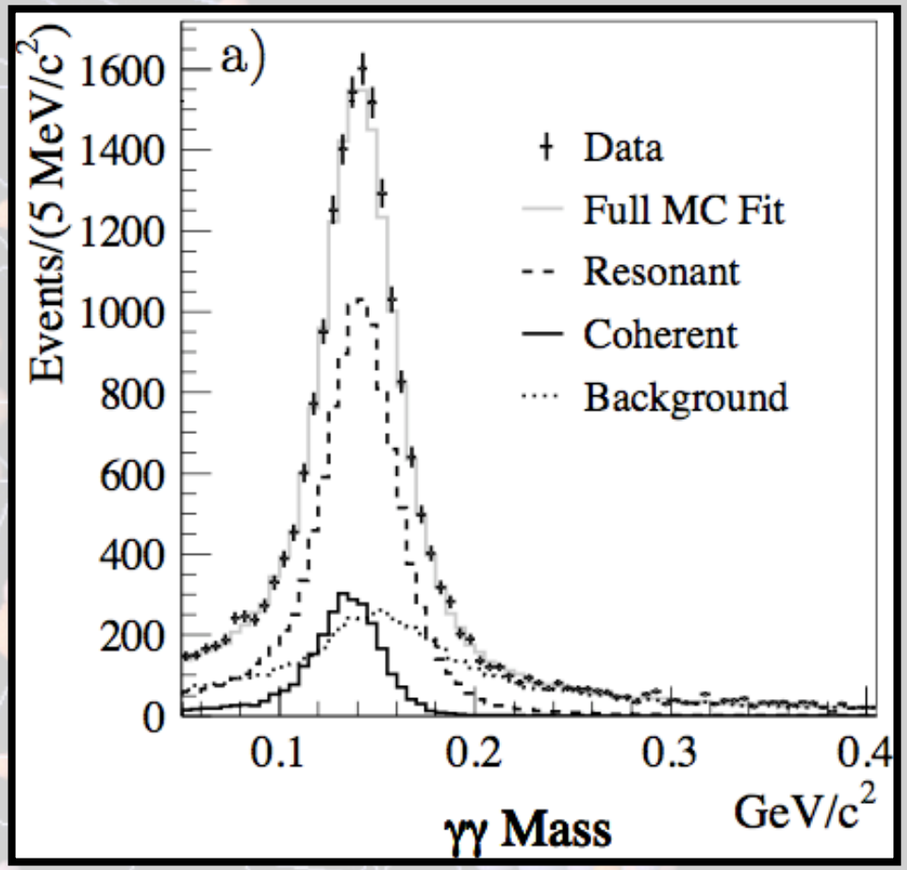
  Physics Letters B619, 255 (2005)
- **2,496 NC-π^0 sample**
  - NC-1π^0 purity (in 1π^0 sample): 71%
    - Resonance: 52%
    - Coherent: 10%
    - Final state interaction: 7%
- $\sigma(NC1\pi^0)/\sigma(CC) = (6.4 \pm 0.1 \pm 0.7)\%$
  - NEUT prediction: 6.5%
- Good agreement with expectations
- Momentum distribution disagrees

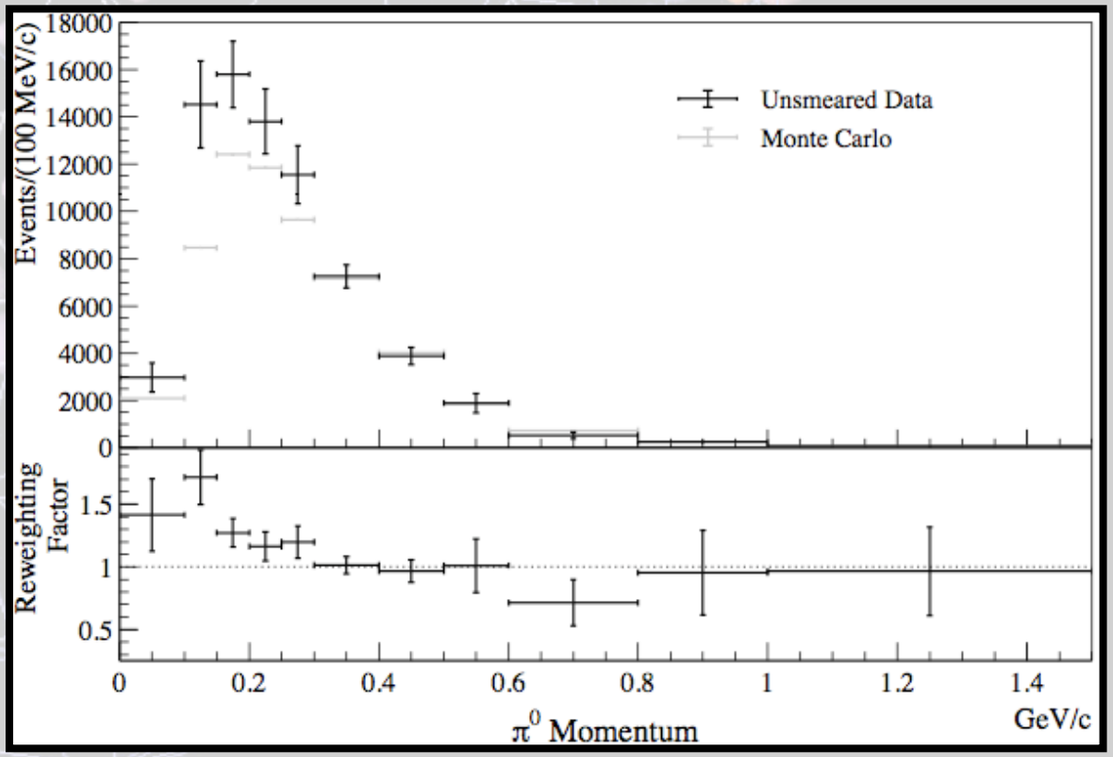




NC-1π^0 meas. at MiniBooNE

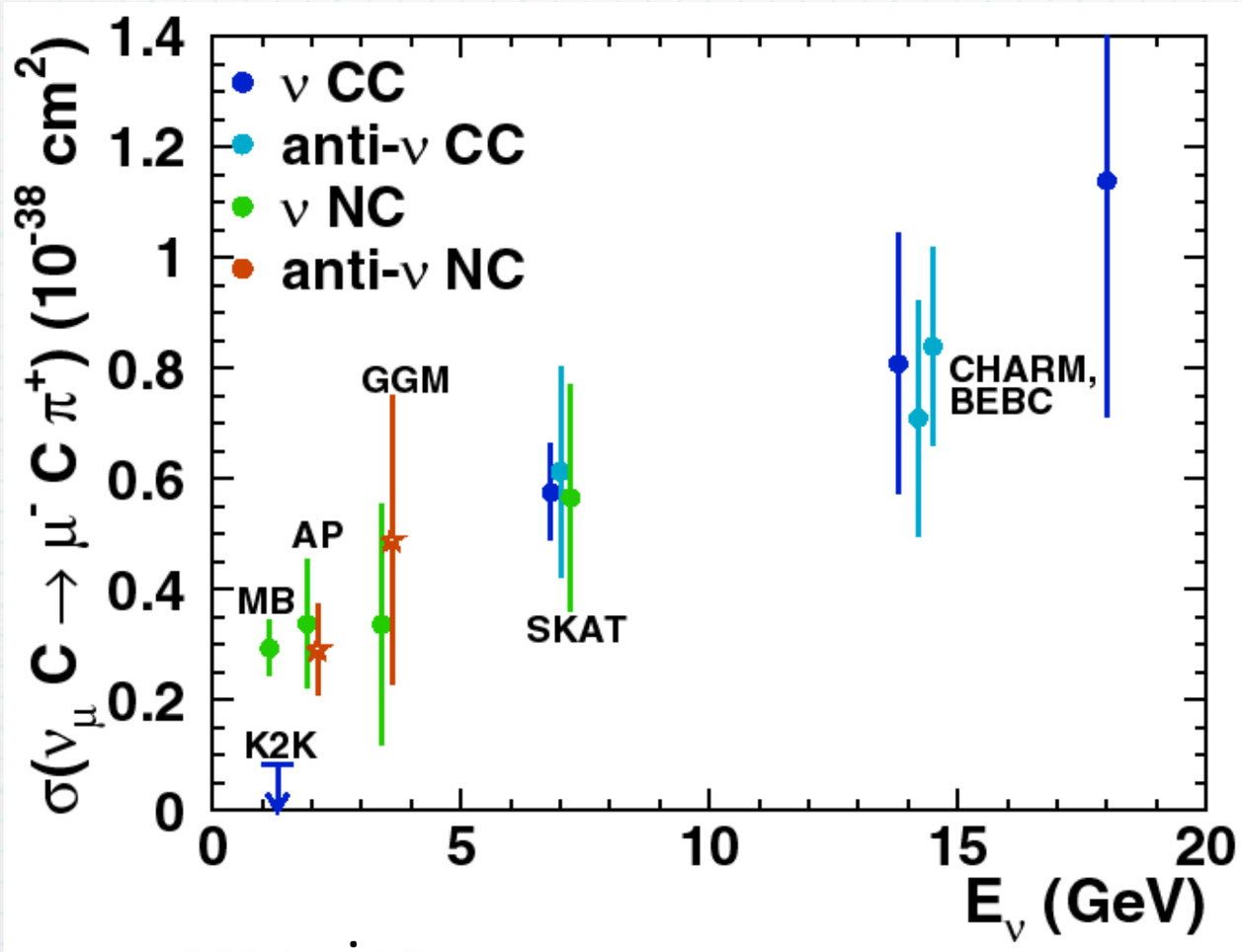
- MiniBooNE detector at FNAL
  - 800 ton mineral oil (CH_2) Cherenkov
- Neutrino energy: 0.7GeV (peak)
- 1st measurement of NC coherent-π^0 below 2GeV Phys. Lett. B664, 41 (2008)
- **28,000 NC-1π^0 events**
  - S/N~30
- Coherent fraction in NC-1π^0;
  $N_{coh}/(N_{coh} + N_{res}) = (19.5 \pm 1.1 \pm 2.5)\%$
  - Model predicted (Rein-Sehgal) 30% fraction.
  - 1.5 times lower than default prediction.
- Higher production rate wrt predictions at low π^0 momentum.





Comparison

Other measurements at higher neutrino energy



assuming

- $A^{2/3}$ dependence
- σ(CC coherent)=2*σ(NC coherent)