Coherent-π production experimental review

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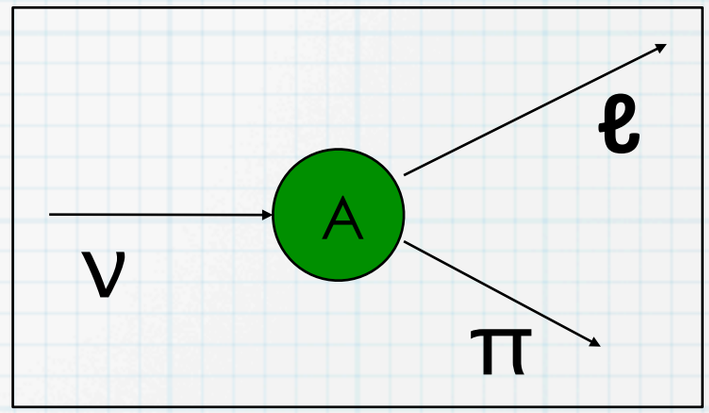
NuFact2010 at Mumbai, 10/21/2010

Outline

- Introduction
- Past Measurements
- Recent results
  - K2K, MiniBooNE, SciBooN, NOMAD
- Future prospect
- Summary

Coherent pion production

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

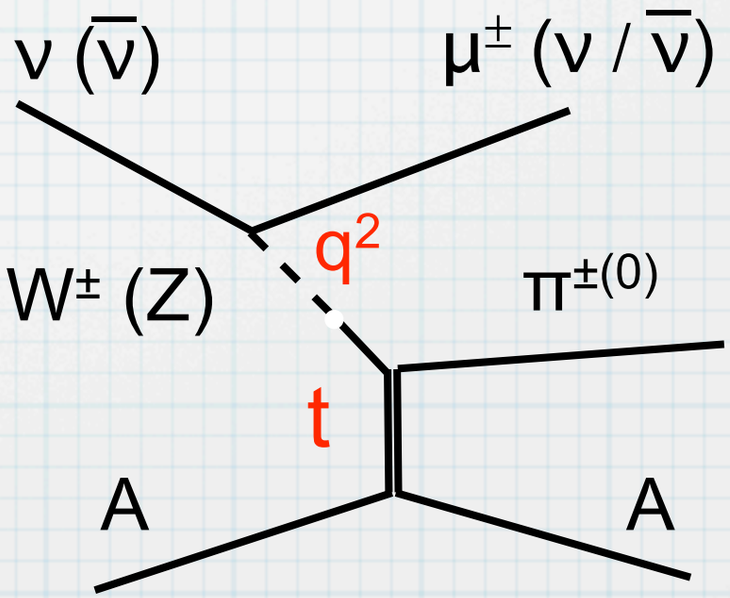


Charged Current (CC): $\nu_\mu + A \rightarrow \mu + A + \pi^+$

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

From the Rein-Sehgal model:

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

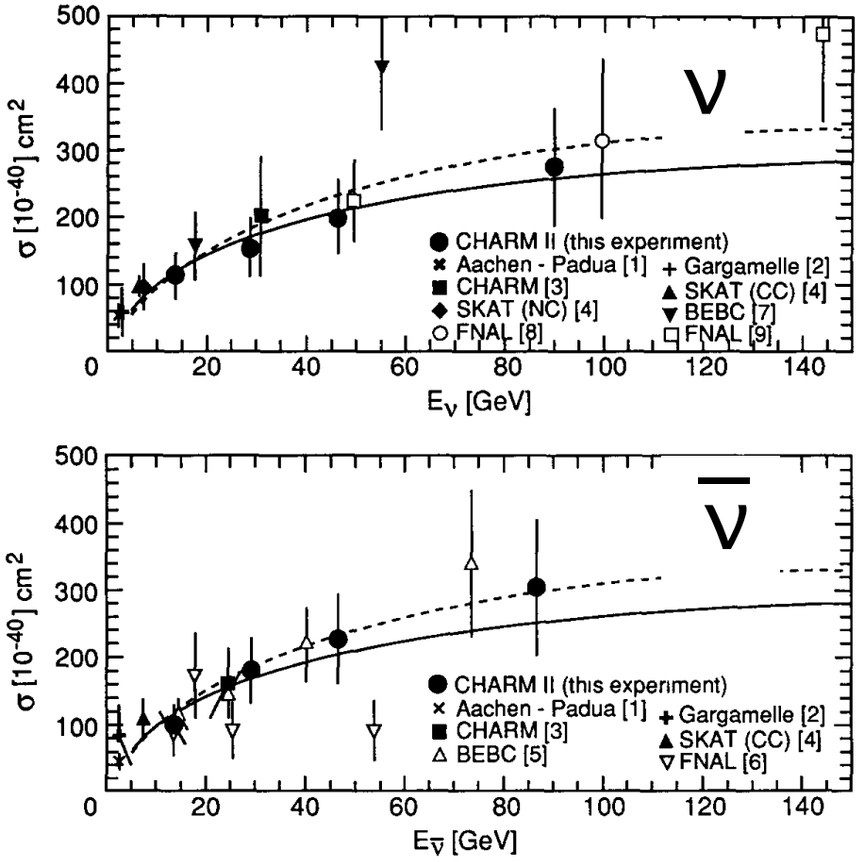


Characterized by a small momentum transfer to the nucleus, forward going π.

Past measurements

- 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.

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



Solid line: Rein-Sehgal model

Dotted line: Bel'kov-Kopeliovich

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 measurements

Recent experimental results

Exp	Detector	Target	ν/ν̄	Mode	Ev (GeV)	Publication
K2K-SciBar	Scintillator Fine-grained	CH	ν	CC	1.3	PRL95, 252301 (2005)
MiniBooNE	Mineral oil Cherenkov	CH_2	ν	NC	0.8	PLB664, 41 (2008)
SciBooNE	Scintillator Fine-grained	CH	ν	CC	0.8	PRD78, 112004 (2008)
NOMAD	Drift Chamber	~C (<A>=12.8)	ν	NC	24.8	PLB682, 177 (2009)
MiniBooNE	Mineral oil Cherenkov	CH_2	ν, ν̄	NC	0.8	PRD81, 013005 (2010)
SciBooNE	Scintillator Fine-grained	CH	ν	NC	0.8	PRD81, 111102 (R) (2010)

- Mostly low energy (<2GeV) region, except NOMAD
- All results of Carbon target
- Rein-Sehgal model employed for coh-π prediction in all four experiments.

CC coherent-π

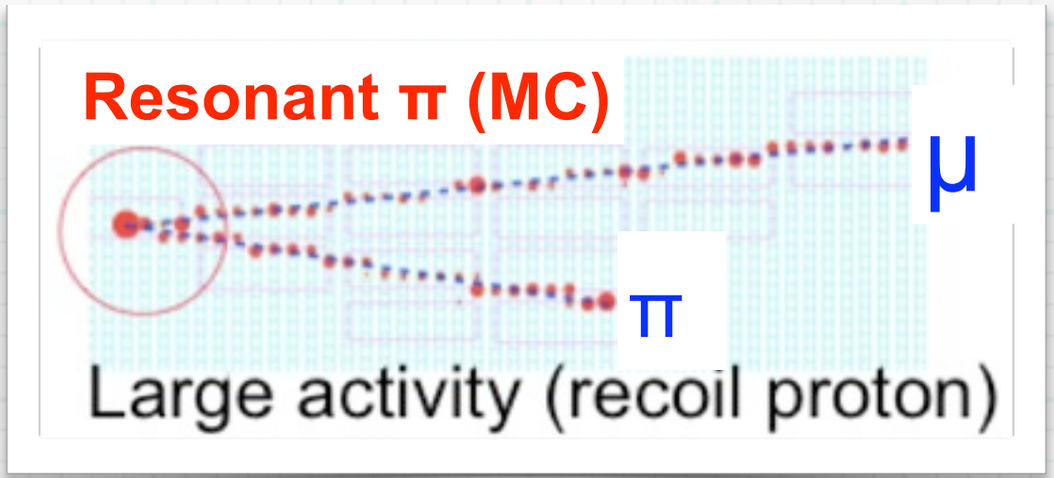
K2K, SciBooNE

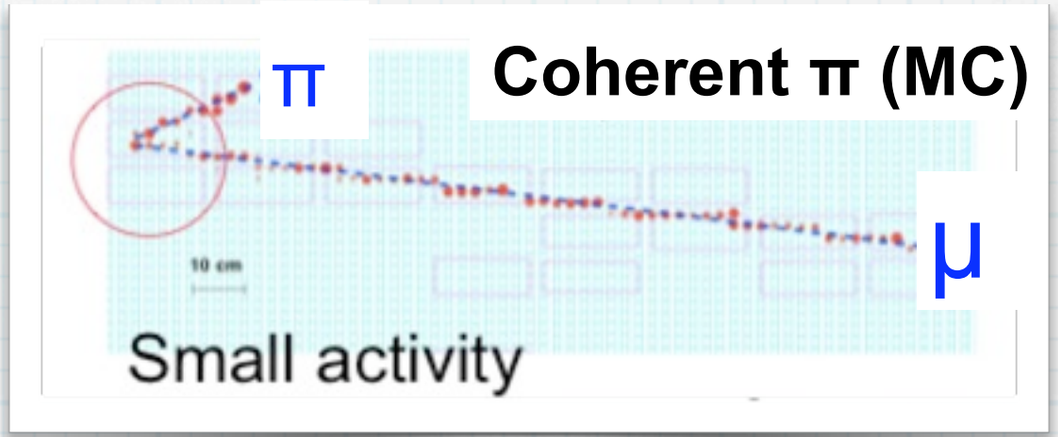
CC coh-π^+ measurements

- Two results from K2K and SciBooNE
  - Both experiments use the same detector (SciBar=Fully-Active Tracking detector) with different ν beam
    - K2K: KEK-PS <Eν>=1.3GeV
    - SciBooNE: FNAL BNB <Eν>=0.8GeV
- Fine-grained detector allows to isolate coherent-π from resonant-π (background) event-by-event.
  - Recoil proton signature

Technique to Identify coh-π

- Separate CC coherent-π from CC resonant-π:
  - Identify recoil proton
    - Resonant π has nucleon in final state
    - No recoiled-nucleon in coherent π
- Low energy proton make an energy deposit around the vertex = vertex activity





● : SciBar ADC hit (area∝energy deposit)

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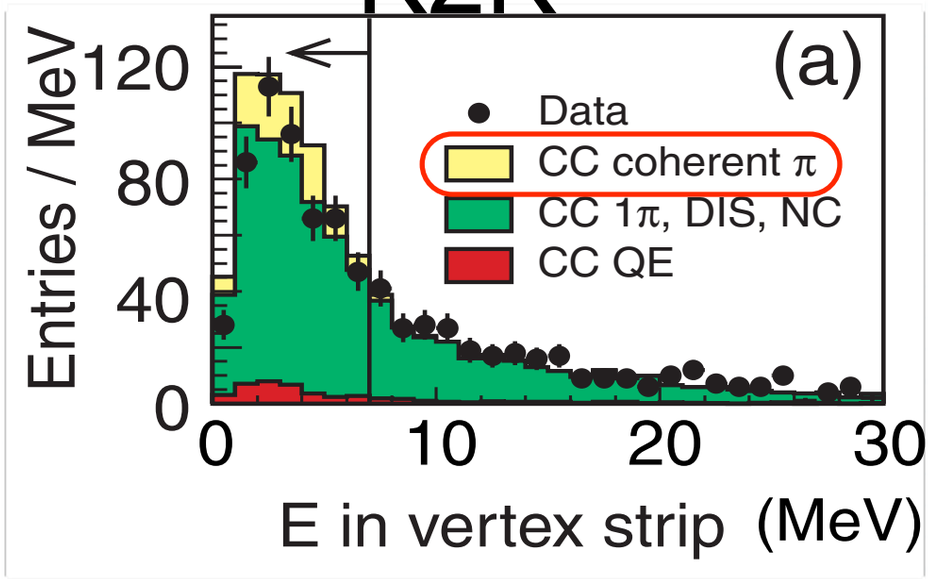
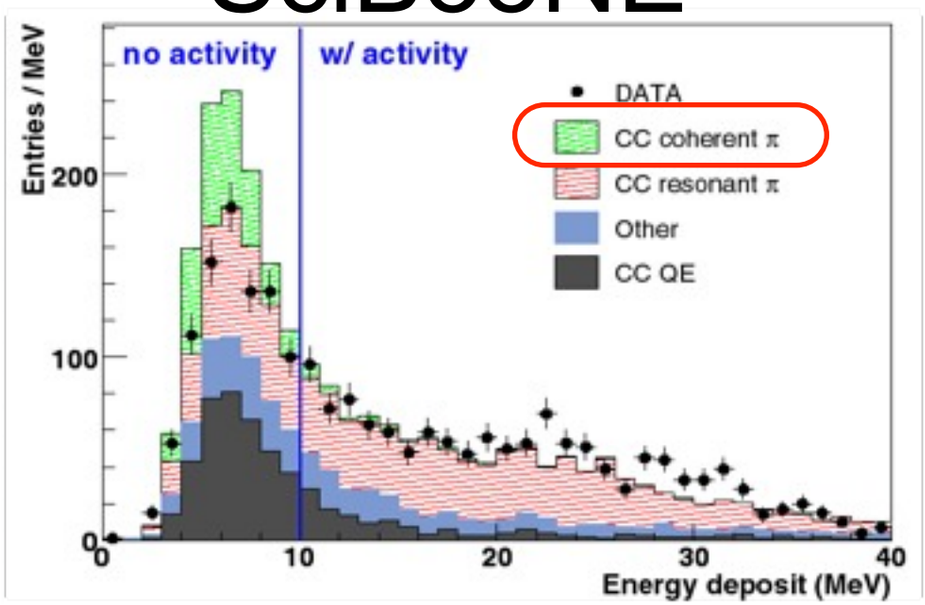
K2K



SciBooNE



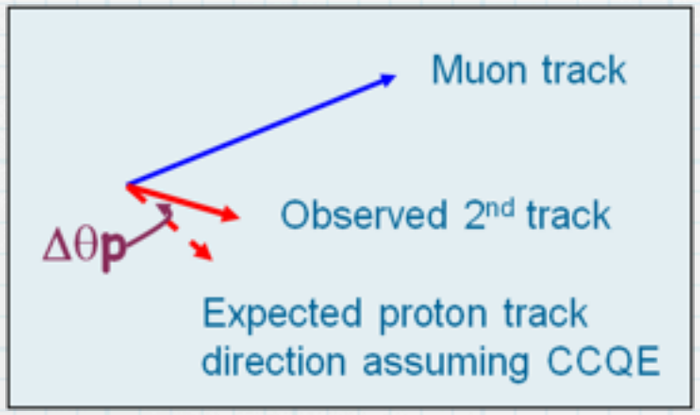
Data deficit at small activity region

Background rejection

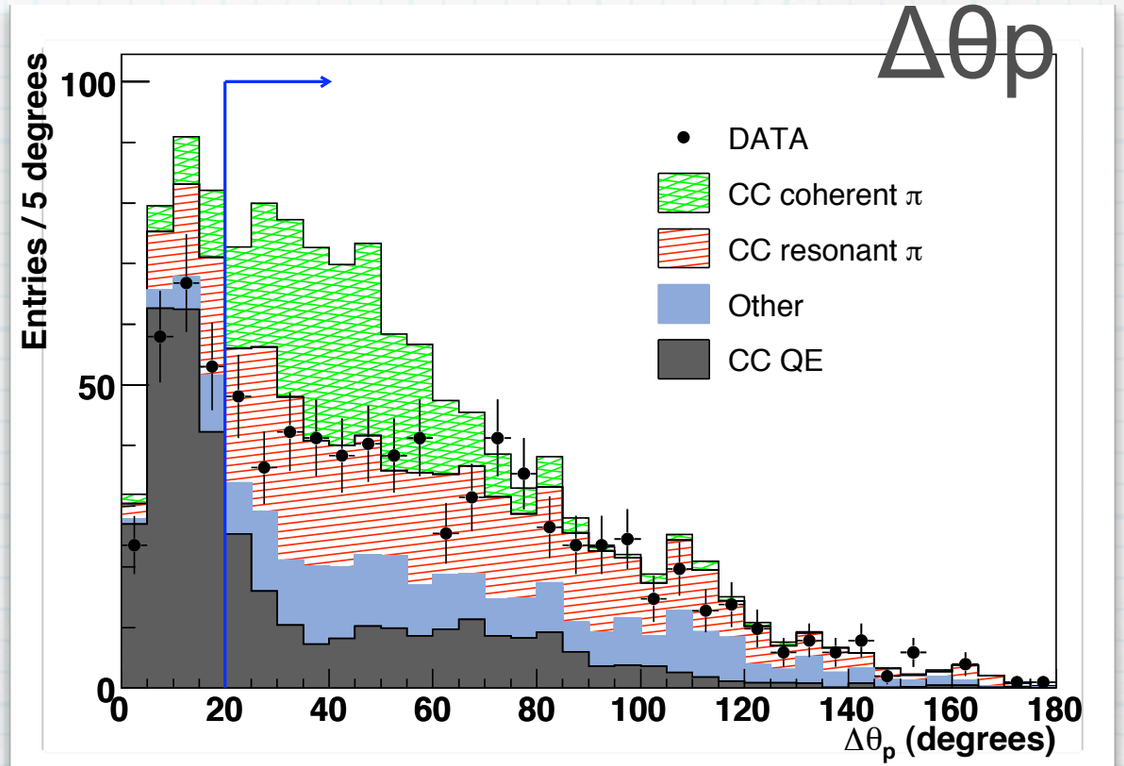
SciBooNE example:

1. CC-QE rejection

Δθp: Opening angle between the observed 2nd track and expected track assuming CC-QE.

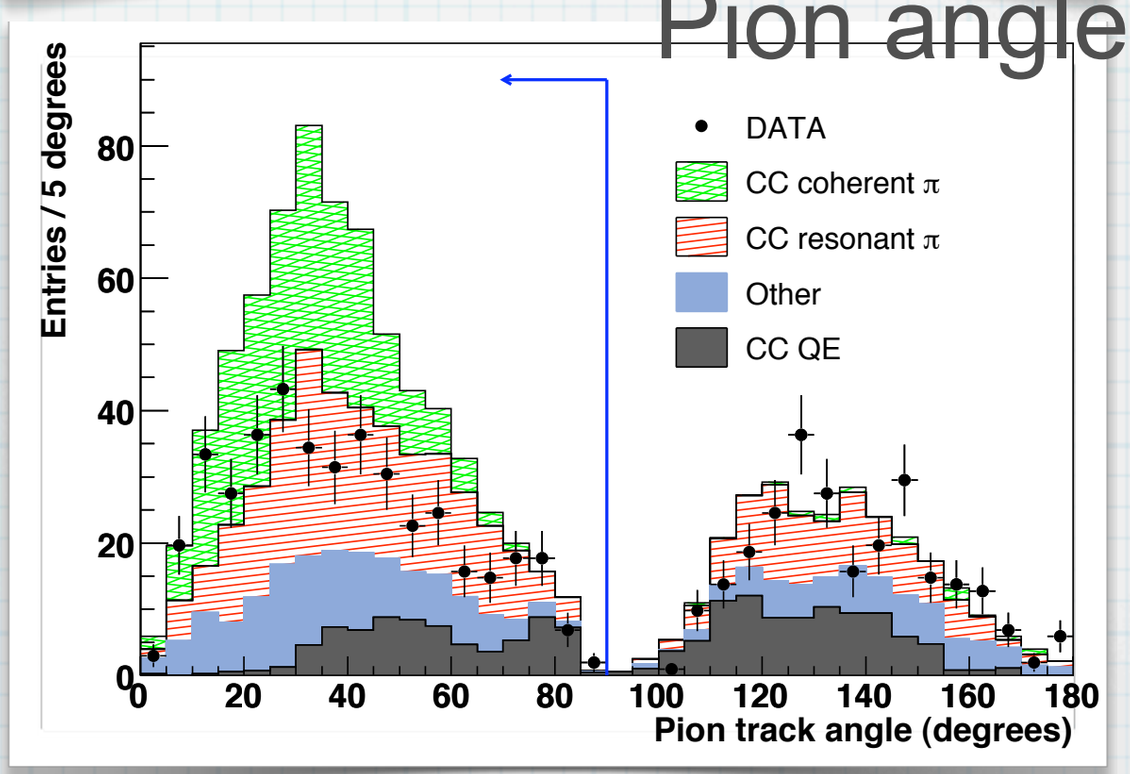


Δθp



2. CC resonant π rejection

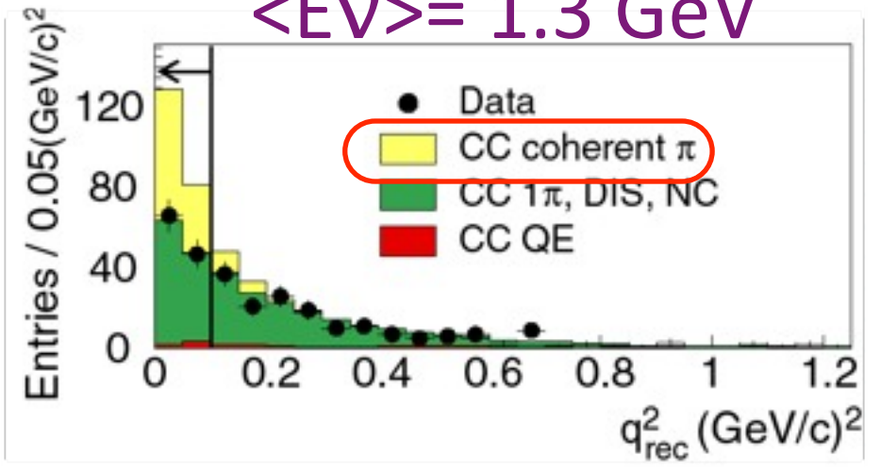
Pion angle



Select forward-going π
(no backward scattering in coherent-π)

CC coherent pion results

<Eν>= 1.3 GeV



K2K

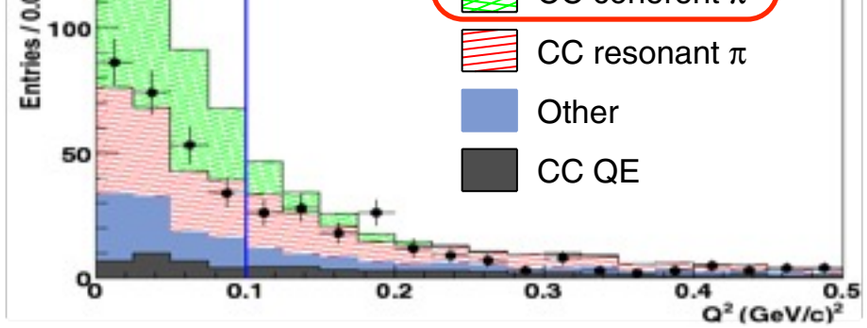
Phys. Rev. Lett. 95, 252301 (2005)

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 pion

<Eν>= 1.1 GeV



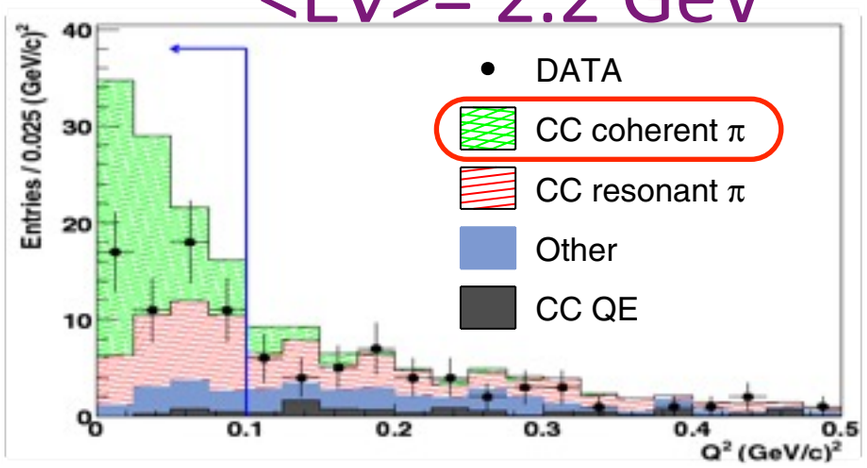
SciBooNE

Phys. Rev. D78, 112004 (2008)

σ(CC coh-π) / σ (CC)

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

<Eν>= 2.2 GeV



σ(CC coh-π) / σ (CC)

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

No evidence of CC coherent pion

Upper limit on cross section

K2K: $\sigma(\text{CC coh }\pi)/\sigma(\text{CC}) < 0.60\times10^{-2}$ $\langle E_\nu\rangle$=1.3GeV

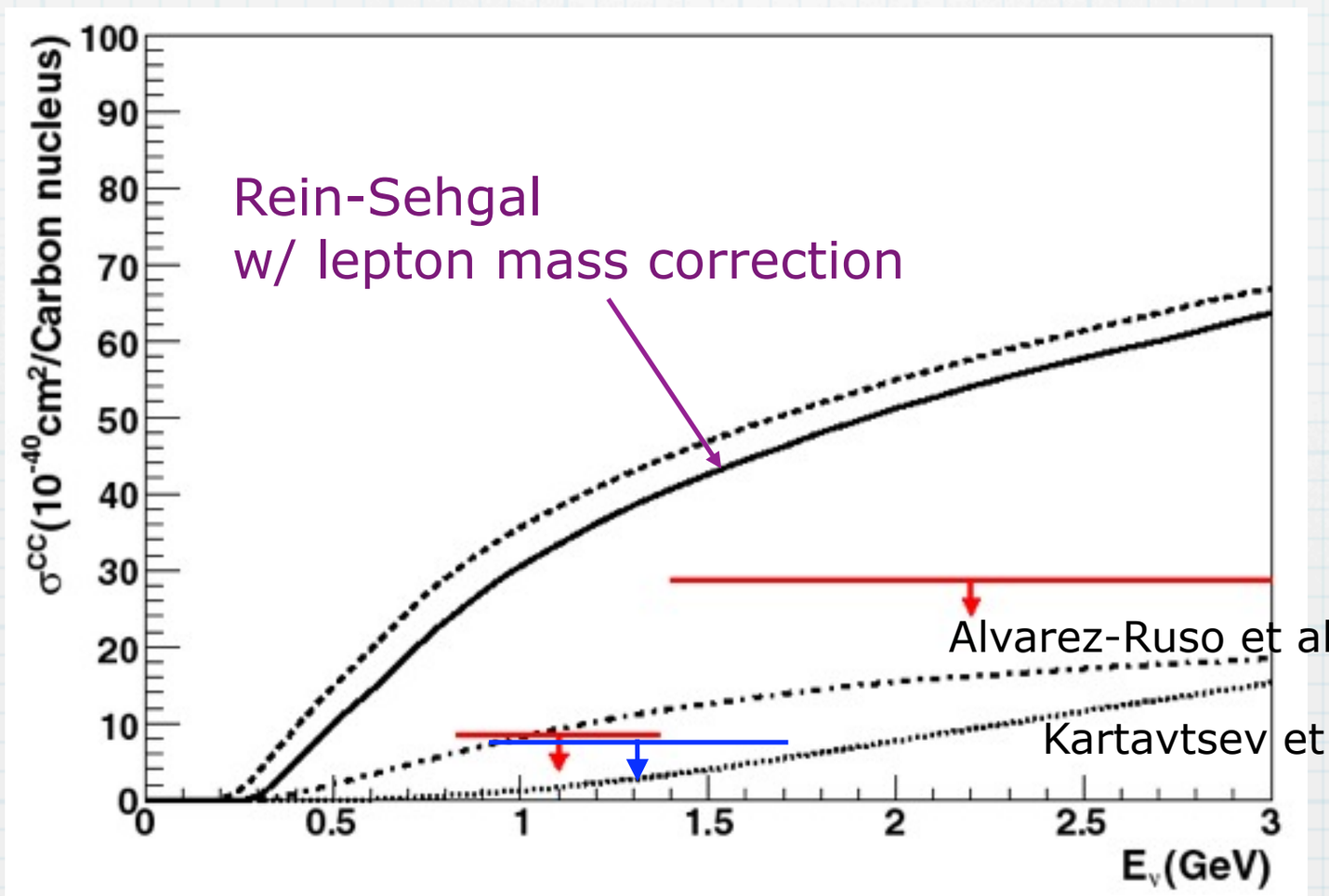
SciBooNE: $\sigma(\text{CC coh }\pi)/\sigma(\text{CC}) < 0.67\times10^{-2}$ $\langle E_\nu\rangle$=1.1GeV

$\sigma(\text{CC coh }\pi)/\sigma(\text{CC}) < 1.36\times10^{-2}$ $\langle E_\nu\rangle$=2.2GeV

K2K and SciBooNE obtained consistent results.

SciBooNE 90% C.L.

K2K 90% C.L.

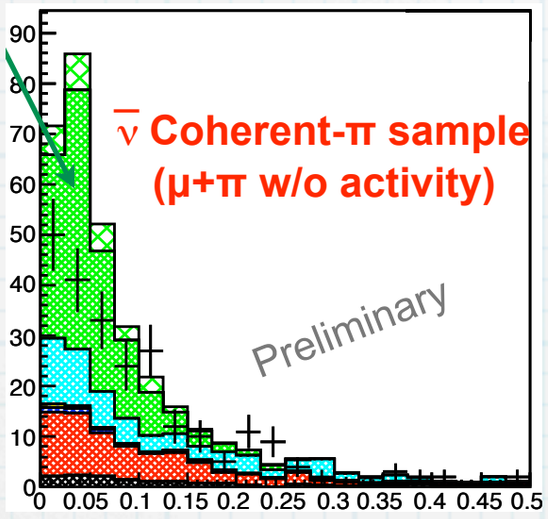


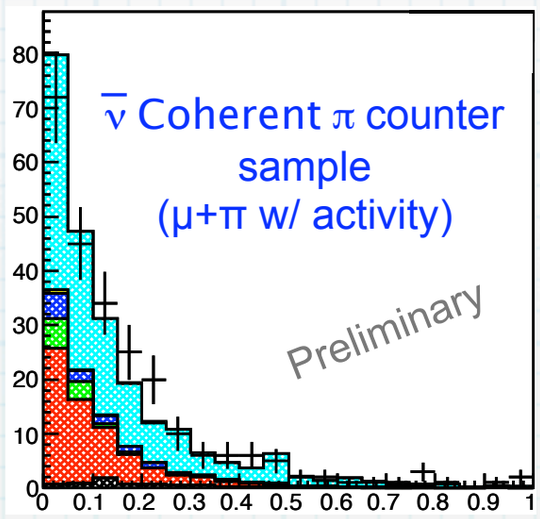
Measured upper limits on $\sigma(\text{CC coherent }\pi)/\sigma(\text{CC})$ ratios are converted to upper limits on absolute cross sections by using $\sigma(\text{CC})$ predicted by MC simulation.

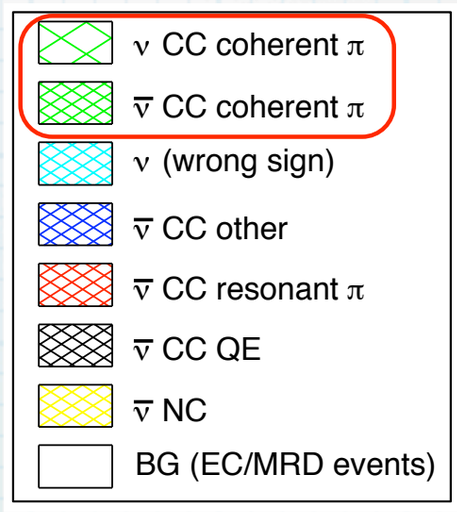
SciBooNE $\bar{\nu}$ CC coh-π search

- $\bar{\nu}$ mode can be more sensitive to see CC coh-π event than ν mode
  - σ(ν coh-π) ~ σ($\bar{\nu}$ coh-π) while σ(νCC-bkg) > σ($\bar{\nu}$CC-bkg)

Reconstructed Q^2 distributions







H. Tanaka, NuInt09

Preliminary & stat. error only

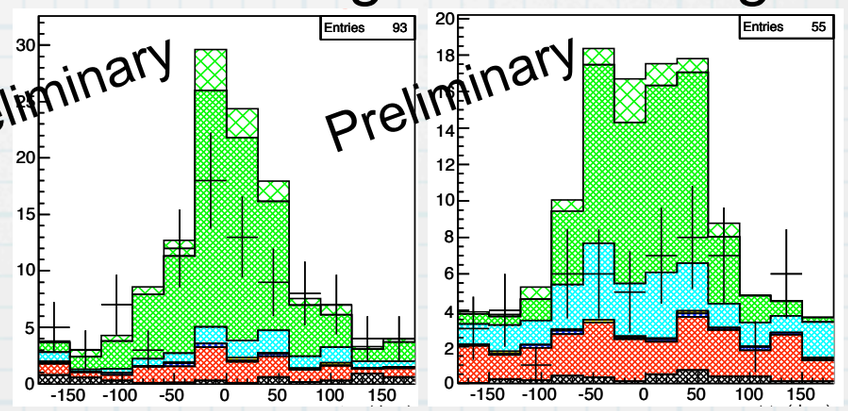
Define signal region: $Q^2 < 0.1$ (GeV/c)^2
- 139 events observed
- 80 incoherent (Bkg) events (NEUT)

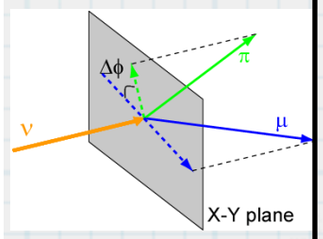
➜ **Data - Bkg = 59 ± 14 (stat)**

cf. NEUT prediction: 151 ($\bar{\nu}$: 130, ν: 21)

Data "excess" from very forward region?

θ_π<35 deg θ_π>35 deg





Similar signature found in ν mode too. (K. Hiraide, NuInt09)

NC coherent-π

MiniBooNE, NOMAD, SciBooNE

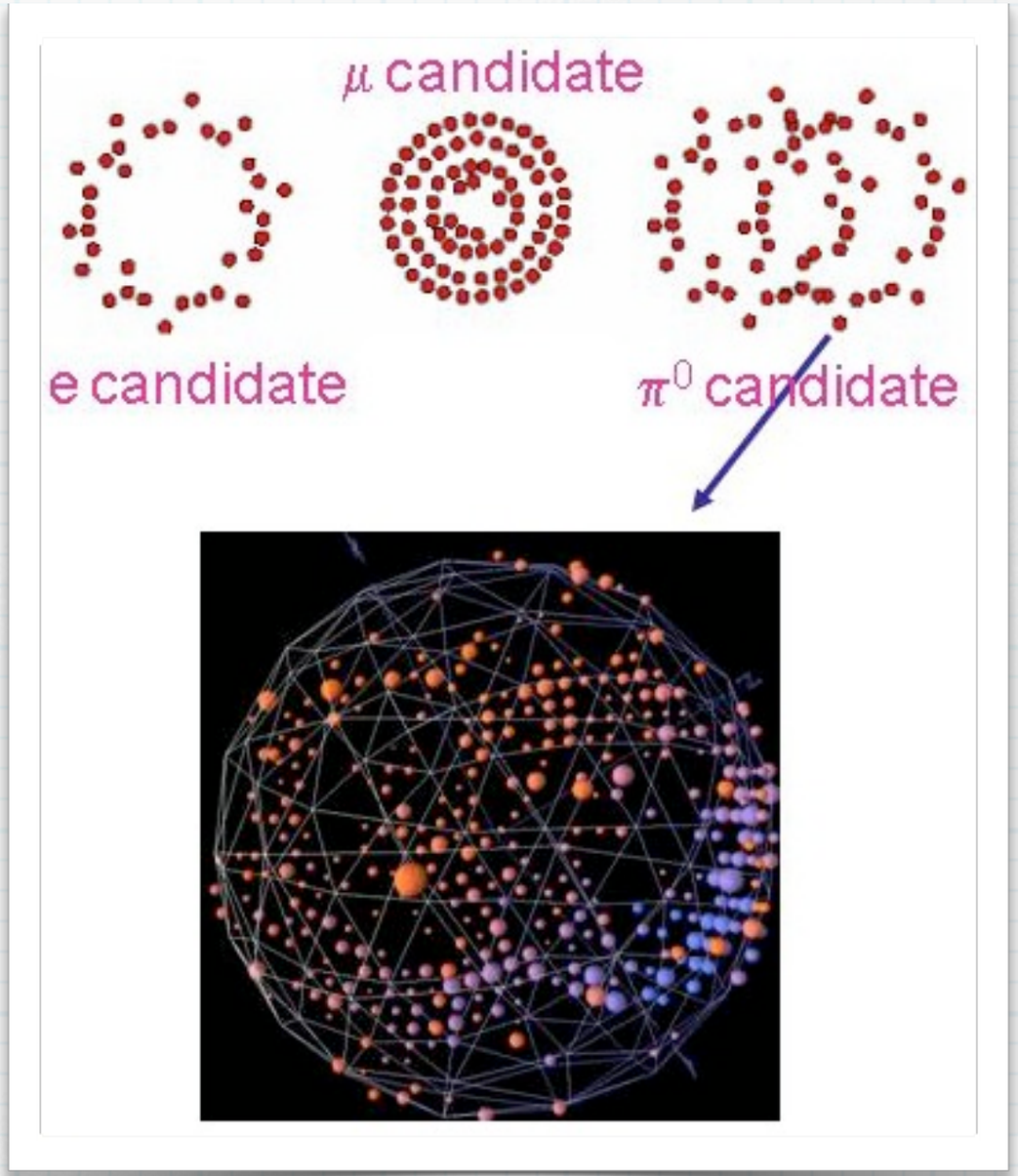
NC coh-π^0 measurements

- Four NC coh-π^0 measurements with three different detectors:
  - MiniBooNE (Cherenkov): ν and $\bar{\nu}$ <Ev>~0.8 GeV
  - NOMAD (Drift Chamber): ν <Ev>~25 GeV
  - SciBooNE (Fine-grained): ν <Ev>~0.8 GeV
- NC coh-π measurement use π^0 angle to identify coh-π events
  - Forward-going π^0
  - + vertex activity (SciBooNE)

MiniBooNE NC coh-π^0

Phys. Lett. B664, 41 (2008)

- Mineral oil Cherenkov detector
- Identify event using hit topology
  - Two e-like rings
- Select NC-π0 events within Mγγ window



- Coherent fraction in NC-1π0:
  - 2D [$E_{\pi 0}(1-\cos\theta_{\pi 0})$, $M_{\gamma\gamma}$] template fit

$N_{coh}/(N_{coh}+N_{res}) = (19.5\pm1.1\pm2.5)\%$

- Clear evidence of NC coh-π0
- The result corresponds to 65% of model prediction (Rein-Sehgal)

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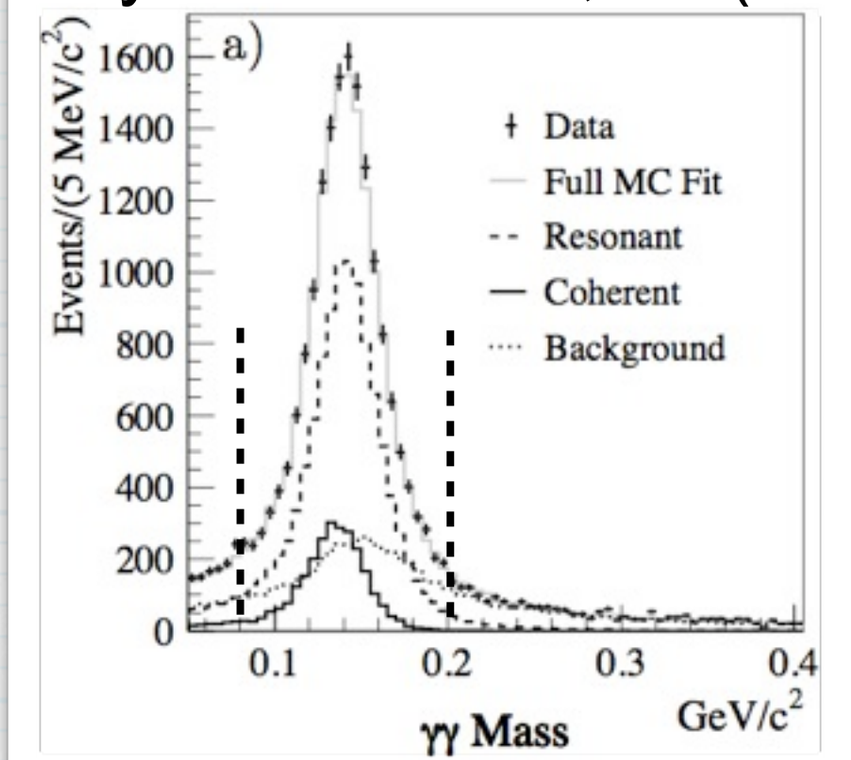
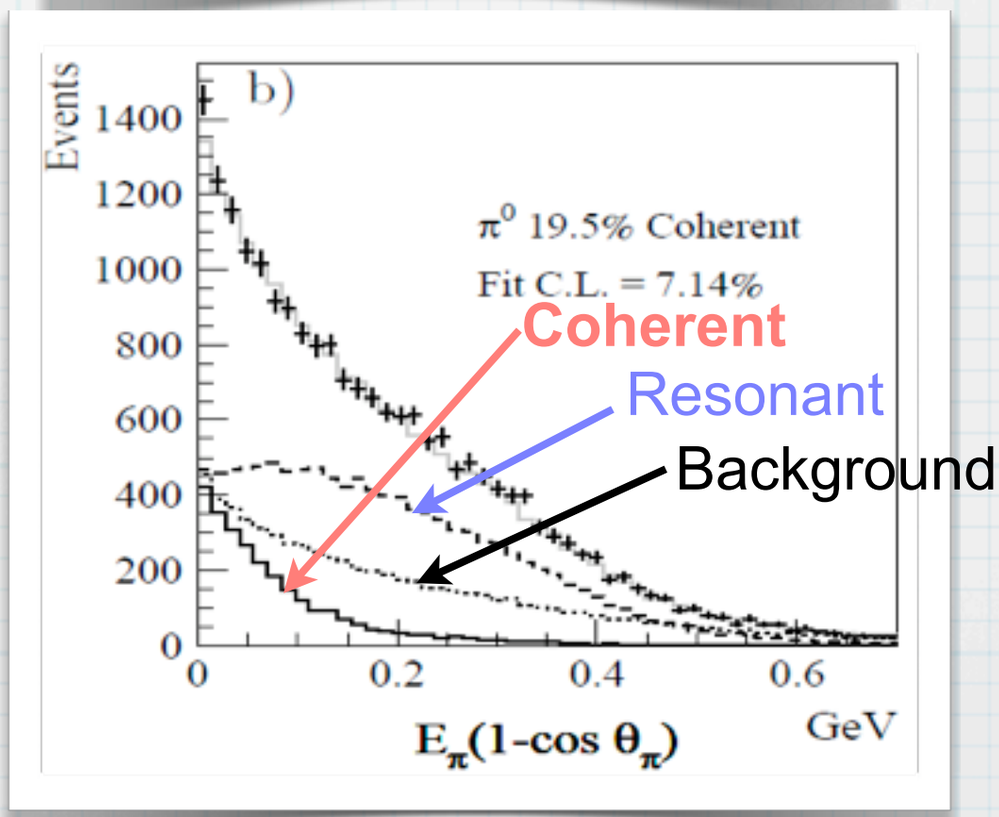


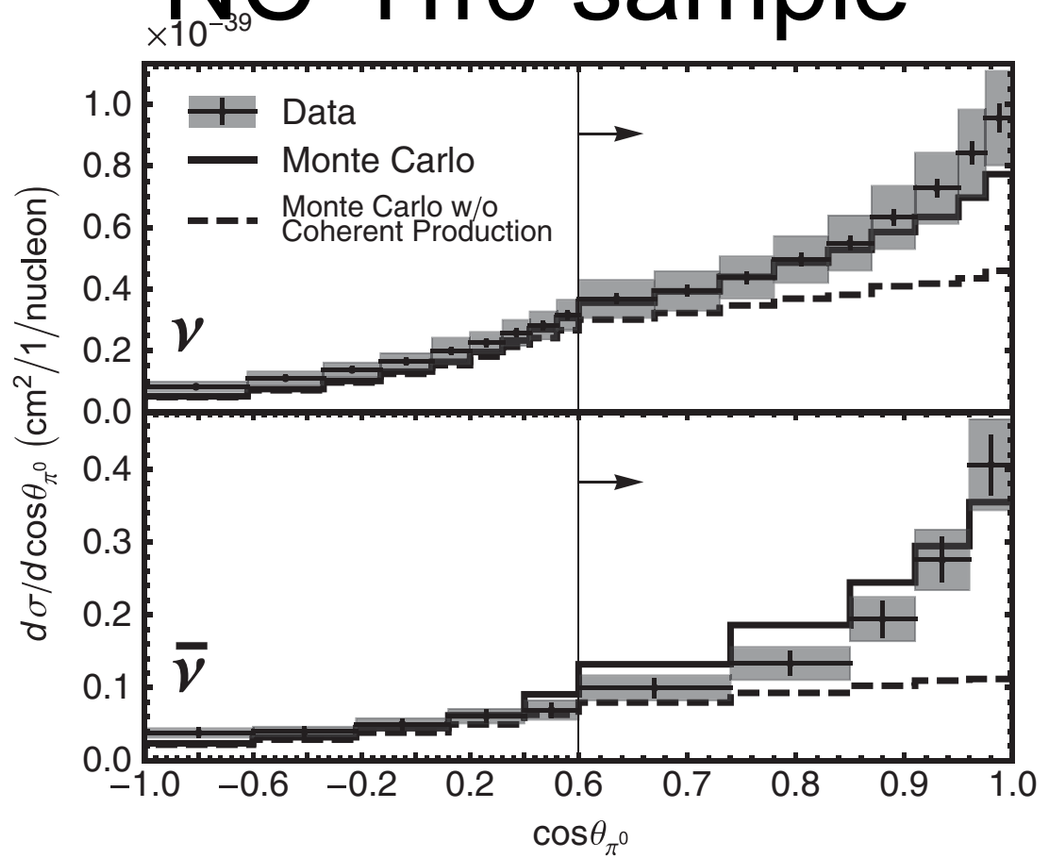


MiniBooNE ν & $\bar{\nu}$ NC-1π^0

- New NC-1π^0 results for both ν and $\bar{\nu}$ beam modes.
- ν and $\bar{\nu}$ data suggest:
  - Clear evidence of non-zero NC coh-π
  - Forward angular region is sensitive to model predictions
- Demonstrated comparison between data and models (in the paper)

Phys. Rev. D81, 013005 (2010)

NC-1π0 sample



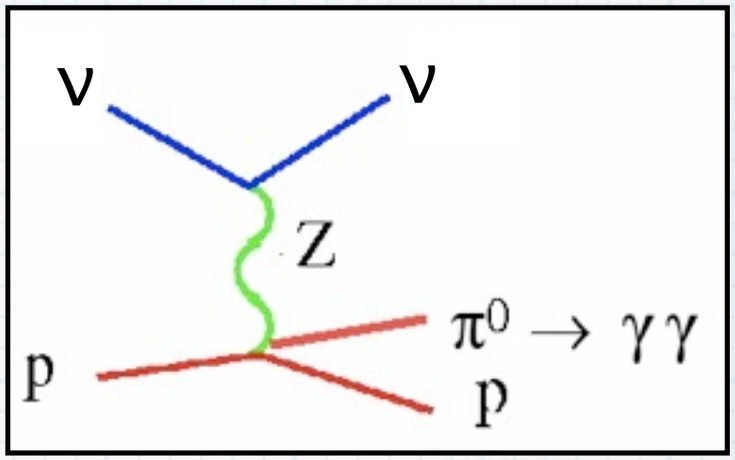
---- : MC w/o coh-π

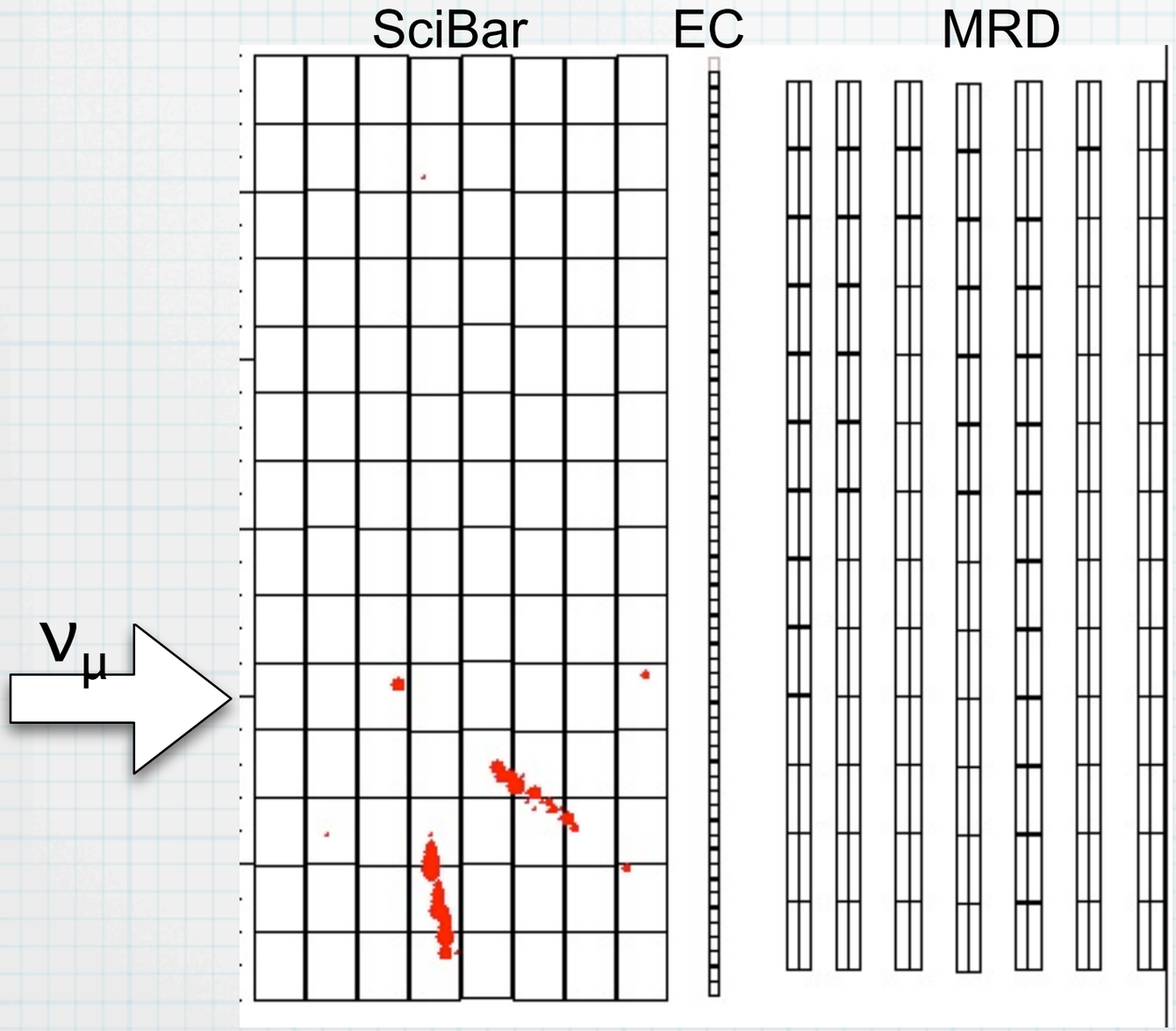
—— : MC w/ coh-π

NOTE: MC distributions are absolutely normalized

SciBooNE NC coh-π^0

Neutral Current Resonant π^0
has nucleon in final state ➜
(no nucleon in coherent π)





Phys. Rev. D81, 111102(R) (2010)

● : SciBar hit, area∝energy deposit

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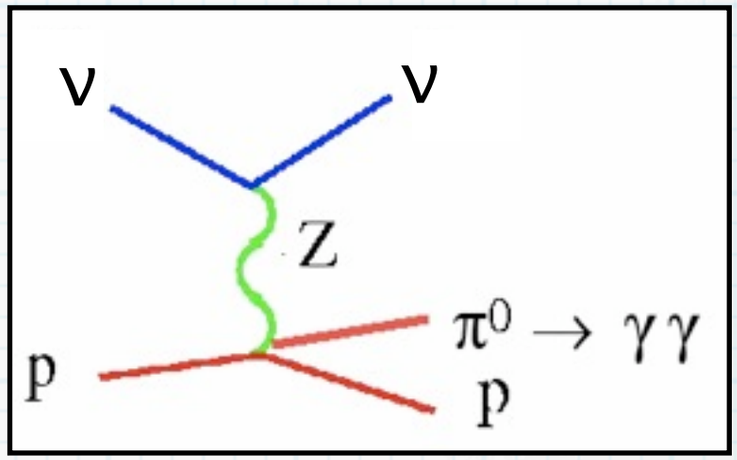

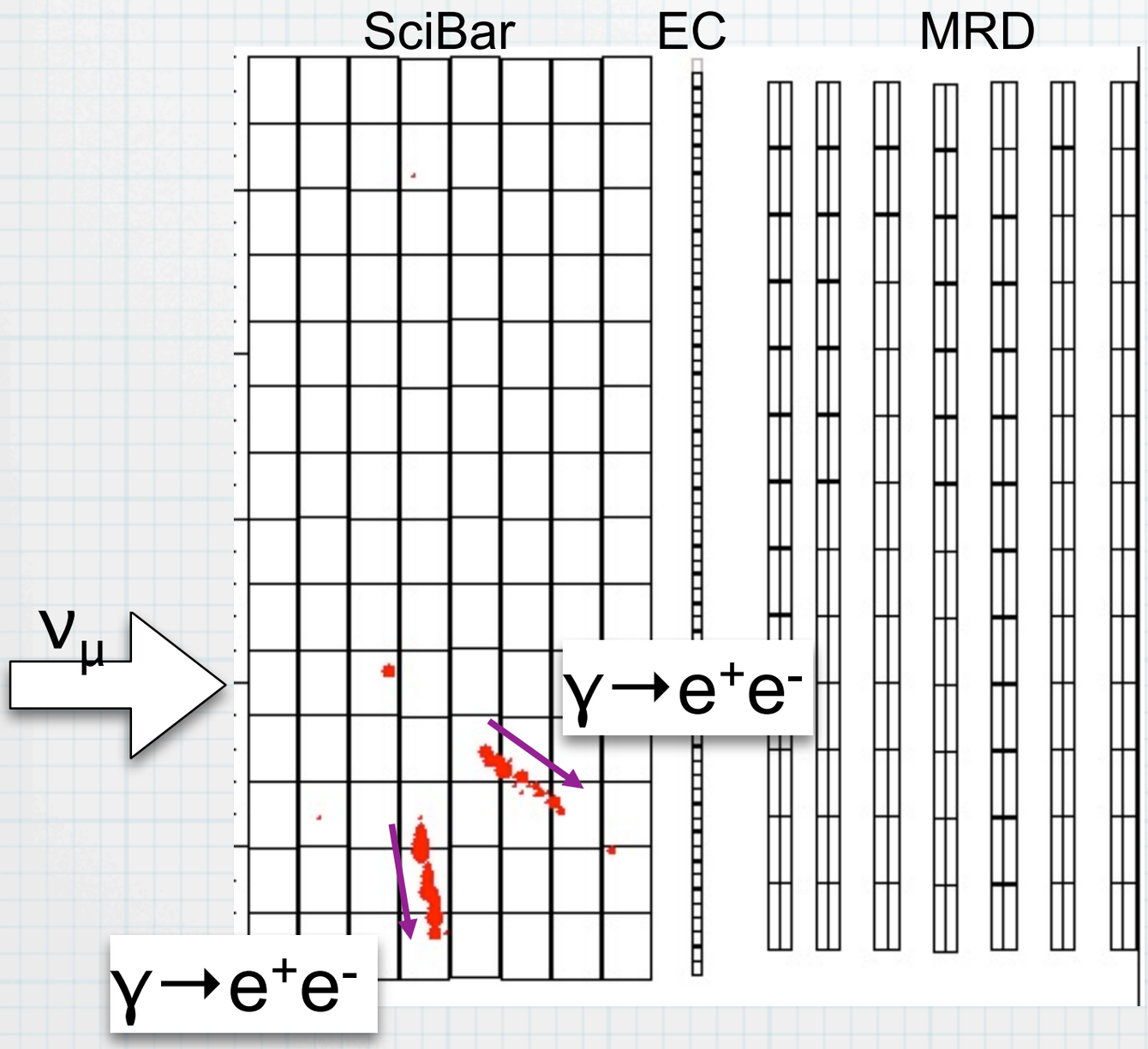

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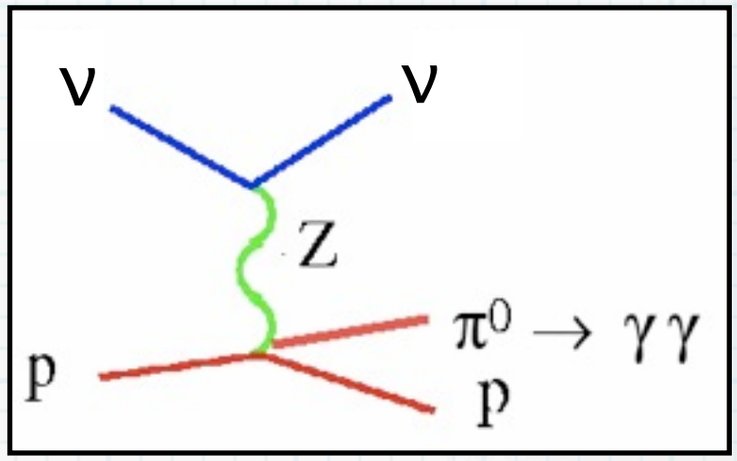

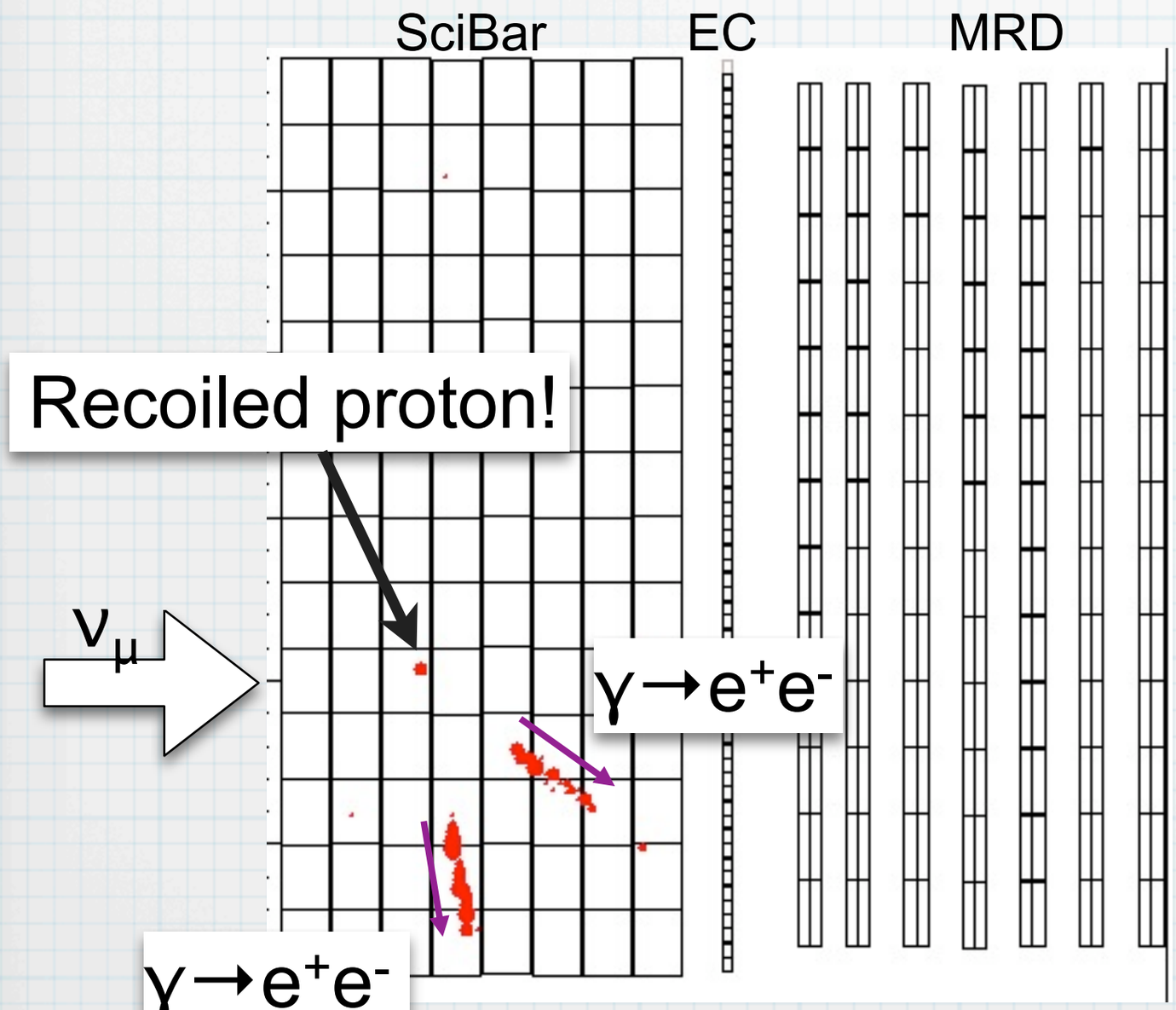

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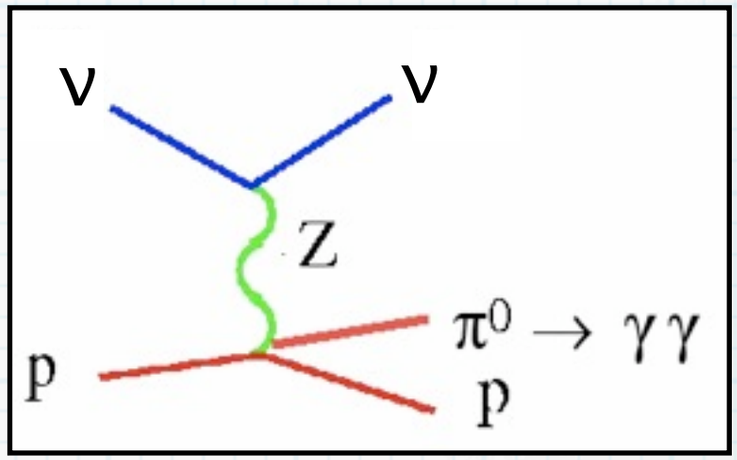
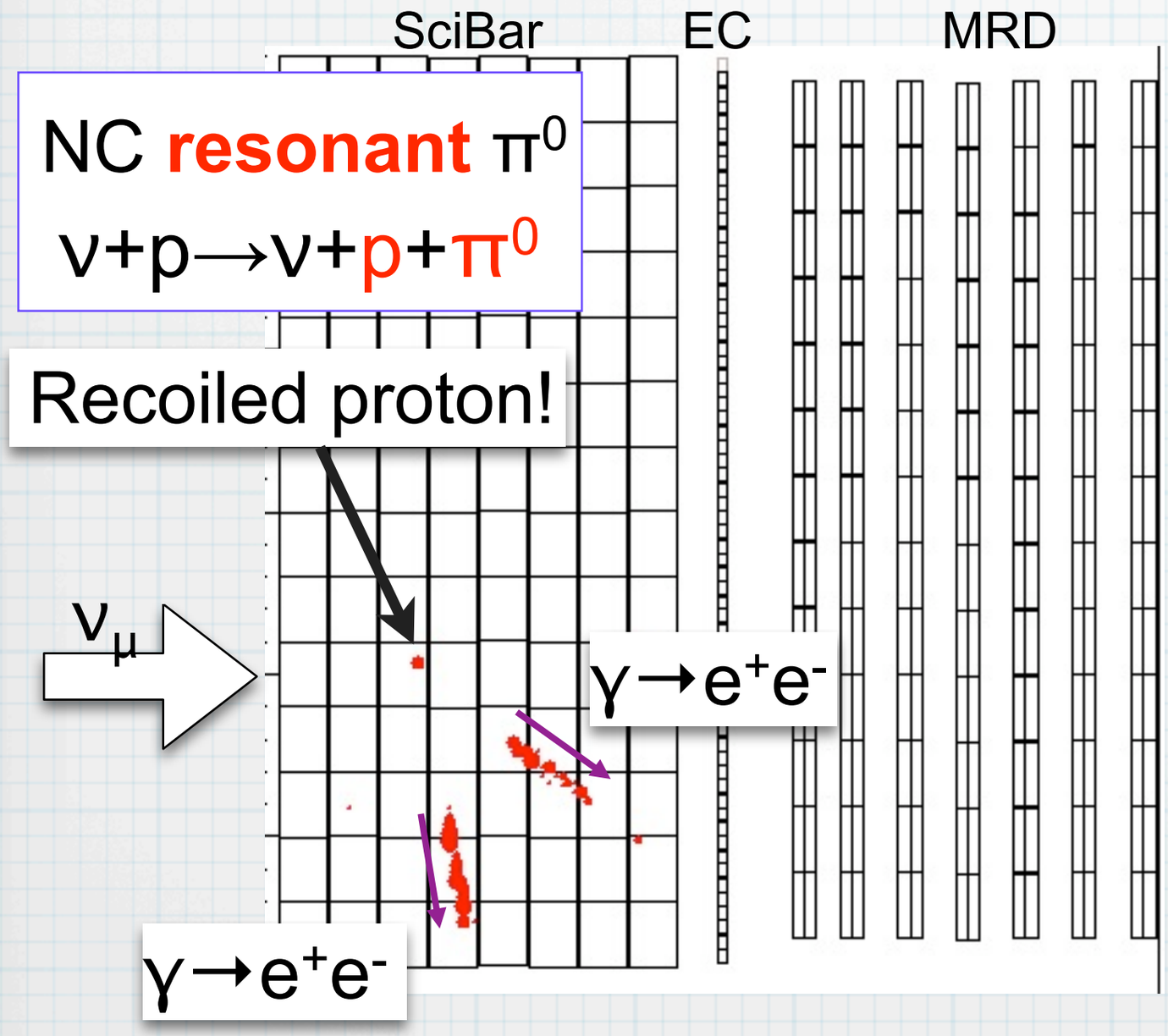


NC **resonant** π^0

$\nu + p \rightarrow \nu + p + \pi^0$



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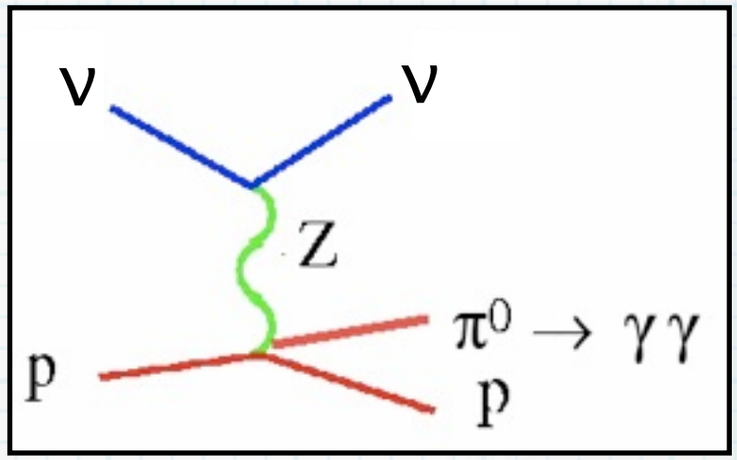
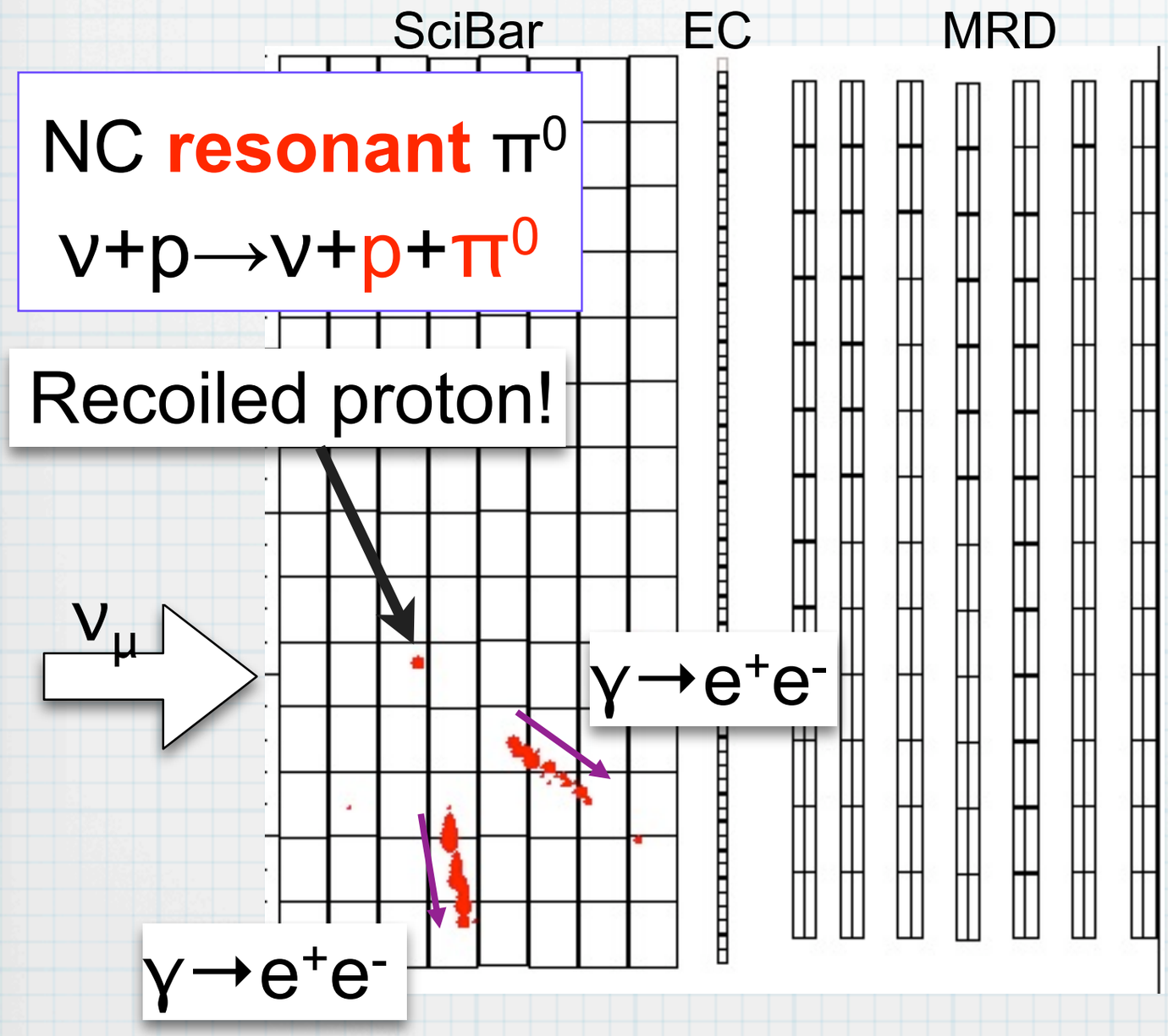
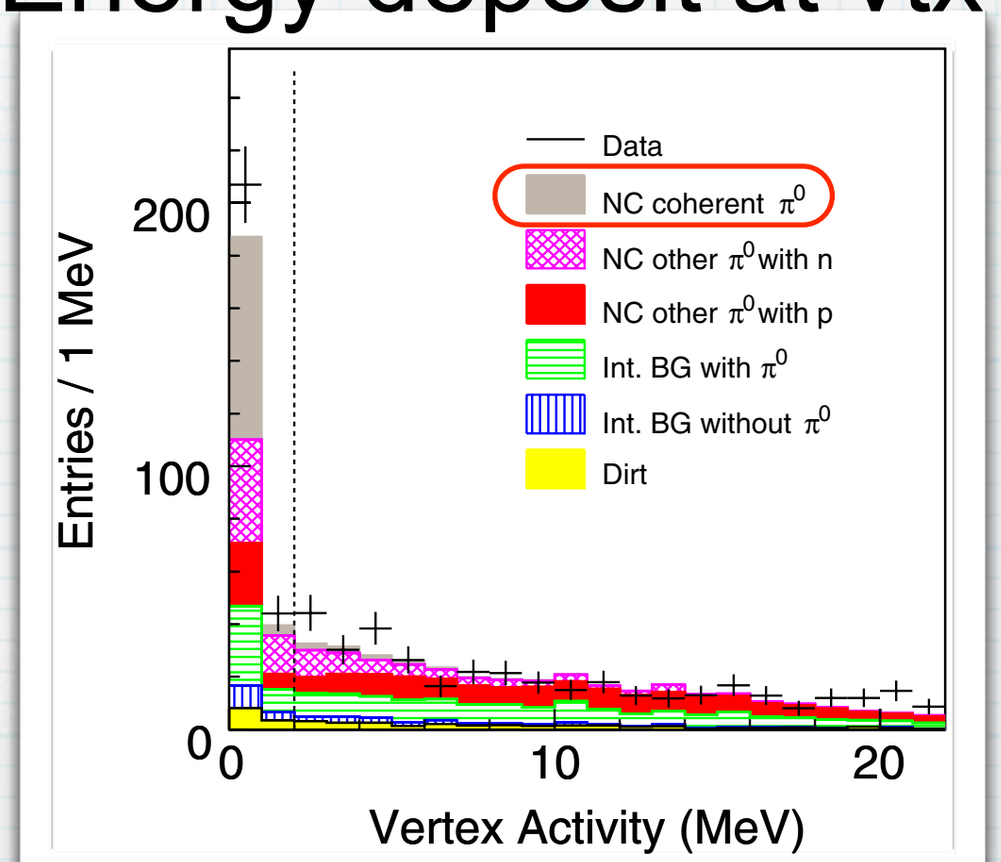


NC **resonant** π^0

$\nu+p \rightarrow \nu+p+\pi^0$



Energy deposit at vtx



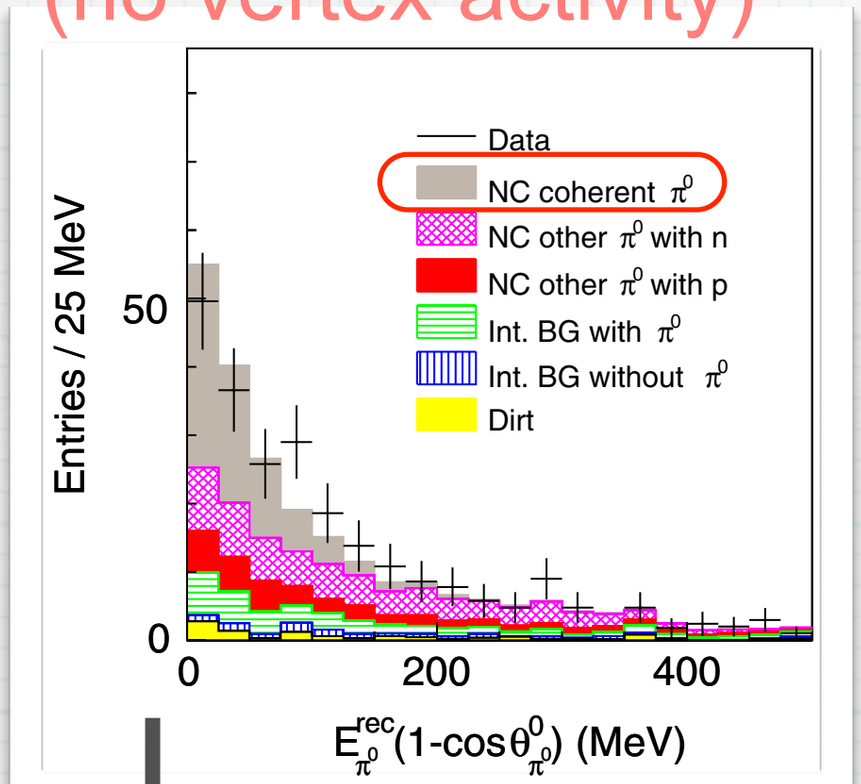
Phys. Rev. D81, 111102(R) (2010)

● : SciBar hit, area∝energy deposit

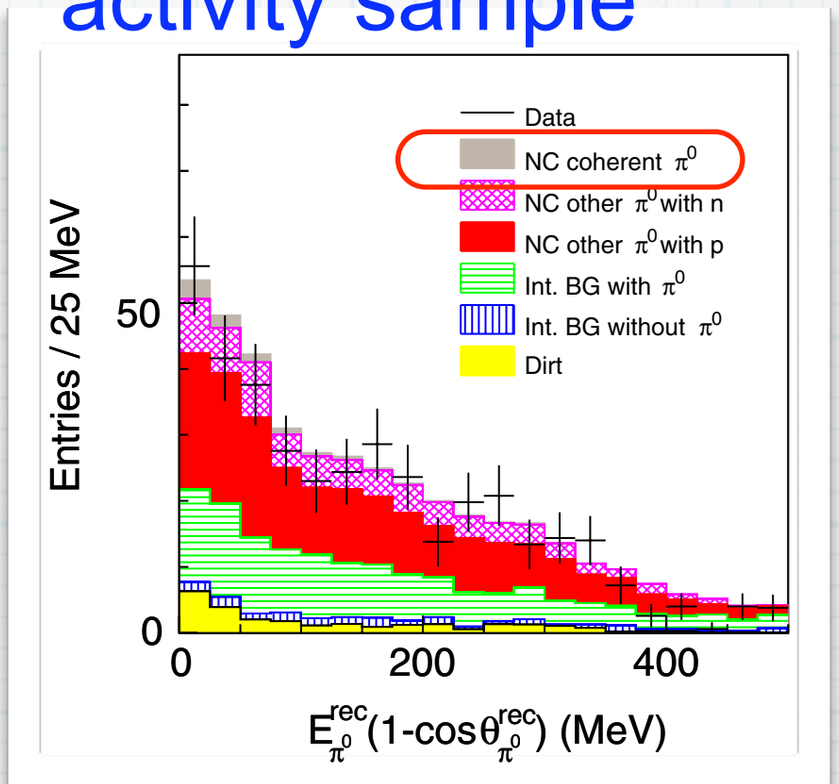
NC coh-π0 cross section

Phys. Rev. D81, 111102(R) (2010)

NC **coherent** π sample (no vertex activity)



NC π^0 with vertex activity sample



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

Clear evidence of NC coherent pion production.

cf. NEUT prediction based on Rein-Sehgal model:
$\sigma(\mathrm{NCcoh}\pi^0)/\sigma(\mathrm{CC}) = 1.21\times10^{-2}$

MiniBooNE & SciBooNE consistency

- SciBooNE performed a consistency test with MiniBooNE results
- MiniBooNE result:

  Coherent-π fraction in NC-1π0 events

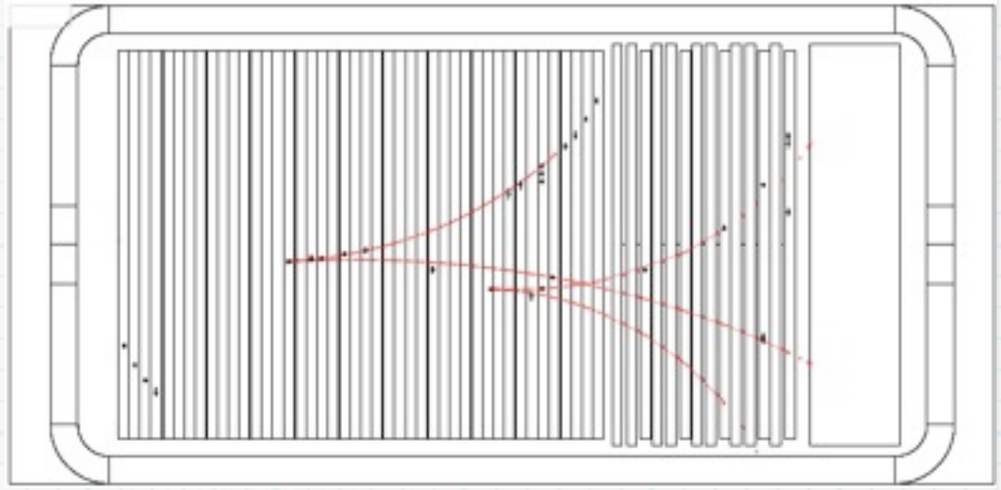
  $R_{coh} = (19.5 \pm 1.1(stat) \pm 2.5(sys))\%$
- SciBooNE evaluated the same quantity using on the NC-π0 sample:

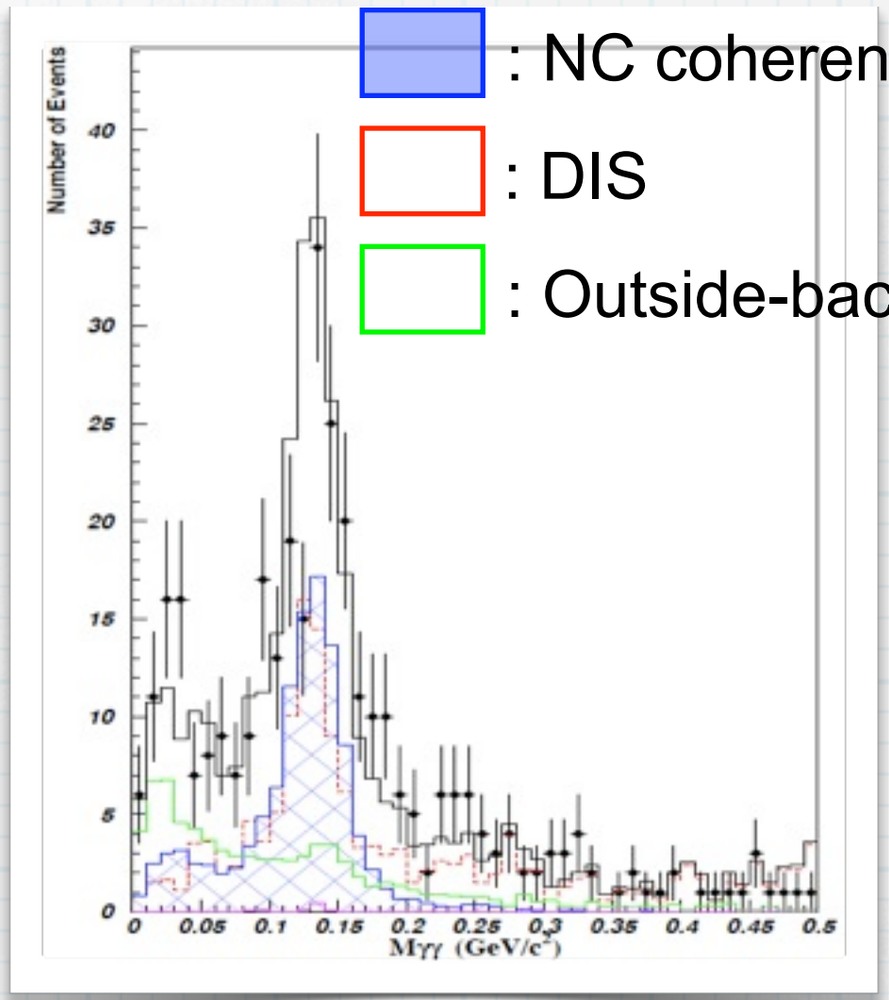
  $R_{coh} = (17.9 \pm 4.1(stat+sys))\%$
- SB and MB consistent with each other, within error.

NOMAD NC coh-π^0

- Drift Chamber target (<A>=12.8 ~ Carbon target)
- <Ev>~25 GeV
  - Major background: NC DIS
- Magnetized detector
  - Momentum reconstruction of e+e- from γ-conversion in DC

Phys. Lett. **B682**: 177 (2009)





NOMAD NC coh-π^0

- Template fit to extract coh-π cross section
  - Eγ(1-cosθγ) and 2γ opening angle
- Clear evidence of NC coh-π0
- Good agreement with past measurements and R-S prediction

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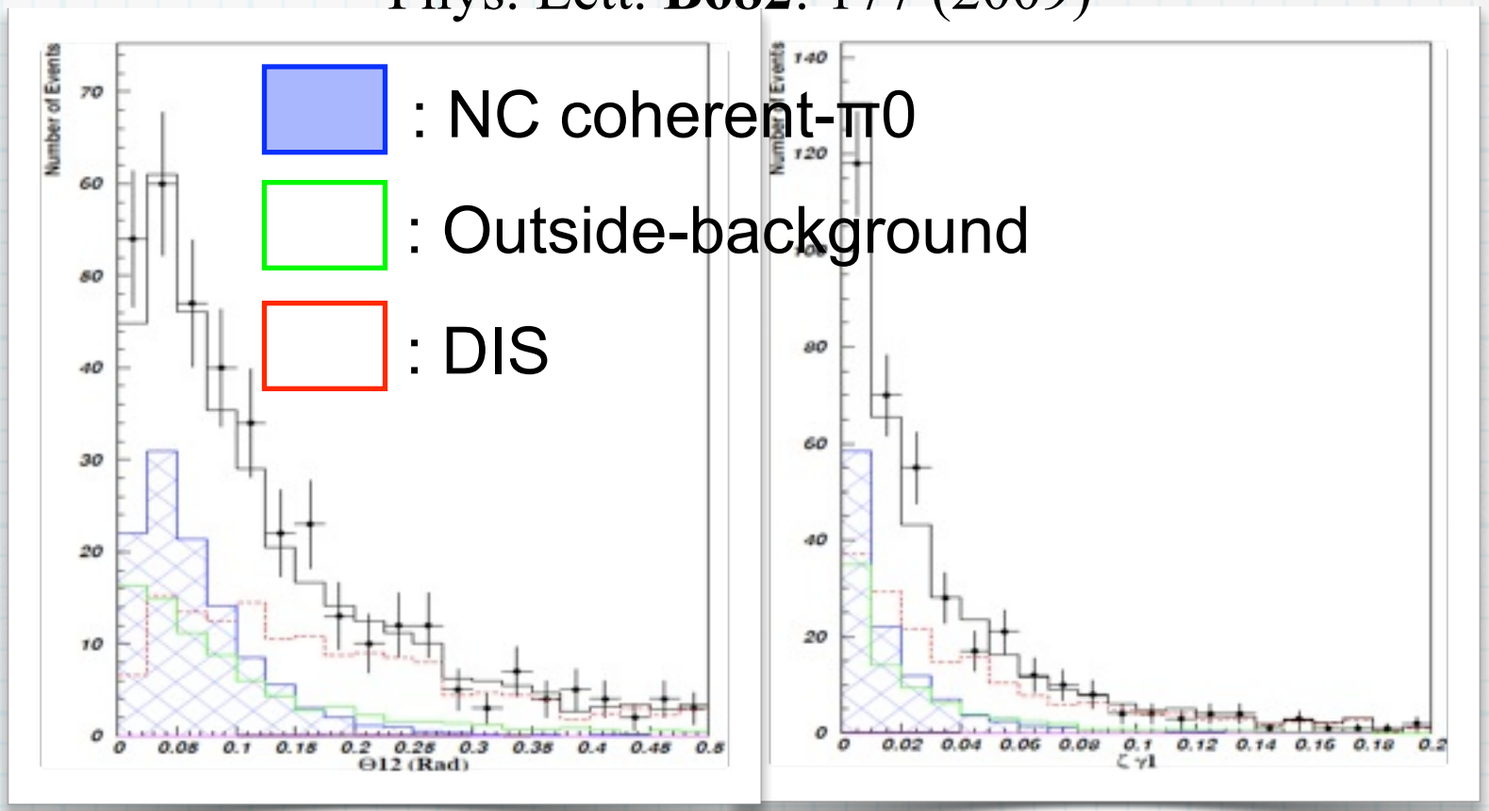


γγ opening angle $E_{\gamma 1}(1-\cos\theta_{\gamma 1})$

$$\frac{\sigma(\mathrm{NCcoh}\pi^0)}{\sigma(\nu_\mu \mathrm{CC})} = (3.21\pm0.36(\mathrm{stat})\pm0.29(\mathrm{sys}))\times10^{-3} \quad \langle E_\nu\rangle = 24.8\ \mathrm{GeV}$$

cf. Rein-Sehgal model: $\sigma(\mathrm{NCcoh}\pi^0)/\sigma(\mathrm{CC}) = 3.5\times10^{-3}$

$$\sigma(\mathrm{NCcoh}\pi^0) = (72.6\pm8.1(\mathrm{stat})\pm6.9(\mathrm{sys}))\times10^{-40}\ \mathrm{cm}^2/\mathrm{nucleus}$$

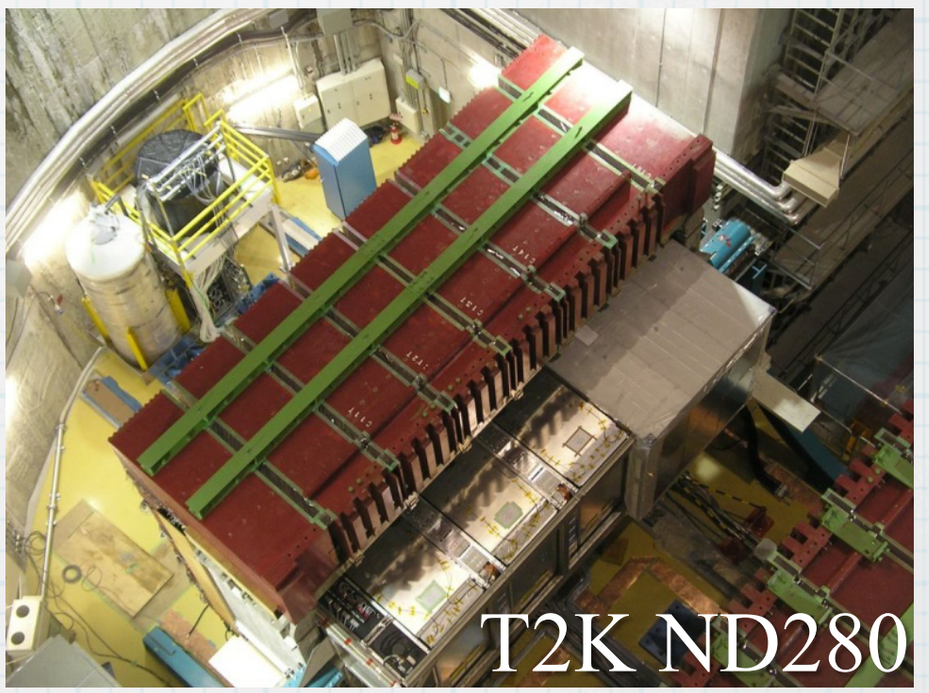
cf. Rein-Sehgal model: $\sigma(\mathrm{NCcoh}\pi0) = 78\times10^{-40}\ \mathrm{cm}^2/\mathrm{nucleus}$

Quick digest of recent results

- CC coherent-π^+: No evidence at low energy (≤2GeV)
  - **K2K**, **SciBooNE**: consistent with each other
  - **BUT** SciBooNE $\bar{\nu}$ CC coh-π search seeing non-zero CC coh-π events? (analysis underway)
- NC coherent-π^0: Clear evidence
  - **MiniBooNE**, **SciBooNE**: consistent with each other
  - **NOMAD**: Consistent with past measurements at high energy
- Puzzle in CC/NC coh-π at low energy...
  - R-S model predict $\sigma(CC{:}\pi^+)/\sigma(NC{:}\pi^0)\sim 2$
- Need a bridge between low and high energies for CC and NC modes ➜ New experiments!

The Future is Here

- T2K and MINERvA are taking data!
- Both detectors designed to measure cross sections
  - Cover wide energy range: ~0.7 - 20 GeV
  - Various targets:
    - MINERvA: He, C, Water, Fe, Pb
    - T2K Near Detector: C, H2O
    - ➜ Can measure *A*-dependence of coh-π production.



Summary

- Recent coherent-π measurements
  - CC: K2K, SciBooNE
  - NC: MiniBooNE, NOMAD, SciBooNE
  - High statistics, systematic error dominating
    (major systematics from background modeling: resonant-π, multi-π, DIS, and their FIS)
- Reliable predictions of backgrounds are important to extract coherent-π.
- Both theoretical and experimental efforts are needed
- Next generation experiments, T2K and MINERvA, can complete the comprehensive study of coherent-π production.