

Coherent- ρ^0 Production in Neutrino Neutral-Current Interactions

$$\nu_{\mu} \mathcal{A} \rightarrow \nu_{\mu} \rho^0 \mathcal{A}$$

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Coherent Processes:

- * **Coherent π^0**
- * **Coherent ρ^0**
- * **Coherent π^+**
- * **Coherent ρ^+**
- ★ **Coherent π^-**
- ★ **Coherent ρ^-**

(* \rightarrow *Different Analyses*)

\Rightarrow *Structure of Weak-Current and its Hadronic-Content*

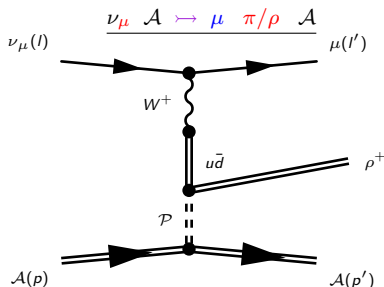
Coh π \Rightarrow Partially conserved axial current (PCAC) & Adler's theorem

Coh ρ \Rightarrow Conserved vector current (CVC) & Vector meson dominance (VMD)

\Rightarrow * **Coh π^- / Coh π^+** : Identical signatures ($\mu\pi$) \Rightarrow Constraint on the $\nu/\bar{\nu}$ Flux

- * **Coh ρ^0** : If/Since CVC and VMD are at work, then using a γ -induced Coh $\rho^- \Rightarrow$
Get an independent measure of the **Absolute Nu & NuBar Flux**;
Coh ρ^+ and Coh ρ^+ provide additional redundancies.

A matrix of measurements leading to a much better modeling of Low- Q^2 processes and provide constraints on Flux that are independent of the usual methods

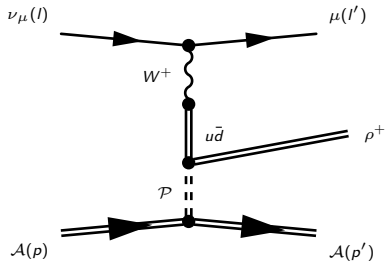


Neutrino-Induced Coherent Rho Production: $\nu_\mu \mathcal{A} \rightarrow \mu^- \pi/\rho \mathcal{A}$

* Hadron Dominance:

Piketty-Stodolsky Model \Rightarrow CVC

ν -Induced $\rho \leftrightarrow \gamma$ -production ρ



$$\frac{d^3\sigma (\nu_\mu \mathcal{A} \rightarrow \mu^- \rho^+ \mathcal{A})}{dQ^2 d\nu dt} = \frac{G_F^2}{4\pi^2} \frac{f_\rho^2}{1 - \epsilon} \frac{|q|}{E_\nu^2} \left[\frac{Q}{Q^2 + m_\rho^2} \right]^2 (1 + \epsilon R) \left[\frac{d\sigma^T(\rho^+ \mathcal{A} \rightarrow \rho^+ \mathcal{A})}{dt} \right]$$

where G_F is the weak coupling constant, $Q^2 = -q^2 = -(k - k')^2$, $t = (p - p')^2$, $\nu = E_\nu - E_\mu$, the polarization parameter $\epsilon = \frac{4E_\nu E_\mu - Q^2}{4E_\nu E_\mu + Q^2 + 2\nu^2}$, and $R = \frac{d\sigma^L/dt}{d\sigma^T/dt}$ with σ^L and σ^T as the longitudinal and transverse ρ -nucleus cross-sections. The ρ form factor f_ρ is related to the corresponding factor in charged-lepton scattering, $f_\rho^\pm = f_\rho^\gamma \sqrt{2} \cos \theta_C$, θ_C is the Cabibbo angle and $f_\rho^\gamma = m_\rho^2/\gamma_\rho$ is the coupling of ρ^0 to photon ($\gamma_\rho^2/4\pi = 2.4 \pm 0.1$).

Meson-Nucleus Absorption:

Following the Rein-Sehgal model of meson-nucleus absorption,

$$\frac{d\sigma^T(\rho^+ \mathcal{A} \rightarrow \rho^+ \mathcal{A})}{dt} = \frac{\mathcal{A}^2}{16\pi} \sigma^2(hn) \exp(-b|t|) F_{abs}$$

where $\sigma(hn)$ is the 'hadron-nucleon' cross-section with the energy of the hadron $\simeq \nu$, $b = R^2/3$ such that $R = R_0 \mathcal{A}^{1/3}$, with $R_0 = 1.12 fm$ and the absorption factor $F_{abs} = 0.47 \pm 0.03$.

* Coherence Condition: $\sqrt{|t|} \leq 1/R_{Nucleus}$

Coherent- ρ^0 -vs- Coherent- ρ^+ :

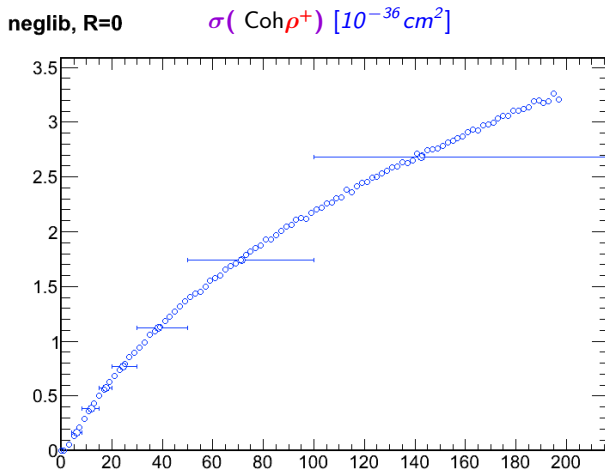
- * Coherent ρ^\pm observed by E546, E632, SKAT, and BEBC
Precision of $\pm 25\text{--}30\%$
- * Measurement of Coherent- ρ^0 has never been reported.
Inclusive- ρ^0 has been measured:
the most precise measurement is by NOMAD
(Nucl. Phys. **B601**, 3[2001])
- * Simple relation between Coherent ρ^0 & Coherent $\rho^\pm \rightsquigarrow$

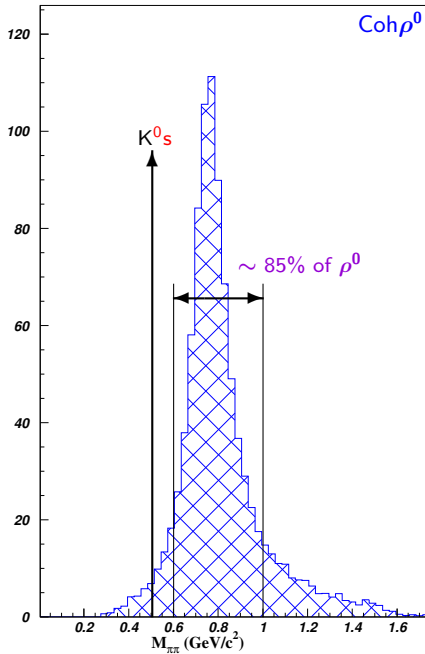
$$\frac{d^3\sigma(\nu_\mu \mathcal{A} \rightarrow \nu_\mu \rho^0 \mathcal{A})}{dQ^2 d\nu dt} = \frac{1}{2} (1 - 2 \sin^2 \theta_W)^2 \left[\frac{d^3\sigma(\nu_\mu \mathcal{A} \rightarrow \mu^- \rho^+ \mathcal{A})}{dQ^2 d\nu dt} \right]$$

$$\Rightarrow \sigma(\text{Coherent-}\rho^0) \cong 0.15 \times \sigma(\text{Coherent-}\rho^+)$$

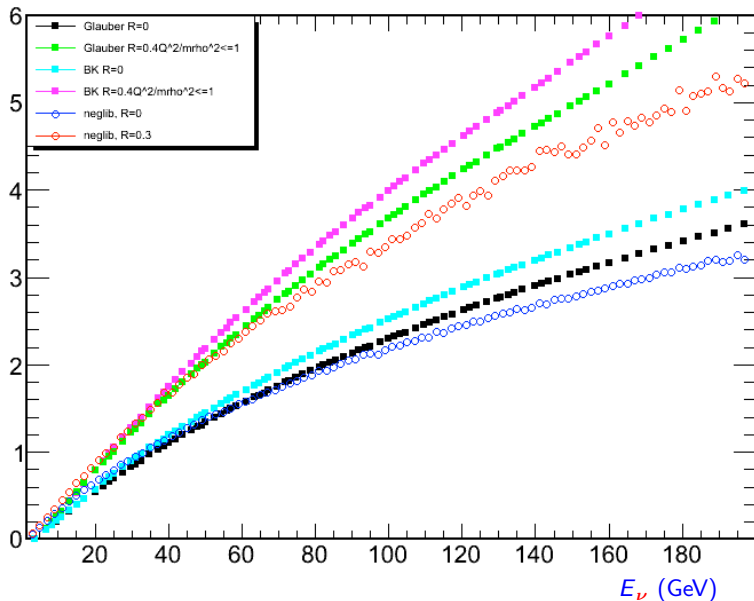
Simulation of Coherent- ρ

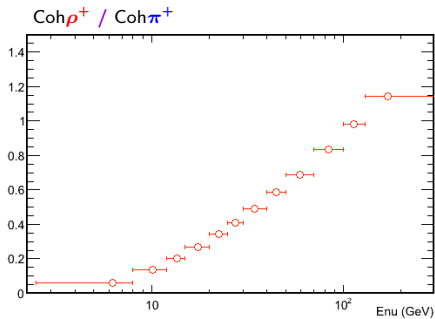
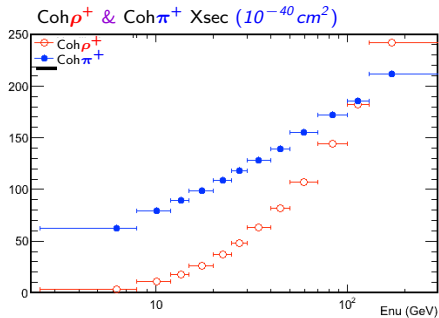
- * Stand-alone program checked against the NEGLIB Coherent- ρ^0 written by the Australian Group (Hyett & Varvell)
- * Coherent- $\rho^0 \sim 0.15 \times$ Coherent- ρ^+



$M_{\pi\pi}$ 

Xsec (10^{-36} cm^2)





Signal

- * $\pi^- \pi^+$ with little else
($\pi\pi$) vector (P, θ) consistent with Coherent- ρ^0 such that
 $\zeta_{\pi\pi} = E_{V^0} * (1 - \cos \theta_{V^0}) \leq \text{Cut (0.075)}$

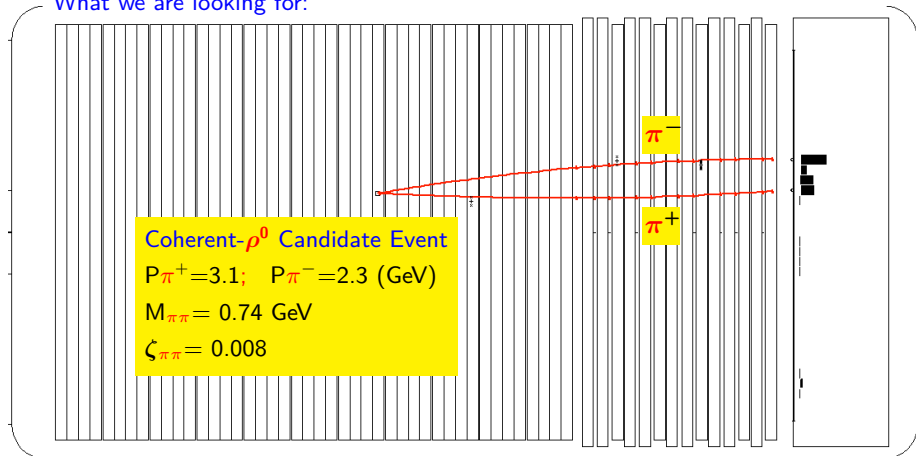
Background

- [1] NC-induced (NC-DIS) background \Rightarrow 2-Track (+,-)
- [2] CC-induced (CC-DIS) background \Rightarrow 2-Track (+,-)
where "-" is a μ^- w/o μ ID
- [3] Outside-Background (OBG) \Rightarrow K^0 s from outside-interactions

Control Sample: CC Data Simulator Correction

- * ν_μ -CC events where the μ^- identified and then 'removed';
the remaining hadronic (+,-) tracks subjected to the analysis.

What we are looking for:



What we are looking for:

Coherent- ρ^0 Candidate Event

$P_{\pi^+}=5.9$; $P_{\pi^-}=1.8$ (GeV)

$M_{\pi\pi} = 0.61$ GeV

$\zeta_{\pi\pi} = 0.024$

π^+

π^-

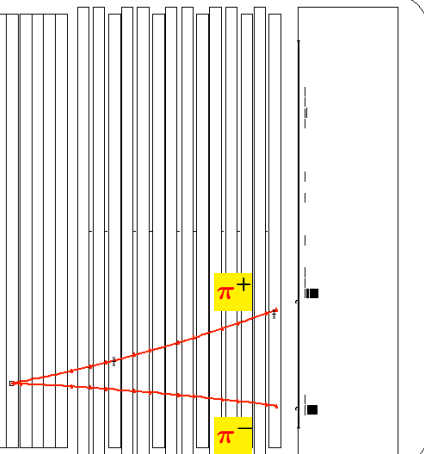
What we are looking for:

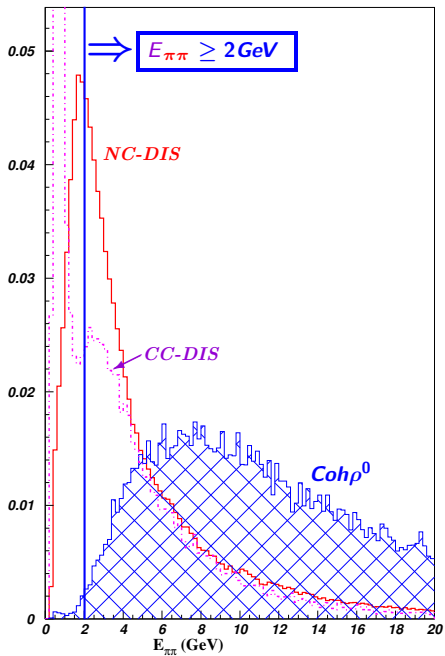
Coherent- ρ^0 Candidate Event

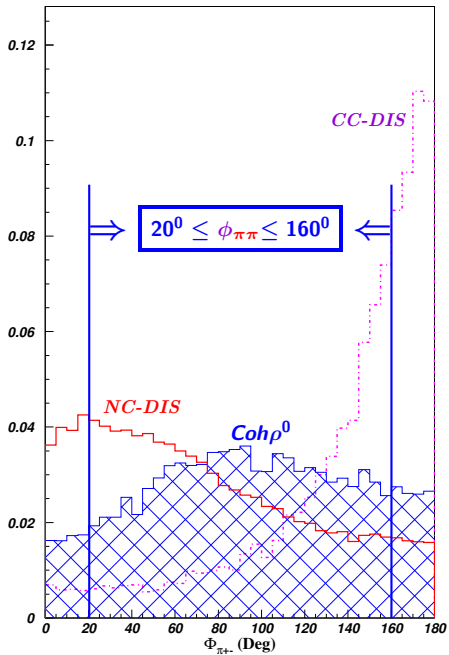
$P_{\pi^+}=1.6$; $P_{\pi^-}=2.6$ (GeV)

$M_{\pi\pi} = 0.69$ GeV

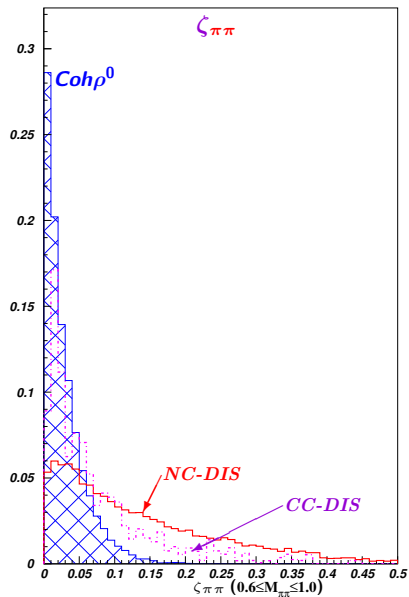
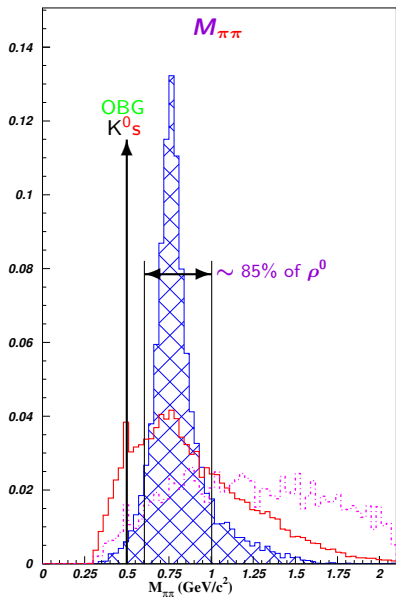
$\zeta_{\pi\pi} = 0.028$



$E_{\pi\pi}$ 

$\phi_{\pi\pi}$ 

Analysis of Coherent ρ^0 : Kinematic Shape Comparison



Coherent- ρ^0 Analysis:

- * 2-Track ($\pi^+\pi^-$) Events in Fiducial Volume w/o μ -ID passing kinematic preselection cuts

- * Calibrate OBG

- ⇒ 2-Track events with vertex outside
 - ⇒ Normalize it to the K^0 peak

- * Calibrate the shape of NC-DIS

The most important variable is the shape of $\zeta_{\pi\pi}$

- ⇒ Use CC-DS (3, 3-&-4 Track events w. μ);
 - ⇒ The $\pi^+\pi^-$ subjected to the standard selection
 - ⇒ Obtain a MC(NC-DIS) Re-Weight based on Data/MC [$P_{\pi\pm}, P_t\pi^\pm, M_{\pi\pi}, \zeta_{\pi\pi}$]

- * Normalize NCDIS (shapes reweighted using Data-Simulator)

- ⇒ Use $\phi_{\pi\pi}$ distribution with $\zeta_{\pi\pi} > 0.075$

- * Result

- ⇒ Plot $M_{\pi\pi}$; impose $0.6 \leq M_{\pi\pi} \leq 1.0$ GeV
 - ⇒ Using $\zeta_{\pi\pi}$, fit for $Coh\rho$ using ≤ 0.1 region
 - ⇒ Check CC-DIS normalization
 - ⇒ Systematic error analysis

Preselection

NC-DIS ($\sim \mathbf{x4}$ Data) \rightarrow 0.44M

CC-DIS ($\sim \mathbf{x4}$ Data) \rightarrow 1.44M

Coh π^+ \rightarrow 10k

Coh ρ^0 \rightarrow 1,000

* Fiducial Cut, Muon-Veto, 2-Tracks, $E_{\pi\pi} \geq 2\text{GeV}$

Sample	#-Events
NC-DIS ($\sim \mathbf{x4}$)	18,400
CC-DIS ($\sim \mathbf{x4}$)	4,600
Data	39,500

Selection

- * 'Other' includes QE, Res, Coh π^+ , Coh π^0
- * Vetos: DC-Veto/tube, Upstream-hanger, V 0 -from-vertex

<i>Selection</i>	<i>NC-DIS*</i>	<i>CC-DIS*</i>	<i>OBG</i>	<i>Other</i>	<i>Cohρ^0*</i>	<i>Total</i>	<i>Data</i>
<i>Veto/UpHanger</i>	10, 262	2, 259	1, 520	526	395	14, 962	15, 850
<i>Photon Veto</i>	6, 846	1, 361	359	260	368	9, 195	9, 490
$20^0 \leq \phi_{\pi\pi} \leq 160^0$	5, 321	787	255	104	305	6, 770	6, 852

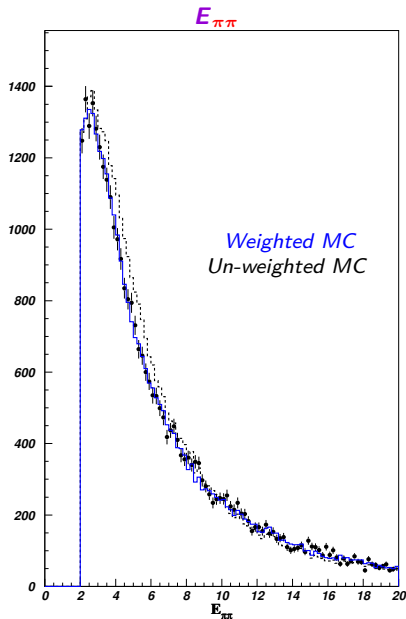
Data Simulator: calibrate the shape of NC-DIS:

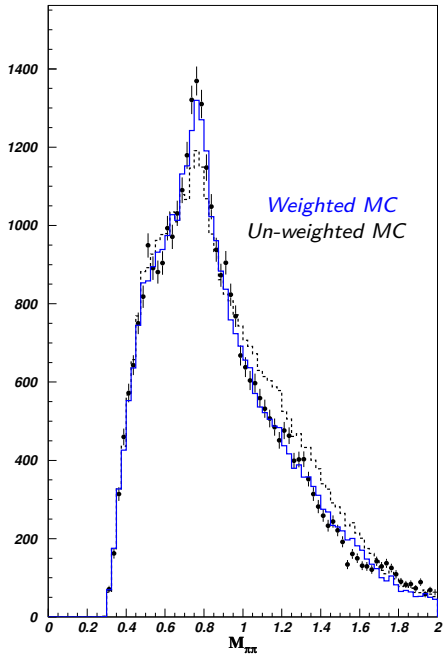
- * Select ν_{μ} -CC events with 3 and 3-&-4 tracks, including the μ
- * Obtain a weight for MC(NC-DIS) using $\text{DS-Correction} = \text{Data}/\text{MC}$
 $[P_{\pi^{\pm}}, P_t \pi^{\pm}, M_{\pi\pi}, \zeta_{\pi\pi}]$
- * Apply the weight to NC-DIS
- * Repeat this study: Re-Weight for MC(NC-DIS) using Data/MC [only $\zeta_{\pi\pi}$]
- * 3-Track and (3+4)-Track ν_{μ} -CC events yield entirely consistent results
 \Rightarrow Use (3+4)-Track sample for the DS-correction

Shape of NC-DIS used in Coherent ρ^0 Analysis: CC Data-Simulator

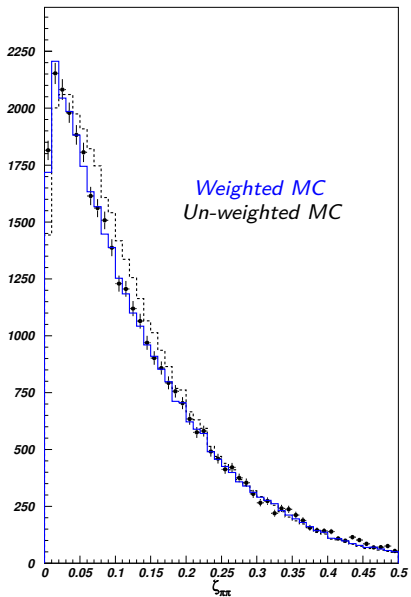
* ν_{μ} -CC with $\mu^- \pi^+ \pi^-$

* DIS weight based upon:
 $[P_{\pi^\pm}, P_t \pi^\pm, M_{\pi\pi}, \zeta_{\pi\pi}] \Rightarrow$

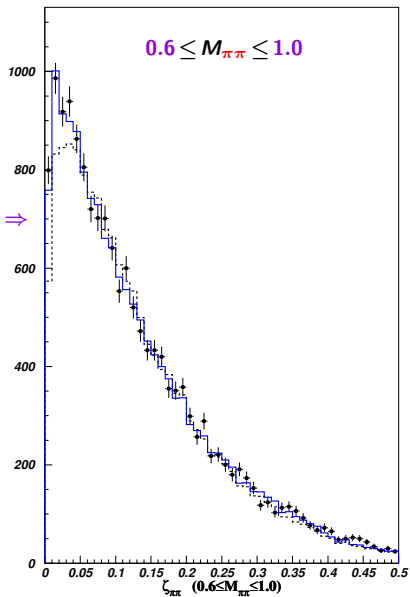




$\zeta_{\pi\pi}$



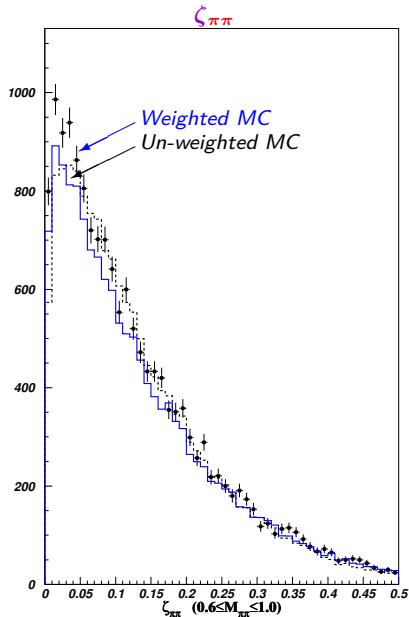
Signal \Rightarrow

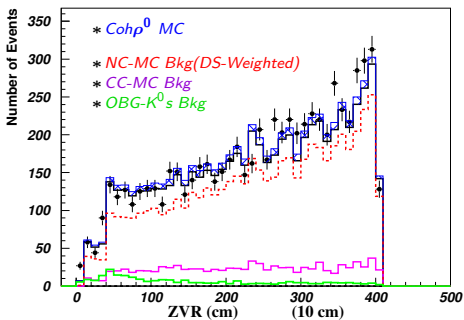
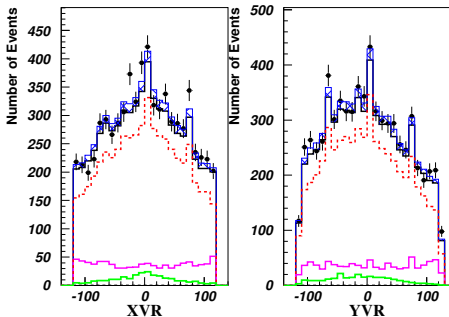


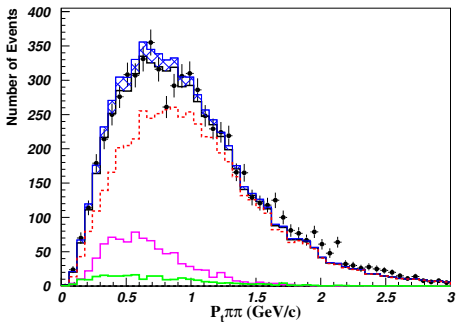
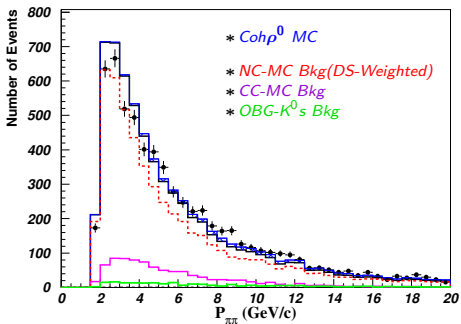
CC Data-Simulator: Variant

* DIS weight based upon only: $[\zeta_{\pi\pi}]$

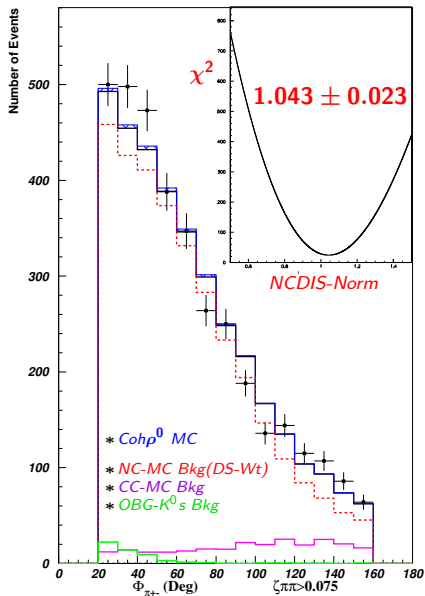
Alternative scheme

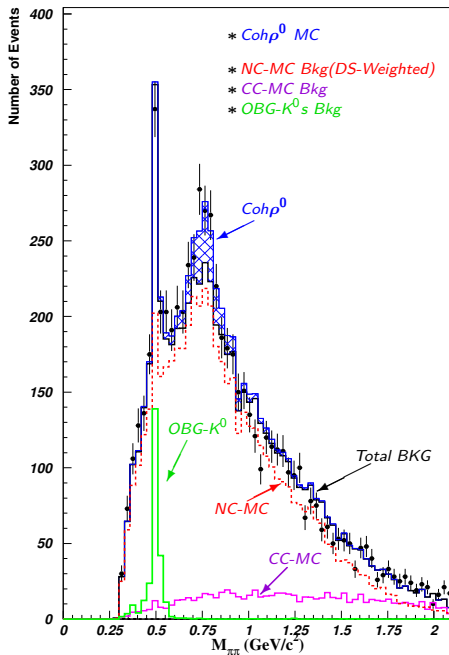


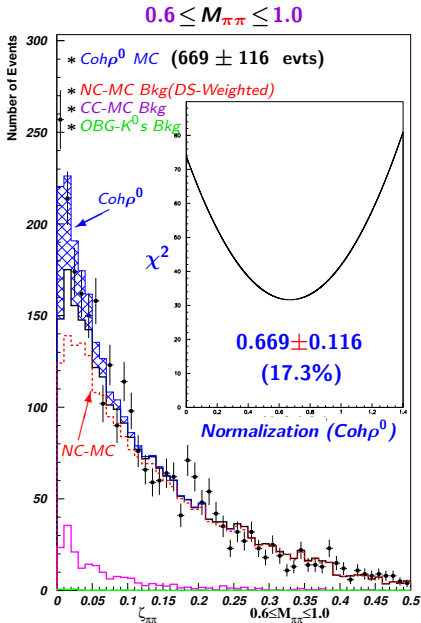
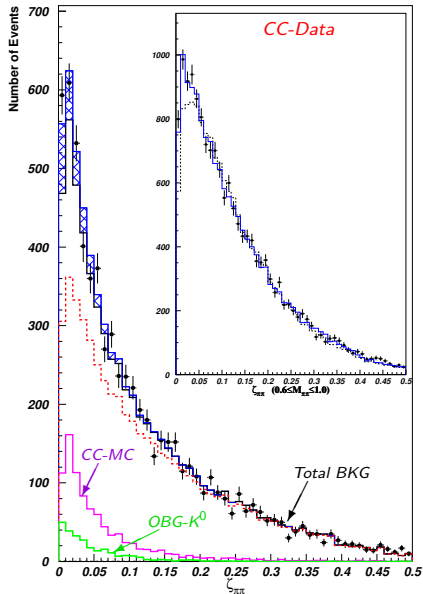




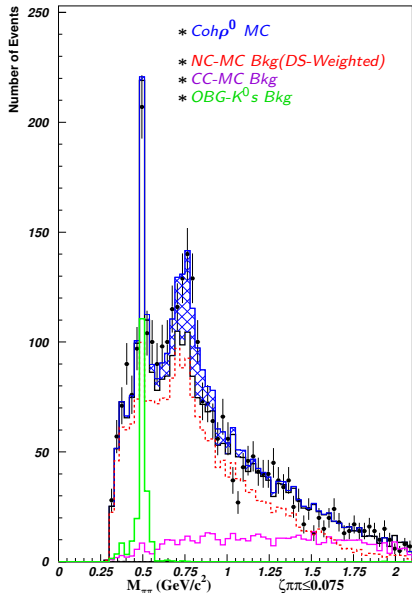
Normalization of NC Background



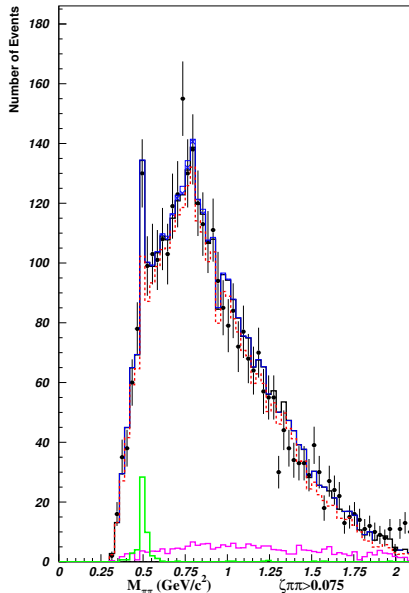




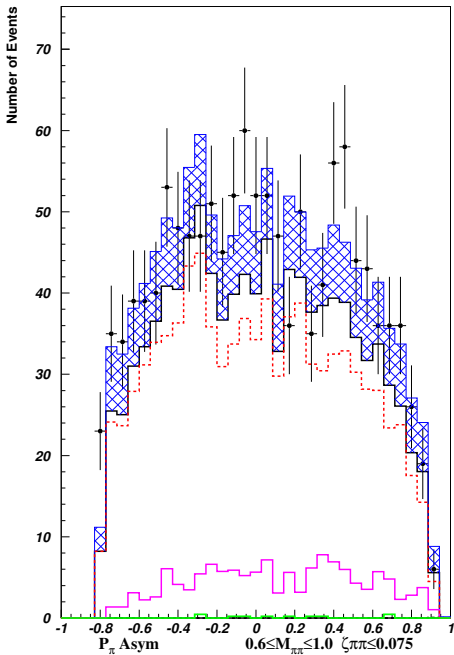
Coherent Region: $\zeta \leq 0.075$



non-Coherent Region: $\zeta > 0.075$



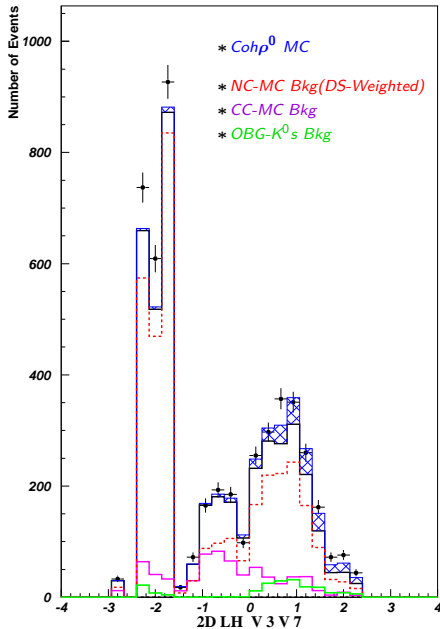
Momentum Asymmetry in Signal Region



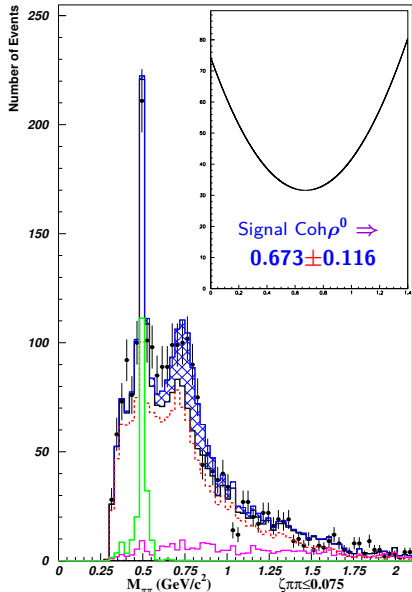
Multi-Variate Analysis of the $\text{Coh-}\rho^0$

- * Identical event selection; DS-Correction applied to the shapes of the NC-DIS.
- * Form a Likelihood function based upon:
$$LH = [\zeta_{\pi\pi}, \phi_{\pi\pi}]$$
- * Coherent-Region $\Rightarrow LH \geq 0.0$
non-Coherent-Region $\Rightarrow LH < 0.0$
- * Chris tried 3 other LH functions based upon other variables, all giving similar results.

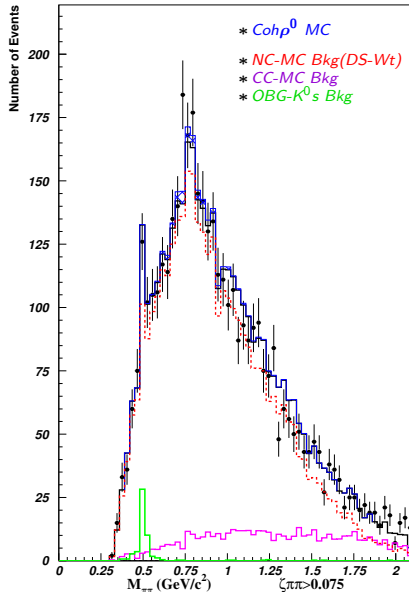
$LH [\zeta_{\pi\pi}, \phi_{\pi\pi}]$



Coherent Region: $LH \geq 0.0$

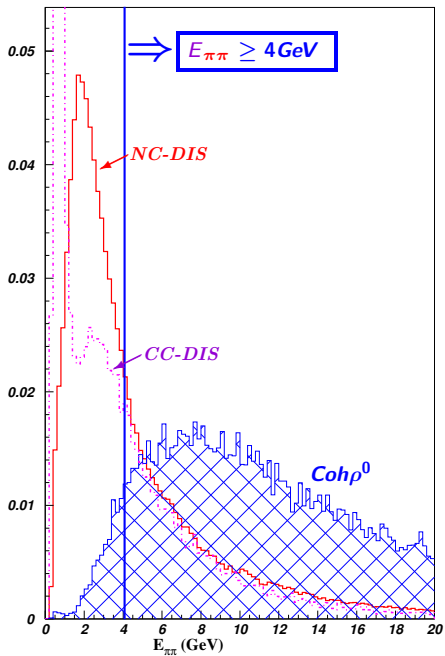


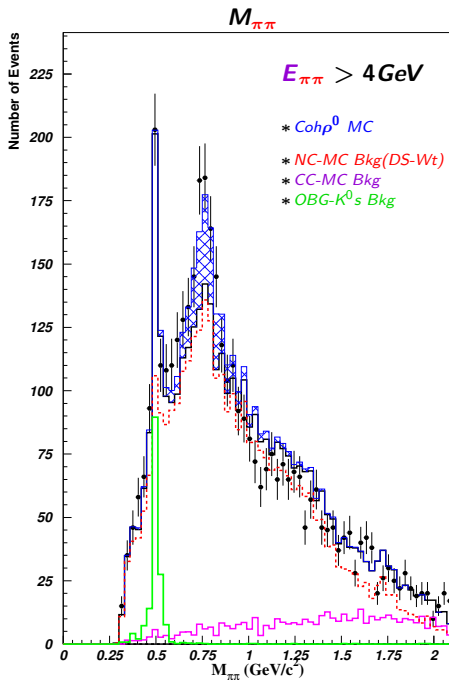
non-Coherent Region: $LH < 0.0$



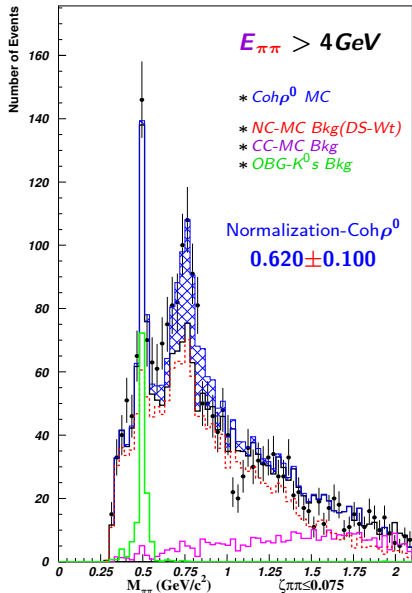
Conclusion of Multi-Variate Analysis of the $\text{Coh-}\rho^0$

- * Results, Coherent and non-Coherent regions, consistent with those presented earlier.
- * Chris tried 3 other LH functions based upon other variables, all giving similar results.
- * But unlike the earlier analysis, LH did not yield any deeper insight. Actually, we found it as charming as M.R. but considerably more consistent.

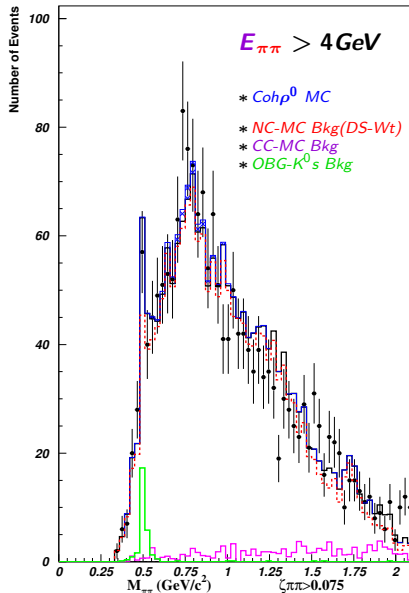




Coherent Region: $\zeta \leq 0.075$



non-Coherent Region: $\zeta > 0.075$



Conclusion of ' $E_{\pi\pi} > 4\text{GeV}$ -Cut' Analysis of the $\text{Coh-}\rho^0$

- * Results, Coherent and non-Coherent regions, consistent with those presented in the standard analysis.
- * The stringent cut, $E_{\pi\pi} > 4\text{GeV}$, lowers the backgrounds (NC-DIS & CC-DIS), and offers a slightly better statistical error on the $\text{Coh-}\rho^0$ signal, but overall error, Stat+Syst, is similar to the analysis with the looser cut.

Systematic Error \Rightarrow

- * Data-Simulator: (Shape of ζ in NC-DIS)

Using only ζ -Wt

(which does not describe the $\pi\pi$ system in CC-data well)

$$\Rightarrow \pm 0.072 \text{ (10.8\%)}$$

=====

- * NC-DIS:

Using $\pm 2.2\%$ variation

(constrained by $\phi_{\pi\pi}$ in the background region)

$$\Rightarrow \pm 0.048 \text{ (7.17\%)}$$

- * CC-DIS:

$$\Rightarrow \pm 0.015 \text{ (2.24\%)}$$

Systematic Error \Rightarrow

- * OBG (K^0):

With 833 data events used to simulate the OBG, a 3.5% variation in its normalization had a negligible effect on the $\text{Coh}\rho^0$ normalization.

$$\Rightarrow \pm 0.000 \text{ (0.0\%)}$$

- * Total Systematic Error:

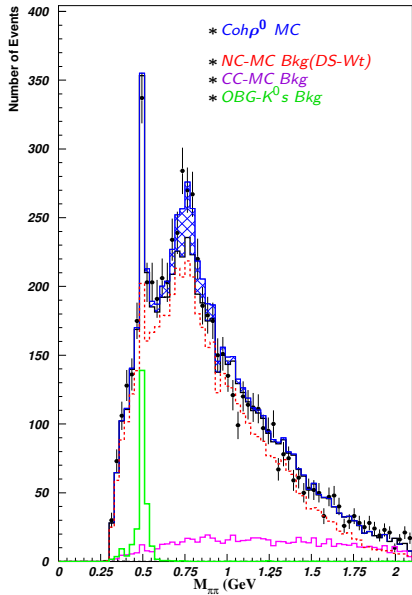
$$\Rightarrow \pm 0.088 \text{ (13.2\%)}$$

- * Total Error:

$$\Rightarrow 0.669 \pm 0.116 \pm 0.088 \text{ (\pm 21.8\%)}$$

$$\text{Conclusion} \Rightarrow \nu_{\mu} \mathcal{A} \rightarrow \nu_{\mu} \rho^0 \mathcal{A}$$

- * We have conducted a measurement of Coherent- ρ^0 production. A clear signal of Coherent- ρ^0 is observed.
- * The analysis is data-driven; the backgrounds are constrained using control samples.
- * We observe:
 $669 \pm 116(\text{Stat.}) \pm 88(\text{Syst.})$ fully corrected Coherent- ρ^0 events.
- * The rate with respect to -CC events ($1.44 * 10^6$) is:
 $(4.65 \pm 1.01) * 10^{-4}$



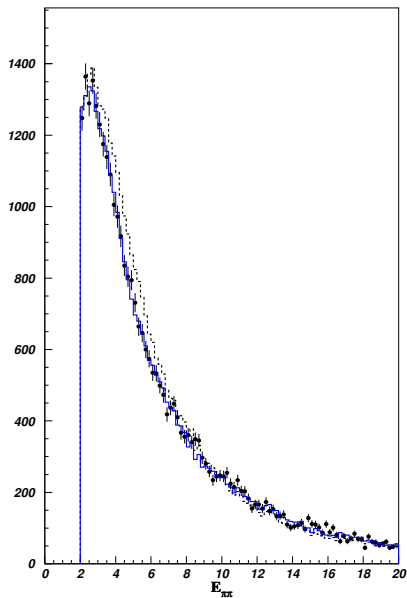
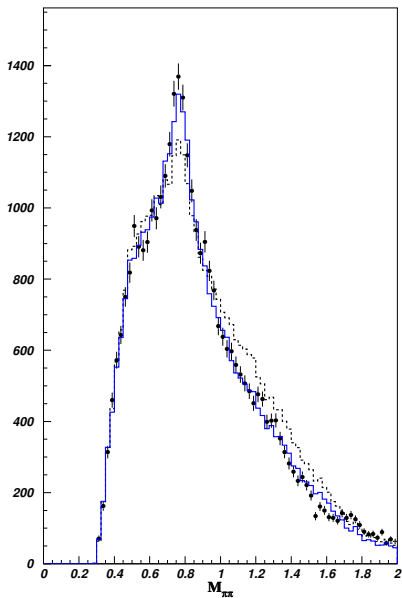
← A beautiful distribution in ν -measurement!

but... useless!

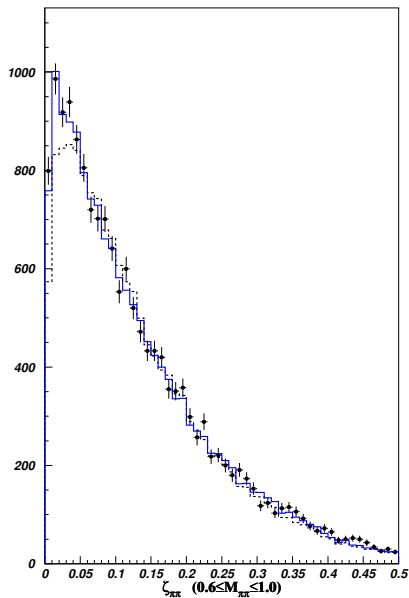
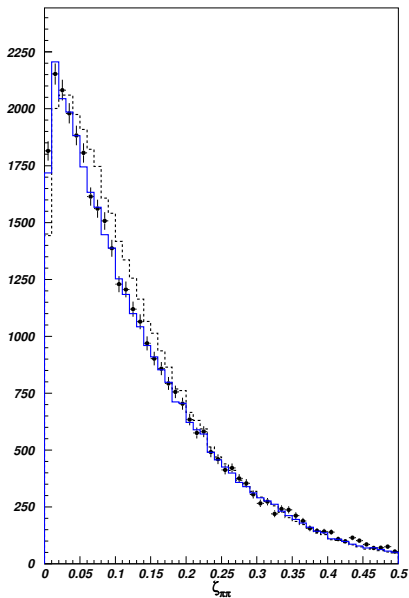
Backup

We can forgive a man for making a useful thing as long as he does not admire it. The only excuse for making a useless thing is that one admires it intensely.

CC Data-Simulator (Standard Reweight)



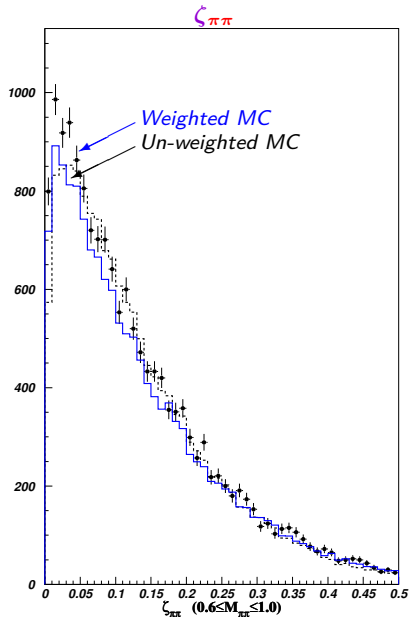
CC Data-Simulator (Standard Reweight)



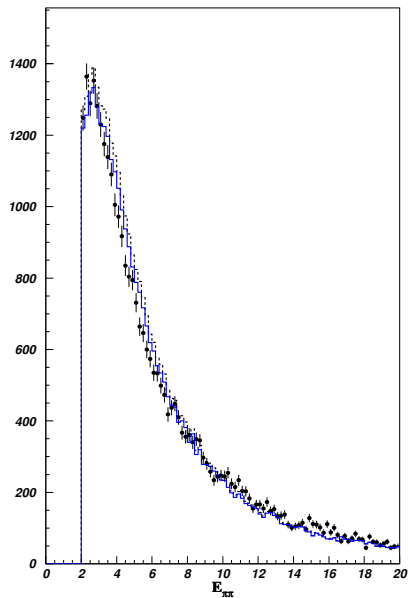
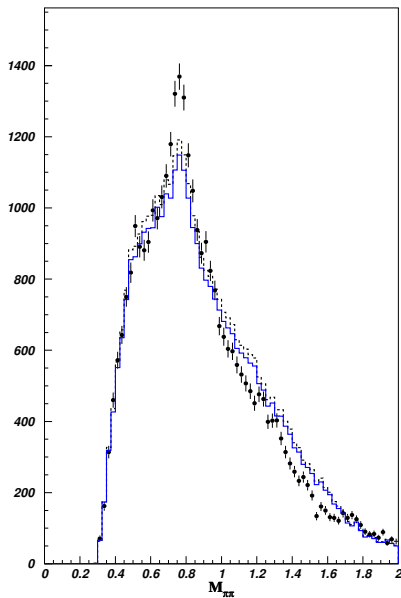
CC Data-Simulator: Variant

* DIS weight based upon only: $[\zeta_{\pi\pi}]$

Alternative scheme



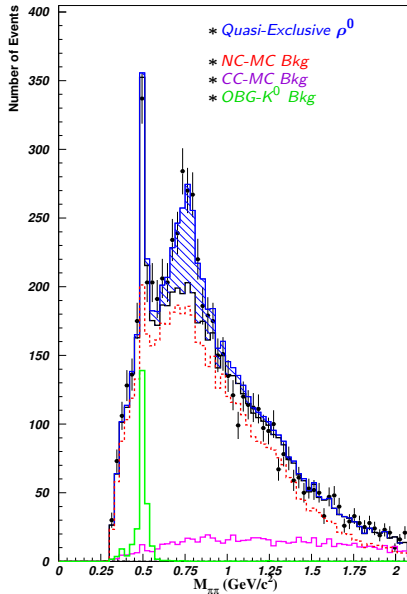
CC Data-Simulator (Variant)



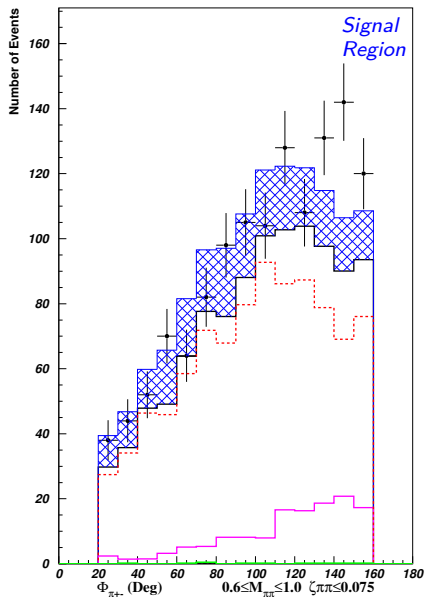
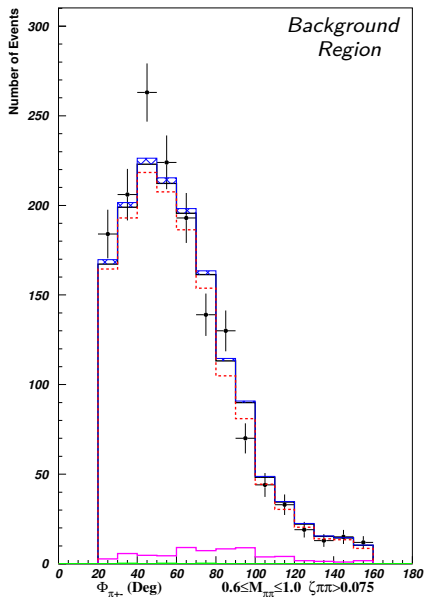
Quasi-Exclusive ρ^0 in NC

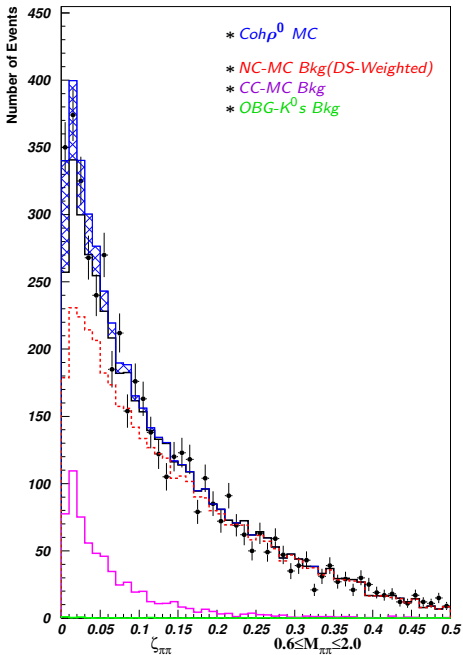
Quasi-Exclusive $\rho^0 \Rightarrow$
 1.192 ± 0.142

Using $\text{Coh}\rho^0$ as an
 efficeincy model \Rightarrow
 $1,192 \pm 142$ Events



$\phi \pi\pi$ with $(0.6 \leq M_{\pi\pi} \leq 1.0)$





$\phi_{\pi\pi}$ Used to Normalize CC-MC

