# *Coherent Meson Production in the NOMAD Experiment*

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# *Outline*

- *Coherent Meson Production*
- *Motivation and the NOMAD Detector*
- *Coherent* $\boldsymbol{\pi^0}$
- *Coherent* $\boldsymbol{\rho^0}$

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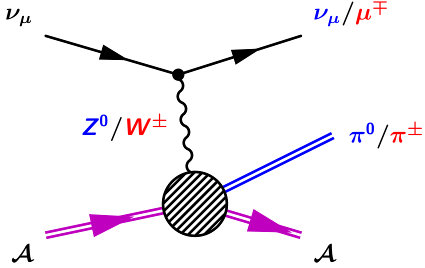
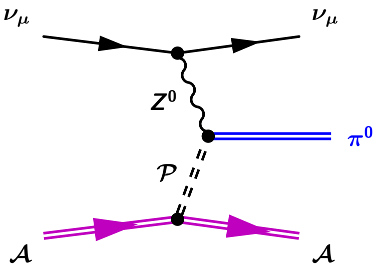
# *Coherent Meson Production in Neutrino Interactions*




- **All nucleons** in target nucleus participate coherently in interaction
- Low momentum transfer to nucleus (else a single nucleon can be ejected)
- Nucleus recoils intact, and in its ground state
- No exchange of quantum numbers (charge, spin, isospin)
- Emerging meson has small angle w.r.t. incident neutrino

# *Neutrino-Induced Coherent Pion Production*

$$\boxed{\nu_\mu \;\; \mathcal{A} \;\rightarrowtail\; \nu_\mu \;\; \mathcal{A} \;\; \pi^0}$$




$*$ Low $Q^2$ with CVC
Goldberger-Treinman relation + PCAC:
$\Rightarrow$ Adler Relation
$\nu$-production $\leftrightarrow$ $\pi$-scattering

$$|\langle\beta|\partial_\lambda A^\lambda|\alpha\rangle|^2 = f_\pi^2|\mathcal{M}(\pi\alpha \to \beta)|^2$$

$$\frac{d^3\sigma\left(\nu\mathcal{A} \to \nu\pi^0\mathcal{A}\right)}{dx\; dy\; dt} = \frac{G_F^2 M E_\nu}{2\pi^2} f_\pi^2 (1-y)\left(\frac{M_A^2}{M_A^2+Q^2}\right)^2\left[\frac{d\sigma(\pi\mathcal{A}\to\pi\mathcal{A})}{dt}\right]$$

where $G_F$ is the weak coupling constant, $M$ the target mass, $M_A$ the axial mass, $y$ the fraction of energy transferred to the hadronic system, $\nu = E_\nu - E_\mu$, $Q^2 = -q^2 = -(k-k')^2$, $x = Q^2/2M\nu$ (target at rest), $t = (p-p')^2$, and $f_\pi$ the pion decay constant.

# *Modeling of the Strong Meson-Nucleus Scattering*

We follow Rein and Sehgal's method of modeling the meson-nucleus scattering on meson-nucleon scattering:

$$\frac{d\sigma(\pi^0\mathcal{A}\to\pi^0\mathcal{A})}{dt} = A^2|F_A(t)|^2 \left.\frac{d\sigma(\pi^0N\to\pi^0N)}{dt}\right|_{t=0}$$

where $A$ gives the number of nucleons. Using the optical theorem to model the meson-nucleon scattering:

$$\left.\frac{d\sigma(\pi^0N\to\pi^0N)}{dt}\right|_{t=0} = \frac{1}{16\pi}\left[\sigma_{tot}^{\pi^0N}\right]^2(1+r^2) \quad ; \quad r = \frac{\mathrm{Re}(f_{\pi N}(0))}{\mathrm{Im}(f_{\pi N}(0))}$$

with $f_{\pi N}(0)$ being the forward $\pi N$ amplitude.
The nuclear form factor is modeled by an exponential:

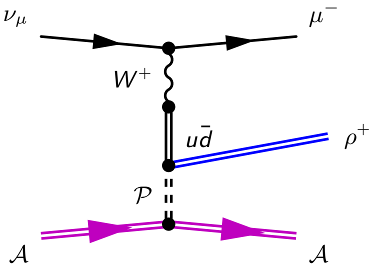
$$|F_A(t)|^2 = \exp\left(-\tfrac{1}{3}R_0^2A^{2/3}|t|\right)F_{abs} \quad ; \quad R_0 = 1.12fm$$

$F_{abs}$ is a factor taking into account the absorption of the pion within the nucleus (assuming homogeneous sphere):

$$F_{abs} = \exp\left(-\frac{9A^{1/3}}{16\pi R_0^2}\left[\sigma_{inel}^{\pi N}\right]\right)$$

# *Neutrino-Induced Coherent Rho Production*

$$\boxed{\nu_\mu \ \mathcal{A} \longrightarrow \mu \ \ \rho \ \ \mathcal{A}}$$




$*$ Hadron Dominance:
Piketty-Stodolsky Model $\Rightarrow$
VMD + CVC
$\boldsymbol{\nu}$-Induced $\boldsymbol{\rho}$ $\leftrightarrow$ $\boldsymbol{\gamma}$-production $\boldsymbol{\rho}$

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

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 $\sigma^L$ and $\sigma^T$ as the longitudinal and transverse $\rho$-nucleus cross-sections. The $\rho$ form factor $f_\rho$ is related to the corresponding factor in charged-lepton scattering, $f_\rho^\pm = f_{\rho^0}^\gamma \sqrt{2}\cos\theta_C$, $\theta_C$ is the Cabibbo angle and $f_\rho^\gamma = m_\rho^2/\gamma_\rho$ is the coupling of $\rho^0$ to photon ($\gamma_\rho^2/4\pi = 2.4 \pm 0.1$).

# $Coherent\text{-}\rho^0$ -vs- $Coherent\text{-}\rho^+$

- Coherent $\rho^\pm$ observed by E546, E632, SKAT, and BEBC
  Precision of $\pm$25–30%

- Measurement of Coherent-$\rho^0$ has never been reported.
  Inclusive-$\rho^0$ has been measured:
  the most precise measurement is by NOMAD
  ( Nucl. Phys. **B601**, 3[2001] )

- Simple relation between Coherent$\rho^0$ & Coherent$\rho^\pm$:

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

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

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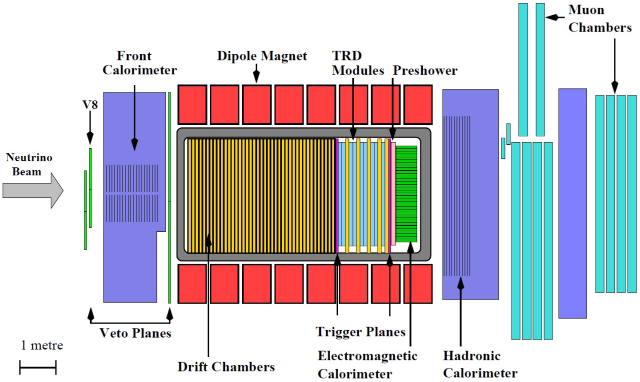
# *Motivation*

- Physics:
  - Structure of the Weak-Current and its Hadronic-Content
  - Coh$\pi$: Partially Conserved Axial Current (PCAC) and
    Adler's relation
  - Coh$\rho$: Conserved Vector Current (CVC) and
    Vector Meson Dominance (VMD)
  - Understanding meson production in $\nu$-interactions

- Practical:
  - Coh$\pi^0$ a background to $\nu_e$-appearance oscillation experiments
  - Precise measurement of coherent mesons could constrain neutrino flux and energy scale with independent systematics

# *The NOMAD Detector*




* CERN SPS neutrino beam ; $\overline{E}_\nu \approx 25$GeV ; $1.4 \times 10^6$ $\nu_\mu$-CC events
* DC (active target): 2.7 tons ; $A = 12.8$ ; $\rho = 0.1 \frac{g}{cm^3}$ ; length $\approx 1X_0$
  $\delta r < 200\mu m$ ; $\delta p \approx 3.5\%$ at $p < 10 GeV/c$ ; Unambiguous charge sep.
* TRD & Muon Chambers for PID ; ECAL (lead glass) & HCAL

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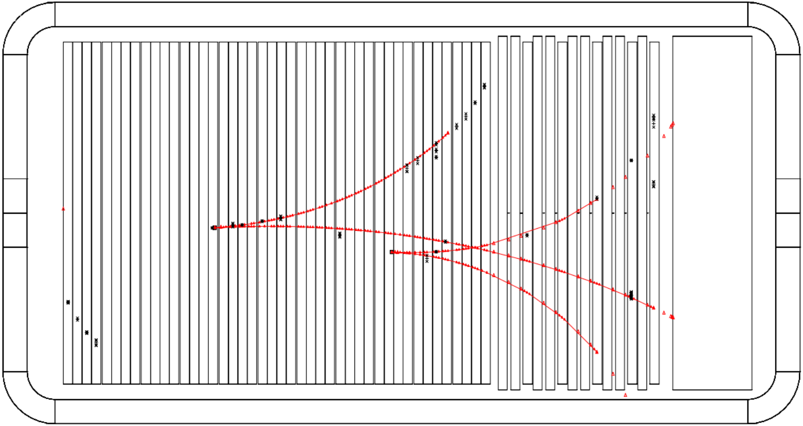
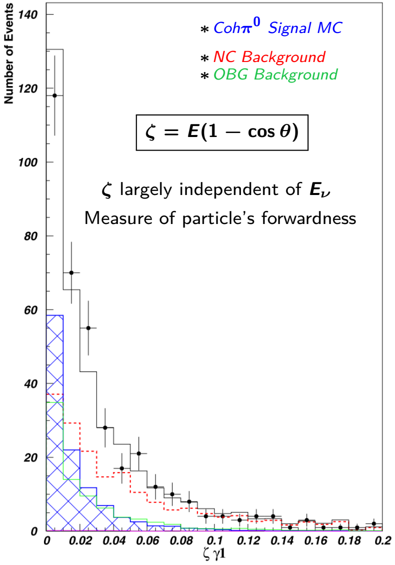
# *Coherent* $\boldsymbol{\pi^0}$ *Candidate Event*



Coh$\pi^0$ Signal: $\pi^0 \to \gamma\gamma$, and nothing else!

Backgrounds: Neutral Current $\pi^0$ production
Outside Background (OBG): Events originating upstream

# $Coh\pi^0$ $\gamma_1$ and $\gamma_2$ $\zeta$ Plots

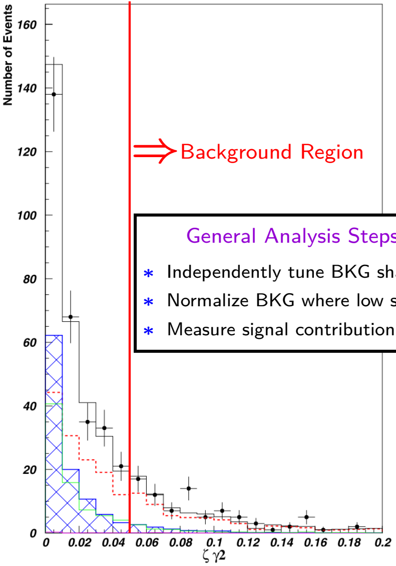



* $Coh\pi^0$ Signal MC
* NC Background
* OBG Background

$$\boxed{\zeta = E(1 - \cos\theta)}$$

$\zeta$ largely independent of $E_\nu$

Measure of particle's forwardness

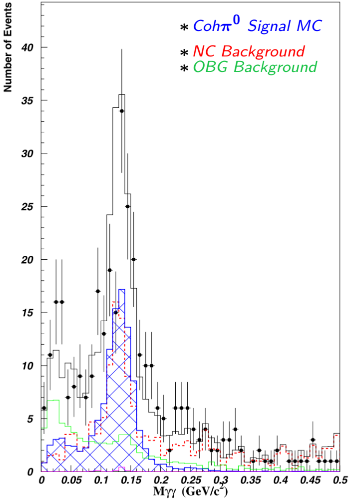


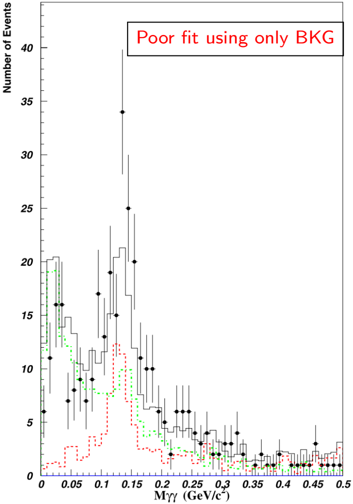

$\Rightarrow$ Background Region

General Analysis Steps:

* Independently tune BKG shapes
* Normalize BKG where low signal
* Measure signal contribution

# $Coh\boldsymbol{\pi}^0$ $M_{\gamma\gamma}$ Plots and Results




$$\sigma(\nu\mathcal{A} \to \nu\mathcal{A}\pi^0) = [72.6 \pm 8.1(stat) \pm 6.9(syst)] \times 10^{-40} cm^2/nucleus$$

Physics Letters B, Volume 682, Issue 2, p. 177-184 (arXiv:0910.0062)

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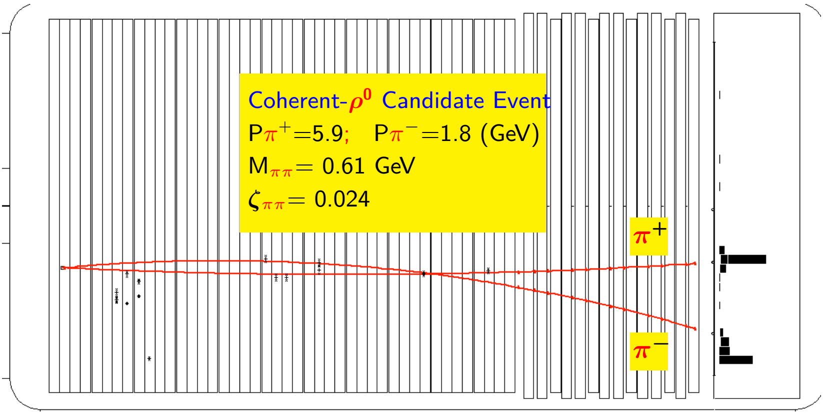
# *Coherent $\boldsymbol{\rho^0}$ Candidate Event*




Coh$\rho^0$ Signal: $\rho^0 \to \pi^+\pi^-$, and nothing else!

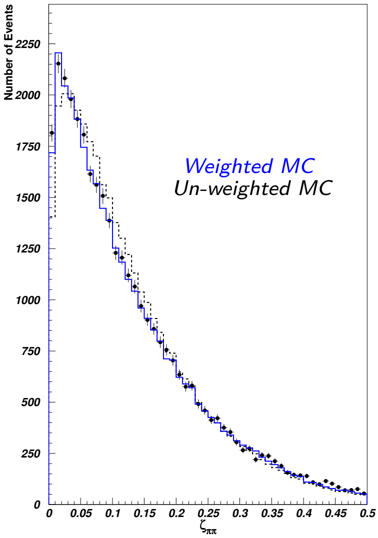
Backgrounds: Neutral Current 2-Track $V^0$
Charged Current 2-Track $V^0$ ($\boldsymbol{\mu}$ w/o $\boldsymbol{\mu}$-ID)
Outside Background (OBG): $K^0$s from outside-interactions

# *Coherent $\rho^0$ Analysis*

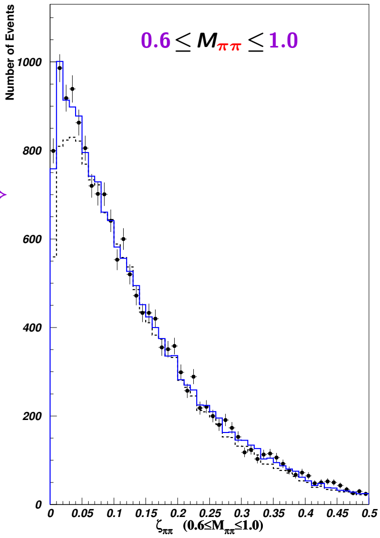
* Calibrate OBG
  - $\Rightarrow$ 2-Track events with vertex outside
  - $\Rightarrow$ Normalize it to the $K^0$ peak
* Calibrate the shape of NC-DIS

  The most important variable is the shape of $\zeta_{\pi\pi}$
  - $\Rightarrow$ Use CC-DS (3, 3-&-4 Track events w. $\mu$);
  - $\Rightarrow$ The $\pi^+\pi^-$ subjected to the standard selection
  - $\Rightarrow$ 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)
  - $\Rightarrow$ Use $\phi_{\pi\pi}$ distribution with $\zeta_{\pi\pi} > 0.075$
* Result
  - $\Rightarrow$ Plot $M_{\pi\pi}$; impose $0.6 \leq M_{\pi\pi} \leq 1.0$ GeV
  - $\Rightarrow$ Using $\zeta_{\pi\pi}$, fit for *Coh*$\rho$ using $\leq 0.1$ region
  - $\Rightarrow$ Check CC-DIS normalization
  - $\Rightarrow$ Systematic error analysis

# *Data Simulator Effect on* $\zeta_{\pi\pi}$

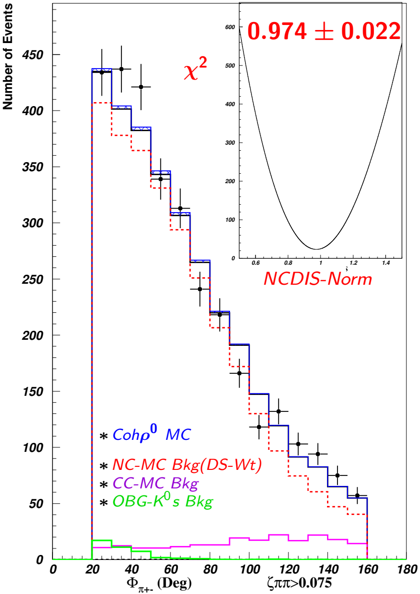


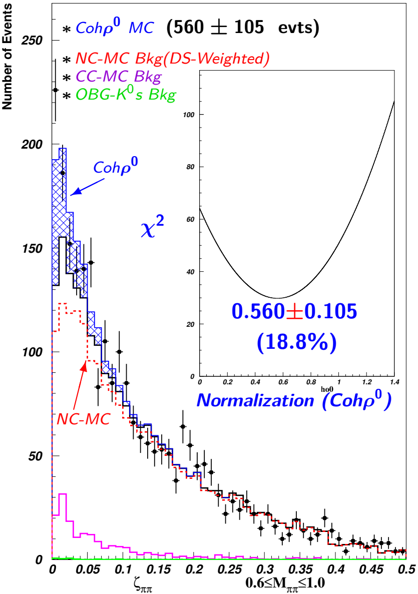

**Signal** $\Rightarrow$



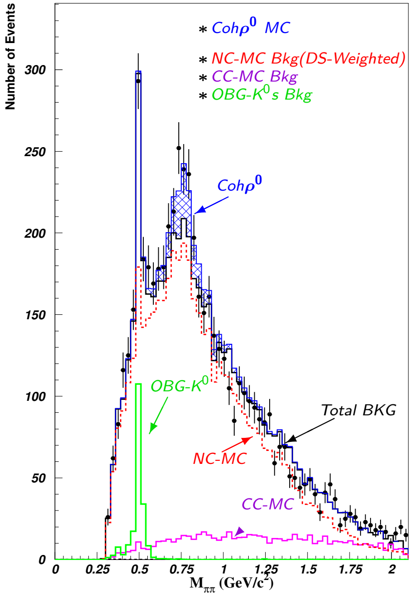
# *Normalization of NCDIS and Coh$\rho^0$*

**$0.6 \leq M_{\pi\pi} \leq 1.0$**

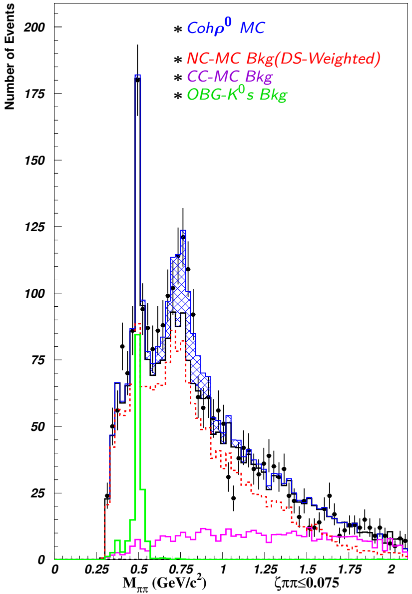


# $Final\ M_{\pi\pi}\ Plots$




**Coherent Region: $\zeta \leq 0.075$**



# *Systematic Error*

- Data-Simulator: (Shape of $\zeta$ in NC-DIS)

  $\Rightarrow \pm\boldsymbol{0.060}\ \boldsymbol{(10.8\%)}$
- NC-DIS:

  Using $\pm 2.3\%$ variation (constrained by $\phi_{\pi\pi}$ in the background region)

  $\Rightarrow \pm\boldsymbol{0.044}\ \boldsymbol{(7.86\%)}$
- CC-DIS:

  $\Rightarrow \pm\boldsymbol{0.013}\ \boldsymbol{(2.32\%)}$
- OBG ($K^0$):

  With 718 data events used to simulate the OBG, a 3.7% variation in its normalization had a negligible effect on the Coh$\rho^0$ normalization.

  $\Rightarrow \pm\boldsymbol{0.000}\ \boldsymbol{(0.0\%)}$
- Total Systematic Error:

  $\Rightarrow \pm\boldsymbol{0.076}\ \boldsymbol{(13.6\%)}$
- Total Error:

  $\Rightarrow \boldsymbol{0.560 \pm 0.105 \pm 0.076\ (\pm 23.2\%)}$

# *Conclusions for Coherent $\rho^0$ Analysis*

* We have conducted a measurement of Coherent-$\boldsymbol{\rho}^{\mathbf{0}}$ production.
  A clear signal of Coherent-$\boldsymbol{\rho}^{\mathbf{0}}$ is observed.

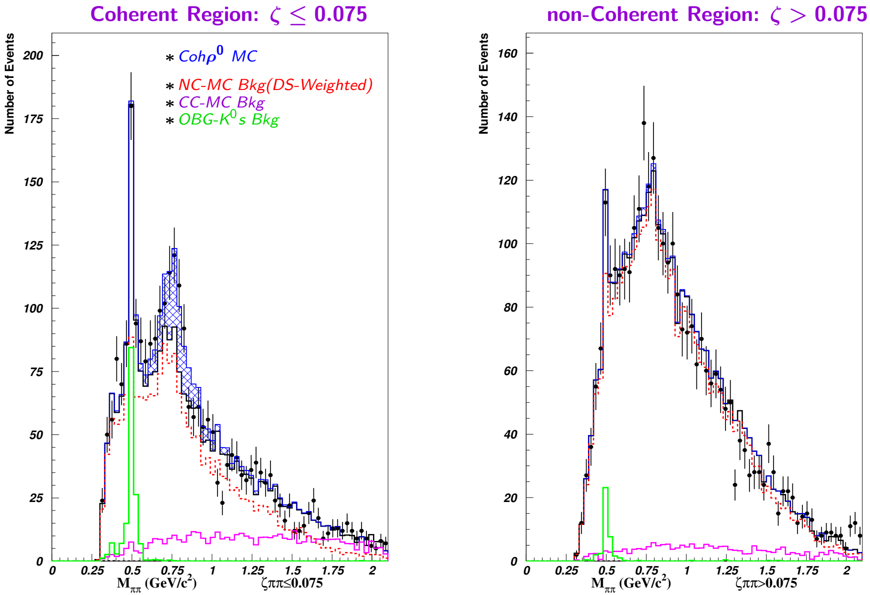
* The analysis is data-driven; the backgrounds are constrained using control samples.

* We observe:
  $560 \pm 105(Stat.) \pm 76(Syst.)$ fully corrected Coherent-$\boldsymbol{\rho}^{\mathbf{0}}$ events.

* The rate with respect to -CC events $(1.44 * 10^6)$ is:
  $(3.89 \pm 0.9) * 10^{-4}$

Backup Slides

# $M_{\pi\pi}$ in $\zeta_{\pi\pi}$ Signal and Background Regions



# *Rein and Sehgal Coh$\pi$ Model Assumptions*

- Target at rest in the lab frame: $\vec{p} = (M, 0, 0, 0)$
- Lepton masses ignored
- Low $Q^2$: $\mathcal{M} = \frac{G_F}{\sqrt{2}} j^\alpha \omega_\alpha \quad ; \quad j^\alpha = \bar{\psi}_\ell \gamma^\alpha (1 - \gamma^5) \psi_\nu$

$$\omega_\alpha = \bar{\psi}_p (V'_\alpha - A'_\alpha) \psi_n = V_\alpha - A_\alpha$$

- If $m_\ell = 0$ then $Q^2 = 2E_\nu E_\mu (1 - \cos\theta) \therefore$ muon and neutrino directions $\parallel$ for $Q^2 \to 0$

$$L^{\alpha\beta} = 16 \frac{E_\nu E_\mu}{\nu^2} q^\alpha q^\beta \quad (q^\alpha q^\beta \text{ acts like a derivative})$$

$$|\mathcal{M}|^2 = 8 G_F^2 \frac{E_\nu E_\mu}{\nu^2} |\partial^\alpha (V_\alpha - A_\alpha)|^2$$

- From CVC $\partial^\alpha V_\alpha = 0$ for low $Q^2 \therefore \boxed{|\mathcal{M}|^2 = 8 G_F^2 \frac{E_\nu E_\mu}{\nu^2} |\partial^\alpha A_\alpha|^2}$

# *Coherent $\pi$ Production*

* Most experiments use the Rein and Sehgal model
* **PCAC**, $\boldsymbol{Q^2 = 0} \rightarrow$ can relate to $\pi$-$\mathcal{A}$ scattering
* Extended to non-zero $Q^2$ with $\left(1 + \frac{Q^2}{m_A^2}\right)^{-2}$ propegator
* Correction factor for low energy CC process `(arXiv:hep-ph/0606185)`

  $$\mathcal{C} = \left(1 - \frac{1}{2}\frac{Q^2_{min}}{Q^2+m_\pi^2}\right)^2 + \frac{1}{4}y\frac{Q^2_{min}(Q^2-Q^2_{min})}{(Q^2+m_\pi^2)^2} \quad ; \quad Q^2_{min} = m_l^2\frac{y}{1-y}$$

* $\sigma_{\pi^+} = \sigma_{\pi^-}$, process dominated by Axial vector current with little Isovector contribution
* $\sigma_{\pi^\pm} = 2\sigma_{\pi^0}$ due to isospin

# *Data Simulator: calibrate the shape of NC-DIS*

* Select $\boldsymbol{\nu_\mu}$-CC events with 3 and 3-&-4 tracks, including the $\mu$
* Obtain a weight for MC(NC-DIS) using DS-Correction=Data/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 $\boldsymbol{\nu_\mu}$-CC events yield entirely consistent results
  $\Rightarrow$ Use (3+4)-Track sample for the DS-correction