Coherent Meson Production in the NOMAD Experiment

Chris Kullenberg   Sanjib R. Mishra

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Outline

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

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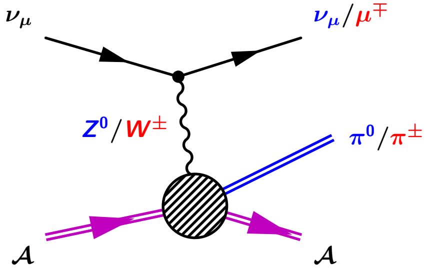
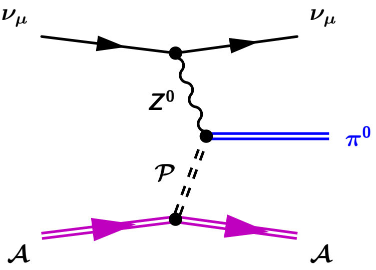
Coherent Meson Production in Neutrino Interactions



* **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

ν-production $\leftrightarrow$ π-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_π 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:

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

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

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

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

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

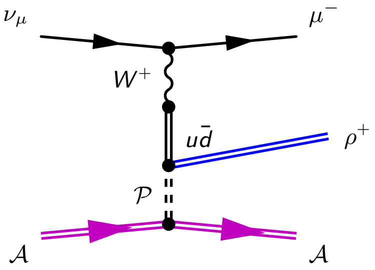
F_{abs} is a factor taking into account the absorption of the pion within the nucleus (assuming homogeneous sphere):

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

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 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, $f_\rho^\pm=f_{\rho^0}^\gamma\sqrt{2}\cos\theta_C$, θ_C is the Cabibbo angle and $f_\rho^\gamma=m_\rho^2/\gamma_\rho$ is the coupling of ρ^0 to photon ($\gamma_\rho^2/4\pi=2.4\pm0.1$).

Coherent-ρ^0 -vs- Coherent-ρ^+

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

- 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 Coherentρ^0 & Coherent$\rho^{\pm}$:

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

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

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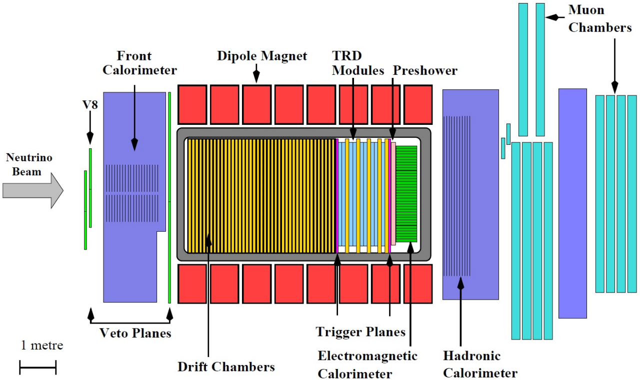
Motivation

* Physics:
  * Structure of the Weak-Current and its Hadronic-Content
  * Cohπ: Partially Conserved Axial Current (PCAC) and
    Adler's relation
  * Cohρ: Conserved Vector Current (CVC) and
    Vector Meson Dominance (VMD)
  * Understanding meson production in ν-interactions

* Practical:
  * Cohπ^0 a background to ν_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 ; $\overline{E}_\nu \approx 25\mathrm{GeV}$; 1.4×10^6 ν_μ-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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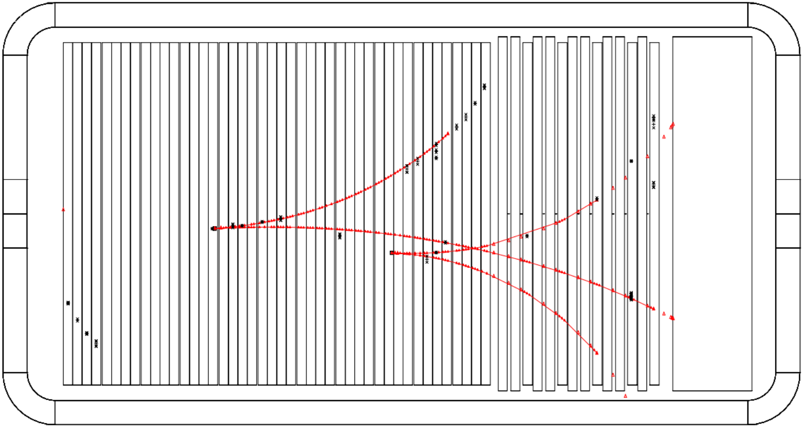
Coherent $\boldsymbol{\pi^0}$ *Candidate Event*

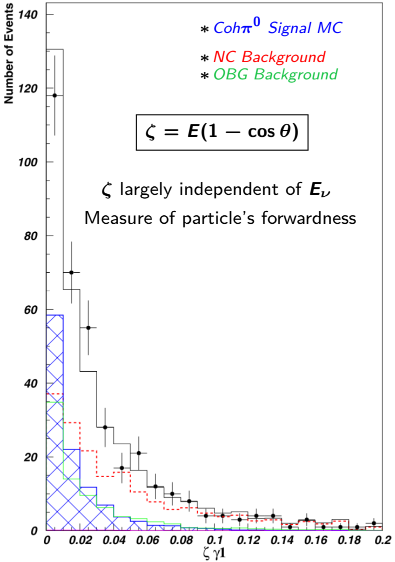


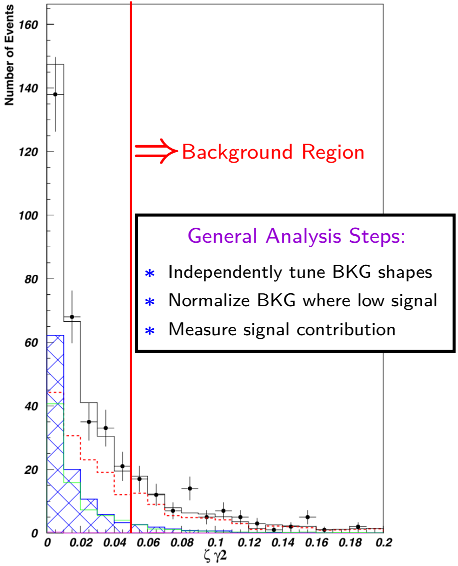
Cohπ^0 Signal: $\pi^0 \rightarrow \gamma\gamma$, and nothing else!

Backgrounds: Neutral Current π^0 production

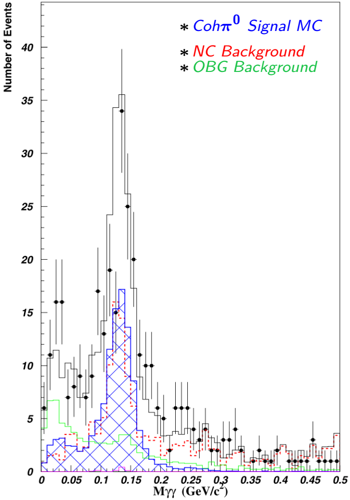
Outside Background (OBG): Events originating upstream

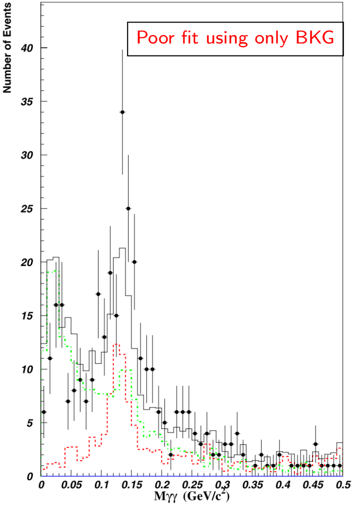
$Coh\pi^0$ γ_1 and γ_2 ζ Plots





$Coh\boldsymbol{\pi^0}$ $M_{\gamma\gamma}$ 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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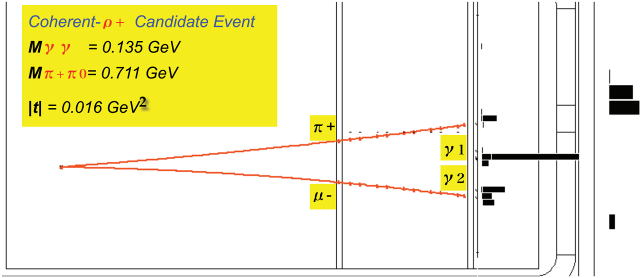
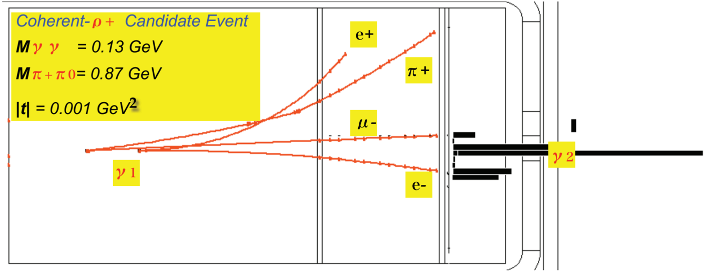
$Coh\boldsymbol{\rho}^+$ Samples (X. Tian)

Signal: $\mu^-\rho^+ \to \mu^-\pi^+\pi^0 \to \boldsymbol{\mu}^-\boldsymbol{\pi}^+\gamma\gamma$



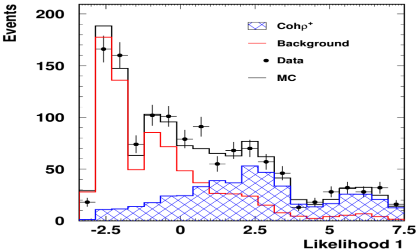
2 Cluster γ^s

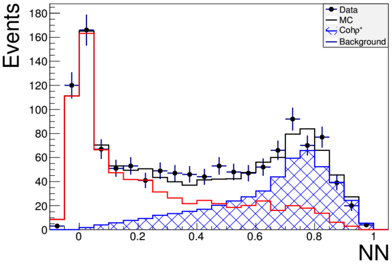


1 Cluster γ

1 V^0 γ

Data Analysis - Likelihood / Neural Network (X. Tian)





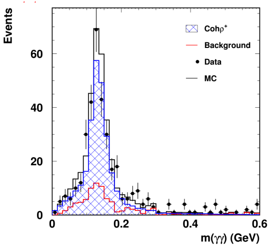
Algorithm	Background	Data	Efficiency	Cohρ^+ Signal
LH	86.1	363	0.064	4318.8$\pm$307.4
NN	76.1	356	0.065	4332.0$\pm$319.4

- The events passing the preselection subjected to multivariate analysis
- The background is constrained using the control (background) region
- Both Likelihood (LH) and Neural Network (NN) have been validated using Mock-data

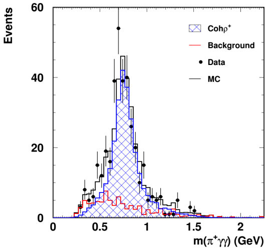
Kinematics in the Signal Region (X. Tian)

Coherent ρ^+ signal must pass four tests:

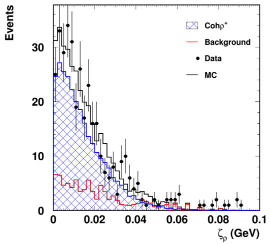
$M_{\gamma\gamma}$ should show π^0 structure



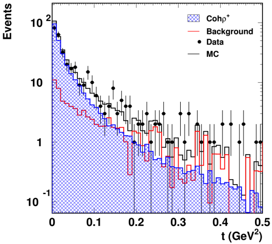
$M_{\pi+\gamma\gamma}$ should show ρ^+ structure



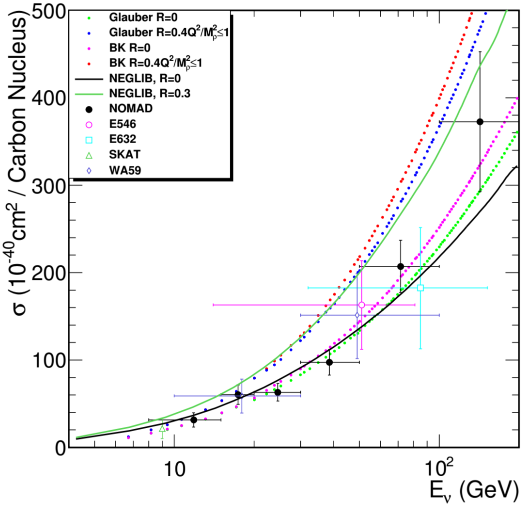
ρ^+ should be collinear with beam direction



t should show "coherence"



Measurement of $\sigma(Coh\rho^+)$ as function of E_ν (X. Tian)



$$\sigma(\nu_\mu + \mathcal{A} \rightarrow \mu^- \mathcal{A}\rho^+) = [67.1 \pm 4.8(stat) \pm 2.6(syst)] \times 10^{-40} cm^2/nucleus$$

arXiv:1310.8547

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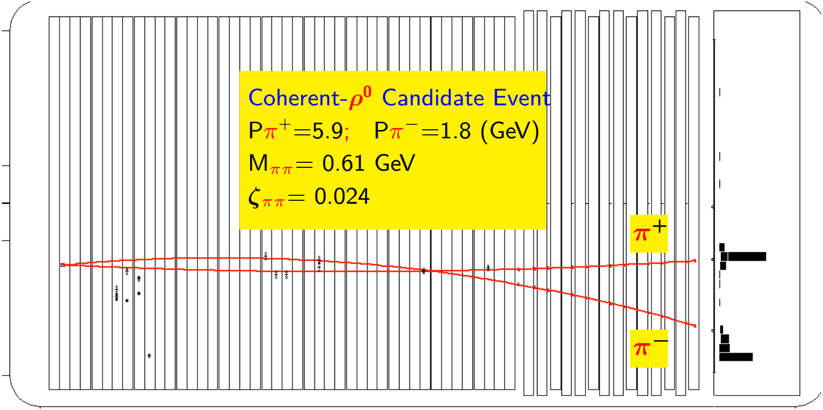
- Coherent ρ^+
- **Coherent ρ^0**

$\textit{Coherent}\ \boldsymbol{\rho^0}\ \textit{Candidate Event}$



Cohρ^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^0s from outside-interactions

Coherent $\boldsymbol{\rho^0}$ *Analysis*

- Calibrate OBG

  We use data to simulate the shape of OBG

  $\Rightarrow$ 2-Track events with vertex upstream of DC

  $\Rightarrow$ Normalize it to the K^0 peak

- Calibrate the shape of NC-DIS

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

  $\Rightarrow$ Correct the shape of NC-DIS MC using independent data sample (more on next slide)

- Normalize NCDIS (shapes reweighted using Data-Simulator)

  $\Rightarrow$ Use $\phi_{\pi\pi}$ distribution with $\zeta_{\pi\pi} > \mathbf{0.075}$

- Result

  $\Rightarrow$ Plot $\boldsymbol{M_{\pi\pi}}$; impose $\mathbf{0.6} \leq \boldsymbol{M_{\pi\pi}} \leq \mathbf{1.0}$ GeV (ρ mass range)

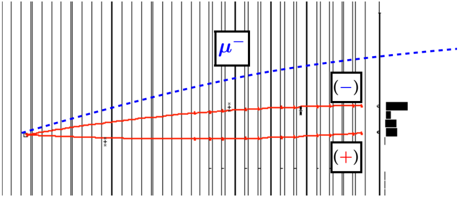
  $\Rightarrow$ Using $\zeta_{\pi\pi}$, fit for *Coh*ρ using ≤ 0.1 region (forward events)

  $\Rightarrow$ Check CC-DIS normalization

  $\Rightarrow$ Iterate normalizations to convergence

  $\Rightarrow$ Systematic error analysis

Data Simulator: calibrate the shape of NC-DIS



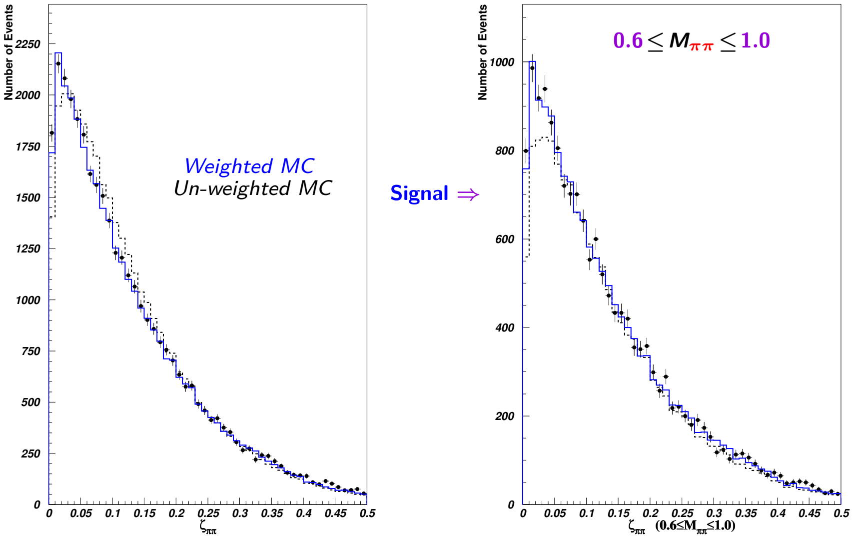
- Select $\boldsymbol{\nu_\mu}$-CC events with 3 (and 3-&-4) tracks
  Ignore the μ and subject $\pi^+\pi^-$ to the standard selection

- Obtain correction function from this sample: DS-Corr = Data/MC
  $[P_{\pi^\pm}, P_t\pi^\pm, M_{\pi\pi}, \zeta_{\pi\pi}]$

- Apply the reweighting to NC-DIS MC

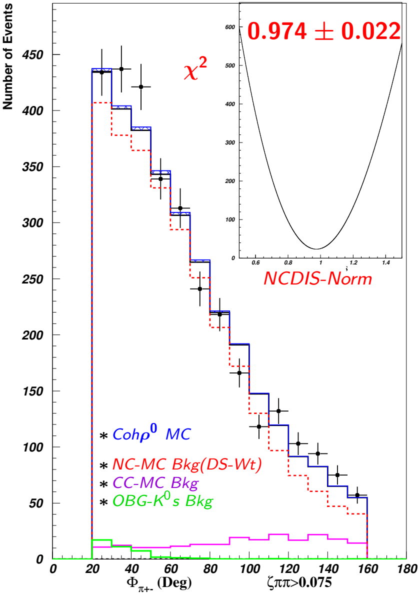
- 3-Track and (3+4)-Track $\boldsymbol{\nu_\mu}$-CC events yield entirely consistent results
  $\Rightarrow$ Nearly 6$\times$ the statistics by including 4-track
  $\Rightarrow$ For 4-track ignore the extra (+) track with lowest momentum

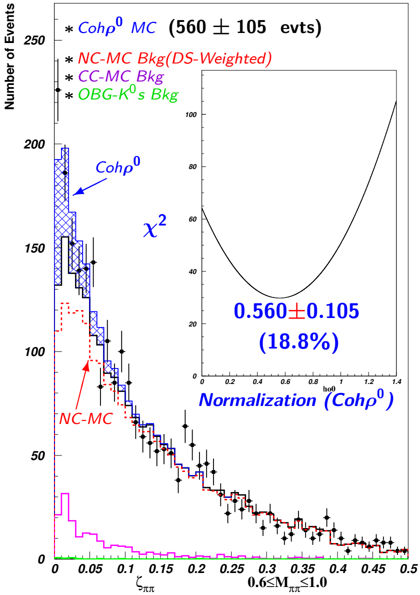
Data Simulator Effect on $\zeta_{\pi\pi}$



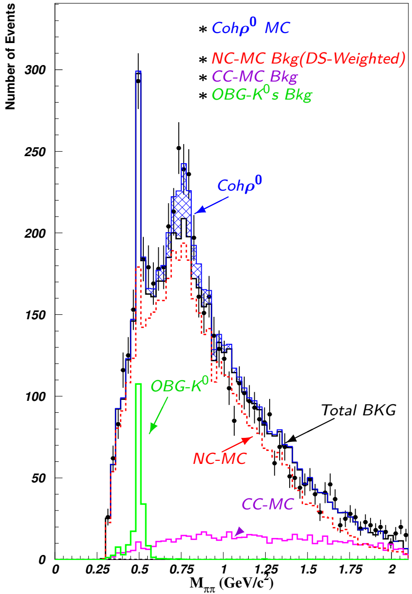
Normalization of NCDIS and Cohρ^0

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

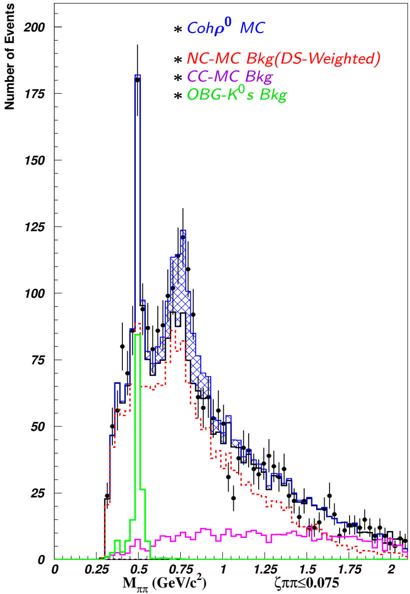




Final $M_{\pi\pi}$ Plots



Coherent Region: $\zeta \leq 0.075$



Systematic Error

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

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

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

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

  $\Rightarrow \pm\boldsymbol{0.013\ (2.32\%)}$
* 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 Cohρ^0 normalization.

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

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

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

Conclusions for Coherent ρ^0 Analysis

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

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

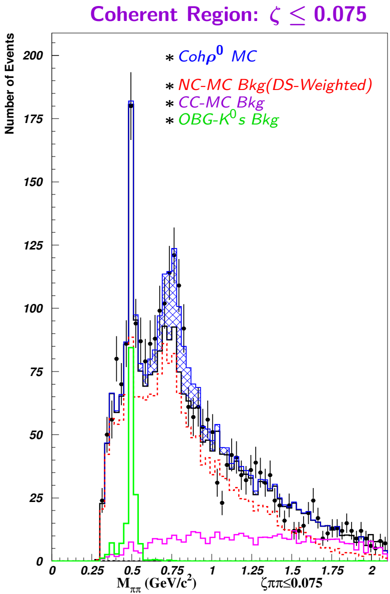
- We observe:
  $560 \pm 105(Stat.) \pm 76(Syst.)$ fully corrected Coherent-$\boldsymbol{\rho^0}$ events.

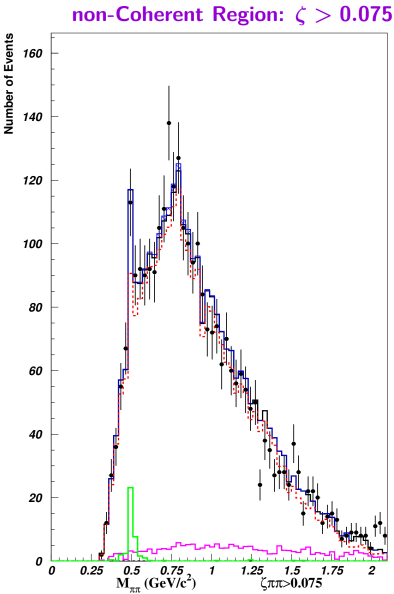
- The rate with respect to ν_μ-CC events $(1.44 * 10^6)$ is:
  $(3.89 \pm 0.9) * 10^{-4}$

- This is compatible with X. Tian's Coherent-$\boldsymbol{\rho^+}$ results

Backup Slides

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





Rein and Sehgal Cohπ Model Assumptions

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

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

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

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

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

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

Coherent π Production

- Most experiments use the Rein and Sehgal model
- **PCAC**, $Q^2 = 0 \rightarrow$ can relate to π-$\mathcal{A}$ 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)`
  $\mathcal{C} = \left(1 - \frac{1}{2}\frac{Q^2_{min}}{Q^2+m_\pi^2}\right)^2 + \frac{1}{4}y\frac{Q^2_{min}(Q^2-Q^2_{min})}{(Q^2+m_\pi^2)^2}$; $Q^2_{min} = m_l^2\frac{y}{1-y}$
- $\sigma_{\pi^+} = \sigma_{\pi^-}$, process dominated by Axial vector current with little Isovector contribution
- $\sigma_{\pi^\pm} = 2\sigma_{\pi^0}$ due to isospin