Coherent Meson Production in the NOMAD Experiment

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Outline

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

- Motivation and the NOMAD Detector

- Coherent $\pi^0$

- Coherent $\rho^+$

- Coherent $\rho^0$
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

\[ \nu_\mu A \rightarrow \nu_\mu A \pi^0 \]

* Low \( Q^2 \) with CVC

Goldberger-Treinman relation + PCAC:

\[ \Rightarrow \text{Adler Relation} \]

\( \nu \)-production \( \leftrightarrow \pi \)-scattering

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

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

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:

\[
\frac{d\sigma(\pi^0 A \rightarrow \pi^0 A)}{dt} = A^2 |F_A(t)|^2 \left. \frac{d\sigma(\pi^0 N \rightarrow \pi^0 N)}{dt} \right|_{t=0}
\]

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

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

with \( f_{\pi N}(0) \) being the forward \( \pi N \) amplitude.

The nuclear form factor is modeled by an exponential:

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

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

\[
F_{\text{abs}} = \exp\left(-\frac{9A^{1/3}}{16\pi R_0^2} \left[ \sigma_{\pi N \text{inel}} \right]\right)
\]
**Neutrino-Induced Coherent Rho Production**

\[
\nu_\mu A \rightarrow \mu \rho A
\]

* Hadron Dominance:
  Piketty-Stodolsky Model \(\Rightarrow\) VMD + CVC

\(\nu\)-Induced \(\rho\) \(\leftrightarrow\) \(\gamma\)-production \(\rho\)

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

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 \(\epsilon = \frac{4E_\nu E_\mu - Q^2}{4E_\nu E_\mu + Q^2 + 2m_\rho^2}\), and \(R = \frac{d\sigma^T/dt}{d\sigma^L/dt}\) 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, \(f_\rho^\pm = f_\rho^\gamma \sqrt{2} \cos \theta_C\), \(\theta_C\) 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-$\rho^0$ -vs- Coherent-$\rho^+$

* 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

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

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

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

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

* **Practical:**
  * $\text{Coh}_{\pi^0}$ 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; $E_\nu \approx 25\text{GeV}; 1.4 \times 10^6 \nu_\mu$-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 $p < 10\text{GeV}/c; \text{Unambiguous charge sep.}$
* TRD & Muon Chambers for PID; ECAL (lead glass) & HCAL
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**Coherent $\pi^0$ Candidate Event**

**Coh$\pi^0$ Signal:** $\pi^0 \rightarrow \gamma\gamma$, 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

$\zeta = E(1 - \cos \theta)$

$\zeta$ largely independent of $E_\nu$
Measure of particle’s forwardness

**General Analysis Steps:**
* Independently tune BKG shapes
* Normalize BKG where low signal
* Measure signal contribution
\(\text{Coh} \pi^0 \ M_{\gamma\gamma} \ \text{Plots and Results}\)

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

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**Cohρ⁺ Samples (X. Tian)**

**Signal:** $\mu^- \rho^+ \rightarrow \mu^- \pi^+ \pi^0 \rightarrow \mu^- \pi^+ \gamma \gamma$

**Coherent-ρ⁺ Candidate Event**
- $M\gamma\gamma = 0.135$ GeV
- $M\pi^+\pi^0 = 0.711$ GeV
- $|t| = 0.016$ GeV²

2 Cluster $\gamma^s$

**Coherent-ρ⁺ Candidate Event**
- $M\gamma\gamma = 0.13$ GeV
- $M\pi^+\pi^0 = 0.87$ GeV
- $|t| = 0.001$ GeV²

1 Cluster $\gamma$
1 $V^0 \gamma$
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

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Background</th>
<th>Data</th>
<th>Efficiency</th>
<th>Coh_ρ^+ Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH</td>
<td>86.1</td>
<td>363</td>
<td>0.064</td>
<td>4318.8±307.4</td>
</tr>
<tr>
<td>NN</td>
<td>76.1</td>
<td>356</td>
<td>0.065</td>
<td>4332.0±319.4</td>
</tr>
</tbody>
</table>
Kinematics in the Signal Region (X. Tian)

Coherent $\rho^+$ signal must pass four tests:

- $M_{\gamma\gamma}$ should show $\pi^0$ structure
- $M_{\pi^+\gamma\gamma}$ should show $\rho^+$ structure
- $\rho^+$ should be collinear with beam direction
- $t$ should show "coherence"
Measurement of $\sigma(C_{\text{Oh}}\rho^+)$ as function of $E_\nu$ (X. Tian)

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

arXiv:1310.8547
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**Coherent $\rho^0$ Candidate Event**

**Coherent-\(\rho^0\) Candidate Event**

\[P_{\pi^+} = 5.9; \quad P_{\pi^-} = 1.8 \text{ (GeV)}\]

\[M_{\pi\pi} = 0.61 \text{ GeV}\]

\[\zeta_{\pi\pi} = 0.024\]

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

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

* Calibrate OBG
  We use data to simulate the shape of OBG
  ⇒ 2-Track events with vertex upstream of DC
  ⇒ Normalize it to the $K^0$ peak

* Calibrate the shape of NC-DIS
  The most important variable is the shape of $\zeta_{\pi\pi}$
  ⇒ Correct the shape of NC-DIS MC using independent data sample
    (more on next slide)

* 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 ($\rho$ mass range)
  ⇒ Using $\zeta_{\pi\pi}$, fit for $Coh\rho$ using $\leq 0.1$ region (forward events)
  ⇒ Check CC-DIS normalization
  ⇒ Iterate normalizations to convergence
  ⇒ Systematic error analysis
Data Simulator: calibrate the shape of NC-DIS

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

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

* Apply the reweighting to NC-DIS MC

* 3-Track and (3+4)-Track $\nu_\mu$-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 $\zeta_{\pi\pi}$

Weighted MC
Un-weighted MC

$0.6 \leq M_{\pi\pi} \leq 1.0$
Normalization of NCDIS and $\text{Coh}\rho^0$

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

![Graph showing normalization of NCDIS and $\text{Coh}\rho^0$.](image)

- $0.974 \pm 0.022$
- $(560 \pm 105 \text{ evts})$
- Normalization (Coh$\rho^0$)

$\chi^2$

-$\text{NC-MC Bkg (DS-Weighted)}$
-$\text{CC-MC Bkg}$
-$\text{OBG-K}^0\text{s Bkg}$
Final $M_{\pi\pi}$ Plots

Coherent Region: $\zeta \leq 0.075$
Systematic Error

* Data-Simulator: (Shape of $\zeta$ in NC-DIS)
  $\Rightarrow \pm 0.060 (10.8\%)$

* NC-DIS:
  Using $\pm 2.3\%$ variation (constrained by $\phi_{\pi\pi}$ in the background region)
  $\Rightarrow \pm 0.044 (7.86\%)$

* CC-DIS:
  $\Rightarrow \pm 0.013 (2.32\%)$

* 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 $\text{Coh}\rho^0$ normalization.
  $\Rightarrow \pm 0.000 (0.0\%)$

* Total Systematic Error:
  $\Rightarrow \pm 0.076 (13.6\%)$

* Total Error:
  $\Rightarrow 0.560 \pm 0.105 \pm 0.076 (\pm 23.2\%)$
Conclusions for Coherent $\rho^0$ Analysis

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

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

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

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

* This is compatible with X. Tian’s Coherent-$\rho^+$ results
Backup Slides
$M_{\pi\pi}$ in $\zeta_{\pi\pi}$ Signal and Background Regions

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

- $\text{Coh}_0^0 \text{ MC}$
- $\text{NC-MC Bkg (DS-Weighted)}$
- $\text{CC-MC Bkg}$
- $\text{OBG-K}^0$s $\text{Bkg}$

**non-Coherent Region:** $\zeta > 0.075$
Rein and Sehgal Cohπ Model Assumptions

* Target at rest in the lab frame: \( \vec{p} = (M, 0, 0, 0) \)

* Lepton masses ignored

* Low \( Q^2 \): \( \mathcal{M} = \frac{G_F}{\sqrt{2}} j^\alpha \omega_\alpha \); \( j^\alpha = \bar{\psi}_\ell \gamma^\alpha (1 - \gamma^5) \psi_\nu \)

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

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

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

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

* From CVC \( \partial^\alpha V_\alpha = 0 \) for low \( Q^2 \). \( \therefore \)

\[
|\mathcal{M}|^2 = 8G_F^2 \frac{E_\nu E_\mu}{\nu^2} |\partial^\alpha A_\alpha|^2
\]
Coherent $\pi$ Production

* Most experiments use the Rein and Sehgal model

* **PCAC**, $Q^2 = 0 \rightarrow$ can relate to $\pi$-$A$ scattering

* Extended to non-zero $Q^2$ with $\left(1 + \frac{Q^2}{m_A^2}\right)^{-2}$ propagator

* Correction factor for low energy **CC** process (arXiv:hep-ph/0606185)

\[
C = \left(1 - \frac{1}{2} \frac{Q_{\text{min}}^2}{Q^2 + m_\pi^2}\right)^2 + \frac{1}{4} \frac{y Q_{\text{min}}^2 (Q^2 - Q_{\text{min}}^2)}{(Q^2 + m_\pi^2)^2}; \quad Q_{\text{min}}^2 = m_l^2 \frac{y}{1-y}
\]

* $\sigma_{\pi^+} = \sigma_{\pi^-}$, process dominated by Axial vector current with little Isovector contribution

* $\sigma_{\pi^\pm} = 2\sigma_{\pi^0}$ due to isospin