Coherent $\rho$ Production in Neutrino-nucleus Interactions

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Outline

Introduction

Coherent $\rho$ production at NOMAD
  Coherent $\rho^+$
  Coherent $\rho^0$

Coherent Meson Production at DUNE/LBNF

Conclusion
Cohρ production in neutrino-nucleus

\[ \nu_\mu A \rightarrow \mu^- A\rho^+ \]
\[ \bar{\nu}_\mu A \rightarrow \mu^+ A\rho^- \]
\[ \nu_\mu A \rightarrow \nu_\mu A\rho^0 \]

- Neutrino scatters coherently off a target nucleus
- No quantum numbers (charge, spin, isospin) exchange
- Small momentum transfer, large energy transfer
- \( \rho \) emitted at small angles with respect to the incident neutrino
Vector Meson Dominance Model

Conservation of Vector Current

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

In simple Rein Sehgal meson absorption model

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

Coh\(\rho^0\) is about 15\% of Coh\(\rho^+\) related by weak mixing angle

\[
\frac{d^3\sigma(\nu_\mu A \rightarrow \nu_\mu \rho^0 A)}{dQ^2 d\nu dt} = \frac{1}{2} (1 - 2\sin^2 \theta_W)^2 \frac{d^3\sigma(\nu_\mu A \rightarrow \mu^- \rho^+ A)}{dQ^2 d\nu dt}
\]
Motivation for Coherent Meson Production Study

Physics

• Structure of Weak-Current and its Hadronic-Content
  • $\text{Coh}\pi$: Partially Conserved Axial Current (PCAC) and Adler’s theorem at high energy ($E_\nu > 2$ GeV) and Microscopic model at low energy ($E_\nu < 1.5$ GeV)
  • $\text{Coh}\rho$: Conserved Vector Current (CVC) and Vector Meson Dominance (VMD)
Motivation for Coherent Meson Production Study

Physics

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Utility

- Precise measurement of Coherent meson, $\pi$ and $\rho$ could constrain neutrino flux and energy scale with independent systematics
The NOMAD Detector

Average neutrino energy is \( \sim 25 \) GeV

<table>
<thead>
<tr>
<th>sub-detectors</th>
<th>performance</th>
</tr>
</thead>
</table>
| Drift Chambers (2.7 tons) \(
\rho = 0.1 \) g/cm\(^3\)                | Target & tracking                                    |
|                                        | \( \delta r < 200 \) \( \mu \) m                    |
|                                        | \( \delta p \sim 3.5\% @ p < 10 \) GeV/c            |
| Transition Radiation Detector (TRD)    | \( e^\pm \) identification                          |
|                                        | 90\% \( e^\pm \) eff. with \( \pi \) rejection \( @10^3 \) |
| Muon Chambers                          | Muon identification                                  |
|                                        | \( \epsilon \sim 97\% @ p_\mu > 5 \) GeV/c         |
| Electromagnetic Calorimeter (ECL)      | Lead glass                                           |
|                                        | \( \frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{3.22\pm0.07}{\%} E(\text{GeV}) \) |
| Hadronic Calorimeter (HCAL)            | neutron and \( K_L^0 \) veto                        |
Coherent \( \rho \) production at NOMAD

### \( \text{Coh}_\rho^{\pm,0} \) Measurements Status

The \( \text{Coh}_\rho^{\pm} \) measurements have very large errors and no measurement of NC-\( \text{Coh}_\rho^{0} \)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \nu/\bar{\nu} )</th>
<th>Channel</th>
<th>Target</th>
<th>( &lt;E_\nu&gt; ) (GeV)</th>
<th>( \sigma ) (10(^{-40}) cm(^2)/nucleus)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E546</td>
<td>( \nu )</td>
<td>( \rho^+ )</td>
<td>Neon (A=20)</td>
<td>51</td>
<td>189.7±59</td>
</tr>
<tr>
<td>BEBC WA59</td>
<td>( \bar{\nu} )</td>
<td>( \rho^- )</td>
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<td>18</td>
<td>73±23</td>
</tr>
<tr>
<td>E632</td>
<td>( \nu + \bar{\nu} )</td>
<td>( \rho^{\pm} )</td>
<td>Neon (A=20)</td>
<td>86</td>
<td>210±80</td>
</tr>
<tr>
<td>SKAT</td>
<td>( \nu )</td>
<td>( \rho^+ )</td>
<td>Freon (A=30)</td>
<td>10</td>
<td>29±16</td>
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</table>
Coherent $\rho^+$

Introduction

Coherent $\rho$ production at NOMAD

Coherent $\rho^+$

Coherent $\rho^0$

Coherent Meson Production at DUNE/LBNF

Conclusion
What we are looking for in CC $\rho^+ - \mu^- \pi^+ + 2$ clusters and little else
What we are looking for in CC $\rho^+ - \mu^- \pi^+ + 1$ cluster + 1 $V_0$ with little else
Data Analysis - Likelihood/Neural-Network

- The events passing the preselection subjected to multi-varient analysis
- The background is constrained using the control (background) region
- Both Likelihood (LH) and Neural-Network (NN) have been fully validated using Mock-data.
Kinematics in the signal region

A 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”
Systematics

Total overall systematic error - ±3.9%

- Background normalization - ±1.6%
  - Dominated by CC-DIS, use the control region in LH to get a normalization factor and error
- Absolute normalization - ±2.5%
  - From inclusive CC cross section measurement
- Efficiency - ±2.5%
  - Mockdata study - < 1%
  - Vary LH-cuts, difference in LH vs. NN - ±1.6%
  - Vary the MC-parameters - ±2.5%
Measurement of $\sigma_{\text{Coh}\rho^+}/\sigma_{\text{CC}}$ as a function of $E_\nu$
Measurement of $\sigma_{\text{Coh}$\rho^+$ as a function of $E_\nu$

NOMAD data favor the model with $R = 0$, i.e. there is little longitudinal contribution in Coh$\rho$ production.
Coherent $\rho^0$

Introduction

Coherent $\rho^+$ production at NOMAD
   Coherent $\rho^0$

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Conclusion
What we are looking for in NC - $\rho^0 \rightarrow \pi^+\pi^-$ with little else

What we are looking for:

Coherent-$\rho^0$ Candidate Event

- $P_{\pi^+} = 3.1$; $P_{\pi^-} = 2.3$ (GeV)
- $M_{\pi\pi} = 0.74$ GeV
- $\zeta_{\pi\pi} = 0.008$
Measure the background: shape and normalization

- Preselection Cuts: Fiducial volume, Muon veto, 2-track, $E_{\pi\pi} > 2$ GeV, Upstream-hanger, Photon veto, $20^\circ < \phi_{\pi\pi} < 160^\circ$
- $0.6 < m_{\pi\pi} < 1.0$ GeV
- $\zeta_{\pi\pi}$ is the critical variable distinguishing $\text{Coh}\rho^0$ from background. Need to know the shape and normalization of background very well.
Background Calibration

- **Outside Background (OBG)**
  - 2-track events with primary vertex outside
  - Normalize it to the $K_0$ peak in $m_{\pi\pi}$ plot

- **NC Background Shape**
  - Use CC-DIS events with 3, 3-&-4 tracks w/ $\mu^-$
  - Remove the muon, (+,-) subjected to the standard selection
  - Obtain a NC-DIS MC Re-weight based on Data/MC ($p_{\pi\pm}$, $p_{\pi\pm}^T$, $m_{\pi\pi}$, $\zeta_{\pi\pi}$)
  - Apply the Re-weight to calibrate the shape of $\zeta_{\pi\pi}$
  - Tried 3 track sample and 3 -&-4 track sample, 1D/2D/3D/4D re-weighting matrix. The difference is within 10%

- **NC Background Normalization**
  - Re-weighted using $\phi_{\pi\pi}$ distribution in $\zeta_{\pi\pi} > 0.075$ control (background) region
NC Background Calibration

- Shape: re-weighted using CC Data-Simulator
- Normalization: re-weighted using $\phi_{\pi\pi}$ distribution in $\zeta_{\pi\pi} > 0.075$ region (background region)
$m_{\pi\pi}$ Distribution

Coherent Region: $\zeta \leq 0.075$

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

non-Coherent Region: $\zeta > 0.075$

Kullenberg, Mishra Coh$\rho^0$ Production April 23, 2015 30 / 52
Results

- Using $\zeta_{\pi\pi}$, fit for $\text{Coh}\rho^0$ in $\leq 0.1$ region
- We observed $669 \pm 116$ (stat.) $\pm 88$ (syst.) fully corrected Coherent $\rho^0$ events. The rate with respect to CC events ($1.44 \text{ M}$) is $-(4.65 \pm 1.01) \times 10^{-4}$
- The first observation of neutrino induced NC Coherent $\rho^0$
Systematics

Total overall systematic error - ±13.4%

- Data-Simulator: shape of $\zeta_{\pi\pi}$ in NC-DIS - ±10.8%
  - Using only $\zeta_{\pi\pi}$ re-weight (which does not describe the $\pi\pi$ system in CC-data well)
- NC-DIS - ±7.17%
  - Using ±2.2% variation (constrained by $\phi_{\pi\pi}$ in the background region)
- CC-DIS - ±2.24%
- Absolute normalization - ±2.5%
  - From inclusive CC cross section measurement
- OBG - ±0.0%
  - With 833 data events used to simulate the OBG, a 3.5% variation in its normalization had a negligible effect on the Coh$\rho^0$ normalization.
Sensitivity Study of Coherent-Meson Production in a Fine Grain Straw Tube Tracker (STT) - the proposed DUNE Near Detector

- The DUNE ND will have a much higher resolution and statistics ($\times 50$) than NOMAD, but lower energy ($\sim 1/4$)
The proposed High Resolution DUNE/LBNF Near Detector

Built on the NOMAD experience

Determination of the beam flux at the Near Site and the measurement of $\nu_e$-appearance backgrounds (Primary purpose)

Precision Standard Model neutrino physics measurements, such as precise measurement of the weak mixing angle

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>FGT</th>
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<tbody>
<tr>
<td>Straw Tube Detector Volume</td>
<td>3.5m x 3.5m x 6.4m</td>
</tr>
<tr>
<td>Straw Tube Detector Mass</td>
<td>8 tonnes</td>
</tr>
<tr>
<td>Vertex Resolution</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>2 mrad</td>
</tr>
<tr>
<td>$E_e$ Resolution</td>
<td>5%</td>
</tr>
<tr>
<td>$E_\mu$ Resolution</td>
<td>5%</td>
</tr>
<tr>
<td>$\nu_\mu/\bar{\nu}_\mu$ ID</td>
<td>Yes</td>
</tr>
<tr>
<td>$\nu_e/\bar{\nu}_e$ ID</td>
<td>Yes</td>
</tr>
<tr>
<td>NC$\pi^0$/CCe Rejection</td>
<td>0.1%</td>
</tr>
<tr>
<td>NC$\gamma$/CCe Rejection</td>
<td>0.2%</td>
</tr>
<tr>
<td>CC$\mu$/CCe Rejection</td>
<td>0.01%</td>
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NOMAD $\text{Coh}\rho^{\pm,0}$ Measurements

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</tr>
<tr>
<td>NOMAD</td>
<td>$\nu$</td>
<td>$\rho^+$</td>
<td>Carbon (A=12.8)</td>
<td>24.8</td>
<td>67.00±5.67</td>
</tr>
</tbody>
</table>

- Most precise measurement of $\text{Coh}\rho^{+}$ up to date
- First observation of $\text{Coh}\rho^{0}$:
  \[ \sigma = (10.30\pm2.25) \times 10^{-40} \text{ cm}^2 / \text{nucleus} \]
- \[ R(\text{Coh}\rho^{0}/\text{Coh}\rho^{+}) = 0.155\pm0.036, \text{ consistent with prediction} \]
Conclusion

- We have conducted a measurement of Coherent $\rho^{+,,0}$ production using NOMAD data - a clear Coherent $\rho^{+,,0}$ signal is observed.
  - We observe $-4318.8\pm307.4$ (stat.)$\pm168.4$ (syst.) fully corrected Coherent $\rho^+$ events. The rate with respect to $\nu_\mu$-CC events (1.44 M) is $(3.00\pm0.24)\times10^{-3}$.
  - We observed $669\pm116$ (stat.)$\pm88$ (syst.) fully corrected Coherent $\rho^0$ events. The rate with respect to CC events (1.44 M) is $-(4.65\pm1.01)\times10^{-4}$. The first observation of neutrino induced NC Coherent $\rho^0$.
  - $R(\text{Coh}\rho^0/\text{Coh}\rho^+)= (669.0\pm145.6)/(4318.8\pm350.5)=0.155\pm0.036$.
- The observed rate and kinematics are consistent with theory (CVC and VMD).
- The analysis is largely data-driven - the backgrounds are constrained using control samples.
- The knowledge from NOMAD analysis of the coherent meson studies is applicable on DUNE ND studies which will have a much a higher resolution and statistics, but lower energy, than NOMAD.
Cross Secton

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

where \(G_F\) is the weak coupling constant, \(Q^2 = -q^2 = -(k - k')^2\), \(t = (p - p')^2\), \(\nu = E_\nu - E_\mu\), \(x = Q^2/(2\nu M)\), \(y = \nu/E_\nu\), \(g_\rho\) is related to the \(\rho\) form-factor, 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, \(f_\rho^\pm = f_\rho^\gamma \sqrt{2}\cos \theta_C\), \(\theta_C\) is the Cabibbo angle and \(f_\rho^\gamma = m_\rho^2/\gamma_\rho\) is the coupling of \(\rho^0\) to photon \((\gamma_\rho^2/4\pi = 2.4 \pm 0.1)\).

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

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

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

NOMAD fiducial area: 2.6m x 2.6m

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>Antineutrino</th>
</tr>
</thead>
<tbody>
<tr>
<td>QEL</td>
<td>0.430</td>
</tr>
<tr>
<td>RES</td>
<td>0.025</td>
</tr>
<tr>
<td>DIS</td>
<td>0.015</td>
</tr>
<tr>
<td>νe</td>
<td>0.0015</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Neutrino</th>
<th>ν/νμ</th>
</tr>
</thead>
<tbody>
<tr>
<td>νμ</td>
<td>1.0</td>
</tr>
<tr>
<td>νμ</td>
<td>0.025</td>
</tr>
<tr>
<td>νe</td>
<td>0.015</td>
</tr>
<tr>
<td>νe</td>
<td>0.0015</td>
</tr>
</tbody>
</table>
• Total $\nu_\mu$-CC is normalized to 1.44 M
• QE is normalized to 33 k
• Resonance is normalized to 43 k ($\sim$ 15% error)
• $\text{Coh}_{\pi^+}$ is normalized to 10 k ($\sim$25% error)
MC

- **Deep Inelastic Scattering (DIS)**
  - Modelled with the help of modified LEPTO 6.1 package
  - Production of all zoo of hadrons is simulated with help of JETSET 7.4
  - Structure functions are calculated for LO GRV 98 pdf according A. Bodek prescriptions

- **Quasi-Elastic scattering (QE)**
  - Based on the Smith-Moniz approach
  - The vector form-factors $F_V$ and $F_M$ are supposed to be well known (the GKex(05) parametrization)
  - The axial form-factor has the dipole form $F_A(Q^2) = F_A(0)[1 + Q^2/M_A^2]^{-2}$

- **Resonance/single pion production**
  - Based on ReinSehgal (RS) model
  - Set of 18th baryon resonances with masses below 2 GeV as in RS but with all relevant parameters updated according to the most recent PDG
  - Factors which were estimated in RS numerically are corrected by using the new data and a more accurate integration algorithm

- **Coherent pion production**
  - Based on Rein-Sehgal (RS) model

- **Final state interactions**
  - Modelled with the help of DPMJET package, based on the Formation Zone Intranuclear Cascade model
NC $\rho^0$: Signal & Background

- Signal: $\rho^0 \rightarrow \pi^+ \pi^-$
- Background
  - NC-DIS: 2-Track (+,-). The largest contribution
  - CC-DIS: 2-Track (+,-) where no muon identified. Small contribution
  - Outside Background (OBG): $K_0$ from outside-interactions. Small contribution
NC $\rho^0$: Control Sample

- Control Sample: CC Data Simulator Correction
  - $\nu_\mu$-CC events where the $\mu^-$ is identified and then “removed”, the remaining hadronic (+,-) tracks subjected to the analysis.