Coherent ρ Production in Neutrino-nucleus Interactions

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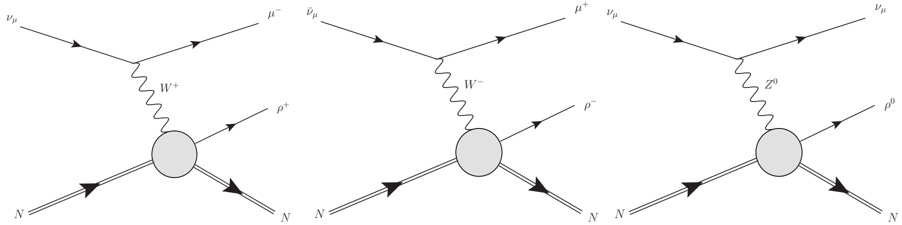
Outline

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
- ρ emitted at small angles with respect to the incident neutrino

Vector Meson Dominance Model

Conservation of Vector Current

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

In simple Rein Sehgal meson absorption model

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

Cohρ^0 is about 15% of Cohρ^+ related by weak mixing angle

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

Motivation for Coherent Meson Production Study

Physics

- Structure of Weak-Current and its Hadronic-Content
  - Cohπ: 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)
  - Cohρ: Conserved Vector Current (CVC) and Vector Meson Dominance (VMD)

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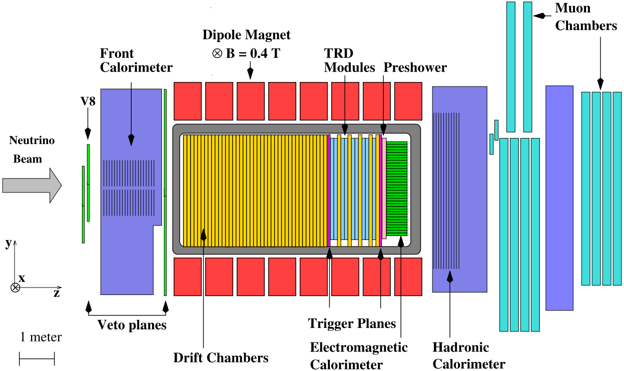
Utility

- Precise measurement of Coherent meson, π and ρ could constrain neutrino flux and energy scale with indepedent systematics

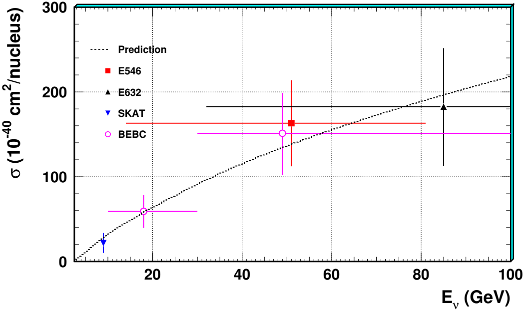
The NOMAD Detector

Average neutrino energy is $\sim$ 25 GeV



sub-detectors		performance
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 π rejection @10^3
Muon Chambers	Muon identification	$\epsilon \sim 97\%@p_{\mu} > 5$ GeV$/c$
Electromagnetic Calorimeter (ECL)	Lead glass	$\frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{3.22\pm0.07}{\%} E(\mathrm{GeV})$
Hadronic Calorimeter (HCAL)	neutron and K_L^0 veto	

Coh$\rho^{\pm,0}$ Measurements Status

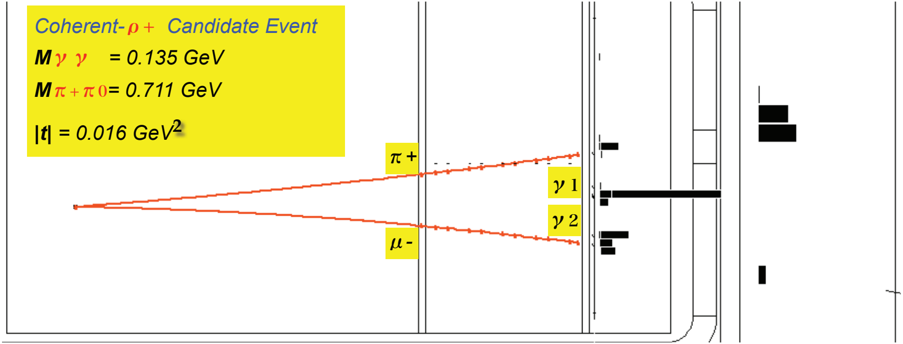


The Coh$\rho^{\pm}$ measurements have very large errors and no measurement of NC-Cohρ^0

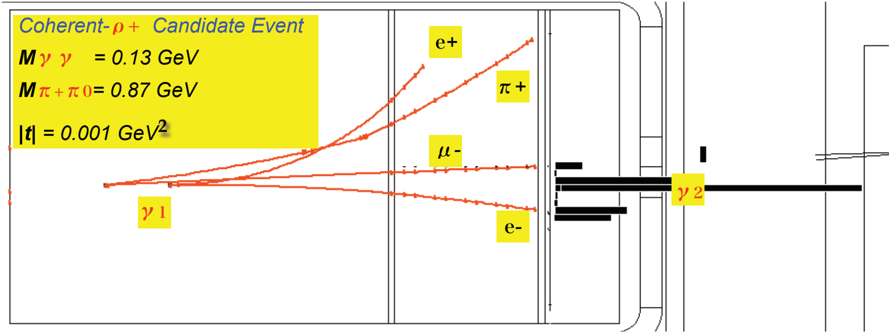
Experiment	$\nu/\bar{\nu}$	Channel	Target	$< E_\nu >$ (GeV)	σ (10^{-40} cm^2/nucleus)
E546	ν	ρ^+	Neon (A=20)	51	189.7±59
BEBC WA59	$\bar{\nu}$	ρ^-	Neon (A=20)	18	73±23
E632	$\nu+\bar{\nu}$	$\rho^{\pm}$	Neon (A=20)	86	210±80
SKAT	ν	ρ^+	Freon (A=30)	10	29±16

Coherent ρ^+

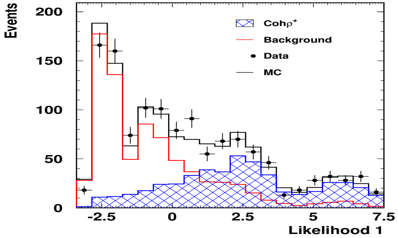
What we are looking for in CC ρ^+ - $\mu^-\pi^+$+2 clusters and little else

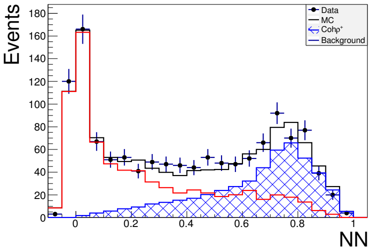


What we are looking for in CC ρ^+ - $\mu^-\pi^+ +$ 1 cluster + 1 V_0 with little else



Data Analysis - Likelihood/Neural-Network





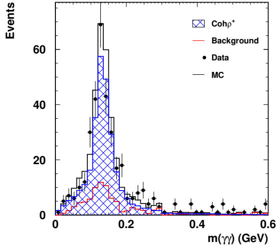
Algorithm	Background	Data	Efficiency	Cohρ^+ Signal
LH	86.1	363	0.064	4318.8$\pm$307.4
NN	76.1	356	0.065	4332.0$\pm$319.4

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

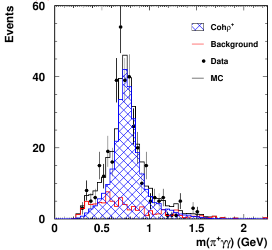
Kinematics in the signal region

A Coherent ρ^+ signal must pass four tests

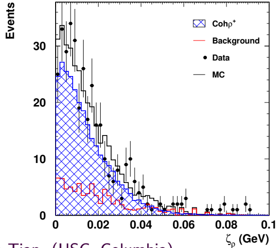
$M_{\gamma\gamma}$ should show π^0 structure



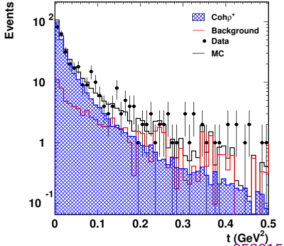
$M_{\pi^+\gamma\gamma}$ should show ρ^+ structure



ρ^+ should be collinear with beam direction



t should show "coherence"

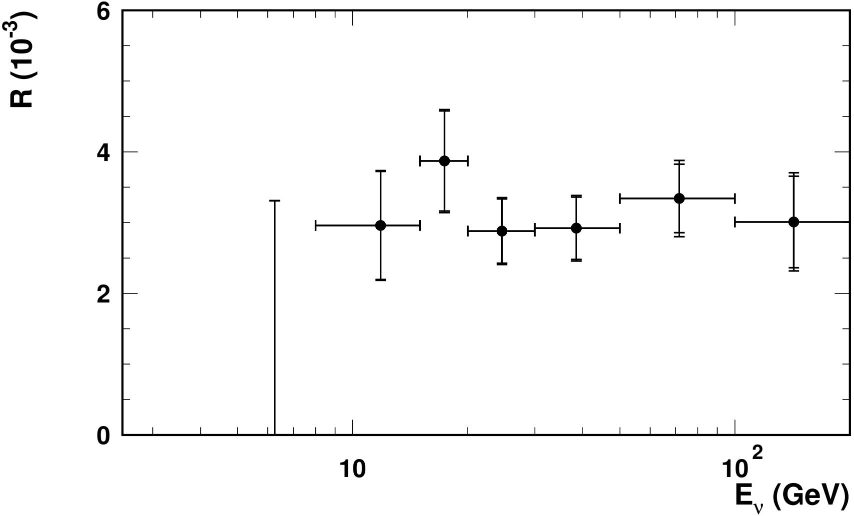


Systematics

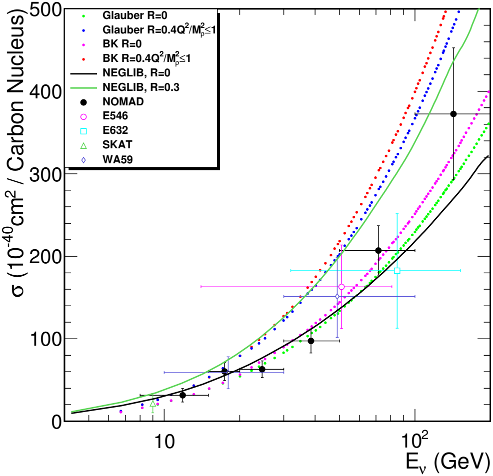
Total overall systematic error - $\pm 3.9\%$

- Background normalization - $\pm 1.6\%$
  - Dominated by CC-DIS, use the control region in LH to get a normalization factor and error
- Absolute normalization - $\pm 2.5\%$
  - From inclusive CC cross section measurement
- Efficiency - $\pm 2.5\%$
  - Mockdata study - $< 1\%$
  - Vary LH-cuts, difference in LH .vs. NN - $\pm 1.6\%$
  - Vary the MC-parameters - $\pm 2.5\%$

Measurement of $\sigma_{\mathrm{Coh}\rho^+}/\sigma_{\mathrm{CC}}$ as a function of E_ν



Measurement of $\sigma_{\mathrm{Coh}\rho^+}$ as a function of E_ν

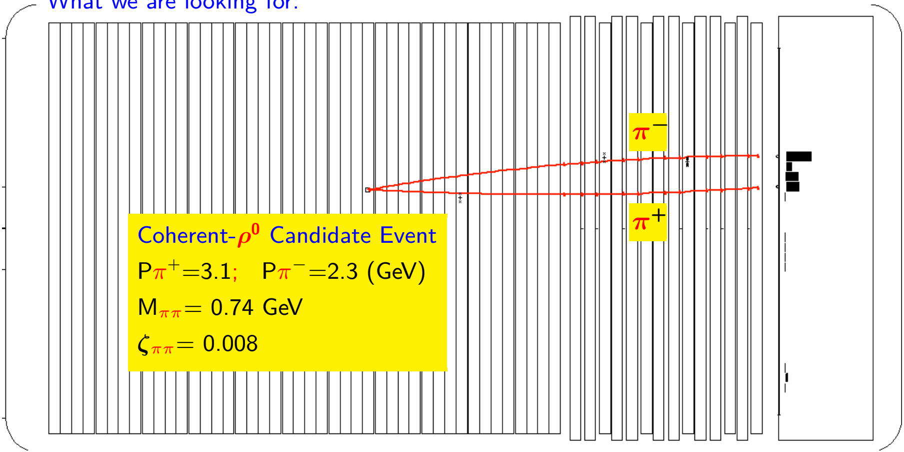


NOMAD data favor the model with $R = 0$, i.e. there is little longitudinal contribution in Cohρ production

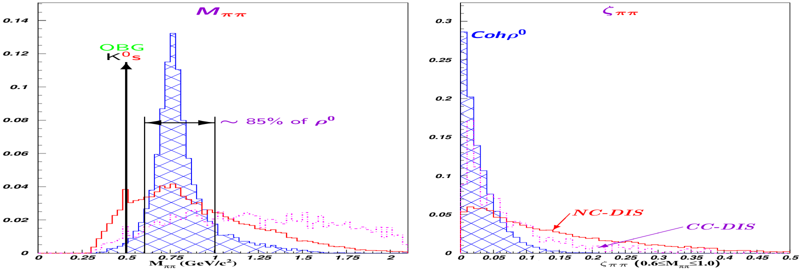
Coherent ρ^0

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

What we are looking for:



Measure the background: shape and normalization

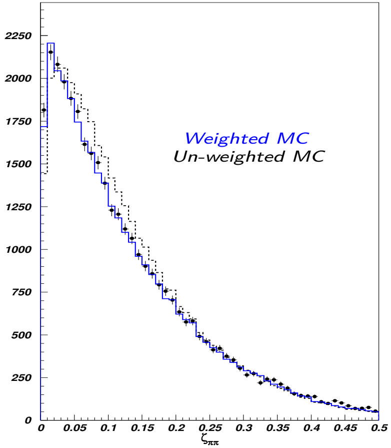


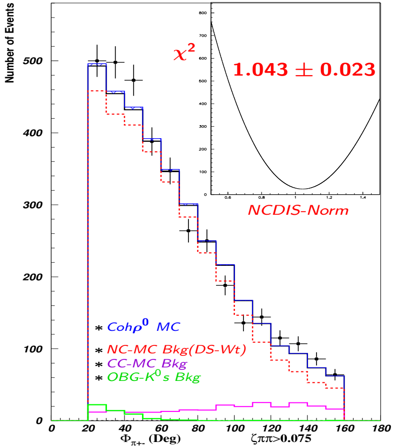
- Preselection Cuts: Fiducial volume, Muon veto, 2-track, $E_{\pi\pi} > 2$ GeV, Upstream-hanger, Photon veto, $20^\circ < \phi_{\pi\pi} < 160^\circ$
- $0.6 < m_{\pi\pi} < 1.0$ GeV
- $\zeta_{\pi\pi}$ is the critical variable distinguishing Cohρ^0 from background. Need to know the shape and normalization 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/ μ^-
  - Remove the muon, (+,-) subjected to the standard selection
  - Obtain a NC-DIS MC Re-weight based on Data/MC ($p_{\pi^\pm}$, $p^{\mathrm{T}}_{\pi^\pm}$, $m_{\pi\pi}$, $\zeta_{\pi\pi}$)
  - 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

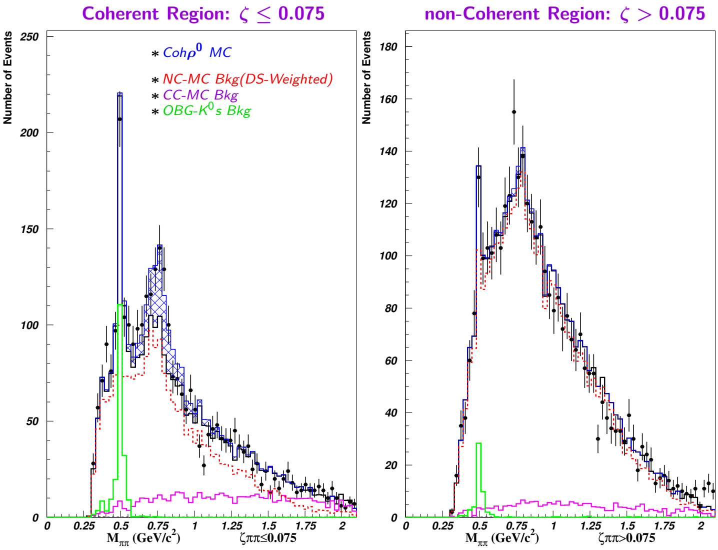
NC Background Calibration





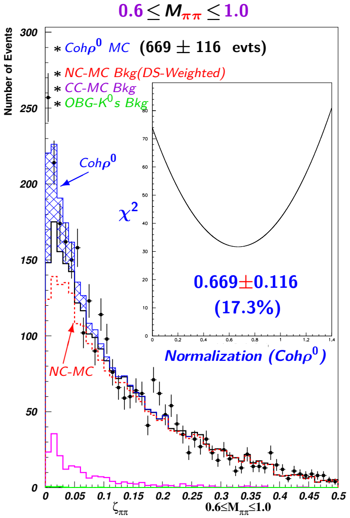
- Shape: re-weighted using CC Data-Simulator
- Normalization: re-weighted using $\phi_{\pi\pi}$ distribution in $\zeta_{\pi\pi} > 0.075$ region (background region)

$m_{\pi\pi}$ Distribution



Results

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



Systematics

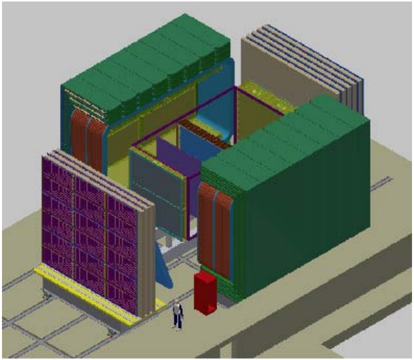
Total overall systematic error - $\pm 13.4\%$

- Data-Simulator: shape of $\zeta_{\pi\pi}$ in NC-DIS - $\pm 10.8\%$
  - Using only $\zeta_{\pi\pi}$ re-weight (which does not describe the $\pi\pi$ system in CC-data well)
- NC-DIS - $\pm 7.17\%$
  - Using $\pm 2.2\%$ variation (constrained by $\phi_{\pi\pi}$ in the background region)
- CC-DIS - $\pm 2.24\%$
- Absolute normalization - $\pm 2.5\%$
  - From inclusive CC cross section measurement
- OBG - $\pm 0.0\%$
  - With 833 data events used to simulate the OBG, a 3.5% variation in its normalization had a negligible effect on the Cohρ^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 a higher resolution and statistics ($\times 50$) than NOMAD, but lower energy ($\sim 1/4$)

The proposed High Resolution DUNE/LBNF Near Detector



Performance Metric	FGT
Straw Tube Detector Volume	3.5m x 3.5m x 6.4m
Straw Tube Detector Mass	8 tonnes
Vertex Resolution	0.1 mm
Angular Resolution	2 mrad
E_e Resolution	5%
E_μ Resolution	5%
$\nu_\mu/\bar{\nu}_\mu$ ID	Yes
$\nu_e/\bar{\nu}_e$ ID	Yes
NCπ^0/CCe Rejection	0.1%
NCγ/CCe Rejection	0.2%
CCμ/CCe Rejection	0.01%

- Built on the NOMAD experience
- Determination of the beam flux at the Near Site and the measurement of ν_e-appearance backgrounds (Primary purpose)
- Precision Standard Model neutrino physics measurements, such as precise measurement of the weak mixing angle

NOMAD Coh$\rho^{\pm,0}$ Measurements

Experiment	$\nu/\bar{\nu}$	Channel	Target	$<E_\nu>$ (GeV)	σ (10^{-40} cm^2/nucleus)
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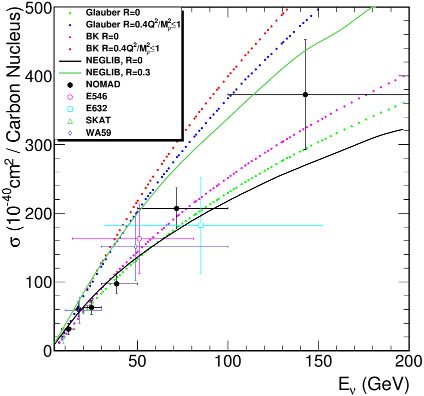
SKAT	ν	ρ^+	Freon (A=30)	10	29±16
NOMAD	ν	ρ^+	Carbon (A=12.8)	24.8	67.00±5.67

- Most precise measurement of Cohρ^+ up to date
- First observation of Cohρ^0: $\sigma=(10.30\pm2.25)\times10^{-40}$ cm^2/nucleus
- R(Cohρ^0/Cohρ^+)=0.155±0.036, 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±307.4 (stat.)±168.4 (syst.) fully corrected Coherent ρ^{+} events, The rate with respect to ν_{μ}-CC events (1.44 M) is (3.00±0.24)×10^{-3}
  - We observed $669 \pm 116\,(\mathrm{stat.}) \pm 88\,(\mathrm{syst.})$ fully corrected Coherent ρ^{0} events. The rate with respect to CC events (1.44 M) is - $(4.65 \pm 1.01) \times 10^{-4}$. The first observation of neutrino induced NC Coherent ρ^{0}
  - R(Cohρ^{0}/Cohρ^{+})=(669.0±145.6)/(4318.8±350.5)=0.155±0.036
- 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

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

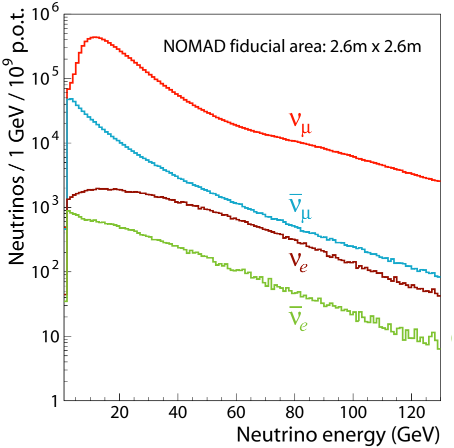
where G_F is the weak coupling constant, $Q^2 = -q^2 = -(k-k')^2$, $t = (p-p')^2$, $\nu = E_\nu - E_\mu$, $x = Q^2/(2\nu M)$, $y = \nu/E_\nu$, g_ρ is related to the ρ form-factor, the polarization parameter $\epsilon = \frac{4E_\nu E_\mu - Q^2}{4E_\nu E_\mu + Q^2 + 2\nu^2}$, and $R = \frac{d\sigma^L/dt}{d\sigma^T/dt}$ with 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 ($\gamma_\rho^2/4\pi = 2.4 \pm 0.1$).

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

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

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 $F_{abs} = 0.47 \pm 0.03$.

The SPS Beam



ν	ν/ν_μ
ν_μ	1.0
$\bar{\nu}_\mu$	0.025
ν_e	0.015
$\bar{\nu}_e$	0.0015

MC

- Total ν_μ-CC is normalized to 1.44 M
- QE is normalized to 33 k
- Resonance is normalized to 43 k ($\sim$ 15% error)
- Cohπ^+ 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 ρ^0: Signal & Background

- Signal: $\rho^0 \to \pi^+\pi^-$
- 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 ρ^0: Control Sample

- Control Sample: CC Data Simulator Correction
  - ν_μ-CC events where the μ^- is identified and then "removed", the remaining hadronic (+,-) tracks subjected to the analysis.