Charged-Current Coherent ρ Production in Neutrino-nucleus Interactions

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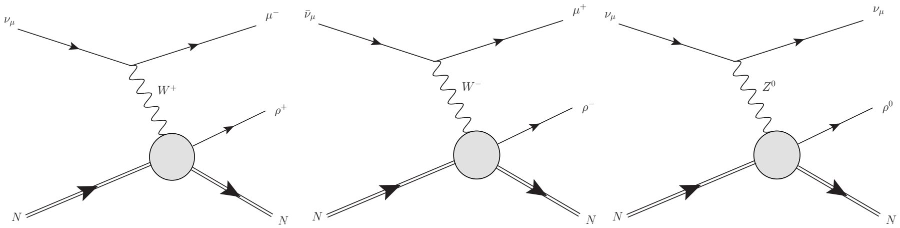
Outline

Vector Meson Dominance Model

$\nu_\mu A \to \mu^- A\rho^+$ $\qquad$ $\bar{\nu}_\mu A \to \mu^+ A\rho^-$ $\qquad$ $\nu_\mu A \to \nu_\mu A\rho^0$



Conservation of Vector Current

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

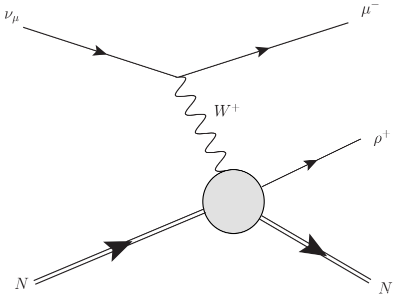
In simple Rein Sehgal meson absorption model

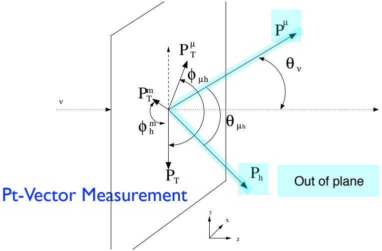
$$\frac{d\sigma^T(\rho^+\mathcal{A}\to\rho^+\mathcal{A})}{dt} = \frac{\mathcal{A}^2}{16\pi}\sigma^2(hn)exp(-b|t|)F_{abs}$$

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

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

Kinematic Variables





$$\nu,\ Q^2,\ x,\ y,\ W^2$$

$$t = [\Sigma_i(E_i - p_{i,L})]^2 + [\Sigma_i(p_{i,T})]^2$$

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

Motivation

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

- Cohπ^+/Cohπ^-: Identical final state ($\mu^\mp\pi^\pm$) to constraint the $\bar{\nu}/\nu$ energy scale
- Neutrino Cohρ measurements $(\pm, 0)$ in conjunction with the photoproduction data on Cohρ^0 will provide a constraint on neutrino flux
- A background in Coh$\pi^\pm$ measurements

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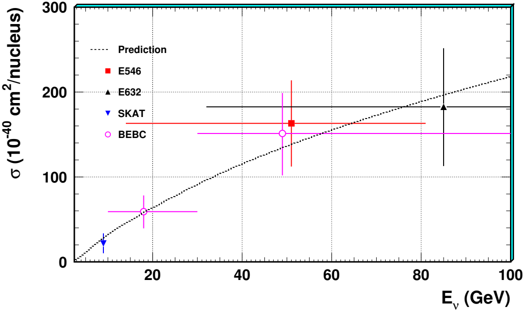
A matrix of 6 coherent-meson measurements leads to much better modeling of low-Q^2 processes and provides constraints on flux that are independent of the usual methods.

Coh$\rho^{\pm}$ Measurements Overview



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

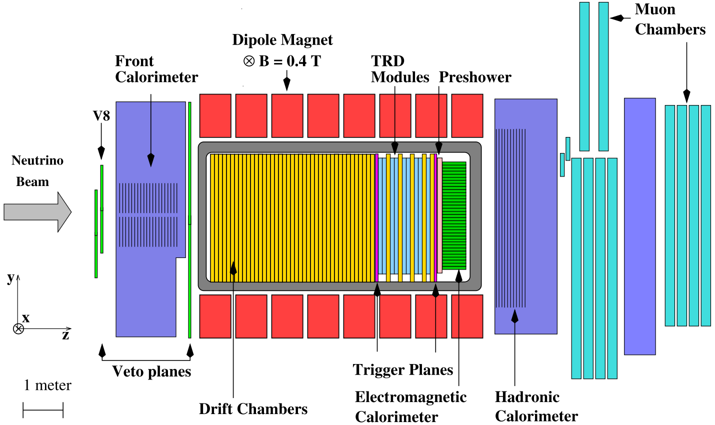
Table: The Coh$\rho^{\pm}$ measurements have very large errors and the first measurement of Cohρ^0 in NC was reported by H. Duyang at this conference, no measurement at low energy.

The NOMAD (Neutrino Oscillation MAgnetic Detector) Experiment Elements

The NOMAD experiment was designed to search for $\nu_\mu \to \nu_\tau$ oscillations at $\Delta m^2 \geq 5$ eV^2 at CERN SPS.

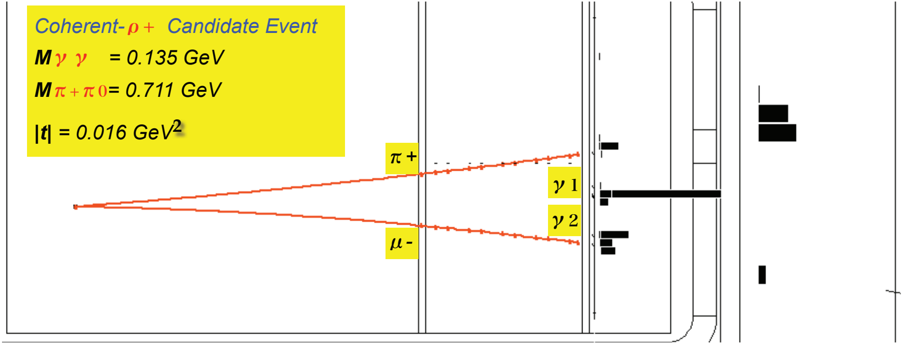
- Beam 450 GeV protons from CERN Super Proton Synchrotron (SPS) incident on a beryllium target producing the neutrino beam (0-300 GeV, average E_ν is ~25 GeV)
- Detector Active target (2.7 tons, mostly "Carbon" with low density ~0.1 g/cm^3) composed of Drift Chamber Tracker embedded in a 0.4 T B-field
- Data High precision data with 1.4 M ν_μ-CC

The NOMAD Detector

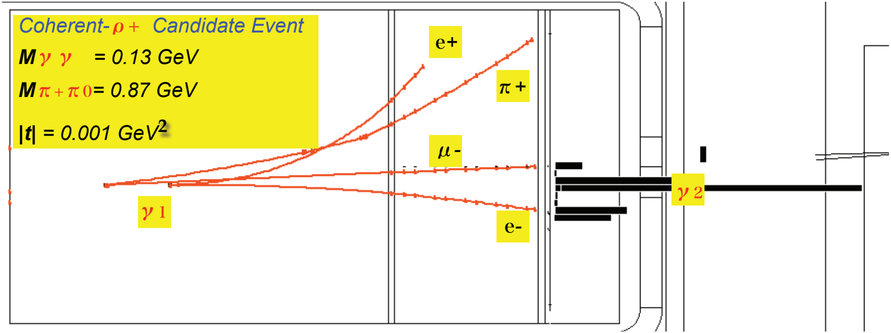


sub-detectors		performance
Drift Chambers (2.7 tons)	Target & tracking	$\delta r < 200\ \mu$m $\delta p \sim 3.5\%@p < 10$ GeV/c
Transition Radiation Detector (TRD)	$e^{\pm}$ identification	90% $e^{\pm}$ eff. with π rejection @10^3
Muon Chambers	Muon identification	$\epsilon \sim 97\%@p_{\mu} > 5$ GeV/c
Electromagnetic Calorimeter (ECL)	Lead glass	$\frac{\sigma(E)}{E} = (1.04 \pm 0.01)\% + \frac{3.22 \pm 0.07}{\%} E(\mathrm{GeV})$
Hadronic Calorimeter (HCAL)	neutron and K_L^0 veto	

What we are looking for - $\mu^- \pi^+ + 2$ clusters



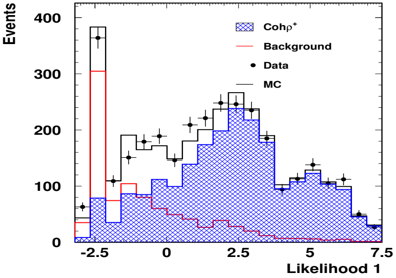
What we are looking for - $\mu^-\pi^+ + 1$ cluster $+ 1$ V_0

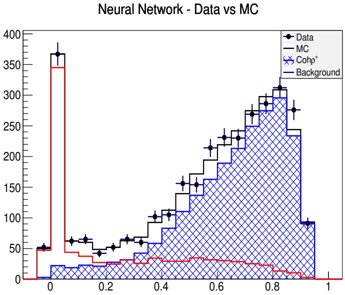


The analysis essentials

- The events passing the preselection were subjected to multi-variant analysis
- The background is constrained using the control (background) region
- Mockdata tests validate the whole analysis chain
- Two independent, Likelihood and Neural-Network analysis yield very consistent results

Mockdata Excercise



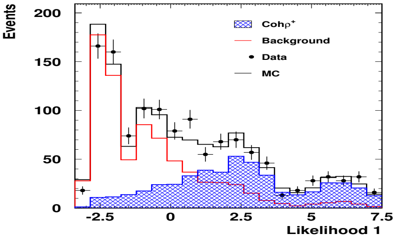


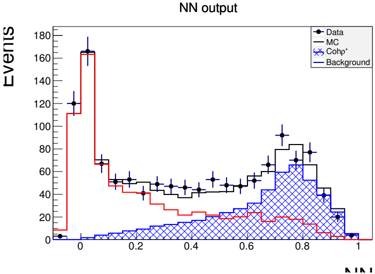
Input	Output
20,363	20144.2±613.5

Input	Output
20,363	20,396± 613.8

Mockdata test also shows that the acceptance and resolution smearing correction work.

Actual Data Analysis - LH/NN distribution





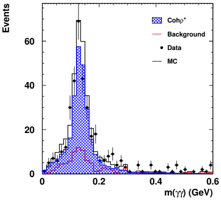
Algorithm	Background	Data	Efficiency	Cohρ^+ Signal
LH	86.1	363	0.064	4318.8$\pm$307.4
NN	76.1	356	0.065	4332.0$\pm$319.4

Note: We do not apply a cut on $M_{\gamma\gamma}$ or $M_{\pi^+\gamma\gamma}$

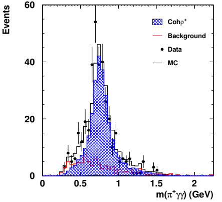
Kinematics in the signal region - MC agrees with Data reasonably well and consistent with Cohρ^+

A Coherent Rho+ signal must pass four tests

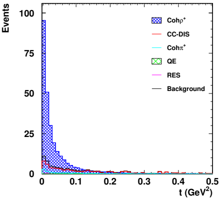
$M_{\gamma\gamma}$ should show π^0 structure



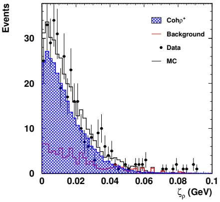
$M_{\pi^+\gamma\gamma}$ should show ρ^+ structure



t should show "coherence"



ρ^+ should be collinear with beam direction

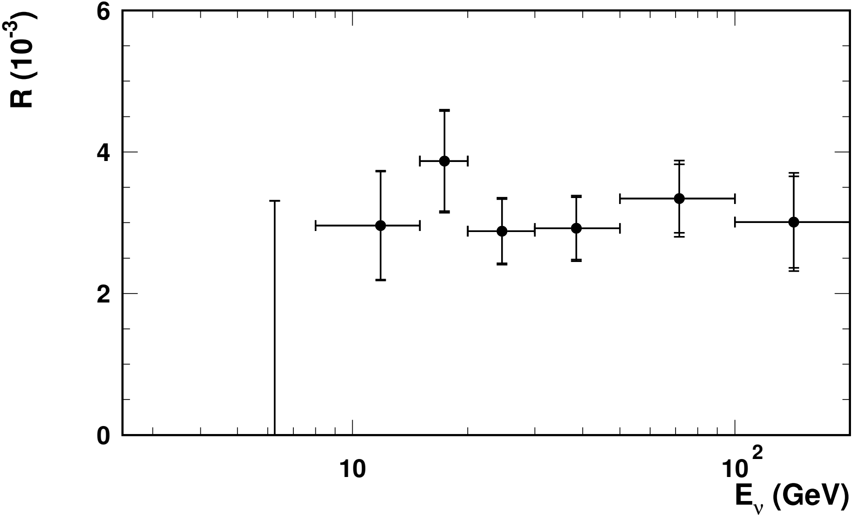


Systematics

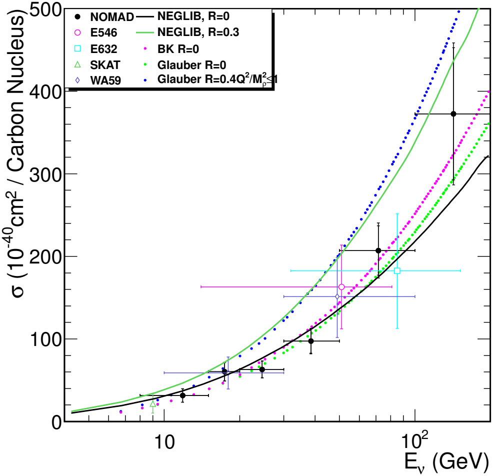
Total overall systematic error - $\pm 3.9\%$

- 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 $N(\mathrm{Coh}\rho^{+})/N_{\mathrm{CC}}$ as a function of E_ν



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

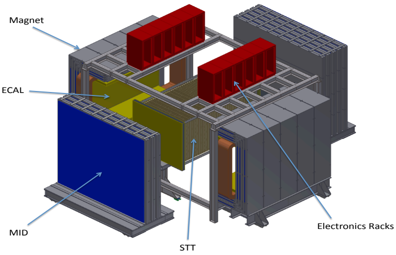


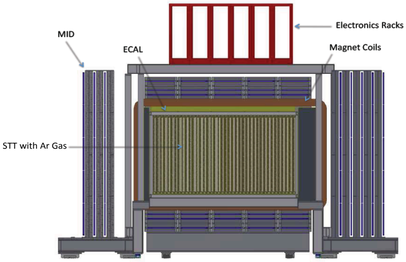
NOMAD data favor the model with $R = 0$, i.e. there is little longitudinal contribution in Cohρ production

Sensitivity Study of Coherent-Meson Production in a Fine Grain Straw Tube Tracker (STT) - the proposed LBNE Near Detector

- The LBNE ND will have a much a higher resolution and statistics ($\times 50$) than NOMAD, but lower energy ($\sim 1/4$)

The proposed LBNE Near Detector - STT (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

Performance Metric	STT
Tracking Detector Mass	7 tons
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%

Conclusion

- We have conducted a measurement of Coherent ρ^+ production using NOMAD data - a clear Coherent ρ^+ signal is observed
  - We observe - 4318.8$\pm$307.4 (stat.)$\pm$168.4 (syst.) fully corrected Coherent ρ^+ events
  - The rate with respect to ν_μ-CC events (1.44 M) is (3.00$\pm$0.24)$\times 10^{-3}$
  - R(Cohρ^0/Cohρ^+)=(634.5$\pm$146.3)/(4318.8$\pm$350.5)=0.147$\pm$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 LBNE ND studies which will have a much a higher resolution and statistics, but lower energy, than NOMAD

Cross Secton

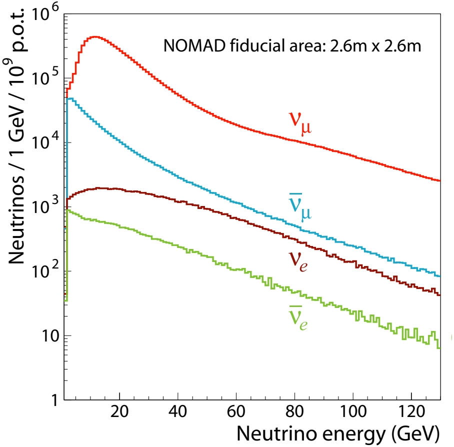
$$\frac{d^3\sigma(\nu_\mu \mathcal{A} \to \mu^- \rho^+ \mathcal{A})}{dQ^2 d\nu dt} = \frac{G_F^2}{4\pi^2} \frac{f_\rho^2}{1-\epsilon} \frac{|q|}{E_\nu^2} \left[\frac{Q}{Q^2 + m_\rho^2} \right]^2 (1 + \epsilon R) \left[\frac{d\sigma^T(\rho^+ \mathcal{A} \to \rho^+ \mathcal{A})}{dt} \right] \quad (1)$$

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