Dimuon and Coherent ρ Production

In the NOMAD Neutrino Oscillation experiment

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What is NOMAD?

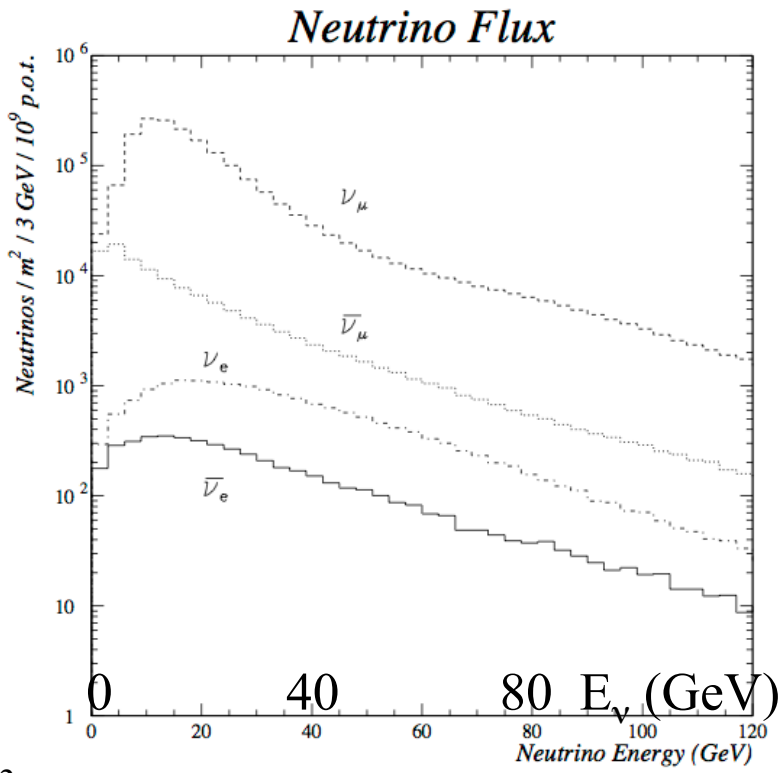
- A Neutrino Oscillation Experiment at CERN
- Collected data 1995-1998
- Searched for

  $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ oscillations at $\Delta m^2 > 10\ eV^2$

  Did not find any but set very good limits at this Δm^2.
- Moved to precision measurements of cross sections and particle production (including strange and charm) particles.
- Still some analysis activity at JINR and at South Carolina

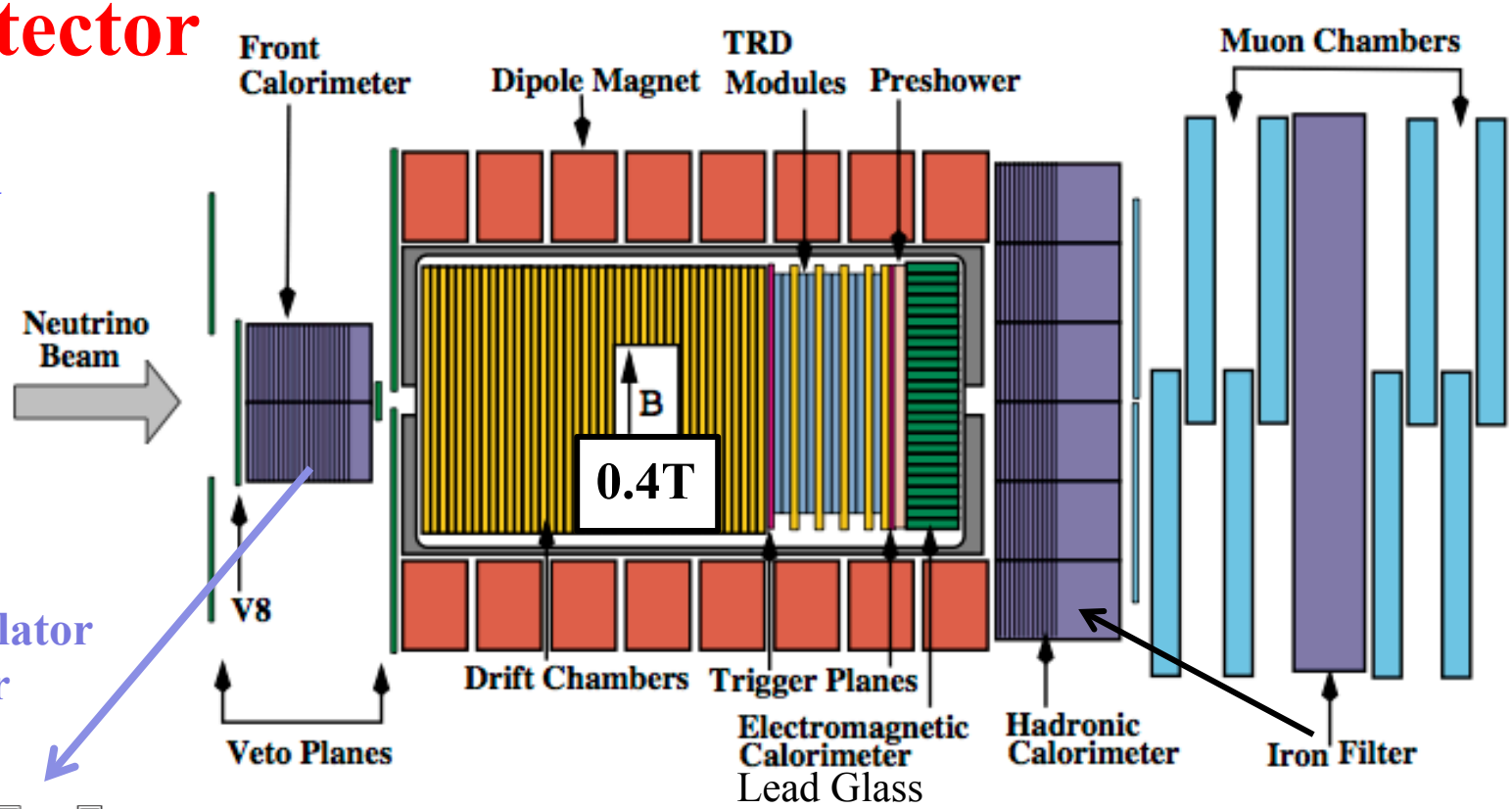
25 Institutes and 159 physicists

$< E_\nu > = 24$ **GeV**

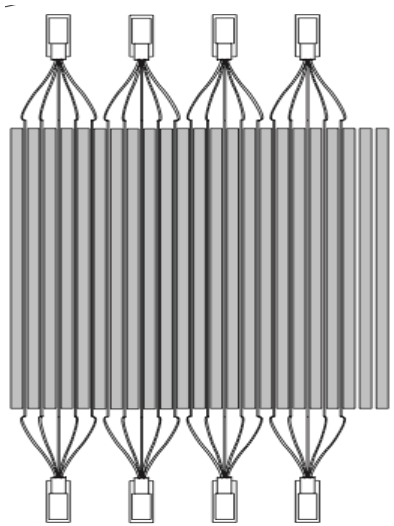


The detector

Top View



FCAL:
Iron-Scintillator
Calorimeter
27.5 tons



Drift Chambers 144 gaps
Density 0.1 gm.cm^{-3}
One radiation length

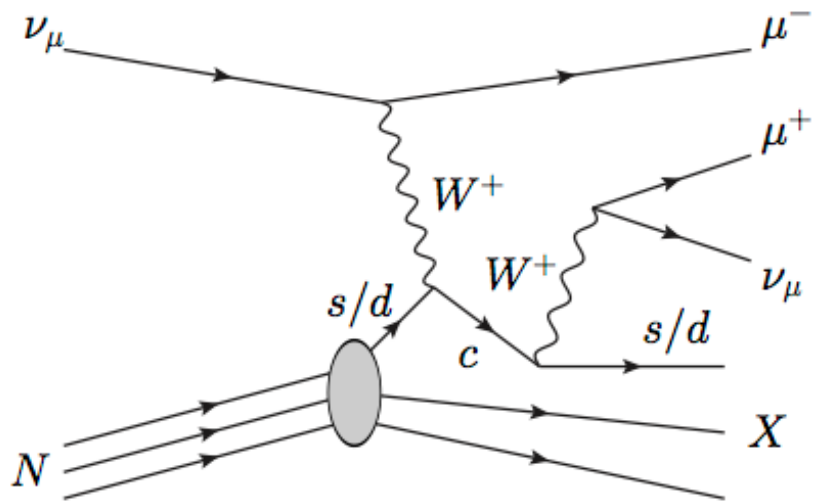
Transition Radiation:
e/π separation

Two Targets:

Drift Chambers: 2.7 tons 1.7 x 10^6 ν interactions → Coh. ρ
Front Calorimeter: 27.5 tons 18 x 10^6 ν interactions → $\mu^+\mu^-$

Dimuon Production

Opposite sign dimuons



f_h = fraction of charm hadron h

$$\frac{d\sigma_{\mu\mu}}{dxdydz} = \frac{d\sigma_c}{dxdy} \sum_h f_h D_c^h(z) Br(h \to \mu X)$$

Br (h→μX) = Semileptonic BR of h

Charm production cross section

Strange and non-strange quarks PDFs

→ Strange Sea Suppression factor

$\kappa_s = (s+\bar{s})/(\bar{u}+\bar{d})$

Slow rescaling variable for heavy quarks

$\xi = x\,(1+m_c^2/Q^2)$ → $\mathbf{m_c}$

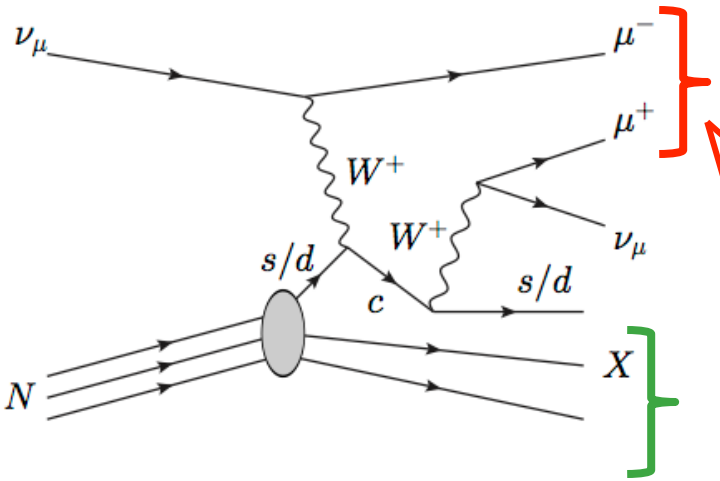
$D^h_c(z)$ = charm fragmentation fraction.

For Collins-Spiller → $\boldsymbol{\varepsilon_c}$

[LO expression for illustration only]

Dimuons in NOMAD

O. Samoylov et al
arXiv(1308.4750) hep-ex.
Accepted for publication in Nucl. Phys. B



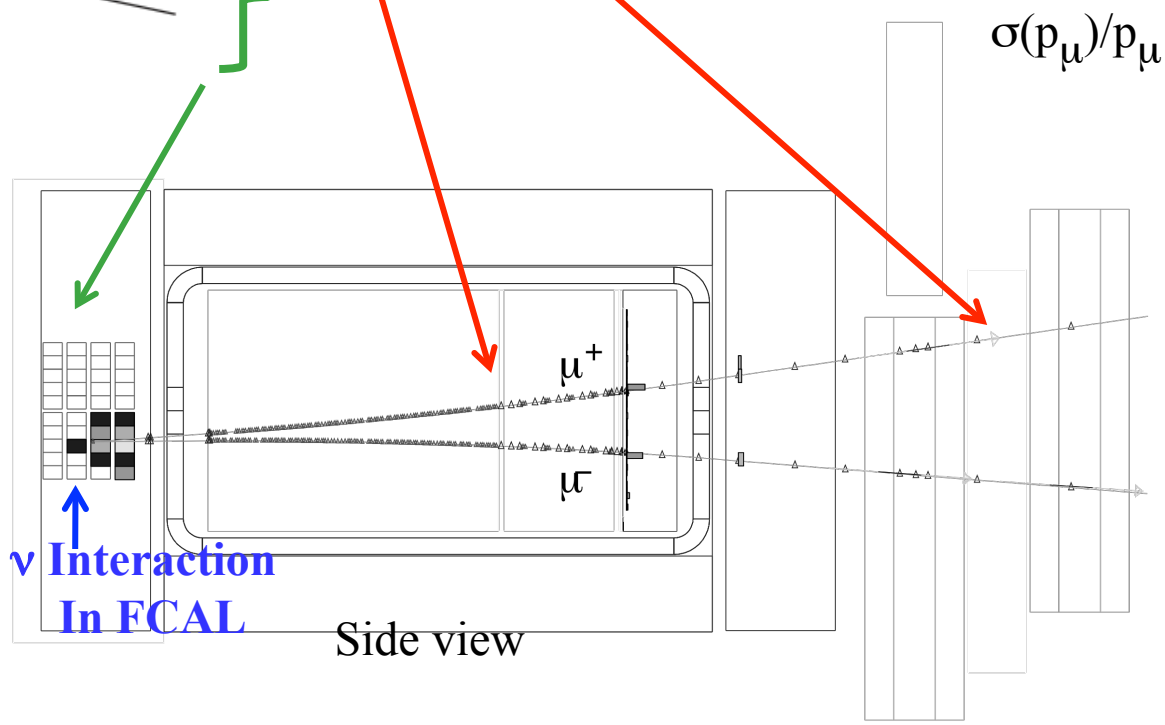
μ^+ , μ^- : Reconstructed in Drift Chambers
Identified in Muon chambers after absorber:
$p_\mu > 3$ GeV/c

$\sigma(p_\mu)/p_\mu \approx 2.5\%$

X = Hadronic system:
Energy Measured in
Front Calorimeter

$\sigma(E)/E = 104\%/\sqrt{E}$

(Cannot measure
INDIVIDUAL tracks
In FCAL)



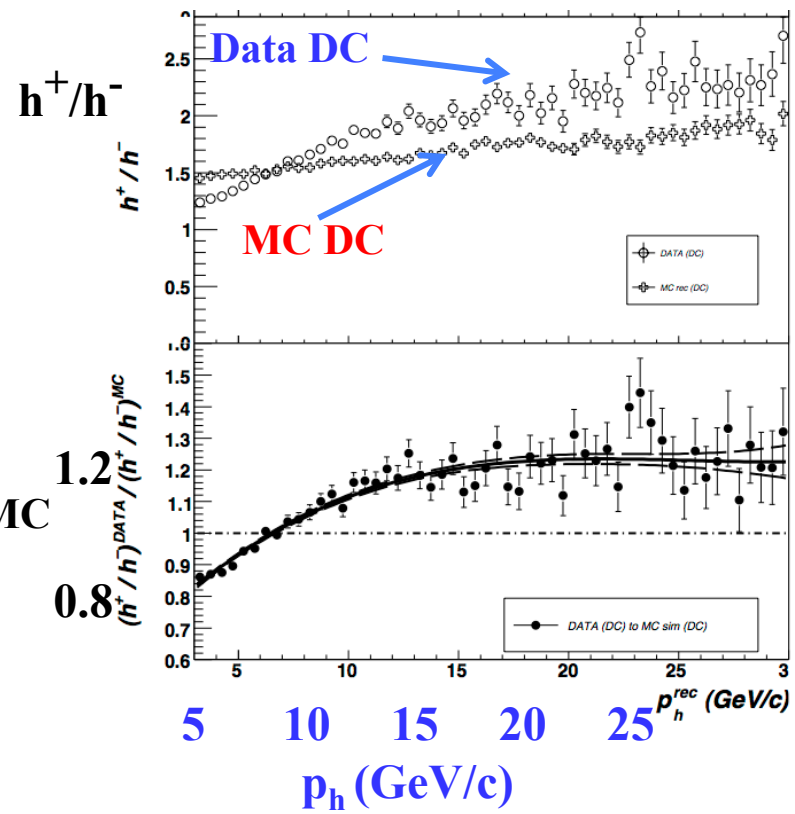
Background

- OPPOSITE SIGN (OSDM) $\mu^-\mu^+$ where the μ^+ is from a π,K → μ in a CC interaction.
- Estimate using LIKE SIGN ($\mu^-\mu^-$) in FCAL.
- $N^{data}(\mu\mu^+_{bg}) = N^{data}(\mu\mu^-).[N^{MC}(\mu^-\mu^+_{bg}) / N^{MC}(\mu^-\mu^-)]$

In FCAL

- But corrected FCAL Monte Carlo ratio:
  - MEASURE **h+/h-** ratio in Drift Chamber (DC) data and compare it to Drift chamber Monte Carlo ratio.
  - Compute a correction and apply it to the FCAL MC ratio.

$(h^+/h^-)^{Data}/(h^+/h^-)^{MC}$

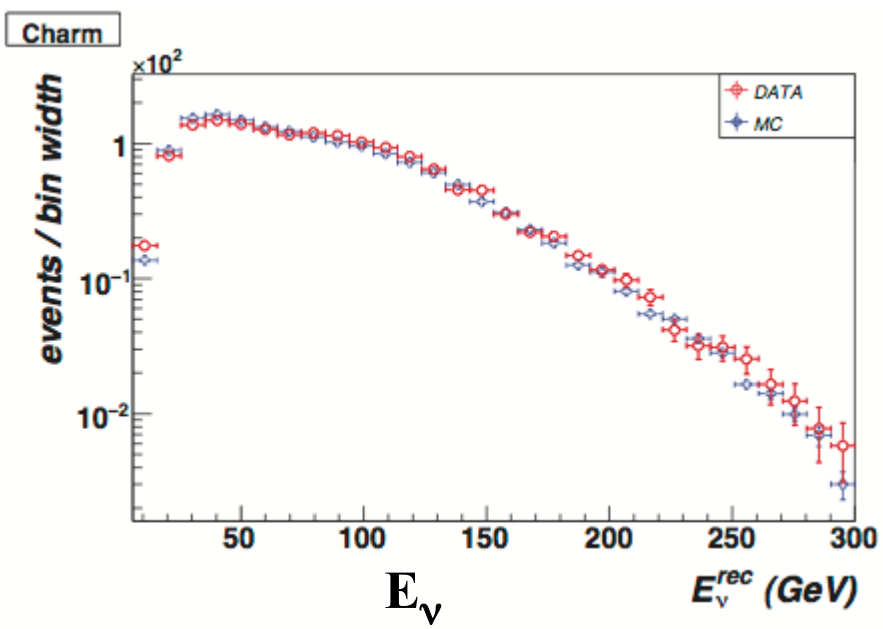


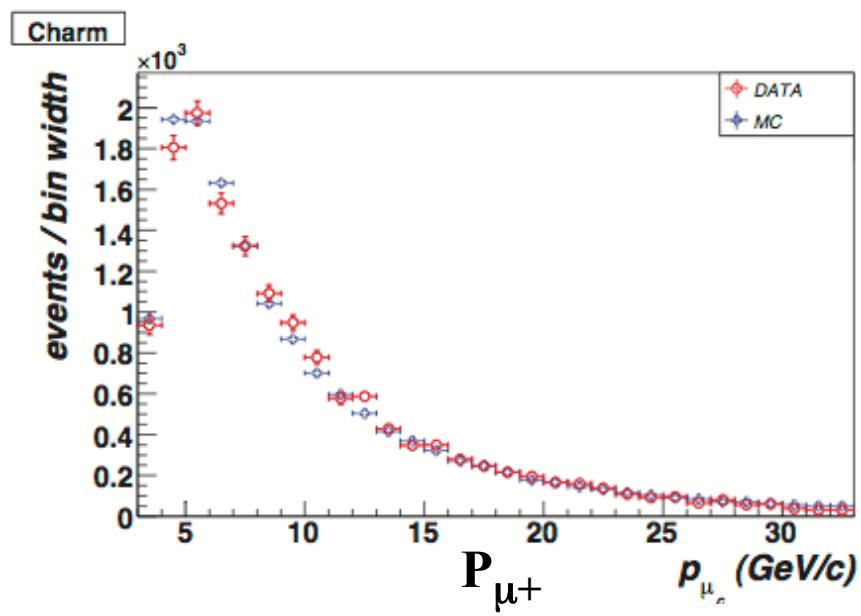
Entire background prediction extracted from data

Signal

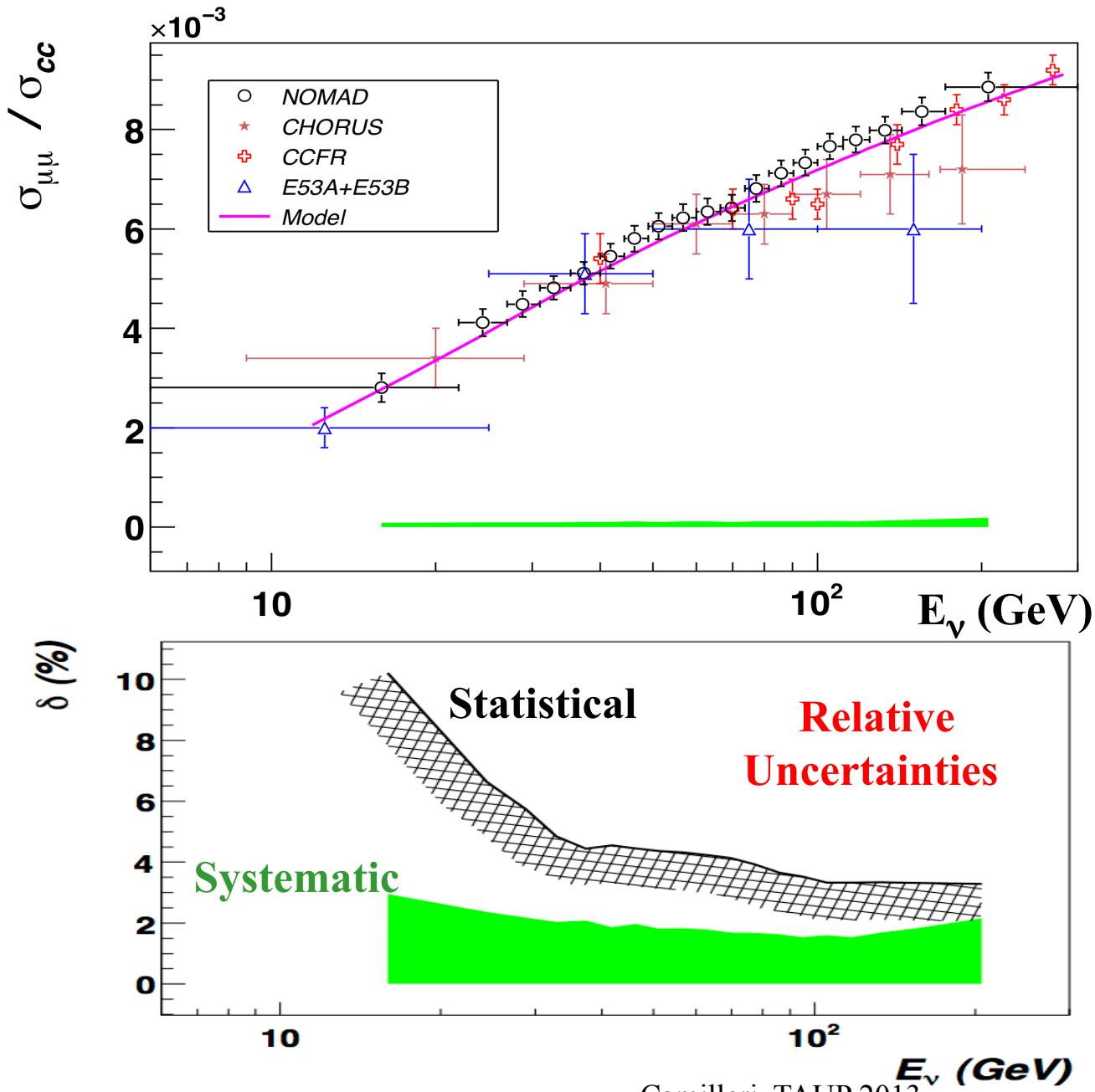
Opposite Sign	Like Sign	Background	**Charm Signal**
$\mu^+\mu^-$	$\mu^-\mu^-$	$\mu^+\mu^-$	$\mu^+\mu^-$
20479	7148	5135	**15344**

Very good agreement between background subtracted data and Charm Monte Carlo in all kinematic variables





Results



Presented as a ratio to 9 x 10^6 reconstructed ν_μ CC events in FCAL

$\sigma_{\mu\mu}/\sigma_{CC}$ (Q^2>1GeV^2/c^2)

=(5.15±0.05±0.07)x10^{-3}

Over NOMAD flux.

Similar ratios as a function of x_{Bj} and $\sqrt{\hat{s}}$

Results of simultaneous Fit of $\sigma_{\mu\mu}/\sigma_{CC}$ distributions as a function of E_ν, x_{Bj}, $\sqrt{\hat{s}}$ to data

Global Fit as in S. Alekhin et al Phys. Lett. **B675**, 433 (2009)

Include:

- Charged Lepton DIS data
- Drell-Yan data

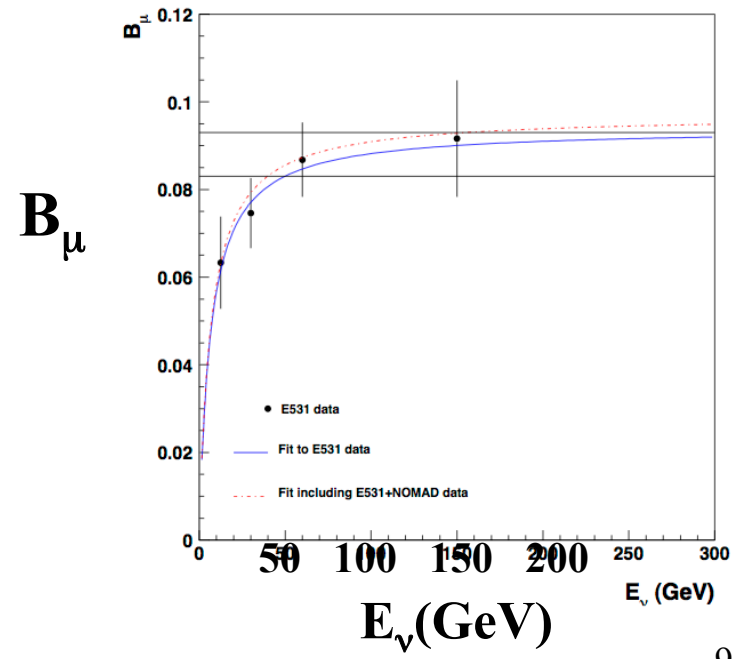
} As input for non-strange PDF's

(Calculation in NLO)

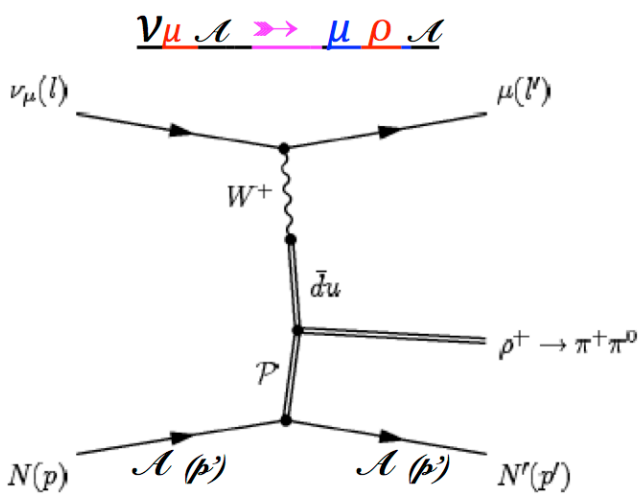
- E531 Charm prod. data to determine energy dependence of B_μ (due to Λ^+_c and D^+_s being more important at low energy)
- NOMAD dimuon data
- (Did NOT include other dimuon data in order to determine charm parameters from NOMAD data alone)

Fit for:

- Charm running mass in $\overline{MS}$ scheme:
  $m_c(m_c) = 1.159 \pm 0.075$ GeV/c^2
- Strange quark suppression factor:
  κ_s (Q^2=20 GeV^2/c^2) = 0.591 ± 0.019
- Collins-Spiller charm fragmentation:
  $\varepsilon_c = 0.165 \pm 0.025$
- Semileptonic Branching ratio:
  $B_\mu = (0.094 \pm 0.004)/(1+[6.0 \pm 1.6]/E_\nu)$



Coherent ρ^+, ρ^0 Production



Coherent Production → Nucleus must act as a whole

- Low momentum transfer to nucleus

$$\sqrt{(|t|)} \leq 1/R_\mathcal{N}ucleus$$

- Forward production

"Forwardness": $\zeta_\rho = E_\rho*(1-\cos\theta_\rho)$ → small

A Test of CVC and VMD

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

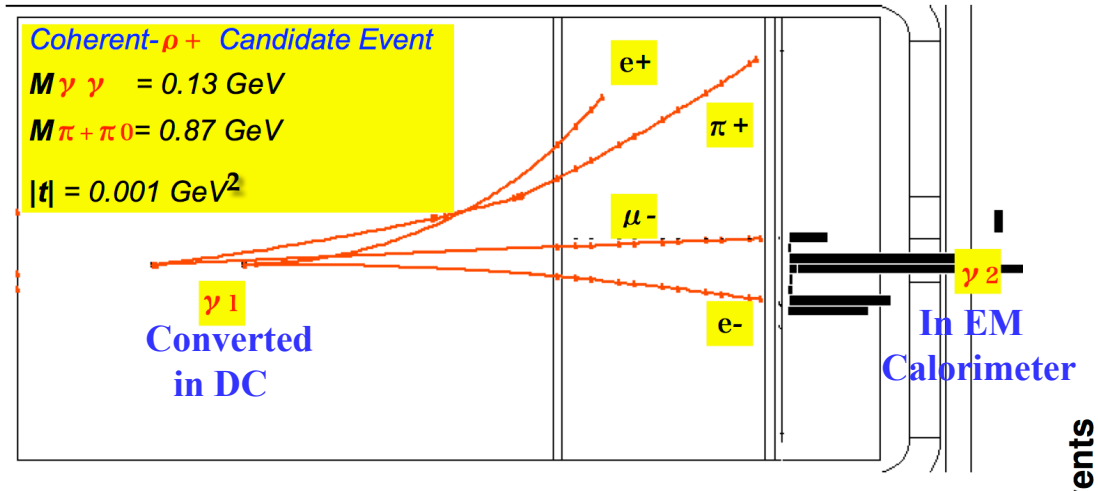
Polarization $d\sigma^L/d\sigma^T$ ρ−Nucleus Transverse cross section

$$\frac{d^3\sigma(\nu_\mu\mathcal{A}\to\nu_\mu\rho^0\mathcal{A})}{dQ^2d\nu dt} = \underbrace{0.5(1-2\sin^2\theta_W)^2}_{\sim 0.15}\frac{d^3\sigma(\nu_\mu\mathcal{A}\to\mu^-\rho^+\mathcal{A})}{dQ^2d\nu dt}$$

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

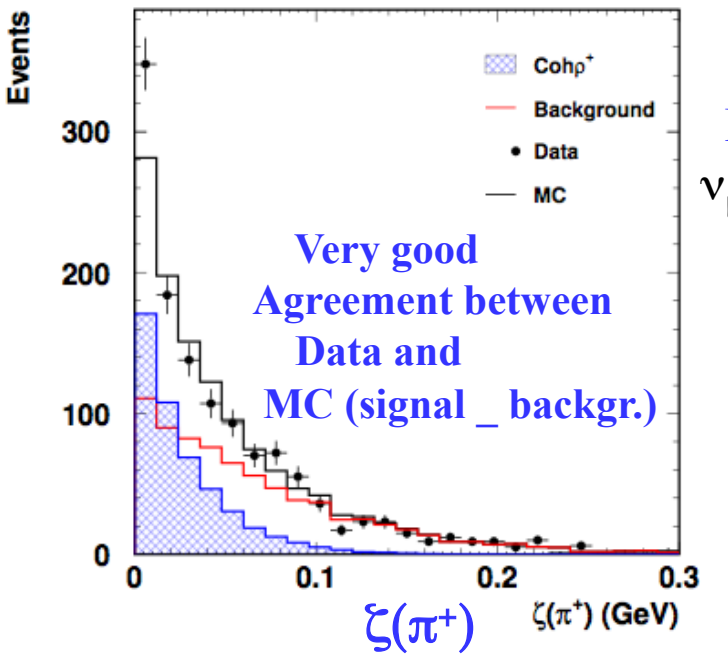
Coherent ρ^+ ($\rightarrow \pi^+\pi^0$) CC process

$\nu A \rightarrow \mu^- \pi^+ \pi^0$



$\pi^0 \rightarrow 2\,\gamma$

- $\gamma 1$, $\gamma 2$ in ECAL
- $\gamma 1$ in ECAL, $\gamma 2$ conversion in DC
- $\gamma 1$,$\gamma 2$ conversions in DC

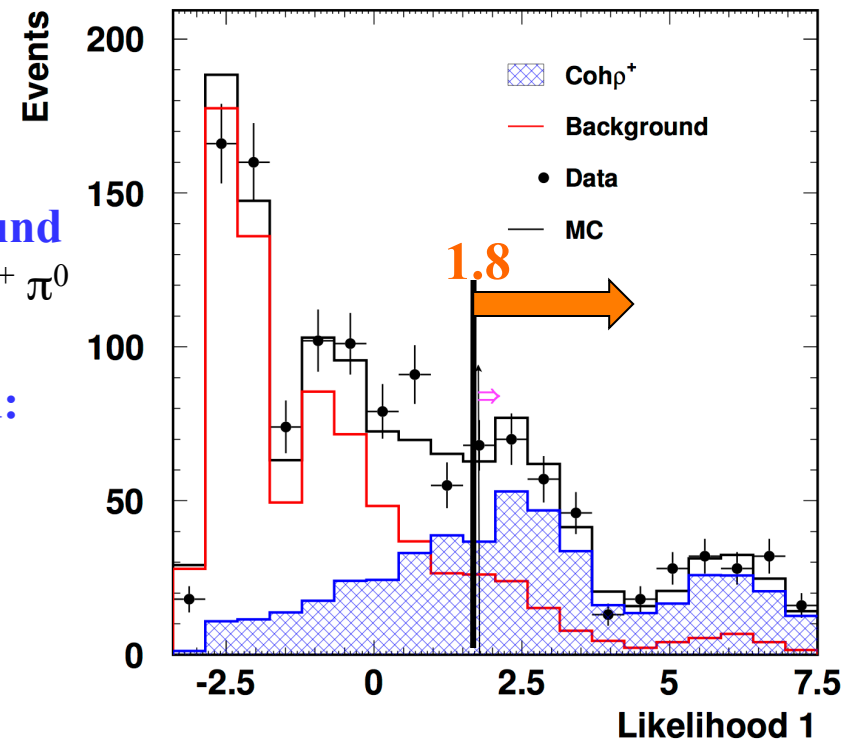


Major Background

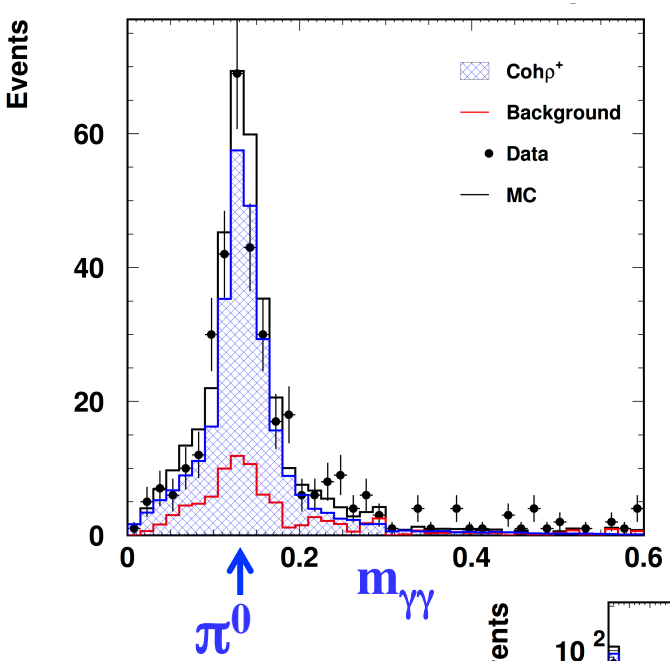
ν_μ CC DIS $\rightarrow \mu^- \pi^+ \pi^0$

Build likelihood:

$\zeta(\pi^+)$, x_{BJ}, y_{BJ}

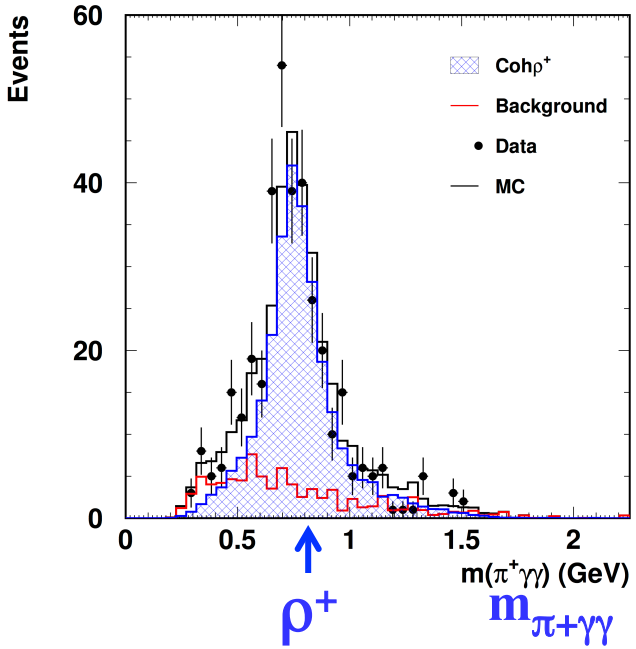


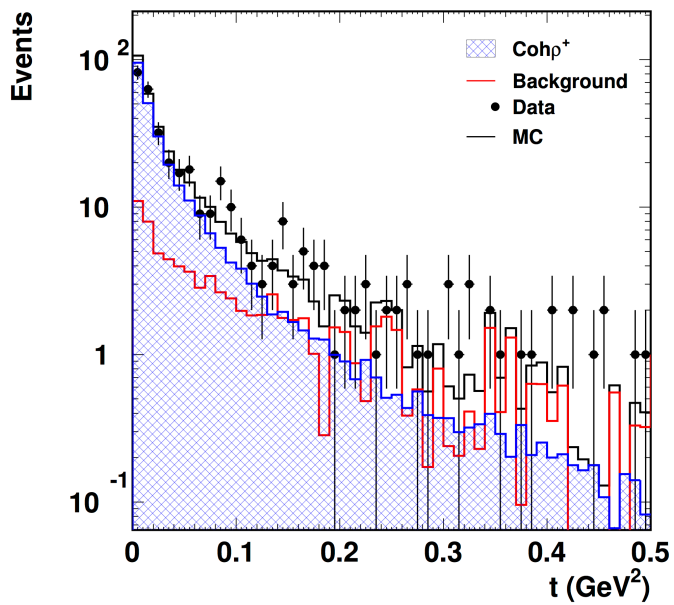
Coherent ρ^+ Signal



Likelihood > 1.8

Note: No a priori cuts on π^0 and ρ^+ mass





Fit gives: $e^{-(28.7\pm0.7)t}$

Consistent with coherence

Coherent ρ^+ Cross section

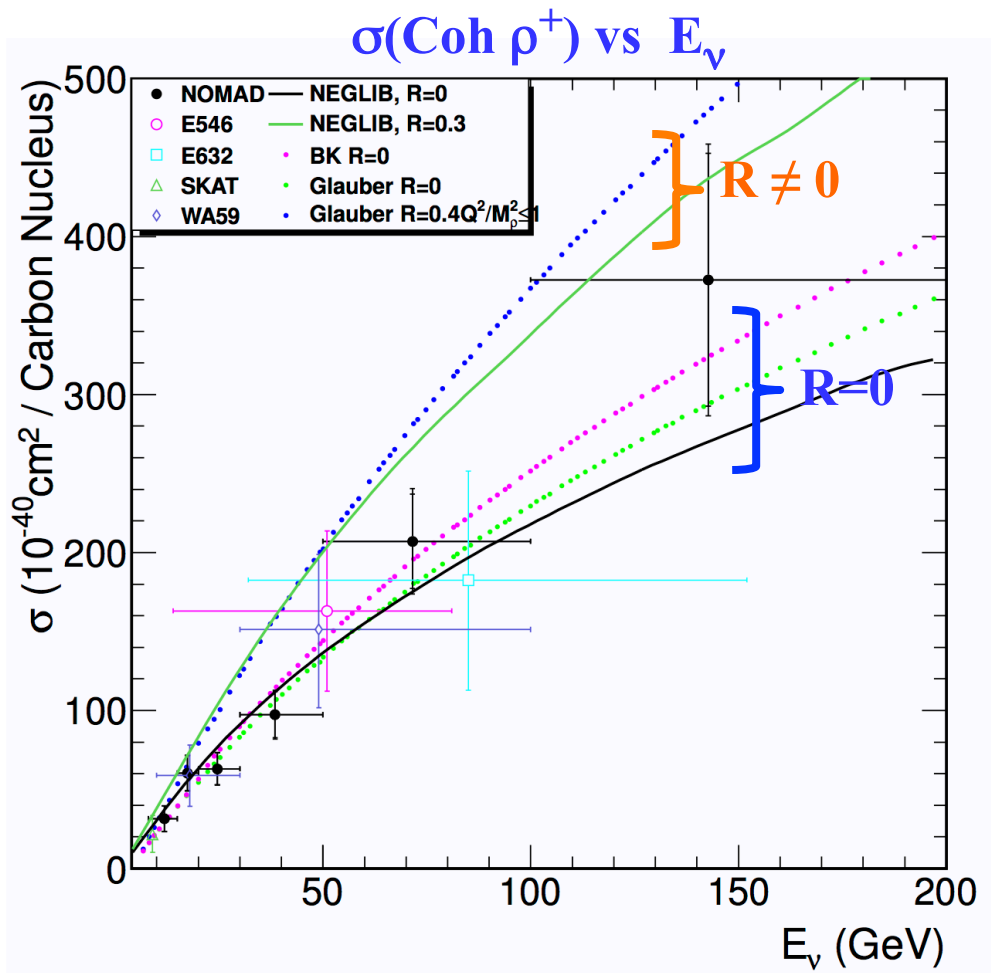
Fully corrected number of ρ^+:

4318.4±307.4(stat) ±168.4(syst)

Rate relative to 1.44 x 10^6 ν_μ CC:

(3.01 ± 0.24) x 10^{-3}

$R = \sigma^L / \sigma^T = 0$ favoured.

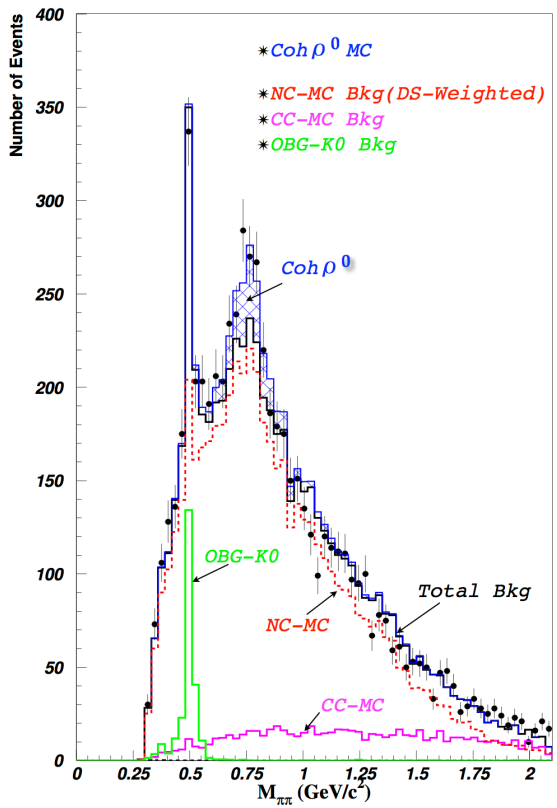


Coherent ρ^0 ($\rightarrow \pi^+\pi^-$) NC process: $\nu A \rightarrow \nu\pi^+\pi^-$

Background sources

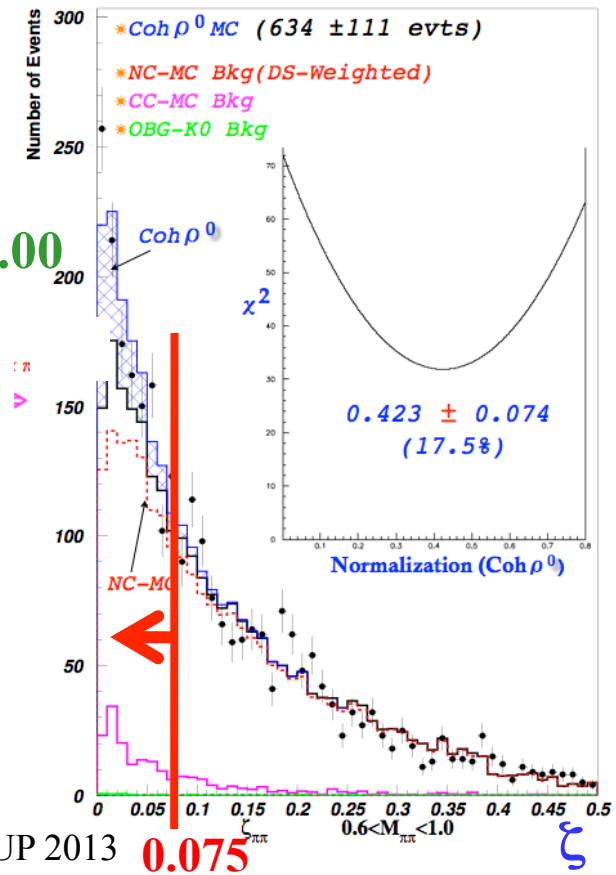
- ν_μ NC DIS $\rightarrow$ $\pi^+ \pi^-$
- ν_μ CC DIS $\rightarrow$ $\mu^- \pi^+$ +….with μ not identified
- K^0_s from outside interactions

- Use ν_μCC with μ removed (in both data and MC) to correct NC MC shapes.
- Use data and MC (coh ρ^0 + background) at $\zeta > 0.075$ to normalize NC DIS MC $\rightarrow$ x 1.027



$M_{\pi\pi}$

$0.6 < M_{\pi\pi} < 1.00$



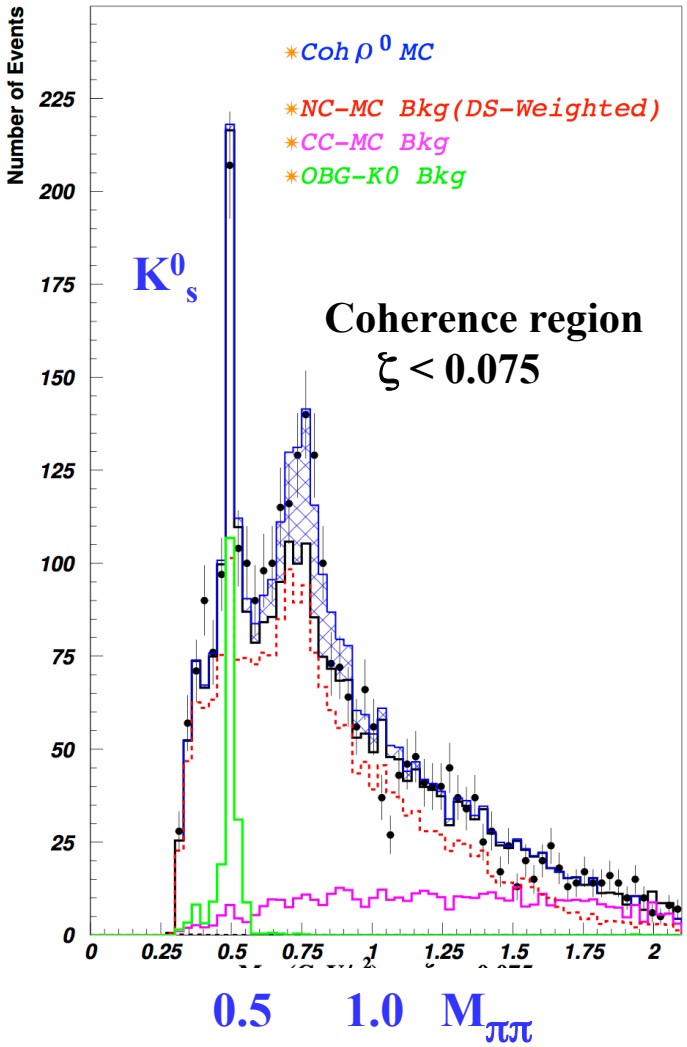
0.075

ζ

Normalize Coh ρ^0 MC sample To fit data

Then use $\zeta < 0.075$

Coherent ρ^0 Results



Fully corrected number of ρ^0:

634.5 ± 111.0 (stat) ± 95.2 (syst)

Rate relative to 1.44 x 10^6 ν_μ CC:

(4.41 ± 1.00) x 10^{-4}

First observation of Coherent ρ^0

$\mathrm{Coh}(\rho^0) / \mathrm{Coh}(\rho^+) = (634.5 \pm 146.2) / (4318.8 \pm 350.5) =$ **0.147 ± 0.036**

In agreement with : $0.5(1- 2\sin^2\theta_W)^2$ **= 0.15**

Conclusions

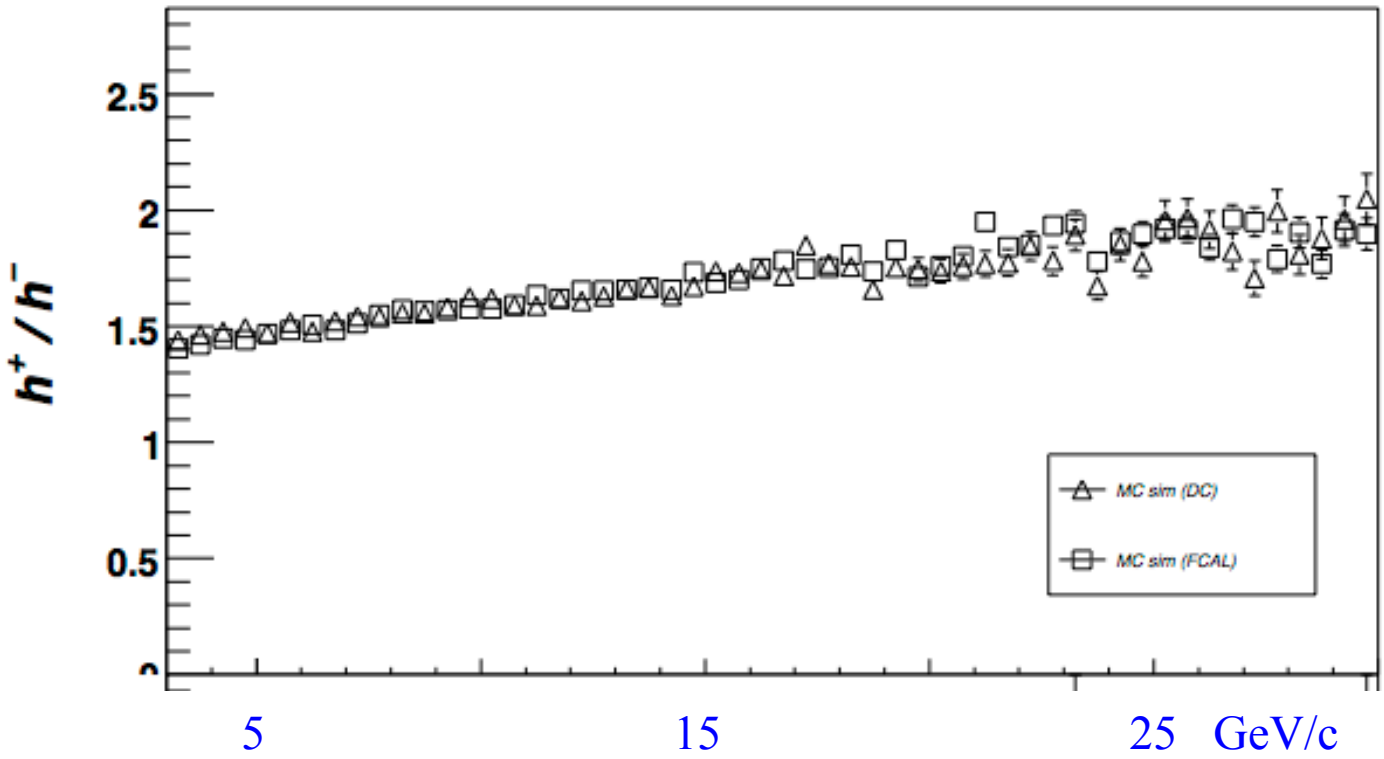
NOMAD has presented:

- Based on 15344 events, the largest dimuon sample with the lowest threshold,
  - the most precise values of the **charm quark mass** in neutrino interactions.
    $m_c(m_c) = 1.159 \pm 0.075$ GeV/c^2
  - and of a factor of **2** improvement in the **strange sea suppression factor**
    κ_s (Q^2=20 GeV^2/c^2) = 0.591±0.019
- The most precise measurement of coherent ρ^+ production
- The first observation of coherent ρ^0

NOMAD
Born 1990 Still going strong!

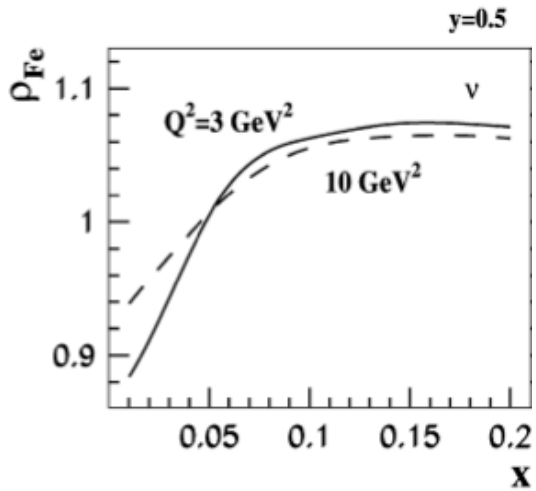
Backup

Dimuons: Equality of h+/h- in FCAL and DC



Dimuons: Fit model

- QCD evolution of PDF's: 3 light flavours and QCD corrections to NNLO:
  S. Moch et al Nucl.Phys. **B688** (2004) 101.
- Cross section calculation to NLO.
- Nuclear corrections (Fe) according to S.A.Kulagin and R. Petti:
  Nucl. Phys. **A765** (2006) 126 and
  Phys. Rev. **D76** (2007) 094023.



- Electroweak corrections:
  A.B. Arbuzov et al: JHEP **0578** (2005) 506 and arXiV:hep-ph/0407203
  K.P. Diener et al: Phys. Rev. **D69** (2004) 073005
- x-dependence of strange quark distribution:

$$xs(x, Q_0^2) = A_s x^{a_s} (1 - x)^{b_s}$$

→ A_s = 0.0899±0.0029 b_s=8.75±0.43 with a_s=-0.240 (NOMAD + E531)

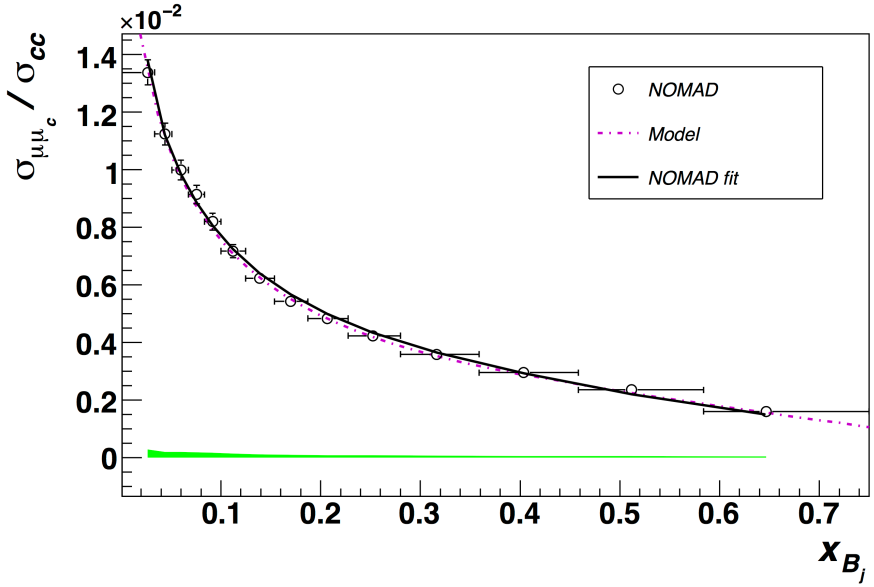
Dimuons: Previous values

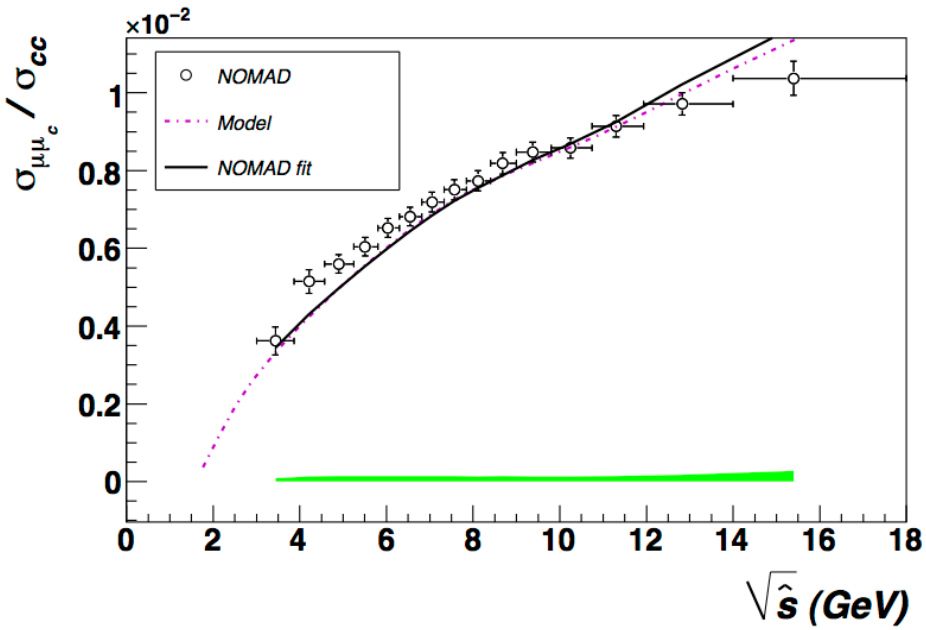
- NuTeV + CCFR fit:

  $\kappa_s\,(Q^2=20\ \mathrm{GeV}^2/c^2) = 0.62 \pm 0.04(\mathrm{exp}) \pm 0.03(\mathrm{QCD})$

- Charm quark mass world average: $m_c = 1.275 \pm 0.025\ \mathrm{GeV}/c^2$

Dimuons: x_{Bj}, $\sqrt{\hat{s}}$ distributions





$\rho^{+,0}$ Systematics

- ρ^+: Total: 3.9%

- Background normalization. Use Likelihood -4.0 → 0.0: 1.6%
- Efficiency. Varying parameters and cuts:2.5%
- Absolute normalization:2.5%

- ρ^0: Total: 15%.

  - Data Simulator: 10.6%
  - NC-DIS 2% variation: 9.5%.
  - CC-DIS: 4.5%
  - Outside background:1%