Precision measurements from the NOMAD experiment

Neutrino Oscillation MAgnetic Detector

Roberto Petti

CERN

for the NOMAD Collaboration

5th Rencontres du Vietnam

Hanoi, August 7th, 2004

OUTLINE

I *Introduction*

- *The NOMAD detector*
- *Data samples and physics analyses*

II *Precision measurements*

- *Measurement of quasi-elastic cross-section*
- *Extraction of* $\sin^2\theta_W$
- *Modelling neutrino interactions*
- *Measurement of Charged Current differential cross-section*
- *NOMAD sensitivity to* $\sin^2\theta_W$

III *Summary*

THE NOMAD DETECTOR

❖ Multi-purpose electronic detector:

I *high resolution tracking*

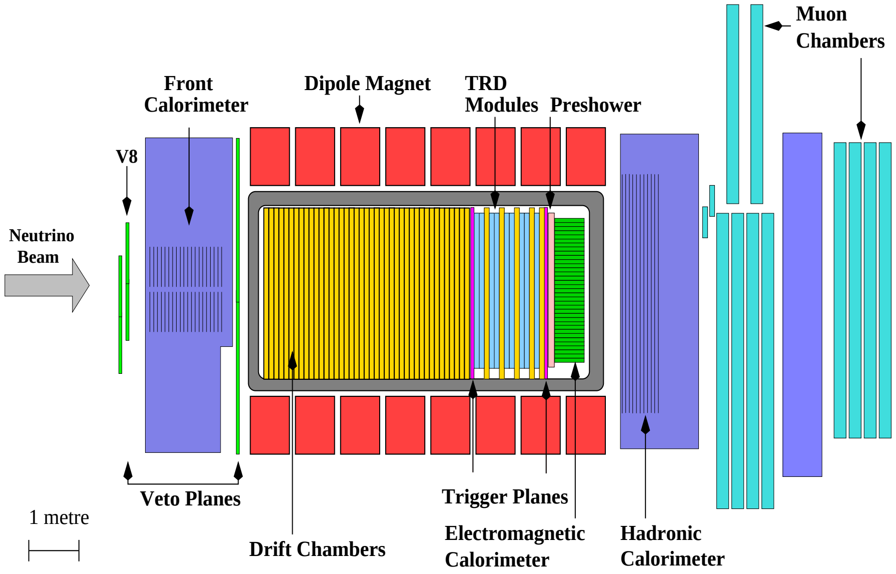
$\Longrightarrow$ *mom. resolution* $\sim$*3.5%* $(p<10\mathrm{GeV}/c)$;

II *fine-grained calorimeter*

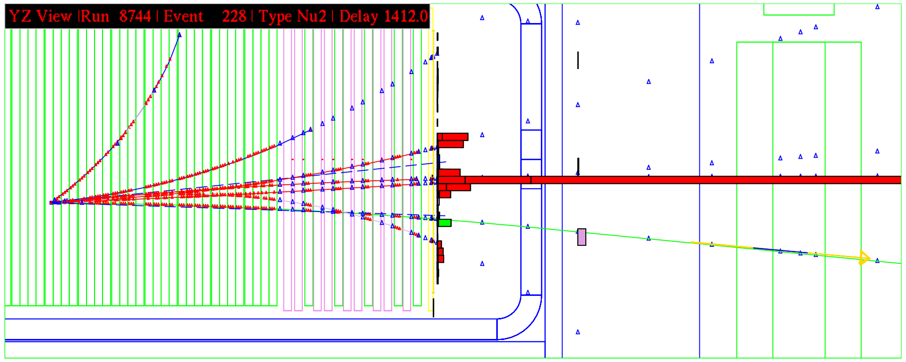
$\Longrightarrow \sigma(E)/E = 3.2\%/\sqrt{E[\mathrm{GeV}]} \oplus 1\%$;

III *excellent lepton identification*
& charge measurement

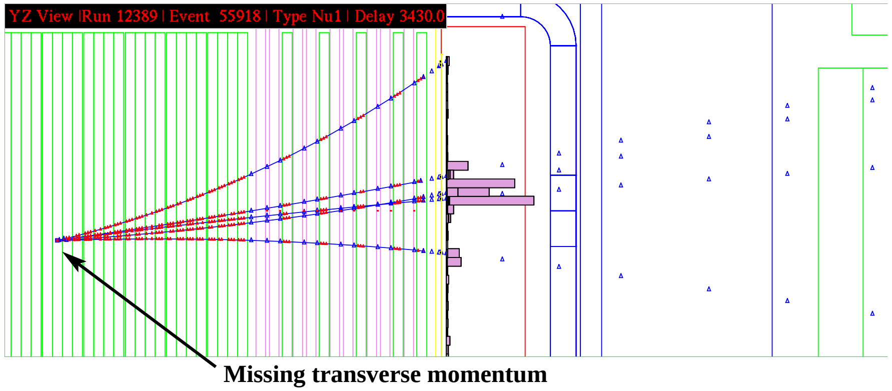
$\Longrightarrow$ *can detect* $\boxed{\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e \ \textbf{CC}}$.



ν_μ Charged Current



Neutral Current



DATA SAMPLES AND PHYSICS ANALYSES

- **Overall, 5.10×10^{19} p.o.t. (0.44×10^{19} with $\bar{\nu}$) provided the following data samples in NOMAD (1995-1998):**

I *Main drift-chamber target (2.7 t, C)*
$\Longrightarrow$ *high resolution data ($\rho \sim 0.1 g/cm^3$)*
total of $\boxed{\textbf{1.3 M } \nu_\mu \textbf{ CC}}$

$\Longrightarrow$

- *Oscillations: $\nu_\mu \to \nu_\tau$; ν_e (completed)*
- $\boxed{\sin^2 \theta_W}$
- $\boxed{\text{Cross-sections and structure functions}}$
- *Particle production and spin physics*
- *Searches for new physics*

II *Front magnet coil (few t, mainly Al)*
$\Longrightarrow$ *still good reconstruction of hadrons going through drift chambers*
total of $\boxed{\textbf{1.5 M } \nu_\mu \textbf{ CC}}$

$\Longrightarrow$

- $\sin^2 \theta_W$
- *Cross-sections and structure functions*
- *Particle production and spin physics*

III *Front calorimeter (17.7 t, Fe)*
$\Longrightarrow$ *high resolution on muon reconstruction + calorimetric meas. of hadronic jet*
total of $\boxed{12 \textbf{ M } \nu_\mu \textbf{ CC}}$

$\Longrightarrow$

- *Multi-muon production*
- *Cross-sections and structure functions*
- *Searches for new physics*

MEASUREMENT OF QUASI-ELASTIC CROSS-SECTION

- *Measurement of $\nu_\mu n \to \mu^- p$ cross-section on C (5% H) in the energy range $3 < E_\nu < 100$ GeV:*
  - *Events with two tracks (reconstructed proton)*
  - *Kinematic selection based upon a 3D likelihood function:*

$$\mathcal{L}_{QE} = [p_T^m, \theta_{\nu p}, \phi_{\mu p}]$$

$\Longrightarrow$ *8192 events with $\varepsilon_{\rm QE} = 25\%$ and purity of 71%.*

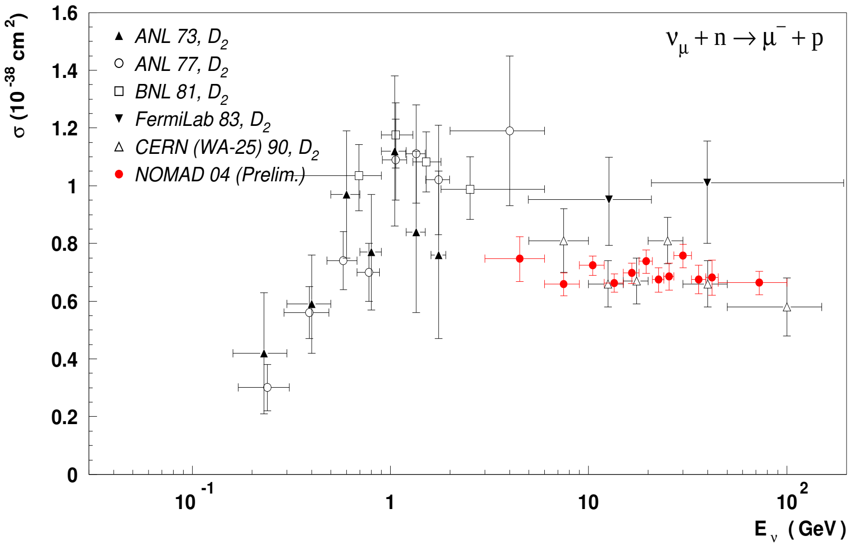
- *Relative measurement of cross-section ratios with respect to known processes. Two independent normalizations provide consistent results:*
  - *Deep Inelastic Scattering ($W^2 > 4$ GeV^2) ν_μ CC events. Absolute cross-section normalization to the world average value on isoscalar target:*

$$\sigma^\nu / E_\nu \; = \; 0.677 \pm 0.014 \times 10^{-38} \; \frac{cm^2}{GeV}$$

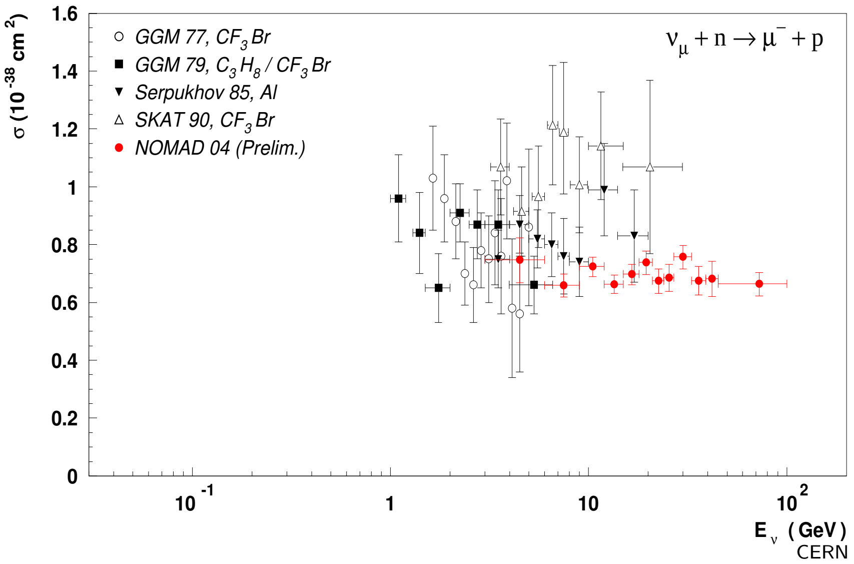
  in the energy range $40 < E_\nu < 200$ GeV.

  - *Inverse Muon Decay (IMD) $\nu_\mu e^- \to \mu^- \nu_e$ events. Absolute cross-section normalization to theoretical IMD cross-section (well known).*

- *Flux predictions $\phi(E_\nu)$ from beam simulations including constraints from SPY data on π, K production in p-Be interactions (hep-ex/0306022).*



Normalization systematics being finalized



MOTIVATIONS FOR A NEW MEASUREMENT OF $\sin^2\theta_W$

- *Measurement from* $\boxed{\nu\text{N DIS}}$ *not the most precise overall (LEP/SLD), but important test for the Standard Model:*
  - *different scale of momentum transfer with respect to LEP/SLD (off Z^0 pole)*
  - *direct measurement of neutrino couplings to Z^0*
    $\Longrightarrow$ *Only other measurement LEP $\Gamma_{\nu\nu}$*

- *NuTeV measured $\sin^2\theta_W$ by comparing NC and CC rate for BOTH neutrinos and antineutrinos:*

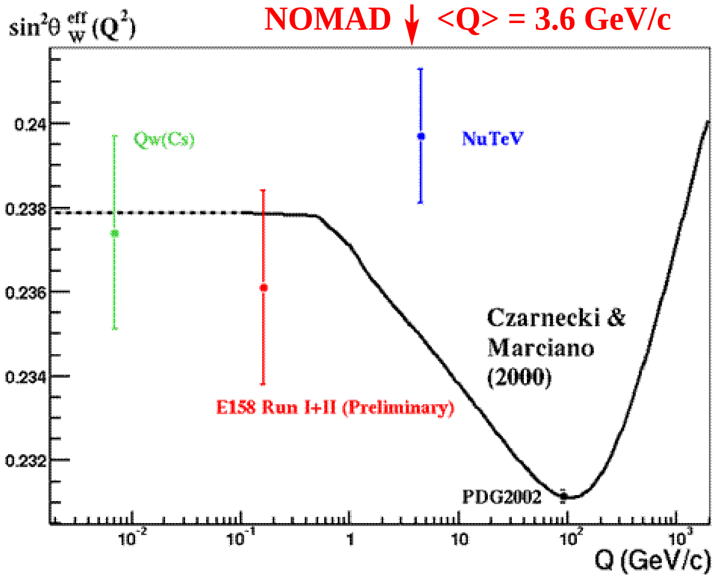
$$\sin^2\theta_W^{\text{on-shell}} \equiv 1.0 - \frac{M_W^2}{M_Z^2} =$$

$$\boxed{0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})}$$

$$\text{SM from LEPEWWG} \quad = \quad 0.2227 \pm 0.0004$$

$$R^\nu = \frac{\sigma^\nu_{\text{NC}}}{\sigma^\nu_{\text{CC}}} = 0.3916 \pm 0.0013 \quad (SM\ 0.3950)$$

$$R^{\bar\nu} = \frac{\sigma^{\bar\nu}_{\text{NC}}}{\sigma^{\bar\nu}_{\text{CC}}} = 0.4050 \pm 0.0027 \quad (SM\ 0.4066)$$

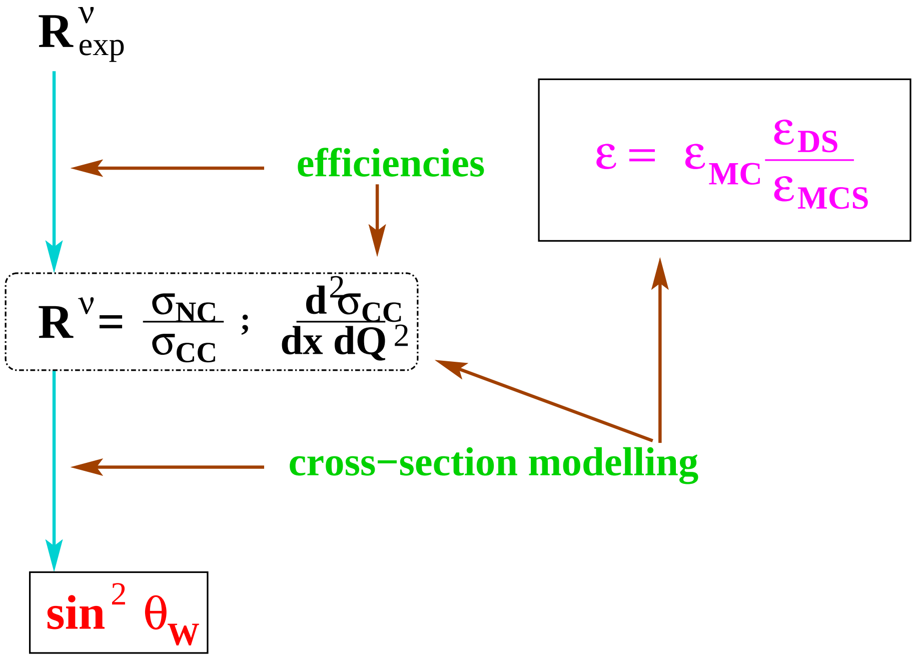


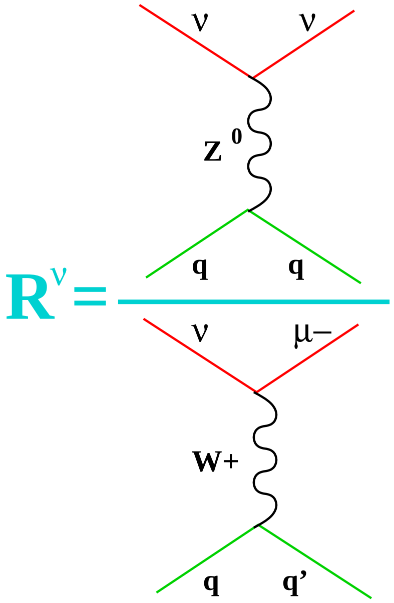
$\Longrightarrow$ *A discrepancy of 3σ with respect to SM in the NEUTRINO data*

$\Longrightarrow$ *An independent measurement from νN DIS could help to clarify the situation!*

THE NOMAD $\sin^2\theta_W$ MEASUREMENT

- *Value of $\sin^2\theta_W$ extracted from a simultaneous* FIT TO BOTH R^ν AND CC *differential cross-section. The CC sample constraints theoretical uncertainties:*



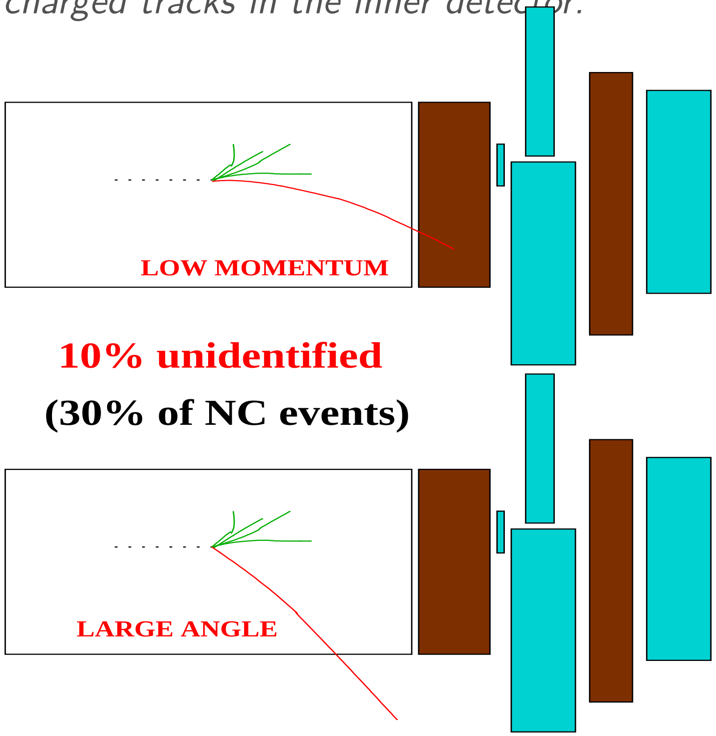


- *Can NOMAD reach an accuracy comparable to NuTeV without $\bar{\nu}$ data? NuTeV itself could extract $\sin^2\theta_W$ from ν ONLY without a major degradation of the total error:*
  - Use BOTH $\bar{\nu}$ and $\nu \longrightarrow \delta\sin^2\theta_W = 0.0016$
  - Use ONLY $\nu \longrightarrow \delta\sin^2\theta_W = 0.0021$

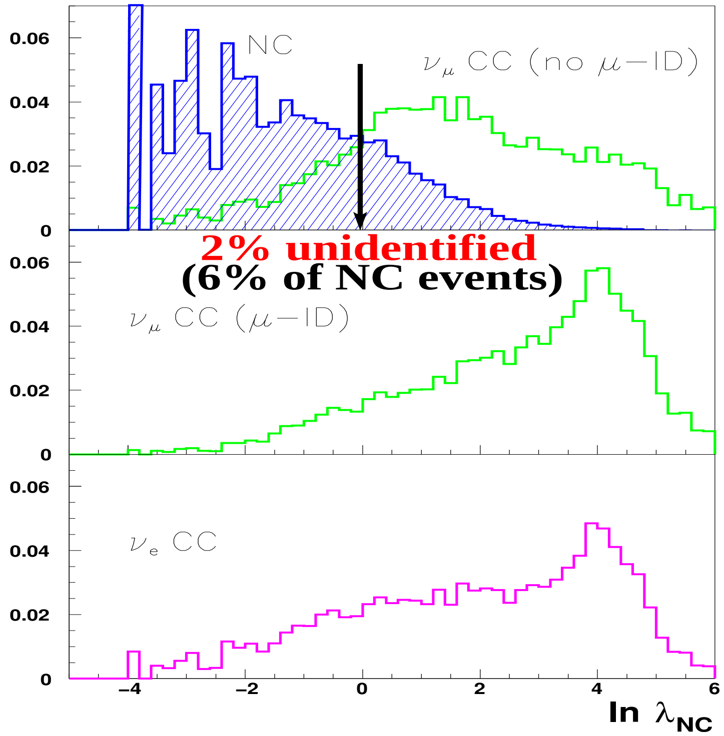
$\Longrightarrow$ *Increased systematics, but reduced statistical uncertainty (mainly from $\bar{\nu}$)*

❖ *The analysis is simply an event classification between* NC AND CC*, which is achieved by two independent steps: detector μ-ID and kinematics*

I μ CHAMBERS *identify muons by matching reconstructed track segments with charged tracks in the inner detector:*



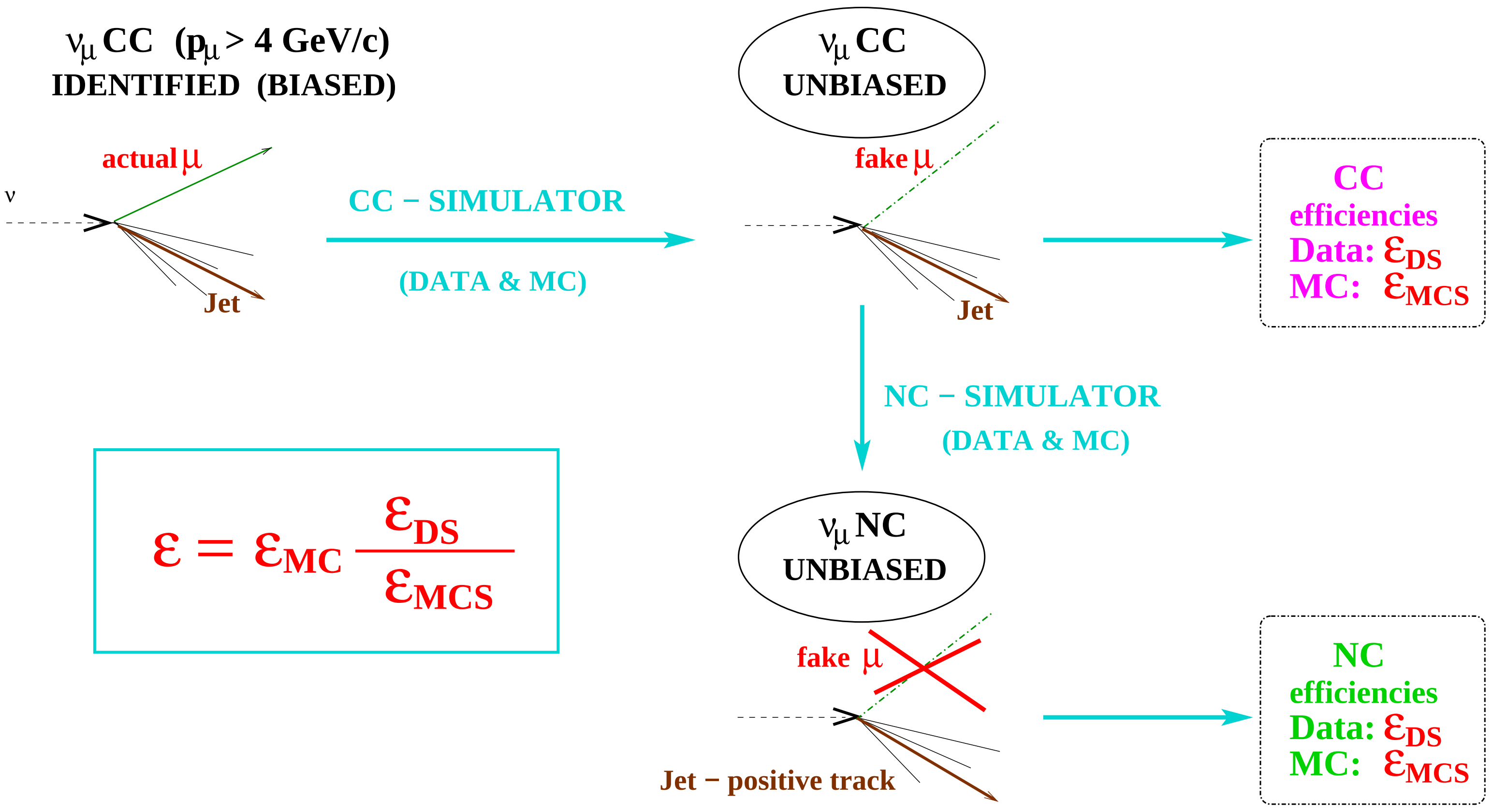
II LIKELIHOOD RATIO *between CC and NC hypotheses from multi-dimensional pdf's exploiting the full event kinematics:*



$\Longrightarrow$ *Kinematic tagging of ν_e CC events ($\sim 80\%$), no specific electron ID required*

$\Longrightarrow$ *Recovery of muon chamber inefficiencies by a second independend criterion*

- *A precise evaluation of ALL selection efficiencies from real data is achieved through a* NC AND CC DATA SIMULATOR *refined technique:*



$$\boxed{\varepsilon = \varepsilon_{MC}\,\frac{\varepsilon_{DS}}{\varepsilon_{MCS}}}$$

$\Longrightarrow$ *The NC-simulator also used for* NC trigger efficiency *(track based)*

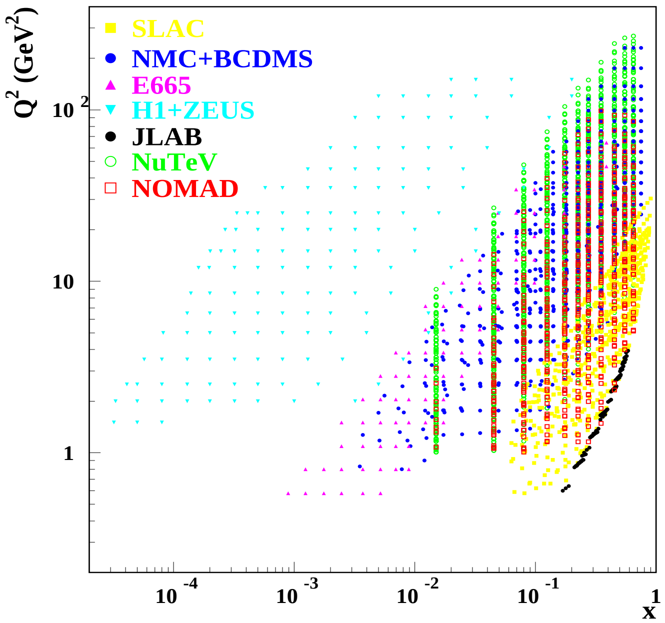
$\Longrightarrow$ *The CC-simulator also used for* *acceptance to muon chambers* .

MODELLING

❖ NNLO calculations are used for *parton distributions* (PDF) and *structure functions* (SF). Analysis in the $\overline{\mathrm{MS}}$ scheme with number of flavours fixed at 3 (FFS). Dedicated fits to extract PDFs for the analysis (with S. Alekhin, see hep-ph/0211096):

$$F_i(x,Q^2) = F_i^{LT,TMC}(x,Q^2) + \frac{H_i^{(4)}(x)}{Q^2} \qquad i = T,2,3$$

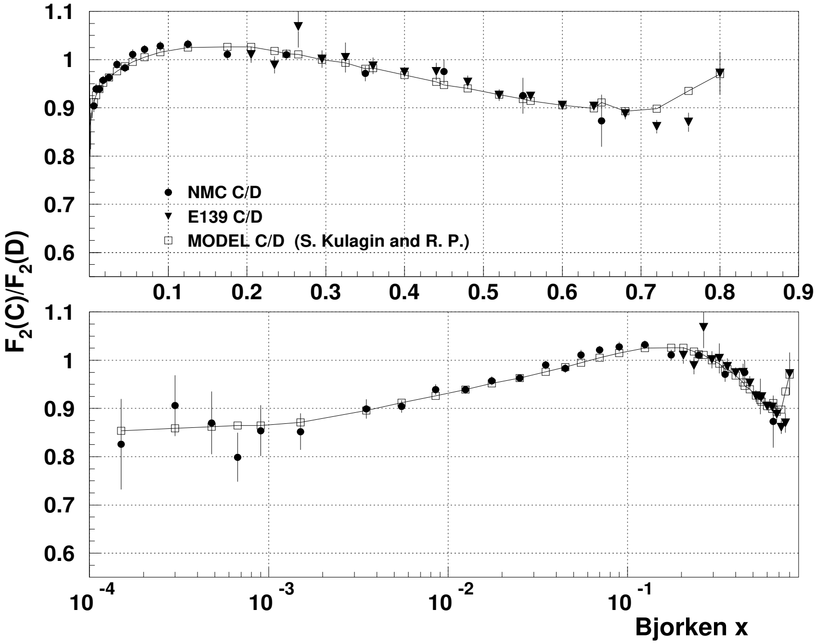
- *Electron and muon scattering data* on p and D from BCDMS,E665,HERA,JLab,NMC,SLAC
- *Neutrino (antineutrino) scattering data* on C and Fe from NOMAD and NuTeV
- Nuclear corrections (D,C,Fe) and electroweak corrections are taken into account (see next)
- Low Q^2 region: stop evolution at $Q^2 = 1$ GeV^2 and extrapolate to the $Q^2 \rightarrow 0$ limit (photoproduction, PCAC)
- Uncertainty bands on PDFs and $H_i(x)$ ($\pm 1\sigma$) from fits



$\Longrightarrow$ *Parameterization of PDFs rather than "effective" empirical functions provides universality of the modelling.*

NUCLEAR EFFECTS *in (anti)neutrino interactions on nuclei are included with a detailed phenomenological model (with S. Kulagin, paper in preparation):*

- *Reproduce e and μ scattering data on D,He,Li,Be,C,Al,Ca,Fe,Cu,Ag,Sn,Au,Pb from BCDMS,EMC,E139,E140,E665,NMC*
- *Shadowing at small x (coherent) with vector meson dominance (VMD) + leading twist*
- *Off-shell, binding energy, Fermi motion at large x in convolution approach*
- *Nuclear pion contributions*
- *Non-isoscalarity (isovector) correction*
- *Independent correction for F_T, F_2 and xF_3*



$\Longrightarrow$ *Data from charged lepton scattering bound uncertainties*

New calculation of EW corrections to partonic processes for the NOMAD analysis (A. Arbuzov, D. Bardin and L. Kalinovskaya, hep-ph/0407203).

- *Fragmentation tuned* (from JETSET) to reproduce hadron yields in ν_μ CC interactions from NOMAD data.

- $\boxed{\text{CHARM PRODUCTION}}$ in CC modelled (at NLO) based upon *NOMAD dimuon* production in the front Fe calorimeter (13659 ± 169 charm events):

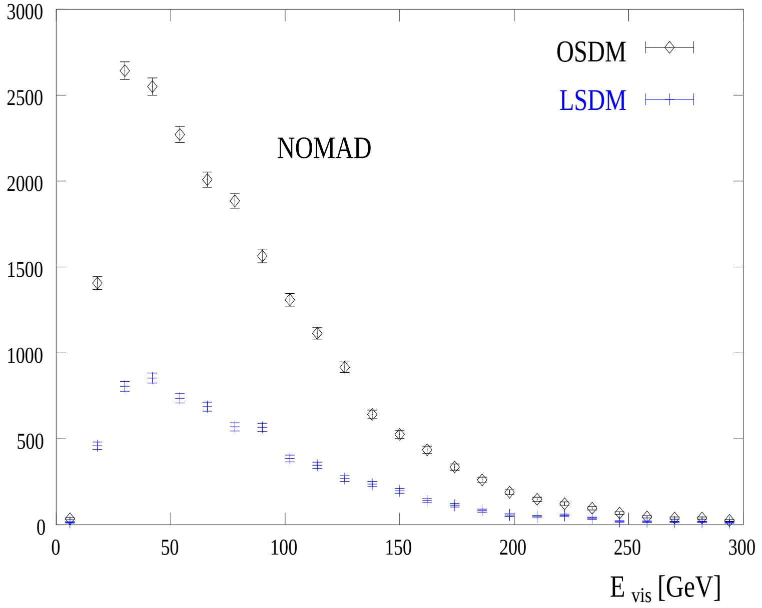
  - *Fit model to E_ν and x_{Bj} distributions* to extract mass of charm quark m_c and strange sea suppression k:

$$\delta m_c(stat.) \quad \sim \quad 30\ MeV$$

  - Use also charm mass ($\overline{MS}$ scheme) from production thresold in e^+e^- collisions (hep-ph/0109084):

$$\bar{m}_c(\bar{m}_c) \quad = \quad 1.304 \pm 0.027\ GeV \quad LO$$
$$\bar{m}_c(\bar{m}_c) \quad = \quad 1.514 \pm 0.034\ GeV \quad NLO$$

  - Strange sea determined by global fit of NOMAD dimuons together with other data used to extract PDFs



$\Longrightarrow$ *Uncertainties bounded by NOMAD & e^+e^- data*

RESULTS ON CC DIFFERENTIAL CROSS-SECTION

- *Measurement of the $\nu_\mu - C$ (5% H) cross-section in the energy range $6 < E_\nu < 300$ GeV:*
  - *Detector μ-ID, $E_\mu > 2.5$ GeV*
  - *$E_{\rm had} > 3.0$ GeV*
  - *$Q^2 > 1.0$ GeV^2*

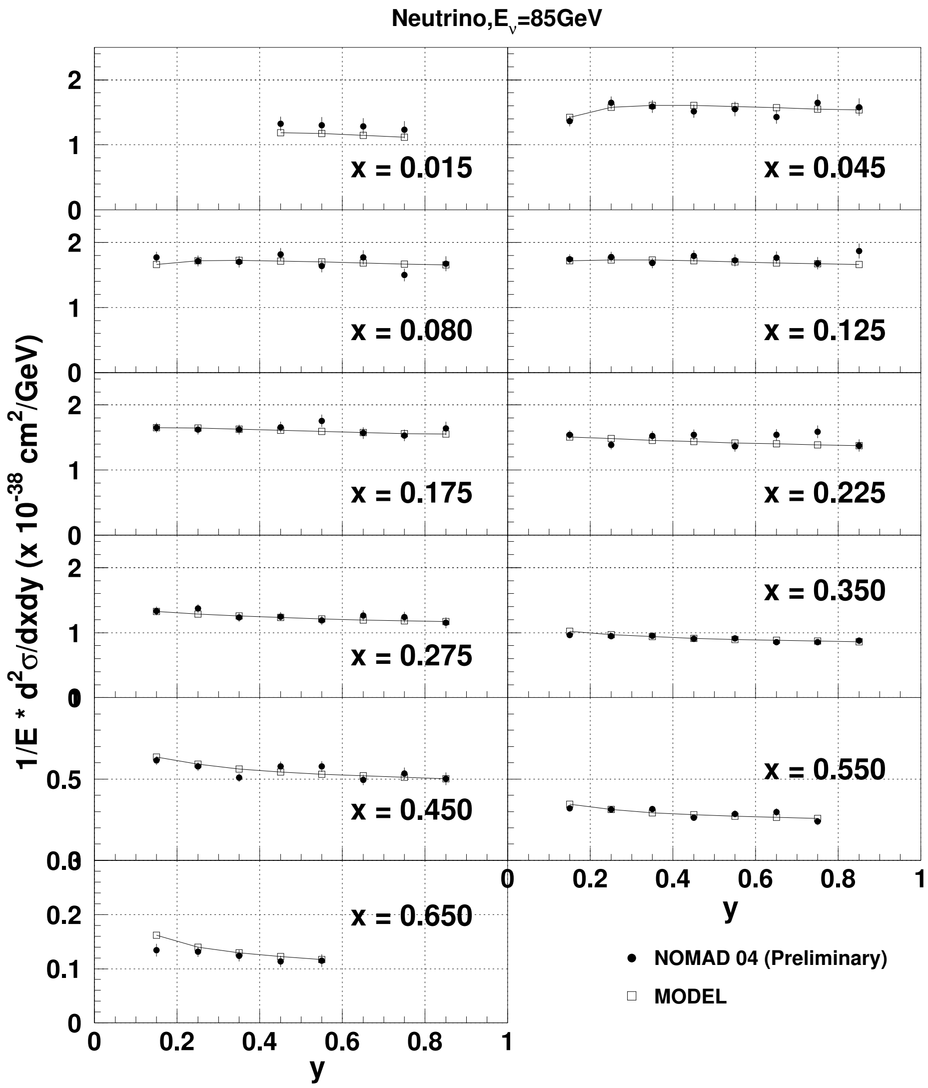
- *Absolute cross-section normalization to the world average value on isoscalar target:*

$$\sigma^\nu / E_\nu \; = \; 0.677 \pm 0.014 \times 10^{-38} \; \frac{cm^2}{GeV}$$

  in the energy range $40 < E_\nu < 200$ GeV.

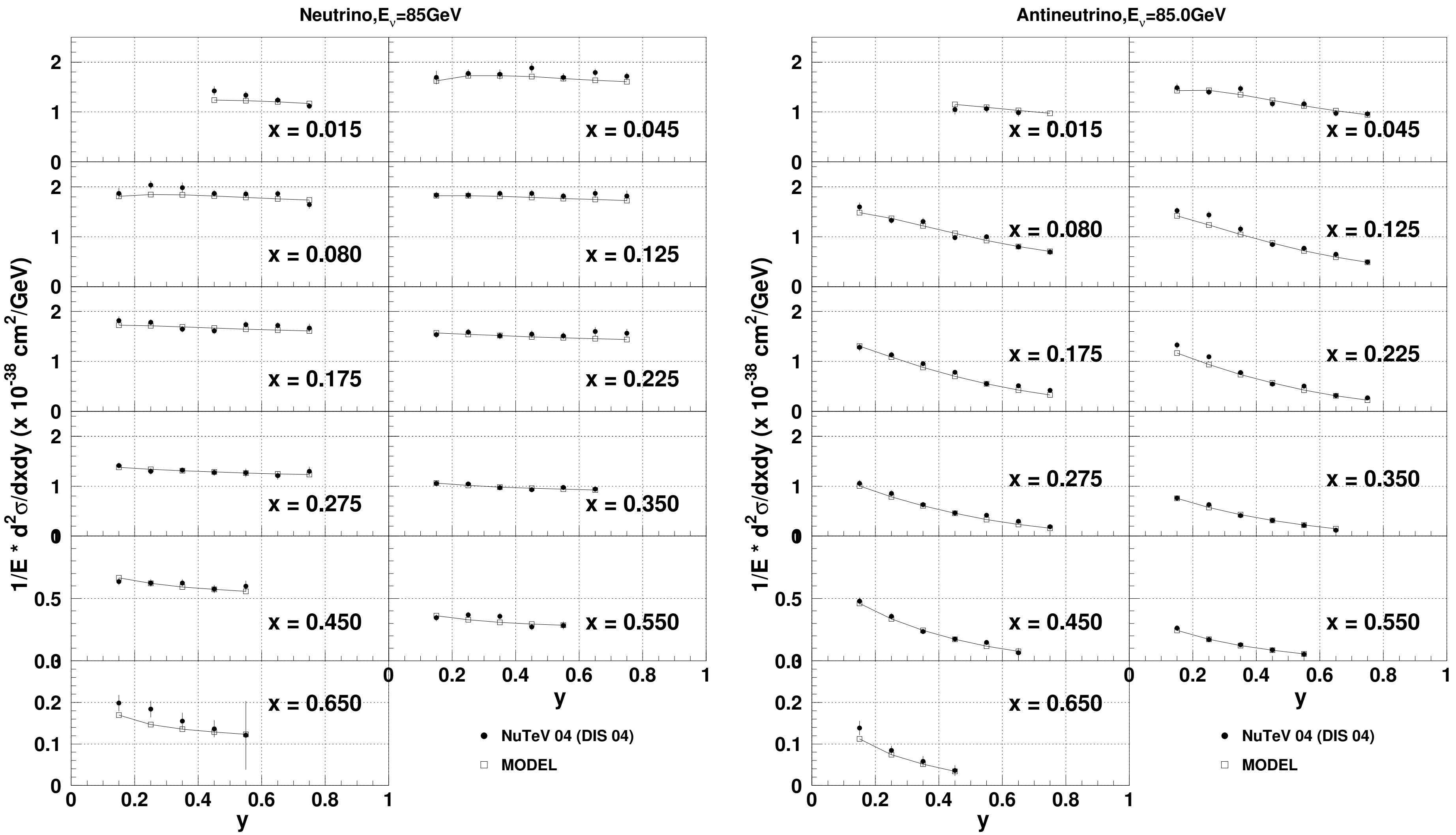
- *Precise flux predictions $\phi(E_\nu)$ were obtained for the oscillation searches:*
  - *Beam simulations including constraints from SPY data on π, K production in p-Be interactions (hep-ex/0306022)*
  - *Empirical parameterization extracting π and K contents from NOMAD ν_μ CC low ν data ($E_{\rm had} < 3$ GeV), further constrained by K/π ratios measured by SPY*

- *Measurement in (E_ν, x_{Bj}, y_{Bj}) bins, values corrected for bin centering.*



Comparison BEFORE adding data to PDF fits

COMPARISONS WITH NuTeV CROSS-SECTIONS



Comparisons BEFORE adding (anti)neutrino data to global PDF fits

NOMAD SENSITIVITY TO $\sin^2\theta_W$

- *Two independent samples* with similar statistics but *different systematic uncertainties* are used for the $\sin^2\theta_W$ measurement:
  - Main sample from drift chamber (DCH) target (2.7 t, C)
  - Events from front magnet coil (few t, Al)

  $\Longrightarrow$ *Complete first the analysis of the DCH sample*

- The *preliminary evaluation of uncertainties* corresponding to the *DCH analysis* indicates a sensitivity comparable to an extraction of $\sin^2\theta_W$ from NuTeV R^ν data ONLY ($\delta R^\nu/R^\nu = 0.0033$)

  Note: measured R^ν 25% smaller than NuTeV one due to reduced CC background

  $\Longrightarrow$ $\delta\sin^2\theta_W \sim 1\%$ *close to NuTeV, E158, APV*

- Experimental systematics are limited by data statistics since all efficiencies are extracted from data

  $\Longrightarrow$ *Analysis of coil events would improve both statistics and experimental systematics*

Source of uncertainty	$\delta R^\nu/R^\nu$
Statistics	**0.00207**
NC trigger Efficiency	0.00100
Charged multiplicity	0.00030
Energy scale	0.00050
Muon ID (detector)	0.00020
μ chamber acceptance	0.00080
Hadron decays (NC)	0.00070
Kinematic selection	0.00100
Integral ν_e flux	0.00020
Integral $\bar\nu_\mu$ flux	0.00040
Integral $\bar\nu_e$ flux	0.00020
Experimental systematics	**0.00194**
Structure functions (LT)	0.00060
High Twists (HT)	0.00025
Strange sea	0.00150
Charm mass	0.00075
Nuclear effects	0.00011
Non-isoscalarity	0.00010
Radiative EW corrections	0.00006
Model systematics	**0.00181**
TOTAL	**0.00336**

SUMMARY

- *The NOMAD experiment collected unprecedent neutrino data samples, allowing at the same time large statistics and high resolution measurements. Several analyses are currently in progress, exploiting the excellent reconstruction quality of NOMAD data.*

  $\Longrightarrow$ *Large potential for neutrino physics.*

- *A measurement of the $\nu_\mu n \to \mu^- p$ quasi-elastic cross-section on carbon has been performed in the energy range $3 < E_\nu < 100$ GeV:*

$$\sigma_{\mathrm{QE}} = 0.692 \pm 0.010(stat.) \pm 0.030(syst.) \times 10^{-38} cm^2$$

  providing the most accurate result available.

- *The NOMAD experiment is measuring $\sin^2\theta_W$ from the ratio R^ν of NC and CC νN DIS interactions. The sensitivity of the analysis based upon the DCH data sample only (the coil sample will be added later) is comparable to NuTeV, E158 and APV and would provide $\delta \sin^2\theta_W \sim 1\%$:*

  - *Results on CC differential cross-section;*
  - *Detailed model of neutrino interactions implemented;*
  - *Completing the ancillary measurements and validations.*

  $\Longrightarrow$ *A chance for a fully independent check of the NuTeV anomaly with neutrinos.*