A study of nuclear effects in ν interactions with the NOMAD detector

Michele Veltri
University of Urbino & INFN Firenze

The First International Workshop on Neutrino–Nucleus Interactions in the Few GeV Region

December 13–16, 2001, KEK, Tsukuba, Japan

for the **NOMAD** Collaboration:

ν_μ NOMAD ν_τ

Neutrino Oscillation MAgnetic Detector

LAPP Annecy, CERN, Cosenza, Dortmund, JINR Dubna, Firenze, Harvard Univ., Johns Hopkins, Lausanne, Melbourne, INR Moscow, Padova, Paris VI and VII, Pavia, Pisa, Roma 3, CEN Saclay, South Carolina Univ. Sydney Univ., UCLA, Urbino, Zagreb, ETH Zurich

Outline

- Physics motivations
- The NOMAD detector
- Identification of backward going p (Bp) and π^- ($B\pi^-$)
- Invariant spectra of Bp and $B\pi^-$
- Backward particle rates
- Effects of reinteractions
- Effects of short range correlations
- Comparison with the NOMAD MonteCarlo
- Summary

Results are published in: Nucl. Phys. B 609(2001) 255

Physics Motivations

We studied nuclear effects by using backward going (w.r.t the ν beam direction) protons and π^-

➜ The production of Bp is kinematically forbidden in an interaction on a free and stationary nucleon

➜ Their production in the high energy reactions off nuclei is a well established experimental fact and indicates the existence of nuclear effects in the scattering process

➜ Backward going mesons, whose production is allowed up to a certain limit, are detected also at momenta above such limit

➜ Important for NOMAD. Nuclear effects distort the event kinematics and can explain part of the observed discrepancy DATA/MC in the distributions of the missing transverse momentum ($< p_T^m >^{DATA} - < p_T^m >^{MC} = 200 MeV/c$)

Physics Motivations

Possible explanations are:

- Reinteractions (intranuclear cascade) inside the target nucleus

  Bp can be produced in multiple scattering and interactions of slow hadrons, produced in the primary ν–nucleus collision, with the other nucleons during their propagation out of the nucleus

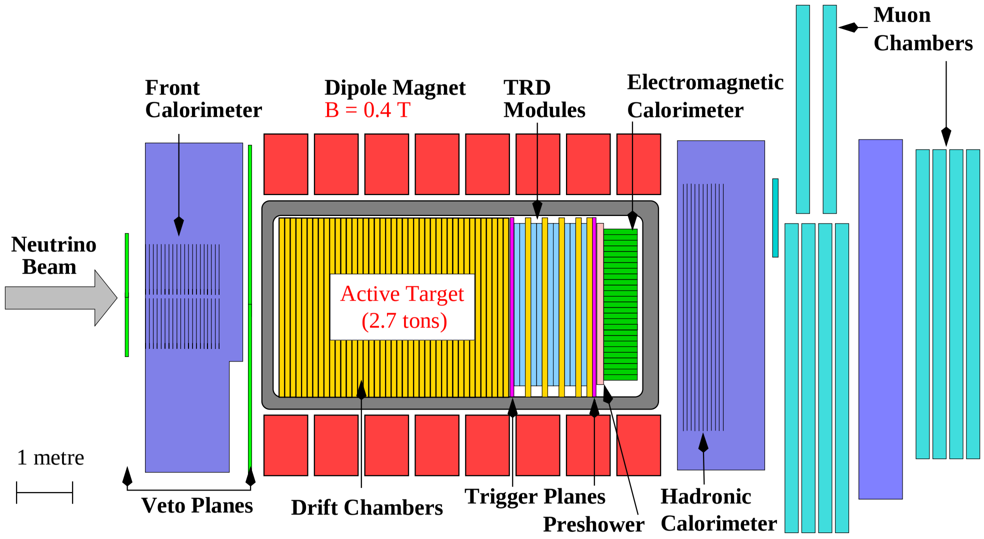
- Short Range Correlations

  Collisions off clusters composed of nucleons/quarks
  The clusters are formed under the action of the short range part of the nuclear force $(r_c = 0.5 - 0.7 fm)$
  The nucleons in these structures can acquire large momenta
  ➜Tail of the Fermi momentum distribution
  The spectrum of the fast backward going particles reflects the momentum distribution of these objects

Production in the backward hemisphere can have contributions from both mechanisms

The NOMAD Detector

NOMAD was originally conceived for the $\nu_\mu \to \nu_\tau$ search
➜ General purpose detector for ν physics
$1.354\ 10^6\ \nu_\mu\ CC$ events collected from 1995 to 1998

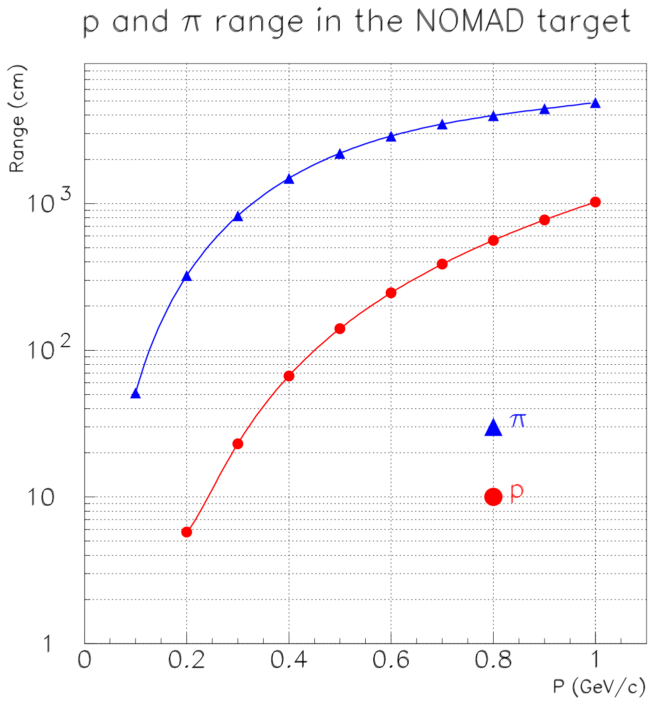


- Trigger $\bar{V} * T_1 * T_2$: ν interactions in the active target
- Drift Chambers: target and momentum measurement
  44+5 in TRD region DC each 2% X_0
  Fiducial mass 2.7 tons with average density $0.1\ g/cm^3$
  Momentum Resolution $\frac{\sigma_P}{P} = \frac{0.05}{\sqrt{L}} \oplus \frac{0.008P}{\sqrt{L^5}}$
  Composition $>\ 90\%$ of C and elements with nearby A
  The target is practically ISOSCALAR
- Transition Radiation Detector: $e^\pm$ identification
  9 modules (315 radiator foils followed by a plane of straw tubes)
  $\pi/e \simeq 10^{-3}, \quad \epsilon_e \geq 90\%$
- Preshower: e and γ identification
  Precise γ position measurement $\sigma(x),\ \sigma(y)\ \sim\ 1\ cm$
- Lead glass electromagnetic calorimeter: energy measurement
  $\sigma(e)/E\ =\ 3.2\%/\sqrt(E(GeV))\ \oplus\ 1\%$
- Hadronic Calorimeter: n and K_L^0 veto
- Muon Chambers: μ identification
  $\epsilon > 97\%(P_\mu > 5GeV/c)$

Bp Identification

Bp identification relies on the momentum–range relation

We look for backward positive tracks ranging out in the DCH volume

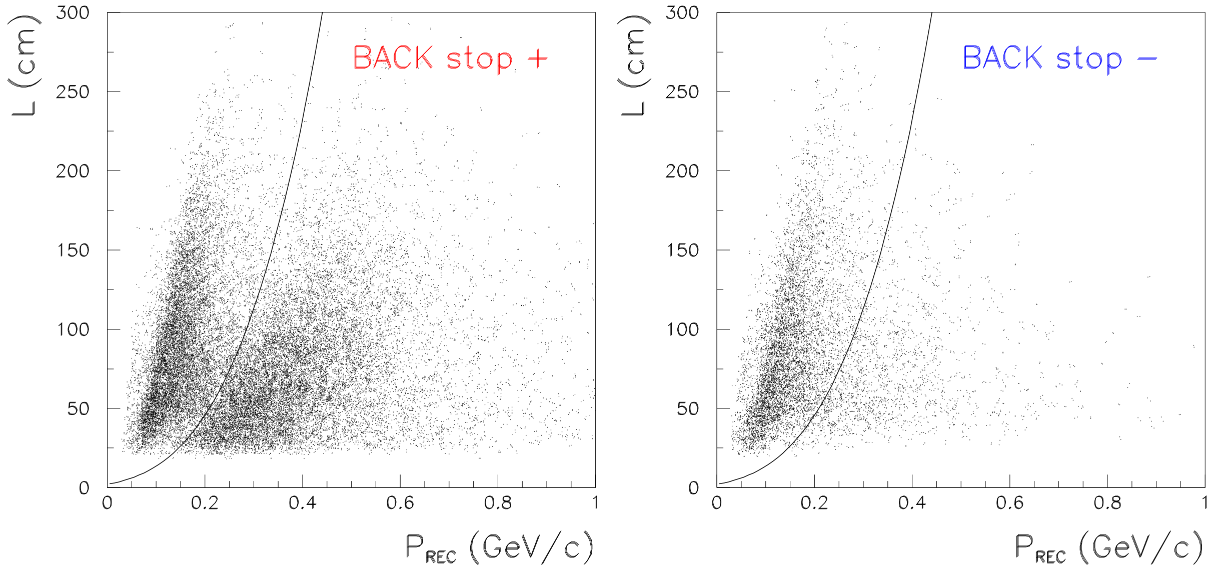


Event Selection: Standard fiducial volume, 1 vertex, nch$\geq$2
1 negative μ attached to the primary vertex
$P_{\mu} > 3$ GeV/c

➜ 944019 ν_{μ} CC events used for this analysis

Bp Identification (cont.)

Track quality cuts:	Attached to the primary vertex nhits≥8, $\Delta P/P \ < \ 0.3$
Tracks must stop in the target:	Restrict the fiducial volume required for the primary vertex No activity close to the last hit of the track

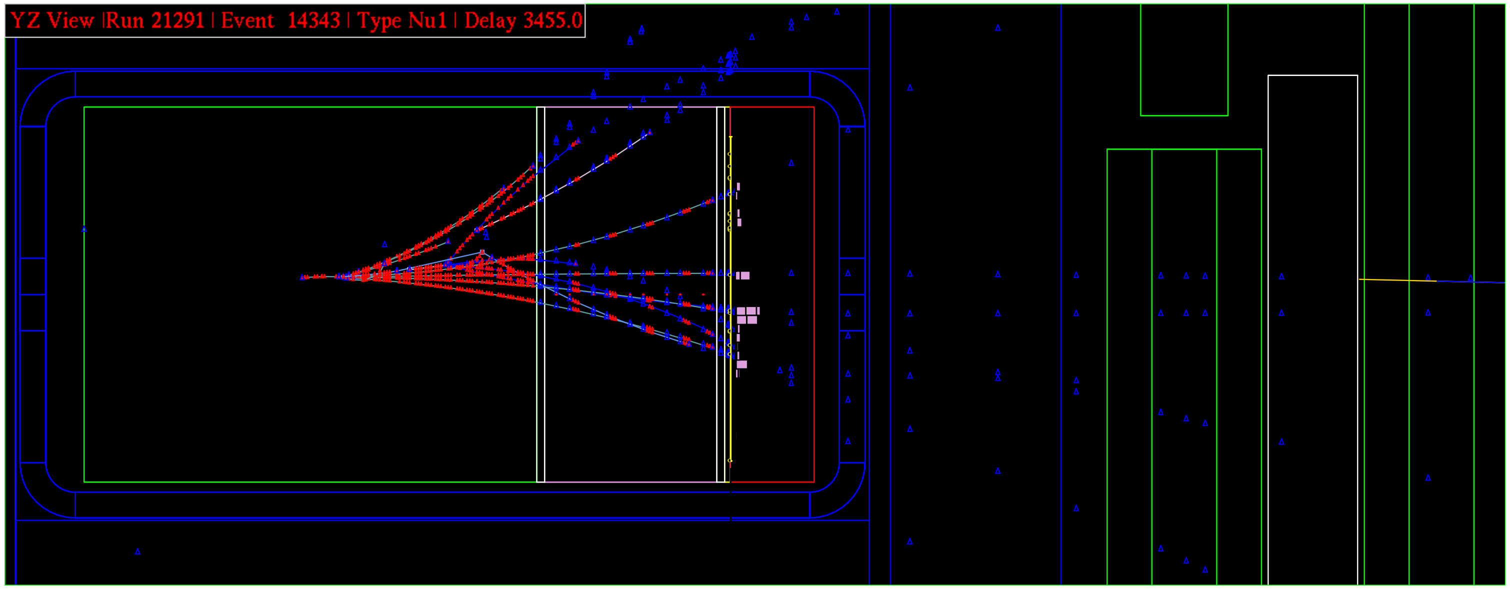


Two populations are visible, Bp accumulate in the lower right part

Any positive backward going track with length smaller than the cut is identified as a p

The sample is then corrected for reconstruction and stopping efficiency and for π^+ contamination ($\approx 8\%$ for P_{REC} >250 MeV/c)

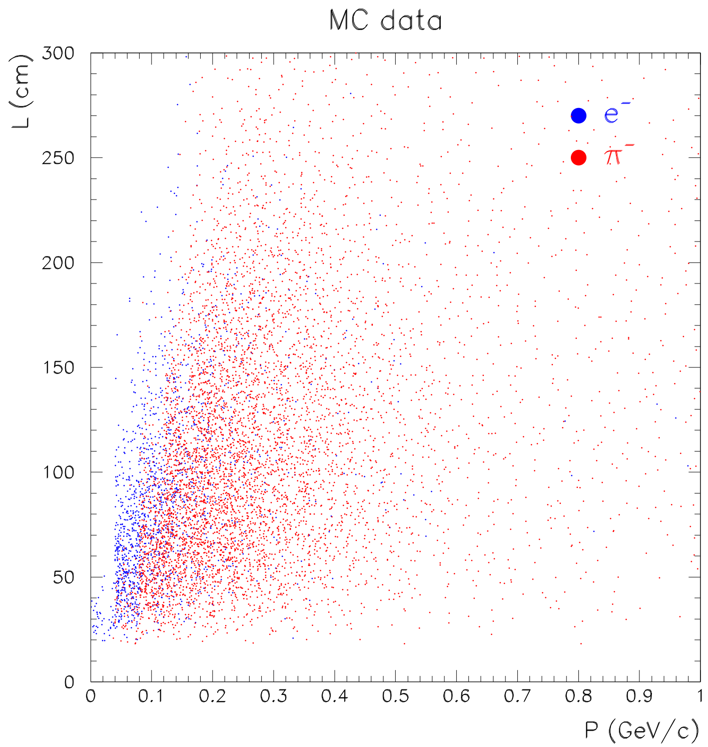
An example of backward going p



- Positive charge
- P = 0.386 GeV/c
- Length = 37.7 cm
- p_{range} = 59.1 cm
- π_{range} = 1385.9 cm

$B\pi^-$ Identification

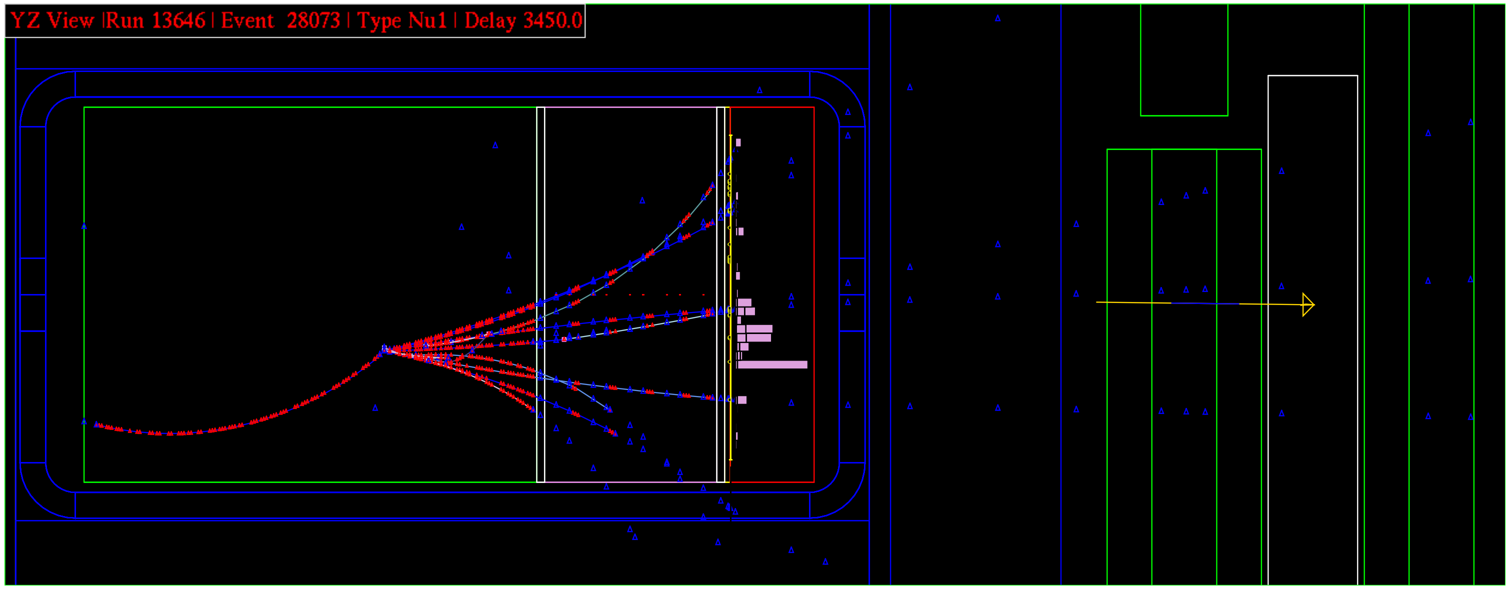
- No need for stopping tracks
- Cleaner sample as compared to π^+ (no p contamination)
- Negligible contamination of e^- (few % above 200 MeV/c)



Any negatively charged backward going track with $P > 200 MeV/c$ is identified as a π^-

The sample is corrected only for reconstruction efficiency

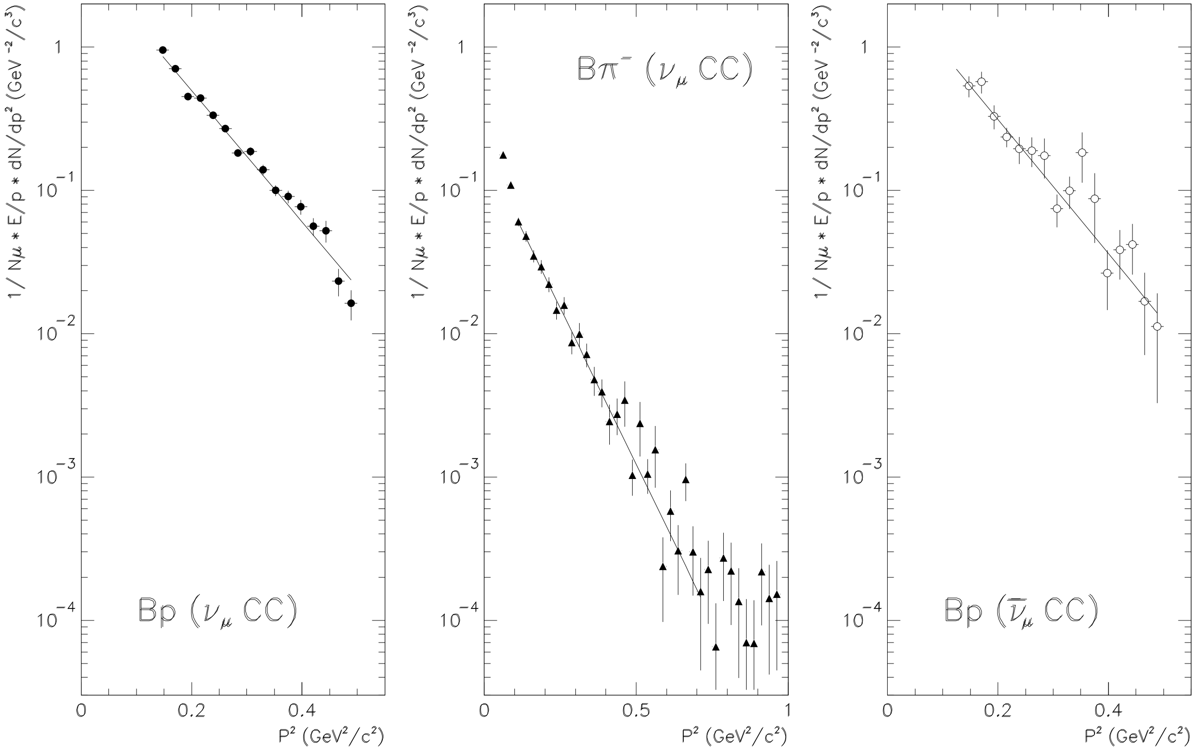
An example of backward going π^-



- Negative charge
- $P = 0.363$ GeV/c
- Length $= 267.5$ cm

Invariant Momentum Distributions

The invariant cross section is usually parametrized as: $\frac{1}{N_{ev}} \frac{E}{P} \frac{dN}{dP^2} = C\ e^{-BP^2}$



- The minimum Bp momentum is limited by the DCH momentum resolution
- The low target density limits to $\approx$ 700 MeV/c the max value of the Bp momentum
- Instead a larger momentum range can be investigated in the case of $B\pi^-$
- Also a statistically limited sample of $\bar{\nu}_\mu$ CC events (61134) has been collected

  ➜ 6% contamination in the ν_μ beam + dedicated runs

  The selection criteria are the same apart from the μ charge

Invariant Momentum Distributions

Momentum range and fit values of B and C

(the first error is the statistical, the second one the systematical)

		ΔP (GeV/c)	$B(c^2/GeV^2)$	$C(c^3/GeV^2)$
Backward p	ν_μ CC	$0.37 \div 0.70$	$10.54 \pm 0.20 \pm 0.5$	$4.08 \pm 0.19 \pm 0.5$
	$\bar{\nu}_\mu$ CC	$0.37 \div 0.70$	10.79 ± 0.78	2.71 ± 0.54
Backward π^-	ν_μ CC	$0.32 \div 0.85$	$10.03 \pm 0.28 \pm 0.3$	$0.17 \pm 0.01 \pm 0.02$

The systematical error was evaluated by:

- Slightly changing the values of the cuts used
- Varying the correction functions
- Changing the size of the fiducial volume

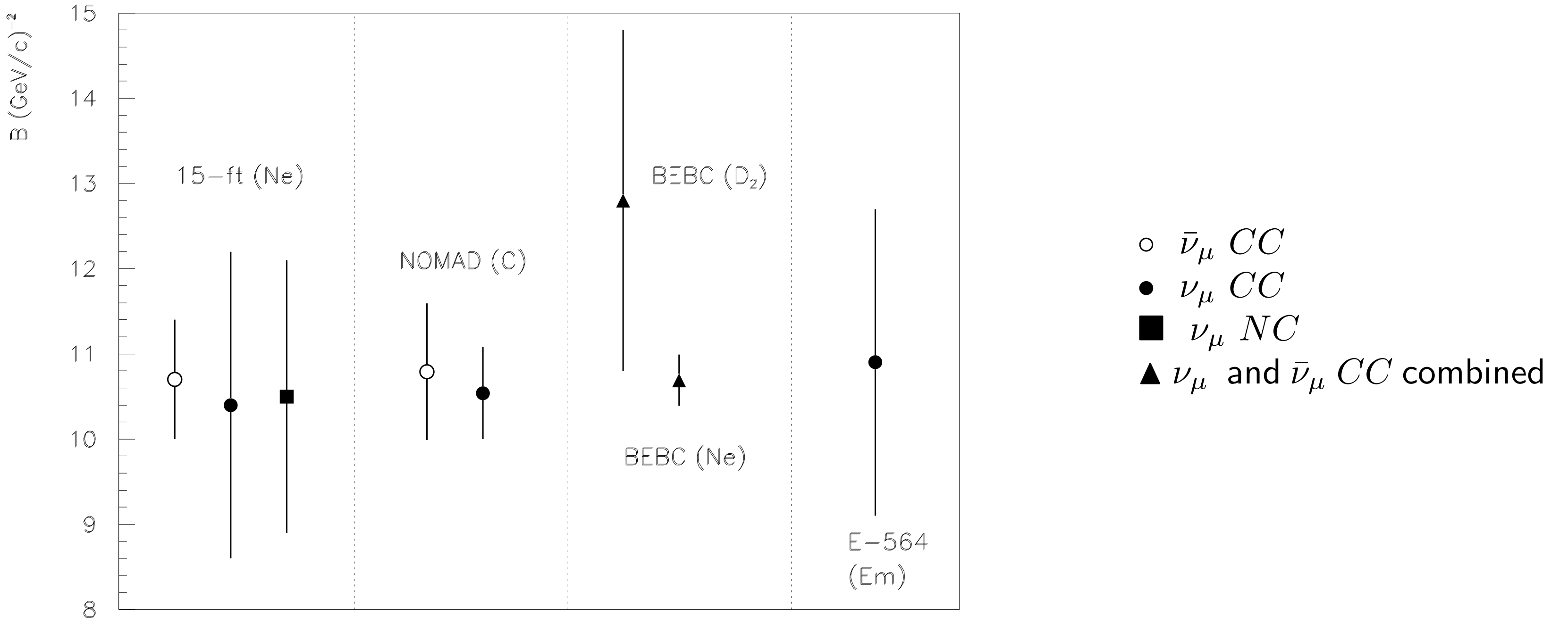
➜ Bp originating from $\bar{\nu}_\mu$ CC events have a slope parameter compatible with those from ν_μ CC ones

➜ $B\pi^-$ invariant cross section is smaller by $\approx$ one order of magnitude w.r.t. the Bp case but has a similar slope

Nuclear Scaling

➜ Well established experimental fact in $h-$nucleus interactions:
The slope parameter B is practically independent of the type of incident particle, its energy and target type

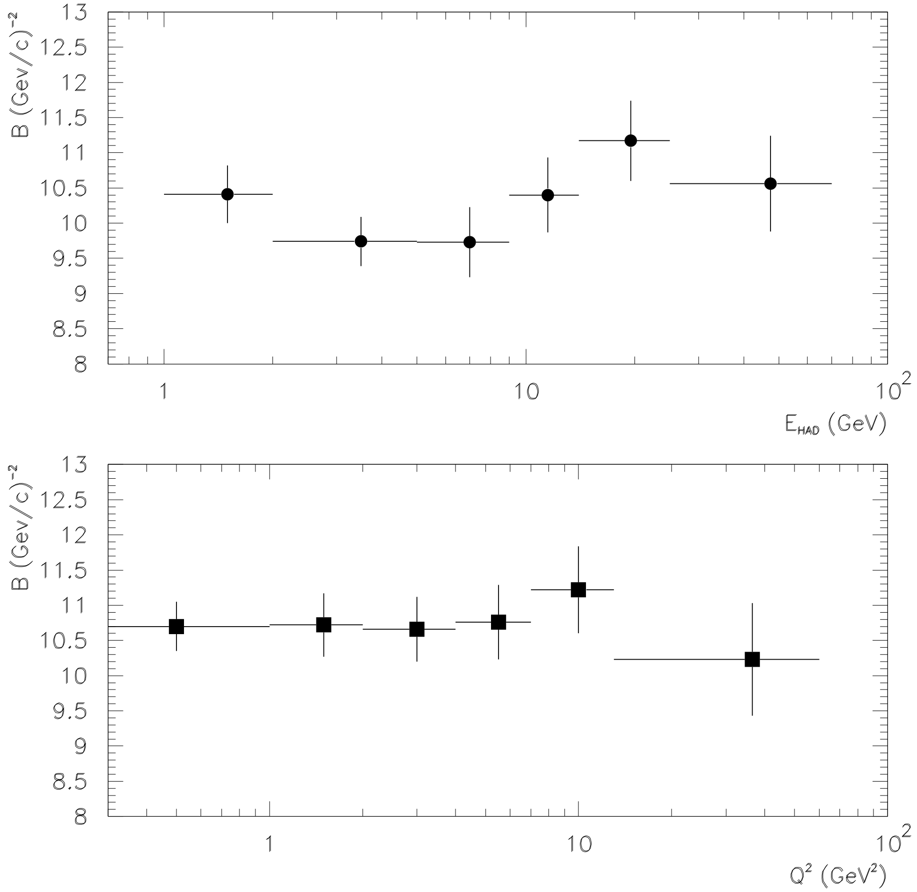
➜ Works also for $\nu-$nucleus reactions



NOMAD data fits well with the results obtained in other $\nu-$nucleus exp.

Nuclear Scaling

...about the projectile energy dependence



Hadronic jet energy
$\Updownarrow$
Beam energy in hadronic exp.

The slope B is independent on these quantities

➜ The range covered by NOMAD is similar to the one covered by different experiments with hadronic beams

In this case however the hadronic jet energy is not fixed but varies from event to event

Backward Particle Rates

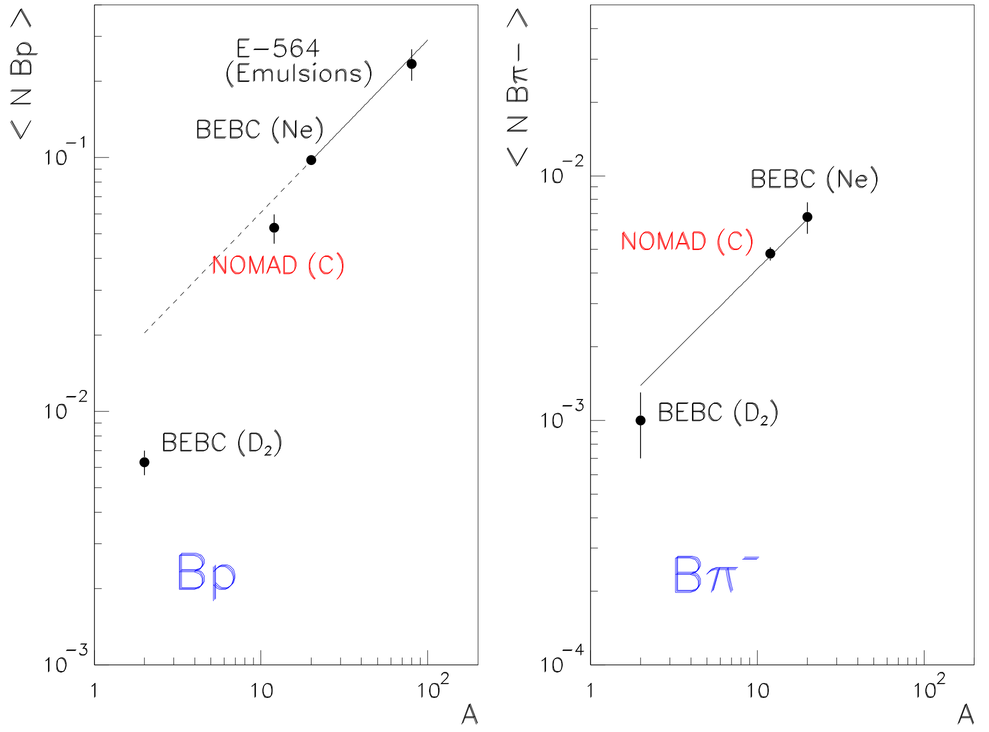
The Bp rate was extrapolated to the momentum range
$350 < P < 800\ MeV/c$ in order to compare with the other ν exp. :

$$< N_{Bp} >_{350\div 800 MeV/c} \quad = [\ 52.8 \pm 0.6(stat.) \pm 7(syst.)] \times 10^{-3}$$

For the $B\pi^-$ it was directly measured:

$$< N_{B\pi^-} >_{350\div 800 MeV/c} \quad = [\ 4.8 \pm 0.1(stat.) \pm 0.3(syst.)] \times 10^{-3}$$

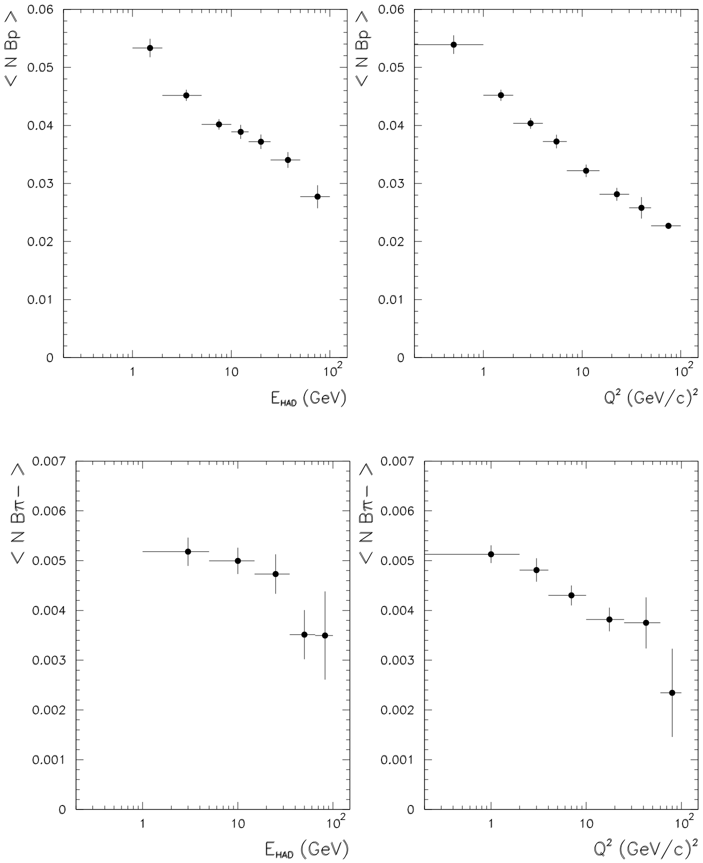
A dependence of Bp and Bπ^- rates in ν exp.



- For "heavy" targets the dependence in the A range 20–80 is $< N_{BP} > \propto A^{\alpha}$, with $\alpha = 0.68 \pm 0.12$
  (M. Dayon et al, Zeit. Phys. C 56(1992) 361)
- Similar power law describes Bp production in hadronic experiments
- NOMAD data at lower A does not fit to this dependence
- In the case of $B\pi^-$ a fit to the BEBC and NOMAD point yields $\alpha = 0.83 \pm 0.25$

Effects of Reinteractions

➜ Both the Bp and $B\pi^-$ rates decrease with increasing E_{HAD} and Q^2



Interpreted in terms of *"formation length"*

$$d^h_{lab} = c\tau^h_{lab} \simeq c\gamma\tau_0$$

$$\rightarrow \quad d^h_{lab} \propto E^h$$

The formation length concept is the commonly accepted explanation for the experimentally observed absence of intranucelar cascade at high energies

The larger is Q^2 (E_{HAD}) the larger is the energy of the secondaries and the larger will be the distance/time needed to the particles to be able to interact as the "usual" hadronic state

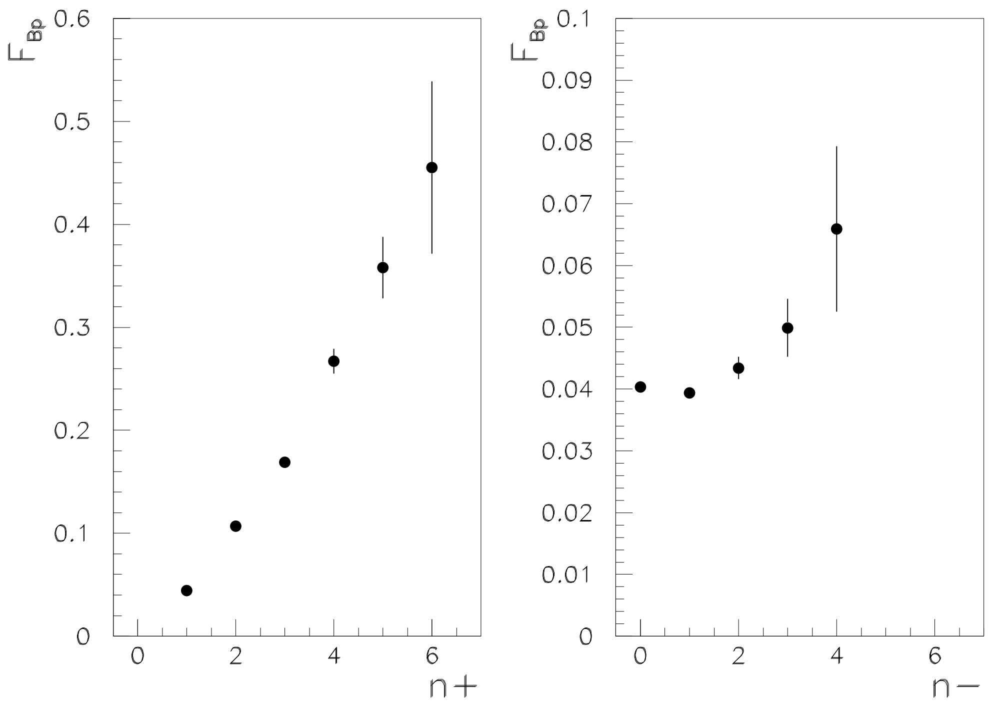
➜ As a consequence reinteractions will decrease and so will the backward particle rates

The decrease is less pronounced for the $B\pi^-$, their production is however kinematically allowed up to a certain limit and other mechanisms can play a role

Effects of Reinteractions (II)

Since the slow hadrons produced inside the nucleus are the responsible of rescattering a correlation is expected between their number and the Bp

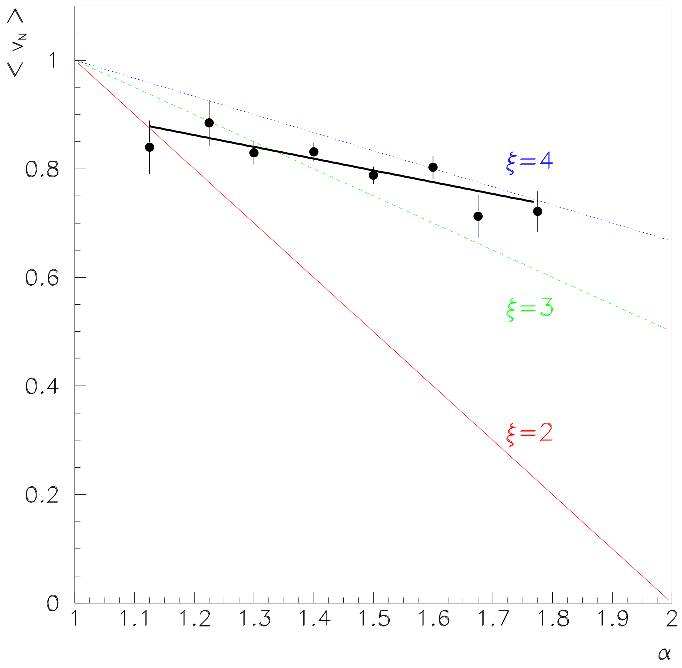
n- is better representative of the "true" slow hadron multiplicity



➜ The fraction of events with at least one Bp increases as a function of the multiplicity of low (P<700 MeV/c) momentum (positively or negatively charged) hadrons

Effects of Short Range Correlations

- Clusters of nucleons are formed under the effect of the short range component of the nuclear force at small interparticle distance ($r_c = 0.5 - 0.7 fm$)
- High momentum components, well above the Fermi momentum, can be found in these structures
- Due to the target motion there exists a correlation between the Bjorken variable $\upsilon = xy = (E_\mu - P^l_\mu)/M$ and the variable $\alpha = (E \ - P_l)/M$ which refers to the Bp



$$< \upsilon_N >= \frac{<\upsilon>_{Bp}}{<\upsilon>_{no\ Bp}}$$

The following relation holds for a cluster of ξ nucleons:

$$< \upsilon_N > \ = \ \left(1 - \frac{\alpha}{\xi}\right) \frac{\xi}{\xi - 1}$$

Fit slope:
$-0.22 \pm 0.06 \quad (\chi^2/ndf = 5.3/6)$

The presence of rescattering could dilute the correlation to the observed level

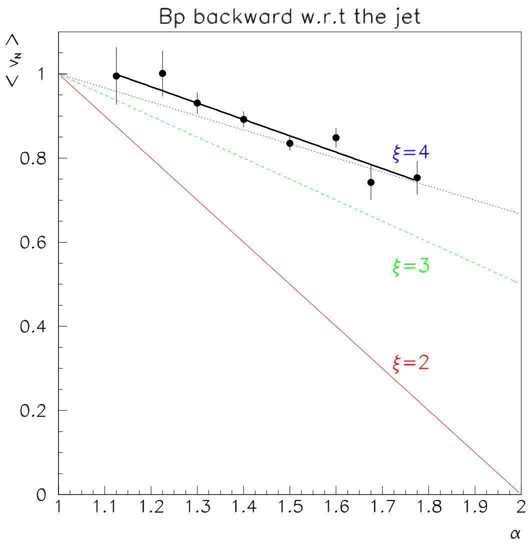
Effects of Short Range Correlations

To reduce the effects of the intranuclear cascades a cut on the number of the slow ($p < 700 MeV/c$) can be applied

n^+	n^-	slope	χ^2/ndf
≤ 3	≤ 2	-0.23 ± 0.06	5.7/6
≤ 2	≤ 1	-0.25 ± 0.07	3.3/6
≤ 2	0	-0.30 ± 0.07	3.7/6
1	0	-0.37 ± 0.10	3.9/6

The degree of (α, v_N) correlation increases as the cuts on the particle multiplicity become thighter

- A strong correlation is present between Bp which go forward w.r.t the jet direction and a low Q^2 of the event
- Large angle (w.r.t the beam) tracks: $< \theta >= 108°$



Fit slope:
$-0.39 \pm 0.07 \quad (\chi^2/ndf = 4.9/6)$

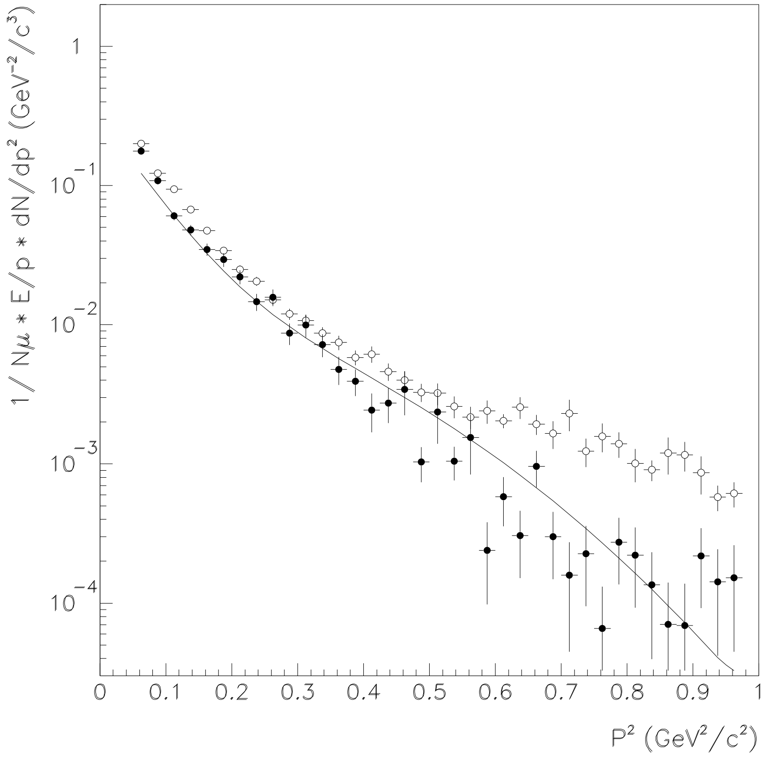
➜ Consistent with the hypothesis of the SRC effects hidden by the intranuclear cascade

SRC and the tail of the Fermi distribution

➜ The spectrum of fast backward going hadrons reflects the "tail" of the Fermi momentum distribution

➜ For this study $B\pi^-$ are better suited than Bp since the do not need to range out in the chambers providing data up to larger momenta

➜ Qualitative estimation of the tail of the Fermi momentum distribution



- NOMAD $B\pi^-$ data

∘ Monte Carlo $B\pi^-$ events simulated using the Fermi distribution of Bodek and Ritchie (tail up to $\approx$ 4 GeV/c)

- Spectrum of $B\pi^-$ from Benhar, Fantoni and Lykasov (tail up to $\approx$ 1 GeV/c)

NOMAD data support the existence of a Fermi distribution with "short" tail

Comparison with the Nomad MonteCarlo

By courtesy of D.Autiero

The NOMAD event generator NEG-N takes fully into account nuclear effects. The tuning of this MonteCarlo code profited a lot of the high statistics and the quality of the sample of charged current interactions collected by NOMAD. For scaling processes it is based on:

- A modified version of LEPTO 6.1 (Deep Inelastic Scattering)
- Jetset 7.4 with fragmentation parameters re-tuned on the NOMAD data
- Formation zone intranuclear cascade (FZIC) code extracted from DPMJET II.4 (J.Ranft)

The non scaling processes QE and RES are described by two generators respectively based on the Lewellyn-Smith formulation and on the Rein-Sehgal model. These events also undergo the simulation of the intranuclear cascade as for the DIS.

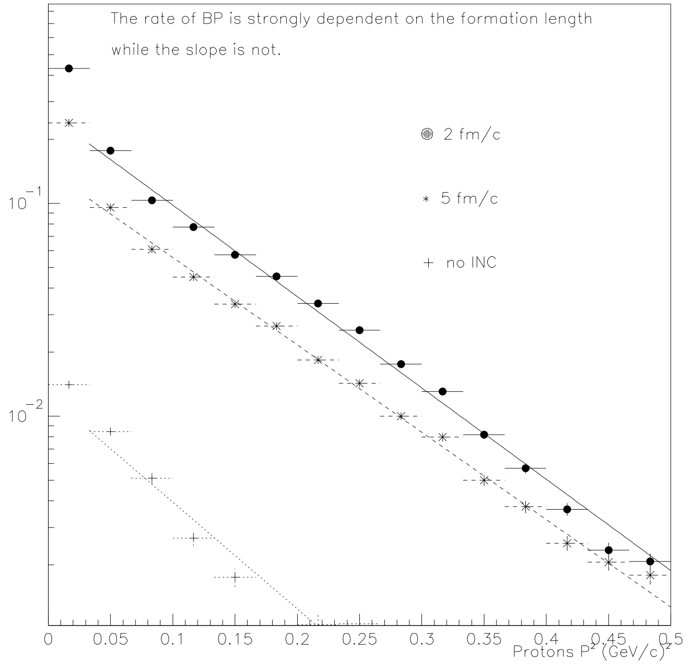
The FZIC code for the hadrons formed inside the nucleus performs a complete simulation of the tracking and the hadronic interactions in the nuclear matter. The cascade is developed through several generations. The Fermi momentum is simulated according to Benhar et al.

Predictions for backward protons

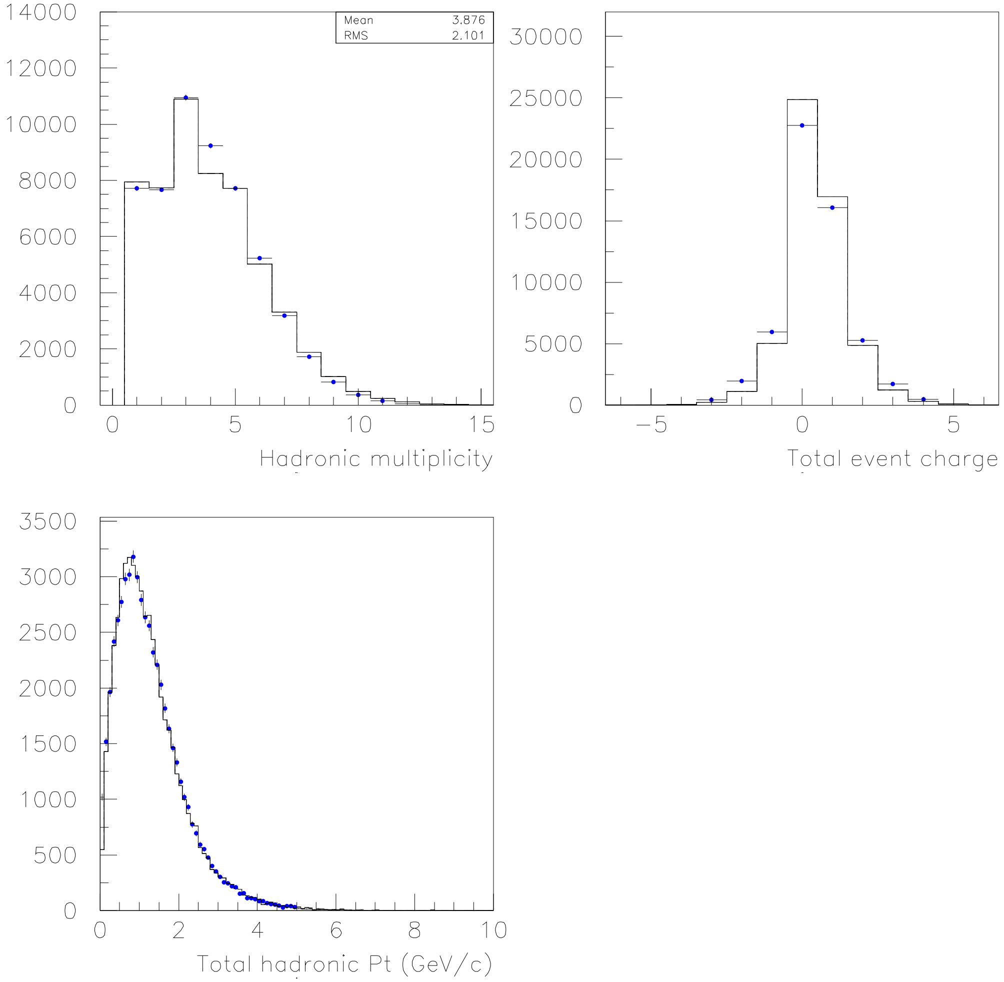
➜ The formation length was tuned on the NOMAD data by aiming at the best agreement for the hadronic distributions:

- multiplicities
- spectra
- angular distributions

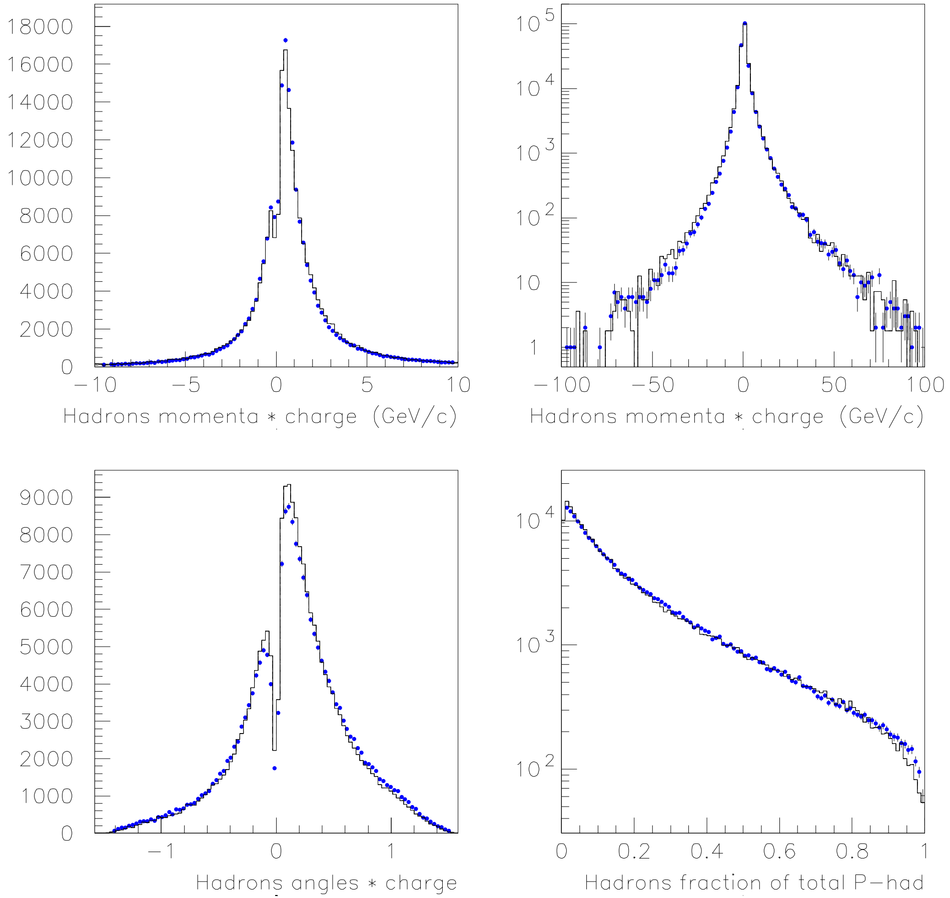
➜ The best agreement is reached for a formation time of 2 fm/c. For this value the MonteCarlo predicts a rate of of $< N_{Bp} >_{350 \div 800 MeV/c} = 53.0 \times 10^{-3}$ with a slope of 10, in excellent agreement with the experimental results



Multiplicities and total hadronic Pt

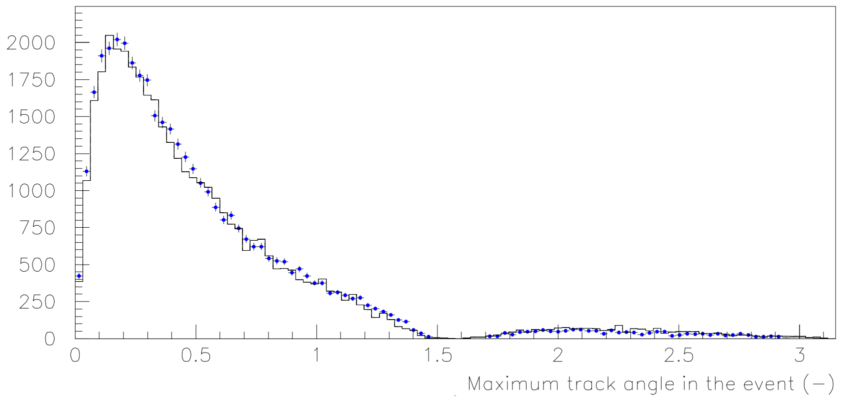


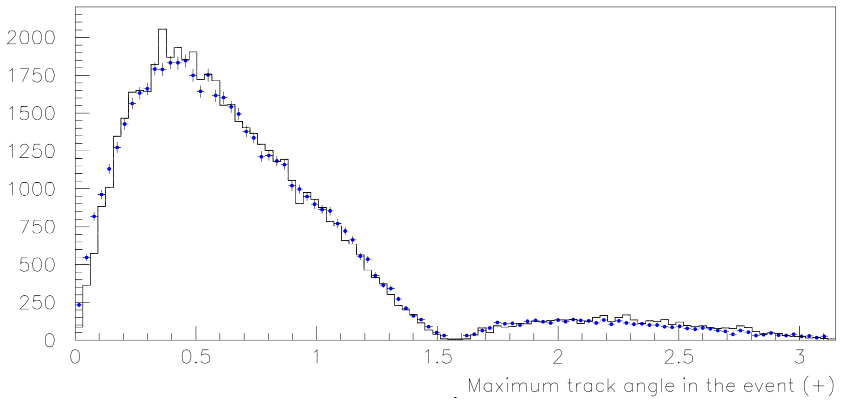
Hadronic spectra and angles



The contributions from the intranuclear cascade are important at small momenta and large angles, e.g. due to the extraction of protons from the nucleus

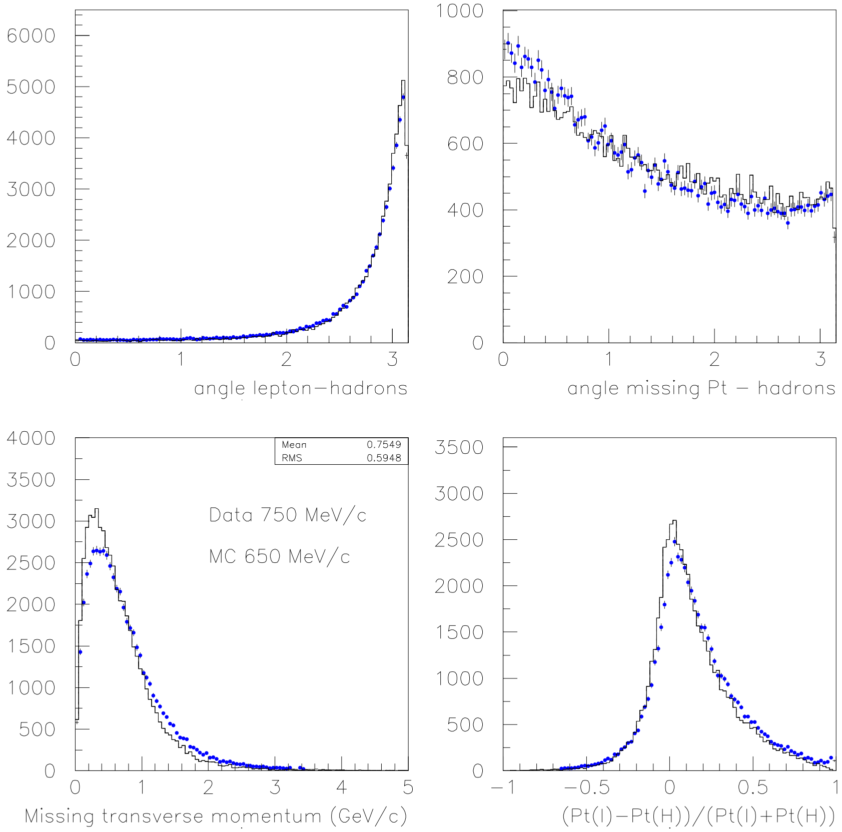
Maxima angles of tracks in an event





In the distribution of the positives it is visible the contribution of the protons. Backward tracks are well reproduced

Global event kinematics

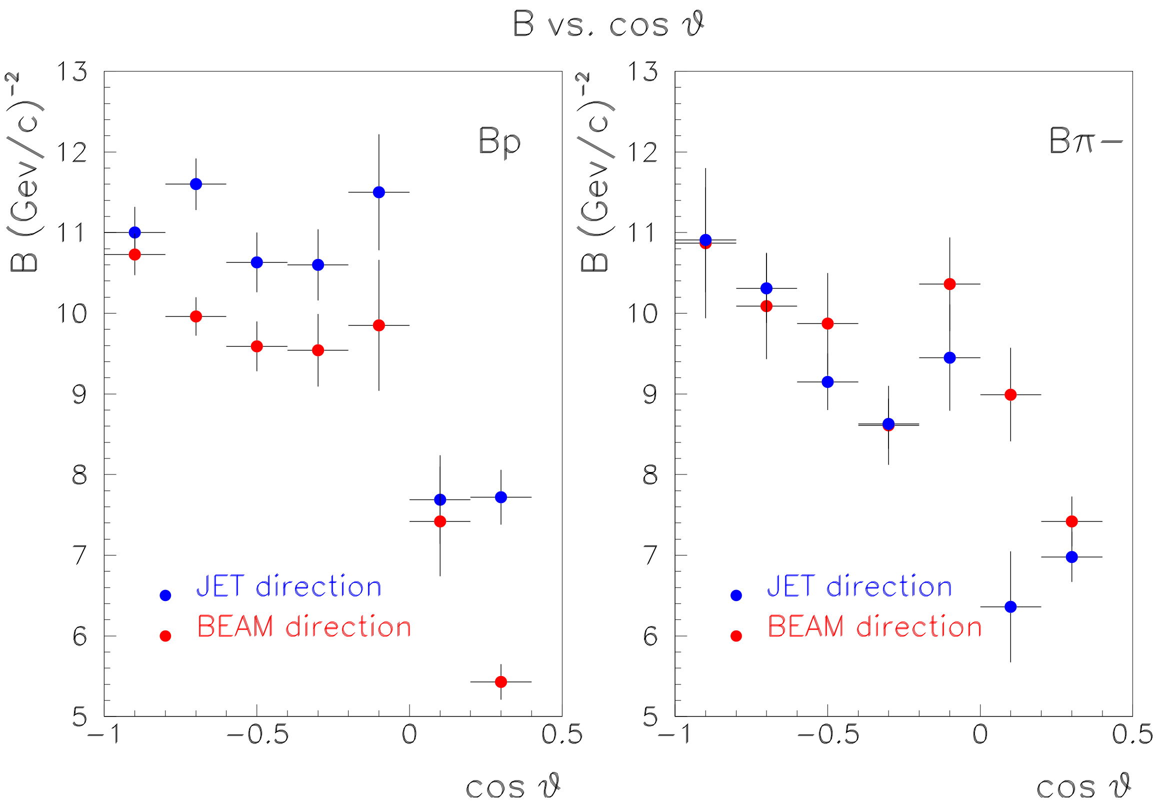


The intranuclear cascade results in a degradation of the hadronic energy (neutrons, soft particles difficult to detect). The nuclear effects reduce by about a factor 2 the discrepancy between data and MC. The remaining difference is probably due to a too optimistic detector simulation.

Summary

- A detailed study of Bp and $B\pi^-$ in ν_μ CC interaction off carbon nuclei has been carried out with the NOMAD detector
- The slope parameter of the invariant cross sections follows the behaviour predicted by the hypothesis of nuclear scaling
- The observed spectrum is not consistent with the existence of a long tail of the Fermi momentum distribution
- The observed energy dependence of the Bp rate is interpreted in terms of formation zone mechanism
- The correlation between the slow hadron multiplicity and Bp events indicates the effect of reinteractions
- The correlations predicted by the SRC models become stronger when the intranuclear cascade contributions are reduced

Angular Dependence of the slope parameter B



- Angular dependence of B w.r.t. the jet direction $\Longleftrightarrow$ Comparison with hadronic beam experiments
- If the beam direction is used B is systematically smaller by $\approx 0.5 - 1(GeV/c)^{-2}$ in the Bp case, the difference is less pronounced for $B\pi^-$
- Larger values are preferred at increasingly backward directions
- This behaviour has already been observed in ν, γ and h nucleus experiments

Kinematical Properties of Events With a Backward Particle

	CC (no Bp, no $B\pi^-$)	CC (Bp)	CC ($B\pi^-$)
$< C >$	0.46	2.11±0.02	0.08±0.02
$< N^{\pm} >$	5.13	6.63±0.03	7.28±0.03
$< E_{vis} >$	40.75	38.9±0.4	39.5±0.5
$< E_{HAD} >$	12.32	11.4±0.2	11.7±0.2
$< Q^2 >$	7.07	5.5±0.1	5.9±0.1
$< x >$	0.32	0.26±0.002	0.28±0.003
$< W^2 >$	17.19	16.4±0.2	17.5±0.3

$< C >$ is biased by the demand of a specific charge in the event

- $< C >^{MC} = 1.21$ for events with at least one backward positive particle
- $< C >^{MC} = -0.41$ for events with at least one backward negative particle

In the events with a backward particle the average event charge $< C >$ and multiplicity $< N^{\pm} >$ increase

➜ Consistent with the presence of "extra" tracks

The average values of the other kinematical variables in events with a Bp $/B\pi^-$ are lower than events without such particles