EXPERIMENTS AT THE CERN PS, AT THE CERN S$\bar{p}$pS COLLIDER, WITH NEUTRINOS FROM THE SPS, AND OTHER MEMORIES

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CERN and University of Pisa

Fisica e Fisici a Pisa nel Novecento
Pisa, November 7th – 9th, 2017

My first steps in experimental particle physics
(July –August 1958, at the end of my 3rd year):

‘’summer student’’ on a cosmic ray experiment at high altitude (2550 m a. s. l.) by a Milan – Pisa collaboration to search for a particle of mass ~550 m_e (~280 MeV) reported by Alikhanian *et al*. in 1956 from a cosmic ray experiment in the Armenian Caucasus (former USSR) at 3200 m a. s. l.

The Pisa group was led by Marcello Conversi →

(here in a 1976 photo)

This experiment has been the subject of Carlo Rubbia’s thesis at the University of Pisa in 1957

← Carlo Rubbia in 1957

The Milan – Pisa detector to search for particles with mass ~ 550 m_e at the Sabbione Cosmic Ray Laboratory, 2550 m a. s. l. (1958 configuration)

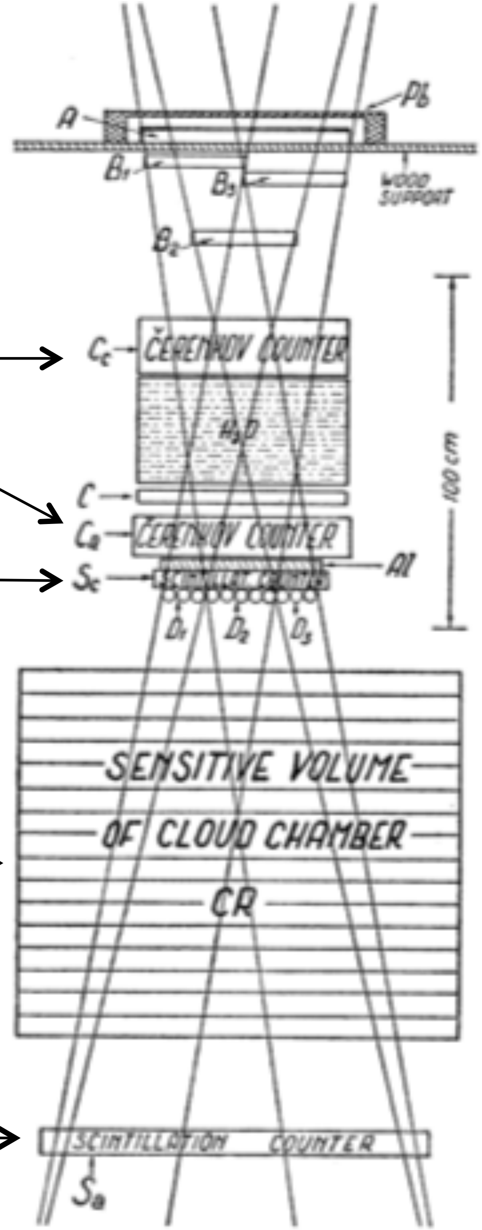
Particle mass determined by dE / dx and range measurement in a multi-plate cloud chamber.

Two water Čerenkov counters are used to identify particles stopping in the cloud chamber

Liquid scintillation counter measures dE / dx

Multi-plate Cloud Chamber (built in Milan) contains 17 0.3 cm thick plexiglas plates

Veto through-going particles

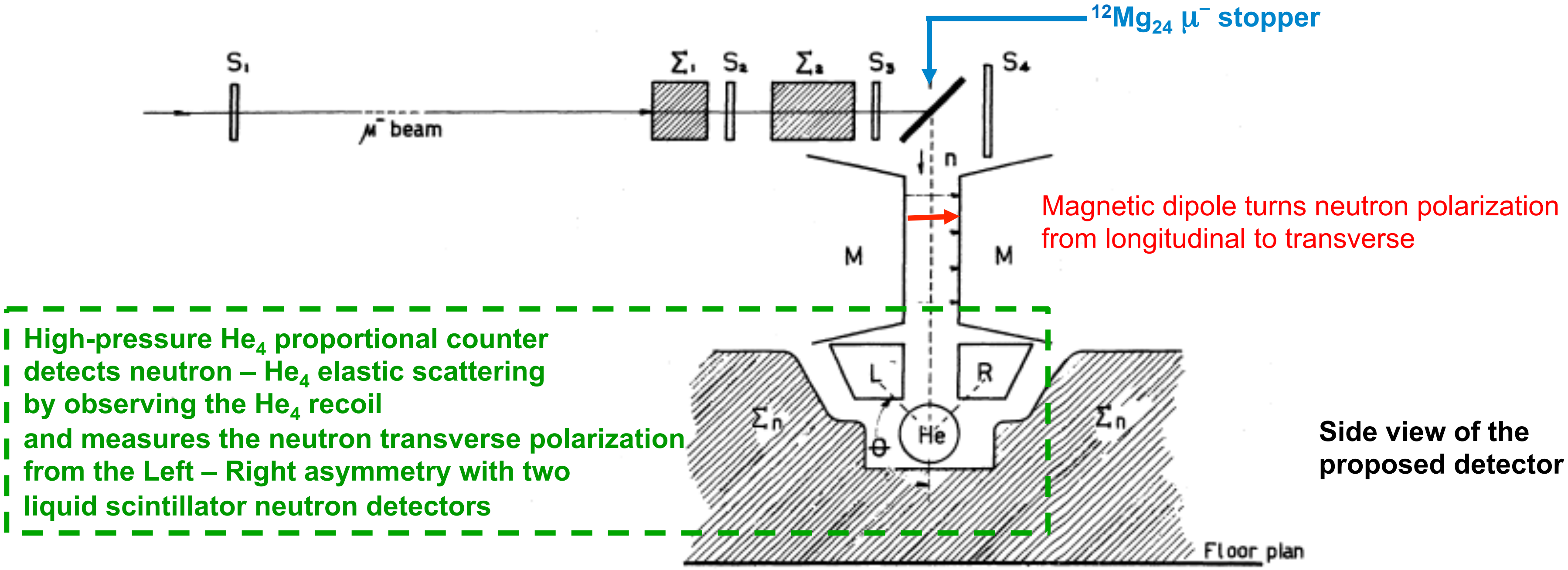


The experiment observed no particle with mass ~550 m_e

(expected number from Alikhanian *et al*. experiment: 25)

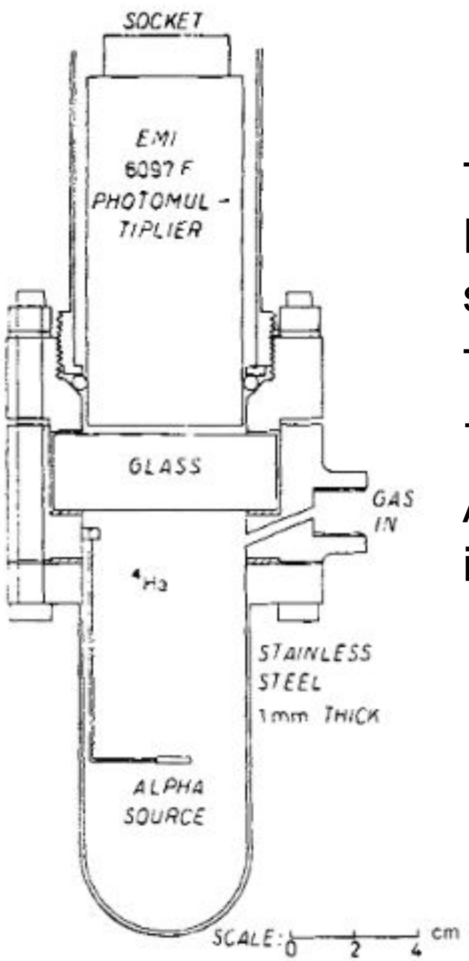
December 1958: proposal to measure the longitudinal polarization of neutrons emitted by μ^- capture in Mg nuclei at the CERN 600 MeV Synchrocyclotron: $\mu^- + p \rightarrow \nu + n$

Longitudinal neutron polarization predicted to be 100% by the V – A theory.
Choice of Mg is compromise between fraction of capture rate (~50% in Mg) and depolarization from final-state interaction (estimated to be ~20% for light nuclei).



(the subject of the thesis for my physics degree from the University of Pisa)

Details of the high-pressure He_4 proportional counter (built in the Workshop of the Physics Institute in Pisa)



The counter was filled with “spectroscopically pure” He_4 gas at 100 atmospheres which produces UV scintillation light.

The inner wall was coated with MgO_2 + a wave-length shifter from UV to visible light.

A Po_{210} 5 MeV α – emitter was permanently installed inside the vessel for stability monitoring.

In the early months of 1959 Marcello Conversi and his group moved to the University of Rome, while I was still a student in Pisa.

From an official CERN document dated September 15th, 1959:

CERN/SC/5372 A
Exp. 27 Page 2

Experimenters' names :	Institutions :
Marcello Conversi	University of Rome and I.N.F.N.
Luigi Di Lella	University of Pisa
Alberto Egidi	University of Rome and I.N.F.N.
Carlo Rubbia	University of Rome and I.N.F.N.
Marco Toller	University of Rome and I.N.F.N.

I began a life of "commuter" (by train) between Pisa and Rome.
During one of these trips I took to Rome by train in my suitcase the He_4 counter filled with 100 atm. spectroscopically pure Helium.

The He_4 counter and associated liquid scintillator neutron detectors were calibrated with 14 MeV neutrons from the d – t reaction at a 200 keV Cockroft – Walton accelerator built by Enrico Fermi and collaborators in the 1930's on the 6th floor of the Advanced Institute for Public Health (Istituto Superiore di Sanità) in Rome.

Sometime near the end of 1959 the physics interests in the group shifted from the measurement of the neutron longitudinal polarization to the search for neutrinoless μ^- capture:

$$\mu^- + Cu \rightarrow e^- + Cu$$

This "forbidden" process was expected to occur mainly coherently, producing a mono-energetic ~105 MeV electron
(NOTE: in 1959 the 2^{nd} neutrino had not yet been discovered !)

It was decided to give the highest priority to a search for this process (a much easier experiment !)

Luckily, the work which I had done on the experiment to measure the neutron longitudinal polarization was deemed to be sufficient to obtain a physics degree.

After receiving my physics degree from the University of Pisa on November 17^{th}, 1959 , I left Pisa and joined the University of Rome.

The measurement of the neutron longitudinal polarization from μ^- capture has never been done, neither at CERN nor elsewhere (was it perhaps too difficult?)

High-energy elastic scattering on polarized protons at the CERN PS

(1967 – 1971)

- A polarized proton target suitable for particle physics experiments had been developed in the late 1950s – early 1960s in Saclay by A. Abragam and collaborators.
- It was brought to CERN in 1962 to be used in an experiment (proposed by Carlo Rubbia) to determine the relative Ξ^- - p parity by measuring the sign of the left – right asymmetry in the process $K^- + p \rightarrow K^+ + \Xi^-$ (in those years, hadrons (mesons and baryons) were being classified into SU(3) multiplets, so it was deemed important to measure their spins and parities).
- Initially, the target was a $La_2Mg_3(NO_3)_{12} \cdot 24H_2O$ (LMN) crystal in a 1.8 T magnetic field and cooled to 1°K. A ~70GHz microwave applied to the crystal produced ~70% polarization of the free protons, which could be reversed by a slight change (~0.24%) of the microwave frequency.
- The LMN crystal contained only 1/16 free, polarized protons.

The experiment to measure the relative Ξ^- - proton parity ended in 1963 producing marginal results which were never published.

A program to measure polarization effects in high-energy scattering at the CERN PS was then started, initially motivated mainly by the presence at CERN of a polarized target and of a strong support group led by Michel Borghini (who had joined CERN from Saclay).

Scattering on polarized protons gives rise to an additional term in the differential cross-section:

$$\frac{d\sigma}{dt} = \left(\frac{d\sigma}{dt}\right)_0 (1 + \vec{P}_0 \cdot \vec{P}_T)$$

where
- $\vec{P}_0$ "polarization parameter"
- $\vec{P}_T$ target polarization

↑ Cross-section on unpolarized protons

$$\vec{P}_0 = \frac{2\,\mathrm{Im}(f^* g)}{|f|^2 + |g|^2} \frac{\vec{k}_{in} \times \vec{k}_{out}}{|\vec{k}_{in} \times \vec{k}_{out}|}$$

$\boldsymbol{f}$: ''non-spin-flip'' elastic scattering amplitude;
$\boldsymbol{g}$: ''spin-flip'' elastic scattering amplitude;
$\vec{k}_{in}$ ($\vec{k}_{out}$) : c.m. incoming (outgoing) pion

The polarization parameter $\vec{P}_0$ (the parameter to be measured) is a vector perpendicular to the scattering plane.

If $\vec{P}_0 \neq 0$, reversing the target polarization induces a left – right asymmetry which can be measured with negligible systematic uncertainties by detectors in fixed positions.

First results on π^- scattering at 6, 8 and 10 GeV in the forward diffraction region ($-t \approx p^2\theta^2 < 0.6$ GeV^2) were obtained by a CERN – Orsay (I.P.N.) group.

Before the experiment started, theorists were suggesting that the polarization parameter at high energies should be zero.

The CERN – Orsay experiment reported P_0 values of 0.15 – 0.20.

These results, presented in 1965, were interpreted in the frame of the Regge pole model as the interference of the non-spin-flip amplitude from Pomeron exchange with the spin-flip amplitude from ρ – pole exchange.

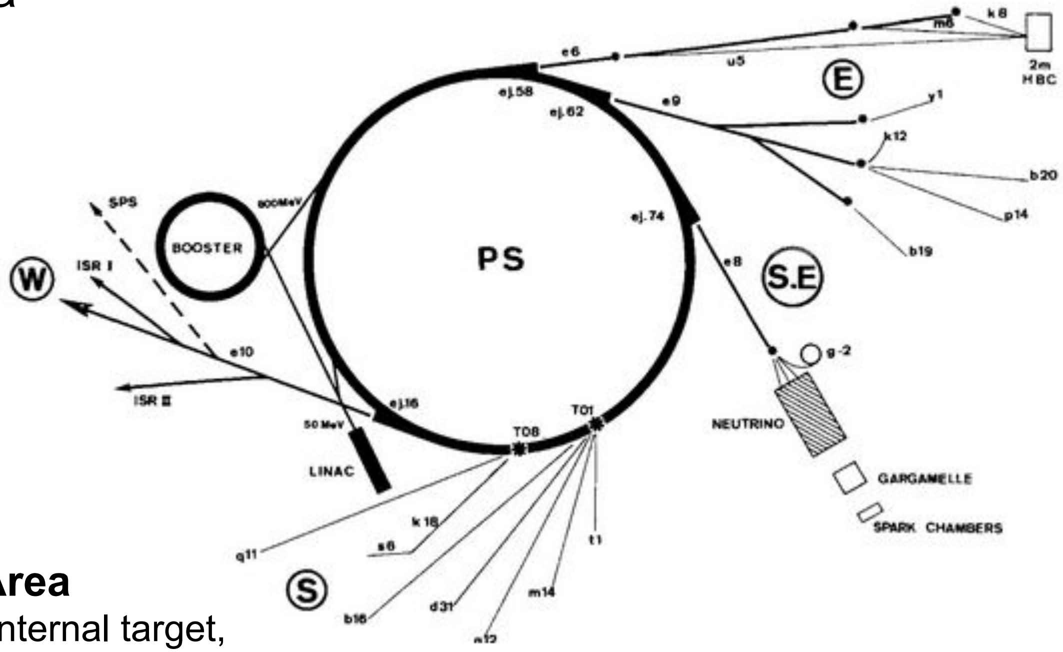
High energy scattering from polarized protons then became a ''hot topic''. Elastic scattering experiments using polarized targets were started at the AGS (BNL), and on $\pi^- + p \rightarrow \pi^0 + n$ at the CERN PS.

An additional prediction of the Regge pole model was that P_0 should have opposite signs for π^+ and π^-, with $P_0 = 0$ near $-t \approx 0.5$ GeV^2.

These predictions were qualitatively verified by the CERN – Orsay experiment in 1966.

Two new developments in 1966 - 67:

- Slow extraction of the circulating proton beam from the PS was achieved, providing high intensity beams of both charge signs in the newly built East Area



PS East Area

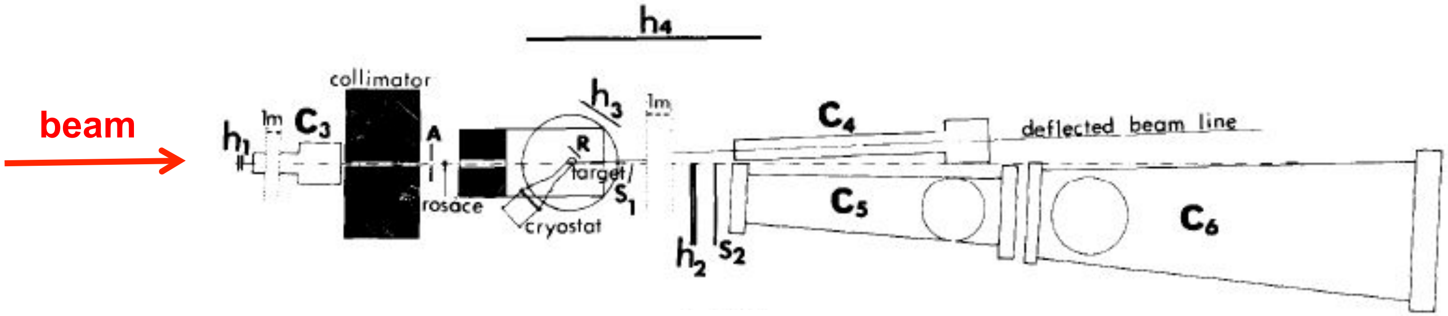
PS South Area

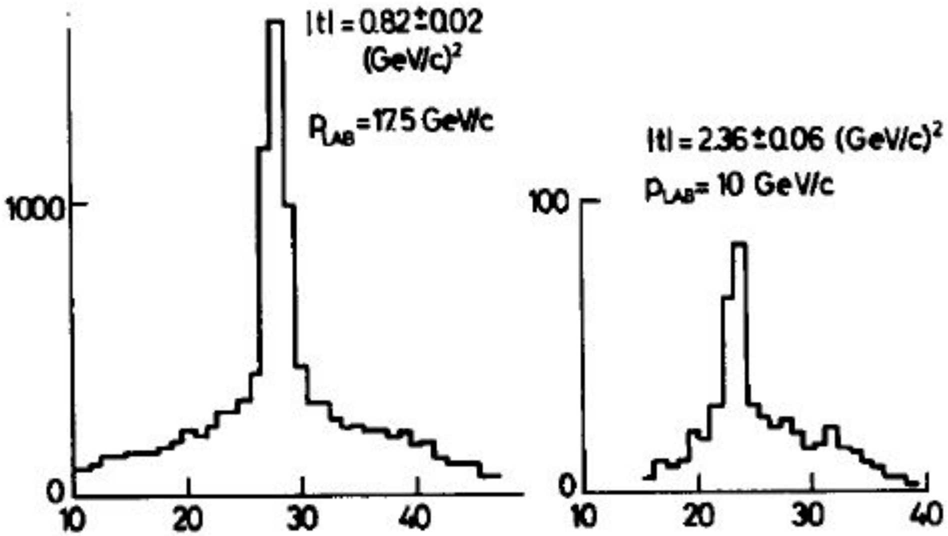
Beams from internal target,
not suitable for high-energy beams
of positive particles)

- A new polarized target consisting of 95% butanol (C_4H_9OH) and 5% water saturated with the free radical porphirexide was developed at CERN by Borghini and collaborators. It was cooled by a He^3 refrigerator, reached 65% polarization and contained 25% free, polarized protons (only 1/16 in the earlier LMN target)

Giorgio Bellettini and his group joined a new scattering experiment in the CERN East Area in 1967.

The apparatus consisted of gas Cerenkov counters to identify incident and scattered particles, and counter hodoscopes to measure the angles of the scattered particle and of the recoil proton.





Opening angle (deg.) between scattered particle and recoil proton

Scattering on free, polarized protons is identified by kinematics (coplanarity and opening angle between the two outgoing particles)

MEASUREMENT OF THE POLARIZATION PARAMETER IN $\pi^{\pm}p$ ELASTIC SCATTERING AT 10, 14 AND 17.5 GeV/c AND FOR $|t| \lesssim 2\ (\mathrm{GeV}/c)^2$

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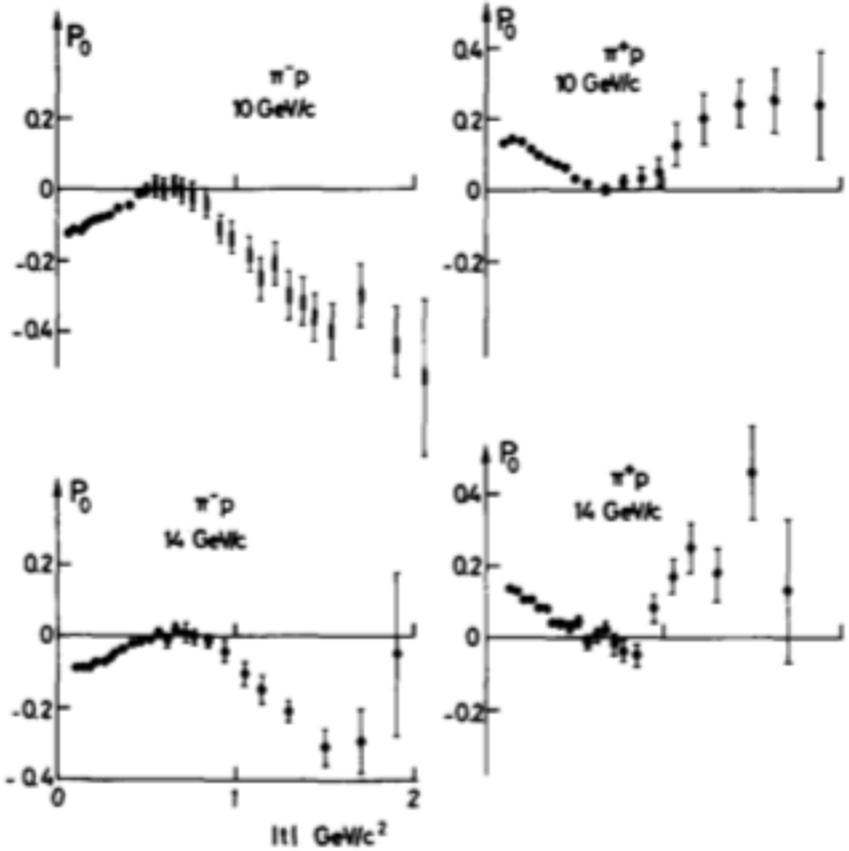
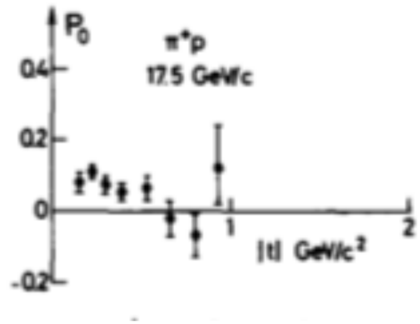
Received 13 August 1971

Polarization parameter in $\pi^{\pm}$ p forward elastic scattering at 10, 14 and 17.5 GeV





A simple Regge-pole model (Pomeron + ρ exchange) did not fit the data.

Reasonable fits could be obtained by adding contributions from additional Regge trajectories

$\pi^- p \to \pi^0 n$ POLARIZATION AT 5.9 AND 11.2 GeV/c

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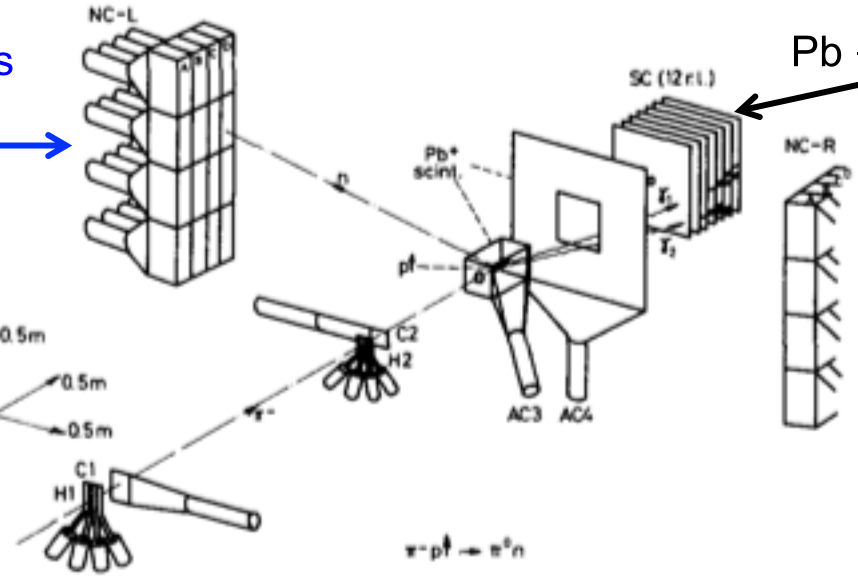
Received 26 October 1966

A Regge-pole model with the exchange of only one trajectory associated with the ρ – meson had given a good fit to $\pi^- p \to \pi^0 n$ data taken with a hydrogen (unpolarized) target.

This model predicted a polarization parameter $P_0 = 0$ for $\pi^- p \to \pi^0 n$ on polarized protons.

Scintillation counters
(neutron detection)



Pb – plate spark chamber
(photon detection)

Scintillation counters
(neutron detection)

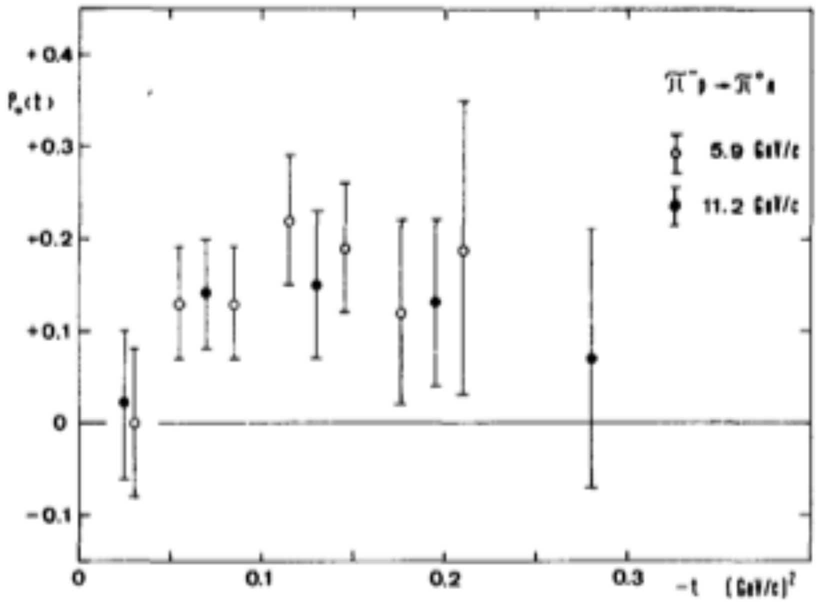


Fig. 3. Polarization parameter $P_0(t)$ at 5.9 GeV/c (open circles) and 11.2 GeV/c (black dots).

P_0 > 0, independent of energy within errors

Adding another Regge trajectory could explain $P_0 > 0$, but it would also predict a fast decrease with incident π^- energy (faster than 1/E)

At the end of the 1960s scattering experiments on polarized protons at high energies had become less interesting :

- Simple Regge models did not fit the data well, models with more Regge trajectories and t-dependent Regge residues had many arbitrary fitting parameters
- Meanwhile, more interesting phenomena had been discovered:
  - CP violation in the neutral K−meson system (discovery of the decay $K^{\circ}_{L} \rightarrow \pi^{+}\pi^{-}$ at the AGS in 1964)
  - Evidence for electrically charged, point-like constituents of protons and neutrons from deep-inelastic electron-nucleon scattering at SLAC (1968). Were these constituents the quarks postulated by Gell-Mann and Zweig in 1964 to describe the hadron SU(3) multiplets?
  - Theoretically, it was demonstrated in 1968 ('t Hooft and Veltman) that the unified electroweak theory with Spontaneous Symmetry Breaking (the Higgs mechanism) was renormalizable.

UA2 experiment at the CERN S$\bar{p}$pS collider (1987 – 1990)

CERN S$\bar{p}$pS collider operation, 1981 - 1990

Year	Collision Energy (GeV)	Peak luminosity (cm^{-2} s^{-1})	Integrated Luiminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2×10^{32}
1982	546	5×10^{28}	2.8×10^{34}
1983	546	1.7×10^{29}	1.5×10^{35}
1984 – 85	630	3.9×10^{29}	1.0×10^{36}
1987 - 90	630	3×10^{30}	1.6×10^{37}

Observation of hadronic jets
W, Z discovery

2nd phase

2nd phase (1987 – 90):

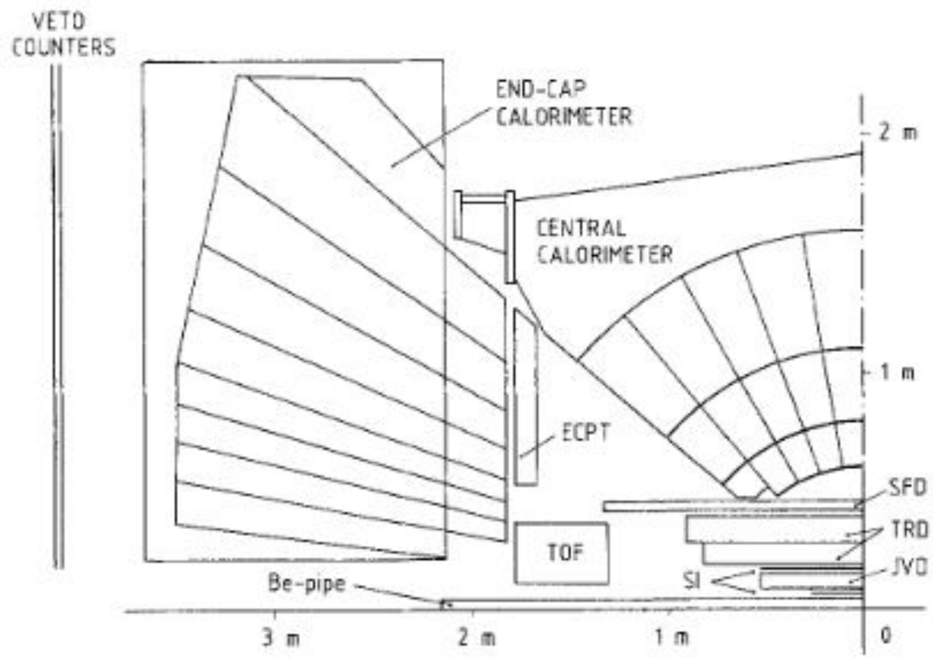
- Higher luminosity (Antiproton Collector + Accumulator)
- Upgraded UA2 detector
- A group from Pisa joins the UA2 collaboration

End of 1990: end of S$\bar{p}$pS operation
(no longer competitive with the 1.8 TeV Fermilab collider)

1987: Antiproton Collector (AC) built around the Antiproton Accumulator (AA)

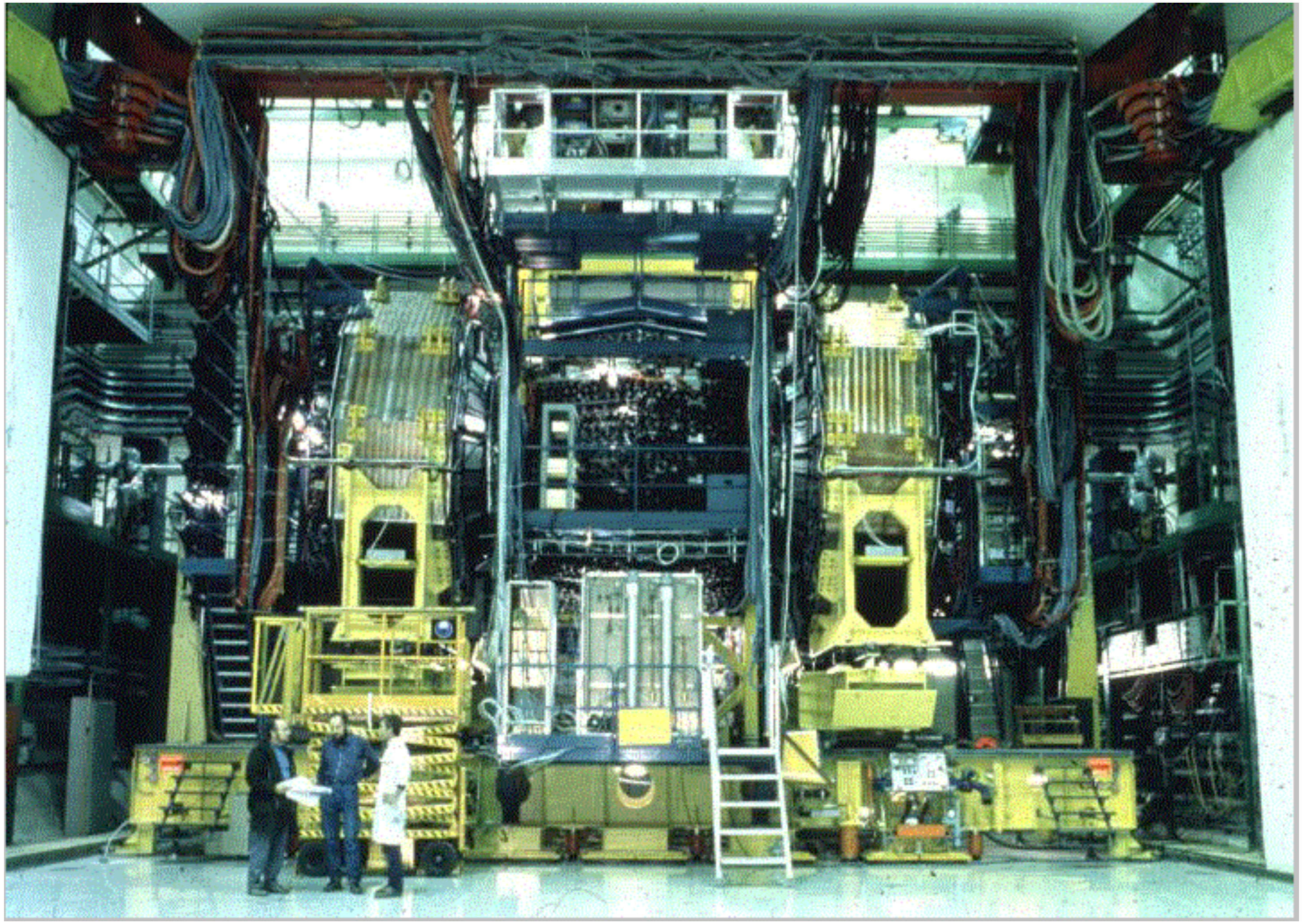
Much larger acceptance than AA to single $\bar{p}$ pulses, increasing $\bar{p}$ stacking rate by almost an order of magnitude

UA2 detector upgrade



- Calorimeters (Pb – scintillator, Fe – scintillator) with full angular coverage ("hermetic" detector)
- New central tracker:
  - Two layers of Silicon pad detectors for *dE/dx* measurement
  - A drift chamber (JVD)
  - Transition Radiation Detector for electron identification
  - Additional tracker made with scintillating fibers, read out by Image Intensifiers + CCDs (including preshower)

The upgraded UA2 detector



The Pisa group built one of the UA2 central trackers

Nuclear Instruments and Methods in Physics Research A283 (1989) 532–538
North-Holland, Amsterdam

PERFORMANCE OF THE UA2 JET VERTEX DETECTOR AT THE CERN COLLIDER *

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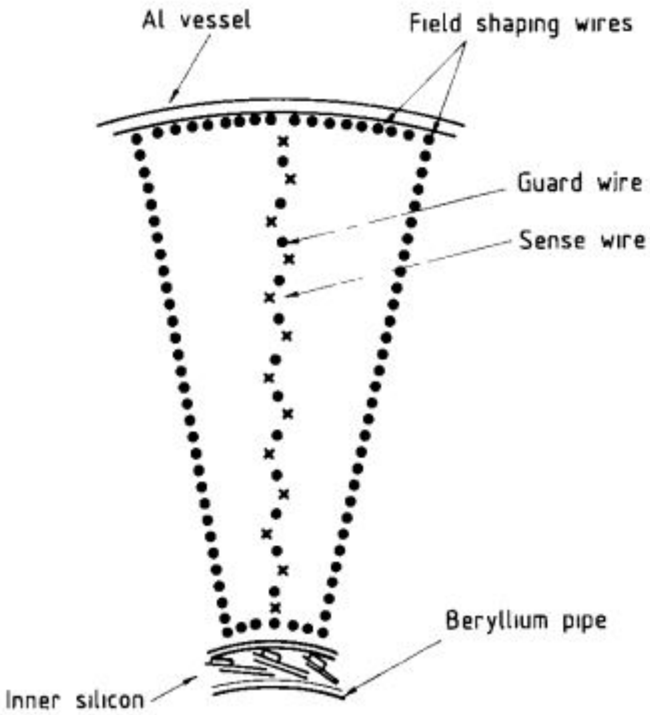


- 16 sectors
- 13 sensitive layers / sector
- 1 m long sensitive volume
- Inner sensitive radius 40 mm
- Outer sensitive radius 123.8 mm
- Transverse space resolution 0.18 mm
- Longitudinal resolution 2.5 mm
  (from charge division)
- Two-track separation 2mm

The main physics goal of the upgraded UA2 detector was the discovery of the top quark, which was possible only if m_{top} < 70 GeV so that energy conservation would allow the decays

$$W^+ \rightarrow t\bar{b},\ t \rightarrow b e^+ \nu \qquad W^- \rightarrow \bar{t}b,\ \bar{t} \rightarrow \bar{b} e^- \bar{\nu}$$

Expected event configuration: one electron, missing transverse momentum and two jets

Six such events (4 with electron, 2 with muon) had been reported by UA1 in 1984, suggesting 30 < m_{top} < 50 GeV, but they were not confirmed by the additional 1984-85 data.

It was also hoped that some physics beyond the Standard Model would show up, such as events with one jet and missing transverse momentum ("monojets") with a production rate higher than expected from conventional Standard Model processes

(Monojets had been reported by UA1 in 1984-85 and initially interpreted as evidence for the production of SuperSymmetric particles)

The top quark was finally discovered in 1995 at the 1.8 TeV Fermilab collider. It was too heavy (m_{top} ~173 GeV) to be produced and observed at the CERN $Sp\bar{p}S$

(Another group from Pisa has contributed to its discovery with the CDF detector)

Physics beyond the Standard Model has not been discovered yet

Physics Letters B 288 (1992) 386–394
North-Holland

PHYSICS LETTERS B

A measurement of single and double prompt photon production at the CERN $\bar{p}p$ collider

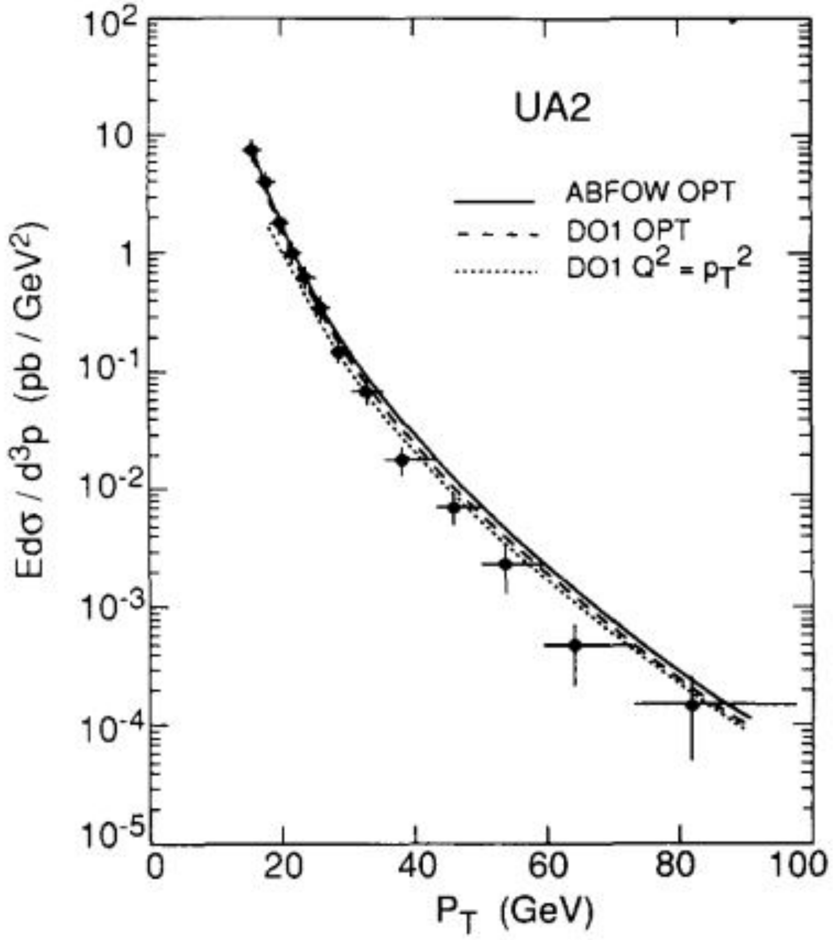
UA2 Collaboration

Bern–Cambridge–CERN–Dortmund–Heidelberg–Melbourne–Milano–Orsay (LAL)–Pavia–Perugia–Pisa–Saclay (CEN)

Background from unresolved photons from π^0 decay was reduced by isolation criteria (suppressing hadronic jets)

The fraction of prompt photons in the final sample was estimated from the measured conversion probability in the 1.5 r.l. thick preshower located in front of the electromagnetic calorimeters

Invariant cross-section for prompt photon production



Physics Letters B 277 (1992) 194–202
North-Holland

PHYSICS LETTERS B

Direct measurement of the W–γ coupling at the CERN $\bar{p}p$ Collider

UA2 Collaboration

Bern–Cambridge–CERN–Dortmund–Heidelberg–Melbourne–Milano–Orsay (LAL)–Pavia–Perugia–Pisa–Saclay (CEN)

Search for final states containing an electron, a photon and a neutrino (detected as missing transverse momentum)

Analysis performed by the Pisa group

Find 16 events with $p_T^e > 10$ GeV, $p_T^\gamma > 4.5$ GeV, $p_T^\nu > 20$ GeV, $M_T(e\nu) > 40$ GeV

Estimated background 6.8 ± 10 events

Signal ($9.2^{+5.2}_{-3.2}$ events) agrees with the Standard Model prediction

Physics Letters B 276 (1992) 354–364
North-Holland

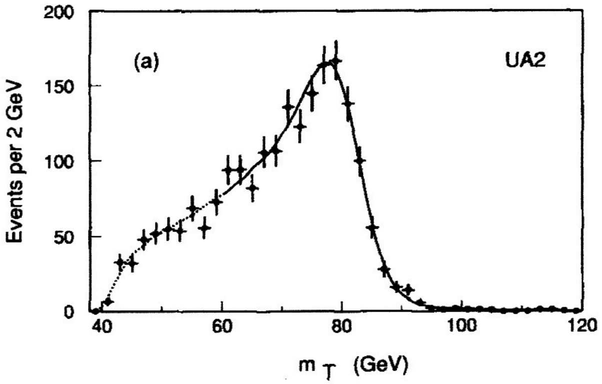
PHYSICS LETTERS B

An improved determination of the ratio of W and Z masses at the CERN p̄p collider

UA2 Collaboration

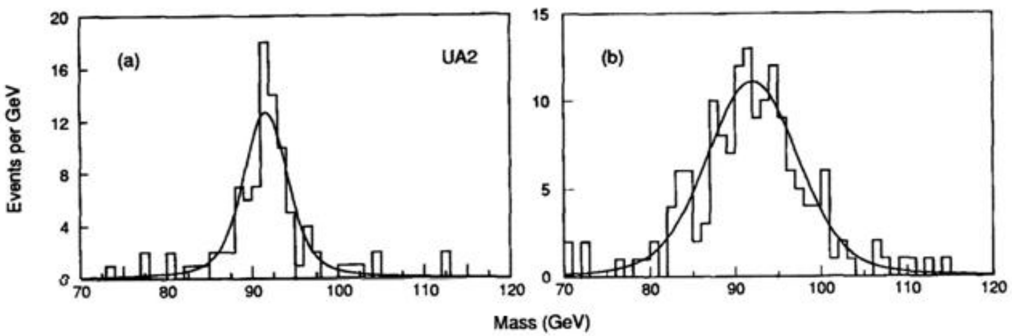
Bern–Cambridge–CERN–Dortmund–Heidelberg–Melbourne–Milano–Orsay (LAL)–Pavia–Perugia–Pisa–Saclay (CEN)

Transverse mass distribution
2065 W → e ν decays



Z → $e^+ e^-$

95 events   156 events



The error on the ratio m_W / m_Z is mainly statistical because of large cancellations of the systematic uncertainty on the calorimeter energy scale (of the order of 1% in the UA2 experiment)

$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$

Stat.

syst. (calorimeter non-linearity)

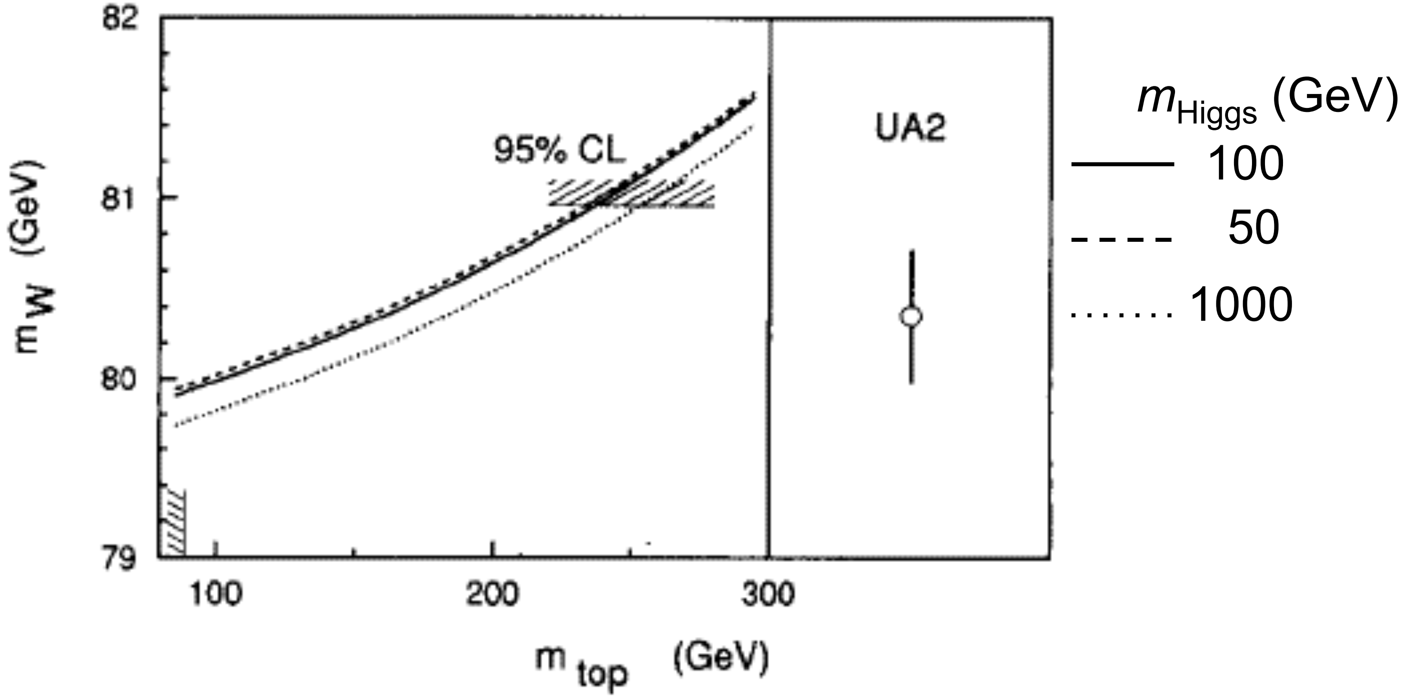
Use the first precise measurement of m_Z at LEP (1991):

$m_Z = 91.175 \pm 0.021$ GeV

to obtain a precise determination of m_W:

$m_W = 80.35 \pm 0.33 \pm 0.17$ GeV

In the Standard Model, for fixed m_Z the value of m_W depends on $(m_{top})^2$ through electroweak radiative corrections from virtual $t\bar{b}$ loops



$$m_{top} = 160^{+50}_{-60}\ \text{GeV}$$

$$m_{top} < 250\ \text{GeV}\ \ (95\%\ \text{C.L.})$$

The NOMAD experiment at the CERN SPS (1993 – 98)

1992: the first results on solar neutrinos from the GALLEX experiment at Gran Sasso were presented at the Neutrino 92 conference.

A ν_e "deficit" of ~50% was observed for low-energy solar neutrinos (< 0.8 MeV), the main component of the solar neutrino flux from the reaction $p + p \rightarrow e^+ + \nu_e + d$, directly related to the Sun luminosity.

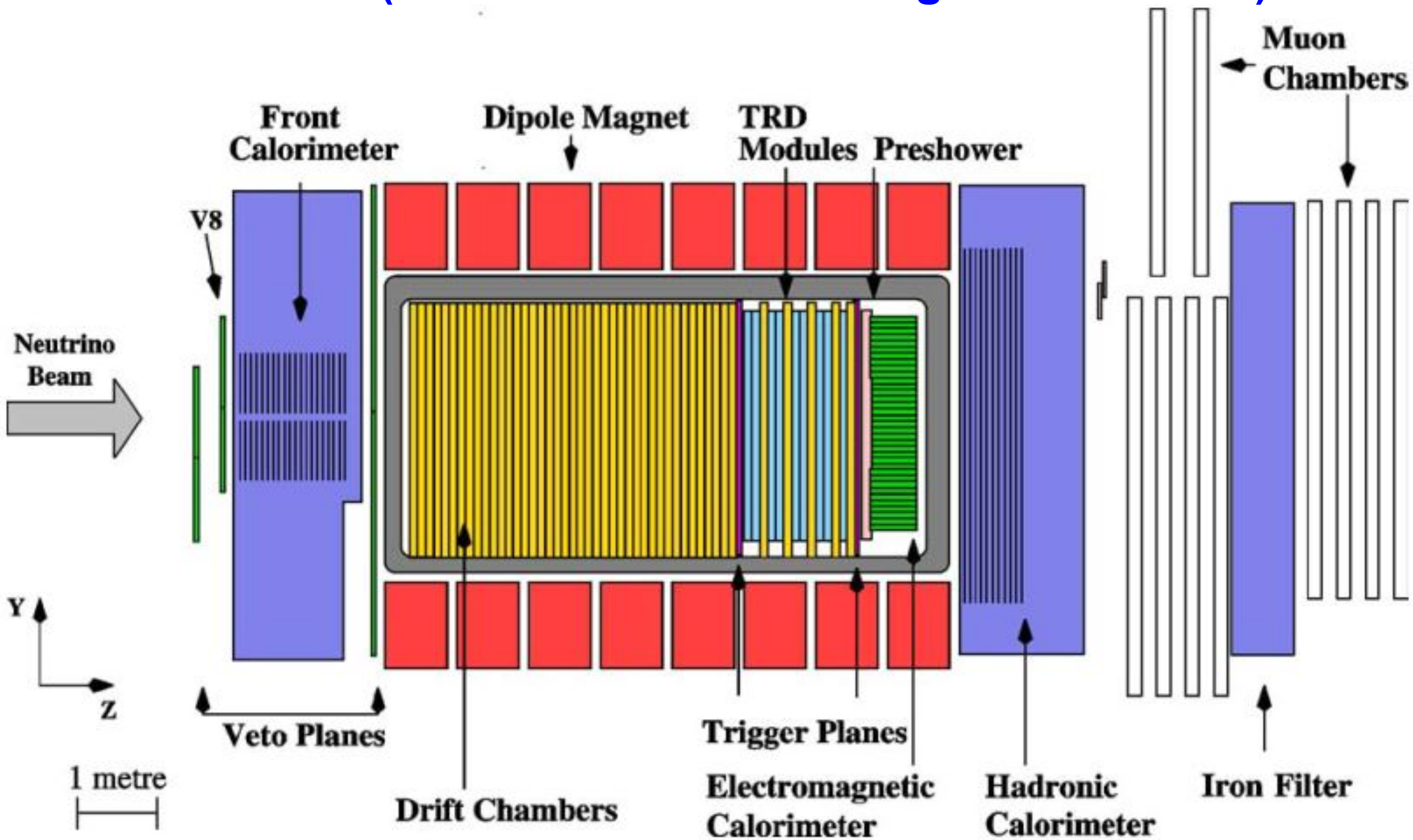
No uncertainty on flux → convincing evidence for solar neutrino oscillations → neutrinos have mass > 0

Theoretical arguments based on the "see-saw" mechanism to describe the small neutrino mass suggested that the 3rd neutrino might have a mass of few eV and be the main component of Dark Matter in the Universe.

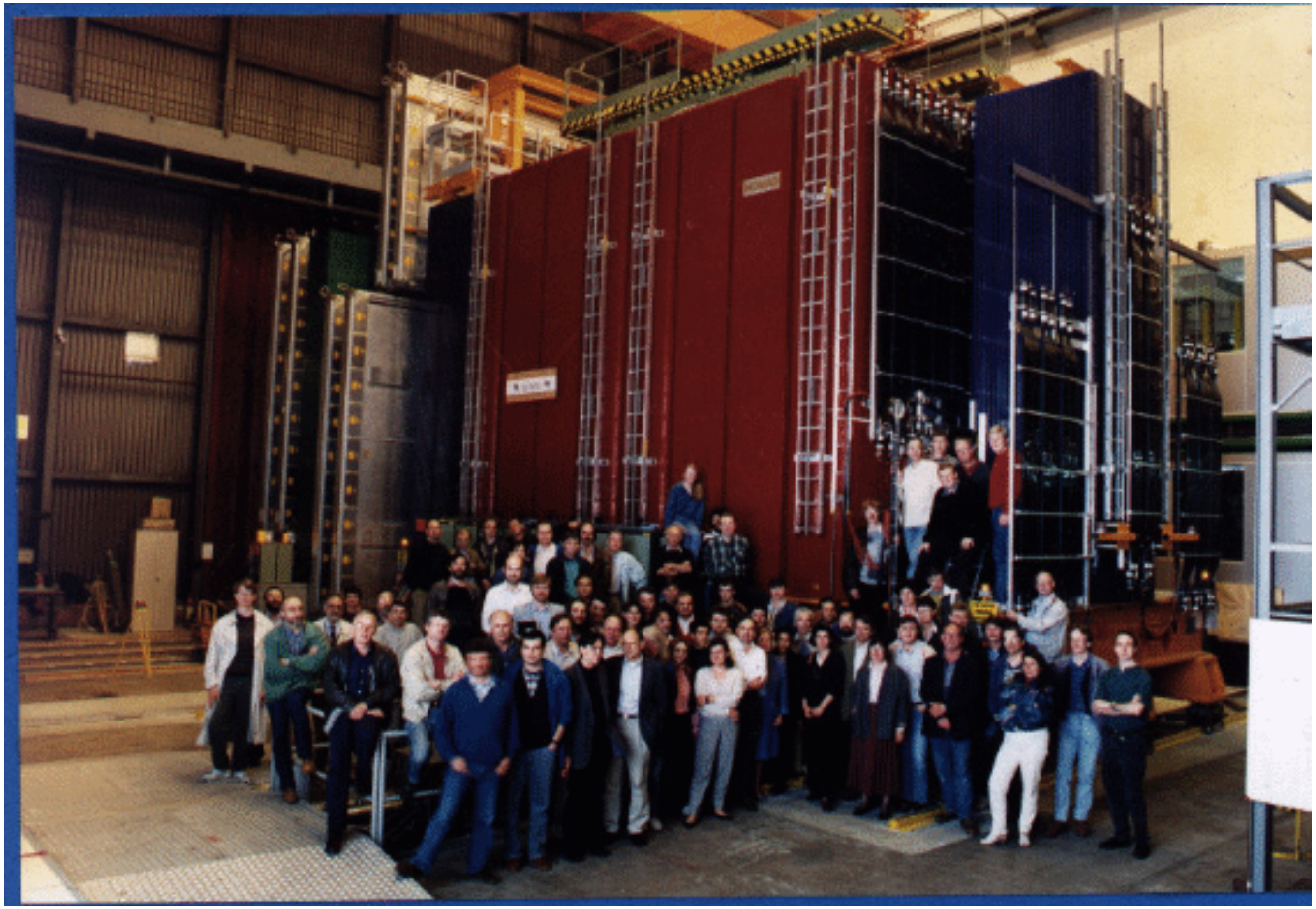
Two experiments were proposed and approved to study $\nu_\mu - \nu_\tau$ oscillations using the broad-band neutrino beam from the CERN SPS:

- CHORUS, to observe directly the τ – decay vertex near the neutrino interaction point using 800 kg nuclear emulsion as neutrino target;
- NOMAD, to detect τ production using kinematical criteria (mainly the p_T inbalance resulting from final state neutrino(s) from τ – decay)

NOMAD (Neutrino Oscillation Magnetic Detector)



Neutrino target: 144 drift chamber planes made of light material (density ~0.1 g/cm3, total mass ~ 2700 kg, total thickness ~1 r.l.) inside the former UA1 magnet (B = 0.4 T along the X-axis in a volume of 3 x 3 x 7 m)



The NOMAD electromagnetic calorimeter was a joint INFN – INR (Russia) project

ELSEVIER

Nuclear Instruments and Methods in Physics Research A 373 (1996) 358-373

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

The electromagnetic calorimeter of the NOMAD experiment

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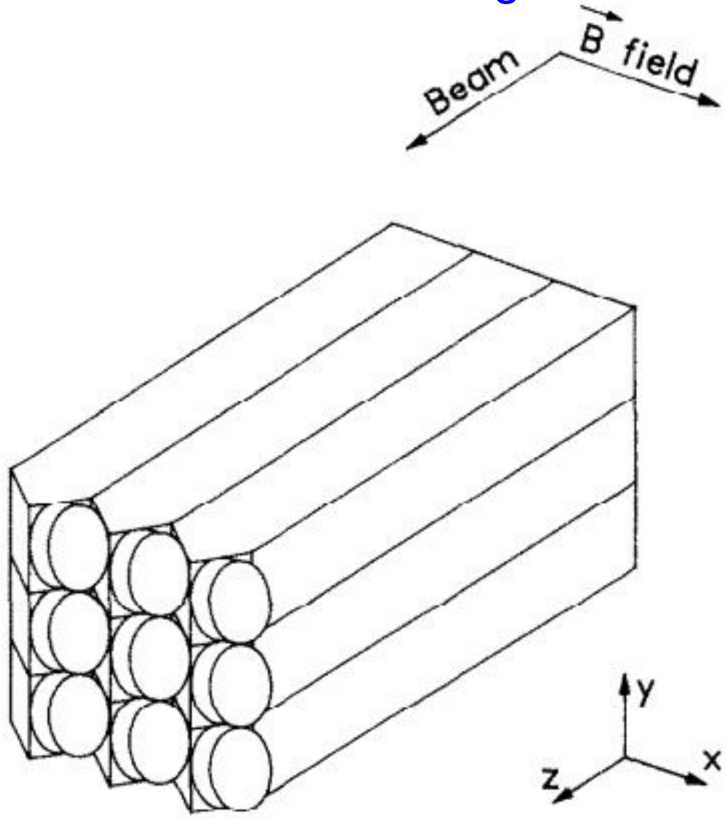
Received 13 November 1995

875 lead-glass counters (35 rows, 25 counters per row), 19 r.l. thick, inside the magnetic field volume

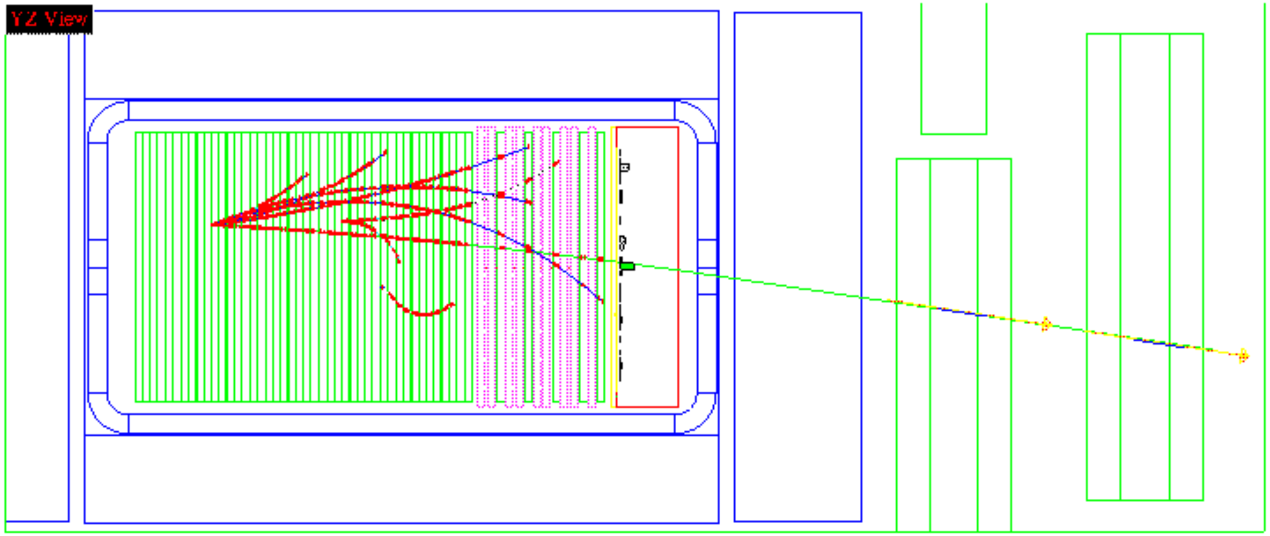
Counter cross-section 112 (h) x 79 (v) mm

Cherenkov light collected by 2-stage photomultipliers (photo-tetrodes) with gain ~40, oriented at 45º to the magnetic field direction

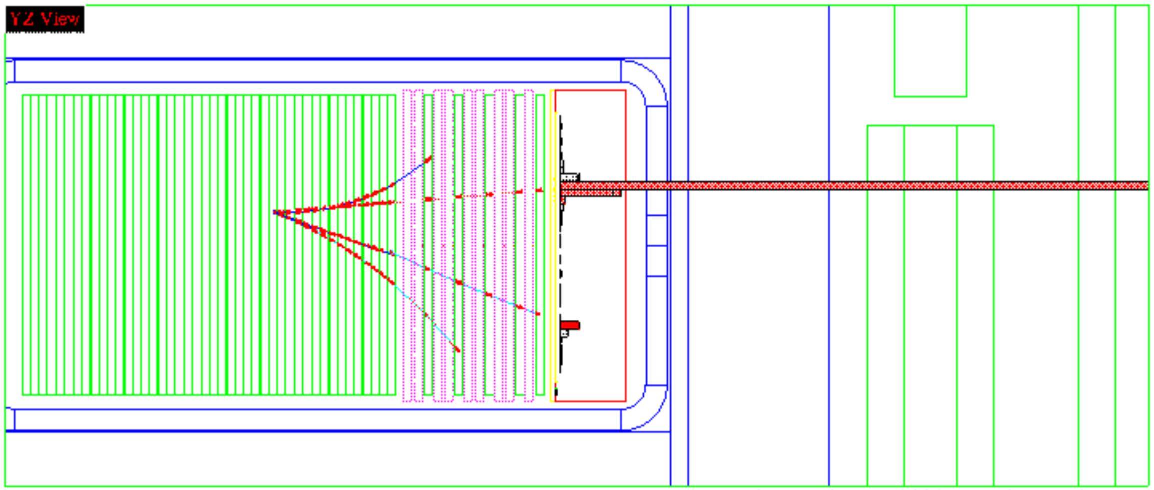


Energy resolution $$\frac{\sigma_E}{E} = \frac{0.032}{\sqrt{E(\text{GeV})}} \otimes 0.01$$

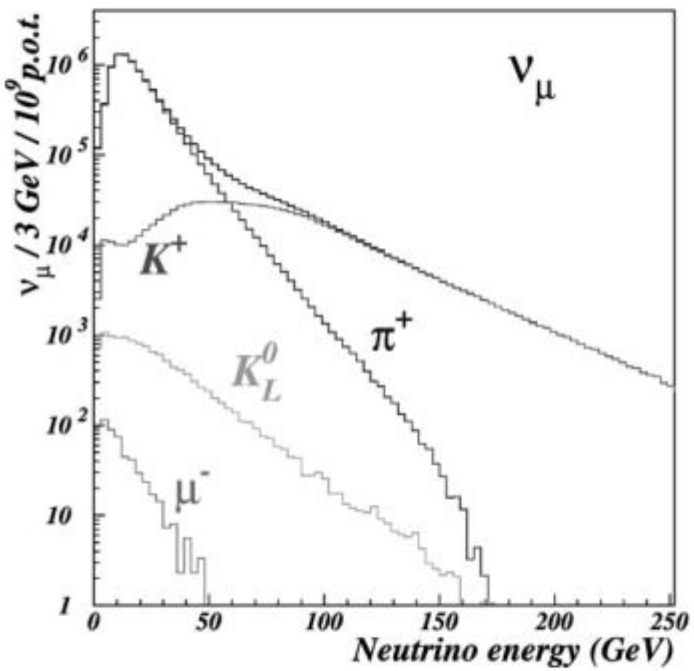
$\nu_\mu + N \rightarrow \mu^- + \text{hadrons}$

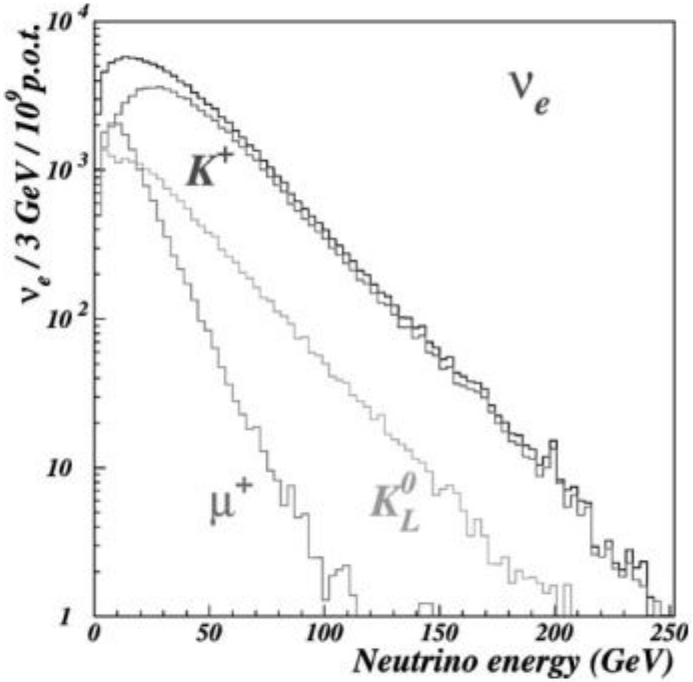


$\nu_e + N \rightarrow e^- + \text{hadrons}$



Neutrino beam in the NOMAD experiment



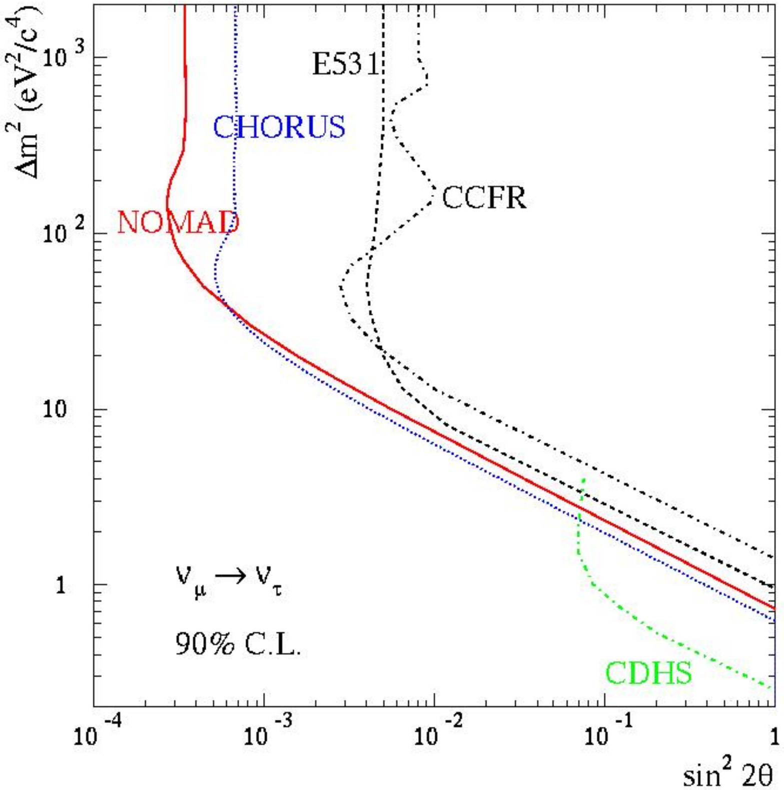


Flavor	Flux		CC interactions	
	$\langle E_\nu \rangle$ [GeV]	Rel. abund.	$\langle E \rangle$ [GeV]	Rel. abund.
ν_μ	24.3	1.0	47.5	1.0
$\bar{\nu}_\mu$	17.2	0.068	42.0	0.024
ν_e	36.4	0.010	58.2	0.015
$\bar{\nu}_e$	27.6	0.0027	50.9	0.0015

The prompt ν_τ component is negligible

Excluded regions for $\nu_\mu - \nu_\tau$ oscillations from short baseline experiments

NOMAD : 1.35×10^6 ν_μ CC interactions



The first observation of $\nu_\mu - \nu_\tau$ oscillations was reported by SuperKamiokande in 1998 using "atmospheric" neutrinos (mostly produced in $\pi \to \mu$ and $\mu \to e$ decays), with with $\Delta m^2 \approx 2.5 \times 10^{-3}$ eV^2 and mixing angle consistent with 45º (full mixing).

Long baseline experiments at accelerators have measured precisely the oscillation parameters:

$$\Delta m^2 \approx (2.50 \pm 0.04) \times 10^{-3}\ \text{eV}^2 \quad ; \quad \sin^2 2\theta = 0.984\ ^{+0.012}_{-0.014}$$

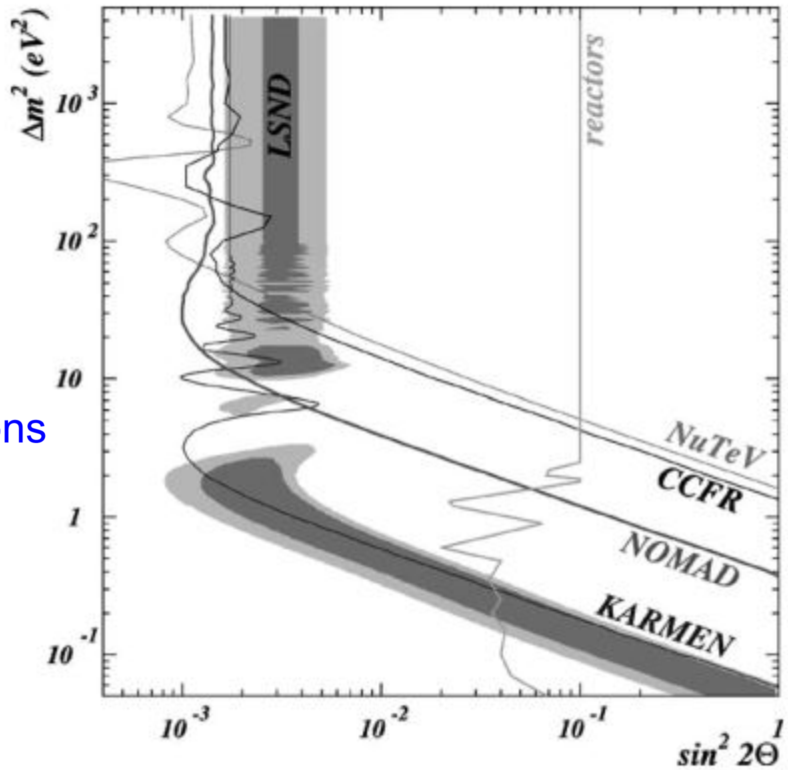
Search for $\nu_\mu - \nu_e$ oscillations

Motivation: the $\nu_\mu - \nu_e$ oscillation signal reported by the LSND experiment at Los Alamos in 1996

The detection of the $\nu_\mu - \nu_e$ oscillation signal requires the subtraction of the $\nu_e \rightarrow e^-$ background from the prompt ν_e component in the beam (1% of ν_μ)

Δm^2 vs $\sin^2 2\theta$:
LSND signal and
exclusion regions
from other experiments

The Pisa group gave major contributions to this analysis
(Ph.D. thesis of A. De Santo)



The LSND signal, if confirmed, would require a 4th ''sterile'' neutrino.
At present, it is still an open problem in neutrino physics

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Bose–Einstein correlations in charged current muon–neutrino interactions in the NOMAD experiment at CERN

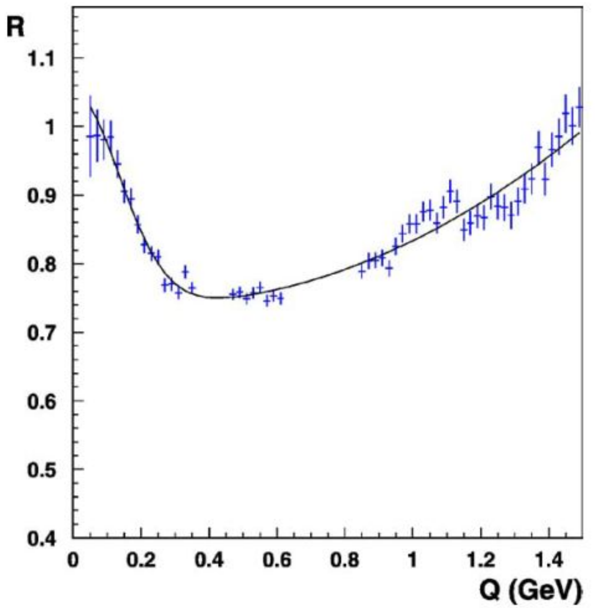
NOMAD Collaboration

A study performed by the Pisa group (A. Lupi Ph. D. thesis subject)

Bose-Einstein correlations: enhancement of the number of identical bosons ($\pi^+\pi^+$, $\pi^-\pi^-$) emitted close to one another in phase space.

Use $\pi^+\pi^-$ pairs as “reference sample (no correlations).

$$R(Q) = \frac{\text{"like-sign" pion pairs}}{\text{"unlike-sign" pion pairs}} = \frac{N_{++}(Q) + N_{--}(Q)}{N_{+-}(Q)} \qquad \left(Q = \left| \vec{p}_1 - \vec{p}_2 \right| \right)$$



Fit using the Goldhaber parametrization
(a 3-parameter fit)
One of the 3 parameters is the pion source radius R_G :

$$R_G = 1.01 \pm 0.05\ ^{+0.09}_{-0.06}\ \text{fm}$$

Conclusion

Since the 1950s , groups of physicists from the University and I.N.F.N. Pisa have worked at the forefront of particle physics, providing invaluable contributions to progress in this field