223

Cours/Lecture Series

1989 - 1990 ACADEMIC TRAINING PROGRAMME

SPEAKER : by A. DONNACHIE / University of Manchester
TITLE : The future of fixed target experiments
DATES : 27, 29 & 30 November
TIME : 11.00 to 12.00 hrs
PLACE : Auditorium

ABSTRACT

The three lectures will be based on the different types of beam available : lepton beams, hadron beams and heavy ion beams.

Lecture 1 : *Deep inelastic muon scattering, structure functions, spin dependence : neutrino interactions, the standard model, the tau neutrino, neutrino oscillations.*

Lecture 2 : *CP violation; charm and beauty physics; glueball and light hadron spectroscopy.*

Lecture 3 : *Relativistic heavy ion physics.*

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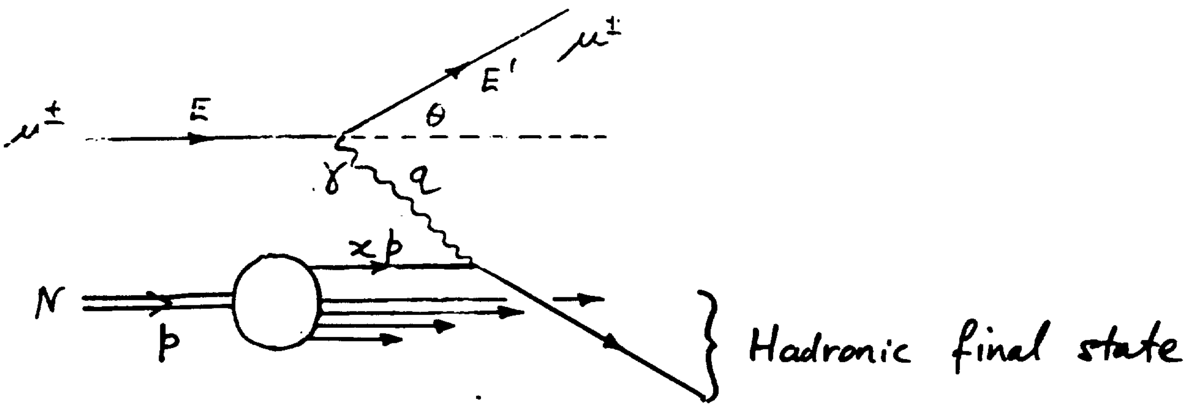
SIS/H/344

		1989	1990	1991	1992	1993
MUONS	EMC	ANALYSIS	✕			
	BCDMS	ANALYSIS	✕			
	NMC	DATA →	✕			
	SMC	APPROVE	INSTALL	+ TEST	DATA →	→
NEUTRINOS	CHARM II	DATA →	- - - ? - - →	INSTALL	→	→
CP	NA31	DATA →	- - - ? - - →	INSTALL	+ TEST	→
CHARM	NA14	COMPLETED	✕			
CHARM	NA32	COMPLETED	✕			
c/B	WA82	DATA →	ANALYSIS	→	→	
BEAUTY	WA84	TEST	?			
HYPERONS	WA89	DATA →	→	→	→	→
QCD	WA69	ANALYSIS	✕			
QCD	WA70	ANALYSIS	✕			
SPECTROSCOPY	WA76	ANALYSIS	→	→	→	
"	WA77	ANALYSIS	✕			
SOFT γ	WA83	ANALYSIS	✕			
SPECTROSCOPY	NA12	ANALYSIS	→	→	→	
$\mu^+\mu^-, e^+e^-$	NA34/1	DATA →	✕			
CHANNELING	NA43	DATA →	?			
H.B.T.	NA44	APPROVE	DATA →	^{32}S DATA		
DARMSTADTON	NA46	APPROVE	DATA →	?		
QCD	UA6	DATA →	- - - ? - - →	✕		

		1986	1987	1988/89	1990	1991
$\mu^+\mu^-$	NA34	DATA	DATA		DATA	
GENERAL	NA35	DATA	DATA		DATA	DATA
STRANGE	NA36	TEST	TEST/DATA		DATA	
J/ψ	NA38	DATA	DATA		DATA	DATA
HBT	NA44				[PROTONS]	DATA
e^+e^-	NA45				TEST	DATA
GENERAL, γ	WA80	DATA	DATA		DATA	DATA
STRANGE	WA85		DATA		DATA	
		^{16}O	^{32}S		^{32}S	^{32}S

- It is hoped to have a lead ion source available in 1993.

μ-N DEEP INELASTIC SCATTERING



$Q^2 \simeq 2EE'(1-\cos\theta) = 4EE'\sin^2\frac{\theta}{2} = -q^2$ Invariant mass of virtual γ

$\nu = E - E'$ Energy of virtual γ in lab.

$y = \nu/E$ Fraction of μ energy carried off by virtual γ.

$x =$ Bjorken scaling variable — fraction of nucleon momentum carried by struck parton

$= \dfrac{Q^2}{2M\nu}$

$$\frac{d^2\sigma}{dQ^2dx} = \frac{4\pi\alpha^2}{Q^4}\cdot\frac{F_2(x,Q^2)}{x}\left[1-y+\frac{y^2}{2(1+R)}\right] \qquad E, Q^2 \gg M$$

$F_2(x,Q^2)$ is parton distribution function weighted by $(\text{charges})^2$

$R(x,Q^2) = \dfrac{\sigma_L}{\sigma_T}$ (virtual γ's have longitudinal as well as transverse polarisation).

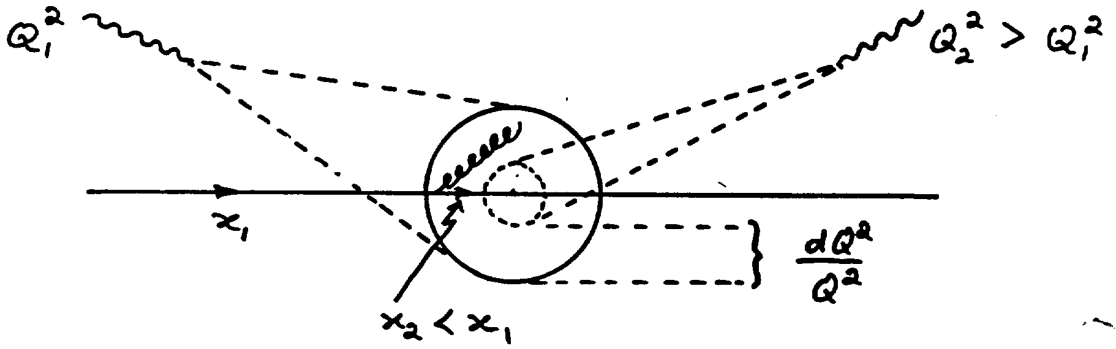
In the naive Quark Parton Model, F_2 scales

$$F_2(x,Q^2) \simeq F_2(x) = x\sum_i e_i^2\left(q_i(x)+\bar{q}_i(x)\right)$$

Effect of R is small, except at high y ie in a region populated mainly by low x, high Q^2 events.

Scaling violation – Altarelli-Parisi equations.

Quarks radiate gluons
Quark distribution $q(x, Q^2)$ changes as Q^2 increases
– radiated gluons are "resolved"



Since no scale is given, fractional change of Q^2 relevant $\frac{dQ^2}{Q^2} = d(\ln Q^2)$

For valence quarks (flavour non-singlet)

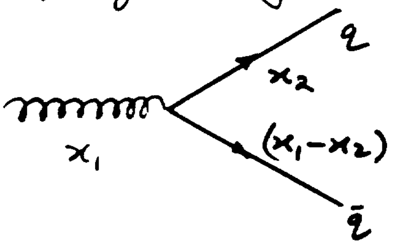
$$\frac{dq^{NS}(x_2, Q^2)}{d(\ln Q^2)} = \frac{\alpha_s(Q^2)}{2\pi}\int_{x_2}^{1} P_{qq}\left(\frac{x_2}{x_1}\right) q^{NS}(x_1, Q^2)\,\frac{dx_1}{x_1}$$

α_s gives probability of radiating a gluon
$P_{qq}\left(\frac{x_2}{x_1}\right)$ is splitting function, – probability of finding a quark with energy fraction (x_2/x_1) inside a quark. – given by the Weizsacker - Williams formula for fermion → fermion + boson (QCD analogue of $e \rightarrow e + \gamma$)

Since $F_2^{NS}(x, Q^2) = x \sum_i e_i^2 \, q_i^{NS}(x, Q^2)$

$$\frac{dF_2^{NS}(x_2, Q^2)}{d(\ln Q^2)} = \frac{\alpha_s(Q^2)}{\pi} \int_{x_2}^{1} F_2^{NS}(x_1, Q^2) \, P_{qq}\!\left(\frac{x_2}{x_1}\right) \frac{x_2}{x_1^2} \, dx_1$$

In the corresponding flavour singlet expression, which involves sea quarks and antiquarks, there is also a term arising from the probability of finding a $q\bar{q}$ pair in a gluon



Additional term in integrand of

$$2 \sum_i e_i^2 \, P_{Gq}\!\left(\frac{x_2}{x_1}\right) x_1 \, G(x_1, Q^2) \, \frac{x_2}{x_1^2}$$

where $x\,G(x, Q^2)$ is the gluon momentum distribution.

Numerically $\int_{x_2}^{1} F_2^{NS}(x_1, Q^2) \, P_{qq}\!\left(\frac{x_2}{x_1}\right) \frac{x_2}{x_1^2} \, dx_1 \simeq K(x_1) \, F_2^{NS}(x_1, Q^2)$

$$\therefore \quad \frac{d(\ln F_2^{NS}(x_1, Q^2))}{d(\ln Q^2)} \simeq \alpha_s(Q^2) \, K(x_1)$$

$\alpha_s = \text{constant} \Rightarrow \ln F_2 = A \ln Q^2 + B$

L.O. QCD $\alpha_s(Q^2) = \dfrac{4\pi}{\beta_0 \ln \frac{Q^2}{\Lambda^2}}$, $\beta_0 = \dfrac{33 - 2f}{3}$

[illegible] M1

Nuclear Effects

The structure function measured on a nucleus is not the same as the structure function measured on a nucleon.

There are 3 regions:

1) $x \gtrsim 0.2$ $F_2(A) < F_2(D)$ "EMC Effect"

2) $x \lesssim 0.05$ $F_2(A) < F_2(D)$ "Shadowing"

3) $0.05 \lesssim x \lesssim 0.2$ $F_2(A) > F_2(D)$ "Antishadowing" — Figs M2,3

These 3 effects can all be understood in a parton framework.

1) • In a nuclear environment, the nucleons overlap.

- The overlapping volume per nucleon, V_A, is large:

  $V_A / V_N \simeq 40\%$ for C, $\simeq 70\%$ for Sn.

  Because of this overlap, partons can find that they are part of two overlapped nucleons i.e that their confinement volume has been increased — they are partially deconfined.

  The effect of this is to degrade the quark distributions to smaller x.

- Simple model: system of N non-interacting massless quarks, in a bag of radius R with the momentum shared equally.
  The normalised distributions are given by

$$q_N(x) = \delta(x - 1/N)$$

Changing the number of quarks to N' means

$$q_{N'}(x) = \delta(x - 1/N') = (N'/N)\, q_N((N'/N)x)$$

- As system is confined, it has rest mass M proportional to the number of quarks and inversely proportional to the only available dimensional scale R. Hence

$$q_{N'}(x) = (M'R'/MR)\, q_N((M'R'/MR)x)$$

- To connect with the quark distribution functions $q(x)$, $q'(x)$ within a nucleus, note that the primed bag carries an enhanced factor (M'/M) of the momentum of the unprimed bag, so

$$q'(x) = (R'/R)\, q((R'/R)x)$$

- Thus in the larger primed bag $(R'/R > 1)$ the quark distribution is degraded to smaller x.

2) - Because of the overlap, a parton from one nucleon can "leak" into a neighbouring nucleon and fuse with one of the latter's partons.
- Gluon fusion will be appreciable at small x where the gluon density is large
  → reduction of gluon density at small x
- The small-x behaviour of quarks is largely governed by the gluon density, so gluon depletion → quark depletion
  i.e. "parton recombination" ≡ shadowing
- Also recombination has the effect of boosting the parton to a higher momentum

3) - Rescaling takes high-x partons to smaller x
- Recombination takes low-x partons to higher x
- Momentum must be conserved
  → antishadowing

Polarised deep inelastic lepton-proton scattering

$J_z^p = +\frac{1}{2}$ $\qquad$ $J_z^\gamma = \pm 1$

- Structure functions $F_1(x, Q^2)$, $F_2(x, Q^2)$ are spin-averaged structure functions.
- If no spin-averaging is done there is an additional structure function $g_1(x, Q^2)$.
- The muon (and hence the virtual γ) automatically polarized: it comes from decay $\pi \rightarrow \mu \nu$.
- The specific muon beam polarisation can be selected by choosing a specific ratio of the parent pion to decay muon momenta: typically ≈ 80%.
- Polarised target (eg. ammonia - NH_3 - EMC
  butanol - C_4H_9OH - SMC)
- Measure $A = \dfrac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}}$

  where $\uparrow\uparrow$ ($\uparrow\downarrow$) denote parallel (antiparallel) μ and p spins.
- Target in two sections with opposite polarisation so $\sigma^{\uparrow\downarrow}$ and $\sigma^{\uparrow\uparrow}$ measured simultaneously. Polarisation directions reversed regularly.

- Fundamental sum rule – Bjorken polarisation sum rule – relates integral of nucleon spin-dependent structure functions to neutron β-decay coupling constants.

$$S_{Bj} \equiv \int_0^1 \left(g_1^p(x) - g_1^n(x) \right) dx = \frac{1}{6} \left| \frac{g_A}{g_V} \right|$$

$$= 0{\cdot}209 \pm 0{\cdot}001$$

QCD corrections $\Longrightarrow$

$$S_{Bj} = \frac{1}{6} \left| \frac{g_A}{g_V} \right| \left\{ 1 - \frac{1}{\pi} \alpha_s(Q^2) \right\} = 0{\cdot}191 \pm 0{\cdot}002$$

- Assuming flavour SU(3) + strange quark sea unpolarised → Ellis-Jaffe sum rules:

$$\left.\begin{aligned} T_p &\equiv \int_0^1 dx\, g_1^p(x) = 0{\cdot}189 \pm 0{\cdot}005 \\ T_n &\equiv \int_0^1 dx\, g_1^n(x) = -0{\cdot}002 \pm 0{\cdot}005 \end{aligned}\right\} \text{with QCD corrections.}$$

- Data available on polarised protons (SLAC, EMC)

Figs. 4,5

$T_p \equiv 0{\cdot}126 \pm 0{\cdot}010 \pm 0{\cdot}019$ (SLAC + EMC)

Discrepancy $= 0{\cdot}063 \pm 0{\cdot}022$ . . . . . 3 s.d.

In quark-parton model,

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 \left[q_i^{\uparrow}(x) - q_i^{\downarrow}(x) \right]$$

Results imply that the fraction of proton spin carried by the quarks is (3 ± 9 ± 17) %.

- For the proton and neutron,

$$\Gamma_p = \frac{4}{18}\Delta u + \frac{1}{18}\Delta d + \frac{1}{18}\Delta s + O(\alpha_s)$$

$$\Gamma_n = \frac{1}{18}\Delta u + \frac{4}{18}\Delta d + \frac{1}{18}\Delta s + O(\alpha_s)$$

with

$$\Delta u = \int_0^1 dx \left[q_u^{\uparrow}(x) + \bar{q}_u^{\uparrow}(x) - q_u^{\downarrow}(x) - \bar{q}_u^{\downarrow}(x) \right] \quad \text{etc.}$$

- Assuming the Bjorken sum rule, and the data,

$$\Gamma_p = 0.126 \pm .021$$

$$\Gamma_n = -0.065 \pm .022$$

- If we assume flavour SU(3) but allow the strange quark sea to be polarised (ie use it to remove the discrepancy) then

	Fraction of proton spin
$u + \bar{u}$	$+(75 \pm 6)\%$
$d + \bar{d}$	$-(50 \pm 6)\%$
$s + \bar{s}$	$-(22 \pm 6)\%$
	$3 \pm 19\%$

This is a surprisingly small result. Explanations?

1) In Q^2 range of the experiments "higher-twist" and/or non-perturbative effects may resolve the problem

2) The effect of orbital angular momentum in a relativistic constituent quark model may be sizeable

3) The proton spin wave function may be substantially affected by gluon exchange

4) Perturbative QCD is wrong

5) There are important gluon contributions to $g_1(x)$, which can be sufficiently large and of the appropriate sign to allow a large quark spin component

6) In the Skyrme model of the nucleon (rotator) and in the chiral limit ($m_q = 0$) and to leading order in the $1/N_c$ expansion it can be shown that none of the proton spin is carried by quarks. If gluons carry ~50% of the proton momentum most of the orbital angular momentum is carried by the quarks and accounts for the proton spin.

7) ......

8) ......

9) ......

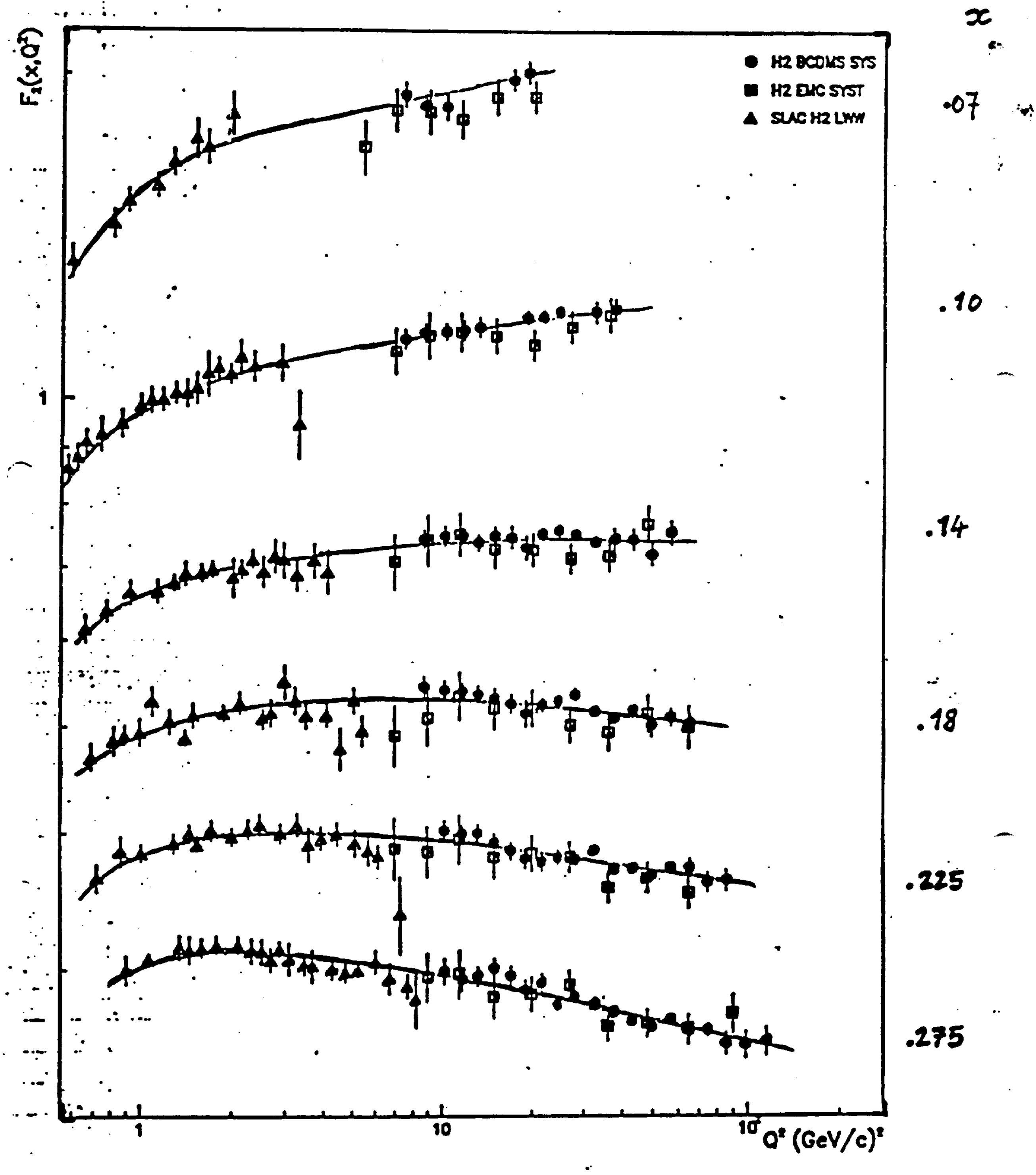
Resolution? Another experiment – SMC.

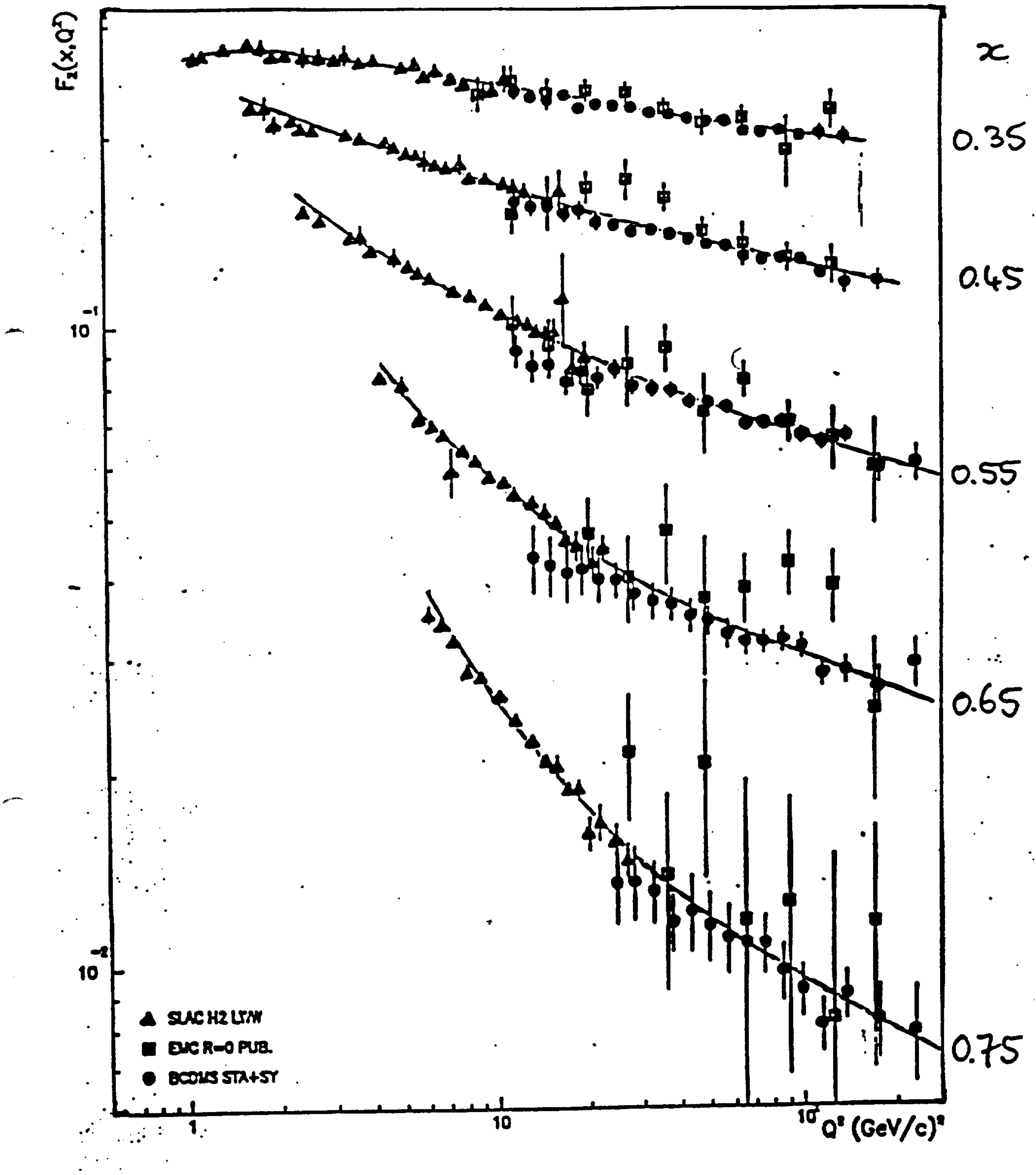
- Improve statistics and systematics by factor ~ 2. Main improvement on systematics is to have frequent polarisation reversals.
- Use deuterium in addition to hydrogen
  - deuterated butanol C_4D_9OD
  - allows direct measurement of Γ_n & hence S_{Bj}
- Aims: $\delta\Gamma_p = 0.006 \pm 0.010$ $(\Gamma_p = 0.126)$

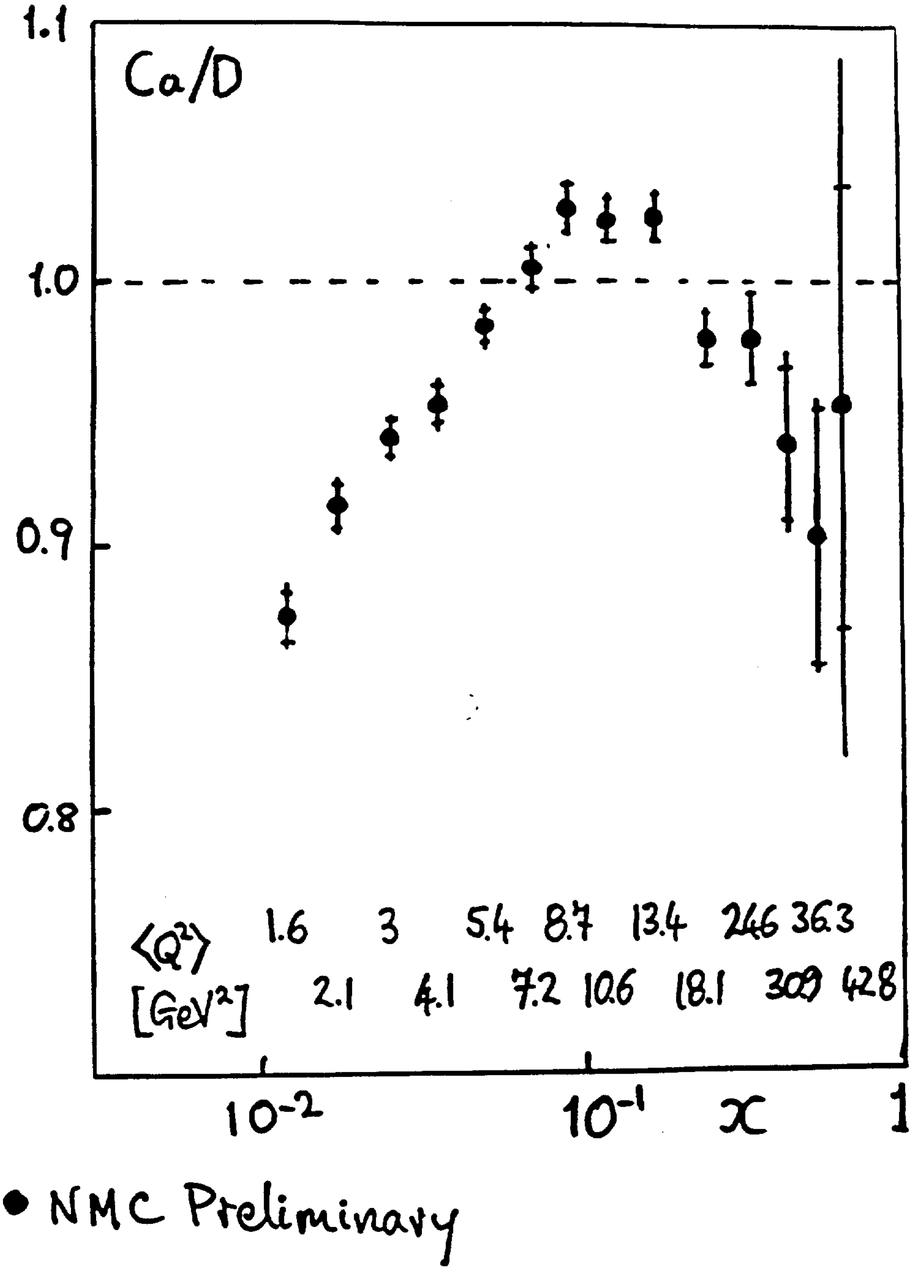
  $\delta\Gamma_n = 0.011 \pm 0.010$ $(\Gamma_n = -0.065)$

  $\delta S_{Bj} = 0.015 \pm 0.018$ $(S_{Bj} = 0.191)$

M 1a


$F_2(x,Q^2)$
x
.07
.10
.14
.18
.225
.275
1
1
10
10^2 Q^2 (GeV/c)^2
● H2 BCDMS SYS
■ H2 EMC SYST
▲ SLAC H2 LWW


F₂(x,Q²)
10⁻¹
10⁻²
1
10
10²
Q² (GeV/c)²
x
0.35
0.45
0.55
0.65
0.75
▲ SLAC H2 LT/W
■ EMC R=0 PUB.
● BCDMS STA+SY


Ca/D
1.1
1.0
0.9
0.8
⟨Q²⟩
[GeV²]
1.6
2.1
3
4.1
5.4
7.2
8.7
10.6
13.4
18.1
24.6
30.9
36.3
42.8
10⁻²
10⁻¹
x
1
● NMC Preliminary

M3

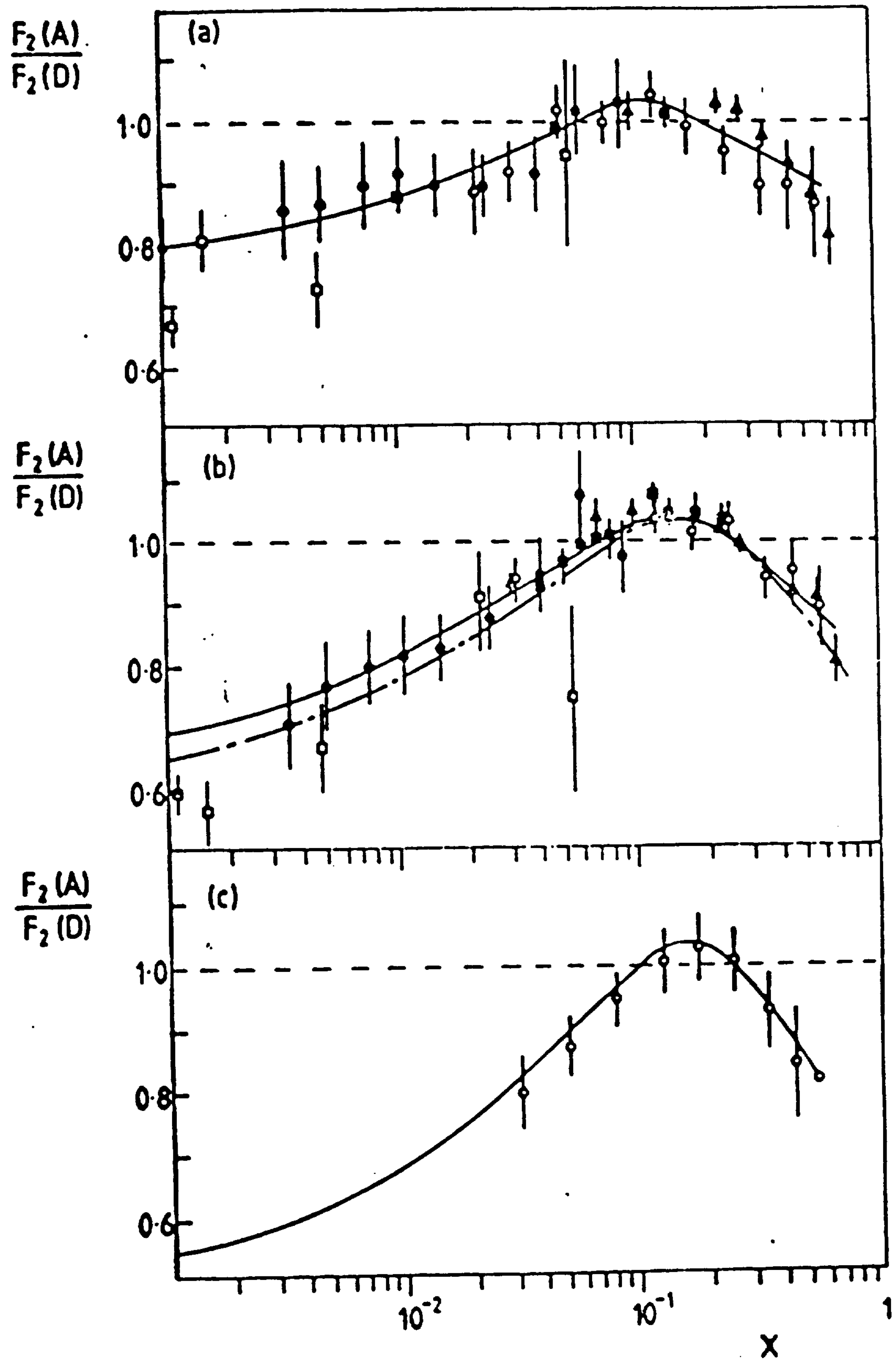
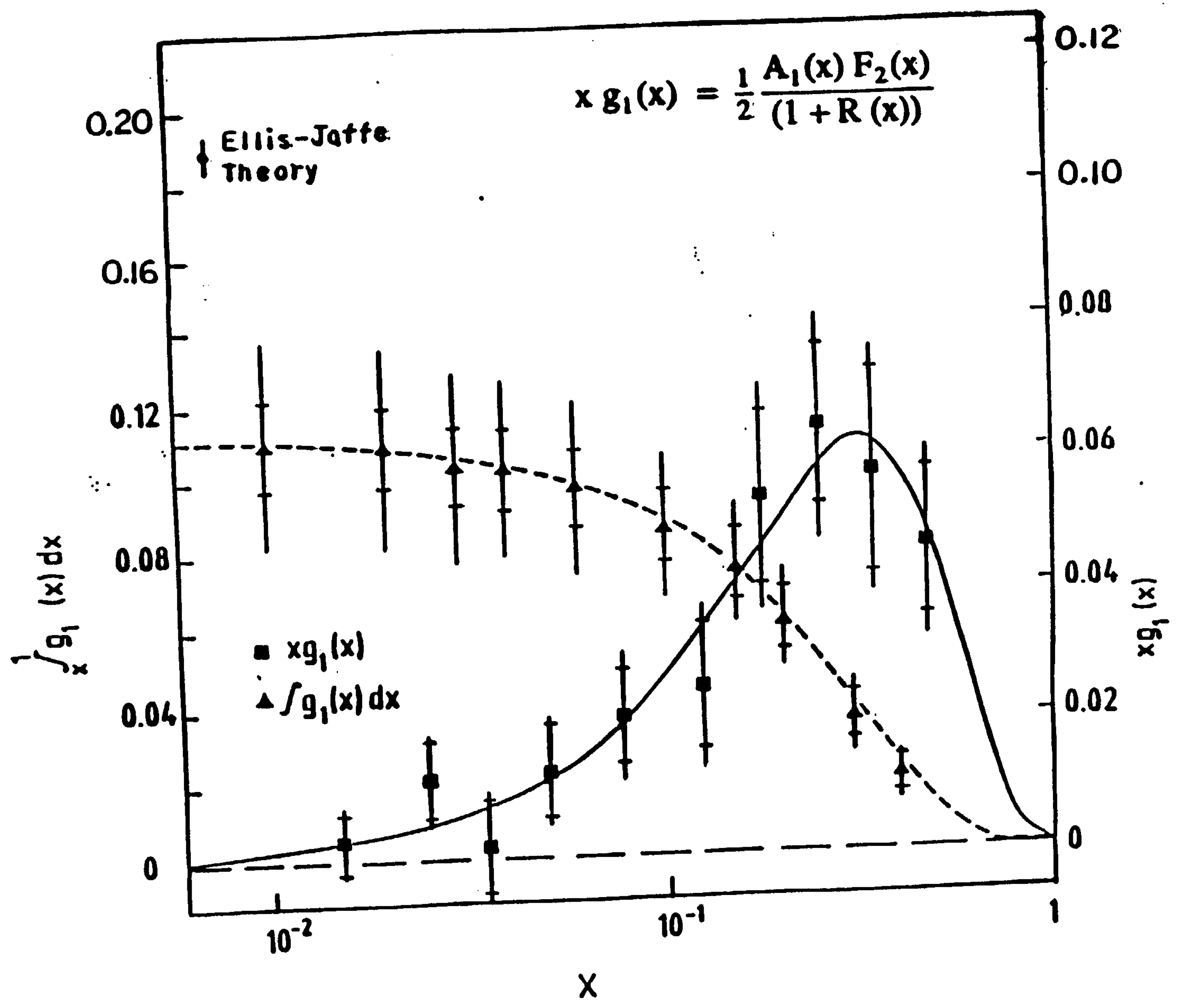


Fig. 1 a–c. Fits to the shadowing data, using (2.2). The nuclear

17

M4


$x\,g_1(x) = \frac{1}{2}\frac{A_1(x)\,F_2(x)}{(1+R(x))}$
Ellis-Jaffe Theory
■ $xg_1(x)$
▲ $\int g_1(x)\,dx$
$\int_x^1 g_1(x)\,dx$
$xg_1(x)$
X
0.20
0.16
0.12
0.08
0.04
0
0.12
0.10
0.08
0.06
0.04
0.02
0
10^{-2}
10^{-1}
1

M5.

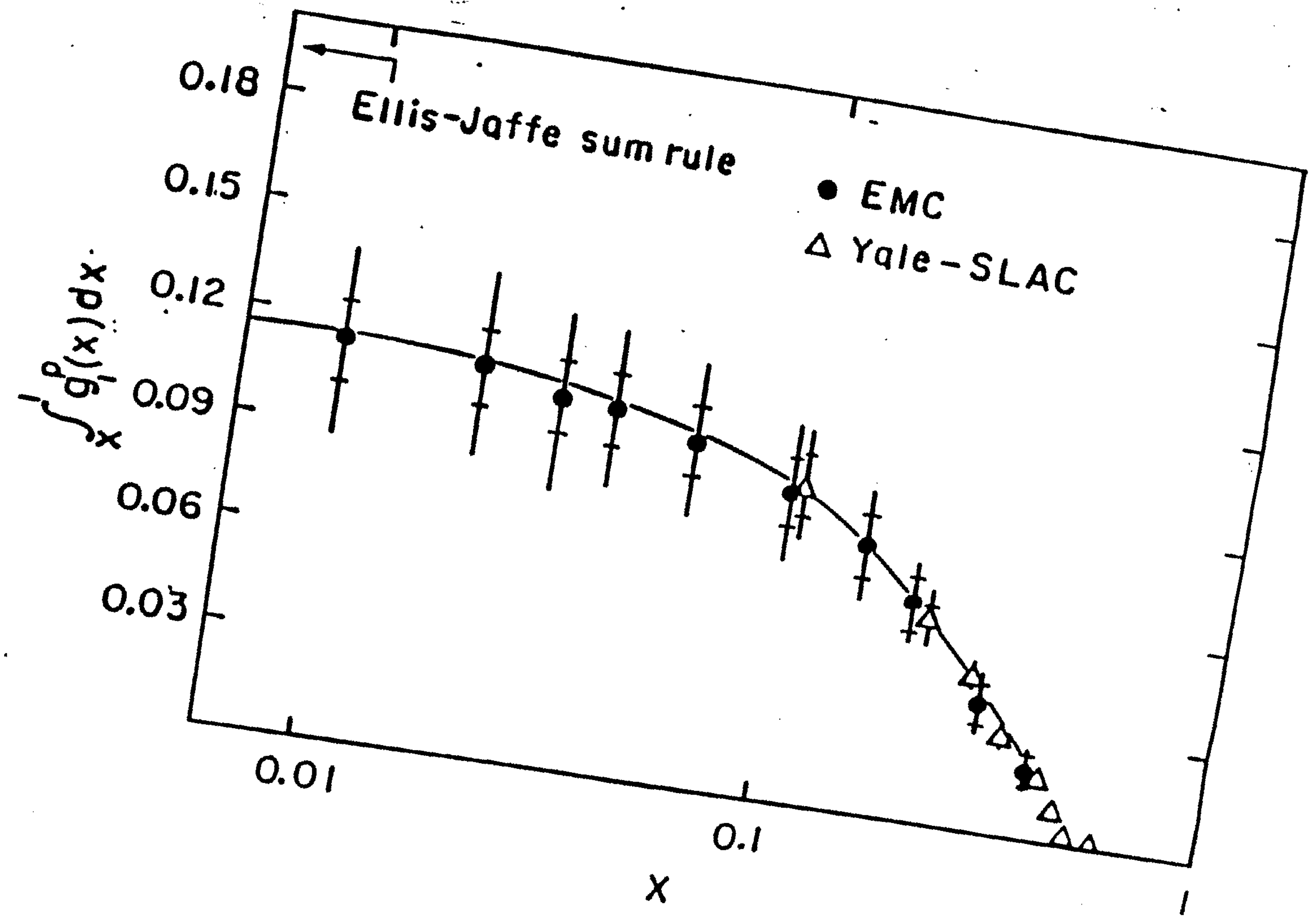

Ellis-Jaffe sum rule
● EMC
Δ Yale-SLAC
$\int_x^1 g_1^p(x)\,dx$
0.18
0.15
0.12
0.09
0.06
0.03
0.01
0.1
1
x

FIG. 2

NEUTRINO EXPERIMENTS

I: $\nu_\mu - e$ SCATTERING

One of the key parameters in the Standard Model of electroweak theory is $\sin^2\theta_W$, where θ_W is the electroweak mixing angle

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

$$\sin^2\theta_W = \frac{1}{2}\left\{1 - \left[1 - \frac{4\pi\alpha/\sqrt{2}G_F}{M_Z^2(1-\Delta r)}\right]^{\frac{1}{2}}\right\}$$

$$\Delta r \equiv \Delta r(\alpha, G_F, M_Z, m_t, m_H)$$

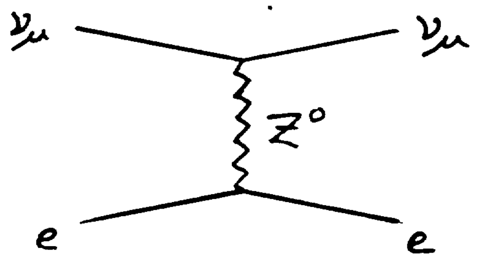
$\sin^2\theta_W$ can be measured directly in $\nu_\mu e$, $\bar{\nu}_\mu e$ interactions through the ratio

$$R = \frac{\sigma(\nu_\mu e)}{\sigma(\bar{\nu}_\mu e)} = 3\,\frac{1 - 4\sin^2\theta_W + \frac{16}{3}\sin^4\theta_W}{1 - 4\sin^2\theta_W + 16\sin^4\theta_W}$$

Latest results (CHARM II) from 762 $\nu_\mu e$ and 1017 $\bar{\nu}_\mu e$ events: (ultimate aim ~ 2000 each)

$$\sin^2\theta_W = 0.233 \pm 0.012 \pm 0.008 \quad (\rightarrow \pm 0.007 \pm 0.003)$$

Angular and energy resolution crucial, as kinematics imply $E\theta^2 < 2m_e$



Figs N 1,2,3

SUMMARY OF PRECISION TESTS

Method	$\sin^2\theta_W$	
M_Z	0.233 ± 0.0013	SLC (+ much better at LEP)
	0.234 ± 0.003	CDF

(These assume $m_t = 90$ GeV, $m_H = 100$ GeV)

$\frac{M_W}{M_Z}$	0.213 ± 0.015	UA2
	0.225 ± 0.012	CDF

(These are direct, but limited by statistics on Z°)

νN	0.235 ± 0.007	CHARM
	0.227 ± 0.007	CDHSW
	0.239 ± 0.011	CCFR

(These are high rate experiments, but have hidden uncertainties from errors on structure functions)

$\nu_\mu e$	0.194 ± 0.022	E734
	0.209 ± 0.037	CHARM I
	0.233 ± 0.014	CHARM II

(Direct, limited only by statistics)

Atomic parity violation	0.217 ± 0.019	Boulder

(This depends on detailed theoretical modelling of the atomic structure)

eD	0.218 ± 0.020	SLAC (Z_0, γ interference)
e^+e^-	0.217 ± 0.024	Global fit

- Universe is filled with cosmological dark matter – accounts for most of the energy
- Probably leads to a "flat" universe i.e. one which has an energy density ρ_0 equal to the critical density ρ_c ie $\Omega = \rho_0/\rho_c = 1$ [$\Omega < 1$, universe "open", $\Omega > 1$, universe "closed"]
- $$\rho_0 = \Omega \rho_c = \Omega . \frac{3H^2}{8\pi G} = \Omega h^2 \, 11 \, \text{keV cm}^{-3}$$

  where H = Hubble parameter
  G = Newtons gravitational constant
  $H = h . 100 \text{ km s}^{-1}/\text{Mpc}$
- Experimentally $\Omega < 2$, $\frac{1}{2} < h < 1$
  Ω, h are not independent but are related by the age of the universe, t_0
  e.g. for $\Omega < 2$, $t_0 > 10^{10}$ yr., $h < 0.57$, $\Omega h^2 < 0.65$
  $\Omega = 1$, $t_0 = 1.5 \times 10^{10}$ yr, $\Omega h^2 = 0.2$
  $\Rightarrow$ reasonable assumption that

  $$0.15 < \Omega h^2 < 0.65$$
- Number density, n_ν, of any flavour of light neutrino is related to the known number density of photons, n_γ, by

  $$n_\nu = \frac{3}{11} n_\gamma \simeq 110 \text{ cm}^{-3}$$

- If ρ_0 is <u>entirely</u> dominated by one flavour of light neutrino, then

$$m_\nu = 100\,\Omega h^2\,\mathrm{eV}$$

or

$$15\,\mathrm{eV} < m_\nu < 65\,\mathrm{eV}.$$

- On basis of quark masses, expect
  $$m_{\nu_\tau} \gg m_{\nu_\mu} \gg m_{\nu_e}$$
  so ν_τ favoured candidate

- On basis of CKM* matrix, expect
  $$\theta_{\tau\mu} \gg \theta_{\tau e}\,, \quad \text{and} \quad \theta_{\tau\mu} \simeq 10^{-2}$$

or

$$\sin^2 2\theta_{\tau\mu} \simeq 4\times10^{-4}$$

- Can only be seen in neutrino oscillation experiment, and $\nu_\mu \longrightarrow \nu_\tau$ expected mode.

- Explanation of solar neutrino deficit?
  $$\nu_e \longleftrightarrow \nu_\mu \quad \Rightarrow \quad m_{\nu_\mu} \sim 10^{-2}\,\mathrm{eV}$$
  $$(m_{\nu_\tau}/m_{\nu_\mu})^2 \simeq (m_\tau/m_\mu)^2 \Rightarrow m_{\nu_\tau} \sim 0{\cdot}2\,\mathrm{eV}.$$

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* Calibbo - Kobayashi - Maskawa matrix which describes the relative strength of the charged current weak interaction between different quark [illegible] [[illegible]]

II ν OSCILLATIONS

- There is no confirmed evidence of neutrino oscillations.

- If observed, they imply mixing of neutrino flavours at some level <u>and</u> at least one of the neutrinos with non-zero mass.

- Appearance experiment

$$P(\nu_i \rightarrow \nu_k) = \sin^2 2\theta_{ik} \; \sin^2\left(1.27 \frac{L(km)}{E(GeV)} \Delta m^2_{ik} (eV)\right)$$

- Disappearance experiment

$$P(\nu_i \rightarrow \nu_i) = 1 - \sum_{k \neq i} P(\nu_i \rightarrow \nu_k)$$

- Present direct m_ν limits:

$m_{\nu_\tau} < 35$ MeV	$\tau \rightarrow \nu_\tau + 5\pi$,	ARGUS
$m_{\nu_\mu} < 250$ keV	$\pi \rightarrow \mu + \nu_\mu$,	SIN
$m_{\nu_e} < \left.\begin{array}{l} 11 \text{ eV} \\ 13.4 \text{ eV} \end{array}\right\}$	$T \rightarrow {}^3He + e^- + \bar{\nu}_e$	$\left\{\begin{array}{l} \text{INS-TOKYO} \\ \text{LOS ALAMOS} \end{array}\right.$

- Explanation of solar ν_e deficit?
$\Rightarrow \delta m^2 \sim 10^{-4} - 10^{-7}$ eV^2

- Limits on $\nu_\mu \leftrightarrow \nu_e$, $\nu_e \leftrightarrow \nu_x$ Fig. N4

- Future CERN experiments would extend limits on $\nu_\mu \rightarrow \nu_\tau$ (SPS), $\nu_\mu \rightarrow \nu_x$ (PS)

Disappearance experiment

- Low energy PS ν-beam: $E_\nu \leq 1$ GeV
- Long baseline: 0.87 km → 4.5 km

} Sensitive to small δm^2

- Uses CHARM detector in two parts:
  150 t at 0.87 km (edge of CERN site)
  500 t at 4.50 km (near Sergy)
- Measure ν_μ flux in the two detectors by charged current interactions: $\nu_\mu \rightarrow \mu$

Two years data-taking:
7500 events in near detector
1000 events in far detector: look for depletion of this number.

Appearance experiment

- High energy SPS ν-beam
- Short baseline

} Sensitive to small $\sin^2 2\theta$

- Looks for ν_τ interactions via

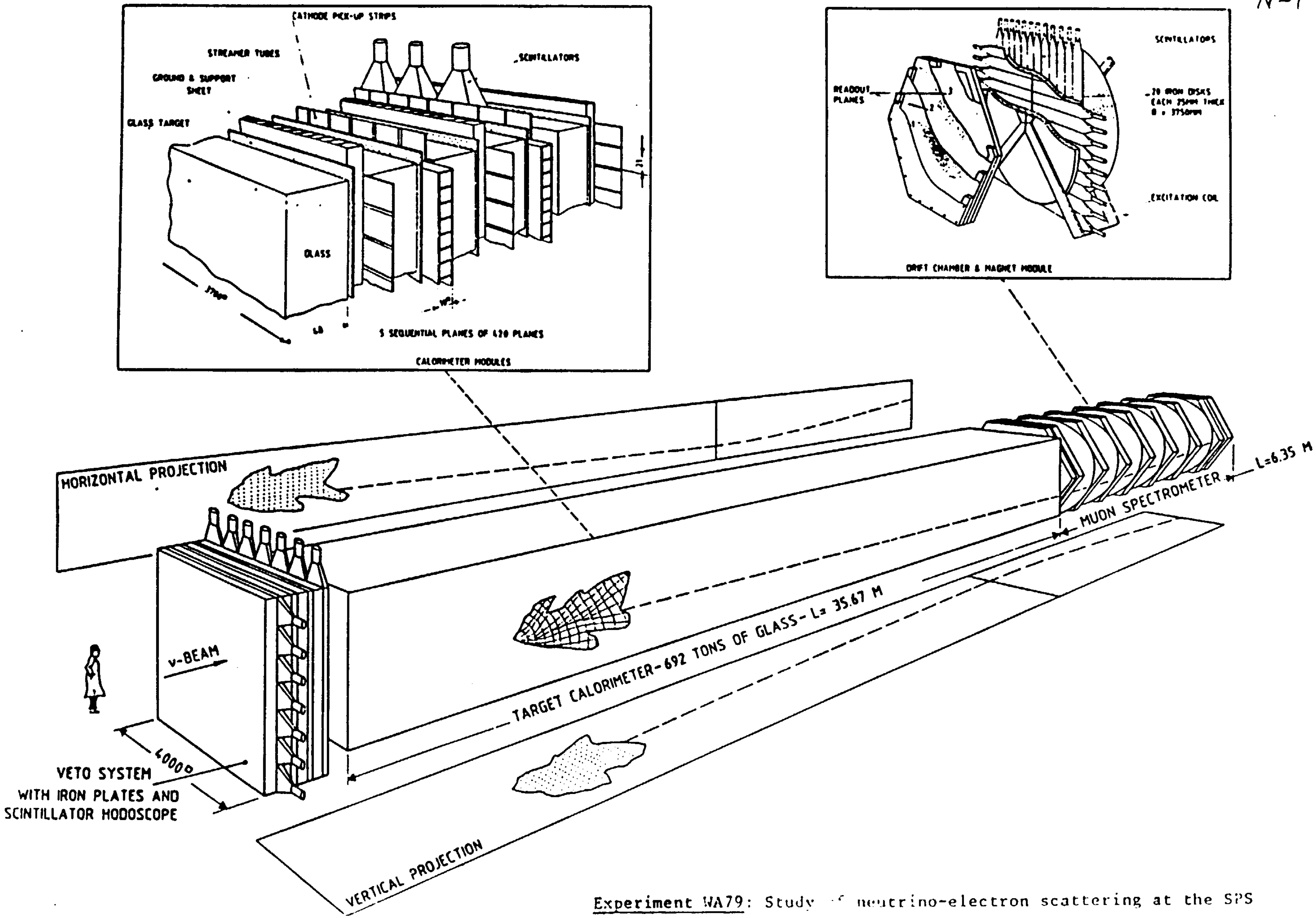
$$\nu_\tau N \rightarrow \tau^- X$$
$$\quad \tau^- \hookrightarrow \mu^- + \nu_\mu + \nu_\tau$$

Kink in track from one-prong decay
Limit is set by background events simulating this decay: expect 6 / year.

- New detector: scintillating fibre + emulsion stacks.

Two years data-taking

N-1



Experiment WA79: Study of neutrino-electron scattering at the SPS

N-2

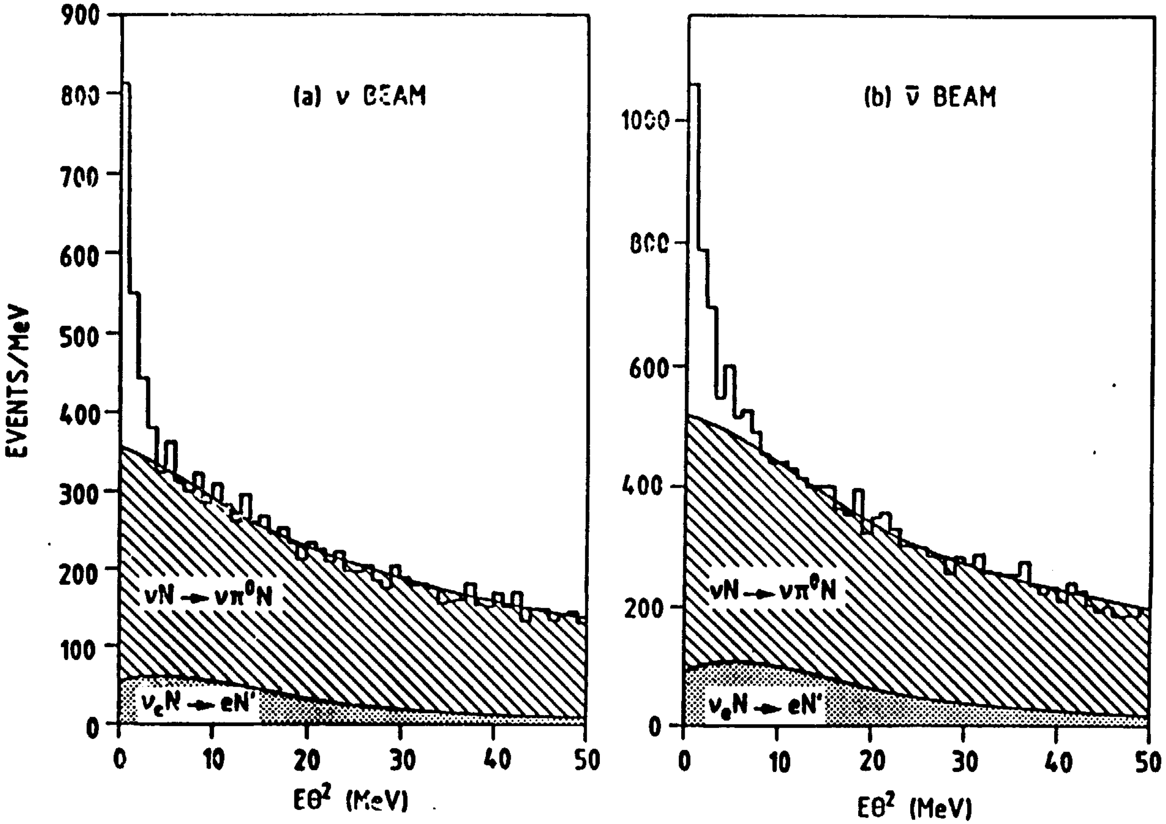


Figure 3

Distribution of selected events as a function of $E\theta^2$, (a) in the neutrino, (b) in the antineutrino beam. The background reactions $\nu_e N \to eN'$ and $\nu N \to \nu \pi^0 N$ are shown separately.

N-3

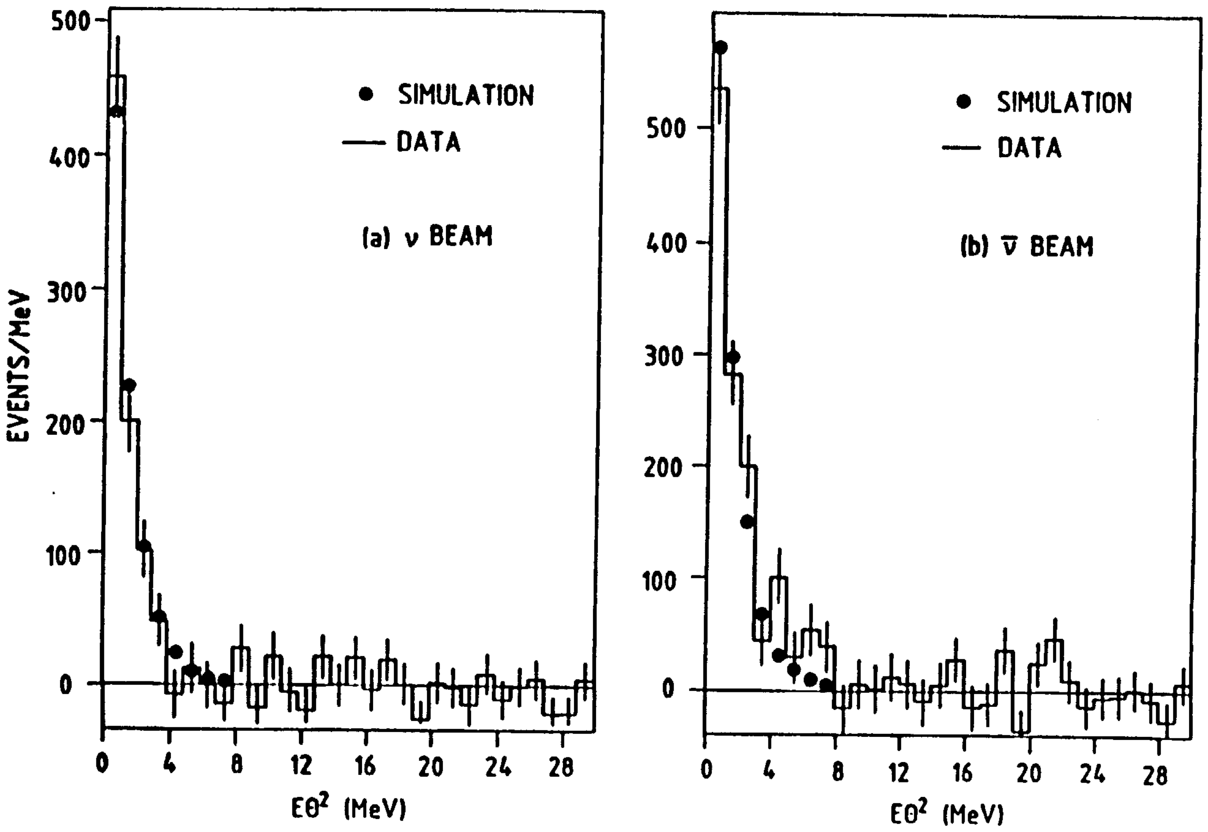
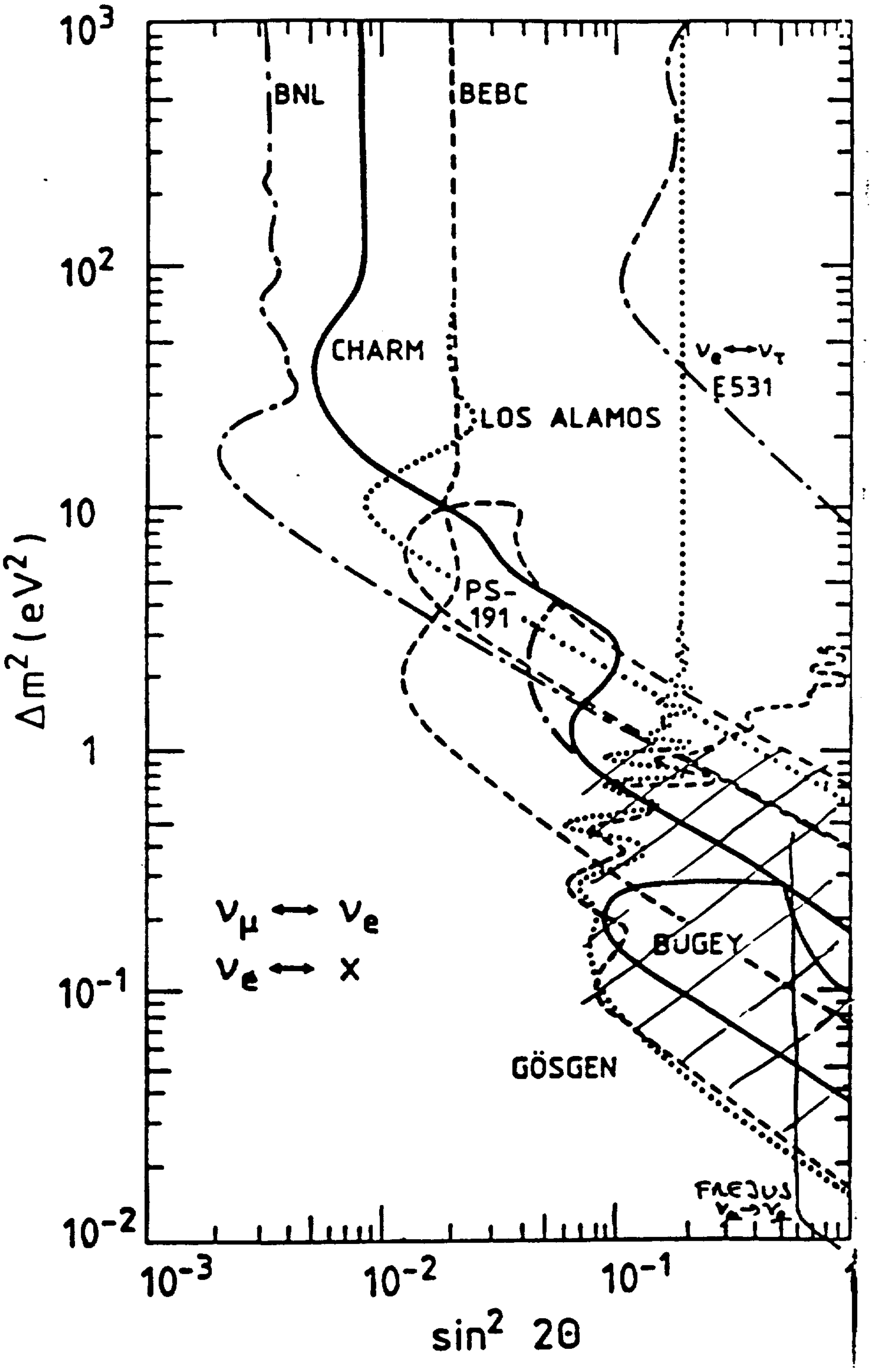


Figure 4

Distribution of νe candidate events as a function of $E\Theta^2$, (a) in the neutrino (b) in the antineutrino beam, after subtraction of the background. The points represent the expected distributions.

N-4


10^3
10^2
10
1
10^{-1}
10^{-2}
Δm^2 (eV^2)
BNL
BEBC
CHARM
LOS ALAMOS
$\nu_e \leftrightarrow \nu_\tau$
E531
PS-191
BUGEY
GÖSGEN
FREJUS
$\nu_e \to \nu_\tau$
$\nu_\mu \leftrightarrow \nu_e$
$\nu_e \leftrightarrow X$
10^{-3}
10^{-2}
10^{-1}
1
$\sin^2 2\Theta$

N-5

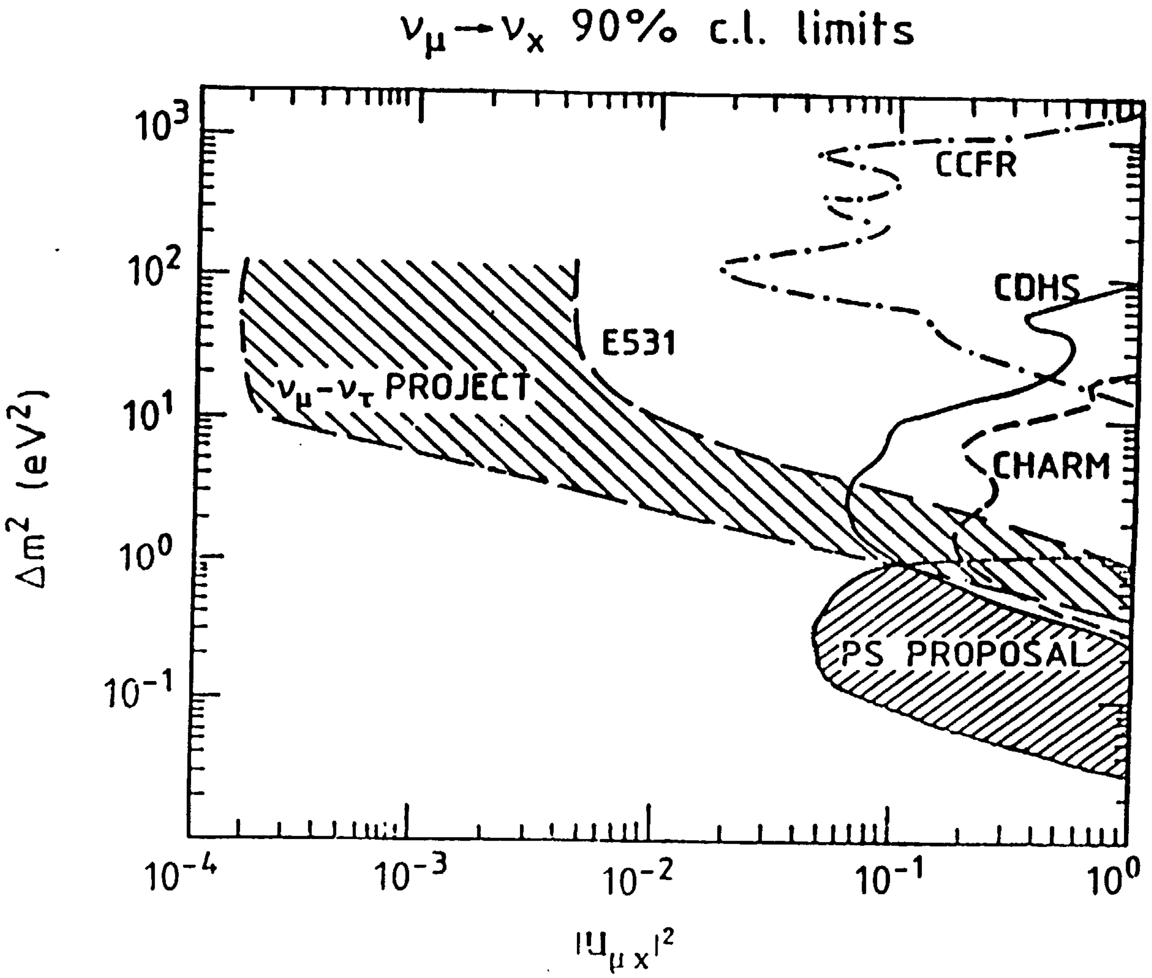


Figure 1 Domains of Δm^2 versus $|U_{\mu\tau}|^2$ explored by previous experiments and to be explored by this experiment and by the PS beam experiment.

N6

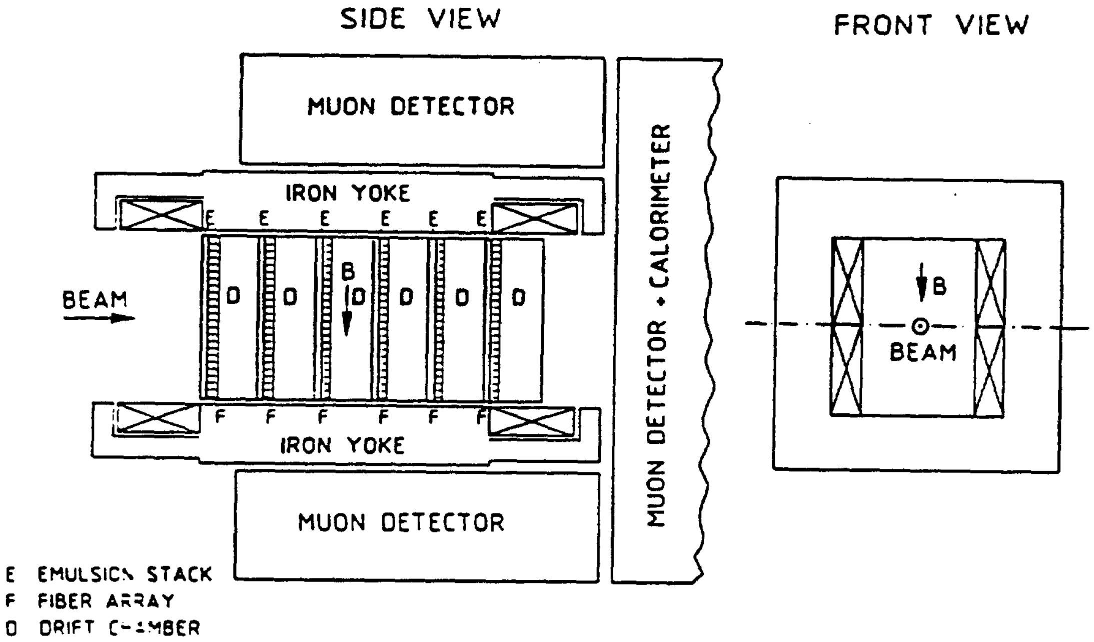
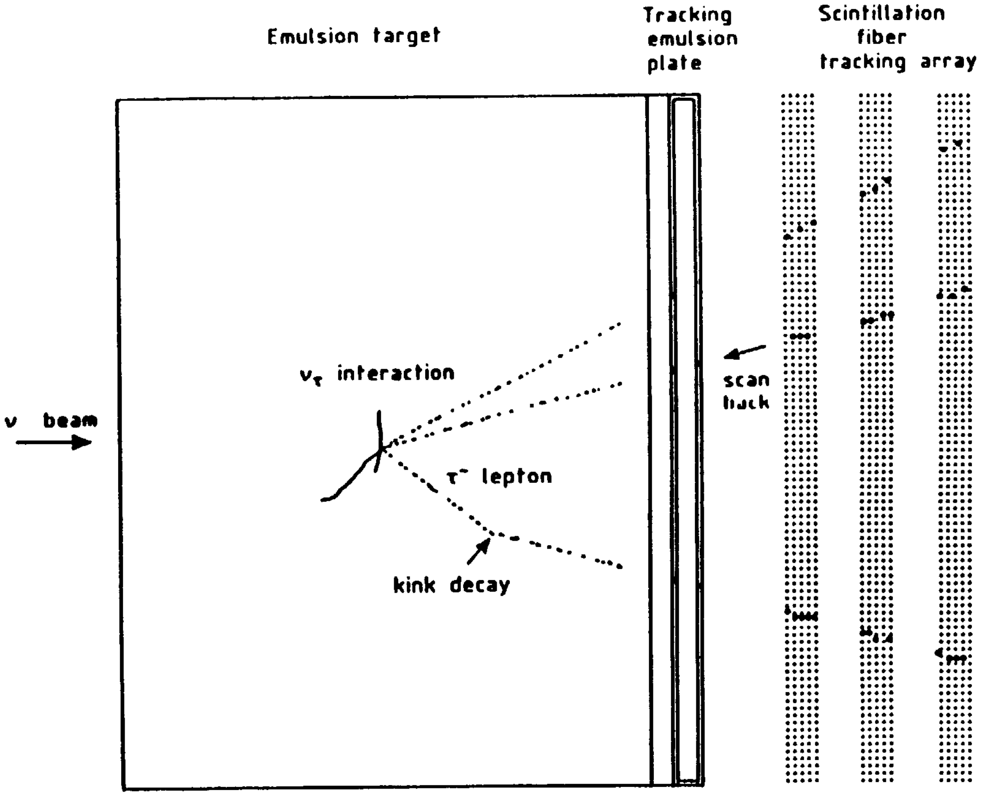


Figure 2

Experimental set-up with six emulsion stacks, scintillating fiber arrays and drift chambers in the spectrometer magnet. Also shown is the muon identifier and the calorimeter.

N-7



ν_τ interaction in emulsion

Figure 4

Schematic view of $\nu_\tau N \rightarrow \tau^- X$ event in the emulsion, with a τ decay kink and track detection in the tracking emulsion plate and in the scintillating fiber array.

CP VIOLATION

- CP violation is observed in the decays of K^0 There are two possible sources.

1) Through the mass matrix i.e. K^0_S and K^0_L, which are the mass eigenstates, are <u>not</u> eigenstates of CP.

There are two states K_1, K_2 which <u>are</u> eigenstates of CP:

$$(CP)\,K_1 = +K_1$$
$$(CP)\,K_2 = -K_2$$

K^0_S and K^0_L are linear combinations of K_1 and K_2

$$K^0_S = K_1 + \varepsilon K_2$$
$$K^0_L = K_2 + \varepsilon K_1$$

As K_1 has $CP = +1$, it decays to $\pi\pi$

As K_2 has $CP = -1$, it decays to $\pi\pi\pi$

The parameter ε introduces some 3π decay into K^0_S and some 2π decay into K^0_L.

2) Through the decay matrix i.e there is an intrinsic 2π decay of the $CP = -1$ eigenstate K_2.

This is allowed in the Standard Model of electroweak theory and can be calculated in terms of the parameters of that theory.

This intrinsic decay is described by a second parameter ε', given by

$$\varepsilon' = \frac{i}{\sqrt{2}} \frac{\mathrm{Im}\, A_2}{A_0} e^{i(\delta_2 - \delta_0)}$$

A_0, A_2 are the $I = 0, 2$ $\pi\pi$ amplitudes
δ_0, δ_2 are the $I = 0, 2$ $\pi\pi$ phase shifts at the mass of the K^0.

- The experimentally observed quantities are

$$\eta_{+-} = \frac{\langle \pi^+ \pi^- | T | K^0_L \rangle}{\langle \pi^+ \pi^- | T | K^0_S \rangle} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \frac{\langle \pi^0 \pi^0 | T | K^0_L \rangle}{\langle \pi^0 \pi^0 | T | K^0_S \rangle} = \varepsilon - 2\varepsilon'$$

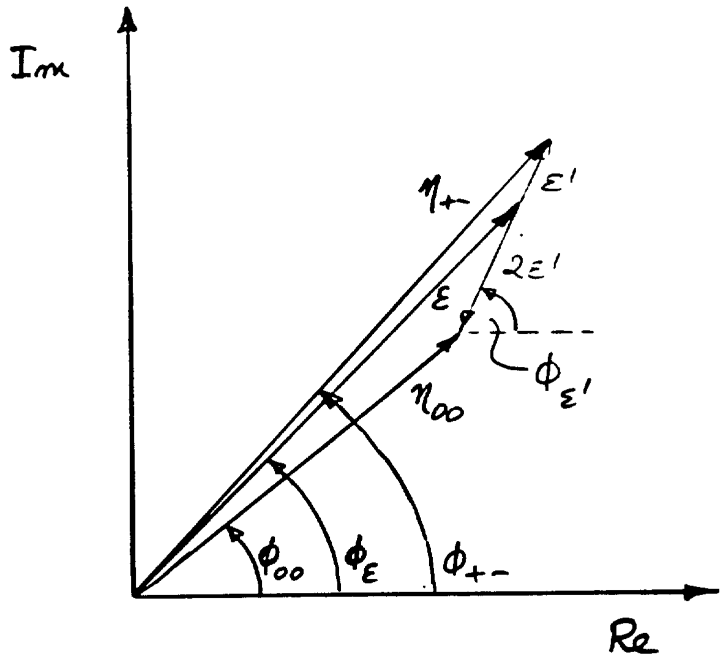
- Before 1988, the experimental situation was

$$|\eta_{+-}| = (2.27 \pm 0.02) \times 10^{-3}$$
$$\phi_{+-} = 44.6^\circ \pm 1.2^\circ$$
$$|\eta_{00}/\eta_{+-}| = 1.00 \pm 0.02$$
$$\phi_{00} = 55^\circ \pm 5^\circ$$

These are consistent with $\varepsilon' = 0$ ie with "superweak" theory

In Standard Model, $\varepsilon' \neq 0$, and $\varepsilon'/\varepsilon \sim O(10^{-3})$ ie too small to be detected by pre-1988 results.

The precise value of ε'/ε depends on m_t and the CP violating phase in the KM matrix



If CPT is good, then $\phi_{+-} = \phi_{00} = \phi_\varepsilon = \phi_{\varepsilon'}$ and all vectors lie along one line.

As $\varepsilon' << \varepsilon$,

$$|\eta_{00}/\eta_{+-}|^2 = \frac{(1-2\varepsilon'/\varepsilon)^2}{(1+\varepsilon'/\varepsilon)^2} \simeq 1-6\varepsilon'/\varepsilon$$

$$\frac{\varepsilon'}{\varepsilon} \approx \frac{1}{6}\left\{1-|\eta_{00}/\eta_{+-}|^2\right\} \equiv \frac{1}{6}\left\{1-R\right\}$$

To obtain R, one measures

$$R = \underbrace{\frac{\Gamma(K_L \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^+\pi^-)}}_{K_L \text{ beam}} \cdot \underbrace{\frac{\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^0\pi^0)}}_{K_S \text{ beam}}$$

NA31 obtain $\frac{\varepsilon'}{\varepsilon} = (3.3 \pm 0.7 \pm 0.8) \times 10^{-3}$

$[R = 0.980 \pm 0.004 \pm 0.005]$

E731 obtain $\frac{\varepsilon'}{\varepsilon} = (-0.5 \pm 1.4 \pm 0.6) \times 10^{-3}$

NA31 have simultaneous collection in $\pi^0\pi^0$, $\pi^+\pi^-$ modes.

Alternate daily K^0_L, K^0_S running by use of 2 production targets. Fig CP-1

E731 have two parallel K^0_L beams, and K^0_S is made by regeneration in one of the beams.
Regenerator moved every spill. Fig CP-2
Simultaneous collection of K^0_L, K^0_S to $\pi^+\pi^-$, $\pi^0\pi^0$

	E731	NA31
$K_L \to \pi^0\pi^0$	300K	109K
$K_L \to \pi^+\pi^-$	400K	295K
$K_S \to \pi^0\pi^0$	900K	932K
$K_S \to \pi^+\pi^-$	1600K	2300K

↑
20% Processed.

ε'/ε key measurement for Standard Model – required to establish the one unknown phase in the Kobayashi-Moskawa matrix.

Also, ε'/ε, m_{top}, $B^0-\bar{B}^0$ mixing must be consistent within the standard model.

A new experiment at CERN.

Aim: to increase intensity by a factor 10
to reduce statistical error
: to reduce systematic error to the same level
i.e. to have both statistical and systematic
errors on $\varepsilon'/\varepsilon \sim 2 \times 10^{-4}$
(recall present errors $\sim 7-8 \times 10^{-4}$)

→ new, intense K^0 beam
better rejection of $K_L \not\to \pi\pi$ decays
⇒ • better mass resolution for $\pi^+\pi^-$
• better rejection of events with additional γ's for $\pi^0\pi^0$.

Two possible scenarios, both of which collect <u>simultaneously</u>

$K^0_L \to \pi^+\pi^-,\ \pi^0\pi^0$
$K^0_S \to \pi^+\pi^-,\ \pi^0\pi^0$

1) Two separate beams converging on the detector
Similar to NA31 in that K_L decays can be collected over ~40m decay region.

Figs CP-3,4,5

2) Combined K^0_L, K^0_S beam
Decay volume common to K^0_L and K^0_S.

The new K^0 beam could be sufficiently intense to provide a source for rare K^0 decays
e.g. $\sim 2.4 \times 10^8$ K^0 per pulse ⇒ $\sim 4 \times 10^6$ in detector.

Cabibbo - Kobayashi - Maskawa Matrix

$$\begin{pmatrix} u \\ c \\ t \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -s_1 c_2 & c_1 c_2 c_3 - s_2 s_3 e^{i\delta} & c_1 c_2 s_3 + s_2 c_3 e^{-i\delta} \\ s_1 s_2 & -c_1 s_2 c_3 - c_2 s_3 e^{i\delta} & -c_1 s_2 s_3 + c_2 c_3 e^{i\delta} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

where $s_i = \sin\theta_i$, $c_i = \cos\theta_i$

The matrix describes the relative strength of the charged current weak interaction between different quark flavours

With $s_2 = s_3 = 0$, $c_2 = c_3 = 1$, we get back to Cabibbo Theory, and $\theta_1 = \theta_c$

$$\begin{pmatrix} u \\ c \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

or

$$u = d\cos\theta_c + s\sin\theta_c$$
$$c = -d\sin\theta_c + s\cos\theta_c$$

The phase δ is the source of CP violation

NA31 SIMULTANEOUS COLLECTION IN $\pi^0\pi^0$, $\pi^+\pi^-$ MODE
ALTERNATE DAILY K^0_L, K^0_S RUNNING BY USE OF 2 PRODUCTION TARGETS.

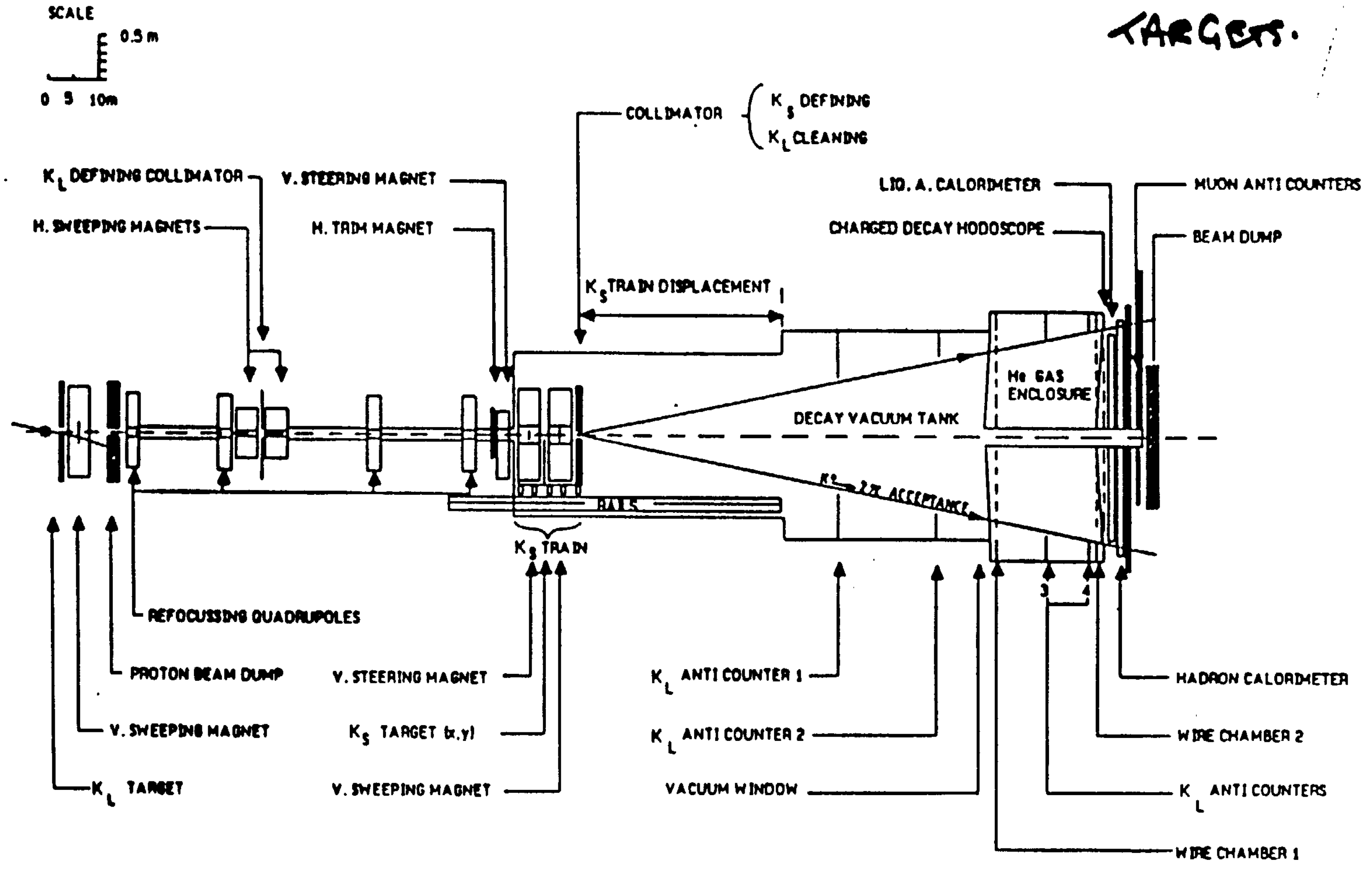


fig. 1a

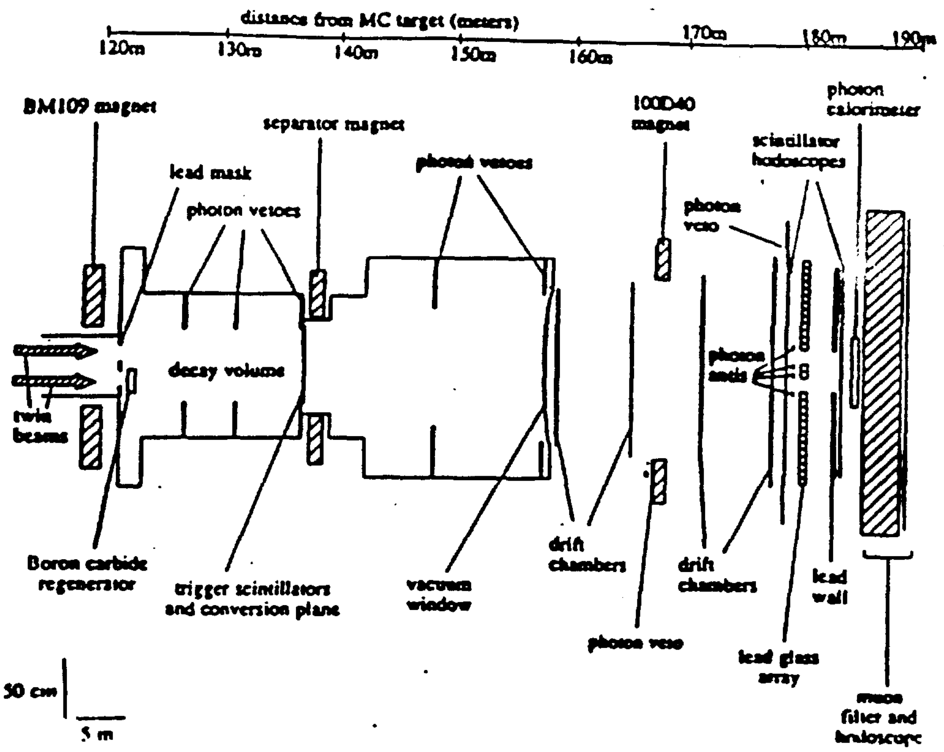


FIG. 1. Detector Schematic, elevation view.

E731 TWO PARALLEL K_L^0 BEAMS

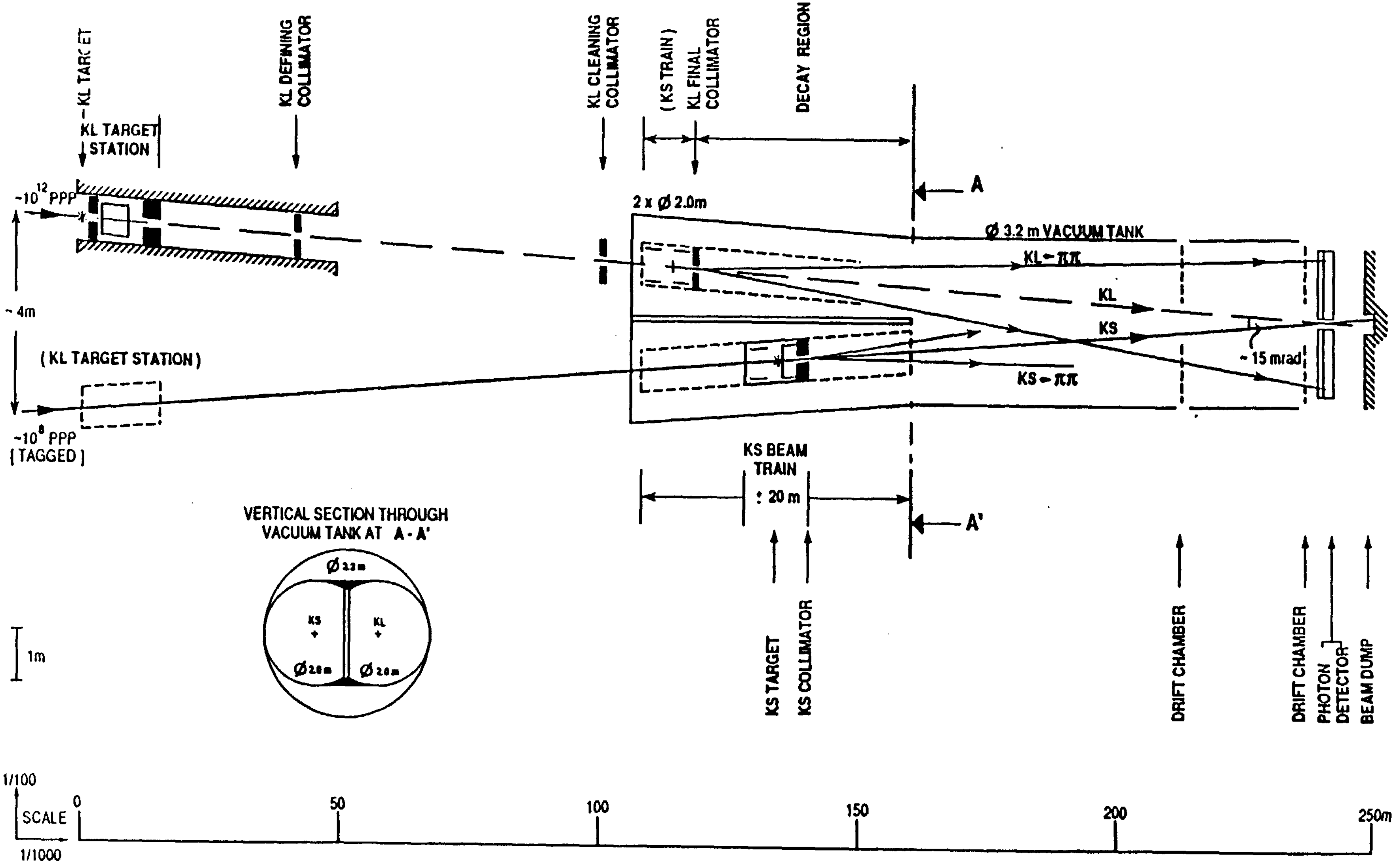
K_S^0 MADE BY REGENERATION IN ONE OF THE BEAMS

REGENERATOR MOVED EVERY SPILL

SIMULTANEOUS COLLECTION OF K_L^0, K_S^0 TO $\pi^+\pi^-$, π^{00}

CP-3

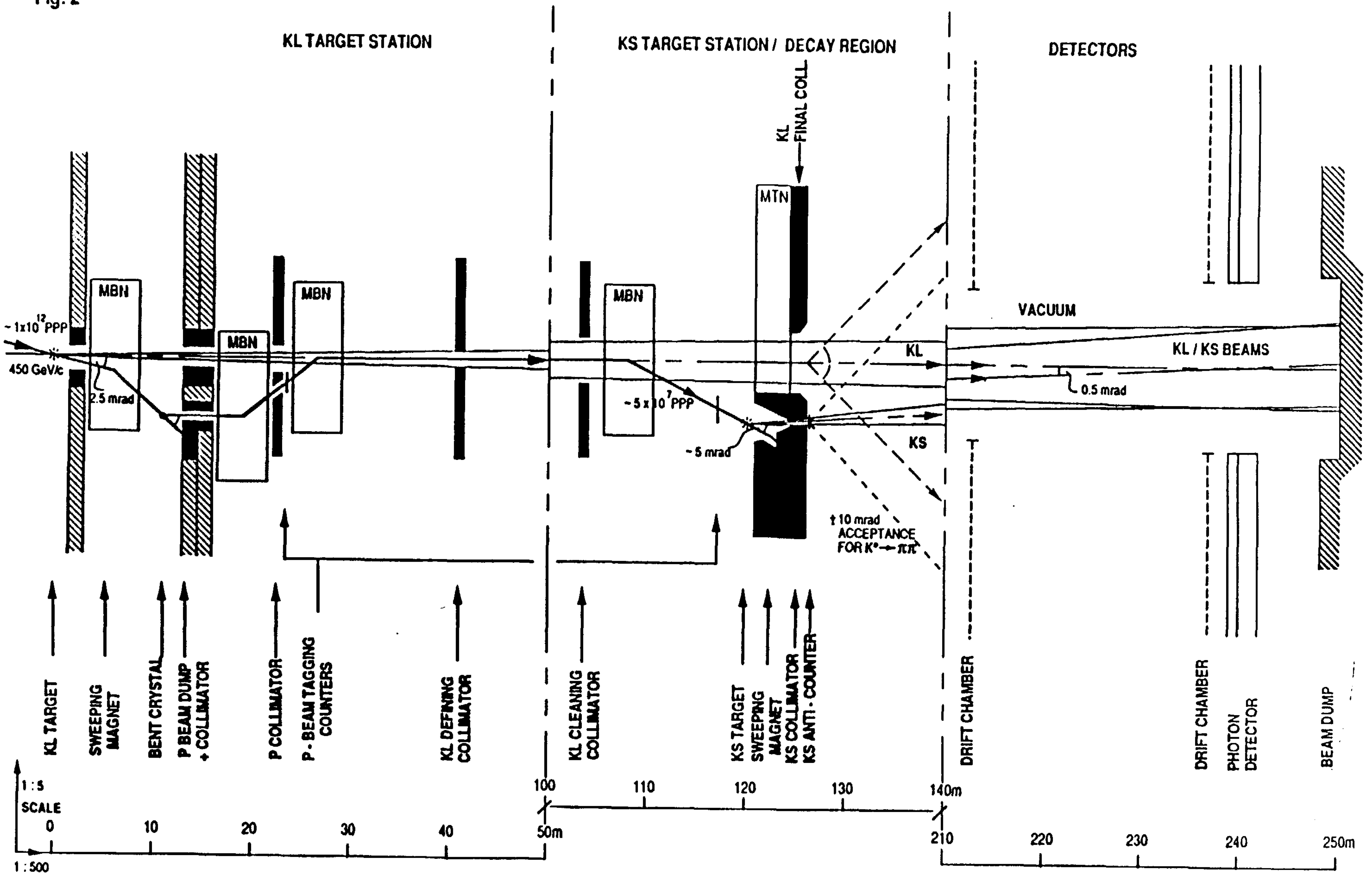
Fig. 1


KL TARGET
KL TARGET STATION
KL DEFINING COLLIMATOR
KL CLEANING COLLIMATOR
(KS TRAIN)
KL FINAL COLLIMATOR
DECAY REGION
~10^12 PPP
~ 4m
(KL TARGET STATION)
~10^8 PPP
(TAGGED)
2 x Ø 2.0m
A
Ø 3.2 m VACUUM TANK
KL → ππ
KL
KS
~ 15 mrad
KS → ππ
KS BEAM TRAIN
± 20 m
A'
VERTICAL SECTION THROUGH VACUUM TANK AT A - A'
Ø 3.2 m
KS
KL
Ø 2.0 m
Ø 2.0 m
1m
KS TARGET
KS COLLIMATOR
DRIFT CHAMBER
DRIFT CHAMBER
PHOTON DETECTOR
BEAM DUMP
1/100
SCALE
1/1000
0
50
100
150
200
250m

42

CP-4

Fig. 2



KL TARGET STATION
KS TARGET STATION / DECAY REGION
DETECTORS
~1x10^{12} PPP
450 GeV/c
2.5 mrad
MBN
MBN
MBN
MBN
MTN
KL FINAL COLL.
~5 x 10^{7} PPP
~5 mrad
KL
KS
± 10 mrad ACCEPTANCE FOR K° → ππ
VACUUM
KL / KS BEAMS
0.5 mrad
KL TARGET
SWEEPING MAGNET
BENT CRYSTAL
P BEAM DUMP + COLLIMATOR
P COLLIMATOR
P - BEAM TAGGING COUNTERS
KL DEFINING COLLIMATOR
KL CLEANING COLLIMATOR
KS TARGET
SWEEPING MAGNET
KS COLLIMATOR
KS ANTI - COUNTER
DRIFT CHAMBER
DRIFT CHAMBER
PHOTON DETECTOR
BEAM DUMP
1 : 5
SCALE
1 : 500
0
10
20
30
40
50m
100
110
120
130
140m
210
220
230
240
250m

CP-5

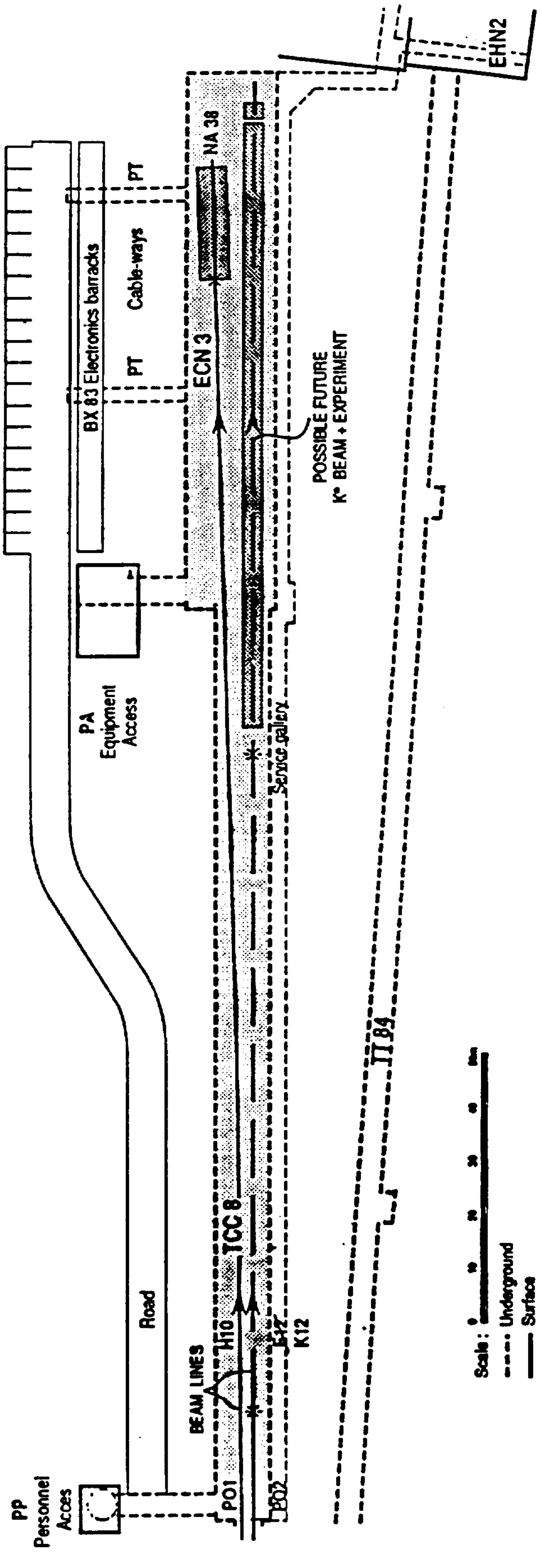

PP
Personnel
Acces
Road
BEAM LINES
H10
TCC 8
P01
P02
E12
K12
PA
Equipment
Access
BX 83 Electronics barracks
PT
Cable-ways
PT
ECN 3
NA 38
Service gallery
POSSIBLE FUTURE
K° BEAM + EXPERIMENT
TT 84
EHN2
Scale : 0 10 20 30 40 50m
Underground
Surface

Fig.4

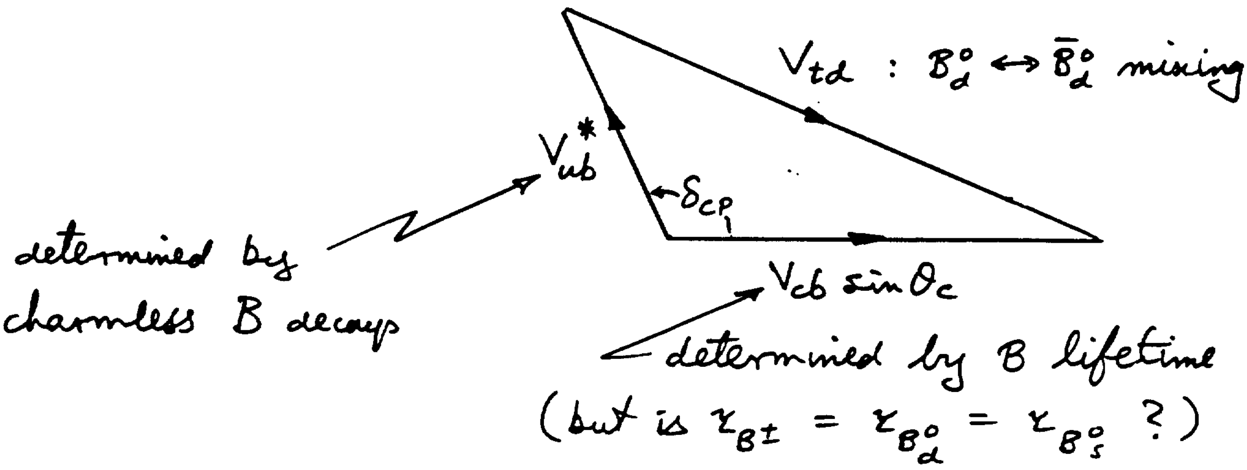
B-PHYSICS.

- B-physics: a primary source of information on CKM matrix elements

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V_{cb}, V_{ub}, V_{td} linked by the unitarity relation

$$V_{cb} \sin \theta_c = V_{ub}^* + V_{td}$$



- By measuring three properties of B-decays

1) lifetimes
2) charmless decays
3) mixing

system is constrained ⇒ consistency check for the S.M.

- Note importance of CP-violation in B-decays Expected to be much stronger than in K-decay No existing accelerator can produce a sufficient

- Basic ingredients for fixed-target beauty experiments are:

1) – Detection of decay vertices
    1) active targets
    2) Si-μstrip vertex detectors or CCD's

Recall that NA14 pioneered Si-M.V.D.'s } charm
NA32 made first use of CCD's }

2) – Large statistics

In charm studies;

NA14, NA32	~ $17 \cdot 10^6$	triggers
WA82	~ $50 \cdot 10^6$	"
E691	~ $100 \cdot 10^6$	"
E769	~ $500 \cdot 10^6$	"

⇒ large processing facilities – ACP farms ----

3) – Faster and more intelligent triggers/processors
    $\sum E_T$, $\sum p_T$ (NA14, E691, E769, WA89 (Hyperons))
    → IP triggers WA82
    → Secondary vertex triggers
        – contiguity processors: WA82
        – data-driven processors: Knapp/Schlein
        – associative memory processers: Amendolia

4) – Extensive use of particle identification (RICH counters): WA82, WA89

- Physics accessibility in fixed-target experiments:
    - Lifetimes **** (recall charm situation)
    - Spectroscopy***
    - QCD tests** (via cross section)
    - Mixing*

WA 82

- At present completing charm experiment.
  Anticipate ~ $50-60 \cdot 10^6$ triggers ⇒ ~ 20K charm
  The trigger is:
  I-level: interaction trigger
  II-level: multiplicity ≥ 3 in ≥ 3 planes of MVD
  + ≥ 3 hits in MWPC
  III-level: impact parameter trigger
  ⇒ ~ 200 events/burst
  ~ 10 enhancement factor.
  Exclusive BR. down to ~ 5‰ accessible.

- These data could have ~ 100-300 $B\bar{B}$ events.
  Try to find by picking $D^+ \rightarrow K^- \pi^+ \pi^+$ missing main vertex by > 80 μm

- Future plans are to study beauty hadroproduction
  - cross sections
  - lifetimes : $B^{\pm}$, B^0_d
  - mixing : $B^0_d \leftrightarrow \bar{B}^0_d$

  Need ~ 10^3 identified B's
  Method would be
  1) observe the $b \rightarrow c$ decay
  ⇒ new vertex detector
  2) select events with strong evidence for a secondary vertex using a faster processor
  ⇒ new trigger algorithm + processor
  ~ 100 - 200 enhancement factor.

- Trigger would be
  - I-level : interaction trigger
  - II-level : "butterfly" hodoscope (p_T) trigger
  - III-level : MVD + MWPC multiplicity
  - IV-level : secondary vertex trigger.

WA82 hope to start taking beauty data in 1991. Note that this will produce ~ 10^5 charm events.

WA84

- Aims the same as WA82, technique different.
- Active target of scintillating fibres ($\phi = 30\mu m$) + use of MVD.
- Hope for ~ 200 $B\bar{B}$ / nb / 50 days [$\sigma \sim 1$-3 nb]
- 1988 test with glass fibres unsatisfactory
- 1989 test with plastic fibres seems satisfactory → full test in Omega in September, then evaluate.

CHARM PHYSICS – HYPERON BEAM

- Hyperon beam installed at the end of H_1, to Omega. $10^5\ \Sigma^-$ / burst, at 360 GeV/c ($2 \cdot 10^{10}$ protons on target)
  - contamination $\sim 10^5\ \pi^-$ /burst – beam TRD to tag π^-.

- Layout: – Λ decay region in front of Omega
  - MVD – enlarged version of WA82 design (spot size $\sim 3 \times 3\ \mathrm{cm}^2$)
  - $\pi/K/p$ separation up to ~ 150 GeV/c with upgraded Omega RICH
  - new Pb-glass array for γ detection
  - beam TRD to tag π^-

- Later: – hadron calorimeter
  - beam RICH to tag Ξ^-, Ω^- for second phase of experiment.

- Physics goals I (1990/91)
  - large sample of $\Xi_c^+ (\rightarrow \Lambda K^- \pi^+ \pi^+)$: few $\times 10^3$
  - observation of Ω_c, $\Xi_c^0 (\rightarrow \Sigma^- K^- \pi^+ \pi^+)$
    $\hookrightarrow n \pi^-$ (hadron calorimeter)
  - look for electromagnetic transitions
    $\Xi_c^* \rightarrow \gamma\, \Xi_c$, $\Omega_c^* \rightarrow \gamma\, \Omega_c$ (Pb-glass)
  - measure various decay modes and B.R.'s
  - measure lifetimes : Ξ_c^+, Ω_c, eventually Ξ_c^0
  - production cross sections
  - search for exotic meson $U(3100) \rightarrow \Lambda \bar{p} \pi^+ \pi^+$ $(Q = +1,\ S = -1)$ seen by WA62
  - Λ_b ?

- Physics goals II (1991/92)
  - use tagged Ξ^-, Ω^- beam
  - study Ξ^*, Ω^* resonances (e.g. ×10 more intensity than WA42, WA46 where two Ω^* were found)
  - study relative charm production rates with Ξ^-, Ω^-
  - rare hyperon decays (eg. $\Omega^- \rightarrow \Xi e \nu$)
  - search for doubly strange dibaryon (uuddss)
    eg → $\Lambda\Lambda$, $\Sigma^- p$
    $\hookrightarrow n\pi^-$ (hadron calorimeter)

FERMILAB FIXED-TARGET CHARM & BEAUTY

E691: $\gamma \sim 150$ GeV
$100 \cdot 10^6$ triggers $\Rightarrow \sim 10{,}000$ charm

E769: π^-, K^- at 250 GeV
$500 \cdot 10^6$ triggers

E791*: π^+, p 500 GeV.
$\gtrsim 10^9$ triggers $\Rightarrow \sim 10^5$ charm ($\sim 5 \cdot 10^3$ baryons)
$\sim 200\ B\bar{B}$

E771*: p 900 GeV, J/ψ trigger
$\Rightarrow \sim 5{,}000\ B\bar{B}$

E781*: (SELEX): Σ^- at 600 GeV.
$\Rightarrow \sim 10^6$ charm baryons.

E789: charmless B-decay (2-body)
$B_d^0 \rightarrow \pi^+\pi^-$
$B_s^0 \rightarrow K^+\pi^-$
$\Lambda_b^0 \rightarrow p\pi^-$
} discovery material
If $|V_{ub}/V_{cb}| \sim 0.1$ (Argus-CLEO) expect ~ 80 events
Very challenging!

Note: $\sigma_B(\text{FNAL}) \sim 10\,\sigma_B(\text{CERN})$
$\sigma_c(\text{FNAL}) \sim 2\,\sigma_c(\text{CERN})$.

HEAVY ION PHYSICS

- At sufficiently high values of energy-density and temperature expect (Debye screening of colour charge)
  - quark deconfinement
  - chiral symmetry restoration
  - quark gluon plasma as a new state of matter.

- Based on computer simulation of lattice QCD
  - statistical QCD
  - hadron collisions : quark dynamics
  - heavy ion collisions : quark thermodynamics.

- Deconfinement parameters? QCD predicts critical energy density and temperature to be

$\varepsilon_c \sim 1.0 - 3.0 \text{ GeV/fm}^{-3}$ [nuclear matter : $\varepsilon \sim 0.15 \text{ GeV fm}^{-3}$]

$T_c \sim 150-200 \text{ MeV}$

- Typical volumes expected:

	S - S	Pb - Pb	
initial	30 fm^3	770 fm^3	geometry × transit time
transition	30 fm^3	780 fm^3	when things begin to happen
freeze-out	300 fm^3	2100 fm^3	when things stop happening

$\swarrow$ compatible with NA35 interferometry results

These are average volumes : can increase them (factor ~ 2) by selecting central collisions eg. events with high transverse energy, E_T

- Energy density

$\varepsilon_0 \sim A^{1/3} \rightarrow \sim 1.5$ for S-S
″ Pb-Pb } For "average" event.
Factor ~2 for high E_T

Experimental probes.

- Initial energy density:

– $(dN/dy)_A$, $(dE_T/dy)_A$, $p_0|_A$

- Freeze-out volume:

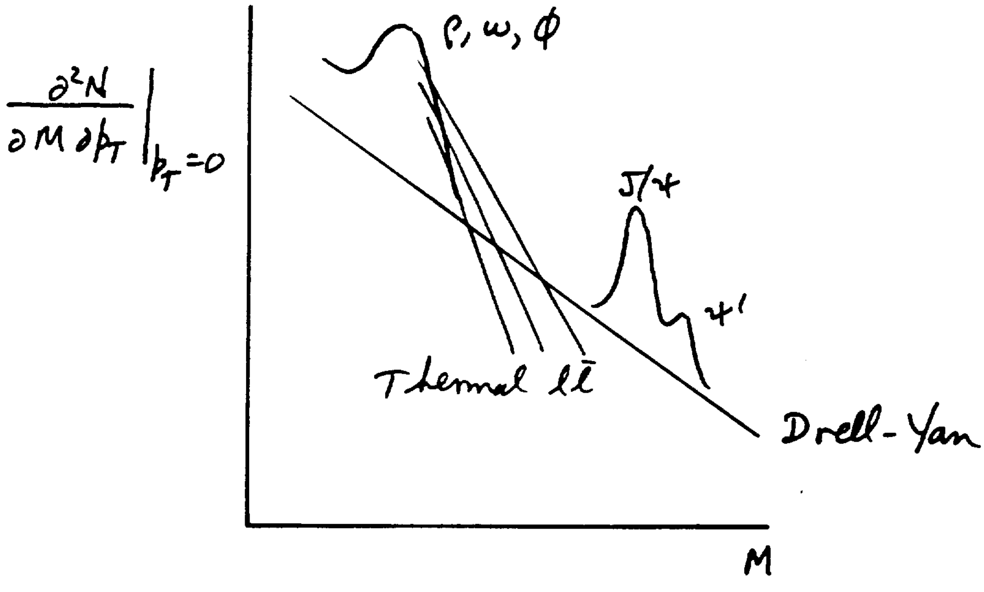
– like particle interferometry: $\pi\pi$, KK *

- Thermal equilibrium, temperature:

– spectrum and polarisation of di leptons

Gas of $q\bar{q}$ or $h\bar{h}$: annihilation $\rightarrow \gamma \rightarrow l\bar{l}$

Spectrum $\partial^2N/\partial M \partial p_T \sim e^{-\frac{1}{T}\sqrt{M^2+p_T^2}}$



$M \gtrsim 2.5 - 3.0$ GeV: Drell-Yan, J/ψ, ψ', ...

$M \lesssim 1.0 - 1.5$ GeV: Hadronic

$1.0 - 1.5 \lesssim M \lesssim 2.5 - 3.0$ GeV: Thermal

Thermal dileptons should appear with increasing A, ϵ_0

Polarisation : Drell-Yan : $dN/d\theta \sim 1 + \cos^2\theta$
Thermal : $\sim$ constant
Hadronic : $\sim$ constant

Pion interferometry

$P(p)$ = probability of observing a pion with 4-momentum p_μ

$$C(p,q) = \frac{P(p,q)}{P(p)\,P(q)}$$

where for identical pions ($\pi^+\pi^+$ or $\pi^-\pi^-$)

$$P(p,q) = \int d^4y_1\, d^4y_2\, \rho(y_1)\rho(y_2)$$

$$\times \tfrac{1}{2}\Big[e^{-ip(x_1-y_1)}e^{-iq(x_2-y_2)} \underset{\nwarrow}{+} e^{-iq(x_2-y_1)}e^{-ip(x_1-y_2)}\Big]^2$$

Interference due to Bose-Einstein

$$= \int d^4y_1\, d^4y_2\, \rho(y_1)\rho(y_2)\, \tfrac{1}{2}\Big[1+1$$

$$+2\,\mathrm{Re}\left\{e^{-ip(x_1-y_1)}e^{-iq(x_2-y_2)}\,e^{iq(x_2-y_1)}e^{ip(x_1-y_2)}\right\}\Big]$$

$$= \int d^4y_1\, d^4y_2\, \rho(y_1)\rho(y_2)\Big[1+\cos\{(p-q)(y_1-y_2)\}\Big]$$

$$C(p,q) = 1 + \frac{\int d^4y_1\, d^4y_2\, \rho(y_1)\rho(y_2)\cos\left[(p-q)(y_1-y_2)\right]}{\left[\int d^4y\, \rho(y)\right]^2}$$

If we assume a simple form for $\rho(y)$
e.g. a Gaussian,

$$\rho(y) \equiv \rho(\underset{\sim}{r}, t) \propto e^{-r^2/R^2}\, e^{-t^2/\tau^2}$$

the integral can be evaluated.

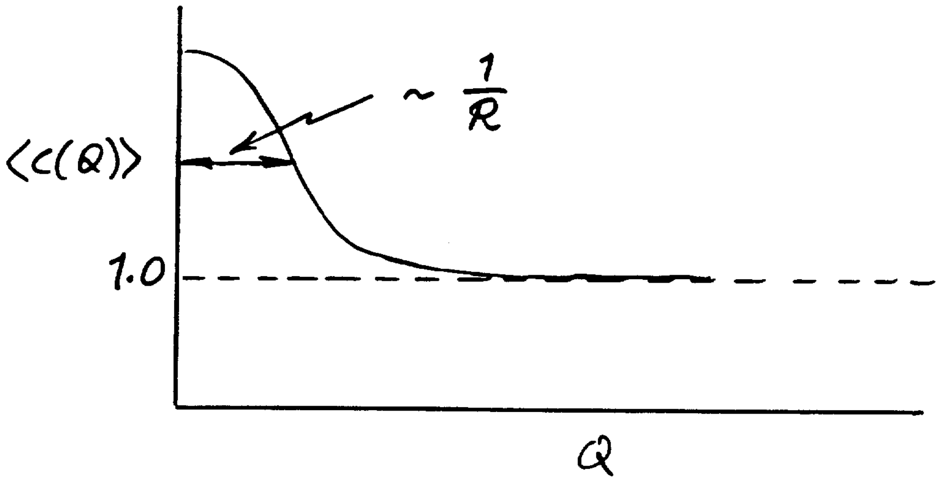
[Here $R \equiv$ radius parameter, τ = lifetime parameter]

The result is

$$C(p,q) \equiv C(p-q) \equiv C(\underset{\sim}{Q}, Q_0) \quad [\,Q \equiv (p-q)\,]$$

$$= 1 + \lambda\, e^{-\frac{1}{2}\underset{\sim}{Q}^2 R^2}\, e^{-\frac{1}{2} Q_0^2 \tau^2}$$

empirical parameter
= 1 for ideal chaotic source.



- Collective behaviour, flavour equilibrium
  – K/π, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$, ... ratios

An equilibrium gas (hadrons or quarks) gives higher ratios than superposition of nucleon-nucleon collisions

– low Q/A baryon clusters –$(3N u, 3N d)$: $Q = N$
–$(2N u, 2N d, 2N s)$: $Q = 0$

– strangelets.

- J/ψ, ψ' suppression cf. Drell-Yan continuum
  – J/ψ should "dissolve" in the plasma when the Debye screening length, r_D, becomes smaller than the Bohr radius, r_B, of the J/ψ.

In the plasma, the normal charmonium potential

$$V(r) = -\frac{\alpha}{r} + \sigma r \quad \text{(gluon exchange + confinement)}$$

is replaced by

$$V(r) = -\frac{\alpha}{r} e^{-r/r_D} \quad \text{(Debye screening + unconfined)}$$

Can solve the Schrödinger equation numerically to find the dissolution condition for J/ψ:

$$r_D \leq 0.84\, r_B$$

The Debye screening radius is inversely proportional to the temperature, and this then gives

$$T_{diss} \gtrsim 200 \text{ MeV}.$$

[Depends on m_c, α and belief in perturbation theory]

- For the formation of bound charm ($J/\psi, \psi', \chi_c$) one can obtain numerical values for the mean radius $\langle r \rangle$, the mean radial momentum $\langle p \rangle$ and the proper formation time τ_0.

Resonance	$\langle r \rangle$ fm	$\langle p \rangle$ GeV/c	τ_0 fm/c
J/ψ	0.453	0.672	0.89
ψ'	0.875	0.768	1.50
χ_c	0.696	0.456	2.07

- If a plasma is formed, is extended in space and has a long lifetime, a $c\bar{c}$ pair may stay inside the plasma for the time required to reach the size of the resonance, screening operates and the J/ψ will not be formed. If the $c\bar{c}$ pair has sufficiently high momentum, it will escape the screening region and the J/ψ will be formed. So expect J/ψ suppression to decrease with increasing p_T.

Questions are beginning to be answered

(i) Is the energy deposition high enough?
It is as high as one could hope it to be.

- with ^{16}O up to 65% of $E_{T\,max}$ } at 200 GeV/A
- with ^{32}S up to 60% of $E_{T\,max}$ }

(ii) Can we trigger on central events?
Yes. We now know that

- missing forward energy
- large transverse energy
- high multiplicity

are equivalent triggers for central collisions.

(iii) Are there any collective excitations?
Yes, this seems to be the case.

- $\pi^-\pi^-$ interferometry

Two-pion correlation function formed by taking all unique pion-pair combinations per event and summing over events to obtain the correlated pair and, to obtain the uncorrelated (background) pairs, by taking all unique pair combinations for pions from different events.
The correlation function $C(q_T, q_L)$ is given by

$$C(q_T, q_L) = 1 + \lambda e^{-\frac{1}{2} q_T^2 r_T^2} e^{-\frac{1}{2} q_L^2 r_L^2}$$

where r_T, r_L are the transverse and longitudinal dimensions of the source of pions, and λ is a "chaoticity" parameter ($\lambda = 1$ implies totally chaotic pion emission)

^{16}O collisions:

$1 < y_{Lab} < 2$: $r_T = 4.3 \pm 0.6$
$r_L = 2.6 \pm 0.6$
$\lambda = 0.34 \pm 0.08$

$2 < y_{Lab} < 3$: $r_T = 8.1 \pm 1.6$
$r_L = 5.6 \pm 1.0$ } 2.5 × Oxygen radius. Fig I-1
$\lambda = 0.77 \pm 0.19$

- Inclusive p_T spectra in ^{16}O collisions.

$2 < y_{Lab} < 3$: "anomalous" peak at low p_T
⇒ inflated fireball before freeze-out. Fig I-2

(iv) Are there anomalous effects in $\frac{dE_T}{dy}$, $\frac{dN}{dy}$, ...?
Nothing seen, but pions are great averagers.

(v) Is there anomalous photon radiation?
An unsettled question, but probably not.

(vi) Is strangeness production enhanced?
There is now evidence that this is the case.

(vii) Is J/ψ production suppressed relative to the μ-pair continuum?
Yes, there are very strong effects.
- at small E_T (i.e. peripheral collisions) the ratio (J/ψ)/continuum is same as in pA collisions.
- at large E_T (i.e central collisions) the ratio is ~ 40% of this value.

- the suppression decreases with increasing p_T
- everything behaves as expected, but data not yet sufficiently precise to be unambiguous. Figs I 3-7

It is clear that there is something new: A large, "spherical" chaotic system in the central region, of high energy density (1-3 GeV fm^{-3}) with a sufficiently long lifetime to support collective phenomena.

- Do we know what it is?

No.
It could be evidence for the formation of a quark-gluon plasma, but it could be a dense pionic system (which would in itself be an interesting object of study).

The keys to our understanding are:
- anomalous low-mass lepton pairs
- "dissolving" light-quark resonances
- strangeness enhancement
- pion (kaon) interferometry
- J/ψ suppression.

Future Programme

- ^{32}S runs in 1990, 1991 each ~ 30days
- Beam intensity up by ~2-3 on previous ^{32}S run
  $\Rightarrow 2-3 \times 10^{7}$ ions/burst.
- Approved experiments are:
- WA80: π^0, η^0, prompt γ correlated with other quantities
- WA85: Omega: strangeness ($K^0, \bar{K}^0, \Lambda, \bar{\Lambda}$) in range $2.2 < y_{lab} < 3.2$, $p_T > 1$ GeV.
- NA34/3: low mass $\mu^+\mu^-$ pairs
- NA35: (Streamer chamber + TPC): overall view + some specifics — in particular $\pi^+\pi^-$ interferometry.
- NA36: (EHS + TPC): strangeness ($K^0, \bar{K}^0, \Lambda, \bar{\Lambda}, \Xi, \bar{\Xi}$) in range $2.0 < y_{lab} < 4.4$, $p_T > 0.6$ GeV.
- NA38: J/ψ production
- NA44*: $\pi^+\pi^-$, K^+K^- interferometry (focussing spectrometer)
- NA45*: low mass e^+e^- pairs.
- Emulsion experiments.

* New experiments for 1991

- Lead beam from 1993 ?
- Experiments:

$$\left.\begin{array}{l}\text{– “low mass” } \mu^+\mu^-/e^+e^- \\ \text{– } J/\psi \\ \text{– interferometry} \\ \text{– strangeness}\end{array}\right\}\text{ specialised.}$$

– large acceptance detector – general.

I-1

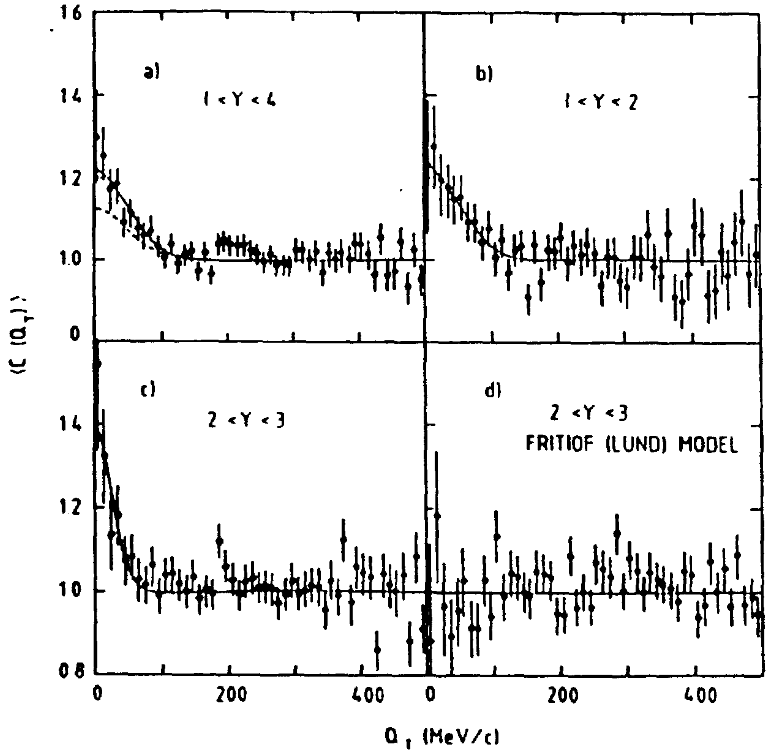
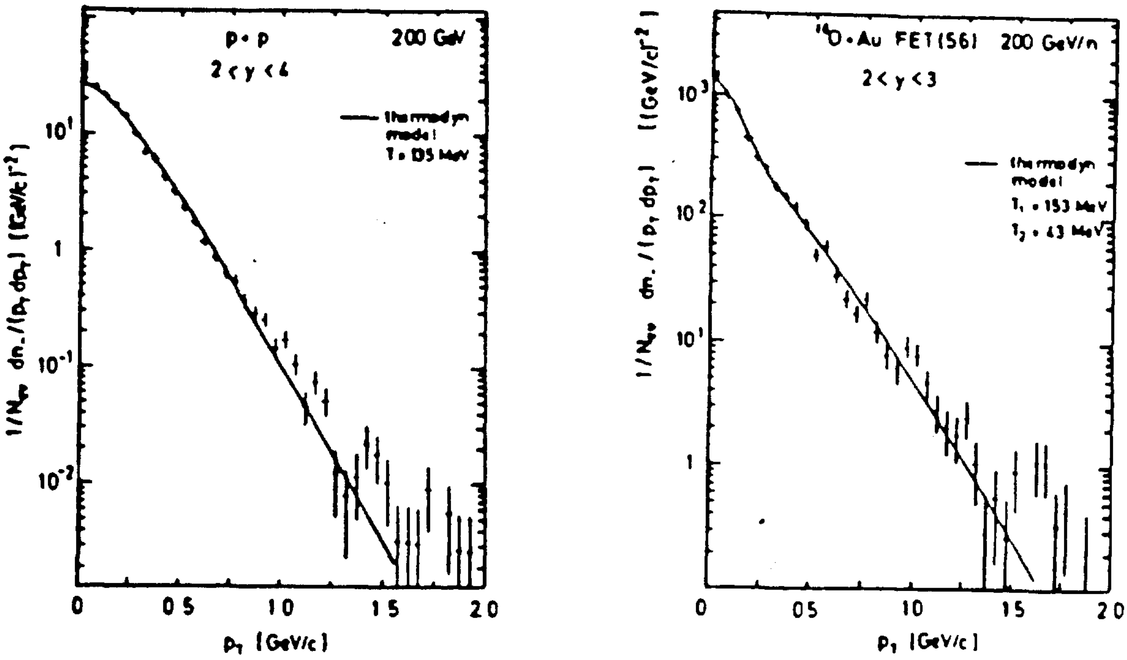


Fig. 4a–d. Correlation function projected on to the Q_t-axis (requiring $Q_L < 100$ MeV) for different rapidity intervals: **a)** $1<y<4$, **b)** $1<y<2$, **c)** $2<y<3$, and **d)** $2<y<3$ using 105 events from the Fritiof (Lund) model. The projected Gaussian fit is shown (solid line) for each case, and in a) the fit to the non-Gamow corrected correlation function is also shown (dashed line)

I-2



Transverse momentum distribution of π^- in pp and oxygen-gold collisions. Results of NA35.

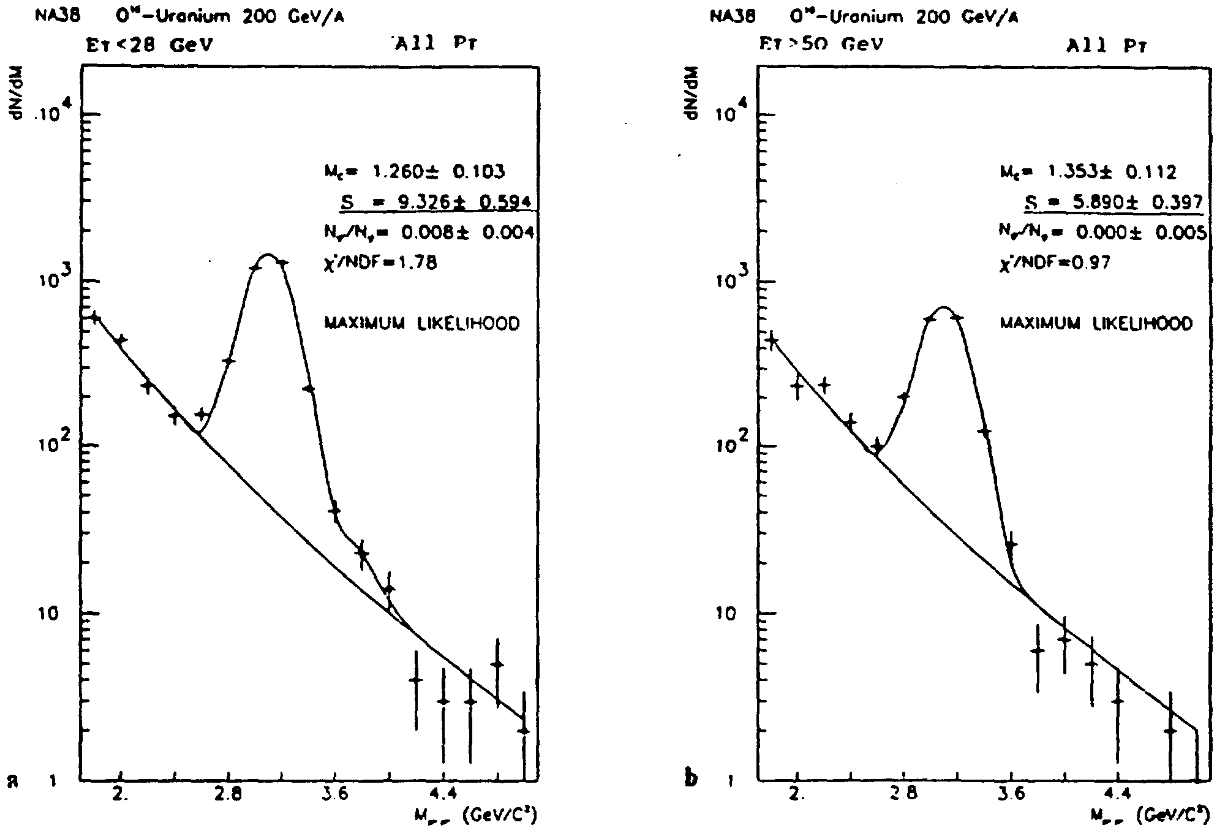
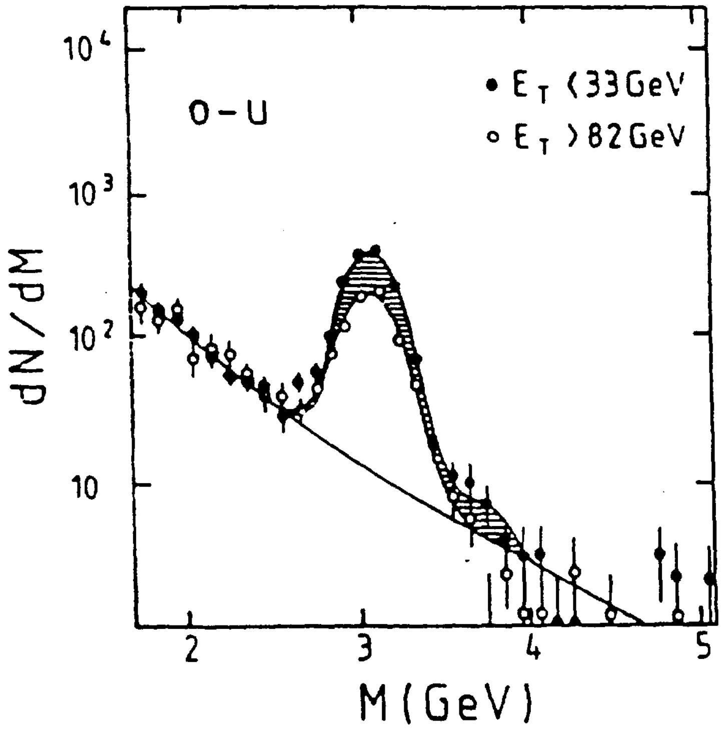


Fig. 5a, b. The fitted mass spectra for events with low transverse energy **a** and for events with high transverse energy **b**



The J/ψ signals for $E_T < 33$ GeV and $E_T > 82$ GeV normalized to the same Drell-Yan background.

I-5

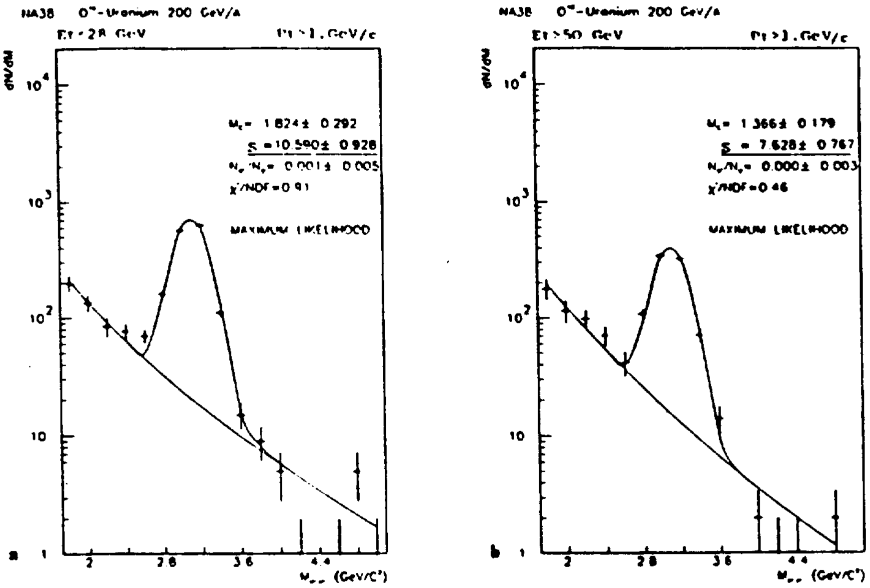


Fig. 6a, b. Same as Fig. 5 but for events with high transverse momentum

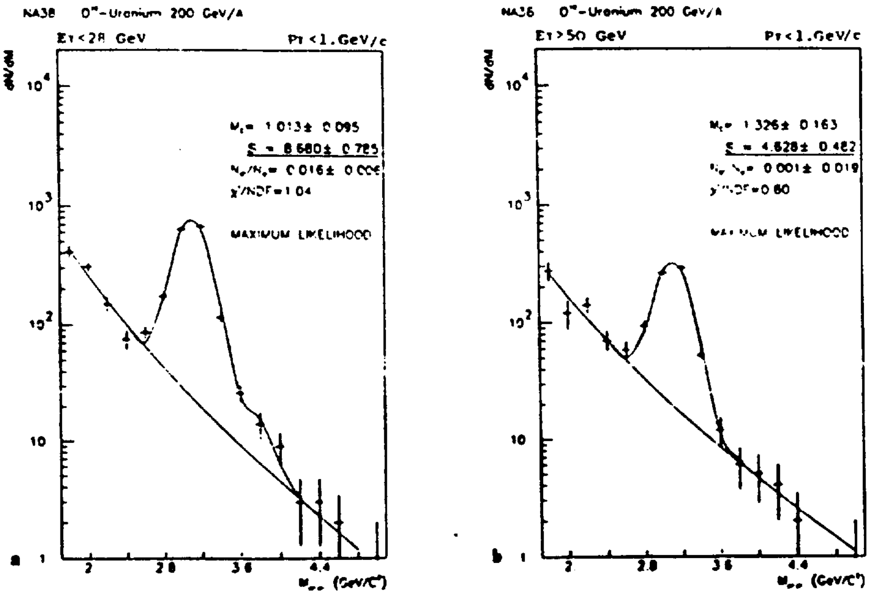
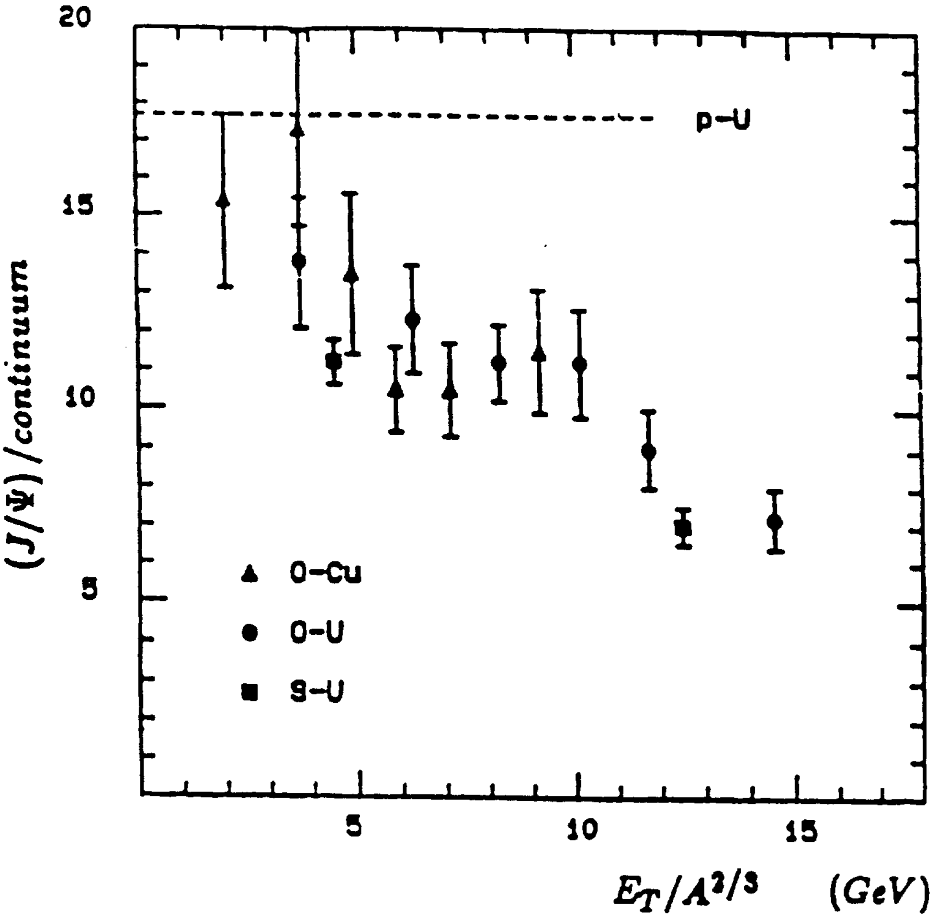
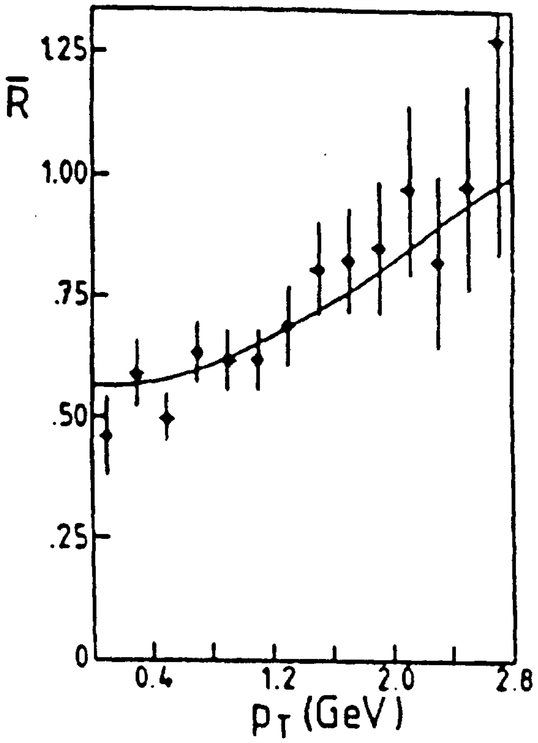


Fig. 7a, b. Same as Fig. 5 but for events with low transverse momentum



J/ψ to continuum ratio as a function of $E_T/A^{2/3}$. Results from NA38.

I-7



The p_T dependence of the J/ψ suppression ratio in oxygen-uranium collisions at 200 GeV/A together with theoretical expectations (Ref. 35).

SUMMARY

- Active and relevant Fixed-Target programme

SPS F.T. represents ~ 22% CERN users
comprising ~ 10% heavy ions
~ 12% others
+ P.S. (LEAR) ~ 8% CERN users

- Questions we have considered are:

Do we understand the proton?	No.
Can we explain universal dark matter?	Let's try.
Is CP violation fully contained in the Standard Model?	We'll find out.
Does a new state of matter exist?	Possibly.
Can CERN contribute sensibly to the development of b- physics.	Yes.

- Many topics NOT covered in these lectures, not because of lack of interest only because of lack of time.