The Intermediate Vector Bosons

a historical review in 4 parts

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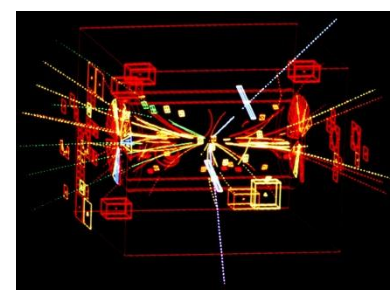


Plan of Talk

Milestones of Weak Interaction Physics

I. Prehistory (1896-1935): *Becquerel to Yukawa*

II. Ancient History (1936-1955): *O. Klein to Lee & Yang*

III. Middle Ages (1957 – 1966): *Landau to T.D. Lee*

IV. Modern Times (1967 – 1983): *GSW to W&Z*

I: Prehistory: 1896-1935

Radioactivity:

Becquerel 1896 (NPP 1903);

Pierre & Marie Curie (NPP 1903)

α, β, γ radioactivity:

Rutherford (NPC 1908) and others

Neutrino hypothesis:

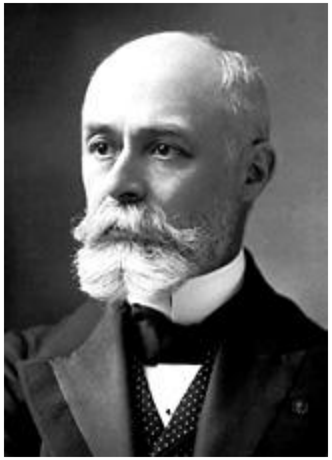
Pauli (NPP 1945 for the Exclusion Principle ("Pauli principle"))

Fermi theory of beta decay:

Enrico Fermi 1934 (NPP 1938)

Concept of carriers of strong and weak forces:

Hideki Yukawa 1935 (NPP 1949)

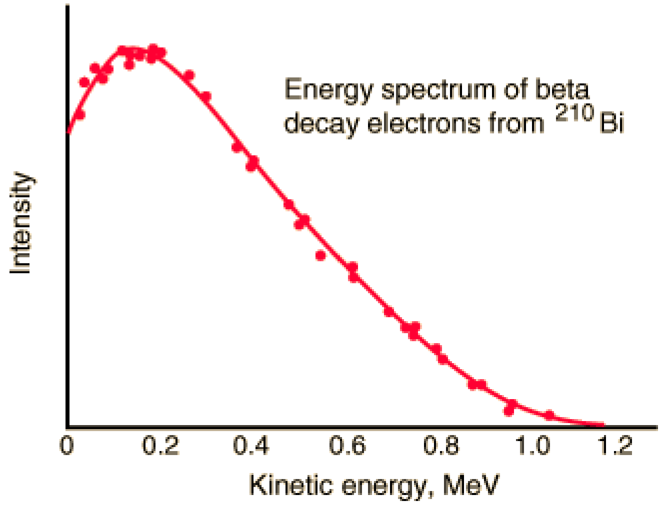
  

Antoine Henri Becquerel, Pierre and Marie Curie – NPP 1903

$$\alpha, \beta, \text{and } \gamma \text{ rays}$$

NPC 1908
Ernest Rutherford

Beta Decay Crisis



$$X(Z,A) \rightarrow X(Z+1,A) + \beta^{-}\ ?$$

Energy conserved statistically on a macroscopic level but not in individual beta decays

But that does not help with angular momentum:

$$C^{14} \rightarrow N^{14} + \beta^{-}$$

$$J = 0 \qquad 1 \qquad 1/2; \quad \Rightarrow \Delta J = 1?$$

Wolfgang Pauli

Dec 1930: Energy and angular momentum conservation saved by "neutron"

"Dear Radioactive Ladies and Gentlemen,

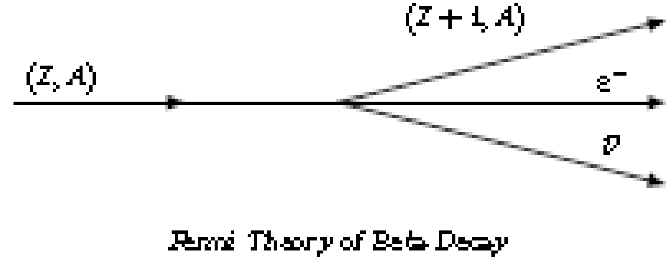
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become …"

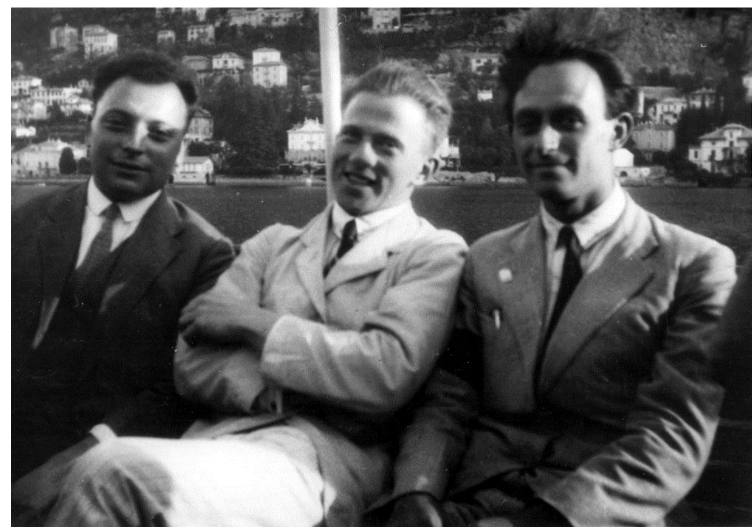
"… Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December.

With my best regards to you, and also to Mr Back.
Your humble servant
W. Pauli "

1934: Fermi theory of beta decay

Enrico Fermi





Fermi and Pauli with Werner Heisenberg

Hideki Yukawa 1935 (NPP 1949)

1. All forces result from the exchange of mesons

2. Mesons couple strongly to nucleons and weakly to leptons.

3. Charged mesons are exchanged between p and n, neutral mesons between p and p or n and n.

4. Mesons are spin-0 bosons.

5. The mass of mesons is estimated from the uncertainty principle:

$$mc^2 \sim \hbar c/R \approx 200\,\mathrm{MeV}$$

assuming $R \approx 1\, fm$

"As an attempt to unify strong and weak interactions, this was 40 years premature." (S.L. Glashow)

From S.L. Glashow, “Threads in a Tapestry”, Nobel Lecture, December 1979:

“… the study of the atomic nucleus soon revealed the need for two additional forces: the strong force to hold the nucleus together and the weak force to enable it to decay. Yukawa asked whether there might be a deep analogy between these new forces and electromagnetism***. All forces, he said, were to result from the exchange of mesons.*** His conjectured mesons were originally intended to mediate both the strong and the weak interactions: they were strongly coupled to nucleons and weakly to leptons. This first attempt to unify strong and weak interactions was fully forty years premature. Not only this, but ***Yukawa could have predicted the existence of neutral currents. His neutral meson, essential to provide the charge independence of nuclear forces, was also weakly coupled to pairs of leptons.***”

II. Ancient History: 1936-1955

Muon discovery 1937:
Anderson (NPP 1936 with V. Hess) & Neddermeyer 1937
Street and Stevenson 1937

1938,1948: Klein's electro-photons – the vector bosons to mediate the weak force

Concept of weak interaction:
from B. Pontecorvo 1947 to M. Gell-Mann 1955

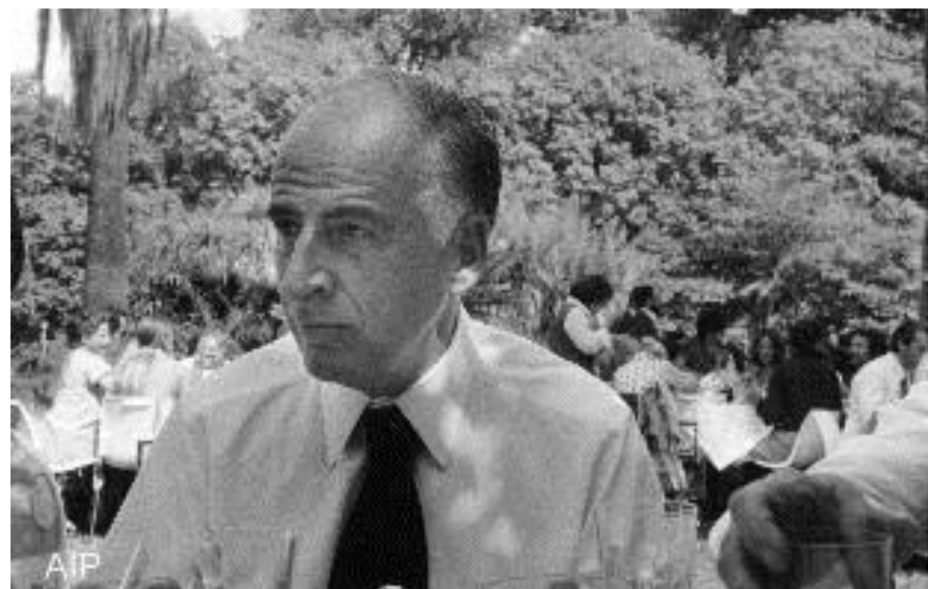
Parity violation: 1956
Lee and Yang; C.S. Wu

Early mention of an Intermediate Vector Boson:
Oskar Klein 1938, Conference talk,
and 1948: Nature, June 5, *Mesons and Nucleons*:

> (1) The ordinary cosmic-ray meson (μ-meson), and its neutral counterpart, are particles of spin $\hbar/2$ with Fermi statistics. The decay of a charged meson is a true β-process, giving rise to a neutral meson, an electron and a neutrino.
>
> (2) These particles interact by means of a Yukawa field corresponding to positively and negatively charged particles of integral spin, Bose statistics, and masses of mesonic order of magnitude. There being only charged particles of this kind, interactions of pair type will be essential. The role of these particles, and their properties, being similar to those of the photons, we may perhaps call them 'electro-photons', reserving the name meson for the particles mentioned in (1). Some σ-mesons may be of this kind, and they

Left: Oskar Klein (1894-1977):
the first to consider vector bosons
as carriers of the weak nuclear force

Right: Bruno Pontecorvo
(1913-1993): here seen at a Garden
Party in Dubna; he was the first
to consider in 1947 the concept of
a weak interaction.

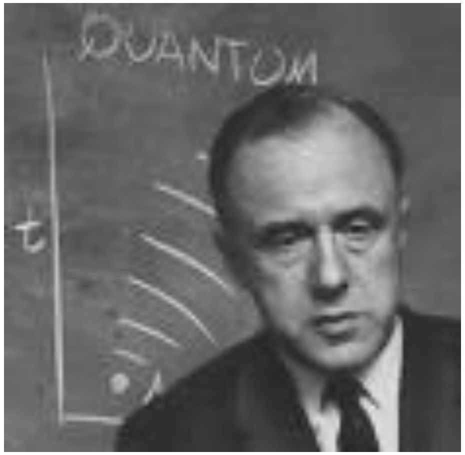


Milestones in weak interactions 1941 -- 1955

Year	What	who
1941	Muon beta decay and lifetime	Rasetti; Rossi, Nerenson
1947	Muon is not a hadron	Conversi, Panchini, Piccioni
1947	Discovery of pion, $\pi\to\mu\nu$ decay	Lattes, Occhialini, Powell
1947-48	Concept of μ-e universality	Pontecorvo; Klein; Puppi
1947	Discovery of hyperons and K mesons	Rochester, Butler
1948	Absence of $\mu\to e\gamma$ decay	Hincks, Pontecorvo; Piccioni
1948	π and μ in accelerators; accurate determination of their masses	Gardner, Lattes
1953	Isospin multiplets of hadrons	Gell-Mann; Nishijima
1955	$K^0 - \overline{K}^0$ oscillations	Gell-Mann, Pais, Piccioni

M.N. Rosenbluth (1927-2003), *whom we know for his famous Rosenbluth formula of the elastic ep cross section*

John A. Wheeler (1911-2008)
best known for work in general relativity



Murray Gell-Mann (1929-, NPP 1969)
– can speak Chinese to Lee and Yang, who can't speak Chinese to each other!
He finally established the concept of weak interactions in his talk at the 1955 HEP conference in Pisa

Bruno Pontecorvo remembers in "Recollections on the establishment of the weak interaction notion" [Proc. Int. Symposium Particle Phys. in the 1950s, CUP 1989, p. 367]:
"In conclusion I would say that at the Pisa conference of 1955, mainly as a result of the wonderful talk of Murray Gell-Mann, the notion of weak interaction, which was introduced in 1947, became finally established".

1956 – Parity violation

Tsung Dao Lee
and Chen Ning Yang

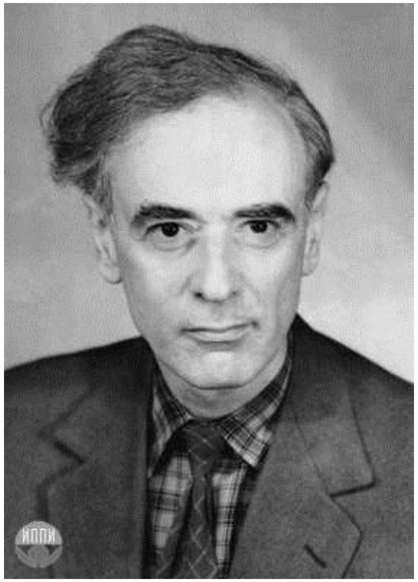
No experiment has ever tested parity conservation …

T.D. Lee with C.S. Wu and others

C.S. Wu *et al*. demonstrated parity violation in cobalt-60 decay (1957)

III. Middle Ages: 1957 - 1966

Two-component theory of the neutrino



L.D. Landau

Parity is violated ***per force*** in a two-component theory of a massless spin-1/2 fermion.

So, the other way round, since parity has been shown to be violated, the theory appropriate for the (massless!) neutrino is a two-component theory.

independently but later by A. Salam

and by T.D. Lee and C.N. Yang

1958 – Architects of V-A

Chiral invariance

Robert Marshak

George Sudarshan

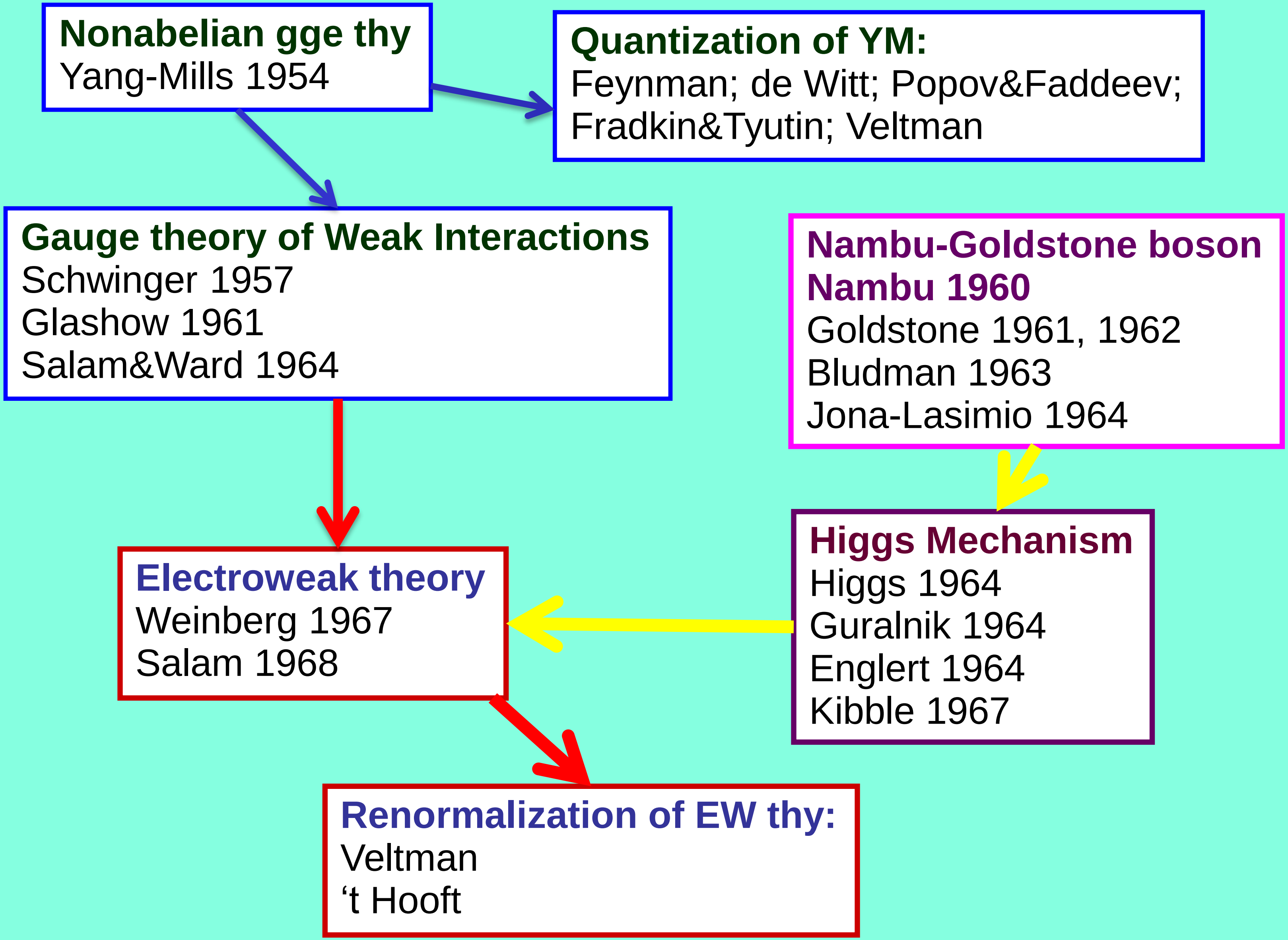
Mass-reversal invariance

Murray Gell-Mann

Richard Feynman

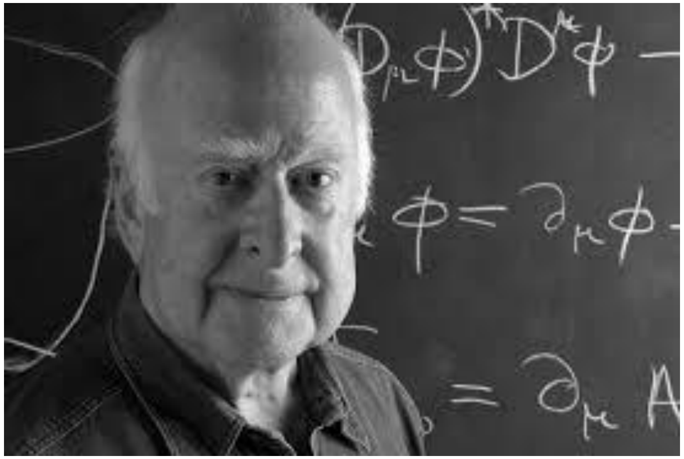
Two-component neutrino

Jun John Sakurai


Nonabelian gge thy
Yang-Mills 1954
Quantization of YM:
Feynman; de Witt; Popov&Faddeev;
Fradkin&Tyutin; Veltman
Gauge theory of Weak Interactions
Schwinger 1957
Glashow 1961
Salam&Ward 1964
Nambu-Goldstone boson
Nambu 1960
Goldstone 1961, 1962
Bludman 1963
Jona-Lasimio 1964
Higgs Mechanism
Higgs 1964
Guralnik 1964
Englert 1964
Kibble 1967
Electroweak theory
Weinberg 1967
Salam 1968
Renormalization of EW thy:
Veltman
‘t Hooft

First steps towards a gauge theory of weak interactions

1957 – Julian Schwinger



Peter Higgs (1929-):
1964 formulated what has become known as the "Higgs mechanism".

Kibble's Theorem (Thomas W.B. Kibble 1967):

Theorem:
A **gauge group** based on a symmetry group with **n generators** contains **n bosons**; if spontaneous breakdown of symmetry leaves the physical vacuum invariant under a **subgroup of dimension m**, then the gauge bosons of this subgroup remain massless, and **the other n-m gauge bosons are massive.**

In SU(2)xU(1) there are 4 bosons (3 for SU(2) and 1 for U(1)); after spontaneous breakdown of symmetry, the physical vacuum remains invariant under a subgroup of dimension 1, leaving 1 gauge boson massless, the other 3 having acquired mass.

To give just a glimpse at the state of minds on the question of the intermediate vector boson, I want to show you a quote from the lecture of T.D. Lee at the 1966 International School of Physics "Enrico Fermi", Course XXXII, "***Weak Interactions and High-Energy Neutrino Physics"***

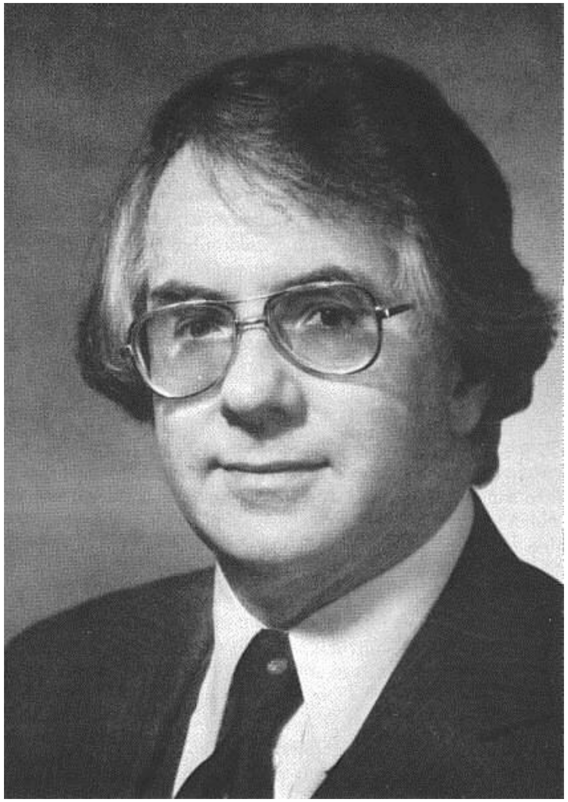
T.D. Lee's lecture is entitled: "Theoretical survey of high energy neutrino interactions".

To present the accumulated understanding of weak interaction phenomena, he shows that there should be 4 vector bosons – two charged and two neutral, and he gives a detailed discussion of their expected properties.

In conclusion he says: *"From a theoretical point of view, it seems to me that the existence of W has an intrinsic appeal. While it still leaves a number of problems unsolved, its existence simplifies and unifies our present picture of weak interactions.* ***The experimental proof of this particle will undoubtedly be a crucial landmark in the understanding of weak interactions****."*

IV Modern Times: 1967 -

(1961) 1967-1968 – Architects of the Electroweak Theory



Sheldon Glashow (1961)

Abdus Salam (1968)

Steven Weinberg (1967)

The Nobel laureates of 1979

1969 – no easy acceptance of the EW theory

Jack Steinberger, "*Weak Interactions*",
in Proc. Int. Conf. Elementary Particles,
Lund 1969, pp. 43-49

Steinberger mentions the IVB only in the Conclusions:

"..., at high energies, the point interaction violates unitarity. The unitarity difficulty can be removed by the introduction of intermediate bosons. The intermediate boson has, however, not as yet been found."

Status of 1972: experimental limits on $\sin^2 \theta_W$

from D.H. Perkins, “Neutrino Interactions”:
in Proc 1972 HEP Conference at NAL (now FNAL):

Reaction	Lab	TECN	Limit @ 90%CL
$\bar{\nu}_e e \to \bar{\nu}_e e$	Savannah R.	Nucl Reactor	< 035
$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	CERN	Gargamelle	< 0.6
$\nu_\mu p \to \nu_\mu p$	CERN	Propane BC	< 0.85

In "Conclusions“ Don Perkins says:
"... Even if in future improved experiments, a clear signal is detected, it is necessary, in order *to* ***finally demolish the Weinberg theory***, [my emphasis-WvS] to prove that the observed signal rate is consistent with the V – A predictions within close limits."

Status of August 1973: experimental lower limits on M_W

C. Franzinetti, "Total neutrino and antineutrino cross sections …" in Proc. Of the 6th International Symposium on Electron and Photon Interactions at High Energies", Bonn, 1973:

Authors	$M_W \geq$
CERN Spark Chamber	2.2 GeV/c^2
CERN HLBC (GGM)	1.8 GeV/c^2
NAL-Cal Tech	4.4 GeV/c^2
NAL-HPW	8.5 GeV/c^2

and he concludes:
"Should the W boson exist, the total cross section v-N would depart from linearity. The higher M_W, the closer to a straight line the cross section would be. The values obtained by the NAL-HPW Collaboration indicate that M_W is unlikely to be smaller than 20 GeV".

Another estimate of the W boson mass comes from G. Myatt, “Neutral Currents”, ibid p. 389:

$$\text{from } \nu \quad \sin^2\theta_W > 0.27$$

$$\text{from } \bar{\nu} \quad \sin^2\theta_W < 0.49$$

hence

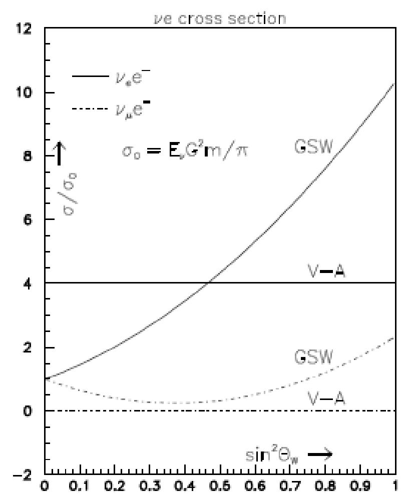
$$53\,\text{GeV} < M_W < 72\,\text{GeV}$$

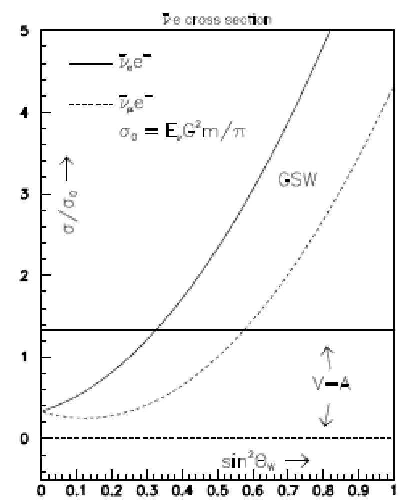
Neutral Currents -- theory:

$$\sigma_{el}(\nu e) = \sigma_0 \left\{ (g_V + g_A)^2 + (g_V - g_A)^2 \right\}; \ \sigma_0 = E_\nu G^2 m_e / \pi$$

Table 1: Leptonic Couplings in $V - A$ and Weinberg theories

Reaction	Weinberg		V-A theory	
	g_V	g_A	g_V	g_A
$\nu_e e^- \to \nu_e e^-$	$1/2 + 2\sin^2\theta_W$	$+1/2$	1	1
$\overline{\nu}_e e^- \to \overline{\nu}_e e^-$	$1/2 + 2\sin^2\theta_W$	$-1/2$	1	1
$\nu_\mu e^- \to \nu_\mu e^-$	$-1/2 + 2\sin^2\theta_W$	$-1/2$	0	0
$\overline{\nu}_\mu e^- \to \overline{\nu}_\mu e^-$	$-1/2 + 2\sin^2\theta_W$	$+1/2$	0	0





Neutral Currents – discovery: 1973-78

By 1971 neutrino beams were available at CERN and at NAL.

At CERN the heavy liquid bubble chamber Gargamelle was installed to study the structure of the proton in CC reactions.
No priority was given to testing the hypothesis of neutral currents!

At NAL (now FNAL) the HPWF counter experiment was ready.

The drama of the discovery of neutral currents was told by D. Haidt in *Prestigious discoveries at CERN* (Springer, 2003).

Gargamelle Heavy Liquid Bubble Chamber

Cylindrical chamber 4 meters long and nearly 2 meters diameter

12000 liters of heavy liquid: propane and/or freon

2 Tesla magnetic field

History of Gargamelle:

1965: CERN-CEA agreement signed

1967: First tests at Saclay using a model of Gargamelle

December 1970: First operation with cosmic rays

28 January 1971: Start of operation with neutrinos from CERN PS

1971 (1972) : 500 000 (370 000) pictures taken with neutrino and antineutrino beams from the PS

1972: (i) First observation of $\bar{\nu}_\mu + p \to \mu^+ + \Lambda$

(ii) Measurement of neutrino-nucleon total cross section

1973: (i) observation of an event which may be interpreted as the reaction

$$\bar{\nu}_\mu + e^- \to \bar{\nu}_\mu + e^-$$

(ii) Observation of hadronic NC candidates

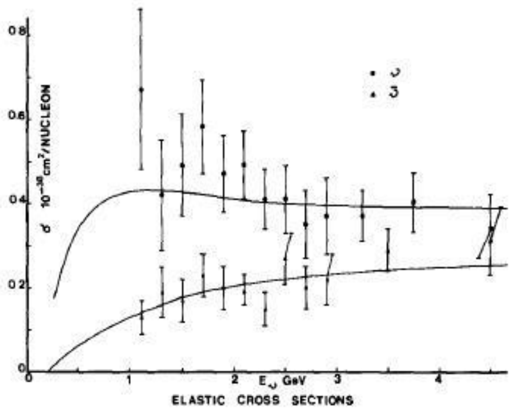


Fig. 2. Elastic neutrino and antineutrino cross-sections as a function of energy.

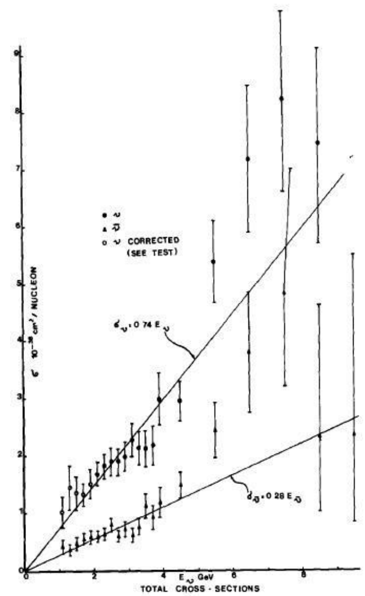


Fig. 1. Total neutrino and antineutrino cross-sections as a function of energy.

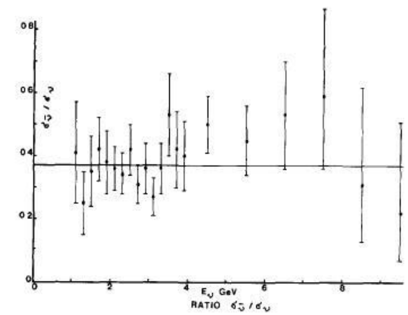


Fig. 3 The ratio $R = \sigma(\bar{\nu})/\sigma(\nu)$ of antineutrino to neutrino cross-sections as a function of energy.

Elastic neutrino and antineutrino cross sections as a function of energy

Total neutrino and antineutrino cross sections (left) and their ratio (right) as a function of energy

1973 Gargamelle BC (Eichten et al.)

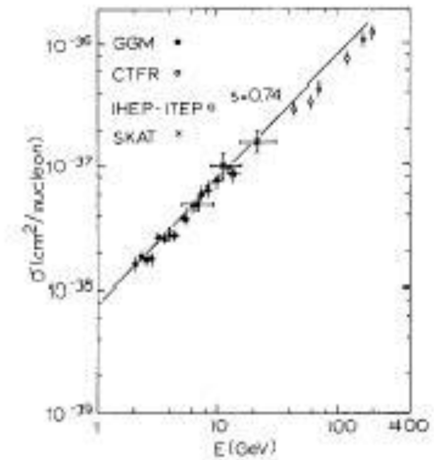


Fig. 3. Neutrino–nucleon total cross section as a function of the neutrino energy. Data from this experiment (×) and previous data [4–5] are shown. Straight line is Gargamelle data one-parameter fit ($S = 0.74 \pm 0.03$).

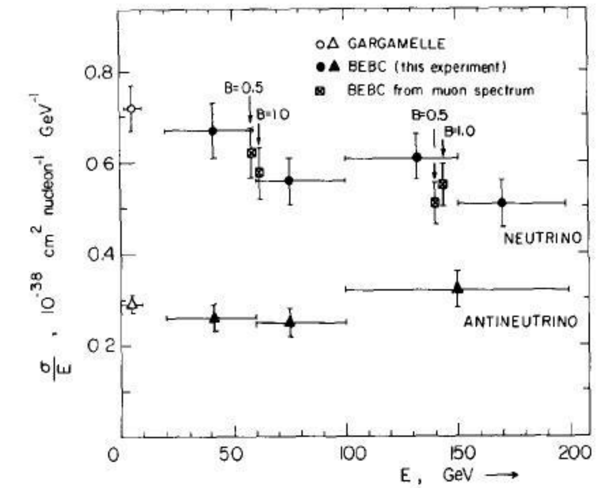


Fig. 2. Neutrino and antineutrino cross sections divided by energy in units of 10^{-38} cm^2 GeV^{-1} nucleon^{-1}. All cross sections have been converted to values for an isoscalar target, assuming $\sigma^{\nu n}/\sigma^{\nu p} = \sigma^{\bar{\nu}p}/\sigma^{\bar{\nu}n} = 2$. Errors shown are statistical (see also table 1).

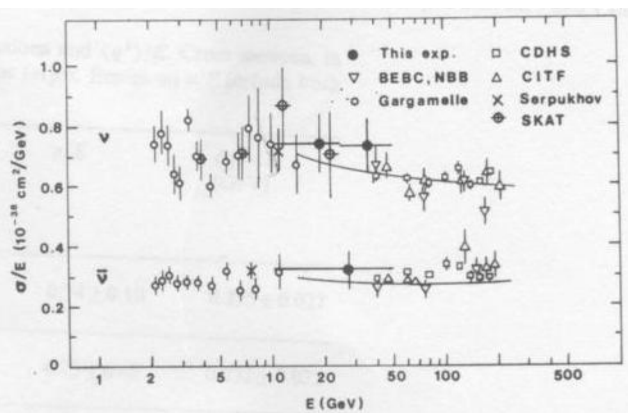


Fig. 4. Neutrino and antineutrino interaction cross sections, divided by the mean value of the energy, calculated for an isoscalar target. For comparison, the measurements [1, 2, 3] are also shown as well as the Quantum Chromodynamics prediction (solid line) computed from [11] (the Λ parameter defined in this reference was set to 0.5). For BEBC (▽) and CDHS (□), the errors are statistical only

In 2003 at the celebration of the 30th anniversary of the discovery of neutral currents, Weinberg remembered:

“Neutral currents were discovered in 1973 at CERN. … the data on NC reactions looked like it exactly fit the electroweak theory, but then a series of other experiments gave contrary results. The most severe challenge came in 1976 from two atomic physics experiments that seemed to show that there was no parity violation in the bismuth atom at the level that would be expected … in the electroweak theory.”

“For most theorists these experiments did not challenge the basic idea that weak interactions arise from a spontaneously broken symmetry, but they threw serious doubt on the specific SU(2)xU(1) implementation of the idea. Many other models were tried during this period. Finally, parity violation in the neutral currents was discovered at the expected level in electron-nucleon scattering at SLAC in 1978, and after that most physicists took it for granted that the electroweak theory is essentially correct.”

S. Weinberg, “The making of the Standard Model”, *in Prestigious Discoveries at CERN*, R. Cashmore, L. Maiani and J.-P. Revol (eds.), Springer 2003

First glimpse of the Z boson in e+e- collisions

By 1980, the PETRA collider at DESY had a total CMS energy of 34 GeV

Experiments : CELLO, JADE, Mark J and TASSO measuring the differential cross section of

$$e^+e^- \to \mu^+\mu^-$$

In the GSW theory, this is of the form

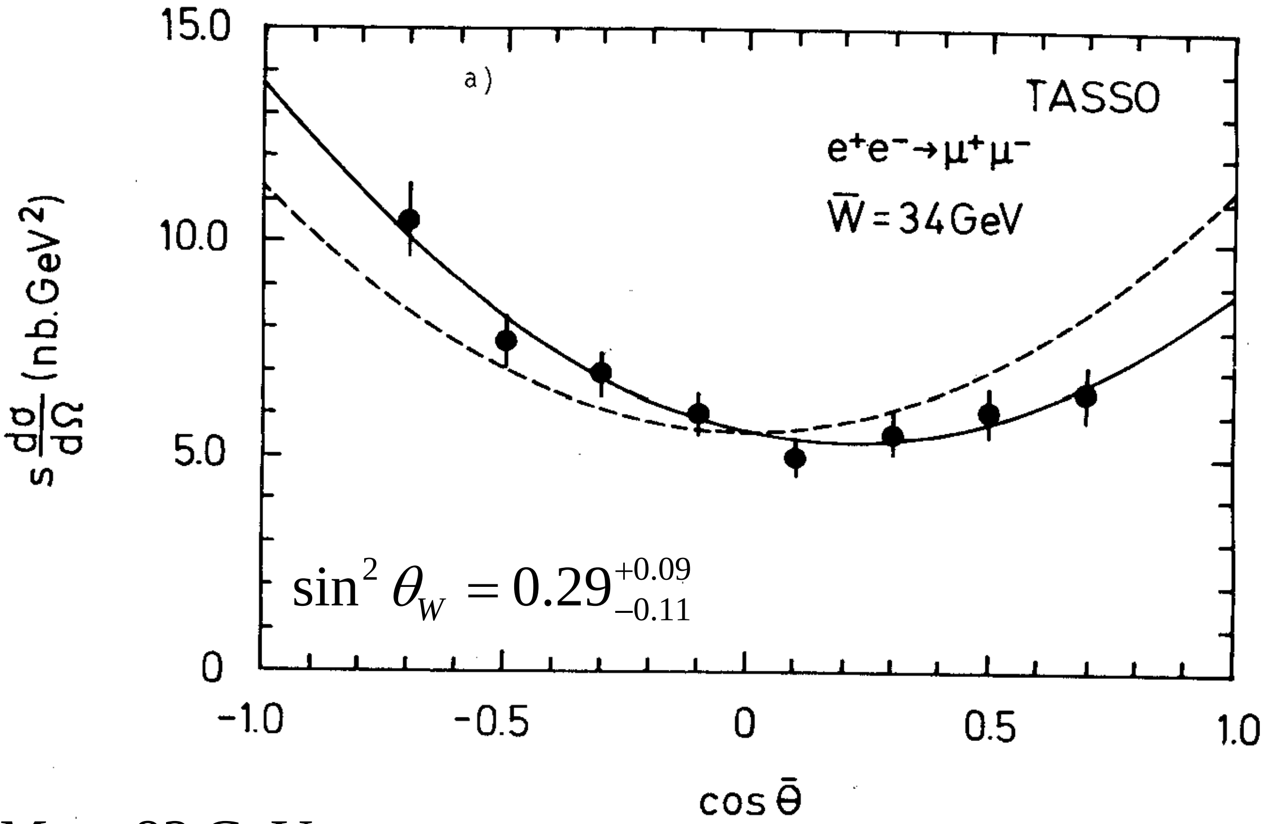
$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left\{a\left(1+\cos^2\theta\right)+b\cos\theta\right\}$$

where a has contributions from e.m. and weak interactions, and $\boldsymbol{b}$ only from weak; $\boldsymbol{b}$ depends on the Z boson mass and on the mixing angle.

$\boldsymbol{b}$ gives rise to a forward-backward asymmetry in the diff cs:

$$A \equiv \frac{\sigma\left(\theta<\pi/2\right)-\sigma\left(\theta>\pi/2\right)}{\sigma\left(\theta<\pi/2\right)+\sigma\left(\theta>\pi/2\right)} \propto \frac{b}{a}$$

First evidence of Neutral Currents from electron-positron collider PETRA



hence $M_Z \approx 82\,\mathrm{GeV}$

TASSO Coll., R. Brandelik et al., Phys. Lett. B110 (1982) 173; DESY 82-002

similar result by JADE Coll., W. Bartel et al., DESY-81-072

Towards the discovery of the W and Z

In the Salam-Weinberg theory, there is one free parameter that can be chosen to be the weak mixing angle Θ_W

In terms of Θ_W the masses of the W and Z bosons are

$$M_W^2 = \frac{\sqrt{2}e^2}{8G}\frac{1}{\sin^2\theta_W}; \quad M_Z = \frac{M_W}{\cos\theta_W}$$

or in numbers

$$M_W = \frac{37.3\,\text{GeV}}{\sin\theta_W}; \quad M_Z = \frac{74.6\,\text{GeV}}{\sin 2\theta_W}$$

so, even without any knowledge of θ_W we have lower bounds:

$$\boxed{M_W \geq 37.3\,\text{GeV}; \quad M_Z \geq 74.6\,\text{GeV}}$$

good enough to start planning an experiment to see the W and Z!

These masses were out of reach of electron-positron colliders for another decade

The most realistic approach to find the W and Z was proton-proton collider or, better still, proton-antiproton collider

At CERN the pp collider ISR had reached a centre of mass energy of 62 GeV in 1973 – not enough to find the W

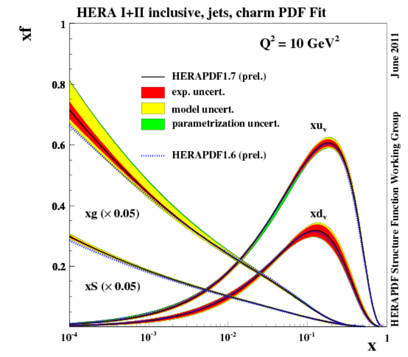
There were plans for a 300 GeV accelerator
but that is expensive, and all CERN member states stalled

At the end of 1970, Margaret Thatcher visited CERN and on return home persuaded the Cabinet to support the 300 GeV project

By February 1971 all but one of the CERN member states had joined, and the project went ahead.

five years later, in June 1976, the first 400 GeV pulse passed around the CERN SPS

First proposal for a proton-antiproton collider: Carlo Rubbia et al., 1976



Neutrino Conference, Aachen 1976:
Carlo Rubbia, P. McIntyre and D. Cline
“Producing Massive Neutral Intermediate Vector Bosons with Existing Accelerators”

(i) Production of IVB out of reach of present electron-positron machines

(ii) The only viable option is a hadron collider to produce IVB in parton collisions

(iii) The CM energy of the parton collision must be close to the expected IVB mass. According to the GSW theory, and with knowledge of the mixing angle, that means

$$\sqrt{\hat{s}} \approx 80 \text{ to } 90\,\mathrm{GeV}$$

(iv) Valence quark distributions peak at x=0.2; so if we collide protons with antiprotons, we need a CM energy of, say, 80/0.2=400 GeV, which is just the energy of the SPS

(v) What is needed is an antiproton source

The CERN antiproton accumulator

At CERN an antiproton source was also available, exploiting stochastic cooling – Simon van der Meer.

This has been tested on the ISR in its last period before shutdown.

The Antiproton Accumulator (AA):

Table 3: pp **and** $\bar{p}p$ **Collider Parameters**

Collider	$Sp\bar{p}S$	Tevatron	LHC
Particles	$p\bar{p}$	$p\bar{p}$	pp
Physics dates	1981-1990	1987-	2009-
Beam energy (TeV)	0.315	0.98	7
Luminosity (10^{30} cm^{-2}s^{-1})	6	171	1×10^4
Bunches per beam	6	36	2808
Time between bunch crossings (ns)	3800	396	25
Bunch length (cm)	20	p: 50, $\bar{p}$: 45	7.5
Particles per bunch ($\times 10^{10}$)	p: 15, $\bar{p}$: 8	p: 24, $\bar{p}$: 6	10
Injection energy (GeV)	26	150	450
Filling time (minutes)	0.5	30	8.6
Acceleration period (seconds)	10	86	1200
Luminosity lifetime (hours)	15	7	15
Circumference (km)	6.91	6.28	26.66

Status of 1981, shortly before the discovery of the W and Z

The best determinations of the weak mixing angle come from neutrino-nucleon reactions

An analysis of all available data by J.E. Kim et al. [*] gave

$$\sin^2 \theta_W = 0.234 \pm 0.013$$

This translates into the following values of IVB masses:

$$\boxed{M_W \simeq 77\,\text{GeV}; \quad M_Z \simeq 88\,\text{GeV}}$$

[*] J.E. Kim, P. Langacker, M. Levine, and H.H. Williams, “A theoretical and experimental review of neutral currents”, Rev. Mod. Phys. 53 (1981) 211.

Once the W boson mass is known, its width is also fixed:

$$\Gamma\left(W^+ \to e^+\nu_e\right) = \frac{G_F M_W^3}{6\sqrt{2}\pi} \approx \left(229 \pm 3\right) \text{ MeV}$$

$$\Gamma\left(W^+ \to u_i\bar{d}_j\right) = C \cdot \frac{G_F M_W^3}{6\sqrt{2}\pi} \cdot |V_{ij}|^2 \approx \left(714 \pm 11\right) |V_{ij}|^2 \text{ MeV}$$

$$\Gamma\left(Z \to f_i \bar{f}_i\right) = C \cdot \frac{G_F M_W^3}{6\sqrt{2}\pi} \cdot \left(V^{i2} + A^{i2}\right)$$

$$\approx \left(162.2 \pm 0.2\right) \text{ MeV for } \nu\bar{\nu}$$

$$\approx \left(83.4 \pm 0.1\right) \text{ MeV for } e^+e^-$$

$$\approx \left(296.1 \pm 0.4\right) \text{ MeV for } u\bar{u}$$

$$\approx \left(382.3 \pm 0.5\right) \text{ MeV for } d\bar{d}$$

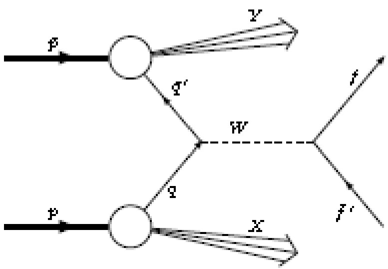
$$V^i = t_{3L}^i - 2q_i \sin^2\theta_W; \quad A^i = t_{3L}^i; \quad C = 3 \cdot \left(1 + \frac{\alpha_s\left(M_W\right)}{\pi}\right)$$

and hence the total widths:

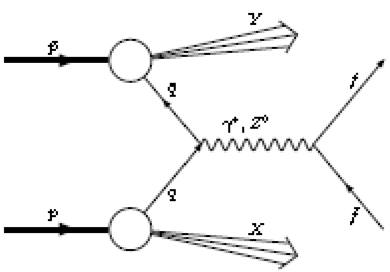
$$\Gamma_W \simeq 2.1\,\mathrm{GeV}; \quad \Gamma_Z \simeq 2.5\,\mathrm{GeV}$$

and hence we can go ahead and calculate the cross sections of the hard sub-processes, and using factorization (and using the known parton distributions), we can calculate the cross sections of all relevant processes.

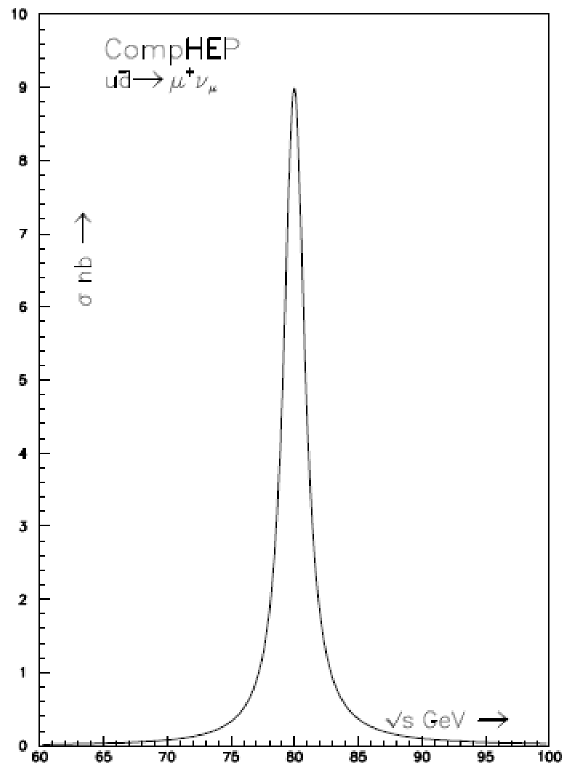
Cross section of $u\bar{d} \to W^+ \to \mu^+\nu_\mu$

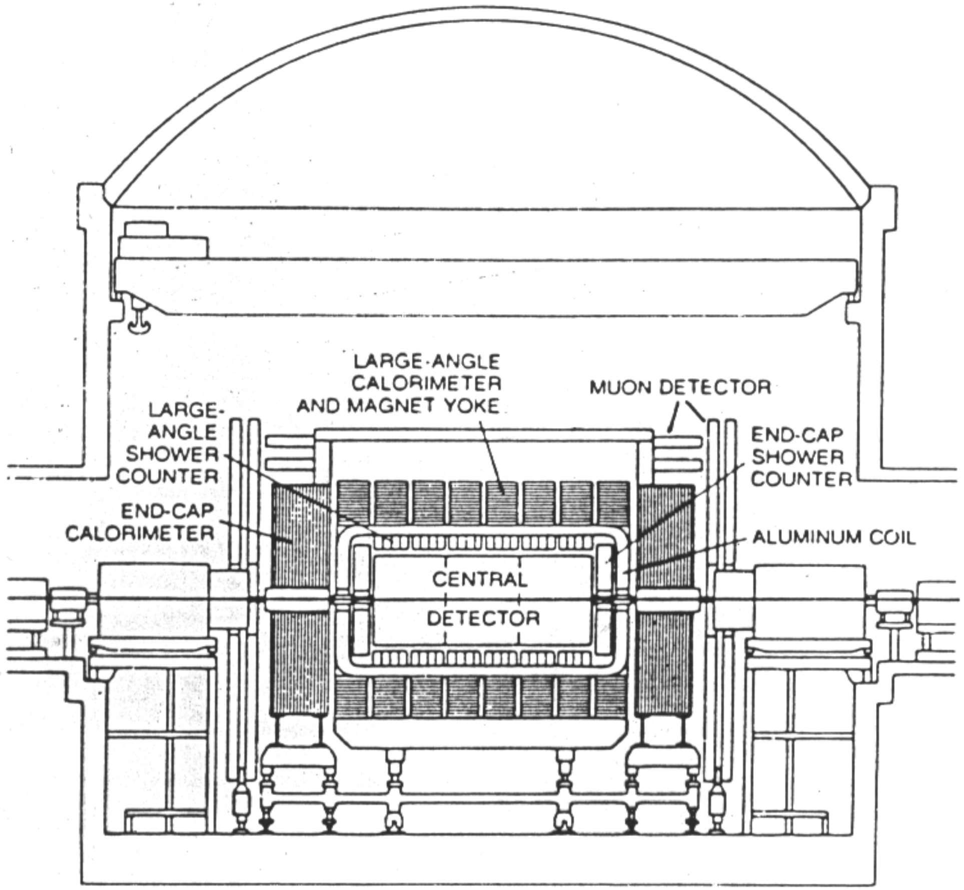


CC Drell-Yan process



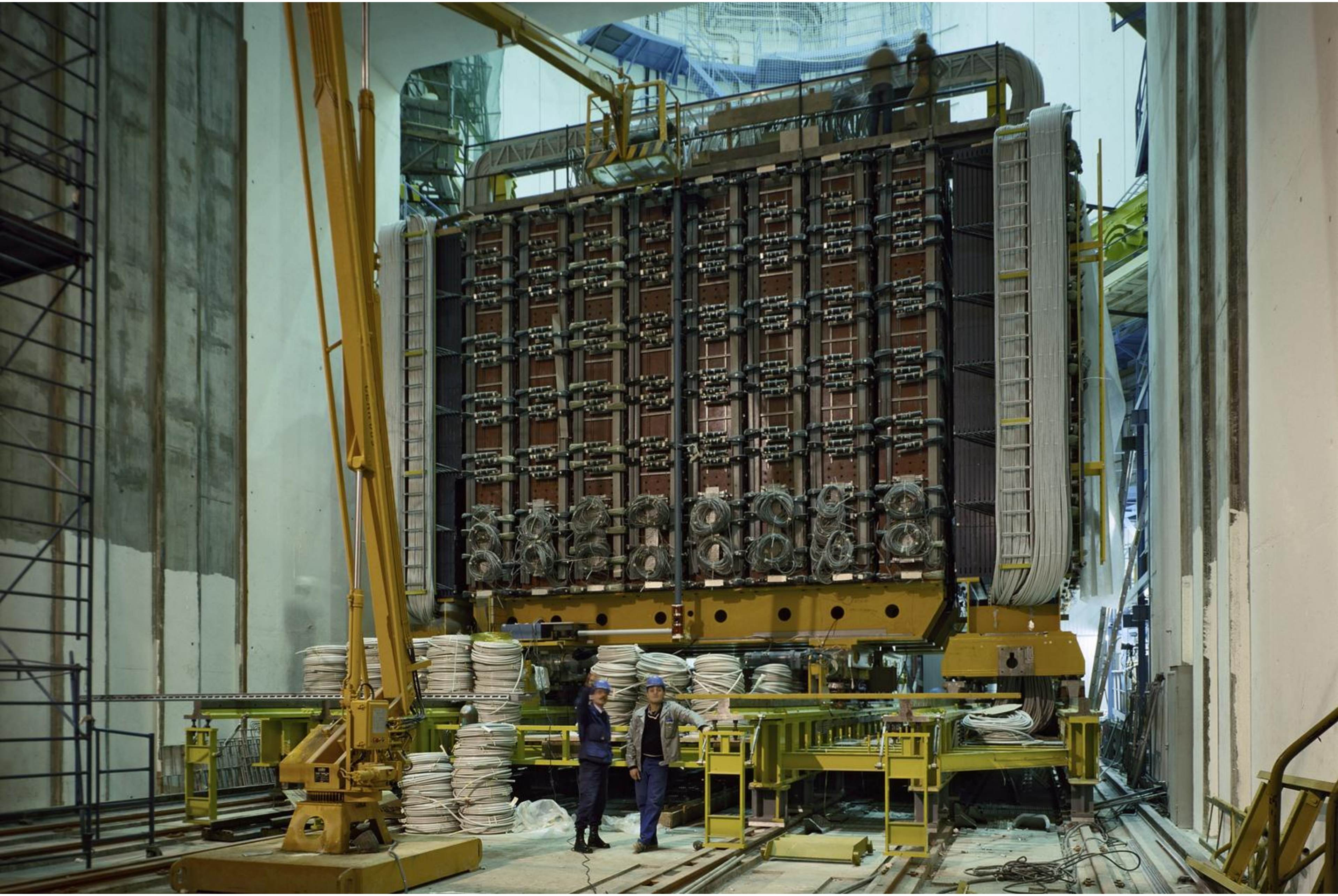
NC Drell-Yan process

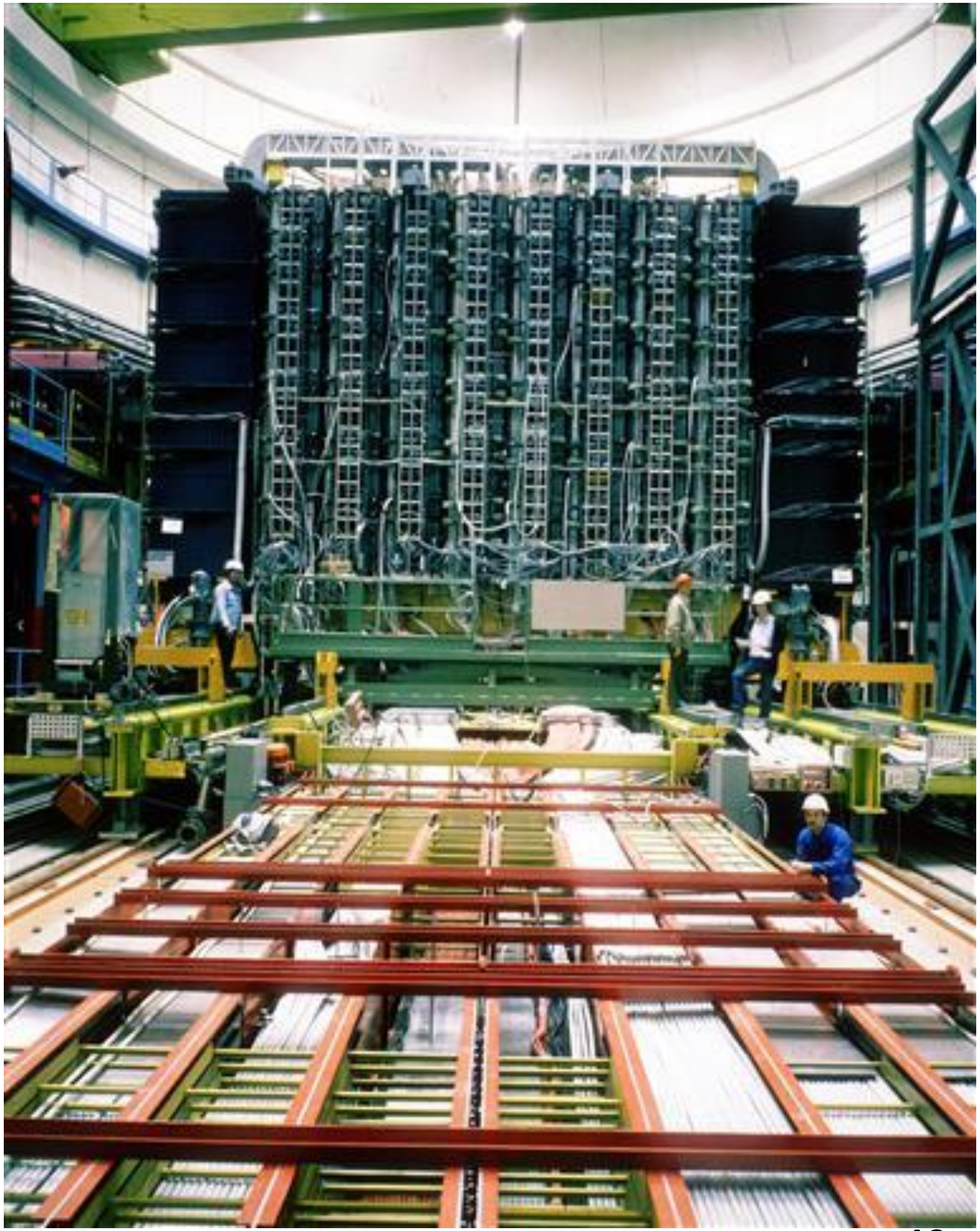


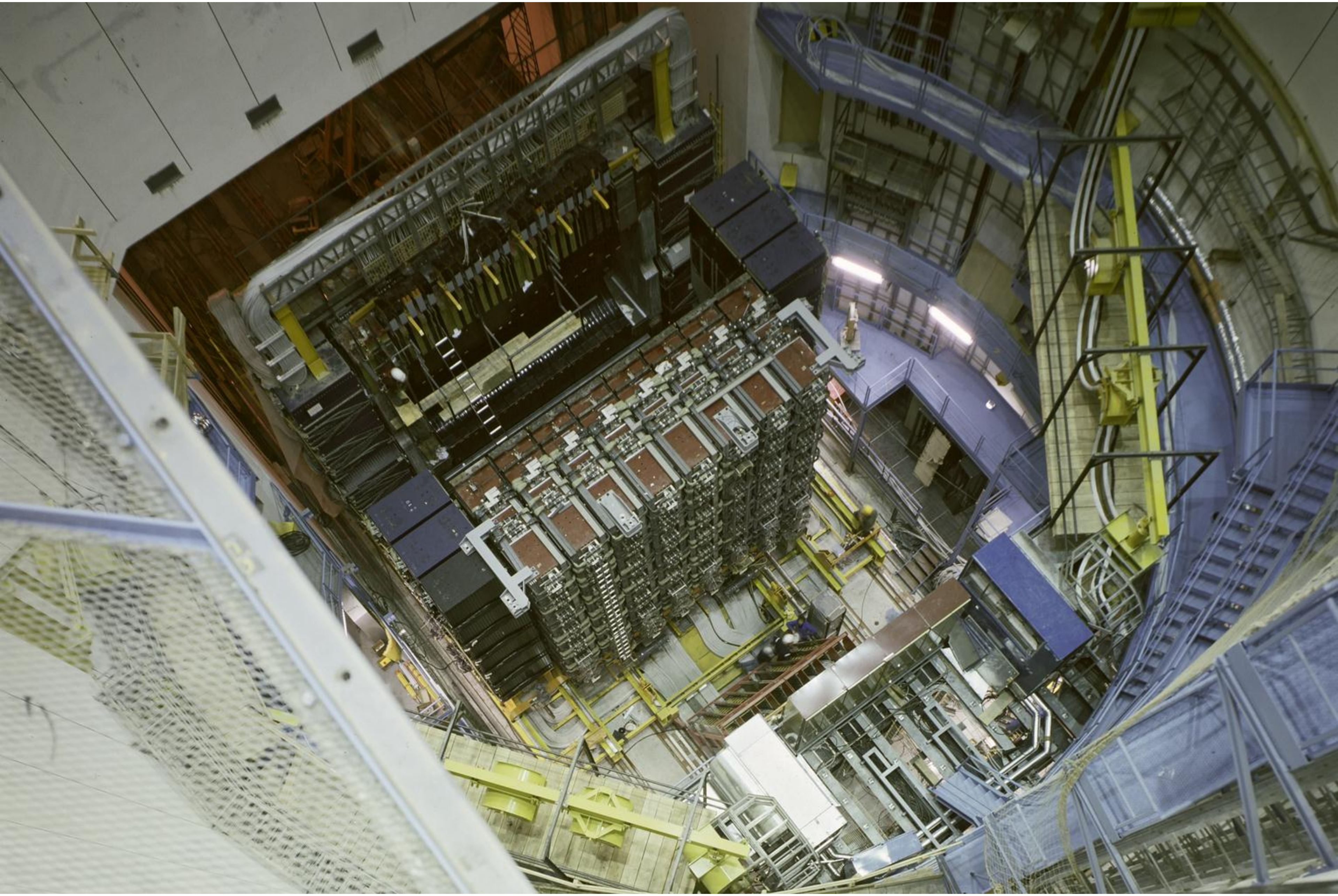


Schematic of the UA1 detector

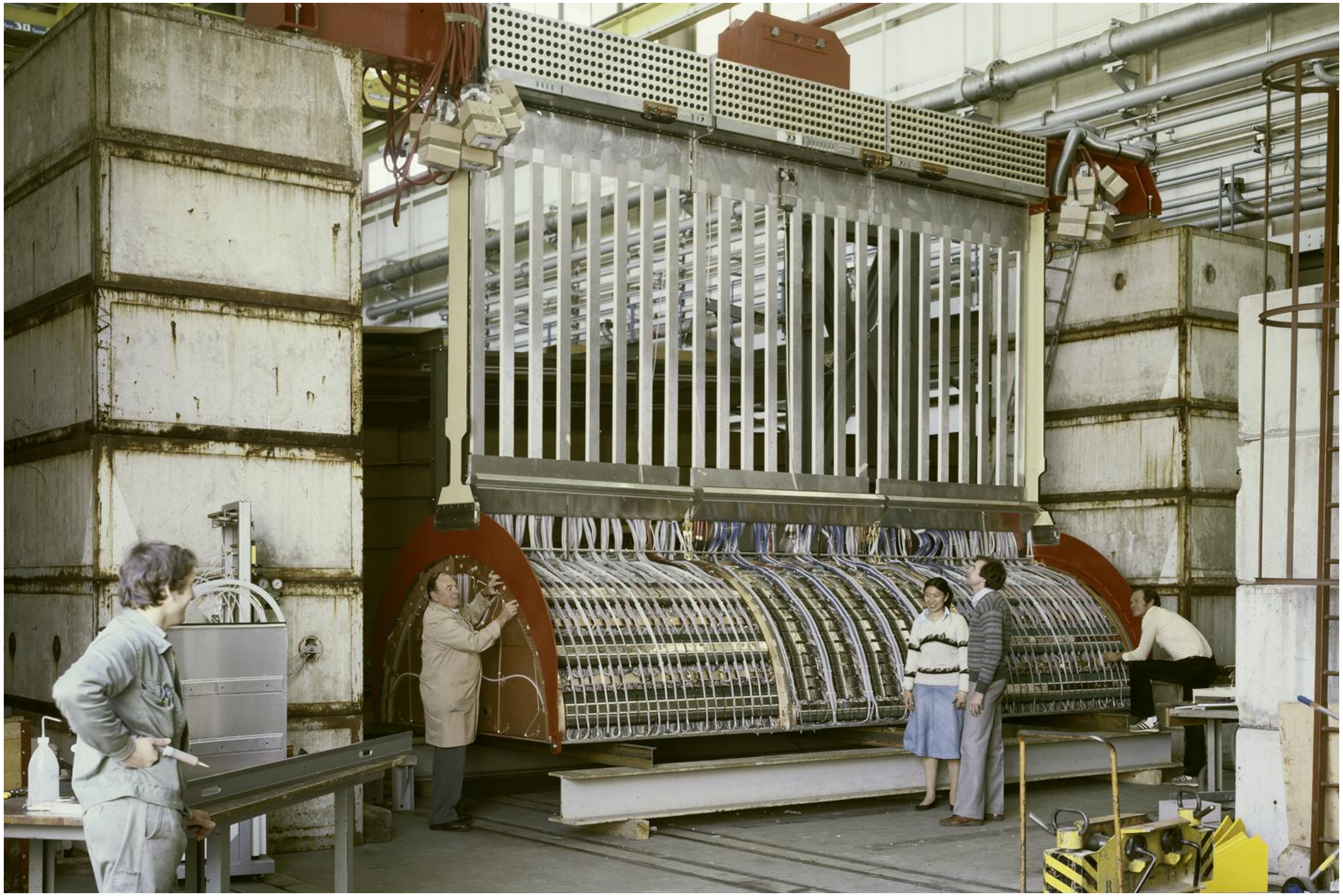

DANGER



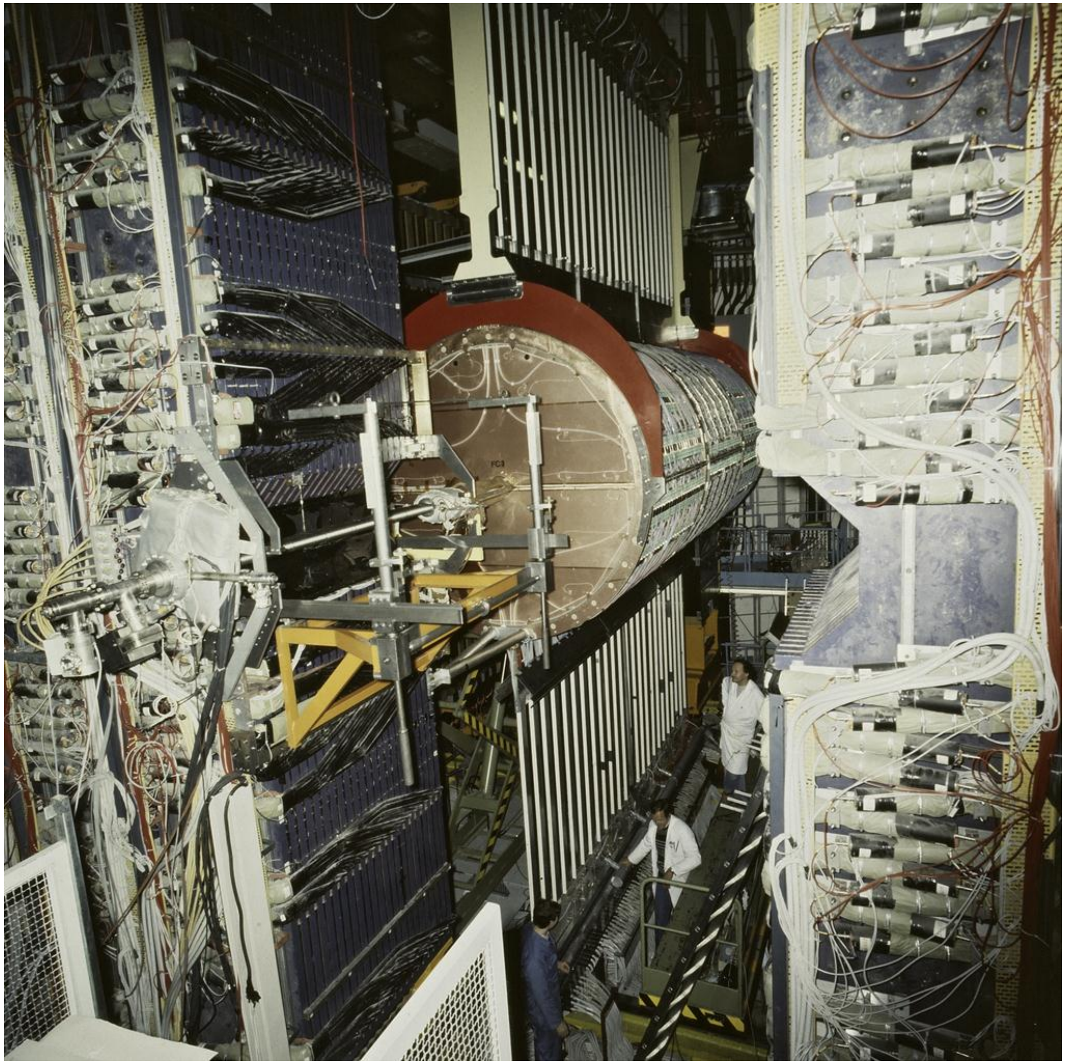




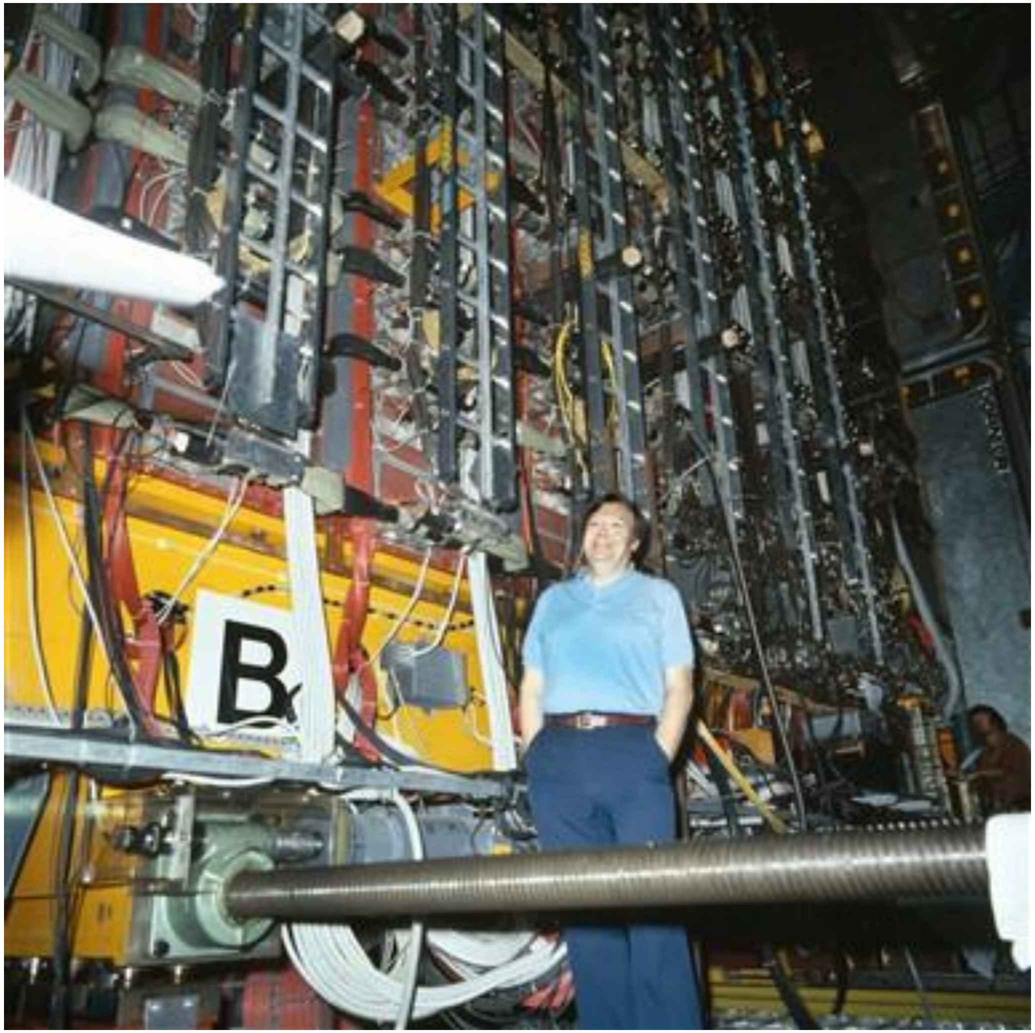
The UA1 Central Detector taking shape



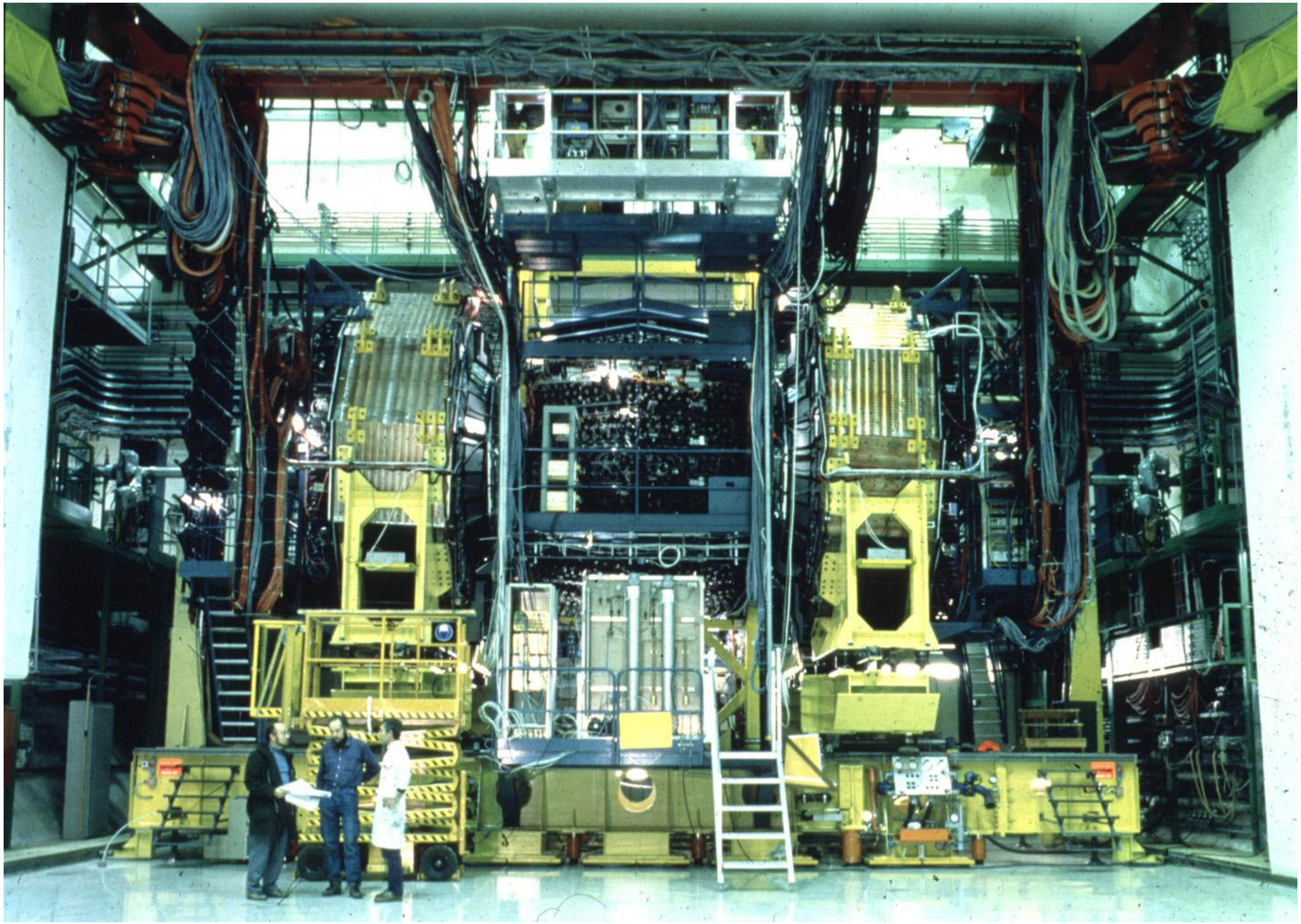
UA1 CD before being closed in by the calorimeters

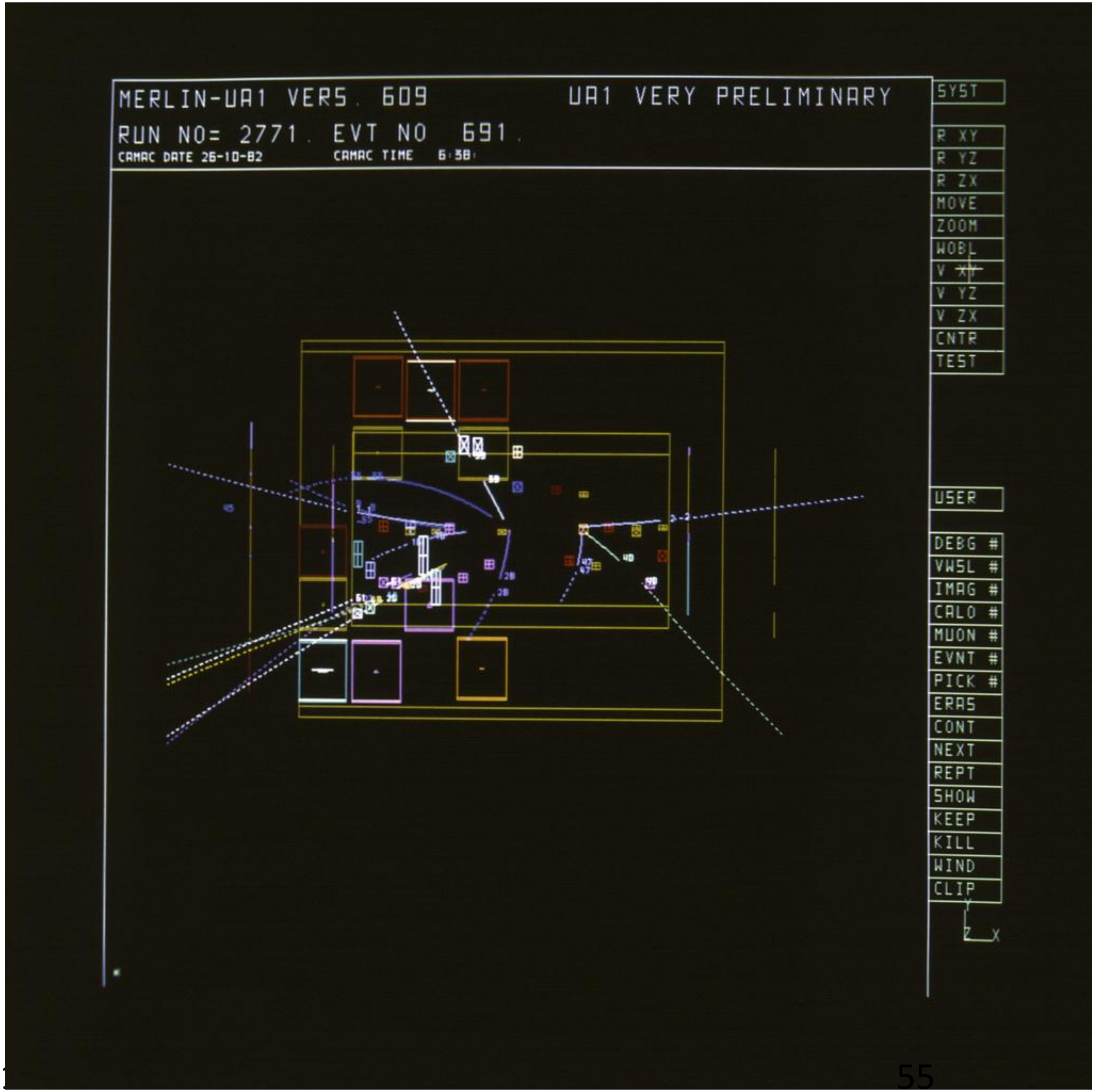


The construction of the UA1 detector is accomplished: a happy Carlo Rubbia



UA2 detector:

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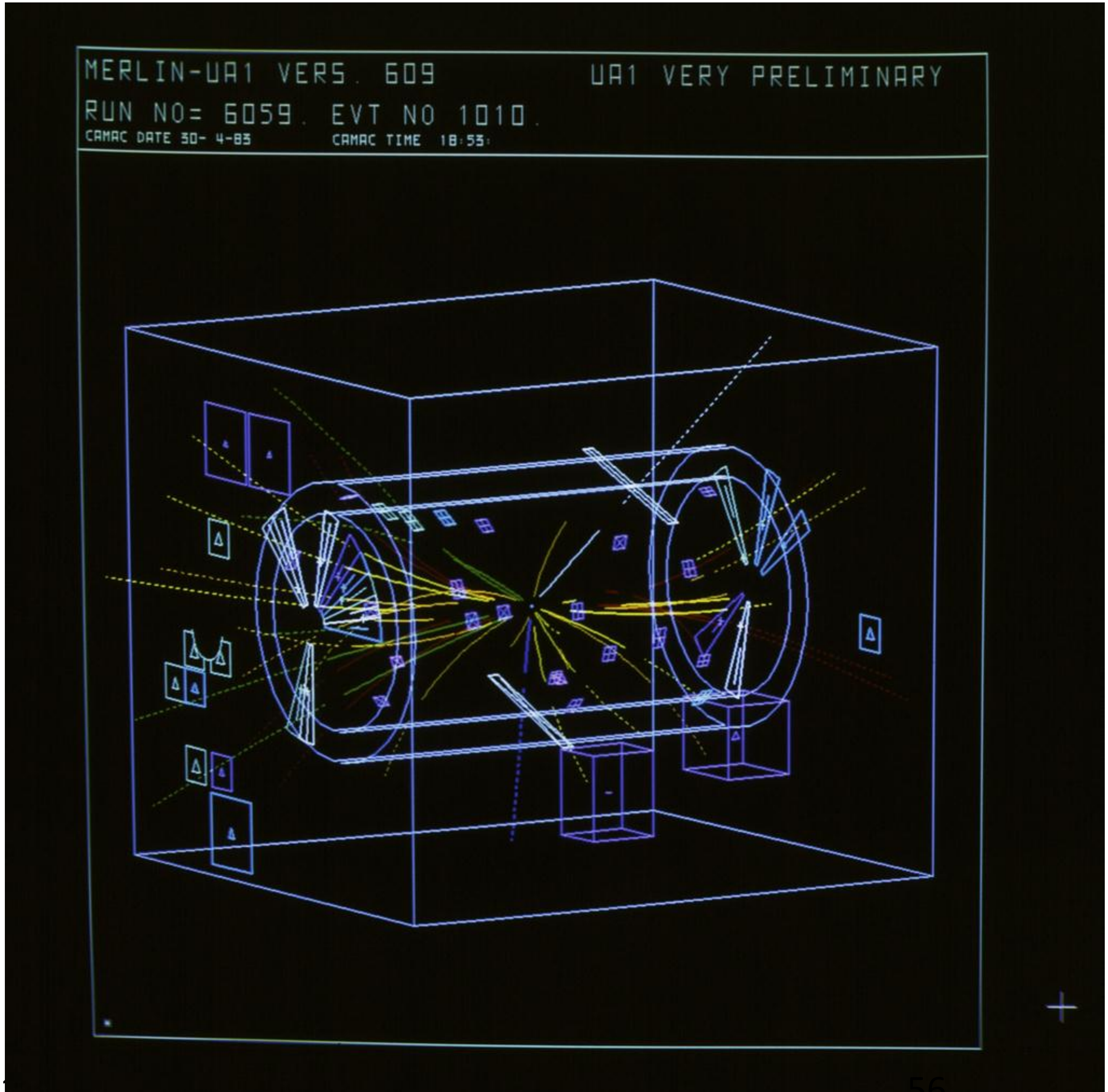
UA1 VERY PRELIMINARY
RUN NO= 2771. EVT NO 691.
CAMAC DATE 26-10-82
CAMAC TIME 6:38:
SYST
R XY
R YZ
R ZX
MOVE
ZOOM
WOBL
V XY
V YZ
V ZX
CNTR
TEST
USER
DEBG #
VWSL #
IMAG #
CALO #
MUON #
EVNT #
PICK #
ERAS
CONT
NEXT
REPT
SHOW
KEEP
KILL
WIND
CLIP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UA1 VERY PRELIMINARY
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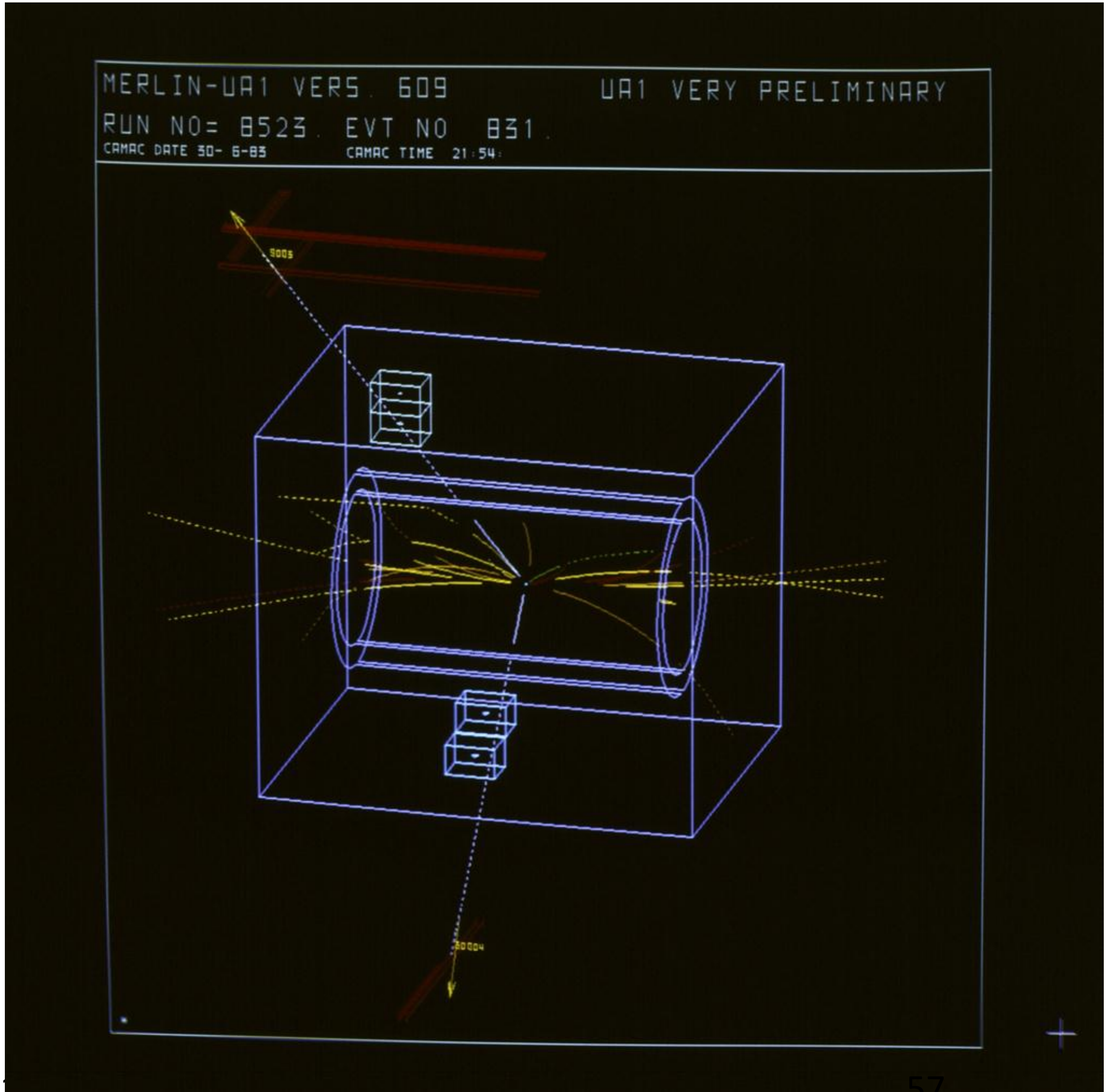
CAMAC TIME 18:53: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UA1 VERY PRELIMINARY
RUN NO= 8523. EVT NO 831.
CAMAC DATE 30- 6-83
CAMAC TIME 21:54:


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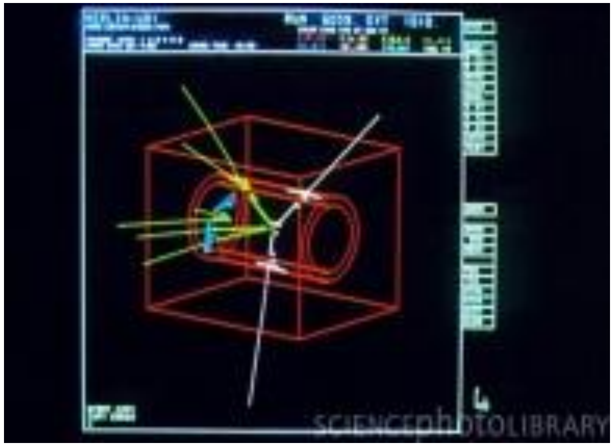
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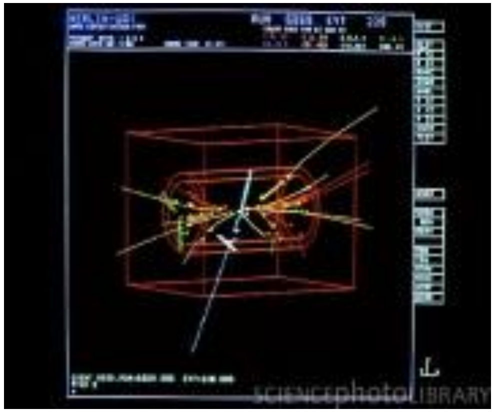
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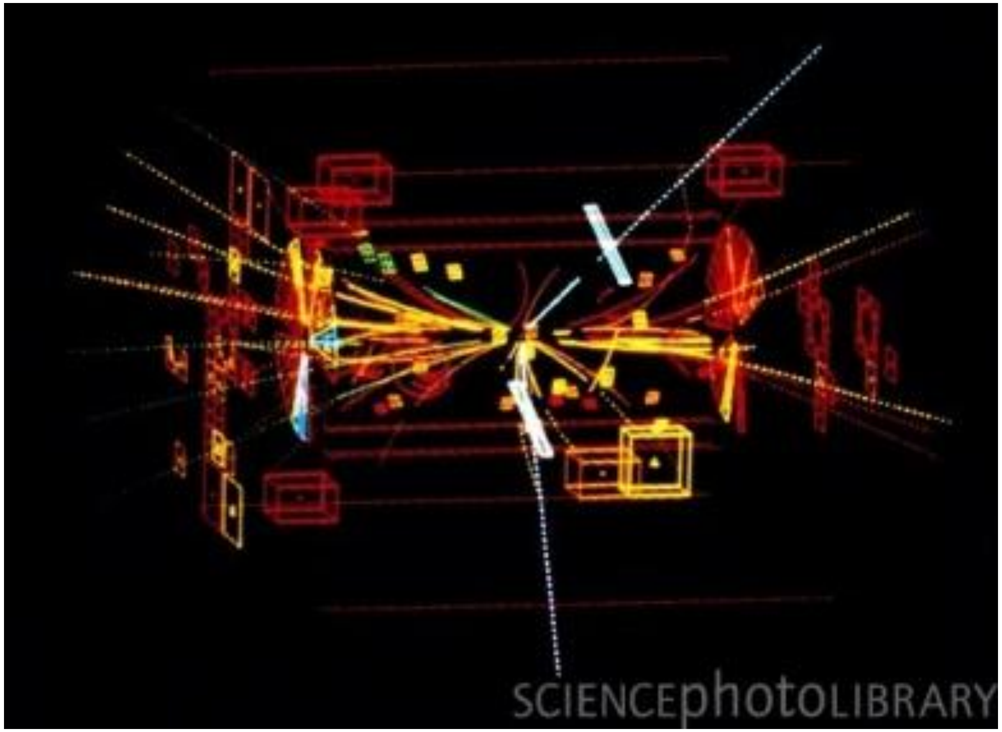

Decay of a Z boson: energy deposited and contained
in the EM calorimeter and associated tracks in the barrel

Nobel Prize Celebration

Carlo Rubbia with Herwig Schopper watching announcement of the award of the 1984 Nobel Prize

Carlo Rubbia and Simon van der Meer greeting the UA1 Collaboration

End

Спасибо за внимание !