Some personal memories of the PS and LEP.

Creation of the PS.

The “strong-focusing” or “alternate gradient” synchrotron was invented by Courant, Livingston and Snyder (3 outstanding physicists) in 1963. Christophilos had invented it some months before, but never published this.

At the time, CERN had the fortune to have an outstanding accelerator team, including John Adams, Marvin Hine, and Simon Vander Meer. The PS was a great achievement.

(Not to remember, in 1960, one of the first PS experiments: my own attempts, together with Roberto Salmeron, to see neutrino events in the Ramm 1m diameter bubble chamber. We didn’t see any.)
where $N_{E'}$ is now a counting rate per constant energy (or range) difference. One can also calculate the total number of electrons of energy $E'$ which escape as a check of the above result. If this is again done for a volume with a square centimeter base at the surface, the total number of electrons of energy $E'$ which escape from a volume element $dV$ is

$$\int \int \int \frac{N_{E'}}{\sin \theta_{app}} = \frac{N_{E'}}{2} \frac{x}{R}.$$

Integration over $\pi$ from 0 to $R'$ gives $N_{E'}/4R'$. If we integrate from $N_{E'}$ over $R' = R$ from 0 to $R$ we get

$$\int \int \frac{N_{E'}}{R} = \frac{N_{E'}}{4}.$$ 

as we should, since the total count due to degraded pulses should equal the total number of electrons escaping.

The above result states that electrons of energy $E'$ which escape from the crystal are degraded with equal probability into all energies below $E'$, since the above result are independent of $E'$ or $E''$. The fraction of electrons of energy $E'$ which escape from the crystal is equal to $1/2$ the fraction of the volume of the crystal which lies in a surface layer of depth $R'$.

These two facts can be used in a graphical method to correct distorted beta-spectra for the effect due to the escape of electrons.

A similar analysis can be made for the escape of photons from a crystal, substituting an exponential absorption for the range. The theorem in this case involves the $\Gamma$-function, which is somewhat awkward, but one can consult tables of this function to obtain numerical answers.

The Strong-Focusing Synchrotron—A New High Energy Accelerator

E. Der Matesian and A. Smith

The Physical Review, Volume 59, Number 5, 1950

Restoring forces due to radially-decreasing magnetic fields lead to stable "betatron" and "synchrotron" oscillations in synchrotrons. The amplitudes of these oscillations are due to deviations from the equilibrum orbit caused by angular and energy spread of the injected beam, scattering by the residual gas, magnetic inhomogeneities, and focusing errors.

\[
\begin{align*}
\text{Region of stability for both radial and vertical oscillations} & \\
\text{with $n_{L}$ and $n_{R}$ values alternating between $n_{1}$ and $n_{2}$,} & \\
\text{where $n_{L} = 2n_{R}$, $n_{1} = 2n_{2}$, and $n_{2} = 2n_{1}$.} & \\
\end{align*}
\]

The effective frequency of the "betatron" oscillations is given by

\[
f_{b} = f_{b} = \left(\frac{n}{2}\right)\omega_{0}.
\]

This can be compared with the frequencies given in Eq. (1) for constant $n$. Therefore, the amplitudes of oscillation and the aperture requirements can be made much smaller by the use of a large number of sectors $S$ and correspondingly large positive and negative values of $n_{S}$ in successive sectors. As a numerical example, consider a synchrotron of 24 alternating sectors, with $n_{L} = 3500$ and $n_{R} = 3500$. The radial aperture requirement is about 1/2 that for the corresponding synchrotron with a constant $n$ of 0.6, and 1/20 for the vertical aperture. Ion trajectories are not sinusoidal as in the standard synchrotron, but are composed of sections of alternating harmonic and hyperbolic functions. Figure 3 is a schematic illustration of two typical oscillating orbits computed for the case discussed in the

\[
\text{Fig. 3. Region of stability for radial and vertical oscillations for a large number of sectors $S$, in terms of the parameters $n_{L}$ and $n_{R}$.}
\]

The coefficient $\mu$ is given by the same expression, with $n_{S}$ and $n_{R}$ replaced by $(1+\mu n_{S})$ and $(1+\mu n_{R})$, respectively.

If the motion is to be stable for both radial and vertical oscillations, the limits are established by the conditions

\[
-1 < \cos 2\mu n_{S} < 1, \quad -1 < \cos 2\mu n_{R} < 1.
\]

These limits have been plotted in Fig. 1 for the specific value $N = 10$, and the region of stability is indicated. It is observed that the region of stability is widest for $n_{S} = n_{R}$. Figure 2 shows the stable region for very large $N$, and the coordinates are given in terms of $n_{L}/n_{R}$ and $n_{R}/n_{L}$. The range of stable values of $n_{S}$ is widest when $N$ is large and when $n_{L} = n_{R}$, and the center of the region of stability ($\cos 2\mu n_{S} = 0$) occurs for $[n] = N/15$.

The effective frequency of the "betatron" oscillations is given by

\[
f_{b} = f_{b} = \left(\frac{n}{2}\right)\omega_{0}.
\]
John Adams
$K_S - K_L$ interference.
After CP violation was discovered in 1964, by Christenson, Cronin, Fitch and Turley, I had the idea that one way to learn more about CP violation was by studying the interference of $K_S$ and $K_L$ in the $\pi^+ - \pi^-$ decay. End of '64 I came to CERN on sabbatical, for half a year, to do this. It turned out to be a longer job, and so I stayed an extra year.
**K_S AND K_L INTERFERENCE IN THE \( \pi^+\pi^- \) DECAY MODE, CP INVARIANCE AND THE K_S-K_L MASS DIFFERENCE**

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J. STEINBERGER †, M. J. TANNENBAUM †† and K. TITTEL *

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**Fig. 3. Observed K → \( \pi^+\pi^- \) decay rate as a function of proper time. The best fit solutions for the cases of interference and no interference are shown, as well as the calculated efficiencies.**

**Fig. 4. Experimental data treated in such a way (see text) as to isolate the interference term \( \cos(\phi + \Delta m \tau) \).**

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Formalism:

\[ \Delta \phi = \Delta m \tau \]

\[ \phi = -90^\circ \]

**Results:**

K_S-K_L interference in \( \pi^+\pi^- \) decay demonstrated

\[ \phi_{\pi^+} - \phi_{\pi^-} = 72^\circ \pm 14^\circ \]

\[ \Delta m = 44 \pm 06 \]
TIME-DEPENDENT INTERFERENCE EFFECTS IN TWO-PION DECAYS OF NEUTRAL KAONS

CERN, Geneva

Received 23 December 1965

Fig. 3a. Time distribution of 2π decays observed behind a 4 cm carbon regenerator. The curve with $\chi^2 = 85$ represents the best fit assuming no interference, the curve with $\chi^2 = 10$ is the best fit assuming interference.

Result demonstrates $K_S - K_L$ interference in $\pi^+ - \pi^-$ decay.

$\phi_\pi - \phi = -71^\circ \pm 21^\circ$

$\phi_{\pi^+}$
Gargamelle, neutral currents, quarks.

In 1973 the weak neutral current was discovered at the PS, using the Gargamelle bubble chamber. This discovery established the E-W unified gauge theory, an enormous event in the history of particle physics. In 1974 the Gargamelle team, comparing deep inelastic neutrino scattering with SLAC results of electron scattering, gave the first clear evidence for the charges and therefore the quark nature of the "partons".
1970–72 Development of "renormalizable" consistent gauge theory which:
- unifies electromagnetic and weak interactions
- predicts "neutral current" weak interaction
- predicts heavy vector particles $W^+, W^-, Z$

1973 CERN Gargamelle B.C.

P. Musset and J.P. Violette, Neutrino physics with Gargamelle

Fig. 4. Gargamelle and its environment.

Discovery of weak neutral current. Establishes Electroweak theory.
Van der Meer Horn for neutrino beam.
OBSERVATION OF NEUTRINO-LIKE INTERACTIONS WITHOUT MUON OR ELECTRON IN THE GARGAMELLE NEUTRINO EXPERIMENT

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Received 25 July 1973

Events induced by neutral particles and producing hadrons, but no muon or electron, have been observed in the CERN neutrino experiment. These events behave as expected if they arise from neutral current induced processes. The rates relative to the corresponding charged current processes are evaluated.

We have searched for the neutral current (NC) and charged current (CC) reactions:

\[ \text{NC } \nu_\mu / \bar{\nu}_\mu + N \rightarrow \nu_\mu / \bar{\nu}_\mu + \text{ hadrons} \]  \hspace{1cm} (1)

\[ \text{CC } \nu_\mu / \bar{\nu}_\mu + N \rightarrow \mu^- / \mu^+ + \text{ hadrons} \]  \hspace{1cm} (2)

which are distinguished respectively by the absence of any possible muon, or the presence of one, and only one, possible muon. A small contamination of \( \nu_\mu / \bar{\nu}_\mu \) exists in the \( \nu_\mu / \bar{\nu}_\mu \) beams giving some CC events which are easily recognised by the \( e^+ e^- \) signature. The analysis is based on 83,000 \( \nu \) pictures and 207,000\( \bar{\nu} \) pictures taken at CERN in the Gargamelle bubble chamber filled with freon of density \( 1.5 \times 10^3 \text{ kg/m}^3 \). The dimensions of this chamber are such that most

*1 A more detailed account of the analysis of this experiment appears in a paper to be submitted to Nuclear Physics.
\[ \nu + p \rightarrow K^+ + \Lambda + \nu \]

K scatters twice, then stops and decays
\[ \Lambda \rightarrow p + \pi^- \]

Gargamelle event without muon.
Event distributions in Gargamelle along chamber (beam) axis, showing nonhadronic origin.

Fig. 35  Distribution of muonless events in Gargamelle along the beam direction. (Ref. 37.)
Lepton neutrino current
\[ \nu + e^- \rightarrow e^- + \bar{\nu} \]
Comparison of N and SLAC structure functions confirms quark model.

STRUCTURE FUNCTIONS FOR EVENTS IN THE SCALING REGION $q^2 > 1 \text{ GeV}^2$, $W^2 > 4 \text{ GeV}^2$.
Multiwire proportional (Charpak) chambers.

1968 Charpak invents the MWP chamber.

1969 A group of us decide to try to use this technology to achieve more precise measurements of CP violation parameters. The design of large, experimentally useful MWP chambers turned out to be a substantial challenge. Successful design was achieved in 1970, permitting very much improved understanding of CP violation in K decay.

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THE USE OF MULTIWIRE PROPORTIONAL COUNTERS TO SELECT AND LOCALIZE CHARGED PARTICLES

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CERN, Geneva, Switzerland

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Fig. 1. Some details of the construction of the multiwire chambers. A copper shield protects the wires at their output from the chamber and contains the solid state amplifiers.

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CONSTRUCTION AND PERFORMANCE OF LARGE MULTIWIRE PROPORTIONAL CHAMBERS

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Received 21 September 1970
A NEW DETERMINATION OF THE $K^0 \rightarrow \pi^+\pi^-$ DECAY PARAMETERS

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Received 4 February 1974

Results:

$|\eta^{+\pi^-}| = (2.30 \pm 0.35) \times 10^{-3}$

$\phi^{+\pi^-} = (49.4 \pm 1.0)^\circ + \left(\frac{\Delta m}{0.540 \times 10^{-15} \text{sec}} - 1\right) \times 305^\circ$

$[\eta_{+\pi^-} = \langle \pi^+\pi^- | T | K_L \rangle = |\eta_{+\pi^-}| e^{i\phi_{+\pi^-}} = \xi + \xi']$

$[\Delta m = m_L - m_S]$
MEASUREMENT OF THE CHARGE ASYMMETRY IN THE DECAYS $K^0_L \rightarrow \pi^\pm e^\mp \nu$ AND $K^0_L \rightarrow \pi^\pm \mu^\mp \nu$

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Results: $\delta_L = \frac{N_+ - N_-}{N_+ + N_-} = 2 R_\varepsilon \varepsilon$ ; $(\eta = \varepsilon + \varepsilon')$

\[ \delta_L, \varepsilon = (3.41 \pm 0.18) \times 10^{-3} \]

\[ \delta_L, \varepsilon' = (3.13 \pm 0.29) \times 10^{-3} \]

\[ R_\varepsilon \varepsilon = (1.67 \pm 0.08) \times 10^{-3} \]

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MEASUREMENT OF THE KAON MASS DIFFERENCE $m_L - m_S$
BY THE TWO REGENERATOR METHOD

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Result: $\Delta m = (1.533 \pm 0.004) \times 10^{-20}$ sec

$\phi_{+} = (45.9 \pm 1.6)^0$

(in agreement with prediction for $e^+ < e^-$, $\phi_{+} = \phi_{2}$ and $\tan \delta_{L} = (43.7 \pm .15)^0$)
A measurement of the total cross-sections for \( \Lambda \) hyperon interactions on protons and neutrons in the momentum range from 6 GeV/c to 21 GeV/c

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CERN, Geneva, Switzerland

and

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**Fig. 3.** (a) and (b) The measured total cross-sections \( \sigma(p\Lambda) \) and \( \sigma(\Lambda\Lambda) \) as a function of momentum. Only statistical errors are shown. The prediction from quark-model additivity sum rules is indicated by the broken lines. The range between the lines covers the uncertainty of the data used in evaluating the sum.

**Conclusion:** the PS permitted good progress in particle physics.
LEP, the “ultimate” $e^+ - e^-$ storage ring collider.

To my knowledge, first suggestion for the “ultimate e+ - e- collider came from Burt Richter, in the 70’s.

N. B.: As best I know, Tini Veltman was responsible for the suggestion, in the late 70’s, and which was accepted, that the tunnel should be constructed so as to permit a future p – p collider, now the LHC.

The beginning of the ALEPH collaboration was summer of ’80, Maybe a dozen of us, including some members of the CDHS neutrino experiment, Jaques Lefrancois, and Rene Turley. We agreed that we would like to focus on a special purpose detector, but soon agreed that we could not think of an interesting “special purpose”, and so focused on a general purpose detector.

My own first concept, given the expected isotropy of the Z decay, was not brilliant: a spherical magnet. This was not adopted.

The most important insight, in my opinion, the one which dominated the ALEPH design, came from Jacques Lefrancois: the electro-magnetic calorimeter should focus on angular, rather than energy, resolution.

ALEPH construction: we were managed beautifully by the Technical Coordinator, Pierre Lazeyras.
Subdivision into equal elements (modules)
(no equal solid angles from input point)

Winding calorimeter wind

Super module 

120° x 120°

Split in 4 x 6° + 6°
LETTER OF INTENT

TO STUDY e+e− ANNIHILATION PHENOMENA AT LEP

Bari-CERN-Demokritos Athens-Dortmund-Ecole Polytechnique Palaiseau-
Edinburgh-Glasgow-Heidelberg-Lancaster-MPI München-Orsay-Pisa-Rutherford
Saclay-Sheffield-Torino-Trieste-Westfield College London-Wisconsin Collaboration

Geneva, 25 January 1982
The aim of this report is to study the \( \mathbf{E} \times \mathbf{B} \) effect measured in the TRIUMF TPC and make some quantitative estimates for the worsening of the \( R\phi \) resolution of our TPC because of this effect.

### SOME DATA ON TRIUMF TPC

- **Effective dimension of the cell**: 6 mm
- **Gas**: 80% A + 20% CH₄
- \( \mathbf{E} \times \mathbf{B} \) angle, at \( B = 8.5 \text{ Kg} \), \( \psi = 32^\circ \) (\( \tan 32^\circ = 0.624 \))
- **Resolution for 0° track**: 0.450 mm
- **Resolution for 32° track**: 0.180 mm
- **Resolution \( \mathbf{E} \times \mathbf{B} \) at 0°**: \( \sigma^2(0^\circ) - \sigma^2(32^\circ) = 0.412 \text{ mm} \)

The shape of the cell is shown in Fig. 2.

From Sauli report [1] at 80% A + 20% CH₄, we have

- **Primary ionization**: \( N_e = 2.67 \text{ pair/mm} \)
- **Total**: \( N_{\text{Tot}} = 8.58 \text{ pair/mm} \)

### 1. DRIFT OF ELECTRONS IN \( \mathbf{E} \) AND \( \mathbf{B} \) FIELDS

The familiar expression for the drift velocity of electrons in gas

\[
\mathbf{v}_d = \frac{e \mathbf{E}}{m} = \mu \mathbf{E}
\]

(with \( \tau \) = mean time between two successive interaction with the gas molecule) is modified in presence of a magnetic field [2]
Momentum resolution of combined tracking system for highest momentum particles (45 GeV muons)

\[ \Delta p/p^2 = 0.0006 \text{ (GeV/c)}^{-1} \]

\[ Z^0 \rightarrow \mu \mu \]

- \( Q = +1 \)
- \( Q = -1 \)

ALEPH

\[ P_{\mu} = 45 \text{ GeV} \]

\[ \frac{\Delta P_{\mu}}{P_{\mu}} = 2.7\% \]
LEGION PLOT: Run 2516, Event 146
(1/3 of a Barrel module)

EMAX = 3.274 GeV
ETOT = 24.738 GeV

\textbf{NEUTRAL CLUSTER}

\[ E_{\text{ch}} = 6.94 \text{ GeV} \]
\[ E_1 = 3.52 \text{ GeV} \]
\[ E_2 = 2.02 \text{ GeV} \]
\[ \Theta_{E_1 E_2} = 2.47^\circ \]
\[ M_{E_1 E_2} = 420 \pm 18 \text{ MeV} \]

\textbf{RESPONSE OF EM CALORIMETERS TO A PARTICULAR QUARK \( \rightarrow \) HADRON SHOWER. ILLUSTRATES IDENTIFICATION OF ELECTRONS, PHOTONS, AND HADRONES.}

\textbf{CHARGED CLUSTER}

\[ H : p = 9.26 \text{ GeV} \]
\[ E_{\text{ch}} = 2.5 \text{ to } 2.6 \text{ GeV} \]
\[ M_{E_3 E_4} = 505 \text{ to } 1350 \text{ MeV} \]

\[ <E_p^{-1}> = 3 \pm 6 \text{\%} \]
Buon Giorno!!

Cosmic ray event

Energy of cosmic ray \sim 10^7 \text{eV}?

A cosmic ray shower of parallel muons in ALEPH.

Courtesy Monica Pepe Altenelli