Particle physics at CERN (and elsewhere) since the early days until the LHC era: a quick survey

D. Treille
CERN (honorarius)
Synoptic of particle physics and related fields

A few guided tours, pre-LHC

Pre-70: no guidance from theory
Post-70: checking and validating SM

Daniel Treille, June 2014
The proton

1909

α

The Varian brothers

klystron

W. Panofsky

1968

NP 1990

Scattering off point-like partons

1957

Hofstadter

0.84-0.87 fm radius

scattering angle

Bjorken Feynman

The constituents of the proton are pointlike non-interacting, charged spin 1/2 particles

→ quarks

* at short distance
neutrino scattering

CDHS 76-84

CHARM

neutrinos select the flavor
study valence quarks

muon scattering

EMC, NA4

and NOMAD, CHORUS

and Gargamelle
violation of scaling (1978)

clear hints for glue and sea quarks
quark structure of bound nucleons different from free nucleons (1983)
spin crisis (1988)
presently COMPASS

hadron scattering → prompt γ and leptons, see backup

high mass lepton pairs 7 experiments
discovery of K-factor i.e. gluon radiation

prompt photons
hard photoproduction (NA14)

HERA took over

HERA I+II inclusive, jets, charm PDF Fit

K

NA3

WA11

√T

also
ISR
pp collider

esential for LHC
strong isospin 1932 SU(2) Yukawa 1935 weak isospin

fermions live in weak isospin space

strange particles come in (47-61)

pre-BC techniques much contributions of future CERN actors

in BC, mostly found at BNL and LBL machines

but

strangeness

the Eighfold Way 1960

with Y. Ne’eman

M. Gell Mann SU(3)

quarks 1964 at CERN

Zweig Aces others?

Petermann

anti-triplet as anti-quarks q. Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q q), etc., while mesons are made out of (q q), (q q q q), etc. It is assuming that the lowest baryon configuration (q q q) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration (q q) similarly gives just 1 and 8.
1963

relative probability that $d$ and $s$ quarks decay into $u$

$$|d'| = \begin{bmatrix} \cos \theta_c & \sin \theta_c \\ -\sin \theta_c & \cos \theta_c \end{bmatrix} |d|$$

$\theta_c = 13.02^\circ$

Cabibbo angle

1970

GIM + Bjorken

1974

J/Psi Richter Ting

charmonium spectroscopy charmed mesons 1976

Kobayashi Maskawa

Lederman discovering beauty 1977

1973

stimulating but frustration at CERN

a lot of heavy flavor spectroscopy at CERN (SPS, LEP, LHC)

1976

charmed mesons

1975

and M.Perl tau

unobserved at that time
pert. QCD understood, but manifestations are complex, e.g. multi jets
Impressive theoretical work to match the needs of LHC physics.
QM

Maxwell 1861

\[ dF = 0 \]
\[ \star d \star F = J \]

Yang-Mills 1954

\[ d_{D}F = 0 \]
\[ \star d_{D} \star F = J \]

non abelian

covariant

QED

Feynman et al 1949  Lamb shift

\[ \psi(x) \rightarrow e^{i\alpha(x)}\psi(x) \]

then clear mission: search for the W and Z, search for the BEH boson

Glashow Salam Weinberg

NP 1979

BEH 1964  't Hooft 1971

\[ (\gamma) = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} (B^0) \]
Neutral Currents

maturation of the BC program at CERN opening to European and US labs 1960: creation of the TCC

Gargamelle decided end 1965

CERN and CEA Weisskopf, Gregory
an odyssey… much scepticism many characters Perkins, Cundy, …

“alternating currents”, see backup

subsequent neutrino experiments R (NC/CC)

\[
\sin^2 \theta_W = 0.225 \pm 0.005 (\text{exp.}) \pm 0.005 (\text{theo.})
\]

now \(0.23146(12)\)

leptonic

\[\bar{\nu}_\mu \ e^- \rightarrow \bar{\nu}_\mu \ e^-\]

Gargamelle freon \(\text{CF}_3\text{Br} \ 12m^3\)

hadronic

Aachen

A. Lagarrigue

A. Salam et P. Musset

W F Fry and D Haidt

neutrinos

neutrons

A. Rousset

Ec. Pol.
**ISR**

“A brilliant start” 71-74

“A somewhat difficult period” 75-77

“A very active and interesting programme” 78-83

**M. Jacob**

**rising total cross-section:** proton size increases with $E$, its shape stays the same. Geometrical scaling

**lepton pair production:** Drell-Yan and onia

1979: first clear (mass peaks) observation of charmed hadrons in hadronic interactions

**great success of the machine**

but J/Psi, charm, beauty, tau, gluon found elsewhere

**End of ISR in 83**

M. Jacob

“I come to bury Caesar not to praise him”

Marc Antony, in Julius Caesar

V. Weisskopf:

“it does not matter where discoveries are made.”

**direct photons:** 1979 to the end. Discovered at ISR. Important test of QCD

**1982 AFS, R11:** evidence for the dominance of 2-jet structure at highest $E_T$. But pp collider already in the game.

**some moral support was needed...**

**Split field**

**focus on forward region**

**lack of theoretical guidance**

**1973:** discovery of the large $p_T$ phenomena partons point-like relative to the strong interaction

**1979:** first clear (mass peaks) observation of charmed hadrons in hadronic interactions

**1982:** rising total cross-section: proton size increases with $E$, its shape stays the same. Geometrical scaling

**1982:** lepton pair production: Drell-Yan and onia

**1982:** direct photons: 1979 to the end. Discovered at ISR. Important test of QCD

**1982:** 1982 AFS, R11: evidence for the dominance of 2-jet structure at highest $E_T$. But pp collider already in the game.

**it came next..**
The $\bar{p}$-p collider

aim: to discover $W$, $Z$
fast decisions, fast realisation
great machine, great detectors
hermeticity, redundancy, innovating techniques
physics “au rendez vous”: hadronic jets, $W$, $Z$, etc

C.Rubbia's determination in somewhat adverse climate
1976 paper by C.Rubbia, P.McIntyre and D.Cline
1977 proposal to CERN and Fermilab, feasibility study
1978 success of ICE  1979 approval of the experiments

UA1 tracker
B.Sadoulet

UA2 calorimetry, 1/3 cost of UA1

UA2 hadronic jets

“L'espoir changea de camp, le combat changea d'âme” (D.Denegri and V.Hugo)
The Collider proved the physical reality of partons inside the proton; it opened the door to quantitative tests of QCD.
Detectors

The rise of Si detectors
from flavor tag to main tracking, i.e. from $m^2$ to hundred $m^2$
spectacular evolution of microelectronics. Decisive role of CMOS high
density circuits, of deep sub-micron technologies intrinsically radiation hard

The reign of bubble chambers
from “années d’apprentissage” to the successes of the large chambers
liquid hydrogen, heavy liquids many techniques of picture analysis
hybrid systems: BEBC external detectors, EHS rapid cycling chamber, ...

Triggered detectors
1949-59: spark chambers development as tracking devices
1962: first massive use of them in BNL, evidence for $v_\mu$
various read out methods, from film to filmless
1972: $\Omega$ optical role of streamer chambers >1964: on line computers

The 68 revolution of G.Charpak
MWPC, drift chamber, multistep (F.Sauli), culminating with TPC (D.Nygren)
1971: CERN-Heidelberg J.Steinberger et al, at PS on CP
1972: Split Field Magnet Charpak, Minten, Innocenti et al, at ISR
Calorimetry: compensation, pointing geometry
Liquid argon, scintillating crystals, etc Si-W?
R/O methods: PMs, APDs

Identification
dE/dx, Cerenkov (threshold, DISC, RICH)

Crucial role of detector R&D (DRD…)
Vital to pursue it (HL LHC, etc)
3D tracking, ultimate calorimetry
perf. CPU/cost $\times 8 \times 10^7$ in 40 yrs
external connectivity: from kbps near 1980 to 100 Gbps now

D. Williams

farms: used at LEP (Aleph, Delphi)

- 1947 The first integrated transistor (Bell Telephone Laboratories)
- 1959 The first bipolar planar transistor
- 1958 The first integrated circuit available as a monolithic chip (flip-flop)
- 1965 The first op-amp
- 1971 The first 4-bit microprocessor (Intel 4004)
- 1972 The first 8-bit microprocessor (Intel 8008)
- 1981 The first IBM PC

C. Piguet
Heavy flavor at SPS  see later LEP, etc
a very active area (about 20 experiments)
considerable impact on QCD
most innovative in terms of Si detectors
hadron, photon (charm fraction x 10), hyperon beams
mostly charm physics (spectroscopy, lifetimes, production mechanisms)
but some beauty physics

<table>
<thead>
<tr>
<th>NA32</th>
<th>CCD 5µ res. 2.0±0.2 10^{-13} s</th>
</tr>
</thead>
<tbody>
<tr>
<td>M(Ω π⁺π⁻) (GeV/c²)</td>
<td>2.6</td>
</tr>
<tr>
<td>M(Δ⁺) (GeV/c²)</td>
<td>1.27</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WA92</th>
<th>WA58 emulsion+Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>158 A GeV/c: d = 60 cm α = 40 mrad</td>
<td></td>
</tr>
<tr>
<td>40 A GeV/c: d = 50 cm α = 72 mrad</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WA97/NA57 Si pixels (RD19)</th>
</tr>
</thead>
<tbody>
<tr>
<td>first time in an experiment</td>
</tr>
</tbody>
</table>
g–2 of the muon

“g-2 is not an experiment: it is a way of life. ”
John Adams

LEP

rare decays, see backup
muon $g-2$

E. Picasso

F. Farley

Uncertainty on $a_{\mu}$ in $10^{-9}$

<table>
<thead>
<tr>
<th>CONTRIBUTION</th>
<th>RESULT ($\times 10^{-11}$) UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td>QED ( leptons )</td>
<td>$116 , 584 , 718.09 \pm 0.14 \pm 0.04_{\alpha}$</td>
</tr>
<tr>
<td>HVP (ho)</td>
<td>$6 , 914 \pm 42_{\text{exp}} \pm 14_{\text{rad}} \pm 7_{\text{PQCD}}$</td>
</tr>
<tr>
<td>HVP (ho)</td>
<td>$-98 \pm 1_{\text{exp}} \pm 0.3_{\text{rad}}$</td>
</tr>
<tr>
<td>H1xL</td>
<td>$105 \pm 20$</td>
</tr>
<tr>
<td>EW</td>
<td>$152 \pm 2 \pm 1$</td>
</tr>
<tr>
<td>Total SM</td>
<td>$116 , 591 , 793 \pm 51$</td>
</tr>
</tbody>
</table>

$a^{\text{SUSY}}_{\mu} \approx 123 \times 10^{-11} \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan \beta$

unsettled…
LEP  great machine  4 good detectors  clean, subtle physics  SM validated at loop level

LEP EWWG '05

ADLO

17M Z

MegaZ

L3

SC RF cavities

Aleph

Delphi
**LEP did much better than expected**

<table>
<thead>
<tr>
<th>Machine</th>
<th>Foreseen (55/95 GeV)</th>
<th>Achieved (46/98 GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current per bunch</td>
<td>0.75 mA</td>
<td>1.00 mA</td>
</tr>
<tr>
<td>Total current</td>
<td>6 mA</td>
<td>8.4 mA/6.2 mA</td>
</tr>
<tr>
<td>Beam-beam vertical parameter</td>
<td>0.03</td>
<td>0.045/0.083</td>
</tr>
<tr>
<td>Ratio of emittances</td>
<td>4.0</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Maximal luminosity (10^{30})</td>
<td>16/27</td>
<td>34/100</td>
</tr>
<tr>
<td>$\beta_x^*$</td>
<td>1.75 m</td>
<td>1.25 m</td>
</tr>
<tr>
<td>$\beta_y^*$</td>
<td>7 cm</td>
<td>4 cm</td>
</tr>
</tbody>
</table>

**Physics**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Expected error</th>
<th>Achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_Z$</td>
<td>50 to 20 MeV</td>
<td>2.1 MeV</td>
</tr>
<tr>
<td>$m_W$</td>
<td>100 MeV</td>
<td>30 MeV</td>
</tr>
<tr>
<td>$N_\nu$</td>
<td>0.3</td>
<td>0.008</td>
</tr>
<tr>
<td>$A_{FB}^0$</td>
<td>0.0035</td>
<td>0.0013</td>
</tr>
<tr>
<td>$A_{FB}^0$</td>
<td>0.0050</td>
<td>0.0017</td>
</tr>
<tr>
<td>$A_r$</td>
<td>0.0110</td>
<td>0.0043</td>
</tr>
</tbody>
</table>

**Ad Augusta per Angusta**
**BEH boson**

**PDG 1988**

Cast-iron \( m_h > 14 \) MeV

Probably \( m_h > 4 \) GeV

(B, Upsilon, K)

**LEP**

**LEP1** \( m_h > 63 \) GeV

**LEP2 mass reach (1993):** \( m_h \approx \sqrt{s} - M_Z \)

2000: Crash against the higgsstrahlung barrier for \( m_h = 206 - M_Z = 115 \) GeV

LEP ended in confusion, sound and fury... no way to increase the energy ...

Some candidates doubtful: constraint physics at the kinematical limit?

LEP stopped

LHC answered: nothing at 115 GeV, something at 125...

**A point of history**

K. Hubner, 2004

The maximum energy of LEP 2 was determined by the decision in 1996 to discontinue the industrial production of the superconducting cavities. Whether the potential of LEP should have been better fully exploited up to its reasonable limit of 220 GeV in the centre-of-mass and whether this would have lead to the discovery of the Higgs particle as a number of models seemed to suggest [36,37], is a matter of speculation. The quest for the Higgs particle will hopefully end with the results obtained by the Tevatron and the LHC. In any case, LEP will stand as a landmark in the development of particle accelerators.
maturity of beauty tag
CP violation in B world
only 2 experiments (or a single one) may lead to tricky situations.

strong and essential collaboration between theory and experiment
Emergency exit

CP violation

heavy ions

neutrinos

dark matter
skipping many results from CERN, proof of direct CP violation: NA31, NA48

1956 parity violation

1964

direct measurement of non invariance by time reversal $P(K_0 \rightarrow \bar{K}_0) - P(\bar{K}_0 \rightarrow K_0) \neq 0$ at 5σ
difference of mass and decay width of $K_0$ and $\bar{K}_0$ compatible with 0 with a sensitivity of $O(10^{-16})$ GeV

CP violation in B physics

LEP, among others, was involved then domain of B factories and LHCb

CPT: does the antiatom behaves as the atom?

1993 idea: $\bar{p}$ make $e^+e^-$ pairs in the Coulomb field of nuclei and can capture the positron 1995 LEAR PS210
9 antiatoms of 0.9c, very mediatic! 1996 TRAP at LEAR: $e^+$ and $\bar{p}$ captured, just before end of LEAR.
AD 2002: in ATHENA (ATRAP) signal from ~50K (17K) antiH. Still too fast. Need <0.06 meV to capture them next: AEGIS, gBAR
heavy ions at SPS

"fusion" of J/ψ

strangeness enhancement

e⁺e⁻ pairs

CERN Press Release February 2000:

New State of Matter created at CERN
W. Pauli 1930

I have done a terrible thing

I have postulated a particle
that cannot be detected.

1956 detection of anti $\nu_e$

Renes Cowan in 1958

1961 at CERN failed attempt of a neutrino program

Brookhaven
2 neutrinos 1962

Lederman, Schwartz, Steinberger

Nobel 1988

Three generations of matter (fermions) spin $\frac{1}{2}$

$N = 2$

$N = 3$

$N = 4$

LEP

3 neutrinos

neutrino oscillation

Super-Kamiokande

Pontecorvo 1957
Homestake 1968
Gallex 1994
still “solar $\nu$ problem”
SNO 2002
Kamland 2004

1958

1998

Koshiba NP 2002

 neutrinos have non zero small masses

$|\Delta m_{21}^2| \approx 7.6 \times 10^{-5} \text{ eV}^2$

$|\Delta m_{31}^2| \approx 2.4 \times 10^{-3} \text{ eV}^2$

at CERN:

searches for oscillations
Chorus, Nomad
unfortunately not in the right domain of parameters

from CERN:
OPERAn


Koshiba

NP 2002

half of the $\nu_\mu$ lost
oscillated to $\nu_\tau$

Pontecorvo
1957

Homestake
1968

Gallex
1994

still “solar $\nu$ problem”

SNO
2002

Kamland
2004

ICARUS/NESSIE

3 LH neutrinos hierarchy? its own antiparticle?

CP? is that all? sterile neutrinos of eV keV GeV ?

see-saw (Minkowski, etc)

$\Sigma m_i < 0.26 \text{ eV}$

SHIP beam dump?
**dark matter**

**galaxy**

**cluster**

**lensing**

**BBN**

**SHIP (?), etc**

**KE_{avg} = \frac{1}{2} GPE_{avg}**

**IAXO**

**CMB**

**ADMX, “shining wall”**

**LHC**

**and other methods**

**PRL.112.091303 (arXiv:1310.8214)**
Without hiding shadows, CERN, well thought from the start, is a great success. Let’s hope this will go on and CERN will keep its leadership at the HE frontier. Impressive bilan: NC, W and Z, LEP physics, BEH boson. What next? Exploit fully what we have now. “Leave no stone unturned”...

**SUSY?**

value of $m_h$ encouraging

hiding well, but limited search

LSP $>$ 500 GeV?

is it reality or a refined mental construction?

or any other BSM scenario?

or did we get all, except DM?

e.g. BEH boson + 3 sterile neutrinos solving all problems, as in νMSM?

or shall we end with anthropic arguments ??????

αδηλον παντι πλην ἢ τῷ θεῷ.
Backup
Main remarks

1/ theory, ideas: until early seventies, no theoretical guidance
after: checking and validating the SM + search for a few new scenarios (SUSY,..)

2/ discoveries
until the Neutral Currents or so, CERN in a learning phase
then came the march towards its present leadership at the HE frontier

3/ detectors
some mutations, most important being the 68 revolution of Charpak
Key role of the progress in parallel of microelectronics, etc

4/ cosmology
not so long that the paradigm of an expanding universe is dominant,
hence PP seen as “archeology” of the first instants
Our world is quantic...

1/ particles too heavy to be "really" produced nevertheless intervene as virtual particles and modify slightly the value of the low energy observables. Accurate measurements can thus bring information on them

2/ "constants" are not constant, but evolve with the energy scale
Yes, they can: quantum effect

Equal production of particles and antiparticles. No track of antiparticles. But we are there! What happened?

Murayama

Yes, they can: quantum effect
kaon rare decays

SM BR

$K_L \to \pi^0 \nu\nu$

$3 \times 10^{-11}$

$K^+ \to \pi^+ \nu\nu$

$8 \times 10^{-11}$

$K_L \to \pi^0 e^+ e^-$

$3.5 \times 10^{-11}$

$K_L \to \pi^0 \mu^+ \mu^-$

$1.5 \times 10^{-11}$

beauty rare decays

LHCb + CMS

B($B_s \to \mu^+ \mu^-) = (2.9 \pm 0.7) \times 10^{-9}$

B($B_d \to \mu^+ \mu^-) = (3.6^{+1.1}_{-0.8}) \times 10^{-10}$

high intensity frontier

LFV

$Br(\mu \to e\nu\nu) < 10^{-14}$ (MEG – II – future)

$Br(\mu \to eee) < 10^{-16}$ (Mu3e – future)

$R_{\mu \to e}^{Tl} < 10^{-18}$ (Comet/Prism, ... – future)

$R_{\mu \to e}^{Al} < 5 \times 10^{-17}$ (Mu2e – future)

$Br(\tau \to \mu \mu\mu) < 10^{-9,10,117}$ (SuperBfactories, SHIP, ... – future)

1 order of magnitude improvement

4 order of magnitude improvement

~4-6 order of magnitude improvement

~2 order of magnitude improvement

eEDM

SuperKEKB

PSI

KEKB operation finished at 9:00 am June 30, 2010

• SuperKEKB budget is partially approved
  • Damping ring: 580M yen (~5.8M USD) (FY2010)
  • Special budget “Very Advanced Research Support Program” 1B yen (~100M USD) (FY2010-2012)

→Start construction (FY2010-2013)
back to CP: skipping many results from CERN, direct CP violation: NA31, NA48

CP Lear \[ p\bar{p} \rightarrow \pi^+ K^- K^0 \quad p\bar{p} \rightarrow \pi^- K^+ K^0 \]
direct measurement of non invariance by time reversal
\[ P(K^0 \rightarrow \bar{K}^0) - P(\bar{K}^0 \rightarrow K^0) \neq 0 \quad \text{at 5}\sigma \]
direct measurement of the CPT parameter, conservation demonstrated 50 times more precisely than before
differences of mass and decay width of \( K^0 \) and \( \bar{K}^0 \) compatibles with 0 with a sensitivity of some \( 10^{-18} \text{ GeV} \)

CP violation in B physics
LEP, among others, was involved
then domain of the beauty factories and of LHCb

CPT: does the antiatom behaves as the atom?

1993 idea: \( \bar{p} \) make \( e^+e^- \) pairs in the Coulomb field of nuclei and can capture the positron 1995 LEAR PS210
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AD 2002: in ATHENA (ATRAP) signal from \( \sim 50K \) (17K) antiH. Still too fast. Need \( <0.06 \text{ meV} \) to capture them
next: AEGIS, gBAR
John Bell
1964 Bell inequalities
Bell et al anomaly

68: model of G. Veneziano, father of strings idea relaunched in 1974 (Scherk-Schwarz) in another context and scale, towards Superstrings

73: J. Wess et B. Zumino: invention of SUSY then S. Ferrara: co-invention of SUGRA J. Ellis, G. Giudice, etc: SUSY phenomenology

91: several authors give upper limit on Higgs mass in the MSSM. In 94, with the top mass, \( m_h \leq 130 \) GeV

80: I. Antoniadis: possibility of large extradimensions

“Si tu ne vas pas à Planck, Planck viendra à toi”

gravity looks weak because it is diluted in extradimensions (ADD) or because it is confined near a “brane” which is not ours (RS)

an industry at LEP and LHC: unfortunately nothing seen
In Europe first “chacun pour soi”, Europe and CERN are learning techniques and the way to collaborate
52 invention of BC (Glaser), then leading role of Alvarez (Berkeley)
58 HBC 10cm in SC (until 60)
59 commissioning of the 72 inch chamber in Berkeley
   “most courageous of scientific decisions”
60 HBC 30 cm at PS (until 62)
Then fast reactions, maturity, towards big successes
61 TC (Peyrou) created
jan 64 R.P. Shutt’s proposal
feb–april 64 definition of Gargamelle (Lagarrigue)
dec 64 recommendation of a large LHBC
end 65 decision about Gargamelle
65 operation of HBC2m (3MSF, until 77, 40 M pictures)
dec 70 commissioning of Gargamelle
67–72 construction of BEBC 75 BEBC fully operating

Nevertheless:
Bright and fruitful “pre–CERN” activities in cosmic ray physics with cloud chambers, e.g. R. Armenteros
many important contributions to hadron spectroscopy from CERN in the first years ex. 1962 $\bar{p}$ 3 GeV, discovery of $\Sigma^-$
ex. 1962: $K^-$ at rest in 81cm BC, relative $\Sigma$–$\Lambda$ parity >0
Later, great successes of the big chambers, crowned by the discovery of NC.
Important role of the last generation of rapid cycling chambers in charm physics

Moreover
Bubble Chamber activities have gradually built the strong and diverse technical expertise of CERN and European laboratories
They allowed Europe and CERN to find the ways to cooperate

no doubt that in the first decade most of the discoveries were made elsewhere

LBL cyclotron 1950 $\pi^0 \rightarrow 2\gamma$ Panofsky, Steinberger
Other cyclotrons (Nevis, Chicago,...)
1953 BNL Cosmotron, 3.3 Gev proton synchrotron, until 1966
1953 V events
1956 $K_L$ 1957 $\Sigma^0$ 1961 $\rho$
1955: LBL Bevatron, 6 Gev protons
1955 antiproton
1958 anti$\Lambda$ 1959 $\Xi^0$ 1960 anti$\Xi^0$
1961 $K^*(892)$, $\Lambda(1400)$, $\omega$, $\eta$ 1964 $\eta'$
1968 Nobel to L. Alvarez
July 1960: AGS, 33 GeV
1962 $\Xi^-$–anti $\Xi^+$, $\varphi$
1964 $\Omega^-$, CP violation

Early non–BC physics at SC (from L. di Lella)

$\pi \rightarrow e\nu$
1955 Steinberger in Nevis <0.6 $10^{-4}$ Chicago < 2 $10^{-5}$
1958 Fidecaro et al $R_\gamma = 1.22 \pm 0.30 \times 10^{-4}$
OK for $e^{-}\mu$ universality of the $A'$ coupling
Cornerstone of our understanding of $V$–$A$ interaction

Also first observation of the pion $\beta$–decay $\pi^+ \rightarrow \pi^0 e^+\nu$

$\mu \rightarrow e \gamma$ ? Some evidence?
1962 Conversi, di Lella, Rubbia,: the process is forbidden for real and virtual $\gamma$. Lepton flavour is conserved

... and $g$–2 of the muon started

Also: helicity of the muon from $\pi \rightarrow \mu \nu$ at PS
Neutral Currents

Petite histoire: from 1.2m HL chamber, limit on ratio of elastic NC to CC events <0.03 published in 64. Simply a mistake uncovered by M.Paty in 1965.

After Siena 63 Lagarrigue, Rousset, Musset worked out a proposal of a neutrino detector aiming at an increased event rate by an order of magnitude. Leprince R. called it Gargamelle. Collaboration built on X–Orsay and former members of the NPA 1m BC. Later 7 european laboratories.

71–72: viable theory of weak interactions. NC? Yes or no?

Competitors: Gargamelle and HPWF counter experiment at NAL

Nov 68: Gargamelle meeting in Milano. NC word not pronounced, low priority. DIS more exciting…


HPWF signal disappeared. Dismay, distrust, one more year of work.

London 74. Confirmation by Gargamelle, HPWF affirms NC… Similarity in structure of weak and em interactions. The term electroweak came into circulation. Experimental beginning of the SM. \( M_w \) predicted near 70 GeV.
HADRON and photon beams

Some seventy SPS experiments in the last 25 years
E. Quercigh, B. French

HARD SCATTERING
High mass lepton pairs Prompt photons Photoproduction

HEAVY FLAVOURS
Charm physics Beauty physics

HADRON SPECTROSCOPY
Light quark hadrons Gluonium Baryonium

SOFT PROCESSES
Particle production Elastic scattering Low mass $\mu\mu$, soft $\gamma$

HEAVY FLAVOURS AT SPS
A most active area (~20 expts) with considerable impact on QCD
Most innovative in term of detectors, in particular
Si detectors: microstrips, active targets, CCD detectors
But still use of emulsions, rapid cycling high resolution BC
Hadron beams, $\gamma$ beams (charm fraction $\times 10$), hyperon beams
Mostly charm physics (spectroscopy, lifetimes, production mechanisms)

But some beauty physics: difficult, higher $s$ needed

HIGH MASS LEPTON PAIRS
7 experiments
DISCOVERY OF $K$-FACTOR
i.e. gluon radiation (WA11, NA3)

NA3

Ex. OMEGA BEAM DUMP:
FIRST RESULTS FROM SPS

EXTRACTION OF HADRON
STRUCTURE FUNCTIONS
STUDY OF QUARKONIA
PRODUCTION MECHANISMS

HARD SCATTERING (suite)
Prompt photons Photoproduction
QED and QCD Compton effects

WA70 $5<p_T<6$ GeV

$\Omega^0$ in WA89
Lifetime $55\pm20 \times 10^{-15}$ s

WA58 emulsion+$\Omega$

NA32 $\Lambda_c$
CCD $5\mu$ res. $2.0\pm0.2 \times 10^{-15}$ s

WA92

Hadron spectroscopy
Light quarks Glueball search Baryonium search

Soft processes
Particle production Elastic scattering Low mass $\mu\mu$, soft $\gamma$

Several sacrifices on the altar of LEP....
Recent developments in perturbative QCD
NLO, NNLO and logarithmic resummation