Collider Particle Physics
- Chapter 4 -

SppS: discovery of the W and Z

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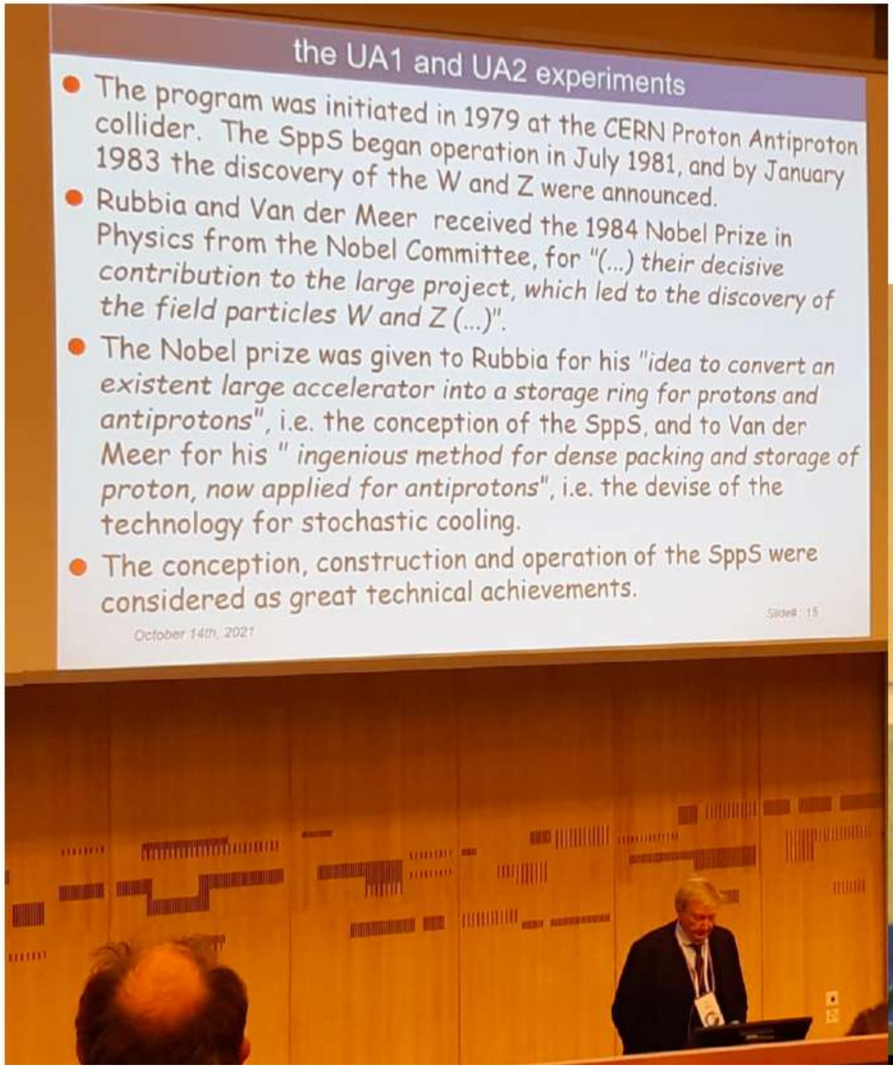
Chapter Summary

- ☐ Toward the Sp$\bar{p}$S collider
- ☐ The Sp$\bar{p}$S parameters
- ☐ UA1 and UA2 Detectors
- ☐ A first look at the data
- ☐ Timeline of the W and Z discoveries

Let’s start from the end



the UA1 and UA2 experiments

- The program was initiated in 1979 at the CERN Proton Antiproton collider. The SppS began operation in July 1981, and by January 1983 the discovery of the W and Z were announced.
- Rubbia and Van der Meer received the 1984 Nobel Prize in Physics from the Nobel Committee, for "(...) *their decisive contribution to the large project, which led to the discovery of the field particles W and Z (...)*".
- The Nobel prize was given to Rubbia for his "*idea to convert an existent large accelerator into a storage ring for protons and antiprotons*", i.e. the conception of the SppS, and to Van der Meer for his " *ingenious method for dense packing and storage of proton, now applied for antiprotons*", i.e. the devise of the technology for stochastic cooling.
- The conception, construction and operation of the SppS were considered as great technical achievements.

October 14th, 2021

Slide# 15

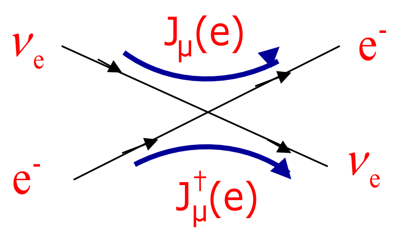
14/10/2021 – 50 years of Hadron Colliders at CERN

https://indico.cern.ch/event/1068633/

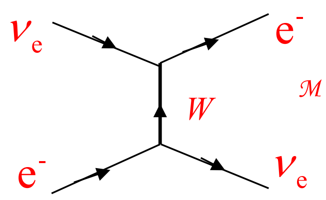
Toward the $Sp\bar{p}S$

W and Z mass prediction

☐ **From the electron-neutrino scattering we can get a relationship between G_F and M_W:**



$$\mathcal{M} = \frac{4G}{\sqrt{2}}\left[\bar{u}_e\gamma^\mu\frac{1-\gamma^5}{2}u_{\nu_e}\right]\left[\bar{u}_{\nu_e}\gamma^\mu\frac{1-\gamma^5}{2}u_e\right]$$



$$\mathcal{M} = \left[\frac{g}{\sqrt{2}}\bar{u}_e\gamma^\mu\frac{1-\gamma^5}{2}u_{\nu_e}\right]\frac{1}{M_W^2-q^2}\left[\frac{g}{\sqrt{2}}\bar{u}_{\nu_e}\gamma_\mu\frac{1-\gamma^5}{2}u_e\right]$$

→ $\boxed{\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2}}$ → $M_W = \sqrt{\frac{g^2\sqrt{2}}{8G}}$

- if we do the hypothesis that g ≈ e: $\frac{e^2}{4\pi} = \alpha = \frac{1}{137} \Rightarrow g^2 \approx e^2 = \frac{4\pi}{137}$; $G = \frac{10^{-5}}{M_p^2}$

- Putting all together we get: $M_W = \sqrt{\frac{\frac{4\pi}{137}\sqrt{2}}{8\cdot 10^{-5}}}\cdot M_p \approx 37.4\ \text{GeV}$

- actually: $e = g\sin(\theta_W) \Rightarrow \text{Mw} \approx \frac{37.4}{\sin(\theta_W)}$ GeV

- **From Gargamelle data (1973) was measured:** $\boxed{\sin^2\theta_W = 0.2 \div 0.4}$ → $\boxed{M_W = 60 \div 84\ \text{GeV}}$

- **From the Standard Model we have:** $M_Z = \frac{M_W}{\cos\theta_W}$ → $\boxed{M_W = 70 \div 101\ \text{GeV}}$

None of the existing accelerators could produce such heavy masses

The proton-antiproton collider idea

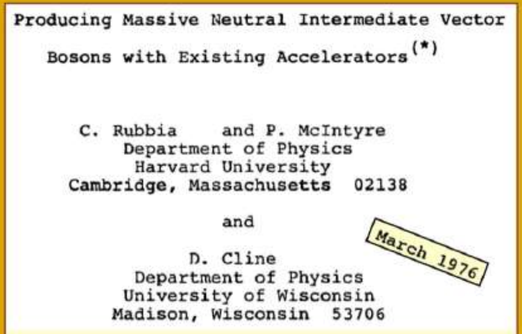
- ☐ In 1976 a study group at CERN started working to prepare a report for the construction of a new e+e- collider (LEP) to produce the Z, but LEP was far in the future.
- ☐ At Brookhaven the proton-proton collider ISABELLE (200+200 GeV) with superconducting magnets was recommended by the HEP Advisory Panel in 1974 and construction began in 1978 before superconducting magnet technology had been achieved. *The project was then cancelled in 1983.*
- ☐ In 1975 and 1976 **Carlo Rubbia** presented in some seminars at Fermilab and at CERN the possibility to convert the existing proton accelerators to proton-antiproton colliders making use of a single magnet ring as for the e^+e^- colliders.
- ☐ The beam of antiprotons were to be produced by means of the "electron cooling" or the "stochastic cooling".
- ☐ Rubbia presented the idea at the 1976 International Neutrino Conference in Aachen:
  C. Rubbia, P. McIntyre and D.Cline:
  Producing Massive Neutral Intermediate Vector Bosons with Existing Accelerators.
- ☐ The proposal by Rubbia and Collaborators was considered unrealistic at Fermilab but was appreciated by **John Adams** and **Leon Van Hove**, the CERN Directors.
- ☐ The game was to convert the SPS to a proton-antiproton collider with 540 GeV c.o.m. energy, but the first not easy step was to provide the antiproton beams.
- ☐ An essential contribution to the project came from the discovery of the "stochastic cooling" of particles by **Simon van der Meer** in 1968-1972.

p̄p collisions: history

Slide from P. Bagnaia

- The antiprotons (p̄) are the antiparticles of the protons (p).
- Therefore **p̄p** and **e⁺e⁻** colliders have similarities (e.g. one mag. channel with head-on collisions).
- … with the bonus of the lack of brem for p̄p: in the same SPS tunnel, p/p̄ were accelerated up to 273/315/450 GeV, while e± up to few GeV only.
- … and the disadvantage of compositeness → in high Q^2 collisions, partons$_{1,2}$ have a momentum $(x_{1,2}\sqrt{s}/2)$ and the energy of the parton collision is $\sqrt{\hat{s}} = \sqrt{s x_1 x_2}$.
- In addition p̄'s are very scarce in our world (also e⁺ are, but they are easy to produce and cheap).
- The real problem is the p̄ "fabrication", accumulation and cooling, which has to happen before the acceleration process.
- It requires lot of clever ideas, both from Physics, Electronics, Engineering.

Once upon a time in 1976 …



Producing Massive Neutral Intermediate Vector Bosons with Existing Accelerators(*)

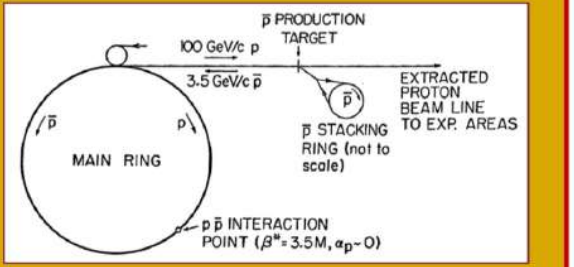
C. Rubbia and P. McIntyre
Department of Physics
Harvard University
Cambridge, Massachusetts 02138

and

D. Cline
Department of Physics
University of Wisconsin
Madison, Wisconsin 53706

March 1976

C. Rubbia, P. McIntyre and D. Cline, Proc. Int. Neutrino Conf., Aachen, 1976 (eds. H. Faissner, H. Reithler and P. Zerwas) (Vieweg, Braunschweig, 1977), p. 683.

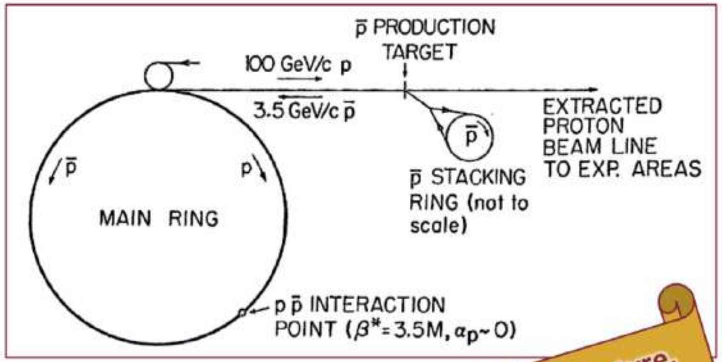


$\bar{p}p$ collisions: sequence

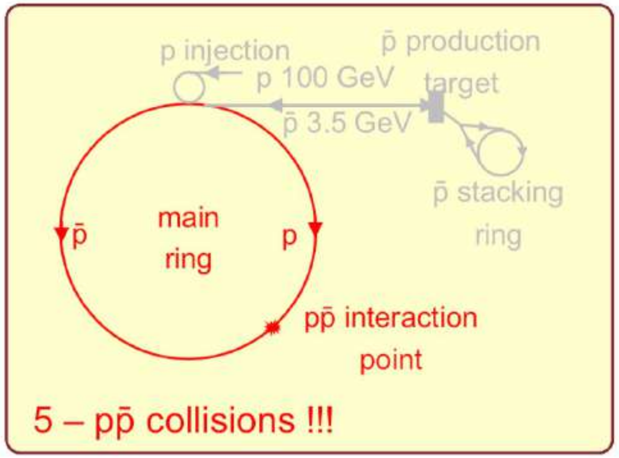
Slide from P. Bagnaia

1. Protons are accelerated to an intermediate suitable energy [*the proposal says E_p = 100 GeV from Fermilab main ring, but it is NOT critical – at CERN E_p = 26 GeV from PS*] .
2. Then the p are extracted and sent onto a target, to produce high intensity collisions.
3. The resultant $\bar{p}$ (very rare) are collected and cooled ("stacked") in a lower energy ring [*at CERN $E_{\bar{p}}$ = 3.5 GeV – can't store $\bar{p}$'s at rest, despite Dan Brown*$^{(*)}$].
4. After hours (days), when enough $\bar{p}$ are available, they are re-extracted and injected in the main ring, together with protons.
5. Both $\bar{p}$ and p are accelerated to the max energy, and then let collide.

Although every step requires ingenuity, step (3) and (4) are the real marvels; have a closer look.



Rubbia, McIntyre, Cline op.cit.



5 – p$\bar{p}$ collisions !!!

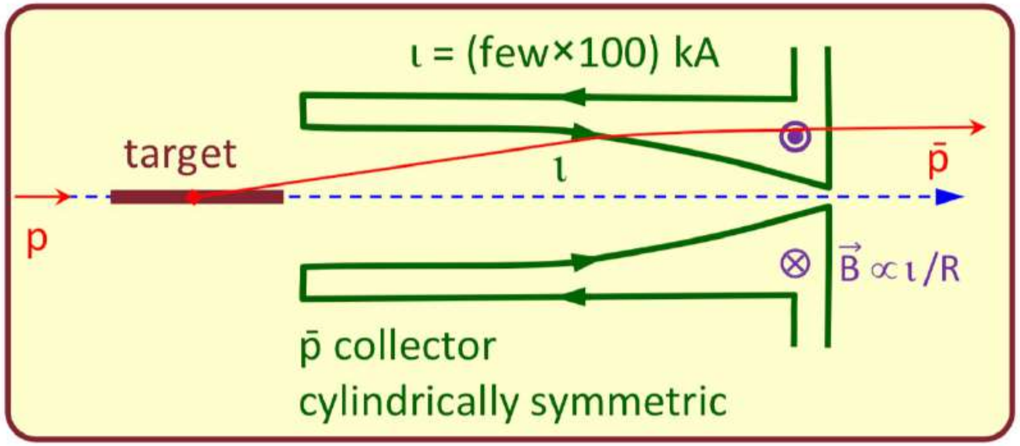
$\bar{p}p$ collisions: the making of $\bar{p}$

Rubbia et al. invented an innovative scheme for $\bar{p}p$ collisions

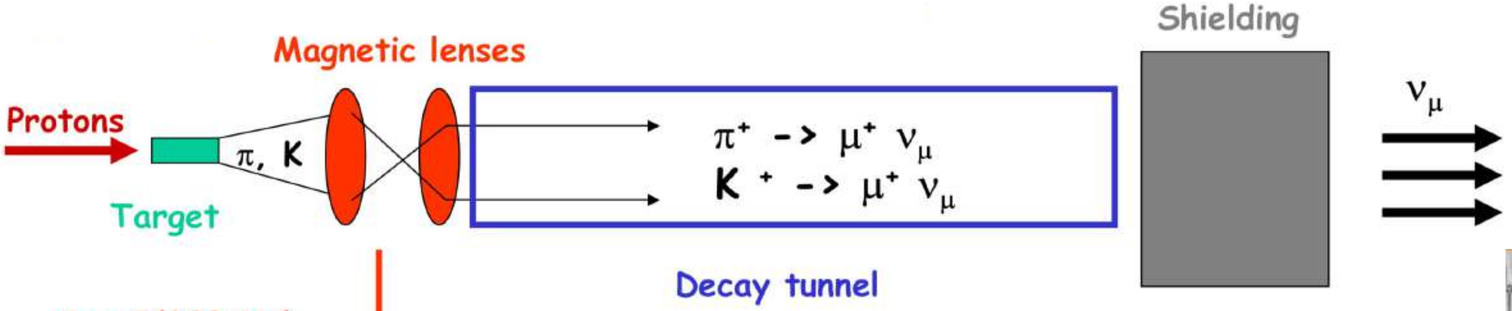
- **Rubbia initially offered it to Fermilab, then he built it at CERN in 1978-81, later somebody else implemented it at Fermilab**
  (the top quark, as we will see later, was discovered at Fermilab in this collider)

- **The key structures were the $\bar{p}$ collectors, which were a new design of the Van der Meer horn … (This was needed to reduce the spread in transverse momentum of the antiprotons entering the Antiproton Accumulator ring)**

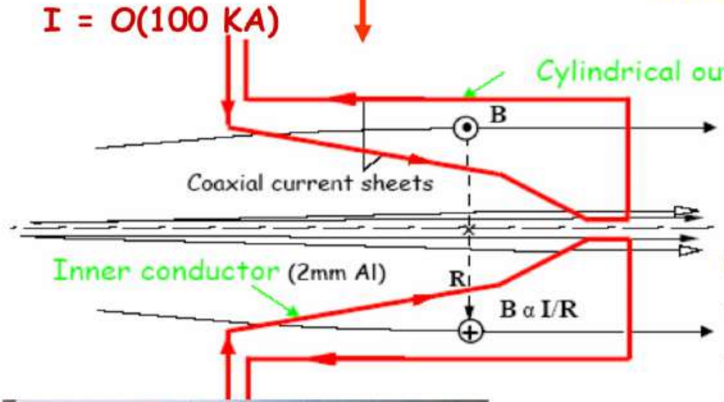
- **… and the $A\bar{A}$ (= Antiproton Accumulator), the ring where the p were collected, cooled, accumulated and stored for up to few days.**



Typical high energy Wide Band neutrino beam



van der Meer invented "his" horn in 1961 to enhance the flux of the neutrino beam at CERN.



Horns: sign selection, focalization: flux x10

Contaminations:

$\bar{\nu}_\mu$ (wrong sign parents)	O(5%)
ν_e (K_{e3} decays, μ decays)	O(1%)
ν_τ (D_s decays)	O(10^{-6})

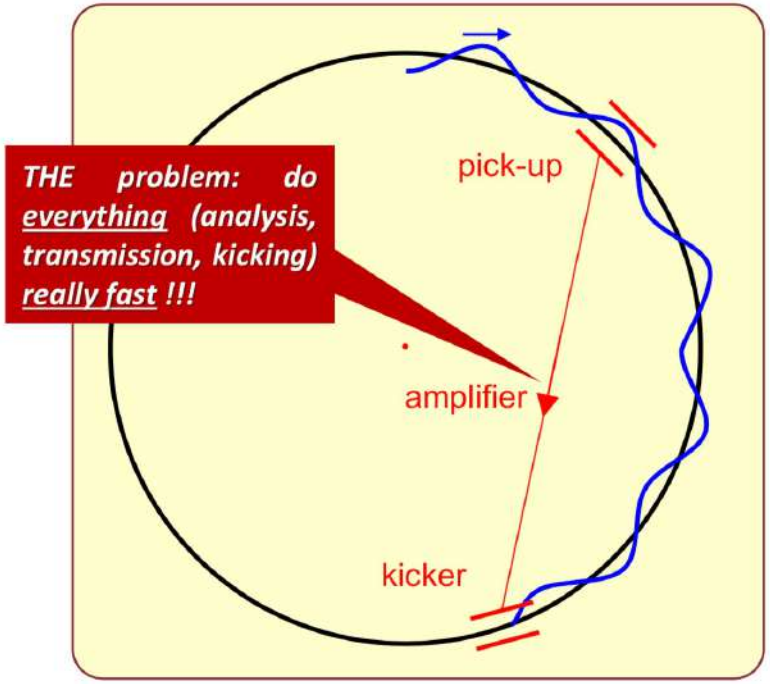
Note that the π/K abundances and spectra at the target are not easy to predict: to reduce systematics perform ad hoc hadron-production experiments (Spy, Harp etc ...)

$\bar{p}p$ collisions: pickup + kicker

Slide from
P. Bagnaia

The main problem : the "cooling" of $\bar{p}$:

- [*why "cooling" ? in classical physics, the <u>temperature</u> of a gas is related to its motion in its CM frame : higher temperature means higher* ($\langle v^2\rangle - \langle v\rangle^2$) *velocity; so "gas cooling" means reducing the **<u>relative</u>** velocity of particles;*]
- analyze a single particle (——) circulating in a ring;
- it oscillates with "<u>betatron oscillations</u>" around the ideal particle (——);
- a "**<u>pick-up</u>**" electrode detects its position respect to the nominal orbit;
- this value, appropriately amplified, is transmitted to a "**<u>kicker</u>**", displaced by (n/2 + ¼) wavelengths;
- **<u>the kicker corrects the orbit</u>**;
- notice that the **<u>space displacement</u>** produces an **<u>angle correction</u>**;
- in reality, the pick-up and kicker are traversed by a large and incoherent number of particles at the same time;
- but if their average displacement is NOT zero, they get a correction and (**<u>in average</u>**) become closer to the ideal orbit.



THE problem: do <u>everything</u> (analysis, transmission, kicking) <u>really fast</u> !!!

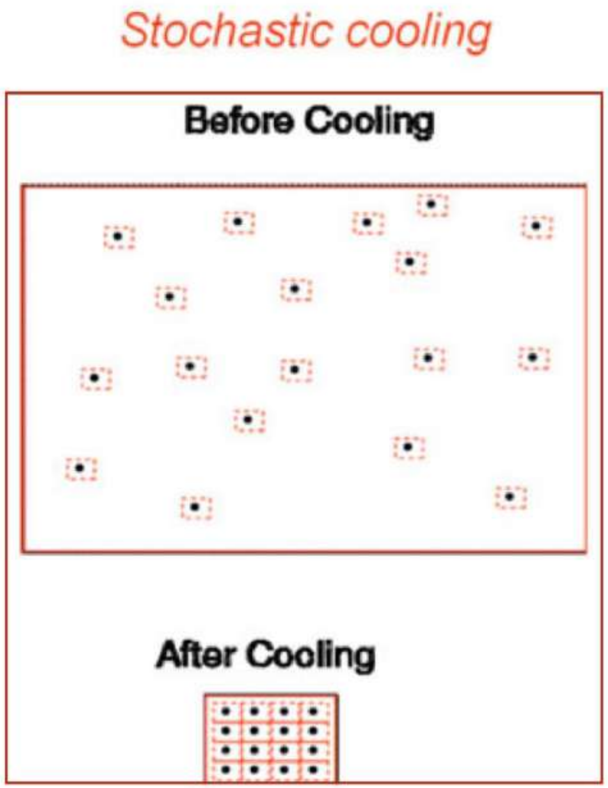
$\bar{p}p$ collisions: pickup + kicker

Slide from
P. Bagnaia

- Wikipedia : "***Liouville's theorem***, *[…] after the French mathematician* *Joseph Liouville, is a key theorem in classical statistical and Hamiltonian mechanics. It asserts that the phase-space distribution function is constant along the trajectories of the system.*"
- A principle well known to experts of beam optics : e.g. a quadrupole, or the principle of strong focusing.
- The cooling of $\bar{p}$ "conflicts" with the theorem: e.g. a squeeze in transverse momentum should result in an increase in space dimensions.
- **Stochastic cooling** : [S. van der Meer, Nobel Lecture] "*Fortunately, there is a trick - and it consists of using the fact that particles are points in phase space with empty space in between. We may push each particle towards the center of the distribution, squeezing the empty space outwards. The small-scale density is strictly conserved, but in a macroscopic sense the particle density increases. This process is called cooling because it reduces the movements of the particles with respect to each other.*"

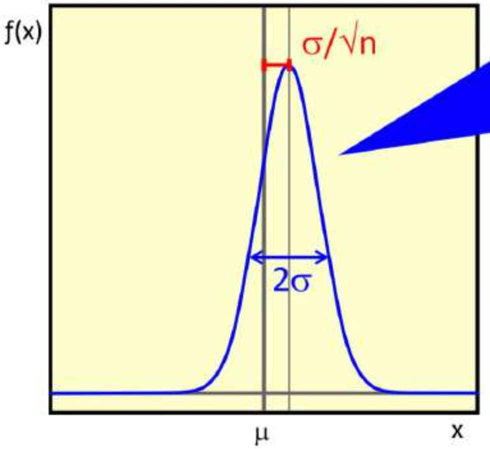
$\bar{p}p$ collisions: (how to avoid) Liouville theorem

Slide from P. Bagnaia



A cartoon by Carlo, to explain the previous sentence of van der Meer and the solution of the "Liouville problem".

- *My understanding : cannot modify individual particle trajectories, but act on packets of n particles, small enough that their means be sensibly different from the ideal orbit ($1/\sqrt{n}$ <u>not</u> negligible).*
- it requires to divide the $\bar{p}$'s in small packets, act on each packet, and then reassemble the beam.
- *A completely different type of cooling exists, **<u>electron cooling</u>**, invented by G.I. Budker. It is used in other accelerators.*



"if a population of n elements is distributed according to a gaussian with average μ and rms σ, <u>its mean</u> is a random variable with average μ and rms = σ/√n."

Electron cooling

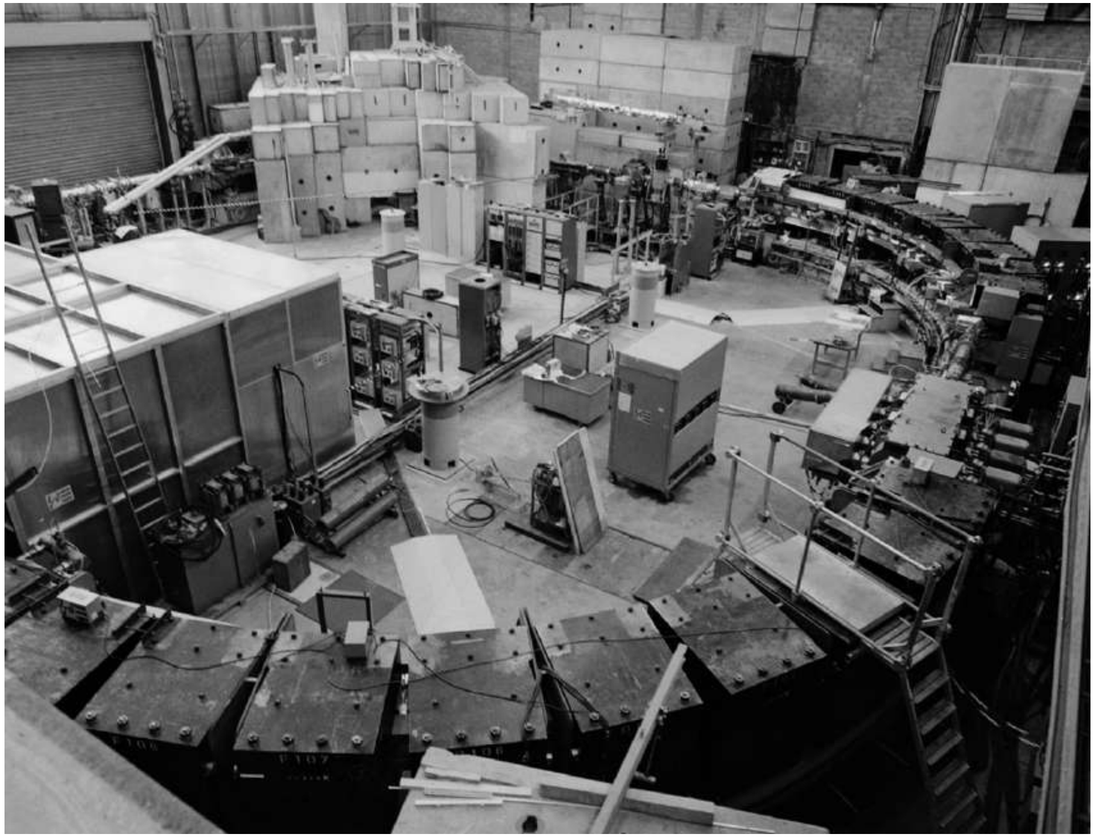
- ❑ **Electron cooling** was invented by Gersh Budker at INP (Novosibirsk) in 1966 for the purpose of increasing luminosity of hadron collider.

  It was first tested in 1974 with 68 MeV protons at NAP-M storage ring at INP.
- ❑ It is used at both operating ion colliders: the Relativistic Heavy Ion Collider (RICH) at BNL and in the Low Energy Ion Ring (LEIR) at CERN.

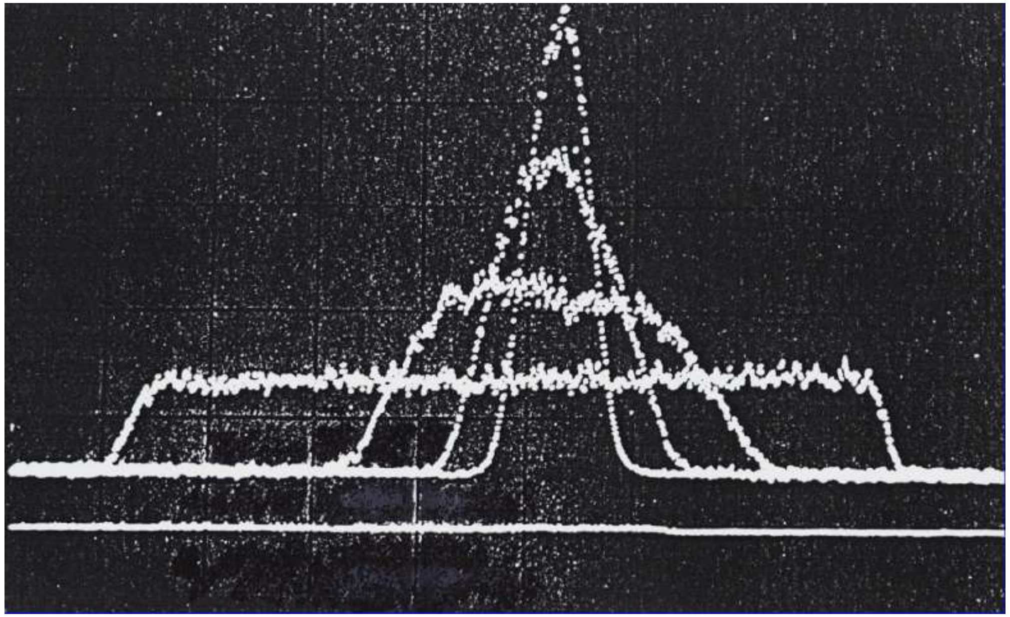
- ❑ Basically, electron cooling works as follows:
  - A beam of dense quasi-monoenergetic electrons is produced and merged with the ion beam to be cooled.
  - The velocity of the electrons is made equal to the average velocity of the ions.
  - The ions undergo Coulomb scattering in the electron “gas” and exchange momentum with the electrons. Thermodynamic equilibrium is reached when the particles have the same momentum, which requires that the much lighter electrons have much higher velocities. Thus, thermal energy is transferred from the ions to the electrons.
  - The electron beam is finally bent away from the ion beam.

Initial Cooling Experiment (ICE): 1978

The ISR results were reproduced in a dedicated experiment (ICE) using protons of 3.5 GeV.
(*ICE used the magnets of the g-2 experiment*)



ICE results



Schottky scan after 1, 2 and 4 minutes.

Signal height proportional to the square root of density and width proportional to Δp/p

Antiprotons

p̄p collisions: the AA

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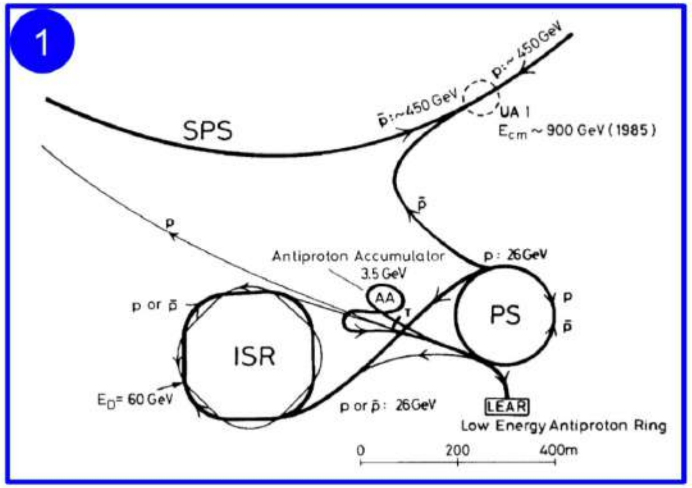
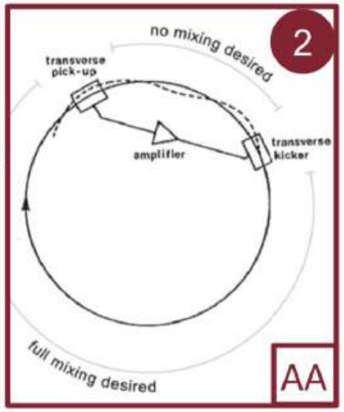
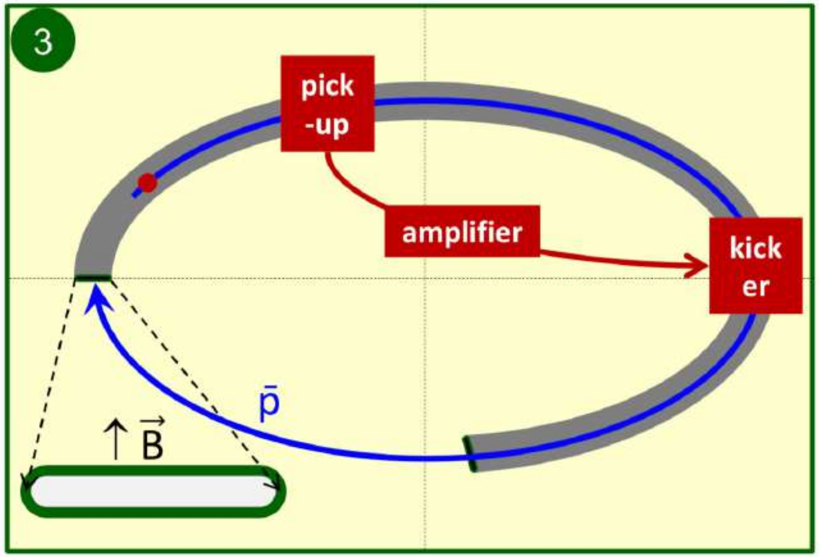
P. Bagnaia



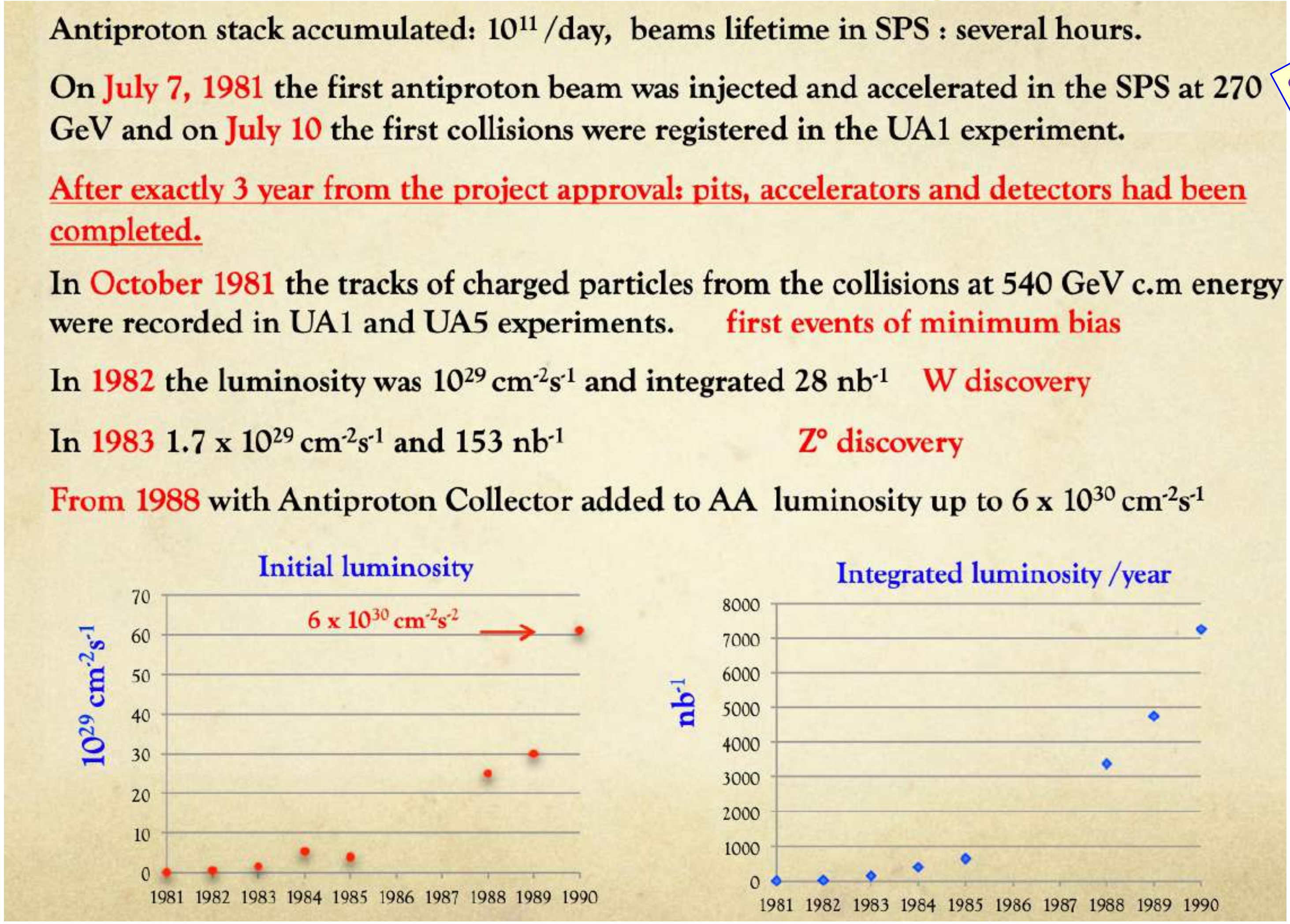
1. A view of the CERN pp̄ complex in the '80s.
2. The AA and the its functioning principle.
3. A scheme of the AA operations.





S$\bar{p}$ps parameters

The Collider performances



Antiproton stack accumulated: 10^{11} /day, beams lifetime in SPS : several hours.

On July 7, 1981 the first antiproton beam was injected and accelerated in the SPS at 270 GeV and on July 10 the first collisions were registered in the UA1 experiment.

After exactly 3 year from the project approval: pits, accelerators and detectors had been completed.

In October 1981 the tracks of charged particles from the collisions at 540 GeV c.m energy were recorded in UA1 and UA5 experiments. first events of minimum bias

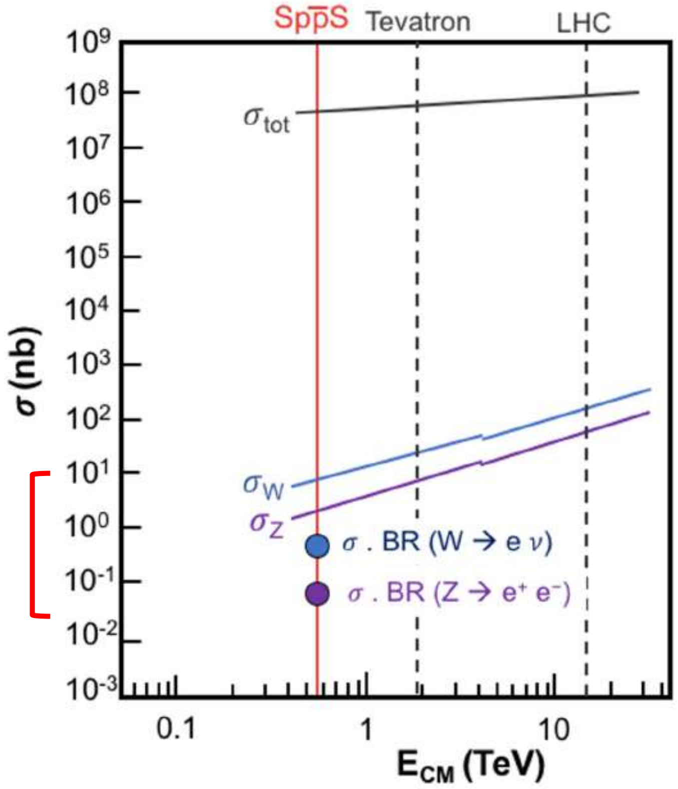
In 1982 the luminosity was 10^{29} cm^{-2}s^{-1} and integrated 28 nb^{-1} W discovery

In 1983 1.7 x 10^{29} cm^{-2}s^{-1} and 153 nb^{-1} Z° discovery

From 1988 with Antiproton Collector added to AA luminosity up to 6 x 10^{30} cm^{-2}s^{-1}

Slide from F. Lacava

Cross sections



$$N_{events} = \sigma \cdot \mathcal{L}_{int}$$

Sp̄pS parameters

Slide from
P. Bagnaia

1983 was the "golden year" of Spp̄S : performances still improving, W± and Z discovery. Notice :

- The rate of p̄ production : a rate ~10^6 paid to convert matter into antimatter.
- The energy for p̄ collection (3.5 GeV) was chosen because it is optimal for production σ and acceptance.
- The cross-section of the design, from an old experiment $\sigma(p\ {}_{74}W \rightarrow \bar{p}X)$, was higher. The project had margins to (barely) survive.
- The Spp̄S performances were considered great, but LHC is × **10^5** in luminosity and × **20** in energy (**30** years later).

The Spp̄S in 1983		
$p\ {}_{74}W \rightarrow \bar{p}\ X$	$\lvert\vec{p}\rvert$ = 26 GeV	10^{13} / 2.4 s
$\bar{p}$	$\lvert\vec{p}\rvert$ = 3.5 GeV	1/(10^6 p) → few × 10^9/h
$\bar{p}\ p$	$\sqrt{s}$ = 546 GeV $^{(*)}$	$\mathscr{L} = 1.6\times10^{29}$ cm^{-2}s^{-1}
$\int\mathscr{L}dt$	153 nb^{-1}	Don't confuse "$_{74}$W" (tungsten,"wolfram") with "W±", the IVB. *[sorry, not my fault, only 26 letters available]*
$N_{events}(\bar{p}p)$	8 × 10^9	
$W^\pm \rightarrow e^\pm\nu$	**90**	
$W^\pm \rightarrow \mu^\pm\nu$ (UA1 only)	**14**	
$Z \rightarrow e^+e^-$	**12**	
$Z \rightarrow \mu^+\mu^-$ (UA1 only)	**4**	
$^{(*)}$ $\sqrt{s}$ = 630 GeV in ≥ 1984.		

S$\bar{p}$pS parameters

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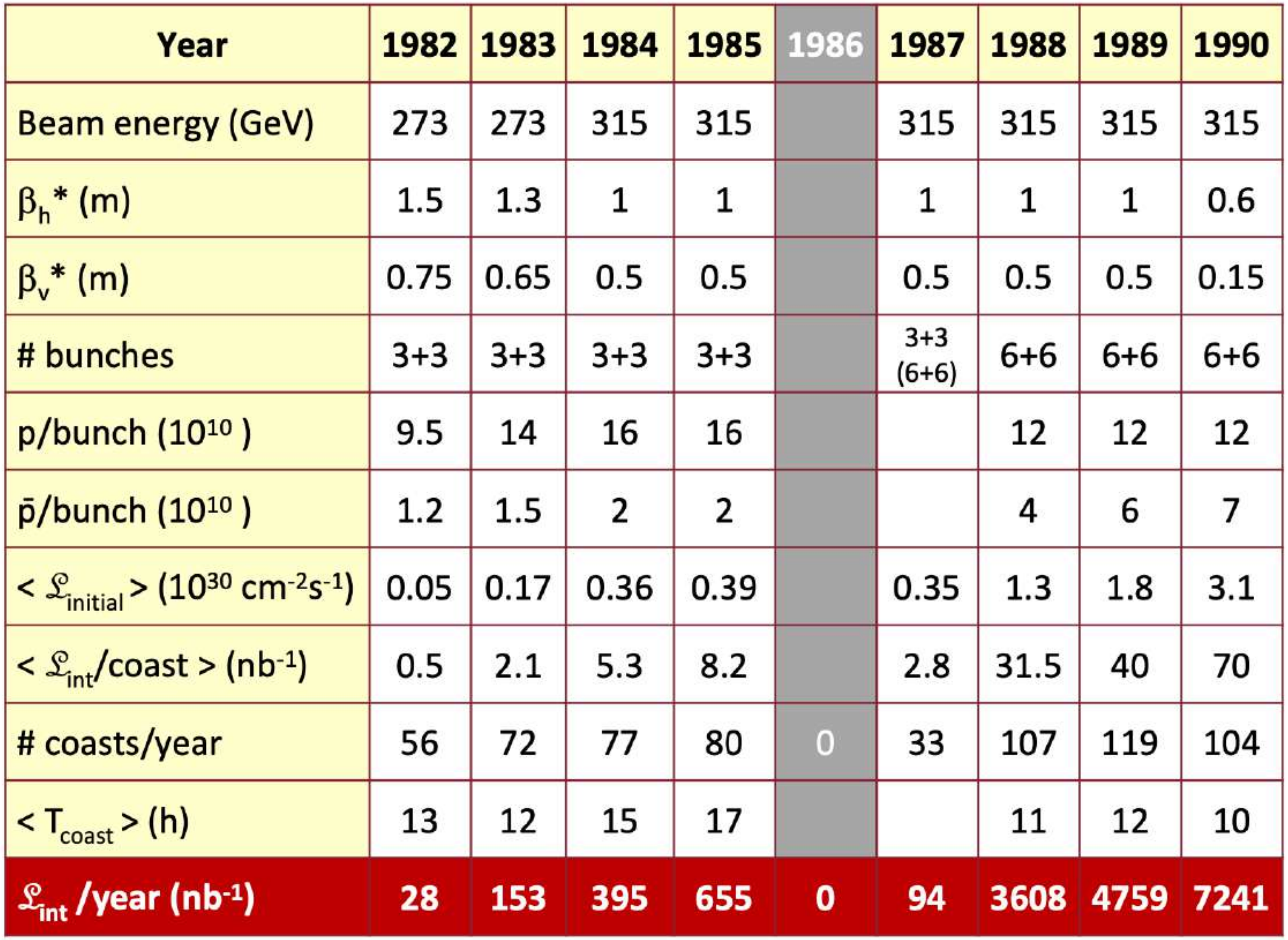
P. Bagnaia

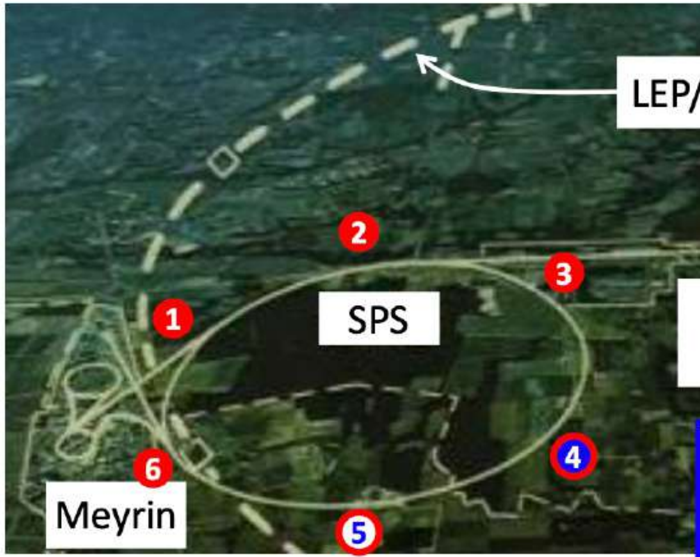


Year	1982	1983	1984	1985	1986	1987	1988	1989	1990
Beam energy (GeV)	273	273	315	315		315	315	315	315
β_h^* (m)	1.5	1.3	1	1		1	1	1	0.6
β_v^* (m)	0.75	0.65	0.5	0.5		0.5	0.5	0.5	0.15
# bunches	3+3	3+3	3+3	3+3		3+3 (6+6)	6+6	6+6	6+6
p/bunch (10^{10})	9.5	14	16	16			12	12	12
$\bar{p}$/bunch (10^{10})	1.2	1.5	2	2			4	6	7
$< \mathscr{L}_{initial} >$ (10^{30} cm^{-2}s^{-1})	0.05	0.17	0.36	0.39		0.35	1.3	1.8	3.1
$< \mathscr{L}_{int}$/coast $>$ (nb^{-1})	0.5	2.1	5.3	8.2		2.8	31.5	40	70
# coasts/year	56	72	77	80	0	33	107	119	104
$< T_{coast} >$ (h)	13	12	15	17			11	12	10
$\mathscr{L}_{int}$ /year (nb^{-1})	**28**	**153**	**395**	**655**	**0**	**94**	**3608**	**4759**	**7241**

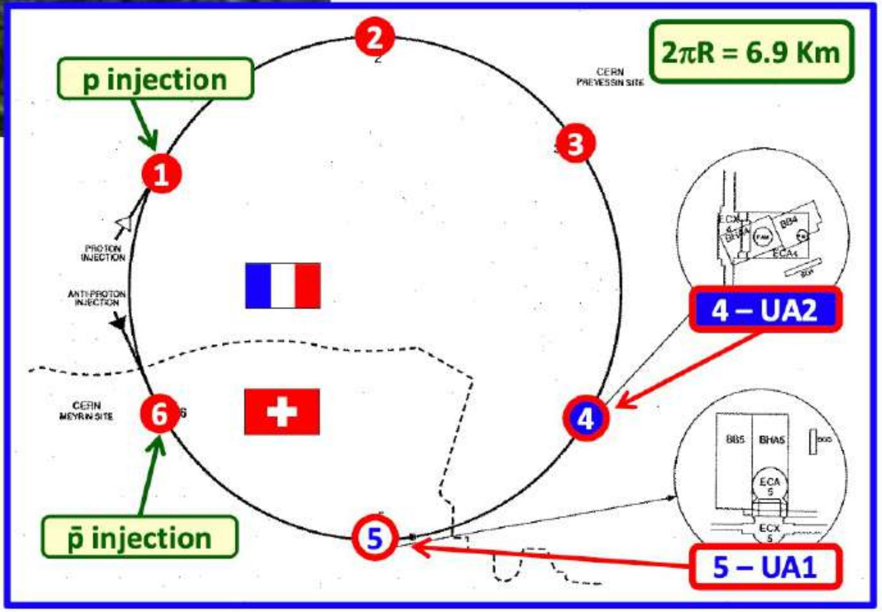
(coast = fill in the LHC language)

The detectors

The detectors



UA1 and UA2 are placed at 60° wrt each other, in the region far from the injection from PS.



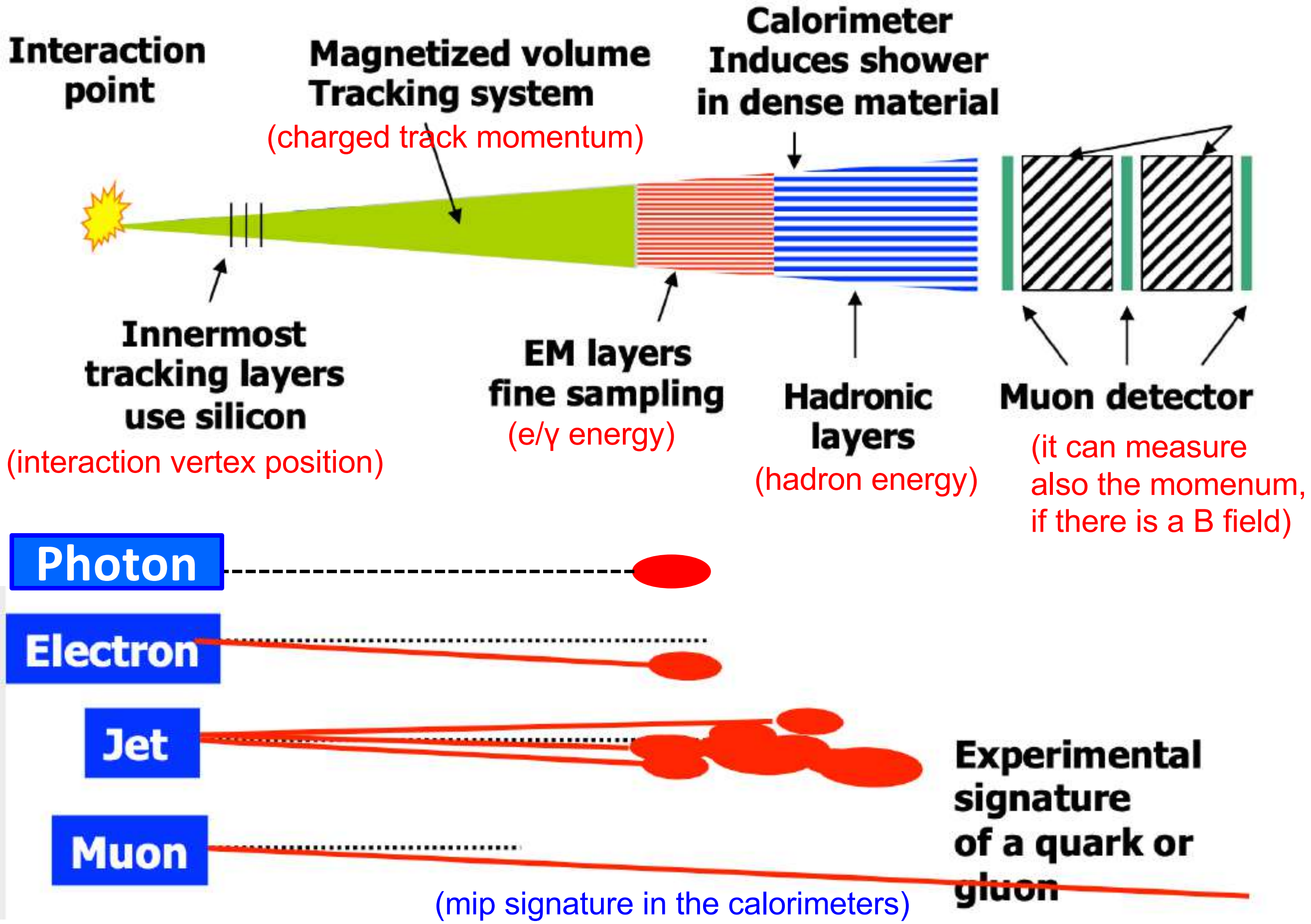
2 big experiments

Collider offered also other experiments to exploit this new energy domain: e.g.:

- UA4: σ_{tot} measurement using Roman pots, 40 m from UA1-IP
- UA5: large streamer chamber allowing to detect charged particles down to < 1°, (a few days of data taking before UA2 was rolled into the tunnel in Nov 1981)

Reminder: how to detect the different type of particles

This layout works also for a fixed target experiment (not for the missing energy)



Interaction point

Magnetized volume Tracking system
(charged track momentum)

Calorimeter Induces shower in dense material

Innermost tracking layers use silicon
(interaction vertex position)

EM layers fine sampling
(e/γ energy)

Hadronic layers
(hadron energy)

Muon detector
(it can measure also the momenum, if there is a B field)

Photon

Electron

Jet

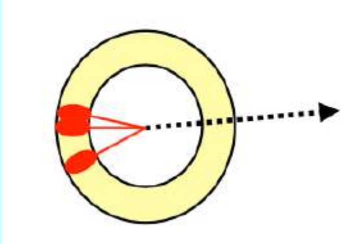
Muon

(mip signature in the calorimeters)

Experimental signature of a quark or gluon

“Missing transverse energy”

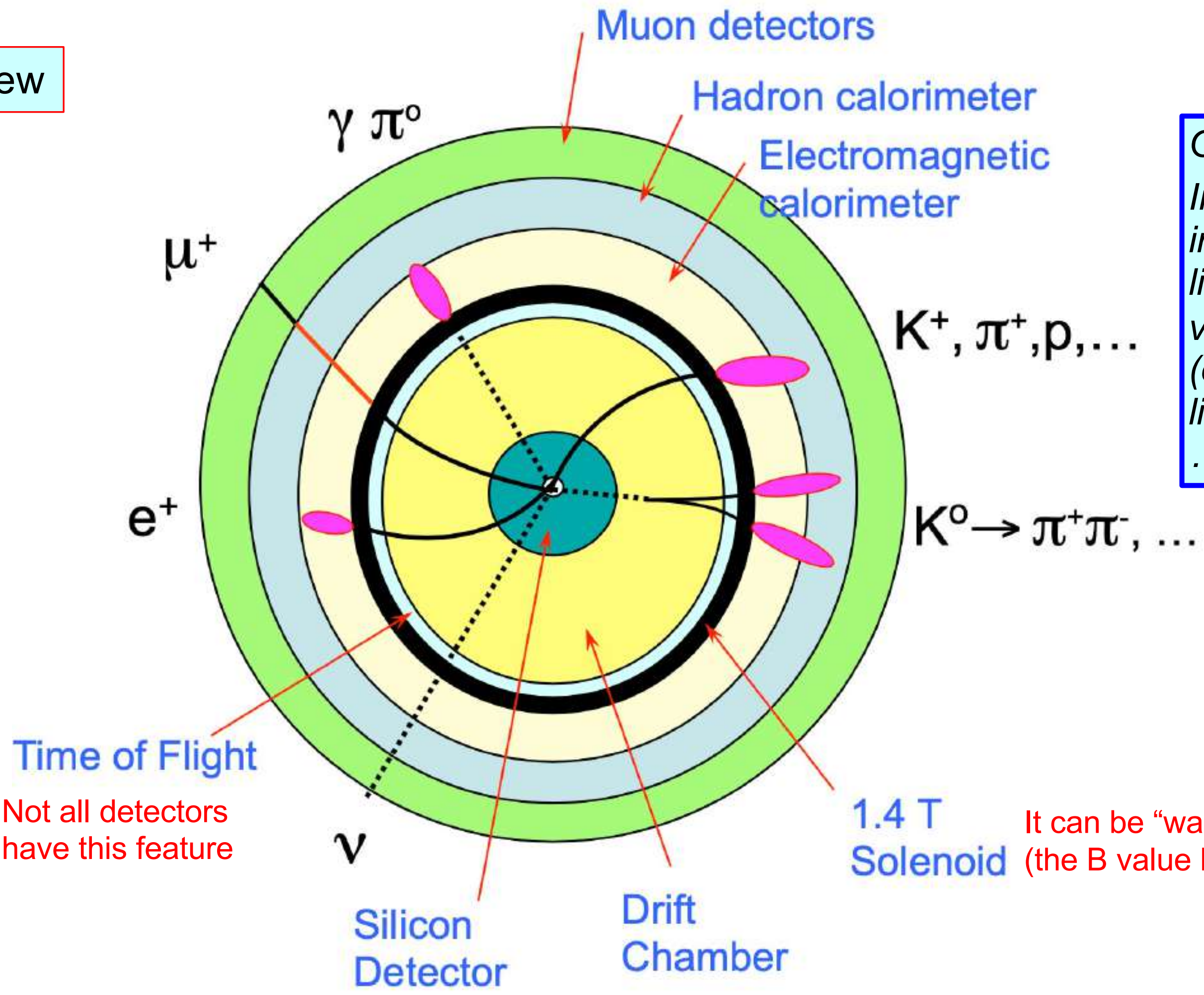
Signature of a non-interacting (or weakly interacting) particle like a neutrino



We have to make sure that we are not missing any particles

Reminder: layout of a generic collider detector

Transverse view



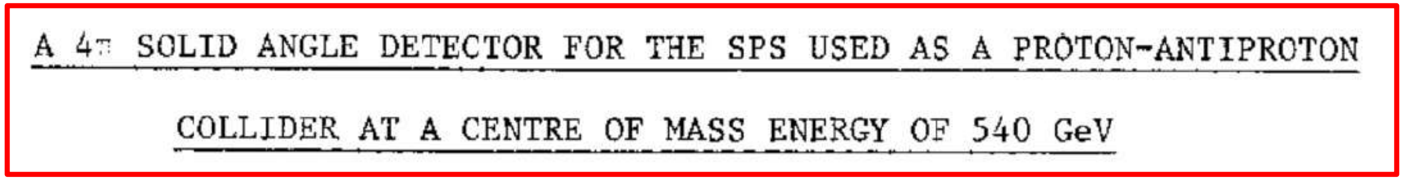
Not all detectors have this feature

It can be “warm” or superconducting (the B value here is just an example)

On “paper”, it is hermetic.

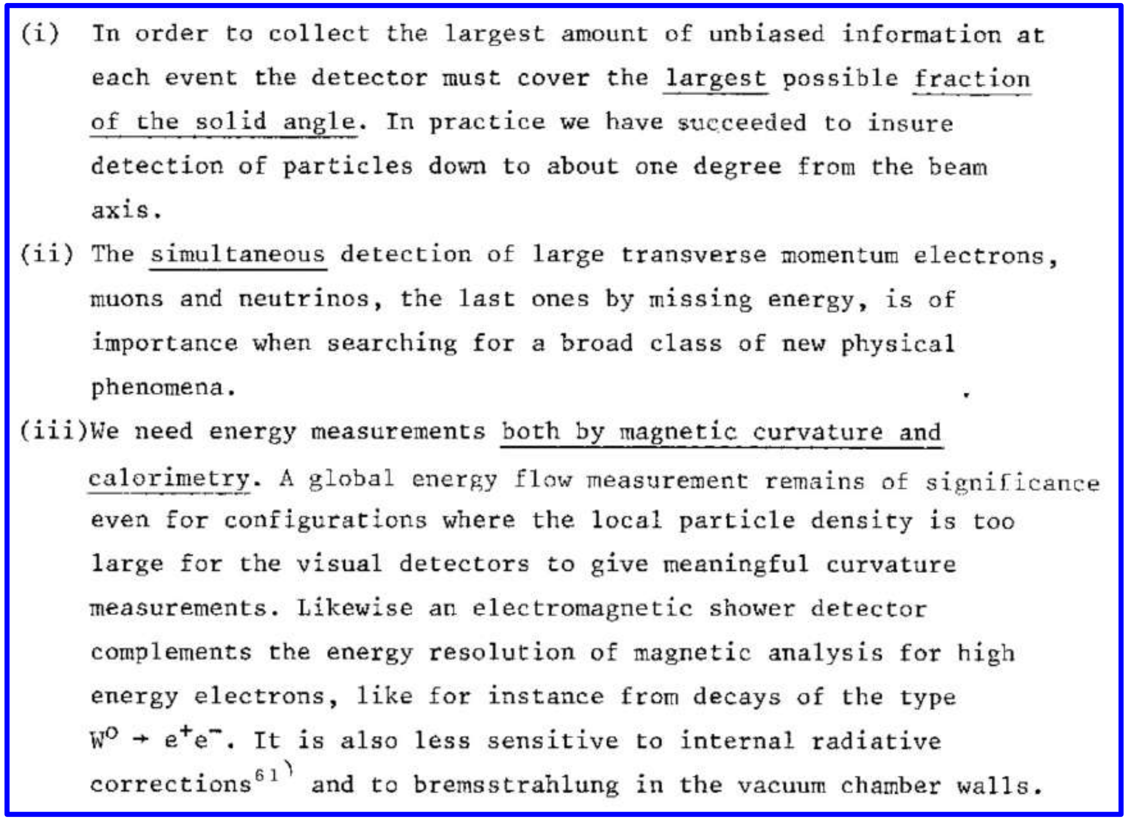
In “practice”, there are holes in order to let pass services, like: low voltage and high voltage cables, signal cables (or optical fibres), gas pipe lines, cooling water pipes, …

S$\bar{p}$pS Detector guidelines



A 4π SOLID ANGLE DETECTOR FOR THE SPS USED AS A PROTON-ANTIPROTON

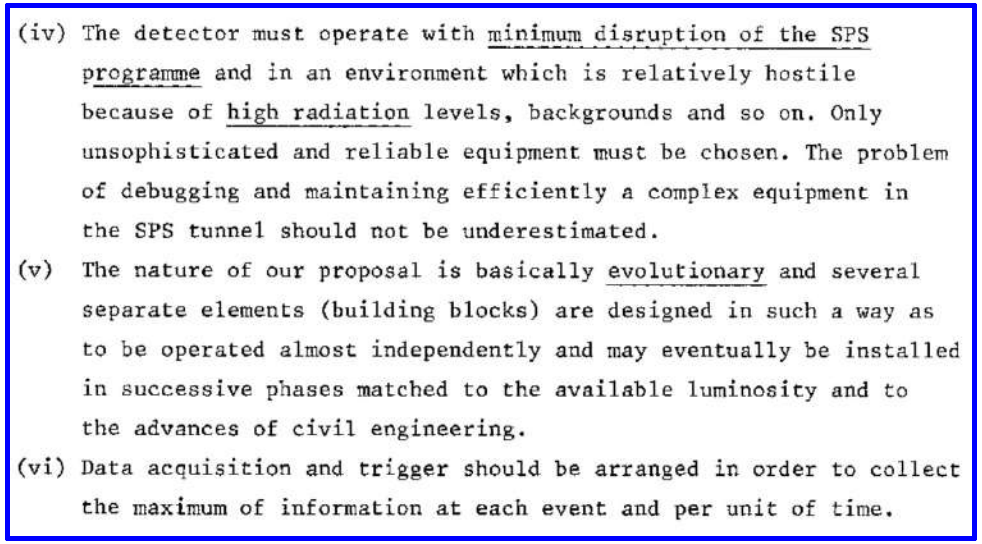
COLLIDER AT A CENTRE OF MASS ENERGY OF 540 GeV



(i) In order to collect the largest amount of unbiased information at each event the detector must cover the largest possible fraction of the solid angle. In practice we have succeeded to insure detection of particles down to about one degree from the beam axis.

(ii) The simultaneous detection of large transverse momentum electrons, muons and neutrinos, the last ones by missing energy, is of importance when searching for a broad class of new physical phenomena.

(iii) We need energy measurements both by magnetic curvature and calorimetry. A global energy flow measurement remains of significance even for configurations where the local particle density is too large for the visual detectors to give meaningful curvature measurements. Likewise an electromagnetic shower detector complements the energy resolution of magnetic analysis for high energy electrons, like for instance from decays of the type $W^o \rightarrow e^+e^-$. It is also less sensitive to internal radiative corrections61) and to bremsstrahlung in the vacuum chamber walls.



(iv) The detector must operate with minimum disruption of the SPS programme and in an environment which is relatively hostile because of high radiation levels, backgrounds and so on. Only unsophisticated and reliable equipment must be chosen. The problem of debugging and maintaining efficiently a complex equipment in the SPS tunnel should not be underestimated.

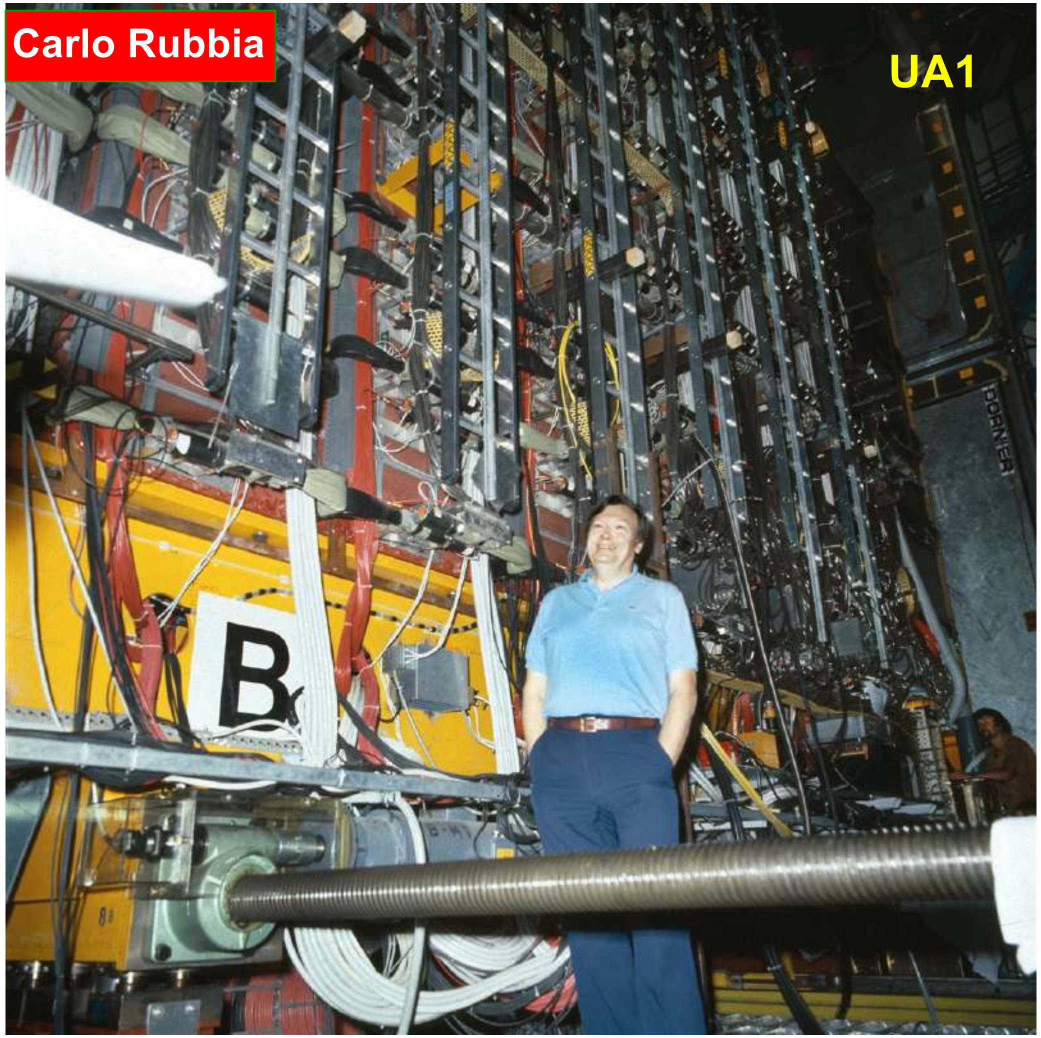
(v) The nature of our proposal is basically evolutionary and several separate elements (building blocks) are designed in such a way as to be operated almost independently and may eventually be installed in successive phases matched to the available luminosity and to the advances of civil engineering.

(vi) Data acquisition and trigger should be arranged in order to collect the maximum of information at each event and per unit of time.

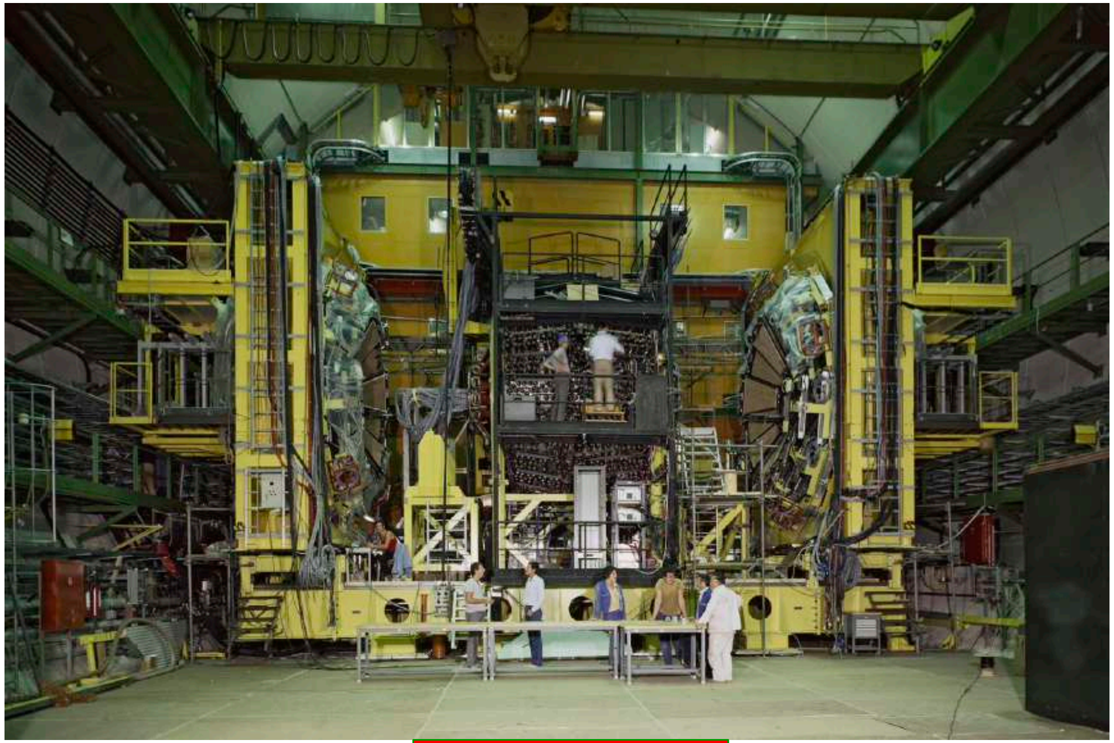
Extracted from the UA1 technical proposal

30 January 1978

The detectors



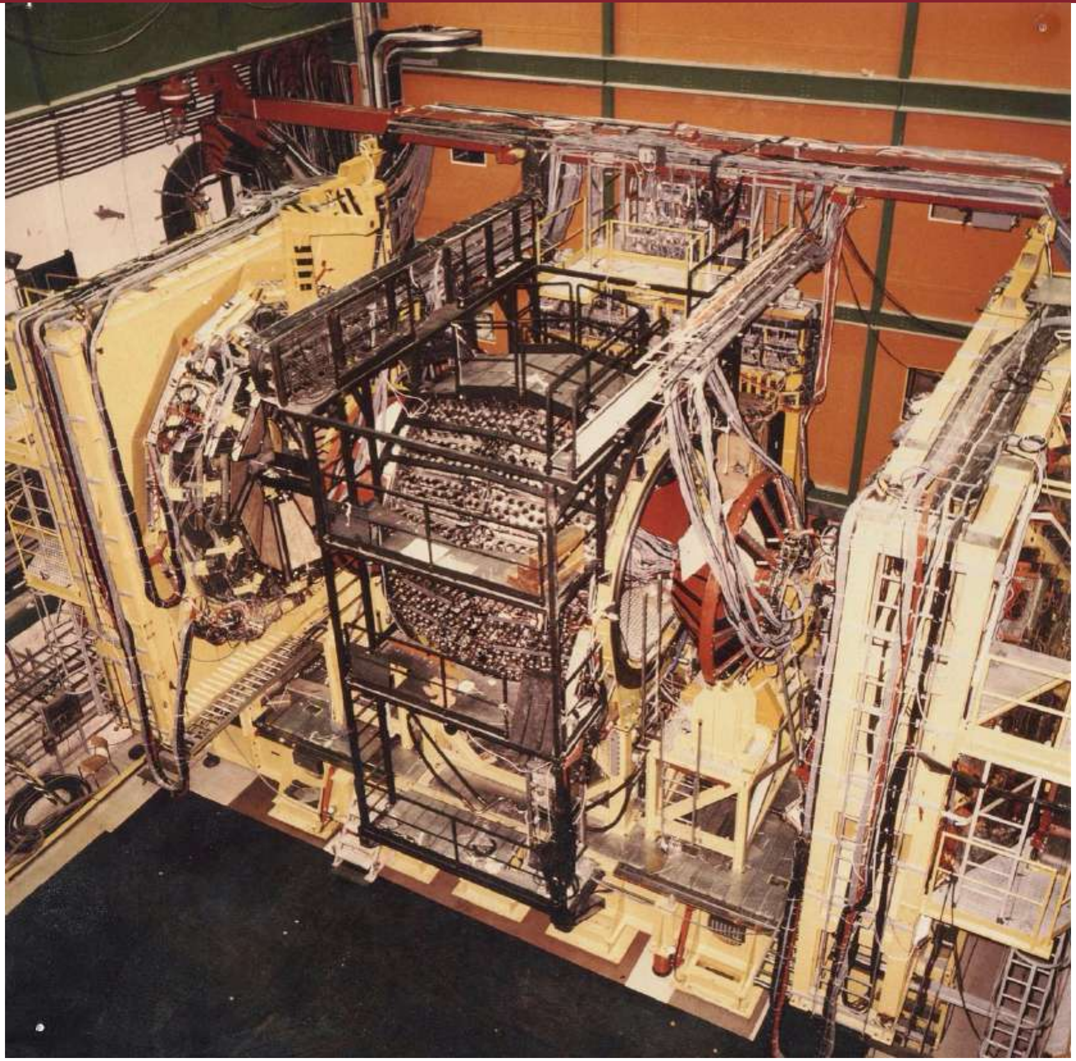
UA2



Pierre Darriulat

The detectors: UA1

The detectors: UA2

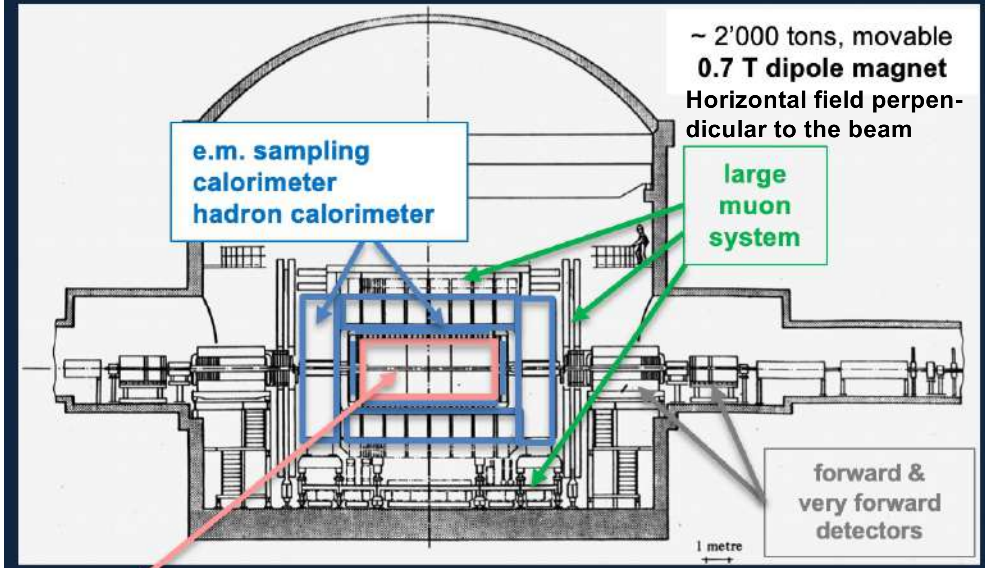


The detector in the open position

The detectors

The UA1 experiment

First multi-purpose 4π (hermetic) detector in particle physics



~ 2'000 tons, movable
0.7 T dipole magnet
Horizontal field perpendicular to the beam

e.m. sampling calorimeter
hadron calorimeter

large muon system

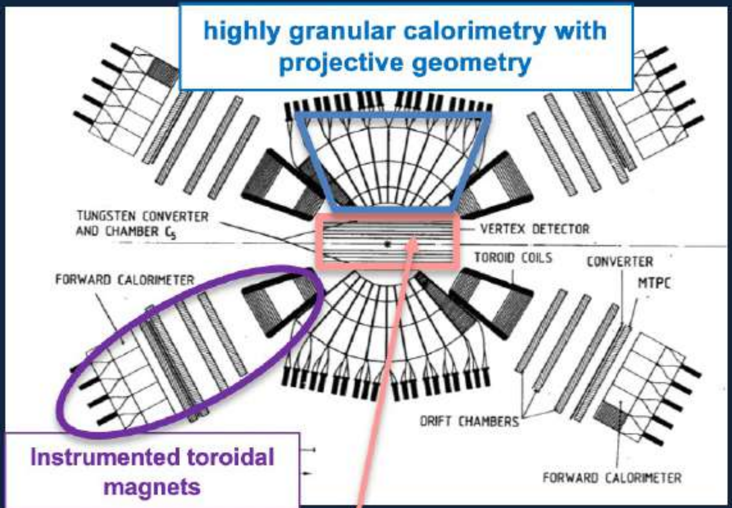
forward & very forward detectors

central detector: drift chamber (L=5.8 m, D=2.3 m)
cutting edge technology, the first "electronic bubble chamber"

Approved in June 1978 – first events observed in June 1981

The UA2 experiment

optimized for W and Z detection in electron channel
no central magnetic field, no muons



highly granular calorimetry with projective geometry

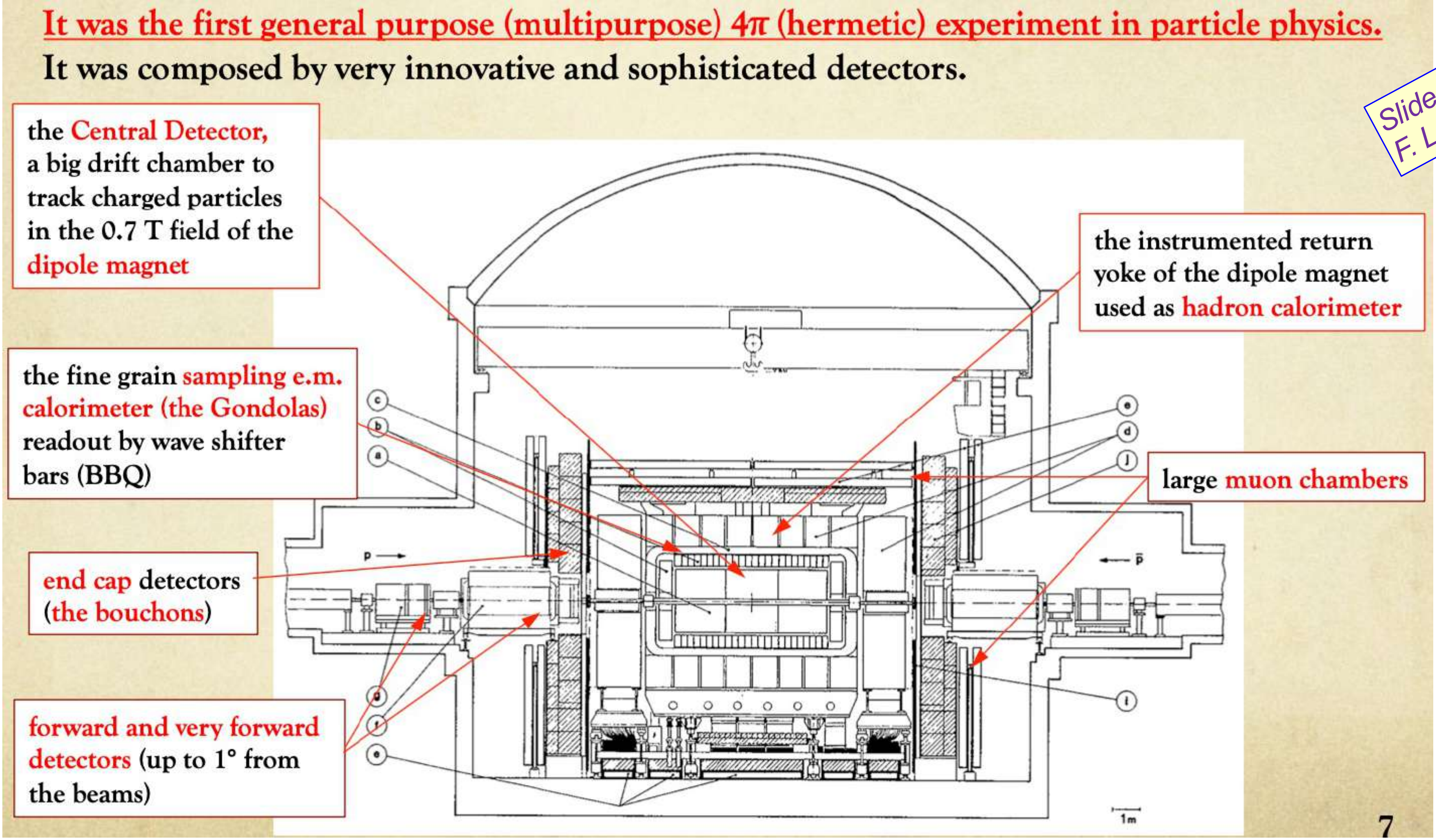
Instrumented toroidal magnets

vertex detector: cylindrical drift chambers + preshower
Upgrade: inner Si pad detector → first incarnation of a Si tracker adapted to collider experiments

Magnetic spectrometer: Upgrade: replaced by calorimeter

Approved in Dec 1978 – first data taking in Dec 1981

The detectors: UA1 layout



It was the first general purpose (multipurpose) 4π (hermetic) experiment in particle physics.

It was composed by very innovative and sophisticated detectors.

the **Central Detector,** a big drift chamber to track charged particles in the 0.7 T field of the **dipole magnet**

the instrumented return yoke of the dipole magnet used as **hadron calorimeter**

the fine grain **sampling e.m. calorimeter (the Gondolas)** readout by wave shifter bars (BBQ)

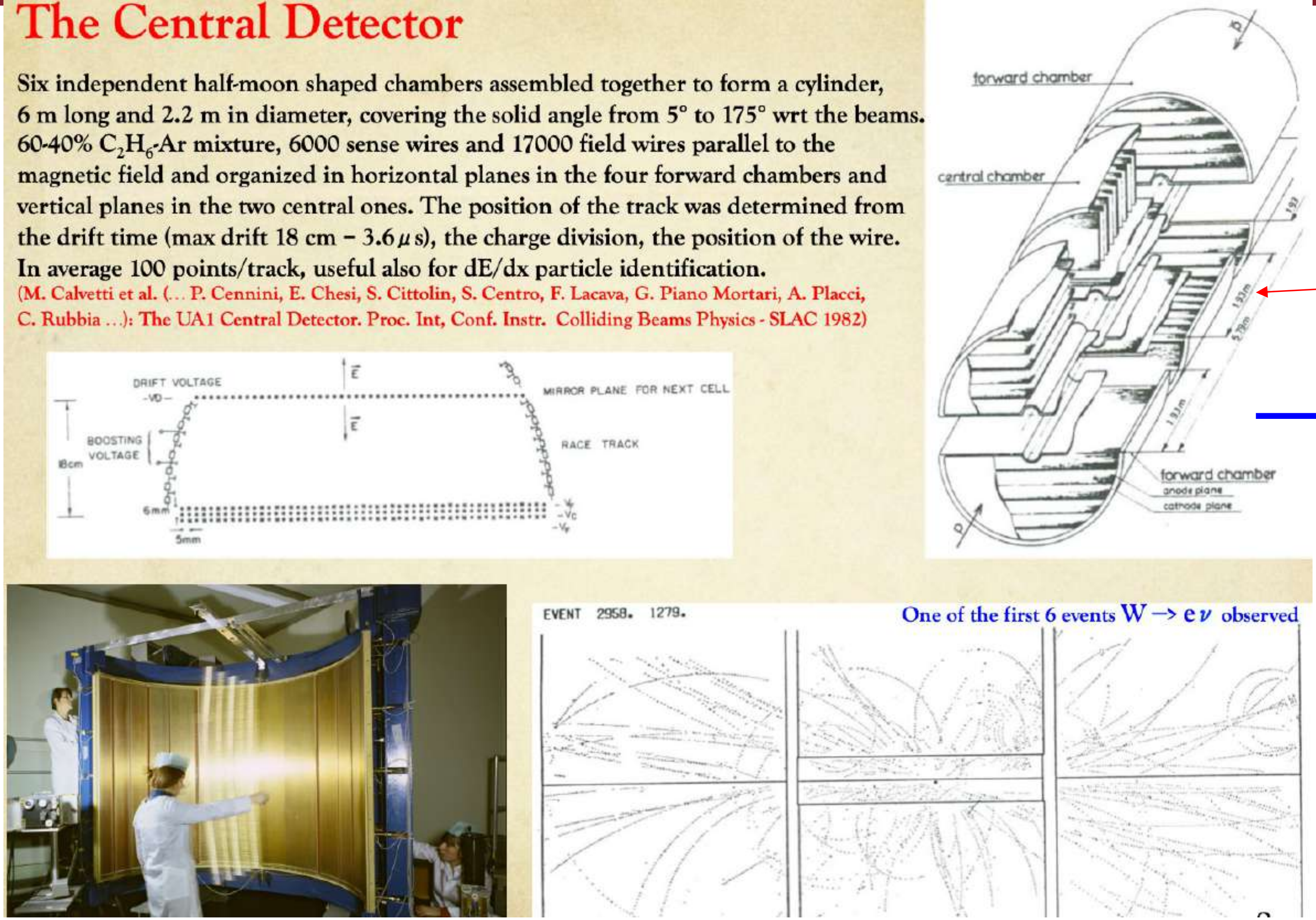
large **muon chambers**

end cap detectors (**the bouchons**)

forward and very forward detectors (up to 1° from the beams)

Slide from F. Lacava

The detector: UA1 central detector



The Central Detector

Six independent half-moon shaped chambers assembled together to form a cylinder, 6 m long and 2.2 m in diameter, covering the solid angle from 5° to 175° wrt the beams. 60-40% C_2H_6-Ar mixture, 6000 sense wires and 17000 field wires parallel to the magnetic field and organized in horizontal planes in the four forward chambers and vertical planes in the two central ones. The position of the track was determined from the drift time (max drift 18 cm – 3.6 μs), the charge division, the position of the wire. In average 100 points/track, useful also for dE/dx particle identification.

(M. Calvetti et al. (… P. Cennini, E. Chesi, S. Cittolin, S. Centro, F. Lacava, G. Piano Mortari, A. Placci, C. Rubbia …): The UA1 Central Detector. Proc. Int, Conf. Instr. Colliding Beams Physics - SLAC 1982)

One of the first 6 events $W \rightarrow e\nu$ observed

Slide from F. Lacava

1.93 m

B field horizontal

The detectors: UA1 Calorimeters (from F. Lacava)

Slide from F. Lacava

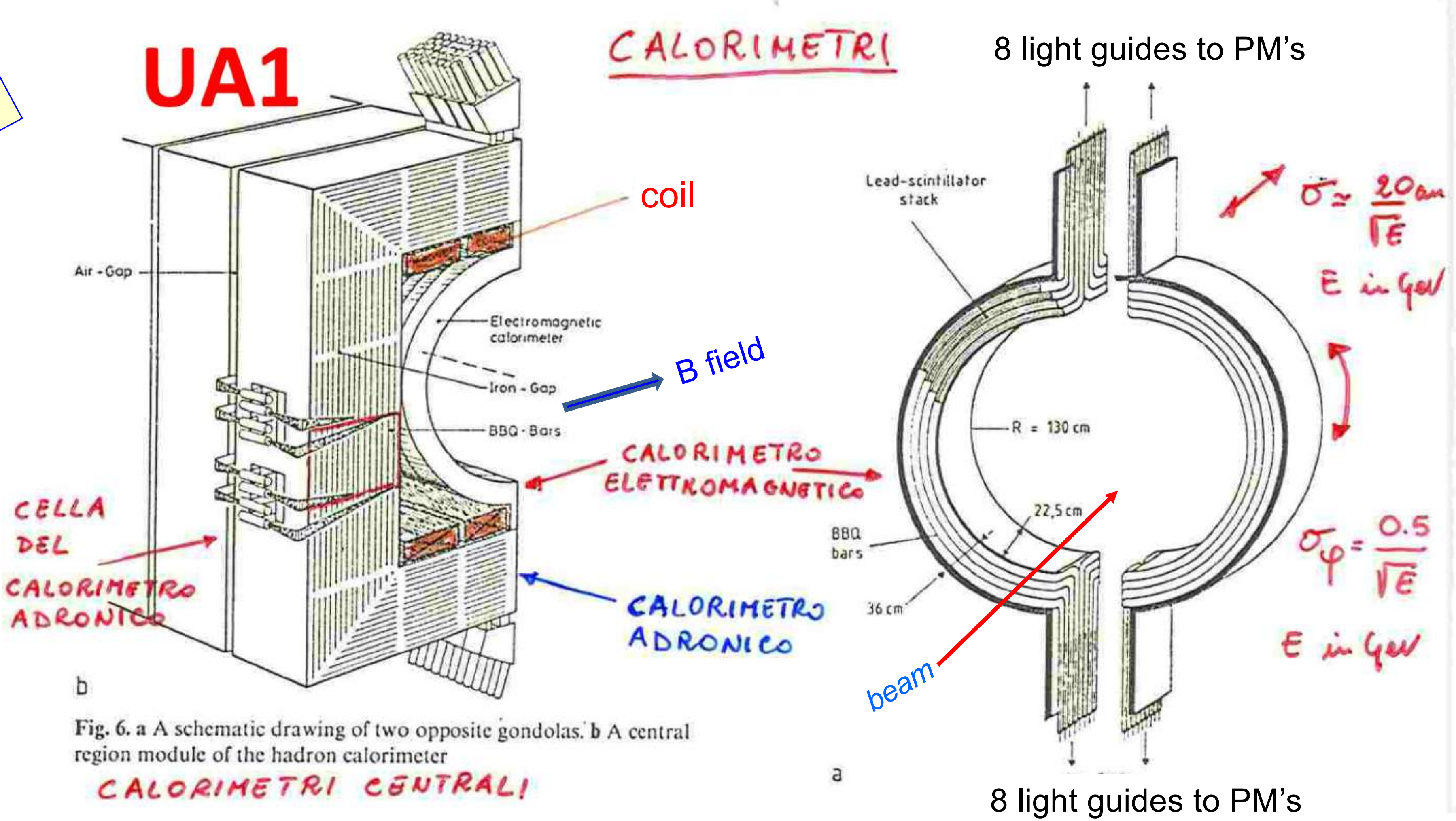


Fig. 6. a A schematic drawing of two opposite gondolas. b A central region module of the hadron calorimeter

CALORIMETRI CENTRALI

The detectors: UA1 parameters

Slide from
P. Bagnaia

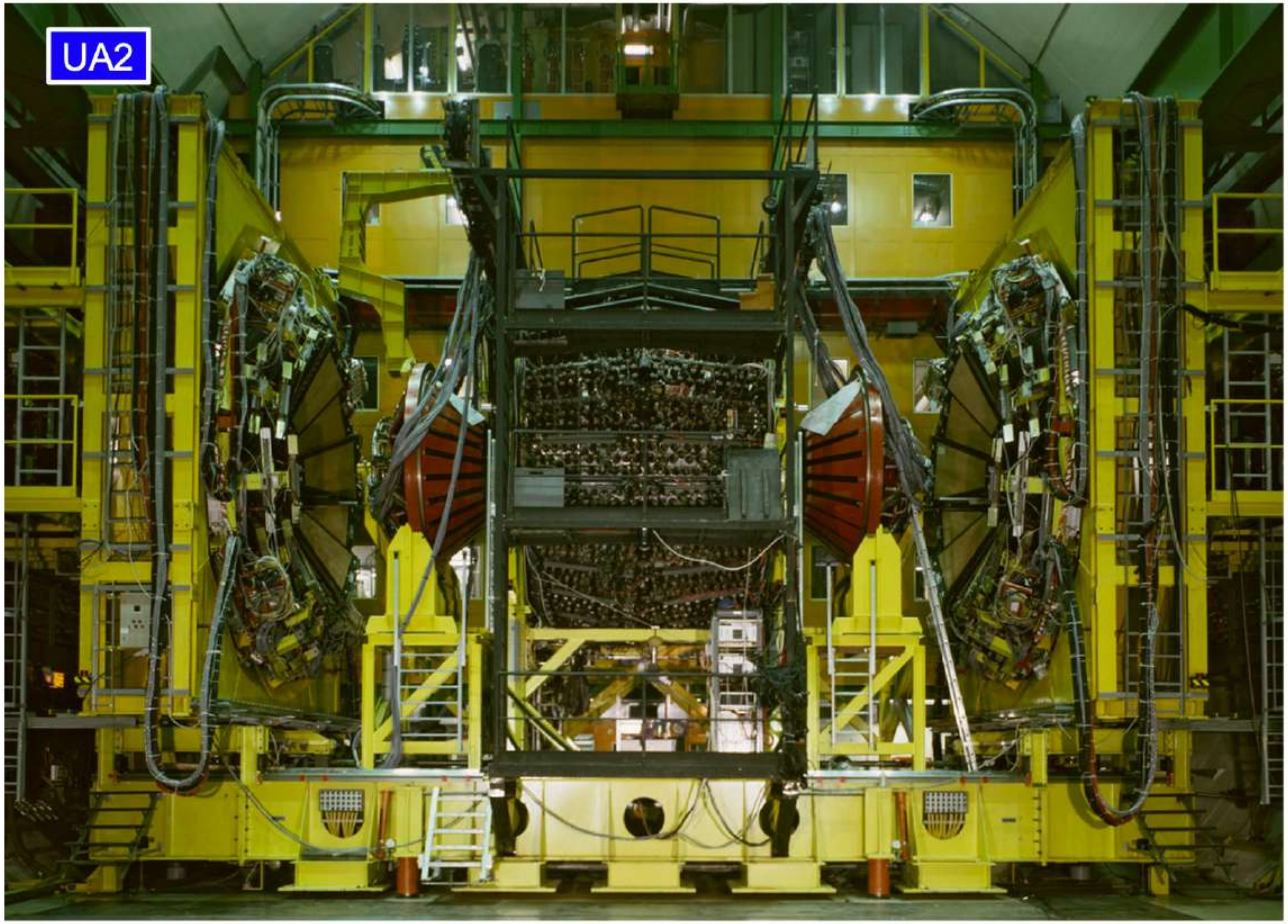
$B = 0.7\ \mathrm{T}$ $\sigma(p)/p = 0.5\%\ p\ (\mathrm{GeV})$

Central drift chamber	Gas	Field	v_{drift}	$\alpha_{Lorentz}$	$N_{sense\ wires}$
	Ar-ethane 40-60	1.5 kV/cm	53 μm/ns	23° @ 0.7 T	6110

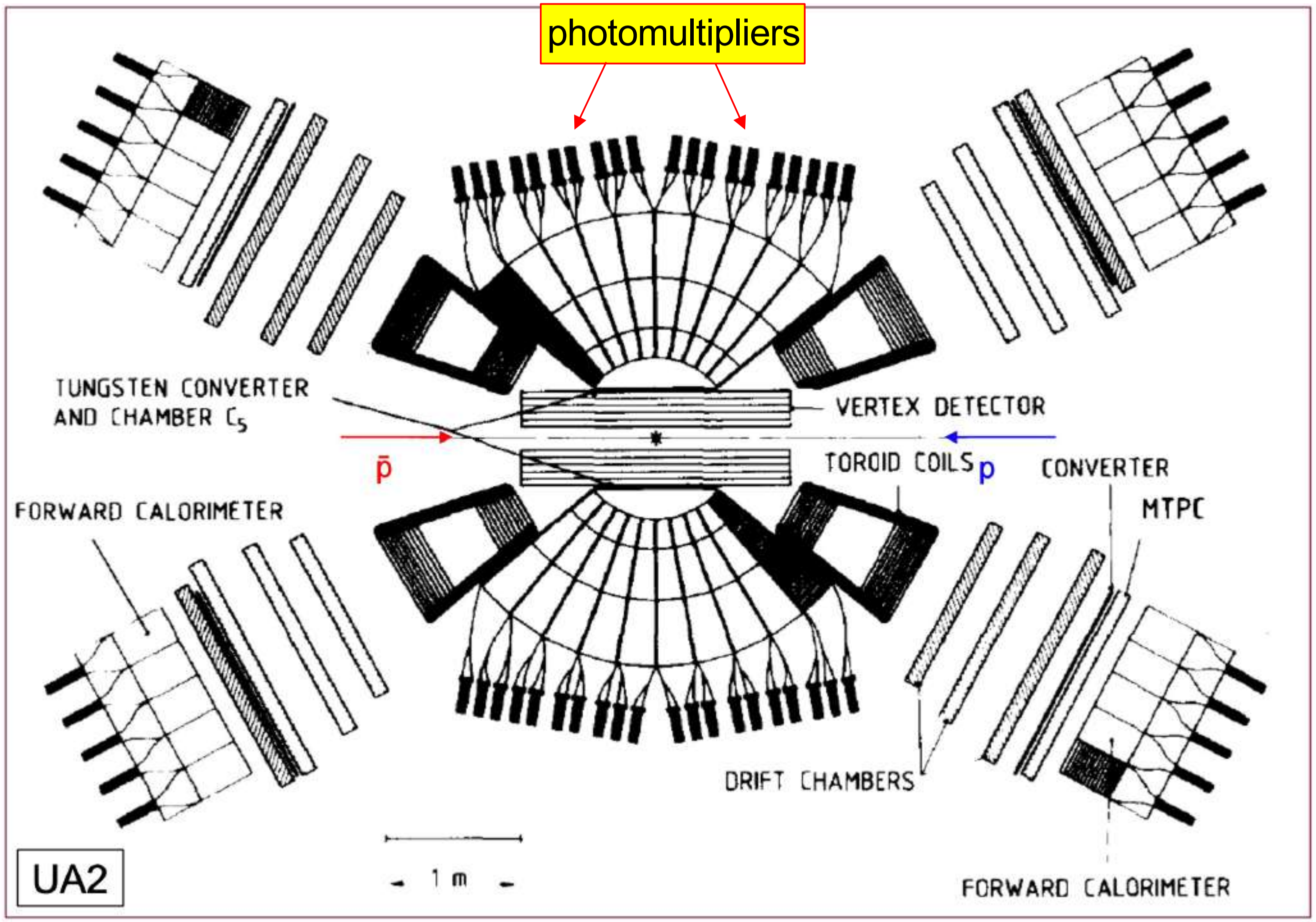
No segmentation in phi

UA1	Zenith θ	type	Name	e.m. rad-length	had. abs-length	Cell $\Delta\theta\times\Delta\phi$	σ_E/E
Central calorimeter	25°–155°	e.m.	gondolas	$26.6/\sin\theta$	$1.1/\sin\theta$	5°×180°	$0.15/\sqrt{E(\mathrm{GeV})}$
		had.	C's	–	$5.0/\sin\theta$	15°×18°	$0.80/\sqrt{E(\mathrm{GeV})}$
Endcap calorimeter	5°–25° 155°–175°	e.m.	bouchons	$27/\cos\theta$	$1.1/\cos\theta$	20°×11°	$0.12/\sqrt{E(\mathrm{GeV})}$
		had.	I's	–	$7.1/\cos\theta$	5°×10°	$0.80/\sqrt{E(\mathrm{GeV})}$

The detectors: UA2



The detectors: UA2 scheme



UA2 detector was optimized for the detection of electrons from W and Z decays.

The emphasis was on a highly granular calorimeter with spherical projective geometry, which also was well adapted to the detection of jets.

Charged particle tracking was performed in the central detector utilising a combination of multi wire proportional chambers, drift chambers and hodoscopes.

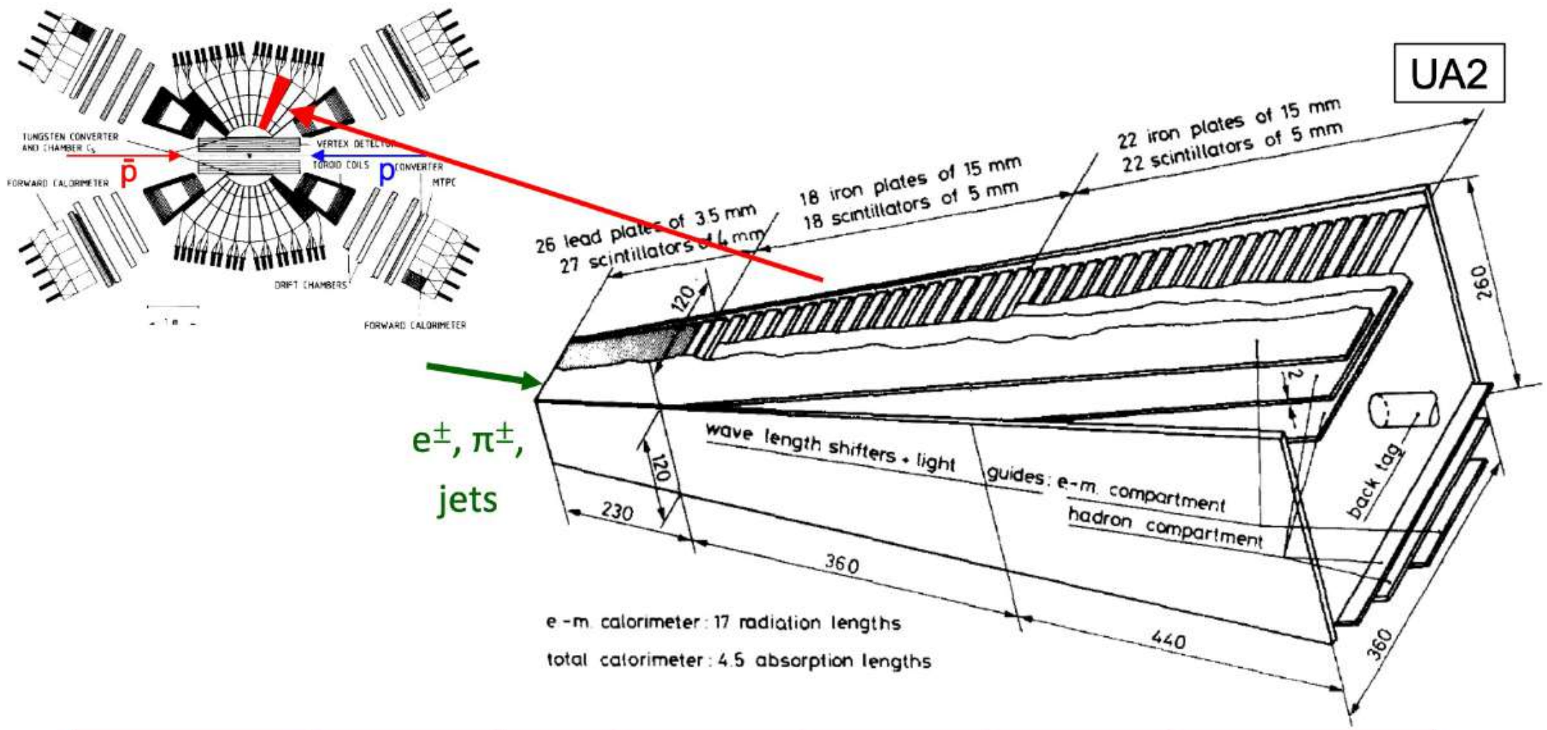
Energy measurements were performed in the calorimeters.

Magnetic field only in the forward region

Unlike UA1, UA2 had no muon detector.

The detectors: UA2 calorimeters

Slide from
P. Bagnaia



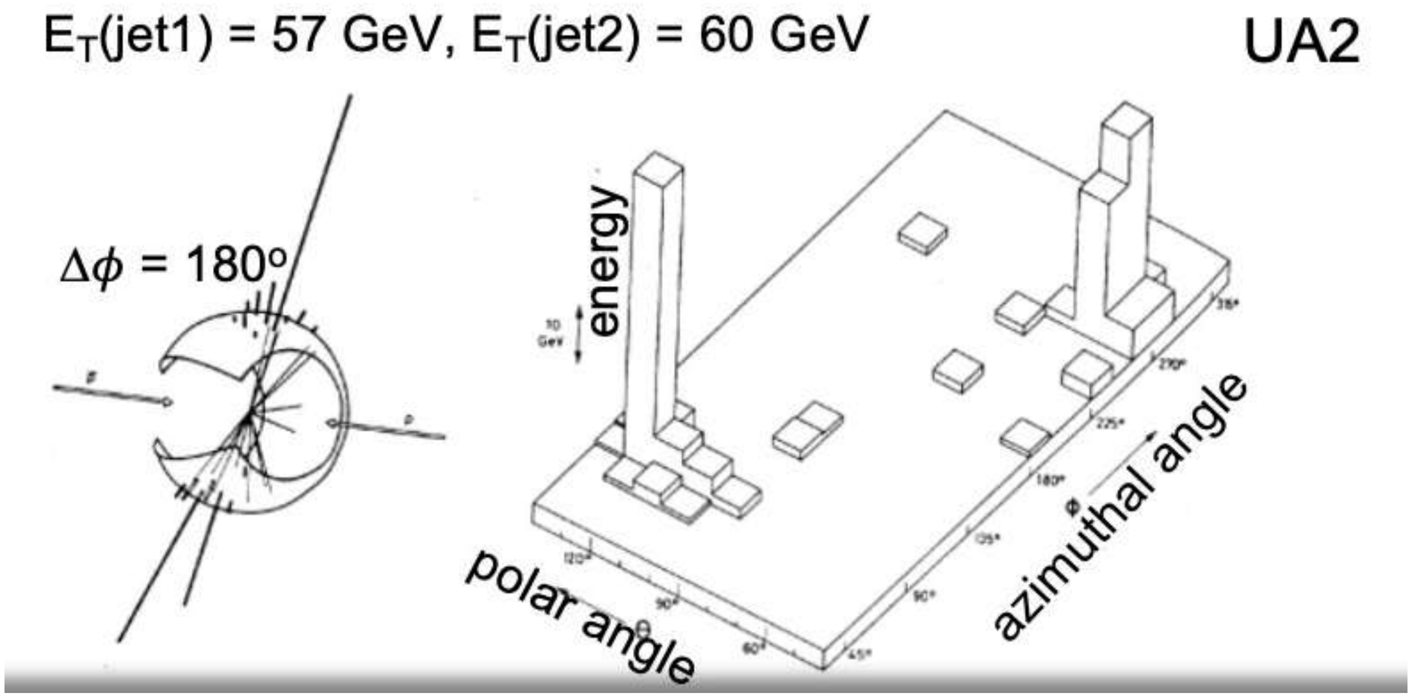
UA2 Central calorimeter	zenith θ	type	e.m. rad-length	had. abs-length	Cell Δθ×Δφ	σ_E/E
	40°−140°	e.m.	17	~0.5	10°×15°	$0.14/\sqrt{E(\text{GeV})}$
		had	–	2+2		32% – 11%

A first look at the data

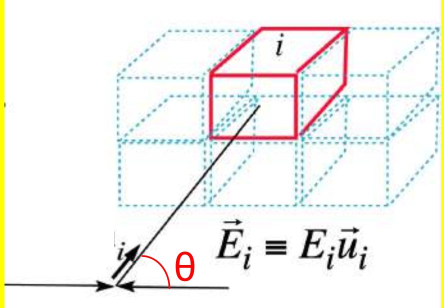
The events: jets discovery

1982: in July (Paris Conference) UA2 announced observation of hadronic jets

$E_T(\text{jet1}) = 57$ GeV, $E_T(\text{jet2}) = 60$ GeV



E_T = transverse energy



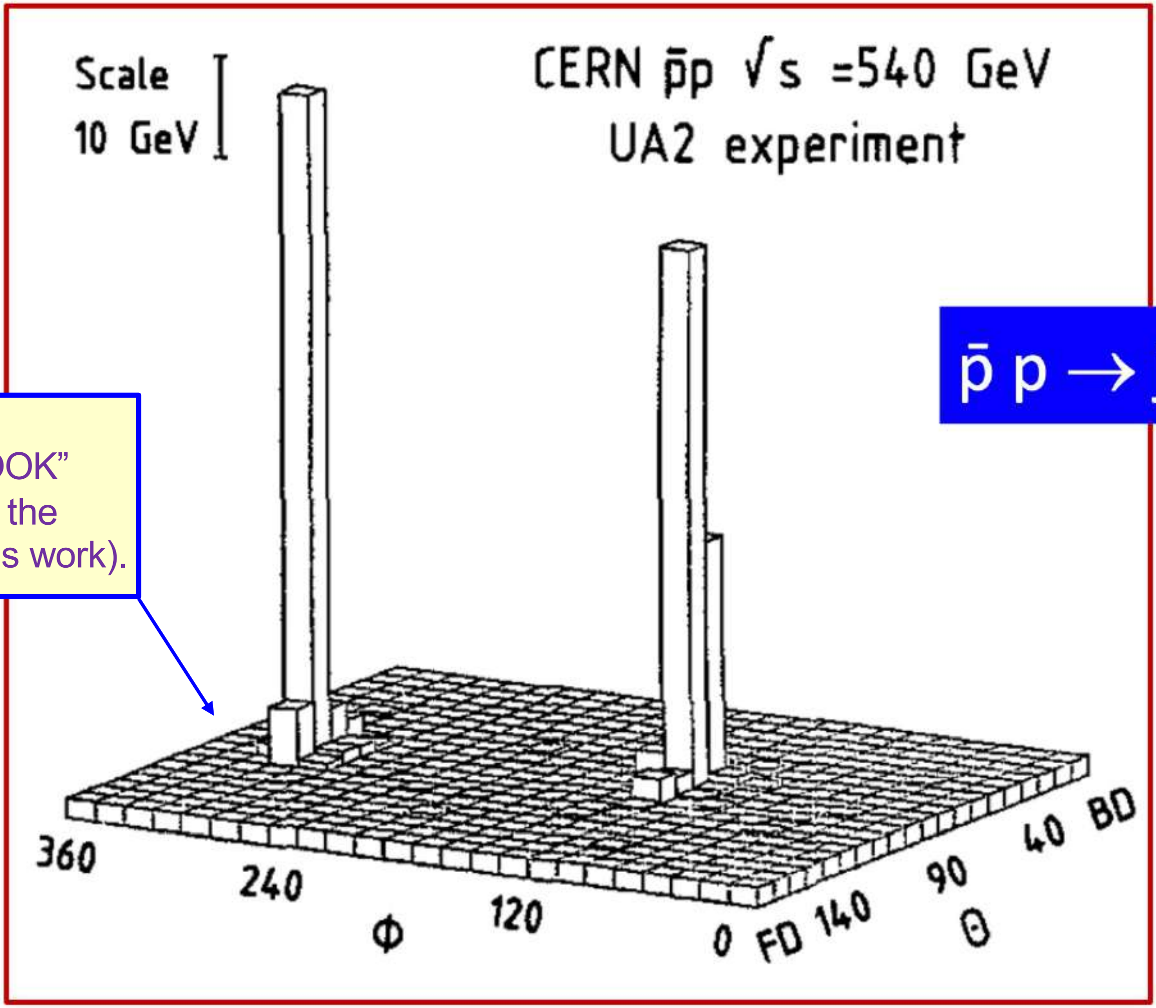
$$E_T = E\sin\theta$$

UA2: a pragmatic approach:

select the highest E_T events, simply "look at" the energy flow in the calorimeter

The events: UA2 jets

Slide from
P. Bagnaia



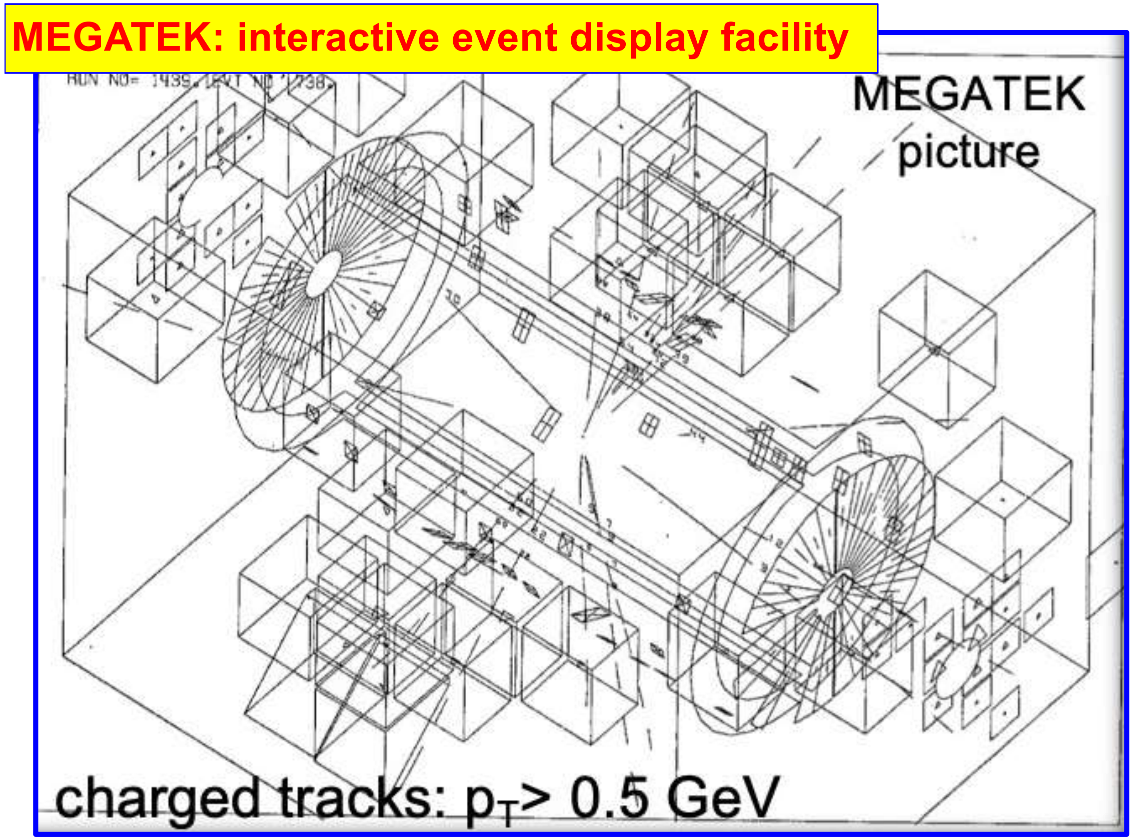
$\bar{p}\,p \rightarrow$ jet jet

Lego plot. 2d histogram included in the tool “HBOOK” used to do histograms in the ’80s (I used it in my thesis work).

Two high energy jets,
well isolated.
They are easy to identify.

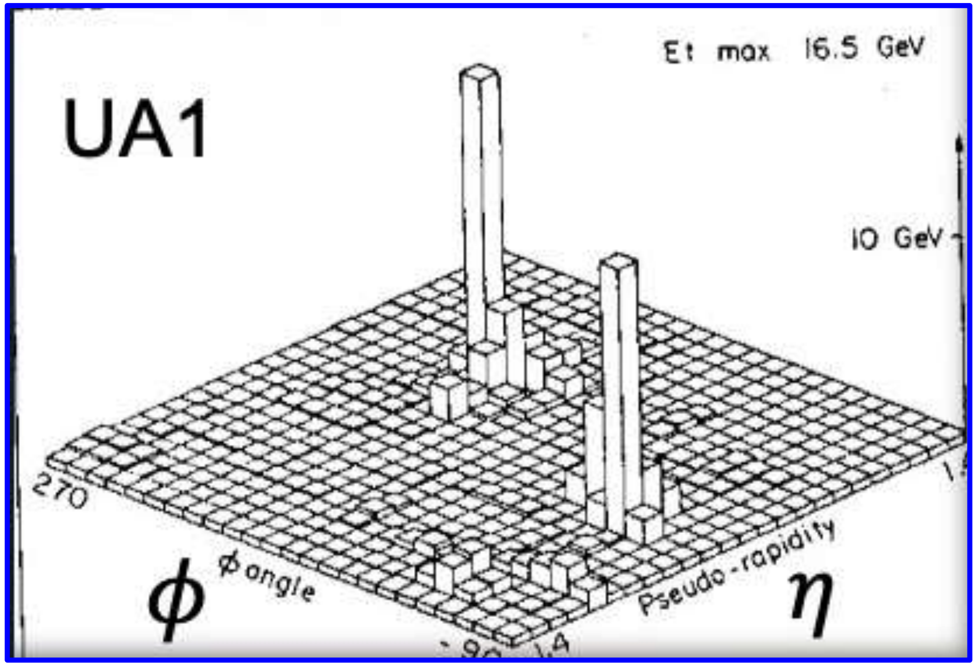
The events: UA1 jets

MEGATEK: interactive event display facility



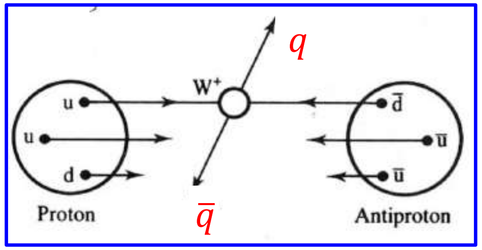
charged tracks: $p_T > 0.5$ GeV

6th European Symposium: 30 August - 3 September 1982
in Santiago de Compostela, Spain
→ **celebration of collider jets**



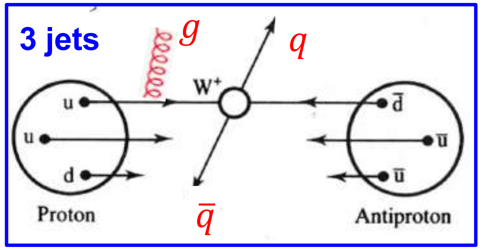
UA1: first looked at correlations of tracks in the central detector
then used tracks or cells for jet algorithm:
$R_{cone}=\sqrt{(\Delta\phi)^2+(\Delta\eta)^2}$, $\eta = -\ln(\tan\theta/2)$
e.g.: $\theta=40^\circ \rightarrow \eta=1.0$ $\theta=5^\circ \rightarrow \eta=3.0$

The events: UA1 jets



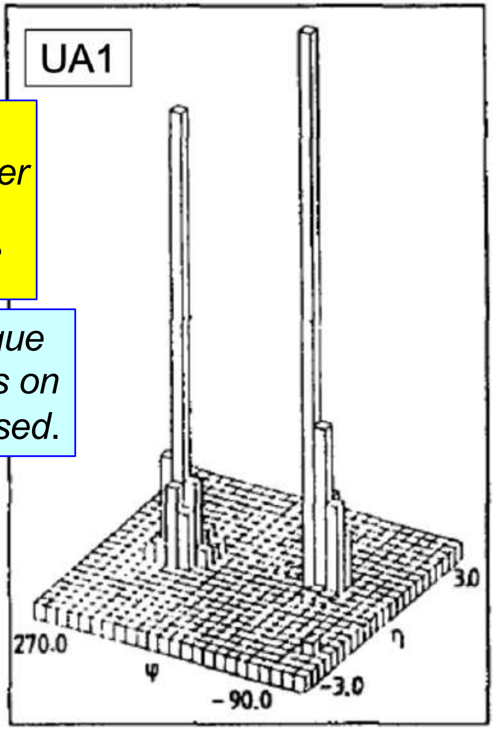
What about events with 3 and 4 jets?

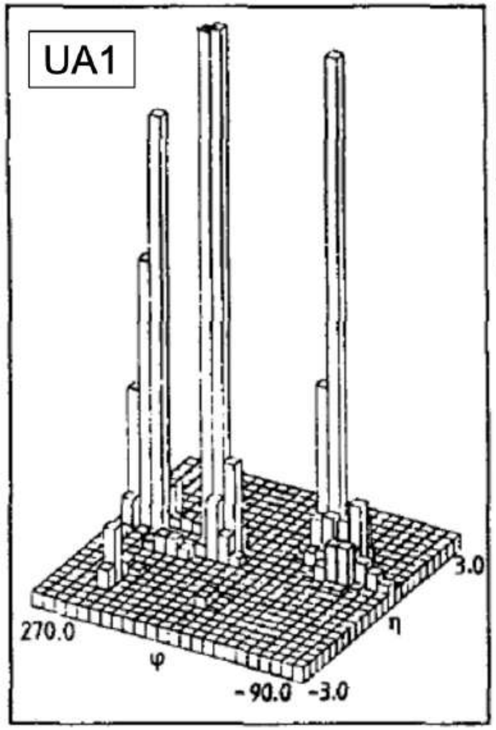
$\bar{p}p \rightarrow 2,3,4$ jets

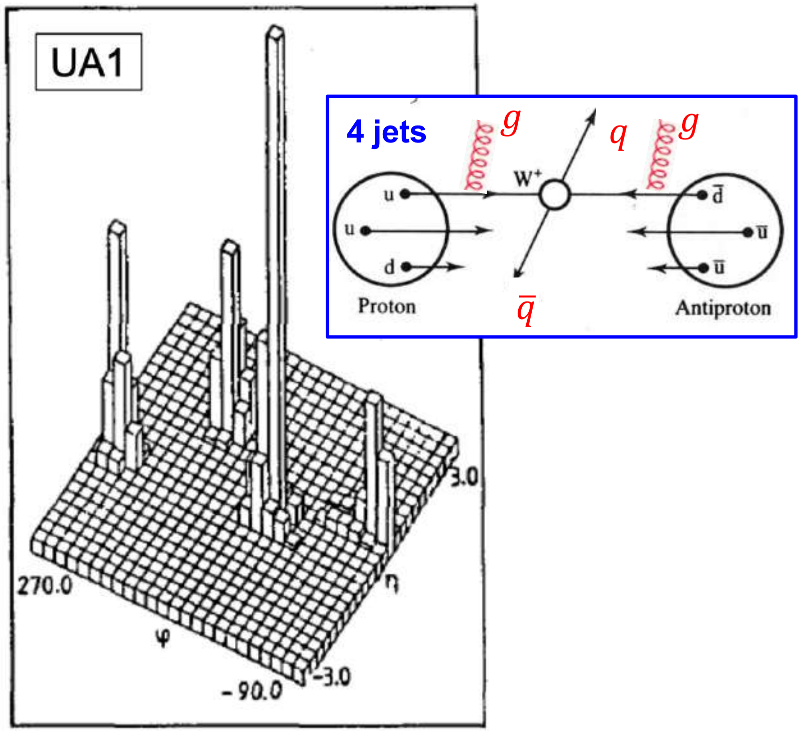


Question: *how to assign a calorimeter cell to a given jet or to another one?*

There is not a unique answer. It depends on the jet algorithm used.

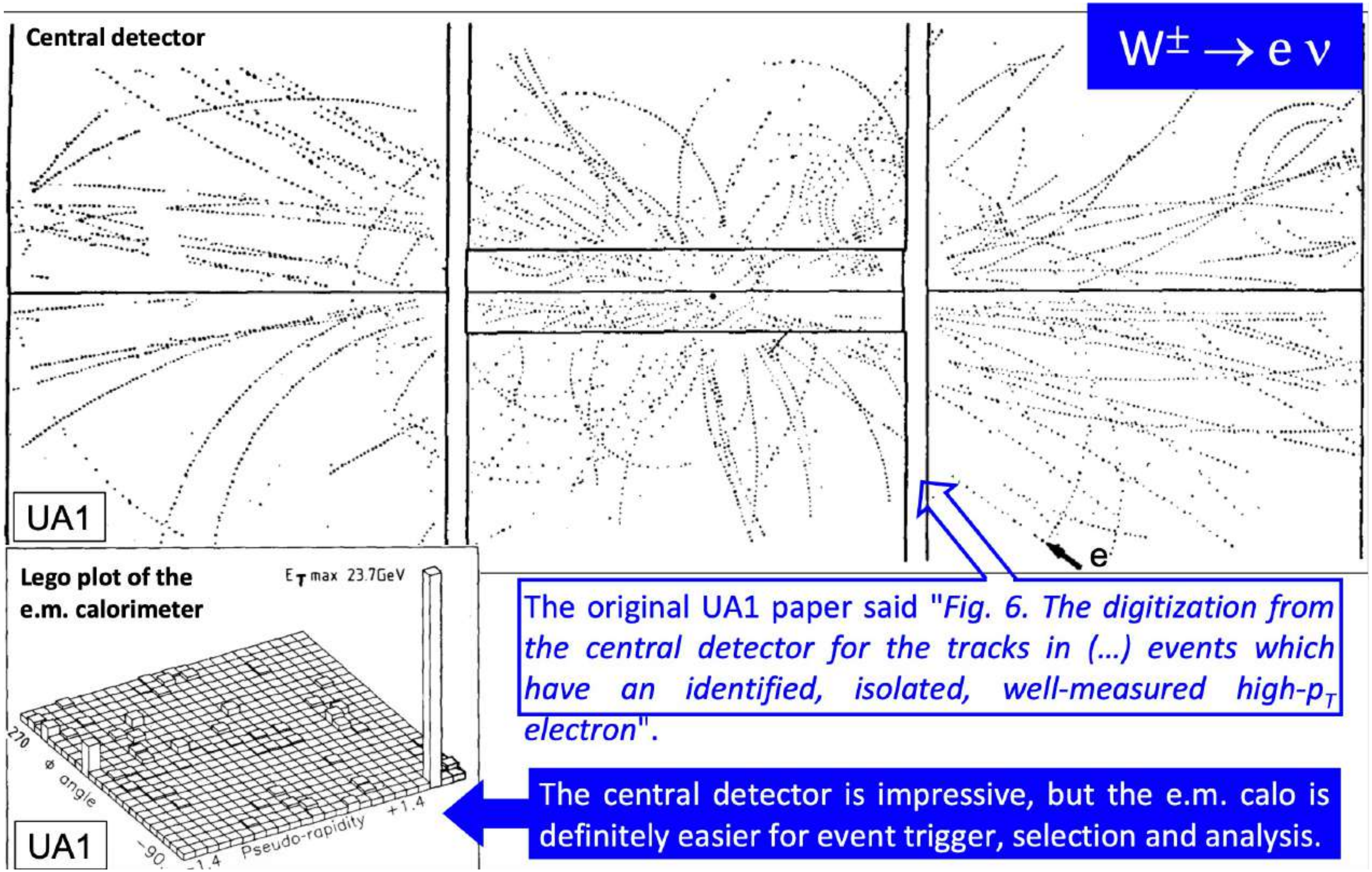






The events: UA1 $W^{\pm} \rightarrow e\nu$

Slide from P. Bagnaia



Central detector

Lego plot of the e.m. calorimeter

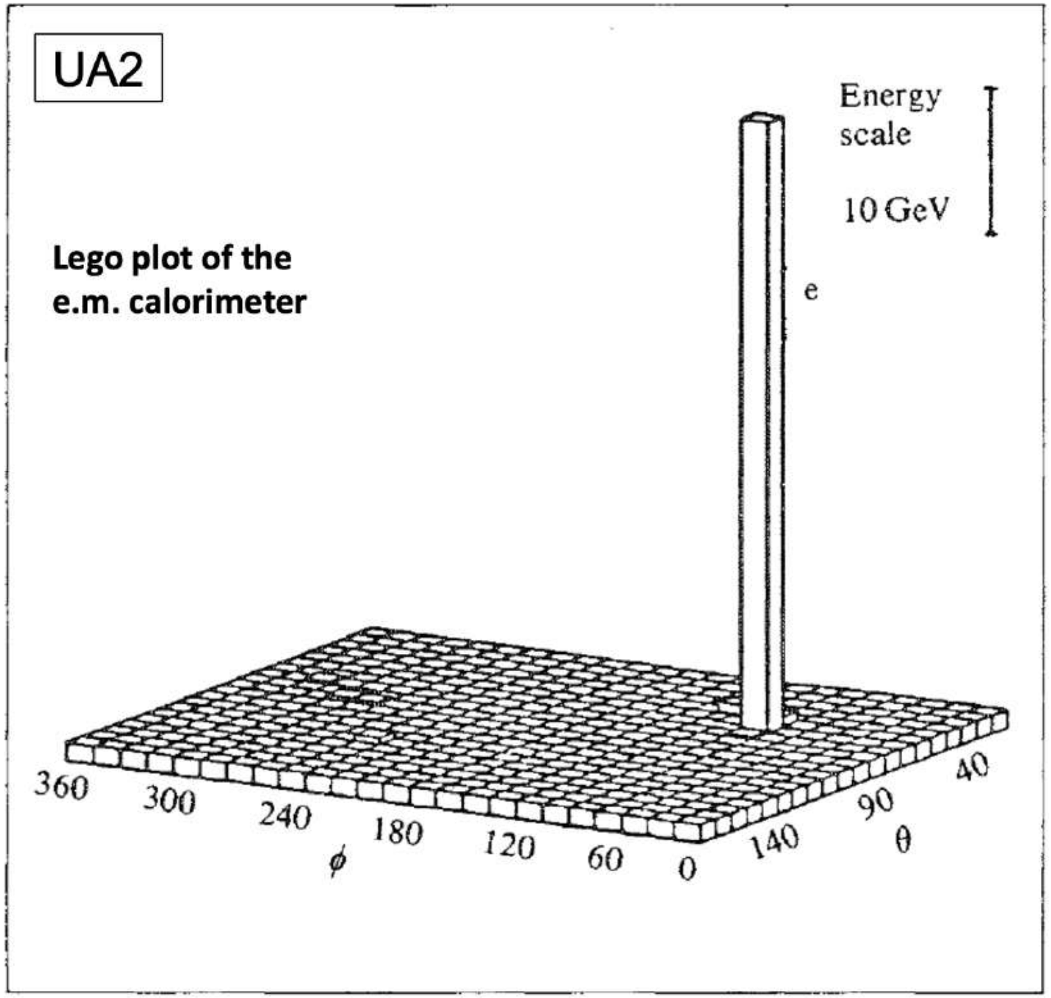
The original UA1 paper said "*Fig. 6. The digitization from the central detector for the tracks in (…) events which have an identified, isolated, well-measured high-p_T electron*".

The central detector is impressive, but the e.m. calo is definitely easier for event trigger, selection and analysis.

The events: UA2 $W^{\pm} \to e\nu$

Slide from
P. Bagnaia

$W^{\pm} \to e\,\nu$

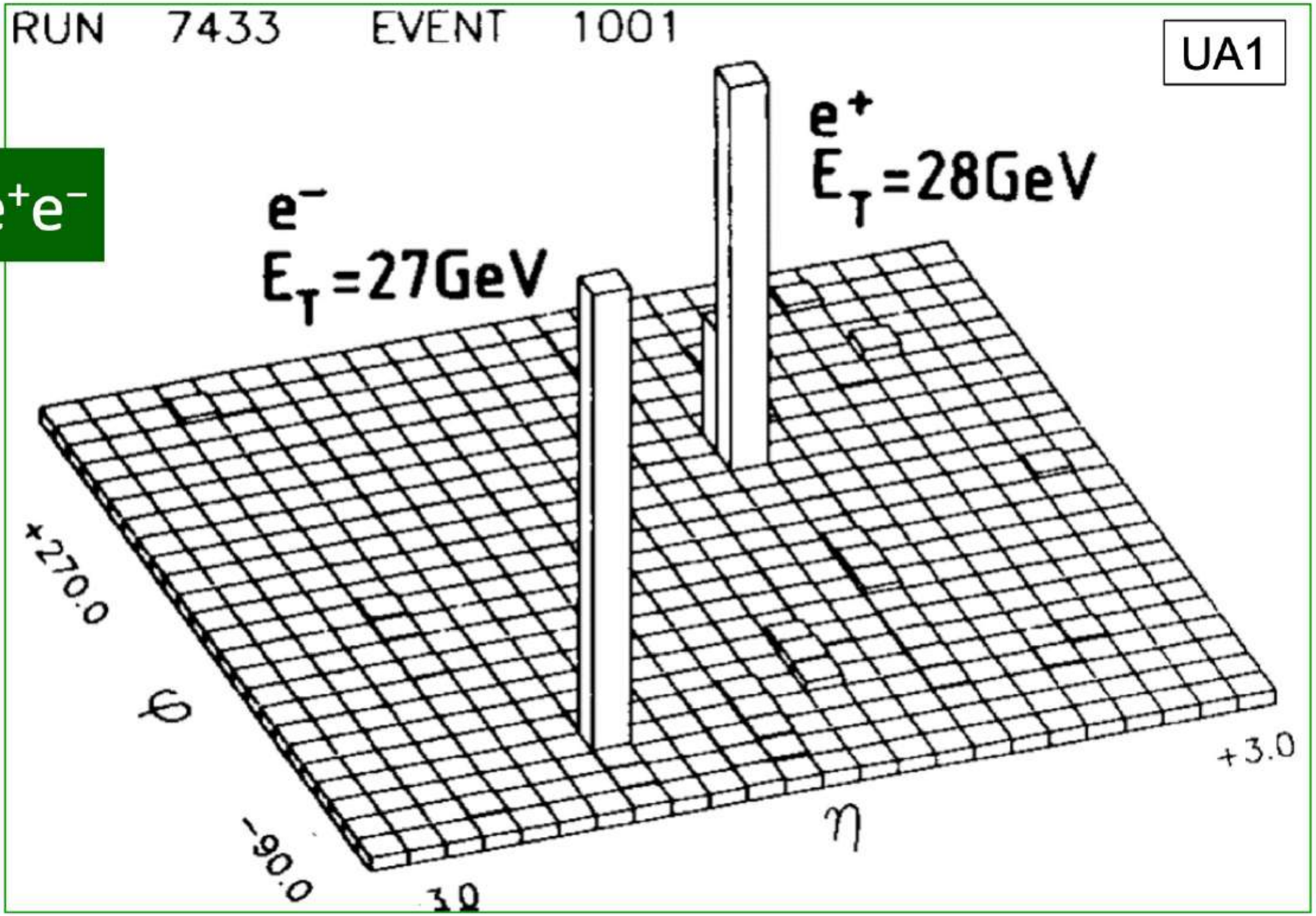


NB UA2 had a magnetic field only in the FB regions to measure $e^{\pm}$ asymmetry; in the central region, $e^{+} \leftrightarrow e^{-}$ were ambiguous.

The events: UA1 $\mathrm{Z} \rightarrow e^{+}e^{-}$

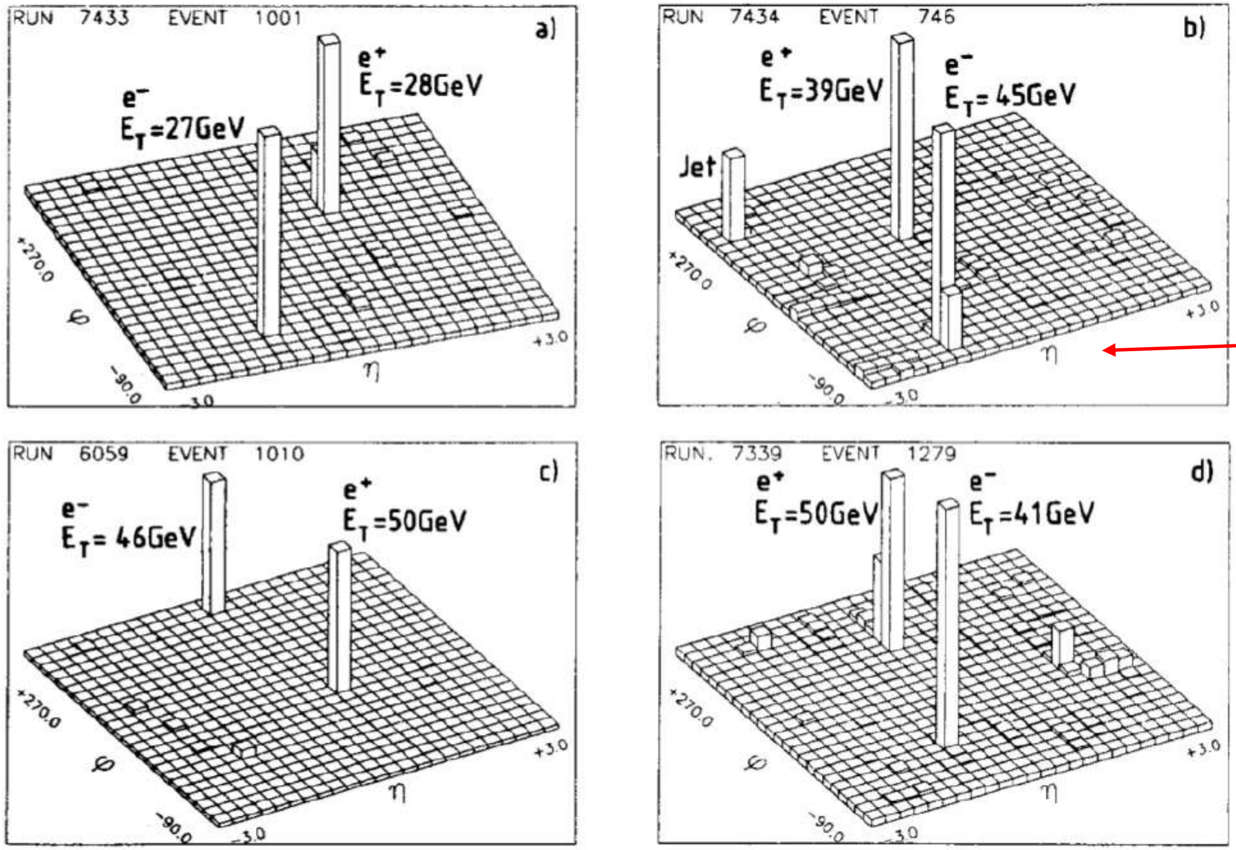
Slide from P. Bagnaia

$\mathrm{Z} \rightarrow e^{+}e^{-}$



The events: UA1 $Z \rightarrow e^+e^-$

Slide from P. Bagnaia



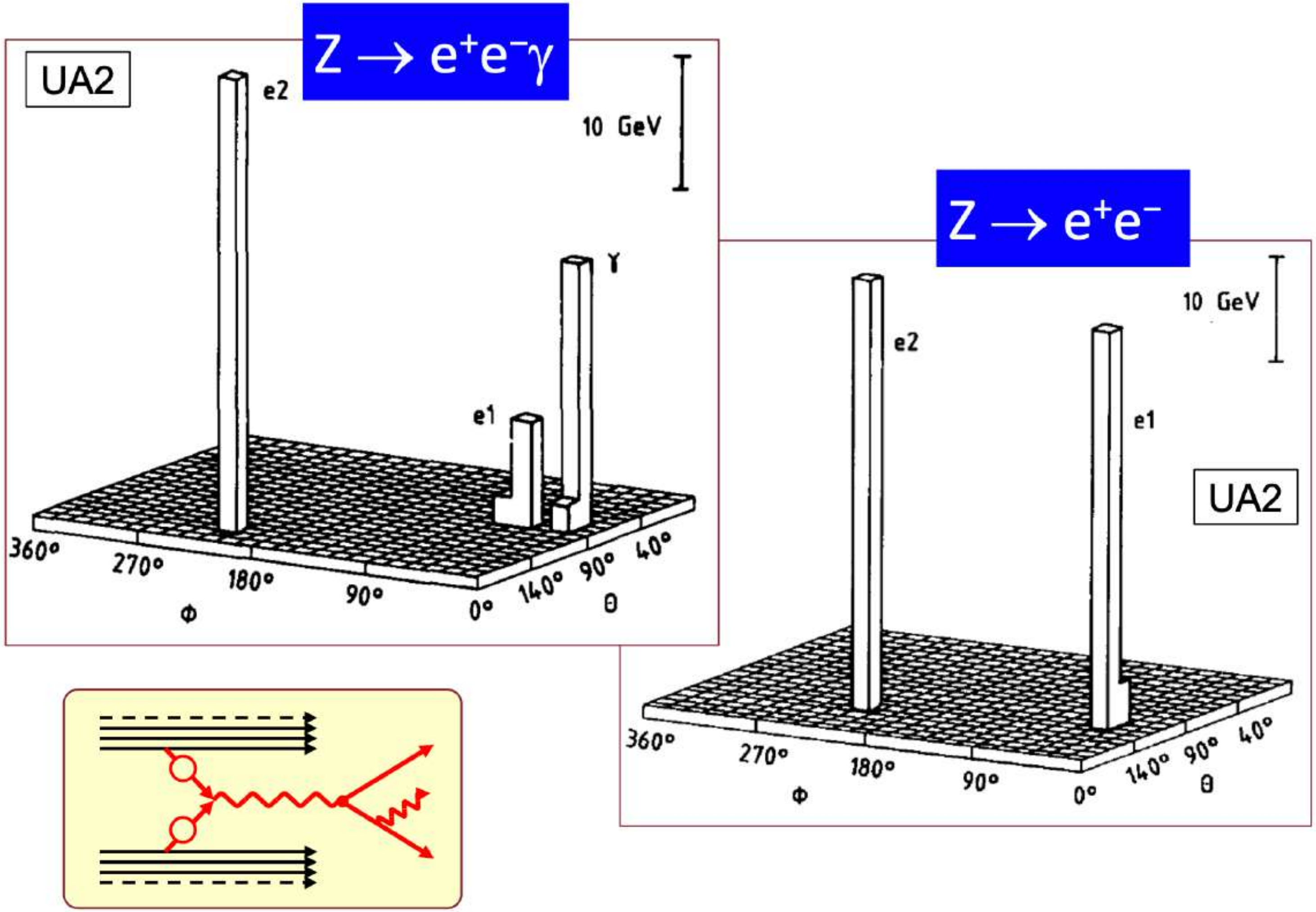
Pseudorapidity

$$\eta = -ln \tan\frac{\theta}{2}$$

Figure 12.3. Lego plots for four UA-1 events that were candidates for $Z^0 \rightarrow e^+e^-$. The plots show the location of energy deposition in ϕ, the azimuthal angle, and $\eta = -\ln\tan(\theta/2)$, the pseudorapidity. The isolated towers of energy indicate the cleanliness of the events (Ref. 12.8).

The events: UA2 $Z \rightarrow e^+e^-$

Slide from P. Bagnaia



The events: UA2 $\mathrm{Z} \rightarrow e^+e^-$

Slide from
P. Bagnaia

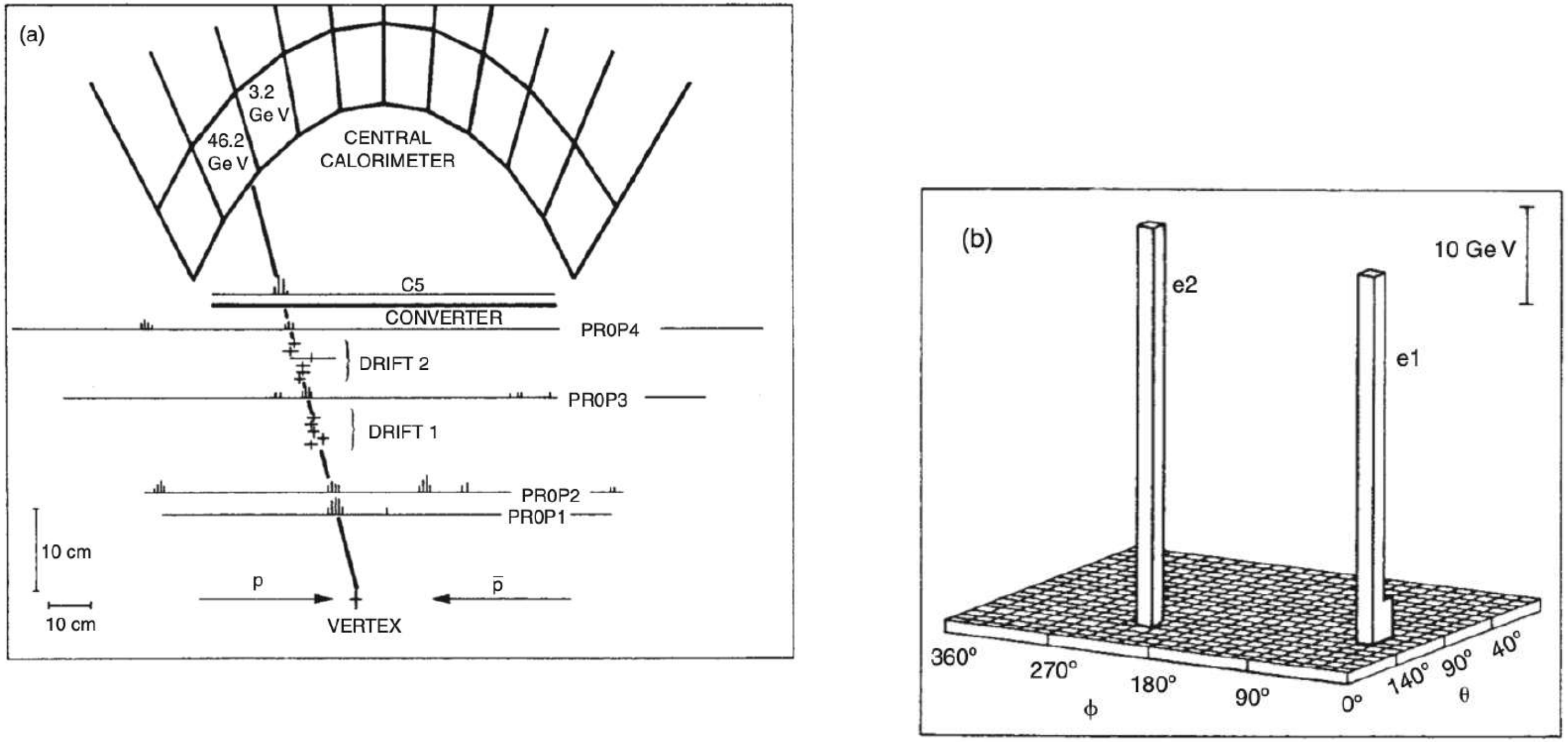
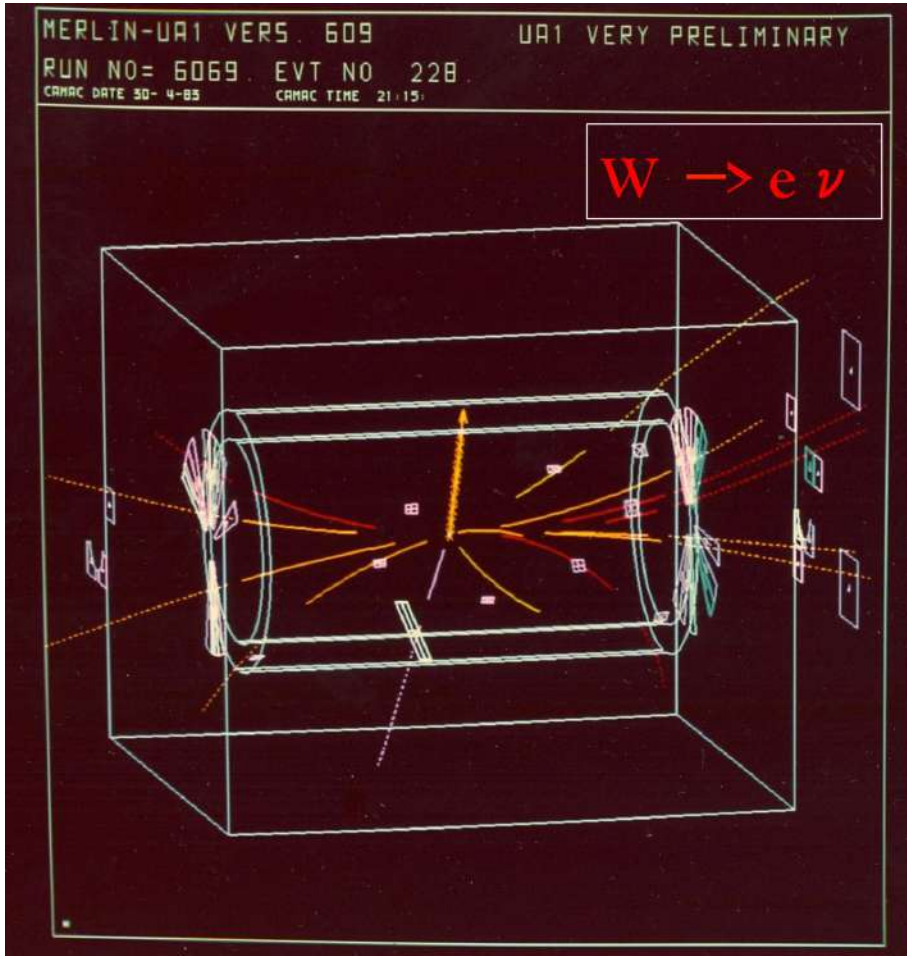
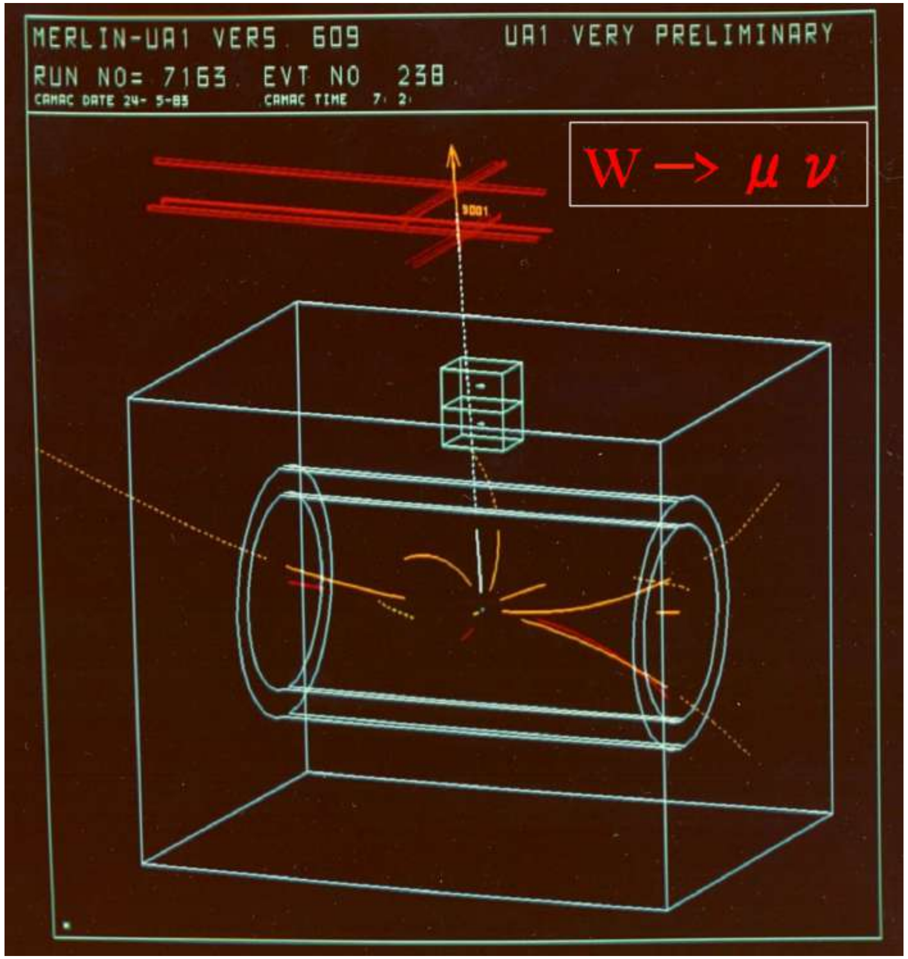


Figure 12.4. A UA-2 candidate for $Z^0 \rightarrow e^+e^-$. The upper diagram shows a track detected by a series of proportional chambers and a chamber following a tungsten converter. The calorimeter cells indicate energy measured by the electromagnetic calorimeter. The lego plot for the event shows two isolated depositions of electromagnetic energy, indicative of an e^+e^- pair (Ref. 12.9).

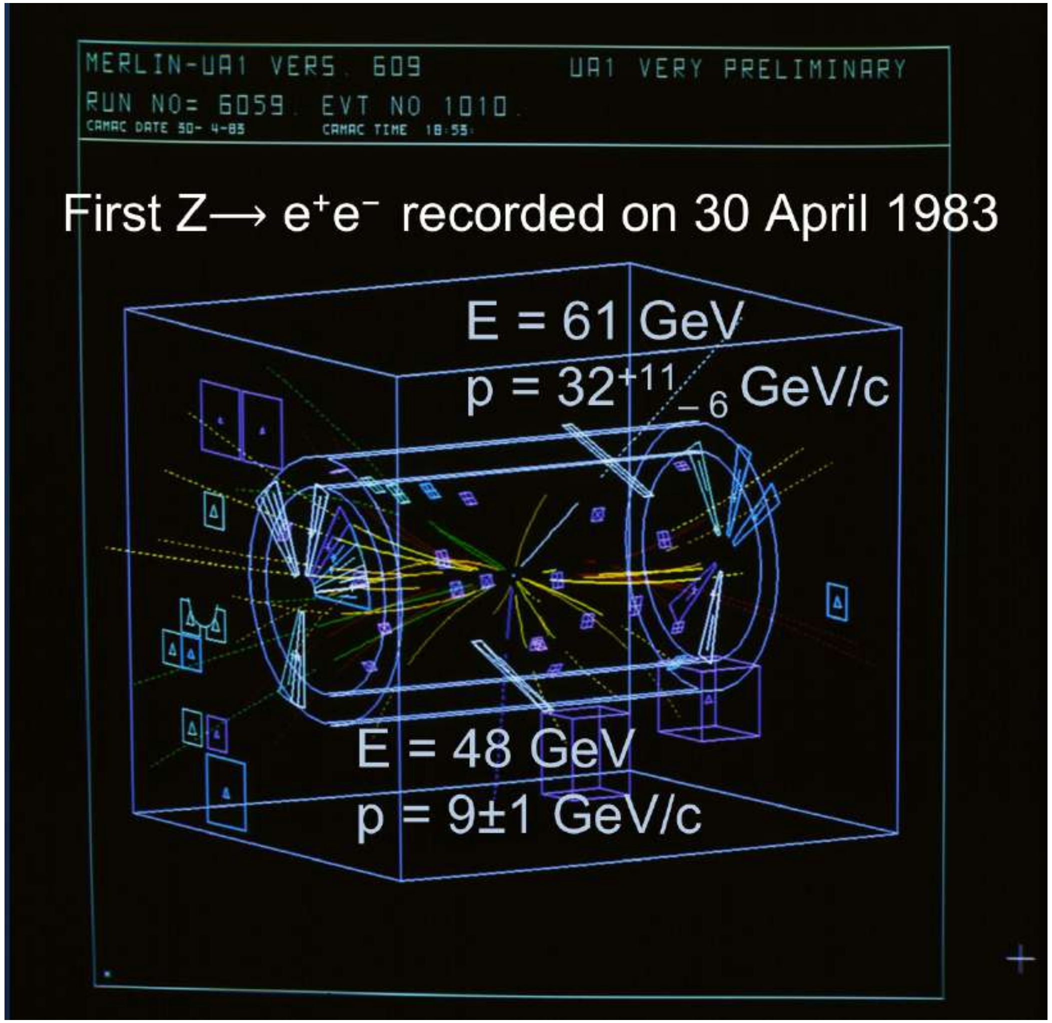
An electron is identified by an e.m. cluster, a track in the central detector and no energy in the hcal behind the cluster

UA1 MEGATEK: W decays





UA1 MEGATEK: Z decays



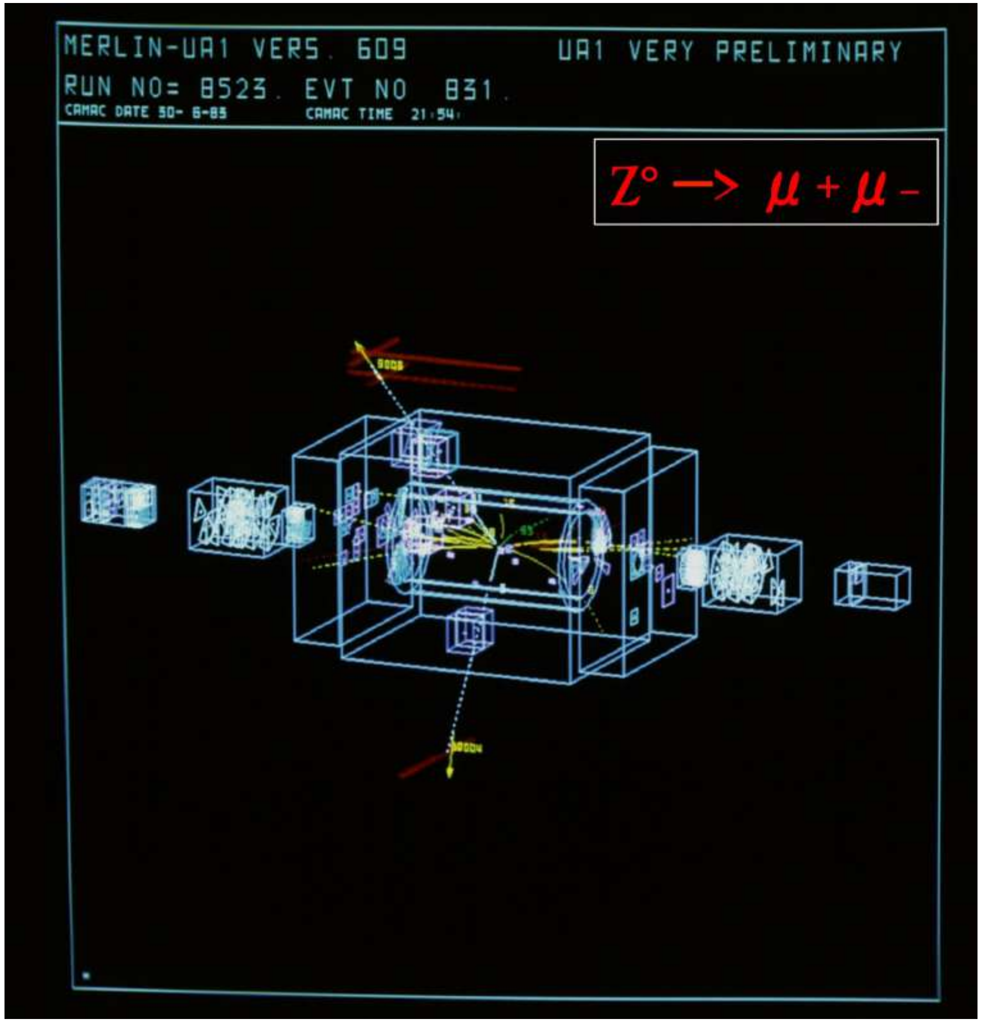
First Z⟶ e^+e^- recorded on 30 April 1983

E = 61 GeV

p = 32^{+11}_{-6} GeV/c

E = 48 GeV

p = 9±1 GeV/c

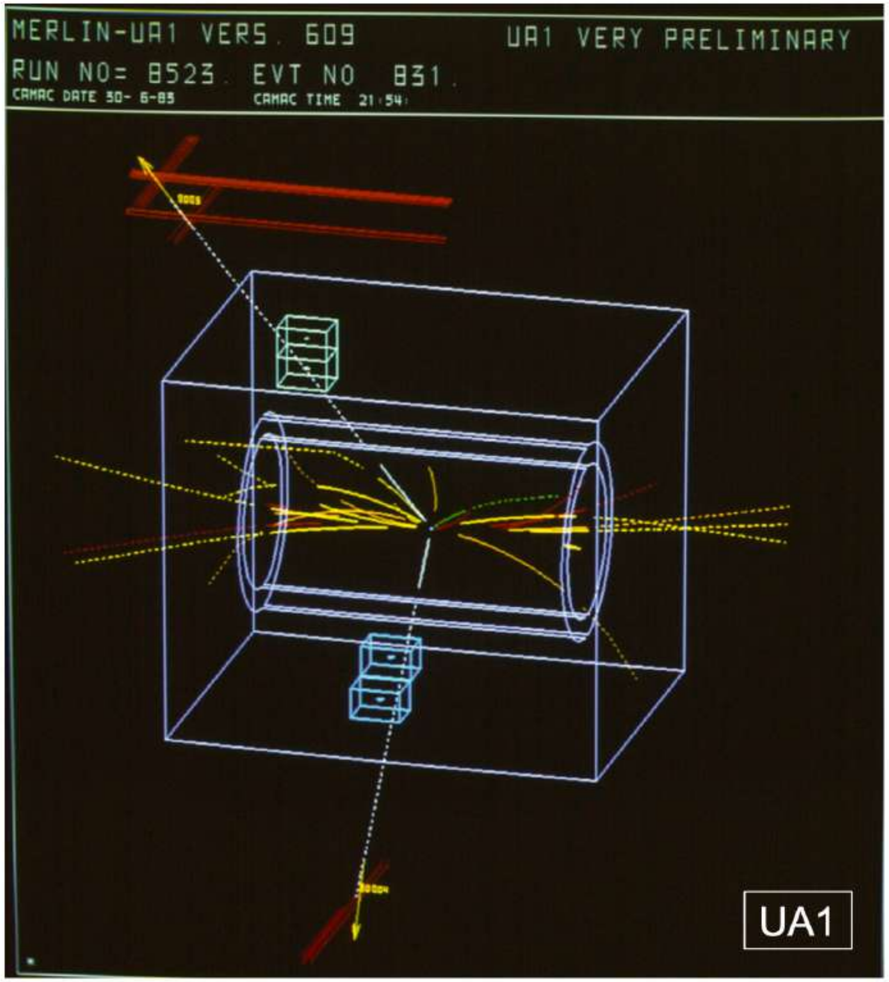


$Z^\circ \longrightarrow \mu^+ \mu^-$

The events: UA1 $Z \rightarrow \mu^+\mu^-$

Slide from
P. Bagnaia

$Z \rightarrow \mu^+\mu^-$



Calorimeters: uncertainties on the energy scale

- **Of course, neither UA1 nor UA2 directly measured the energy lost by the particle(s), but they measured the light produced by the particles traversing the layers of scintillator material. The chain is:**

Energy lost in the scintillators

Light production

Light partially collected by the wavelength shifters and brought to the photomultiplier

photoelectrons produced at the photocathode

electrons multiplied by dynodes

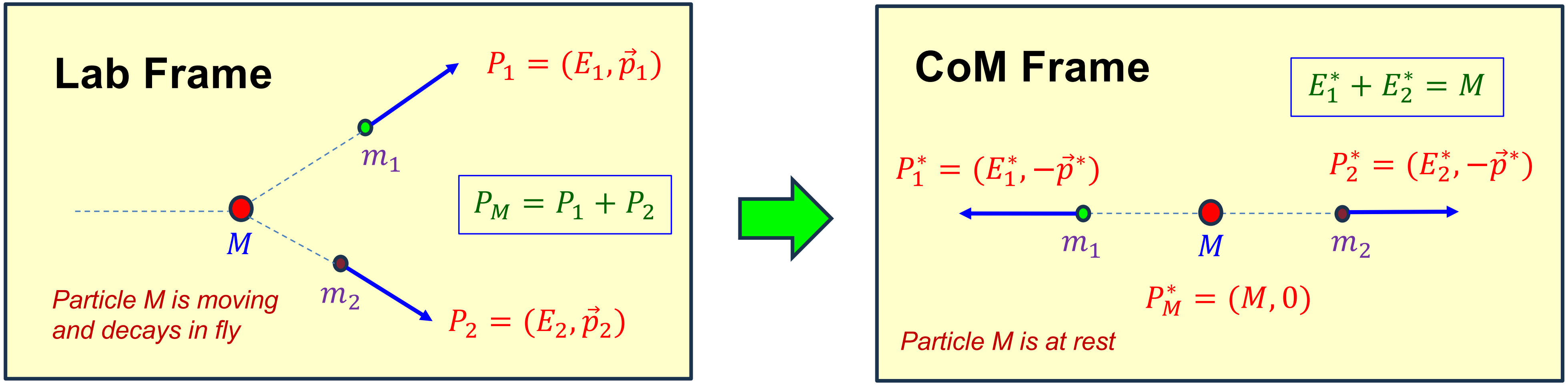
ADC conversion

- **The entire chain must be calibrated on a test beam with electrons and pions of known energies to get the calibration constants, namely the factor to go from the response in voltage to the energy of the incoming particle.**
- **The calibration constants take into account also the sampling fraction (namely the energy lost in the scintillator with respect to the energy lost in the absorber material).**

- **… but the calibration constants are not "constant" at all since they change with time (material ageing, radiation damages, etc …), so it is necessary to monitor them constantly, either with dedicated devices (xenon lamps, radioactive source), or with the data itself using resonances of known mass (π^0, J/ψ … today, Z)**

- **UA1: big modules, scale uncertainty = 3% ; UA2: small modules, scale uncertainty = 1.6%**

Reminder: invariant mass



Lab Frame

$P_1 = (E_1, \vec{p}_1)$

m_1

$P_M = P_1 + P_2$

M

Particle M is moving and decays in fly

m_2

$P_2 = (E_2, \vec{p}_2)$

CoM Frame

$E_1^* + E_2^* = M$

$P_1^* = (E_1^*, -\vec{p}^*)$

$P_2^* = (E_2^*, -\vec{p}^*)$

m_1 M m_2

$P_M^* = (M, 0)$

Particle M is at rest

❑ **The total quadrimomentum squared is a relativistic invariant (for Lorentz transformation).**

Lab Frame

$$P_M^{\mu} \cdot P_{M,\mu} = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

CoM Frame

$$P_M^{*,\mu} \cdot P_{M,\cdot}^{*} = M^2$$

$$M_{inv} = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

❑ **The same relationship holds also if the particle M decays into three or more particles, like for instance in the Higgs boson decays into four leptons**

Timeline of the W and Z discoveries

1983: W discovery in e-channel

- 12-14 Jan: Rome meeting: W-candidates shown by UA1 and UA2
- CERN Seminar:

  20 Jan 1983, Carlo Rubbia presented 6 candidate events for UA1

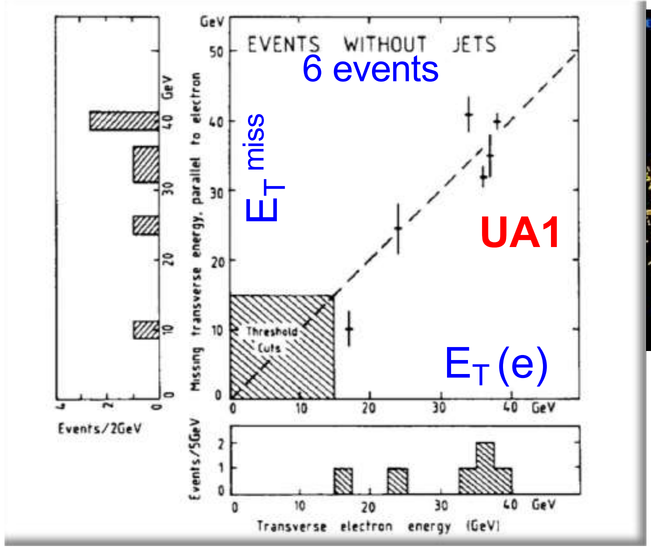
  21 Jan 1983, Luigi Di Lella presented 4 candidate events for UA2

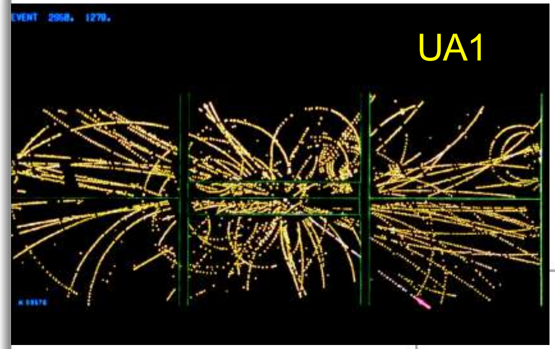
SE SONO
ROSE,
FIORIRANNO

Carlo Rubbia the following week:

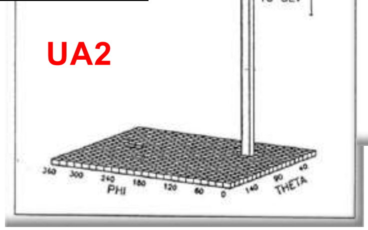
“They look like Ws, they feel like Ws, they smell like Ws, they must be Ws”

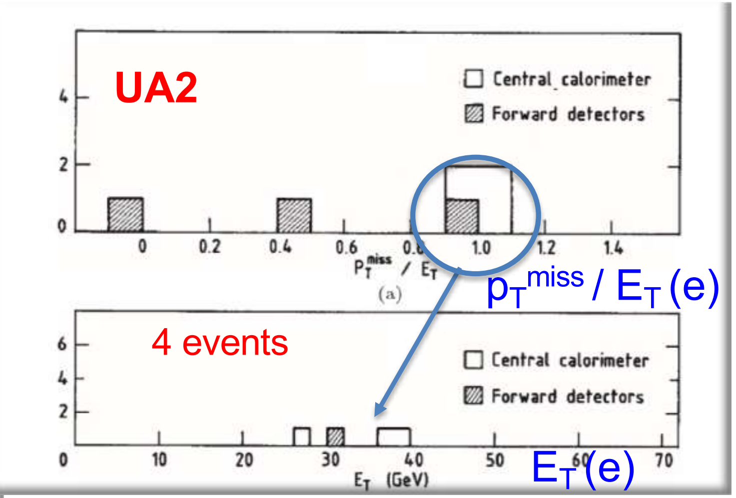
introduction of E_T^{miss} signature as new analysis tool: $\vec{E}_T^{miss} + \sum_{cells} \vec{E}_T = 0$





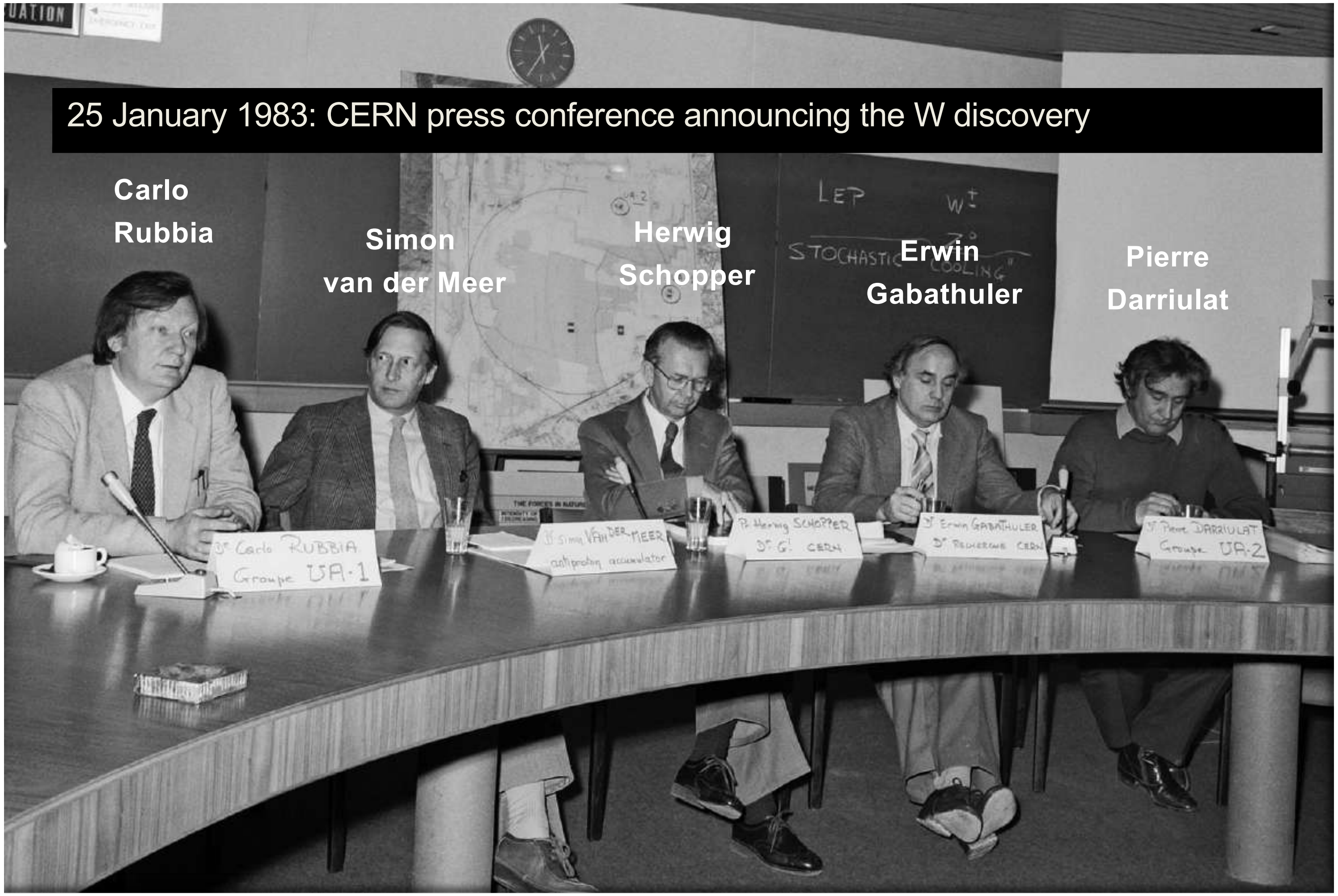
$m_W = 81 \pm 5$ GeV





$m_W = 80^{+10}_{-6}$ GeV

W discovery went public



25 January 1983: CERN press conference announcing the W discovery

Carlo Rubbia

Simon van der Meer

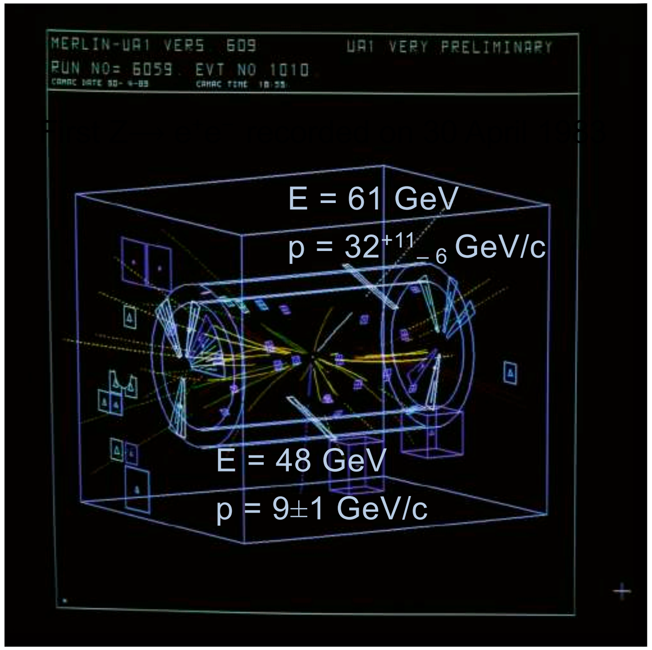
Herwig Schopper

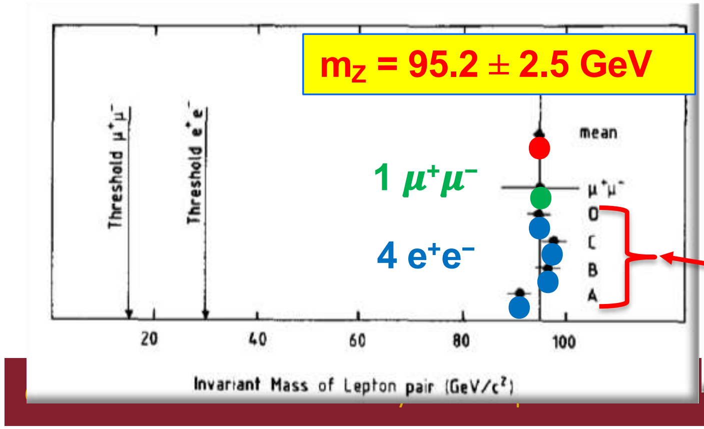
Erwin Gabathuler

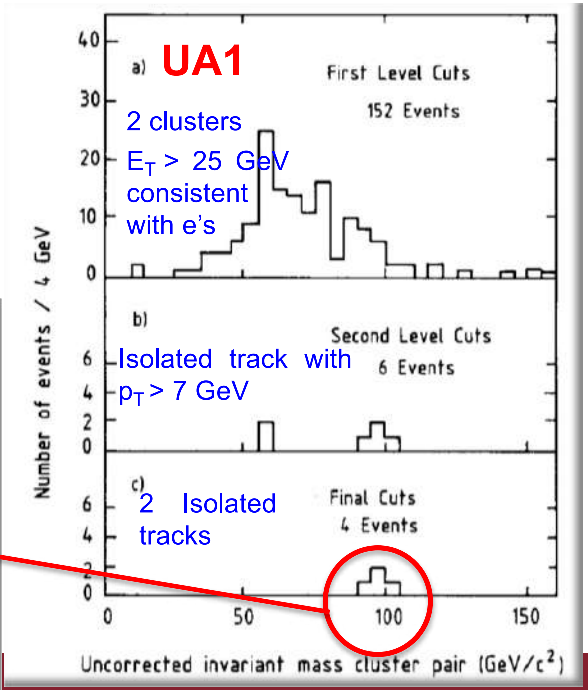
Pierre Darriulat

1983: Z discovery - UA1

- 27 May: seminar at CERN by Carlo Rubbia: first Z events (e^+e^- and $\mu^+\mu^-$)
- 1 June: press conference announcing Z discovery
- 6 June: paper submitted for publication (Phys.Lett.B)








1 June 1983: CERN press conference announcing the Z discovery

The Z discovery crossed the Ocean

The New York Times

Founded in 1851

ADOLPH S. OCHS, *Publisher 1896-1935*
ARTHUR HAYS SULZBERGER, *Publisher 1935-1961*
ORVIL E. DRYFOOS, *Publisher 1961-1963*

6 June 1983

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Europe 3, U.S. Not Even Z-Zero

A team of 126 scientists at the CERN accelerator in Geneva reports proof of an important new subatomic particle, the Z-zero. The discovery carries two messages. The good news is that it confirms a major theory about the fundamental forces of nature. The bad news is that Europeans have

American physicists blame lack of Federal support. But some observers, like the President's science adviser, George Keyworth, blame the physicists for routinely spreading funds among the three major American research centers. "Our world leadership in high energy physics has been dissipated."

The New York Times

OPINION Europe 3, U.S. Not Even Z-Zero

Published: June 6, 1983

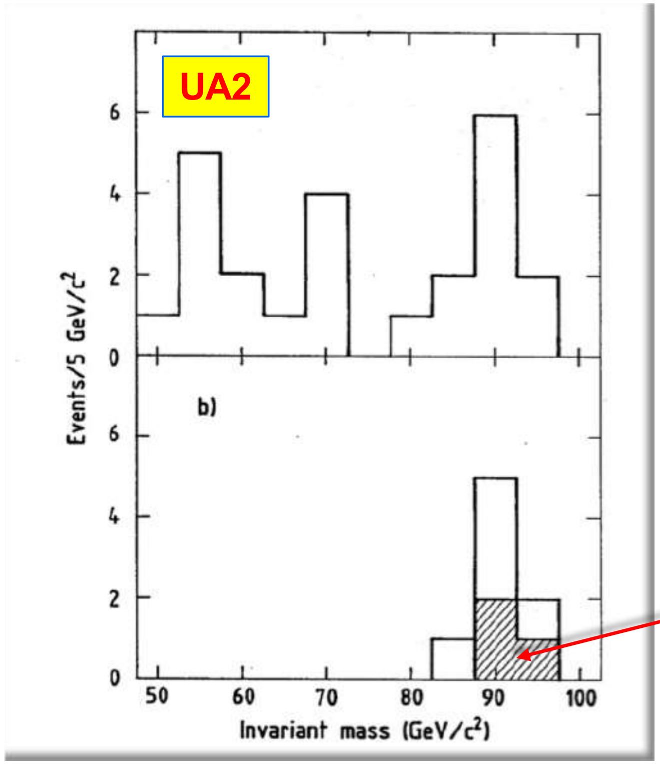
A team of 126 scientists at the CERN accelerator in Geneva reports proof of an important new subatomic particle, the Z-zero. The discovery carries two messages. The good news is that it confirms a major theory about the fundamental forces of nature. The bad news is that Europeans have taken the lead in the race to discover the ultimate building blocks of matter.

18

1983: Z discovery – UA2

7 July 1983: CERN seminar by P. Darriulat to announce Z discovery

11 August: paper submitted for publication (Phys.Lett.B)



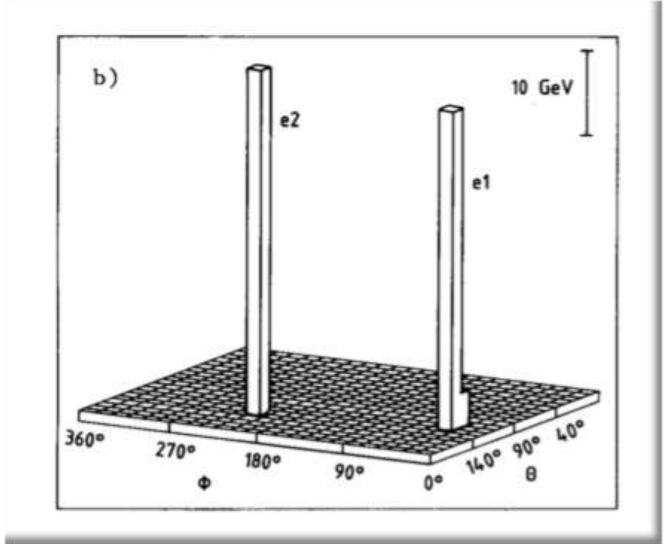
Two energy clusters with $E_T > 25$ GeV, consistent with electrons → 24 events

A track identified as an isolated electron pointing to at least one of the two clusters → 8 events

Shaded area: Tracks identified as an isolated electron pointing to both energy clusters

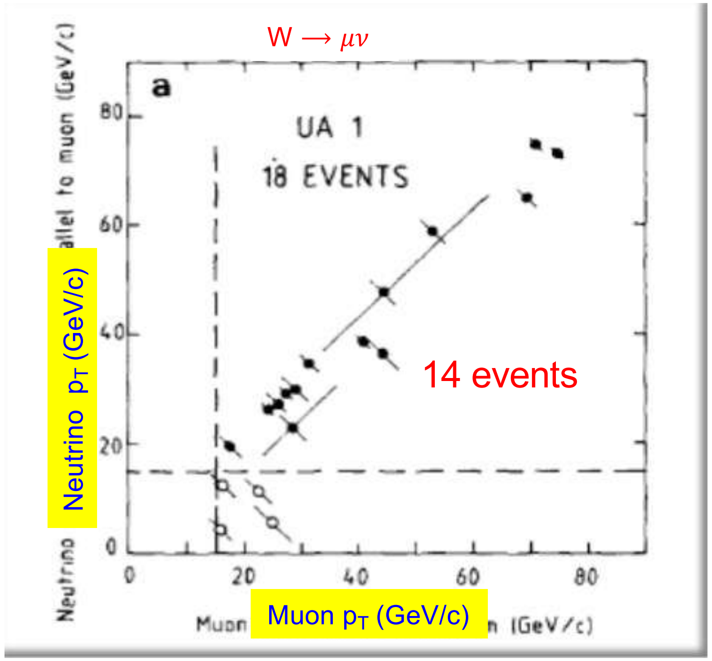
→ 3 events

UA2 Z-candidate



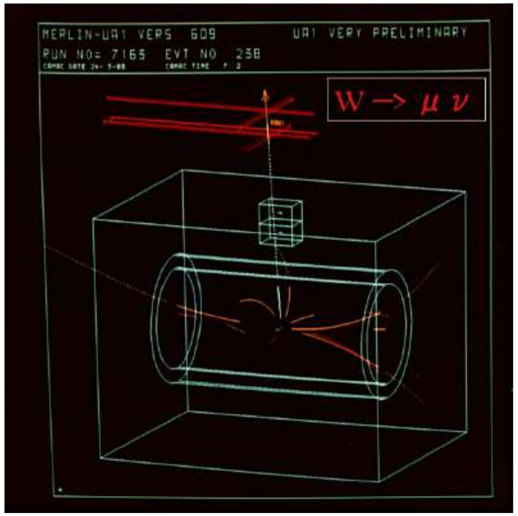
$m_Z = 90.7 \pm 2.1$ GeV/c^2

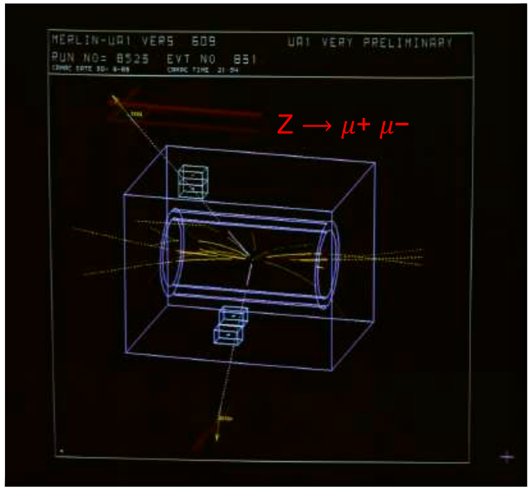
UA1: analysis of 1983 data: $W \to \mu\upsilon$; $Z \to \mu^{+}\mu^{-}$

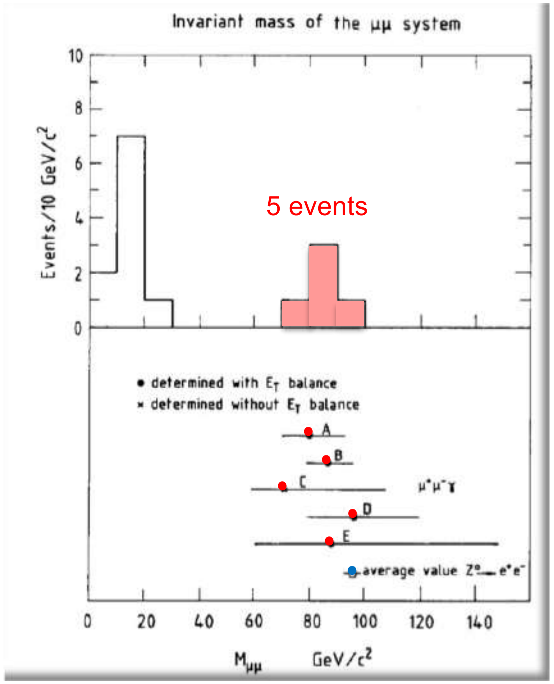


$m_W = 81\ ^{+6}_{-7}$ GeV

Compared to 43 W ⟶ e ν events







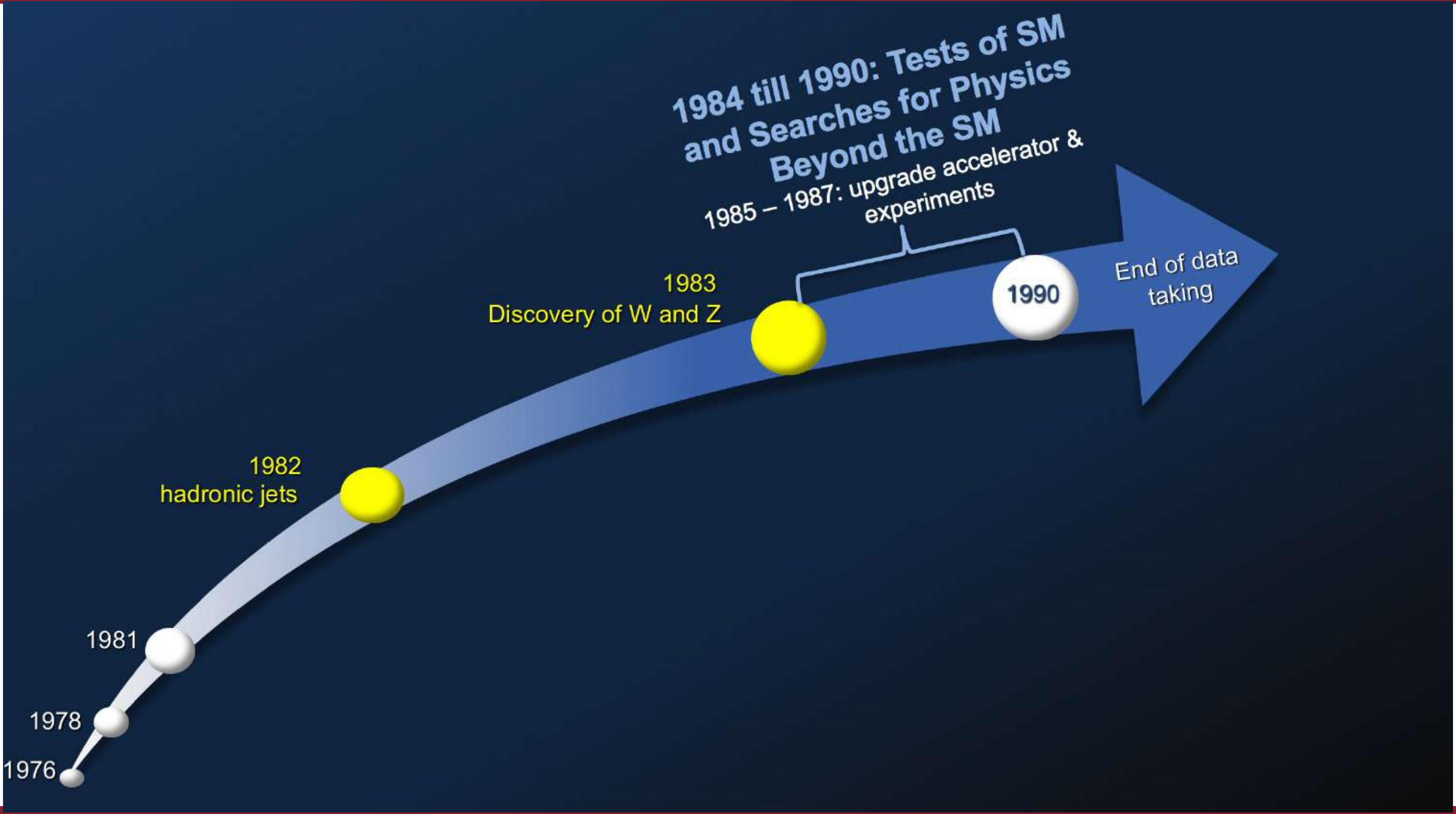
$m_Z = 85.8\ ^{+7.0}_{-5.4}$ GeV

The Rest is history

Stockholm, 10 December 1984

First row: G. Salvini, E. Picasso, A. Leveque
Second row: A. Astbury, L. DiLella, **C. Rubbia, S. van der Meer,**
P. Darriulat, A. Kernan, D. Cline, B. Aubert

Timeline



1984 till 1990: Tests of SM and Searches for Physics Beyond the SM

1985 – 1987: upgrade accelerator & experiments

1976

1978

1981

1982
hadronic jets

1983
Discovery of W and Z

1990

End of data taking

SAPIENZA
UNIVERSITÀ DI ROMA

End of chapter 4