Collider Particle Physics
- Chapter 4 -

SppS: discovery of the W and Z

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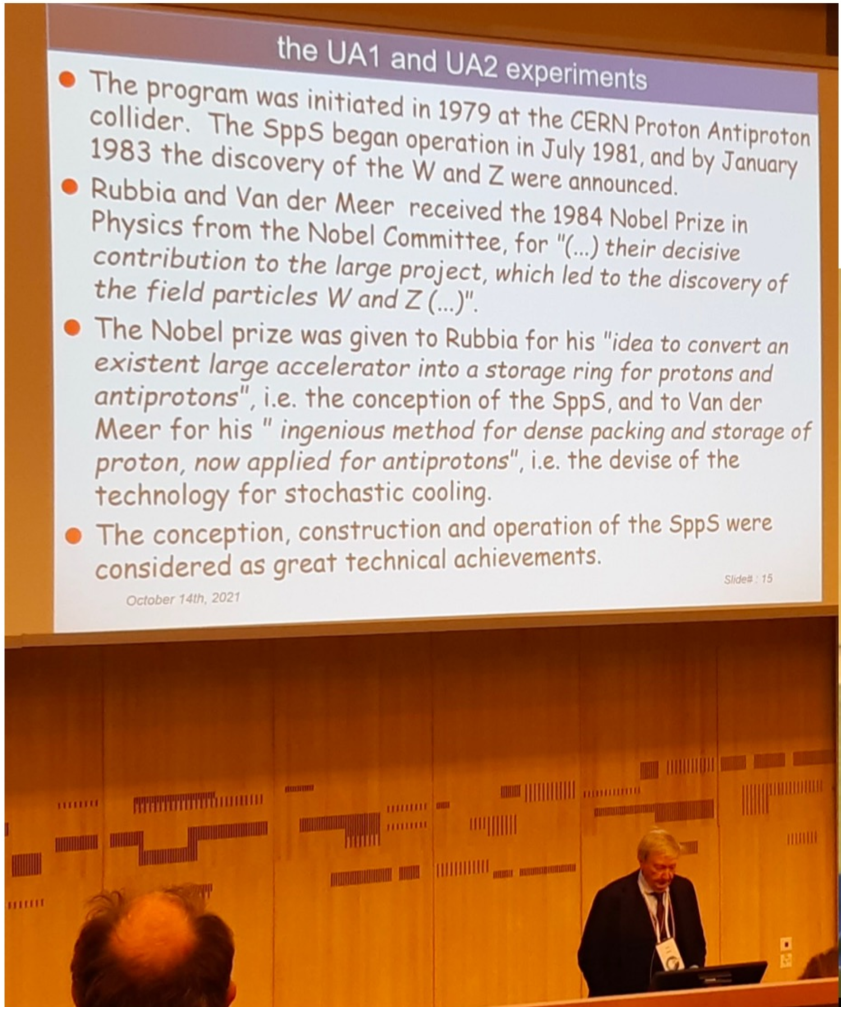
Chapter Summary

- 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



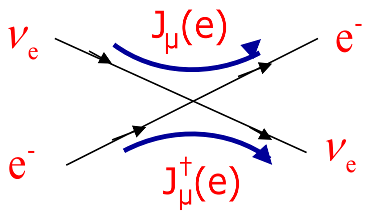
14/10/2021 – 50 years of Hadron Colliders at CERN

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

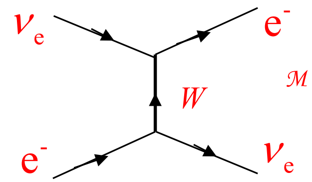
Toward the Sp$\bar{p}$s

W and Z mass prediction

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



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



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

$$\frac{G}{\sqrt{2}} = \frac{g^2}{8M_W^2} \quad \Rightarrow \quad M_W = \sqrt{\frac{g^2\sqrt{2}}{8G}}$$

- 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: $M_W = \sqrt{\frac{\frac{4\pi}{137}\sqrt{2}}{8\cdot 10^{-5}}}\cdot M_p \approx 37.4$ GeV

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

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

- **From the Standard Model we have:** $M_Z = \frac{M_W}{\cos\theta_W}$ ⇒ $M_W = 70 \div 101$ 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.

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Once upon a time in 1976 …

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

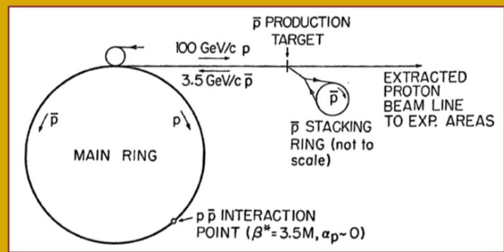
C. Rubbia and P. McIntyre
Department of Physics
Harvard University
Cambridge, Massachusetts 02138

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.



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- **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.**

Why the projet was judged unrealistic?

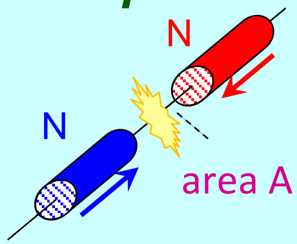
- **Center of mass energy is important … but luminosity as well !**

$$L = \frac{kN^2 f \gamma}{4\pi \beta^* \varepsilon} \cdot F$$

1. We need a lot of antiprotons
2. We need a narrow beam of antiprotons (low emittance)

$$\sigma = \sqrt{\varepsilon\beta}$$

$$\rightarrow \boldsymbol{\varepsilon\beta \approx A}$$



- **Antiprotons are difficult to produce:**

p $_{74}$W → p̄ X	$\lvert\vec{p}\rvert$ = 26 GeV	10^{13} / 2.4 s Proton on Target

→

p̄	$\lvert\vec{p}\rvert$ = 3.5 GeV	1/(10^6 p) → few × 10^9/h

- **Then the antiproton must be stored and accumulated in a storage ring. They need to have a small momentum spread before entering the ring, otherwise they could be lost during the storage and, more important, they will have a large emittance while they enter the acceleration chain.**

  - **one could select only the antiprotons with the right momentum but, in this case, their flux will be even more reduced;**
  - **or a new brilliant idea was needed to reduce the antiprotons emittance, like the discovery of the "stochastic cooling" of particles by Simon van der Meer in 1968-1972. (…** ***and the van der Meer horn*****)**

1972: stochastic cooling paper by S. van der Meer

CERN/ISR-PO/72-31

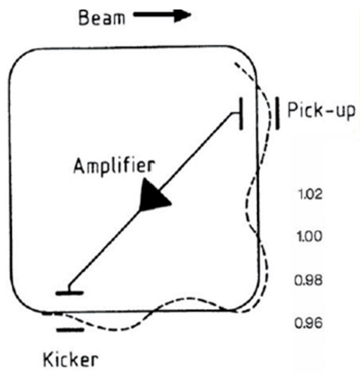
STOCHASTIC DAMPING OF BETATRON OSCILLATIONS

IN THE ISR

by

S. van der Meer

W. Schnell took the challenge and tried to implement the van der Meer proposal in the ISR.

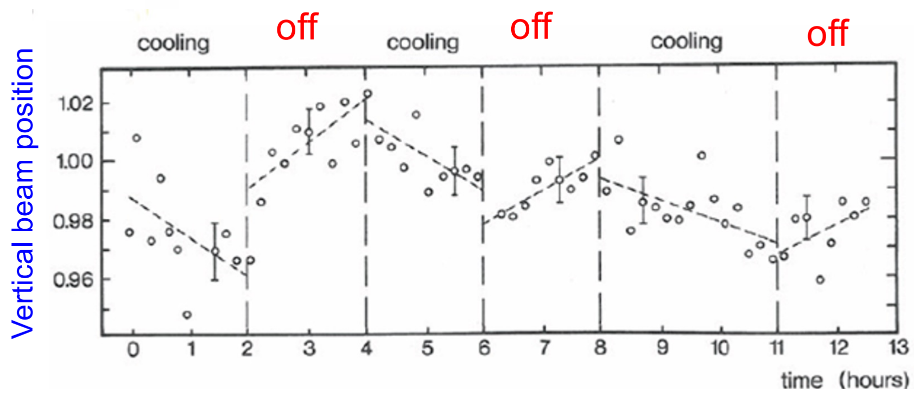


A pick-up sensor detect the fluctuation of the average position of the protons with respect to the ideal orbit and send a signal to a kicker, displaced by (n/2+1/4) wawelenghts, to push them "inside" the beam.
In average the beam is "squeezed".

4. FINAL NOTE

This work was done in 1968. The idea seemed too far-fetched at the time to justify publication. However, the fluctuations upon which the system is based were experimentally observed recently. Although it may still be unlikely that useful damping could be achieved in practice, it seems useful now to present at least some quantitative estimation of the effect.

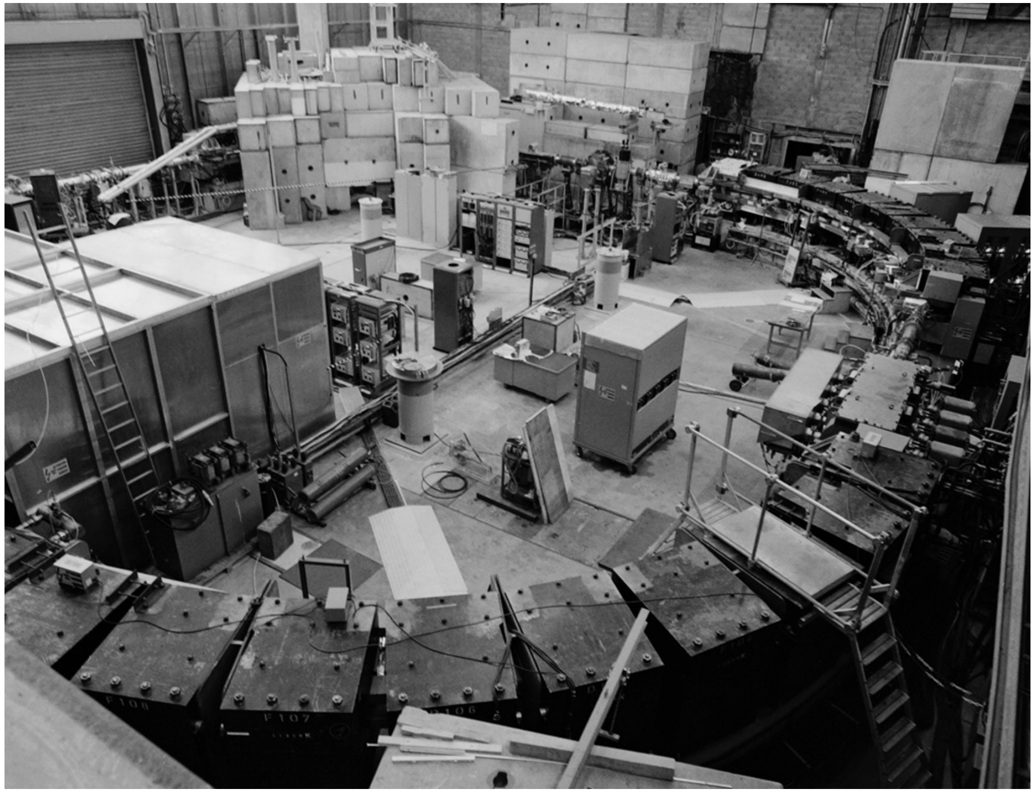
In 1918 W. Schottky described the spontaneous fluctuations from DC electrons beam (Schottky signal)



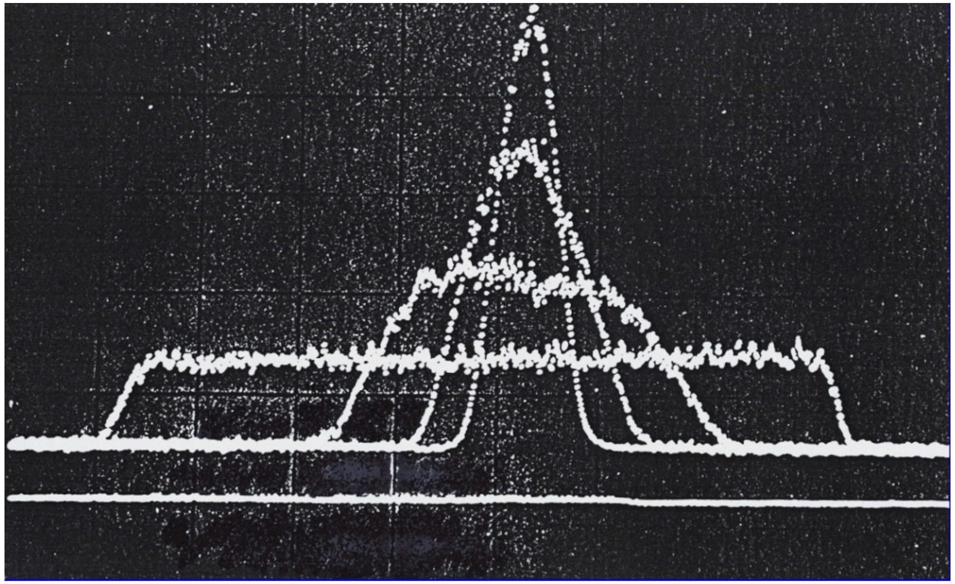
The cooling effect was visible

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

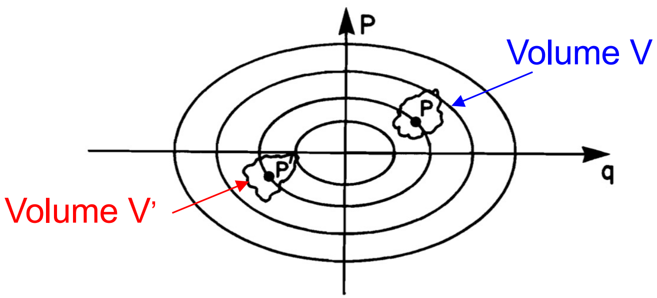


Schottky scan after 1, 2 and 4 minutes.

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

Stochastic cooling and Liouville's theorem

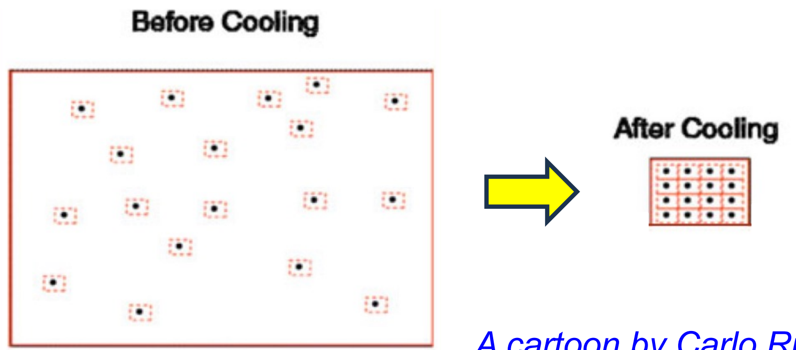
- Wikipedia: "**Liouville's theorem**, […] *after the French mathematician Joseph Liouville, is a key theorem in classical statistical and Hamiltonian mechanics. It asserts that the phase-space distribution function is costant along the trajectories of the system.*"



- All points in the volume V' around P' go in some points in the volume V around P during the evolution of the system. The two volumes V' and V are identical.

- The cooling of the antiprotons seems to be in "conflict" with the theorem, because a sqeeze in transverse momentum should result in an increase in space dimensions, therefore the beam emittance is not reduced.

- **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."*

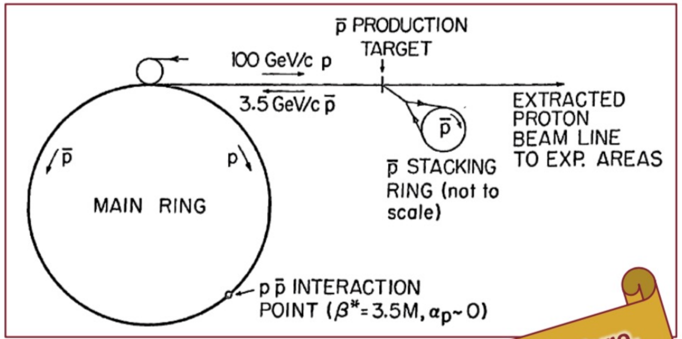


A cartoon by Carlo Rubbia.

- **The point is that the Liouville's theorem holds for an infinite number of points, while in a beam we have a finite number of particles.**

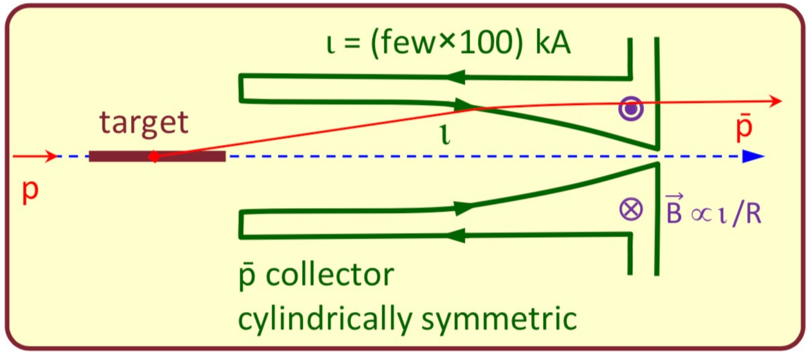
Antiproton production and collection

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 axtracted 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 $E_p = 3.5\ GeV$ from PS]

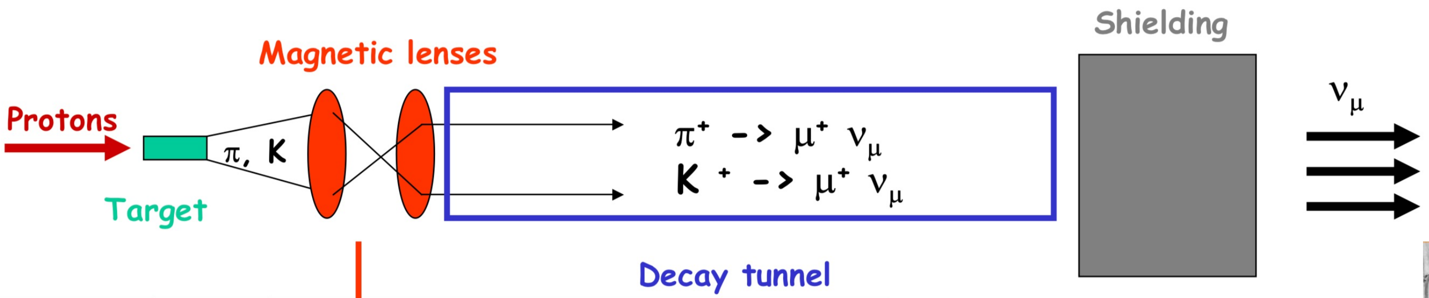


Rubbia, McIntyre, Cline op.cit.

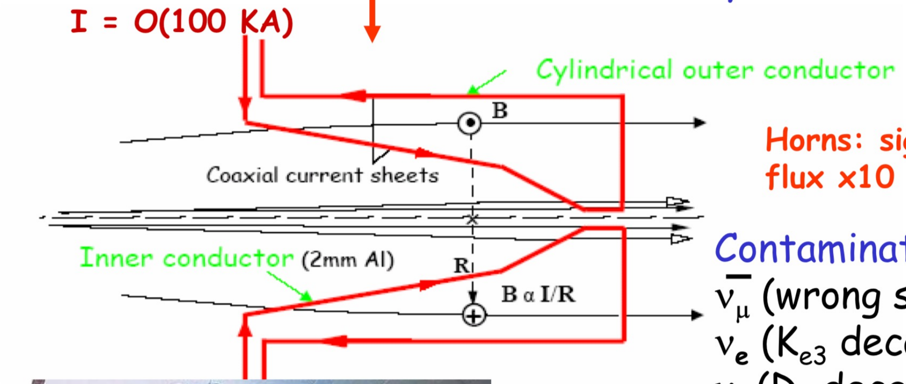
- **First step to have low emittance: reduce the $\bar{p}$ momentum spread before entering the lower Ring (Antiproton Accumulator Ring).**
  - **It was done using a new design of the Van der Meer horn:**

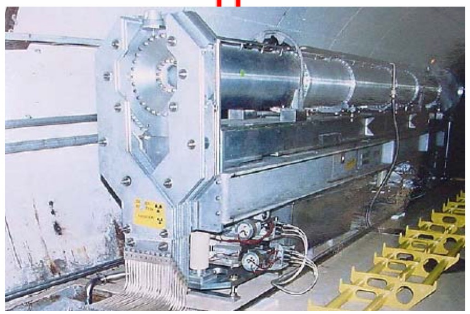


Typical high energy Wide Band neutrino beam



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





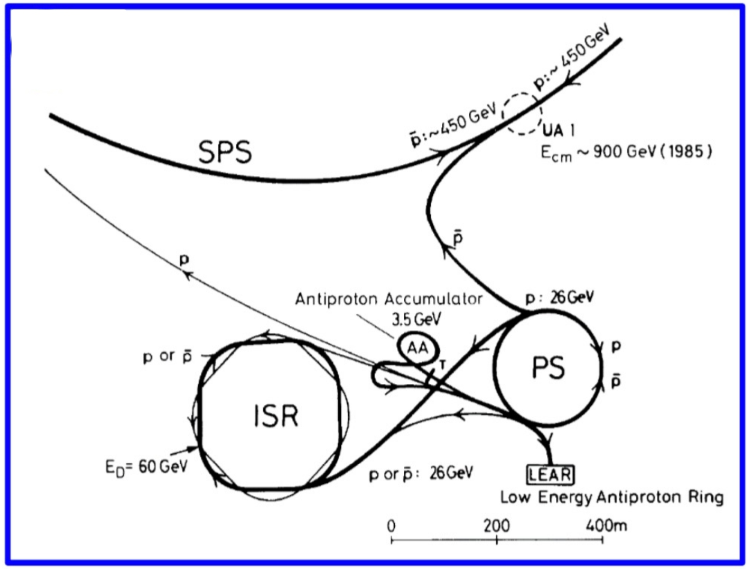
Horns: sign selection, focalization: flux x10

Contaminations:

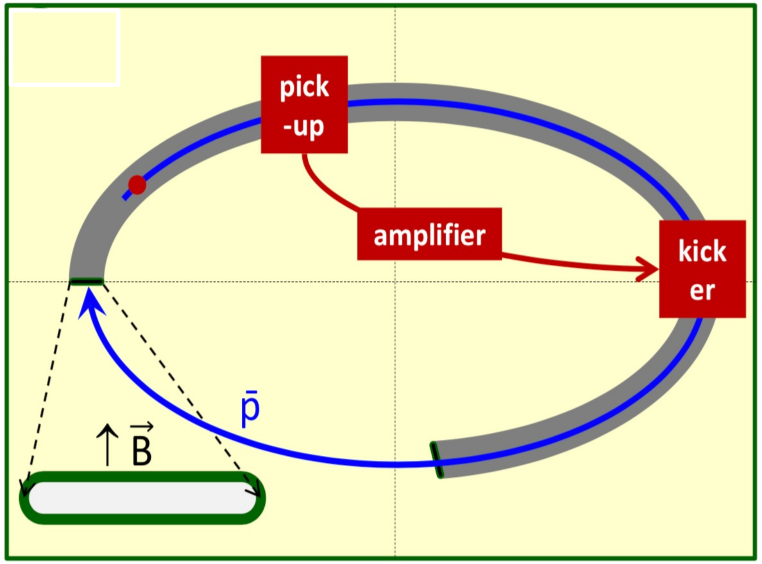
$\bar{\nu}_\mu$ (wrong sign parents)	O(5%)
ν_e (K_{e3} decays, μ decays)	O(1%)
ν_τ (D_s decays)	O(10^{-6})

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 …)

the Antiproton Accumulator ring



CERN $p\bar{p}$ complex in the '80s



- Antiprotons are stored ("stacked") in the AA ring where they are "cooled".
- After hours (days), when enough antiprotons are available, they are re-extracted and injected in the PS, where they are accelerated until 26 GeV, and then finally to SppS

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.

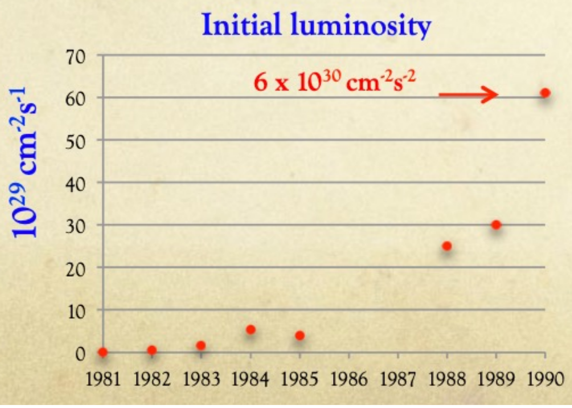
After exactly 3 year from the project approval: pits, accelerators and detectors had been completed.

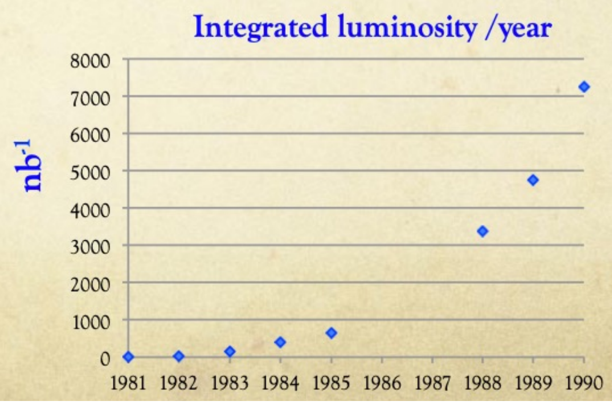
In October 1981 the tracks of charged particles from the collisions at 540 GeV c.m energy were recorded in UA1 and UA5 experiments. first events of minimum bias

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

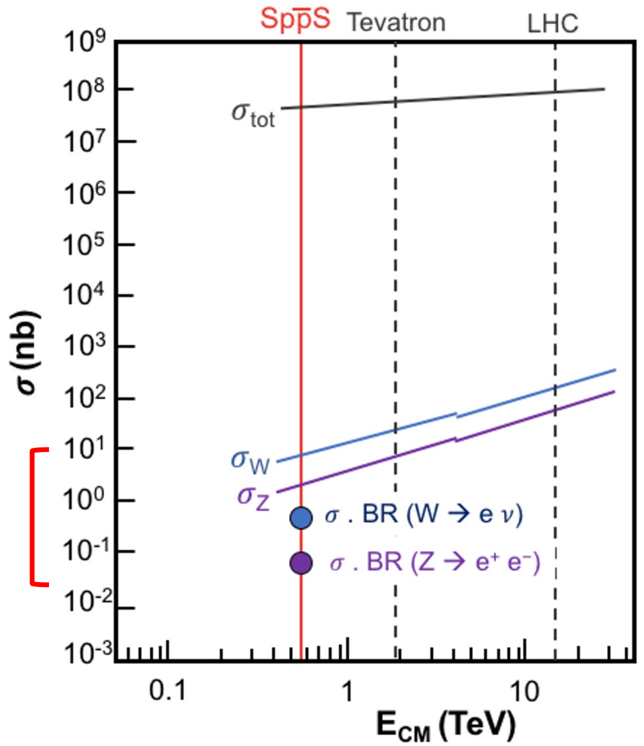
From 1988 with Antiproton Collector added to AA luminosity up to 6 x 10^{30} cm^{-2}s^{-1}





Slide from F. Lacava

Cross sections



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

S$\bar{p}$pS parameters

Slide from 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**

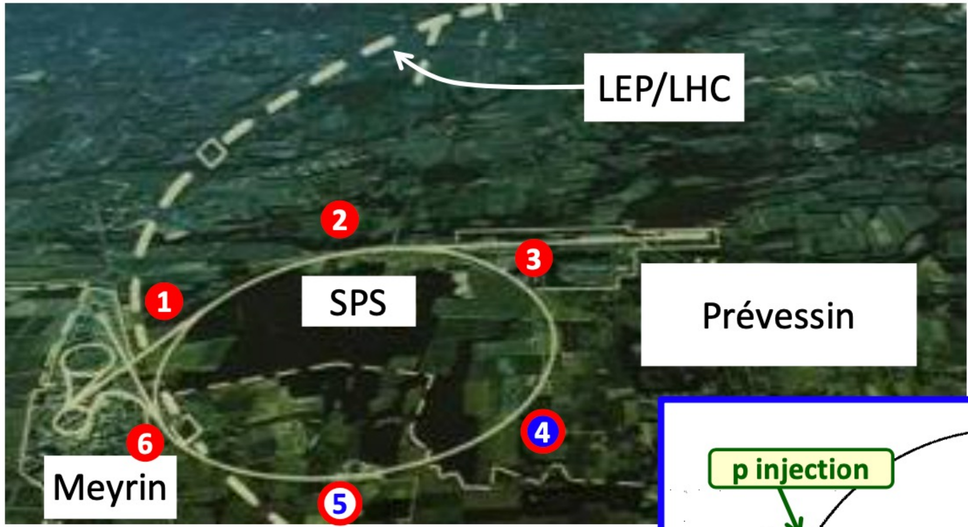
W and Z produced in 1983, the"golden year" of SppS

$\int\mathscr{L}dt$	153 nb^{-1}
$N_{events}(\bar{p}p)$	8×10^9
$W^\pm \to e^\pm\nu$	**90**
$W^\pm \to \mu^\pm\nu$ (UA1 only)	**14**
$Z \to e^+e^-$	**12**
$Z \to \mu^+\mu^-$ (UA1 only)	**4**

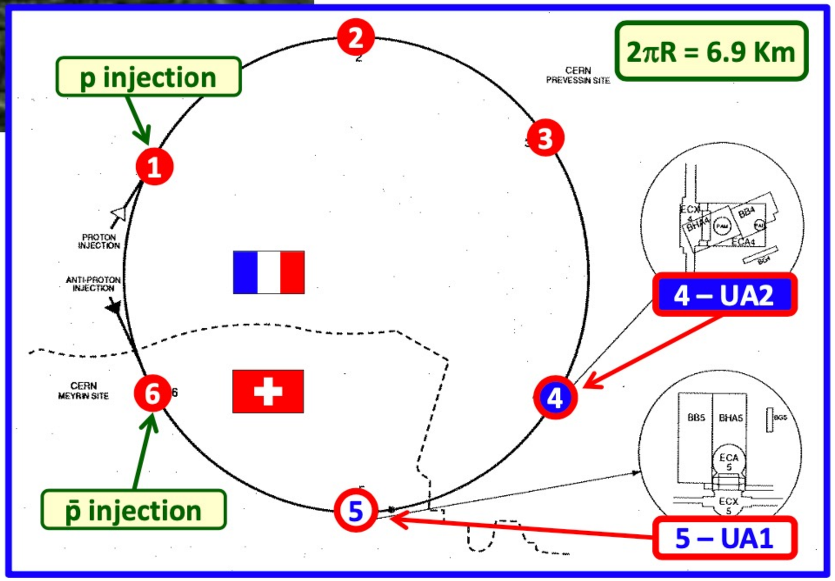
(coast = fill in the LHC language)

The detectors

The detectors



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



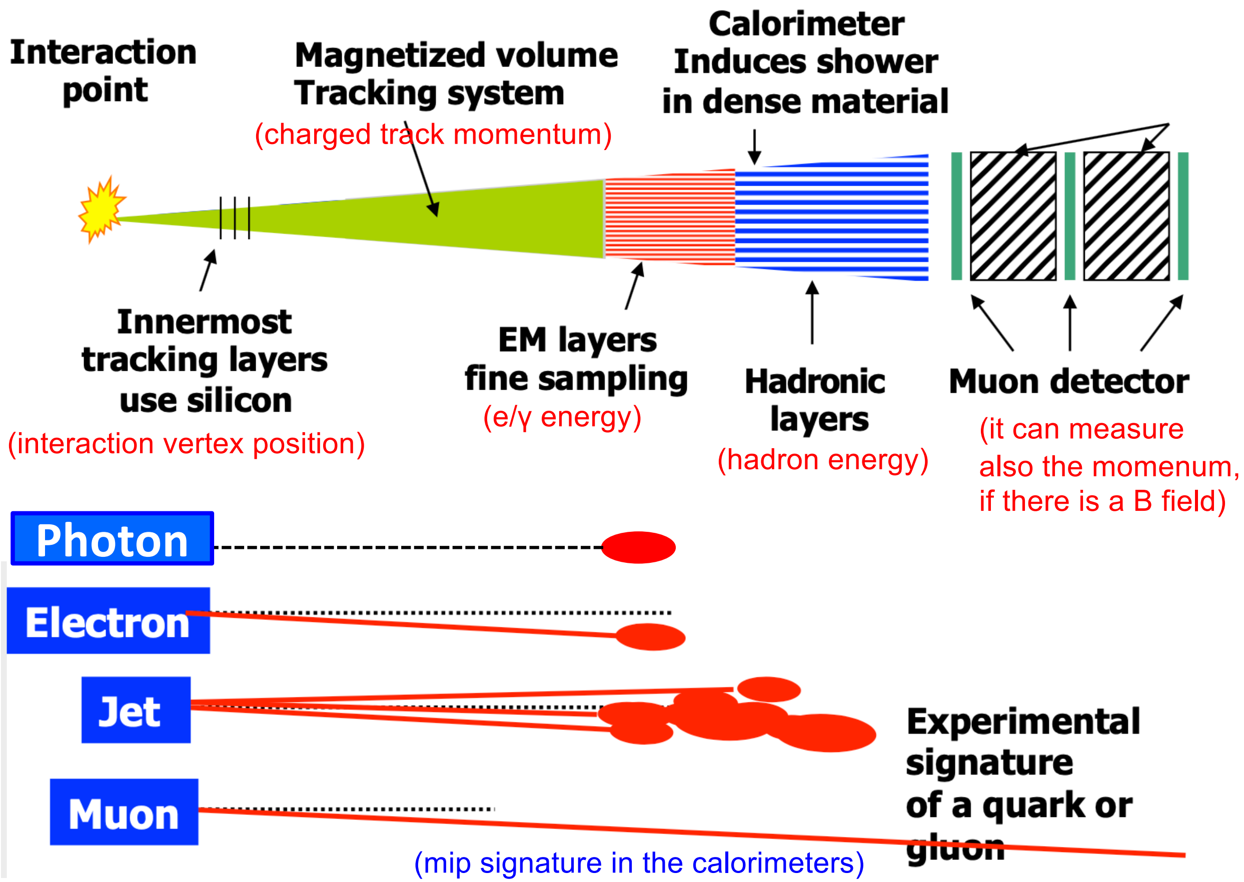
2 big experiments

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 < 1º, (a few days of data taking before UA2 was rolled into the tunnel in Nov 1981)

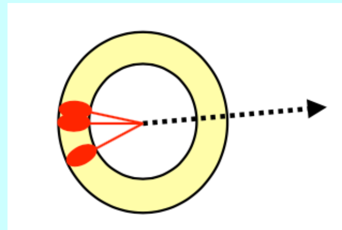
Reminder: how to detect the different type of particles

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



"Missing transverse energy"

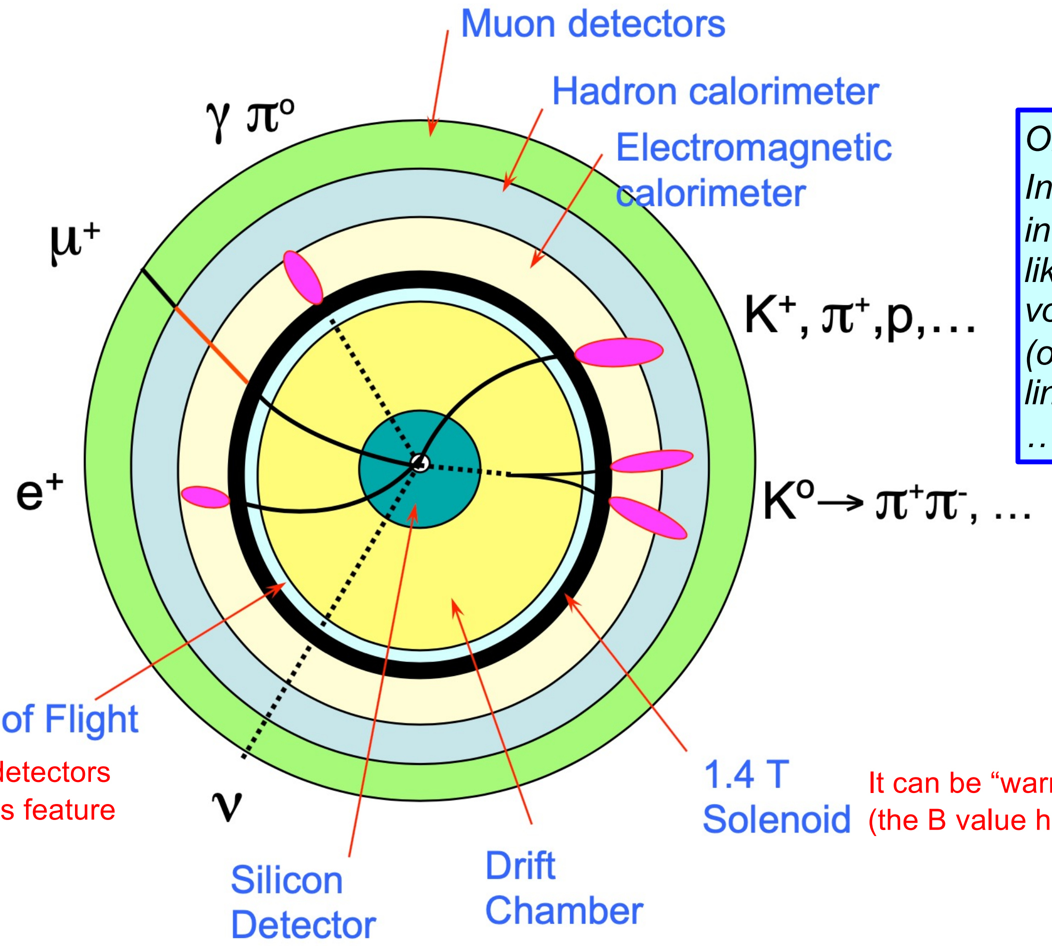
Signature of a non-interacting (or weakly interacting) particle like a neutrino



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 $W^0 \rightarrow e^+e^-$. It is also less sensitive to internal radiative corrections[61] 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.

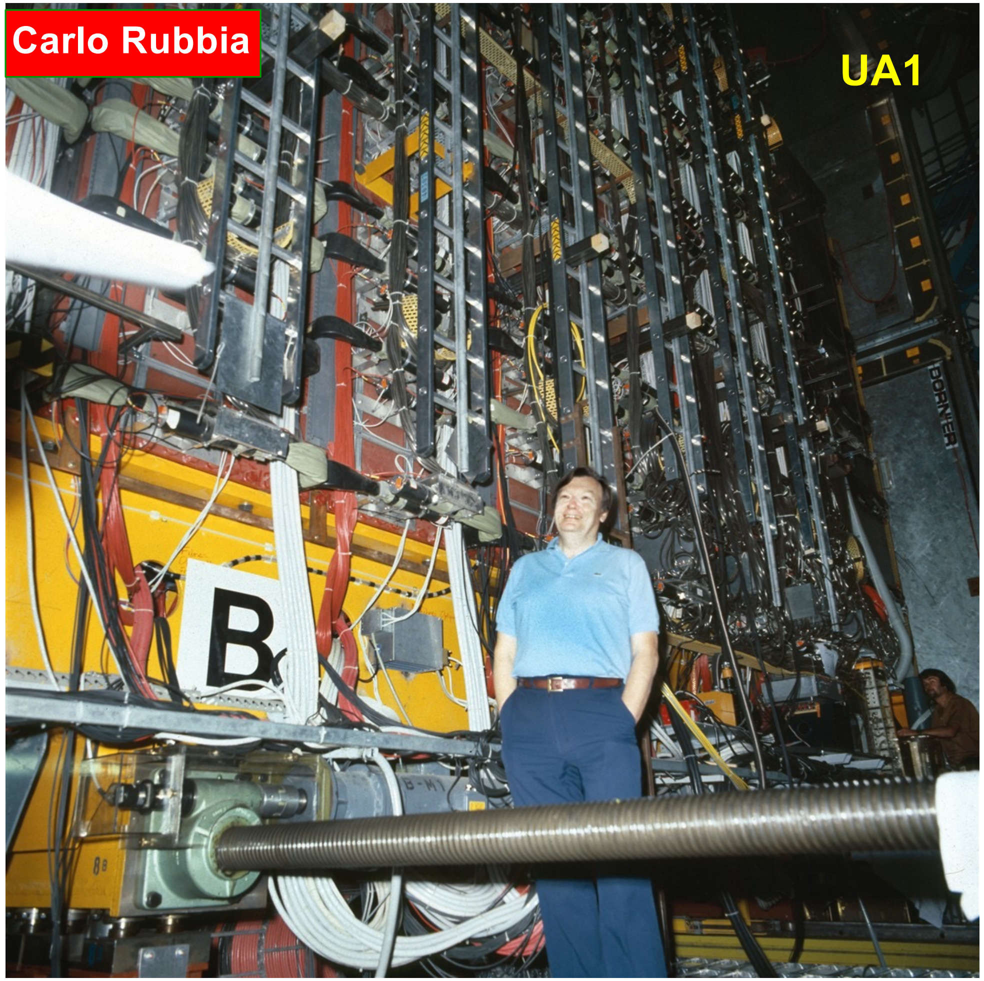
(v) The nature of our proposal is basically evolutionary and several separate elements (building blocks) are designed in such a way as to be operated almost independently and may eventually be installed in successive phases matched to the available luminosity and to the advances of civil engineering.

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

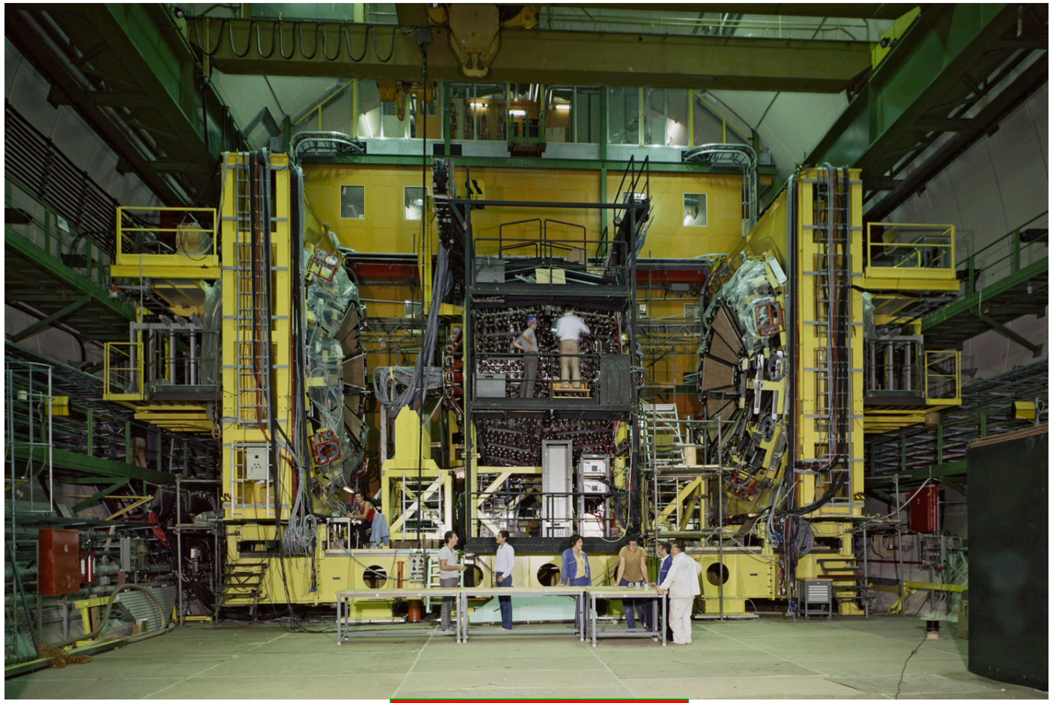
Extracted from the UA1 technical proposal

30 January 1978

The detectors



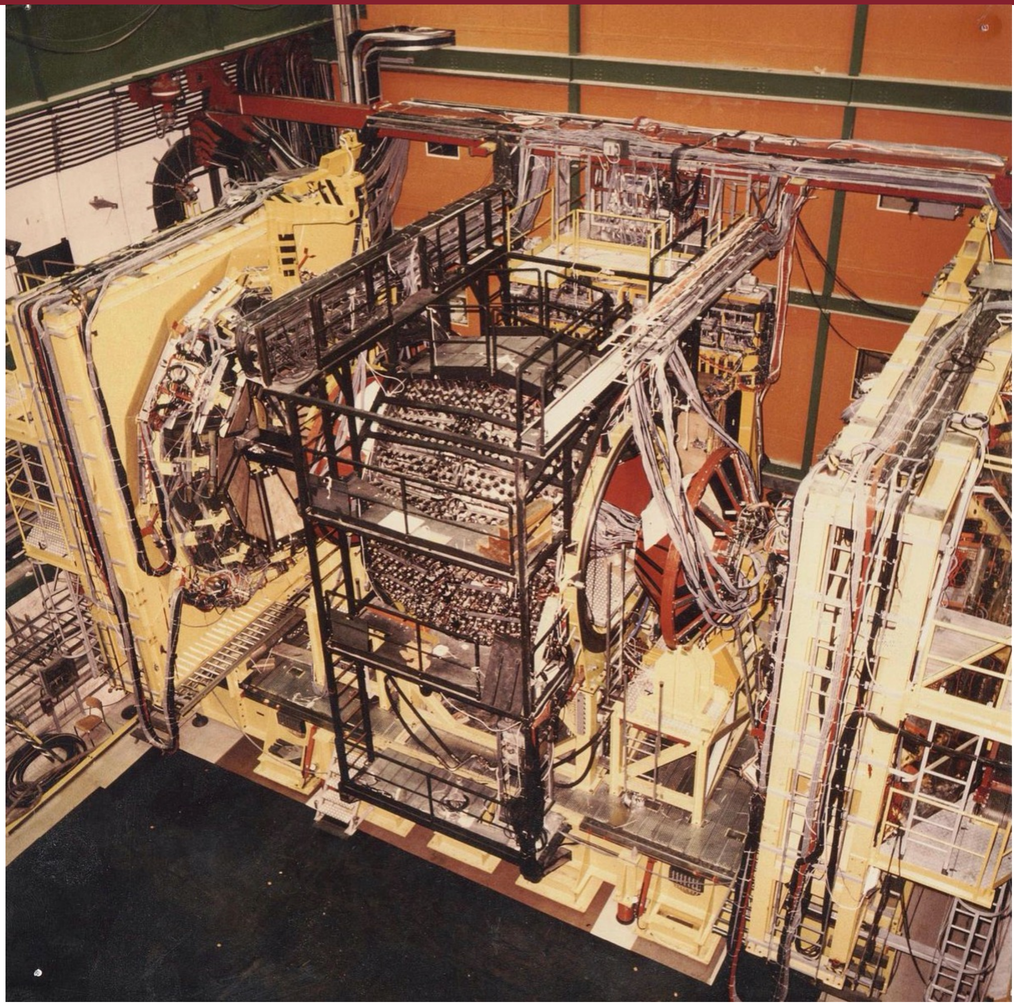
UA2



Pierre Darriulat

The detectors: UA1

The detectors: UA2

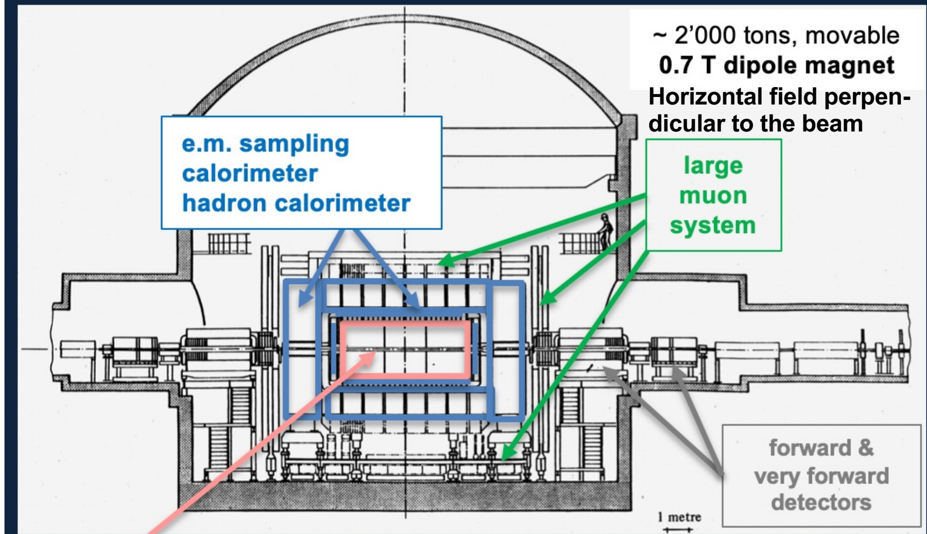


The detector in the open position

The detectors

The UA1 experiment

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

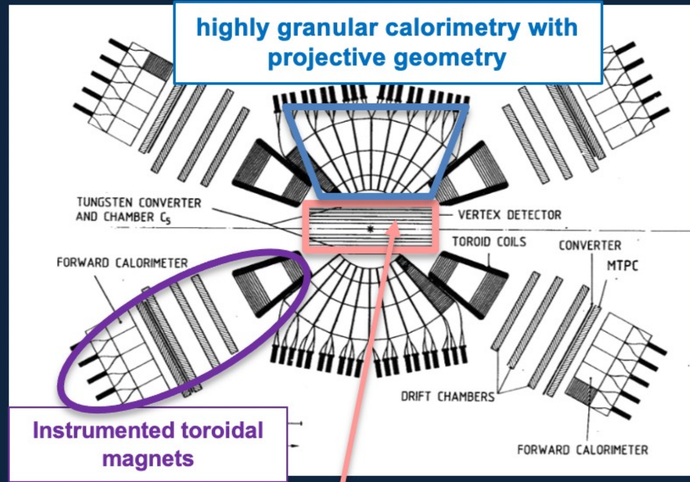


central detector: drift chamber (L=5.8 m, D=2.3 m)
cutting edge technology, the first "electronic bubble chamber"

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



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.

Slide from F. Lacava

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

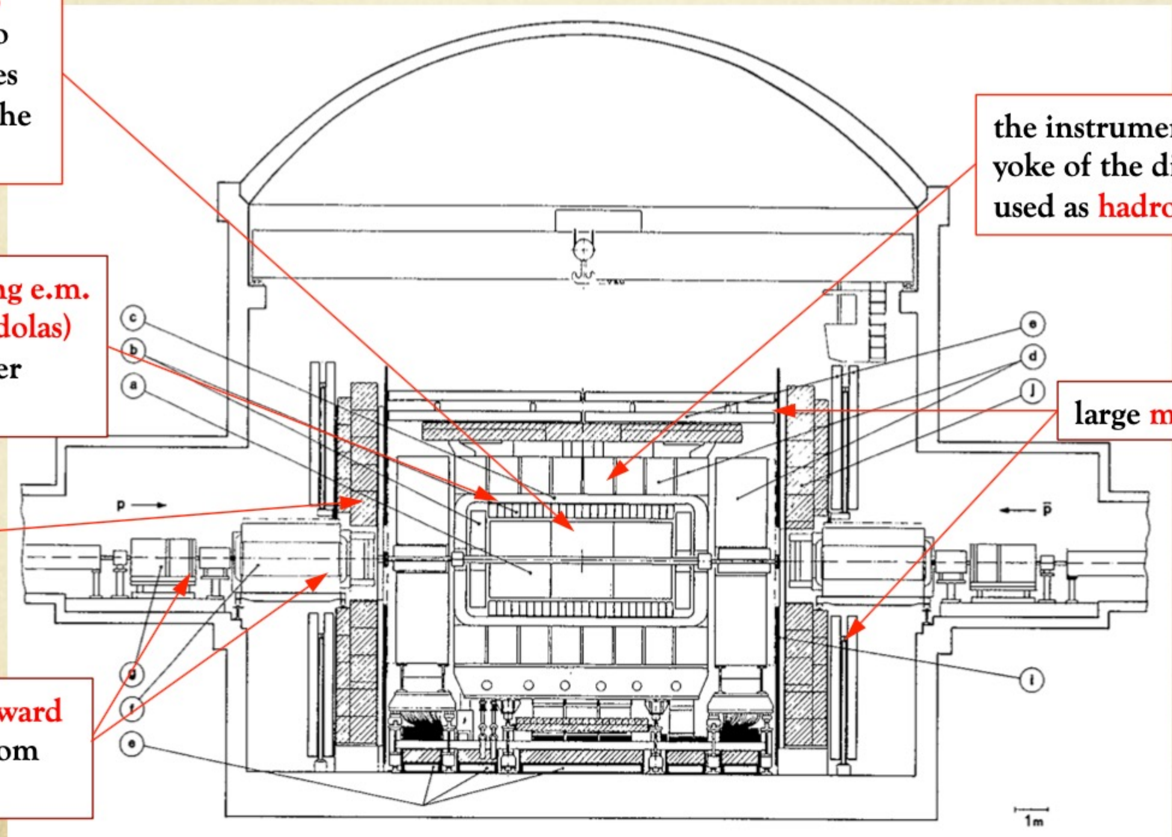
the instrumented return yoke of the dipole magnet used as hadron calorimeter

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)



7

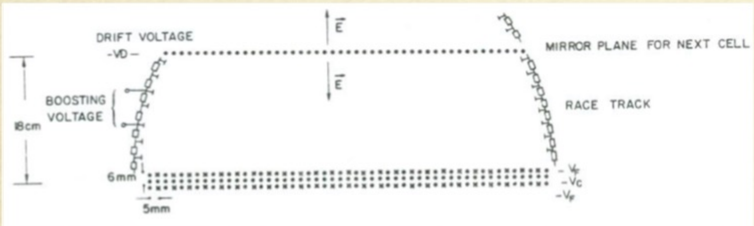
The detector: UA1 central detector

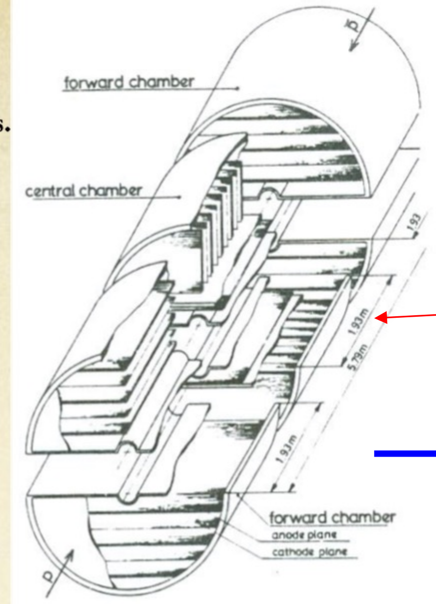
Slide from F. Lacava

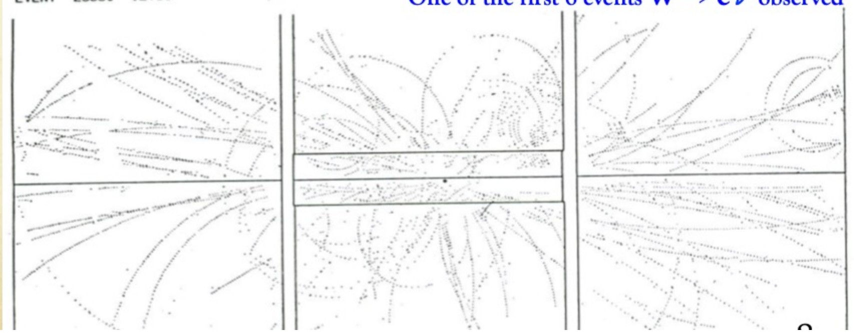
The Central Detector

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 –> e ν observed

The detectors: UA1 Calorimeters (from F. Lacava)

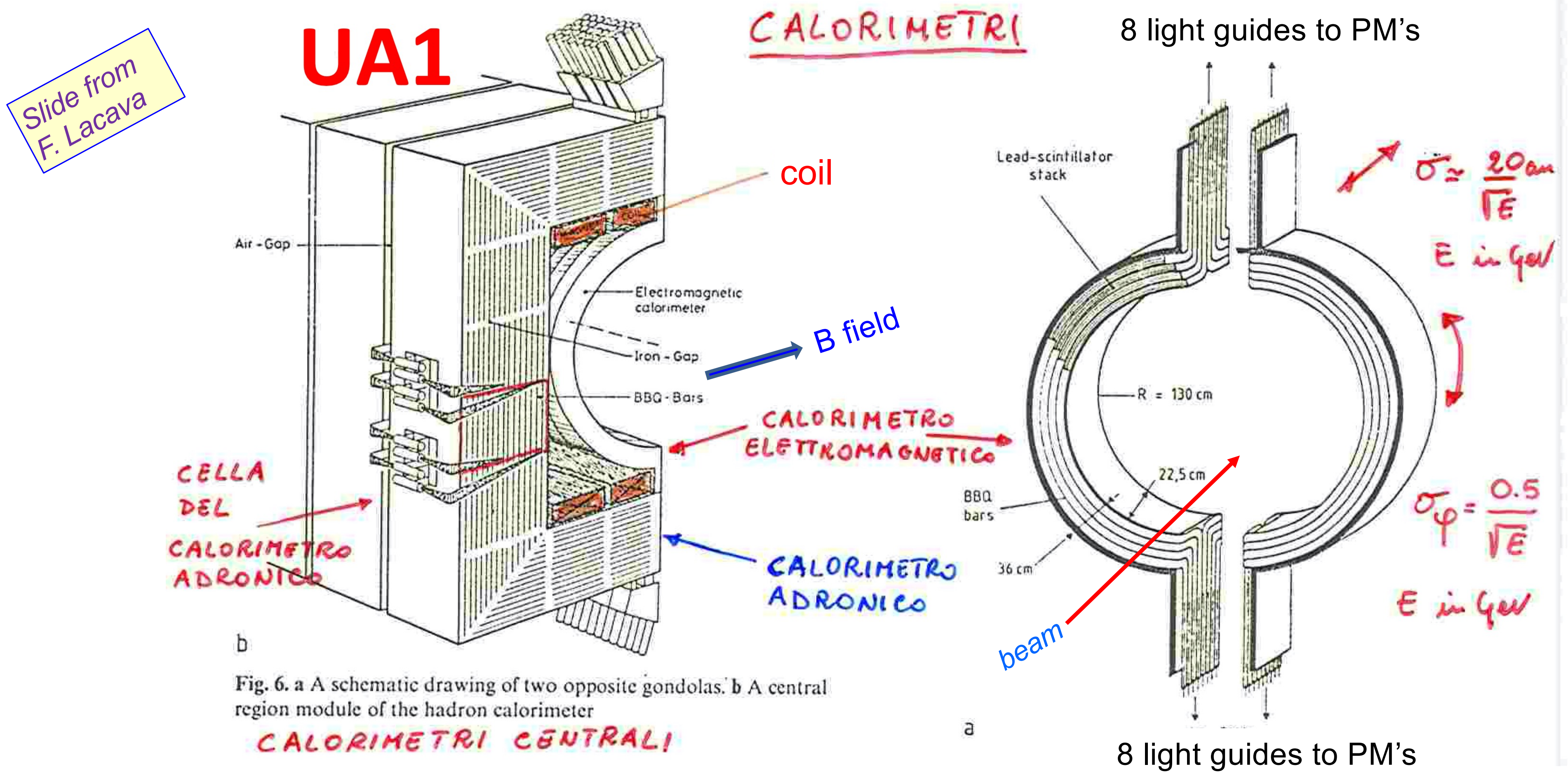


Fig. 6. a A schematic drawing of two opposite gondolas. b A central region module of the hadron calorimeter

CALORIMETRI CENTRALI

The detectors: UA1 parameters

Slide from P. Bagnaia

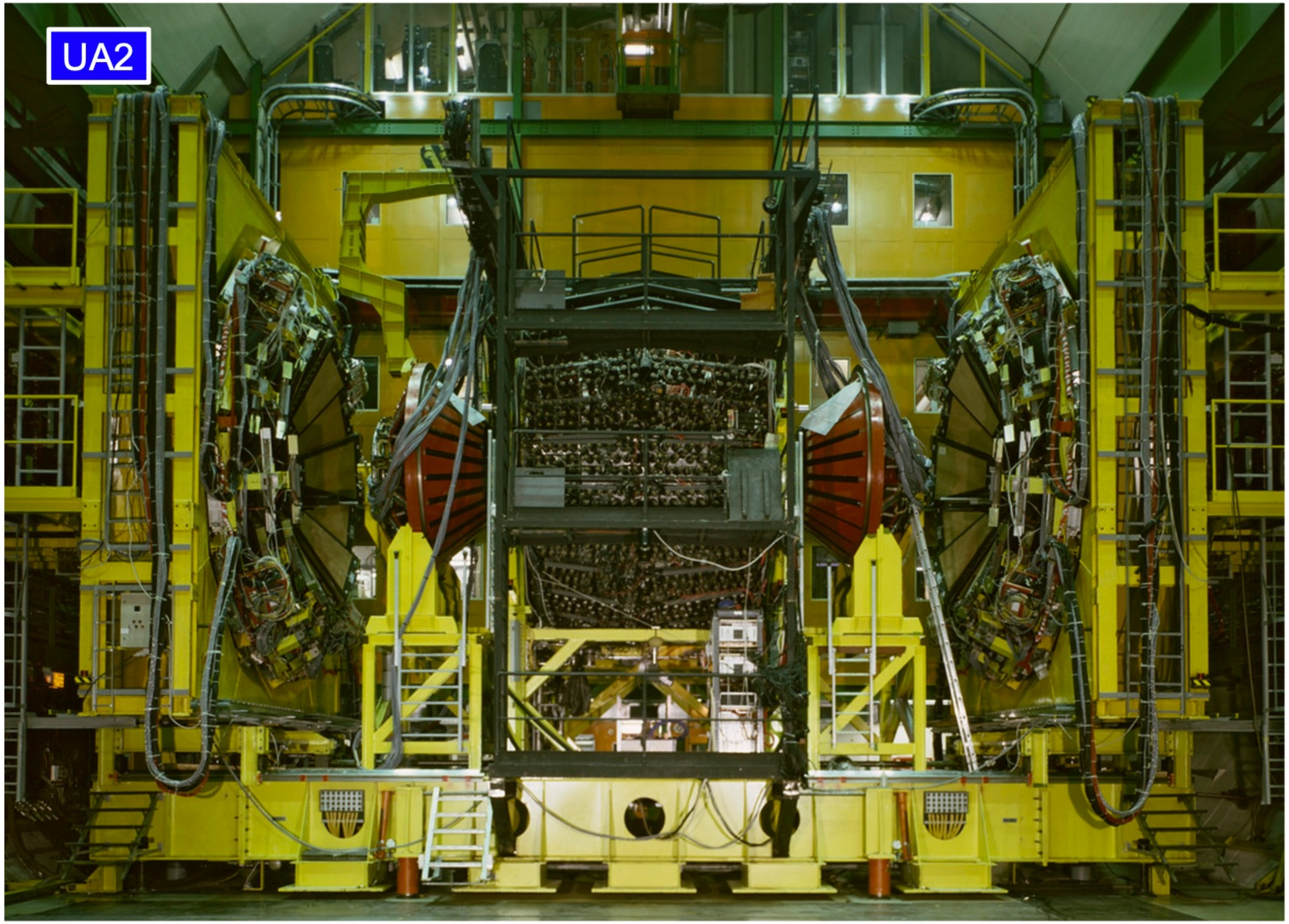
$B = 0.7$ T $\sigma(p)/p = 0.5\%$ p (GeV)

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

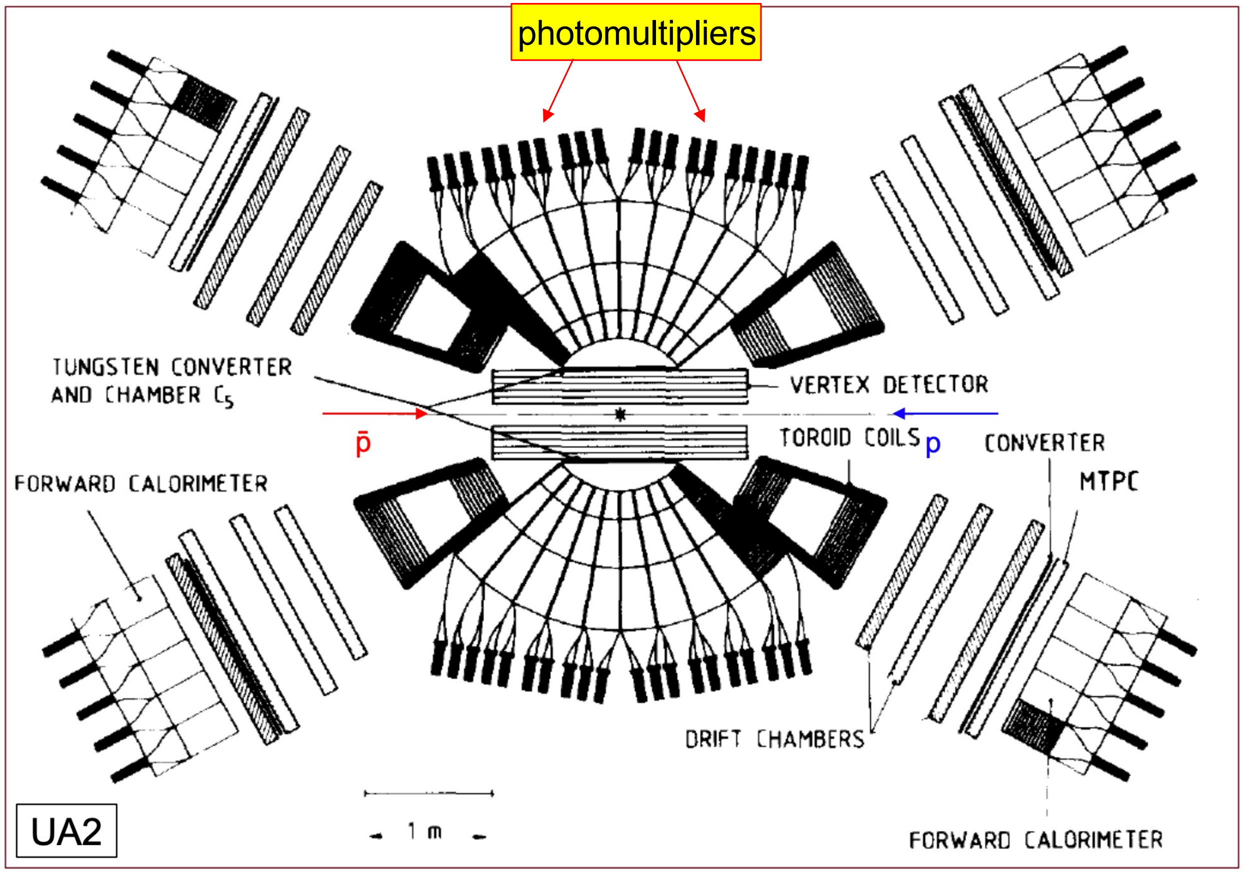
No segmentation in phi

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/sinθ	1.1/sinθ	5°×180°	0.15/√E(GeV)
		had.	C's	–	5.0/sinθ	15°×18°	0.80/√E(GeV)
Endcap calorimeter	5°–25° 155°–175°	e.m.	bouchons	27/cosθ	1.1/cosθ	20°×11°	0.12/√E(GeV)
		had.	I's	–	7.1/cosθ	5°×10°	0.80/√E(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.

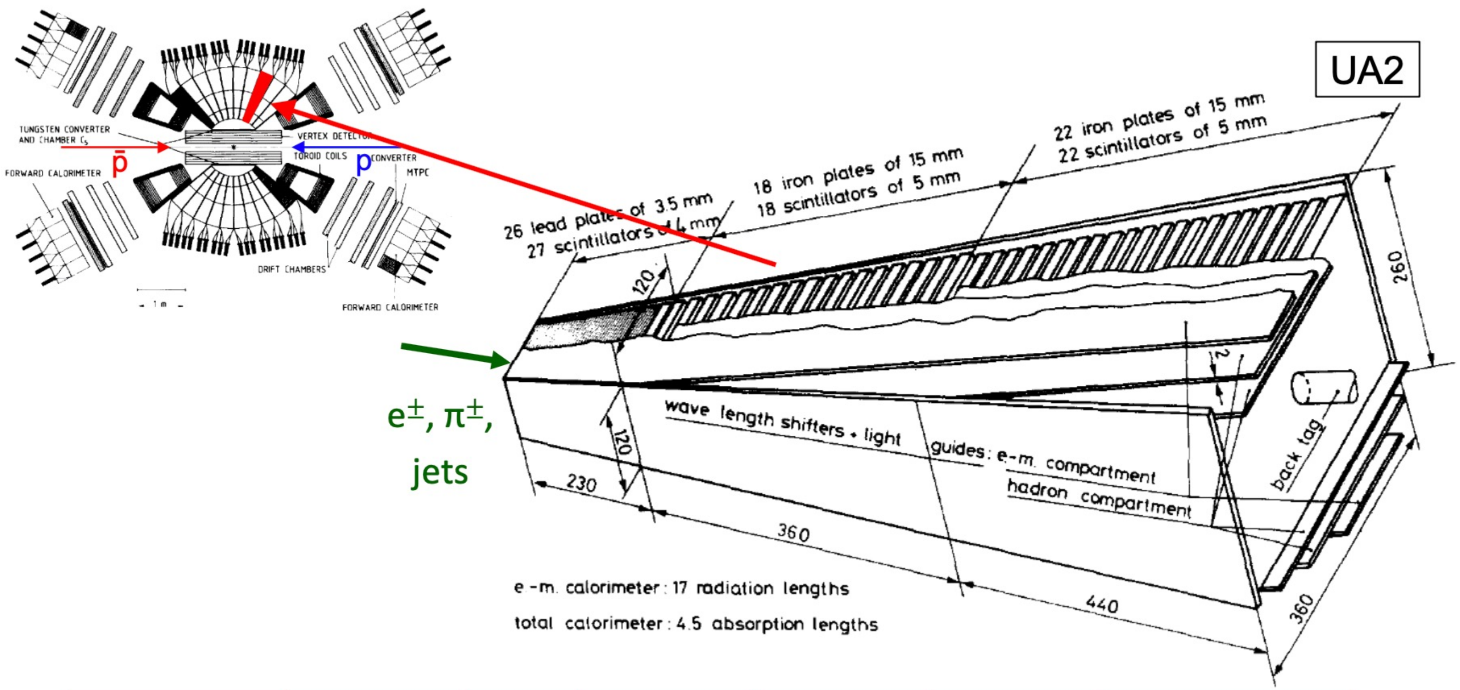
Energy measurements were performed in the calorimeters.

Magnetic field only in the forward region

Unlike UA1, UA2 had no muon detector.

The detectors: UA2 calorimeters

Slide from P. Bagnaia

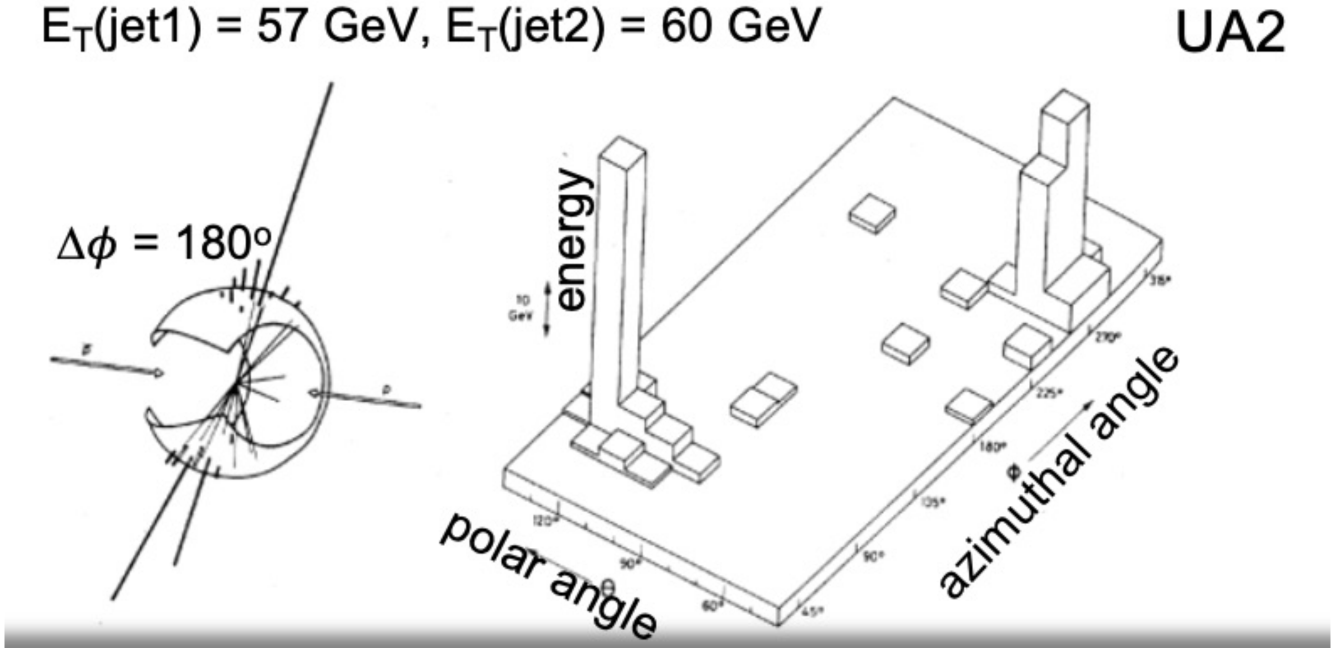


UA2 Central calorimeter	zenith θ	type	e.m. rad-length	had. abs-length	Cell Δθ×Δϕ	σ_E/E
	40°−140°	e.m.	17	~0.5	10°×15°	0.14/√E(GeV)
		had	–	2+2		32% – 11%

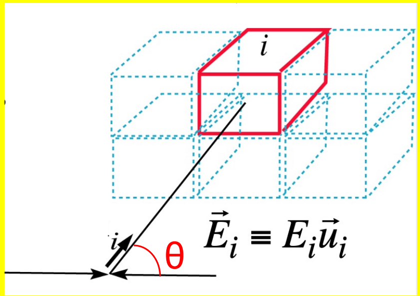
A first look at the data

The events: jets discovery

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



E_T = transverse energy

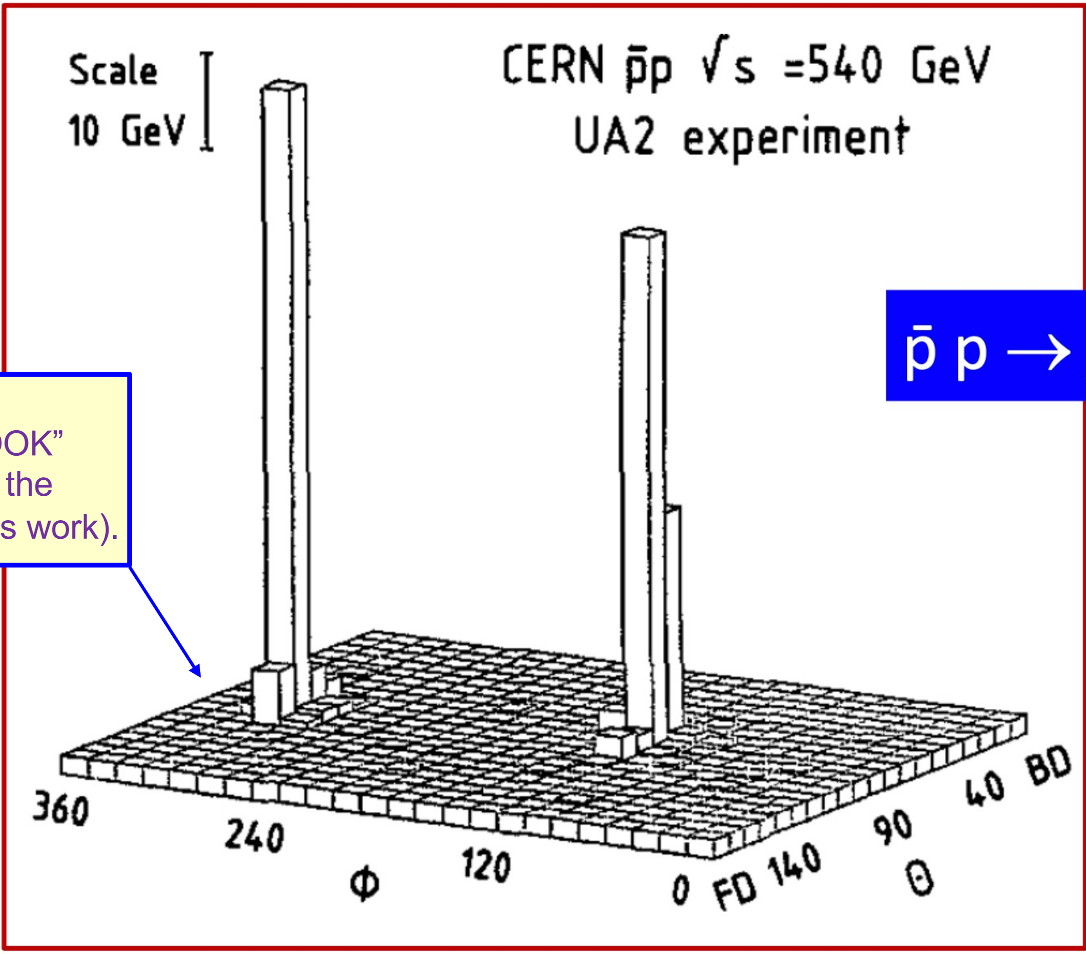


$$E_T = E \sin\theta$$

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



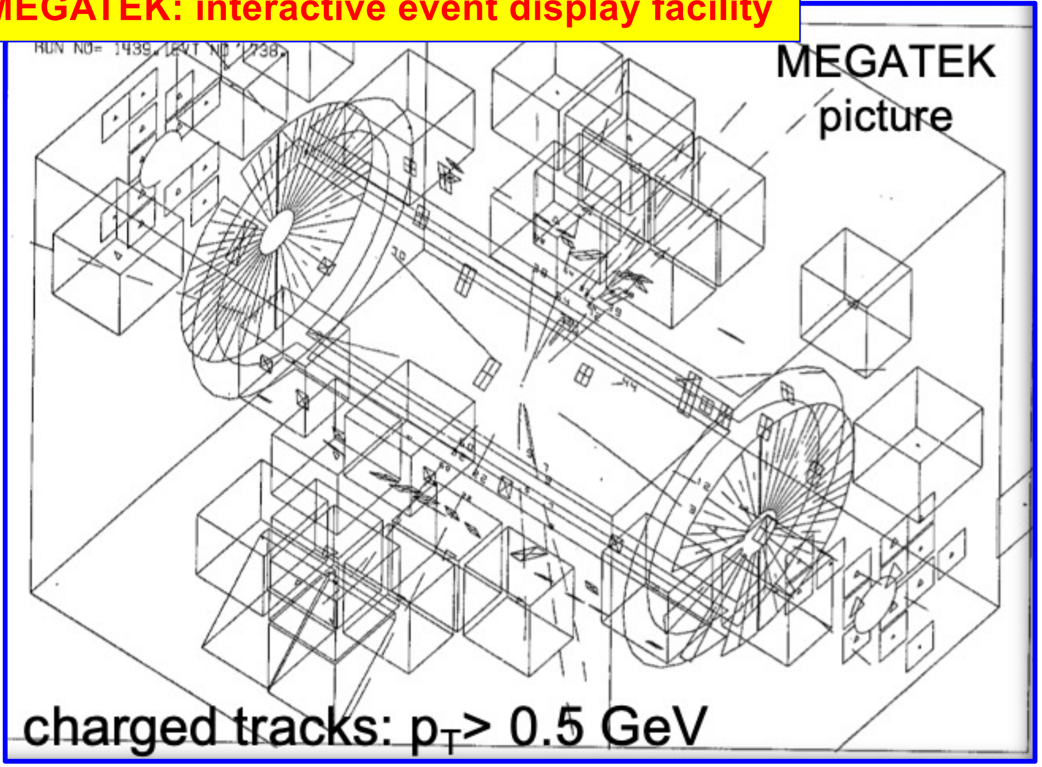
$\bar{p}\,p \rightarrow$ jet jet

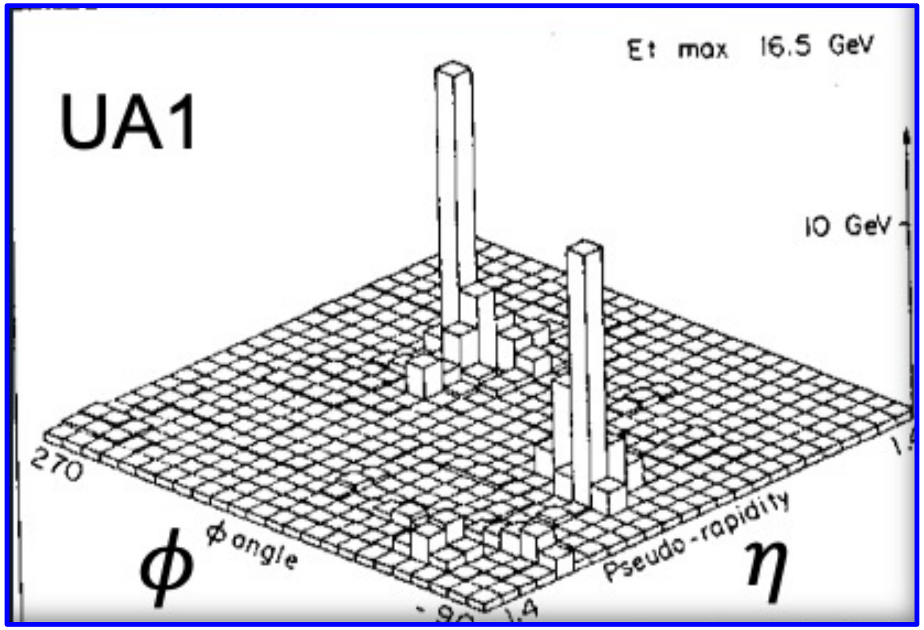
Lego plot. 2d histogram included in the tool "HBOOK" used to do histograms in the '80s (I used it in my thesis work).

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

The events: UA1 jets

MEGATEK: interactive event display facility

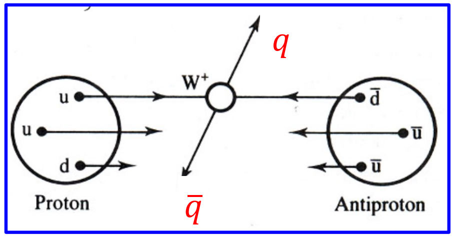




6th European Symposium: 30 August - 3 September 1982
in Santiago de Compostela, Spain
→ **celebration of collider jets**

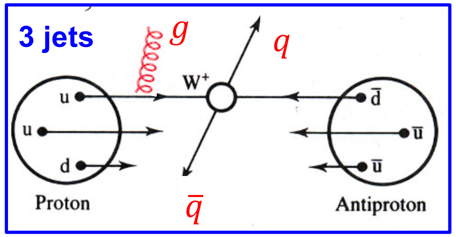
UA1: first looked at correlations of tracks in the central detector
then used tracks or cells for jet algorithm:
$R_{cone} = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$, $\eta = -\ln(\tan\theta/2)$
e.g.: $\theta=40^o \rightarrow \eta=1.0$ $\theta=5^o \rightarrow \eta=3.0$

The events: UA1 jets



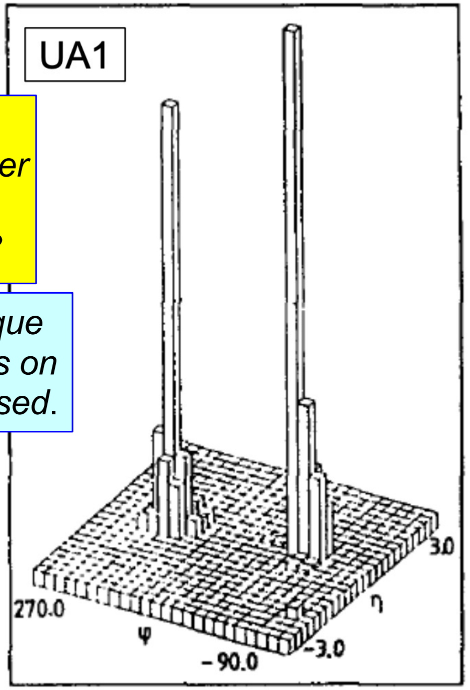
What about events with 3 and 4 jets?

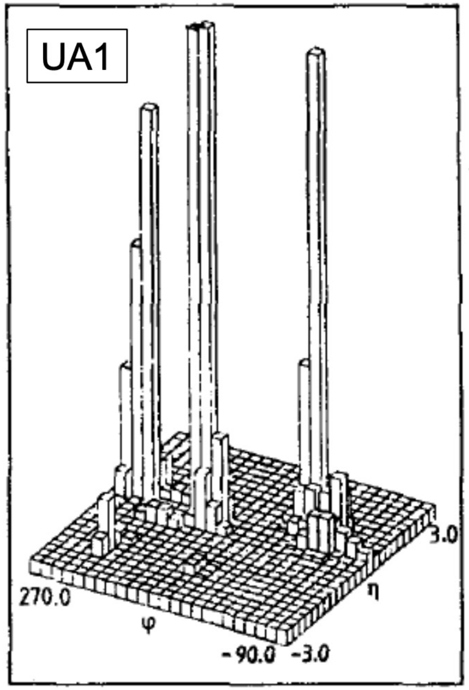
$\bar{p}p \rightarrow 2,3,4$ jets

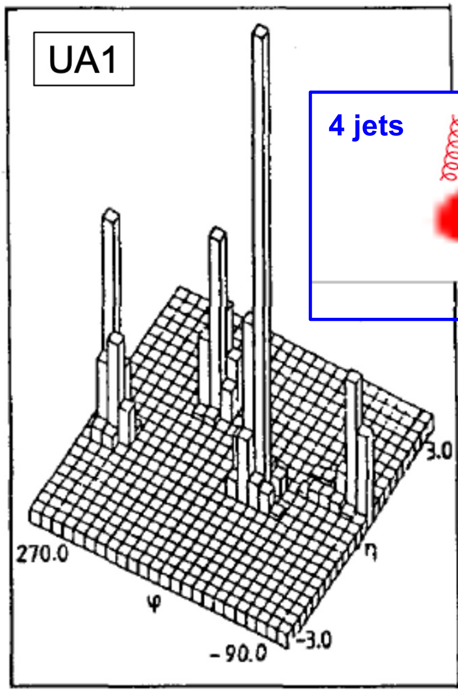


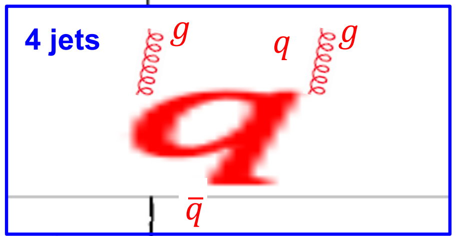
Question: *how to assign a calorimeter cell to a given jet or to another one?*

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



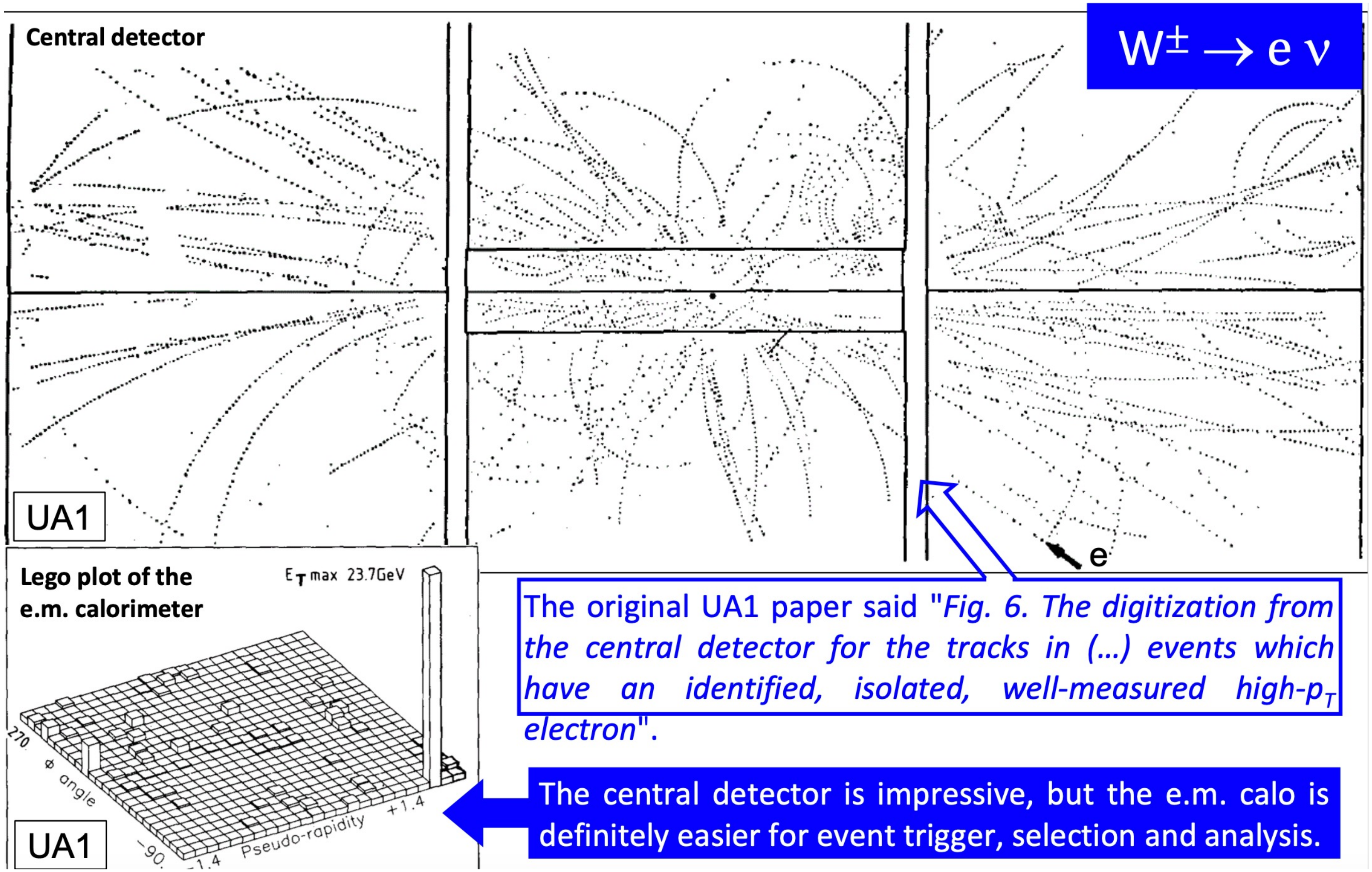






The events: UA1 $W^{\pm} \rightarrow e\nu$

Slide from P. Bagnaia



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

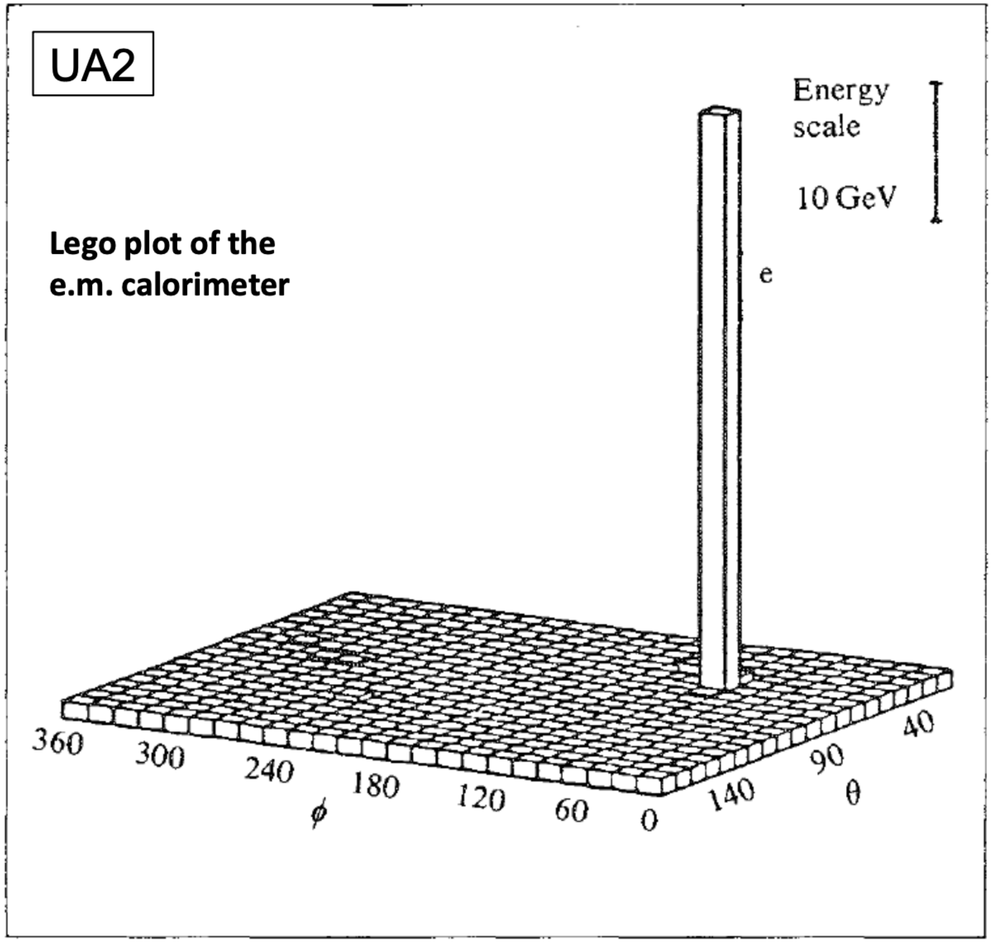
The original UA1 paper said "*Fig. 6. The digitization from the central detector for the tracks in (…) events which have an identified, isolated, well-measured high-p_T electron*".

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

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

Slide from P. Bagnaia

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

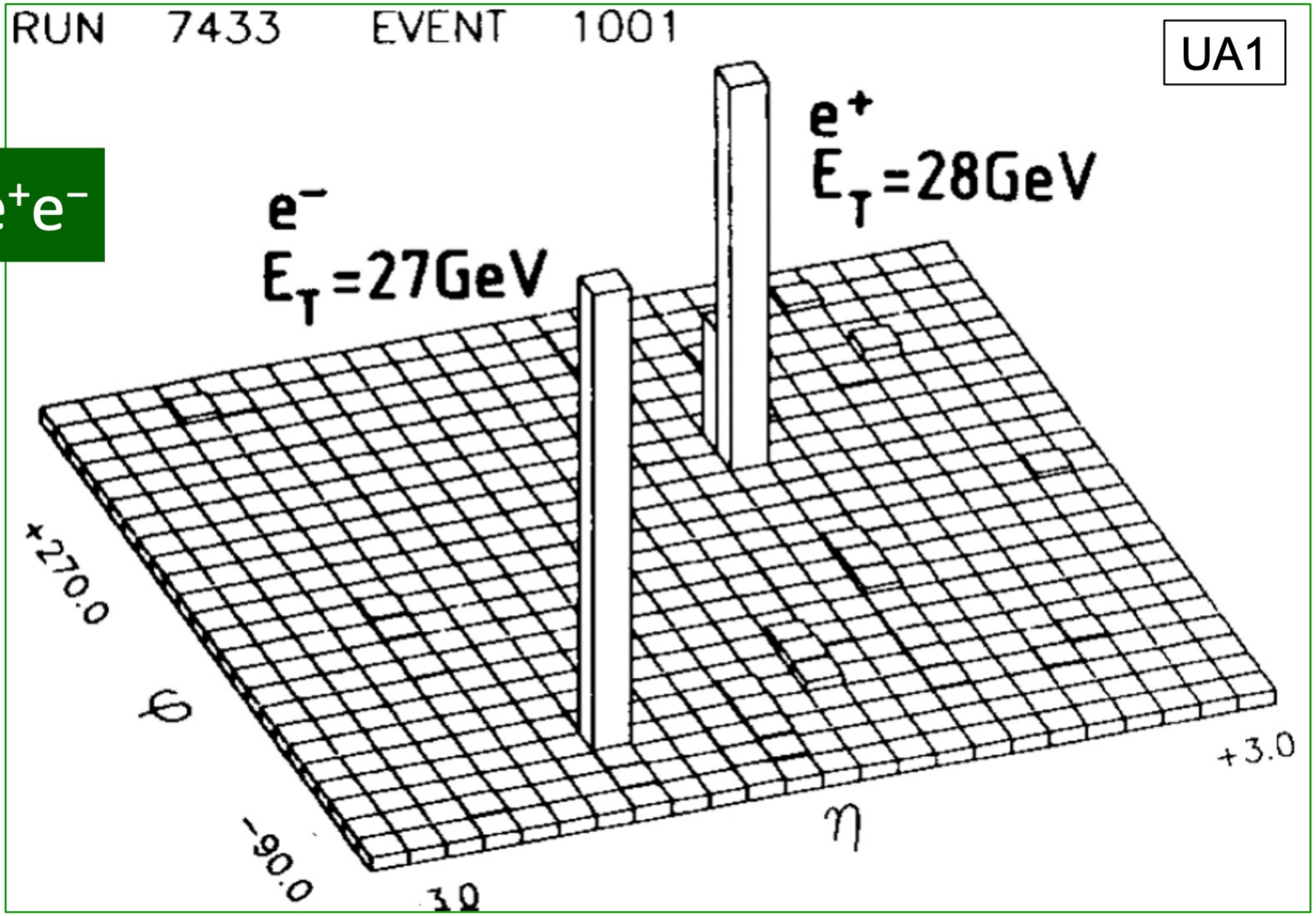


NB UA2 had a magnetic field only in the FB regions to measure $e^{\pm}$ asymmetry; in the central region, $e^{+} \leftrightarrow e^{-}$ were ambiguous.

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

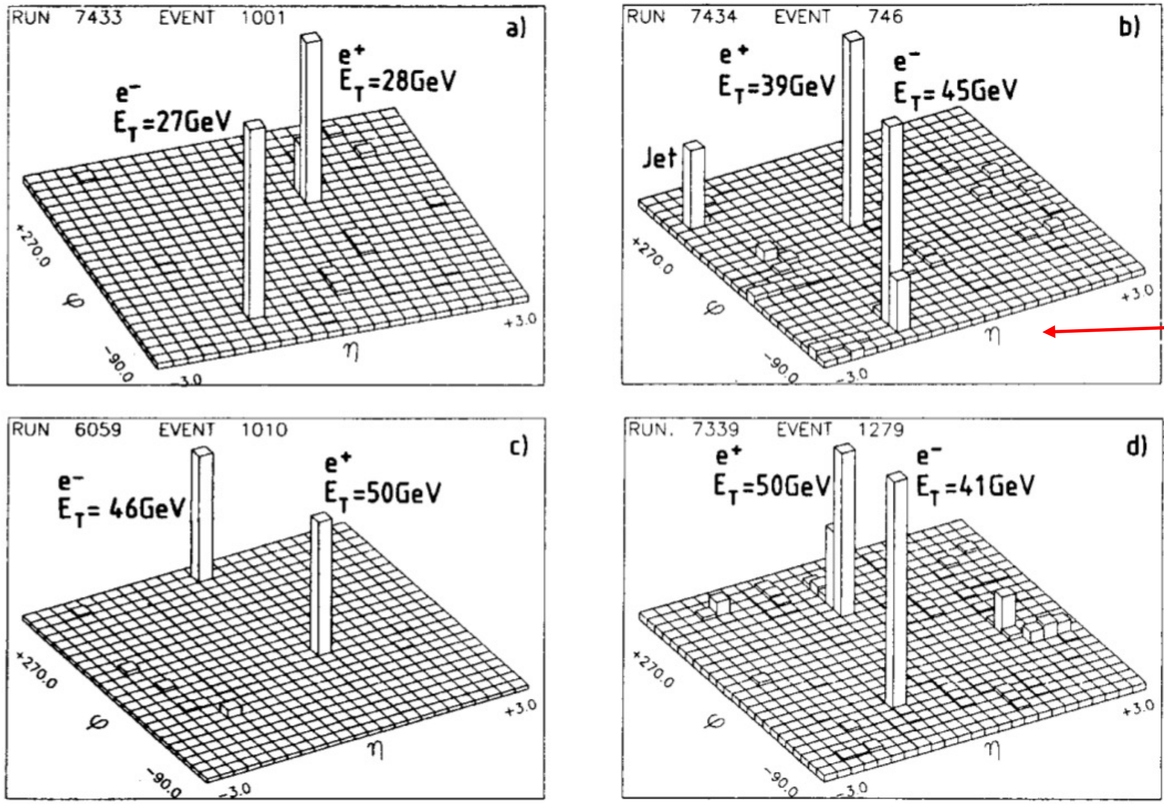
Slide from P. Bagnaia

$Z \rightarrow e^+e^-$



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

Slide from P. Bagnaia



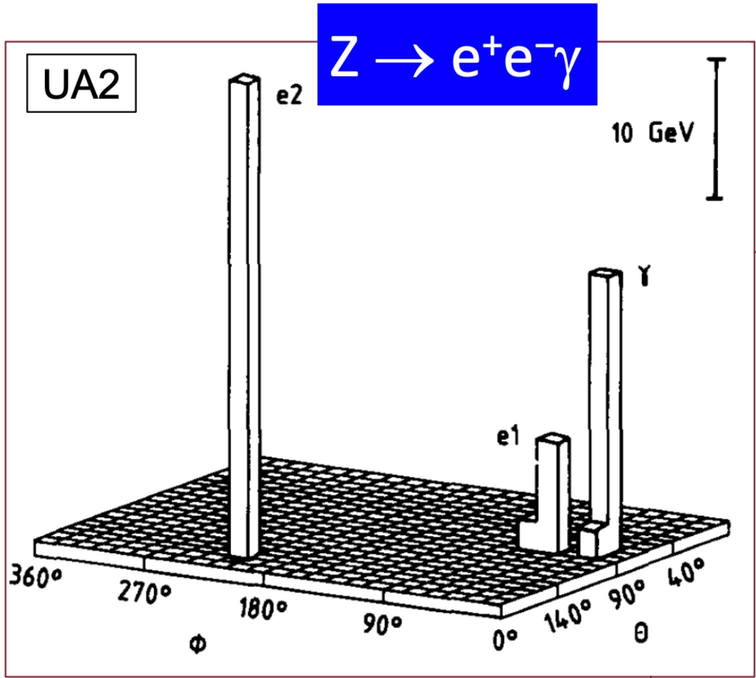
Pseudorapidity

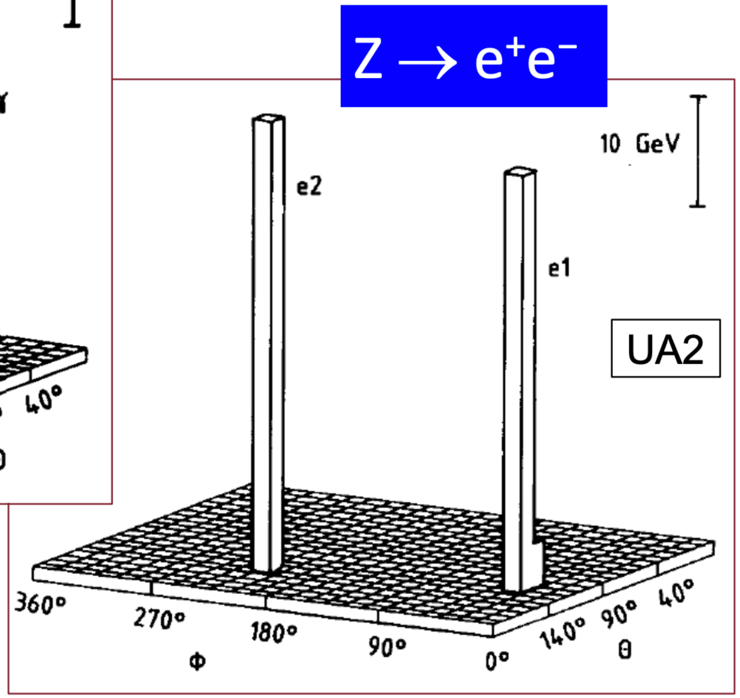
$$\eta = -ln \tan\frac{\theta}{2}$$

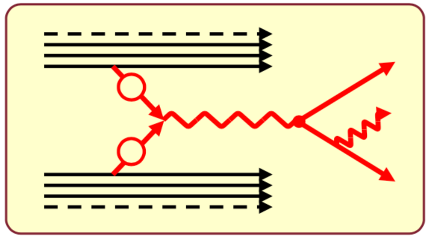
Figure 12.3. Lego plots for four UA-1 events that were candidates for $Z^0 \to e^+e^-$. The plots show the location of energy deposition in ϕ, the azimuthal angle, and $\eta = -\ln\tan(\theta/2)$, the pseudorapidity. The isolated towers of energy indicate the cleanliness of the events (Ref. 12.8).

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

Slide from
P. Bagnaia

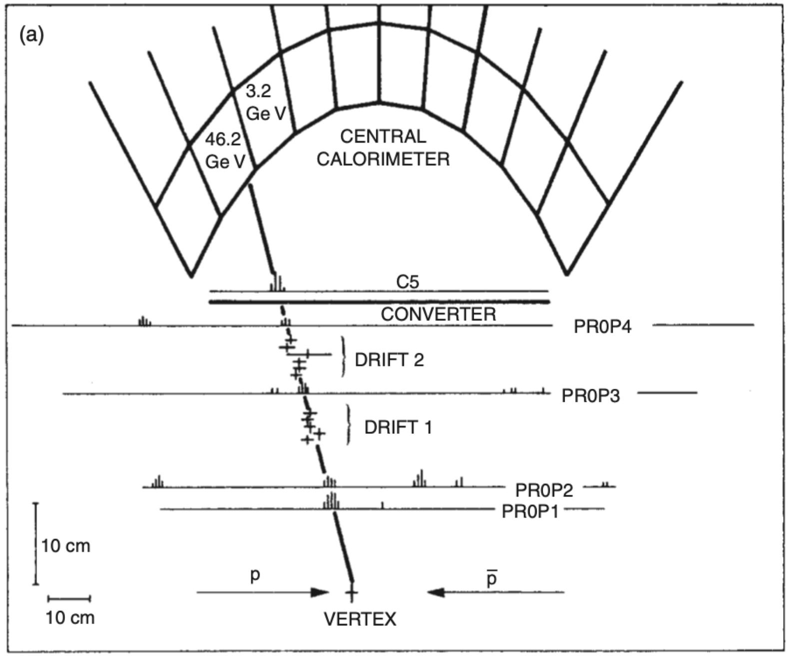


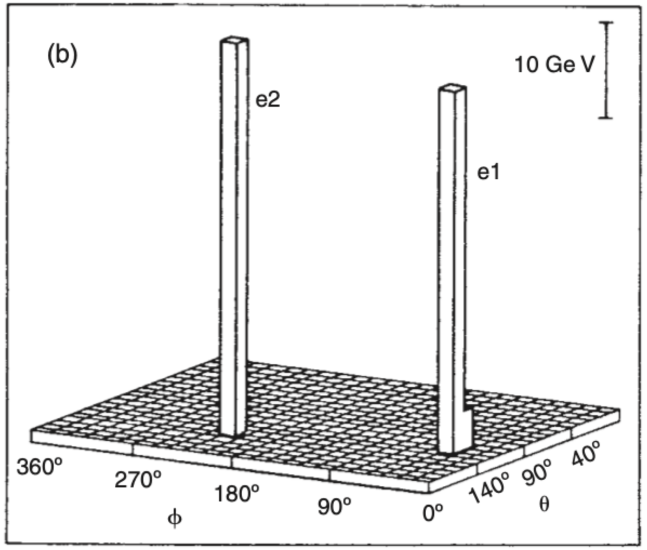




The events: UA2 $Z \rightarrow e^+e^-$

Slide from P. Bagnaia

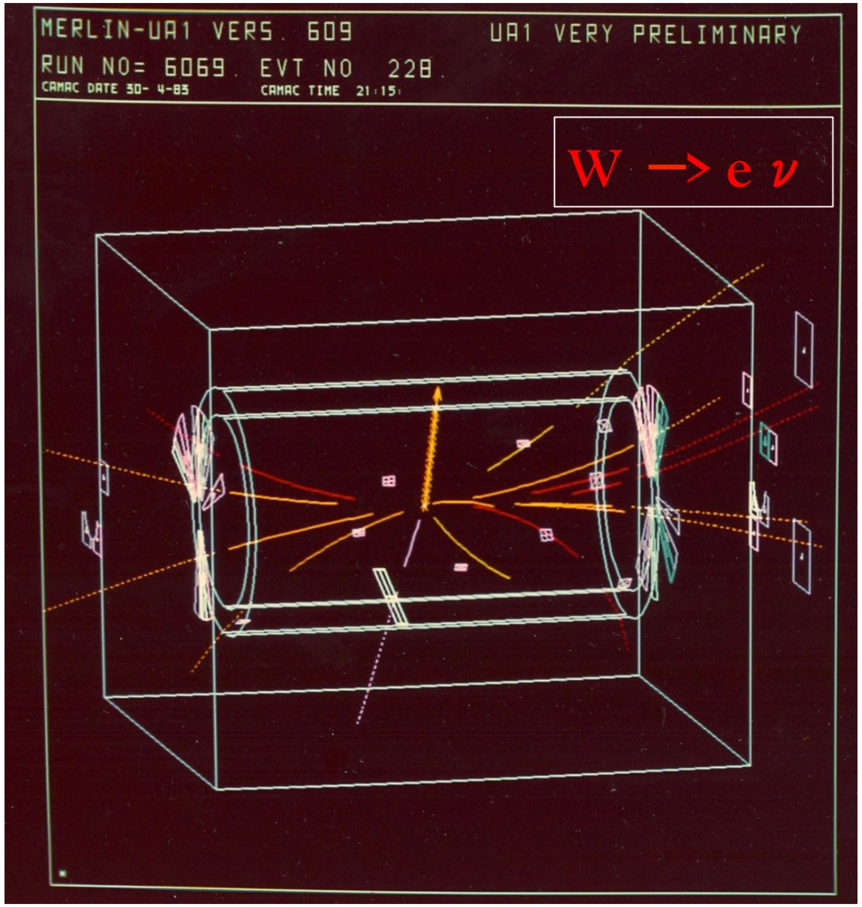


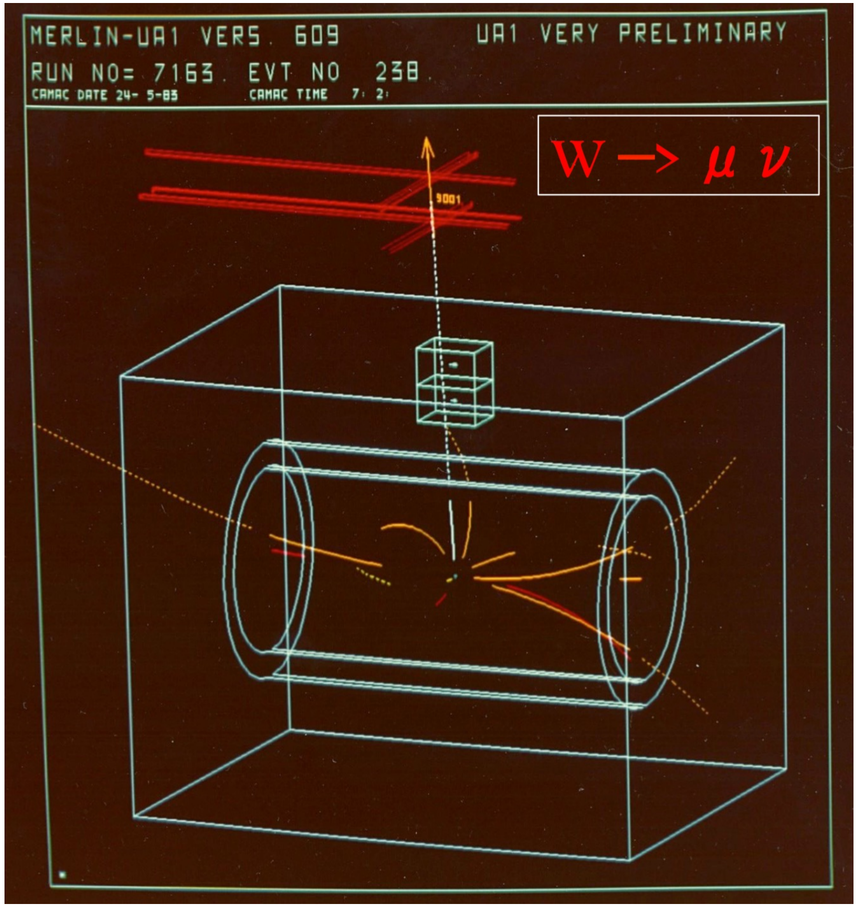


An electron is identified by an e.m. cluster, a track in the central detector and no energy in the hcal behind the cluster

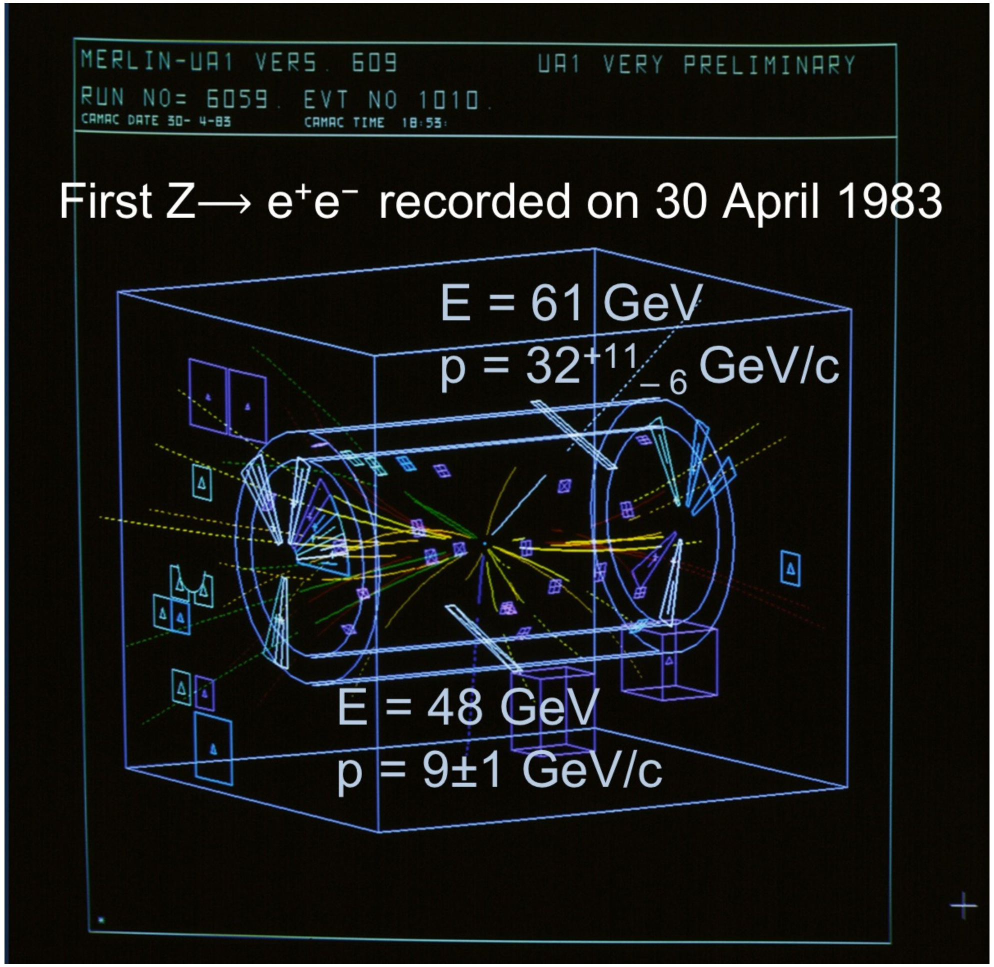
Figure 12.4. A UA-2 candidate for $Z^0 \rightarrow e^+e^-$. The upper diagram shows a track detected by a series of proportional chambers and a chamber following a tungsten converter. The calorimeter cells indicate energy measured by the electromagnetic calorimeter. The lego plot for the event shows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

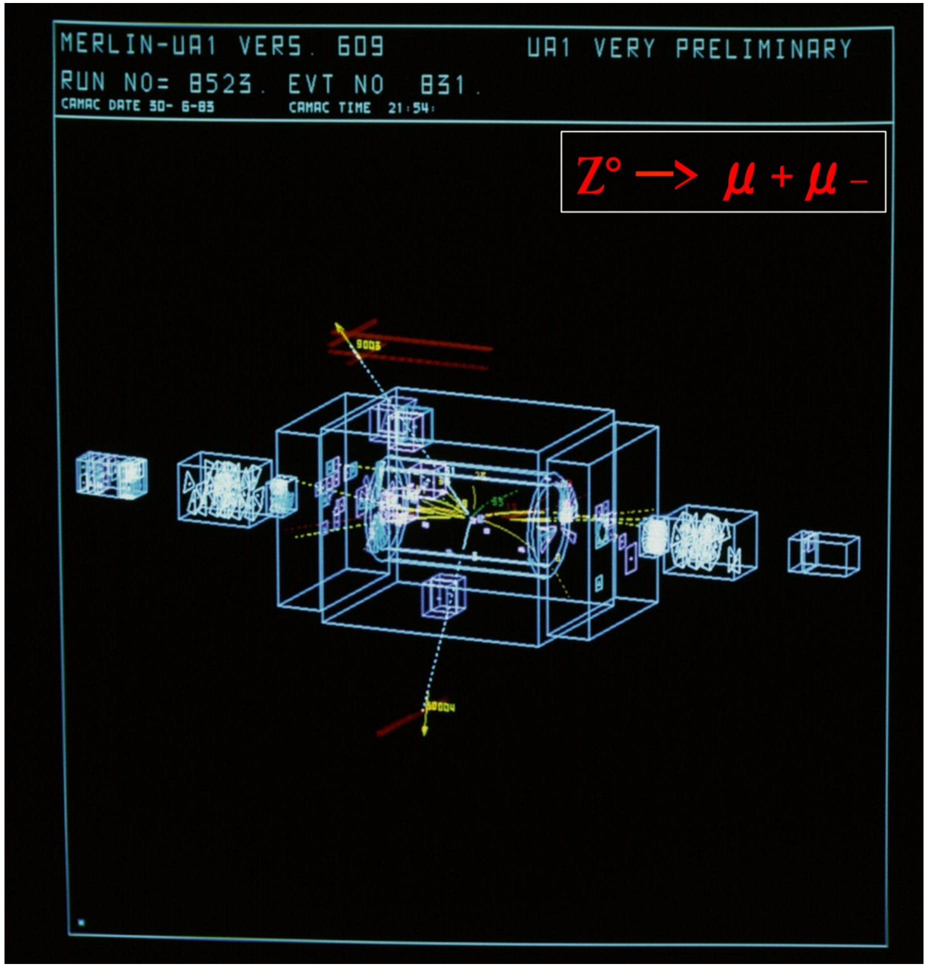
UA1 MEGATEK: W decays





UA1 MEGATEK: Z decays

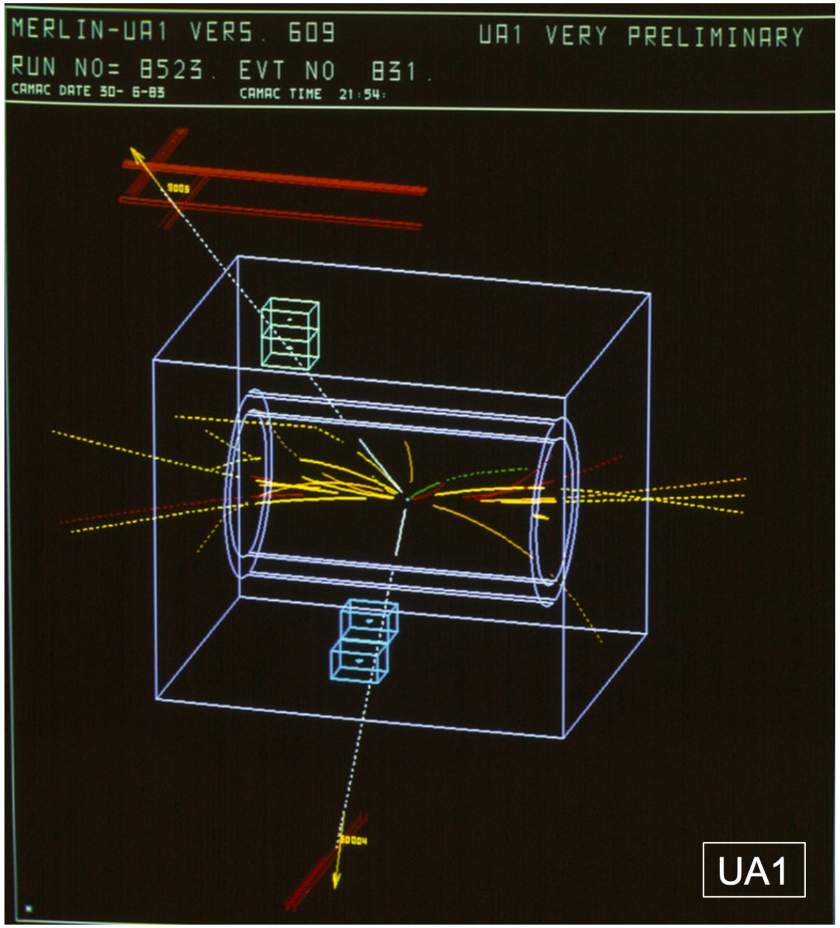




The events: UA1 $Z \to \mu^+\mu^-$

Slide from P. Bagnaia

$Z \to \mu^+\mu^-$



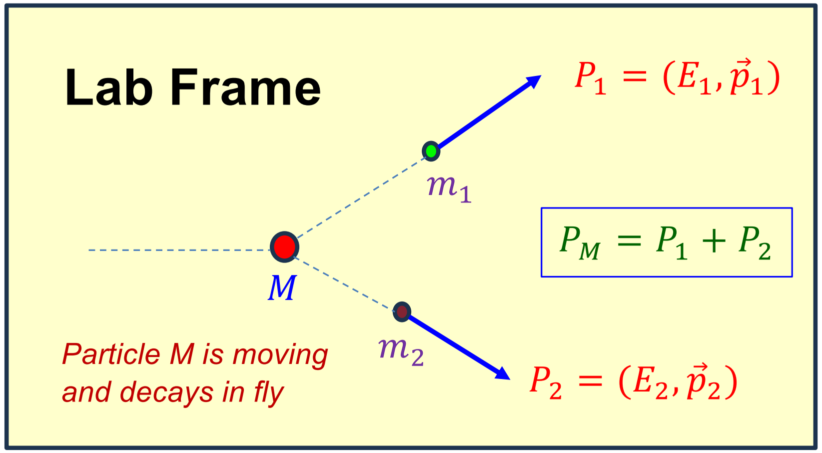
Calorimeters: uncertainties on the energy scale

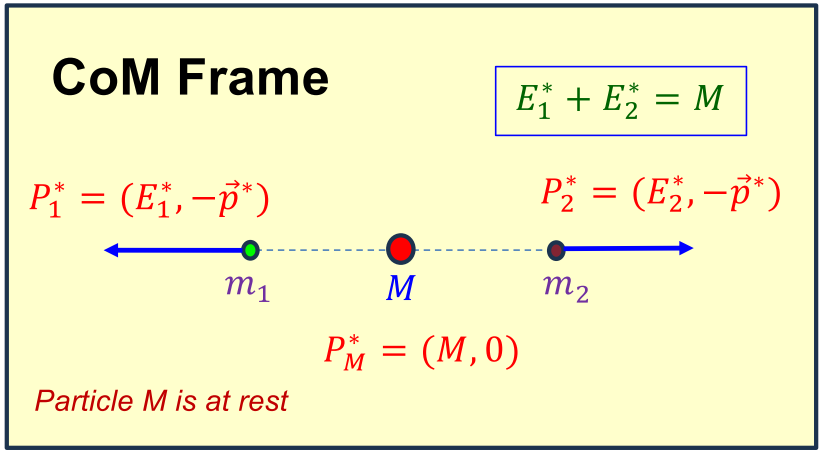
- **Of course, neither UA1 nor UA2 directly measured the energy lost by the particle(s), but they measured the light produced by the particles traversing the layers of scintillator material. The chain is:**

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





- **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

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

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

DON'T CALL IT "s" !!

- **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**

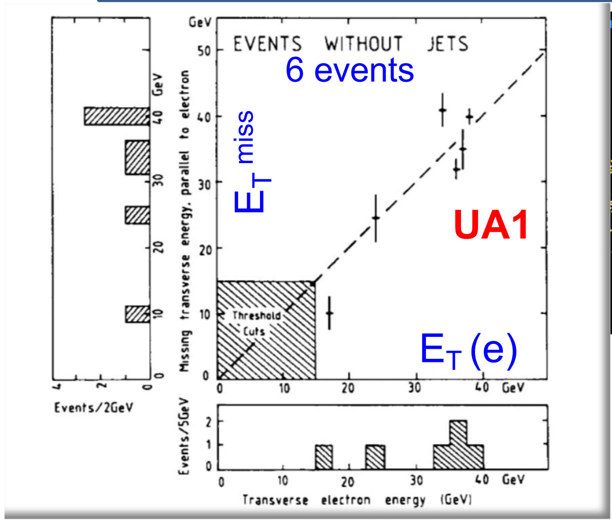
Timeline of the W and Z discoveries

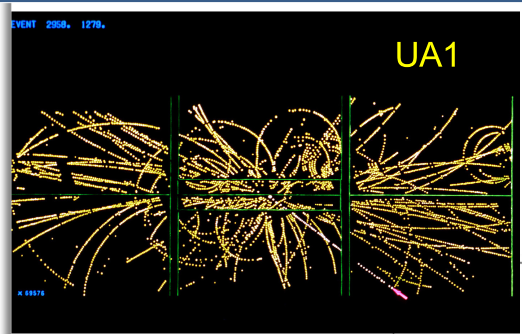
1983: W discovery in e-channel

- 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

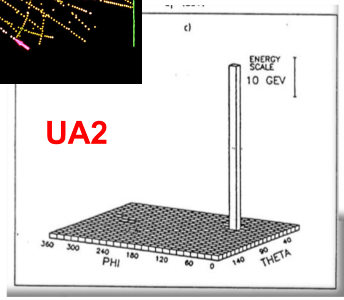
Carlo Rubbia the following week:
"They look like Ws, they feel like Ws, they smell like Ws, they must be Ws"

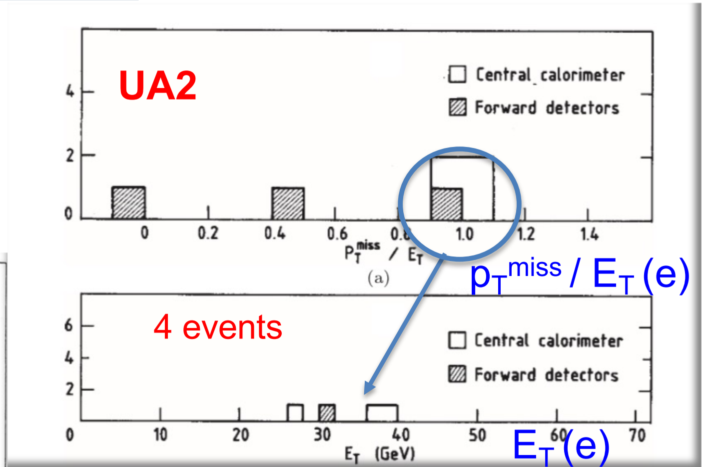
introduction of E_T^{miss} signature as new analysis tool: $\vec{E}_T^{miss} + \sum_{cells} \vec{E}_T = 0$





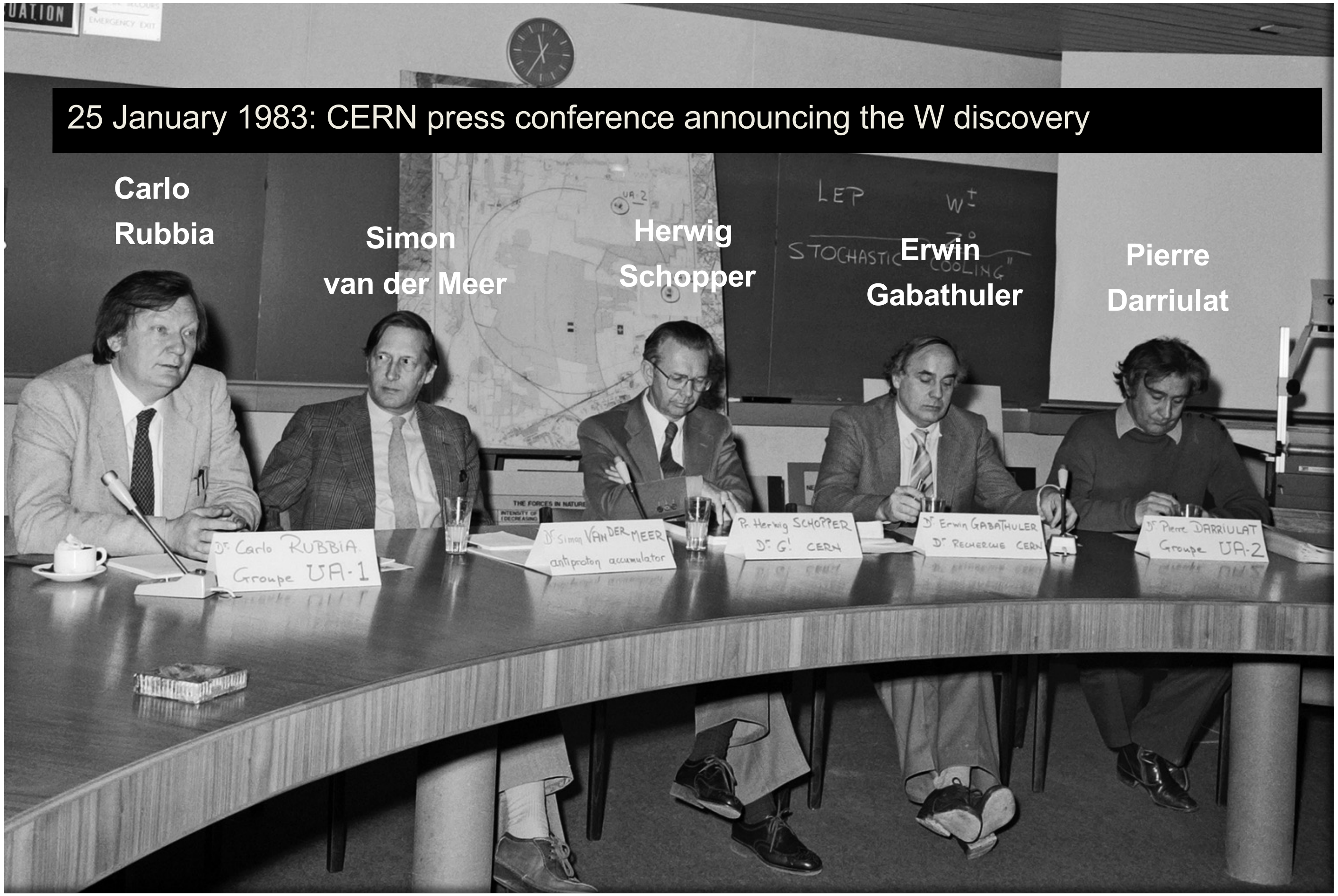
$m_W = 81 \pm 5$ GeV





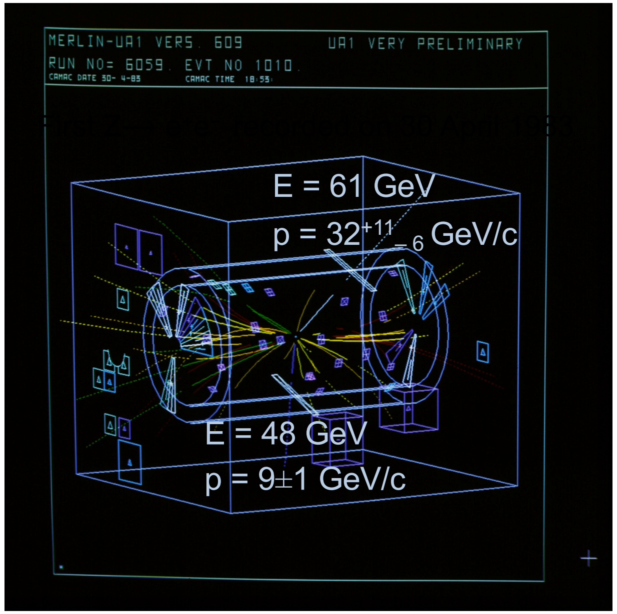
$m_W = 80^{+10}_{-6}$ GeV

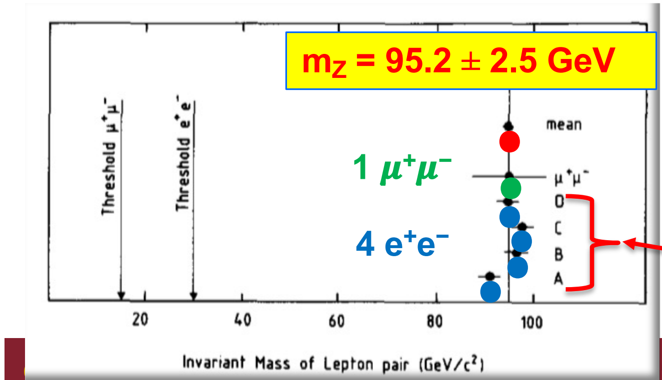
W discovery went public

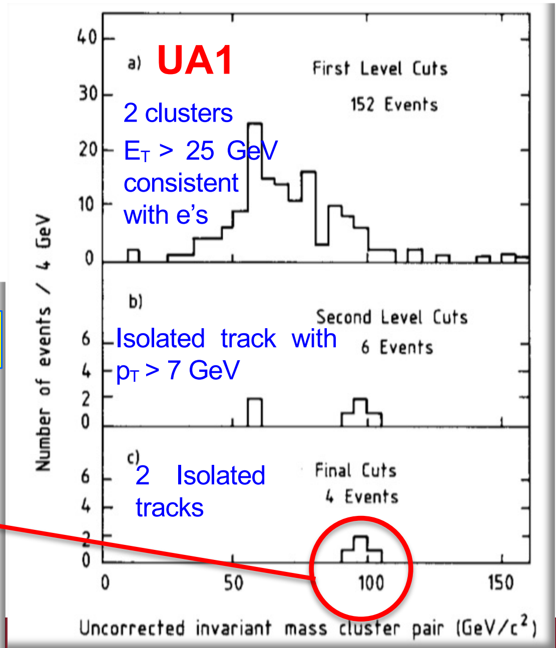


1983: Z discovery - UA1

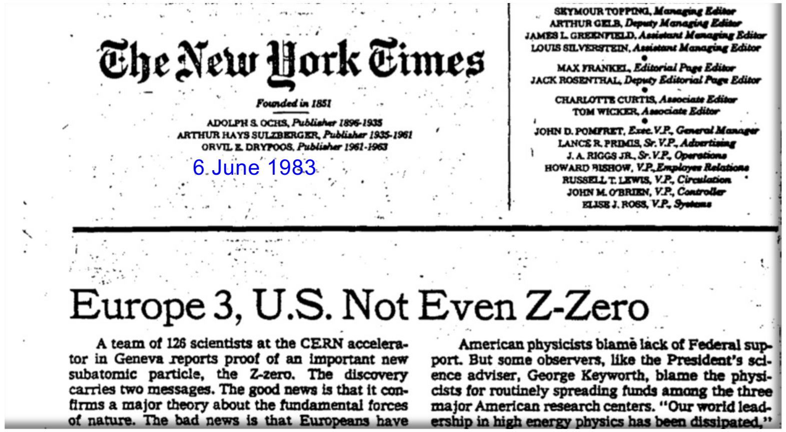
- 27 May: seminar at CERN by Carlo Rubbia: first Z events (e^+e^- and $\mu^+\mu^-$)
- 1 June: press conference announcing Z discovery
- 6 June: paper submitted for publication (Phys.Lett.B)







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**

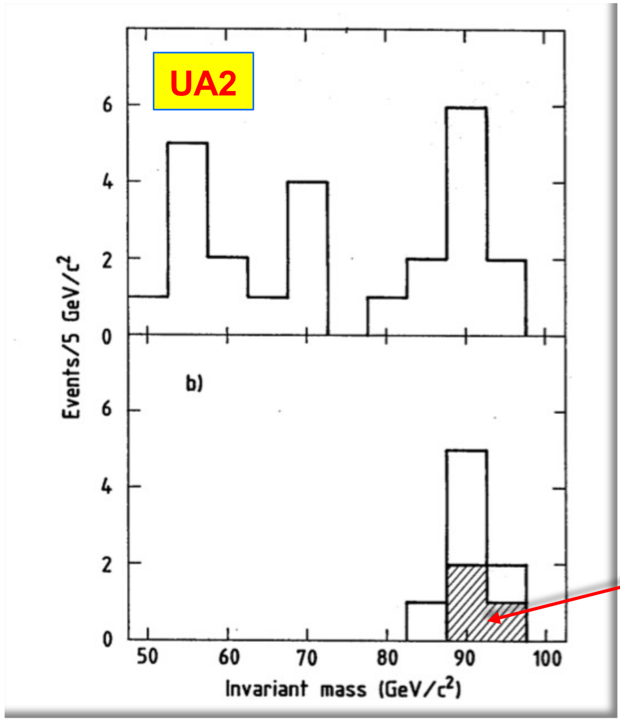
Published: June 6, 1983

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)

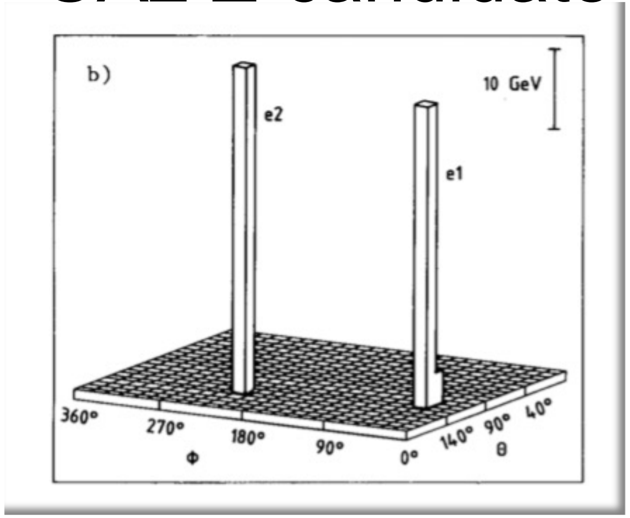


Two energy clusters with E_T > 25 GeV, consistent with electrons → 24 events

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

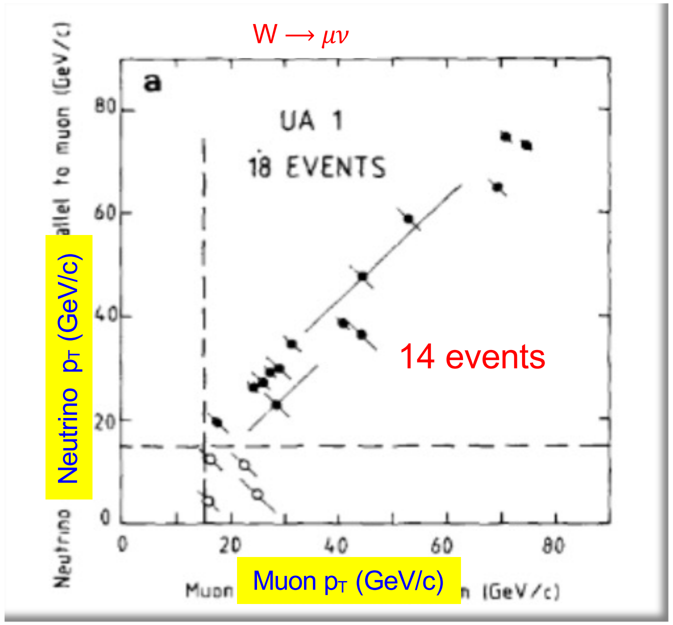
Shaded area: Tracks identified as an isolated electron pointing to both energy clusters
→ 3 events

UA2 Z-candidate



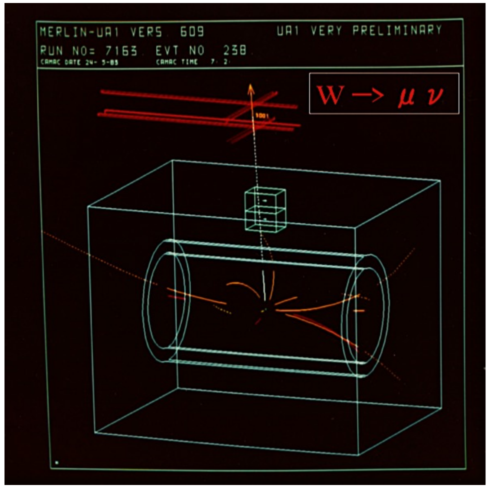
$m_Z = 90.7 \pm 2.1$ GeV/c^2

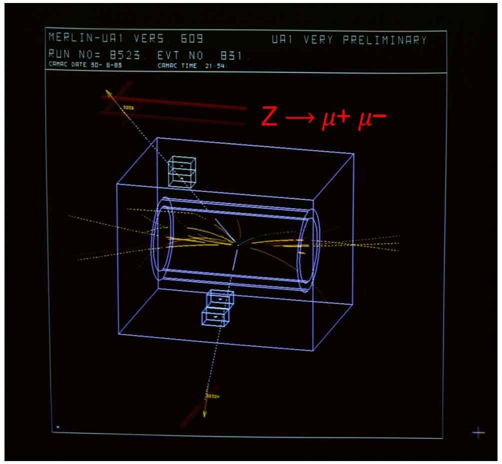
UA1: analysis of 1983 data: $W \to \mu\upsilon$; $Z \to \mu^+\mu^-$

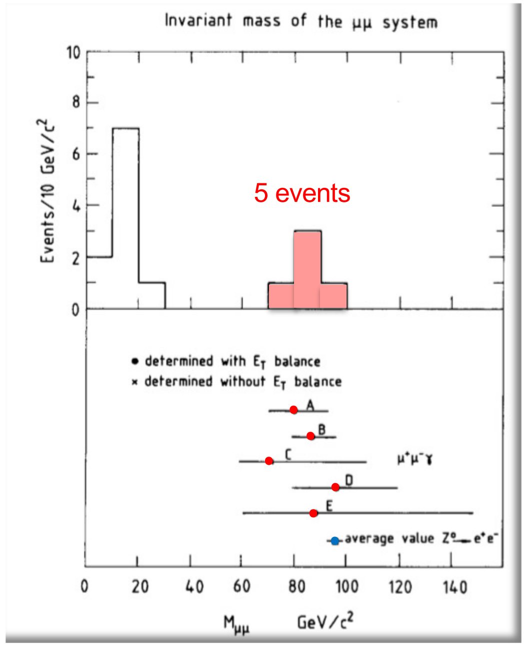


$m_W = 81\ ^{+6}_{-7}$ GeV

Compared to 43 W ⟶ e ν events





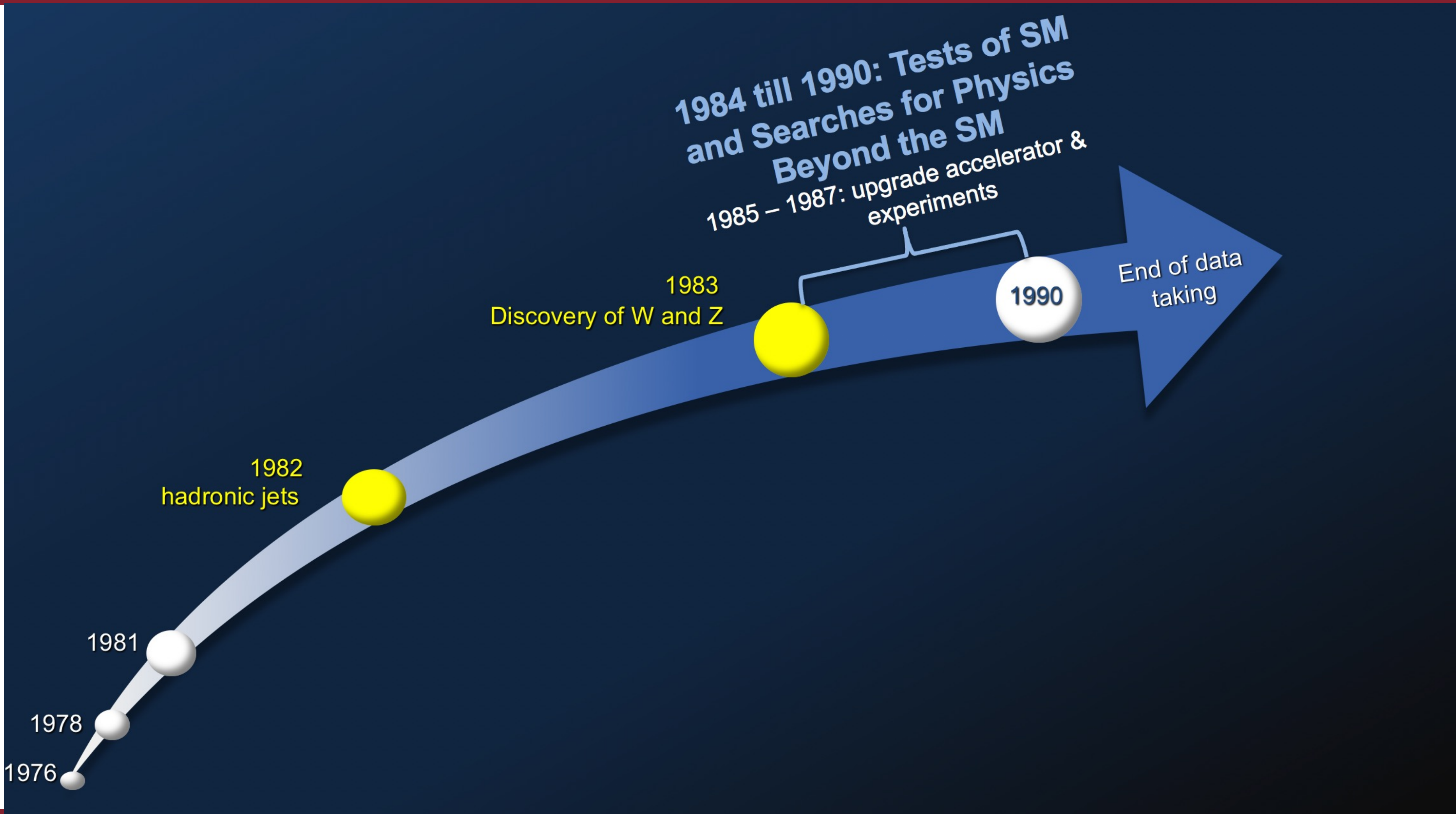


$m_Z = 85.8\ ^{+7.0}_{-5.4}$ GeV

The Rest is history

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
1983
Discovery of W and Z
1990
End of data
taking
1982
hadronic jets
1981
1978
1976

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End of chapter 4