The discovery of the W and Z bosons at the CERN proton – antiproton collider

Luigi Di Lella
Phys. Dept., University of Mainz

- Discovery of Neutral – Current neutrino interactions
- The proton – antiproton collider
- UA1 and UA2 detectors
- Discovery of the W and Z bosons
- Measurement of W and Z properties

The rise of particle physics, Rome, 23-24 September 2024

1973: Discovery of neutral – current neutrino interactions

$$\nu_\mu + N \rightarrow \nu_\mu + hadrons$$

$$\overline{\nu_\mu} + N \rightarrow \overline{\nu_\mu} + hadrons$$

the first experimental evidence for the weak neutral boson *Z* predicted by the electro-weak theory.

First measurement of the weak mixing angle θ_W from the cross-section ratio

$$\frac{\sigma(NC)}{\sigma(CC)} = \frac{\sigma[\nu_\mu(\overline{\nu_\mu}) + N \rightarrow \nu_\mu(\overline{\nu_\mu}) + hadrons]}{\sigma[\nu_\mu(\overline{\nu_\mu}) + N \rightarrow \mu^-(\mu^+) + hadrons]}$$

➡ **first quantitative prediction of the $W^\pm$ and Z mass values:**

$$m_W = 60 – 80 \text{ GeV/c}^2$$

$$m_Z = 75 – 95 \text{ GeV/c}^2$$

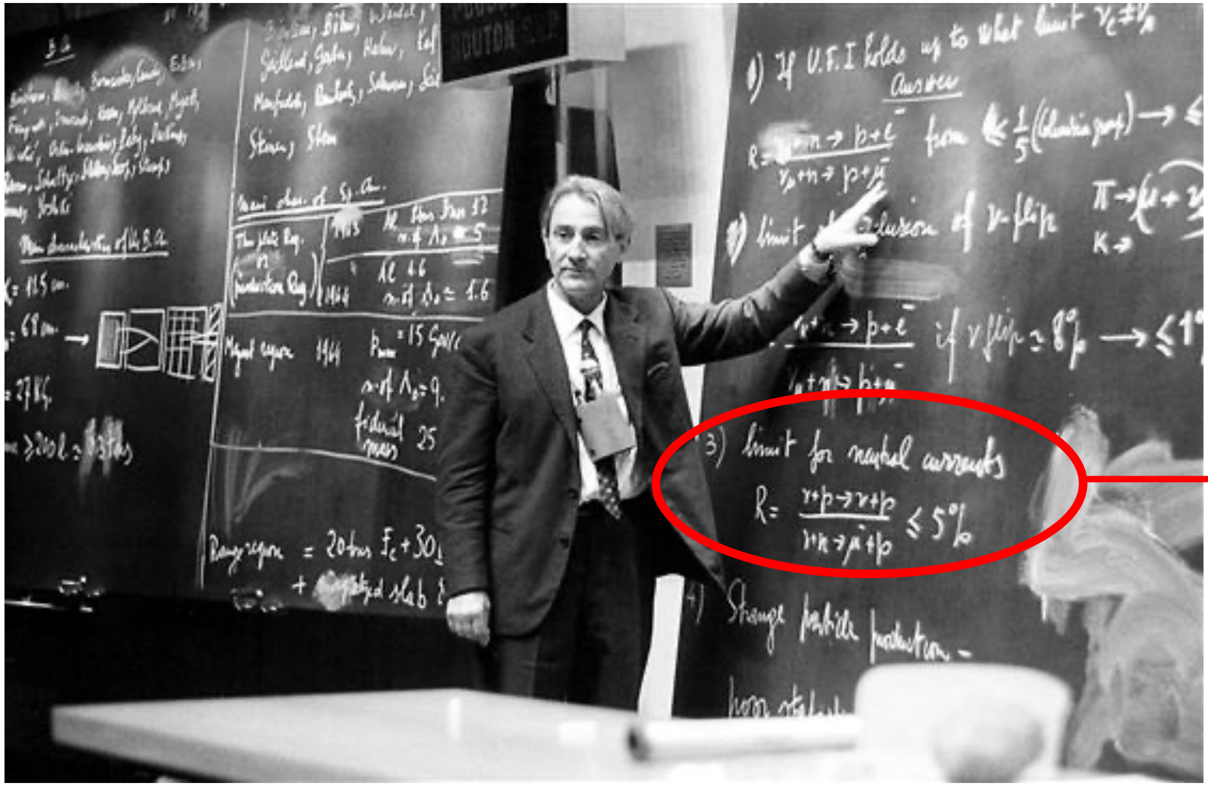
The ideal machine to produce and study the W and Z bosons: a high-energy e^+e^- collider

$$e^+e^- \rightarrow Z \qquad\qquad e^+e^- \rightarrow W^+W^-$$

still far in the future in the 1970's (first operation of LEP in 1989)

In the 1960s, all experiments with neutrino beams had observed events with final states consisting of hadrons only – all interpreted as background from neutrons produced in ν_μ or $\bar{\nu}_\mu$ CC interactions near the end of the shielding wall, with the $\mu^\pm$ missing the detector.

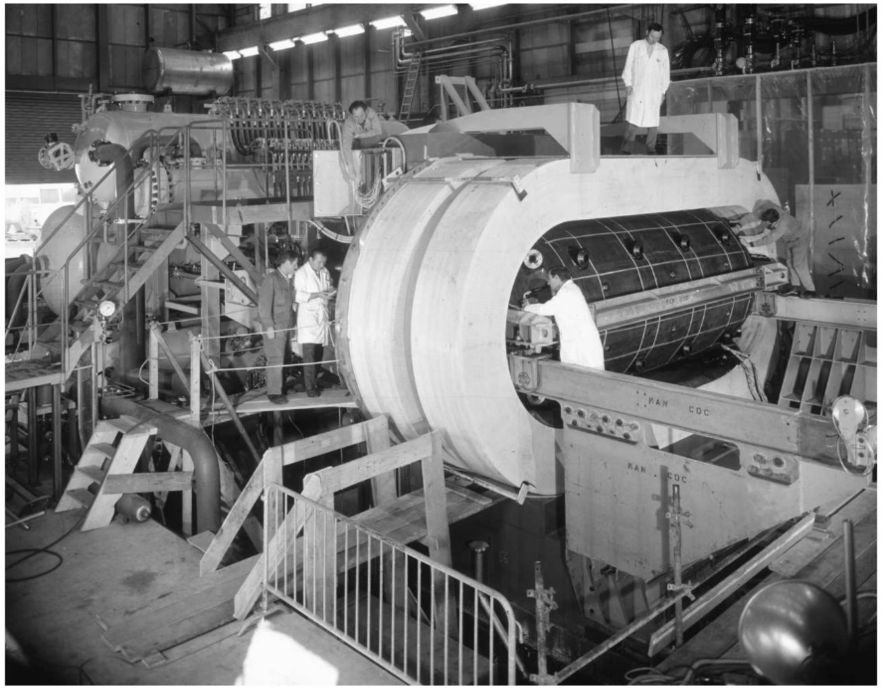
1964: Gilberto Bernardini reporting in the CERN auditorium results from neutrino experiments presented at the 1963 HEP Conference



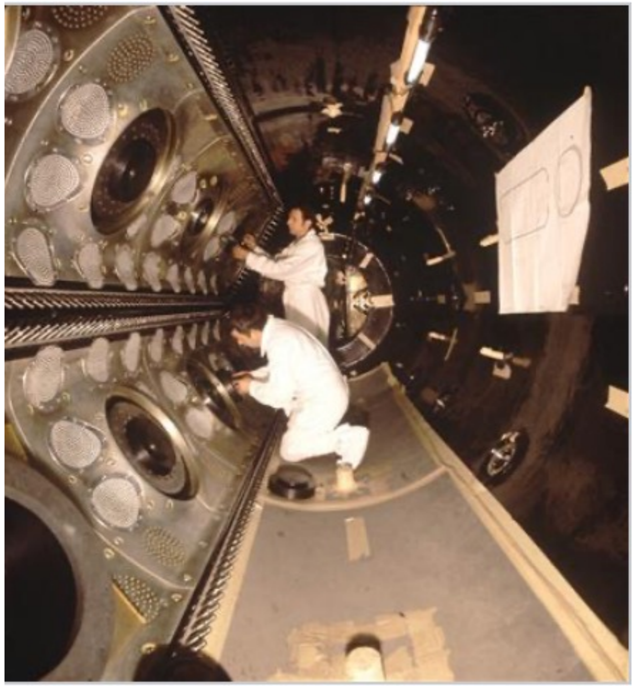
True ratio is ~20%

1964: André Lagarrigue (Ecole Polytechnique, Paris) proposes to build a large-volume bubble chamber (named "Gargamelle"), filled with heavy liquid, to be installed on the neutrino beam from the CERN 26 GeV Proton Synchrotron (PS)

1965 – 1970: Construction in Saclay, followed by installation at CERN



During installation



Inside Gargamelle

Cylindrical volume, length 4.8 m, diameter 1.8 m;
Horizontal magnetic field of 2 T orthogonal to beam axis;
Filled with liquid Freon-13 (CF_3Br) : density 1.5 g/cm^3, radiation length 11 cm,
mean nuclear interaction length 78 cm.

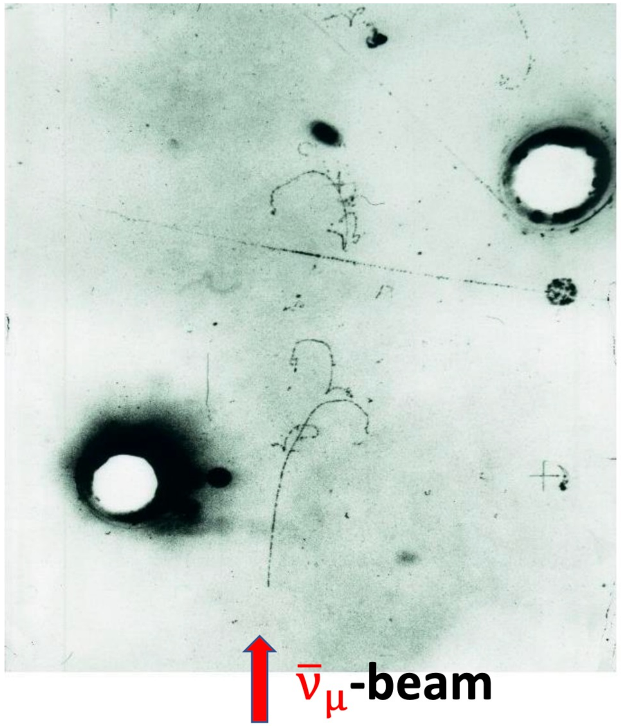
1971: Start data taking with ν_μ and $\bar{\nu}_\mu$ beams (energy ~ 1 – 10 GeV)

Gargamelle at CERN today

The Gargamelle collaboration

Aachen – Brussels – CERN – Ecole Polytechnique, Paris – Milano – Orsay – UC London

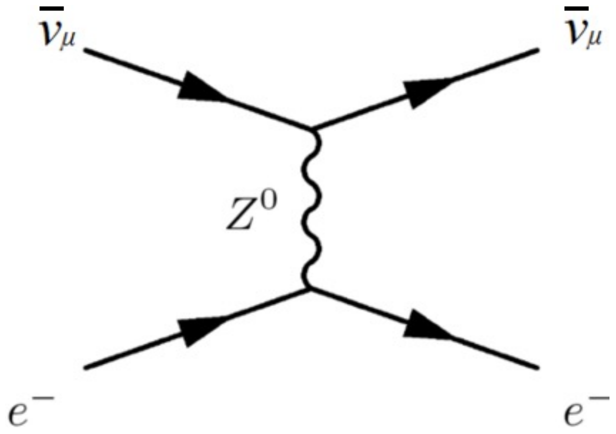
December 1972: observation of an event consisting of a single electron only from data taken with the $\bar{\nu}_\mu$ beam



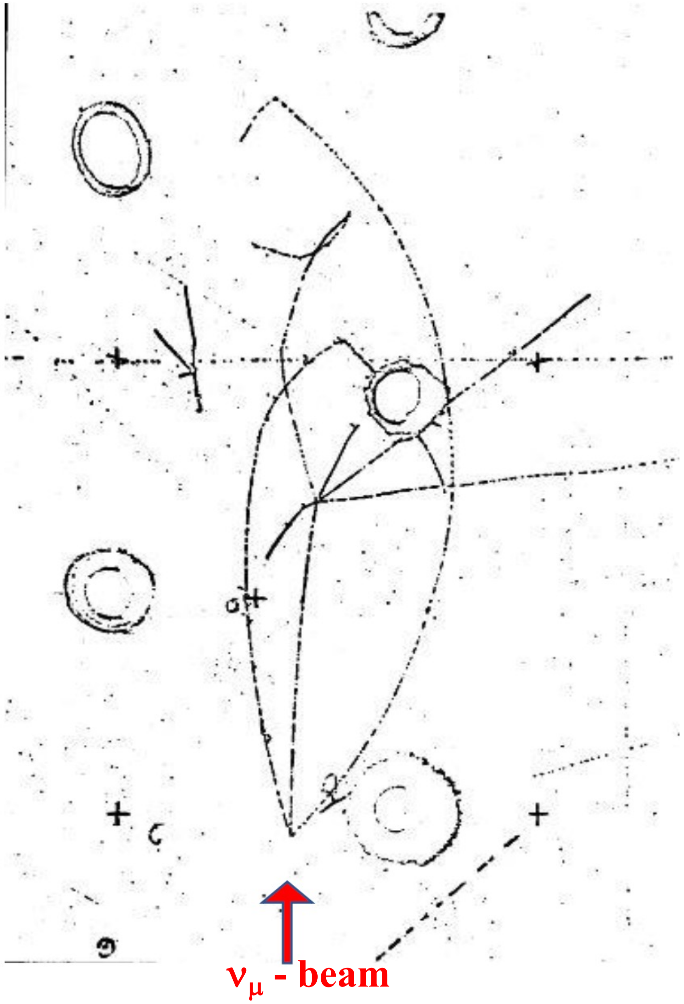
Electron energy 385 ± 100 MeV

Electron angle to beam axis $1.4^{O} \pm 1.4^{O}$

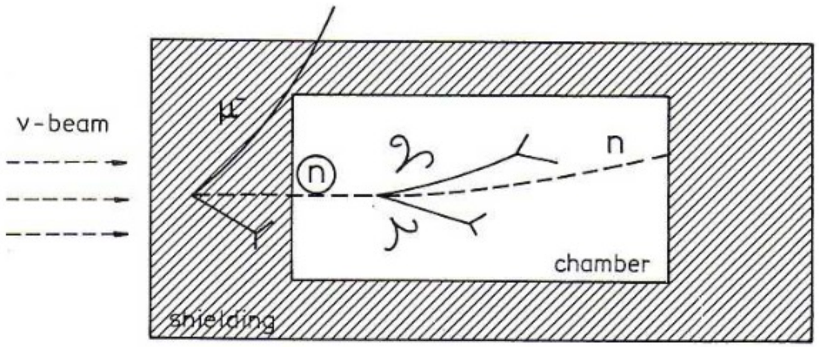
Consistent with $\bar{\nu}_\mu - e^-$ elastic scattering , as expected from the electroweak theory



A ν_μ interaction with only hadrons in the final state

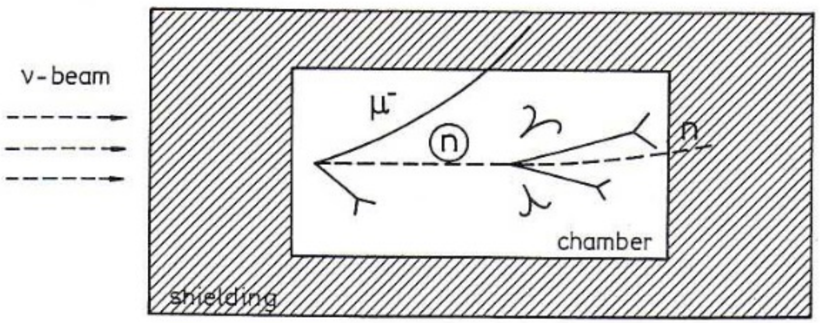


- Clean 3 – prong event
- Final state has only identified hadrons
- Total visible energy ~ 6 GeV



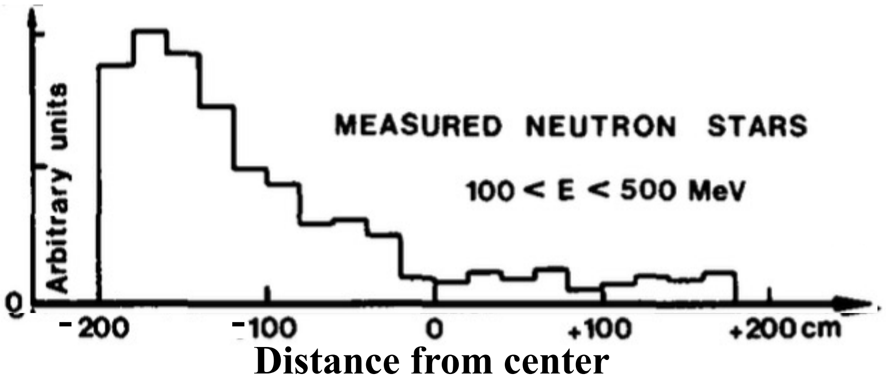
Sketch of a neutron background event

The neutron is produced by a ν_μ CC interaction with the μ^- and all other final-state particles missing the detector



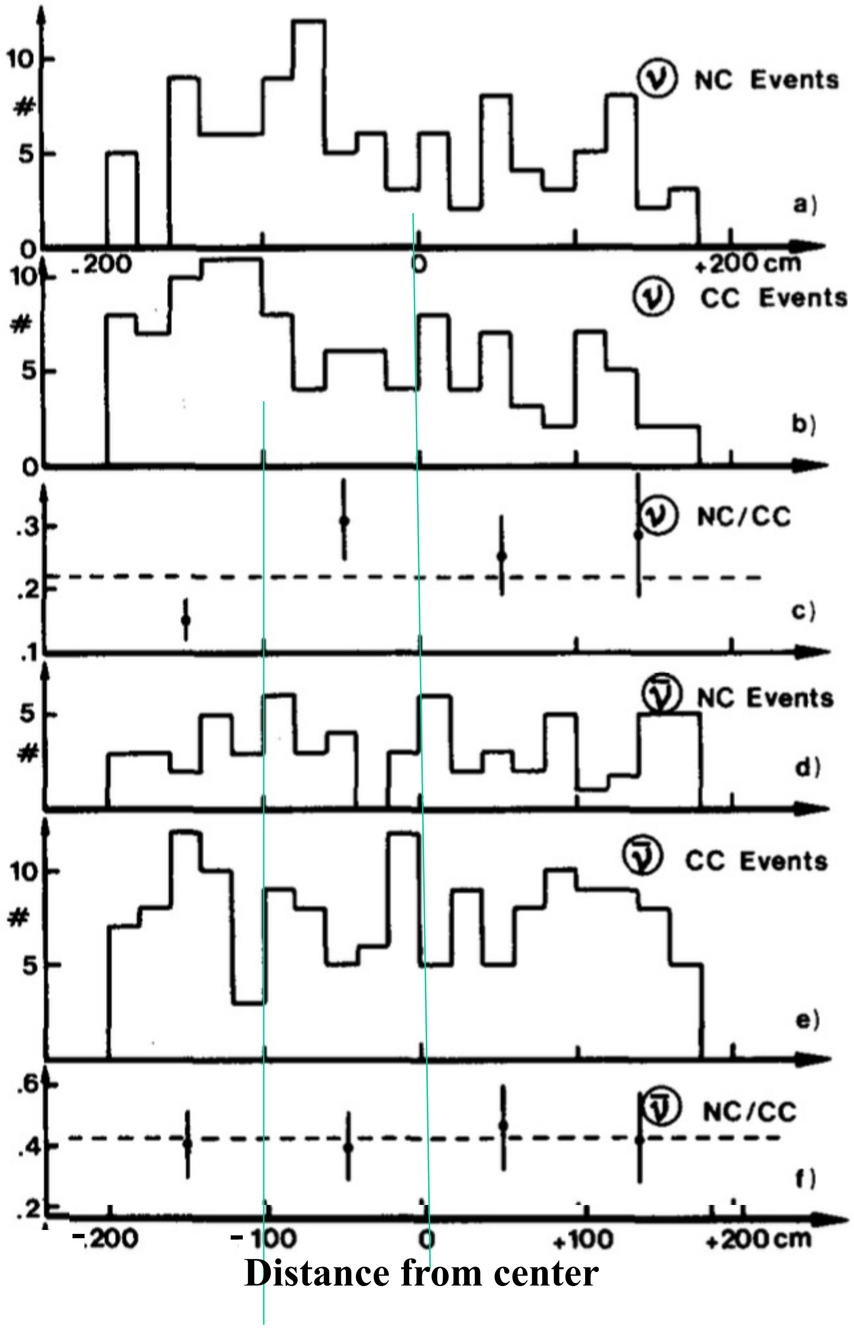
Neutron interactions in the detector can be measured by looking at ν_μ CC interactions occurring near the chamber entrance

The visible energy from neutron interactions in the detector is mostly < 500 MeV



Distribution fall-off as expected from neutron mean interaction length

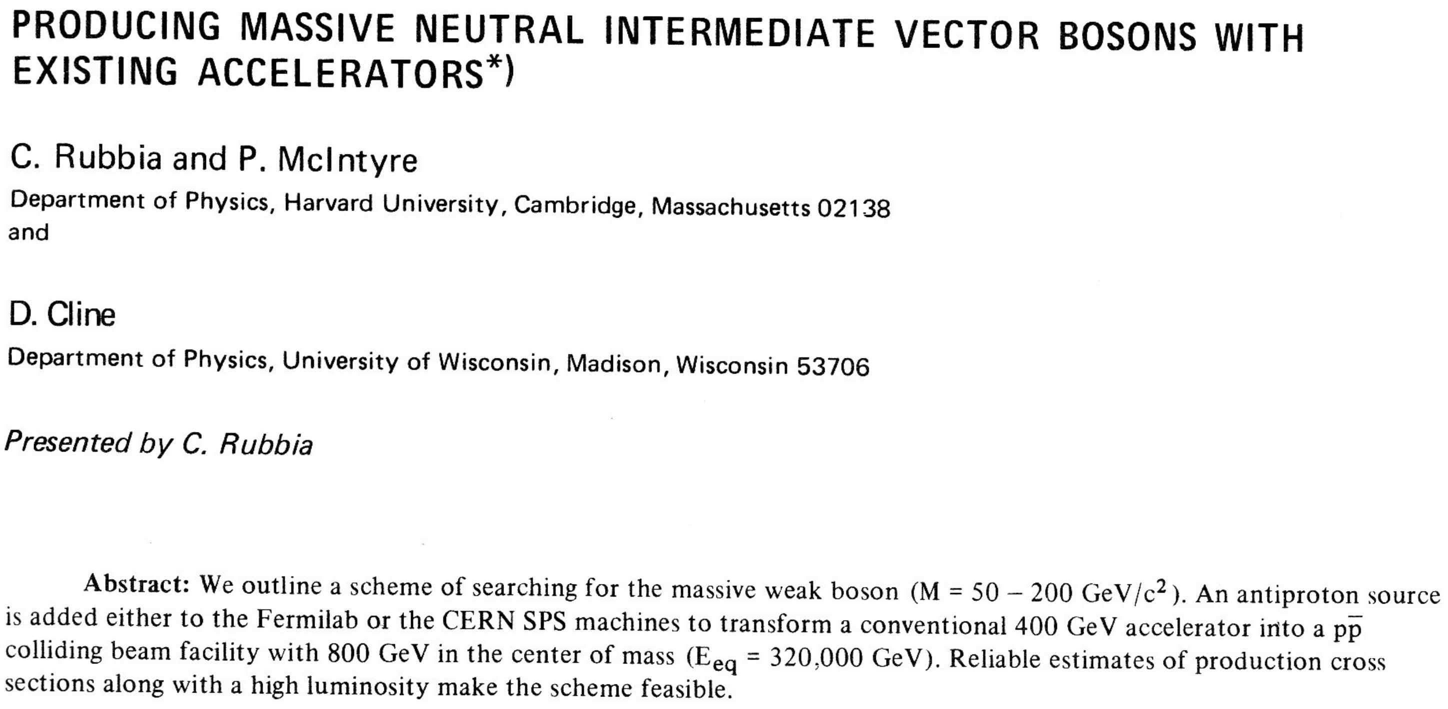
Events with only hadronic final states
Visible energy > 1 GeV



Event distribution uniform
along the beam direction
as expected for neutrino interactions

1976: the shortcut to W and Z production

(presented at the Neutrino 76 conference in Aachen)



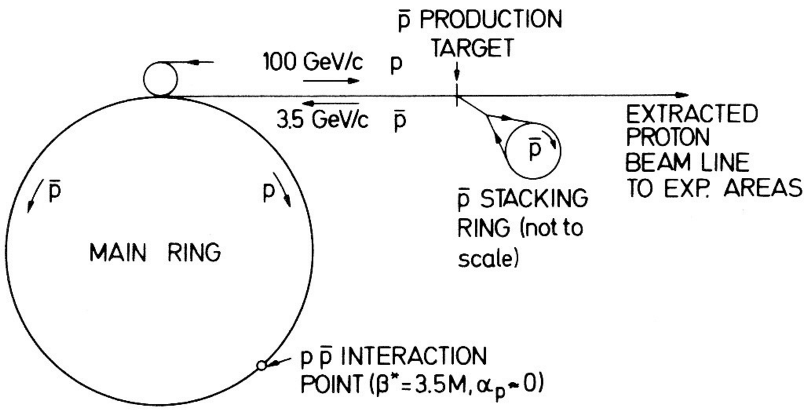
PRODUCING MASSIVE NEUTRAL INTERMEDIATE VECTOR BOSONS WITH EXISTING ACCELERATORS*)

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

Presented by C. Rubbia

Abstract: We outline a scheme of searching for the massive weak boson ($M = 50 - 200$ GeV/c^2). An antiproton source is added either to the Fermilab or the CERN SPS machines to transform a conventional 400 GeV accelerator into a $p\bar{p}$ colliding beam facility with 800 GeV in the center of mass ($E_{eq} = 320{,}000$ GeV). Reliable estimates of production cross sections along with a high luminosity make the scheme feasible.



Dominant W and Z production processes at a proton – antiproton collider:

$u + \bar{d} \rightarrow W^+$ $\quad\quad$ $\bar{u} + d \rightarrow W^-$

$u + \bar{u} \rightarrow Z$ $\quad\quad$ $d + \bar{d} \rightarrow Z$

Cross-sections calculable from electroweak theory + knowledge of proton structure functions

- **Energy requirements:**

  proton (antiproton) momentum at high energies is carried by gluons (~ 50%) and valence quarks (antiquarks) (~ 50%)

On average: $\text{quark momentum} \approx \frac{1}{6}(\text{proton momentum})$

collider energy ≈ 6 x boson mass ≈ 500 – 600 GeV

- **Luminosity requirements:**

  Inclusive cross-section for $\bar{p} + p \rightarrow Z + \text{anything}$ at ~ 600 GeV: $\sigma \approx 1.6$ nb
  Branching ratio for $Z \rightarrow e^+ e^-$ decay ≈ 3%

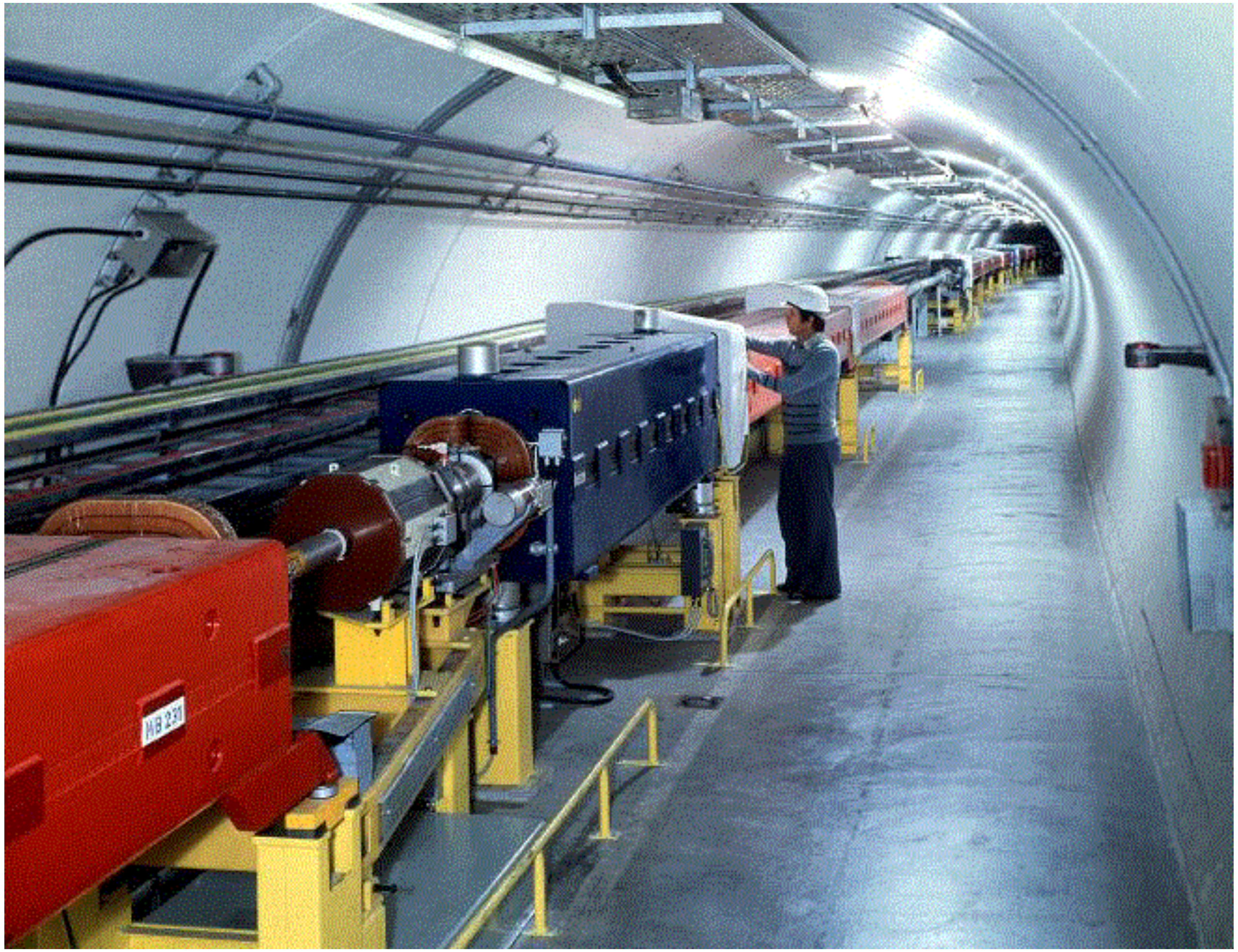
$$\sigma(\bar{p}p \rightarrow Z \rightarrow e^+e^-) \approx 50\,\text{pb} = 5 \times 10^{-35}\ \text{cm}^2$$

Event rate = $L\,\sigma$ $[\text{s}^{-1}]$ $\quad$ ($L \equiv$ luminosity)

1 event / day ⇒ $L \approx 2.5 \times 10^{29}\ \text{cm}^2\ \text{s}^{-1}$

CERN accelerators in 1976

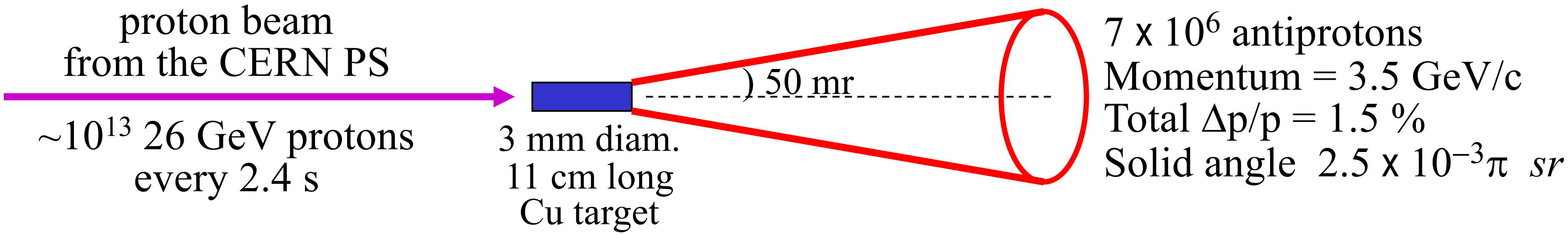
- 26 GeV proton synchrotron (PS) in operation since 1959
- 450 GeV proton synchrotron (SPS) just starting operation



A view of the CERN SPS

To achieve luminosities $\geq 10^{29}$ cm^{-2} s^{-1} need an antiproton source capable of delivering once per day 3 x 10^{10} $\bar{p}$ distributed into few (3 – 6) tightly collimated bunches within the angular and momentum acceptance of the SPS

Antiproton production:



proton beam
from the CERN PS

~10^{13} 26 GeV protons
every 2.4 s

3 mm diam.
11 cm long
Cu target

7 x 10^{6} antiprotons
Momentum = 3.5 GeV/c
Total $\Delta p/p$ = 1.5 %
Solid angle 2.5 x $10^{-3}\pi$ *sr*

Number of antiprotons / PS cycle OK

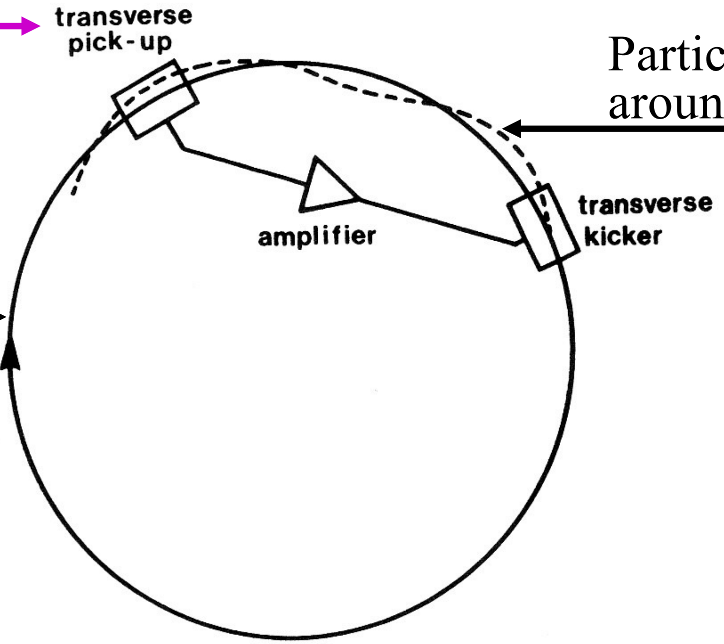
but phase space volume too large by a factor $\geq 10^{8}$ to fit into SPS acceptance even after acceleration to the injection energy of 26 GeV

must increase the antiproton phase space density by $\geq 10^{8}$ before sending them to the SPS ("cooling")

“Stochastic” cooling

(invented at CERN by Simon van der Meer in 1972)

Example: cooling of the horizontal motion



Measure particle distance from central orbit

Particle oscillating around central orbit

kick particle onto central orbit

Central orbit

In practice, the pick-up system measures the average distance from central orbit of a group of particles (depending on frequency response)

Independent pick-up – kicker systems to cool:

- **horizontal motion**
- **vertical motion**
- **longitudinal motion (decrease of $\Delta p/p$)**
  (signal from pick-up system proportional to Δp)

A few initial recommendations by the CERN Research Board

November 1976: Recommendation to carry out an experiment on proton cooling:
Initial Cooling Experiment (ICE)
Test cooling of 2 GeV protons in a storage ring built from components of a dismantled ring used to measure the muon g-2

May 1978 : The ICE group reports the achievement of successful stochastic cooling
→ **Recommendation to go ahead with $\bar{p}p$ beams in the SPS (S$\bar{p}$pS)**

June 1978: Approval of proposal P92, becoming the UA1 experiment
(UA1 : Underground Area 1)

Concern that the inclusion of a second underground area at another intersection region may not be possible due to budgetary limitations

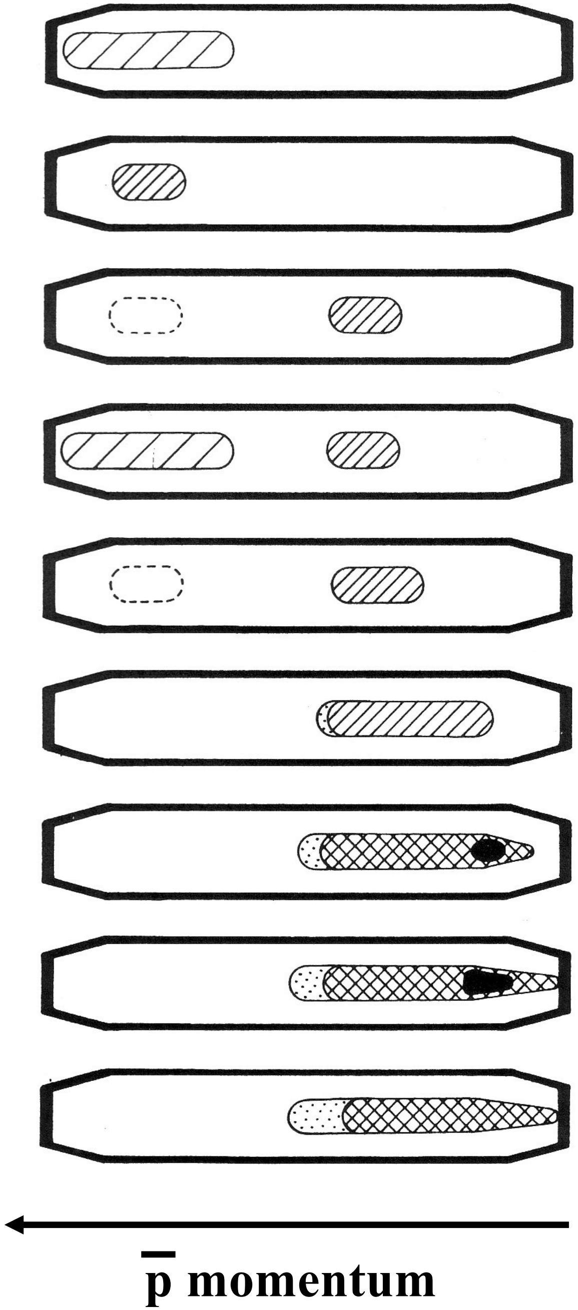
December 1978: Resources for a second underground area are found
→ **Approval of proposal P93, becoming UA2**

The CERN Antiproton Accumulator (AA)

3.5 Gev/c large-aperture ring for antiproton storage and cooling

(during construction)

AA operation


Section of the AA vacuum chamber

The first pulse of 7×10^6 $\bar{p}$ has been injected

Precooling reduces momentum spread

First pulse is moved to the stack region where cooling continues

Injection of 2^{nd} $\bar{p}$ pulse 2.4 s later

After precooling 2^{nd} pulse is also stacked

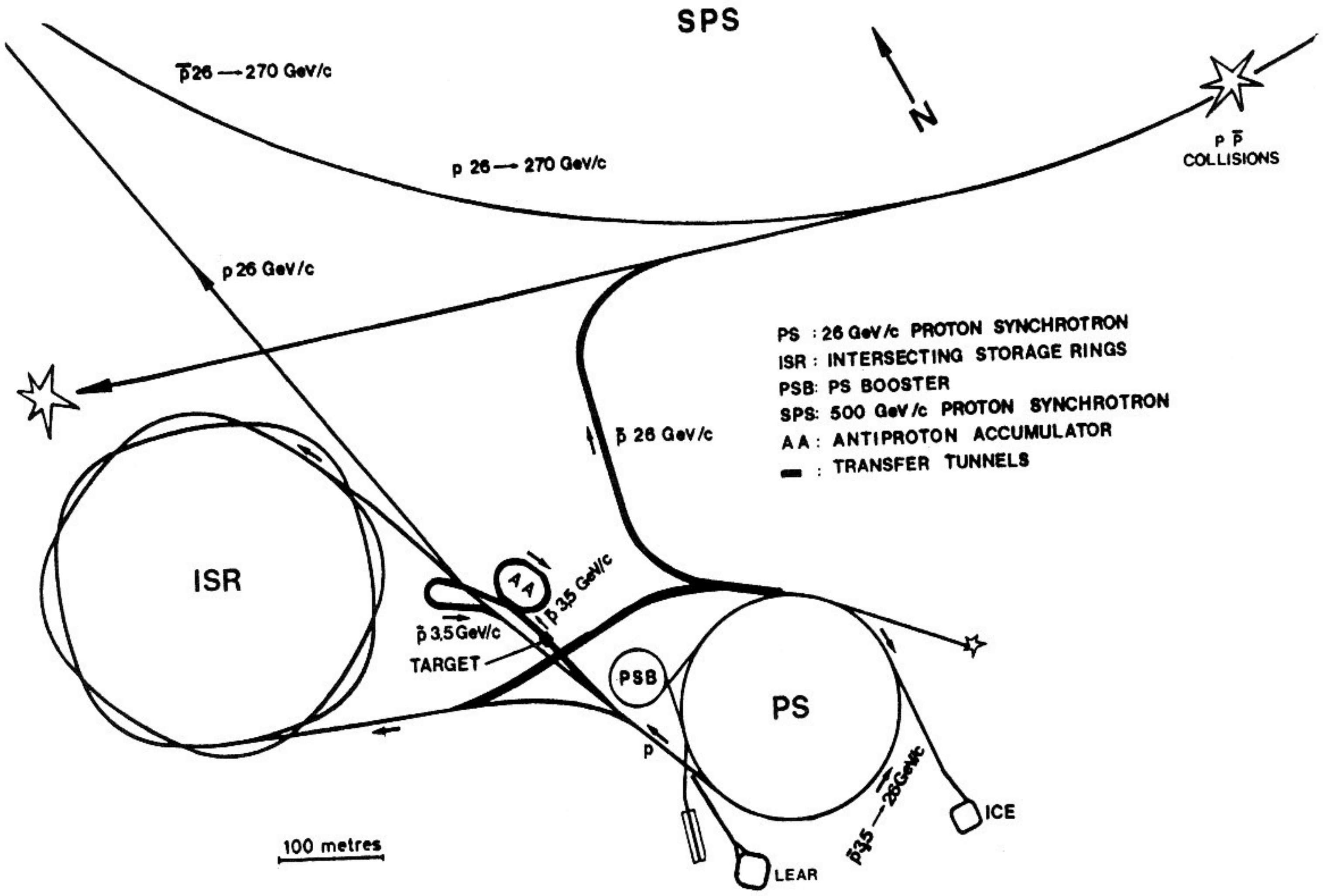
After 15 pulses the stack contains 10^8 $\bar{p}$

After one hour a dense core has formed inside the stack

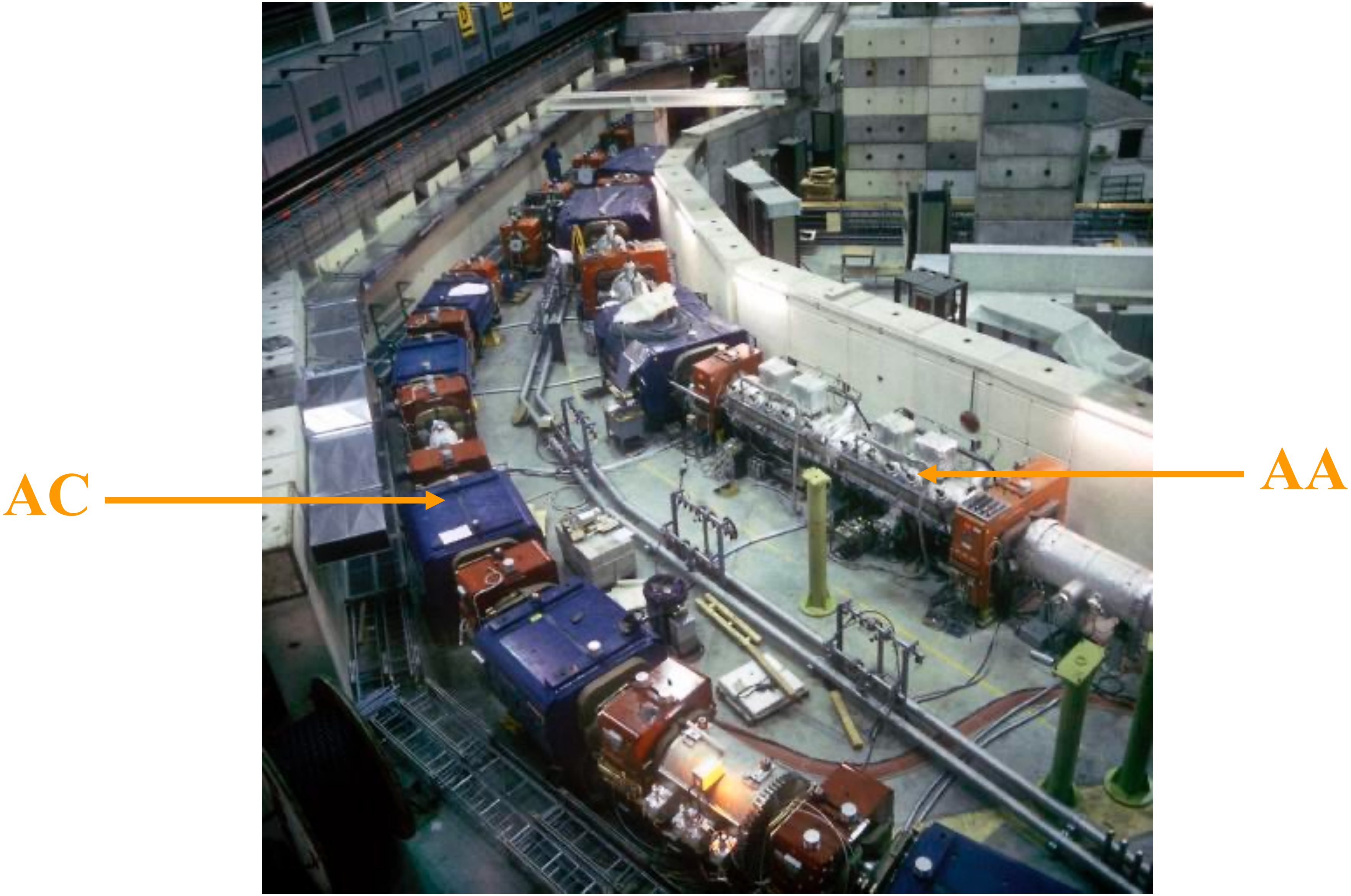
After one day the core contains enough $\bar{p}$'s for transfer to the SPS

The remaining $\bar{p}$'s are used for next day accumulation

Sketch of the CERN accelerators in the early 1980's



1986 – 90: add another ring (“Antiproton Collector” AC) around the AA – larger acceptance for single $\bar{p}$ pulses (7 x 10^7 $\bar{p}$ / pulse ⇒ ~ tenfold increase of stacking rate)



Proton – antiproton collider operation, 1981 - 90

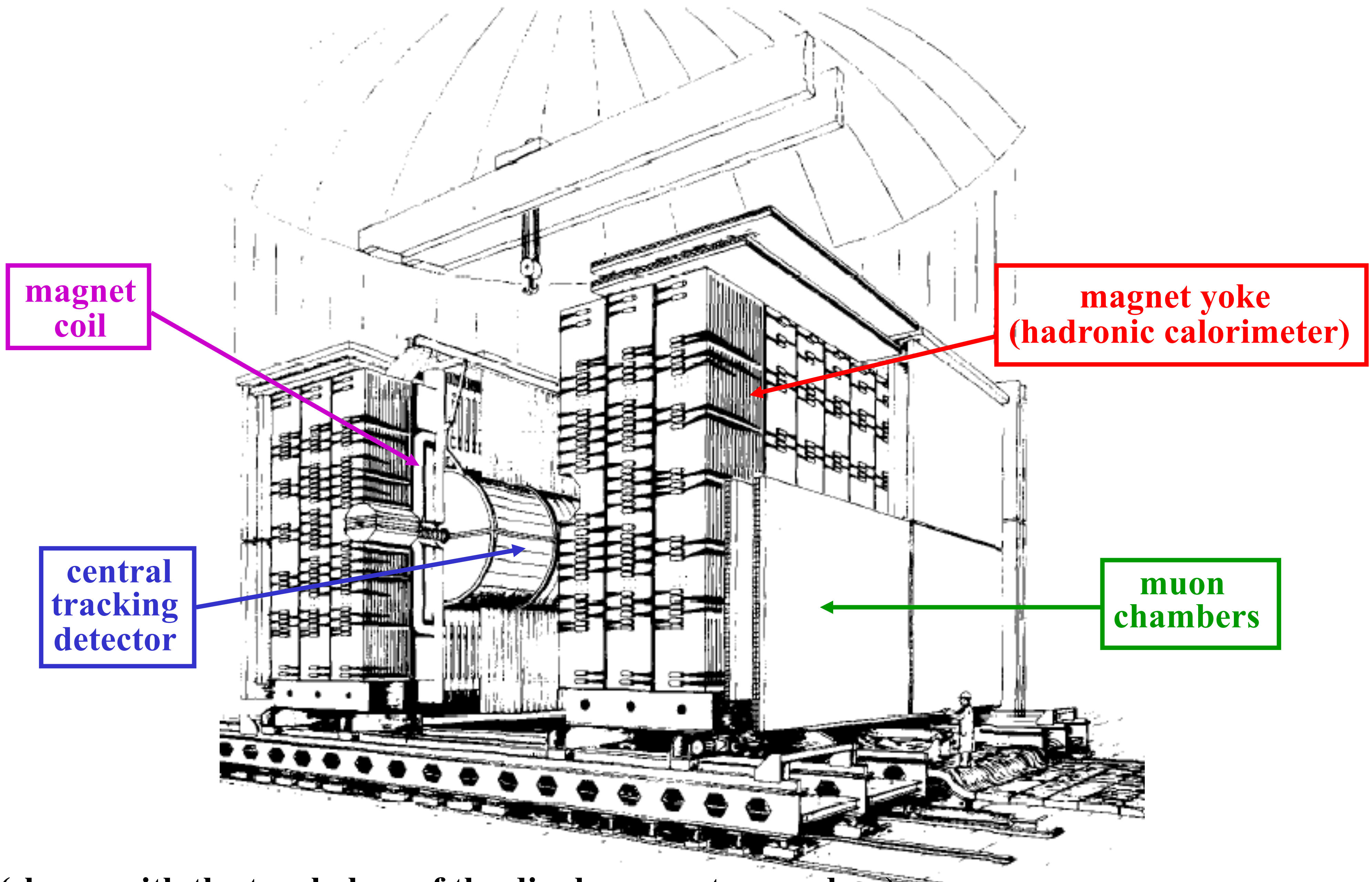
Year	Collision Energy (GeV)	Peak luminosity (cm^{-2} s^{-1})	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2.0×10^{32}
1982	546	5×10^{28}	2.8×10^{34}
1983	546	1.7×10^{29}	1.5×10^{35}
1984-85	630	3.9×10^{29}	1.0×10^{36}
1987-90	630	$\sim 2 \times 10^{30}$	1.6×10^{37}

← W discovery

← Z discovery

1991: end of collider operation

UA1 detector



magnet coil

magnet yoke (hadronic calorimeter)

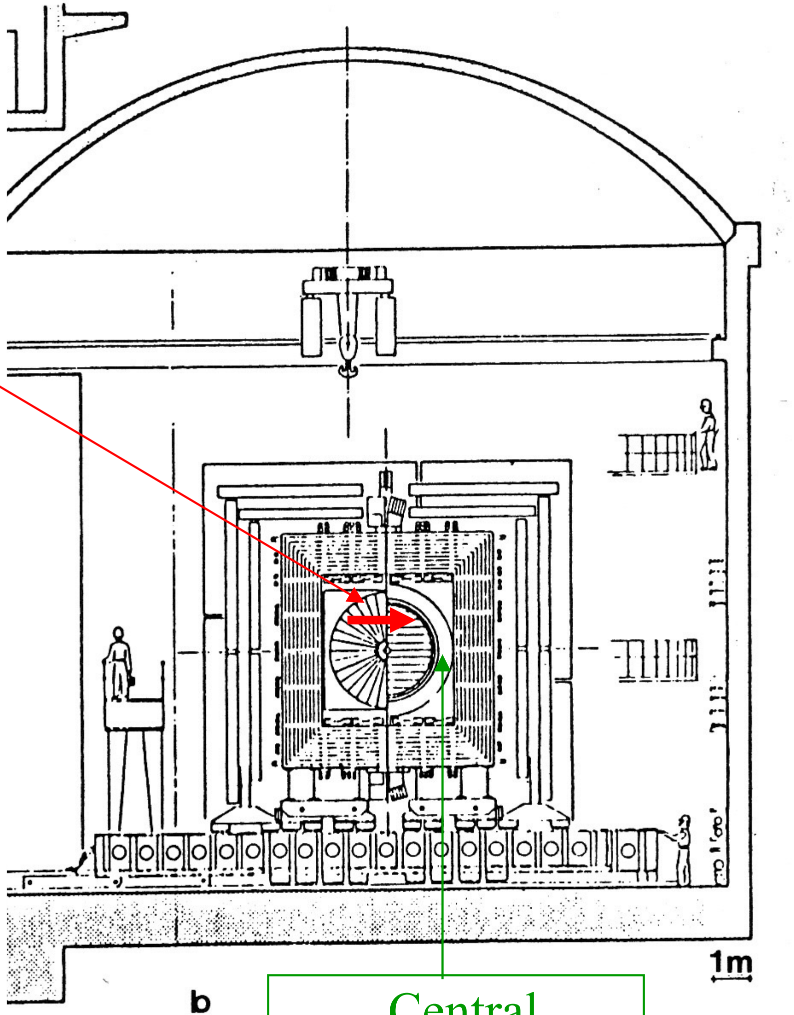
central tracking detector

muon chambers

(shown with the two halves of the dipole magnet opened up)

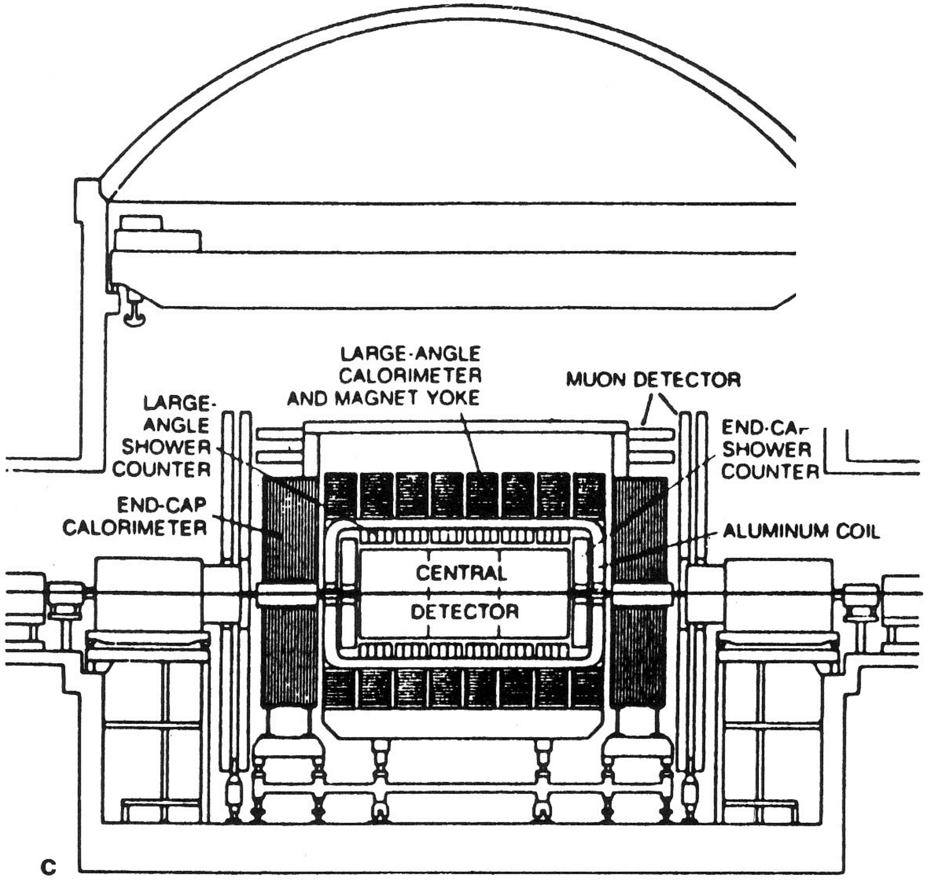
View normal to beam axis

Magnetic field direction
B = 0.7 T

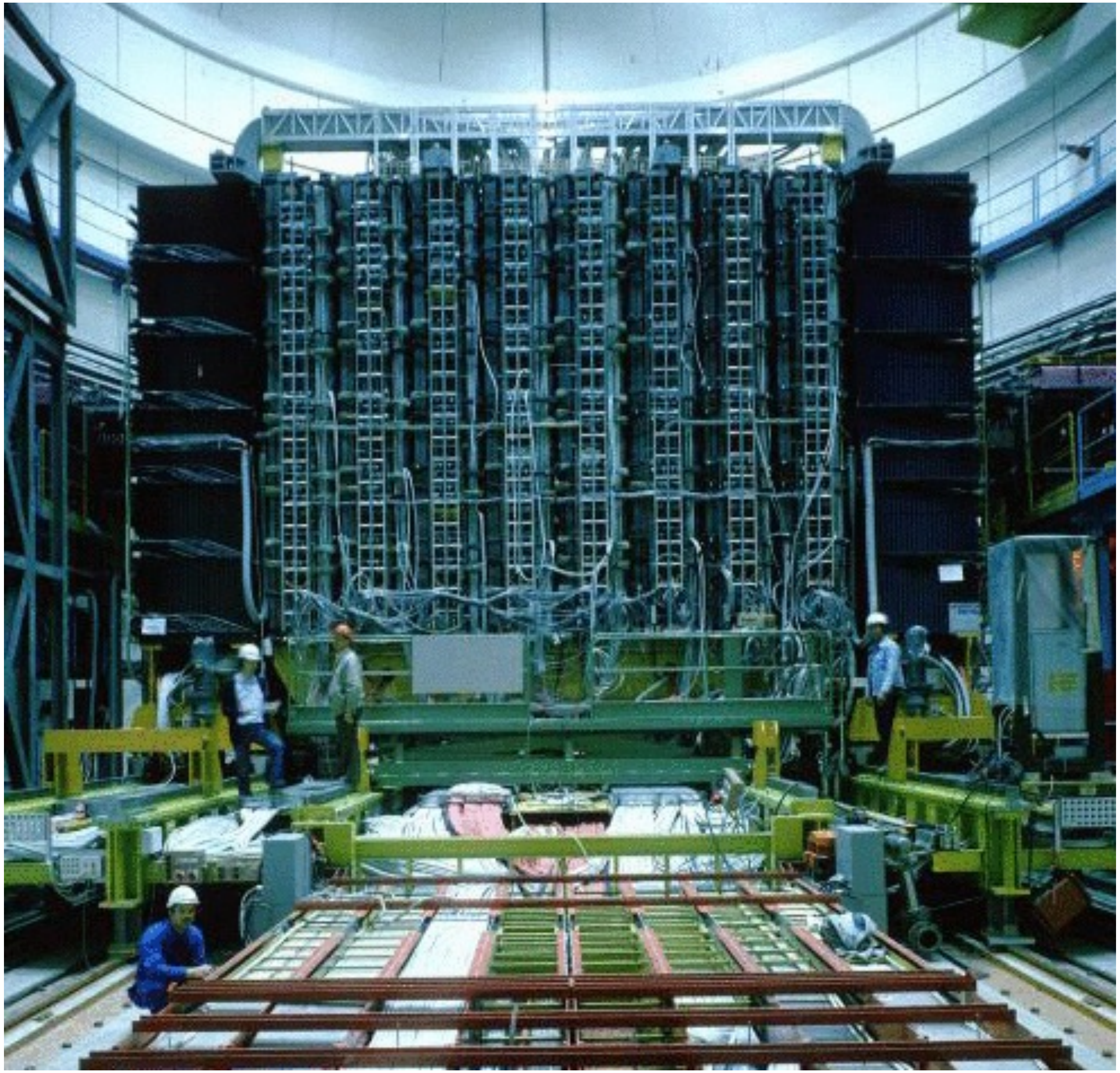


Central electromagnetic calorimeter

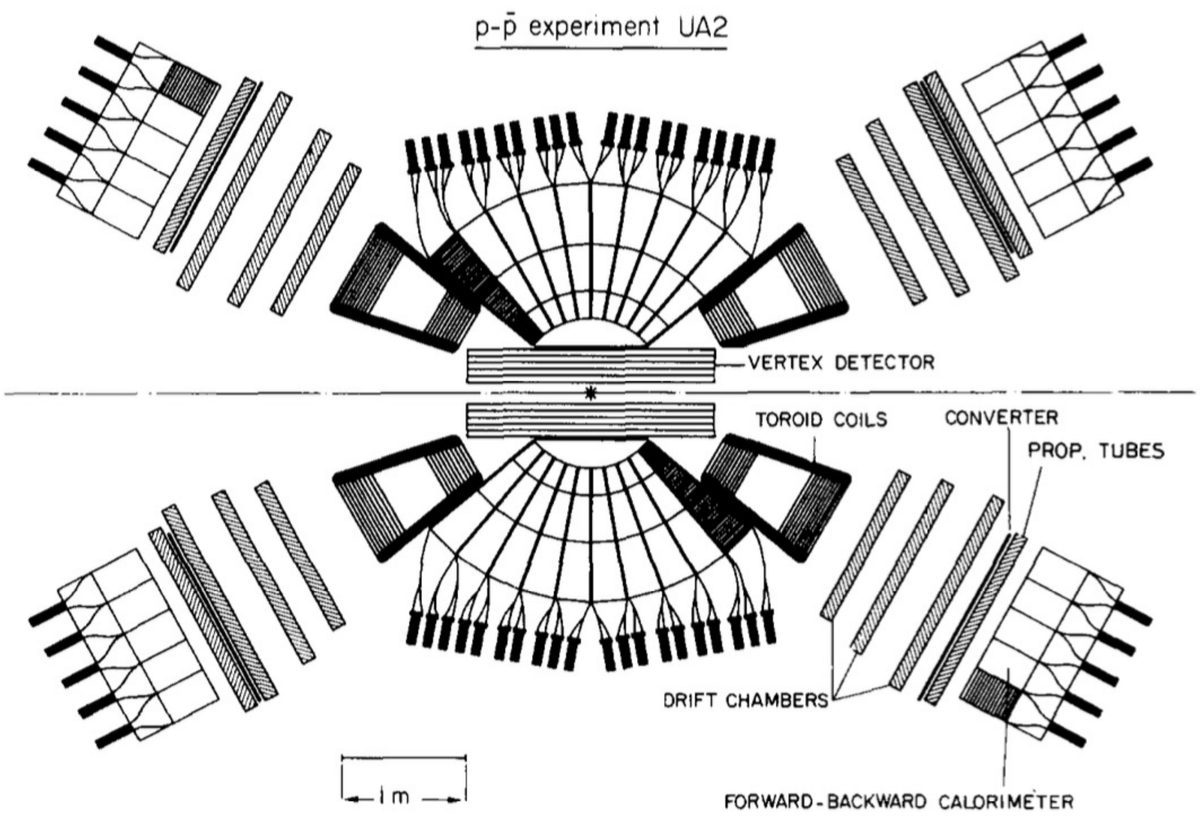
Vertical section along beam axis



UA1 detector during assembly



UA2 Detector 1981 - 85

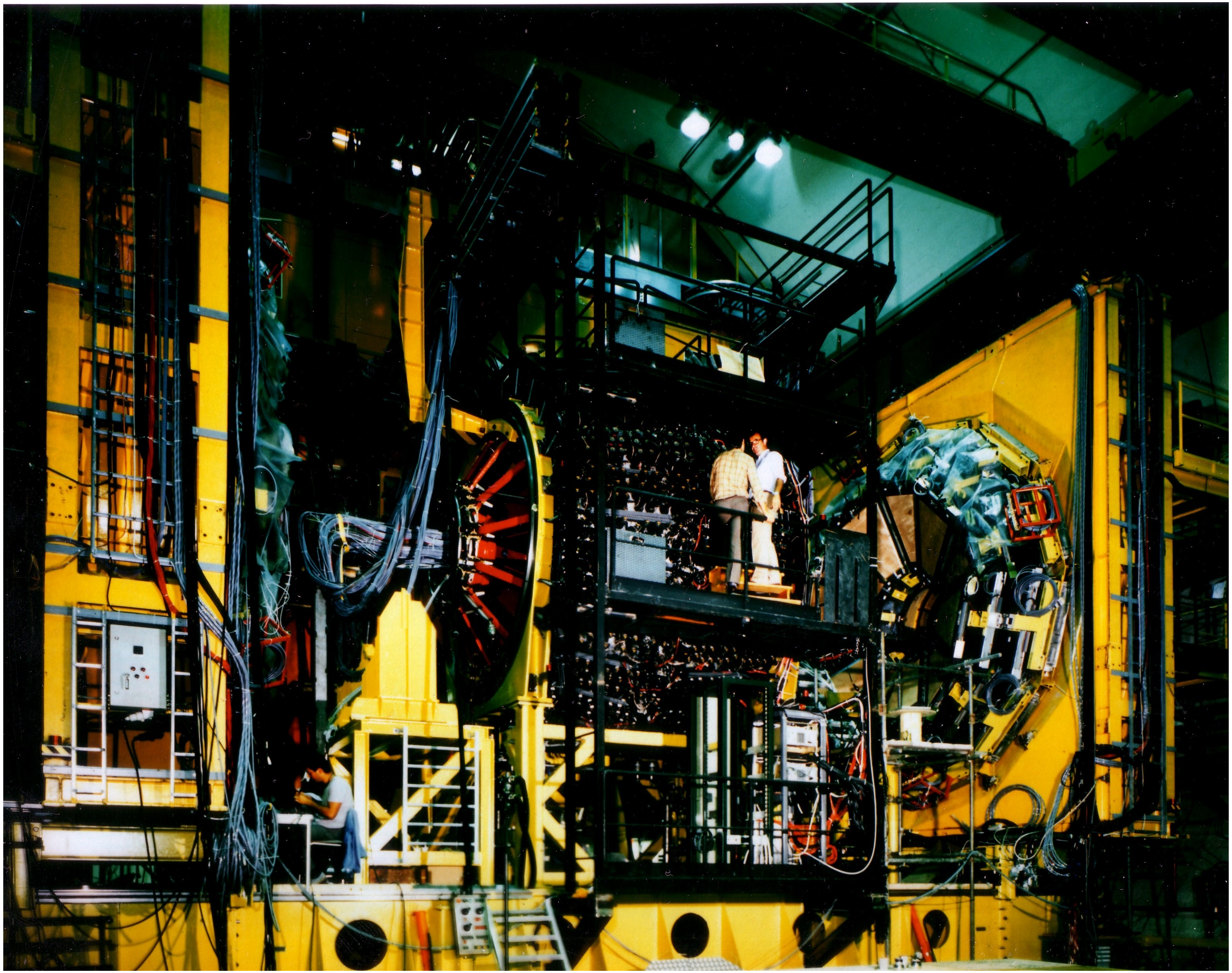


Central region: tracking detector ("vertex detector");
"pre-shower" detector (tungsten cylinder 1.5 X_0 thick + MWPC)
electromagnetic and hadronic calorimeters ($\Delta\theta = 10^{O}$, $\Delta\phi = 15^{O}$)
no magnetic field

20° – 40° regions : toroidal magnetic field;
tracking detectors;
"pre-shower" detector + electromagnetic calorimeter.

No muon detector

UA2 detector during assembly



Electron identification

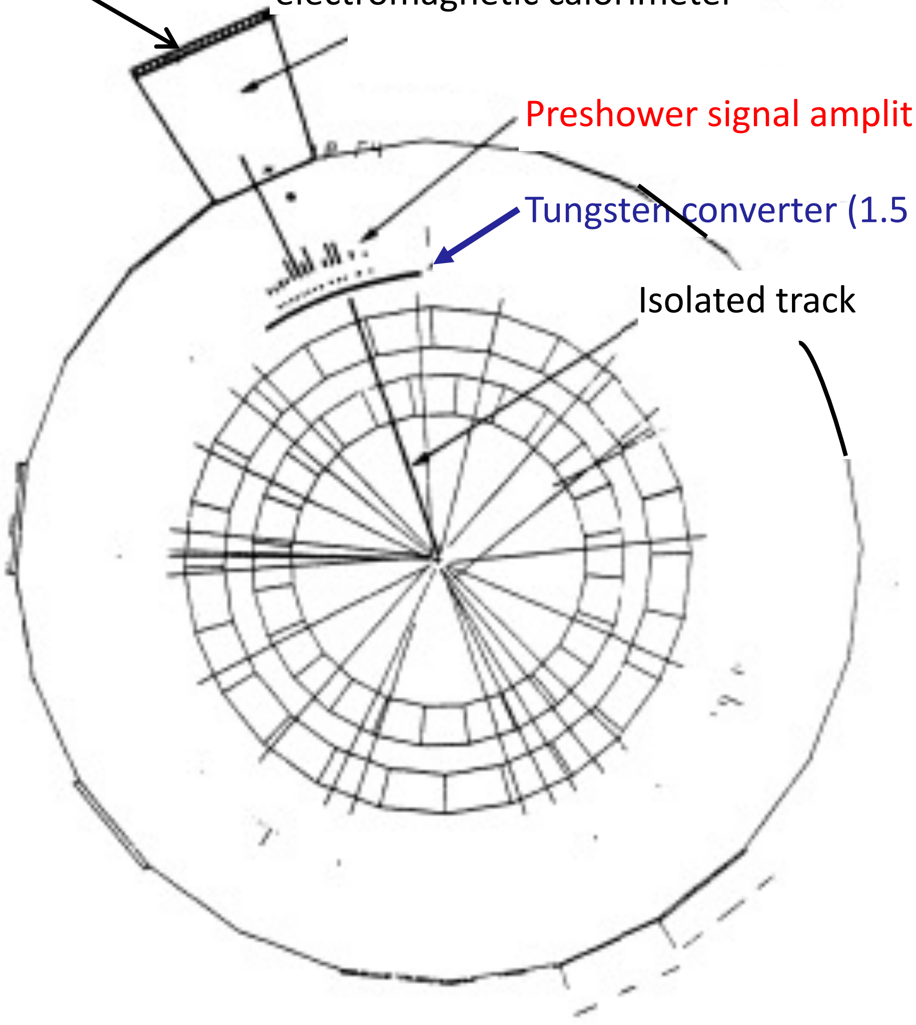
Calorimeter requirements (UA1, UA2) : energy deposition consistent with an isolated electron (fraction of energy deposited in the electromagnetic calorimeter > 90%, limited shower lateral size).

- UA1, UA2: isolated track pointing to the calorimeter energy cluster.
- UA1: track momentum consistent with energy deposition.
- UA2: "preshower" detector in front of the e.m. calorimeter to measure the track – associated energy in a MWPC located after a high-Z converter.

Muons (UA1 only)

- Tracks with energy deposition in calorimeters consistent with energy loss by ionization, detected in muon chambers.
- Track momentum measurement from curvature in magnetic field; momentum measurement ~10 times less precise than electron energy measurement in calorimeter.

UA2



Energy deposition in hadronic calorimeter

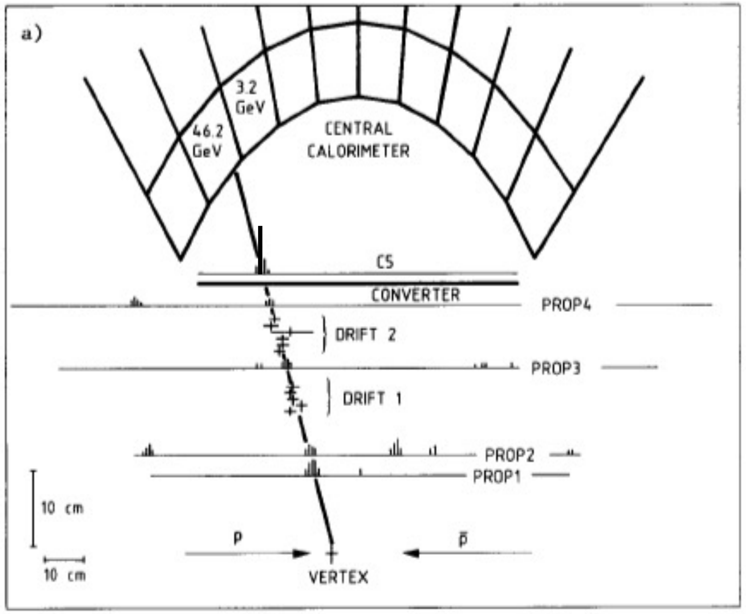
Energy deposition in electromagnetic calorimeter

Preshower signal amplitude

Tungsten converter (1.5 X_O)

Isolated track

Most likely, conversion
of a high-energy photon
in the preshower converter



Electron
from Z → e^+e^- decay

W discovery

Dominant decay mode (~70%) $W \to q\,\bar{q}' \to$ two hadronic jets ovewhelmed by two-jet background from QCD processes

⇒ search for leptonic decays:

$W^+ \to e^+ + \nu_e$ (UA1, UA2) $W^+ \to \mu^+ + \nu_\mu$ (UA1 only) (and charge-conjugate decays)

Expected signal from $W \to e\,\nu$ decay:

- **large transverse momentum (p_T) isolated electron**
- **p_T distribution peaks at $m_W / 2$ ("Jacobian peak")**
- **large missing transverse momentum from the undetected neutrino**

(W produced by quark-antiquark annihilation, e.g. $u + \bar{d} \to W^+$, is almost collinear with beam axis; decay electron and neutrino emitted at large angles to beam axis have large p_T)

NOTE

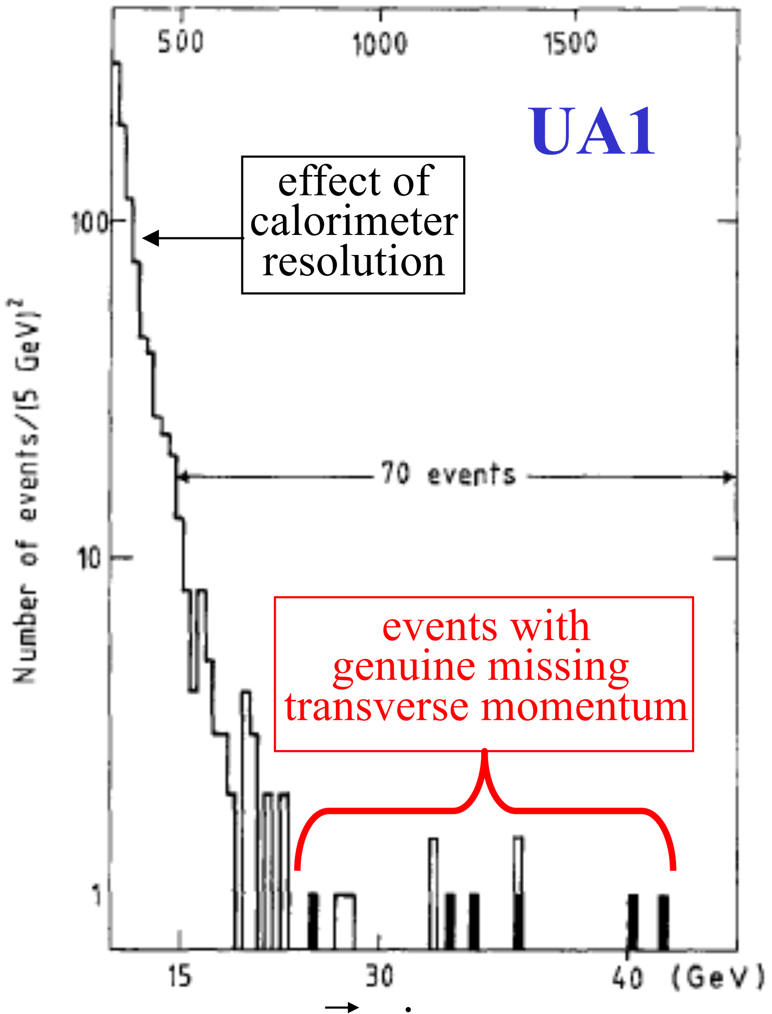
Missing longitudinal momentum cannot be measured at hadron colliders because of large number of high-energy secondary particles emitted at very small angles inside the machine vacuum pipe

Missing transverse momentum ($\vec{p}_T^{\,\text{miss}}$)

- **Associate momentum vector $\vec{p}$ to each calorimeter cell with energy deposition > 0**
- **Direction of $\vec{p}$ from event vertex to cell centre**
- **$|\vec{p}|$ = energy deposited in cell**
- **Definition:**

$$\vec{p}_T^{\,\text{miss}} + \sum_{cells} \vec{p}_T = 0$$

(momentum conservation in plane perpendicular to beam axis)



UA1

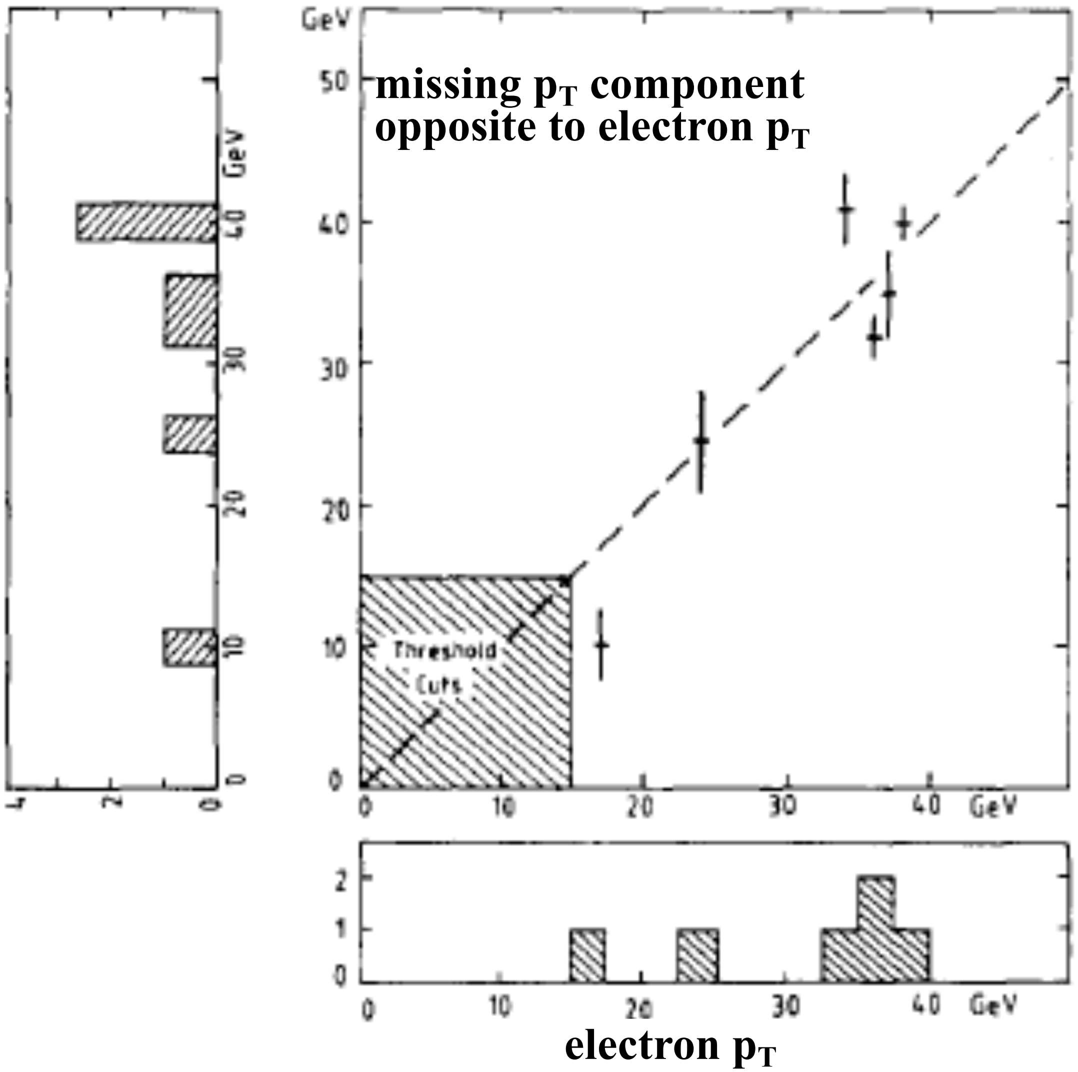
effect of calorimeter resolution

events with genuine missing transverse momentum

$|\vec{p}_T^{\,\text{miss}}|$ (GeV/c)

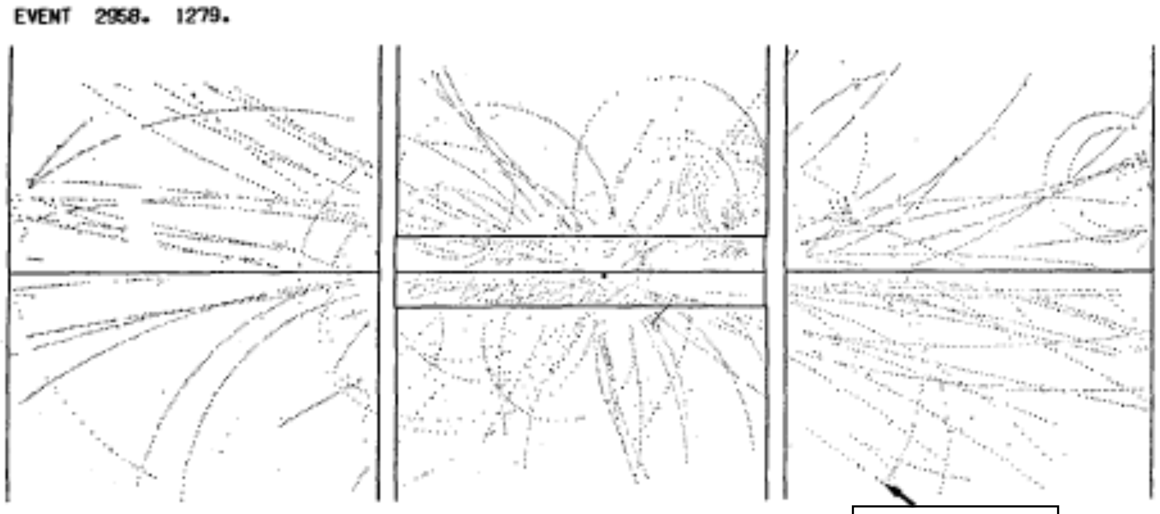
▌ Six events containing a large p_T electron

UA1: correlation between electron p_T and missing p_T

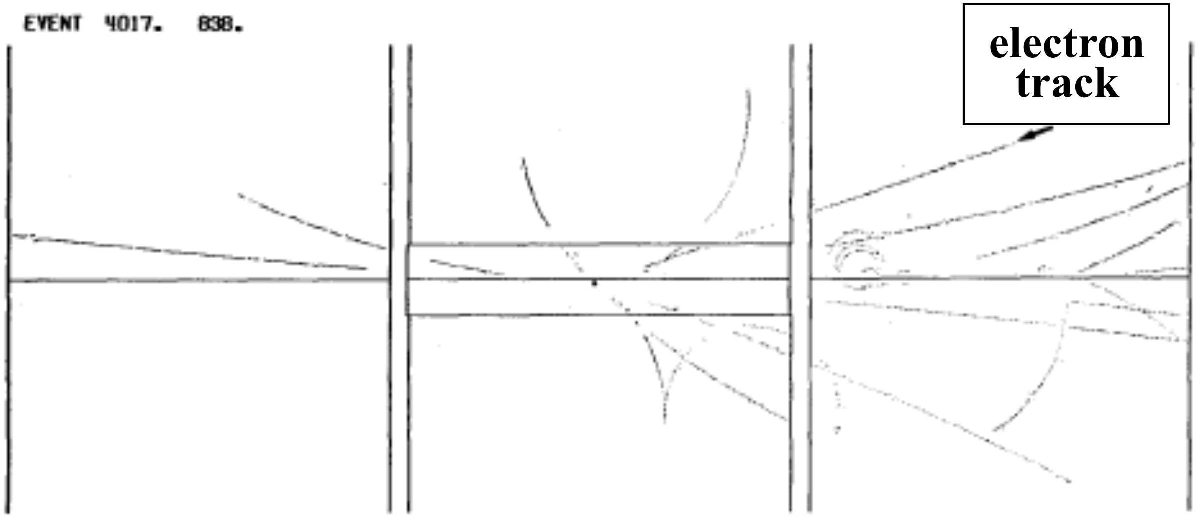


Six events with large p_T electron and large missing p_T opposite to electron p_T consistent with $W \rightarrow e\,\nu$ decay
(result announced at a CERN seminar on January 20, 1983)

Two UA1 W → e ν events



electron track



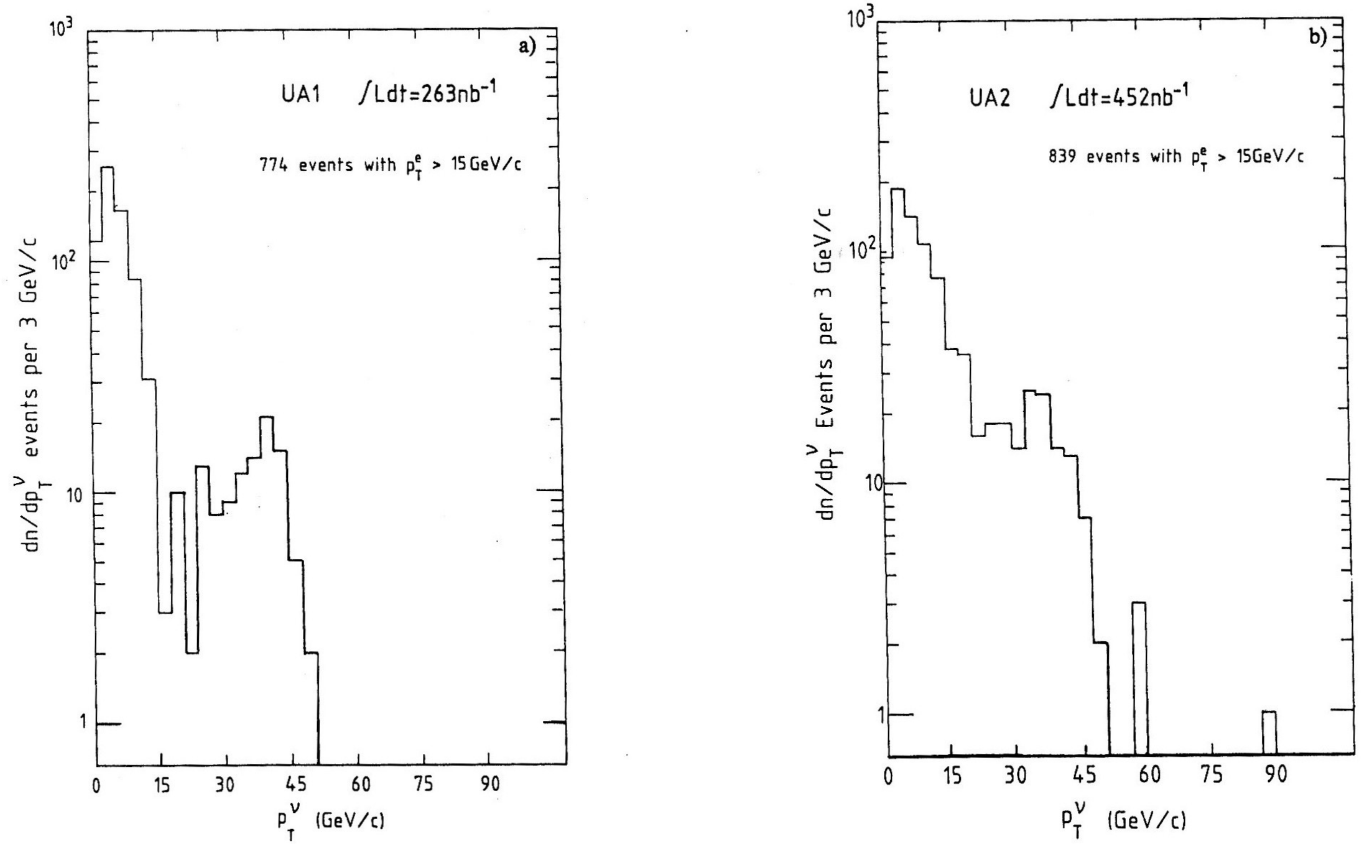
electron track

Measurement of the missing transverse momentum

Before the analysis of the first $\bar{p}$ p collider data (1981 – 82), the importance of measuring the missing transverse momentum (p_T^{miss}) had not been fully acknowledged.
The lack of full calorimeter coverage in the UA2 detector could introduce unknown systematic errors in the p_T^{miss} measurement.

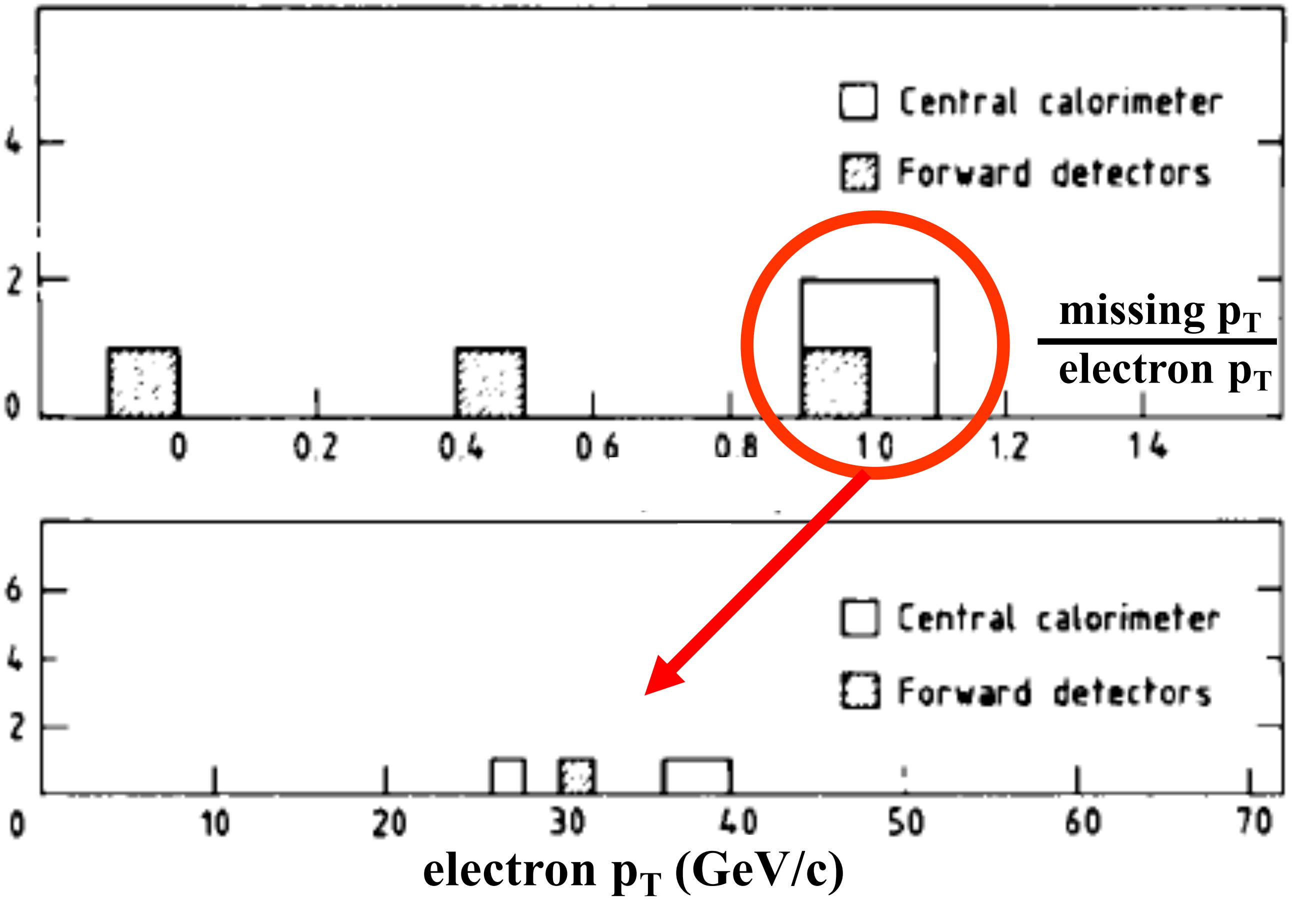
UA1 – UA2 comparison of p_T^{miss} distributions in events containing p_T > 15 GeV/c electrons

(from all data collected until 1985)

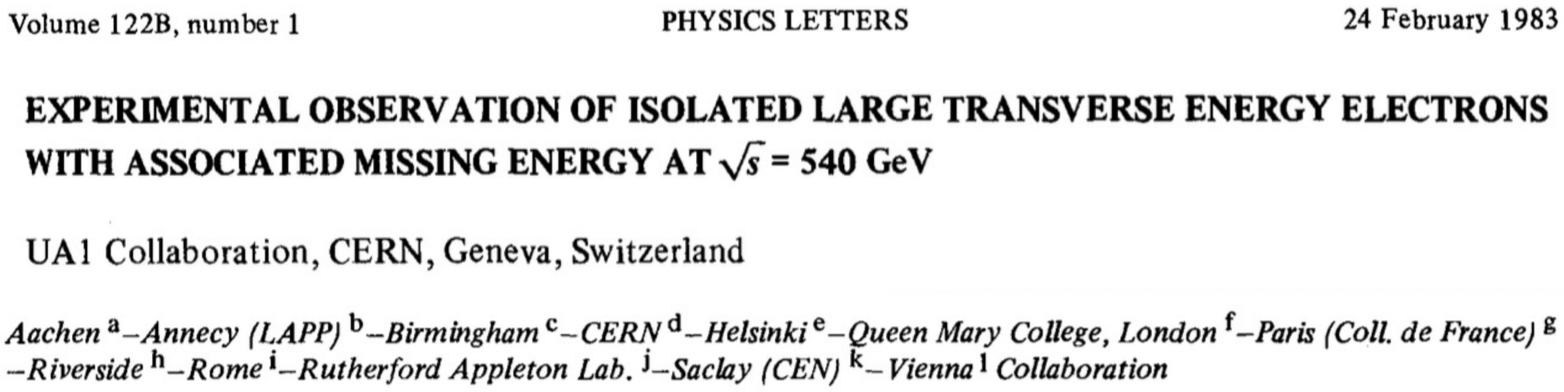


The effect of the incomplete UA2 calorimeter coverage is evident

UA2 : Six events containing an electron with $p_T > 15$ GeV/c



Result announced at a CERN seminar on January 21, 1983

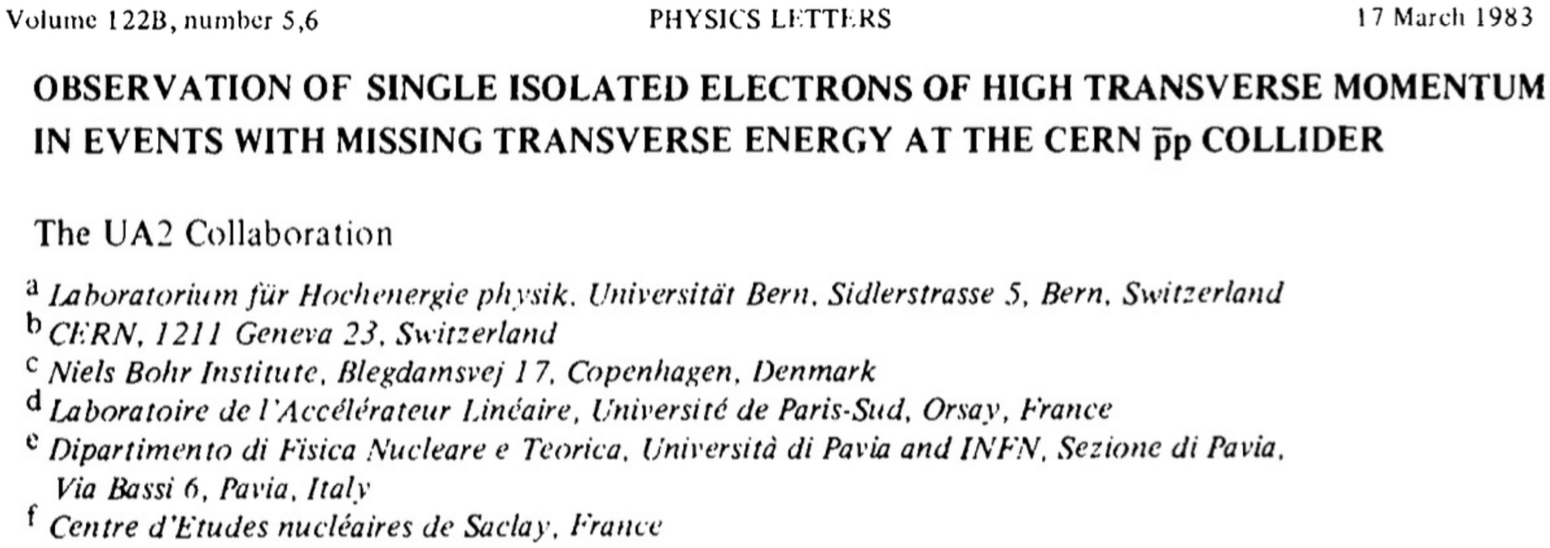


Volume 122B, number 1 PHYSICS LETTERS 24 February 1983

EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s}$ = 540 GeV

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen [a]*–Annecy (LAPP)* [b]*–Birmingham* [c]*–CERN* [d]*–Helsinki* [e]*–Queen Mary College, London* [f]*–Paris (Coll. de France)* [g]*–Riverside* [h]*–Rome* [i]*–Rutherford Appleton Lab.* [j]*–Saclay (CEN)* [k]*– Vienna* [l] *Collaboration*



Volume 122B, number 5,6 PHYSICS LETTERS 17 March 1983

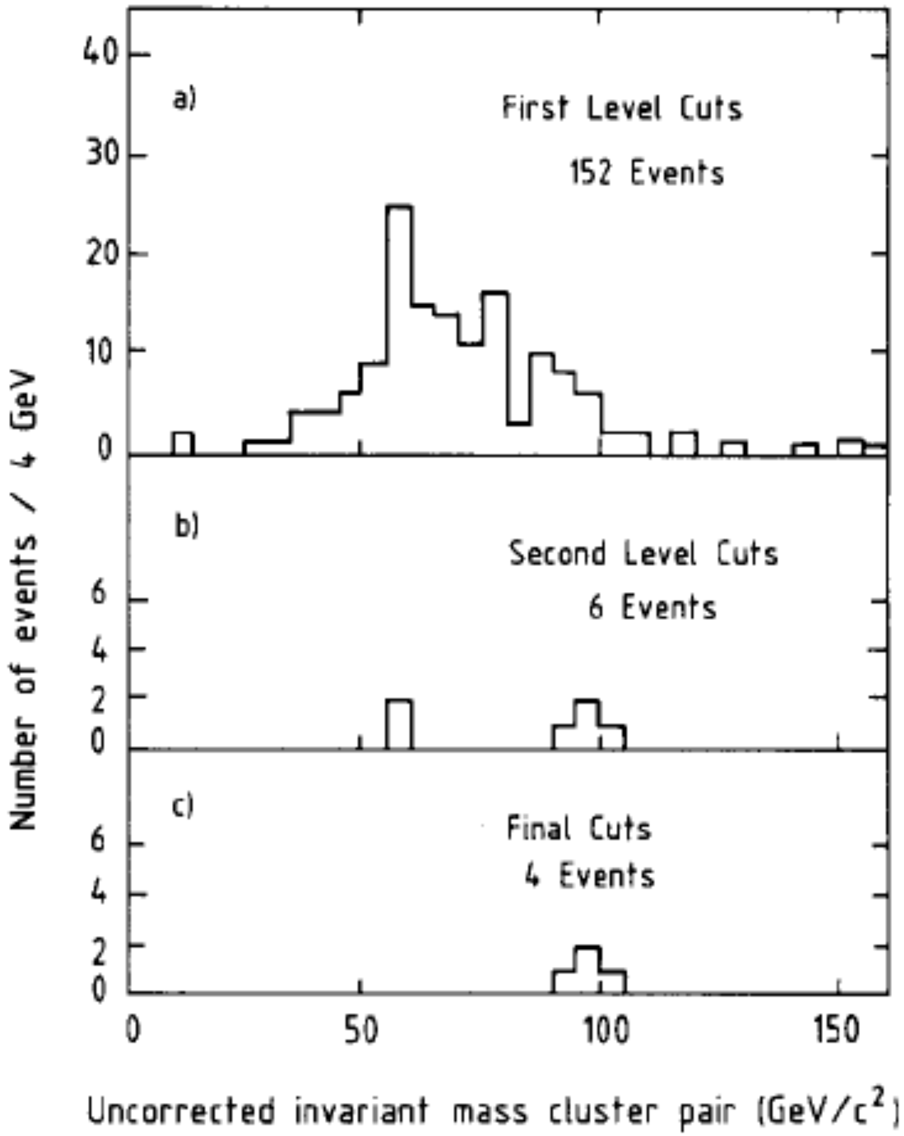
OBSERVATION OF SINGLE ISOLATED ELECTRONS OF HIGH TRANSVERSE MOMENTUM IN EVENTS WITH MISSING TRANSVERSE ENERGY AT THE CERN $\bar{p}p$ COLLIDER

The UA2 Collaboration

[a] *Laboratorium für Hochenergie physik, Universität Bern, Sidlerstrasse 5, Bern, Switzerland*
[b] *CERN, 1211 Geneva 23, Switzerland*
[c] *Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark*
[d] *Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Orsay, France*
[e] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via Bassi 6, Pavia, Italy*
[f] *Centre d'Etudes nucléaires de Saclay, France*

UA1: observation of $Z \rightarrow e^+ e^-$

(May 1983)

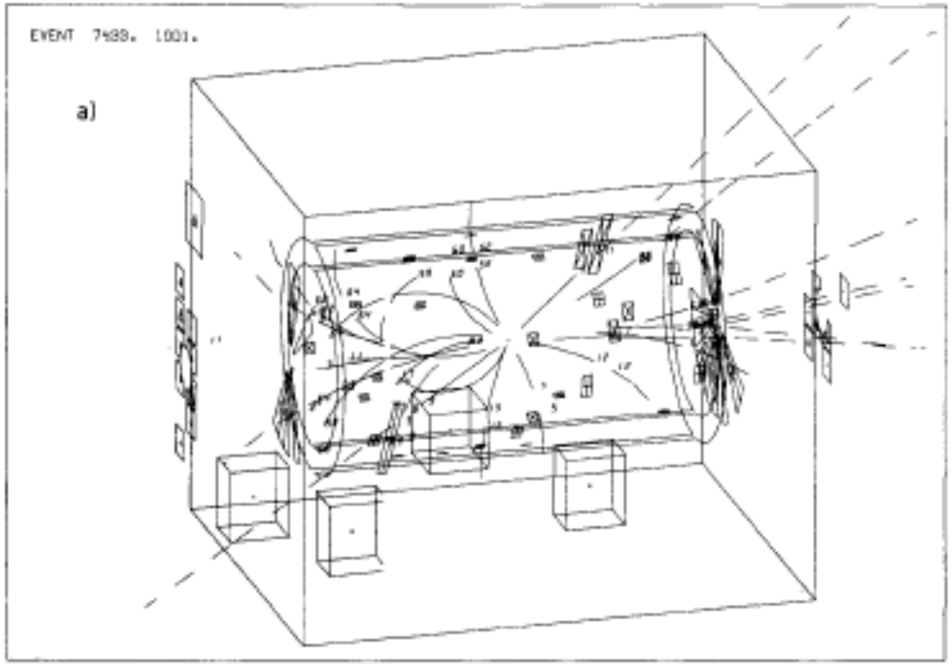


Two energy clusters ($p_T > 25$ GeV) in electromagnetic calorimeters; energy leakage in hadronic calorimeters consistent with electrons

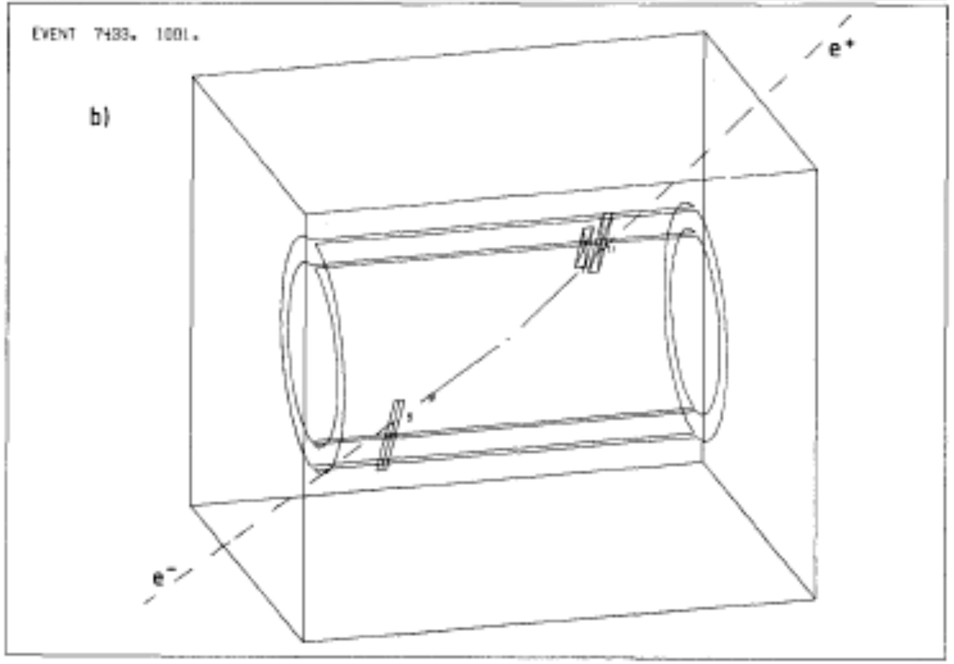
Isolated track with $p_T > 7$ GeV pointing to at least one cluster

Isolated track with $p_T > 7$ GeV pointing to both clusters

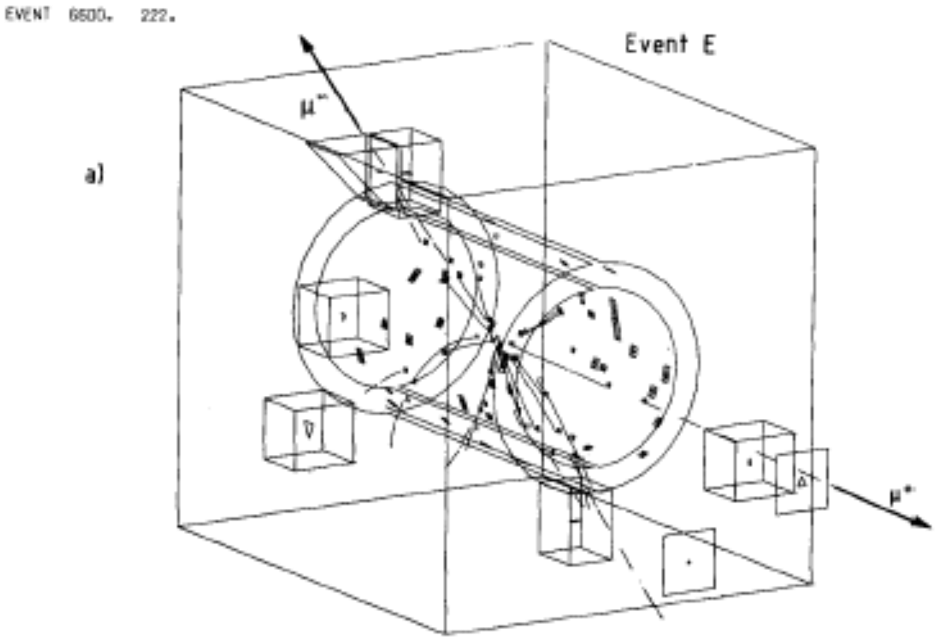
UA1 Z → $e^+ e^-$ event



Display of all reconstructed tracks and calorimeter hits



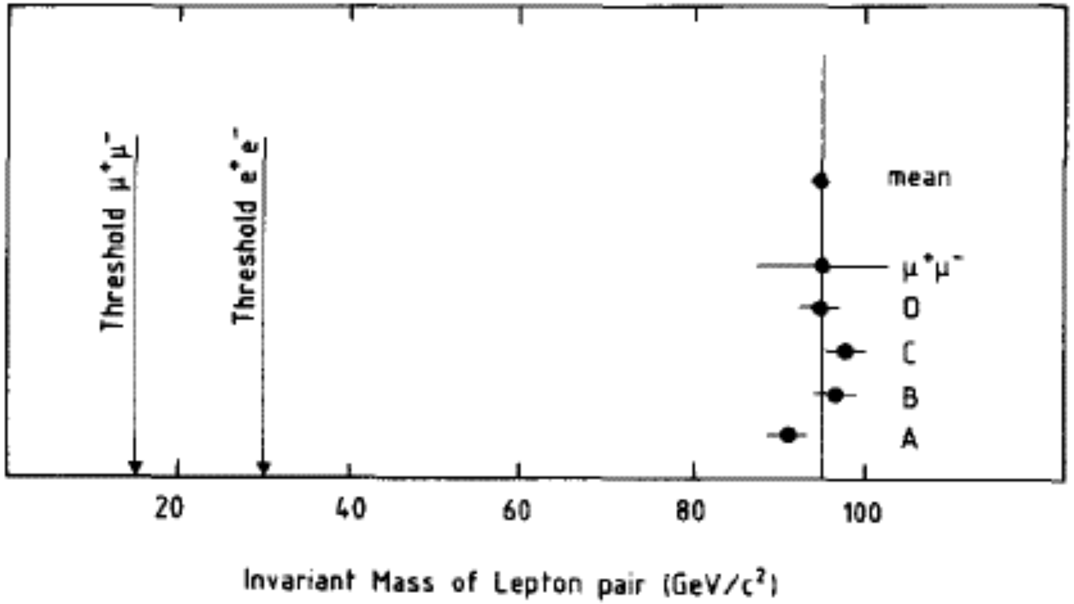
Display of tracks and calorimeter hits with $p_T > 2$ GeV



UA1 $Z \rightarrow \mu^+ \mu^-$ event

(May 1983)

The only $\mu^+ \mu^-$ pair observed during the 1983 collider run

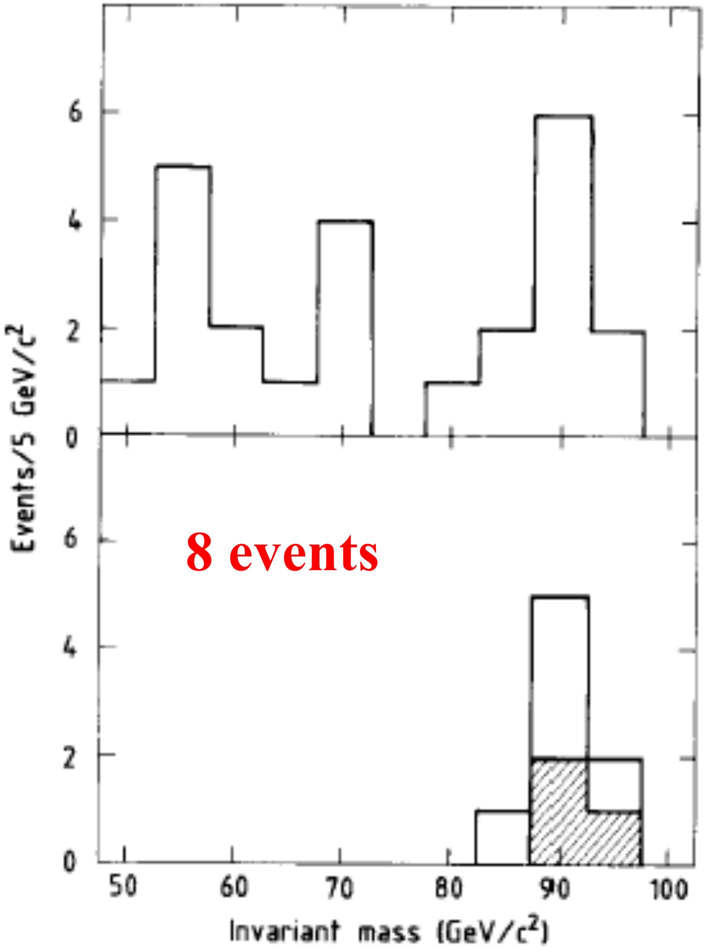


UA1:
all lepton pairs
from the 1983 run

$$m_Z = 95.2 \pm \underset{\text{(stat)}}{2.5} \pm \underset{\text{(syst)}}{3.0}\ \text{GeV}/c^2$$

UA2: observation of $Z \rightarrow e^+ e^-$

(June 1983)



8 events

Two energy clusters with $p_T > 25$ GeV
in electromagnetic calorimeters;
energy leakage in hadronic calorimeters
consistent with electrons

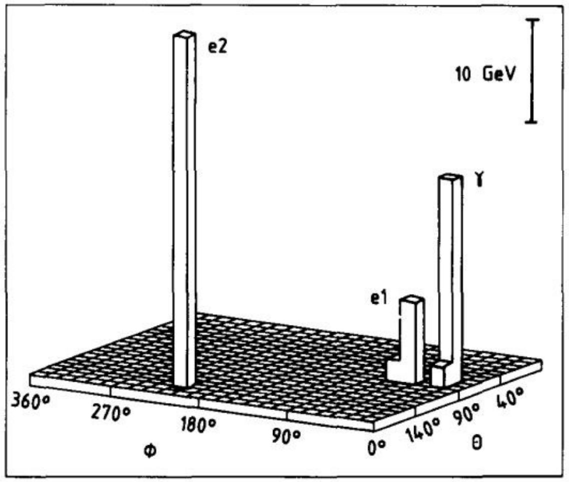
A track identified as an isolated electron
pointing to at least one of the two clusters

▨ Track identified as an isolated electron
pointing to both energy clusters

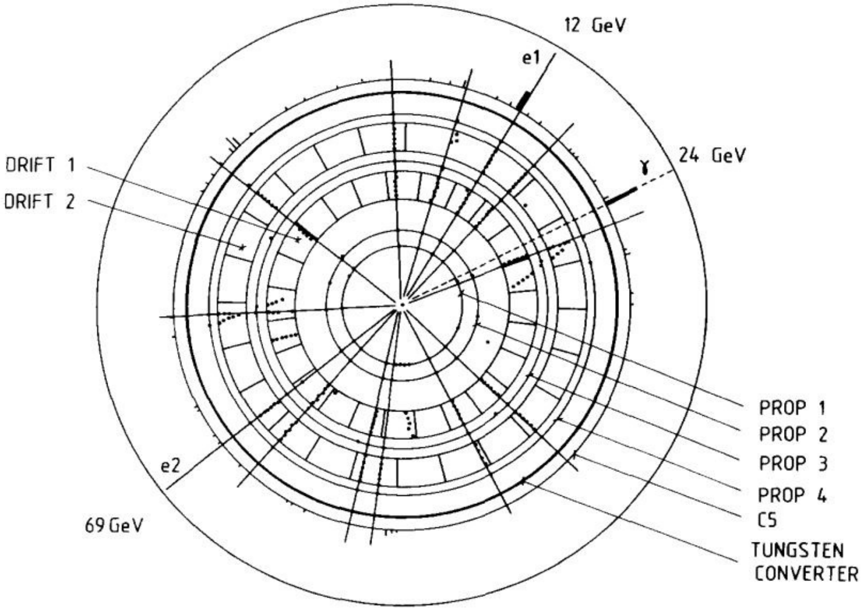
$$m_Z = 91.9 \pm \underset{\text{(stat)}}{1.3} \pm \underset{\text{(syst)}}{1.4} \text{ GeV/c}^2$$

One of the 8 events : a Z → $e^+e^-\gamma$ decay with a hard photon (24 GeV) well separated from the nearer electron.

Estimated probability from radiative corrections:
~ 1/200 Z → $e^+e^-(\gamma)$ decays.



Nevertheless, several theoretical papers were published interpreting this event in terms of new physics beyond the Standard Model.



At the end of UA2 (1990), the final Z → e^+e^- decay sample consisted of ~250 events with no other $e^+e^-\gamma$ event with non-collinear, hard photons.

BEWARE OF STATISTICAL FLUCTUATIONS !

Volume 126B, number 5 PHYSICS LETTERS 7 July 1983

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c^2 AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen [a] *–Annecy (LAPP)* [b] *–Birmingham* [c] *–CERN* [d] *–Helsinki* [e] *–Queen Mary College, London* [f] *–*
Paris (Coll. de France) [g] *–Riverside* [h] *–Rome* [i] *–Rutherford Appleton Lab.* [j] *–Saclay (CEN)* [k] *– Vienna* [h] *Collaboration*

Volume 129, number 1,2 PHYSICS LETTERS 15 September 1983

EVIDENCE FOR $Z^0 \rightarrow e^+e^-$ AT THE CERN $\bar{p}p$ COLLIDER

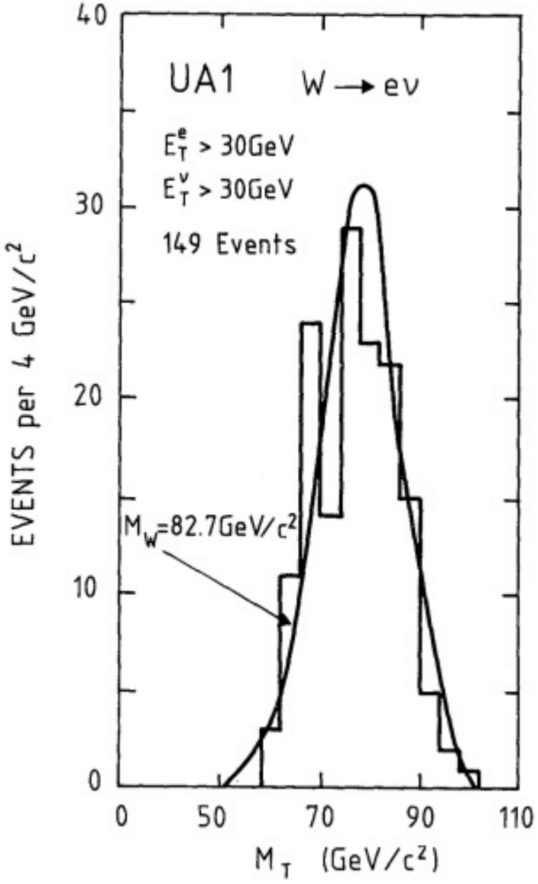
The UA2 Collaboration

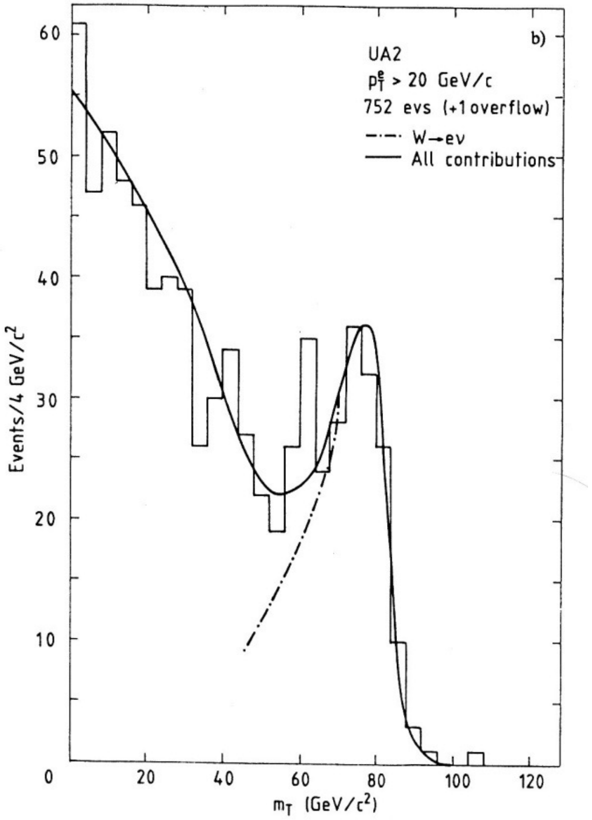
[a] *Laboratorium für Hochenergiephysik, Universität Bern, Sidlerstrasse 5, Bern, Switzerland*
[b] *CERN, 1211 Geneva 23, Switzerland*
[c] *Niels Bohr Institute, Blegdamsvej 17, Copenhagen, Denmark*
[d] *Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, Orsay, France*
[e] *Dipartimento di Fisica Nucleare e Teorica, Università di Pavia and INFN, Sezione di Pavia, Via Bassi 6, Pavia, Italy*
[f] *Centre d'Etudes Nucléaires de Saclay, France*

W → e ν : results from 1982 – 85 data
"transverse mass" (m_T) distribution

m_T : invariant mass calculated using electron and neutrino momentum components orthogonal to beam axis (m_T does not depend on W p_T)

$$m_T{}^2 = \left(\left|\vec{p}_T^{\,e}\right| + \left|\vec{p}_T^{\,\nu}\right|\right)^2 - \left(\vec{p}_T^{\,e} + \vec{p}_T^{\,\nu}\right)^2$$

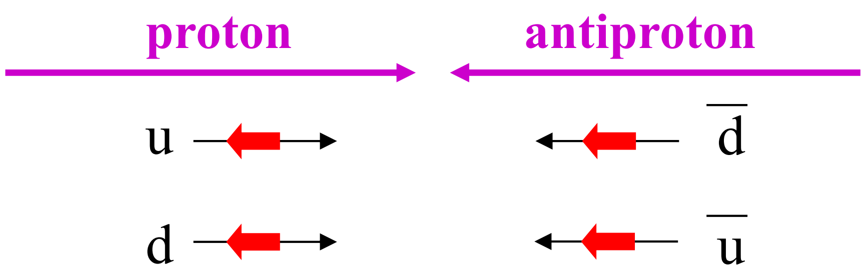




UA1: m_W = 82.7 ± 1.0(stat) **± 2.7**(syst) **GeV/c²**

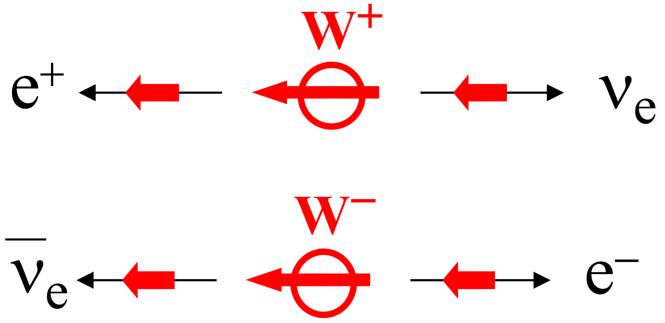
UA2: m_W = 80.2 ± 0.8(stat) **± 1.3**(syst) **GeV/c²**

Charge asymmetry in $W \to e\,\nu$ decay



$W^{\pm}$ polarization along antiproton direction
(consequence of V – A coupling)

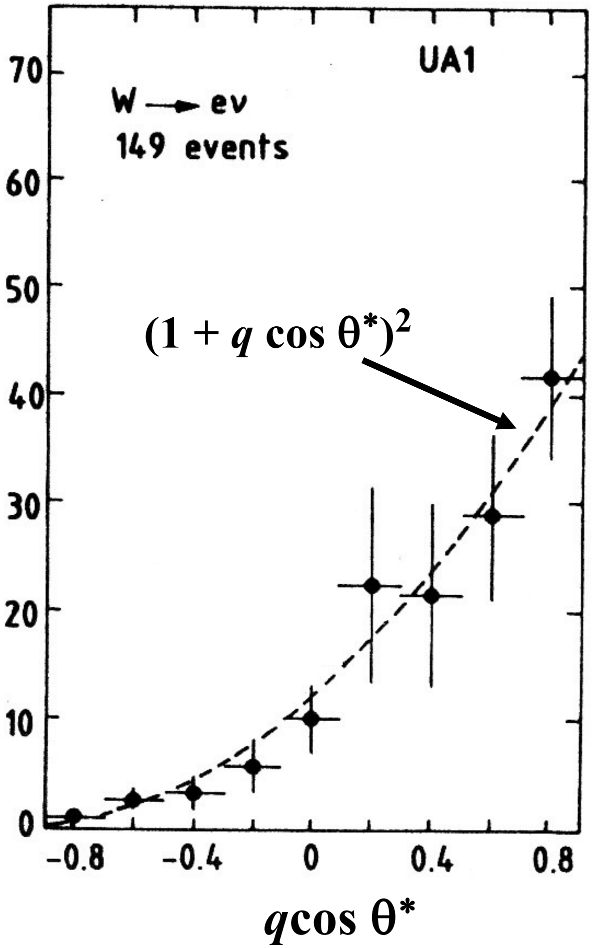
In the W rest frame:



Electron (positron) angular distribution:

$$\frac{dn}{d\cos\theta^*} \propto \left(1 + q\cos\theta^*\right)^2$$

$q = +1$ for positrons; $q = -1$ for electrons
$\theta^* = 0$ along antiproton direction

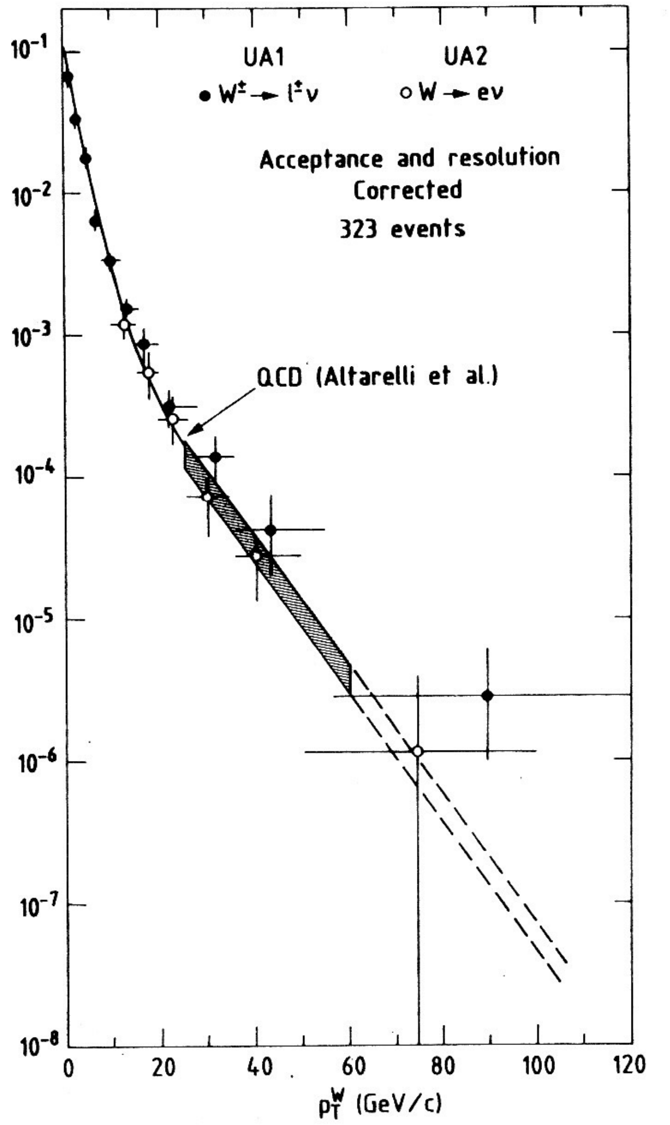


W transverse momentum ($\vec{p}_T^{\,W}$)

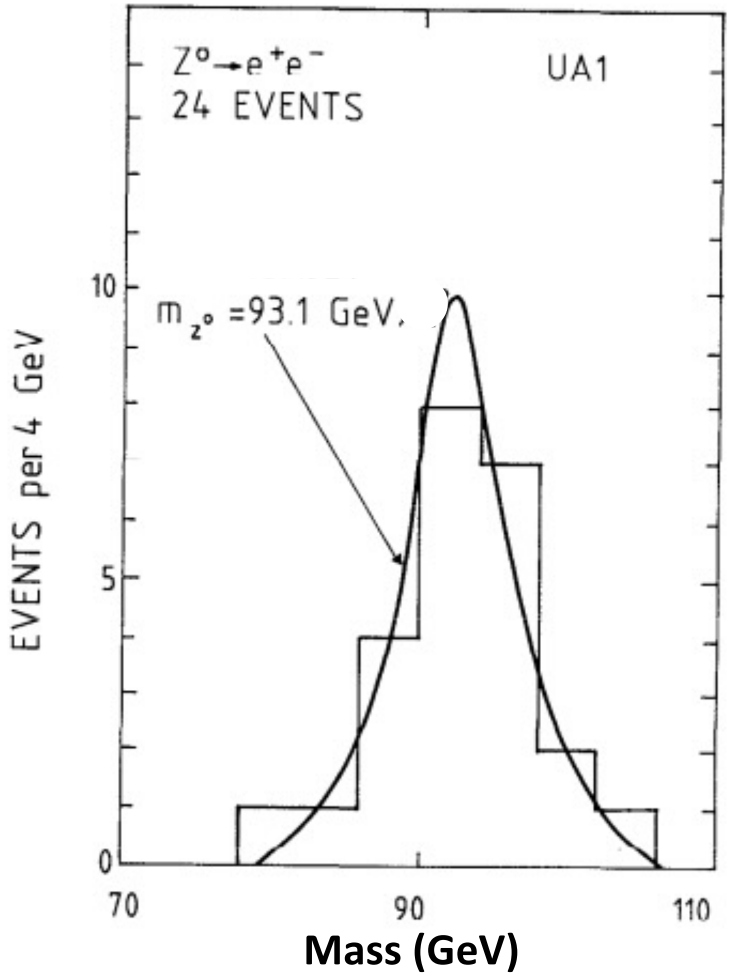
- $p_T^W \neq 0$ because of initial-state gluon radiation
- p_T^W equal and opposite to total transverse momentum carried by all hadrons produced in the same collision:

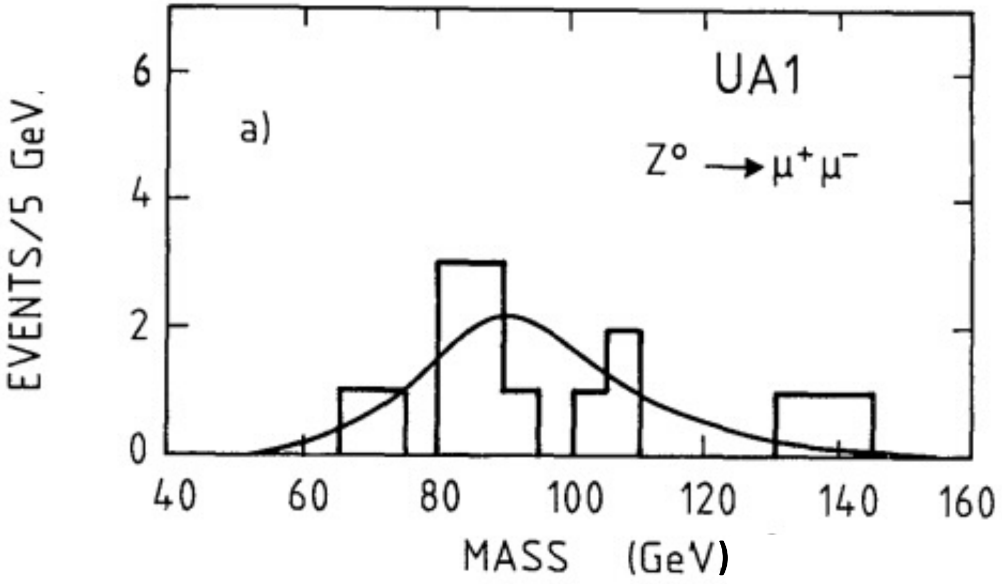
$$\vec{p}_T^{\,W} = -\sum_{hadrons} \vec{p}_T$$

- p_T^W distribution can be predicted from QCD



$Z \rightarrow e^+ e^-$: UA1 results, 1982 – 85 data

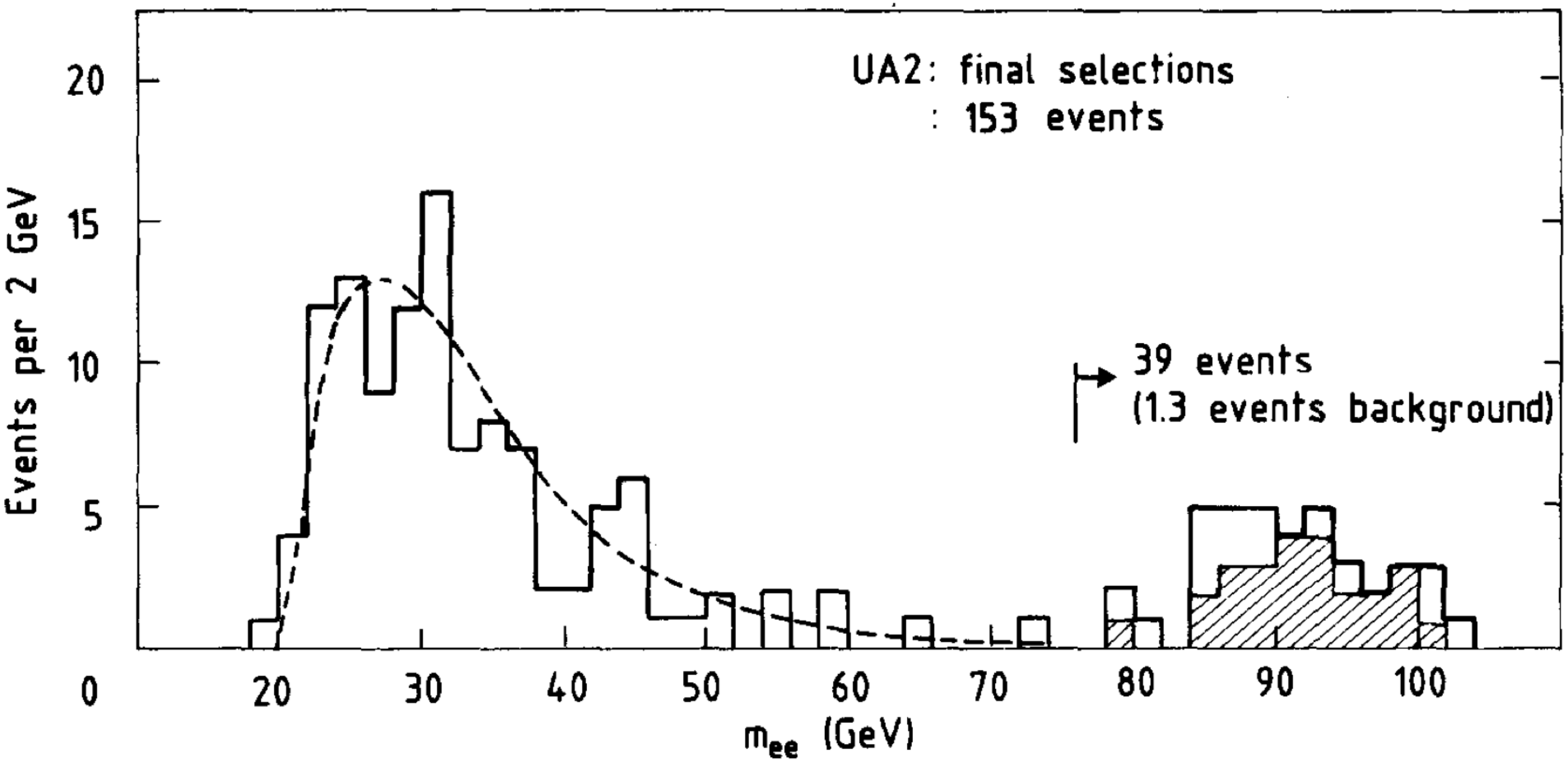




$Z \rightarrow \mu^+ \mu^-$: m_Z = **93.1 ± 5.0**(stat) **± 3.2**(syst) **GeV/c^2**

$Z \rightarrow e^+ e^-$: m_Z = **93.1 ± 1.0**(stat) **± 3.1**(syst) **GeV/c^2**

$Z \rightarrow e^+ e^-$: UA2 results, 1982 – 85 data



$$m_Z = \mathbf{91.5 \pm 1.2}(\text{stat}) \pm \mathbf{1.7}(\text{syst})\ \mathbf{GeV/c^2}$$

Production cross-section X decay branching ratio at $\sqrt{s} = 630$ GeV

$\sigma_W B(W \to e\nu) = 0.60 \pm 0.05 \pm 0.09$ nb (UA1)

$0.59 \pm 0.05 \pm 0.07$ nb (UA2)

stat. syst.

Theory : $0.45^{+0.14}_{-0.08}$ nb

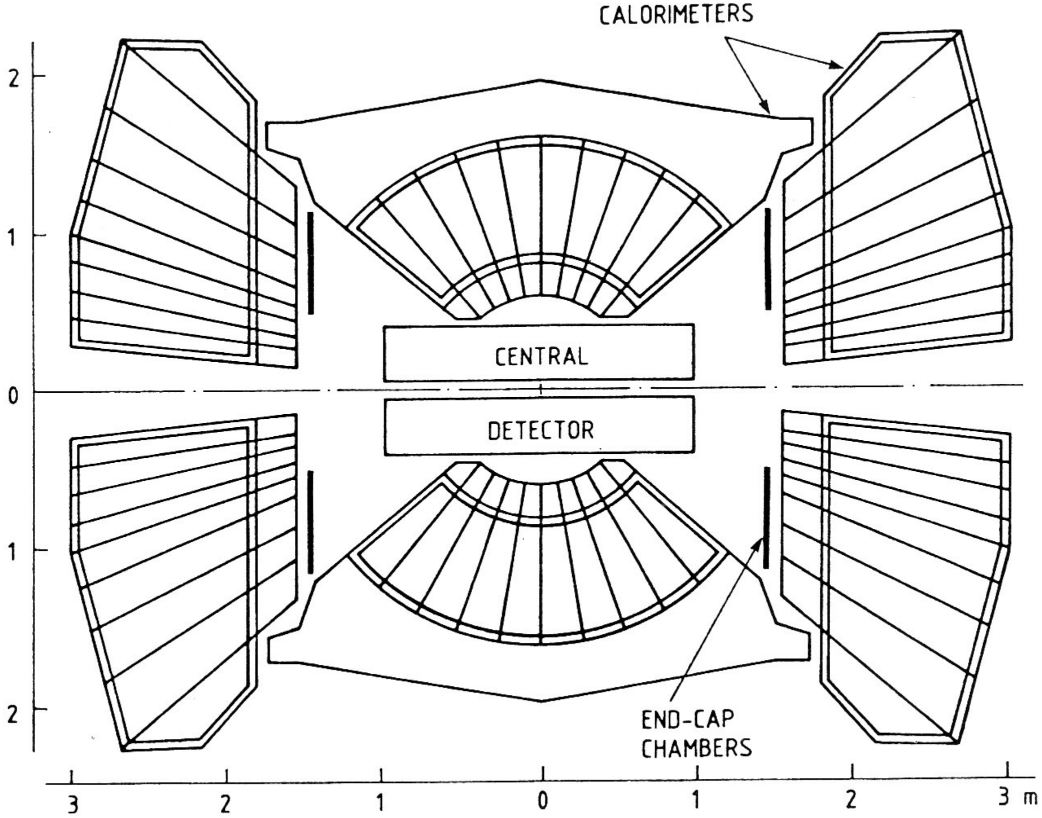
$\sigma_Z B(Z \to e^+e^-) = 73 \pm 14 \pm 11$ pb (UA1)

$73 \pm 15 \pm 10$ pb (UA2)

stat. syst.

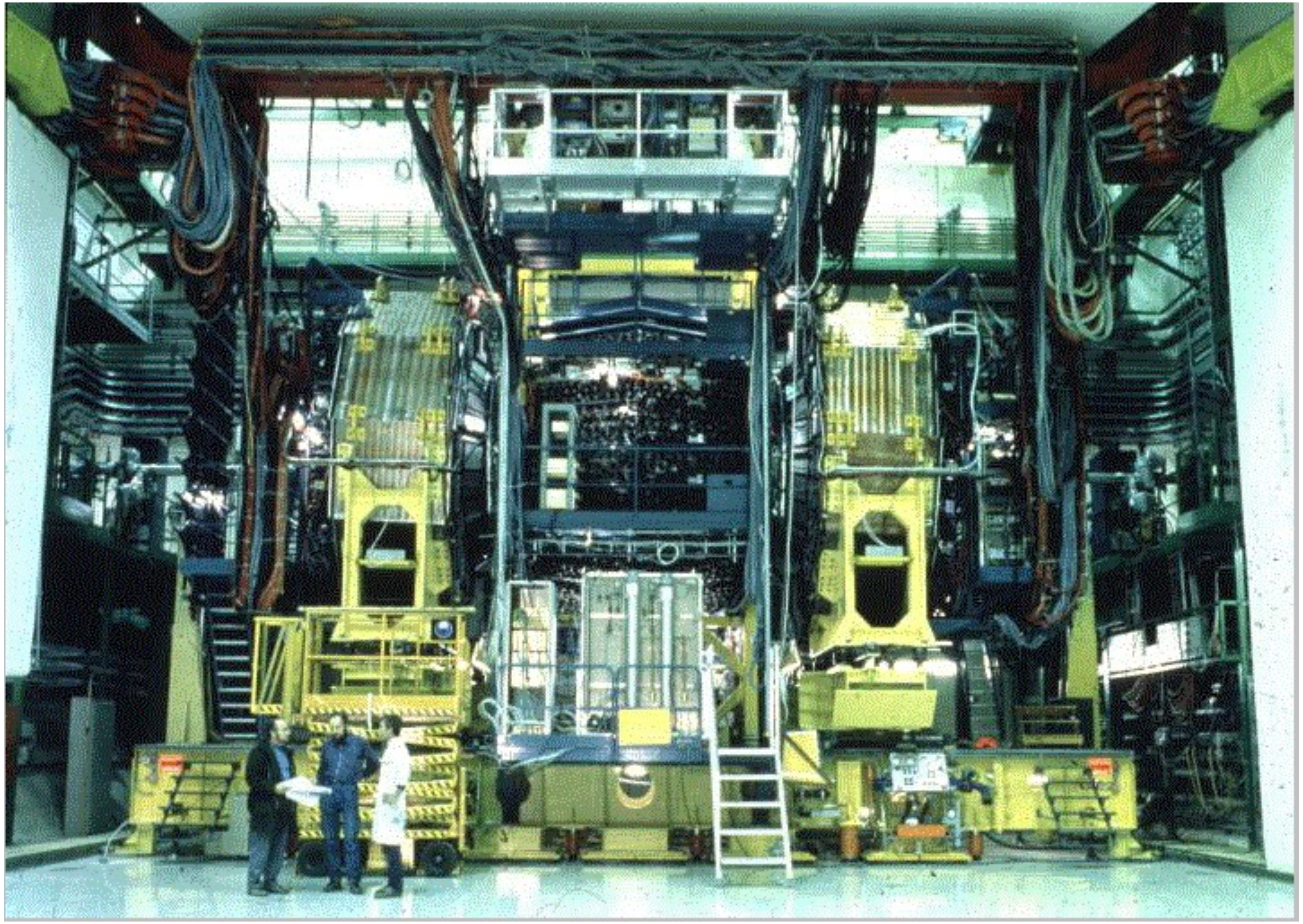
Theory : 51^{+16}_{-10} pb

UA2 detector 1987 – 90

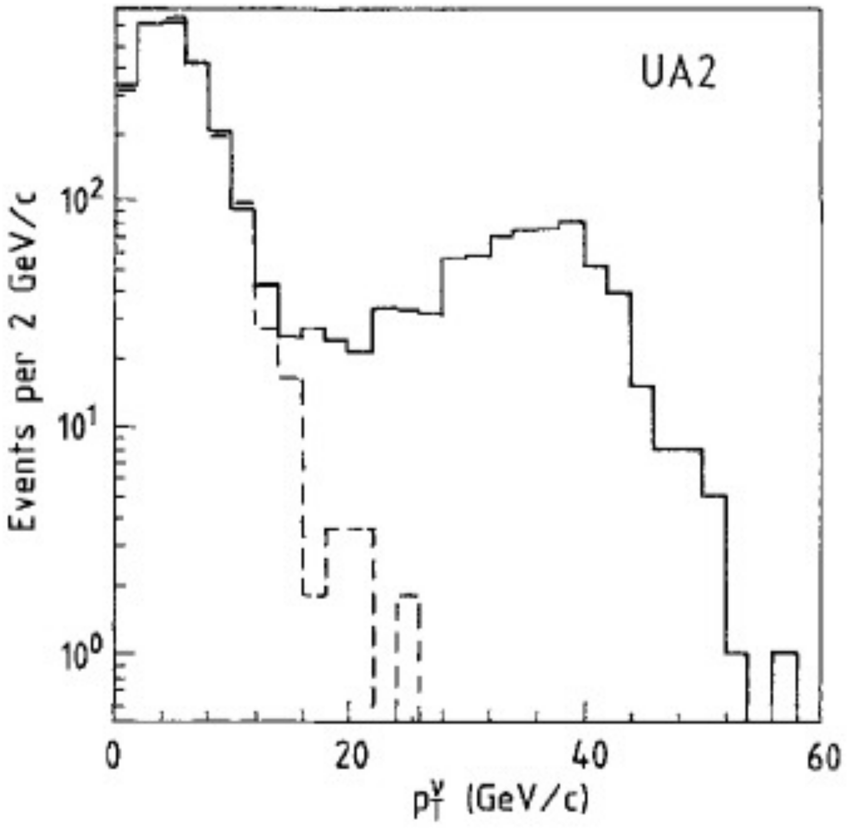


- **Tenfold increase of collider luminosity**
- **Full calorimetry down to ~5° ⇒ improved measurement of missing p_T**
- **No magnetic field, no muon detectors**

UA2 detector 1987 – 90



p_T^{miss} distribution in the UA2' detector



—— Events containing an electron with $p_T > 15$ GeV/c

- - - Events containg an electron with $p_T < 11$ GeV/c (mostly events without outgoing neutrinos)

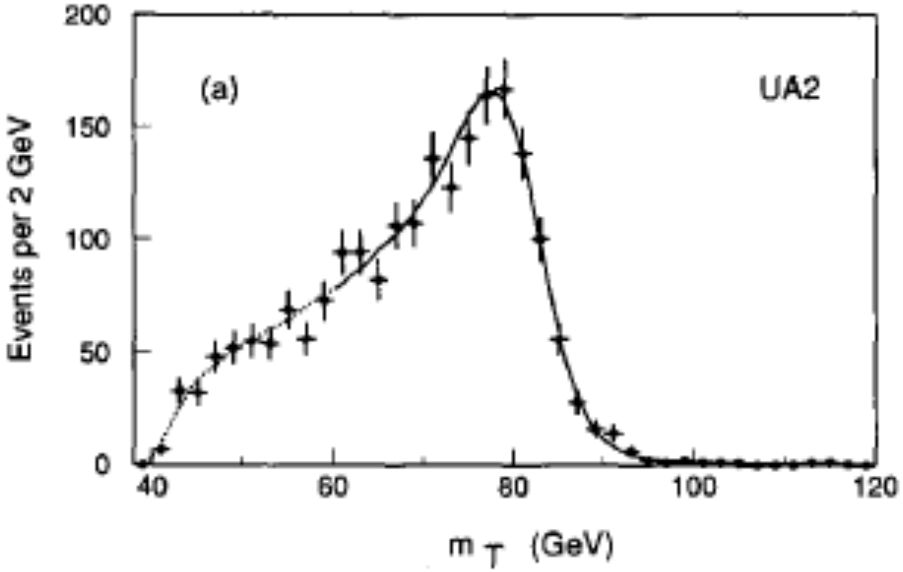
UA2: precise measurement of $\frac{m_W}{m_Z}$

(mass ratio has no uncertainty from calorimeter calibration)

2065 W → e ν events with the electron in the central calorimeter (θ = 90° ± 50°)

Distribution of “transverse mass” m_T

(**m_T :** invariant mass using only the e and ν momentum components normal to beam axis – the longitudinal component of the ν momentum cannot be measured at hadron colliders)



Fit of the distribution with m_W as fitting parameter:

$$m_W = 80.84 \pm 0.22 \ \mathrm{GeV/c^2}$$

Two samples of $Z \to e^+ e^-$ events :

- **both electrons in central calorimeter (95 events)**

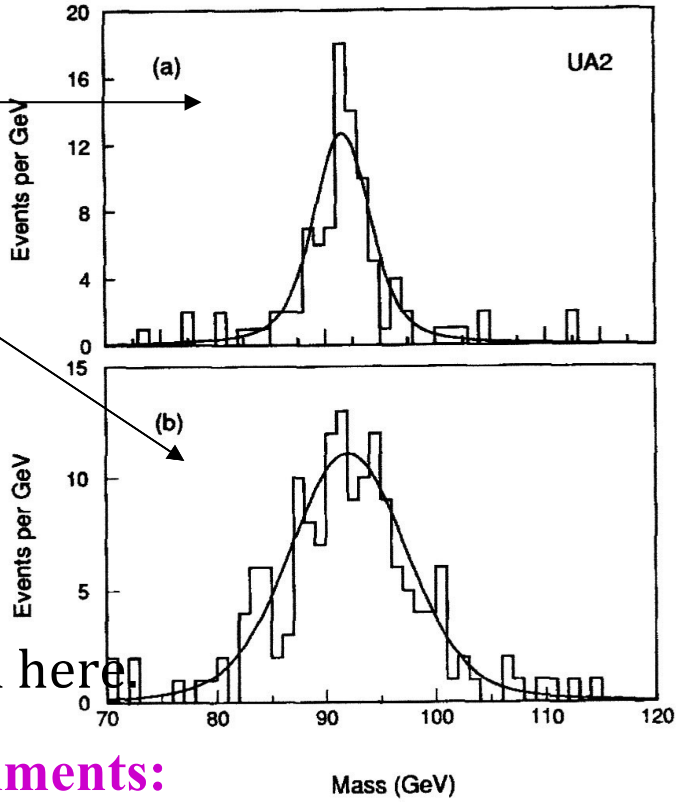
$$m_Z = 91.65 \pm 0.34 \text{ GeV/c}^2$$

- **only one electron in central calorimeter (156 events)**

$$m_Z = 92.10 \pm 0.48 \text{ GeV/c}^2$$

- **combined samples:**

$$m_Z = 91.74 \pm 0.28 \text{ GeV/c}^2$$



$$\frac{m_W}{m_Z} = 0.8813 \pm 0.0036 \pm 0.0019$$

Type equation here.

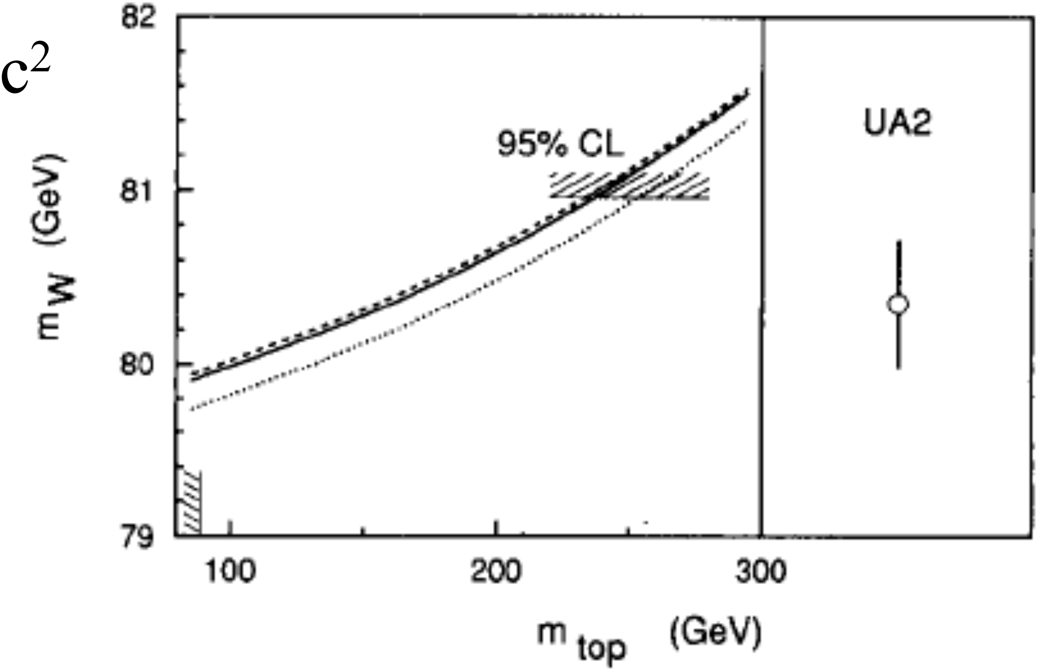
Using precise measurement of m_Z from LEP experiments:

$$m_W = 80.35 \pm 0.33 \pm 0.17 \text{ GeV/c}^2$$

bounds on the mass of the top quark from one-loop corrections :

$$m_{top} = 160^{+50}_{-60} \text{ GeV/c}^2$$

(five years before the top quark discovery at Fermilab)



CONCLUSIONS

The CERN Proton – Antiproton Collider:
initially conceived as an experiment to detect the $W^{\pm}$ and Z bosons;
in the end, a general – purpose accelerator facility exploring hadron collisions at centre-of-mass energies an order of magnitude larger than those previously available.

Among the main physics results:

- **$W^{\pm}$ and Z detection and studies (tests of the electroweak theory)**
- **study of hadronic jets and photons at high p_T (tests of perturbative QCD)**
- **heavy flavour physics (first indirect evidence of $B° – \overline{B}°$ mixing by UA1)**

The prevailing opinion before the first operation of the CERN $\overline{p}$ p Collider:
proton – proton (and antiproton – proton) collisions are "DIRTY", "COMPLICATED" and "DIFFICULT TO INTERPRET"

The physics results (and those from the Fermilab $\overline{p}$ p collider at 1.8 TeV) have shown that this pessimistic view is wrong if the experiments are designed to look at the basic "physics building blocks":

- **hadronic jets at large p_T (representing quarks, antiquarks, gluons)**
- **leptons**
- **photons**
- **missing transverse momentum (neutrinos, other possible weakly interacting particles)**

THE SUCCESS OF THE CERN PROTON – ANTIPROTON COLLIDER
HAS OPENED THE ROAD TO THE LHC