The achievements
of the CERN proton – antiproton collider

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- **Motivation of the project**
- **The proton – antiproton collider**
- **UA1 and UA2 detectors**
- **Discovery of the W and Z bosons**
- **Hadronic jets at high transverse momentum**
- **First indirect evidence for $\overline{B}^o$ – B^o mixing**

IMFP 2004, Alicante, 5 March 2004

1973 Discovery of neutral – current neutrino interactions:
the first experimental evidence in favour of the unified electro-weak theory;

first measurement of the weak mixing angle θ_w

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

$$m_W = 60 – 80 \text{ GeV}$$

$$m_Z = 75 – 95 \text{ GeV}$$

too large to be produced by any existing accelerators

The ideal machine to produce and study the W and Z bosons in the most convenient experimental conditions: 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)

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*)

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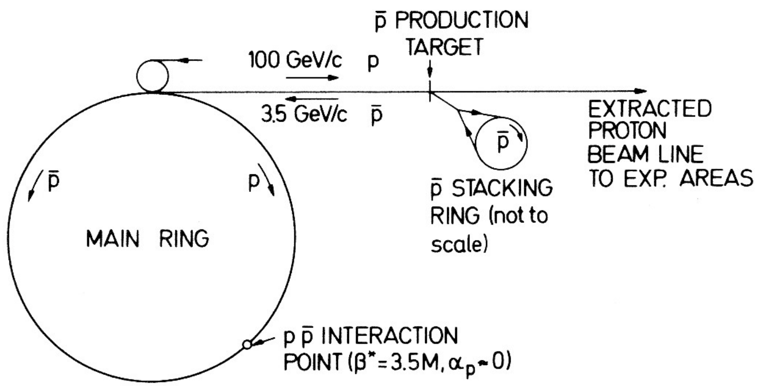
Presented by C. Rubbia

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 $\bar{p} + p \rightarrow Z$ + anything at ~ 600 GeV: $\sigma \approx 1.6$ nb

  Branching ratio for $Z \rightarrow e^+ e^-$ decay ≈ 3%

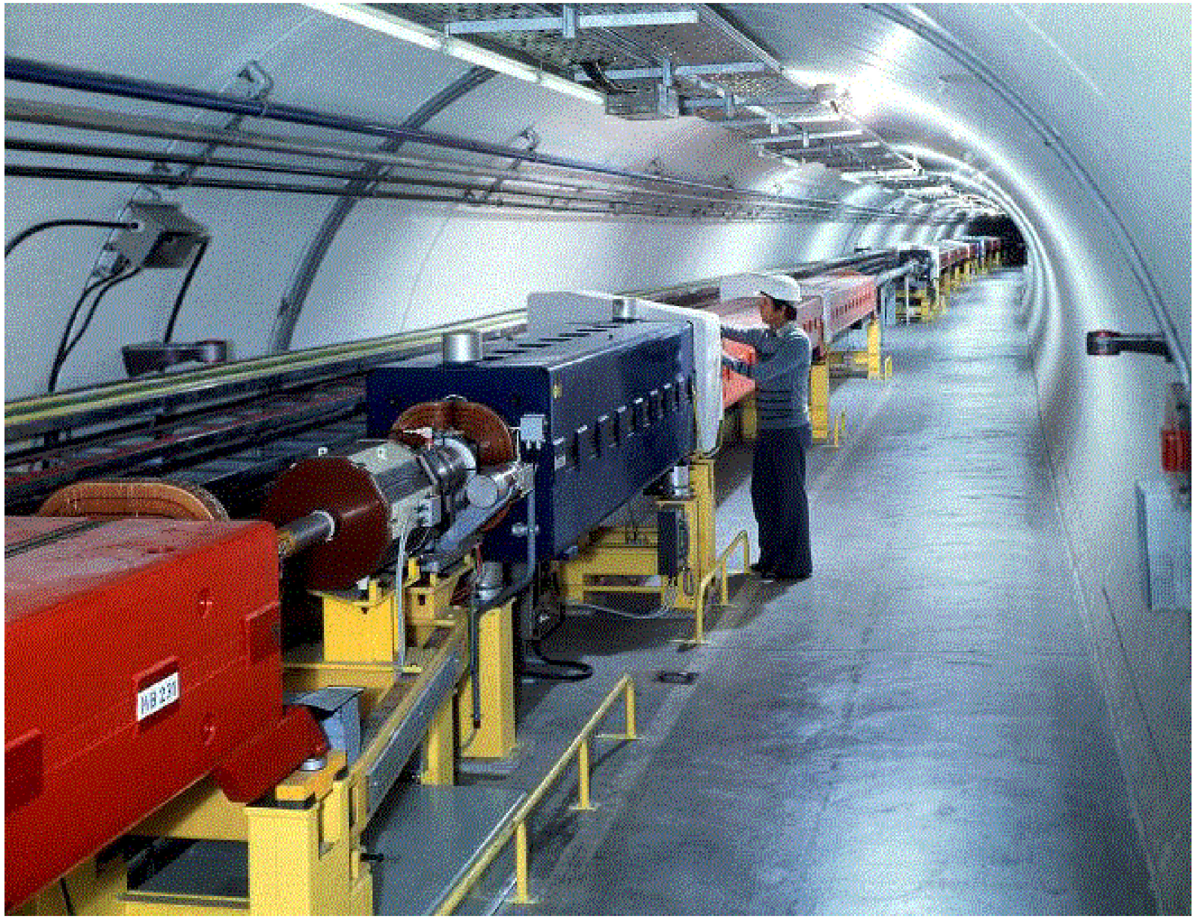
$$\sigma(\bar{p}p \rightarrow Z \rightarrow e^+e^-) \approx 50\ \text{pb} = 5 \times 10^{-35}\ \text{cm}^2$$

Event rate = L σ [s^{-1}] $\quad$ (L ≡ luminosity)

➡ **1 event / day $\Rightarrow$ L ≈ 2.5 x 10^{29} cm^2 s^{-1}**

CERN accelerators in 1976

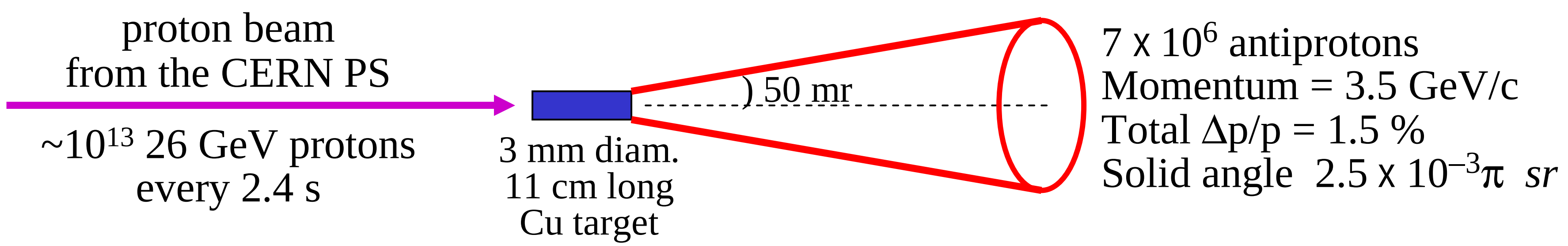
- 26 GeV proton synchrotron (PS) in operation since 1959
- 450 GeV proton synchrotron (SPS) just starting operation



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 3×10^{10} $\bar{p}$ distributed into few (3 – 6) tightly collimated bunches within the angular and momentum acceptance of the SPS

Antiproton production:



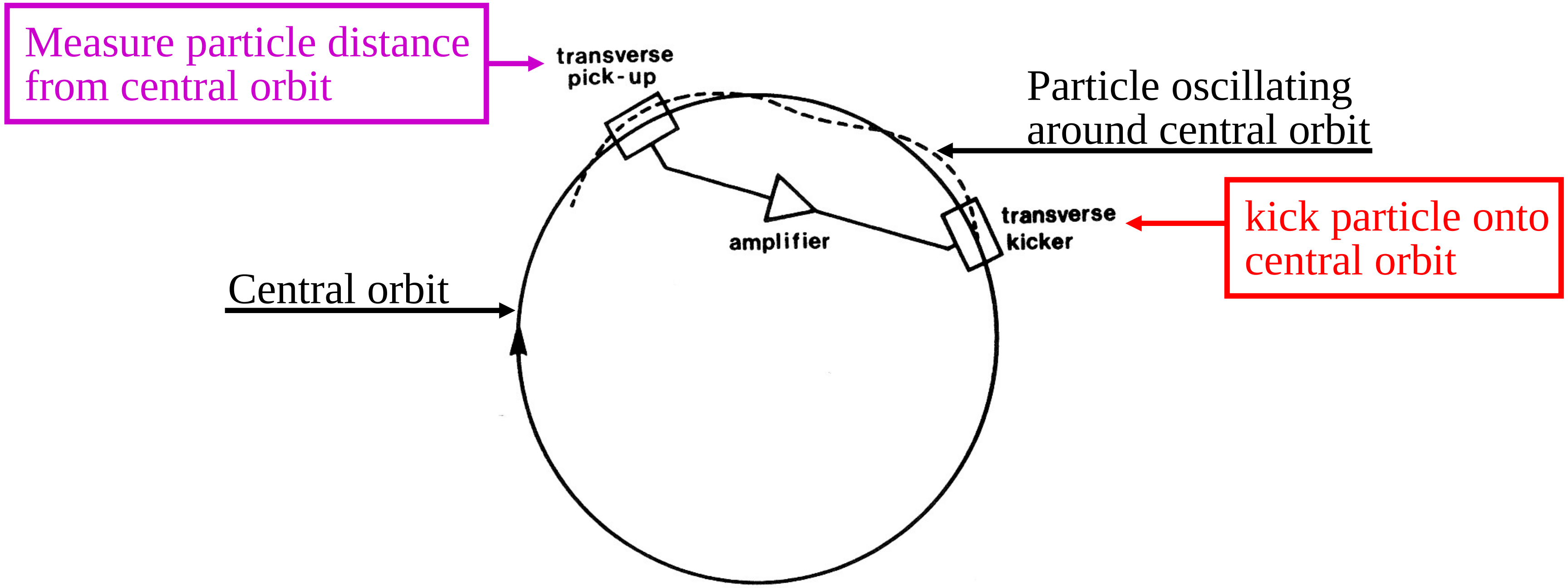
Number of antiprotons / PS cycle OK
but phase space volume too large by a factor $\geq 10^8$ to fit into SPS acceptance even after acceleration to the injection energy of 26 GeV

⇒ **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



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)

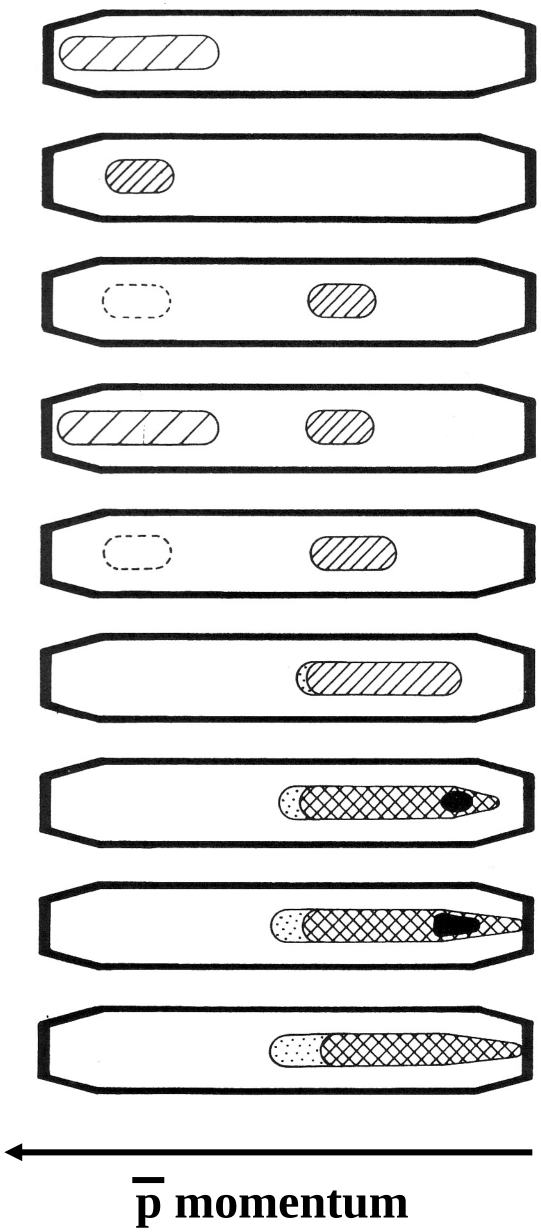
The CERN Antiproton Accumulator (AA)

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 x 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

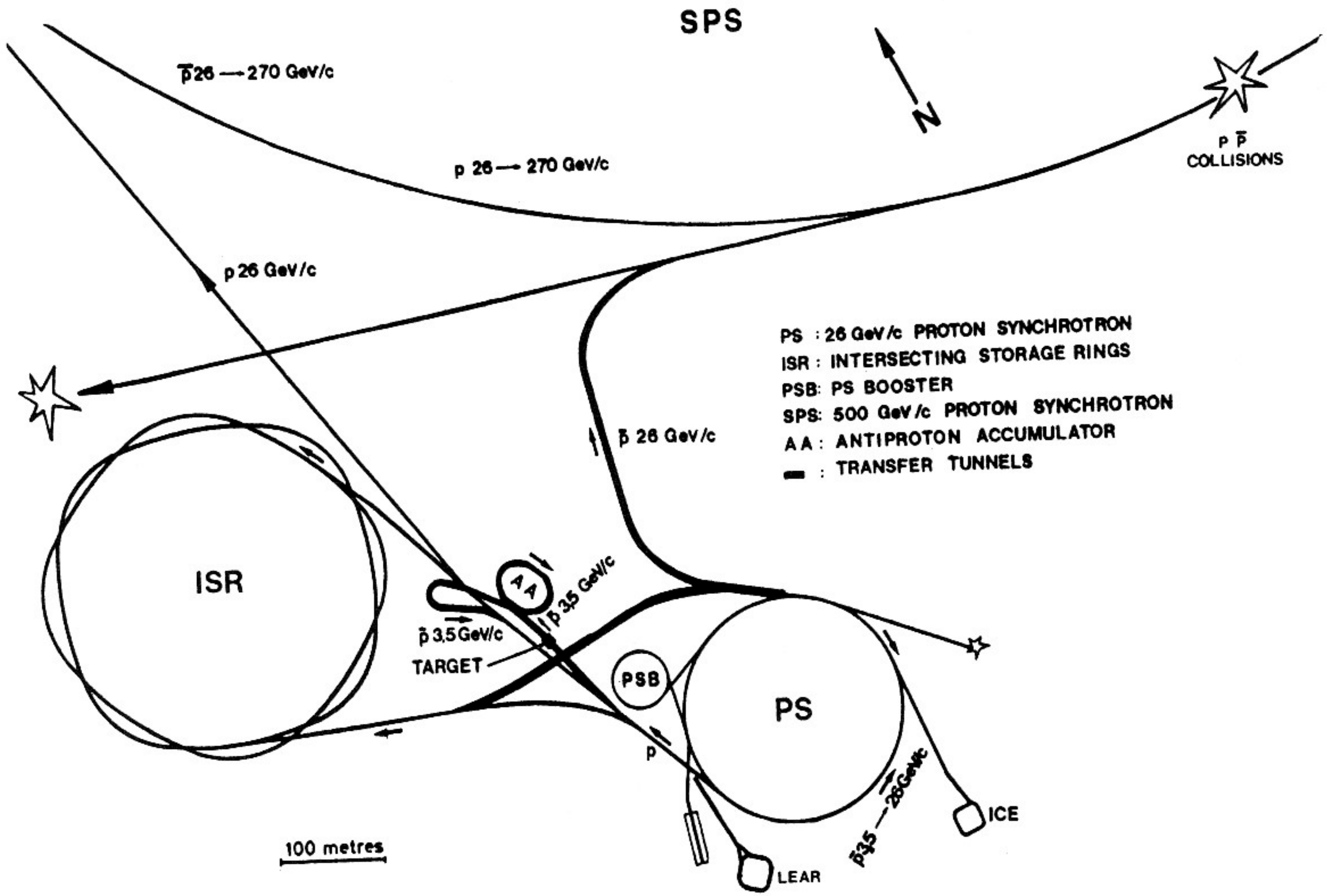
After 15 pulses the stack contains 10^8 $\bar{p}$

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 (7×10^7 p / pulse $\Rightarrow$ ~ tenfold increase of stacking rate)

AC

AA

Proton – antiproton collider operation, 1981 - 90

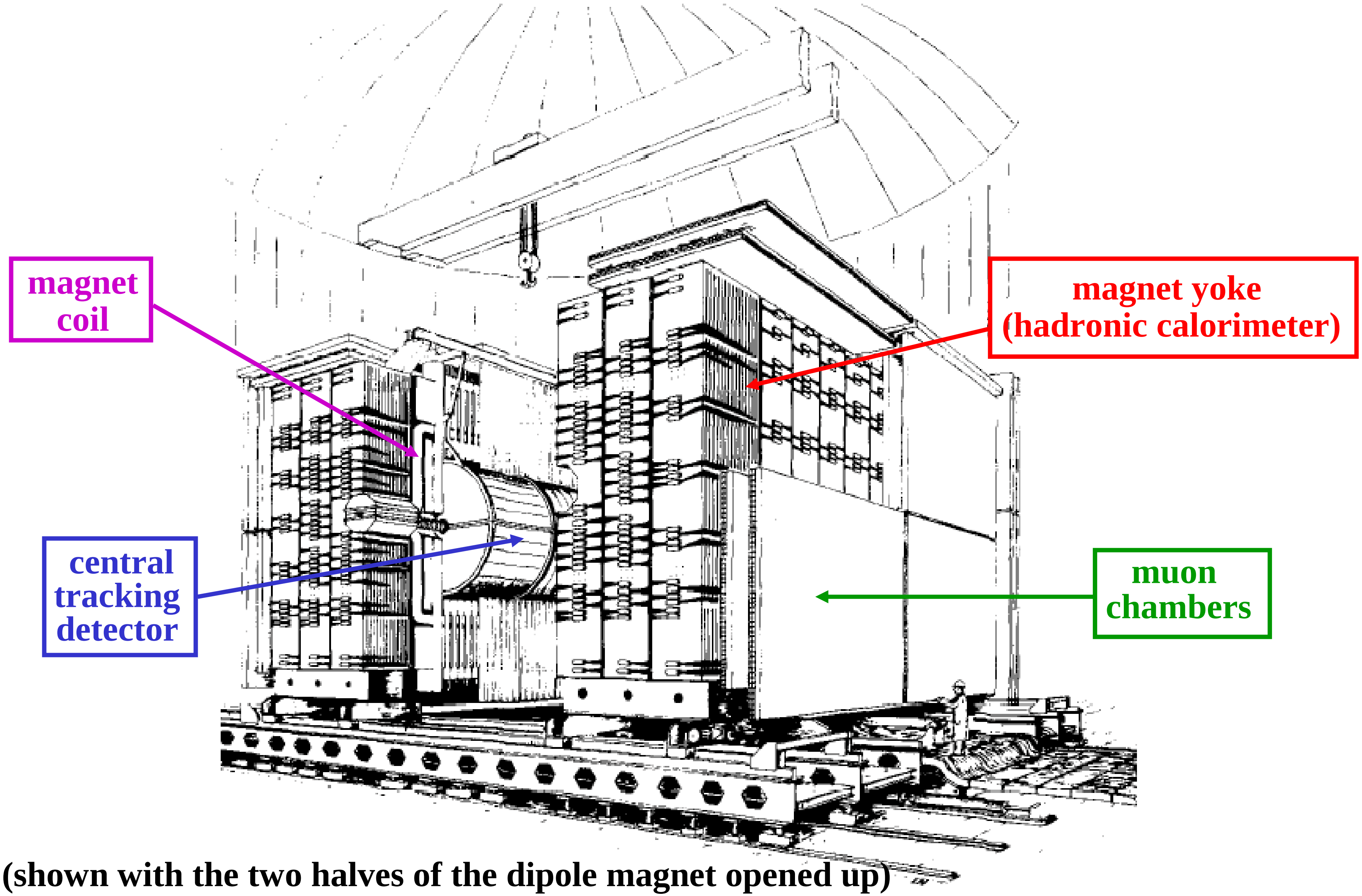
Year	Collision Energy (GeV)	Peak luminosity ($cm^{-2}\ s^{-1}$)	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	2.0×10^{32}
1982	546	5×10^{28}	2.8×10^{34}
1983	546	1.7×10^{29}	1.5×10^{35}
1984-85	630	3.9×10^{29}	1.0×10^{36}
1987-90	630	$\sim 2 \times 10^{30}$	1.6×10^{37}

← W discovery (1982)

← Z discovery (1983)

1991: end of collider operation

UA1 detector

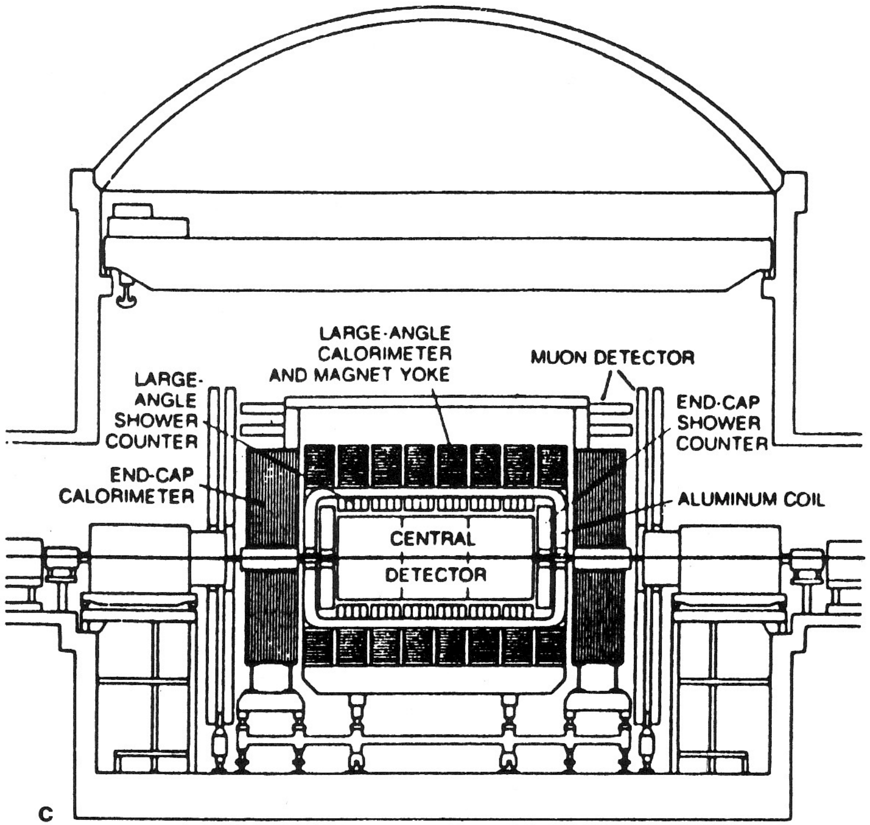


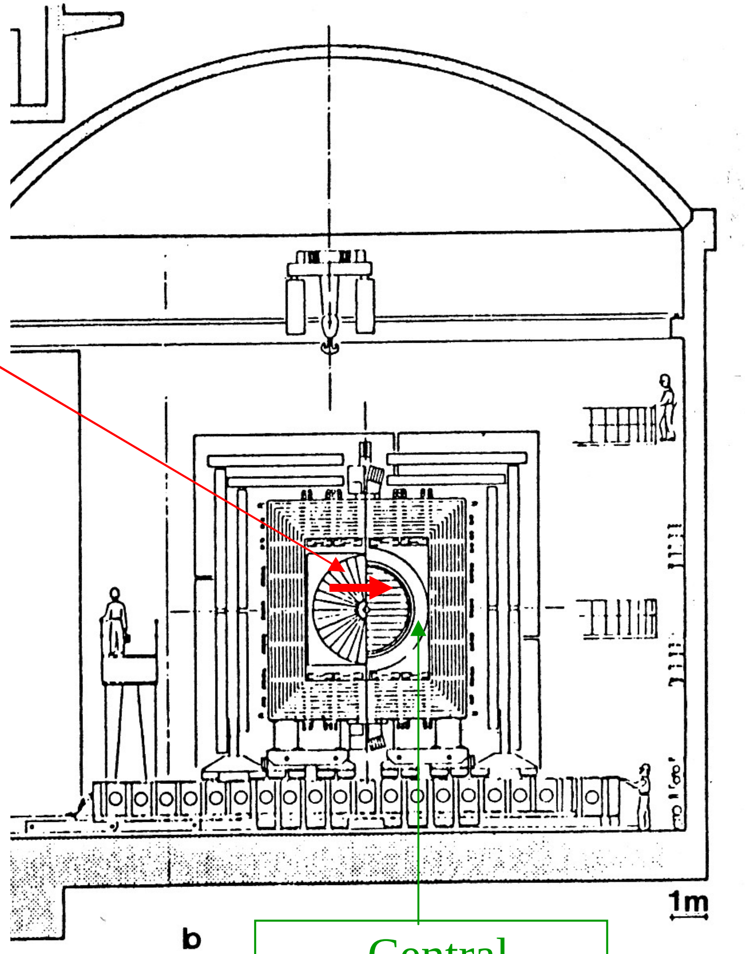
(shown with the two halves of the dipole magnet opened up)

View normal to beam axis

Magnetic field direction

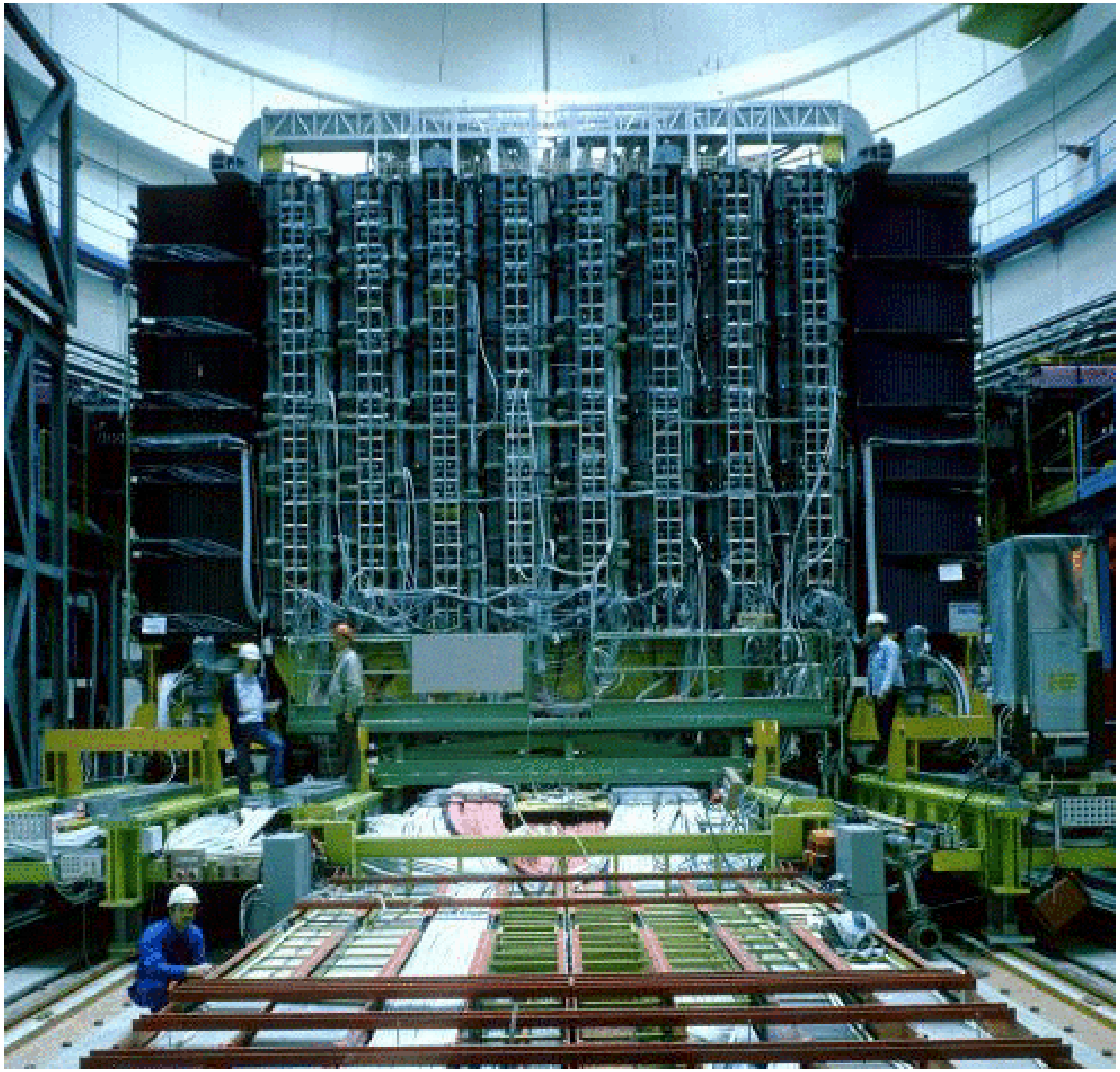
Vertical section along beam axis



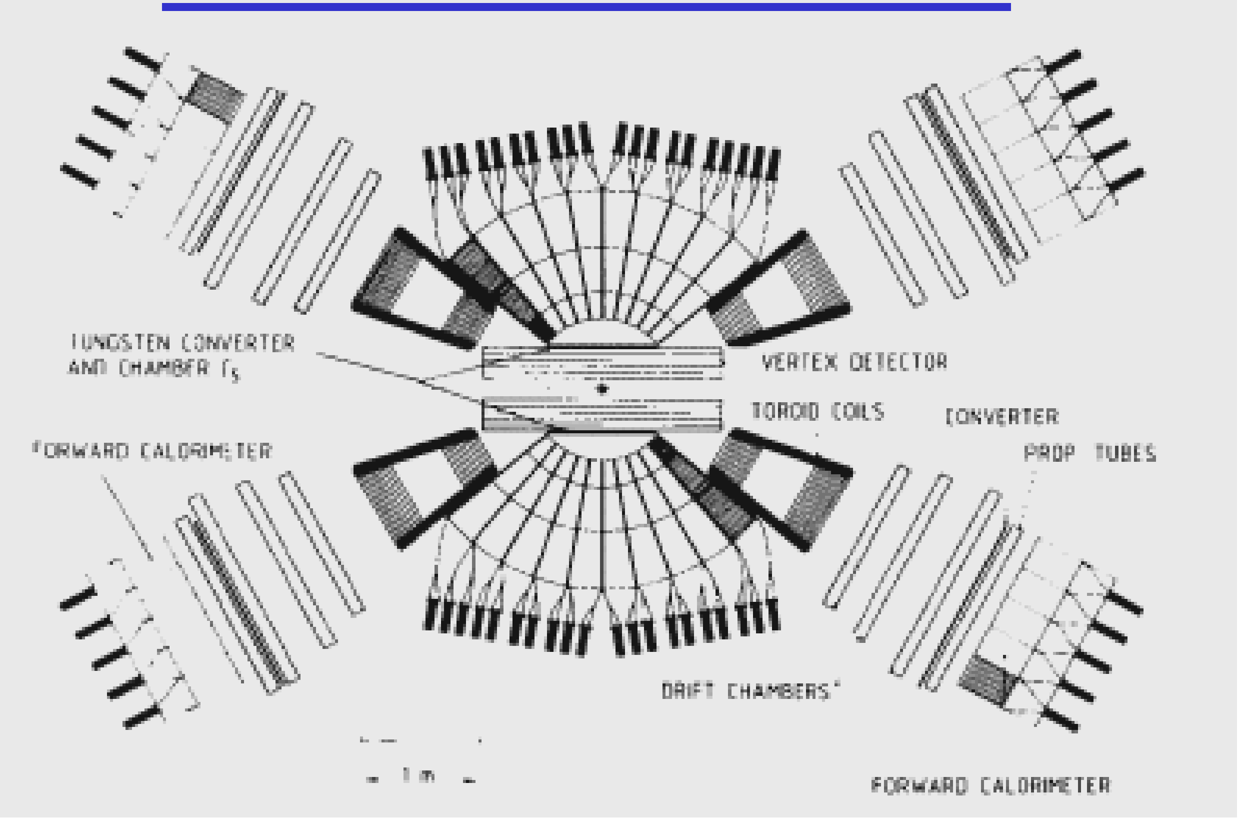


Central electromagnetic calorimeter

UA1 detector during assembly



UA2 Detector 1981 - 85

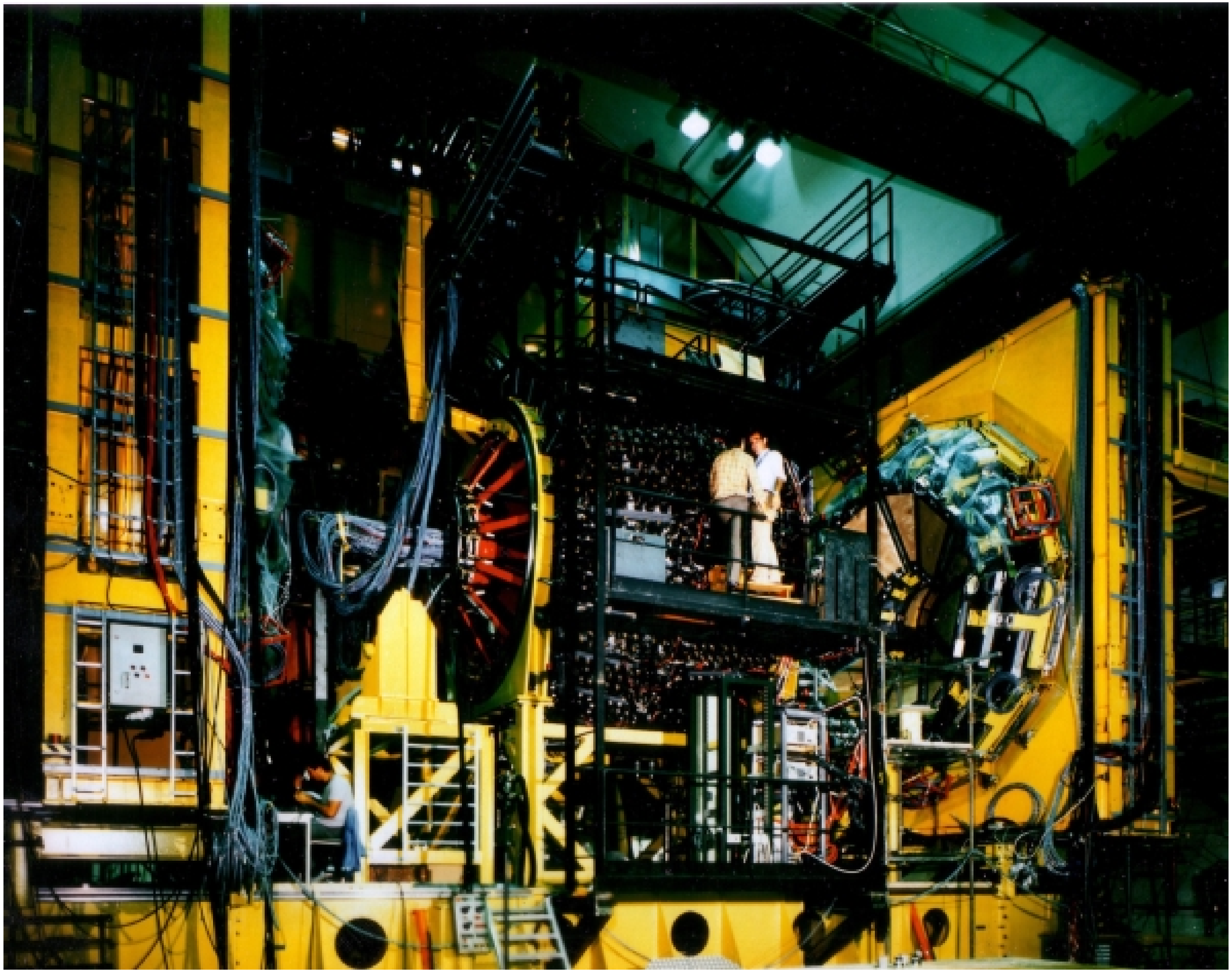


Central region: tracking detector ("vertex detector");
"pre-shower" detector
electromagnetic and hadronic calorimeters;
no magnetic field

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

No muon detector

UA2 detector during assembly



W discovery

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

⇒ search for leptonic decays:

$$W^+ \rightarrow e^+ + \nu_e \qquad \text{(UA1, UA2)}$$

$$W^+ \rightarrow \mu^+ + \nu_\mu \qquad \text{(UA1 only)}$$

(and charge-conjugate decays)

Expected signal from $W \rightarrow e\,\nu$ 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. $u + \bar{d} \rightarrow W^+$, is almost collinear with beam axis; decay electron and neutrino emitted at large angles to beam axis have large p_T)

<u>NOTE</u>

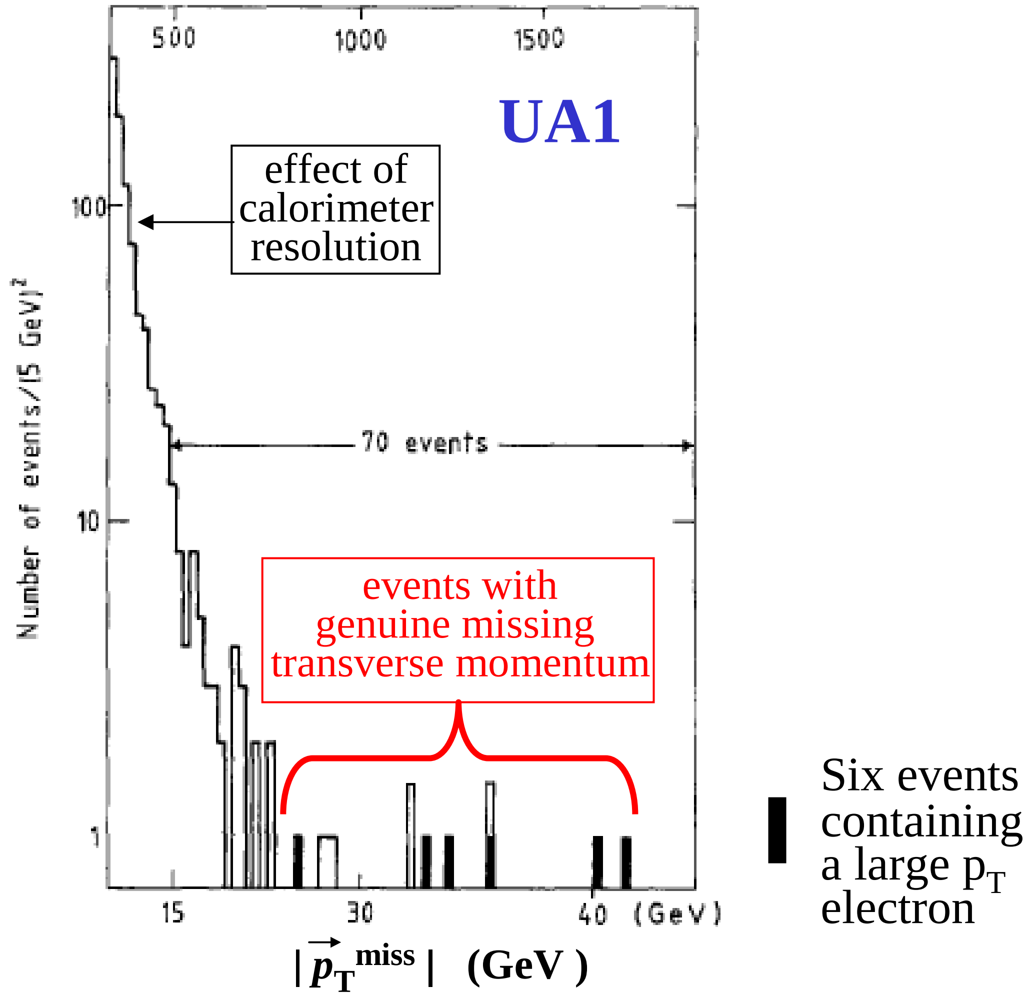
Missing longitudinal momentum cannot be measured at hadron colliders because of large number of high-energy secondary particles emitted at very small angles inside the machine vacuum pipe

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

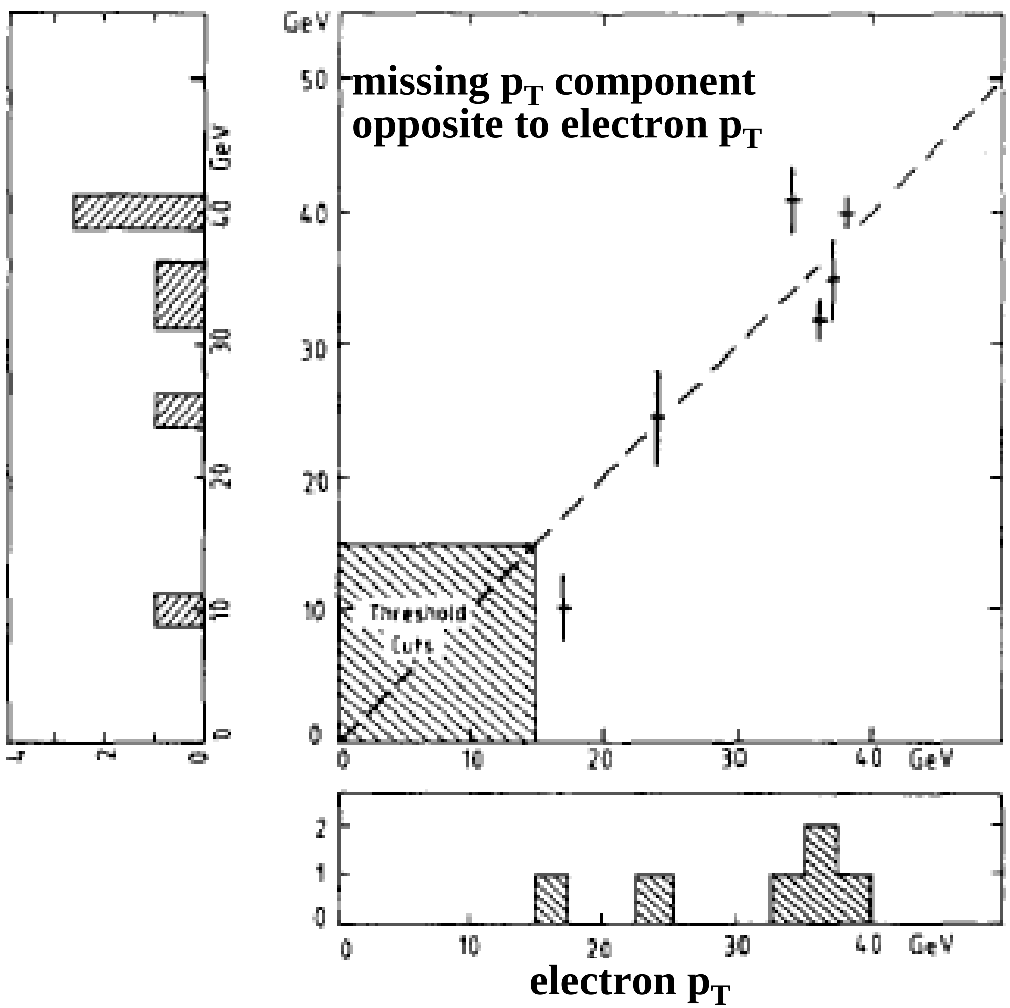
- **Associate momentum vector $\vec{p}$ to each calorimeter cell with energy deposition > 0**
- **Direction of $\vec{p}$ from event vertex to cell centre**
- **$|\vec{p}|$ = energy deposited in cell**
- **Definition:**

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

(momentum conservation in plane perpendicular to beam axis)

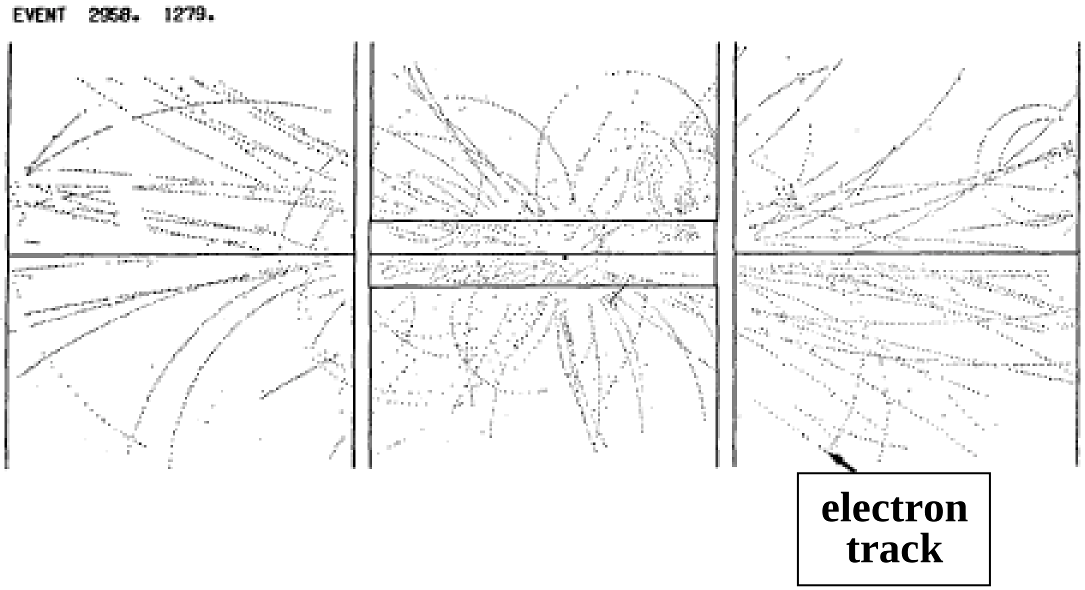


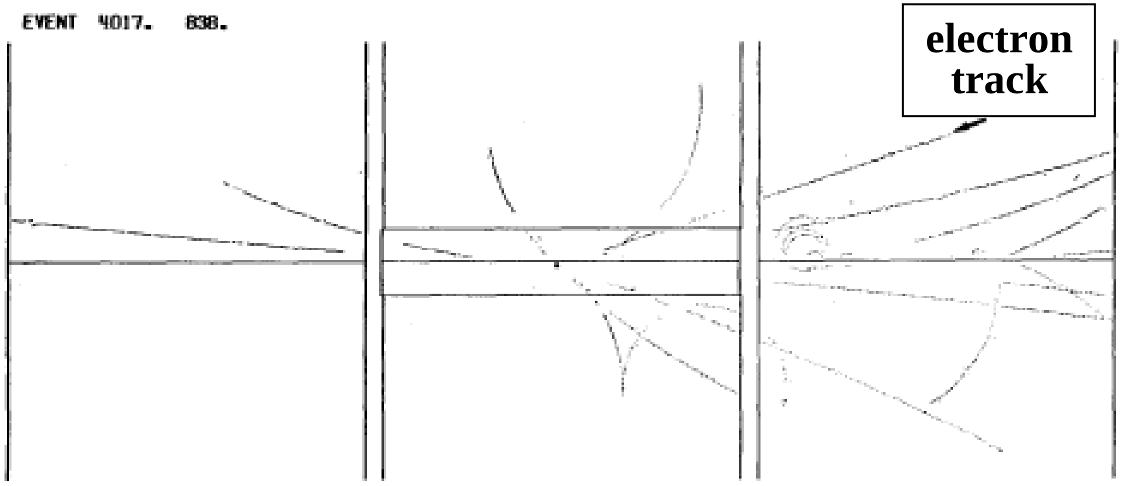
UA1: correlation between electron p_T and missing p_T



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)

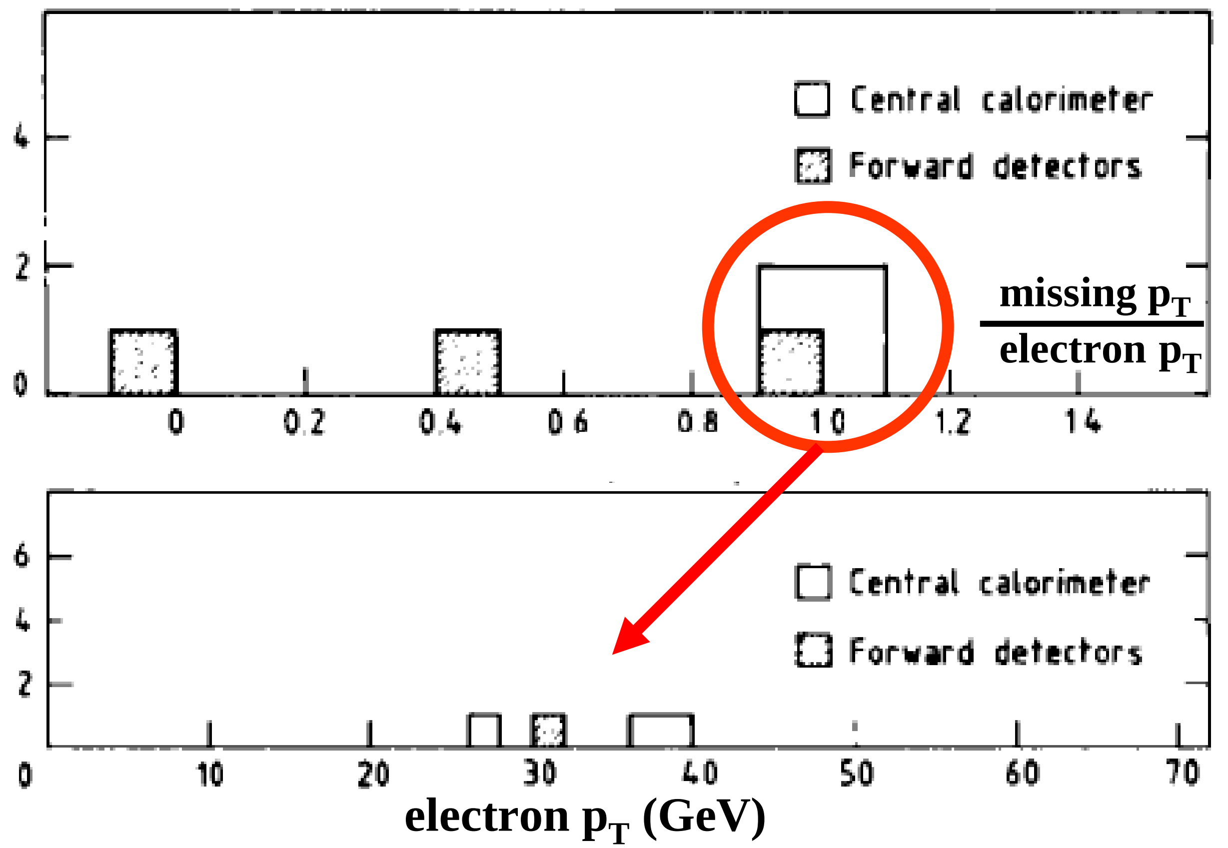
Two UA1 W → e ν events





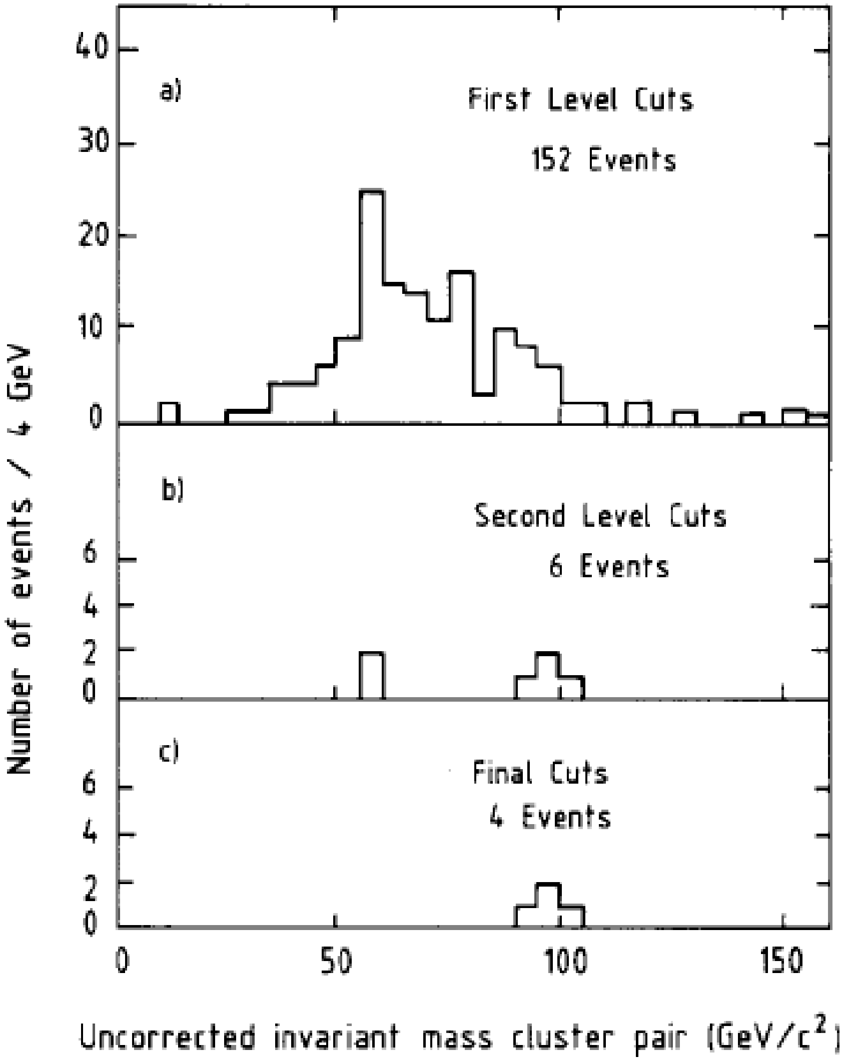
UA2: results presented at a CERN seminar on January 21, 1983

Six events containing an electron with $p_T > 15$ GeV



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

(May 1983)

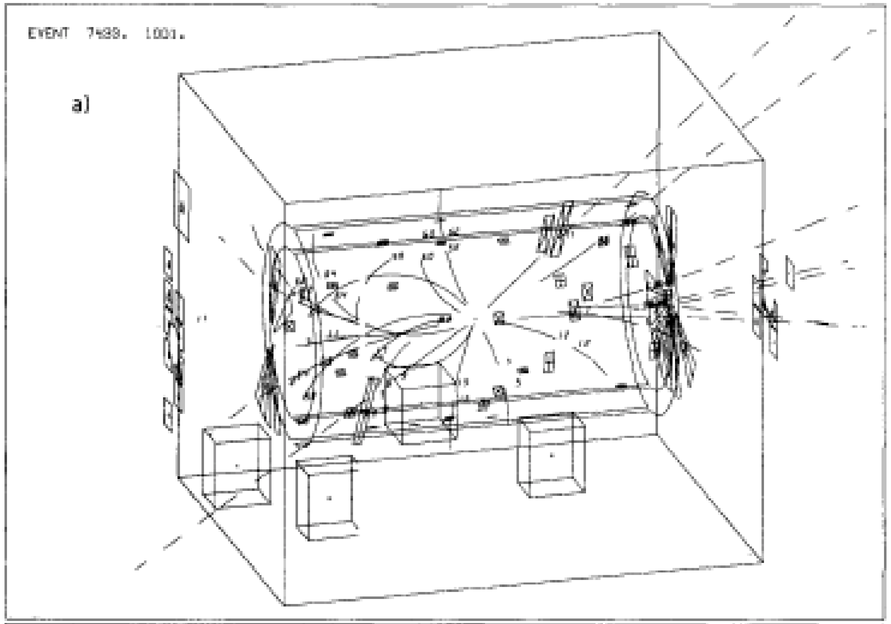


Two energy clusters ($p_T > 25$ GeV) in electromagnetic calorimeters; energy leakage in hadronic calorimeters consistent with electrons

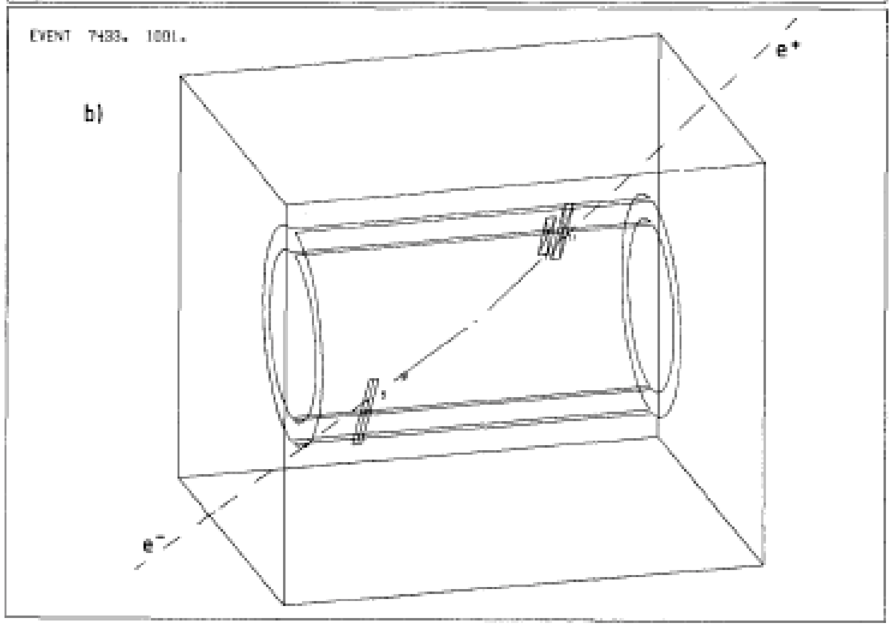
Isolated track with $p_T > 7$ GeV pointing to at least one cluster

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

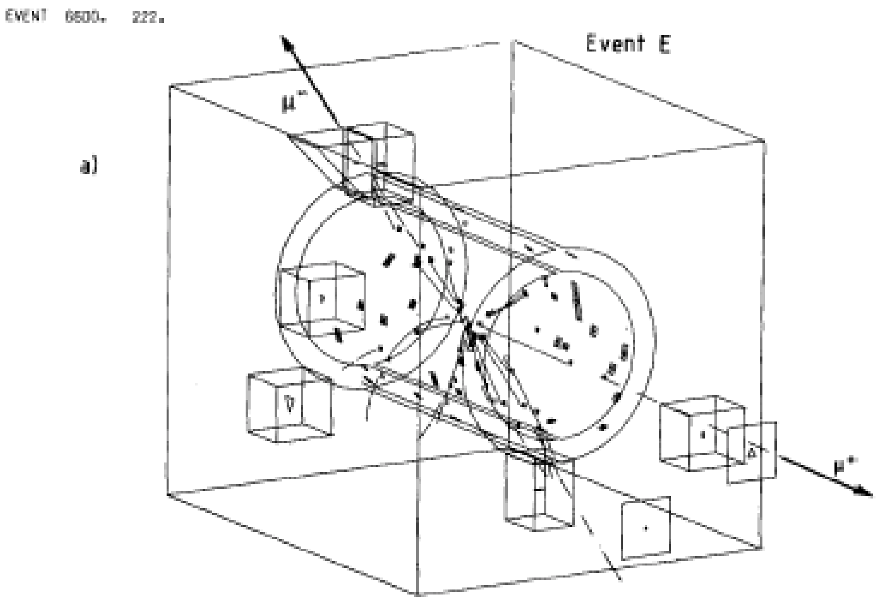
UA1 Z → $e^+ e^-$ event



Display of all reconstructed tracks and calorimeter hits



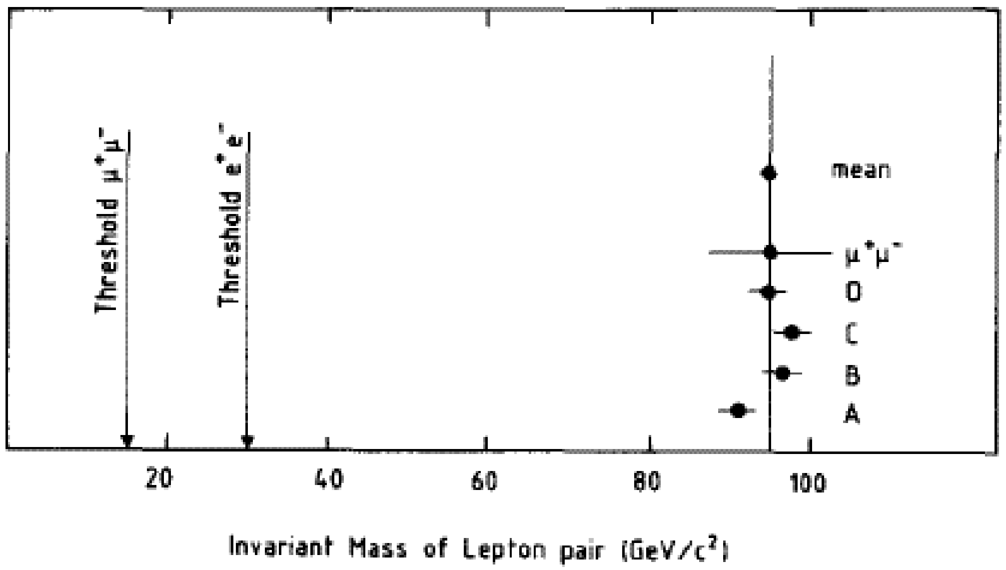
Display of tracks and calorimeter hits with p_T > 2 GeV



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

(May 1983)

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

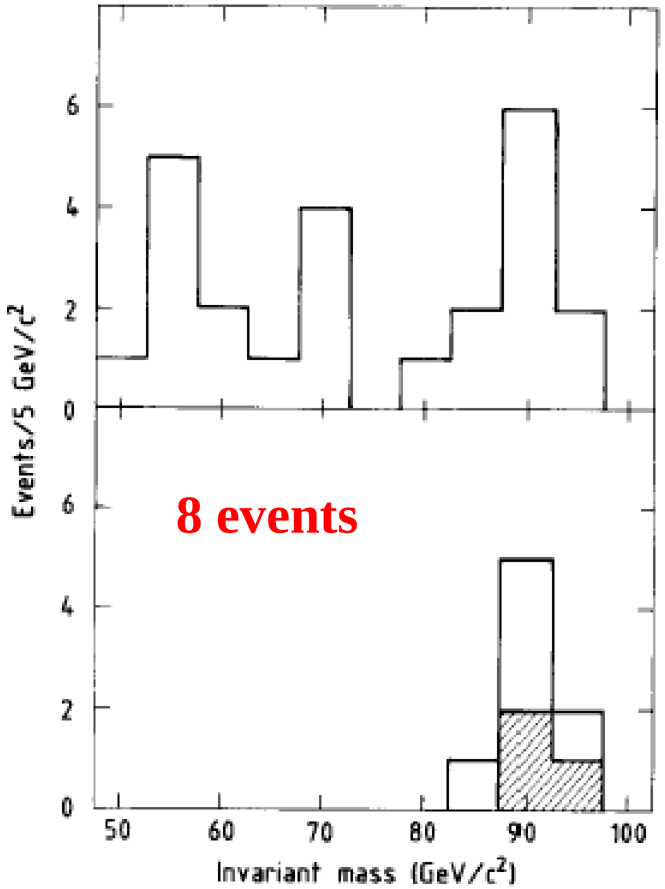


UA1:
all lepton pairs from the 1983 run

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

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

(June 1983)



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

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

The Nobel Prize in Physics 1984

"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"

Carlo Rubbia

1/2 of the prize

Italy

CERN
Geneva, Switzerland

b. 1934

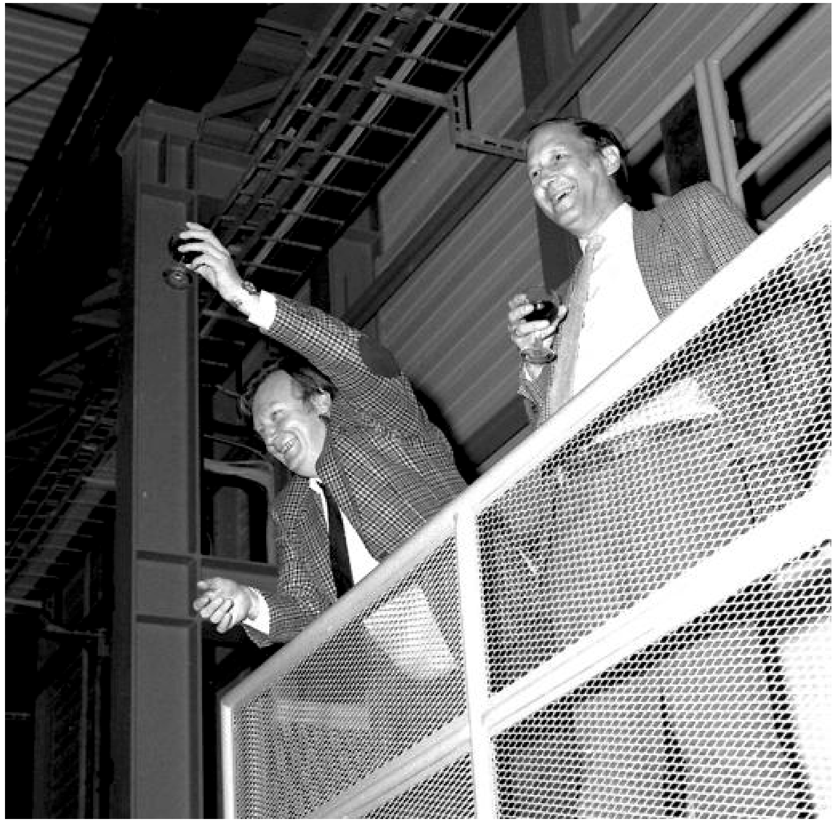
Simon van der Meer

1/2 of the prize

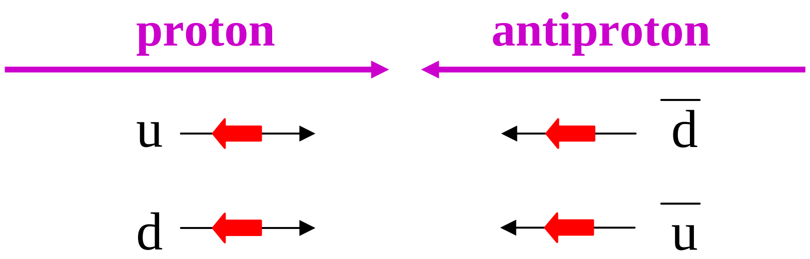
the Netherlands

CERN
Geneva, Switzerland

b. 1925

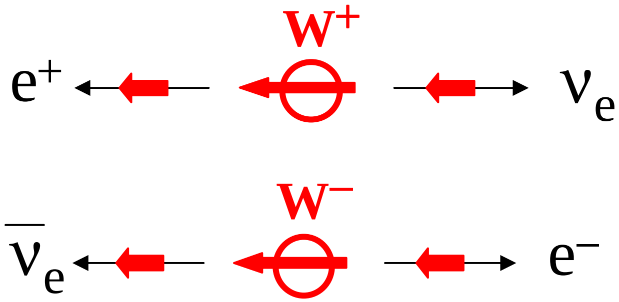


Charge asymmetry in $W \to e\,\nu$ decay



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

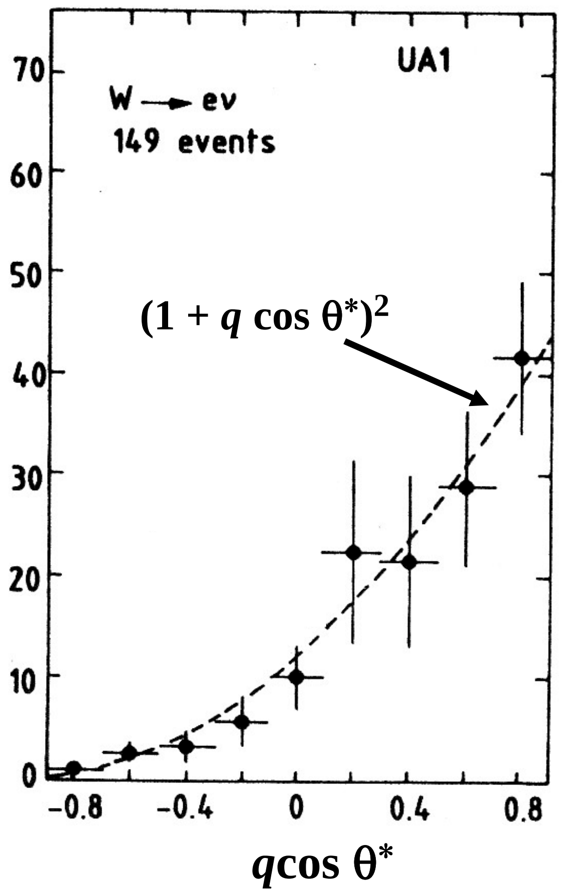
In the W rest frame:



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**
θ^* = 0 along antiproton direction

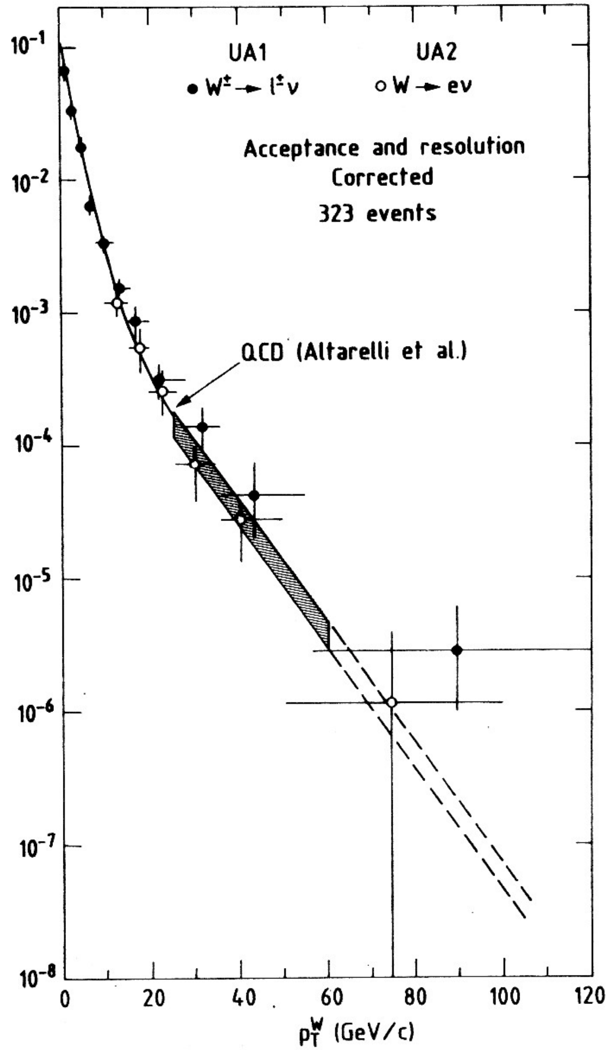


W transverse momentum $(\vec{p}_T^{\,W})$

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

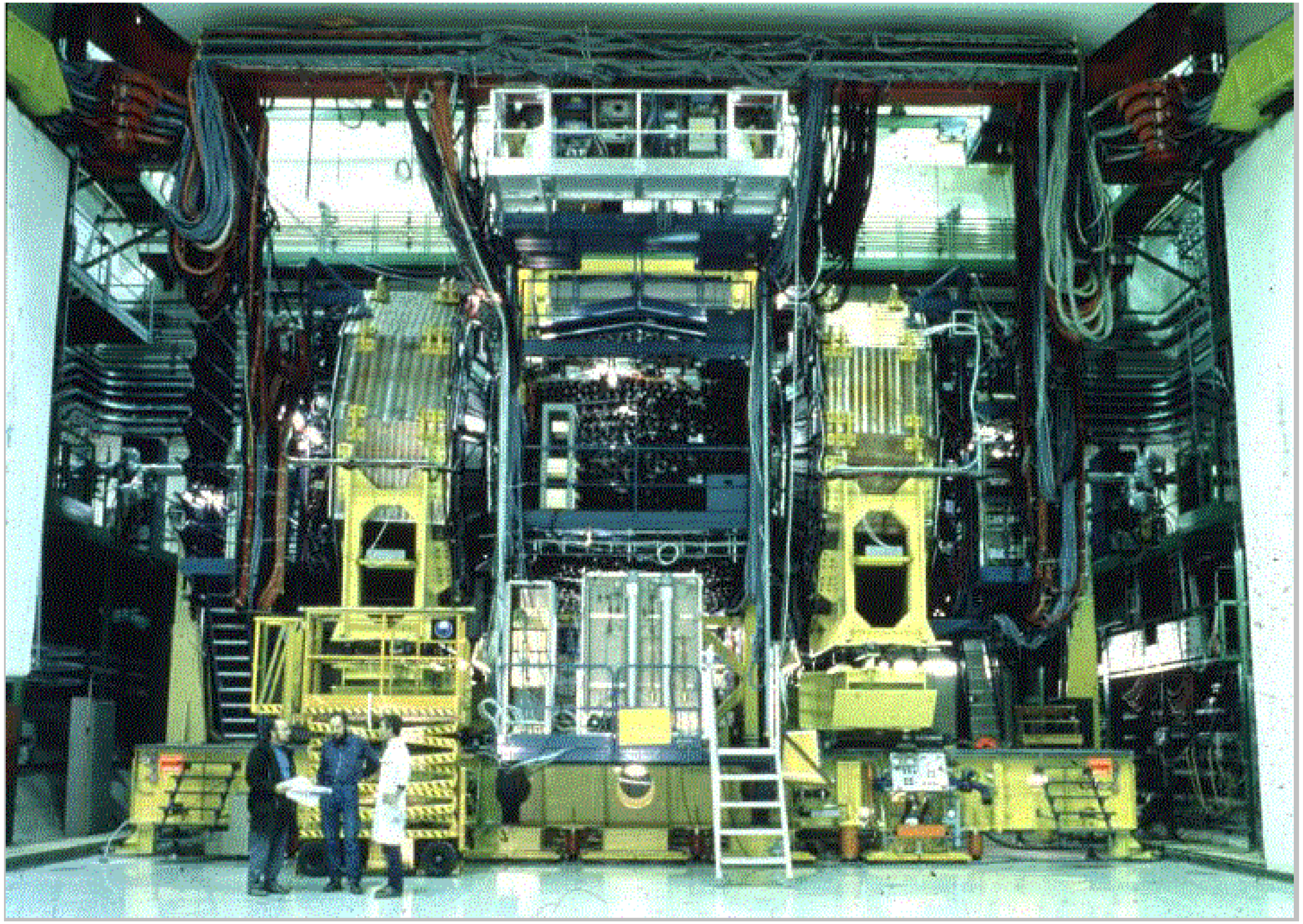
$$\vec{p}_T^{\,W} = -\sum_{hadrons} \vec{p}_T$$

- p_T^W distribution can be predicted from QCD



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



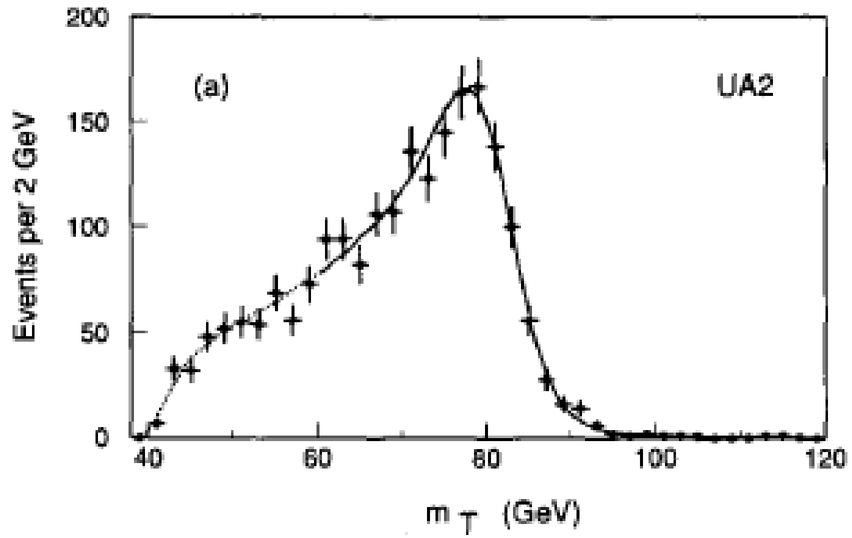
UA2: precise measurement of $\frac{m_W}{m_Z}$

(mass ratio has no uncertainty from calorimeter calibration)

2065 $W \to e\,\nu$ events with the electron in the central calorimeter ($\theta = 90° \pm 50°$)

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:

$$m_W = 80.84 \pm 0.22\,\text{GeV}$$

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

- both electrons in central calorimeter (95 events)

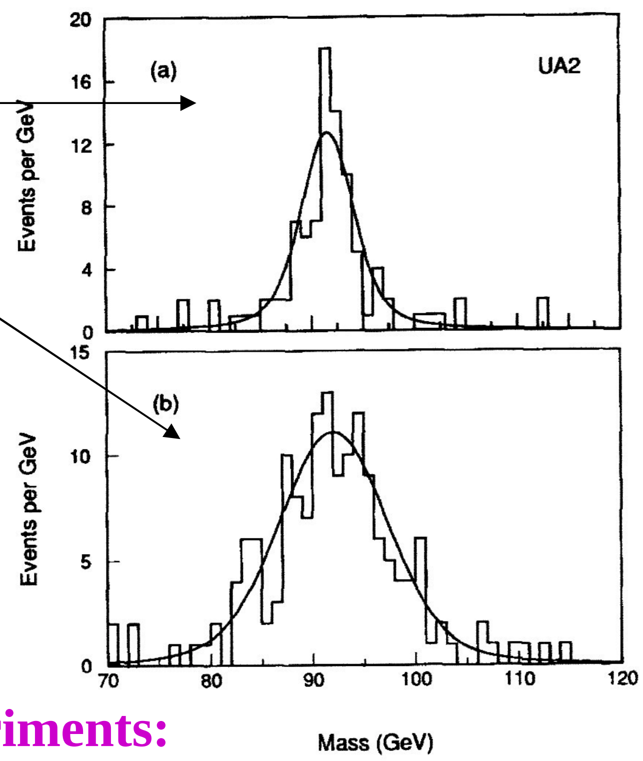
$$m_Z = 91.65 \pm 0.34\,\text{GeV}$$

- only one electron in central calorimeter (156 events)

$$m_Z = 92.10 \pm 0.48\,\text{GeV}$$

- combined samples:

$$m_Z = 91.74 \pm 0.28\,\text{GeV}$$



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

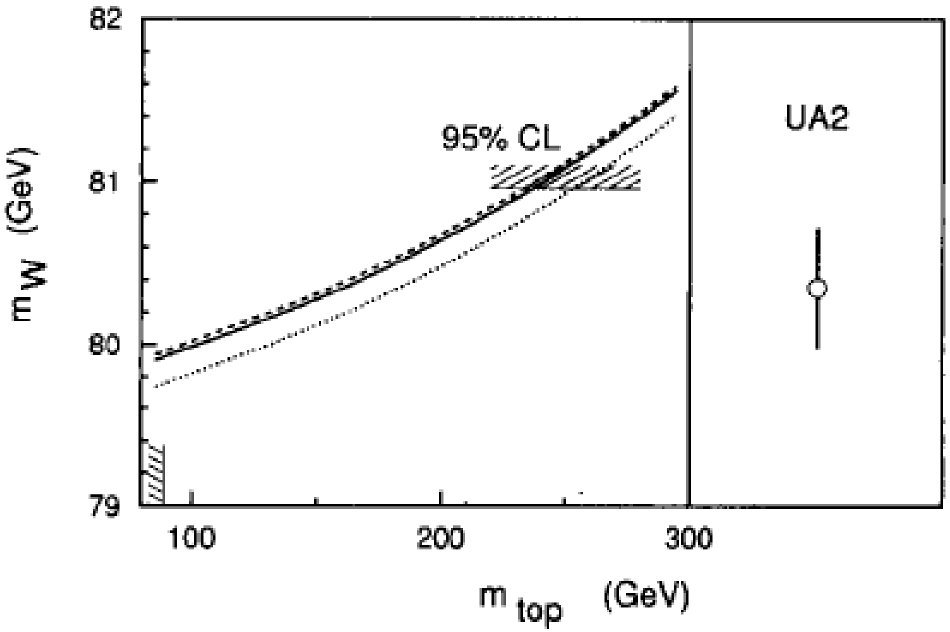
Using precise measurement of m_Z from LEP experiments:

$$m_W = 80.35 \pm 0.33 \pm 0.17\,\text{GeV}$$

bounds on the mass of the top quark in the frame of the Standard Model:

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

(five years before the top quark discovery at Fermilab)

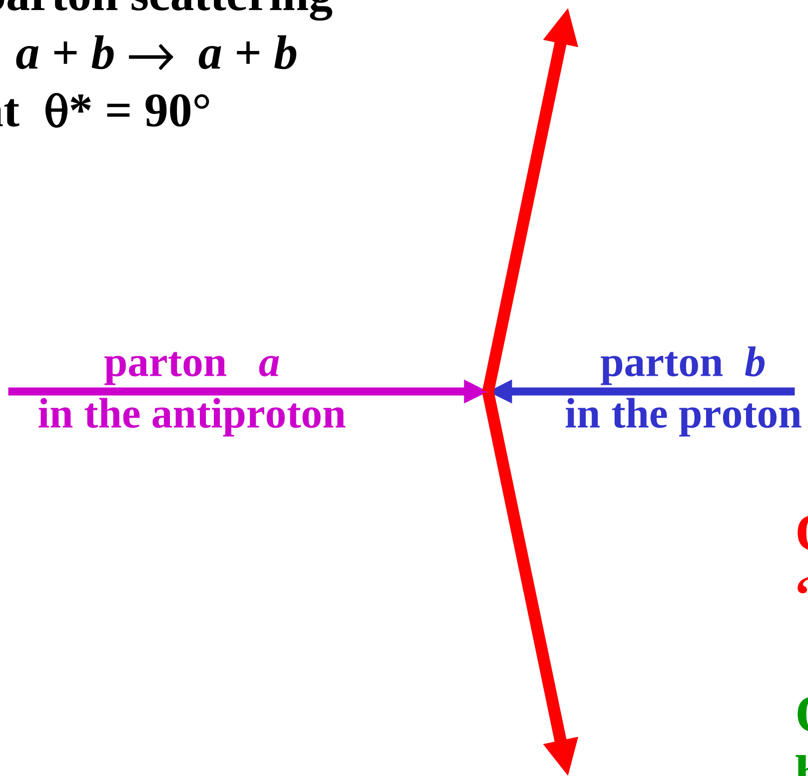


Jet production at high transverse momentum

Proton – antiproton collisions at high energy ≡ collisions between two broad-band beams of quarks, antiquarks, gluons ("partons")

Parton – parton scattering at large angles ⇒ two hadronic jets at large p_T

<u>EXAMPLE</u>:
parton scattering
$a + b \rightarrow a + b$
at $\theta^* = 90°$



Elementary processes :

$$\bar{q} + q \rightarrow \bar{q} + q$$
$$\bar{q} + g \rightarrow \bar{q} + g$$
$$g + q \rightarrow g + q$$
$$g + g \rightarrow g + g$$
$$\bar{q} + q \rightarrow g + g$$
$$g + g \rightarrow \bar{q} + q$$

Outgoing partons ⇒ hadronic jets
"Hadronization": an effect of parton confinement

Outgoing jets are <u>COPLANAR</u> ($\Delta\phi$ = 180°) but not <u>COLLINEAR</u>

UA2

- For each calorimeter cell define "transverse energy":

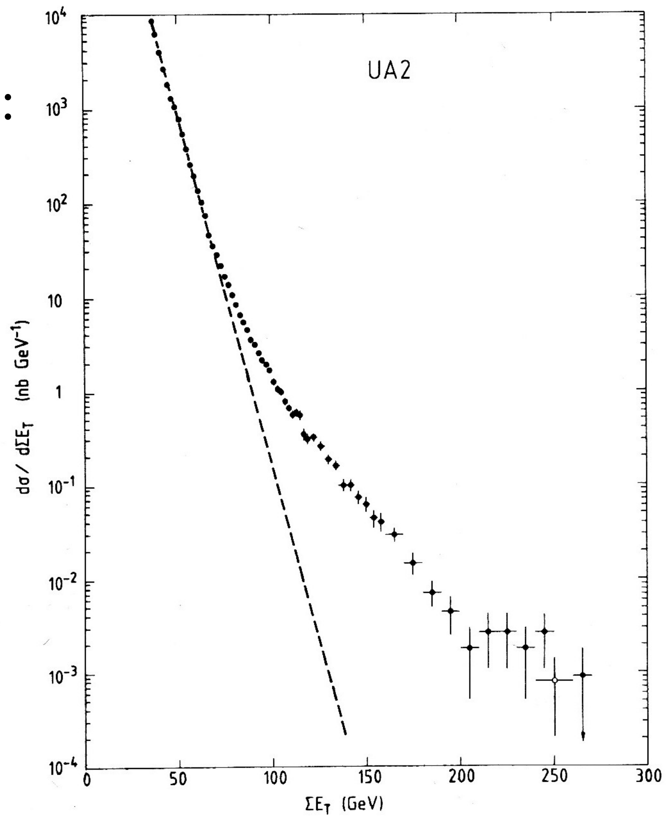
$$E_T = E \sin\theta$$

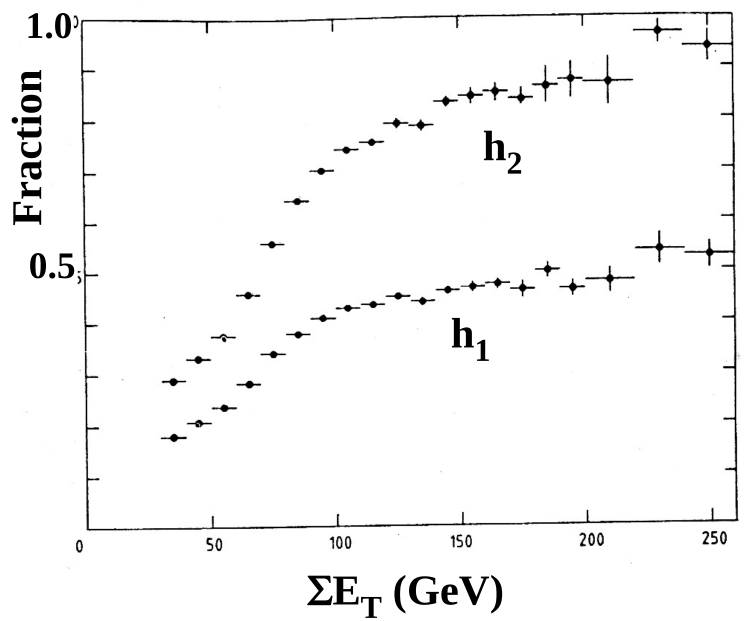
(**E:** energy deposition; **θ** : polar angle of cell centre)

- On-line selection of events ("trigger"):

$\Sigma E_T >$ **threshold** (sum over all calorimeter cells)

- Build "clusters": groups of adjacent cells, each with $E_T > 0.4$ **GeV**
- Define cluster transverse energy by adding E_T over all cells in cluster
- Order clusters: $E_T^1 > E_T^2 > \ldots\ldots > E_T^n$

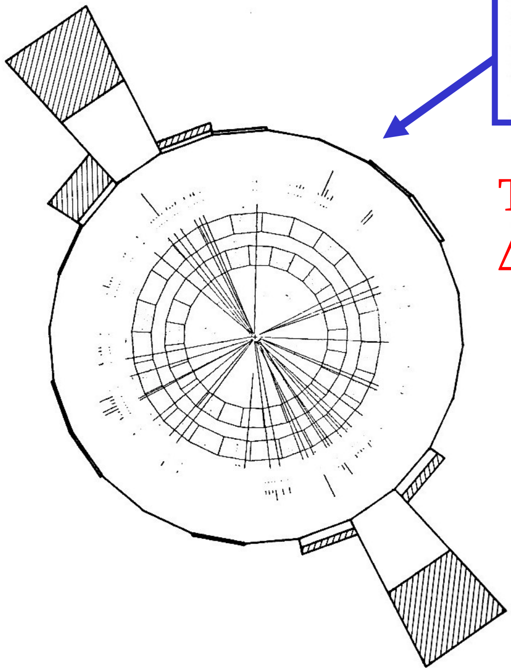




$$h_1 = \frac{E_T^1}{\Sigma E_T}$$ fraction of total E_T carried by leading cluster

$$h_2 = \frac{E_T^1 + E_T^2}{\Sigma E_T}$$ fraction of total E_T carried by the two leading clusters

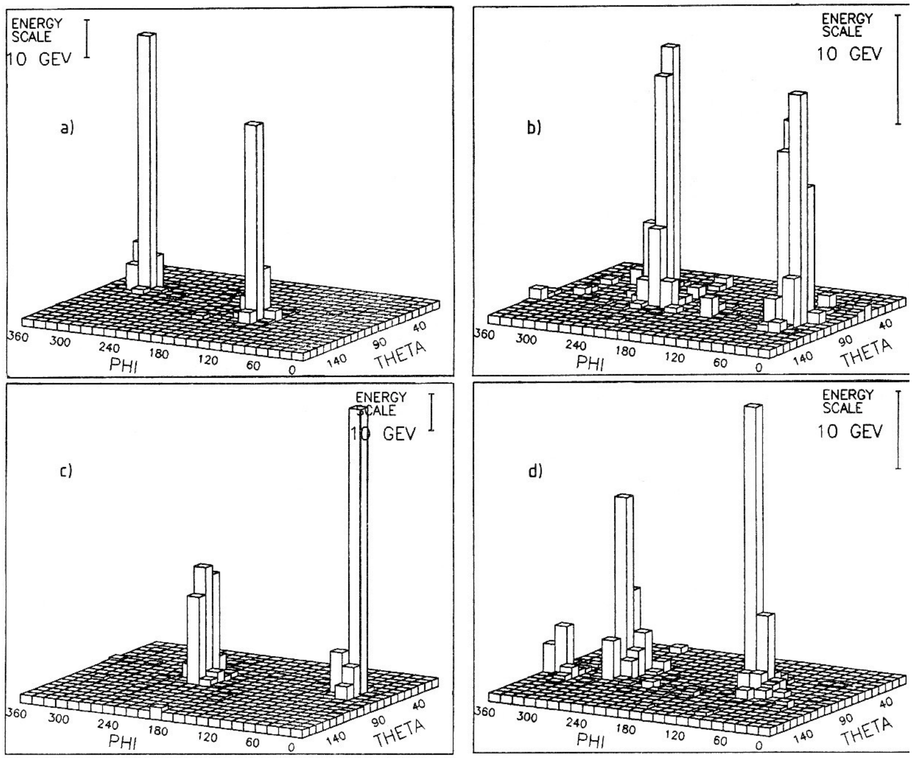
For large values of ΣE_T, the total transverse energy is mainly concentrated into two clusters



View of a typical event with large total transverse energy in a plane perpendicular to the beam axis

The two leading clusters consist of a small number of cells
$\Delta\phi \approx 180°$ as expected for two-jet production

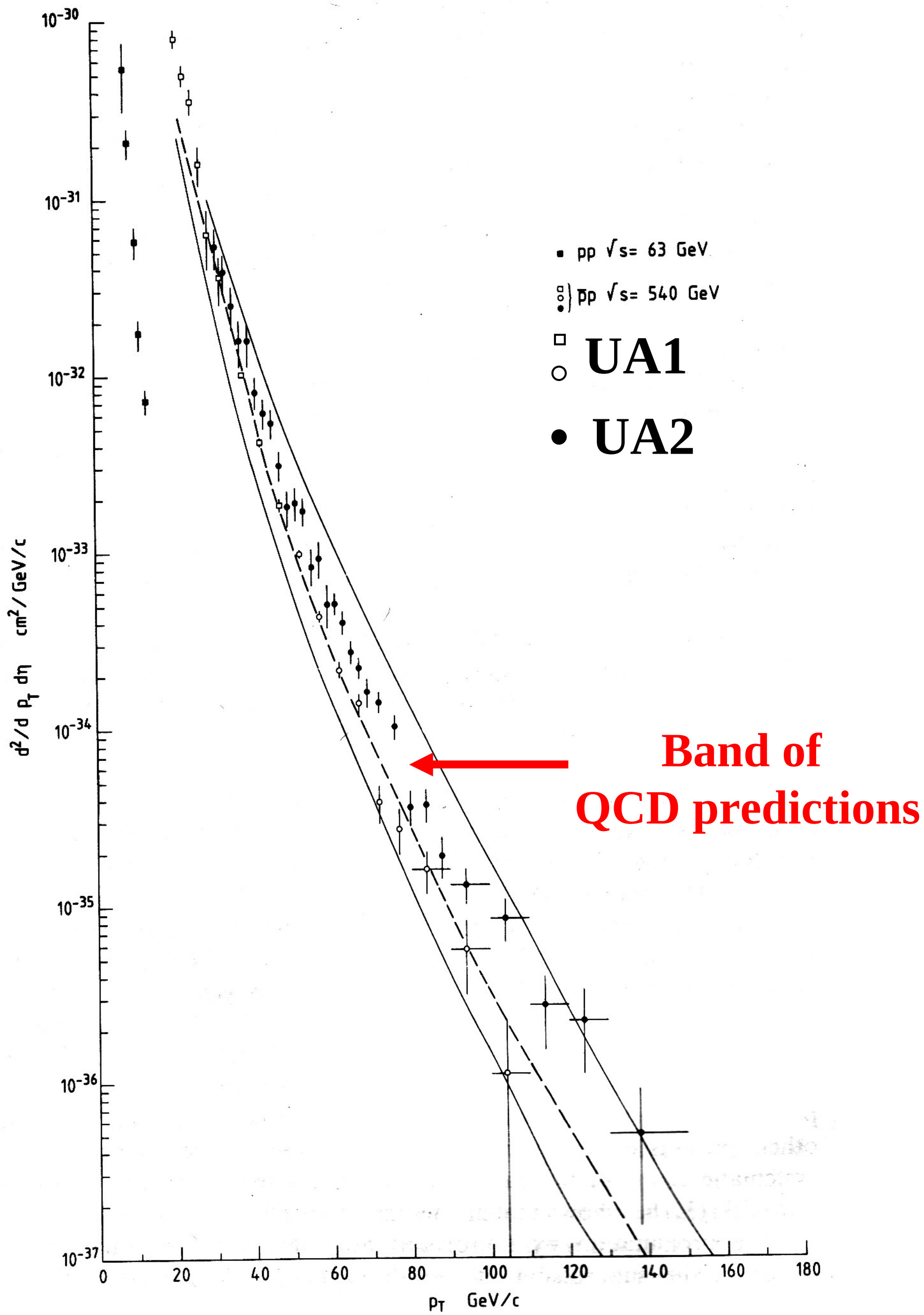
Transverse energy distribution
in the $\phi - \theta$ plane
for four typical events
with large total transverse energy



Differential cross-section for inclusive jet production at 90°

Relative contributions of parton scattering processes:

$\bar{q}+q \rightarrow \bar{q}+q$	1.0
$\bar{q}+g \rightarrow \bar{q}+g$ $g+q \rightarrow g+q$	1.2
$g+g \rightarrow g+g$	6.0

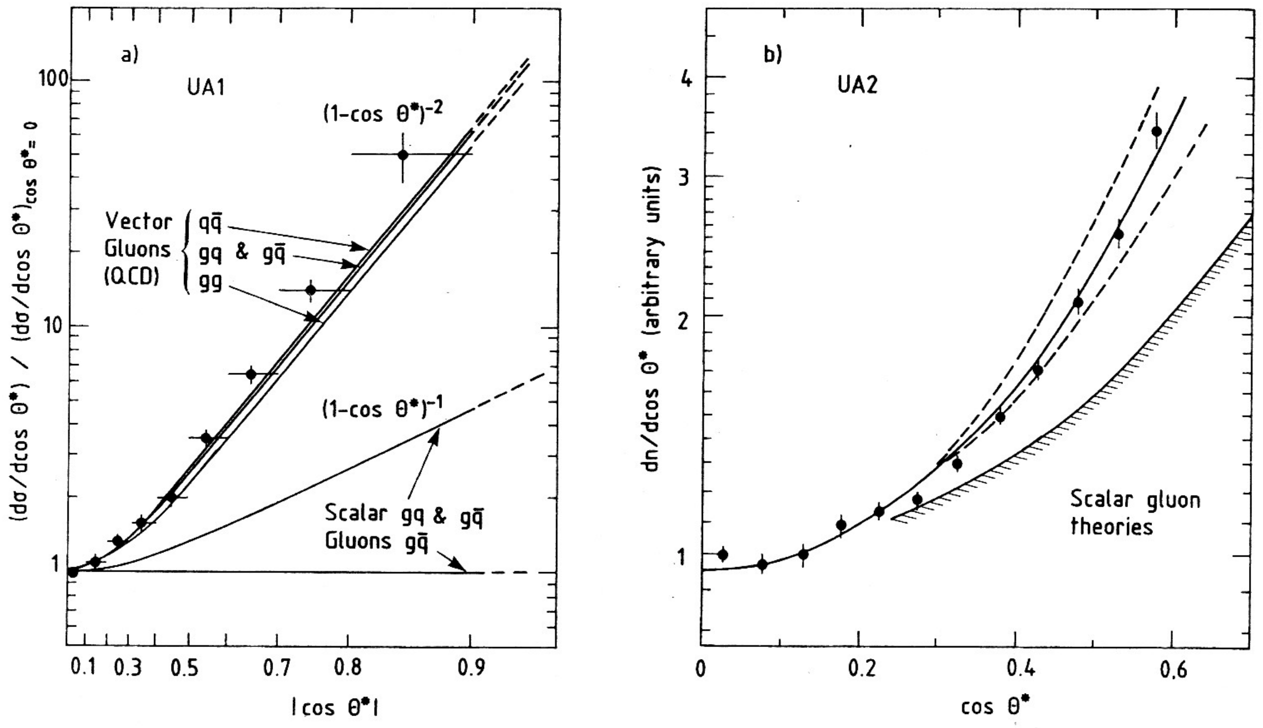


Angular distribution of parton-parton scattering

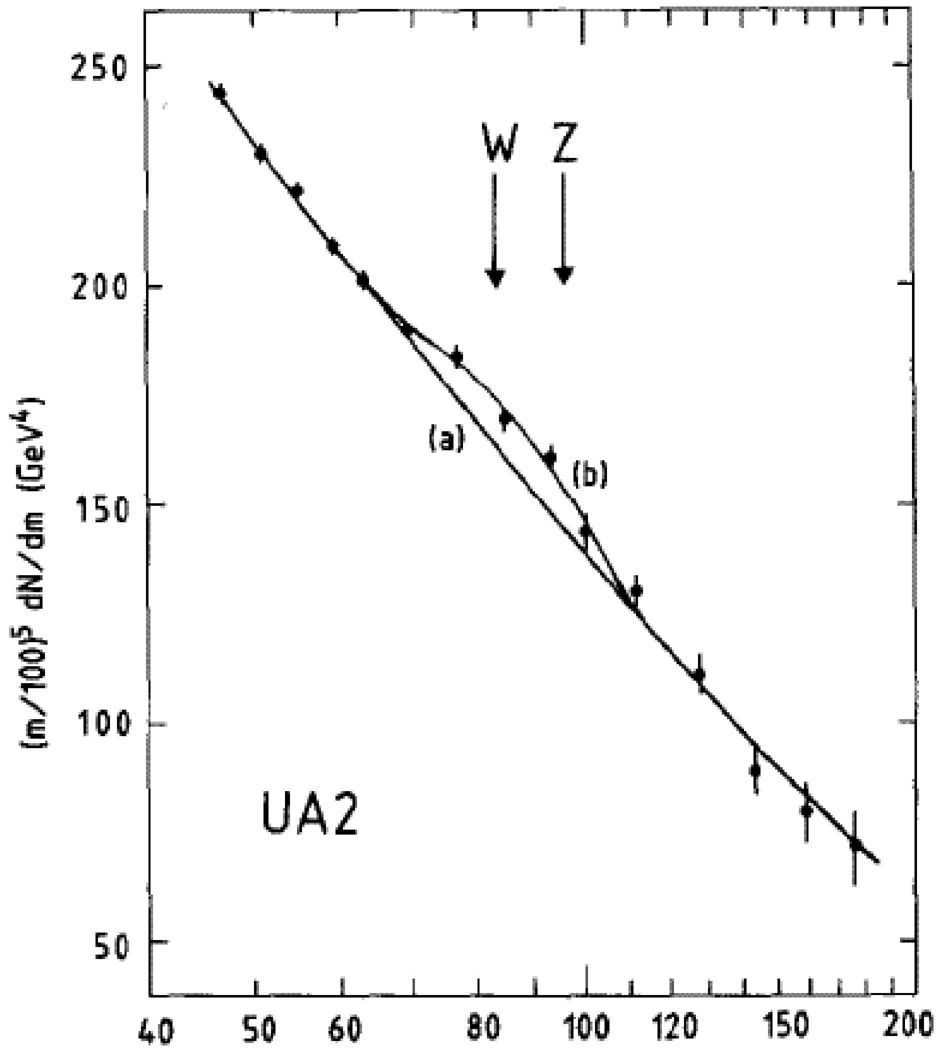
Transform the two jets to the centre-of-mass of the two-jet system
⇒ can measure the parton-parton scattering angle θ^*
(without distinguishing between θ^* and $\pi - \theta^*$)

All elementary parton scattering processes are dominated by gluon exchange in the t – channel ⇒ expect "Rutherford formula" for spin-1 gluons:

$$\frac{d\sigma}{d\cos\theta^*} \propto \frac{1}{\sin^4(\theta^*/2)} \propto \frac{1}{(1-\cos\theta^*)^2}$$ (as for one-photon exchange)



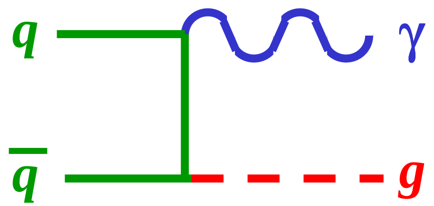
UA2: search for $W^{\pm} \rightarrow q\,\bar{q}'$ and $Z \rightarrow q\,\bar{q} \Rightarrow$ 2 jets



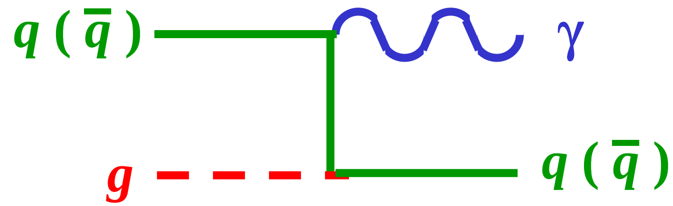
Two-jet invariant mass [GeV]

UA2: comparison of inclusive jet and direct photon production

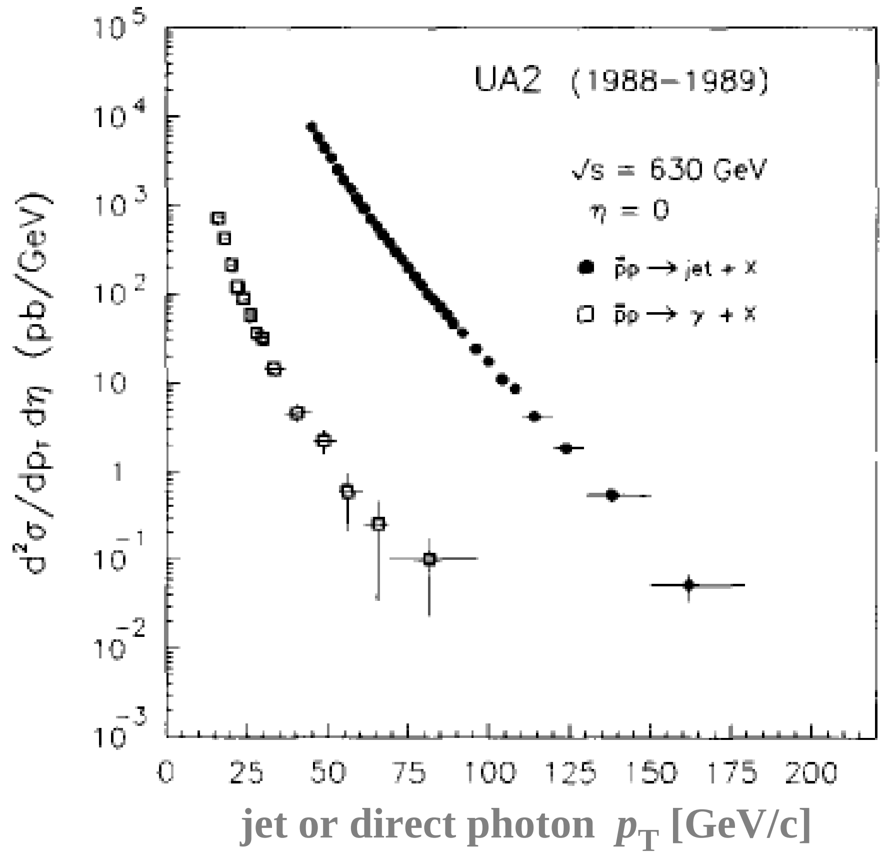
Diagrams for direct photon production:



$q + \bar{q} \to \gamma + g$



$g + q(\bar{q}) \to \gamma + q(\bar{q})$



UA1: First indirect evidence for $B^\circ - \overline{B}^\circ$ mixing

Study of 399 events containing two "non-isolated" muons (produced near other hadrons): $p_T(\mu) > 3$ GeV/c ; invariant mass $M_{\mu\mu}$ between 2 and 6 GeV

257 $\mu^+\mu^-$ **142 $\mu^+\mu^+$ or $\mu^-\mu^-$**

Main source of $\mu^+\mu^-$ events: production of $b\overline{b}$ quark pairs followed by muon decays:
$b \to c\,\mu^-\,\overline{\nu}_\mu$ and $\overline{b} \to \overline{c}\,\mu^+\,\nu_\mu$

Main source of $\mu^+\mu^+$ and $\mu^-\mu^-$ events: production of $b\overline{b}$ quark pairs followed by:
$b \to c\,\mu^-\,\overline{\nu}_\mu$ and $\overline{b} \to \overline{c}\,X$; or $b \to c\,X$ and $\overline{b} \to \overline{c}\,\mu^+\,\nu_\mu$

$\overline{c} \to \overline{s}\,\mu^-\,\overline{\nu}_\mu$; $c \to s\,\mu^+\,\nu_\mu$

After background subtraction (mainly $\pi^\pm \to \mu^\pm\nu$, $K^\pm \to \mu^\pm\nu$ decays in flight):

$$R = \frac{N(++) + N(--)}{N(+-)} = 0.42 \pm 0.07_{\text{stat.}} \pm 0.03_{\text{syst.}}$$

Prediction: $R = 0.26 \pm 0.03$

Difference between measurement and prediction interpreted as evidence for $B^\circ - \overline{B}^\circ$ oscillation : $B^\circ \to \overline{B}^\circ \to X\,\mu^-\,\overline{\nu}_\mu$ (and charge conjugate)
($B^\circ \equiv B_d^\circ$ or B_s°)

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 $B^{\circ} – \overline{B}^{\circ}$ mixing)**

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