Discovery of the $W^{\pm}$ and Z^0 Bosons

Status of the Standard Model ~1980

Planning the Search for $W^{\pm}$ and Z^0

SppS, UA1 and UA2

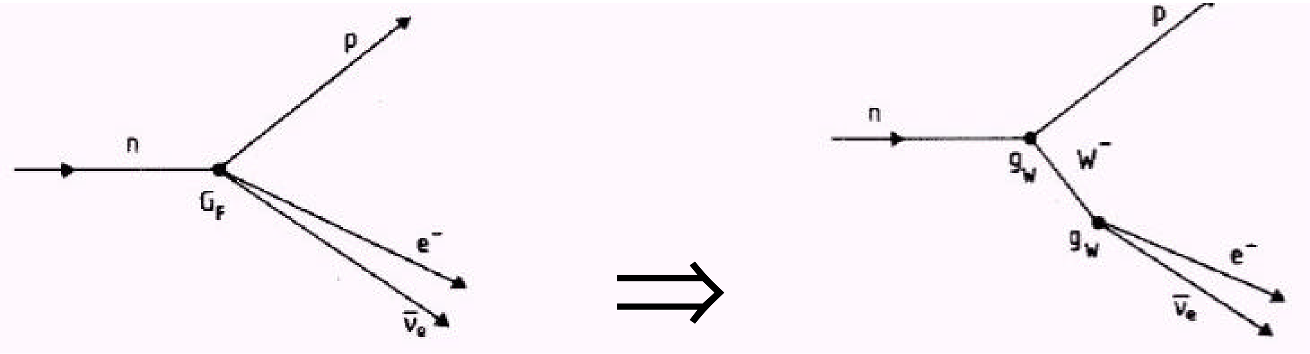
The analyses and the observed events

First measurements of $W^{\pm}$ and Z^0 masses

A Bit of History...

1960's: Glashow, Salam, Weinberg: electroweak unification:

- consistent with observed charged current interactions (exchange of $W^{\pm}$ boson):



- But: predicted neutral current interactions (exchange of γ, Z^o) which had never been observed...

Neutral Currents

- Until 1973 all observed weak interactions were consistent with only a charged boson.
- CERN, 1973: first neutral current interaction observed (see *Martin & Shaw*, p. 185):

$$\nu_\mu + \text{nucleus} \longrightarrow \nu_\mu + p + \pi^- + \pi^o$$

- suddenly very urgent to observe $W^\pm$, Z^o bosons directly to test electroweak theory.

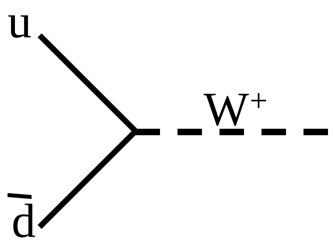
Planning the Search

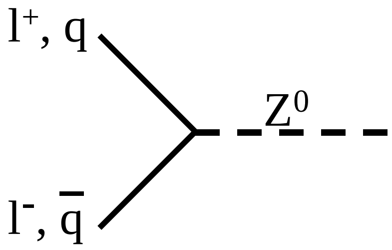
To find $W^{\pm}$ and Z^0, needed to understand:

- how they could be produced
  - in order to find or design a collider that could create them.
- how they would decay
  - in order to design detectors that could see them.

W and Z Production

- For $W^\pm$ and Z^0, electroweak theory predicted:
  - their masses:
    - $m_{W^\pm} \cong 83 \pm 3$ GeV
    - $m_{Z^0} \cong 94 \pm 3$ GeV
  - they would couple to leptons and quarks.





⇒ Needed a lepton or hadron collider capable of creating particles with masses in the 100-GeV range.

SPS → SppS

- No machine in existence could reach this energy
  - CERN's ISR collider (p-p): $\sqrt{s} = 61$ GeV
  - some new colliders being planned (e.g. LEP) but would not be ready soon
  - SPS was a proton accelerator for fixed target experiments ($E_{proton} = 400$ GeV; but for fixed target $\sqrt{s} = \sqrt{2mE}$, m = mass of target particle ⇒ too low!)

⇒ Rubbia, van der Meer: upgrade SPS into SppS (Super proton-antiproton Synchrotron)

The SppS

- $\sqrt{s}$ = 540 GeV
- 3 bunches protons, 3 bunches antiprotons, 10^{11} particles per bunch
- Luminosity = 5 x 10^{27} $cm^{-2}sec^{-1}$
- first collisions in December 1981

W and Z Decay Modes

$W^{+} \rightarrow$

- $e^{+} \nu_e$
- $\mu^{+} \nu_\mu$
- $\tau^{+} \nu_\tau$
- u d
- c s
- t b

$W^{-} \rightarrow$ the charge conjugates of the above

$Z^0 \rightarrow$

- $l^{+} l^{-}$ ($l = e, \mu, \tau$)
- $\nu_l \nu_l$ ($l = e, \mu, \tau$)
- q q (q = u,d,c,s,t,b)

Choosing a Decay Mode

Recall that at p-p(bar) colliders:

- most events are due to soft collisions, which have low-$p_\perp$ final-state particles.
- much high-$p_\perp$ background is jets from quark and gluon scattering (‘QCD background’).

$$\Downarrow$$

Most promising decay modes are the leptonic ones.

Signatures in the Detectors

$\boxed{W^{+} \rightarrow l^{+} \nu_{l}}$

- a high-$p_{\perp}$ electron or muon
- large missing $E_{\perp}$ (due to the ν)

$\boxed{Z^{0} \rightarrow l^{+} l^{-}}$

- two electrons or two muons with
  - high $p_{\perp}$
  - opposite charge

Detector Requirements

The detector(s) must be capable of:

- charged lepton
  - detection,
  - identification,
  - momentum and/or energy measurement.
- Missing-$E_\perp$ measurement.

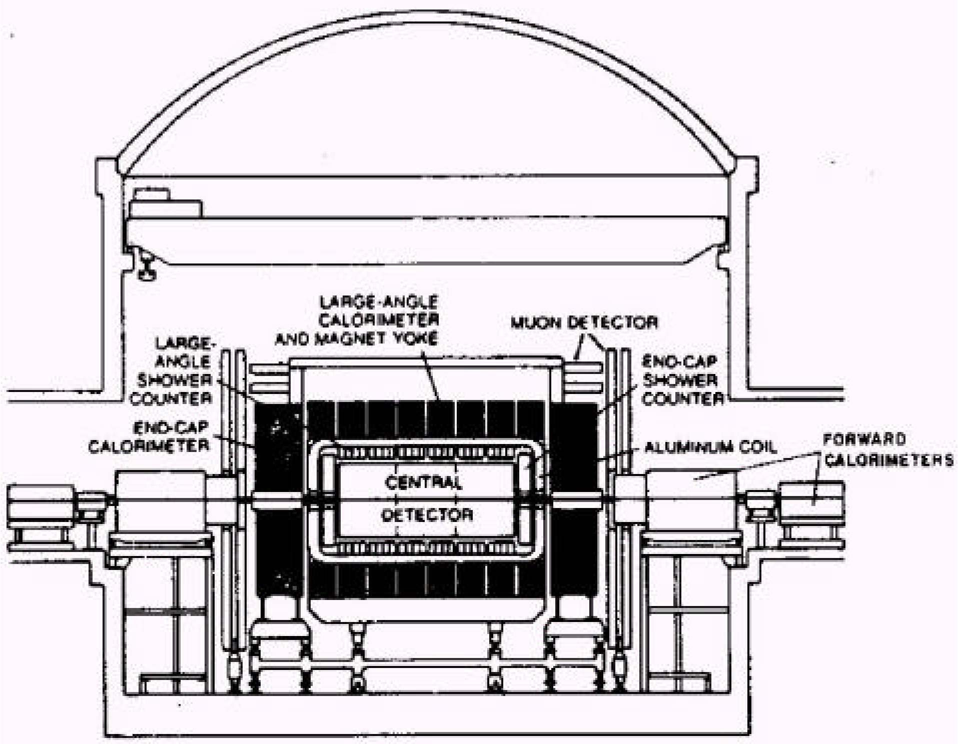
The SppS Experiments

6 detectors:

- UA1, UA2, UA3, UA4, UA5, UA6 *
- UA1 and UA2 were the only ones able to see $W^{\pm}$, Z^{0}

* UA = Underground Area.

The UA1 Detector



- all-purpose detector
- Excellent hermeticity (i.e. very few gaps) - good for missing $E_\perp$ measurement
- tracker and electromagnetic calorimeter immersed in magnetic field
- Magnet return yoke = hadronic calorimeter
- 8-layer muon detector

UA1, cont'd

Advantages

- magnetic field in tracker
- hermetic
- muon detection

Disadvantages

- ecal not great:
  - poor granularity
  - no position detection in barrel
  - difficult to calibrate

UA1's W $\rightarrow$ e ν Search

- Using 18 nb^{-1} (~10^9 collisions) from late 1982...
- Need a high-$p_\perp$ electron. Looked for events with:
  - – an ecal cluster with $E_\perp$ > 15 GeV
  - – an isolated high-$p_\perp$ track pointing to cluster
  - – ecal energy measurement matches tracker energy measurement
  - – no associated energy in hadronic calorimeter

$\Rightarrow$ 39 such events !

UA1's W → e ν Search, cont'd

- Looked closely at those 39 events:
  - 5 events had:
    - no jets
    - missing $E_\perp \cong$ electron $E_\perp$.
  - The other 34 events had:
    - one or two jets
    - no missing energy.
- Similar analysis performed on end-cap region yielded one more event with an electron and no jets.
- Parallel analysis concentrating on finding events with missing $E_\perp$ yielded the same 6 events.

UA1's W $\rightarrow$ e ν Search: Background Evaluations

Could these events be something other than $W^{\pm}$s?

- A high-$p_{\perp}$ hadron or mostly-neutral jet misidentified as an electron?
- π^0, η^0 or $\gamma \rightarrow e^+e^-$, with one e missed?
- Jet with electron (rest undetected) + jet with neutrino (rest undetected)?

- Used knowledge of:
  - detector response
  - expected rates of such background events
  - deliberate searches for such background events in the data

to conclude that these backgrounds were negligible.

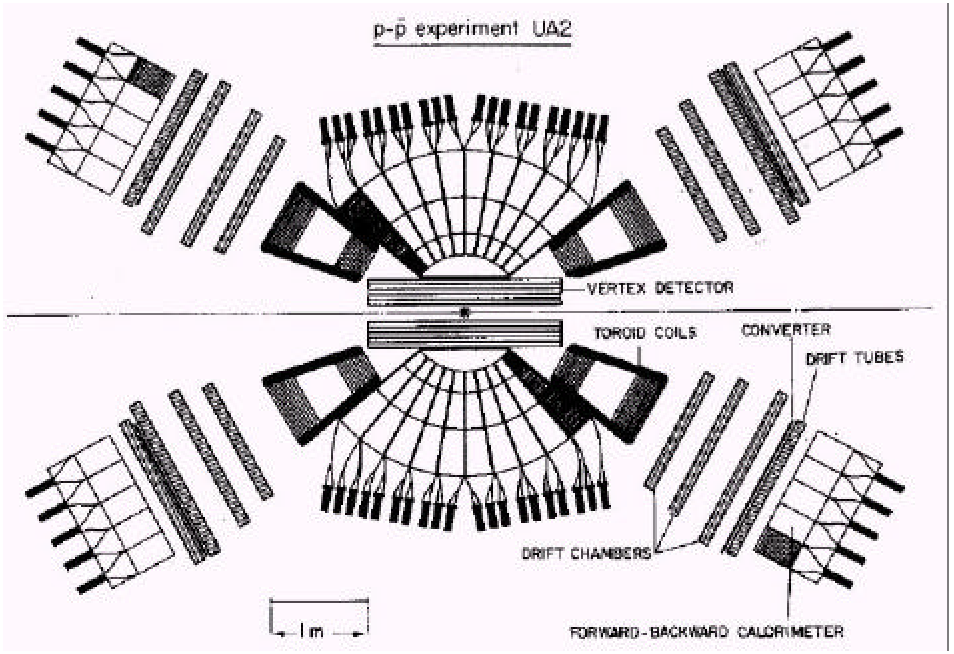
UA1 announced their observation the following February:

Physics Letters 122B (1983) p103:

“Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s}$ = 540 GeV’’

The UA2 Detector

- Principally for $W^{\pm}$, Z^0 decays to high-$p_{\perp}$ electrons
- well instrumented in central region
- Inner tracker
  - no central magnetic field
    - $\Rightarrow$vertexing only for high-$p_{\perp}$ tracks
- finely-segmented calorimeters
  - electron ID
  - energy measurement



UA2, cont'd

Advantages

- good ecal, esp. in barrel region:
  - good granularity
  - tower structure points to origin
  - everything could be calibrated in-beam

Disadvantages

- no magnetic field in central region
- no endcap-region calorimetry
- no muon detection

UA2’s $W \rightarrow e\,\nu$ Search

UA2 performed a similar analysis on the data they collected during the same period (November-December 1982), and found 4 $W \rightarrow e\,\nu$ events.

Physics Letters 122B (1983) p476:

“Observation of Single Isolated Electrons of High Transverse Momentum in Events with Missing Transverse Energy at the CERN pp Collider’’

Z search

$Z^0 \rightarrow$ leptons rarer than $W^\pm \rightarrow$ leptons

$\Rightarrow$ no Z^0 discovery in 1982 data.

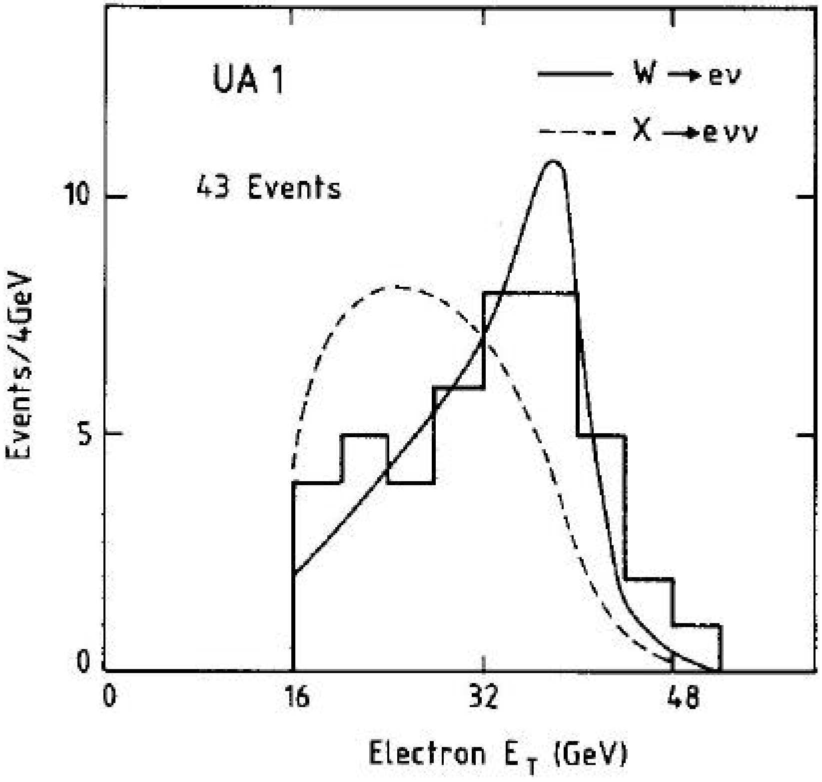
More collisions in 1983 produced enough additional data for Z^0 to be observed...

Observation of Z^0

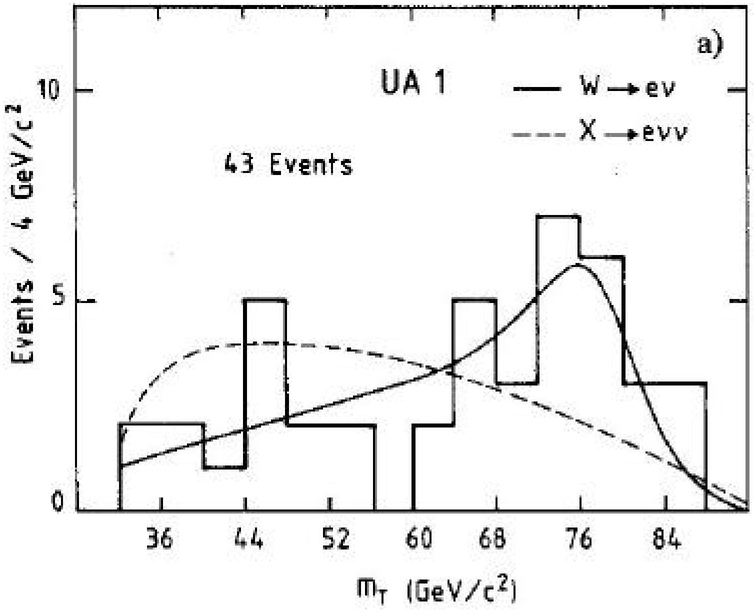
- For $Z^0 \rightarrow e^+e^-$, need:
  - one high-$p_\perp$ electron and one high-$p_\perp$ positron, chosen ~ as for $W^\pm$ search.
  - No missing $E_\perp$.
  - UA1: 3 events, UA2: 4 events
- For $Z^0 \rightarrow \mu^+\mu^-$ (UA1 only), need:
  - two oppositely-charged isolated high-$p_\perp$ tracks in central tracker with matching tracks in muon chambers
  - no missing $E_\perp$.
  - 1 event found

Determination of W Mass

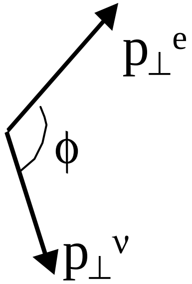
- Two methods:
  - lepton $E_{\perp}$ spectrum peaks at $m_W/2$ ⇒
    - compare measurement to Monte Carlo prediction
    - can be affected by transverse momentum of W
  - transverse mass method (see next slide...)



W Transverse Mass



In the plane transverse to the beam:



- $M_T^2 = (E_\perp^e + E_\perp^\nu)^2 - (p_\perp^e + p_\perp^\nu)^2$
- neglecting m_e, m_ν:

$$m_T^2 = 2E_\perp^e E_\perp^\nu (1-\cos\phi)$$

  - compare measurement to Monte Carlo prediction
  - ~independent of transverse momentum of $W^\pm$

Determination of Z Mass

Invariant mass of the lepton system forms a peak at m_{Z^0} .

Invariant Mass

(see *Martin & Shaw*, Appendix A)

- Consider a system of N particles:

$$E = E_1 + E_2 + \ldots + E_N$$

$$p = p_1 + p_2 + \ldots + p_N$$

- The invariant mass of the system (M) is defined by:

$$M^2c^4 = E^2 - |p|^2c^2$$

- M has the same value in any reference frame.

W, Z Mass Measurements

Using all data from 1982-3, and combining results from UA1 and UA2:

$$m_{W^{\pm}} = 82.1 \pm 1.7 \text{ GeV}$$

$$m_{Z^{0}} = 93.0 \pm 1.7 \text{ GeV}$$

Current values:

$$m_{W^{\pm}} = 80.43 \pm 0.04 \text{ GeV}$$

$$m_{Z^{0}} = 91.188 \pm 0.002 \text{ GeV}$$