Discovery of W Boson

Presenting results from the UA1 collaboration (1983)

Romal Kumar

For the discussion of science...

Friday, 2021-05-07

Outline

1 Introduction
2 Detector
3 Electron and Neutrino Identification
4 Data-Taking
5 Background Evaluations
6 Search for Electron and Neutrino Candidates
7 Conclusion

Prelude

- A theoretical unified electroweak theory by Weinberg, Salam, and Glashow
  - 1961 Glashow proposes an electroweak unified model with $SU(2) \times U(1)$ gauge group and proves existence of neutral currents
  - 1967-1968 Weinberg and Salam complete the electroweak unification and predict **three** (massive) Intermediate Vector Bosons (IVBs)
- Experimental discovery of weak neutral currents at the Gargamelle detector at CERN in 1973 ✓
- Mass of the IVBs were theoretically predicted using *relevant input parameters*
- Cross-sections of $p, \bar{p}$ reactions(collisions) were well studied

Introduction

Back to the present (circa 1983)

- To search for the two charged IVBs and verify its predicted mass
- Study the collision of proton, anti-proton $(p, \bar{p})$ beams at the CERN Super Proton Synchrotron (SPS)
- Enhancement of quark + anti-quark $\rightarrow e^{\pm} + \nu$ cross-section near the IVB mass (pole) [so called, "bump search"]
- $\sigma(p\bar{p} \rightarrow W^{\pm} \rightarrow e^{\pm} + \nu) \simeq 0.4 \times 10^{-33}\ k\ \mathrm{cm}^2$ ($k \sim 1.5$ due to Drell-Yan processes)

What to look for

If $W^{\pm}$ exists, then it would produce $e^{\pm} + \nu$. So we look for charged electron tracks to confirm an electron, and for missing (transverse) energy to confirm a neutrino.

The experimental setup

- SPS operated at $\sqrt{s} = 540\,\mathrm{GeV}$
- To cover largest possible solid angle around the interaction point
- 3 main parts
  - Central Detector (CD): Cylindrical drift chamber
  - Electromagnetic Calorimeter (ECAL) and Hadronic Calorimeter (HCAL)
  - Muon chambers surrounding the magnet

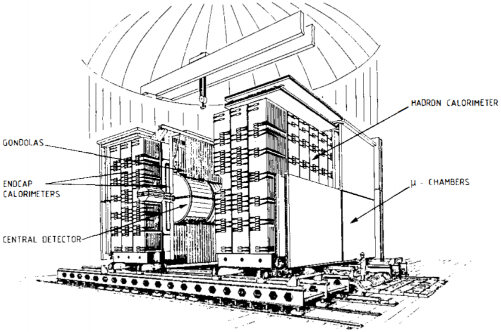


Figure: UA1 detector: side view

4 regions of covering around CD. Up to 0.2° about the beam-axis.

The central and endcap hadron calorimeters serve as a return yoke of the UA1 magnet.

In the drift chamber, conditions are adjusted such that maximum drift time is less than the minimum bunch separation in the SPS.

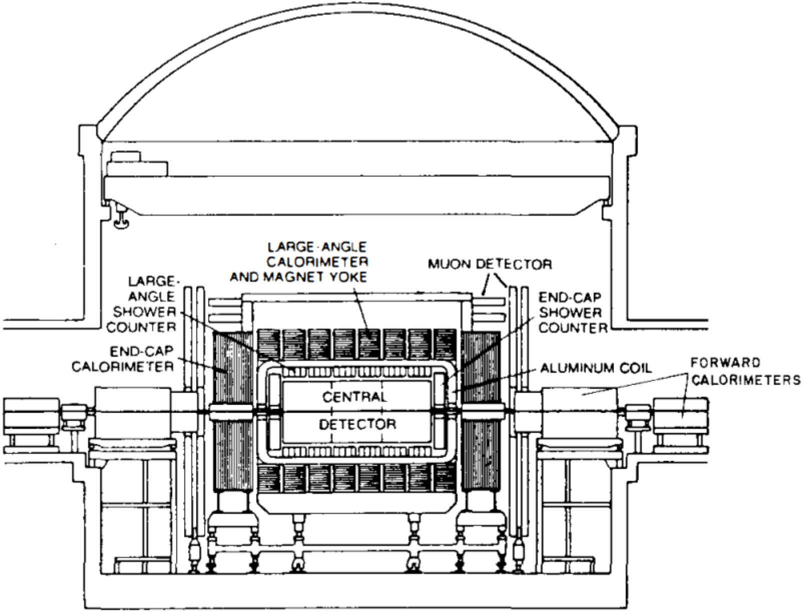


Figure: UA1 detector: front view

Precise detector description for the curious!

Part/Device	Remarks
Cylindrical drift chamber	Operating in a dipole magnetic field of 0.7 T over a volume of $7 \times 3.5 \times 3.5\,\mathrm{m}^3$
Angular coverage around CD	$90° - 25°$ for central covering, $25° - 5°$ for endcap covering, $5° - 0.7°$ for forward covering, $0.7° - 0.2°$ for very forward covering
Muon chamber	$500\,\mathrm{m}^2$ of muon chambers surrounding the magnet
CD	For 1 m long track, ±20% accuracy at $p = 40\,\mathrm{GeV}$; ionization tracks measured by the truncated mean of 60% lowest readings (to obtain better statistics)
ECAL	2×24 half-cylinders called "gondolas" with alternate layers of scintillator material and Photo Multiplier Tube (PMT). Azimuthal angle resolution: $\Delta\phi(\mathrm{rad}) = \frac{0.3}{\sqrt{E\,(\mathrm{GeV})}}$
ECAL & HCAL	Techniques employed can identify electrons over a pseudorapidity interval of $\|\eta\| < 3$ with full azimuthal coverage
Endcap electromagnetic shower counters	Called 64 petals (bouchons). Measurements (attenuation length varied with polar angle) chosen such that one could directly readout the transverse energy deposited

Electron and Neutrino identification

Electron identification

EM showers identified and noted for their lack of penetration in HCAL. Detector performance extensively studied with test beams as a function of energy, angle of incidence, and the location of impact (and previous run at an integrated luminosity of 5 nb^{-1}). Fraction of pions below a given HCAL threshold is negligible. 98% of electrons detected.

Neutrino identification

Look for missing energy. This requires the calorimeters to be *hermetic* (or "airtight") down to 0.2°. Missing energy due to muons is well estimated by analyzing muon tracks.

On Data-Taking

Data-Taking

- Data taking over a period of 30 days during November and December 1982
- Final run at an integrated luminosity of 18 nb^{-1} with $\sim 10^9$ $p, \bar{p}$ collisions

Trigger conditions

- Recognize EM energy deposition of at least 10 GeV either in two gondola elements or in two bouchon petals
- Jet trigger with more than 15 GeV in ECAL and HCAL
- Global $\mathrm{E_T}$ trigger with $|\eta| < 1.4$
- Muon trigger with $|\eta| < 1.3$ with at least one penetrating track in the muon chamber

In total, 9.75×10^5 triggers collected out of which 1.4×10^5 were flagged as an electron trigger.

After further filtering; for reconstruction, **2125** *good quality* events with $\mathrm{p_T} > 7$ GeV were identified. Majority of the events taken from gondolas. Bouchon events were largely discarded.

Background Evaluations

1. High $\mathrm{p_T}$ $\pi^{\pm}$ misidentified as an electron or π^0 misidentified in an EM cascade
    - searched for single-track events with $\mathrm{p_T} > 20$ GeV, no jet and more than 600 MeV in HCAL → high $\mathrm{p_T}$ background is negligible
2. High $\mathrm{p_T}$ π^0, η^0, γ
    - Show up as EM conversions per rapidity in bouchons. EM cascade is theoretically well understood using Bethe-Heitler, Kroll-Wada formula. Taking a very conservative estimate for these conversions, this background is still negligible
3. Heavy quark associated production and pathological fragmentation which produces an electron, neutrino, and jets
    - Imposing high $\mathrm{p_T}$ cut-offs, trigger conditions makes this background process negligible

Inference

No background process is capable of simulating (giving a false signature) electron and neutrino events that have been isolated in the analysis.

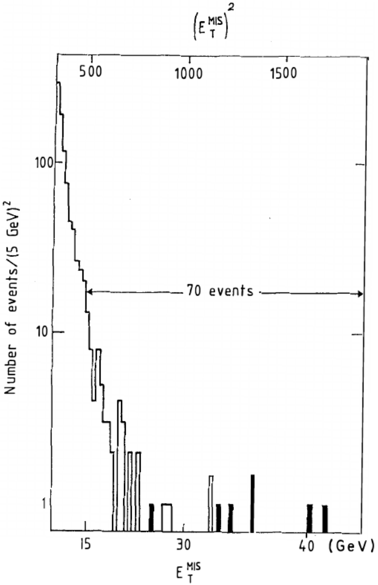


Figure: For those events which survive the cuts requiring association of the central detector isolated track and a struck gondola in the missing-energy search

Five conditions and the aftermath for electron candidates

Three conditions to ensure that the track is isolated

1. Look for high p_T events in (adjacent) pair of gondolas
2. Energy recorded by a pair of gondolas for other charged tracks should not exceed 2 GeV
3. Azimuthal measurement must agree within 3σ between gondola's PMT and impact of the track

Two conditions to ensure a track deu to e^+ or e^-

1. Energy deposited in HCAL should not exceed 600 MeV
2. Momentum measurement between gondolas and trackers must be within 3σ

After the five conditions were imposed on good quality events, they were left with **39** events which were individually examined.

$$39\ \text{events} \rightarrow \underbrace{5\ \text{no jet activity}} + \underbrace{11\ \text{single jets}} + \underbrace{23\ \text{two jets}}$$

no jet $\sim$ yes neutrino!

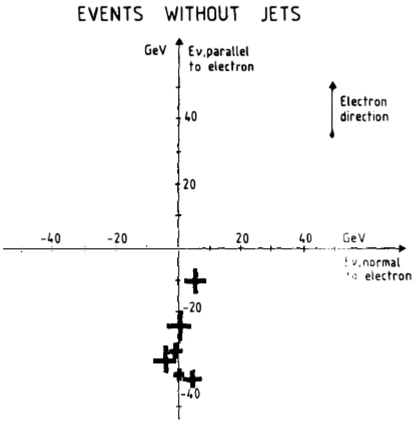


Figure: Missing transverse energy for events yielded by the electron search – without jets

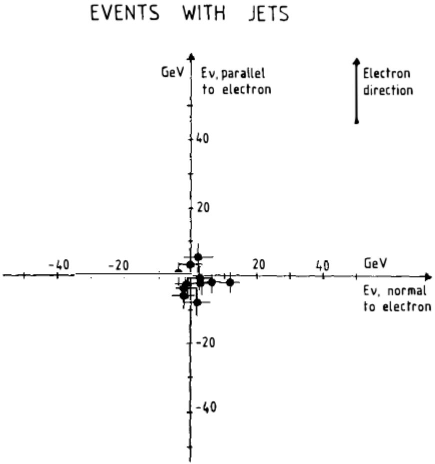


Figure: Missing transverse energy for events yielded by the electron search – with jets

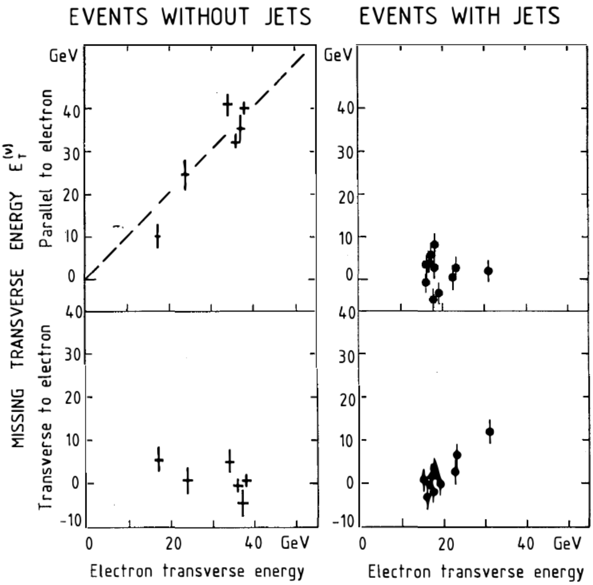


Figure: Missing transverse energy for events yielded by the electron search – without and with jets

Neutrino candidates

To conclusively prove that no jets are likely the neutrinos:

- From good quality events, look for events with high missing transverse energy
- Missing energy validated by removing low resolution tracks around the corners and ducts
- Big secondary interactions in the beam pipe are removed
- Candidate track should be well isolated, i.e., $p_T > 1.5$ GeV in a 30° cone

After all is said and done, they were left with **18** events which were individually examined.

$$\text{18 events} \rightarrow \underbrace{\text{7 no detectable jet}} + \underbrace{\text{11 with jet activity opposite to the track}}$$

Of course, the electron track and the missing energy event must be simultaneous (from 2-body decay of the W boson!)

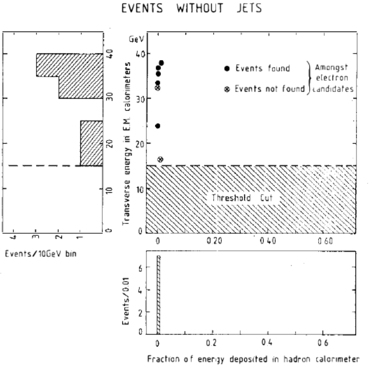


Figure: In the EM calorimeter which survive the missing energy search – without jets

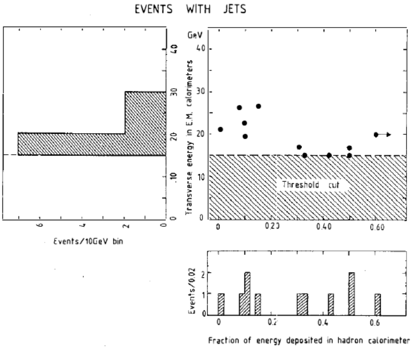
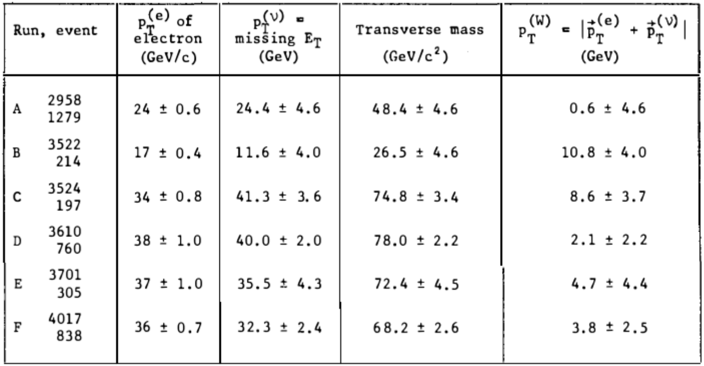


Figure: In the EM calorimeter which survive the missing energy search – with jets



Run, event	$p_T^{(e)}$ of electron (GeV/c)	$p_T^{(\nu)}$ = missing E_T (GeV)	Transverse mass (GeV/c^2)	$p_T^{(W)} = \lvert\vec{p}_T^{(e)} + \vec{p}_T^{(\nu)}\rvert$ (GeV)
A 2958 1279	24 ± 0.6	24.4 ± 4.6	48.4 ± 4.6	0.6 ± 4.6
B 3522 214	17 ± 0.4	11.6 ± 4.0	26.5 ± 4.6	10.8 ± 4.0
C 3524 197	34 ± 0.8	41.3 ± 3.6	74.8 ± 3.4	8.6 ± 3.7
D 3610 760	38 ± 1.0	40.0 ± 2.0	78.0 ± 2.2	2.1 ± 2.2
E 3701 305	37 ± 1.0	35.5 ± 4.3	72.4 ± 4.5	4.7 ± 4.4
F 4017 838	36 ± 0.7	32.3 ± 2.4	68.2 ± 2.6	3.8 ± 2.5

Table: Six final events which prove the existence of the W boson

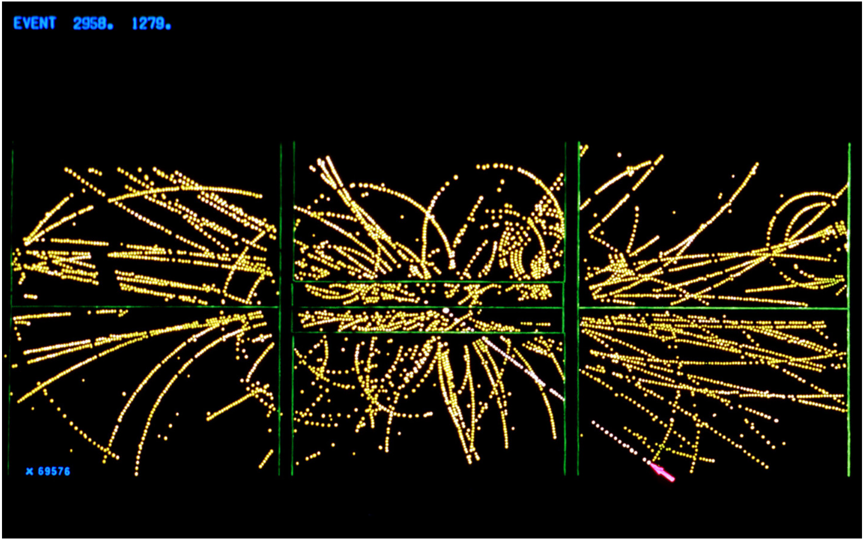


Figure: Event–A (credits CERN)

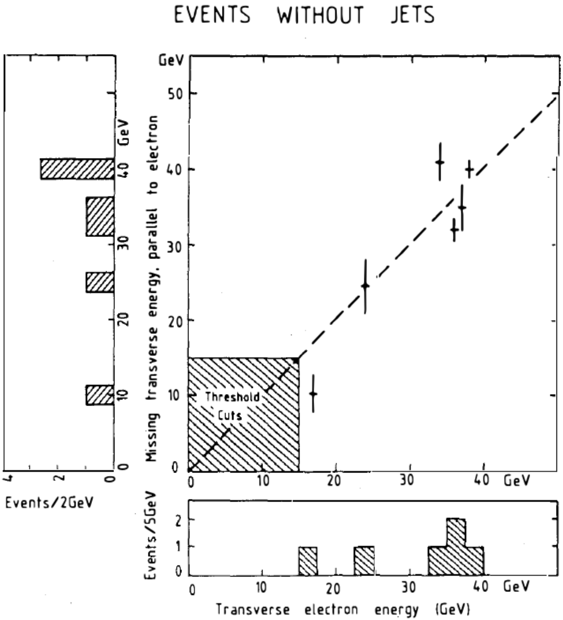


Figure: Plot for the final six electron events without jets (5 gondolas, 1 bouchon)

Conclusion

- Simultaneous detection of an electron and neutrino of approximately equal and opposite transverse momenta suggesting the presence of a two-body decay of the W boson
- Invariant transverse mass of electron and neutrino gives transverse W mass. Mass of the W boson then estimated using azimuthal data, in good agreement with theoretically predicted value $m_W > 73\,\text{GeV}$ (90% confidence level)
- Good agreement of the fitted electron momenta vs expected number of events with theoretical calculations considering full QCD smearing, confirming theoretically predicted W mass; $m_W = 74^{+4}_{-4}\,\text{GeV}$
- The final result after accounting for the transverse W motion from the imbalance, on an event-to-event basis gives $m_W = 81^{+5}_{-5}\,\text{GeV}$ as the final result

“Future” (1980s–1990s)

UA1 detects many more W boson events and also goes on to observe W decays via the tau lepton (followed by hadronic decay). Its cousin UA2 goes on to discover the Z boson and also observed W boson events. They went on to carry out electroweak precision tests.

Your very own W boson!

W BOSON

W-, W+

The **W BOSON** is a messenger particle which communicates the weak force. Unlike the photon and gluon bosons, it has a mass. Like the Z boson, it is one of the most short-lived particles known, with a mere 10^{-25} second lifetime. It can be negatively charged (W-) or positively charged (W+). Luckily you can have both, as the toy is double-sided.

Acrylic felt with gravel fill for maximum mass.