W & Z Discoveries with UA1
40 years ago

Jean-Pierre Revol/CERN, October 31, 2023

Electroweak milestones - 50 years of neutral currents, 40 years of W and Z bosons
Introduction

- I arrived at CERN as a fellow in January 1982, just in time to take part in the most incredible period of my professional life.

- In this presentation, I will not have time to do justice to all the physics and technical aspects of the project, and to the many members of the UA1 team Carlo had assembled around him.

- I would like to simply try and show how improbable the whole proton-antiproton collider project was, how innovative it was, and how large an impact it had on the future of CERN.
A bit of CERN history

1971  SPS approved by CERN Council on 19 February 1971, after 6 years of political saga – **brilliantly resolved by John Adams**

1972  S. Van der Meer, Stochastic damping of betatron oscillations, Internal Report, CERN/ISR PO/72-31 (1972)

1973  Discovery of weak neutral currents with Gargamelle proposed by André Lagarrigue

1974  Approval of ISABELLE at Brookhaven (200 GeV x 200 GeV)

1976  CERN working group on the construction of an e+e− collider (LEP), large enough to allow discovery of W± and Z0

**17 June:** End of SPS commissioning at 300 GeV (Fermilab Main Ring at 400 GeV)

\[
M_W = \left[ \frac{\pi \alpha}{\sqrt{2} G_F} \right]^{\frac{1}{2}} \frac{1}{\sin(\theta_W)}
\]

\[
M_Z = \frac{M_W}{\cos(\theta_W)}
\]

\[
sin^2(\theta_W) \sim 0.3
\]

\[
M_Z < 100 \text{ GeV} / c^2
\]

D. Cline, P. McIntyre, F. Mills and C. Rubbia, Collecting antiprotons in the Fermilab booster and very high-energy proton-antiprotons interactions, Fermilab Internal Report TM 689 (1976)

C. Rubbia, P. McIntyre and D. Cline, Proposal for a proton-antiproton collider (Sp¯¯pS), Proc. Int. Neutrino Conf. Aachen, June 8-12, 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

Presented by C. Rubbia

Aachen, June 8-12, 1976
All the ingredients present in C. Rubbia et al.

“The search for these massive bosons requires three separate elements to be successful: a reliable physical mechanism for production, very high center of mass energies, and an unambiguous experimental signature to observe them.”

C. Rubbia, P. McIntyre, D. Cline, Aachen, June 8-12, 1976

➢ **Production mode**: Collider as opposed to fixed target; Antiproton-proton as opposed to proton-proton collisions (USA choosing pp collider with ISABELLE (200 GeV + 200 GeV)

➢ **Beam energy and luminosity**: As the W & Z masses were constrained to be of order 50 to 100 GeV, 300 GeV beams and Luminosity ≈ 3x10^{29} cm^{-2} s^{-1} at the SPS should do it. A detailed description on how to achieve the antiproton beam

➢ **Event signature**: μ channel for “cleanest experimental signature”, use of mass peak for Z^0 and Jacobian peak for W^±
The accelerator challenge

 Convert the SPS to a proton-antiproton collider

- Only way: produce antiprotons from the 26 GeV CERN PS proton beam (~ one 3.5 GeV antiproton per $10^6$ protons)
- Move antiprotons to an accumulator ring and condense them before acceleration in PS and injection into SPS
- Resolve the issue of operating the machine with large beam-beam tune shift and no damping, unlike electron-positron machines
- Allow SPS operation in fixed target mode at least part of the year while constructing detectors

"Leon van Hove supported the project from the beginning, while the accelerator community was initially sceptical, but was soon filled by the enthusiasm of undertaking a very challenging enterprise". Giorgio Brianti

"... the conversion of the SPS into a proton-antiproton collider was a vital step in understanding beam-beam tune shift ...

... the proton-antiproton collider proved to be an absolutely essential prototype for defining the parameters of the LHC." Lyndon Evans
**Initial Cooling Experiment**

- ICE setup, building a test synchrotron re-using the g-2 experiment magnets, to test both stochastic cooling and electron cooling

- Antiproton lifetime measured to be long enough \( \tau \text{ (antiproton)} > 32 \text{ hours (95% C.L.)}, \) previously \( > 1.2 \times 10^{-4} \text{ s (95% C.L.)}, \) by S.N. Ganguli, et al. Phys. Lett., 74B (1978)

Momentum cooling of \( 5 \times 10^7 \) particles in ICE
Spread reduced from \( 3.5 \times 10^{-3} \) to \( 5.0 \times 10^{-4} \) in 4 mn

A bit of CERN history

1978  **January**: C. Rubbia et al., UA1 Proposal

A relatively small collaboration by today’s standards (52 authors, 9 institutes), but considered very large at the time

**June**: The success of the ICE experiment led immediately to the approval of the SpśS project and of UA1 by CERN Council
UA1 detector: a truly innovative concept

The challenges:
- multi-purpose detector
- Hermeticity (down to 0.2° from beam line $|\eta| < 6.35$), key to $W$ identification
- Size
- Complexity requiring dedicated technical coordination

UA2 proposal encouraged by CERN management, and approved 6 months after UA1
Construction required a "garage" position.
The Central Detector (CD)

- The wire chamber concept invented by Georges Charpak taken to a new dimension, providing 3-D track reconstruction through charge division (6 m long, 2.2 m diameter)

- Major role: providing momentum analysis (E/p matching for high momentum electrons and muon track matching from $W^\pm$ and $Z^0$ decays); study of underlying event and backgrounds in general; main input to event display

- Phase transition from “Bubble Chambers” to “Electronic Detectors”, which can be triggered
On-line event display in UA1 Control Room at LSS5 (voices of Carlo Rubbia and Hans Hoffmann)
Innovative DAQ and

- On-line event display – a powerful monitoring tool
- DAQ was an brilliant synthesis of end-of-century emerging information technology applied to UA1 data handling
  - Full data digitization of front-end
    - Flash ADC and TDC for pulse-shape and time digitalization (CTD), ReadOut Processor (ROP) and programmable logic
  - Programmable apparatus
    - Extensive use of microprocessor and data network technologies (CAVIAR microcomputer, CAMAC, MacVEE, ADLC and VME industry standards)
  - Real time data analysis and event selection
    - Online Introduction of IBM emulators (first online computing farm)
    - Offline interactive event analysis with personal computer (MEGATEK)
3-D event visual scanning on the MEGATEK
A bit of CERN history

1981

July 10: 1st $p\bar{p}$ collisions, observed in UA1 forward hodoscopes
Carlo Rubbia reports in Lisbon only a few hours after collisions

Oct. – Dec., 1st Sp$\bar{p}$S run: $\sqrt{s} = 540$ GeV; $\mathcal{L}_{\text{max}} \sim 10^{27}$ cm$^{-2}$ s$^{-1}$; $\int \mathcal{L} dt \sim 0.2$ nb$^{-1}$

First tracks recorded in UA1 and UA5

November: UA2 replaced UA5

First collider physics results: multiplicity (UA5, UA1), momentum spectra (UA1)


1982

July: UA2 announces observation of hadronic jets / confirmed by UA1 end of August

Not everything going smoothly: pollution of CD gas mixture while baking beam pipe, rupture of major water pipe flooding the pit, shortly before August 12, but Carlo remained confident
Thatcher's visit to CERN
Margaret Thatcher’s visit

The story behind the scene

In a presentation we told her that if we could get enough luminosity in the coming run and if we believed in Santa Claus we might get the W for Christmas. Schopper was furious, insisting she would remember.

Alan Astbury, UA1 Deputy Spokesperson

And she did, in December. CERN DG Herwig Schopper felt obliged to write to her
Dear Prime Minister,

In presenting you with my respects and best wishes for the New Year, I am ever mindful of the promise I made on the occasion of your visit to CERN, in August of this year, that I would report to you immediately and directly on the day CERN obtained confirmed experimental evidence for the existence of the "intermediate boson" (W\', W\'', and Z') for which we are actively searching.

I should have liked to combine seasonal greetings with the report that such a discovery had indeed been made, but, in the absence of incontrovertible evidence, I am nevertheless pleased to inform you, in strict confidence, that results recently obtained point to the imminence of such a discovery. Indeed, a few events have been seen containing one electron and missing energy on the opposite side, compatible with the decay mode W\'' = e^+\nu_y.

As soon as final and irrefutable evidence is available, I shall immediately communicate the news to you.

Meanwhile, I have the honour to remain, dear Prime Minister,

Very respectfully,

Yours,

cc.: Sir Alec Merrison

Harwig Schopper
**The W run**

1982  **Oct. – Dec., 2nd SpS run:** $\mathcal{L}_{\text{max}} \sim 5.10^{28} \text{ cm}^{-2} \text{ s}^{-1}$; $\int \mathcal{L} dt \sim 28 \text{ nb}^{-1}$

**Nov:** UA1 finds the 1st W candidate in the electron channel

Relief that the hadron collision background was manageable by the UA1 detector
MEGATEK Display:

Example of $W$ event candidate, with remarkably low background.

Great achievement by UA1 software team:
Innovative UA1 reconstruction software ready on time and up to the job!
1983: the discovery year

January 12-14: Topical workshop on Proton Antiproton Collider Physics, in Rome
- Carlo Rubbia presents the UA1 analysis of 6 $W \rightarrow e\nu$ candidates
- Pierre Darriulat presents the UA2 analysis of 4 $W \rightarrow e\nu$ candidates

Carlo’s conclusion: “se sono rose, fioriranno”

January 20: Carlo Rubbia presents the UA1 analysis in an overflowing CERN main Auditorium
Unambiguous W signature with few events

- Isolated high-$p_T$ electron \textbf{and} missing “transverse energy” due to neutrino escaping on the other side
**1983: the discovery year**

1983

- **January 21:** Luigi Di Lella presents the UA2 analysis in CERN main Auditorium
- **January 25:** CERN Press Conference with Herwig Schopper (DG), Erwin Gabathuler (Research Director), Carlo Rubbia (UA1 Spokesperson) and Pierre Darriulat (UA2 Spokesperson) to announce the discovery of the W

The W in hand, the search for the Z^0 reached a paroxysm of excitement when the next run starts

April – June, 3rd SpP̅S run: $\mathcal{L}_{\text{max}} \sim 1.6 \times 10^{29}$ cm$^{-2}$ s$^{-1}$; $\int \mathcal{L} dt \sim 153$ nb$^{-1}$

The express line made the difference:

– on line selection of a small sample of events to be reconstructed and scanned on the MEGATEK
**First $\text{Z}^0$ candidate**

**April 30, 1983:** 1st $\text{Z}^0$ event registered in UA1

**June 1:** CERN Press Conference, Carlo Rubbia announces the $\text{Z}^0$ discovery by UA1

**July 7:** UA2 presents their $\text{Z}^0$ search

V-A nature of the W decay (not possible in pp) C. Rubbia, Nobel Lecture
Another date to remember

17th October 1984

Mirella Keller
CONCLUSION

- The Sp̅p̅S collider project was a most unlikely project, which allowed not only major discoveries but also important innovations in several domains: A “game changer” project.

- The schedule was amazing!
  - Sp̅p̅S project approved within 2 years of the proposal
  - UA1 experiment ready within 3 years of the proposal

- It gave CERN tremendous recognition world-wide and paved the way for future large collaborations, first at LEP and later at the LHC.

- It earned CERN its first Nobel Prize, in 1984 when Carlo Rubbia already had his thoughts on the LHC (OC and summary talk of the 1984 Lausanne LHC workshop).
W discovery publication

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

UA1 Collaboration, CERN, Geneva, Switzerland


Received 23 January 1983

Z0 discovery publication

EXPERIMENTAL OBSERVATION OF LEPTON PAIRS OF INVARIANT MASS AROUND 95 GeV/c² AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland


Received 6 June 1983
RESERVE
The weak interaction chapter

1899  Ernest Rutherford discovers $\beta$ decay

1933  Enrico Fermi 4-fermion interaction model

“The credit for proposing an intermediate boson for the weak interaction is usually given to Italy’s successor to Galileo, Enrico Fermi”, Sheldon Glashow, Interactions, 1988

1938  Oskar Klein proposed a boson exchange for charged weak processes, at the Warsaw Conference on Modern Physics

1956  Discovery of parity violation by Chien-Shiung Wu

1956  Sheldon Glashow, Abdus Salam, Steven Weinberg proposed a unification of electromagnetic and weak interactions. Non-Abelian gauge (Yang-Mills) theory with spontaneous SU(2)xU(1) symmetry breaking, to become the Standard Model, with 3 massive weak bosons accompanying the massless photon
EXPERIMENTAL OBSERVATION OF ISOLATED LARGE TRANSVERSE ENERGY ELECTRONS 
WITH ASSOCIATED MISSING ENERGY AT $\sqrt{s} = 540$ GeV

UA1 Collaboration, CERN, Geneva, Switzerland


Received 23 January 1983

We report the results of two searches made on data recorded at the CERN SPS Protone Antiproton Collider: one for isolated large-$E_T$ objects, the other for large-$E_T$ neutrinos using the technique of measuring transverse energy. Search rules converge to the same events, which have the signature of a two-body decay of a particle of mass $\sim 40$ GeV/$c^2$. The topology as well as the number of events fits well the hypothesis that they are produced by the process $p + p \rightarrow W^+ + X$, where $W^+$ is the Intermediate Vector Boson postulated by the unified theory of weak and electromagnetic interactions.

3 University of Wisconsin, Madison, WI, USA.
4 NIKHEF, Amsterdam, The Netherlands.

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

UA1 Collaboration, CERN, Geneva, Switzerland


Received 6 June 1983

We report the observation of four electron–positron pairs and one gamma pair which have the signature of a two-body decay of a particle of mass $\sim 95$ GeV/$c^2$. Three events fit well the hypothesis that they are produced by the process $p + p \rightarrow Z^0 \rightarrow Z^0 \rightarrow e^+e^- + \gamma$, where $Z^0$ is the Intermediate Vector Boson postulated by the electroweak theories as the mediator of weak neutral currents.

1 University of Wisconsin, Madison, WI, USA.
2 University of Wisconsin, Madison, WI, USA.
3 NIKHEF, Amsterdam, The Netherlands.
4 Visitor from the University of Liverpool, England.
UA1 implements the Express Line

- Event filtering online with 168/E, predecessors of the 3081/E later installed in emulator farms at LSS5, Rome and HEPL (Harvard/MIT).
- Special express line data tapes taken by hand to the computing center.
- One special date to remember …

IBM 168 Main Frame Emulator
A bit of CERN history

1984
Large Hadron Collider in the LEP Tunnel, Lausanne, 21-27 March, 1984

Carlo Rubbia, one of the organizers, gave the summary talk

Denis Linglin reporting for the DAQ and Offline computing working group mentions the need for “inter-computer network”, based on the experience with UA1
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 taken the lead in the race to discover the ultimate building blocks of matter.

Spurred by an esthetic faith that nature’s laws are at root elegantly simple, physicists have long tried to embrace the four basic forces of nature within a unified framework. A theory that unites two of the forces, electromagnetism and the “weak” nuclear force seen in radioactivity, predicts three new particles known as intermediate vector bosons. Dubbed the W+, the W-, and the Z-zero, the bosons would mediate the weak force just as the photon mediates the force of electromagnetism.

Looking for the bosons was to be a prime task of the $200 million accelerator being constructed at Brookhaven on Long Island. But while the Brookhaven machine fell behind schedule, the Geneva accelerator was cunningly upgraded to the energy range at which bosons might be created.

CERN announced discovery of the two W bosons last January and has now found the Z-zero. With that and the previous discovery of “gluons” at a German machine, European accelerators have established a better record of success than any of the three American laboratories.

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,” he has said. “In the years American physicists squandered on a pork barrel squabble, the Europeans moved boldly ahead.”

Narrow national comparisons have little meaning in physics. Several of the “European” successes were due to American physicists working at European machines. But competition is a useful spur, and American accelerators should be designed to win or not be built at all. The string of European successes underscores the strengths of cautious design, consolidated effort and plans and budgets that allow machines to come in on time.

A panel of American physicists is meeting this week at Woods Hole to decide the fate of the limping Brookhaven accelerator and to plan a new machine for the future. The tougher the competition they can arrange for their European colleagues, the faster will be the advance of knowledge.

The 3-0 loss in the boson race cries out for earnest revenge. The physics team needs to try harder, and coach Keyworth should reward any sensible new strategy with management’s full support.
UA1 DAQ and detector control

Also a major area of innovation

- Use of flash ADCs for pulse shape measurement
- Development of VME to IBM interface
- Use of Macintosh for control (MacVEE interface module)
- Setting up of a third level trigger (IBM emulators)
- Central Detector on-line event display played a major role in online monitoring of data taking