Karlsruher Institut für Technologie

Teilchenphysik 2 — W/Z/Higgs an Collidern

Sommersemester 2019

Matthias Schröder und Roger Wolf | Vorlesung 3

INSTITUT FÜR EXPERIMENTELLE TEILCHENPHYSIK (ETP)

2. The Electroweak Sector of the Standard Model

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2.1 Gauge theory

- Global and local phase transformations
- Example: QED
- Abelian and non-Abelian gauge theories

2.2 The electroweak sector of the Standard Model – I

- Properties of the weak interaction, weak isospin
- Formulation of the Standard Model (without masses)

2.3 Discovery of W and Z bosons

- History towards discovery
- Experimental methods

2.4 The Higgs mechanism

- Problem of massive gauge bosons and massive fermions
- Idea of the Higgs mechanism: examples of spontaneous symmetry breaking

2.5 The electroweak sector of the Standard Model – II

- The Standard Model Higgs mechanism
- Yukawa couplings and fermion masses
- The Higgs boson

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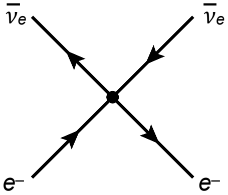
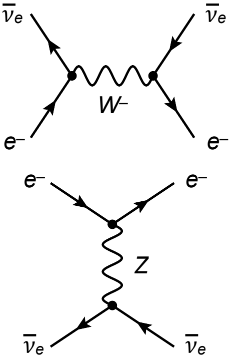
Weak Interaction: Divergencies

- Divergence 1: **contact interaction** in Fermi theory of weak interaction
  - Coupling constant G_F dimensional quantity $[G_F] = \text{energy}^{-2}$
  - Predicted scattering cross-section grows as $\sigma \propto E_{cms}^2 = s$
- Solution: **exchange of massive vector bosons**

$e\nu$ scattering as contact interaction



$e\nu$ scattering with vector-boson exchange

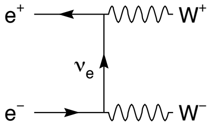


$$G_F = 1.16639(2) \cdot 10^{-5}\,\text{GeV}^{-2}$$
$$\rightarrow m_V \approx \mathcal{O}\left(\frac{1}{\sqrt{G_F}}\right) = \mathcal{O}(100\,\text{GeV})$$

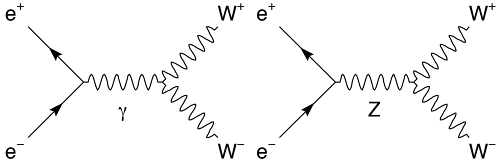
Weak Interaction: Divergencies

- Divergence 2: **WW pair production** in $V - A$ theory
  - Solution: require direct interaction among three gauge bosons (trilinear couplings, or triple gauge couplings, TGC)
    $\rightarrow$ indirect hint to existence of **Z boson**

Neutrino exchange



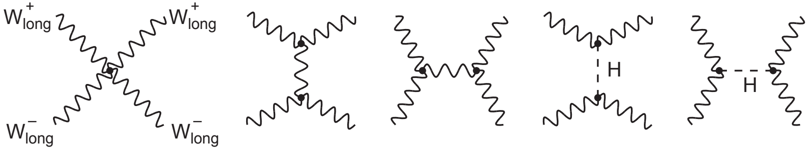
Photon and *Z* boson exchange



Weak Interaction: Divergencies

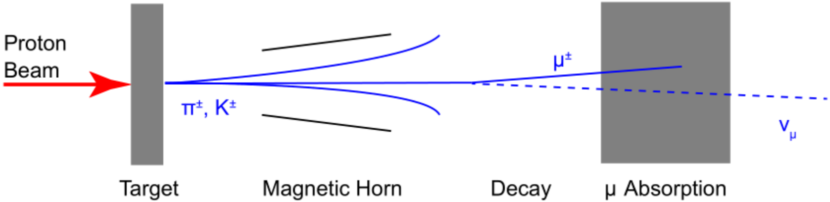
- Divergence 3: **longitudinal W boson scattering** ($W_L W_L \rightarrow W_L W_L$)
  - Solution: additional contributions to scattering amplitude from exchange of scalar particles $\rightarrow$ indirect hint to existence of **Higgs boson**

Quartic and trilinear gauge boson couplings **Higgs-boson exchange**

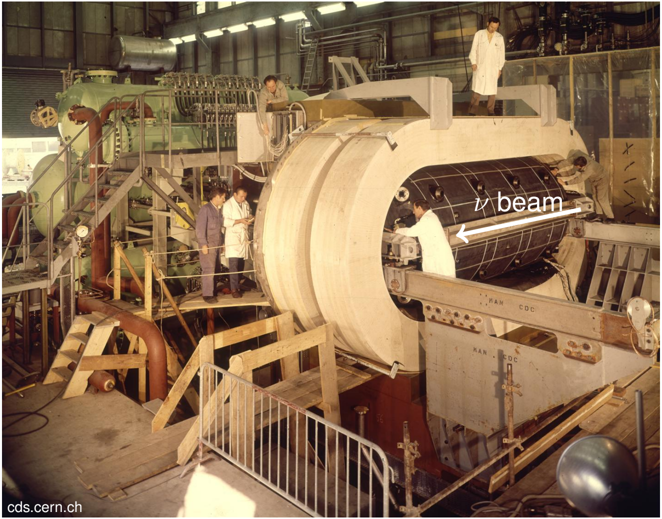


Search for Neutral Currents

- Strategy: interactions of neutrinos
  - No electromagnetic processes
  - Charged-particle scattering: huge background of electromagnetic processes $\rightarrow$ impossible
- CERN **neutrino beam** (since 1970)
  - Protons from CERN PS on target: **muon neutrinos**, e. g. $\pi^+ \rightarrow \mu^+ \nu_\mu$
  - Detection: **bubble chamber** experiment Gargamelle

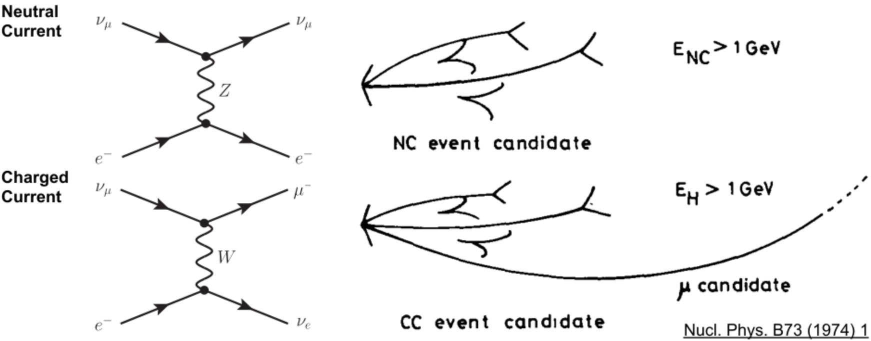


The Gargamelle Bubble Chamber



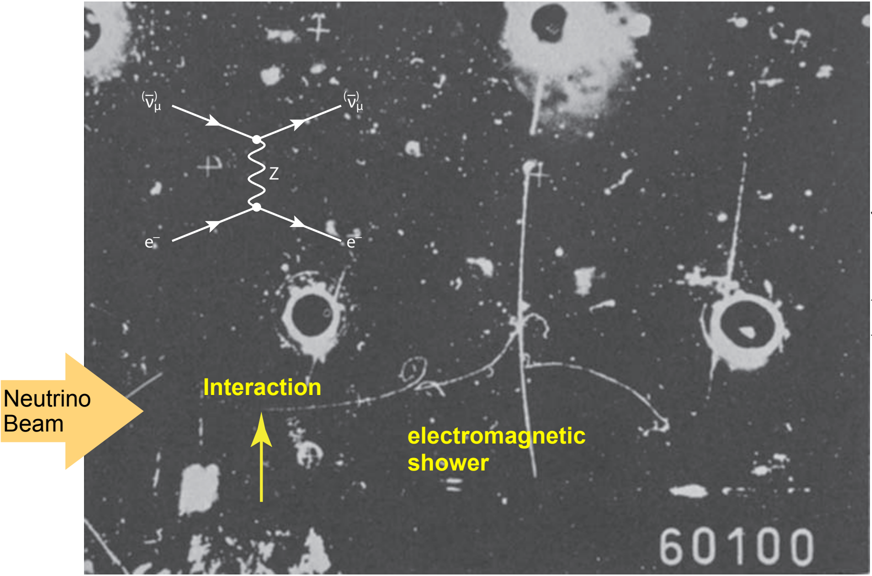
Discovery of Neutral Currents

- Gargamelle: neutrino beam hits **heavy liquid** (freon)
- Neutrinos interact with **electrons** and atomic **nuclei**



- **Neutral-current** interaction: scattered electron → electromagnetic shower (bremsstrahlung and e^+e^- production)
- **Charged-current** interaction: muon in final state → long track

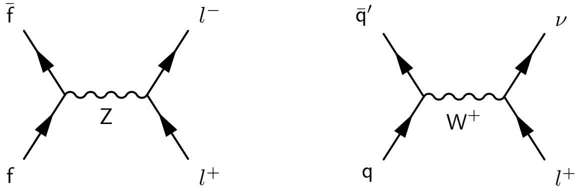
Neutrino–Electron Neutral Currents



Phys. Lett. B46 (1973) 121

W and Z Boson Production

- **Production process**: lepton production in hadronic interactions ("Drell–Yan process")
- Requirement to produce **real W and Z bosons** at accelerators: E_{cms} of initial-state fermions at expected boson mass ($\approx 100\,\mathrm{GeV}$)



- **Fixed-target** setup: $\sqrt{s} = \sqrt{2 m_p E} \rightarrow E = 5\,\mathrm{TeV} \rightarrow$ unrealistic
- **Electron-positron collider**: $\sqrt{s} = E_1 + E_2 \rightarrow 50\,\mathrm{GeV}$ beam energy $\rightarrow$ technically feasible only from the 1990s, only Z production
- **Proton-antiproton collider**: W/Z production by annihilation of valence quark in proton and valence antiquark in antiproton

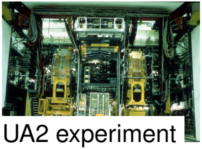
Sp$\bar{\text{p}}$S

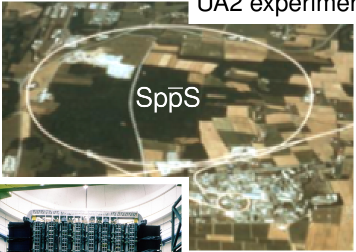
- p$\bar{\text{p}}$ collider reach
  - Momentum fractions of colliding valence (anti)quarks $x_1 \approx x_2 \approx 0.2$

$\rightarrow$ estimated E_{cms}: $\sqrt{\hat{s}} \approx \sqrt{x_1 x_2 s} \overset{!}{=} 100\,\text{GeV} \rightarrow \sqrt{s} = 500\,\text{GeV}$

- SPS (Super Proton Synchrotron) at CERN
  - 6.9 km circumference
  - 400 GeV protons

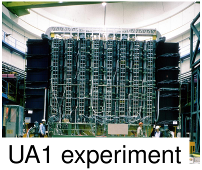
Idea (C. Rubbia, 1976): upgrade to a p$\bar{\text{p}}$ collider


UA2 experiment



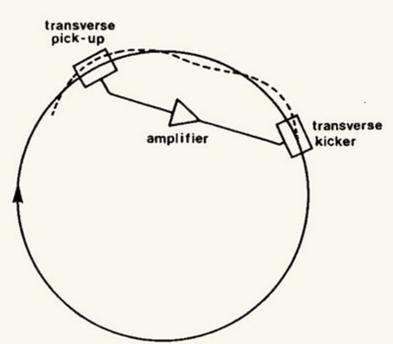
Sp$\bar{\text{p}}$S

- $E_{\text{cms}} = 540\,\text{GeV}$ initially later upgrade to 630 GeV
- UA1 and UA2 experiments data taking from 1981


UA1 experiment

Sp$\overline{\text{p}}$S

- **Antiprotons**
  - p beam on target: approximately 1 $\overline{\text{p}}$ in 10^9 final-state particles
  - Very large **emittance** of $\overline{\text{p}}$ beam: reduction without violating Liouville's theorem?
  - Solution (S. van der Meer, 1968): **stochastic cooling**[1] with pick-up and kicker
- Further challenges
  - p and $\overline{\text{p}}$ share **same beam pipe**
  - **Hermetic** 4π **detectors** for the first time at hadron colliders

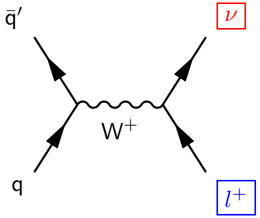


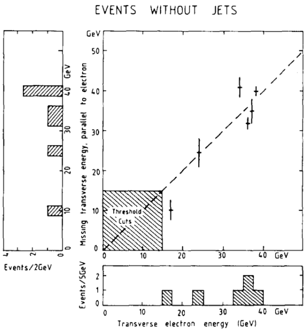
cerncourier.com

[1] Details e. g. Nucl. Instrum. Meth. A532 (2004) 11

Discovery of the W Boson (1983)

- Process $p\bar{p} \to W \to l\nu$ ($l = e, \mu$)





Phys. Lett. B122 (1983) 103

- Analysis strategy: charged lepton + $\not{E}_T$
  - **Charged lepton**: clean detector signature
  - Neutrino: **missing transverse momentum**
  - **2-body decay** $W \to l\nu$: lepton and neutrino ($\not{E}_T$) back-to-back in W-boson rest frame
  - QCD jet production **background**: no preferred relative directions of lepton and $\not{E}_T$

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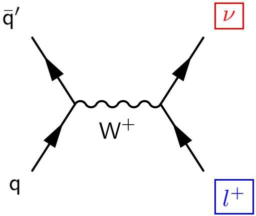

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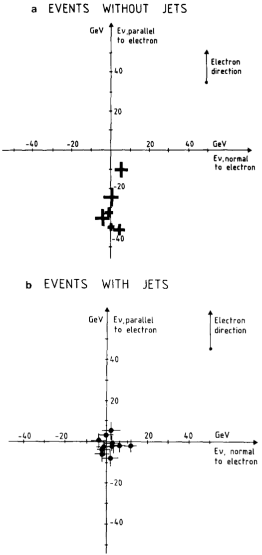
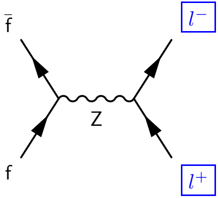


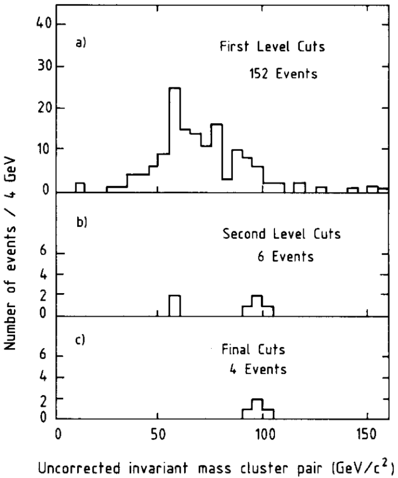
Phys. Lett. B122 (1983) 103

Discovery of the Z Boson (1983)

- Process $p\bar{p} \to Z \to l^+ l^-$ ($l = e, \mu$)



- Analysis strategy: **charged leptons**
  - **Invariant mass** of lepton pair
  - Depends on lepton momenta and opening angle (lepton masses neglected)

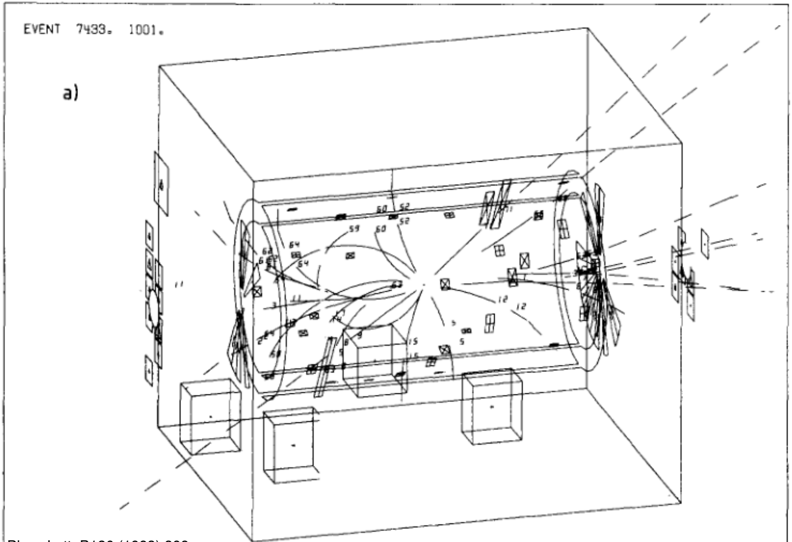


Phys. Lett. B126 (1983) 398

$$m_Z^2 \approx 2 \cdot |\vec{p}_{l^+}| \cdot |\vec{p}_{l^-}| \cdot (1 - \cos\phi_{l^+l^-})$$

Discovery of the Z Boson

Candidate event with 2 electrons: before cuts



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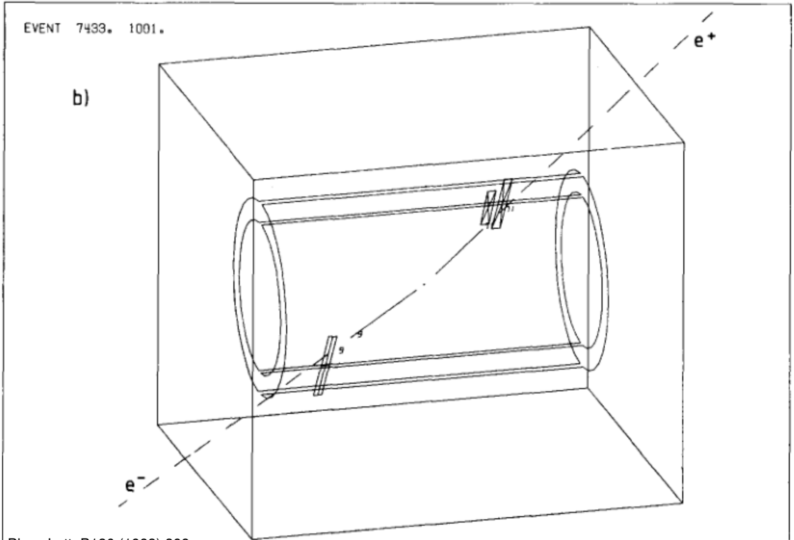


Phys. Lett. B126 (1983) 398

Nobel Prize 1984

Karlsruher Institut für Technologie

C. Rubbia

S. van der Meer

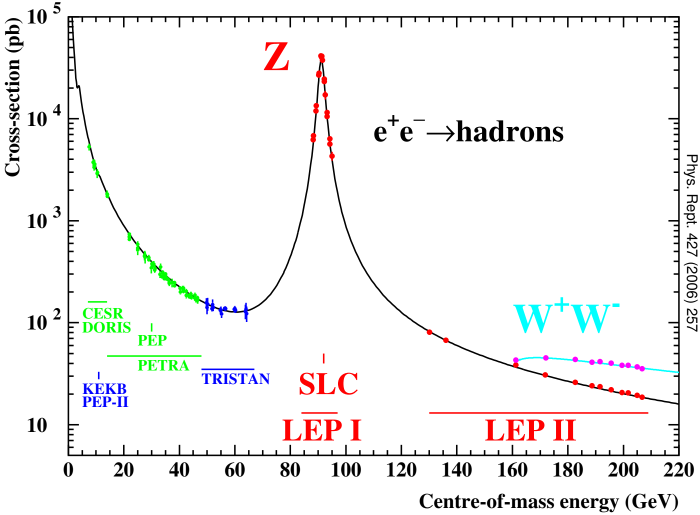
“for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction”

[nobelprize.org]

Summary

- **Central prediction of the electroweak theory confirmed**
  - New **neutral current interactions** observed in neutrino-electron and neutrino-nucleus scattering (Gargamelle, CERN 1973)
  - Mediator particles **W boson and Z boson** produced in $p\bar{p}$ collisions (UA1 and UA2 at $Sp\bar{p}S$, CERN 1983)
    - W signature: lepton+$\not{E}_T$, back-to-back
    - Z signature: same-flavour (SF) opposite charge-sign (OS) lepton pair with large invariant mass
- $p\bar{p}$ collider $Sp\bar{p}S$
  - **Stochastic cooling**: $\bar{p}$-beam emittance reduced
  - Experiments (**UA1, UA2**) with electronic readout

Summary



Cross-section (pb)
10 5
10 4
10 3
10 2
10
Z
e+e−→hadrons
Phys. Rept. 427 (2006) 257
W+W-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

Programme

Date	Room	Type	Topic
Wed Apr 24.	Kl. HS B	LE 01	1. Organisation and introduction: particle physics at colliders + W/Z/H history
Tue Apr 30.	30.23 11/12	—	*no class*
Wed May 01.	Kl. HS B	—	*no class*
Tue May 07.	30.23 11/12	LE 02	2.1 Gauge theory & 2.2 The electroweak sector of the SM I
Wed May 08.	Kl. HS B	LE 03, EX 01	2.3 Discovery of the W and Z bosons & EX gauge theories
→ Tue May 14.	30.23 11/12	LE 04	2.4 The Higgs mechanism
Wed May 15.	Kl. HS B	EX 02	Exercise “SM Higgs mechanism”
Tue May 21.	30.23 11/12	—	*no class*
Wed May 22.	Kl. HS B	LE 05	2.5 The electroweak sector of the SM II (Higgs mechanism + Yukawa couplings)
Tue May 28.	30.23 11/12	SP 01	Specialisation of 2.4 and 2.5
Wed May 29.	Kl. HS B	LE 06	3.1 From theory to observables & 3.2 Reconstruction + analysis of exp. data
Tue Jun 04.	30.23 11/12	EX 03	Exercise “Trigger efficiency measurement”
Wed Jun 05.	Kl. HS B	LE 07	3.3 Measurements in particle physics (part 1)
Tue Jun 11.	30.23 11/12	EX 04	Exercise on statistical methods
Wed Jun 12.	Kl. HS B	LE 08	3.3 Measurements in particle physics (part 2)
Tue Jun 18.	30.23 11/12	SP 02	Specialisation “Limit setting”
Wed Jun 19.	Kl. HS B	SP 03	Specialisation “Unfolding”
Tue Jun 25.	30.23 11/12	LE 09	4.1 Determination of SM parameters
Wed Jun 26.	Kl. HS B	LE 10	4.2 Measurement and role of W/Z bosons at the LHC
Tue Jul 02.	30.23 11/12	EX 05	Paper seminar “Z pole measurements”
Wed Jul 03.	Kl. HS B	LE 11	4.3 Processes with several W/Z bosons
Tue Jul 09.	30.23 11/12	EX 06	Paper seminar Higgs
Wed Jul 10.	Kl. HS B	LE 12	5.1 Discovery and first measurements of the Higgs boson
Tue Jul 16.	30.23 11/12	EX 07	Exercise “Machine learning in physics analysis”
Wed Jul 17.	Kl. HS B	LE 13	5.2 Measurement of couplings and kinematic properties
Tue Jul 23.	30.23 11/12	EX 08	Presentations: results of ML challenge
Wed Jul 24.	Kl. HS B	LE 14	5.3 Search for Higgs physics beyond the SM & 5.4 Future Higgs physics