Discovery of the W- and Z-boson (recap)

https://cds.cern.ch/record/2103277/files/9789814644150_0006.pdf

Historical situation at the end of the 1970:

- Standard Model unifying the electromagnetic and the weak interaction was developed in the course of the 1960s (S. Glashow (1959), A. Salam (1959), S. Weinberg (1967)): Theory predicts massive W and Z bosons.
- Experimental evidence in favor of a unique description of the weak and electromagnetic interactions was obtained in 1973, with the observation of neutral current neutrino interaction which could only be explained by the exchange of a virtual heavy neutral particle. The measurements allowed a first estimation of $\sin^2\theta_w$ and together with the coupling G_F of the muon decay an estimation of the masses of the W and the Z-boson:

$$m_{W} \approx 60...80 \text{ GeV}$$
 $m_{Z} \approx 75...92 \text{ GeV}$

Masses too large to be accessible by any accelerator in operation at that time.

In 1976 Rubbia, Cline and McIntyre proposed the transformation of an existing high-energy proton accelerator (SPS) into a proton–antiproton collider (SppS) as a quick and cheap way to achieve collisions above thresholds for W and Z.

$$p\overline{p} \to Z \to f\bar{f} + X$$
 $p\overline{p} \to W \to \ell \,\overline{v_{\ell}} + X$



Colliding quarks (at the envisaged CMS energy dominantly valence quarks) carry momentum fraction x of the proton/antiproton momentum w/ $<x> \approx 0.17$.

To achieve a quark-antiquark CMS energy of ~90 GeV proton-antiproton CMS energies of ~540 GeV are necessary: $\sqrt{\hat{s}_{q\bar{q}}} = x \cdot \sqrt{s_{p\bar{p}}} \rightarrow 90$ GeV $\approx 0.17 \cdot 540$ GeV

For a luminosity of L $\approx 2.5 \times 10^{29} \text{ cm}^{-2} \text{ s}^{-1}$ one expects typically only one Z \rightarrow ee event per day: $\sigma(pp \rightarrow Z \rightarrow e^+e^-) \approx 50 \text{ pb} = 5 \cdot 10^{-35} \text{ cm}^{-2} \text{ w/ BR}(Z \rightarrow ee) \approx 3\%$. Beside the energy the luminosity thus was a challenge to measure sufficient Z,Ws!

Antiproton beam

Antiproton source must be capable to deliver daily $\sim 3 \times 10^{10}$ anti-protons distributed in few (3–6) tightly collimated bunches within the angular and momentum acceptance of the CERN SPS.

CERN 26 GeV proton synchrotron (PS) is capable of producing antiprotons at the desired rates:



Sufficient antiprotons but they occupy a phase space volume which is too large by a factor $\geq 10^8$ to fit into the SPS acceptance, even after acceleration to the SPS injection energy of 26GeV (emittance of the beam is too large!).

 \rightarrow Increase the antiproton phase space density at least 10⁸ times before sending the antiproton beam to the SPS. This process is called "cooling" (in analogy to a hot gas where the particle have very different momenta)

Stochastic cooling (S. van der Meer, 1972)

Reminder: Liouville theorem forbids any compression of phase volume by conservative forces such as electromagnetic fields \rightarrow emittance (defining the area of the phase space ellipse) cannot be reduced by fields acting on all particles of the beam. Need to act on individual (or group of individual) particles.



Idea to cool betatron oscillation:

Measure deviation of group of particles at point where maximal. Pick-up signal proportional to deviation is amplified and provided to kicker at a place where particle crosses central orbit.

Pick-up is sensitive only to a group of particles (depends on geometry and on frequency response)

Cooling was performed in the Antiproton Accumulator AA: includes several independent cooling systems to cool horizontal and vertical oscillations, and also to decrease the beam momentum spread (cooling of longitudinal motion).



AA - a large aperture ring of different magnets - during construction.

Cooling and injection cycle:



When a sufficiently dense anti-proton stack has been accumulated in the AA, beam injection into the SPS is achieved using consecutive PS cycles.

Firstly, three proton bunches (six after 1986), each containing $\sim 10^{11}$ protons, are accelerated to 26 GeV in the PS and injected into the SPS. Then three p bunches (six after 1986), of typically $\sim 10^{10}$ antiprotons each, are extracted from the AA and injected into the PS accelerated to 26 GeV and injected into SPS.



Year	Collision energy (GeV)	Peak luminosity $(cm^{-2} s^{-1})$	Integrated luminosity (cm^{-2})
1981	546	$\sim 10^{27}$	$2 imes 10^{32}$
1982	546	$5 imes 10^{28}$	$2.8 imes10^{34}$
1983	546	$1.7 imes 10^{29}$	$1.5 imes10^{35}$
1984 - 85	630	$3.9 imes 10^{29}$	$1.0 imes10^{36}$
1987–90	630	$3 imes 10^{30}$	1.6×10^{37}

Table 1 CERN proton-antiproton collider operation, 1981–1990.

Two Detectors: UA1 and UA2

UA1 detector



Discovery of the Z-boson

(historically W discovery was a few weeks earlier)



Discovery of the W-boson





How can the W mass be reconstructed ?

W → e v



Fig. 16b. The same as picture (a), except that now only particles with $p_T\!>\!l$ GeV/c and calorimeters with $E_{\tau}\!>\!l$ GeV are shown.



Fig. 11. UA1 scatter plot of all the events from the 1982 data which contain a high-pT electron and large $|\vec{p}_{\rm T}^{\rm miss}|$. The abscissa is the electron $|\vec{p}_{\rm T}|$ and the ordinate is the $\vec{p}_{\rm T}^{\rm miss}$ component antiparallel to the electron $\vec{p}_{\rm T}$.

<u>W mass measurement</u>



In the W rest frame:

- $\left|\vec{p}_{\ell}\right| = \left|\vec{p}_{\nu}\right| = \frac{M_{W}}{2}$
- $\left| \boldsymbol{\rho}_{\ell}^{T} \right| \leq \frac{M_{W}}{2}$

Jacobian Peak:

$$\frac{dN}{p_{T}} \sim \frac{2p_{T}}{M_{W}} \cdot \left(\frac{M_{W}^{2}}{4} - p_{T}^{2}\right)^{-1/2}$$

In the lab system:

- W system boosted only along z axis
- \boldsymbol{p}_{T} distribution is conserved

(assumes flat distribution of the electron – not correct, see next page)





V-A coupling of the W-boson



Electron (positron) angular distribution in lab: $\frac{dN}{d\cos\theta^*} \propto \left(1 + q\cos\theta^*\right)^2$

q = +1 for positrons, -1 for electrons θ^* = angle w/r to antiproton directions



Confirms V-A coupling to quarks and leptons: charge asymmetry between proton / antiproton direction

Precision study of the Z boson at LEP

All measurements and plots (if not mentioned differently) from:

Precision Electroweak Measurements on the Z Resonance

ALEPH, DELPHI, OPAL, L3, SLD Collaborations, Phys.Rept.427:257-454,2006. arXiv:hep-ex/0509008

Recap: Z couplings



$$g = rac{e}{\sin heta_w} \qquad g' = rac{e}{\cos heta_w}$$

Fermion current:

$$J_{f} = \frac{e}{\sin\theta_{w}\cos\theta_{w}}\overline{\psi}_{f}\gamma^{\mu}\frac{1}{2}(g_{V}^{f} - g_{A}^{f}\gamma^{5})\psi_{f}$$

$$g_v^f = I_3^f - 2Q_f \sin^2 \theta_W$$
 and $g_A^f = I_3^f$

$$\rho = \frac{g_z^2}{M_z^2} \left/ \frac{g^2}{M_w^2} = \frac{g^2}{M_z^2 \cos^2 \theta_w} \right/ \frac{g^2}{M_w^2} = \frac{M_w^2}{M_z^2 \cos^2 \theta_w} = 1 \quad \text{(at tree level)}$$

Fermion couplings to the Z-boson: (Recap)

V, A couplings:
$$c_v^f = I_3^f - 2Q_f \sin^2 \theta_W$$
 $c_A^f = I_3^f$
L, R couplings: $c_L^f = \frac{1}{2}(c_V^f + c_A^f)$ $c_R^f = \frac{1}{2}(c_V^f - c_A^f)$

In the lecture we often use $g_{V,A}$ and $g_{L,R}$ instead of $c_{V,A}$ and $c_{L,R}$. It is just the same – only different symbols!

	$g_{\scriptscriptstyle V}$	$g_{\scriptscriptstyle A}$	$g_{\scriptscriptstyle V}$	$g_{\scriptscriptstyle A}$	$g_{\scriptscriptstyle L}$	g _R
V	1/2	1/2	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	0
ℓ^-	$-\frac{1}{2} + 2\sin^2\theta_W$	$-\frac{1}{2}$	-0.04	$-1/_{2}$	-0.27	+0.23
u – quark	$+\frac{1}{2}-\frac{4}{3}\sin^2\theta_w$	$\frac{1}{2}$	+0.19	1/2	+0.35	-0.15-
d – quark	$\frac{-1}{2} + \frac{2}{3} \sin^2 \theta_w$	$-\frac{1}{2}$	-0.35	$-\frac{1}{2}$	-0.42	+0.08

 $\sin^2 \theta_w \approx 0.231$

1.1 Z-Boson parameters

Cross section for $e^+e^- \rightarrow \gamma/Z \rightarrow ff$ $|M|^2 = |\gamma + \gamma |$ for $e^+e^- \rightarrow \mu^+\mu^-$ Vanishes for massless positrons: $M_{\gamma} = -ie^{2}(\overline{u}_{\mu}\gamma^{\nu}v_{\mu})\frac{g_{\nu\rho}}{q^{2}}(\overline{v}_{e}\gamma^{\rho}u_{e})$ $\frac{1}{2}k_{\sigma}\overline{v}_{e}\gamma^{\sigma} = \frac{1}{2}\overline{v}_{e}K = 0$ = Dirac Eq for ingoing positron $M_{Z} = -i\frac{g^{2}}{\cos^{2}\theta_{W}}\left[\overline{u}_{\mu}\gamma^{\nu}\frac{1}{2}(g_{V}^{\mu} - g_{A}^{\mu}\gamma^{5})v_{\mu}\right]\frac{g_{\nu\rho} - q_{\nu}q_{\rho}/M_{Z}^{2}}{(q^{2} - M_{Z}^{2}) + iM_{Z}\Gamma_{Z}}\left[\overline{v}_{e}\gamma^{\rho}\frac{1}{2}(g_{V}^{e} - g_{A}^{e}\gamma^{5})u_{e}\right]$ Unphysical pole: Z propagator must be modified to account

for finite Z width for $q^2 \approx M_Z^2$ (real particle w/ finite lifetime)

With a "little bit" of algebra similar as for M_{γ} in QED one obtains $\langle |M_Z|^2 \rangle$

If you want to do the calculation yourself - here is the Z amplitude:

$$M_{fi} = -\frac{g_{2}^{2}}{(s - m_{2}^{2}) + im_{2}T_{2}} \cdot \left[\bar{v}(p_{2}) \gamma^{M} \frac{1}{2} (c_{v}^{2} - c_{A}^{2} \gamma^{5}) w_{v}(p_{v}) \right] g_{\mu\nu}$$

$$= \frac{g_{2}^{2}}{P_{2}(s)} \cdot \left[\bar{v}_{v}(p_{3}) \gamma^{M} \frac{1}{2} (c_{v}^{2} - c_{A}^{2} \gamma^{5}) y_{v}(p_{v}) \right]$$

$$\begin{split} \left| M_{RR} \right|^{2} = |P_{2}(s)|^{2} g_{2}^{4} s^{2} (C_{R}^{e} C_{R}^{\mu})^{2} \cdot (1 + \cos\theta)^{2} \\ & |H_{LL}|^{2} = \cdots - (C_{L}^{e} C_{L}^{\mu})^{2} \cdot (1 + \cos\theta)^{2} \\ e^{-} & |H_{RL}|^{2} = \cdots - (C_{L}^{e} C_{L}^{\mu})^{2} (1 - \cos\theta)^{2} \\ & |H_{LR}|^{2} = \cdots - (C_{L}^{e} c_{R}^{\mu})^{2} (1 - \cos\theta)^{2} \\ & |H_{LR}|^{2} = \cdots - (C_{L}^{e} c_{R}^{\mu})^{2} (1 - \cos\theta)^{2} \\ & = > \langle |H|^{2} \rangle = \frac{1}{4} \geq |H_{1j}|^{2} (\sin e^{+e^{-s}} P_{j}^{\mu}) \\ & \text{with} \quad \frac{d\sigma}{ds_{L}} = \frac{1}{64\pi^{2}} \cdot \frac{1}{s} \cdot \left(\frac{P_{L}^{*}}{P_{L}^{*}}\right) \cdot \langle |H|^{2} \rangle \quad \text{one} \quad \text{fund}D : \\ & = 4 \text{ for mass two} \\ & \text{formula} \end{split}$$

$$\frac{d\sigma}{ds2} \left(e^{\frac{1}{2}} \rightarrow 2 \rightarrow N'N\right) = \frac{1}{256\pi^2 s} \frac{g_2^{\nu} s^2}{\left(s - m_2^2\right)^2 + m_2^2 l_2^2}$$

$$\int \frac{1}{4} \left[\left(c_V^e\right)^2 + \left(c_A^e\right)^2 \right] \left[\left(c_V^N\right)^2 + \left(c_A^N\right)^2 \right] \left(2 + \cos^2\theta\right) + 2c_V^e c_A^e c_V^N c_A^N + \cos^2\theta \right]$$

For the total differential cross section of γ and Z contribution one finds:



asymmetric in $\cos\theta$

$$F_{Z}(\cos\theta) = \frac{1}{16\sin^{4}\theta_{W}\cos^{4}\theta_{W}} \left[(g_{V}^{e^{2}} + g_{A}^{e^{2}})(g_{V}^{\mu^{2}} + g_{A}^{\mu^{2}})(1 + \cos^{2}\theta) + 8g_{V}^{e}g_{A}^{e}g_{V}^{\mu}g_{A}^{\mu}\cos\theta \right]$$

<u>Asymmetric angular distribution</u> → forward-backward asymmetry

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + \frac{8}{3}A_{FB}\cos\theta \quad \text{with} \begin{cases} A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} \\ \sigma_{F(B)} = \int_{0(-1)}^{1(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta \end{cases}$$

At this point A_{FB} is an observable \rightarrow linear in couplings.

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J.Mnich, Experimental Tests of Standard Model in ee→ff at the Z resonance



Expectations:

Large forward-backward asymmetries away from the Z pole caused by γ/Z interference.

Cross section at the Z-pole $\sqrt{s} \approx M_Z$: Breit-Wigner Resonance (ignore QED contribution, interference vanishes because of finite Z lifetime)

$$\sigma_{tot} \approx \sigma_{Z} = \frac{4\pi}{3s} \frac{\alpha^{2}}{16\sin^{4}\theta_{w}\cos^{4}\theta_{w}} \cdot \left[(g_{V}^{e})^{2} + (g_{A}^{e})^{2} \right] \left[(g_{V}^{\mu})^{2} + (g_{A}^{\mu})^{2} \right] \cdot \frac{s^{2}}{(s - M_{Z}^{2})^{2} + (M_{Z}\Gamma_{Z})^{2}}$$

With partial and total widths:
$$\Gamma_f = \frac{\alpha M_Z}{12 \sin^2 \theta_w \cos^2 \theta_w} \cdot \left[(g_V^f)^2 + (g_A^f)^2 \right] \qquad \Gamma_Z = \sum_i \Gamma_i$$

(one could have immediately given this formular for the resonnce)

Breit-Wigner Resonance:

 $\sigma_{Z}\left(\sqrt{s} \approx M_{Z}\right) \approx \frac{12\pi}{M_{Z}^{2}} \frac{\Gamma_{e}\Gamma_{\mu}}{\Gamma_{Z}^{2}} = \frac{12\pi}{M_{Z}^{2}} BR(Z \rightarrow ee)BR(Z \rightarrow ff)$

 $\sigma(s) = 12\pi \frac{\Gamma_{\rm e}\Gamma_{\mu}}{M_{\tau}^2} \cdot \frac{s}{(s - M_{\tau}^2)^2 + M_{\tau}^2 \Gamma_{\tau}^2}$

Cross sections and widths can be calculated within the Standard Model if $sin^2\theta_w$ and M_Z are known.

From the couplings one expects
the following BR (independent of
M _Z)

	$BR = \Gamma_{\rm f}/I$	z
e, μ , τ	3.5%	Remind
ν_{e} , ν_{μ} , ν_{τ}	7%	color factor:
hadrons (= $\sum_{q} q\bar{q}$)	69% ←	N _c =3

No final state photon bremsstrahlung and no gluon bremsstrahlung considered.

Large corrections for hadronic final states from gluon final state bremsstrahlung:



Opens a way to measure α_s (M_Z).

Similarly there are final state QED corrections to take into account (formally similar but much smaller):

$$R_{QED} = 1 + \frac{\alpha(m_Z^2)}{\pi} + \dots$$
 Important: $\alpha(m_Z^2) = \frac{1}{129}$

Measurement of Z-lineshape

