E213 : Analysis of Decays of heavy vector boson Z^0

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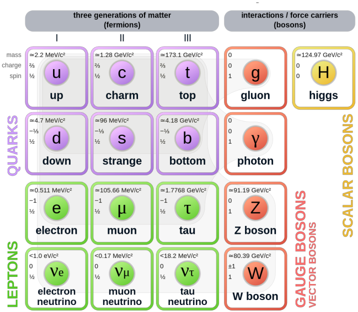
Outline

Introduction

- Goal: to understand how data from a particle accelerator is analysed and to deduce different properties of the Z^0 boson
- Important physical quantities: Z^0 mass and decay width
- Data collected from the OPAL (Omni-Purpose Apparatus at LEP) detector
- Part I: Carried out event display analysis on smaller datasets to understand how to separate out different Z^0 decay channels
- Part II: Cuts (constraints) imposed on the data are refined and statistical analysis done on larger real world data $\rightarrow$ deduce physical quantities

Standard Model

- Standard Model: provides the most fundamental description of nature by incorporating the elementary particles and their interactions
- Two families: fermions (half integer spins), and bosons (integer spins)
    - EM interactions $\rightarrow$ photon (γ)
    - Strong force $\rightarrow$ gluons (g)
    - Weak force $\rightarrow$ $W^{\pm}, Z^{0}$
    - Gravity $\rightarrow$ graviton (hypothesized; not included in SM)



Standard Model [1]

[1] *Standard Model*. https://en.wikipedia.org/wiki/Standard_Model.

Standard Model

- Fermions: three generations of quarks and leptons
  - Six flavours of quarks: up (u), down (d), charm (c), strange (s), top (t) and bottom (b)
  - Six flavours of leptons: electron (e), muon (μ) and tau (τ), and associated neutrinos (ν_e, ν_μ and ν_τ)
- Composite particles: three quark combinations, called baryons ($qqq/\bar{q}\bar{q}\bar{q}$) or quark-antiquark pairs, called mesons ($q\bar{q}$)
- Mathematically, elementary particles $\rightarrow$ elements of representations of certain symmetry groups
- Gauge fields coupling to these particles $\rightarrow$ consequence of invariance of corresponding Lagrangian under local phase transformations [2]
- Gauge symmetry that governs the Standard Model is given by:

$$SU(3)_{\text{Colour}} \times SU(2)_{\text{Left chiral}} \times U(1)_{\text{Y(Weak hypercharge)}}$$

[2] Mark Thomson. *Modern Particle Physics*. Cambridge University Press, 2013. DOI: 10.1017/CBO9781139525367.

Electroweak Theory

- Initially, EM and the theory of weak interactions formulated separately
- At higher energies ($\sim$ 246 GeV [3]), unified into single force $\rightarrow$ GSW electroweak model - 1960s
- Impose local gauge invariance on $SU(2)_L$ symmetry group $\rightarrow$ three gauge fields: $W^{(1)}$, $W^{(2)}$ and $W^{(3)}$
- Physical W^+ and W^- bosons found to be linear combinations:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}\left(W_\mu^{(1)} \mp \mathrm{i}\mathrm{W}_\mu^{(2)}\right) \tag{1}$$

[3] J. Erler and A. Freitas. *Electroweak Model and Constraints on New Physics*. English. Mar. 2018. URL: https://pdg.lbl.gov/2019/reviews/rpp2019-rev-standard-model.pdf.

Electroweak Theory

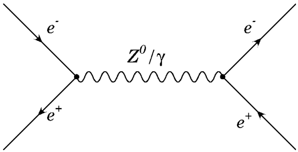
- $W_\mu^{(3)}$ field (no physical interpretation ?)
- Additional symmetry, the $U(1)_Y$ group is introduced
- B_μ field arising from $U(1)_Y$ symmetry (no physical meaning ?)
- Linear combinations of $W_\mu^{(3)}$ and B_μ fields $\rightarrow$ photon and the Z^0 boson:

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^{(3)} \end{pmatrix} \tag{2}$$

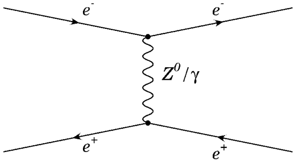
θ_W : weak mixing/Weinberg angle

Angular Dependence of γ/Z^0 Mediated Processes

- $e^+e^- \to e^+e^-$: t-channel as well as s-channel component
- $e^+e^- \to f\bar{f}$ (f other than e^-): only s-channel



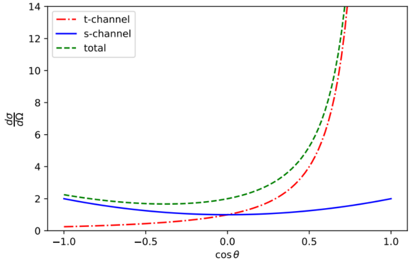
s-channel Bhaba scattering



t-channel Bhaba scattering

Angular Dependence of γ/Z^0 Mediated Processes

- s channel angular dependence: $\left(\frac{d\sigma}{d\Omega}\right)_s \propto (1+\cos^2\theta)$ Cross section has a major contribution at large angles (or small values of $\cos\theta$)
- t channel angular dependence: $\left(\frac{d\sigma}{d\Omega}\right)_t \propto (1-\cos\theta)^{-2}$ Cross section increases asymptotically at small angles (or large values of $\cos\theta$)[4]
- Essential step ! : Remove t-channel contribution while finding inherent forward backward asymmetry in $e^+e^- \rightarrow e^+e^-$ process



s and t-channel angular distribution

[4] Universität Bonn. *Instructions for E213: Analysis of Z^0 decay.*

Forward-Backward Asymmetry

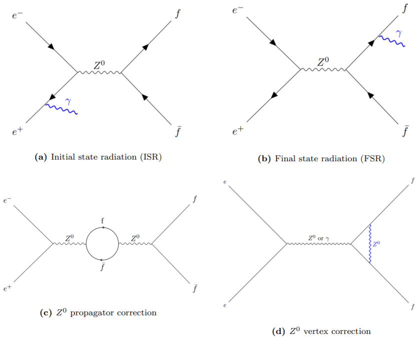
- Consider Z^0 mediated s-channel process $e^+e^- \to f\bar{f}$
- Angular dependence: $\left(\frac{d\sigma}{d\Omega}\right)_{s\ (Z^0)} \propto a(1+\cos^2\theta) + 2b\cos\theta$
- No. of fermions in forward dir., $(\theta > \pi/2) \neq$ no. of fermions in backward dir., $(\theta < \pi/2)$
- Asymmetry term b: Due to unequal coupling of Z^0 to right handed and left handed fermions $b = \left[(g_L^e)^2 - (g_R^e)^2\right]\left[(g_L^f)^2 - (g_R^f)^2\right]$
  - g_L^f: coupling of Z^0 to left handed fermions
  - g_R^f: coupling of Z^0 to right handed fermions

Forward-Backward Asymmetry

- FB asymmetry factor given as the ratio: $\mathcal{A}_{fb} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \dfrac{3b}{4a}$
  - σ_F, σ_B: cross sections in forward and backward directions respectively
- At Z^0 resonance, $\mathcal{A}_{fb}$ simplifies to [5]: $\mathcal{A}^f_{fb} \approx 3\left(\dfrac{g^f_V}{g^f_A}\right) = 1 - 4\sin^2\theta_W$
- From this, ratio of g^f_V to g^f_A can be found
- In turn gives us the Weinberg (weak mixing) angle θ_W

[5] Thomson, *Modern Particle Physics*.

Background Processes: Radiative Corrections



Some radiative corrections

To test out predictions of the Standard Model at high precision, need to account for higher order processes [6]:

- **ISR:** radiation of photons in the initial state → decreases $\sqrt{s}$ and affects Z^0 peak parameters
- **FSR:** radiation of photons or gluons in final state → partial widths increase
- **Electroweak corrections:** Virtual processes like loops in Z^0 propagator and vertex corrections

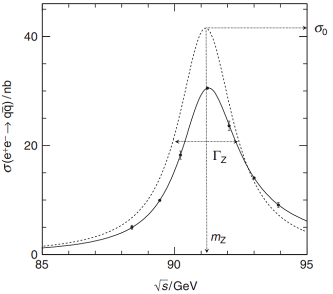
[6] G. Abbiendi et al. and "The OPAL" Collaboration. "Precise determination of the Z resonance parameters at LEP: "Zedometry"". In: *The European Physical Journal C - Particles and Fields* 19.4 (Mar. 2001), pp. 587–651. ISSN: 1434-6052. DOI: 10.1007/s100520100627. URL: https://doi.org/10.1007/s100520100627.

Breit Wigner Distribution

- Contribution of Z^0 boson exchange propagator to the matrix element:
  $\mathcal{M}_{Z^0} \propto \dfrac{g^2_{Z^0}}{q^2 - m^2_{Z^0}} = \dfrac{g^2_{Z^0}}{s - m^2_{Z^0}}$
- Around the Z^0 resonance ($\sqrt{s} \sim m_{Z^0}$), propagator diverges
- Correction $\rightarrow$ modify propagator for a decaying state
- For unstable particle having decay rate Γ, wavefunction modified to:
  $\psi \propto e^{-imt} \rightarrow e^{-imt} e^{-\Gamma t/2}$
- Equivalent to introducing an additional imaginary term in the mass:
  $m \rightarrow m - i\dfrac{\Gamma}{2}$
- Z^0 propagator then changes to: $\dfrac{1}{s - m^2_{Z^0}} \rightarrow \dfrac{1}{s - \left(m_{Z^0} - i\Gamma_{Z^0}/2\right)^2}$

Breit Wigner Distribution

- Complete form of cross section in process $e^+e^- \to Z^0 \to f\bar{f}$ is: $\sigma_f(s) = \frac{12\pi}{M_Z^2} \frac{s\Gamma_e\Gamma_f}{(s-M_Z^2)^2+\left(\frac{s\Gamma_Z}{M_Z}\right)^2}(\hbar^2 c^2)$
- **Breit-Wigner distribution:** Probability distribution that characterizes this dependence of cross section on centre of mass energy
- Various physical parameters can be extracted by fitting this theoretical distribution to the observed data



Breit Wigner distribution of the cross section for $e^+e^- \to q\bar{q}$ process [7]

[7] Thomson, *Modern Particle Physics*.

The LEP Experiment

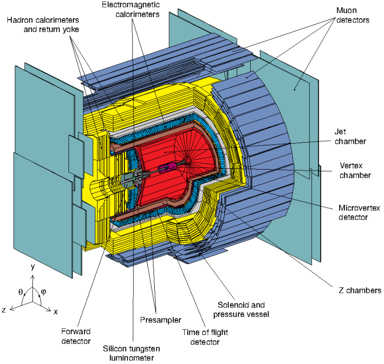
- LEP built at CERN; started operating in 1989
- One of the major goals: make high precision measurements of Z^0 boson properties
- Produced e^+e^- collisions at $\sqrt{s}$ close to Z^0 resonance
- Recorded about 17 million $e^+e^- \to Z^0$ events (1989-95) [8]
- Collisions at four different points in the circular collider $\to$ four detectors:
    - ALEPH (Apparatus for LEP PHysics)
    - DELPHI (DEtector with Lepton, Photon and Hadron Identification)
    - L3 (Third LEP experiment)
    - OPAL (Omni-Purpose Apparatus for LEP)

[8] Thomson, *Modern Particle Physics*.

OPAL Detector and its Components

Starting from origin, as e^+e^- collision products fly outwards, various detector components are encountered. These are discussed here in brief:

- **Vertex detector:**
  - Surrounds the central beam pipe
  - Key role: locating vertices of short-lived decay products
  - Improves momentum resolution
- **Jet chamber:**
  - Has good spatial and track resolution
  - Records events associated with jets
  - Also determines dE/dx of charged particles



Cross sectional view of the OPAL detector [9]

[9] *Das OPAL Experiment*. https://www-static.etp.physik.uni-muenchen.de/fp-versuch/node7.html.

OPAL Detector and its Components

- **z chambers:**
  - Locates z coordinates of decay particles
  - Helpful in improving the resolutions of the polar angle
- **Solenoid:**
  - Surrounds central detector
  - Generates a uniform magnetic field of 0.435 T along beam dirn.
  - $\vec{B}$ field $\rightarrow$ particles have helical path $\rightarrow$ momenta can be measured
- **Time of flight (TOF) system:**
- **ECAL:**
- **HCAL:**
- **Muon detector:**

References

Abbiendi et al., G. and "The OPAL" Collaboration. "Precise determination of the Z resonance parameters at LEP: "Zedometry"". In: *The European Physical Journal C - Particles and Fields* 19.4 (Mar. 2001), pp. 587–651. ISSN: 1434-6052. DOI: 10.1007/s100520100627. URL: https://doi.org/10.1007/s100520100627.

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Standard Model. https://en.wikipedia.org/wiki/Standard_Model.

Thomson, Mark. *Modern Particle Physics*. Cambridge University Press, 2013. DOI: 10.1017/CBO9781139525367.

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