Karlsruher Institut für Technologie

Vorlesung 15:

Teilchenphysik I (Particle Physics I)

Tests of the Electroweak Theory

Günter Quast

Fakultät für Physik
Institut für Experimentelle Kernphysik

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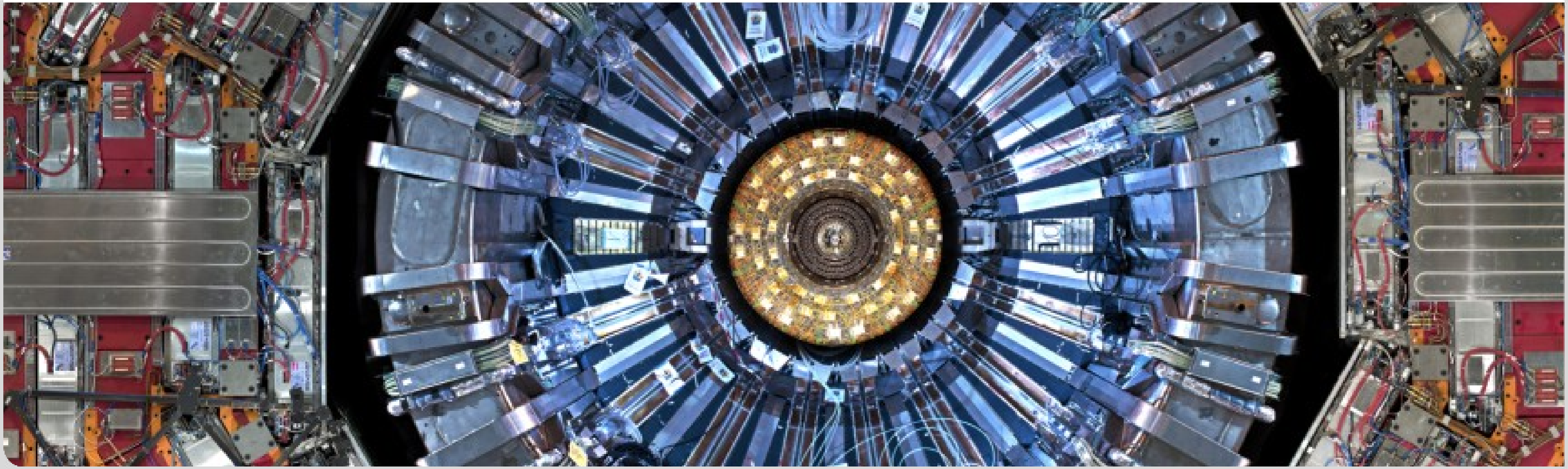


1. History
2. Basics principles
3. Detectors and Accelerators
4. Theoretical Foundations
    1. Relativistic Quantum Mechanics
    2. Quantum Field Theory and symmetries
    3. Elctroweak Symmetry and Higgs Mechanism
5. QCD and Jets
6. Analysis Chain

7. Flavour Physics
    1. Quark mixing and CKM Matrix
    2. Meson-Antimeson Mixing
    3. CP Violation

8. Tests of Electroweak Theory
    1. Discoveries
    2. Precision Physics with Z bosons
    3. W Boson and electroweak fit

Overview

During 1960s and early 1970s: electroweak theory proposed theoretically

- Formulation: S. Glashow (1961), Brout-Englert-Higgs-Mechanism as important ingredient (P. Higgs et. al. 1964), S. Weinberg, 1967)
- established as a renormalizable theory: G. ‘t Hooft, M. Veltman (1971)

Since then: Electroweak Theory established experimentally
Questions:

- Do neutral currents exist ?
- Do massive gauge bosons W and Z exist ?
- Are all coupling strengths as predicted ?
- Does the Higgs boson exist ?

This part of the lecture:

overview of first steps towards
establishing the Electrowek Theory experimentally

Search for Neutral Currents

Neutral Currents: mediated by neutral exchange boson,
coupling fermion-gntifermion pairs to fermion-antiferminon pairs,
like electromagnetic interactions mediated by photons

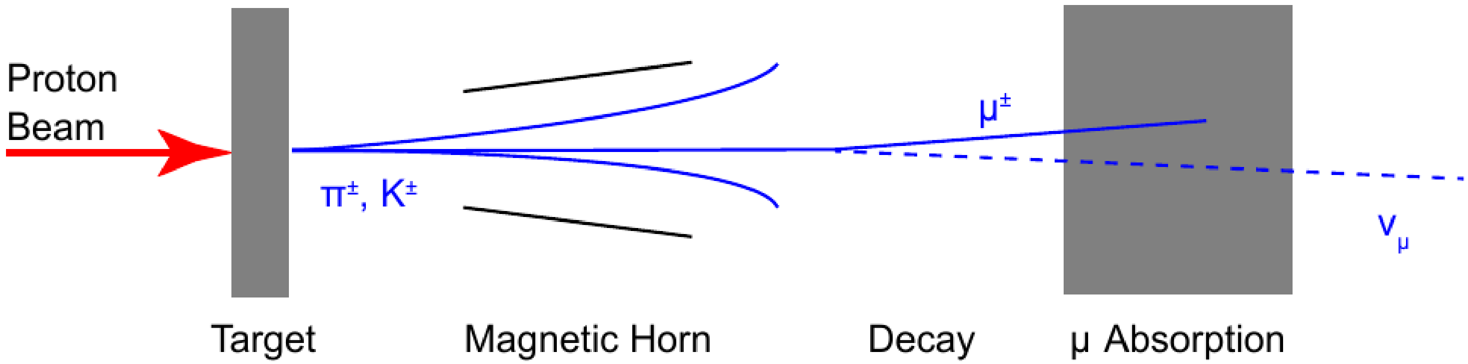
→

Electroweak interactions of charged particles at low energeries
are dominated by electromagnetic processes
→ impossible to observe neutral currents.

The way out: scattering experiments with neutrinos

CERN **neutrino beam** (since 1970):

- Protons from CERN PS on target → muon neutrinos, e.g. from $\pi^+ \rightarrow \mu^+ \nu_\mu$
- Detection: **bubble chamber** experiment Gargamelle



Bubble Chamber Gargamelle

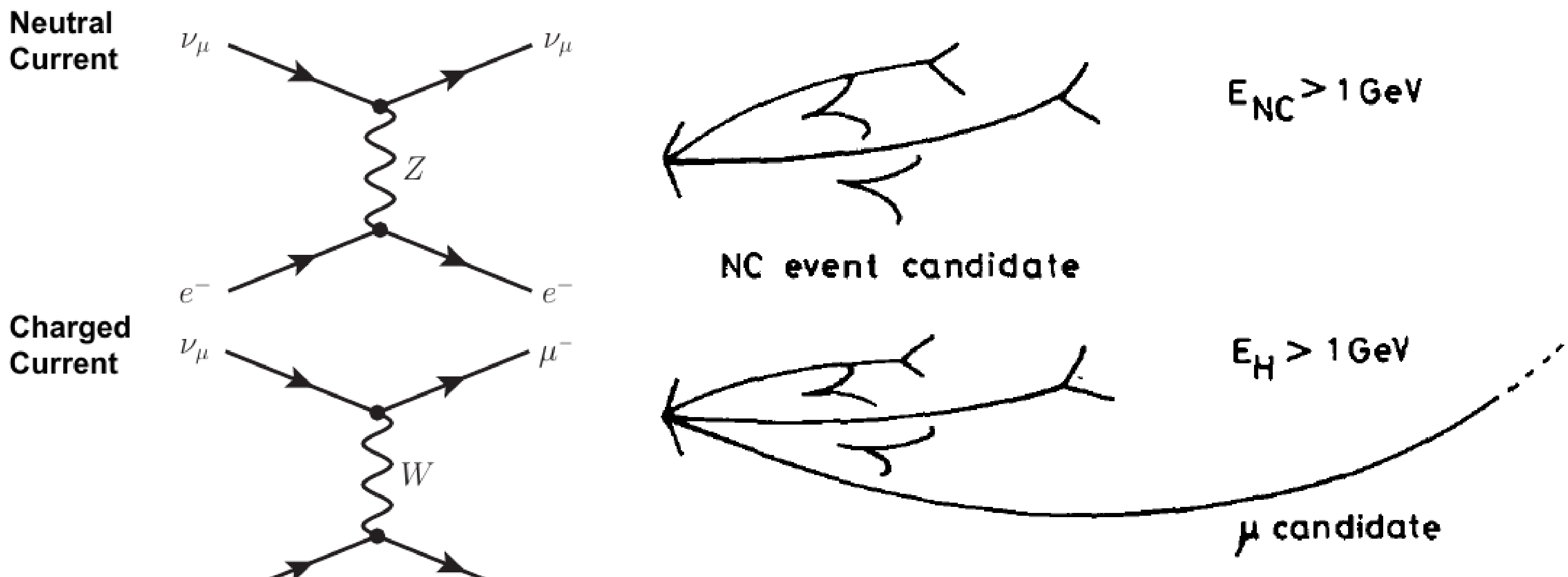
One of the largest bubble Chambers ever built

- a cylinder 4.8 m long, 1,9 m diameter,
  filled with 12’000 liters of liquid Freon (CF_3Br)
- operated close to boiling point
  → ionisation of charged particles leads to gas bubbles along the track
- events registered on photorgraphic film
- digitised by humans using an early version of a computer mouse

cds.cern.ch

Discovery of Neutral Currents

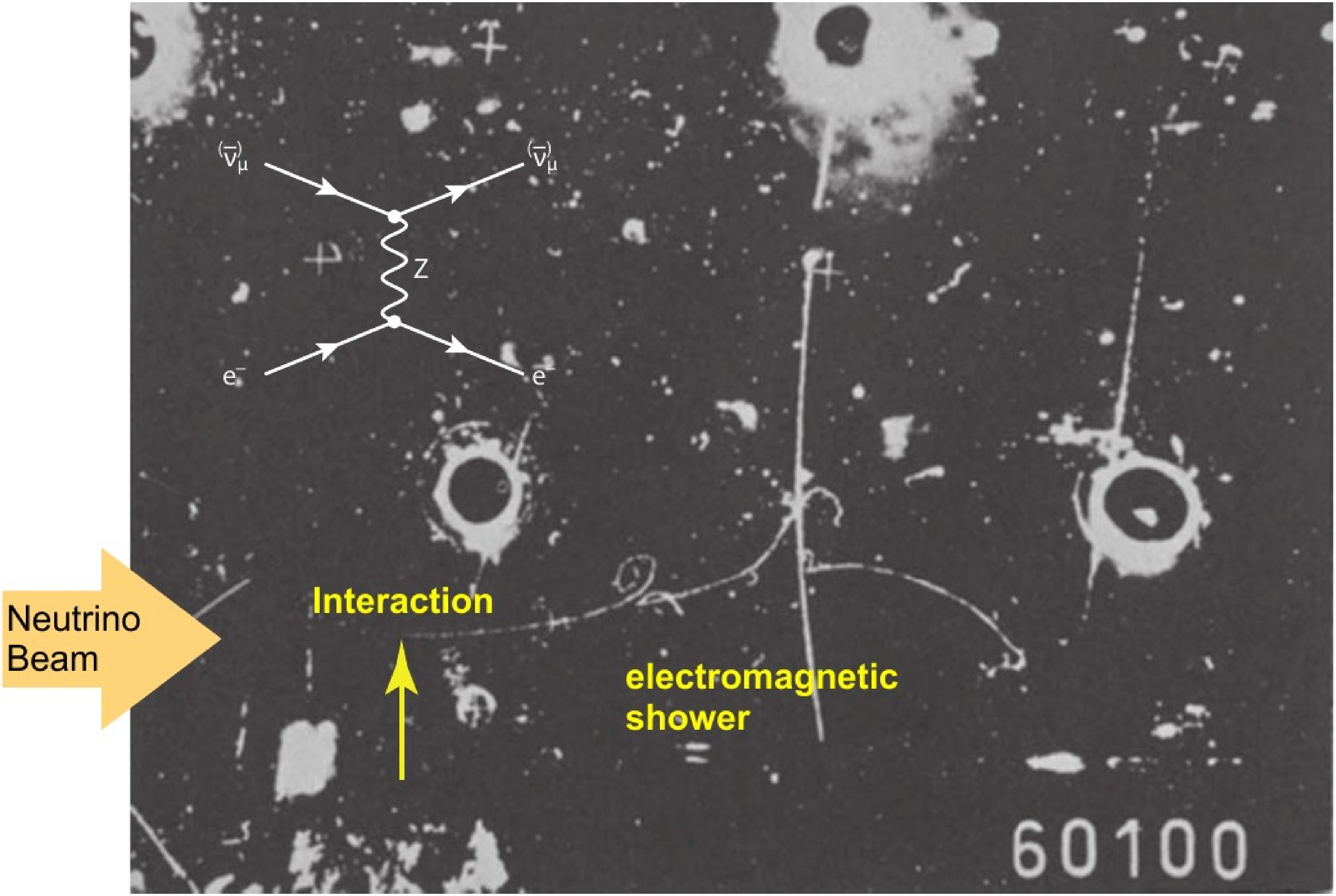
t-channel reaction of a muon-neutrino with electrons or nuclei
without a muon in final state



Nucl. Phys. B73 (1974) 1

- Neutrinos interact with **electrons** and atomic **nuclei**
- Sign of charged-current interaction: **muon** in final state → **long track**
- Sign of neutral-current interaction: **scattered electron** → **electromagnetic shower** (bremsstrahlung and e^+e^- pair production)

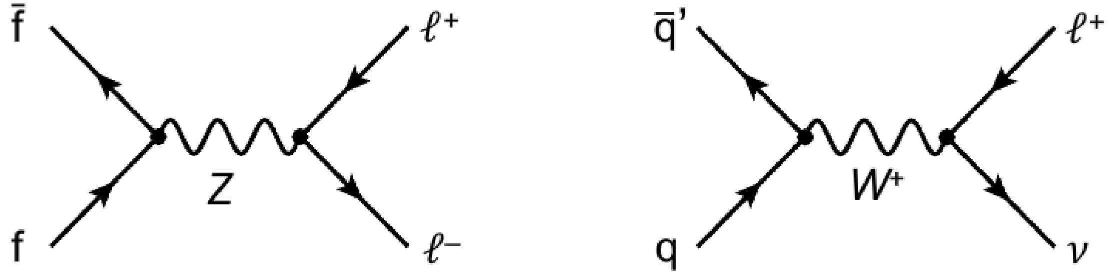
A Neutral-Current Neutrino-Electron interaction



Phys. Lett. B46 (1973) 121

W and Z Bosons

Production process ("Drell-Yan prozess"):
lepton production in hadronic interactions



Requirements to produce **real *W* and *Z* bosons** at accelerators:

- Center-of-mass energy of fermions in initial state around expected boson mass (approx. 100 GeV)
- **Fixed-target** setup: $\sqrt{s} = \sqrt{2m_pE} \rightarrow$ 5000 GeV beam energy → unrealistic
- **Electron-positron collider**: $\sqrt{s} = E_1 + E_2 \rightarrow$ 50 GeV beam energy → technically feasible only from the 1990s, only *Z* production
- **Proton-antiproton collider**: production of *W* and *Z* bosons by annihilation of valence quark in proton and valence antiquark in antiproton → ok

  Momentum fractions of colliding valence (anti)quarks $x_1 \approx x_2 \approx 0.2$
  → estimated center-of-mass energy:

$$\sqrt{\hat{s}} \simeq \sqrt{x_1 x_2 s} = 100\,\mathrm{GeV} \rightarrow \sqrt{s} = 500\,\mathrm{GeV}$$

Sp$\bar{p}$S -The CERN Super Proton Antiproton Synchrotron

- **SPS** (Super Proton Synchrotron):
  new CERN syncrotron (from 1976)
  6.9 km circumference, 400 GeV protons
- Idea (C. Rubbia, 1976): **upgrade** SPS to a **proton-antiproton collider** → Sp$\bar{p}$S
- Sp$\bar{p}$S center-of-mass energy: initially 540 GeV, later upgraded to 630 GeV

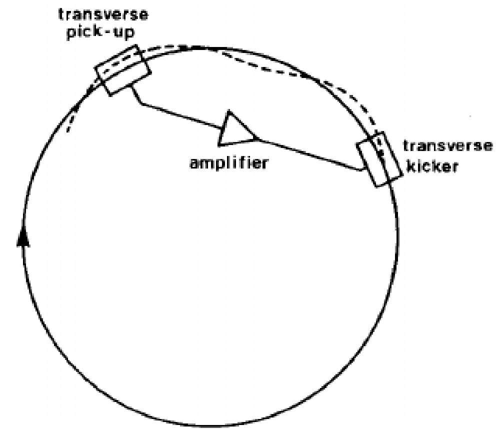
Challenges for antiproton beam:

- Antiproton production: proton beam on target: approx. one antiproton for each 10^9 final state parties
- Problem: very large antiproton **emittance** → reduction without violating Liouville's theorem

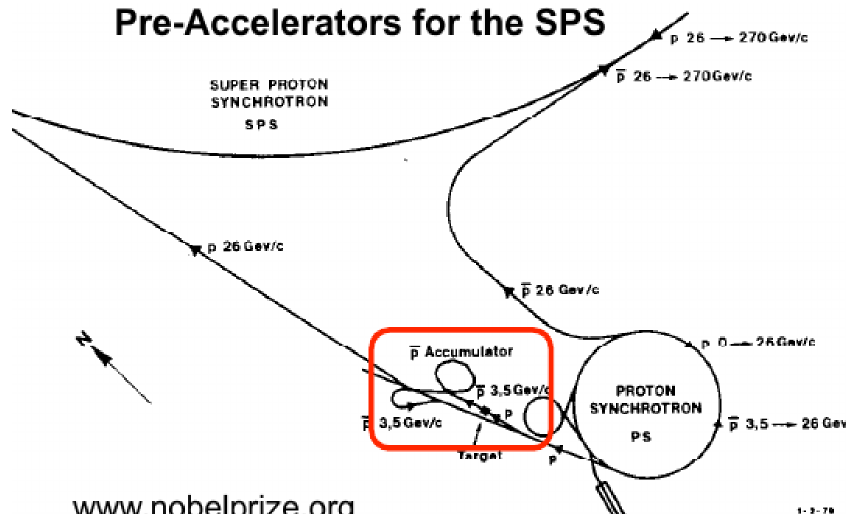
Idea: stochastic cooling with beam pick-up and kicker (S. van der Meer, 1968)

1984: S. van der Meer and C. Rubbia

Stochastic Cooling: Principle



Pre-Accelerators for the SPS



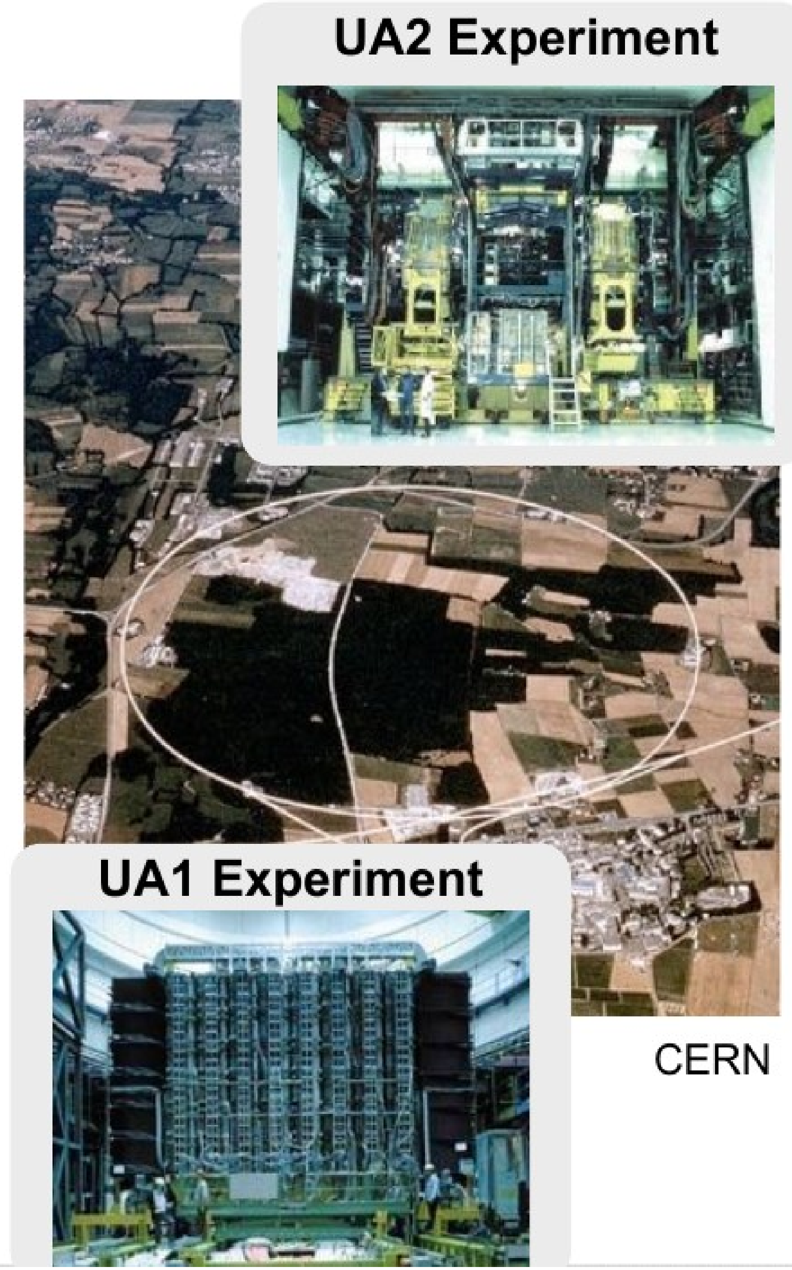
www.nobelprize.org

$Sp\bar{p}S$ and the Detectors UA1 and UA2

Further Challenges:

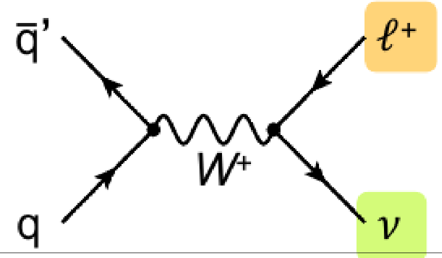
- Protons and antiprotons share the **same beam pipe**
- Detectors: **hermetic 4π detector** for the first time at hadron colliders

UA1 and UA2 experiments
(“underground area”),
data taking from 1981



Discovery of the W Boson

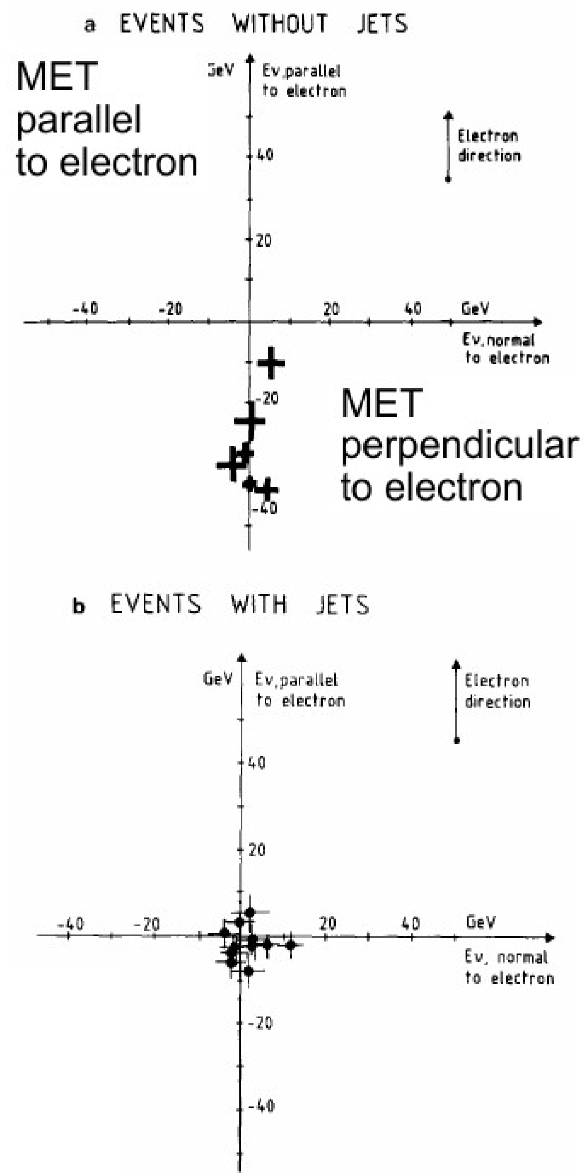
Process: $p\bar{p} \rightarrow W \rightarrow \ell\nu\ (\ell = e, \mu)$



Analysis strategy:

- Starting point: **charged leptons**
  → clean detector signature (approach still used at hadron colliders today)
- Neutrino detection: **missing transverse momentum** (MET) MET = Missing E_T:
  is determined from sum of transverse momenta of all particles in detector → **hermeticity is crucial !**

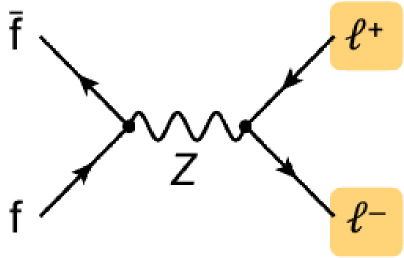
- **Two-body decay** $W \rightarrow \ell\nu$: lepton and neutrino (MET) emitted back to back in W-boson rest frame
- **Background**: QCD jet production → no preferred relative directions of lepton and MET



Phys. Lett. B122 (1983) 103

Discovery of the Z Boson

Process: $p\bar{p} \rightarrow Z \rightarrow \ell^+\ell^- (\ell = e, \mu)$



Analysis strategy:

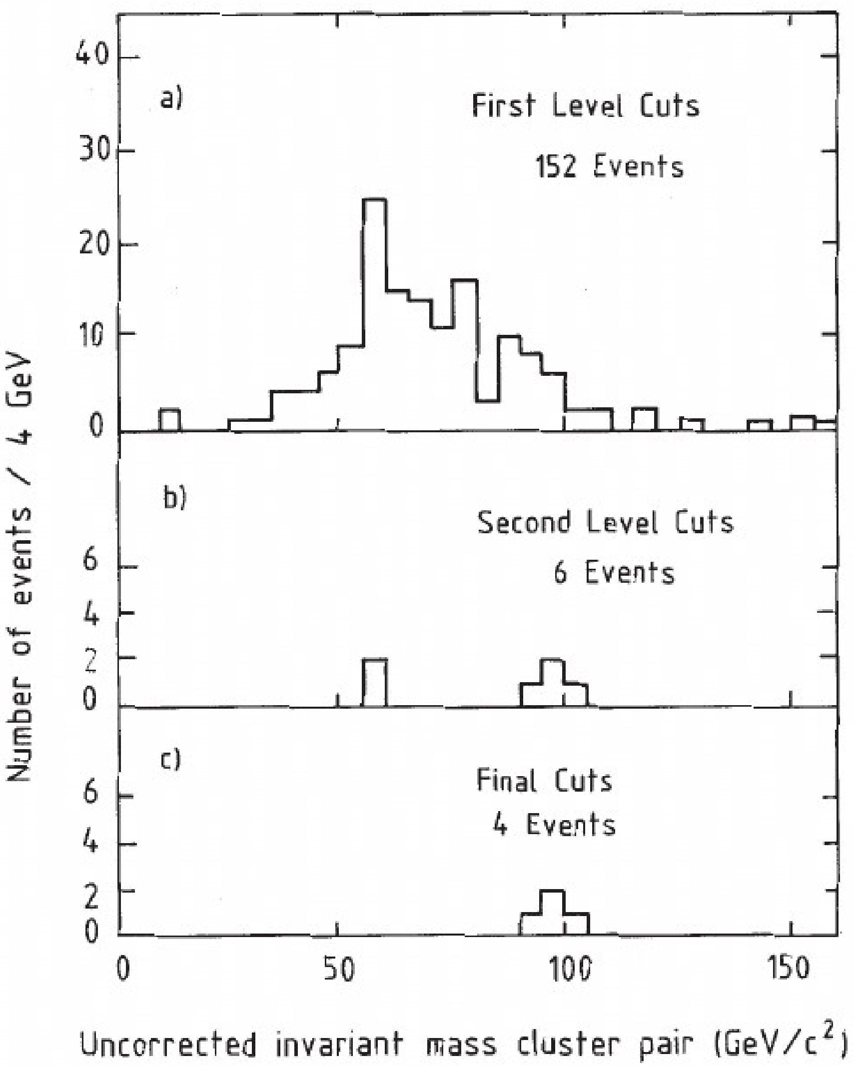
- **Invariant mass** of the lepton pair:

$$m_Z^2 = m_{\ell^+\ell^-}^2 = \left[\begin{pmatrix} E_{\ell^+} \\ \mathbf{p}_{\ell^+} \end{pmatrix} + \begin{pmatrix} E_{\ell^-} \\ \mathbf{p}_{\ell^-} \end{pmatrix}\right]^2$$

$$= m_{\ell^+}^2 + m_{\ell^-}^2 + 2\left(E_{\ell^+}E_{\ell^-} - |\mathbf{p}_{\ell^+}||\mathbf{p}_{\ell^-}|\cos\phi_{\ell^+\ell^-}\right)$$

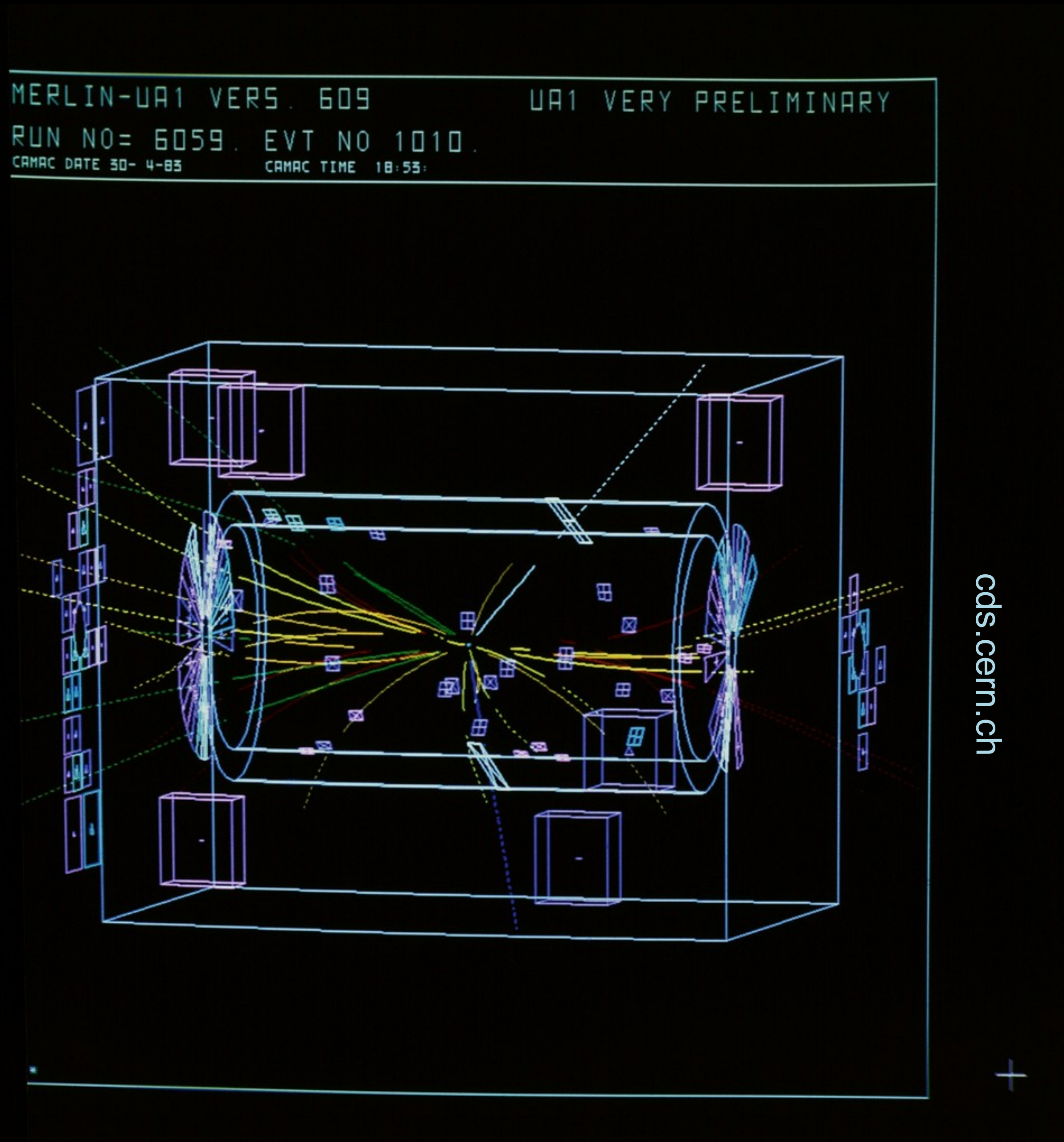
$$\approx 2|\mathbf{p}_{\ell^+}||\mathbf{p}_{\ell^-}|\left(1 - \cos\phi_{\ell^+\ell^-}\right)$$

- Depends on lepton **momenta** and **opening angle** (lepton masses neglected)



Phys. Lett. B126 (1983) 398

UA1 event picture



Neutrino - Electron Scattering

Studies of neutral currents with neutrinos revealed the structure of the Z – couplings to neutrinos and electrons

Z is a mixture of the $SU(2)_L$ and the U(1) gauge boson, given by the weak mixing angle and the fermion charge →

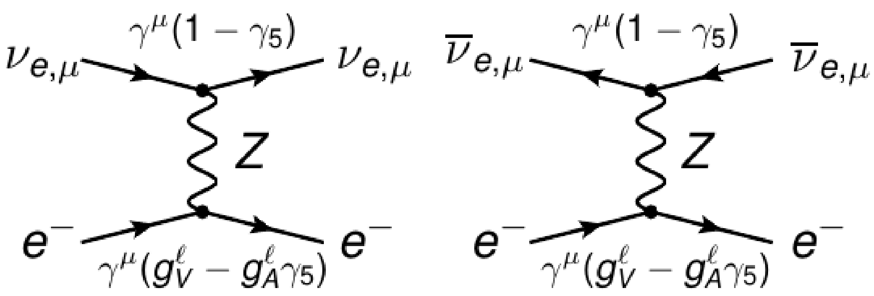
- neutrino coupling is purely left-handed, i.e. has equal contributions from vector (coupling in front of γ_μ term) and axial vector coupling ($\gamma_5\gamma_\mu$ term)
- electron coupling is not purely left-handed, with different vector and axial vector components

Example: **CDHS**

- CERN-Dortmund-Heidelberg-Saclay (Warsaw) collaboration
- Iron-scintillator sampling calorimeter → hadron calorimeter and spectrometer at the same time
- Calorimeter interleaved with drift chambers

Neutrino - Electron Scattering

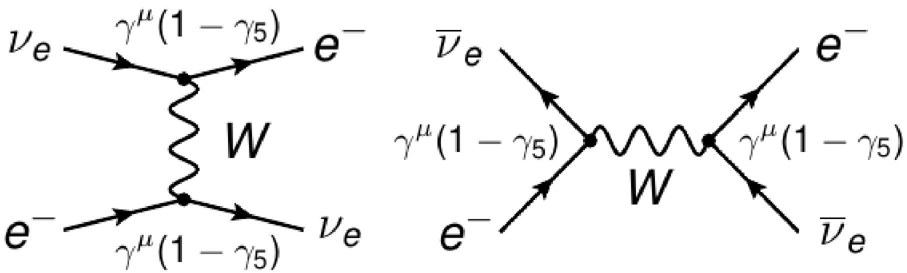
(Anti-)Neutrino Beam: NC



Difference between ν_e and ν_μ:

- ν_μ: only ***Z*-Boson exchange** (NC)
- ν_e and e: members of the same isospin doublet: ***W*-boson exchange** (CC) possible

Electron-(Anti-)Neutrino Beam: CC



Couplings:

- Neutrinos: **pure *V–A* coupling** to *W* and *Z* boson ($g_V = g_A = 1$)
- Electrons: g_V, $g_A \neq 1$

Neutrino - Electron Scattering

Total cross sections expressed in terms of vector (γ_μ) and axial vector ($\gamma_5\gamma_\mu$) couplings:

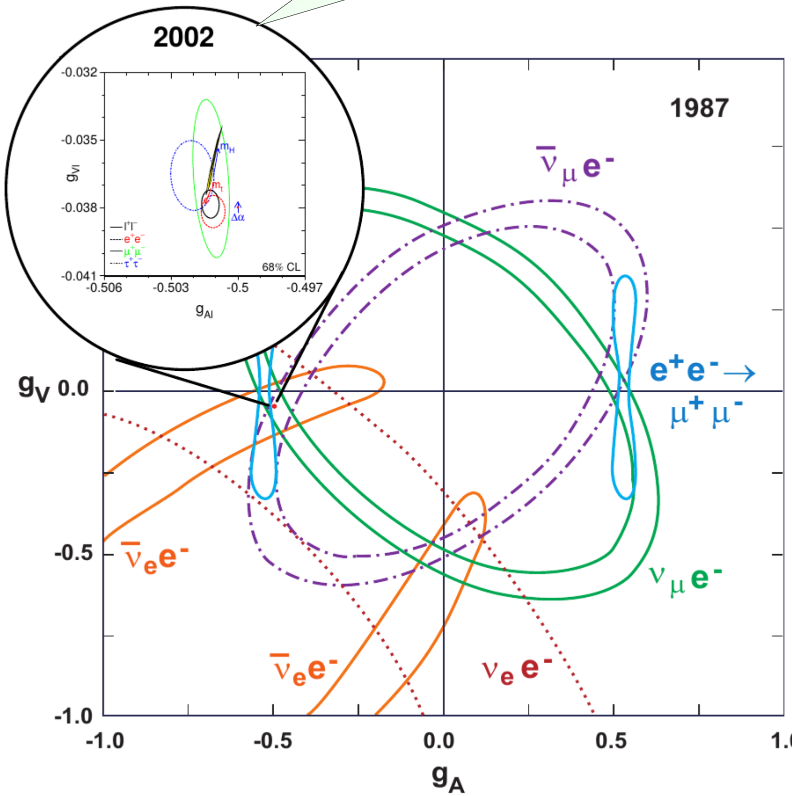
$$\sigma(\nu_\mu e^- \to \nu_\mu e^-) = \frac{G_F^2 s}{3\pi}\left[(g_V^\ell)^2 + g_V^\ell g_A^\ell + (g_A^\ell)^2\right]$$

$$\sigma(\overline{\nu}_\mu e^- \to \overline{\nu}_\mu e^-) = \frac{G_F^2 s}{3\pi}\left[(g_V^\ell)^2 - g_V^\ell g_A^\ell + (g_A^\ell)^2\right]$$

$$\sigma(\nu_e e^- \to \nu_e e^-) = \frac{G_F^2 s}{3\pi}\left[(g_V^\ell+1)^2 + (g_V^\ell+1)(g_A^\ell+1) + (g_A^\ell+1)^2\right]$$

$$\sigma(\overline{\nu}_e e^- \to \overline{\nu}_e e^-) = \frac{G_F^2 s}{3\pi}\left[(g_V^\ell+1)^2 - (g_V^\ell+1)(g_A^\ell+1) + (g_A^\ell+1)^2\right]$$

Precision today totally dominated by results on the Z resonance (see later)



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These are the equations of ellipses in the g_V - g_A plane

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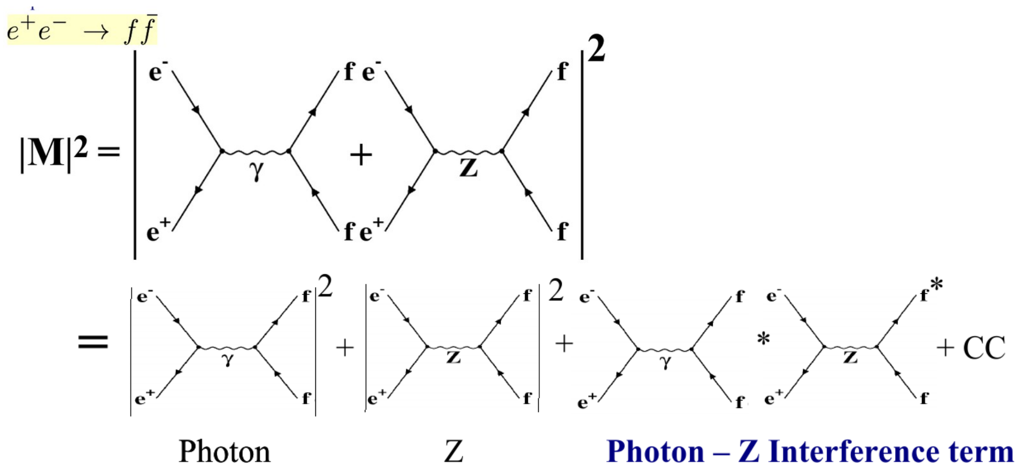
Electroweak precision tests at "Z Factories"

Studies of the Z-boson couplings to fermions test the heart of the EW interaction, the **mixing of the neutral Bosons of the U(1) and the SU(2)$_L$** symmetries

$$\begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix}$$

$$\sin\theta_W = \frac{g'}{\sqrt{g^2+g'^2}} \qquad \cos\theta_W = \frac{g}{\sqrt{g^2+g'^2}}$$

The matrix element M of Z → $f\bar{f}$ processes (in leading order)



Cross section: $\sigma(e^+e^- \to f\bar{f}) = \sigma_{\gamma^*} + \sigma_{\gamma^*/Z} + \sigma_Z$

- $\sqrt{s} \ll m_Z$: **photon exchange** dominates → only QED effects
- $\sqrt{s} \simeq m_Z$: ***Z* boson exchange** dominates, photon exchange and interference term negligible

Weak mixing angle $\sin^2\theta_W$ and Z-boson couplings

Electroweak theory in lowest order:

weak mixing angle $\sin^2\theta W$ give by

- ratio of left- and right-handed fermion-couplings or
- ratio of squared W and Z boson masses

$$\sin^2\Theta_\mathrm{W} = \frac{I_3^\mathrm{f}}{2Q^\mathrm{f}}\left(1 - \frac{g_v^\mathrm{f}}{g_a^\mathrm{f}}\right) = 1 - \frac{m_\mathrm{W}^2}{m_\mathrm{Z}^2}$$

$g_a^\mathrm{f} = I_3^\mathrm{f}$ axial vector coupling (factor of $\gamma_5\gamma_\mu$ term in $\mathcal{L}$)

$g_v^\mathrm{f} = I_3^\mathrm{f} - 2\,Q^\mathrm{f}\sin^2\Theta_\mathrm{W}$ vector coupling (factor of γ_μ term in $\mathcal{L}$)

or, equivalently:

$g_l^\mathrm{f} = \frac{1}{2}(g_v^\mathrm{f} + g_a^\mathrm{f})$ left-handed coupling

$g_r^\mathrm{f} = \frac{1}{2}(g_v^\mathrm{f} - g_a^\mathrm{f})$ right-handed coupling

In higher orders, couplings receive "radiative corrections" depending on all parameters of the theory, including so far unobserved new particles (→ later)

The $e^+e^- \to f\bar{f}$ cross section (lowest order)

$$\frac{2s}{\pi}\frac{1}{N_c^{\mathrm{f}}}\frac{d\sigma_{\mathrm{ew}}}{d\cos\theta}(\mathrm{e}^+\mathrm{e}^- \to \mathrm{f}\bar{\mathrm{f}}) \;=$$

"color factor"; 3 for quarks, 1 for leptons

$$\underbrace{|\alpha|^2\,(1+\cos^2\theta)}_{\gamma}$$

$$\underbrace{-8\alpha\Re\{\chi(s)\}\left[g_{\mathrm{Ve}}g_{\mathrm{Vf}}(1+\cos^2\theta)+2g_{\mathrm{Ae}}g_{\mathrm{Af}}\cos\theta\right]}_{\gamma-\mathrm{Z\ interference}}$$

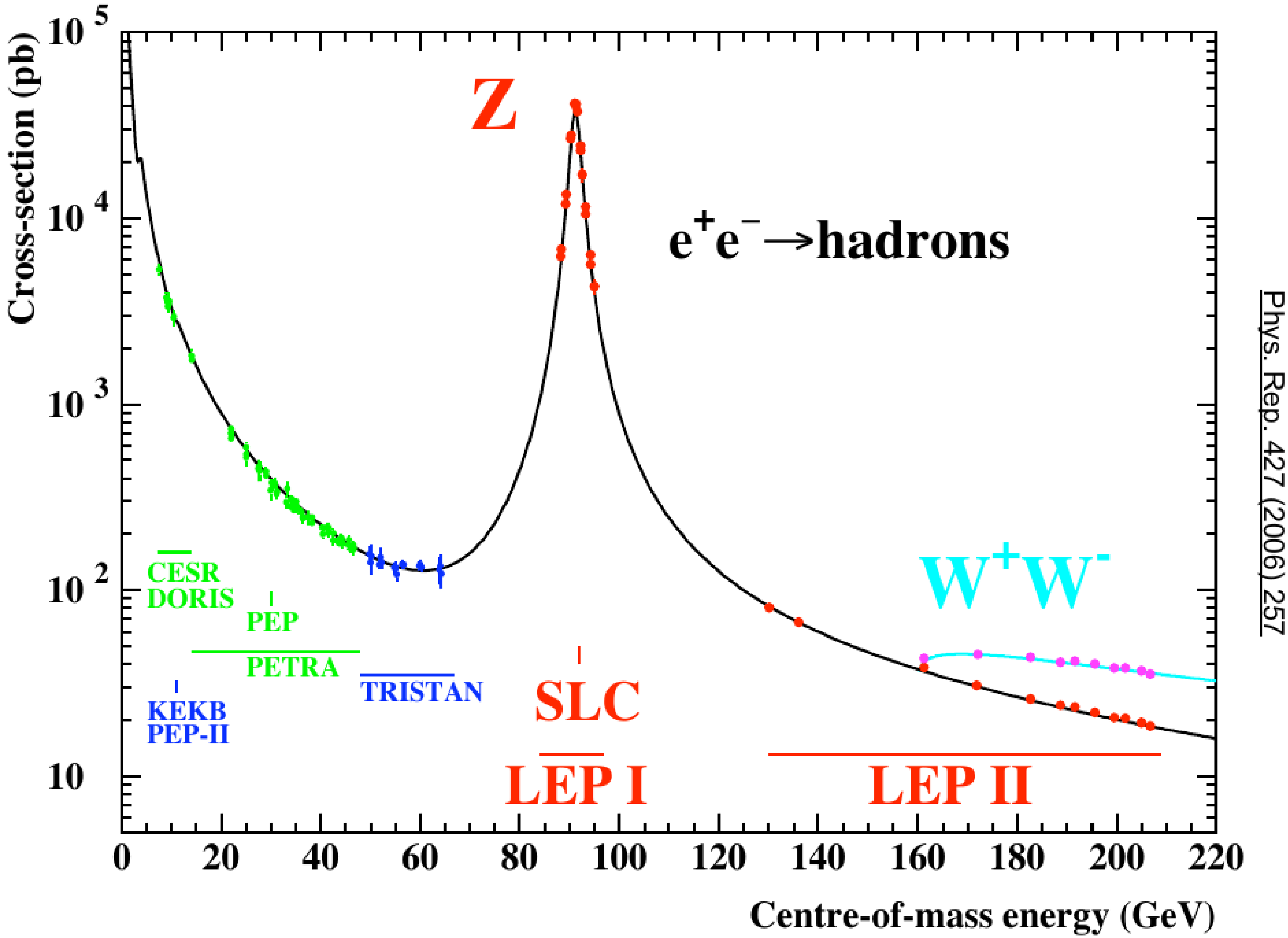
$$\underbrace{+16|\chi(s)|^2\left[\,(g_{\mathrm{Ve}}^2+g_{\mathrm{Ae}}^2)(g_{\mathrm{Vf}}^2+g_{\mathrm{Af}}^2)(1+\cos^2\theta) + 8g_{\mathrm{Ve}}g_{\mathrm{Ae}}g_{\mathrm{Vf}}g_{\mathrm{Af}}\;\cos\theta\,\right]}_{\mathrm{Z}}$$

with $\chi(s)=\frac{m_{\mathrm{Z}}^2}{8\pi\sqrt{2}}\frac{s}{s-m_{\mathrm{Z}}^2+i\Gamma_{\mathrm{Z}}m_{\mathrm{Z}}}$

Γ_Z : Z boson total width

Breit-Wigner Propagator

Measurements of e+e- → f$\bar{f}$



Cross Section at Z resonance almost a factor ~1000 higher than that of QED (photon exchange) processes

Experimental Measurements

The task: Measurement of the
differential cross section at different energies around the Z peak

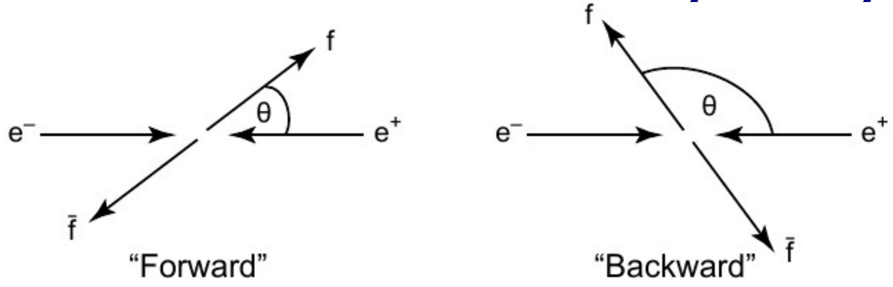
- terms **proportional to cos² θ** contribute to **total cross section**

$$\sigma_{\mathrm{tot}} = \frac{N_{cand} - N_{bkg}}{\epsilon \cdot \int L}$$

- terms **proportional to cos θ** contribute to **forward-backward asymmetry**

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

$$\sigma_F = \int_0^{\pi/2} \frac{d\sigma}{d\cos\theta} d\theta, \quad \sigma_B = \int_{\pi/2}^{\pi} \frac{d\sigma}{d\cos\theta} d\theta$$



- $\sigma_{\mathrm{tot}}(\sqrt{s})$ and $A_{\mathrm{FB}}(\sqrt{s})$ are the basic measruements at e^+e^- colliders
- polarised electrons (SLC) give additional information
- in final states with tau leptons, polarisation can be measrued as well

Early measurement of Forward-Backward asymmetry

with this knowledge, can go back in time:

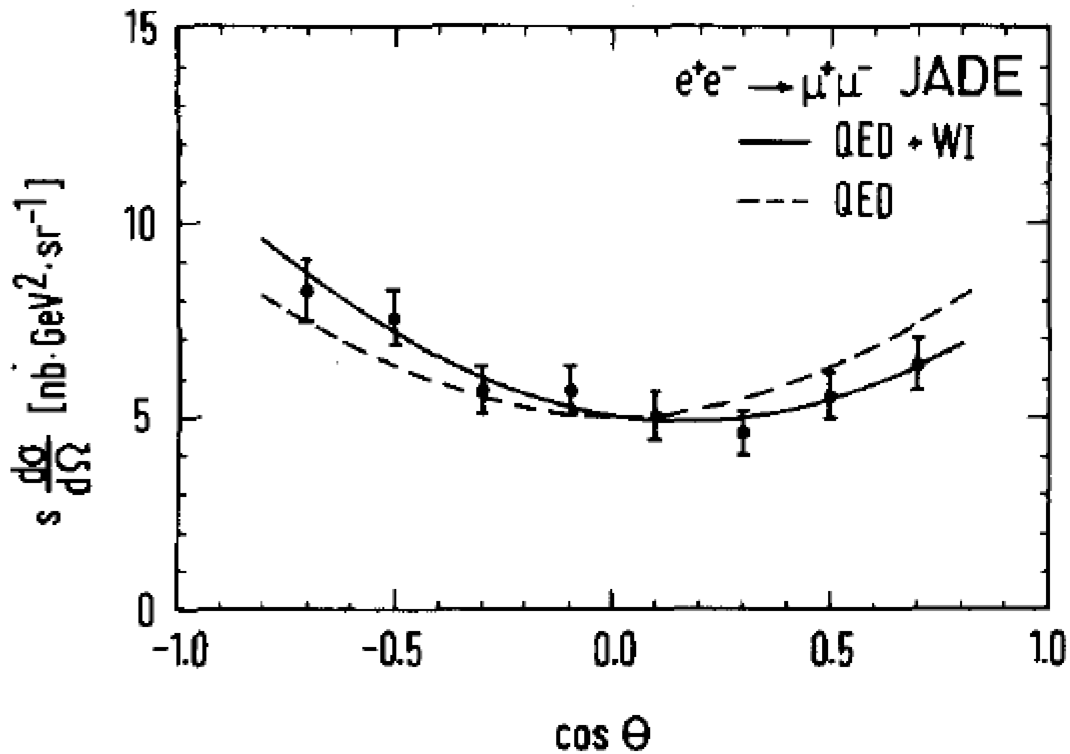
DESY, Hamburg, e^+e^- storage ring PETRA, 1981

Interference between γ^* and Z boson exchange already visible for $\sqrt{s} < m_Z$

Example JADE experiment:

Angle between outgoing μ^+ and incoming e^+ with fits to the data:
$p(1+\cos^2\theta) + q\cos\theta$ (full curve)
and $p(1+\cos^2\theta)$ (dashed curve)

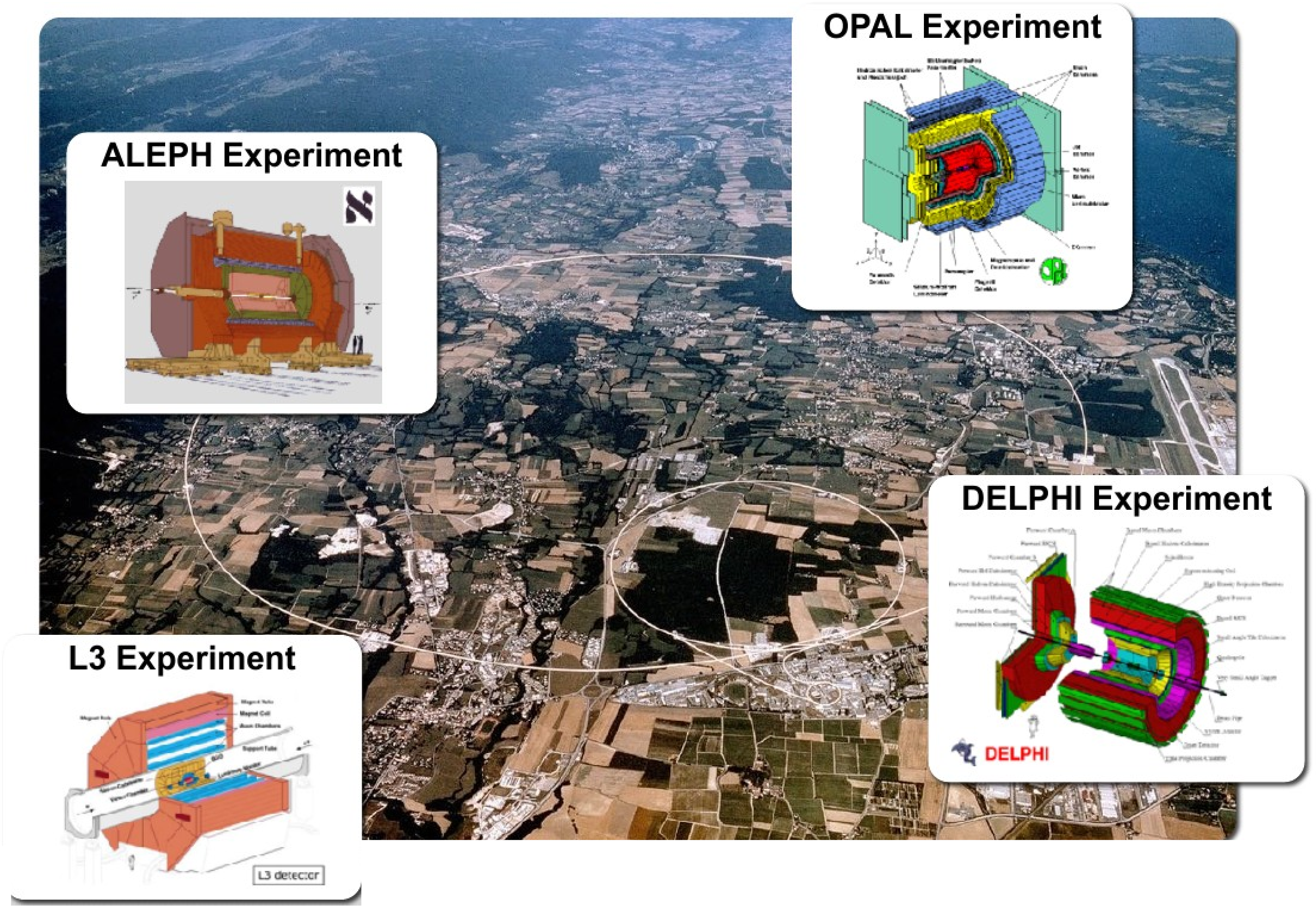
Observed asymmetry:
$A_{FB} = (-11.8 \pm 3.8)\%$
at average $\sqrt{s}$ = 33 GeV



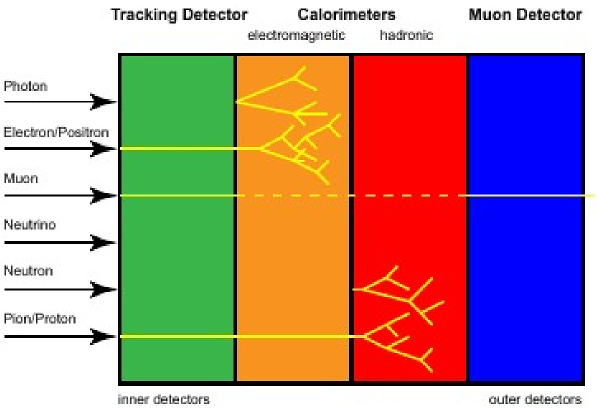
Phys. Lett. 108B 2 (1982)

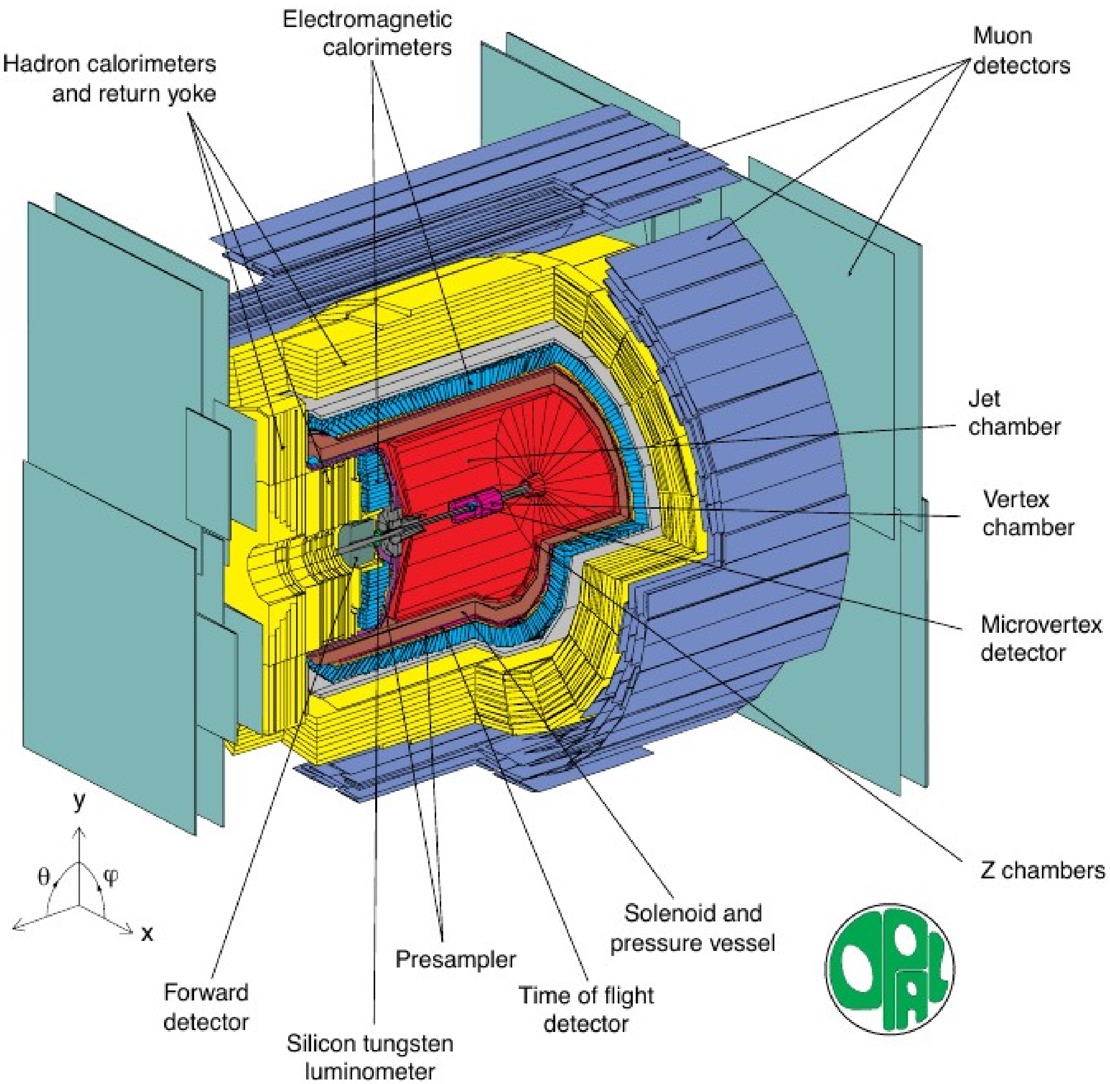
Combined results of the DESY Experiments Jade, MARK J, Pluto and TASSO:
$A_{FB} = (-7.7 \pm 2.4)\%$ → **indirect evidence of the Z-Resonance before the discovery of the Z Boson**

Z-Factories:
the Large Electron Positron Collider LEP



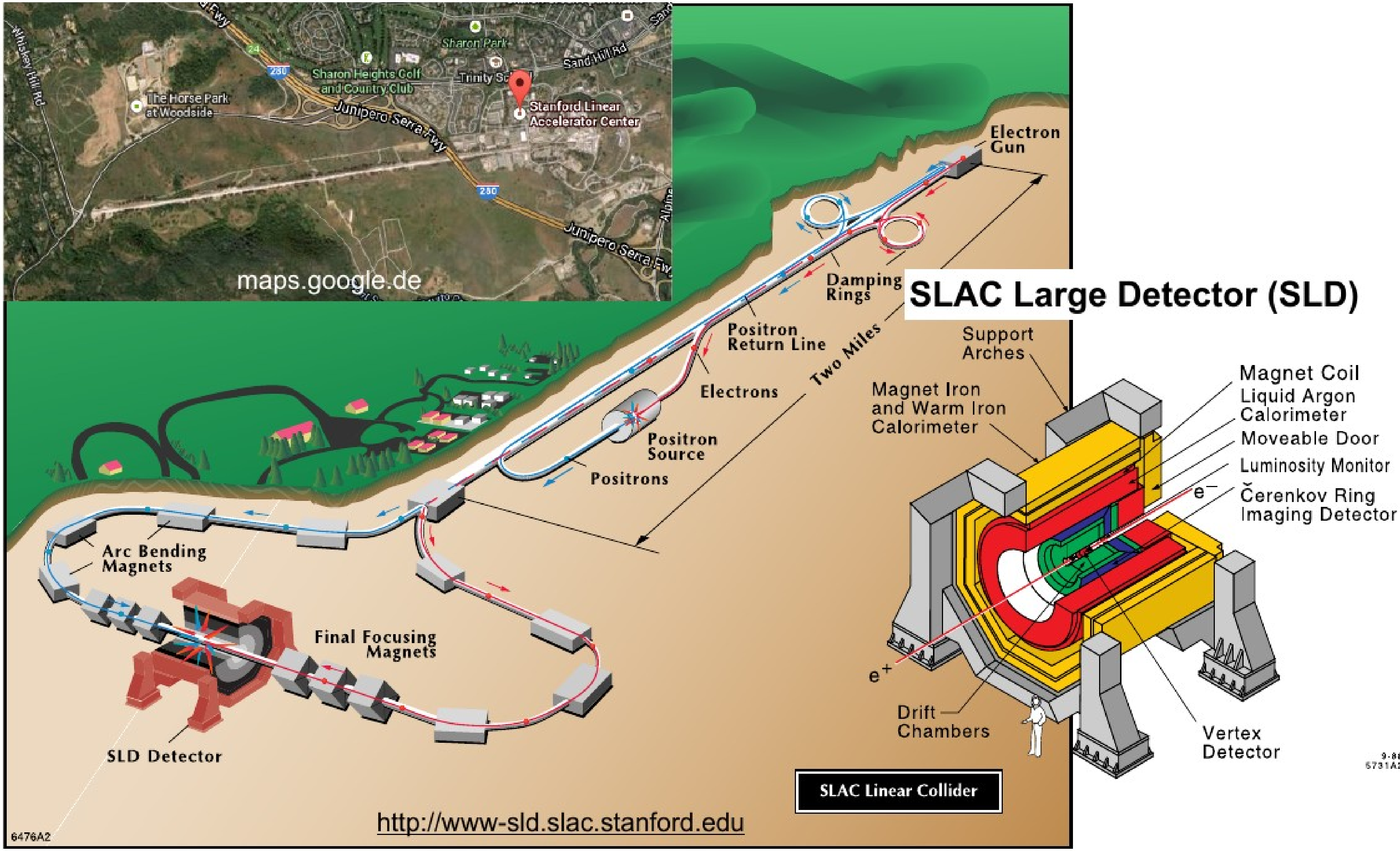
Example: Opal Experiment





http://opal.web.cern.ch/Opal/

Z-Factories:
The Stanford Lineaer Collider



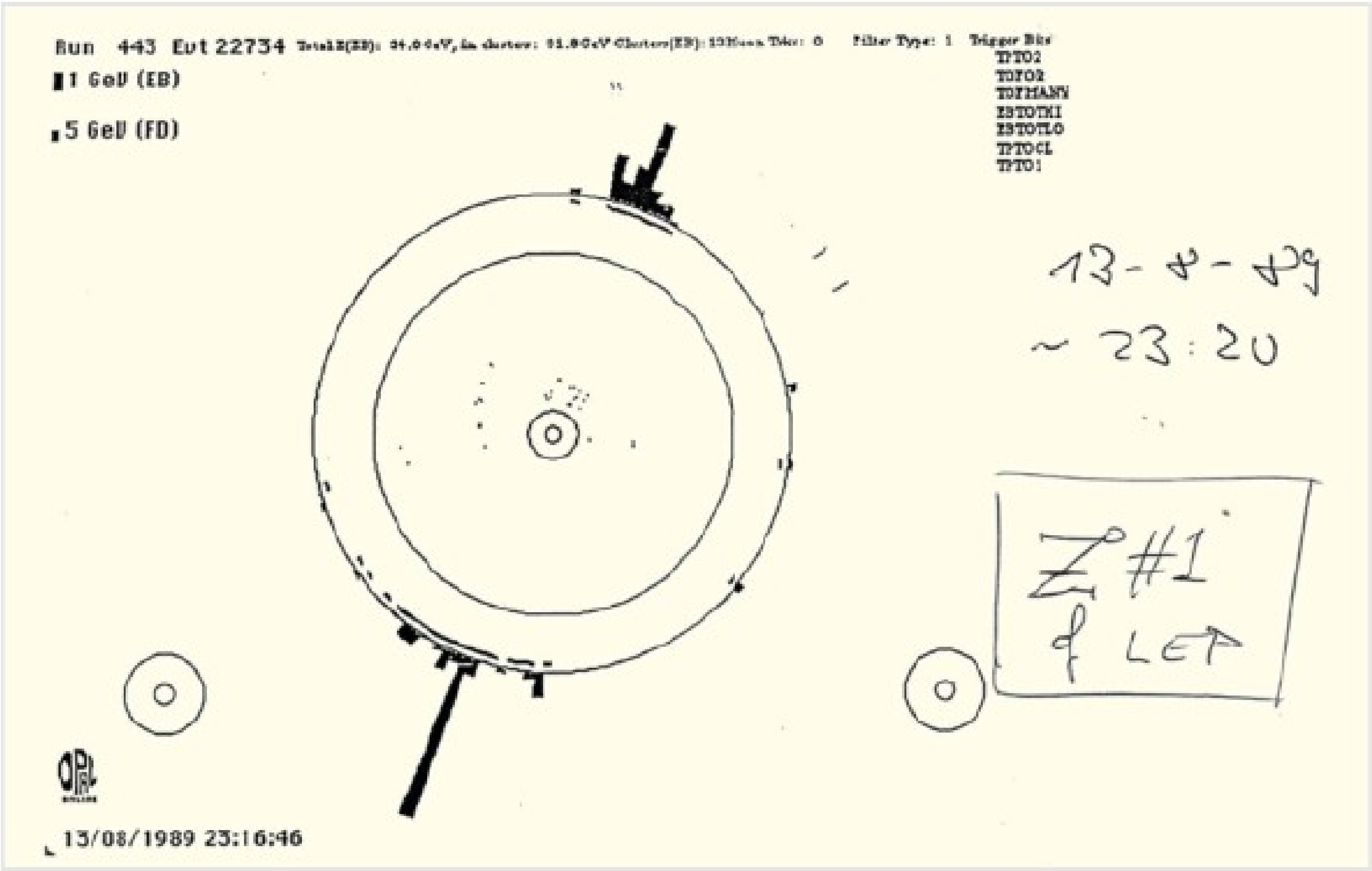
Z-Factories: Overview

e^+e^- collider with $\sqrt{s} = m_Z \approx 91$ GeV („at the Z pole")

Experiments: hermetic 4π detectors

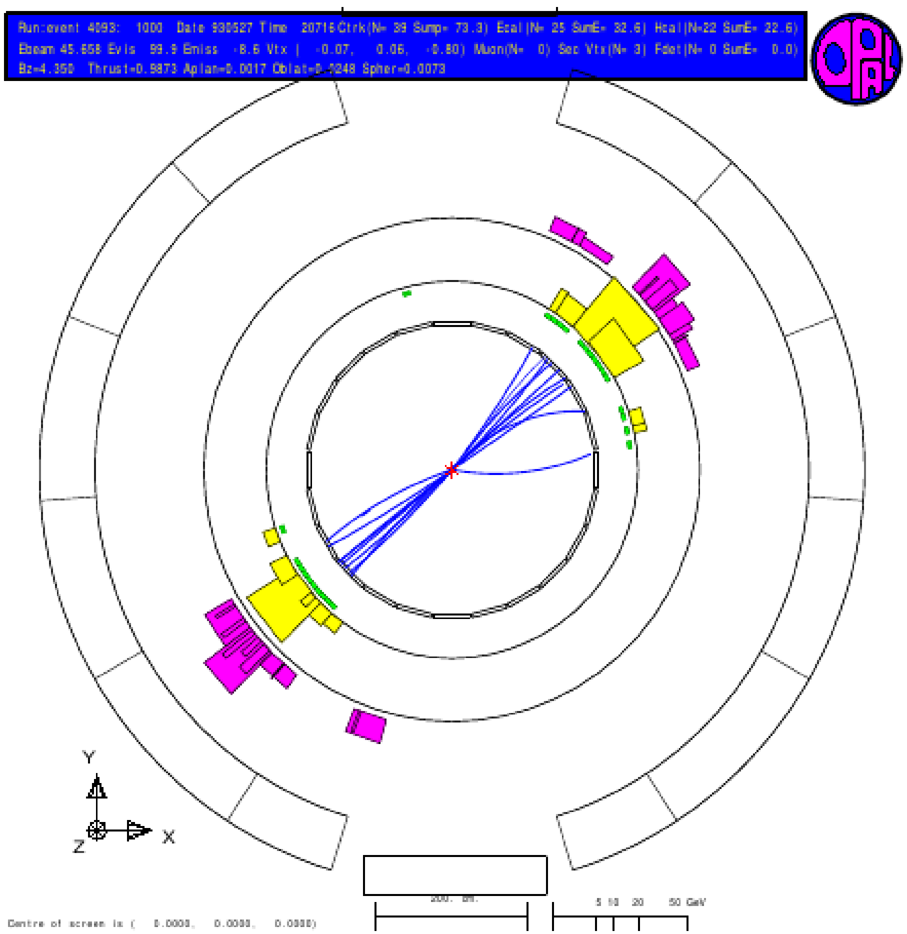
	LEP (1989-2000)	SLC (1989-1998)
Data-Taking Periods	LEP 1 (1989-1995): $\sqrt{s} \approx m_Z \approx 91$ GeV LEP 2 (1996-2000): $\sqrt{s}$ = 160–207 GeV	$\sqrt{s} \approx m_Z \approx 91$ GeV Polarized electrons since 1992
Experiments	ALEPH, OPAL, DELPHI, L3	Mark II (until 1991), SLD (1992-1998)
Z Boson Decays Recorded	17,000,000	600,000 (polarized)

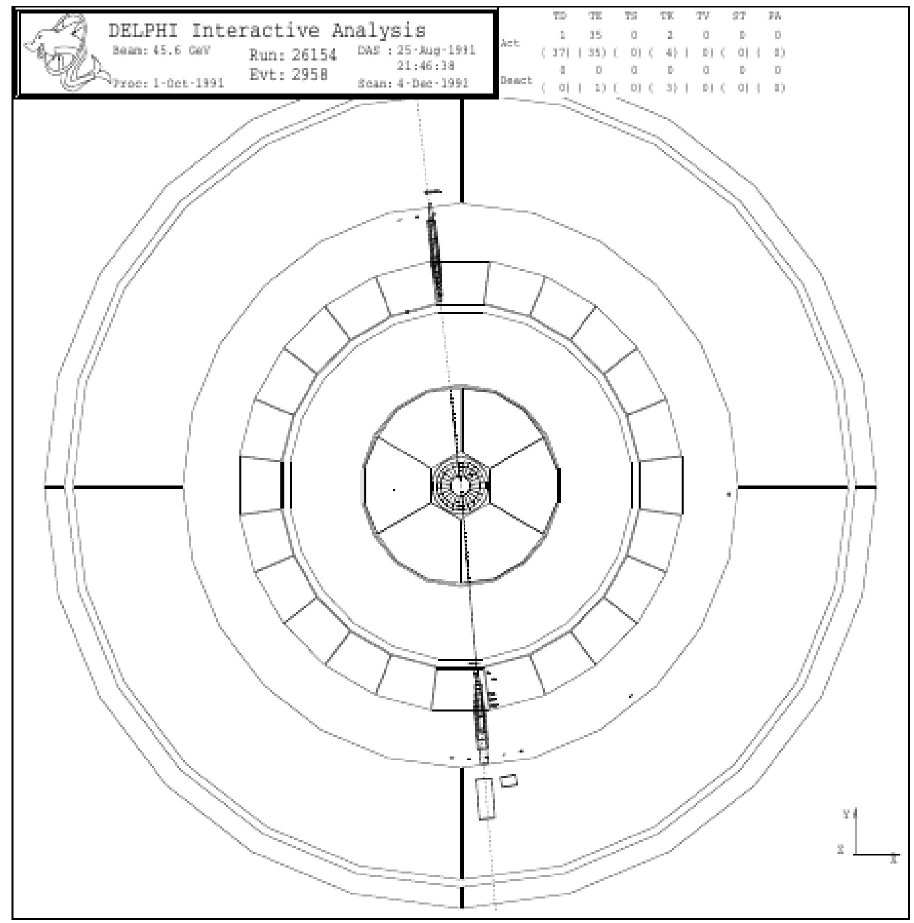
The first Event at LEP



OPAL fruits The OPAL logbook entry for the first Z boson seen at LEP, recorded late on 13 August 1989. Credit: CERN

Event Pictures





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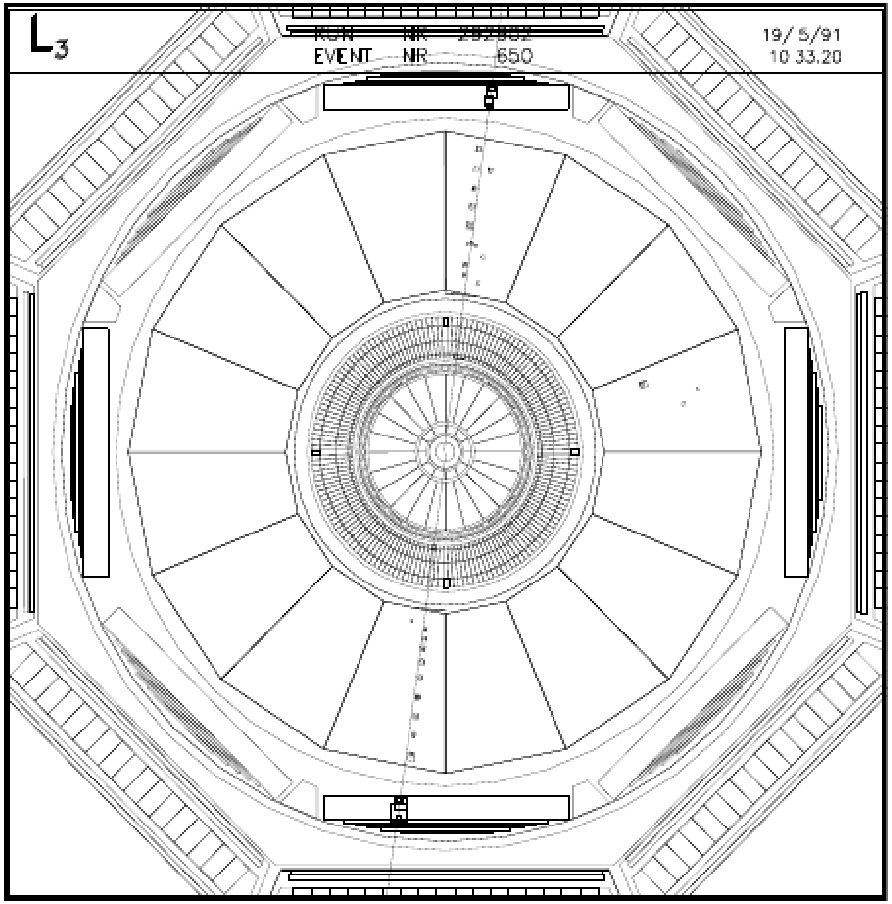
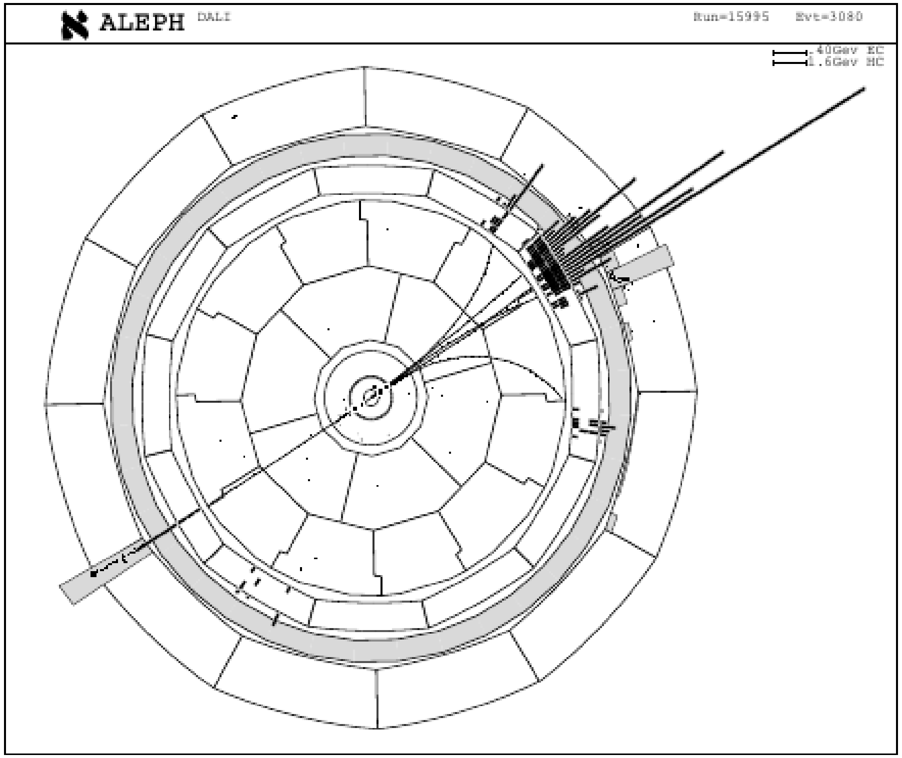
Event Pictures (2)





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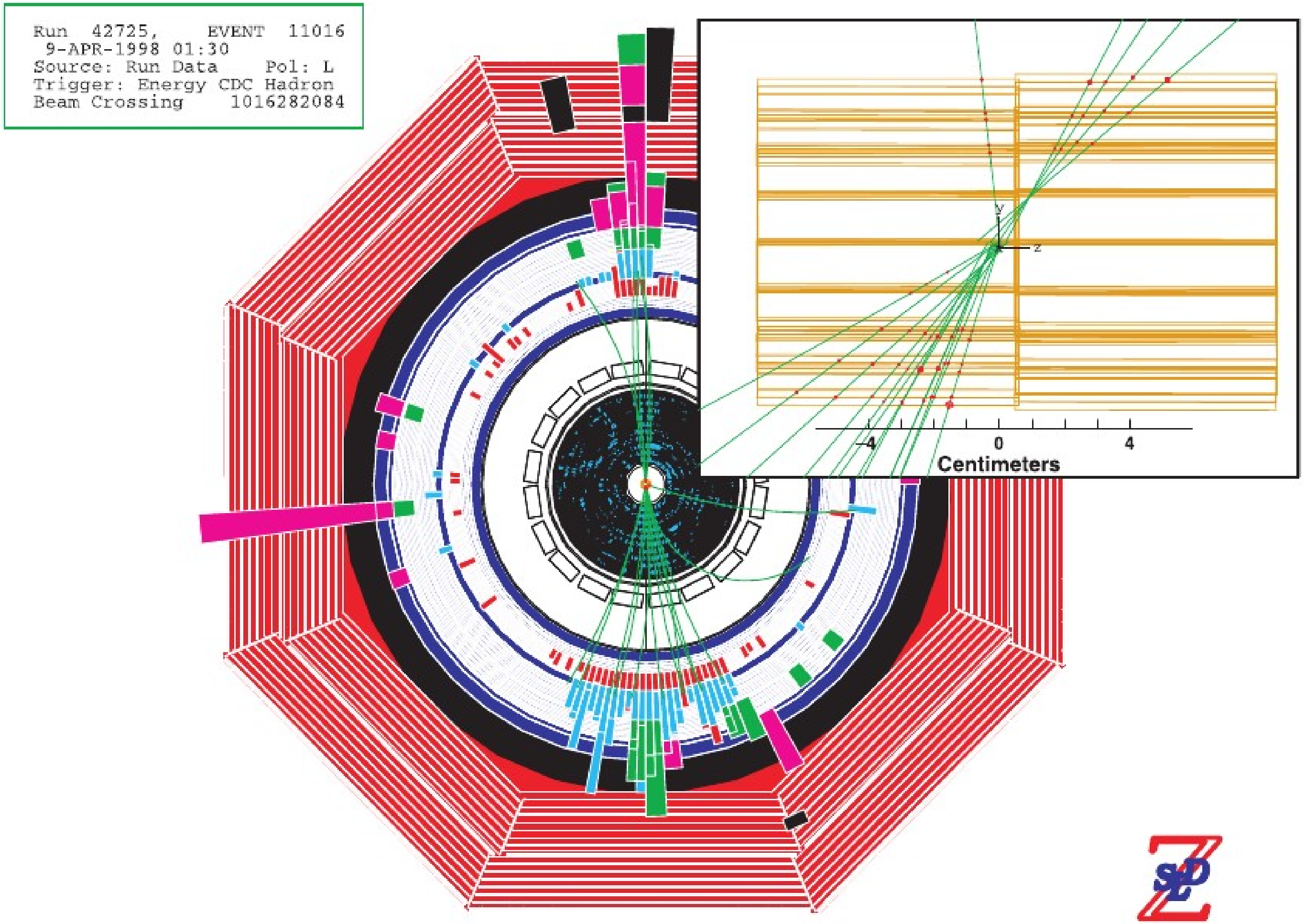
Event Pictures (3)



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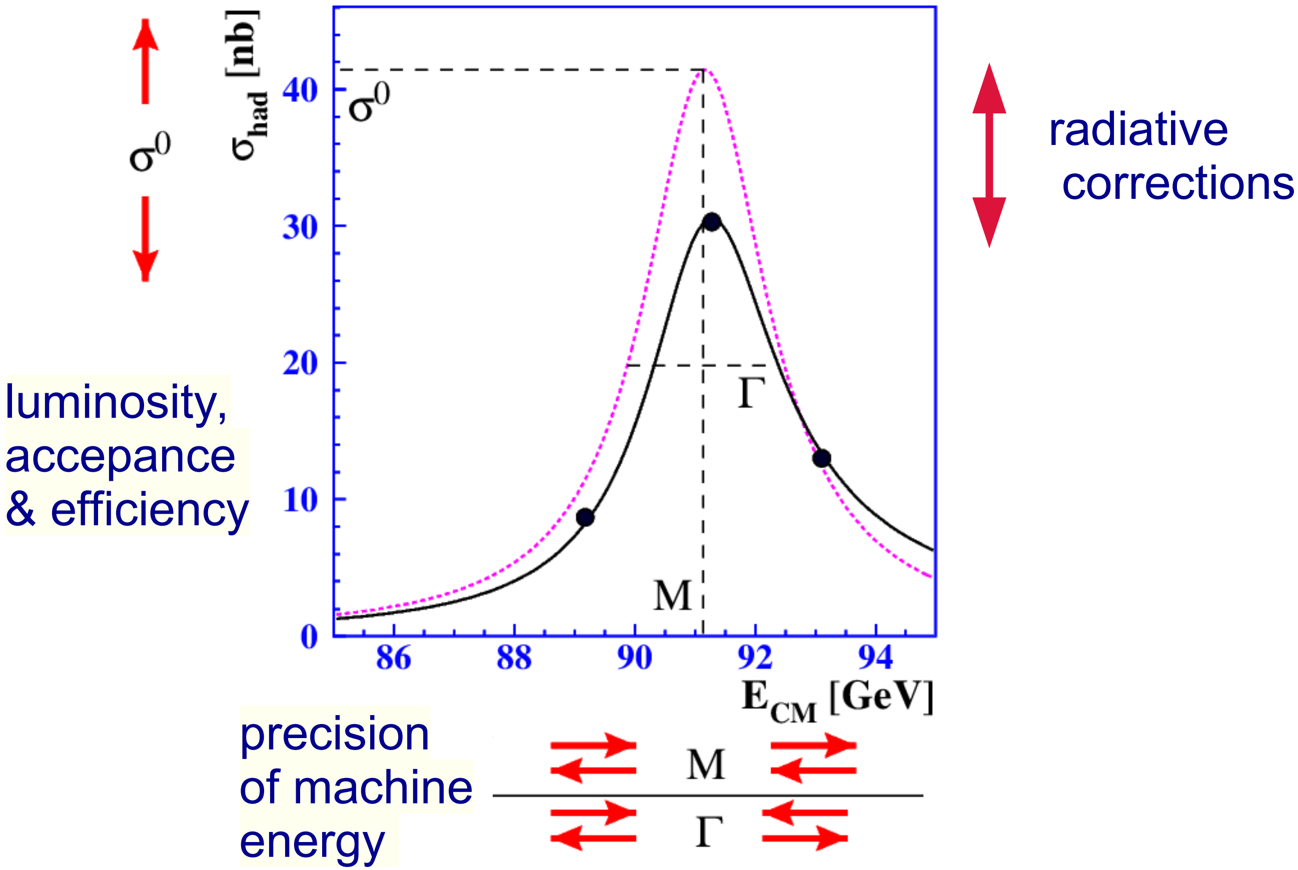
The Measurement Task

Precision-measurement of a resonance shape

→ **energy-dependent cross-section measurement for different final states *f***

$$\sigma^{\mathrm{f}}(\sqrt{s}) = \frac{N^{\mathrm{f}}_{\mathrm{obs}}(\sqrt{s}) - N^{\mathrm{f}}_{\mathrm{bkg}}(\sqrt{s})}{\epsilon(\sqrt{s}) \cdot \int \mathcal{L}(\sqrt{s})}$$



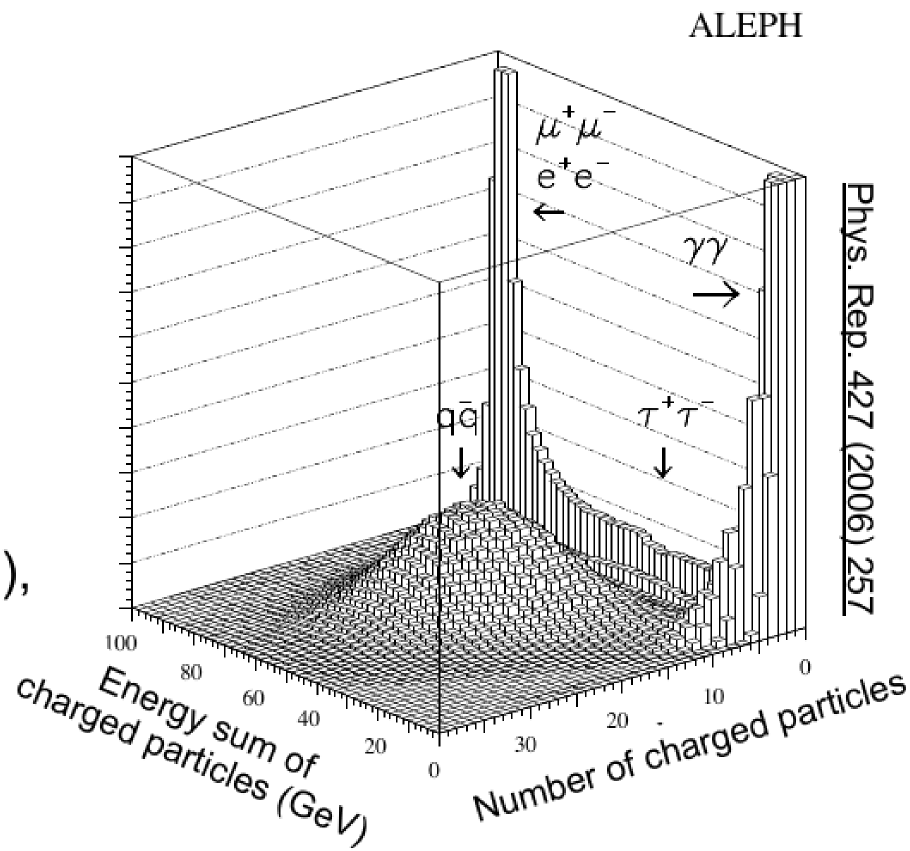
Measurement example : Identification of final states

Select **subset** of recorded data:

- **Enrich** certain classes of events (“signal events”)
- **Suppress** background = non-signal events with the same signature as signal events

Examples of selection criteria:

- **Analysis objects**: cut on kinematic properties (e.g. momenta and angles of jets and leptons) or **object ID** (e.g. ECAL shower shape)
- **Events**: count number of candidates for certain particle types (leptons, jets), energy sums, missing energy
- Often combined in **multivariate** methods (BDT, neural network, …)



Acceptance and Efficiency

$$\sigma = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\int \mathcal{L}\,dt \cdot \varepsilon}$$

In master equation for σ: **ε = acceptance × detection efficiency**

- Often determined using Monte Carlo simulation: number of selected MC events divided by total number of MC events generated

$$\varepsilon = \frac{N_{\text{gen}}^{\text{sel}}}{N_{\text{gen}}}$$

Acceptance: fraction of signal/background events that **could be detected in principle** (→ process dependent)

- **Geometric** acceptance: solid-angle coverage of detector
- **Detection threshold**: e.g. momentum interval in which detector and trigger are sensitive (note: detection turn-on curve ≠ step function)

Detection efficiency: fraction of signal events inside the detector acceptance that **have actually been reconstructed** (→ process dependent)

- Sources of inefficiency: e.g. dead-time, defective detector modules

Luminosity

$$\sigma = \frac{N^{obs} - N^{bkg}}{\int \mathcal{L}\,dt \cdot \varepsilon}$$

The **integrated luminosity** could in principle be taken from parameters of the accelerator (see lecture 6, slide 30). However, this is by far not precise enough.

Instead, a theoretically well-known referece reaction is used, the forward-scattering of electrons under very small angles, the **"Bhabha" process** $e^+e^- \rightarrow e^+e^-$

$$\int \mathcal{L} = N_{\text{Bhabha}} / \sigma_{\text{Bhabha}}$$

- Scattered e^+ and e^- at angles between ~25 and ~60 mrad
- special forward calorimeters with a precisely defined acceptance
- systematic uncertainties match or are even smaller than the theoretical precision on σ_{Bhabha} of 5.4×10^{-4}
- N_{Bhaba} must, of course, be corrected for backgroud and acceptance:

$$N_{Bhabha} = (N_{obs} - N_{bkg}) / (\alpha \cdot \varepsilon)$$

Energy Scale

Measurement of a resonance shape requires precise knowledge of the **centre-of-mass energy**

An essential ingredient: **The LEP energy calibration**

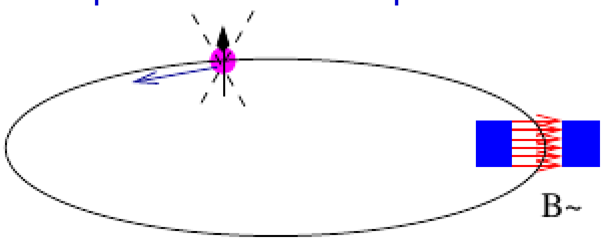
Beam energy is proporional to the integrated magnetic field along the particle path: $E_{\mathrm{beam}} \propto \int B \mathrm{d}l$

several methods available:

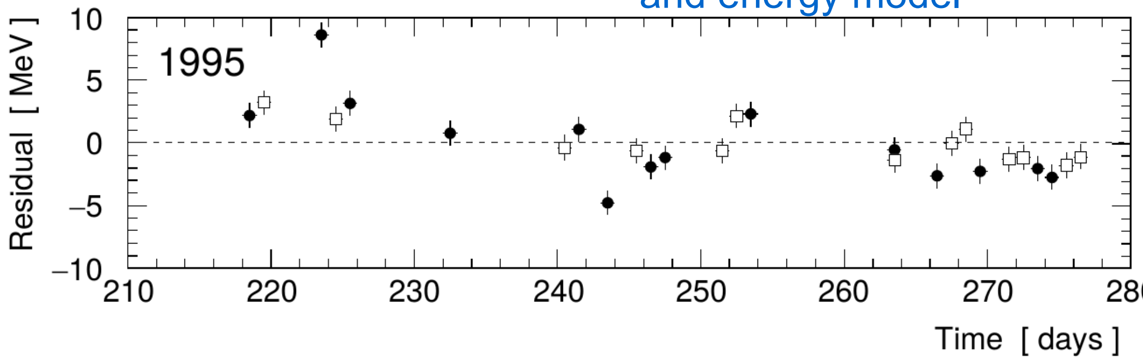
- measruement of B-field:
  - flux loop in reference magnet
  - **N**uclear **M**agnetic **R**esonance devices near ring dipoles
- most precise method:
  - determine **spin precession** frequency by **resonant depolarisation** of transversely polarised beam & tracking of energy changes between calibrations

Method takes into account the Earth's magnetic field, quadrupole contributions for non-central beam orbits, remnant magnetic fields

Principle of resonant depolarisation



differences between calibration and energy model



absolute precision: ±1.7 MeV
relative precision: ± 1.2 MeV

Literature on Z-Pole results

- Results of the LEP Electroweak Working Group on Physics at the Z-pole
  - Web page: http://lepewwg.web.cern.ch/LEPEWWG/
  - Comprehensive journal publication: ALEPH, DELPHI, L3, OPAL, SLD: *Precision Electroweak Measurements on the Z Resonance*, Phys. Rep. 427 (2006) 257

- CERN Courier, LEP's electroweak leap
  https://cerncourier.com/a/leps-electroweak-leap/

- Lecture *W, Z and Higgs boson physics,* summer semester