Outline

- Relativistic Kinematics
  - (4-momentum)2 invariance, invariant mass
  - Hypothesis testing, production thresholds
  - Cross-sections, flux and luminosity, accelerators
  - Particle lifetime, decay length, width
- Classification of particles
  - Fermions and bosons
  - Leptons, hadrons, quarks
  - Mesons, baryons
- Quark Model
  - Meson and baryon multiplets
  - Isospin, strangeness, c, b, t quarks
- Particle Interactions
  - Colour charge, QCD, gluons, fragmentation, running couplings
  - Strong and weak decays, conservation rules
  - Virtual particles and range of forces
  - Parity, charge conjugation, CP
  - Weak decays of quarks
  - Charmonium and upsilon systems
- Electroweak Interactions
  - Charged and neutral currents
  - W, Z, LEP experiments
  - Higgs and the future
- LHC Experiments
- Future – introduction to accelerator physics

Today

- Lecture 20 (4 slides/page) Weak neutral currents (Z) and experiments
  - Perkins, p317-318;
  - Griffiths, pp. 72-74;

Previous lecture

- Lecture 19 (4 slides/page) Electroweak interaction
  - Perkins, pp. 208; 316-317
  - Griffiths, pp. 74-79;

Weak Interaction

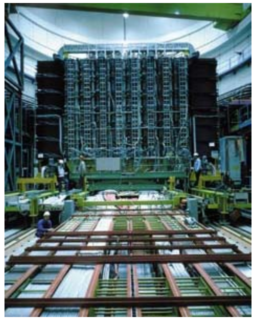
- Universal: acts on all quarks and all leptons
- Characterised by long lifetimes and small cross-sections
- At low energies, WI overwhelmed by SI and EM
  - Can be observed when SI and EM forbidden, or by very precise measurements
- Often involve neutrinos, e.g. $n \to p e^- \bar{\nu}_e$
- Charged current WI change quark flavour
  - Observed change in hadron flavour $D^+ \to \bar{K}^0 \pi^+$

$$(c\bar{d}) \to (s\bar{d})(u\bar{d})$$

- Can violate parity and charge conjugation invariance
  - At much lower level, also violates T and the combined symmetry of CP

W/Z discoveries at CERN: 1983

UA1 Experiment



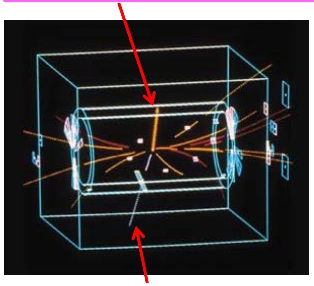
UA2 Experiment

UA1 event display (with hits)

UA1 W and Z events (leptonic decays)

UA1: W → eν

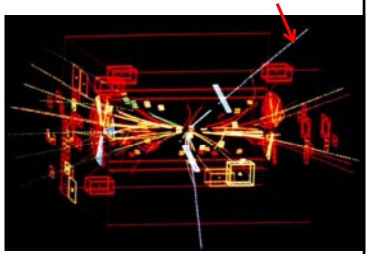
“missing” energy (from vector sum)



e

UA1: Z → e^+e^-

e

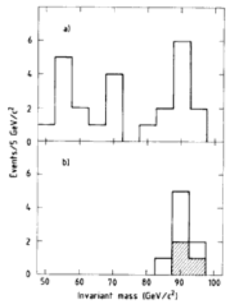


e

Early results...

UA2: Physics Letters B
Volume 129, Issues 1-2, 15 Sep.1983

EVIDENCE FOR $Z^0 \to e^+e^-$ AT THE CERN $\bar{p}p$ COLLIDER



UA1: Physics Letters B
Volume 122, Issues 1, 24 Feb. 1983

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

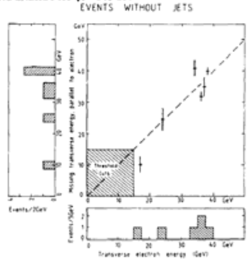
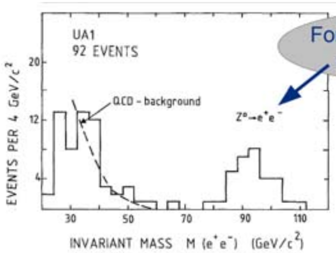
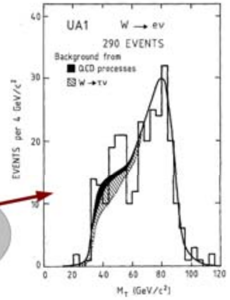


Fig. 8. The missing transverse energy component parallel to the electron, plotted versus the transverse electron energy for the final six electron events without jets (5 gondolas, 1 bouchon). All the events in the gondolas appear well above the threshold cuts used in the searches.

Later data



For Z, invariant mass of e^+e^- should be M_Z

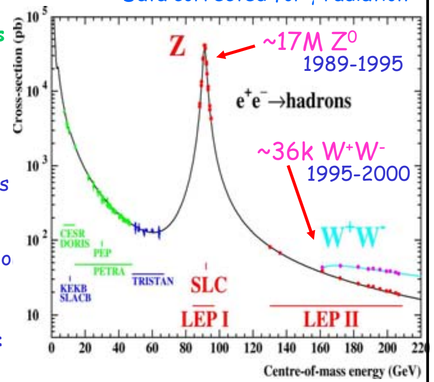


For W, have to infer ν momentum from overall momentum balance – and cannot measure component along beam axis at all

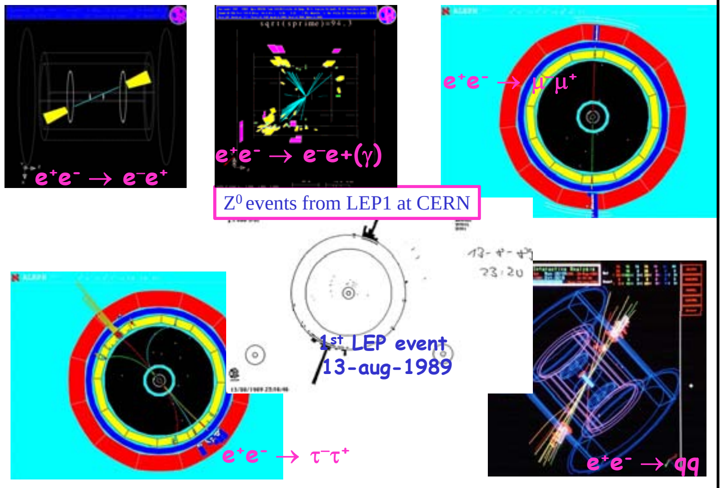
LEP: 1989-2001

- Precise measurements $\sqrt{s} \sim m_Z$
  - No. neutrinos
  - Couplings, mixing angles
- $f\bar{f}$ physics above m_Z
- W^+W^- production, properties
- Neutral boson pair productio
- SM interpretations of data:
  - Higgs mass

Data corrected for γ radiation

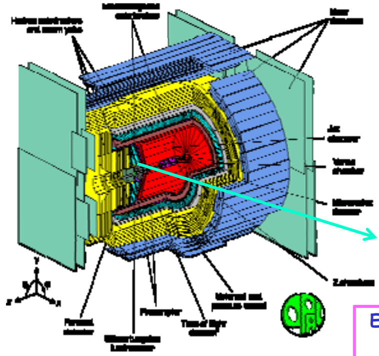


Example LEP (e+e- collider) events



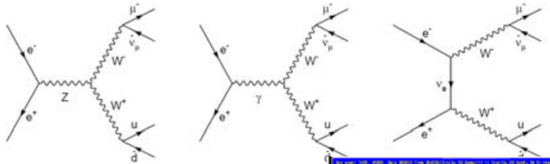
Anatomy of e^+e^- collider experiment

- Typical cylindrical construction
- Minimise dead areas, hermetic design
- Multiple measuring techniques, optimised for different particle species

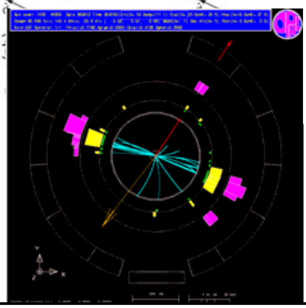


Electromagnetic calorimeter "endcap"
1132 lead glass blocks
Front face ~10x10cm^2
Weight ~25kg/block

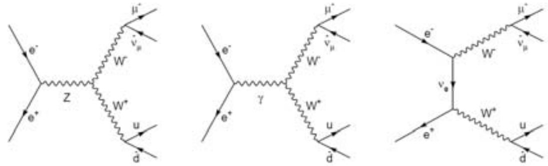
Weak Neutral Current



- At high energies (e.g. LEP2, 1996-2001), real W produced
- Three diagrams (Z, ν, γ propagators) required for finite cross-section at higher energies
- Have to include Z^0 (mass=91.187GeV)
- Essential to describe experimental data
- One example final state shown in Feynman diagrams
  - W^+ decays hadronically
  - W^- decays leptonically



Weak Neutral Current



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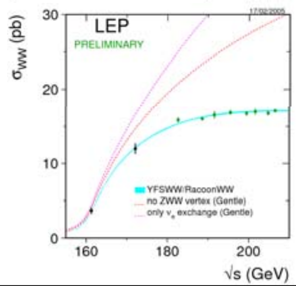
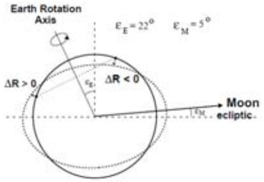


Earth Tides

Tide bulge of a celestial body of mass M at a distance d :

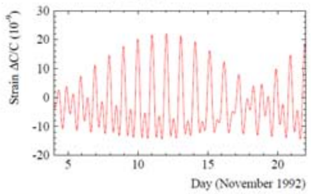
$$\Delta R \sim \frac{M}{2d^3}(3\cos^2\theta - 1)$$

θ = angle(vertical,the celestial body)



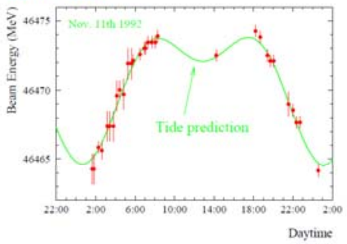
Earth tides :

- The Moon contributes 2/3, the Sun 1/3.
- NO 12 hour symmetry (direction of Earth rotation axis).
- Not resonance-driven (unlike Sea tides !).
- Accurate predictions.



Moonrise over LEP

Fall of 1992 : The historic tide experiment !



The total strain is 4 x 10^{-8} (ΔC = 1 mm)

Success in the Press !

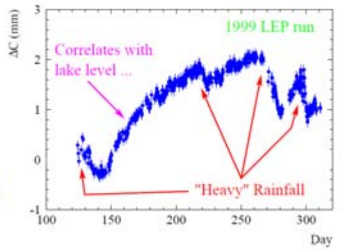
Underground Water

1993 : Unexpected energy "drifts" over a few weeks were traced to cyclic circumference changes of ~ 2 mm/year.

Driving "forces" :

- Underground water
  - → Rainfall
- Lake levels
- Other ?

Circumference change measured with the radial beam position.

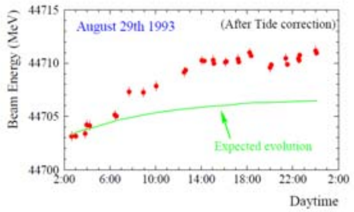


The Crack in the Model

Spring of 1994 : the beam energy model seemed to explain all observed sources of energy fluctuations...

EX CEPT :

An unexplained energy increase of 5 MeV was observed in ONE experiment.



It will remain unexplained for two years...

The Field Ghost

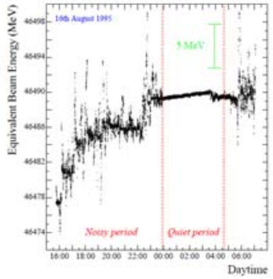
Summer 1995 : the first field measurements inside ring dipoles.

The data showed (unexpected) :

- Short term fluctuations
- Long term increase (hysteresis)
- ➡ Energy increase of ~ 5 MeV over a LEP fill !
- Quiet periods in the night !

Human activity !

But which one ??

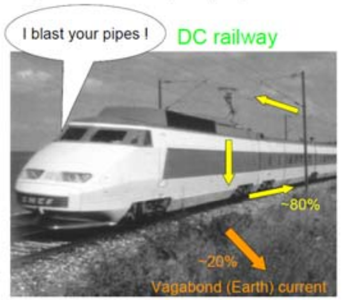


Pipebusters

The explanation was given by the Swiss electricity company EOS...

Vagabond currents from trains and subways

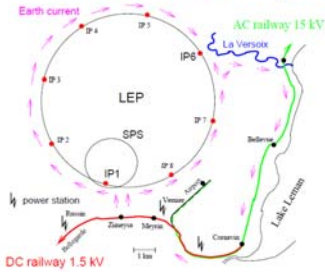
Source of electrical noise and corrosion (first discussed in ...189 8 !)



Vagabonding Currents

LEP is affected by the French DC railway line Geneva-Bellegarde

➡ A DC current of 1 A is flowing on the LEP vacuum chamber.



Entrance/exit points :

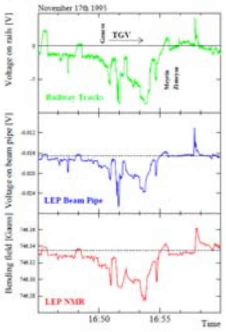
- Injection lines (Point 1)
- Point 6 (Versoix river)

TGV for Paris

November 1995 : Measurements of

- The current on the railway tracks
- The current on the vacuum chamber
- The dipole field in a magnet

correlate perfectly !

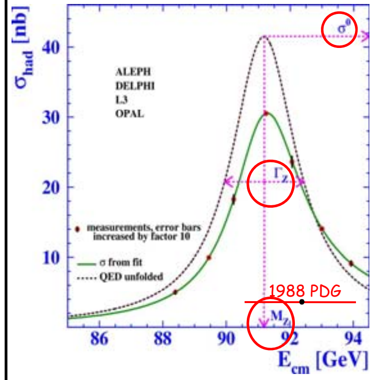


Because energy calibrations were usually performed :

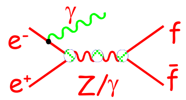
- At the end of fills (saturation)
- During nights (no trains !)

we "missed" the trains for many years !

LEP Lineshape: 1989+…final results



- 3 parameters: m_Z, Γ_Z, σ^0_{had}
- Observe



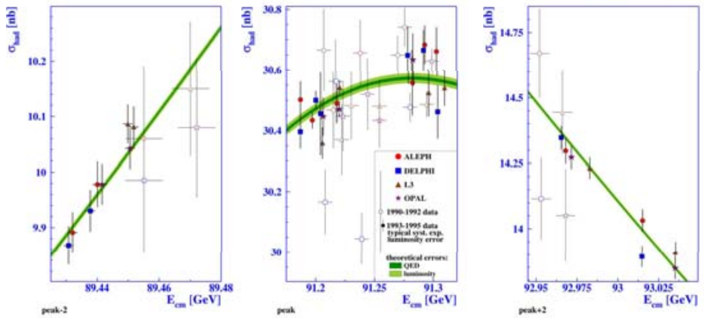
- …EW radiative corrections absorbed in effective couplings
- Deconvolve to Born cross-section
- Obtain

m_Z = 91,187.5 ± 2.1 MeV
Γ_Z = 2,495.2 ± 2.3 MeV
σ^0_{had} = 41.540 ± 0.037 nb

Combined measurements, LepI sample

Final LEPI "Z^0 lineshape" measurements
See Physics Reports,Vol. 427, Nos. 5-6, May 2006

Details of LepI Cross-Section Data



All 4 LEP experiments and years of LepI

No. of Neutrino Generations

- "Invisible width", $\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - 3\,\Gamma_\ell$
- No. of generations = Γ_{inv} / Γ_ν^{SM} SM: $\Gamma_\nu^{SM} = \frac{G_F m_Z^3}{6\pi\sqrt{2}}(g^2_{v,\nu} + g^2_{a,\nu}) \approx$ 166 MeV
  - Measure Γ_{inv}
- Direct: measure $\sigma(e^+e^- \to \nu\bar{\nu}\gamma)$ soft γ + nothing else…challenging!
- Indirect: measure m_Z, Γ_Z, R_ℓ, σ^0_{had} $\sigma^0_{had} \equiv \frac{12\pi\Gamma_e\Gamma_{had}}{(m_Z\Gamma_Z)^2}$

$$\Gamma_{inv} / \Gamma_\nu^{SM} = \left(\frac{12\pi}{m_Z^2\sigma^0_{had}}\right)^{\frac{1}{2}} - R_\ell - 3$$

$\Rightarrow$ N_ν = 2.9841 ± 0.0083 for $m_\nu \le \frac{1}{2} m_Z$ ~ 45 GeV

- For N_ν = 3, width from new Z decay modes = -2.7 ± 1.6 MeV
- Still room for heavy or sterile neutrinos

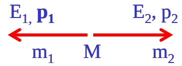
Helicity for massive fermions

- W couples preferentially to LH fermions (RH anti-fermions)

$$\frac{W-RH\ \ fermion}{W-LH\ \ fermion}=\left(\frac{m_{fermion}}{E_{fermion}}\right)^2=\frac{1}{\gamma^2_{fermion}}$$

- "Wrong" helicity states strongly suppressed
- Suppression greater for lighter fermions (of a given energy)
- Example: charged pion decay

Calculation of helicity suppression



- π^+ decays to particles 1, 2
- $E_1+E_2=M$
- $|p_1|=|p_2|$
- Use $E^2=p^2+m^2$, solve for E_1, find
  - $E_1=(M^2+m_1^2-m_2^2)/2M$
- Consider particle 1 as either μ^+ or e^+, particle 2 as ν_μ, ν_e
- Masses (MeV/c^2) : π^+=139.6, μ^+=105.7, e^+=0.511

Particle 1	Energy (MeV)	Lorentz γ
μ	109.8	1.039
e	69.8	139.6

- Relative suppression= $(\gamma_\mu/\gamma_e)^2$=18000 (expt. ~10^{-4})