Building the Standard Model

- **Part 1: Electroweak Physics**
  - Neutrino, W, Z, Higgs …
  - Electromagnetic-Weak Unification

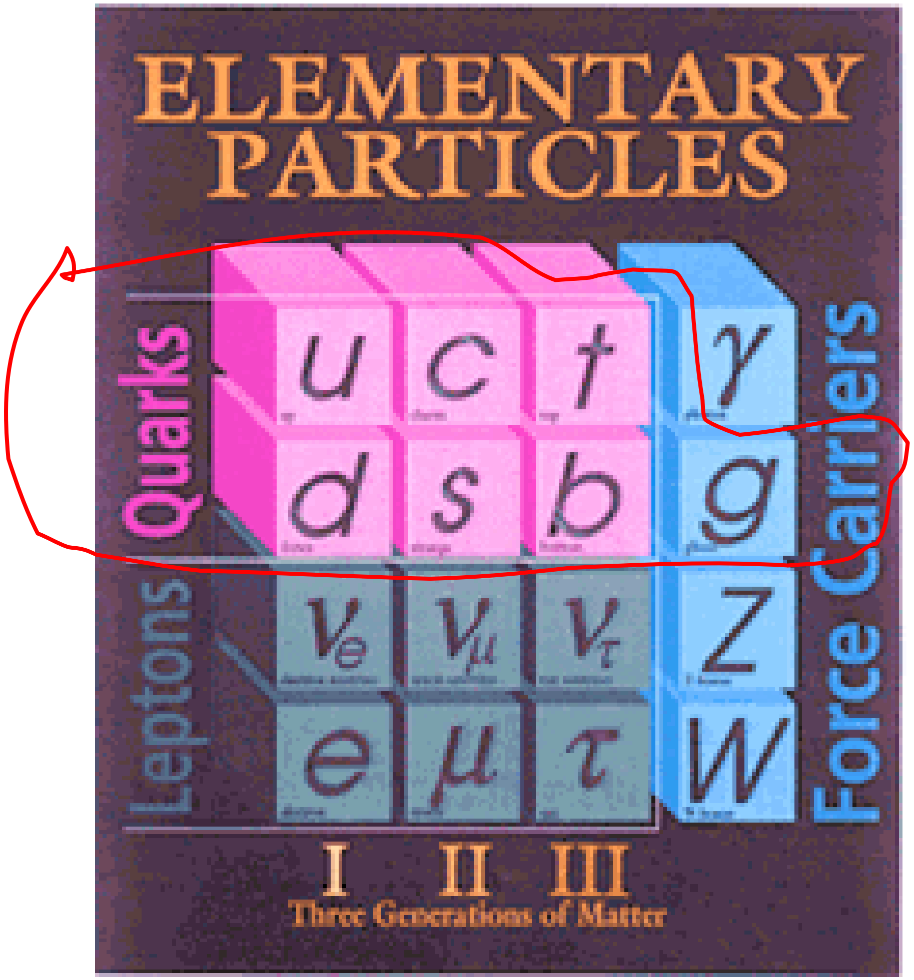
- **Part 2: Quantum Chromodynamics**
  - Quarks, Gluons and Colour
  - Running coupling constant α_s

Change of Topic: QCD

Quantum Chromodynamics

- Quantum Chromodynamics (QCD) is the *gauge theory* of the *strong interaction* (formulated ~ 1973)
- It is quite *similar* to the gauge theory of the *EW interaction* but there are some important *differences*
  - the coupling strength is ~ 15 x larger $\alpha_s / \alpha \sim 0.12 \times 137$
  - *higher order* process are much more important!
  - a new *type of charge* called *colour* is carried by the particles involved in this force - the *quarks* and the *gluons* (the *exchanged* particles of the strong interaction) - but not W,Z,γ and leptons
  - there are 8 gluons (c.f. only 4 force carriers in the EW theory)
  - QCD exhibits *confinement* - the strong force *increases* as the distance between quarks *increases* - the EW theory does not
    - consequently, *free quarks* or *gluons* are never observed
    - they always undergo *hadronisation* - i.e. combine with other quarks and gluons to form *bound states* - namely, *hadrons*

QCD



ELEMENTARY PARTICLES
Quarks
u c t
d s b
Leptons
ν_e ν_μ ν_τ
e μ τ
Force Carriers
γ g Z W
I II III
Three Generations of Matter

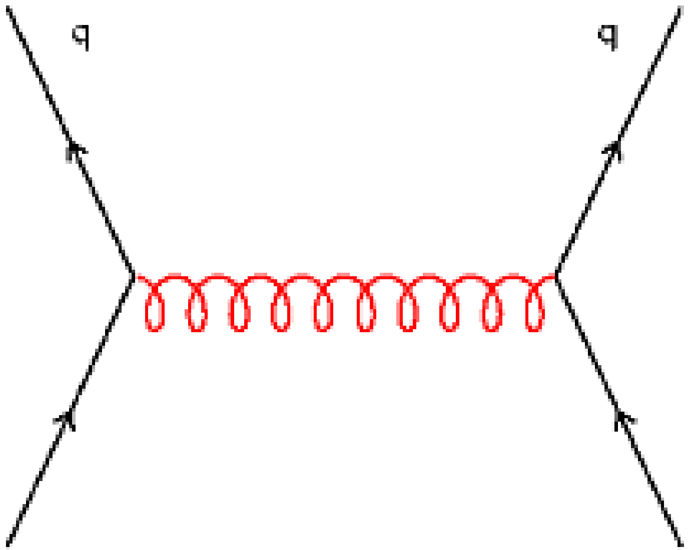
A Century of *Strong* Nobel Prizes

• Discovery of the Neutron (1932)	Chadwick 1935
• Pion Exchange Theory (1935)	Yukawa
• Discovery of the Pion (1947)	Powell
• Discovery of the Antiproton (1955)	Segr🕗
• Proton Form Factor (1959)	Hofstadter
• The Quark Model (1964)	Gell-Mann 1969
• Discovery of Quarks (1968)	Friedman/Kendall/Taylor 1990
• Discovery of Charm (1976)	Richter and Ting 1976
• Discovery of τ-Lepton/3rd Family (1976)	Perl 1995
• Asymptotic Freedom (1973)	Gross/Politzer/Wilczek

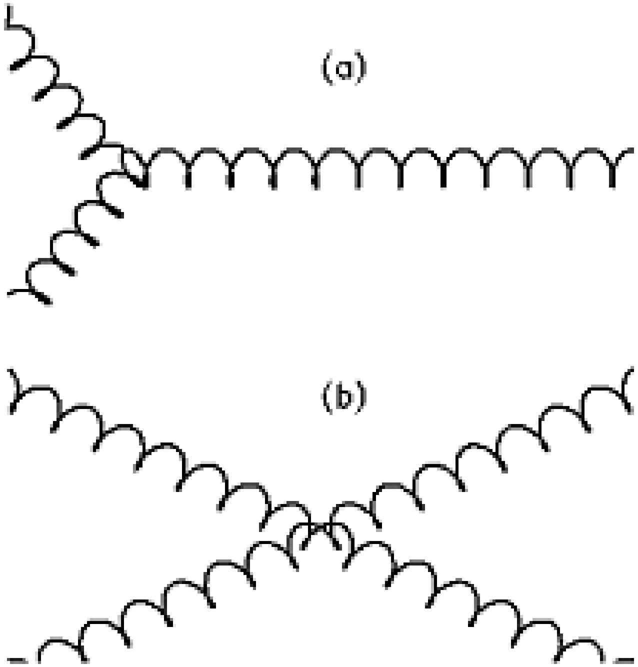
- no Prize for top quark discovery (too many physicists involved!)

The Running Coupling Constant

Feynman Diagram of Quark–Quark Scattering



Gluon Interactions

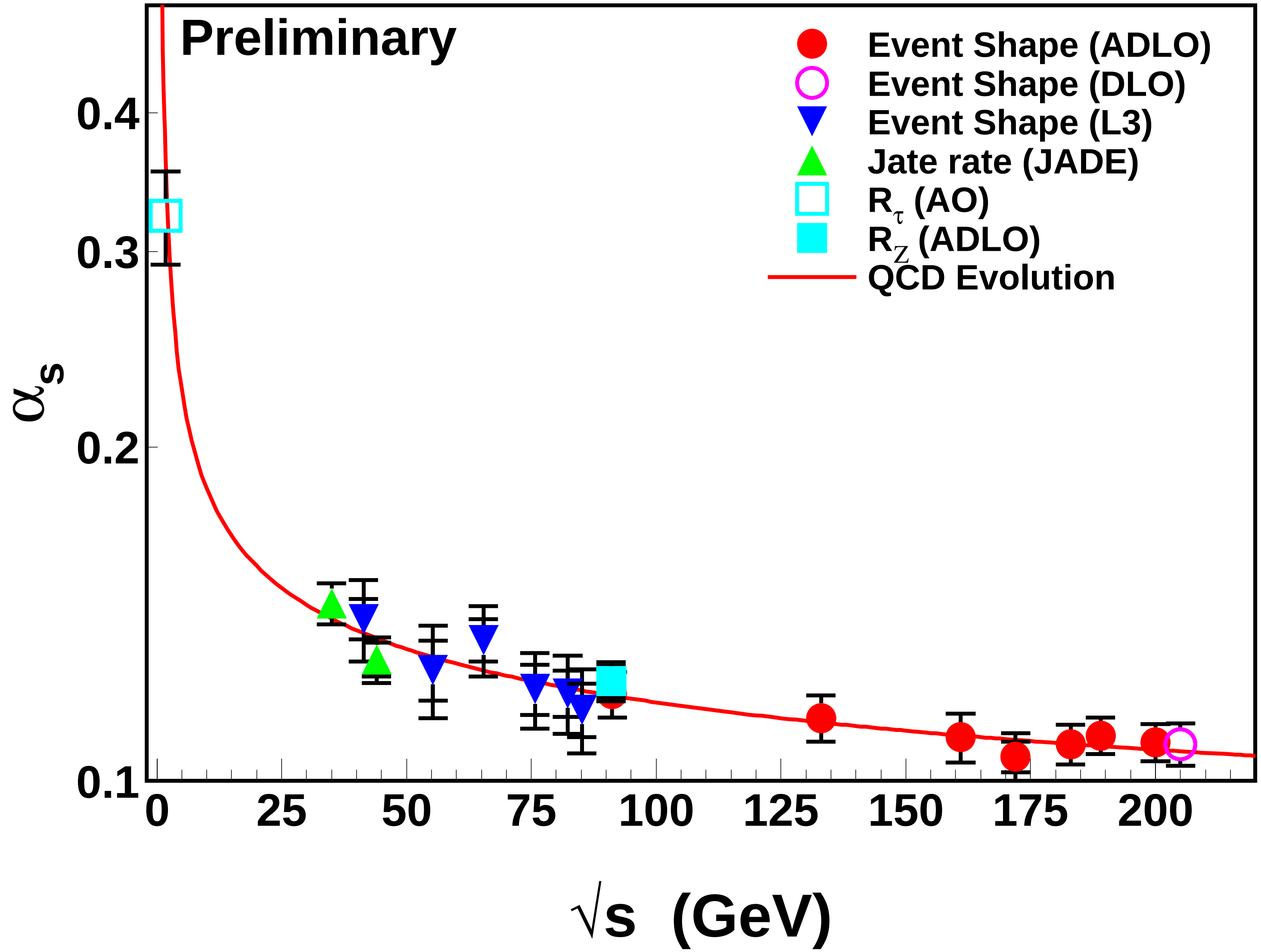


The Running Coupling Constant

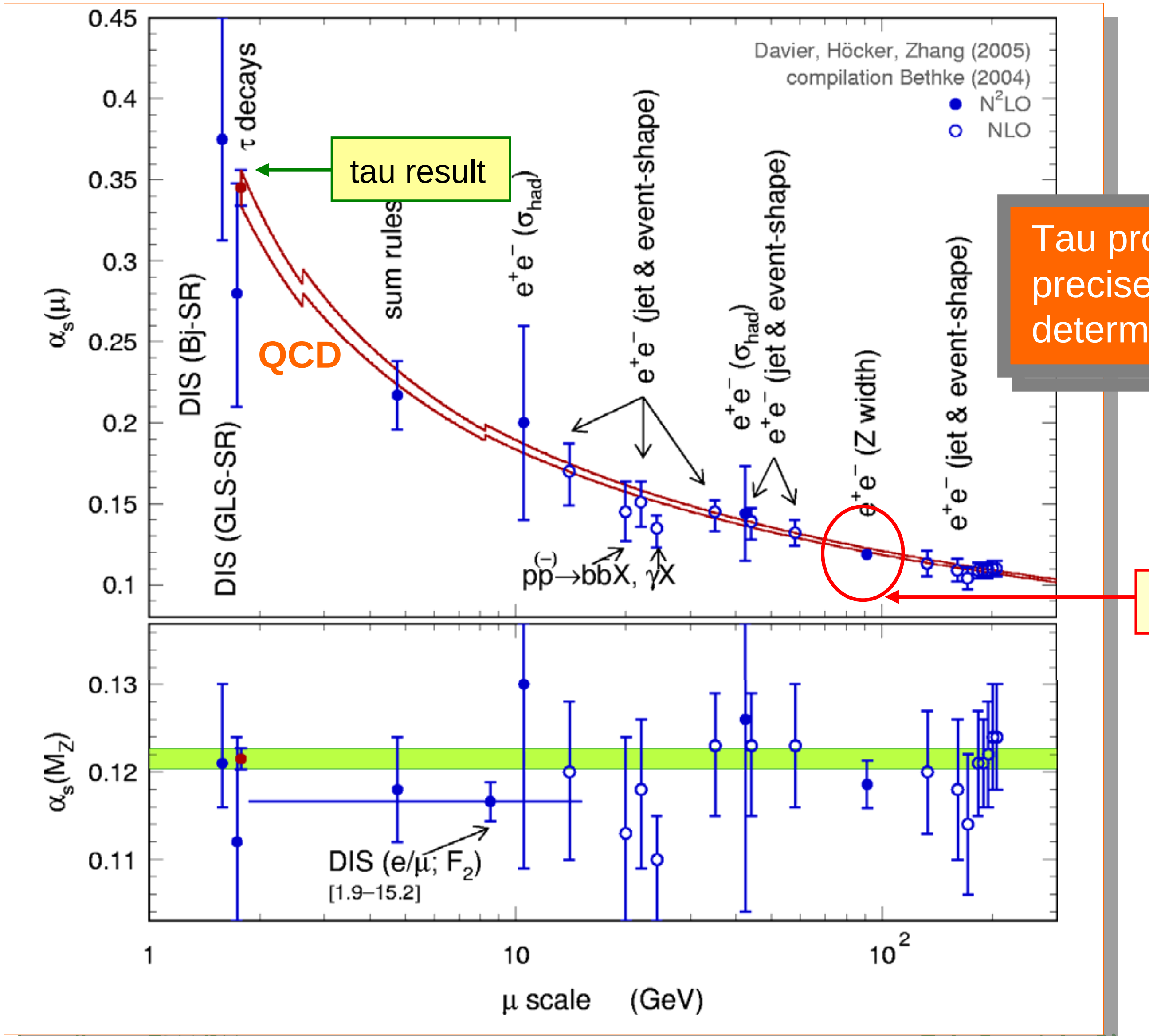
- in QCD, screening of a quark's colour charge also occurs as a result of the creation of *virtual* quark-antiquark pairs due to fluctuations in the *gluonic* fields of the vacuum
- … however, the fluctuations in the gluonic fields of the vacuum also produce additional gluons (because of gluon self-coupling) and these have the opposite effect - they produce *antiscreening* of the bare quark's colour charge and this is the dominant effect
- consequently, at short distances the force becomes *weaker* while at long distances it becomes *stronger* !

- **This variation of the strong force with distance is absorbed into the QCD *running* coupling constant which varies (or "runs") with Q^2**
  - $\alpha_s = 12\pi/(33 - 2N_f) \log_e(Q^2/\Lambda^2)$
    - N_f is # of quark flavours and $\Lambda = 0.21 \pm 0.02$ GeV (expt.)
  - α_s has now been extracted from a wide range of measurements over a large enough range of Q^2 to demonstrate running ...

The Running Coupling Constant



α_s running II

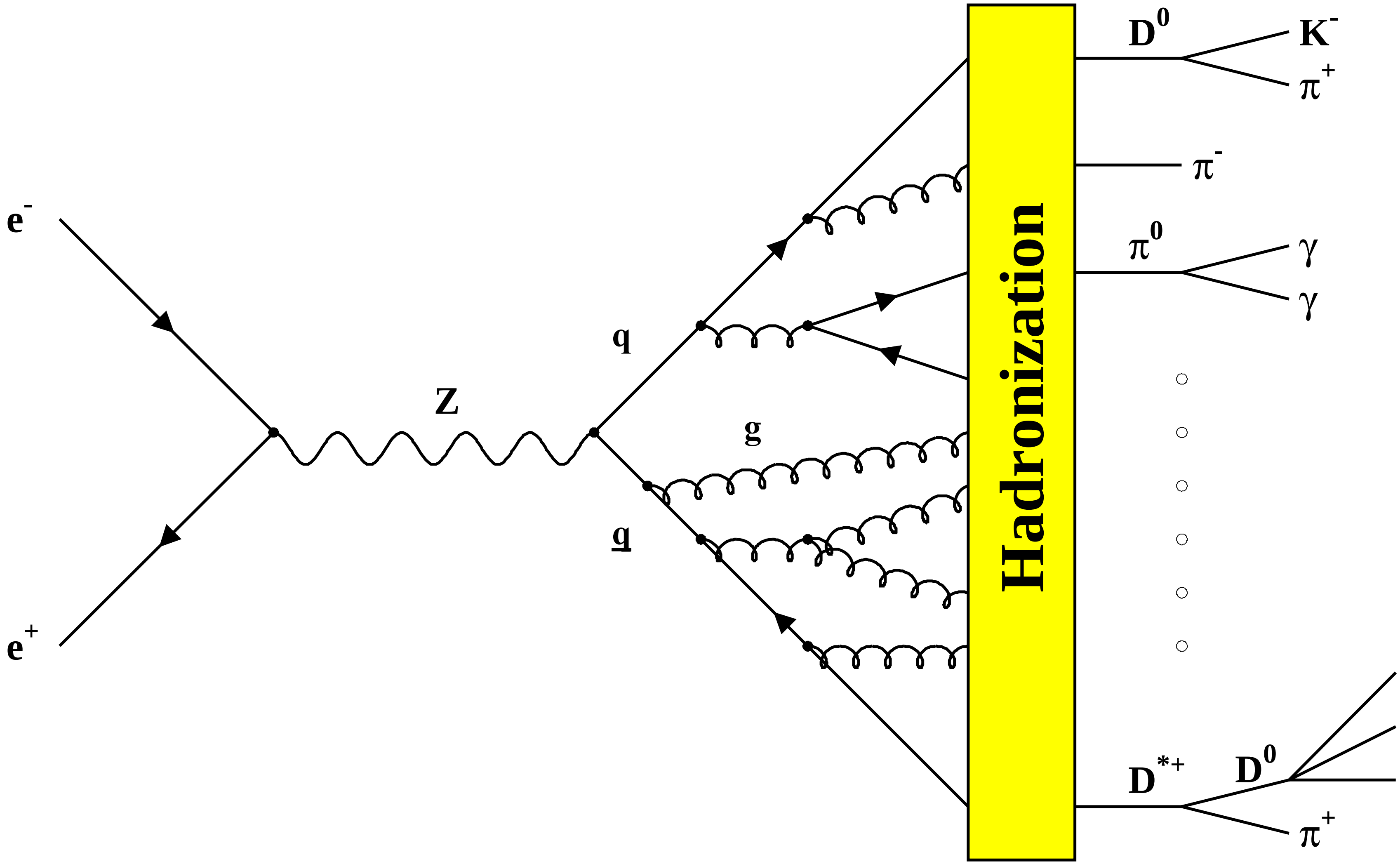


Tau provides most precise $\alpha_s(M_Z^2)$ determination

Hadronisation

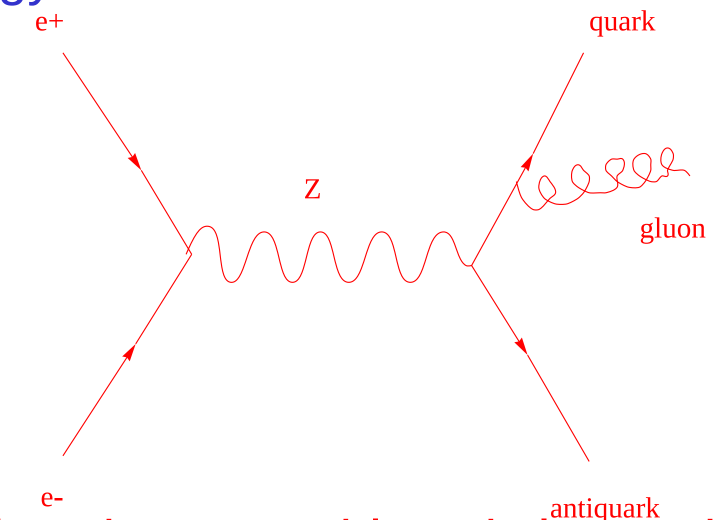
- Due to *confinement*, when the quarks produced in $e^+e^- \rightarrow q\bar{q}$ move apart the force F between them grows with separation ...
  - Energy = $\int F.dx$ and so, as the quarks move apart, the potential energy stored in the *colour field* between them also grows …
  - … until the potential energy > rest mass energy of a $q\bar{q}$ pair …
  - … and a new $q\bar{q}$ pair is created between the original pair
- This process is repeated numerous times until there is insufficient energy to make any more $q\bar{q}$ pairs …
  - … the quarks and antiquarks combine with neighbours into colour singlet bound states - *hadrons*
- The original $q\bar{q}$ (or secondary $q\bar{q}$) can radiate gluons which can split into further $q\bar{q}$ or gg pairs (via the ggg vertex) … this phase is called a *parton shower* and precedes the *hadronisation* phase
- There is no unambiguous theory of hadronisation - but several successful models exist - the large value of αs precludes a perturbation theory approach to calculations

Hadronisation



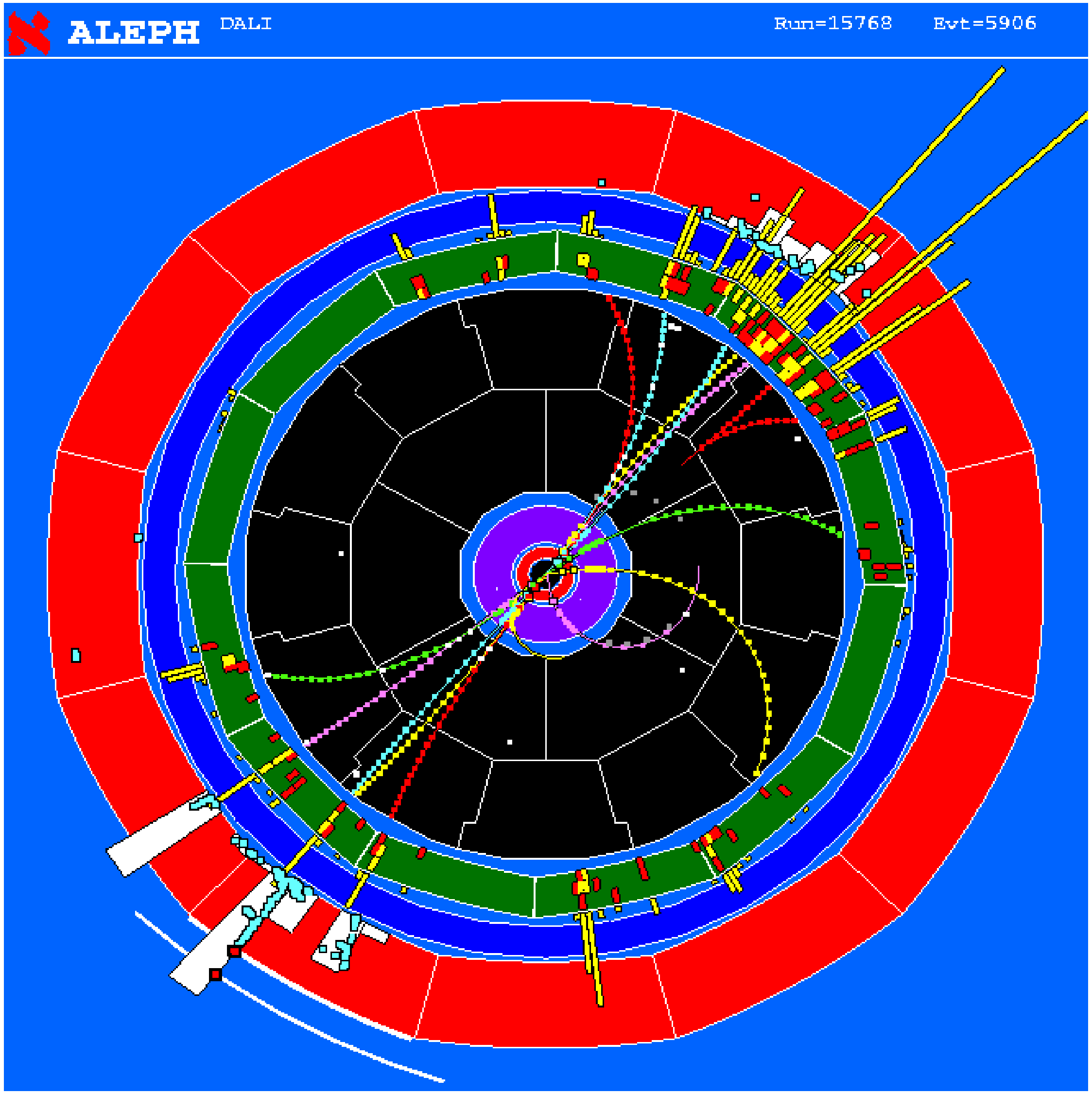
Observation of Gluons

- Gluon *bremsstrahlung* from *either* quark in an e+e- → q$\bar{q}$ annihilation event results in 3 *partons* in the final state
- The partons then *hadronise* into jets of hadrons resulting in a distinctive 3-jet final state topology

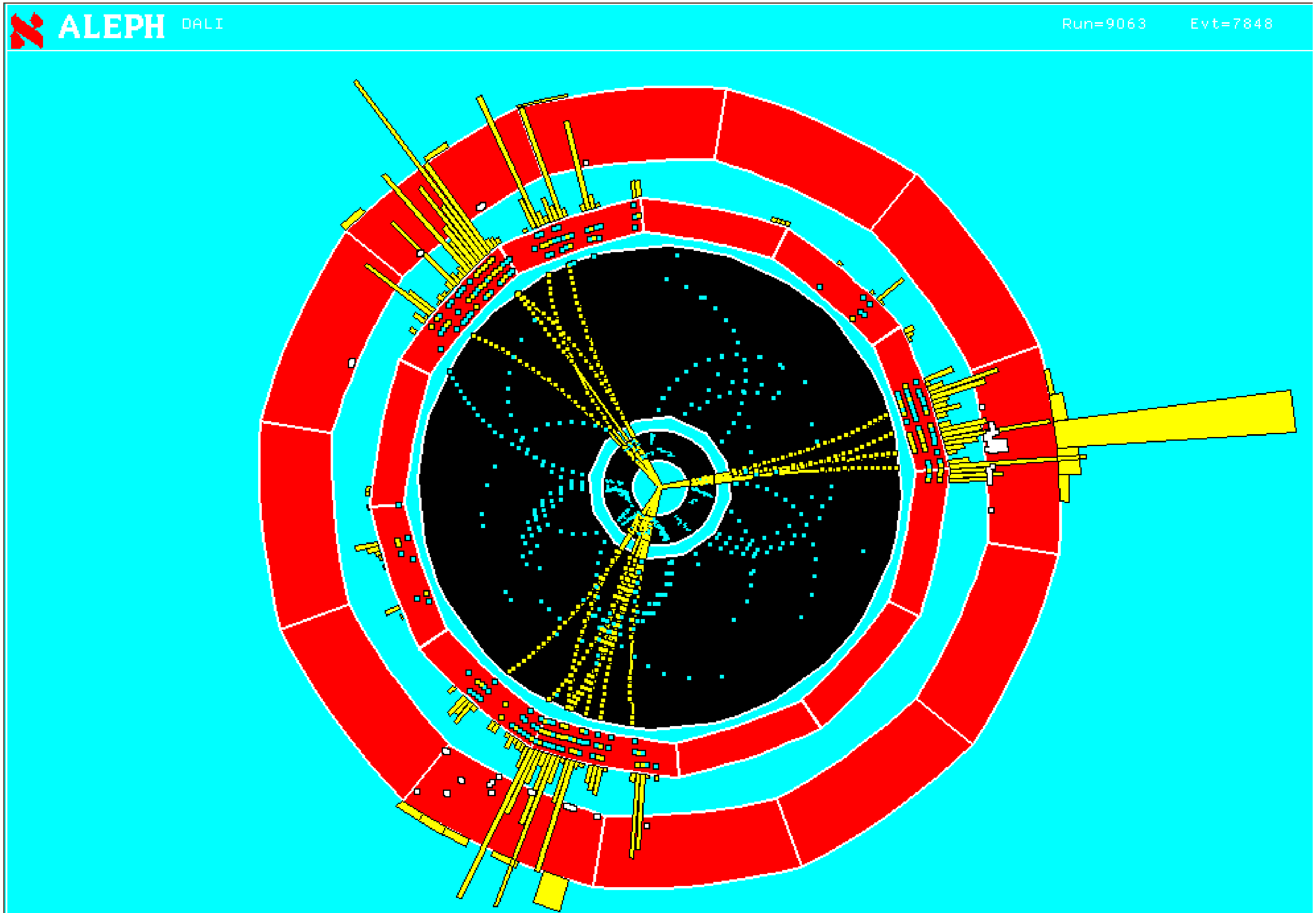


- probability for *gluon* bremsstrahlung is larger than *photon* bremsstrahlung by a factor $\alpha_s / \alpha = 0.12 / (1/137) \approx 15$
- in some cases a large amount of the initial quark energy can be transferred to the gluon resulting in 3 widely separated jets

e+e- → q$\bar{q}$ → 2 jets



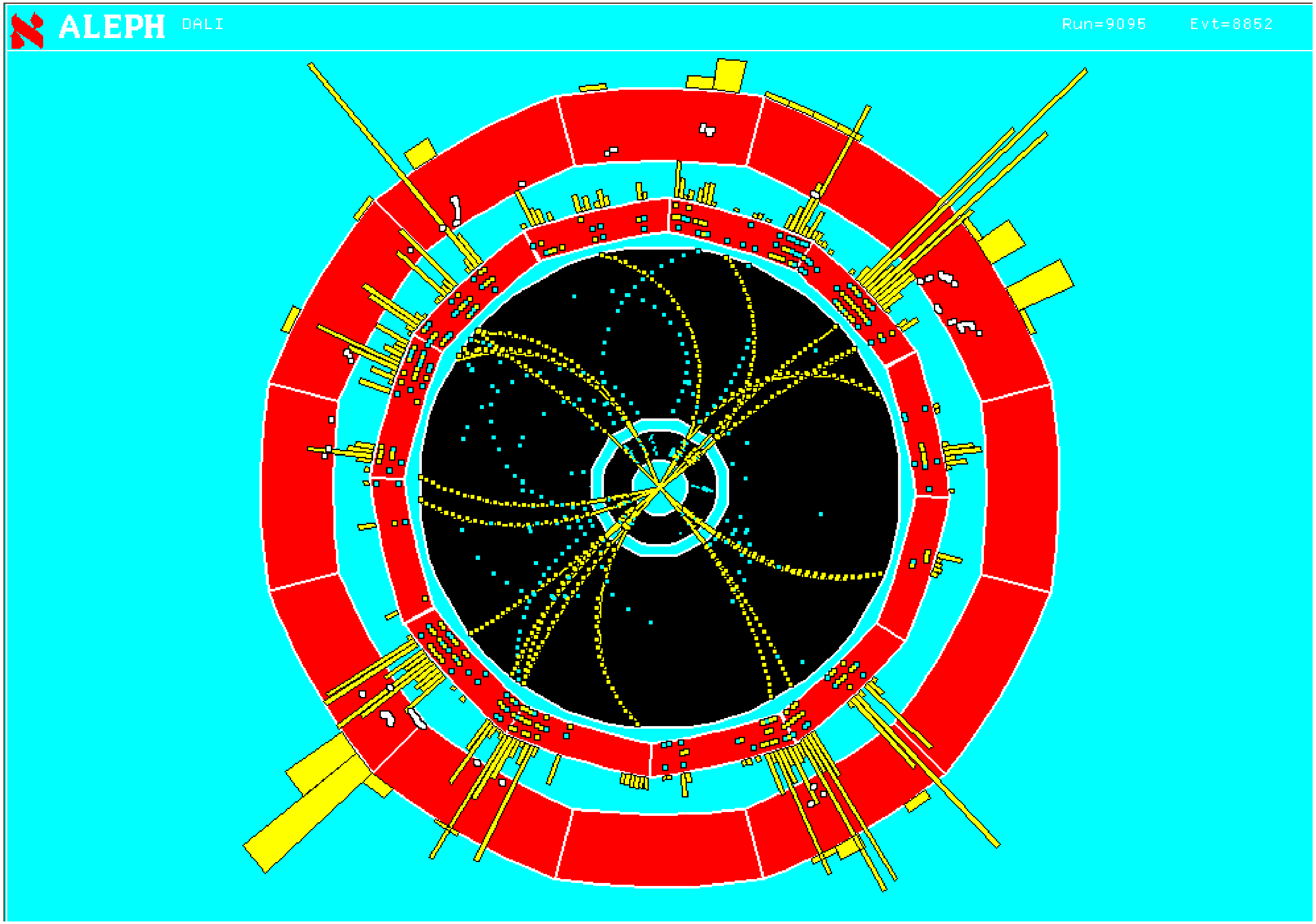
e+e- → qq̄g → 3 jets



Observation of Gluons

- Gluon jets were first observed in 1979 at the PETRA e+e- collider (Hamburg) operating at $E_{cm} \sim 35$ GeV
  - at much lower energy e+e- colliders the energy was too low to produce spatially separated jets
  - angular distribution of jets confirmed that gluon is Spin-1
- With large data samples of e+e- $\rightarrow q\bar{q}$ events the probability for *double gluon bremstrahlug* cannot be neglected - this results in a *4 -jet* final state topology
  - naïve estimate suggests: 4-jet rate/3-jet rate ~ $\alpha_s^2/\alpha_s \sim 0.12$
  - the triple gluon vertex (a prediction of QCD) contributes to the rate for 4-jet events and its effect has been verifed at LEP
    - in this case *single gluon radiation* from a quark is followed by the *splitting* of the gluon into a pair of gluons $\rightarrow$ 2 jets
- Jets of hadrons from quarks and gluons are very similar and quite hard to distinguish

e+e- → q$\underline{q}$gg → 4 jets



Tests of QCD

- QCD is not nearly as precisely tested as QED or the Electroweak Theory: e.g. error on $\alpha_s(M_Z^2) \sim \pm 2\%$
  - this is because of the largeness of α_s and hence the *non-perturbative* nature of the theory
    - which means that higher order diagrams cannot be ignored
  - and because uncertainties in the *hadronisation* process mask the underlying *parton shower* phase of an interaction
- Nevertheless, substantial progress has been made at LEP and hadron colliders in testing a wide range of detailed predictions of QCD
- Several important predictions remain to be confirmed
  - the existence of the *quark- gluon plasma* phase of matter
  - the existence of *glueballs* (quark-free hadrons, i.e. gluonic bound states) with *exotic* quantum numbers (not permitted for baryons or mesons)

How to construct a Gauge Theory?

Out of the “Handbook for Particle Physics Theory …”

- ***How to construct a Gauge Theory?***
  - Choose the gauge group G with NG generators
  - Add NG vector fields (gauge bosons) in a specific representation of the gauge group
  - Choose the representation for the matter particles (elementary particles)
  - Add scalar fields to give mass to (some) vector bosons
  - Define the covariant derivative and write the most general Lagrangian, invariant und G, which couples all fields
  - Shift the scalar fields in such a way that the minimum of the potential is zero
  - Apply the usual techniques of quantum field theory to verify the renormalizability and to make predictions

  - **Check with nature if the model has anything to do with reality**
  - ***If not, try again and restart from the beginning …***

Precision SM Tests …

A clear domain of experiment ….

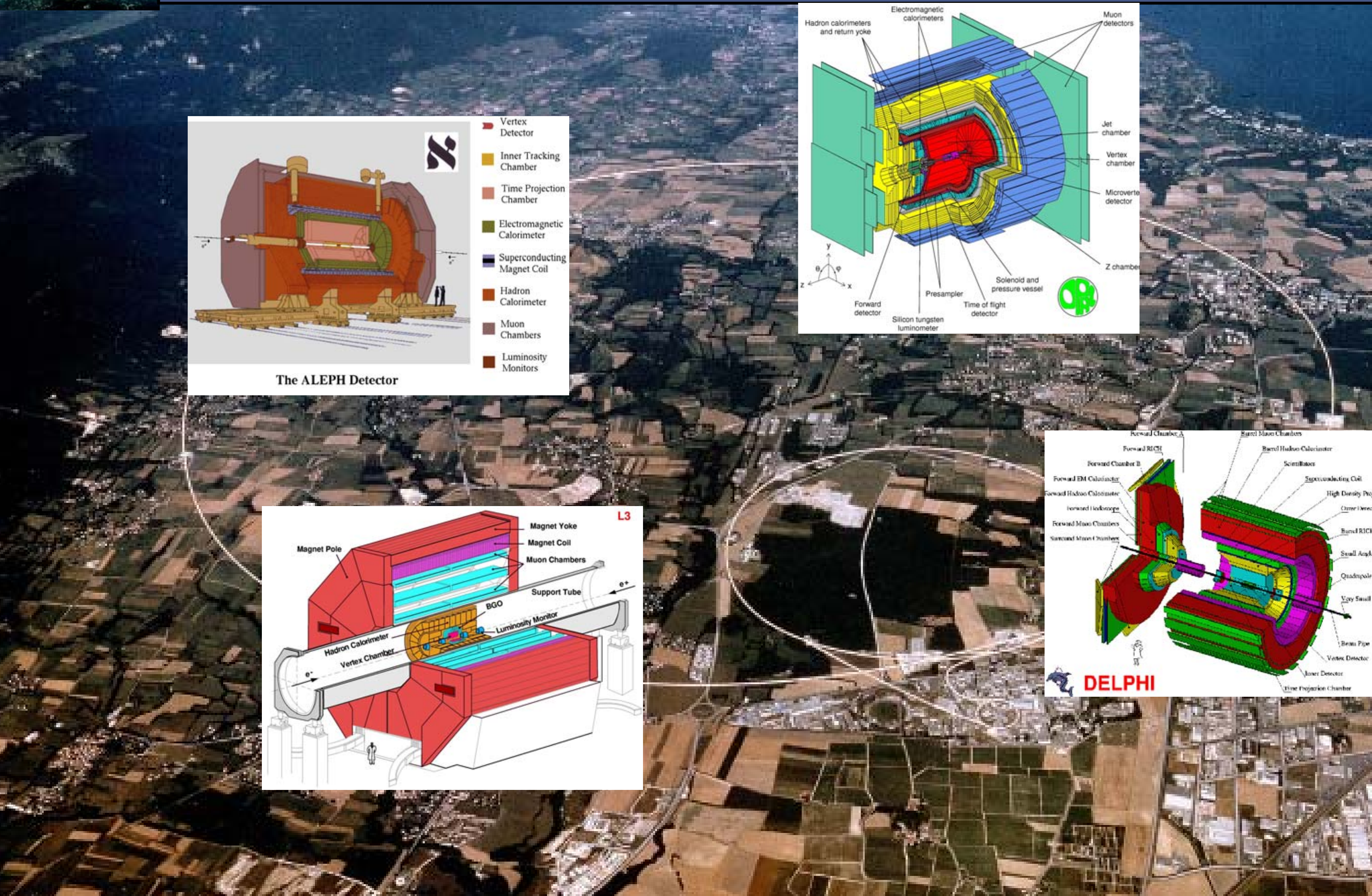
LEP and SLD

- Conventional collider e^+e^- ring;
- Energy upgradeable;
- Energy measurable;
- Four detectors (A,L,D,O);
- Large luminosity;

COMPLEMENTARY to LEP

- "Linear" e^+e^- Collider (with arcs);
- Electron polarized;
- Small beam transverse dimensions

LEP and its four Detectors



"LEP in a Nutshell"

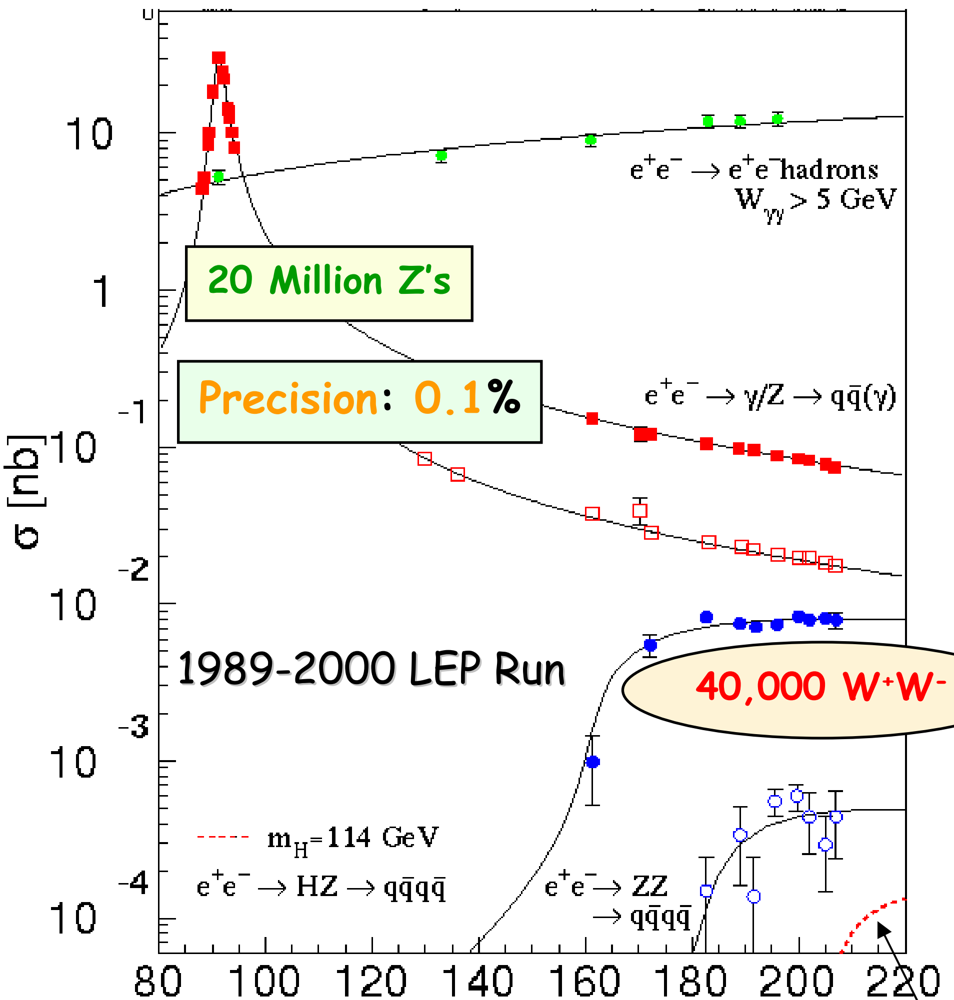
- ALEPH DELPHI L3 OPAL

- LEP I (1989 – 1995) $\sqrt{s} \approx m_Z$
  - Z boson physics
- LEP II (1995 – 2000) 130 GeV $\leq \sqrt{s} \leq$ 208 GeV
  - W boson physics
  - searches
- High luminosity
  $\approx$ 1 fb^{-1}/experiment collected
  $\Rightarrow$ > $4 \cdot 10^6$ Z decays & $\approx$ 10 k WW events
- Precise beam energy calibration:
  < ± 1 MeV (LEP I) $\approx$ ± 15 MeV (LEP II)
- To date $\approx$ 1300 publications by the four experiments

LEP and SLD

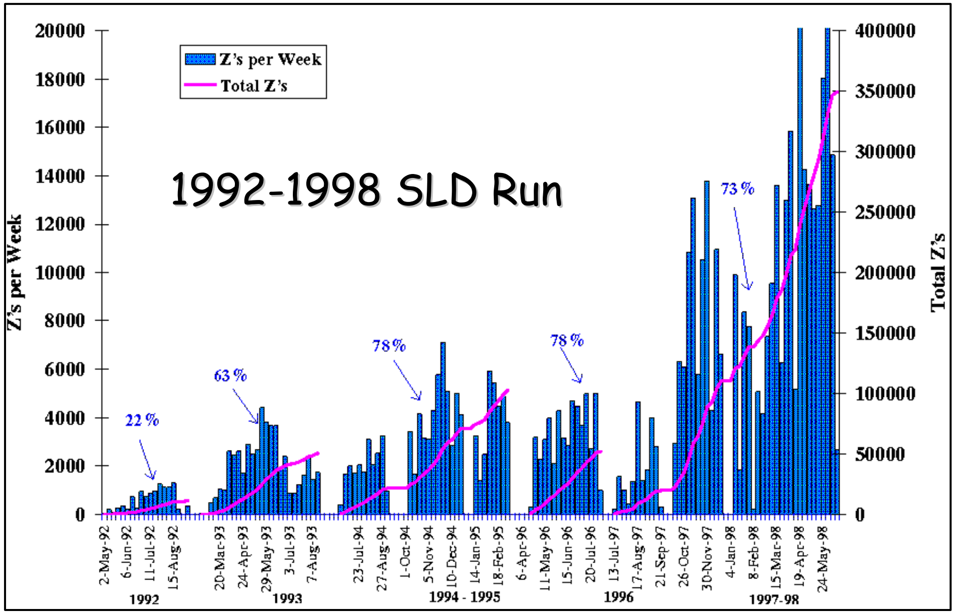
Total Luminosity: 1000 pb^{-1}

550,000 Z decays



Energy: 88 → 209.2 GeV

A few Higgses?



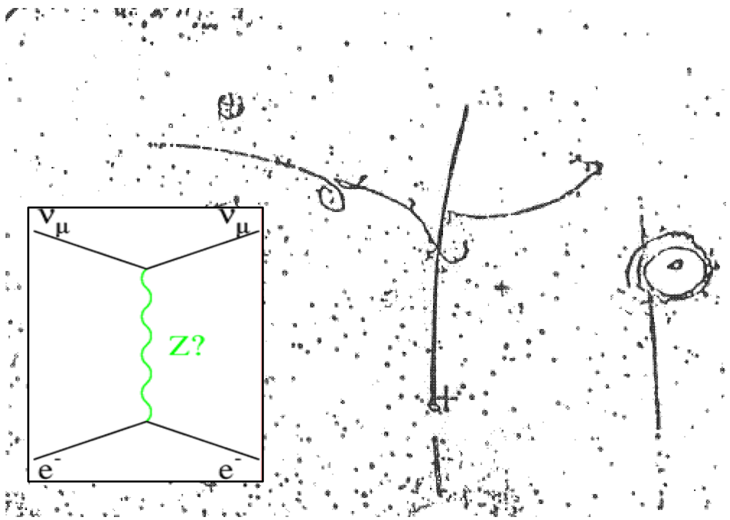
Average e^- Polarization: 73%

- Small transverse beam sizes;
- Small beam pipe;

Again some History

1967: Electroweak unification, with W, Z and H (Glashow, Weinberg, Salam);

1973: Discovery of neutral currents in $\nu_\mu e$ scattering (Gargamelle, CERN)

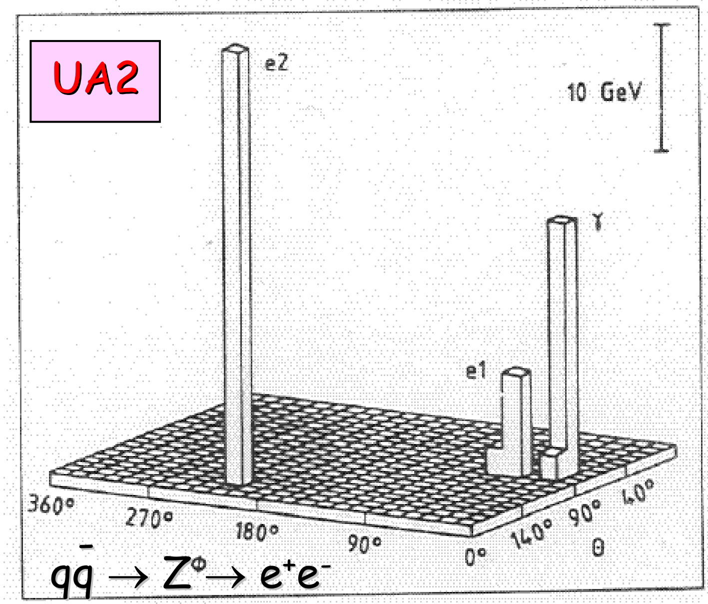


1974: Complete formulation of the standard model (Illiopoulos)

1981: The CERN SpS becomes a $p\bar{p}$ collider; LEP and SLC approved before W/Z discovery;

1983: W and Z discovery (UA1, UA2); LEP and SLC construction start;

First Z detected in the world:



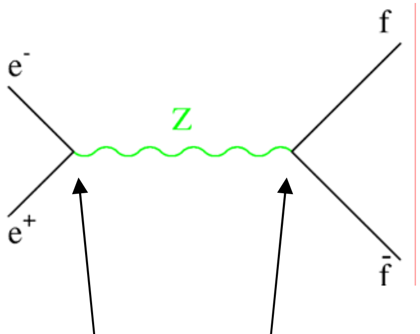
1989: First collisions in LEP and SLC; Precision tests of the SM (m_{top});

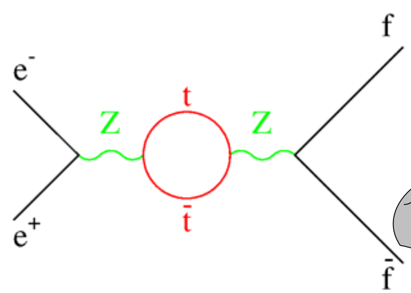
1995: Discovery of the top (FNAL); Precision tests of the SM (m_H);

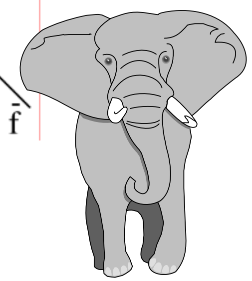
LEP: Luminosity, Energy, Precision

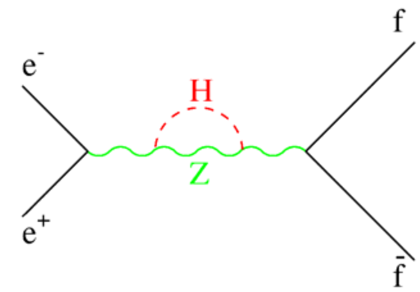
Why is Precision Needed?

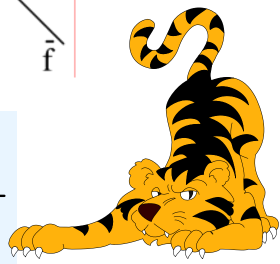
Electroweak Observables (i.e., related to W and Z) sensitive to vacuum polarization effects:











L Couplings (v+a)
≠
R Couplings (v-a)

$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$

$$-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}$$

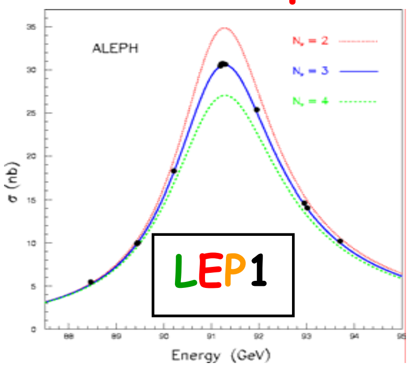
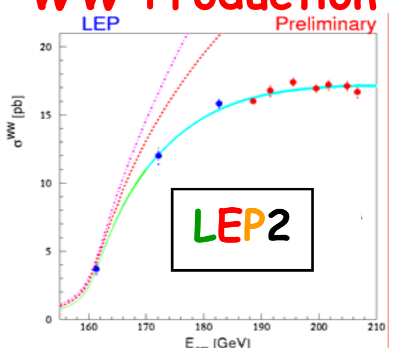
0.1% Precision needed!

Tree-Level →	Corrected
$a_0 = \pm 1/2$	$a = a_0(1+\Delta\rho)$
$v_0 = a_0(1-4\lvert Q\rvert \sin^2\theta_W)$	$v = a(1-4\lvert Q\rvert \sin^2\theta_W^{eff})$
$\sin^2\theta_W = 1 - m_W^2/m_Z^2$ ($m_W = m_Z \cos\theta_W$)	$\sin^2\theta_W^{eff} = 1 - m_W^2/m_Z^2(1+\Delta\rho)$
$\alpha(0) = 1/137.0359895(61)$	$\alpha(m_Z) = 1/128.968(27)$

with
$$\Delta\rho = \frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} - \frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2} + \cdots$$

- Determine $\Delta\rho$ and $\sin^2\theta_W$ from LEP/SLD data;
- Predict m_{top} and m_W;
- Compare with direct measurements;
- Predict m_H;
- Compare with direct measurements.

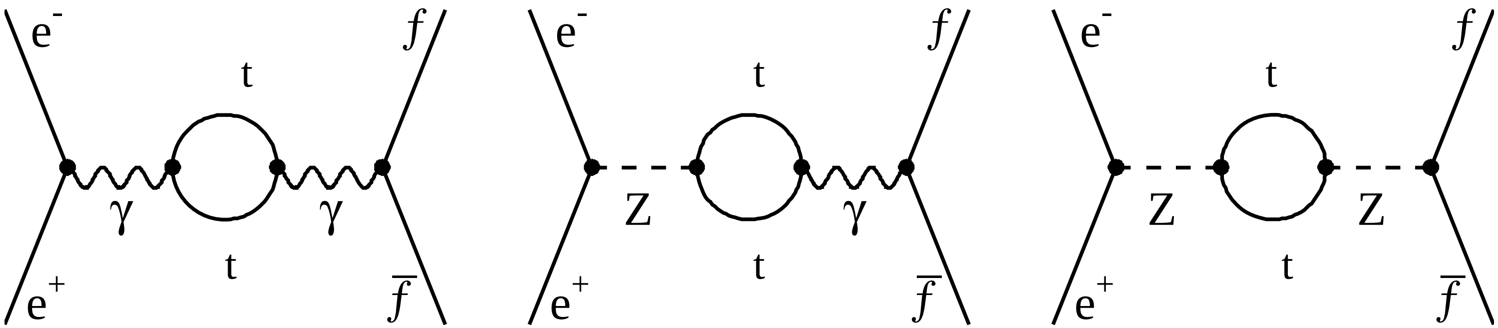
Precision Electroweak Observables (I)

Experiment	Observable	Main technology	Precision	Physics output
Z Lineshape 	m_Z Γ_Z σ_{peak} $R_\ell = \frac{\Gamma_{hadron}}{\Gamma_{lepton}}$	Absolute beam energy (+ ISR QED calculations) Relative beam energy (+ ISR …) Absolute luminosity Final state identification	2.10^{-5} 10^{-3} 10^{-3} $1.2.10^{-3}$	Input! $\Delta\rho, \alpha_s, N_\nu$ N_ν α_s, m_{top}
WW Production 	m_W	-Absolute *Beam energy *Luminosity -Final state Identification	5.10^{-4}	m_H vs m_{top}
Heavy Flavour Rates 	$R_b = \frac{\Gamma_{b\bar{b}}}{\Gamma_{hadron}}$ $R_\ell = \frac{\Gamma_{c\bar{c}}}{\Gamma_{hadron}}$	b-tagging (Vertex detector) c-tagging (mostly SLD)	3.10^{-3} 2%	m_{top}

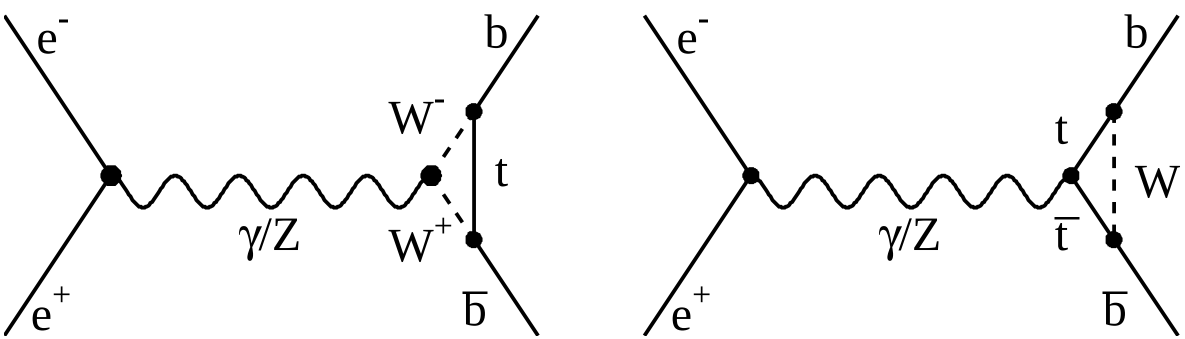
Higher Orders and the Top Quark

- Higher order Feynman diagrams involving the *top quark* produce small (~1%) shifts in V/A couplings which depend on m_{top} and (less strongly) on M_{Higgs}

All final states



b$\underline{\text{b}}$ final state only

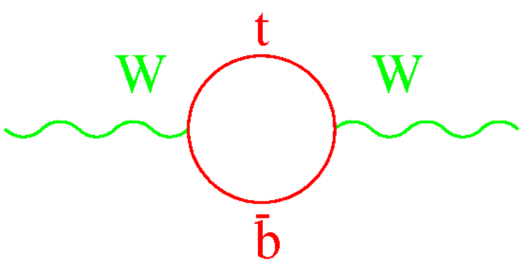


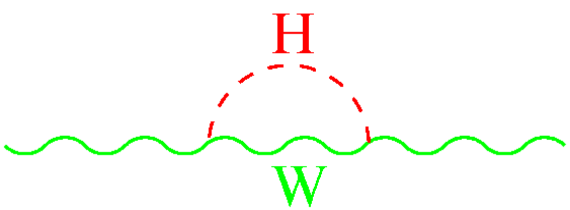
Constraining the Top Quark Mass

- Measuring many different decay widths and FB asymmetries at LEP, a significant constraint was placed on the *top quark mass* mt by mid-1990's : 150 < mt < 200 GeV
  - The top quark is *too heavy* to be directly observed at LEP but *precise* measurements at Z energies are senstive to it!
- This pointed the way to the discovery of the top quark at Fermilab's Tevatron collider (where the top is not too heavy to produce): mt = 174 $\pm$ 5 GeV … consistent with LEP !
- Knowing mt and Mw accurately leaves the Higgs boson mass MH as the only *unknown parameter* of the electroweak theory …
- … and precise LEP and Tevatron measurements are now producing meaningful constraints on MH ...

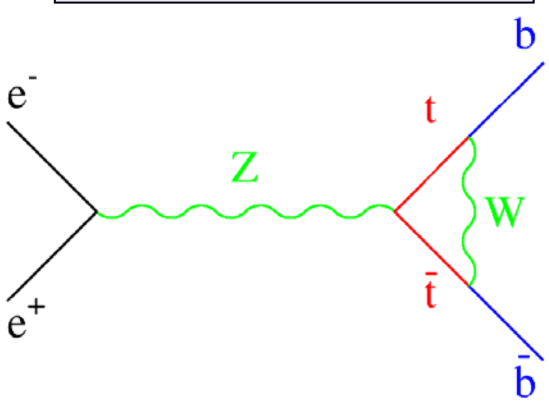
Dependence on m_{top}, m_H of m_W and R_b

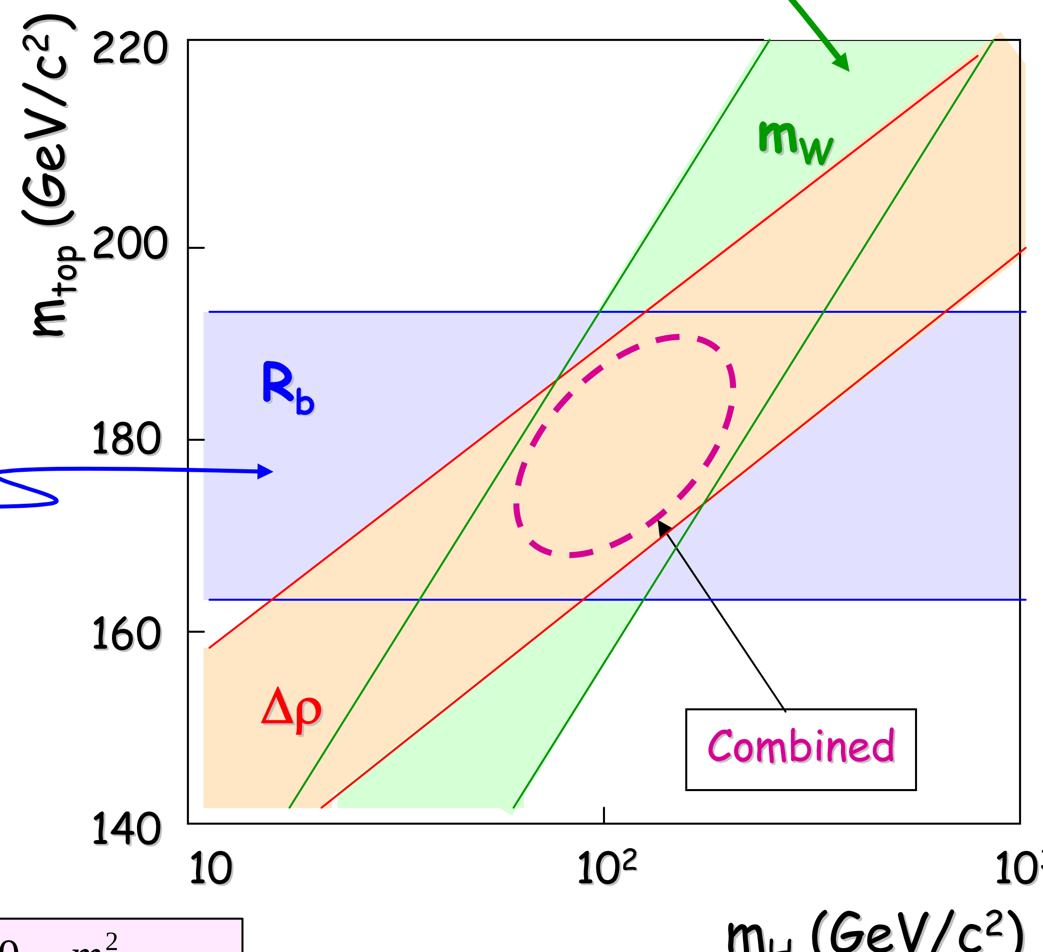
$$(m_W/m_Z)^2 \rightarrow (m_W/m_Z)^2 \times (1 + \Delta r)$$





$$R_b \rightarrow R_b\,(1 + \delta_{Vb})$$



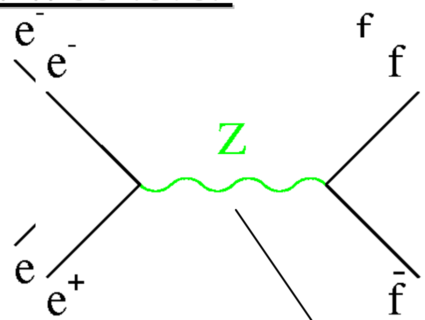


$$\delta_{Vb} = -\frac{20}{13}\alpha\frac{m_t^2}{m_Z^2} \approx 5\%$$

0.5% Precision needed

The Z Lineshape at LEP

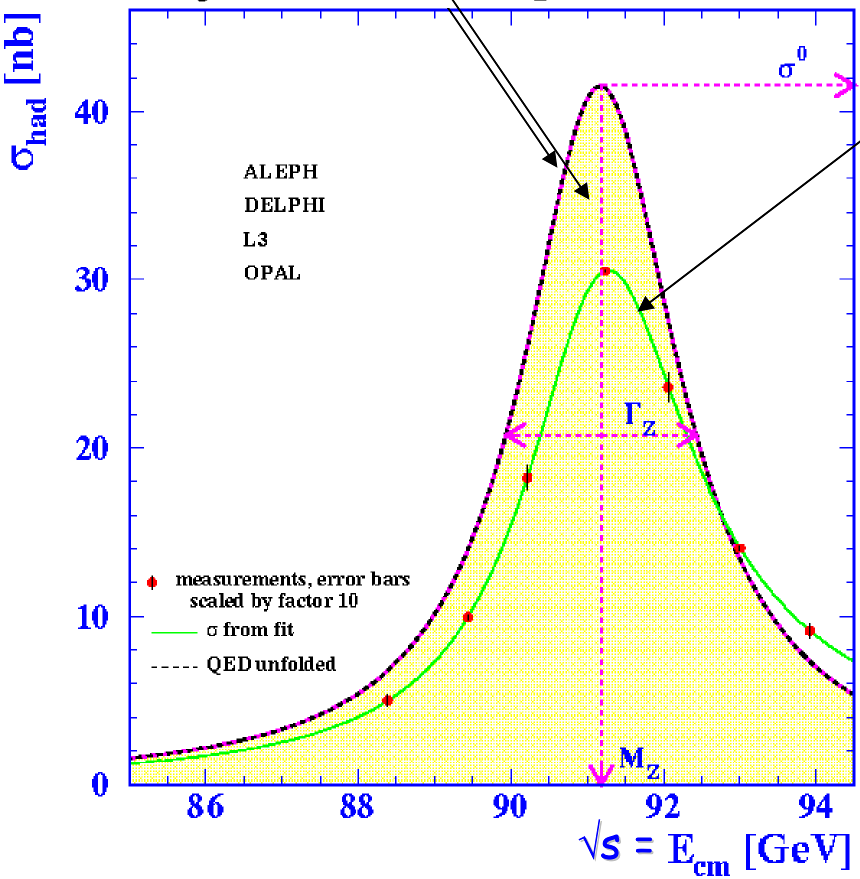
At tree-level:



$$\sigma_{f\bar f} \approx \sigma^0_{f\bar f} \times \frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2} \quad \text{with}$$

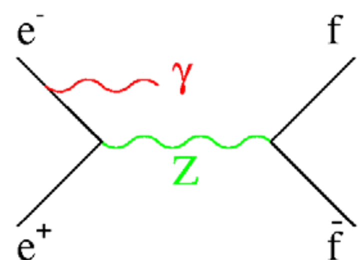
$$\sigma^0_{f\bar f} = \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2} \quad \text{and} \quad \Gamma_{ff} = \frac{G_F m_Z^3}{6\pi\sqrt{2}} \times (v_f^2 + a_f^2) \times N_{col}$$

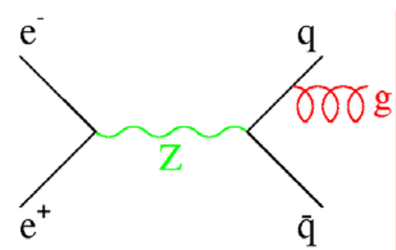
$\propto (1+\Delta\rho)^2$



1) Measure σ and s

2) Correct for QED and QCD



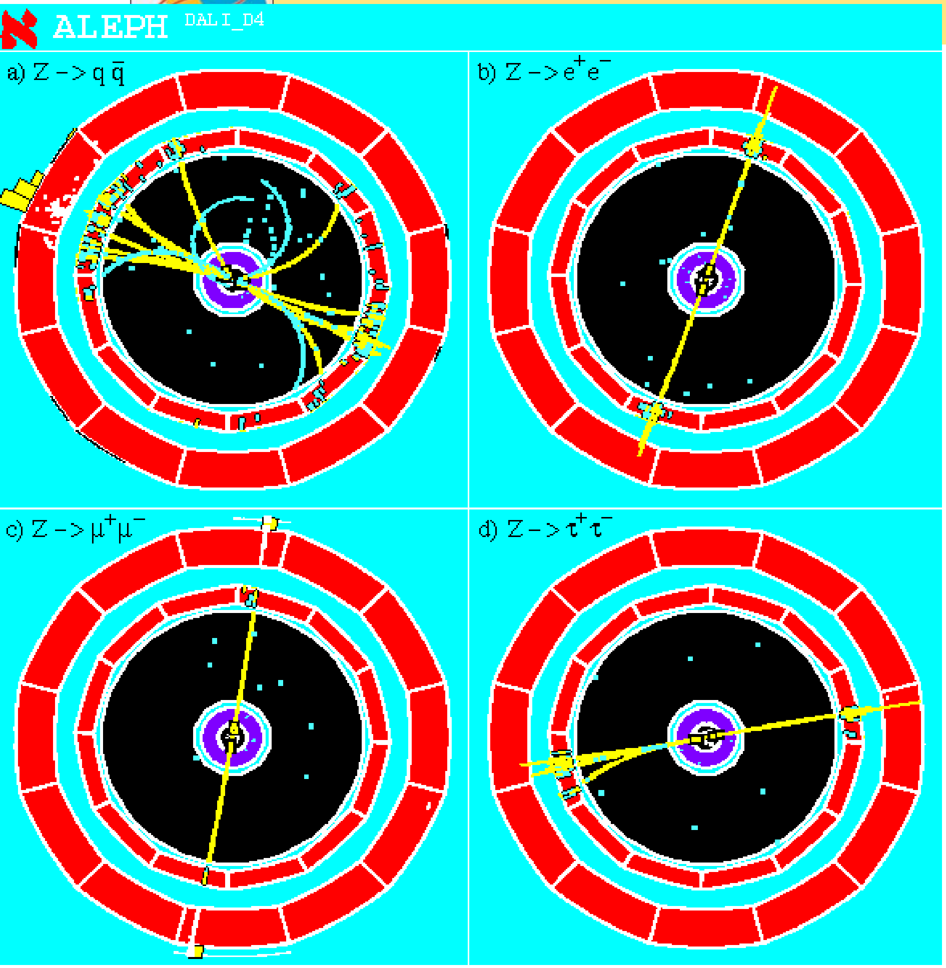


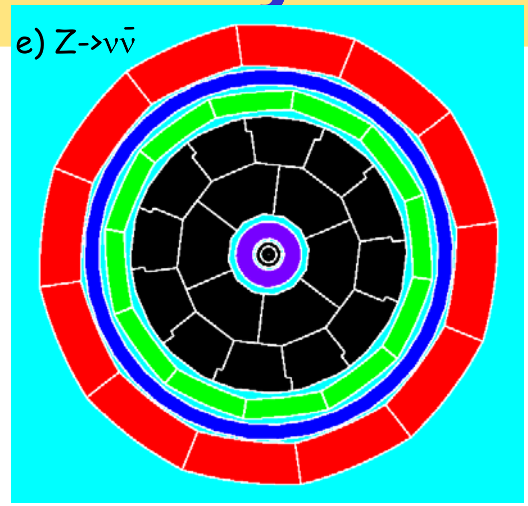
-30% for σ^0
+200 MeV for m_Z

+4% for Γ_{qq}

3) Fit for the Z parameters
(mass, total width, peak cross section and partial widths)

Z Boson Decays





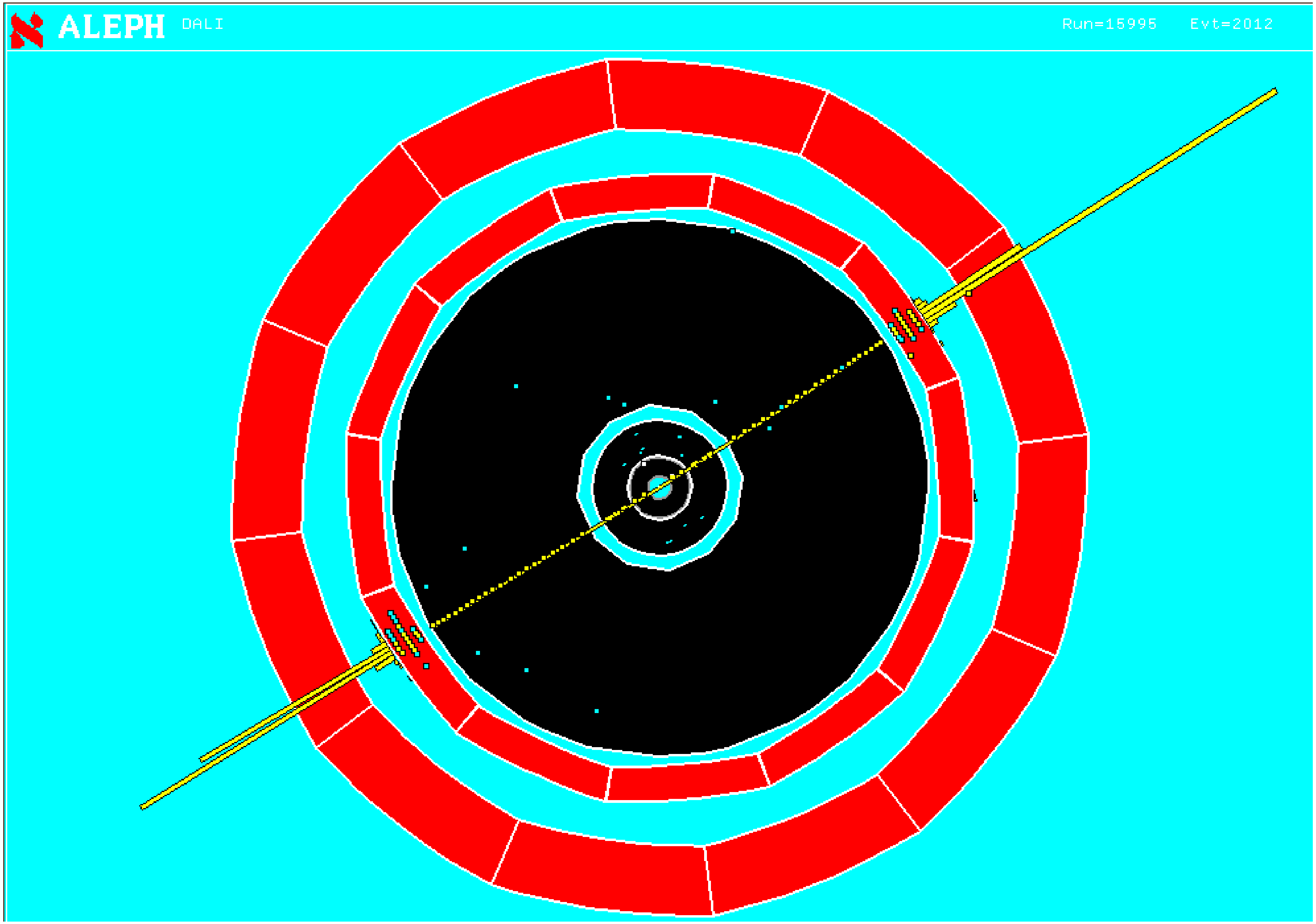
- $Z \rightarrow \nu\bar{\nu}$: Not detectable.

- $Z \rightarrow \tau^+\tau^-$: Two low multiplicity jets + missing energy carried by the decay neutrinos

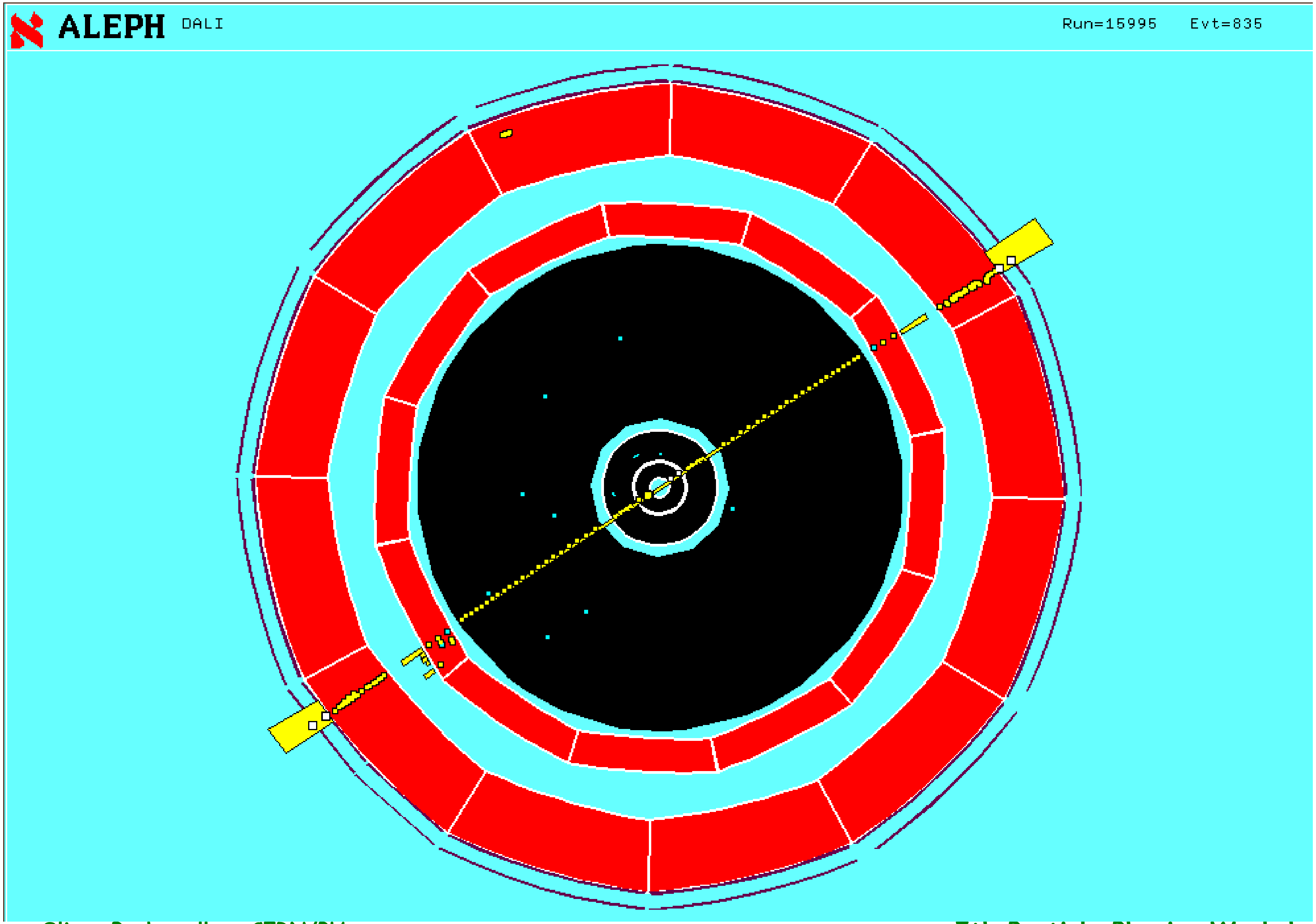
Channel	Partial Width	Branching Ratio
Hadrons	1.739 GeV	70%
Neutrinos	0.497 GeV	20%
Leptons	0.250 GeV	10%

- $Z \rightarrow q\bar{q}$: Two jets, large particle multiplicity.
- $Z \rightarrow e^+e^-, \mu^+\mu^-$: Two charged particles (e or μ.)

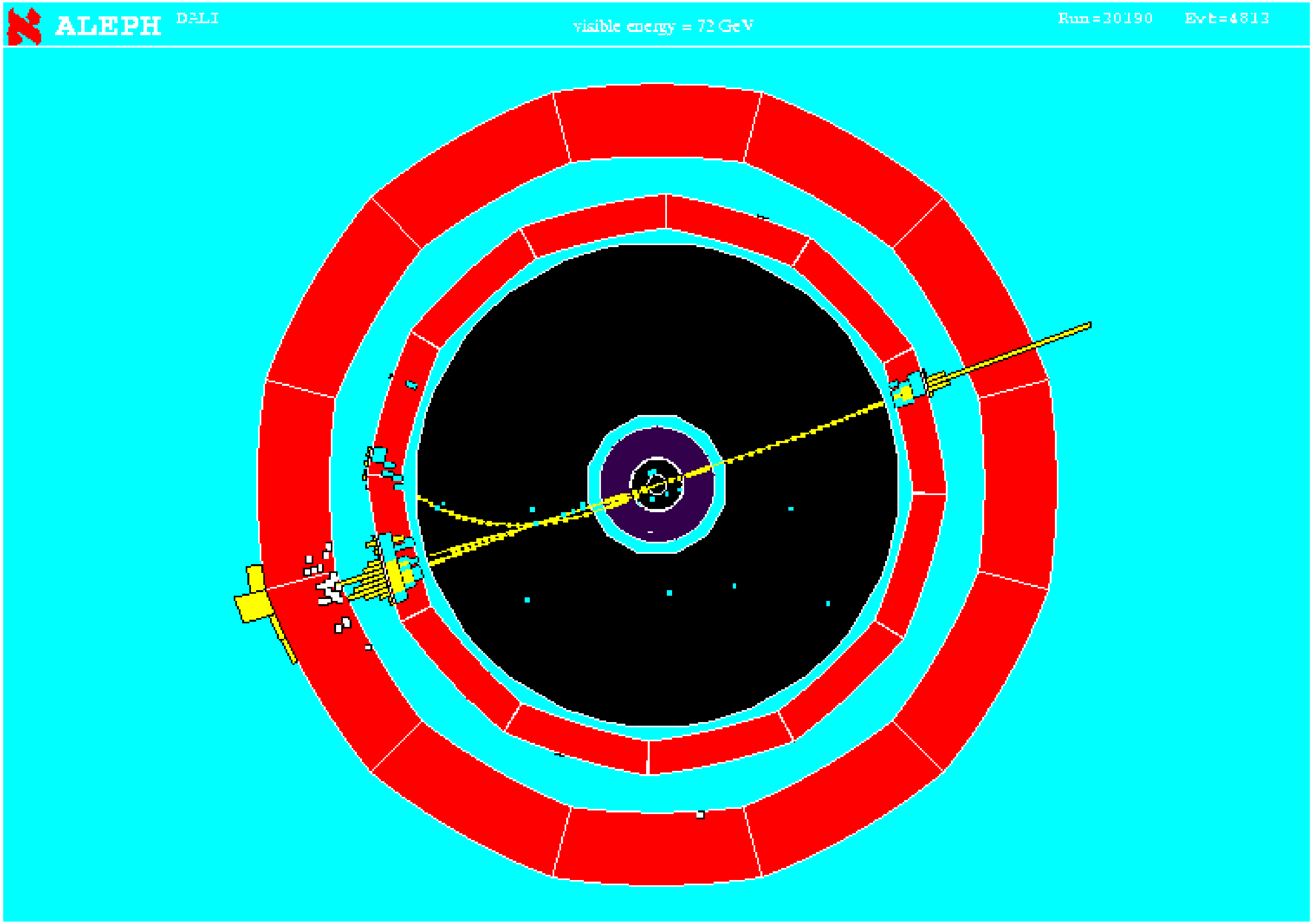
Z Boson Decay→ e+e-



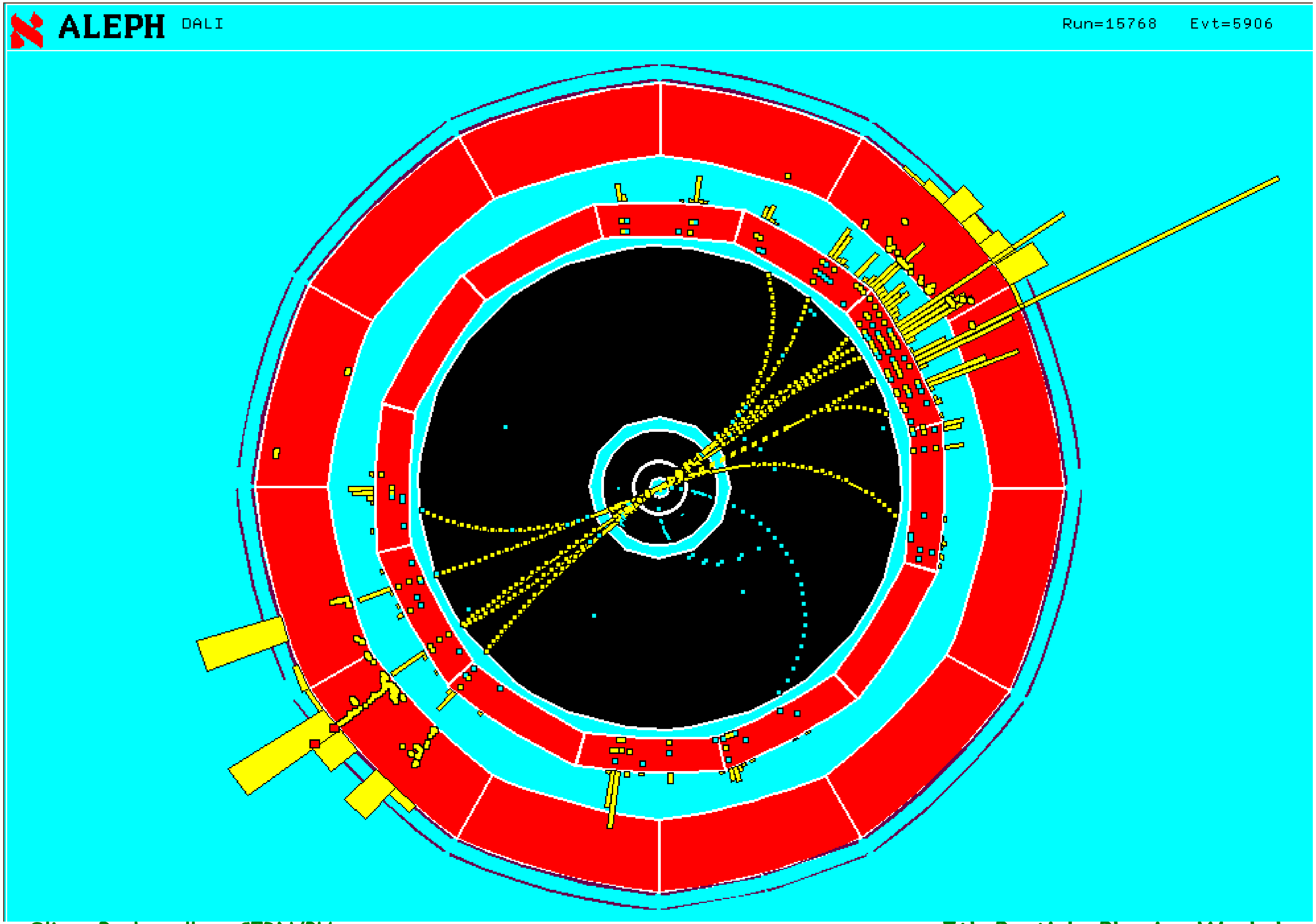
Z Boson Decay→ μ+μ-



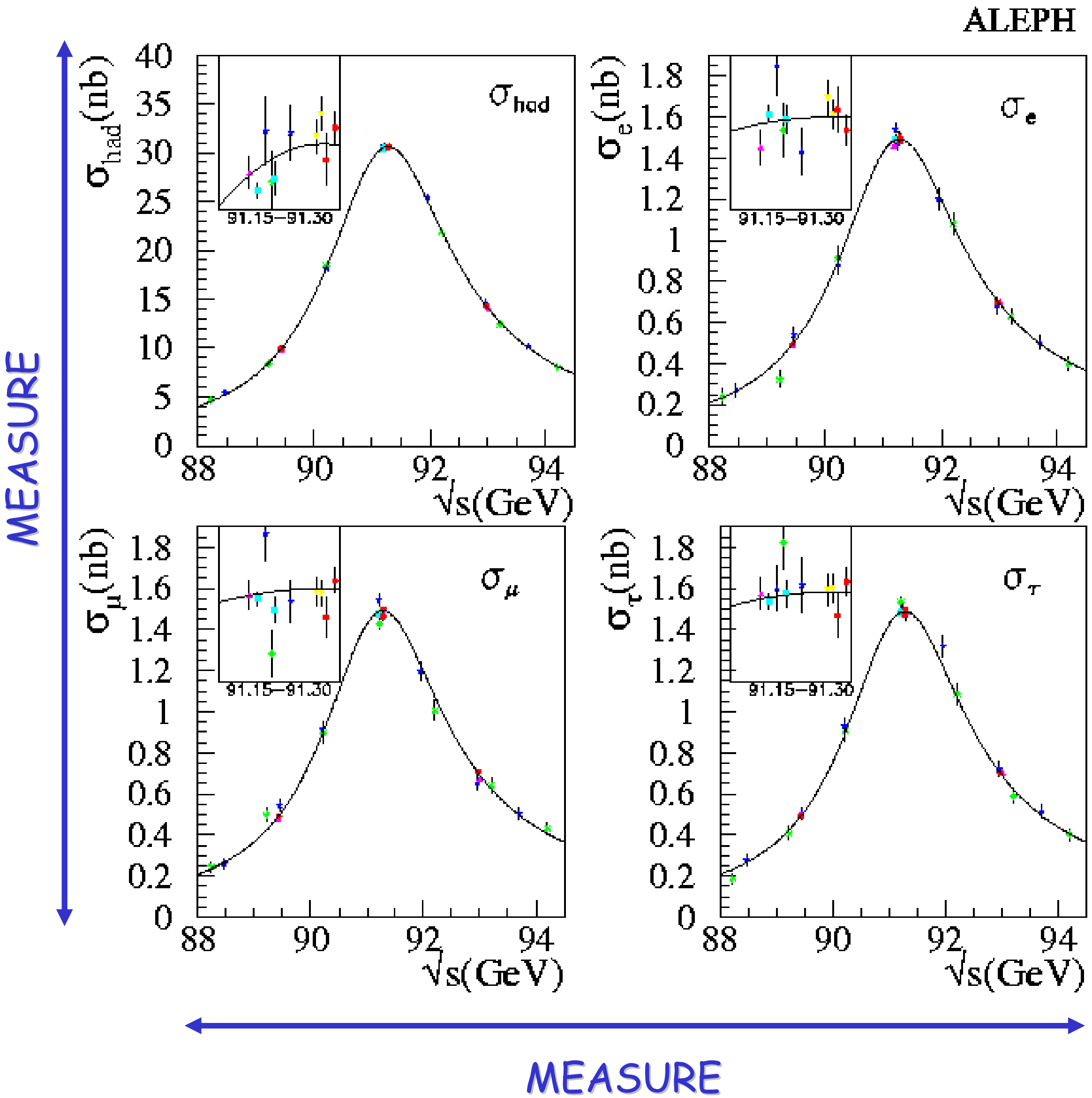
Z Boson Decay→ τ+τ- (e- + jet)



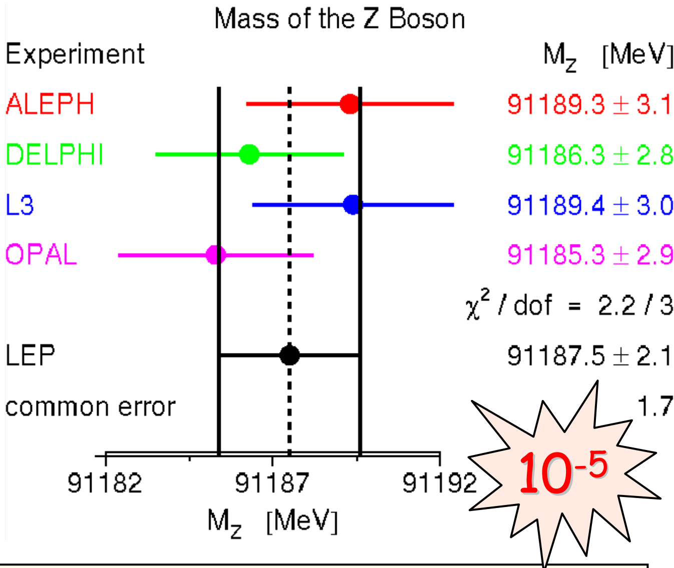
Z Boson Decay→ Hadrons (q$\bar{q}$ jets)



Z Lineshape: Results (I)



- √s varied from 88 to 94 GeV;
- Points are from data in both coordinates;
- Lines are from a standard model fit to the Z parameters;

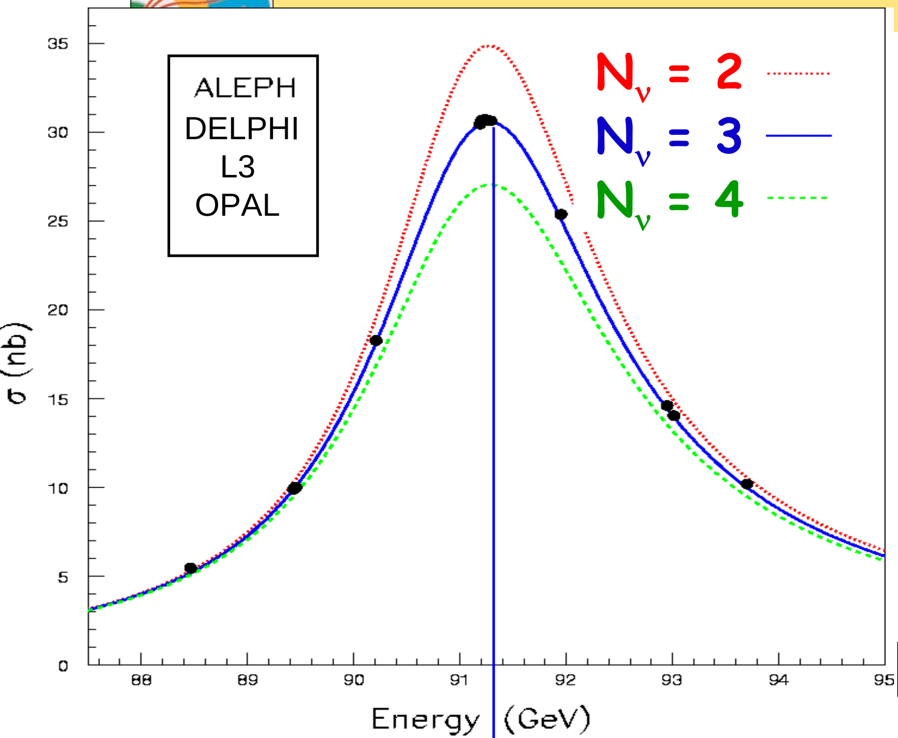


Dominant (and common) error:
LEP Beam Energy Measurement

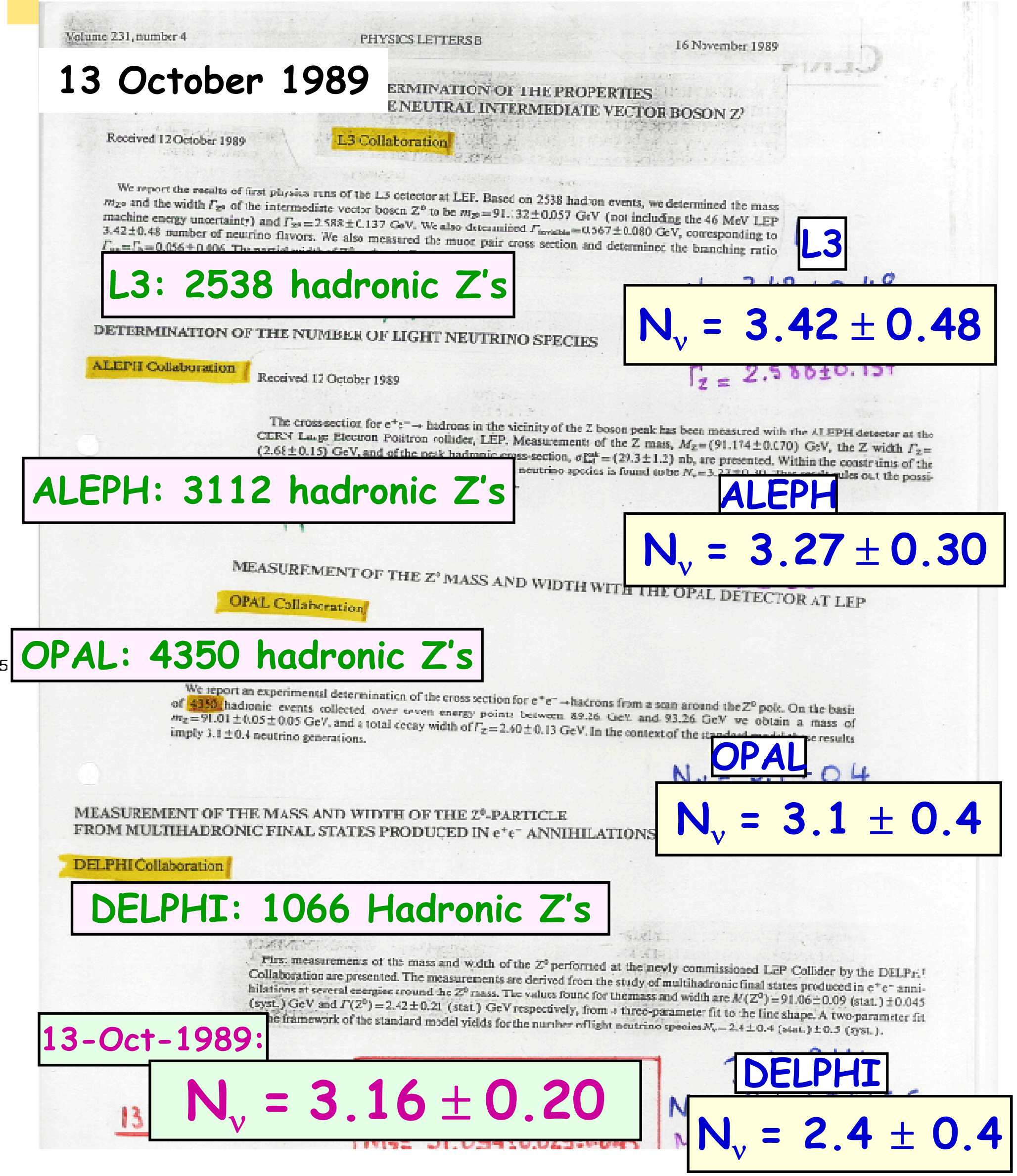
Number of Neutrino Types

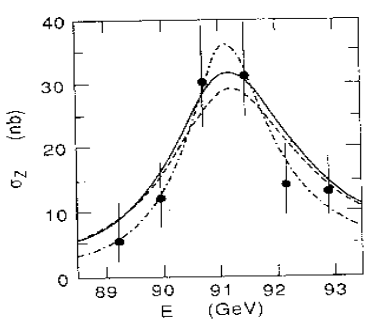
- The peak cross-section for e+e- $\rightarrow$ X (at E = M_Z) is
  - $\sigma_{peak} \sim 12\pi\Gamma_e \Gamma_X / M_z^2 \Gamma_z^2$
- The *total decay width* of the Z is
  - $\Gamma_Z = \Gamma_{had} + \Gamma_{lep} + \Gamma_{inv}$ (hadrons + leptons + invisible)
- and the *invisible width* of the Z is
  - $\Gamma_{inv} = N_\nu \Gamma_{\nu\, SM}$
- where the Standard Model decay width of the Z $\rightarrow \nu\underline{\nu}$ for a *single neutrino type* ($\Gamma_{\nu\, SM}$) is precisely calculable
- Thus both Γ_Z and σ_{pk} depend on N_ν - the *number of neutrino types* - and hence a careful *scan* of the Z resonance shape and size can determine N_ν (and M_Z)
  - With 3 *known families* of quarks and leptons $N_\nu \geq 3$
  - $N_\nu = 4$ => a new *heavy family* with m_q *and* $m_L > M_Z/2$
  - but *not* sensitive to new families if $m_\nu > M_Z/2$!

Z Lineshape: Results (II)



$N_\nu = 2.984 \pm 0.008$





MarkII, Aug. 1989,
with 106 Z decays:
$N_\nu = 3.8 \pm 1.4$.

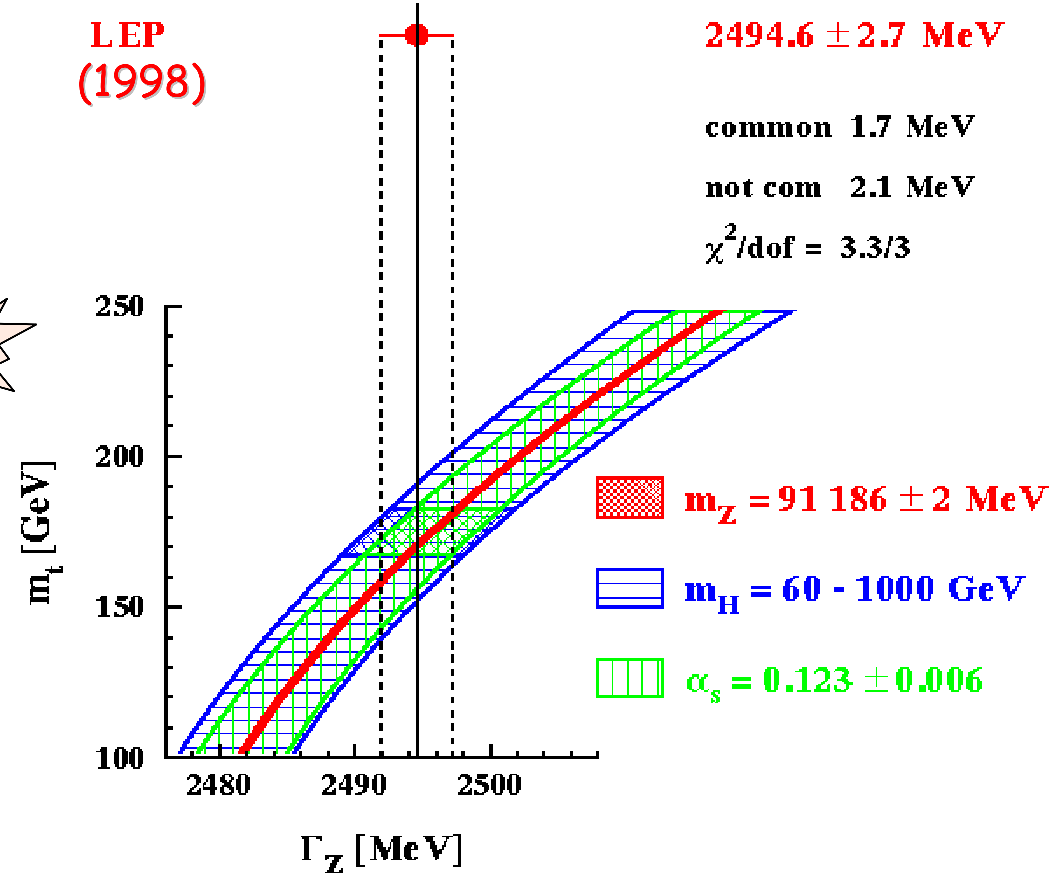
Z Lineshape: Results (III)

Obs.	Value	Error
m_Z	91187.5	2.1 MeV
Γ_Z	2495.2	2.3 MeV
σ^0	41.540	0.037 nb
R_l	20.767	0.025

10^{-3}

$\sigma^0_{had}/\sigma^0_l$

500 MeV in 1989



$$\Gamma_Z \propto (1 + \Delta\rho)^2$$

With this measurement alone:

$m_{top} \sim 165 \pm 25$ GeV/c^2

(+small sensitivity to m_H)