Standard Model Lecture

- Introduction to the SM
- Precision Test of SM (Part I)
- Precision Test of SM (Part II)

5th Particle Physics Workshop

Islamabad, Pakistan

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Few Books and Sources

- **Particle Physics (2nd ed) - Martin and Shaw (Wiley)**
- **Particle Physics: A Los Alamos Primer, Ed. by N. G. Cooper and G. B. West, Cambrige U. Press, 1988.**
- **Introduction to Elementary particles, by David Griffiths, Wiley 1987.**
- **Introduction to High Energy Physics (3rd ed) - D.H.Perkins (Addison Wesley)**
- **The Fundamental Particles and their Interactions - W.Rollnick (Addison Wesley)**

- **World Wide Web - limitless source of info!**
  - CERN public pages at *public.web.cern.ch/Public*
  - Fermilab public pages at*www.fnal.gov/pub/hep_descript.html*
  - Stanford Virtual Visitor Center at *www2.slac.stanford.edu/vvc/home.html*

Lecture Material Sources

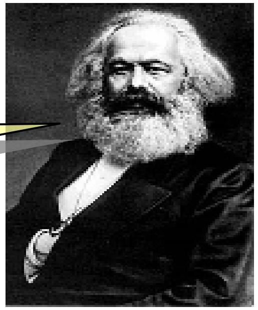
Here a few important sources of inspiration and more …

- Peter Ratoff - Particle Physics Lecture ..
- Patrick Janot - LEP & SLD …
- Joachim Mnich - LEP & LHC …
- Alexandre Nikitenko - Higgs @ LHC …
- Martin Gruenewald - SM Fits …
- …

“Standard Model Laudation”

- **The standard model makes precise and accurate predictions**
- **It provides an understanding of what nucleons, atoms, stars, you and me are made of**

But (like capitalism!) the SM contains the seeds of its own destruction

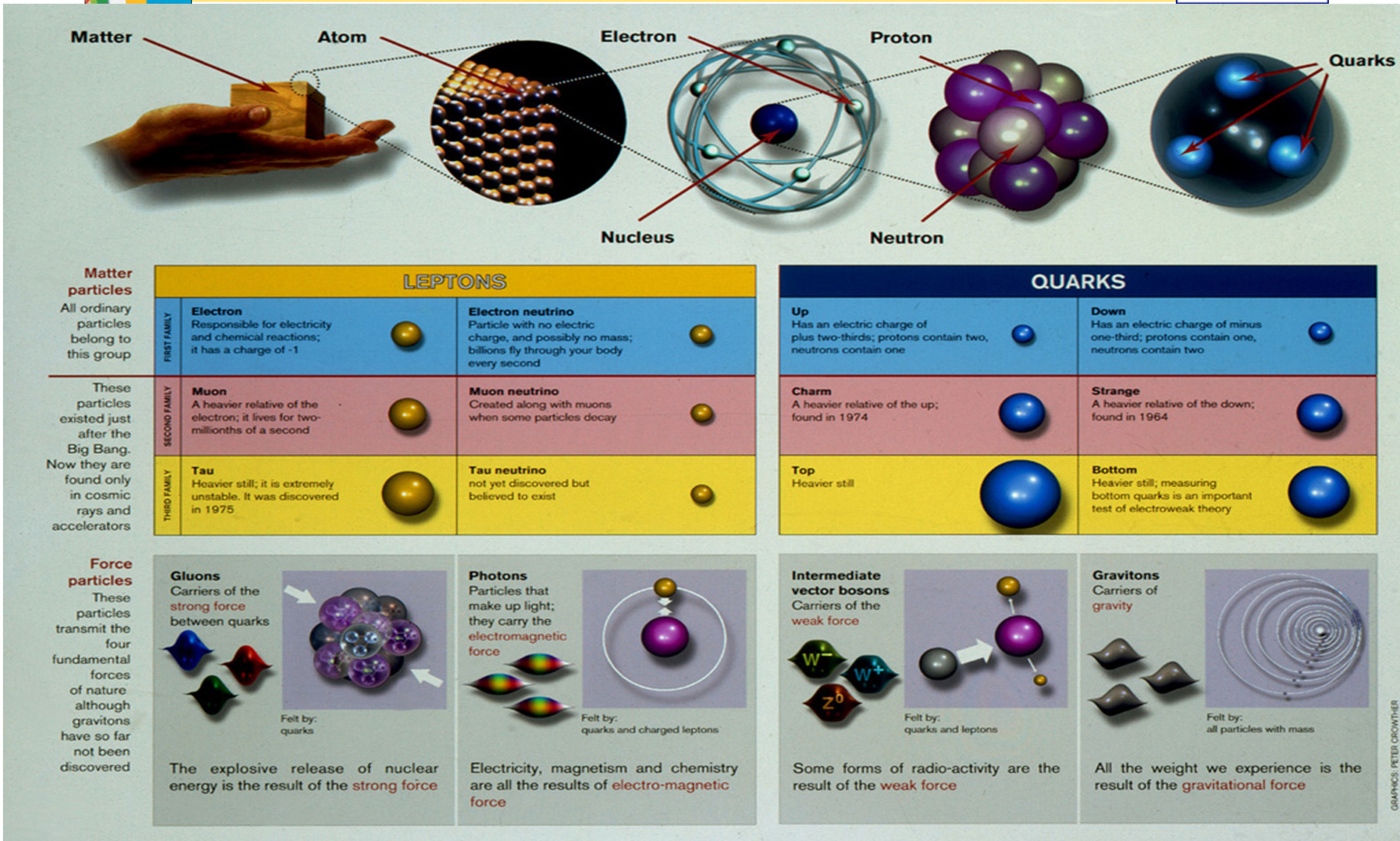


- **Its spectacular success in describing phenomena at energy scales below 1 TeV is based on**
  - At least one unobserved ingredient
    - the SM Higgs
  - Whose mass is unstable to loop corrections
    - requires something like supersymmetry to fix
- **The way forward is through experiment (and only experiment)**
  - tantalizing – we know the answers are accessible
  - and also a bit frustrating – we have known this for 20 years…

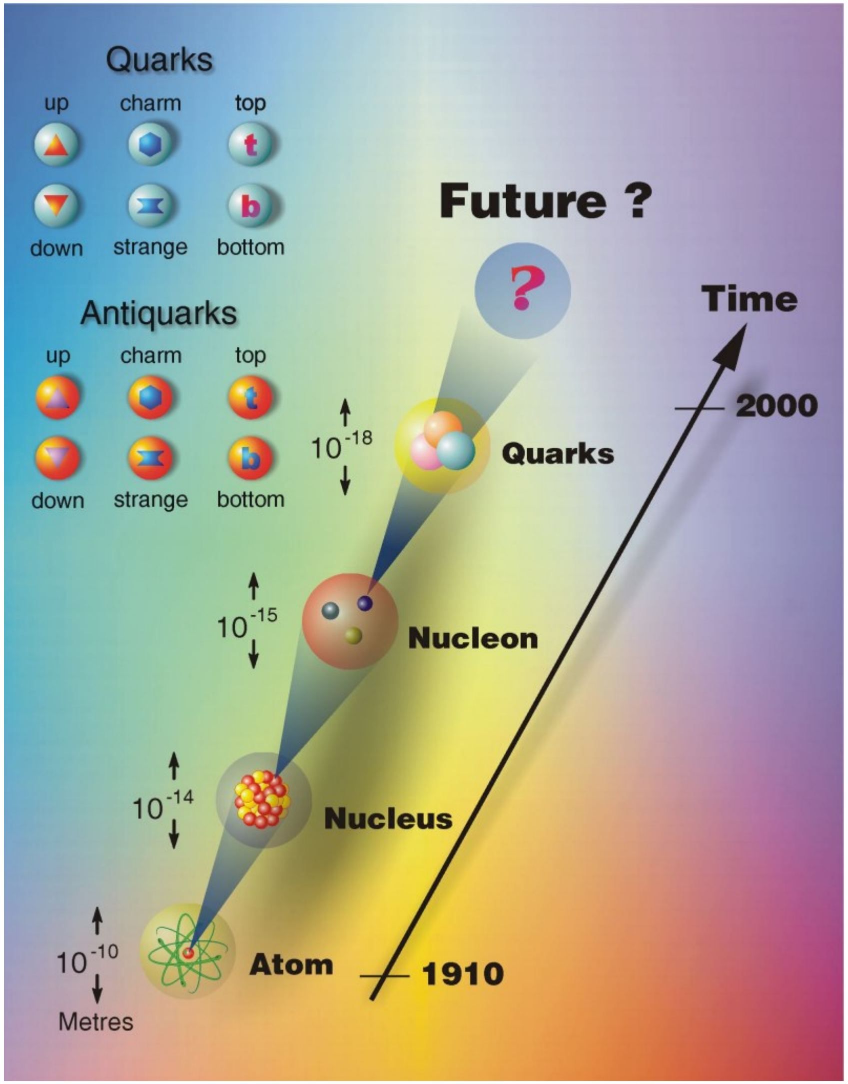
The Standard Model

- **The main components of the Model are:**
  - The particles and fields
    - Matter particles
    - Force particles
    - The Higgs Boson
  - A theoretical framework
    - Re-normalizable Yang-Mills Gauge Theory
    - The Standard Model Lagrangian

The Standard Model: Matter and Force Particles



Involved “Scales”



Yang-Mills Gauge Theory

- **Success of QED theory in 1940's (R.Feynman et al Nobel Prize 1965) prompted theorists to analyse mathematical properties of the theory and seek generalisation to apply to other forces**
- **$\Rightarrow$ Discovery of the *Gauge Principle* - QED is locally gauge invariant - and *renormalization* (cancellation of infinities from higher-orders)**
- **Yang and Mills (1954) generalised the idea of local gauge invariance but a theory of weak interactions based on this principle was only renormalizable with massless force particles, inconsistent with the short range nature of weak interactions**

Electroweak unification

- P.Higgs (1964) introduced the idea of *spontaneous symmetry breaking* permitting the construction of a theory of weak interactions with massive force particles (W bosons)
- In the 1960's Weinberg, Salam and Glashow (Nobel Prize 1979) used the Higgs mechanism to construct a unified theory of weak and electromagnetic interactions, predicting the existence of Z bosons
- The electroweak theory was proven to be completely renormalizable in 1974 (G. t'Hooft and M.Veltman Nobel Prize 1999)

The SM Lagrangian

- **Success of electroweak unification immediately prompted a gauge theory of the strong interaction, Quantum Chromodynamics (QCD), based on the exchange of massless *coloured gluons* between quarks**
- **The Standard Model is the sum of QCD and the electroweak theory which together account for the interactions of the 3 families of quarks and leptons**
- **All the interactions between the particles of the SM are specified by the *Lagrangian* - including the coupling strengths and dynamical properties**
- **The full SM Lagrangian contains many terms, even in the most compact notation, and covers several pages when written out in full !**

The Electroweak Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\mathrm{MSM}} &= \mathcal{L}_{\mathrm{QED}} + \mathcal{L}_{\mathrm{free\ V}} + \mathcal{L}_{\mathrm{ffW}} + \mathcal{L}_{\mathrm{ffZ}} + \mathcal{L}_{\mathrm{3V}} + \mathcal{L}_{\mathrm{4V}} \\
&\quad + \mathcal{L}_{\mathrm{free\ H}} + \mathcal{L}_{\mathrm{ffH}} + \mathcal{L}_{\mathrm{VVH}} + \mathcal{L}_{\mathrm{VVHH}} + \mathcal{L}_{\mathrm{3,4H}}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\mathrm{QED}} &= -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_j \left\{ \bar{f}_j (i\partial^\mu \gamma_\mu - m_j) f_j - iQ_j \bar{f}_j \gamma^\mu A_\mu f_j \right\} \\
\mathcal{L}_{\mathrm{free\ V}} &= -\frac{1}{2} W^*_{\mu\nu} W^{\mu\nu} - m_W^2 W^*{}_\mu W^\mu - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} - \frac{1}{2} m_Z^2 Z_\mu Z^\mu \\
\mathcal{L}_{\mathrm{ffW}} &= i\frac{e}{s_w\sqrt{8}} \sum_{j=u,k=d} \left\{ \bar{f}_j (1+\gamma^5) \gamma_\mu W^{*\mu} f_k V_{jk} + \mathrm{h.c.} \right\} \\
\mathcal{L}_{\mathrm{ffZ}} &= i\frac{e}{4 s_w c_w} \sum_j \bar{f}_j (v_j + a_j \gamma^5) \gamma_\mu Z^\mu f_j \\
\mathcal{L}_{\mathrm{3V}} &= ie \left(\frac{c_w}{s_w} Z_\nu - A_\nu \right) \left[W_\mu W^*{}_{\mu\nu} - W^*{}_\mu W_{\mu\nu} + \partial_\mu \left(W^\mu W^{*\nu} - W^{*\mu} W^\nu \right) \right] \\
\mathcal{L}_{\mathrm{4V}} &= e^2 \left(g^{\mu\rho} g^{\nu\sigma} - g^{\mu\nu} g^{\rho\sigma} \right) \left[\frac{1}{2 s_w^2} W^*{}_\mu W_\nu W^*{}_\rho W_\sigma \right. \\
&\qquad \left. + \left(\frac{c_w}{s_w} Z_\mu - A_\mu \right) \left(\frac{c_w}{s_w} Z_\nu - A_\nu \right) W^*{}_\rho W_\sigma \right] \\
\mathcal{L}_{\mathrm{free\ H}} &= -\frac{1}{2} (\partial_\mu H)(\partial^\mu H) - \frac{1}{2} m_H^2 H^2 \\
\mathcal{L}_{\mathrm{ffH}} &= -\frac{e}{2 s_w} \sum_j \frac{m_j}{m_W} \bar{f}_j f_j H \\
\mathcal{L}_{\mathrm{VVH}} &= -e \frac{m_W}{s_w} W^\mu W^*{}_\mu H - e \frac{m_Z}{2 s_w c_w} Z^\mu Z_\mu H \\
\mathcal{L}_{\mathrm{VVHH}} &= -\frac{e^2}{4 s_w^2} W^\mu W^*{}_\mu H^2 - \frac{e^2}{8 s_w^2 c_w^2} Z^\mu Z_\mu H^2 \\
\mathcal{L}_{\mathrm{3,4H}} &= -e^2 \frac{m_H^2}{4 m_w s_w} H^3 - e^2 \frac{m_H^2}{32 m_W^2 s_w^2} H^4
\end{aligned}
$$

Building the Standard Model

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

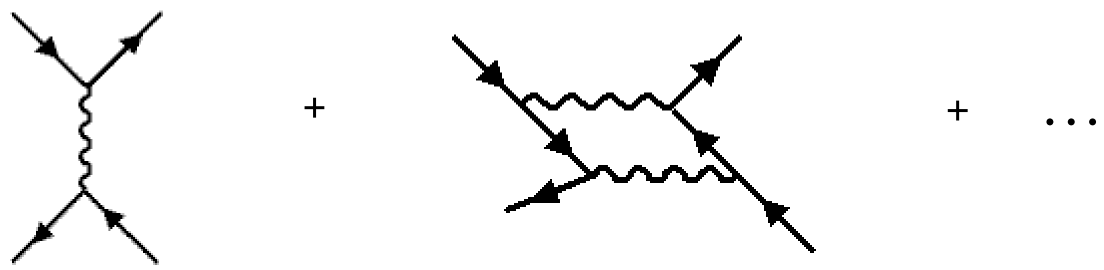
- **Part 2: Quantum Chromodynamics**
  - Quarks, Gluons and Colour
  - Running coupling constant α_s

A Century of Electroweak Nobel Prizes

Discovery	Nobel Prize
Electron discovered (1897)	JJ Thomson 1906
Photoelectric effect (1905)	Einstein 1921
Compton scattering (1923)	Compton 1927
Dirac equation (1928)	Dirac 1933
Positron discovered (1932)	Anderson 1936
QED (1947)	Feynman-Tomonaga-Schwinger 1965
Parity Violation (1956)	Lee-Yang 1957
Neutrinos observed (1959)	Reines 1995
CP Violation (1964)	Cronin-Fitch 1980
Electroweak (1967)	Glashow-Salam-Weinberg 1979
Gauge Theory Renormal’n (1972)	t’Hooft-Veltman 1999
W/Z bosons (1983)	Rubbia-van der Meer 1984

Quantum Electrodynamics (QED)

- Building on success of Dirac equation, Feynman, Tomonaga and Schwinger *independently* derived a self-consistent relativisitic theory of quantum mechanics (QED) - a theory of interactions between *electrons, positrons and photons*
- Important feature of QED are *higher order* processes, distinct from the *lowest order* or *tree-level* (Feynman diagrams show this clearly)
  - e- e- scattering proceeds via single photon exchange at lowest order but complete calculation requires higher orders



Towards a Weak Interaction Theory

- Pauli proposed existence of *neutrino* (1930) to account for non-conservation of energy-momentum in *nuclear β decay* - observed by Reines/Cowan (1959)
- Wide variety of reactions/decays involving hadrons and/or leptons recognised to be closely related to β decay - classified as *weak interactions* (slow rates)
  - $\mu \rightarrow e\nu\nu$ muon decay (*leptonic decay*)
  - $\pi \rightarrow \mu\nu$ pion decay (*semi-leptonic decay*)
  - $\Lambda \rightarrow p\pi$ lambda baryon decay (*non-leptonic decay*)
  - $\nu p \rightarrow \mu n$ neutrino-proton scattering (*reaction*)
- 3 types of ν (and anti- ν) and 3 separate conserved *lepton numbers* (L_e, L_μ, L_τ ; +1 for ν, -1 for anti- ν)
- Fermi proposed *4 - point interaction* theory (1934)

The V-A Theory and High Energies

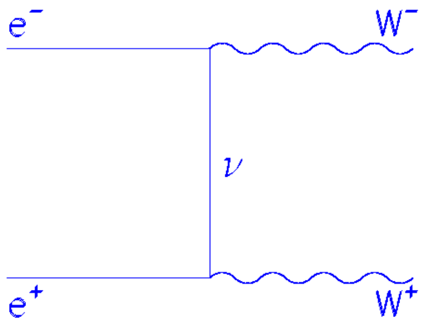
- EM force is a parity conserving pure *vector* interaction
- Weak force - *parity violating* - cannot be pure *vector* !
- Careful experiments show that the Weak Hamiltonian contains a mixture of *vector* and *axial-vector* terms
  - Feynman and Gell-Mann (1958) proposed a Weak Hamiltonian with equal amounts (opposite signs) of each type (still a 4-point int.)
  - … the "V minus A" (V-A) theory of weak interactions
- V-A works very well for low energies (nuclear β decay) but at high energies (neutrino beam scattering) problems emerge:
  - cross-section (ν_μ + e- $\rightarrow$ μ + ν_e) ~ E^2 in CM frame (V-A theory)
  - cross-section (ν_μ + e- $\rightarrow$ μ + ν_e) ~ $1/E^2$ in CM frame (Unitarity)

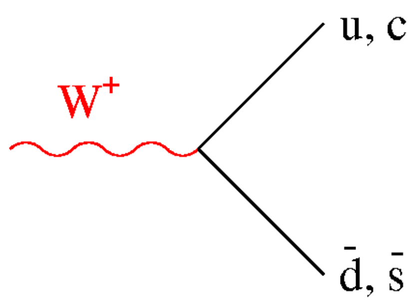
W Bosons and High Energies

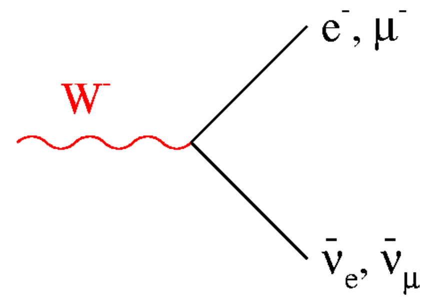
- At some energy $\sigma_{V-A}(\nu_\mu + e^- \rightarrow \mu + \nu_e) \sim E$ must exceed $\sigma_{unitarity}(\nu_\mu + e^- \rightarrow \mu + \nu_e) \sim 1/E$ and *unitarity* (or conservation of probability) would be violated !
- Only sensible conclusion: V-A theory must be wrong!
- Solution ? Try to mimic QED …
  - introduce an exchanged particle (analogous to photon in QED)
  - exchange particle must be *massive* due to *short-range* nature of the force
  - exchange particle must be *electrically charged* (+e and -e) in order to couple neutrinos to charged leptons
  - exchanged particle must have spin-1 to mediate a V-A force
- … which introduces the W+ and W- *bosons*
  - at low energies ($q \rightarrow 0$) *W propagator* $\sim 1/(q - M_W) \sim 1/M_W$ which is a constant, and the 4-point theory is recovered!

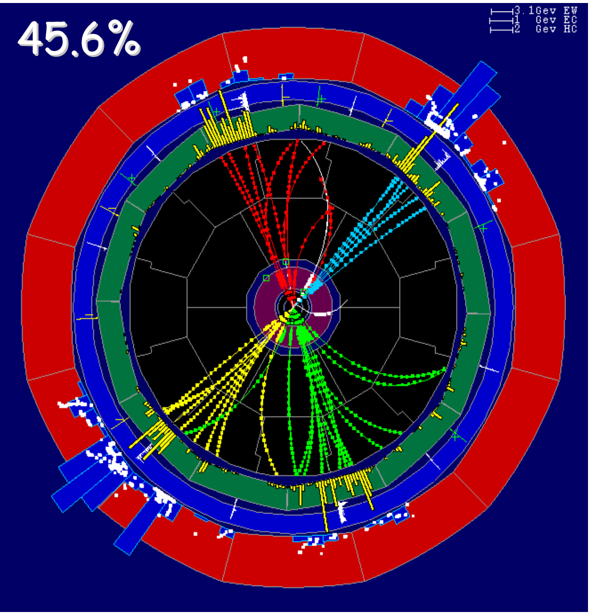
W Boson at LEPII

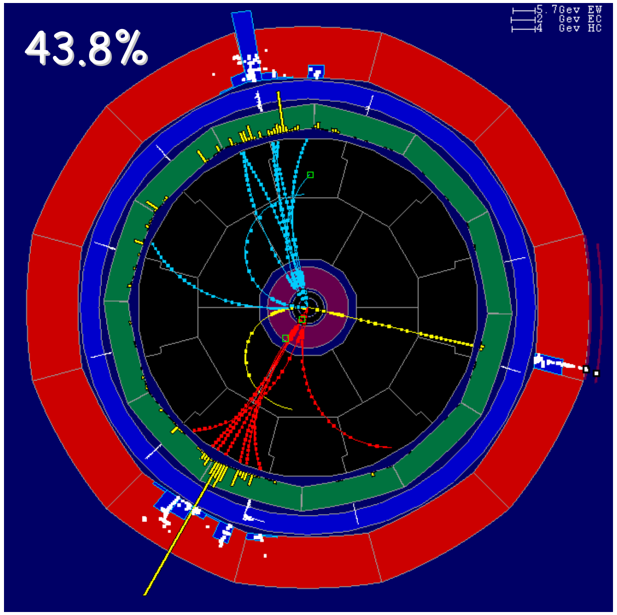
$\sqrt{s} \geq 2m_W$

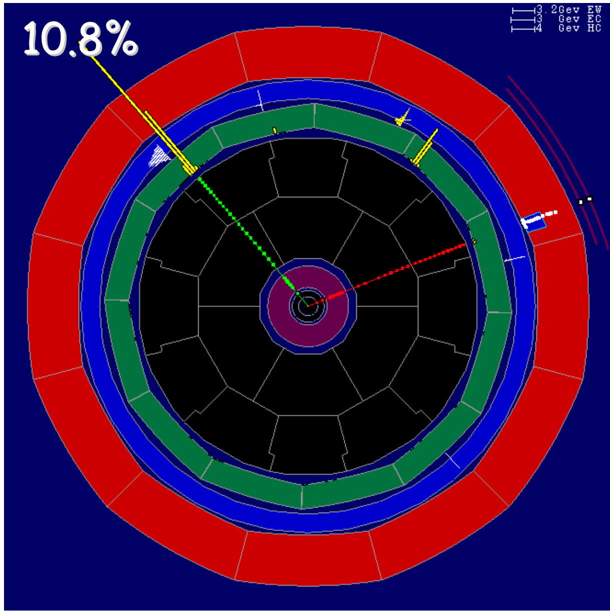












$W^+W^- \rightarrow q_1\bar{q}_2q_3\bar{q}_4$:

Four well separated jets.

$W^+W^- \rightarrow q_1\bar{q}_2 l\bar{\nu}$:

Two hadronic jets,

One lepton, missing energy.

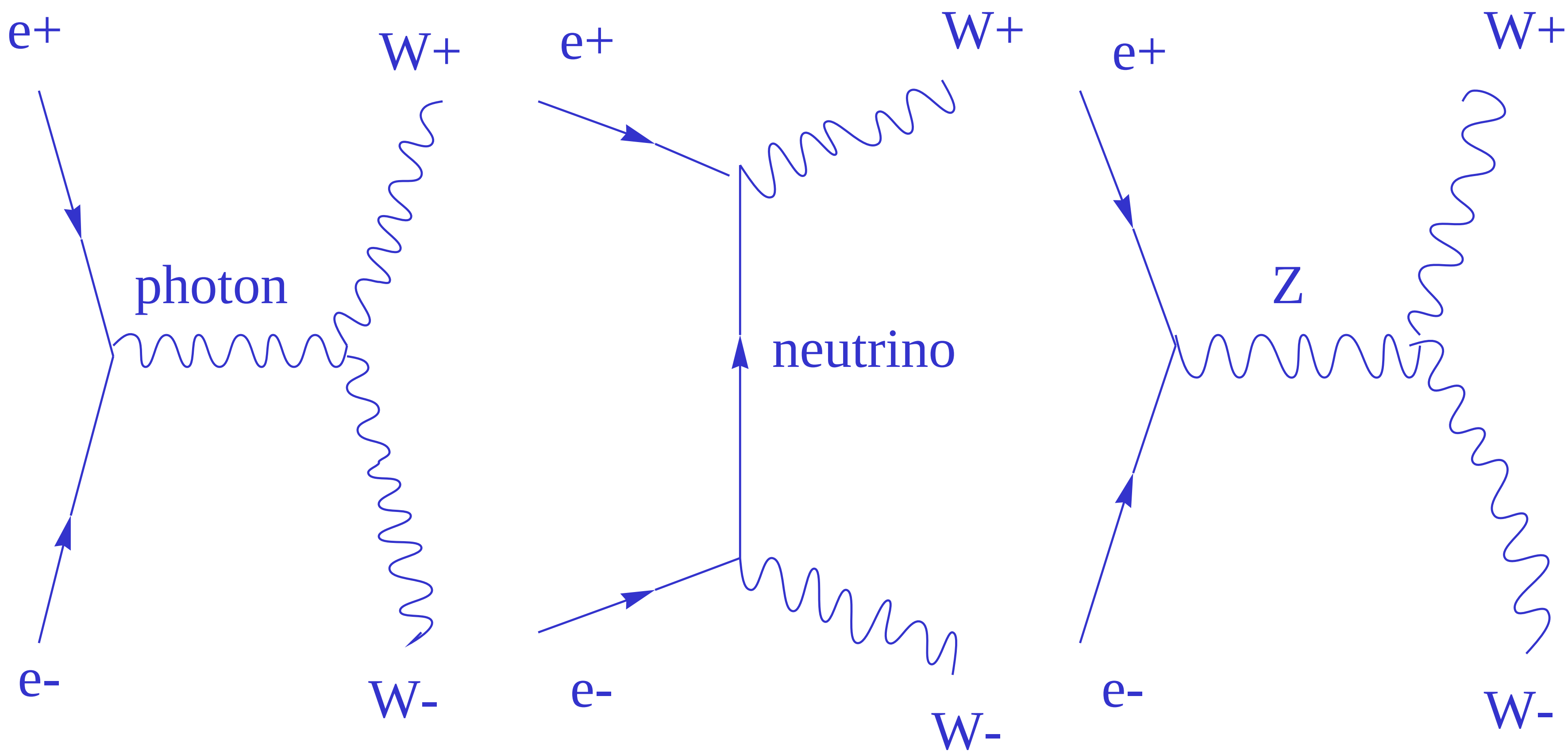
$W^+W^- \rightarrow l_1\nu_1 l_2\bar{\nu}_2$:

Two leptons, missing energy

The Z Boson

- While the massive (charged) W Boson solves some of the unitarity problems there are still some deficiencies left …
  - There are lowest order *tree level* processes which have *divergent amplitudes* !
    - » e.g. (e-) + (e+) $\rightarrow$ (W+) + (W-) via exchange of *virtual neutrino*
    - » n.b. this process, along with the *annihilation* channel (virtual photon) has been exhaustively studied at LEP from 1995-2000
    - » The only viable solution is to introduce a new exchange particle into the weak interaction … the neutral Z boson, with a contribution to the total amplitude which *cancels* the divergence

The Z Boson



(a) (b) (c)

Electroweak Unification

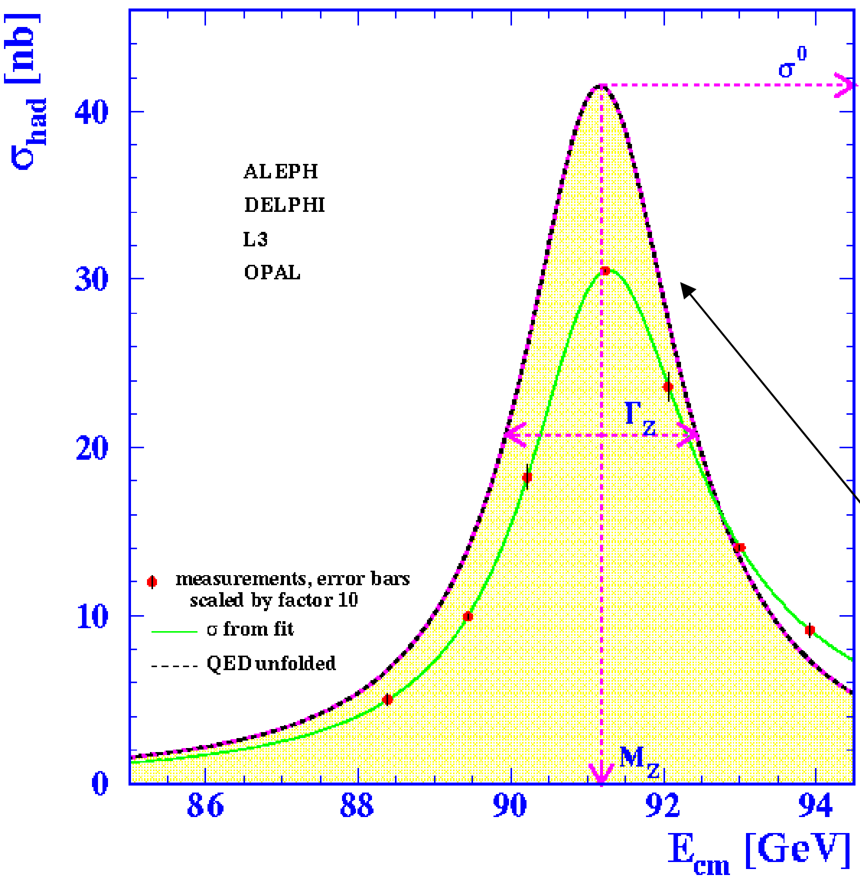
- 3 diagrams for (e-) + (e+) $\rightarrow$ (W+) + (W-) each have a different *Lorentz structure*
  - γ annihilation is a pure *vector* (V) interaction
  - ν exchange is a V-A interaction (involves νWe- vertices)
  - Z annihilation interaction *must* be a mixture of V and A but *not* simply V-A !
    - » Why? Because the Z exchange amplitude A_Z is required to *cancel the divergence* due to the ν exchange A_ν amplitude and make the total amplitude ($A_\gamma + A_\nu + A_Z$) non-divergent
    - » To achieve this the V and A type *couplings* of the Z to electrons and W bosons must be carefully chosen and as a result the V and A couplings are of unequal magnitude
    - » Consequently, Z bosons couple to both *left- and right-handed particles* (or antiparticles) but with different strengths, whereas the W only couples to left-handed particles (or right-handed antiparticles)

Electroweak Unification

- The V and A couplings of the Z to fermions show that the Weak and EM interactions are intimately related and that their couplings are of similar strength ...
- $g_{Zff} \approx g_{Wff} \approx g_{\gamma ff} = e$
- This, in essence, is the *electroweak unification* !
  - The existence of the Z is an inevitable consequence of the unification - its discovery would was a decisive test of the theory
  - The unified theory made its 1st appearance with the *Weinberg-Salam Model* (1967)
  - *Weak neutral currents* in the reaction ν_μ + e- $\rightarrow$ ν_μ + e- (via the exchange of a virtual Z) were observed at CERN in 1973
  - Real (not virtual!) W and Z bosons were observed at CERN in proton-antiproton collisions during 1982-3

Z Boson

1989-95: Z properties
- precision determination at LEP (and SLD)



1983: W and Z discovery (UA1, UA2);

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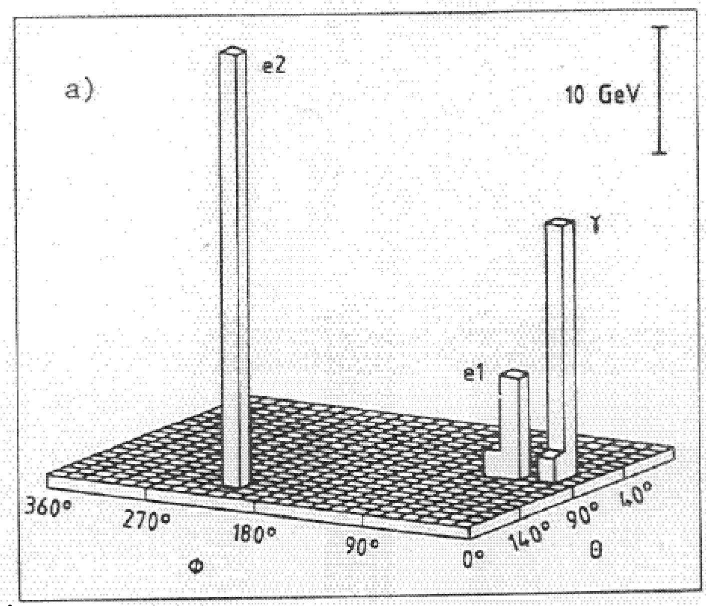
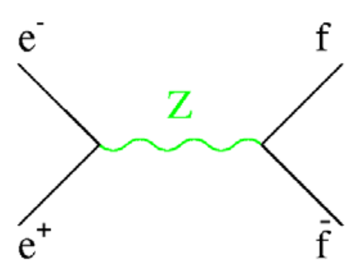
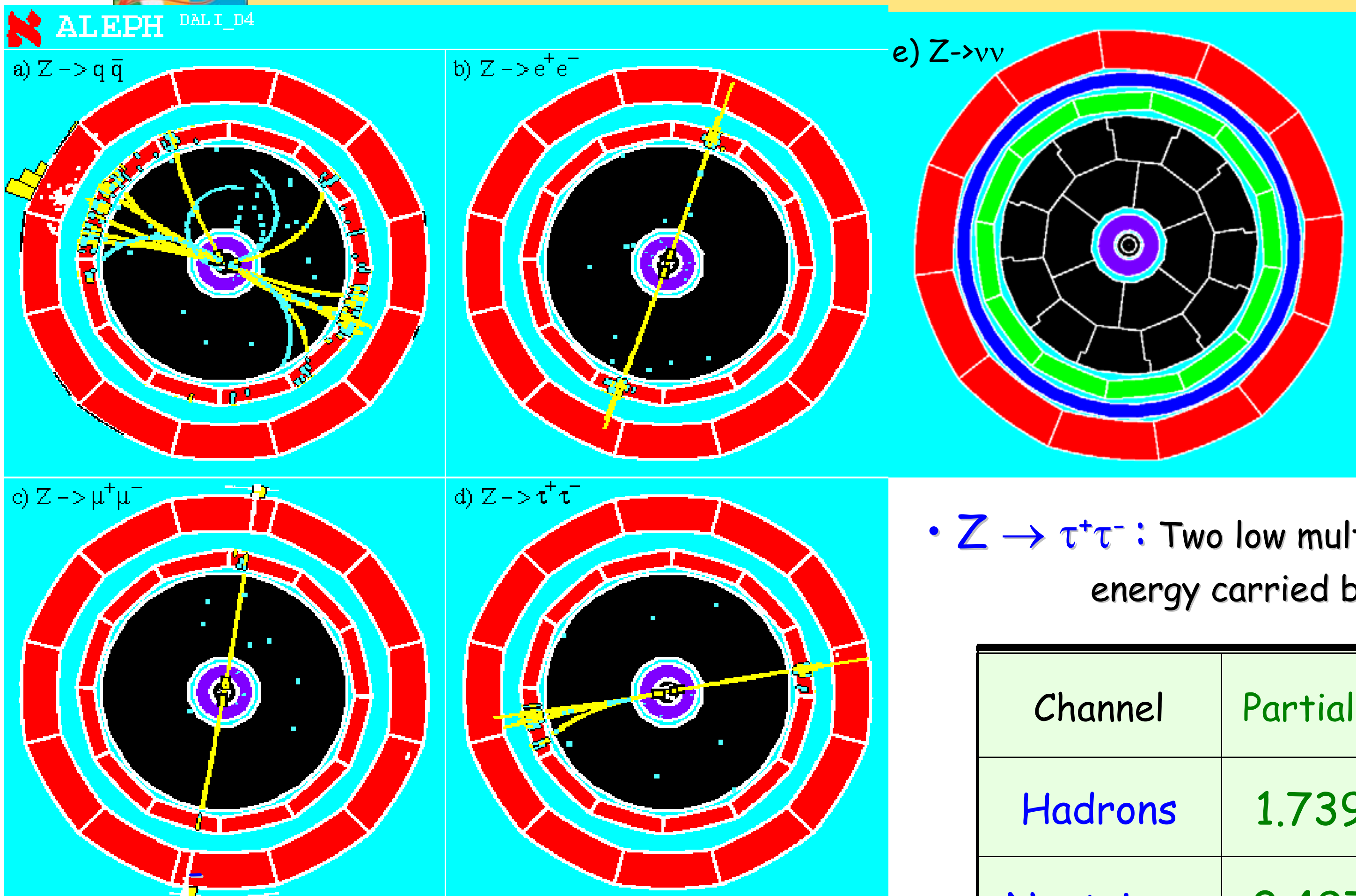
First Z detected in the world:



At tree-level:



Z Boson at LEP

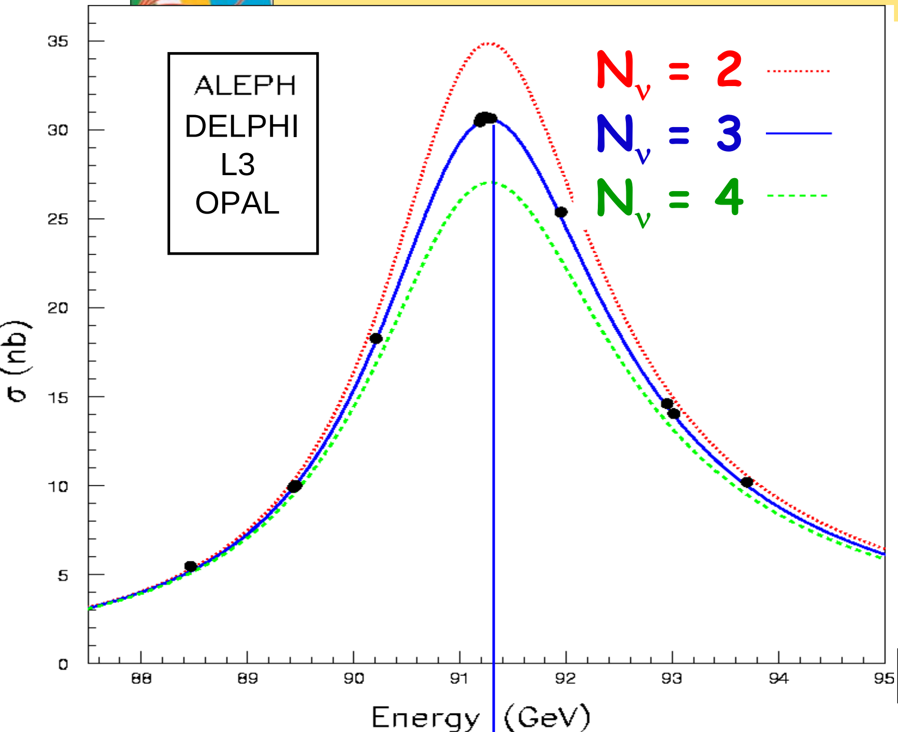


- $Z \to \nu\bar{\nu}$: Not detectable.
- $Z \to \tau^+\tau^-$: Two low multiplicity jets + missing energy carried by the decay neutrinos

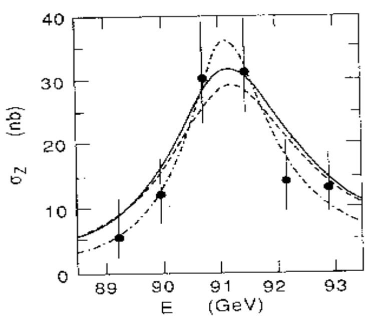
Channel	Partial Width	Branching Ratio
Hadrons	1.739 GeV	70%
Neutrinos	0.497 GeV	20%
Leptons	0.250 GeV	10%

- $Z \to qq$: Two jets, large particle multiplicity.
- $Z \to e^+e^-, \mu^+\mu^-$: Two charged particles (e or μ.)

of Neutrino Generations

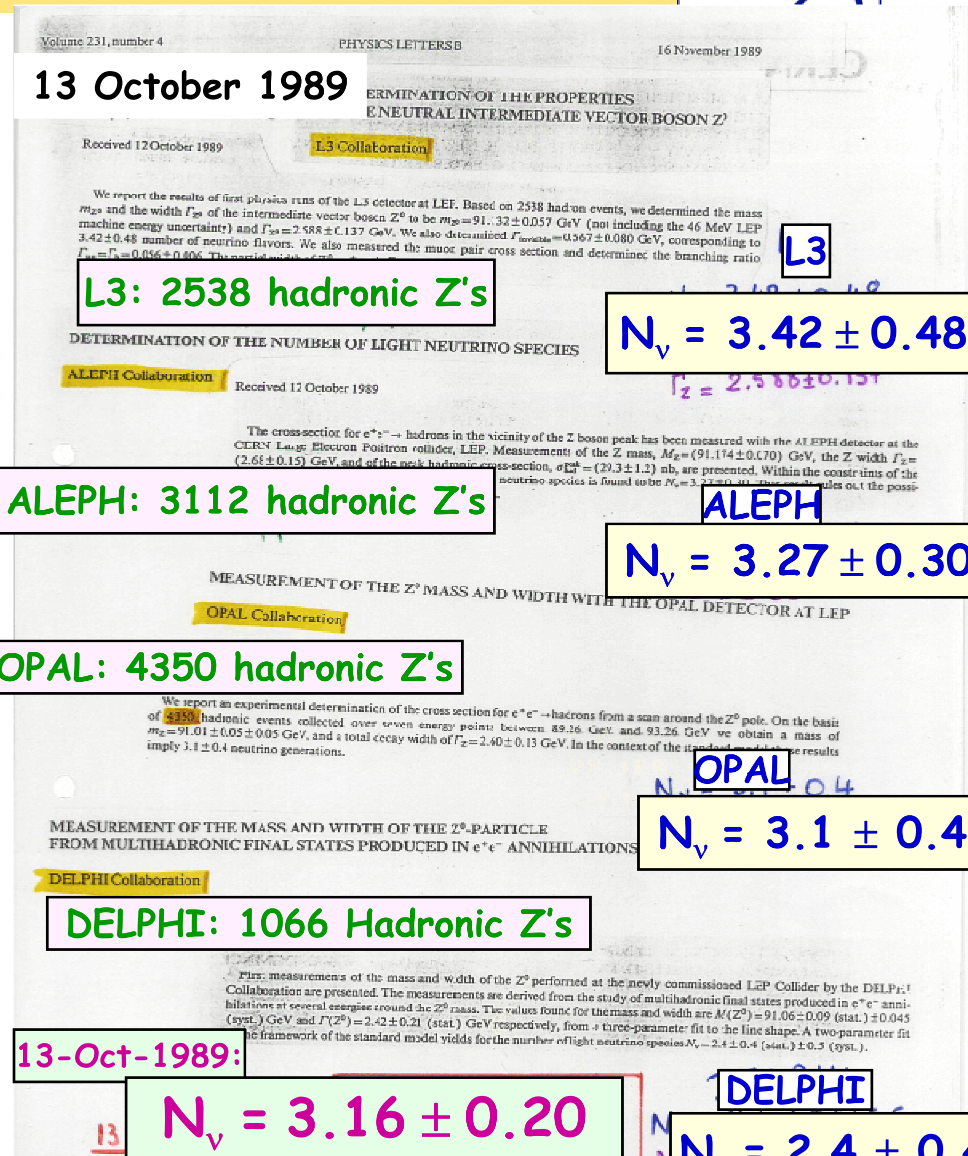


$N_\nu = 2.984 \pm 0.008$



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

13 October 1989


Volume 231, number 4 PHYSICS LETTERS B 16 November 1989

ERMINATION OF THE PROPERTIES
E NEUTRAL INTERMEDIATE VECTOR BOSON Z⁰

Received 12 October 1989

L3 Collaboration

DETERMINATION OF THE NUMBER OF LIGHT NEUTRINO SPECIES

ALEPH Collaboration

Received 12 October 1989

MEASUREMENT OF THE Z⁰ MASS AND WIDTH WITH THE OPAL DETECTOR AT LEP

OPAL Collaboration

MEASUREMENT OF THE MASS AND WIDTH OF THE Z⁰-PARTICLE FROM MULTIHADRONIC FINAL STATES PRODUCED IN e^+e^- ANNIHILATIONS

DELPHI Collaboration

L3: 2538 hadronic Z's

L3

$N_\nu = 3.42 \pm 0.48$

ALEPH: 3112 hadronic Z's

ALEPH

$N_\nu = 3.27 \pm 0.30$

OPAL: 4350 hadronic Z's

OPAL

$N_\nu = 3.1 \pm 0.4$

DELPHI: 1066 Hadronic Z's

13-Oct-1989: $N_\nu = 3.16 \pm 0.20$

DELPHI

$N_\nu = 2.4 \pm 0.4$

The Higgs Boson

- *But we are not yet done - there are even more "infinity"problems …*
  - when all 4 bosons in the reaction $Z + Z \rightarrow (W+) + (W-)$ are *longitudinally polarised the process becomes divergent*!
- The only way to achieve the necessary cancellations is to introduce a new *scalar* particle (spin=0) which can appear as an exchanged particle in ZZ (WW) annihilation
  - this is the same particle as the Higgs boson predicted as a result of the mass generation mechanism in the Standard Model
  - the WWH and ZZH vertex couplings must be selected to yield the necessary cancellation of amplitudes in $Z + Z \rightarrow (W+) + (W-)$
  - as a result of this a further constraint emerges (believe me!) …
    - » $\sin\theta_W = 1 - M_W^2/M_Z^2$ or $M_W = M_Z \cos\theta_W$
  - which provides for the 1st time a bound on M_Z
  - and measuring M_W and M_Z then specifies all of the V and A couplings of the Z to fermions (quarks and leptons)

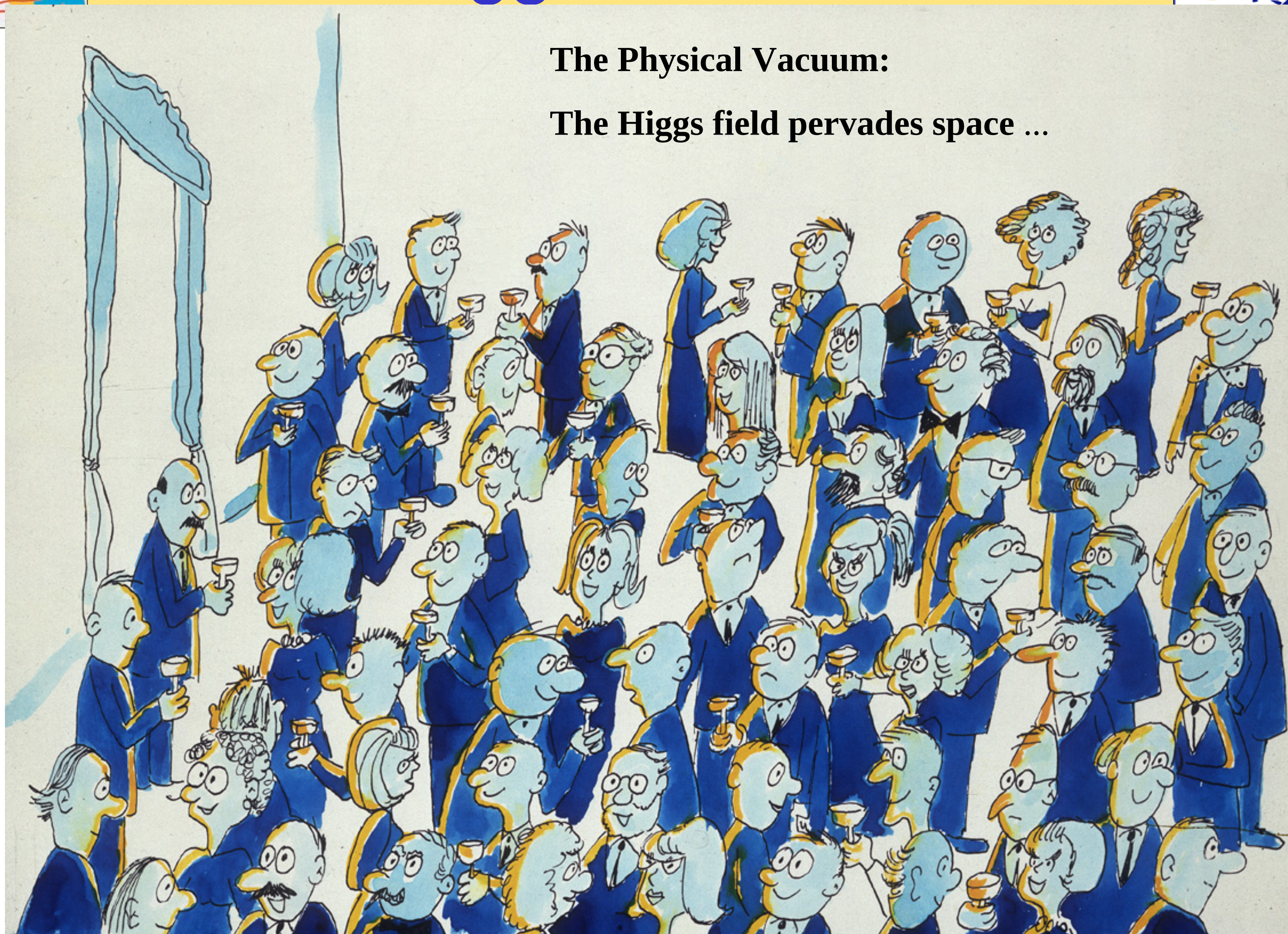
The Higgs Mechanism

- In this *particular way* of presenting electroweak unification, the Higgs boson has been introduced to cancel a divergence appearing in the amplitude for $Z + Z \rightarrow (W+) + (W-)$ (there is no alternative cure)
- It has to be a *scalar* particle (spin=0) to achieve this (since W_L , Z_L)
- It has also resulted in a *relation between* the W and Z *masses* and the strengths of the V and A *couplings* of the Z to fermions (via $\cos\theta_W$)
- The strength of the Higgs boson *coupling to fermions* is proportional to the *fermion mass*
- The Higgs boson is a *self-interacting particle* !
  - The Higgs boson is clearly intimately connected to the *masses* of the other particles in the theory (leptons, quarks and vector bosons) …

The Higgs Mechanism

- **The connection to mass …**
  - A direct consequence of the Higgs mechanism - the means by which the SM particles acquire mass - is the existence of a neutral *scalar*, the Higgs boson, with a mass M < 200 GeV
  - This particle has not been observed and the current experimental constraint is
    - M > 114 GeV (95% CL)
  - Finding the Higgs boson is the primary goal of particle physics at the LHC!

The Higgs Mechanism 1

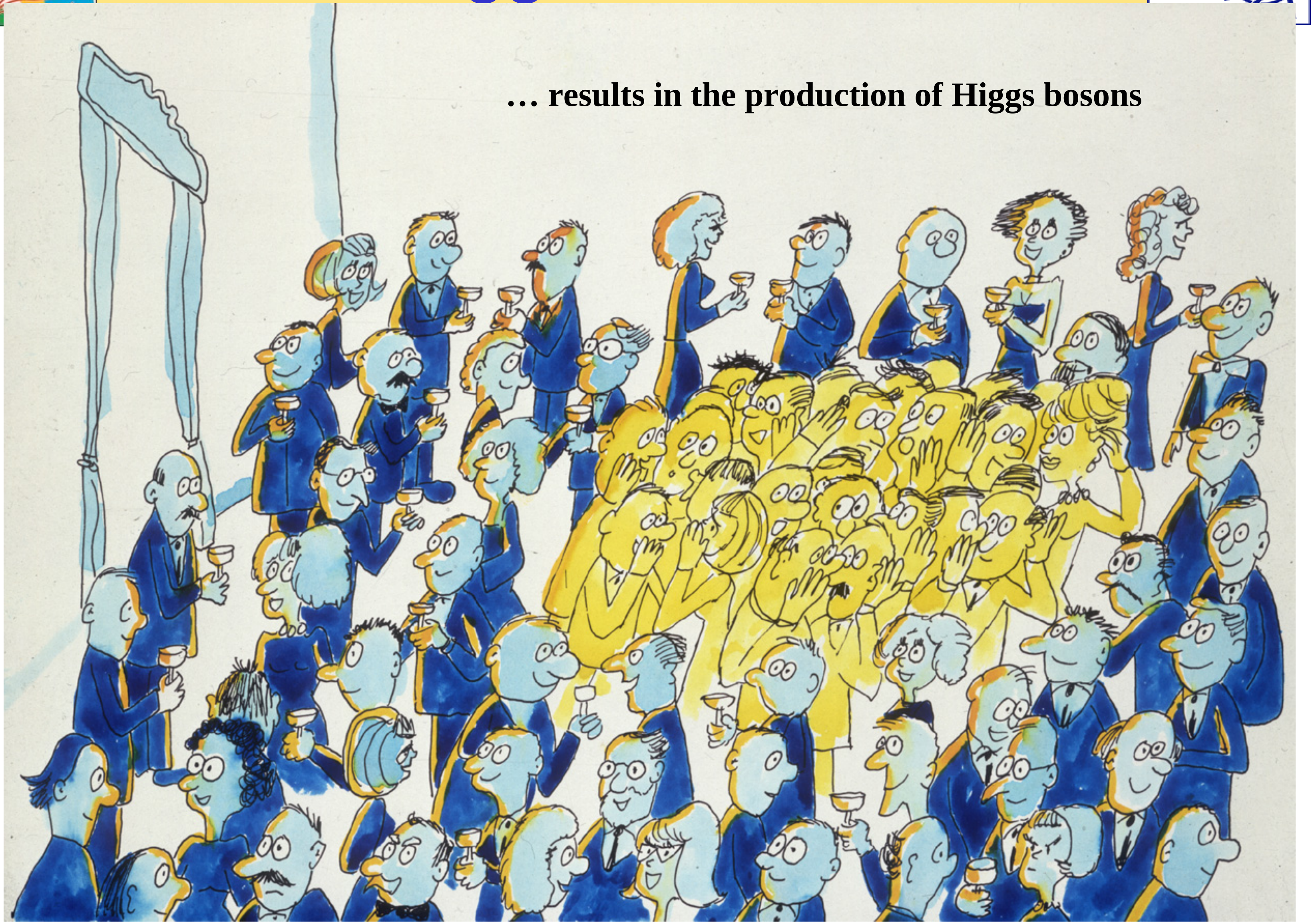


The Higgs Mechanism 2

The Higgs Mechanism 3

The Higgs Mechanism 4

The Higgs Mechanism 5

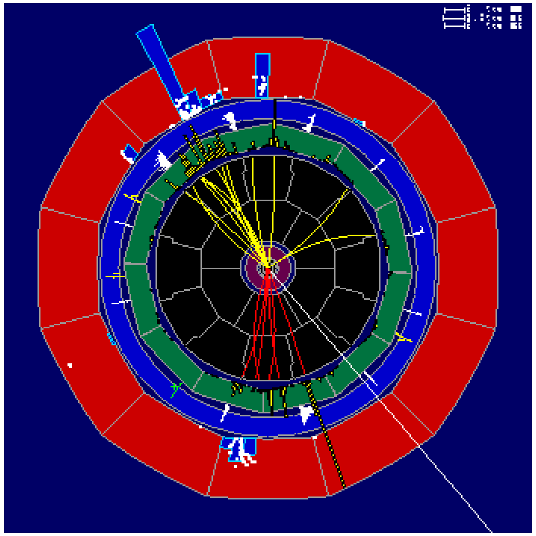


Higgs Phenomenology

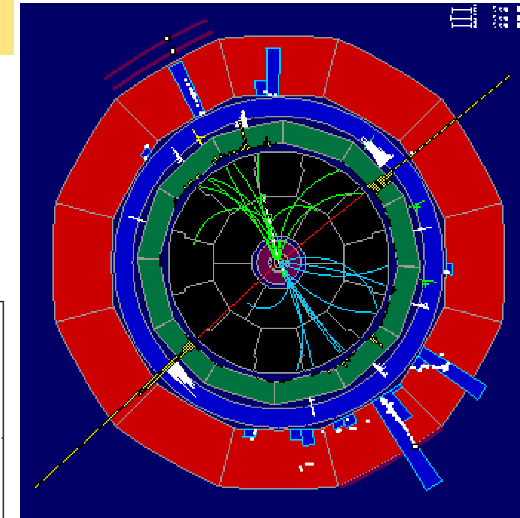
- Existence of the Higgs field has 3 main consequences
  - W and Z bosons *acquire mass* in the ratio $M_W/M_Z = \cos\theta_W$
  - neutral Higgs bosons H° *must exist* !
  - interactions with the Higgs field can *generate* fermion masses
- *This is the most important prediction of the Standard Model which has not been verified by experiment*
- Designing experiments to search for H° is not easy ...
  - the theory does *not predict* the mass of the Higgs boson
  - however, the theory does predict its couplings to other particles
    - e.g. *coupling to fermions* $g_{ffH} \sim m_f$
  - Since H° couples strongly to W and Z the best places to search for it are at LEP and at Hadron Colliders …
- Precise EW data places important limits on M_H ...

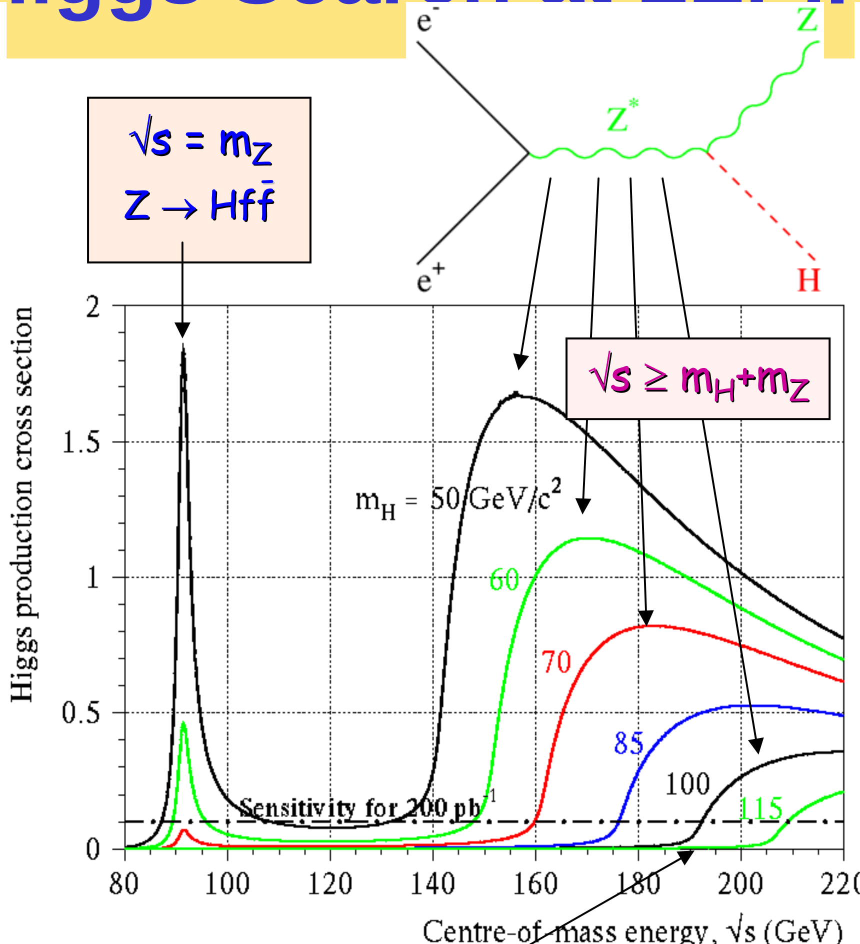
Higgs Search at LEPII

$H\nu\bar{\nu}$

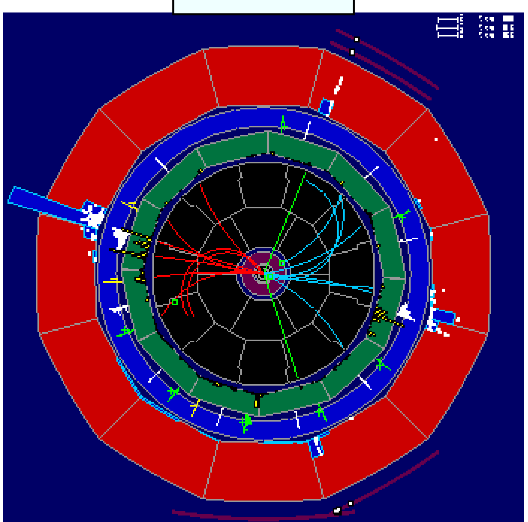


He^+e^-

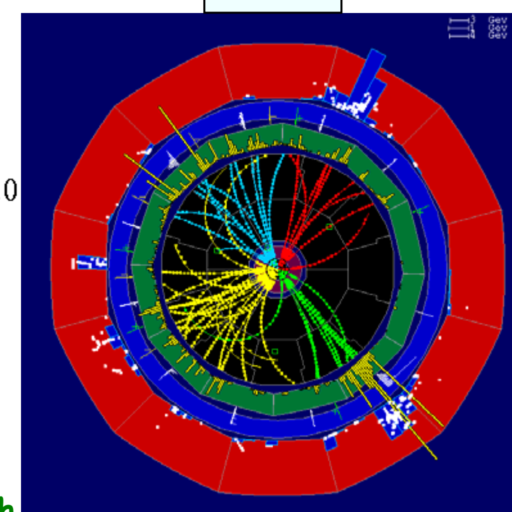




$H\mu^+\mu^-$



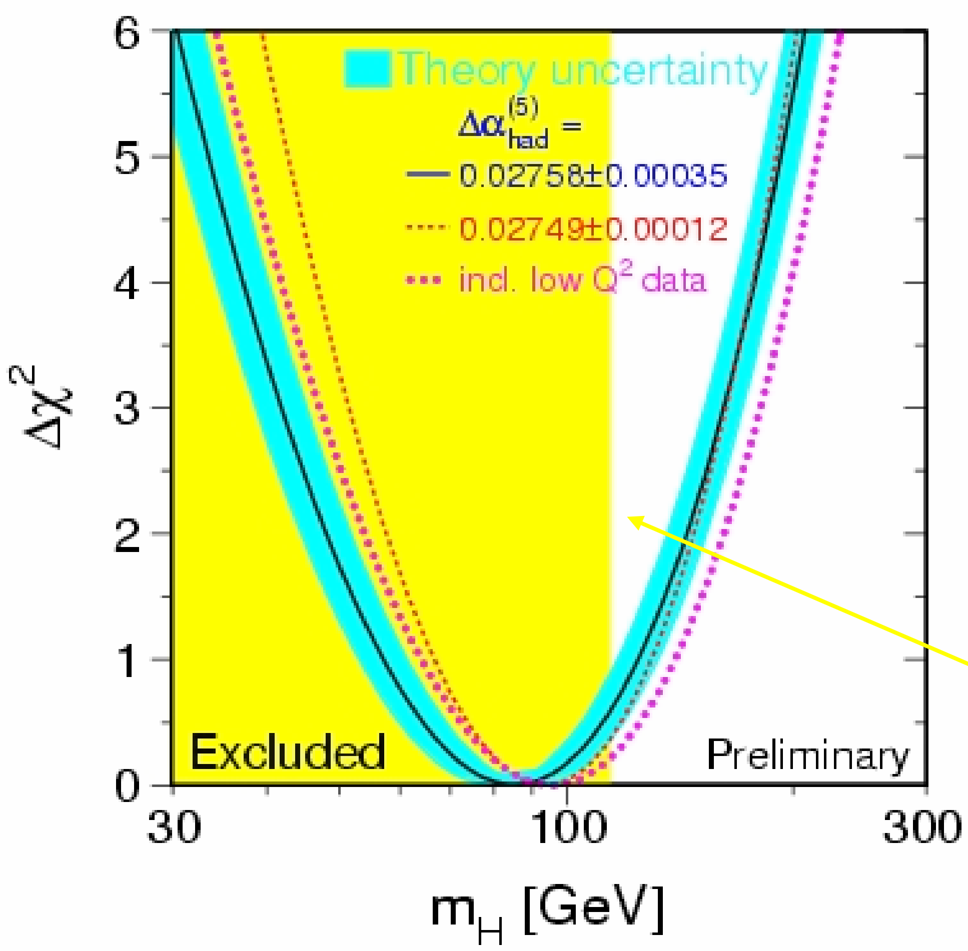
$Hq\bar{q}$



5σ sensitivity for 200 pb^{-1}:

- $\sqrt{s}$ = 192 GeV for m_H = 100 GeV/c^2;
- $\sqrt{s}$ = 210 GeV for m_H = 115 GeV/c^2;

Constraint on Higgs Mass



$$m_{\text{Higgs}}^{\text{EW}} = 85\,^{+39}_{-28}\ \text{GeV}/c^2$$

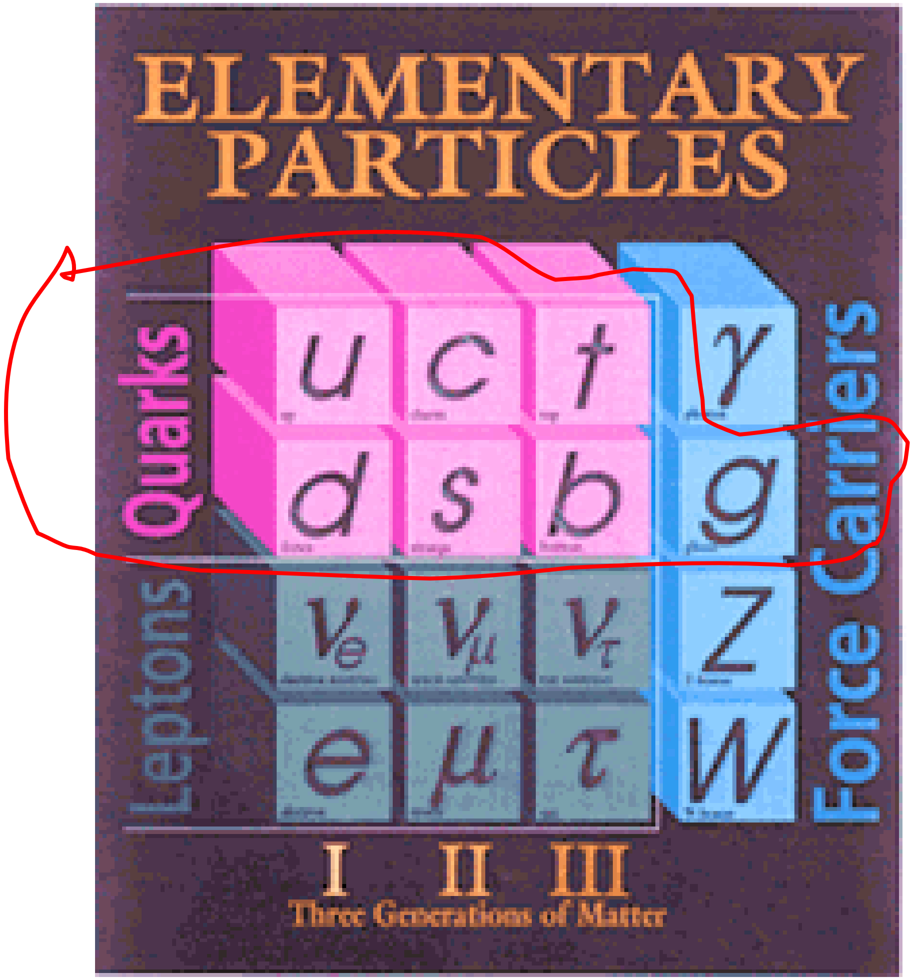
$$m_{\text{Higgs}} \leq 166\ \text{GeV}/c^2 \ \text{at 95\% C.L.}$$

Direct search from LEP

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*


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

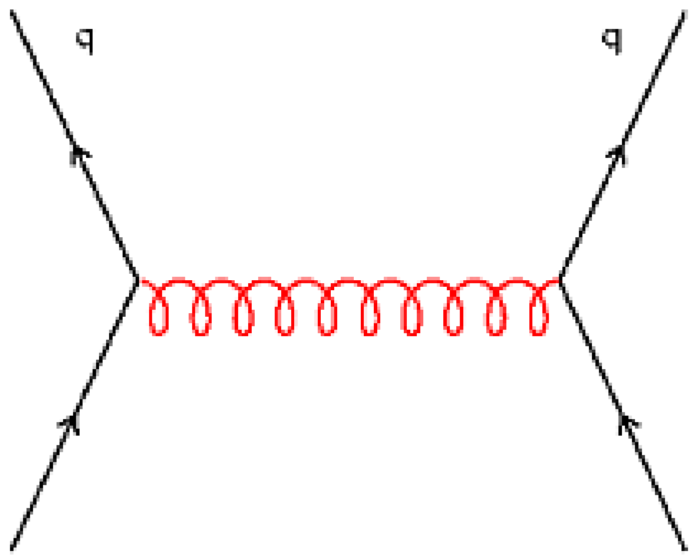
A Century of *Strong* Nobel Prizes

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

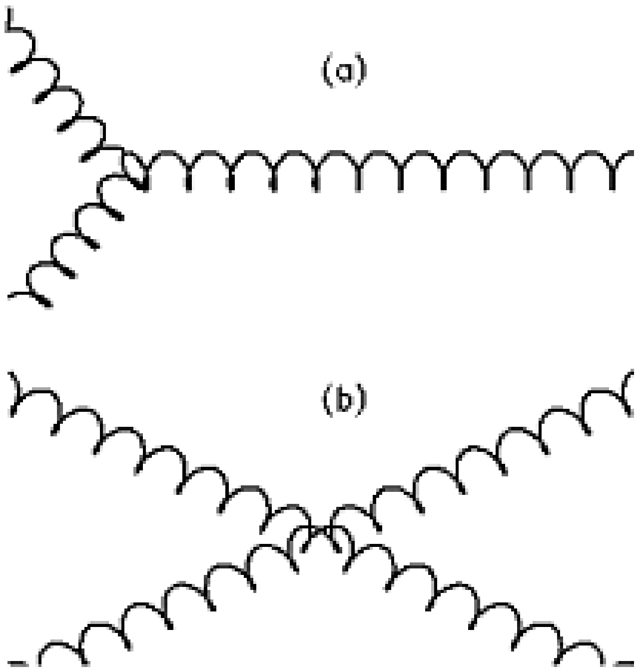
- no Prize for top quark discovery (too many physicists involved!)

The Running Coupling Constant

Feynman Diagram of Quark–Quark Scattering



Gluon Interactions

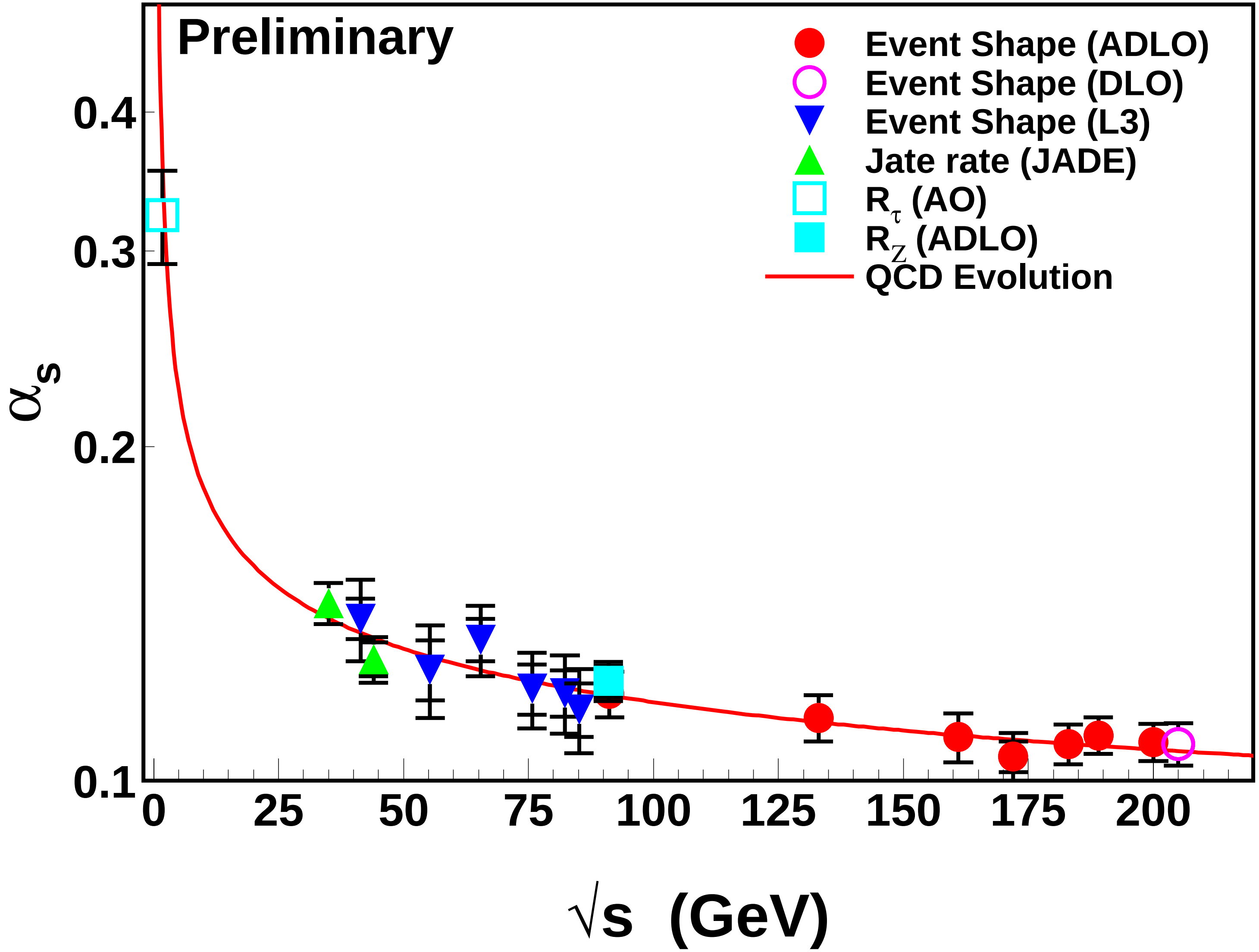


The Running Coupling Constant

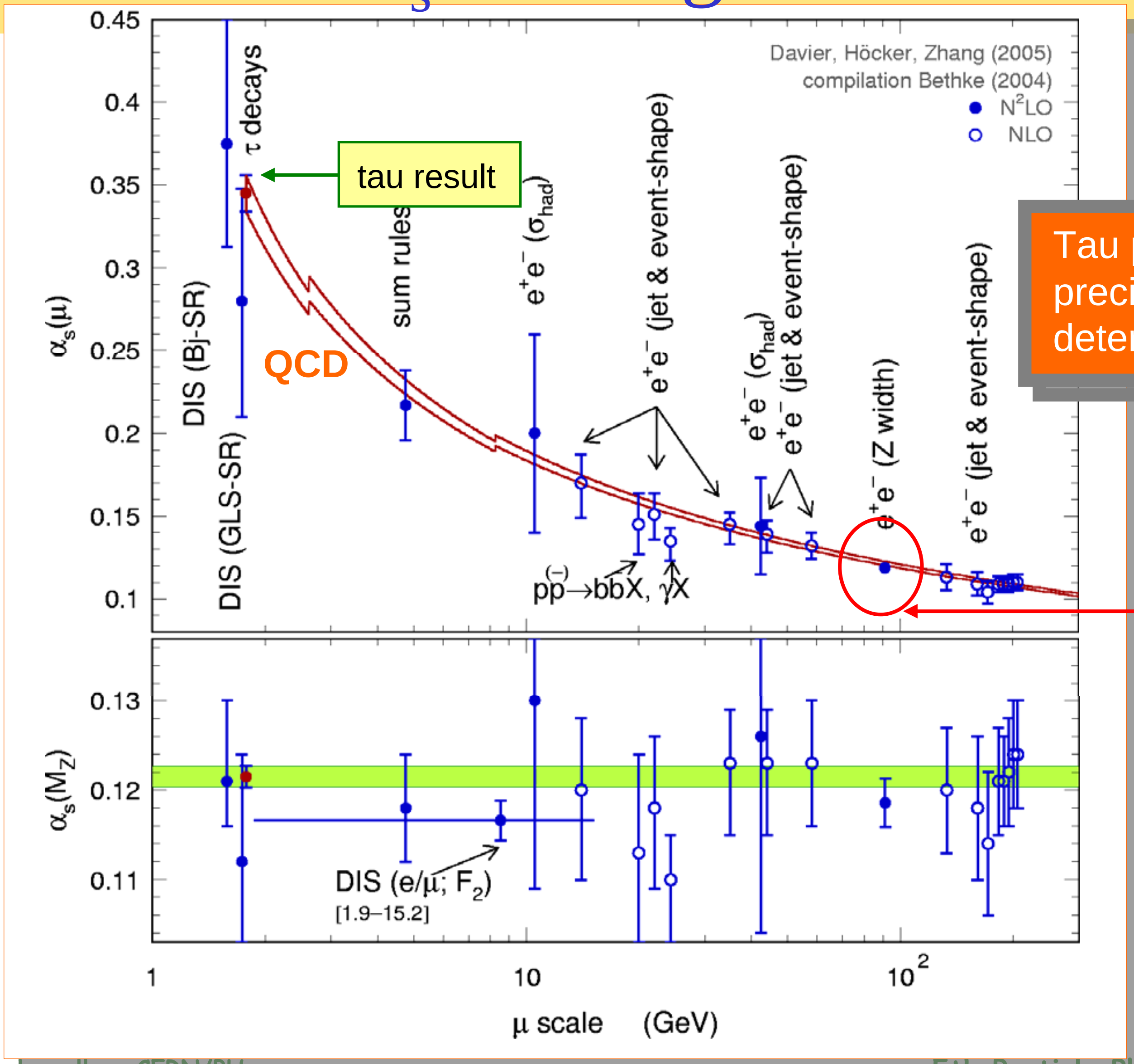
- in QCD, screening of a quark's colour charge also occurs as a result of the creation of *virtual* quark-antiquark pairs due to fluctuations in the *gluonic* fields of the vacuum
- … however, the fluctuations in the gluonic fields of the vacuum also produce additional gluons (because of gluon self-coupling) 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

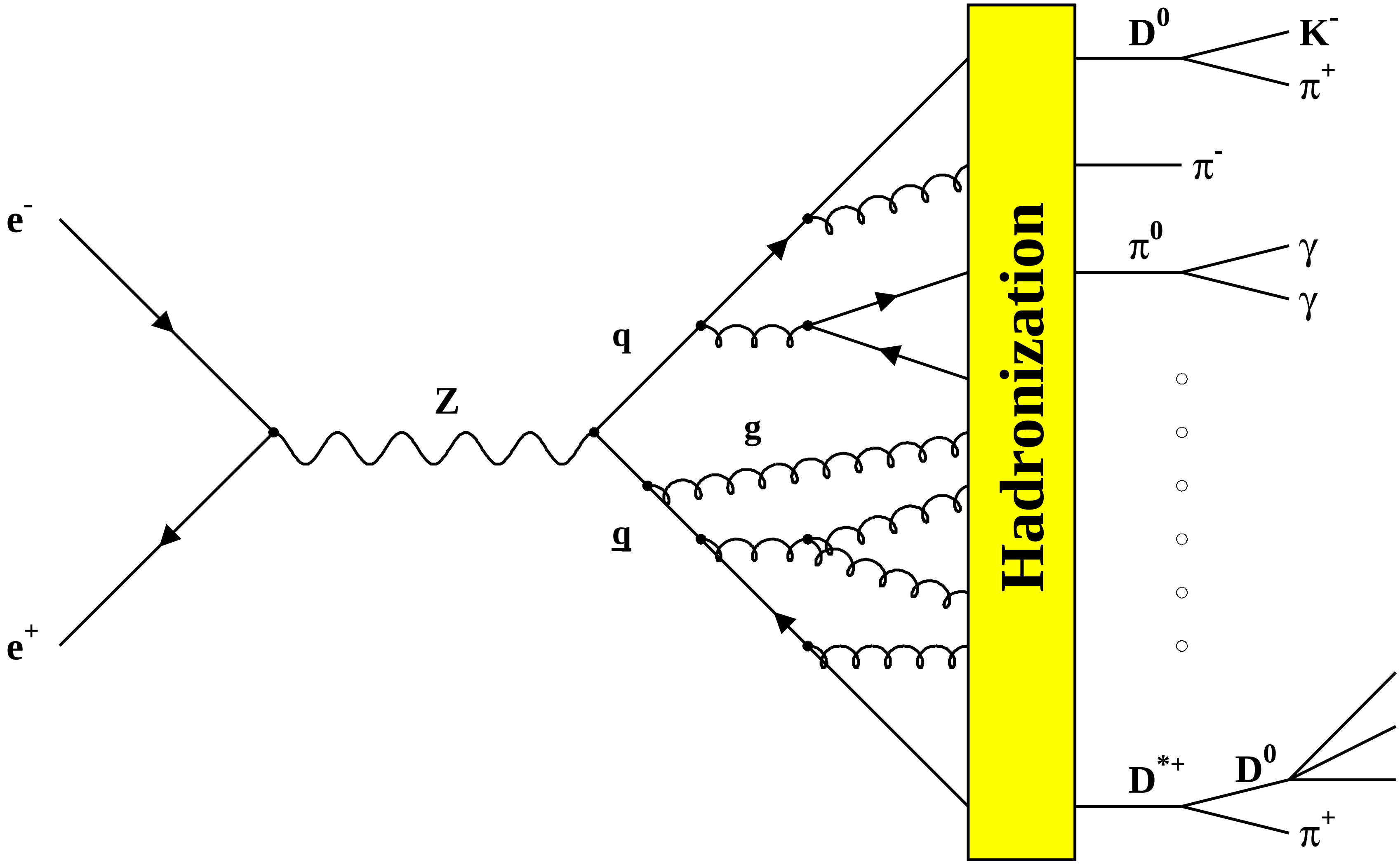


Tau provides most precise $\alpha_s\,(M_Z^2)$ determination

Hadronisation

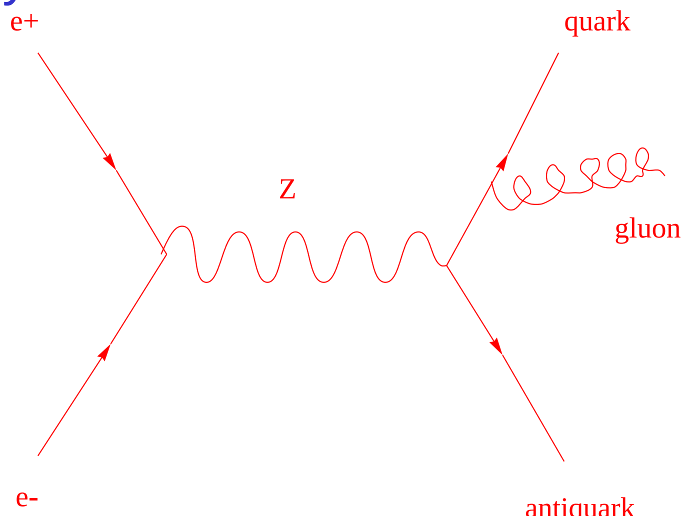
- Due to *confinement*, when the quarks produced in $e^+e^- \rightarrow q\bar{q}$ move apart the force F between them grows with separation ...
  - Energy = $\int$ F.dx and so, as the quarks move apart, the potential energy stored in the *colour field* between them also grows …
  - … until the potential 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 α_s precludes a perturbation theory approach to calculations

Hadronisation



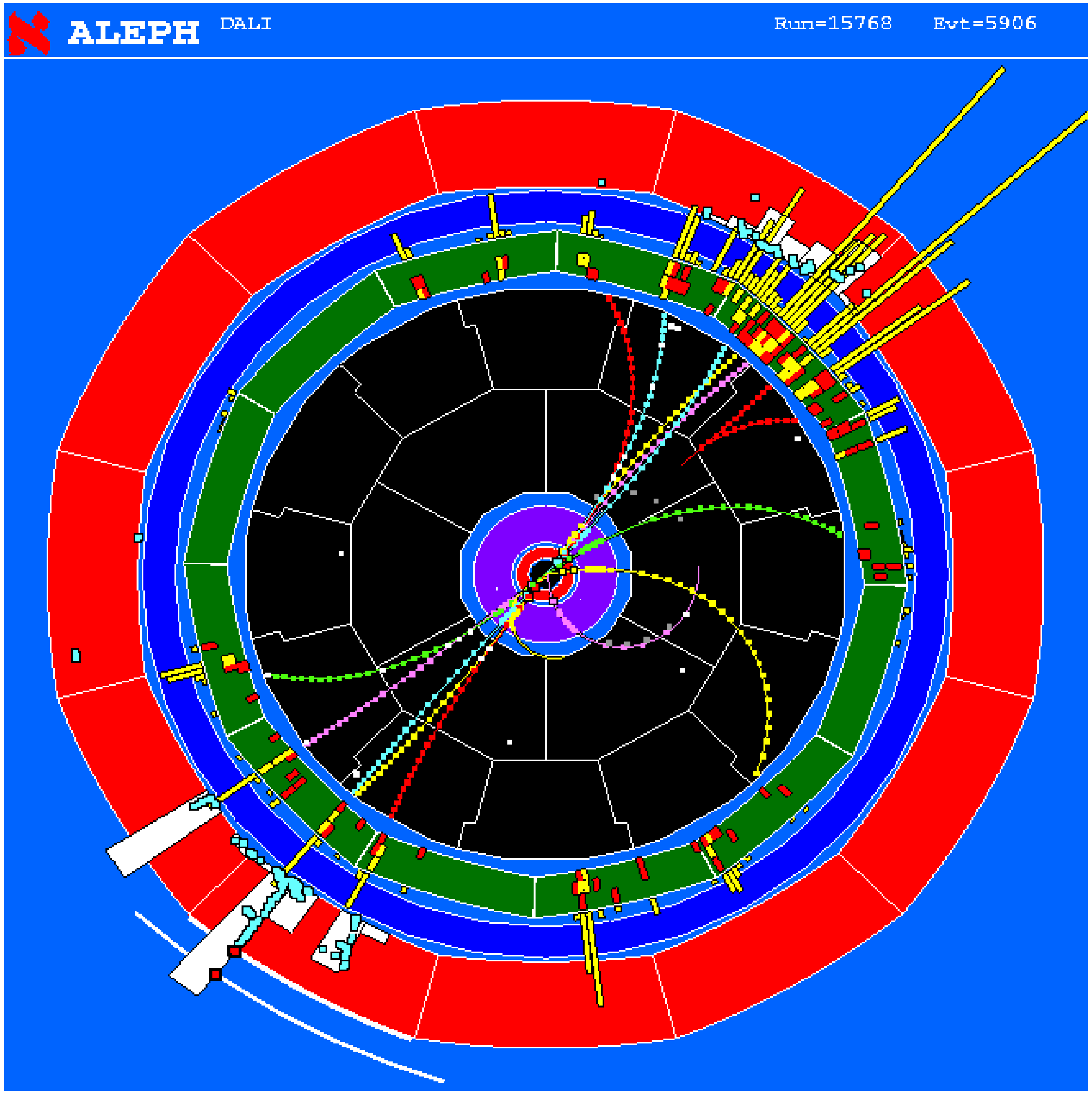
Observation of Gluons

- 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

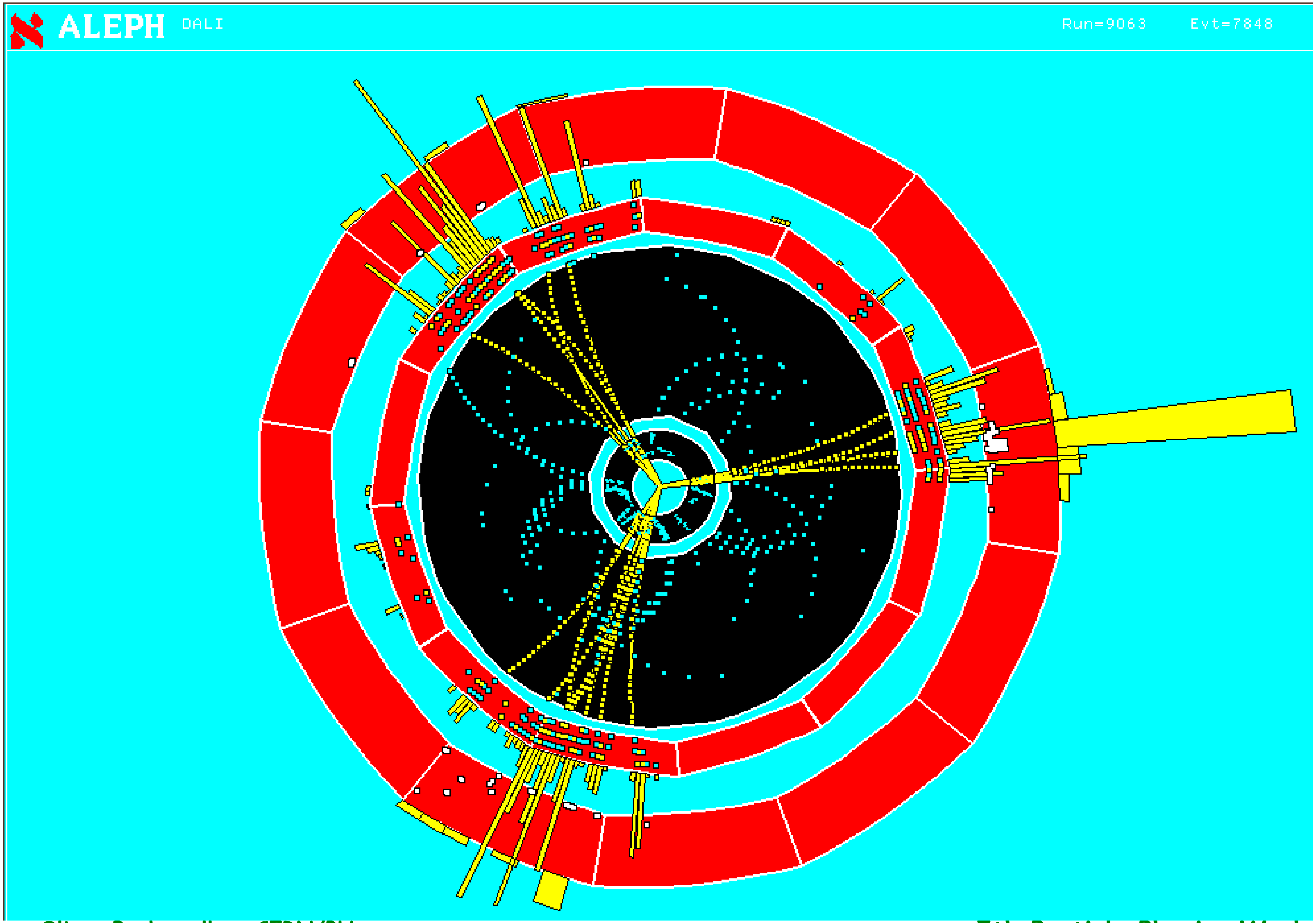


- probability for *gluon* bremsstrahlung is larger than *photon* bremsstrahlung by a factor $\alpha_s / \alpha = 0.12 / (1/137) \approx 15$
- in some cases a large amount of the initial quark energy can be transferred to the gluon resulting in 3 widely separated jets

e+e- → qq̄ → 2 jets



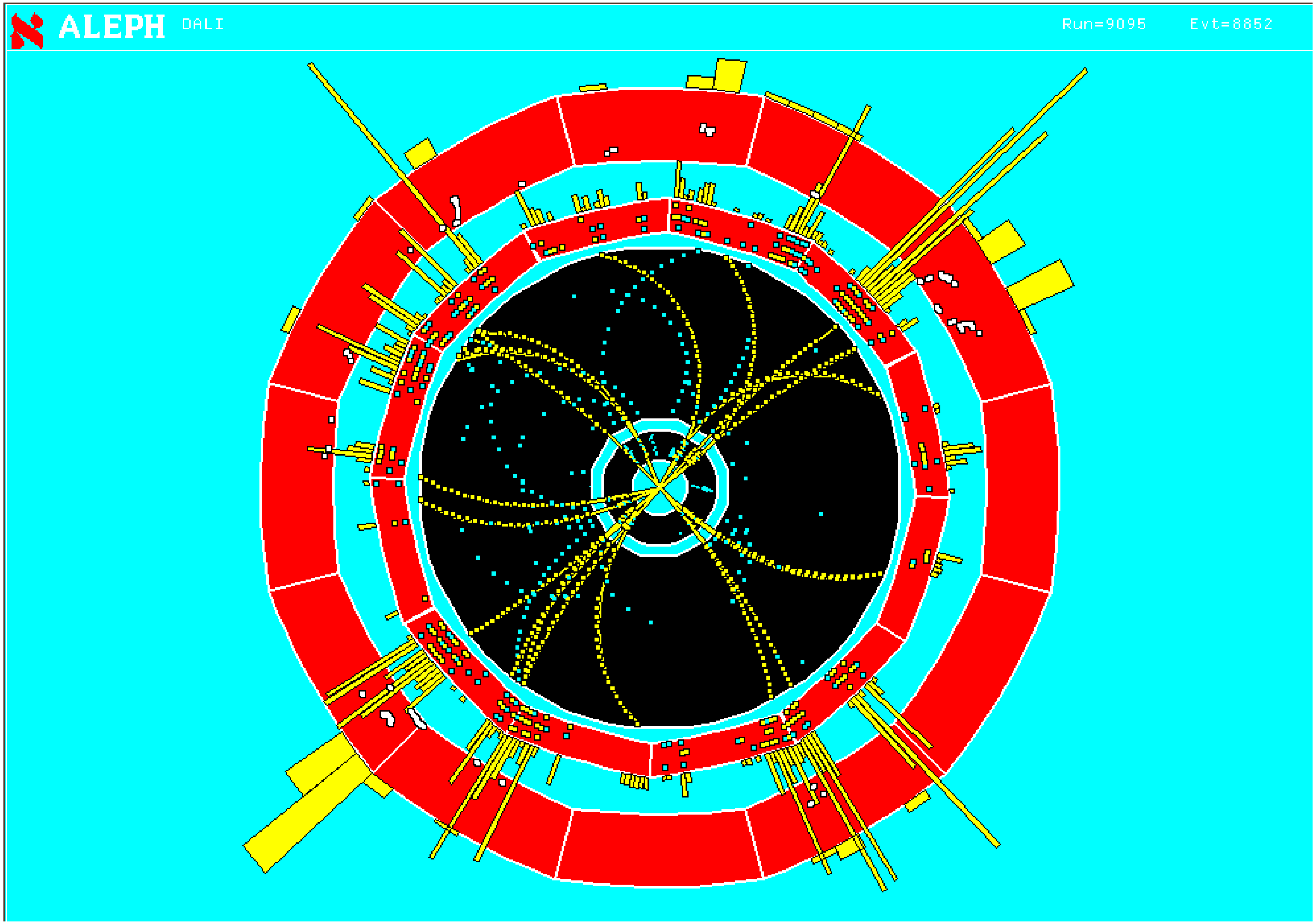
e+e- → qqg → 3 jets



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 $\sim \alpha_s^2 / \alpha_s \sim 0.12$
  - 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

$e^+e^- \to q\bar{q}gg \to$ 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)