Introduction to the Standard Model of Strong and Electroweak Interactions

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Historical Survey

Discovery of Elementary Particles

Year	Discovery		
1891	e^-	G.J. STONEY	name coined : unit of electricity
1897		J.J. THOMSON	measurement of m/e
		W. KAUFMANN	
1899		J.J. THOMSON	measurement of $e \simeq 6.8 10^{-8}$ esu
1914	p	E. RUTHERFORD	H–particle
1920			term: *proton* 1st used
1932	n	J. CHADWICK	$\alpha + Be^9 \rightarrow C^{12} + n$
1931	e^+	C.D. ANDERSON	cosmic rays
1936	μ	S.H. NEDDERMEYER	cosmic rays
		C.D. ANDERSON	
1947	$\pi^\pm$	C. LATTES et al.	cosmic rays
1947	K^0, Λ	G.D. ROCHESTER,	cosmic rays
		C.C. BUTLER	
1950	π^0	A.G. CARLSON et al.	$\pi^- + p \rightarrow \pi^0 + n$
		R. BJORKLAND et al.	
1956	ν_e	C.L. COWAN et al.	$\overline{\nu}_e + p \rightarrow e^+ + n$
1962	ν_μ	G. DANBY et al.	$\nu_\mu + n \rightarrow p + \mu^-$
			$\overline{\nu}_\mu + p \rightarrow n + \mu^+$
1964	Ω^-	V.E. BARNES et al.	$K^- + p \rightarrow \Omega^- + K^+ + K^0$
1974	J/ψ	J.J. AUBERT et al.	pN BNL
		J.E. AUGUSTIN et al.	e^+e^- SPEAR
1975	τ	M. PERL et al.	$e^+e^- \rightarrow \tau^+\tau^-$, SPEAR
1978		R. BRANDELIK et al.	1st mass measurement
			DASP, DORIS
1977	Υ	S.W. HERB et al.	pN FNAL (400 GeV)

Table 1:

Towards the Fundamental Forces

Year	Discovery		
1900	γ	P. VILLARD	γ rays
1905		A. EINSTEIN	photo–electric effect light quanta
1923/25		A.H. COMPTON et al.	$\gamma e^- \to \gamma e^-$
1926		G.N. LEWIS	term: *photon* 1st used
1896	Radioactivity	H. BECQUEREL	$K_2UO_2(SO_4)2H_2O$
1899	β^-		separated β^- particles
1914		J. CHADWICK	continous! β^- spectrum
1973	NC	F.J. HASERT et al.	$\nu_\mu e^- \to \nu_\mu e^-$ GARGAMELLE, CERN
1979	g	R. BRANDELIK et al.	3 jets in e^+e^- TASSO, DORIS
1983	W, Z	G. ARNISON et al. M. BANNER et al.	$p\bar{p}$, UA1, CERN UA2

Table 2:

$\mathcal{C}, \mathcal{P}$ and $\mathcal{CP}$ Violation

Year	Discovery		
1957	$\mathcal{C}, \mathcal{P}$ violation	C.S. WU et al.	Co^{60} decays
1964	$\mathcal{CP}$ violation	J.H. CHRISTENSEN et al.	$K_L^0 \to \pi^+\pi^-$

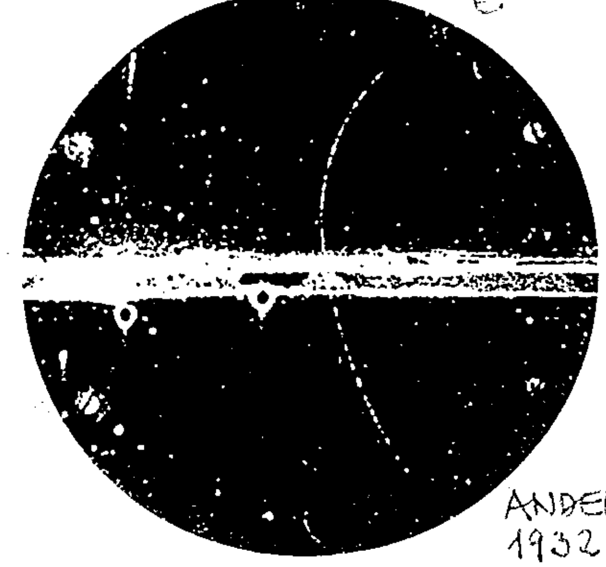
Table 3:

Study of the Nucleon Structure

Year	Discovery	
1911	Atomic Nuclei	E. RUTHERFORD
1933	anomalous magnetic moment of p	R. FRISCH, O. STERN
1933 1940	anomalous magnetic moment of n	R. BACHER L. ALVARZ, F. BLOCH
late 1950ies	charge distribution inside p and n	R. HOFSTADTER et al.
1969	scaling of structure functions	E.D. BLOOM et al. M. BREIDENBACH et al.
1970ies	scaling violations	νN and μN experiments
$\sim$ 1975	1st extraction of quark and gluon distributions from DIS data	νN experiments

Table 4:

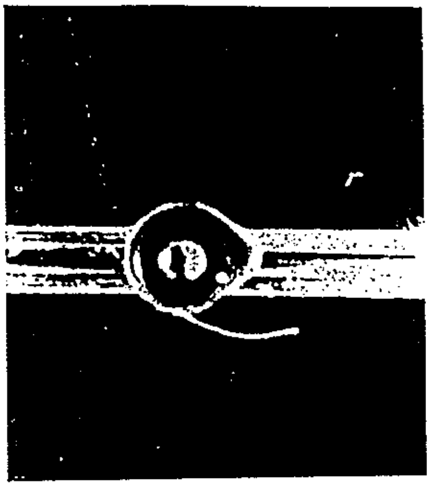
e^+



ANDERSON
1932

Fig. 1.2: Wilsonkammeraufnahme eines Positrons. Das Teilchen dringt von unten in die Kammer, verliert in der Materialschicht (Mitte) Energie, so daß die Krümmung der Spur stärker wird. Aus Magnetfeldrichtung und Ionisierungsdichte schloß Anderson auf ein positiv geladenes Teilchen mit der Masse des Elektrons [An 33].

μ

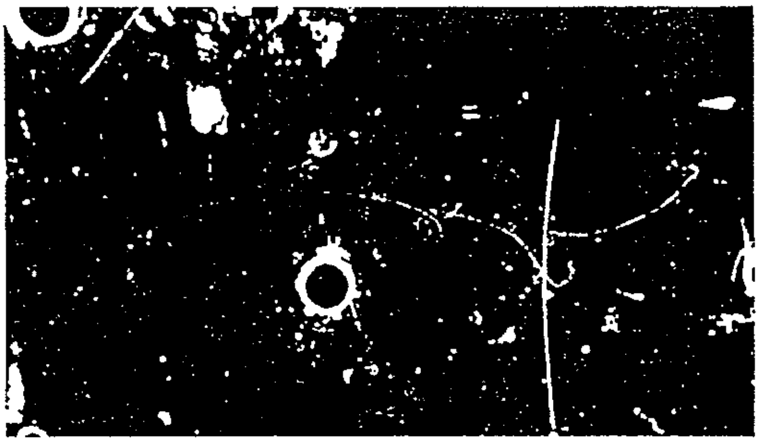


~ 1936

Fig. 1.3: Spur des Myons in der Wilsonkammer. Das Myon dringt von oben ein. Es hat nach Durchdringen von Materialschichten (Zählrohrwände) eine geringere Energie und wird stärker abgelenkt. Die Dichte der Spur ist wesentlich größer als die einer Elektronenspur mit gleichem Krümmungsradius [Ne 38].

ANDERSON,
NEDDERER-
MEYER

NEUTRAL CURRENTS



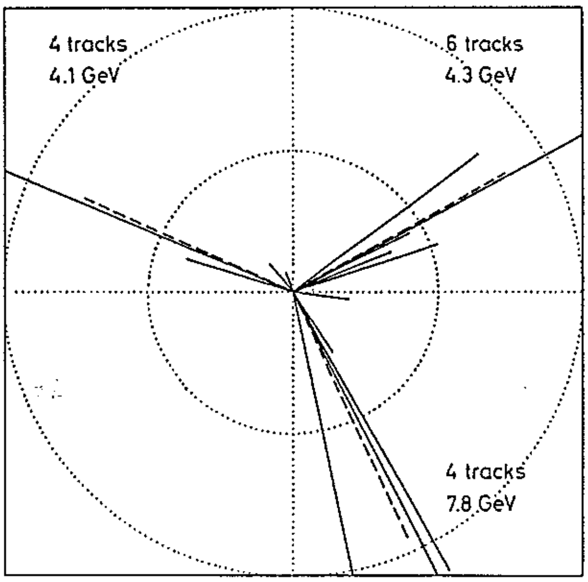
NC

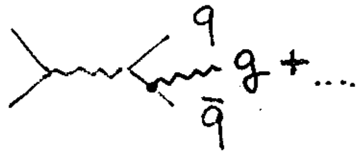
$\overset{(-)}{\nu}_\mu e^- \rightarrow \overset{(-)}{\nu}_\mu e^-$

1973

This portion of an image from Gargamelle captures an historic moment – the first example of a neutrino reacting with an electron via the weak neutral current. The track beginning towards the left of the picture is due to a lone electron, knocked from an atom in the liquid by an invisible high-energy neutrino. The electron's track displays the characteristic short curly branches due to interactions with other electrons in the liquid. (The white spots with black centres are some of the ring-shaped flashlights used to illuminate the trails of bubbles.) (CERN.)

GARGAMELLE





1979 TASSO

(B. Wiik, BERGEN
v '79)

Fig. 3. The first three-jet event at PETRA, seen in TASSO [2]. The tracks are projected into the event plane. The computed jet directions are shown as dashed lines.

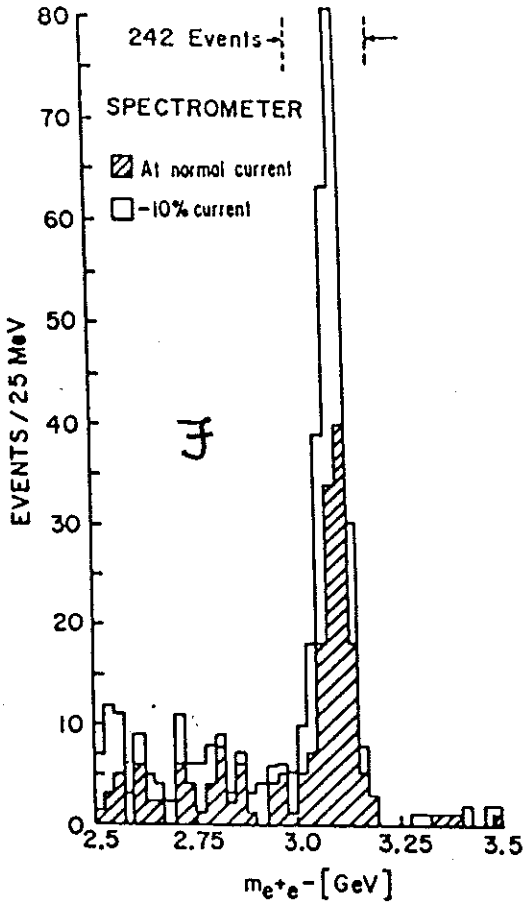


FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

BNL.

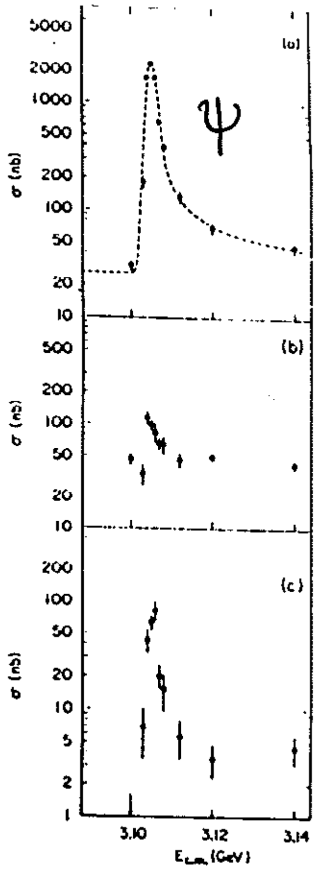
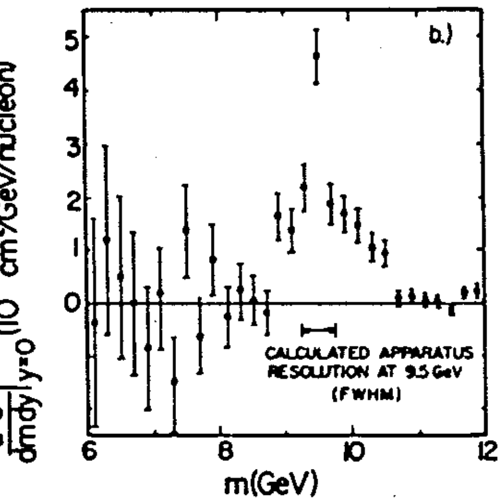


FIG. 1. Cross section versus energy for (a) multihadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

SPEAR

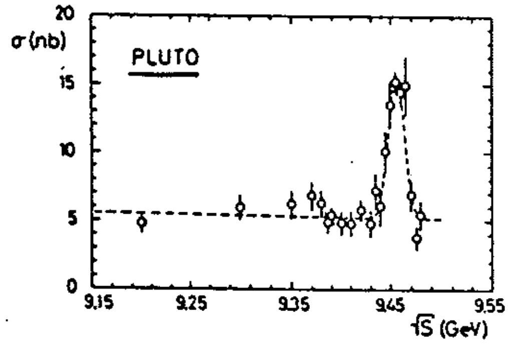
1974



Υ

FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 9–10-GeV region in more detail.

FNAL 400 GeV



e^+e^-

'78

Fig. 2. Total cross section for hadron production in e^+e^--annihilation as a function of center of mass energy. There is an additional systematic error (not shown) of 20%. Contributions from the heavy lepton are included.

1977

DORIS

6

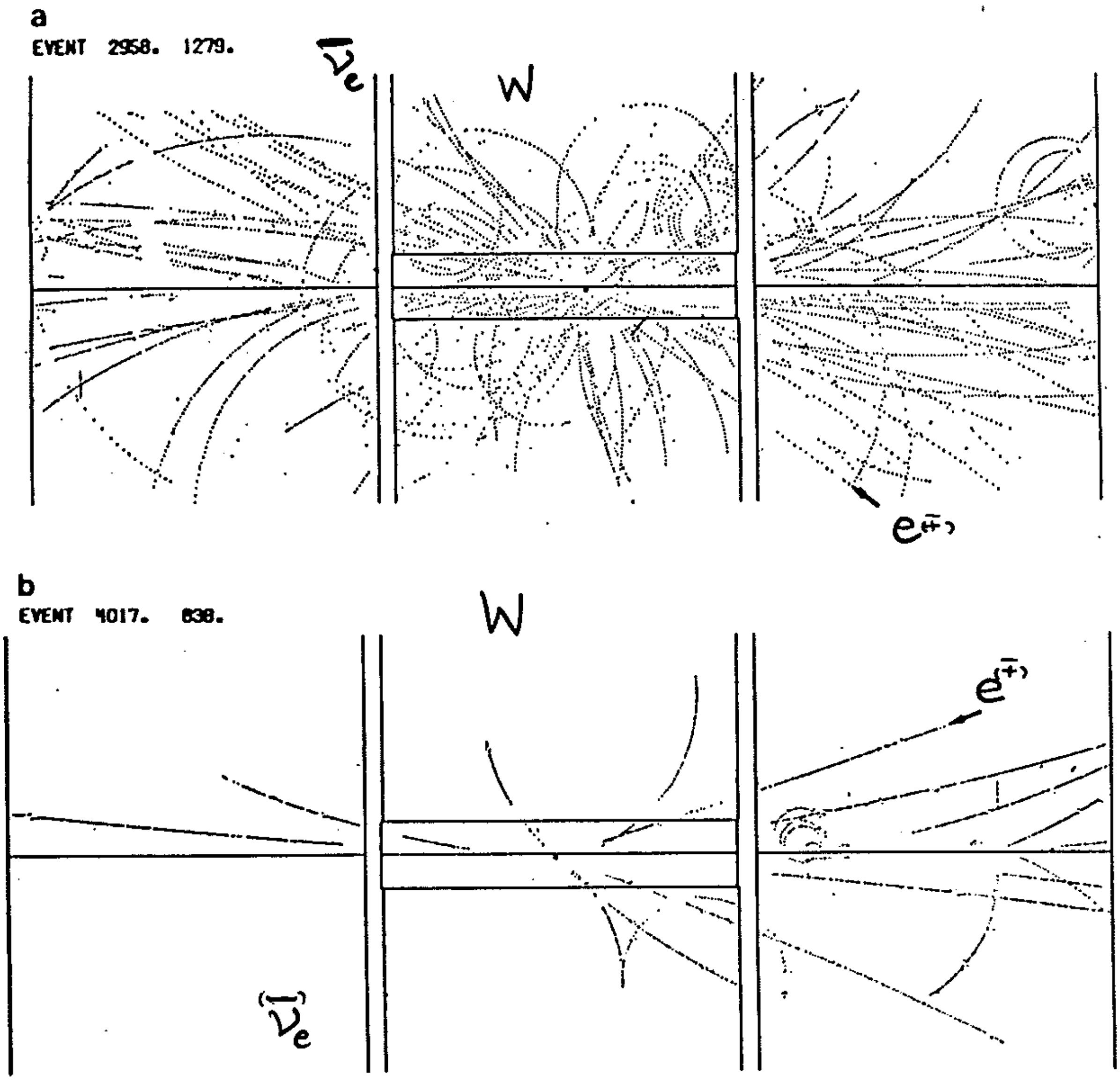
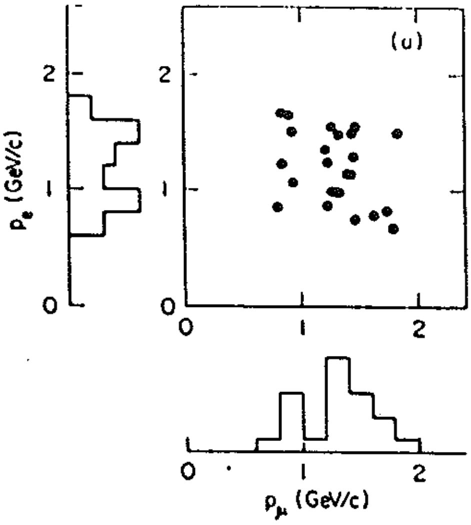


Fig. 6. The digitization from the central detector for the tracks in two of the events which have an identified, isolated, well-measured high-p_T electron: (a) high-multiplicity, 65 associated tracks; (b) low-multiplicity, 14 associated tracks.

UA 1

e



μ

$\tau^\pm \to \nu_\tau\, e^\pm \overset{(-)}{\nu}_e$

$\tau^\mp \to \overset{(-)}{\nu}_\tau\, \mu^\pm \overset{(-)}{\nu}_\mu$

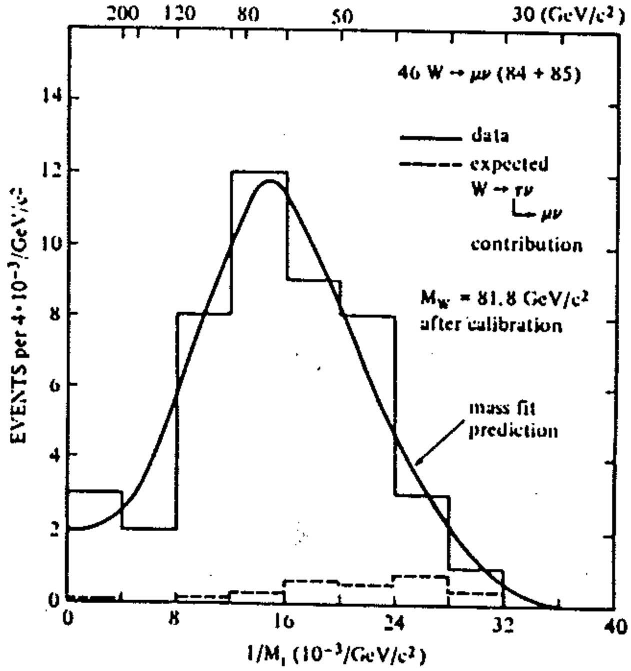
$e^+e^- \to \tau^+\tau^-$

Perl et al. 1975

SPEAR (SIGNATURE)

1ST: $m_\tau = 1807 \pm 20$ MeV

DASP (DORIS).



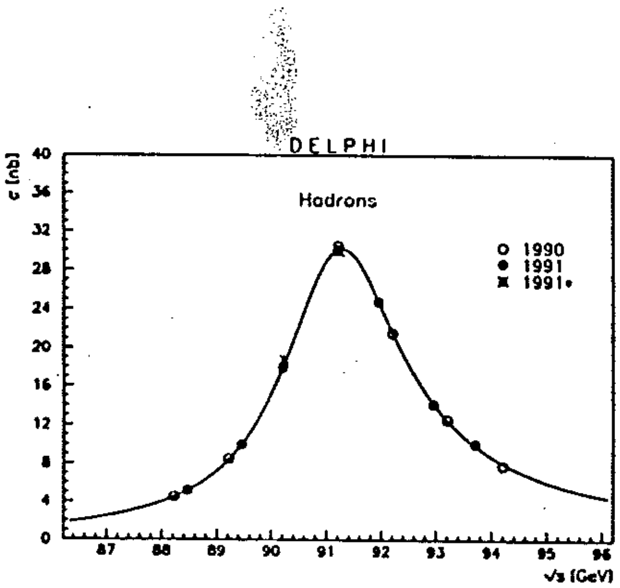
W's 1984,85

UA2

statistics

$Sp\bar{p}S$

Fig. 4.3.10 Inverse transverse mass distribution for muon-neutrino pairs in UA1. The variable $1/m_T$ is chosen instead of m_T, because the error resulting from momentum resolution is Gaussian in $1/m_T$ and not in m_T.



Z peak, DELPHI

Z → hadrons.

(1992)

LEP

HOFSTADTER et al
1950'ies

CHARGE DISTRIBUTION OF NUCLEONS

(OLSON, SCHOPPER & WILSON, 1961)

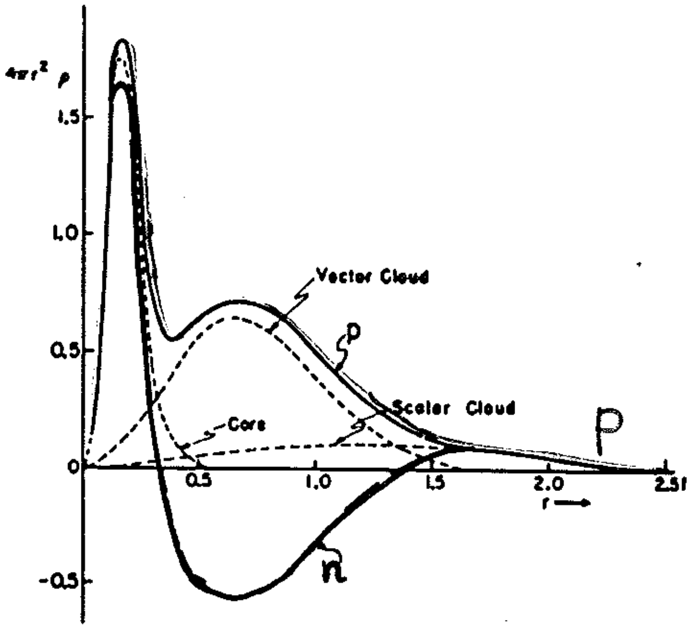


FIG. 4. Charge distribution for the proton and the neutron implied by the form factors shown for the fit (b) in Fig. 2(b).

OBSERVATION OF SCALING

SLAC-MIT

early 1970'ies

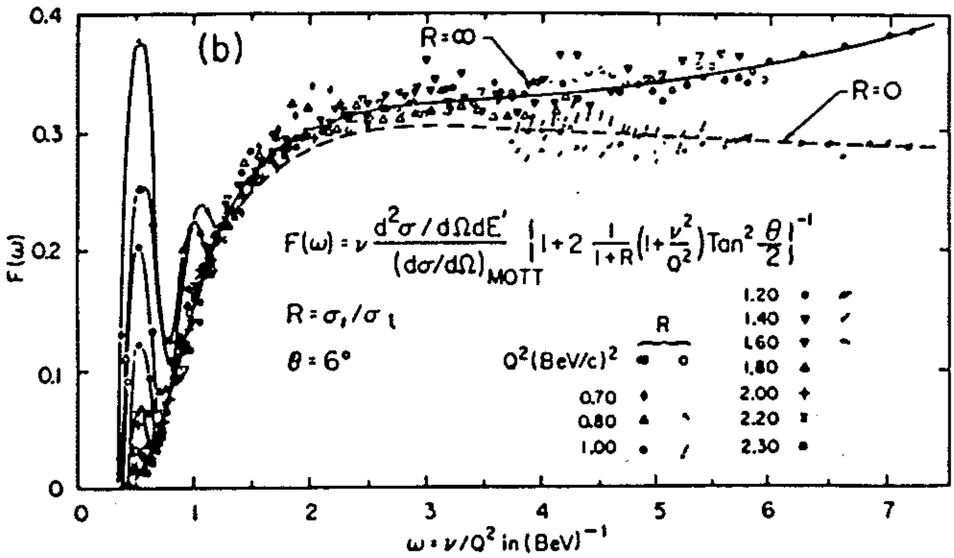
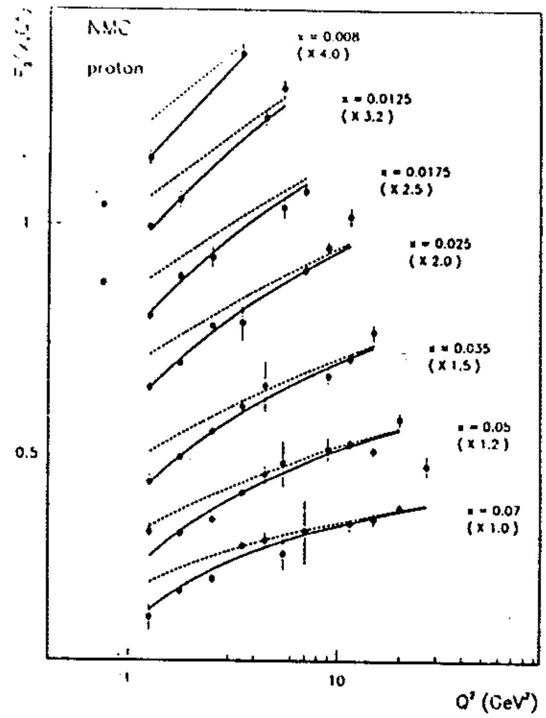
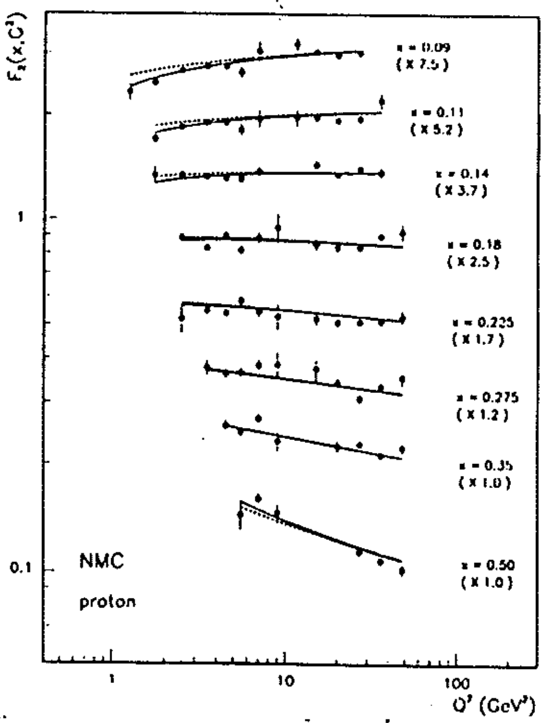
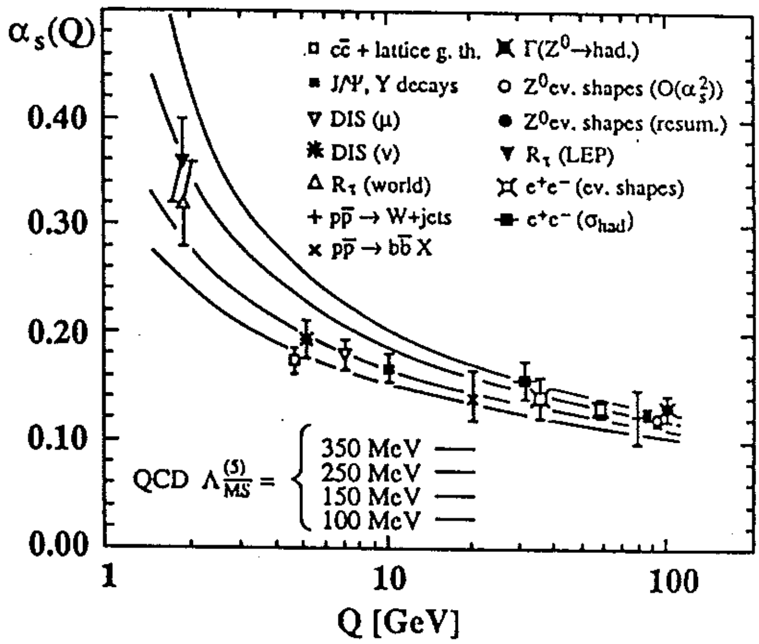


FIG. 12. (a) The inelastic structure function $W_2(\nu,q^2)$ plotted against the electron energy loss ν. (b) The quantity $F_1=\nu W_2(\omega)$. The "nesting" of the data observed here was the first evidence of scaling. The figure is discussed further in the text.







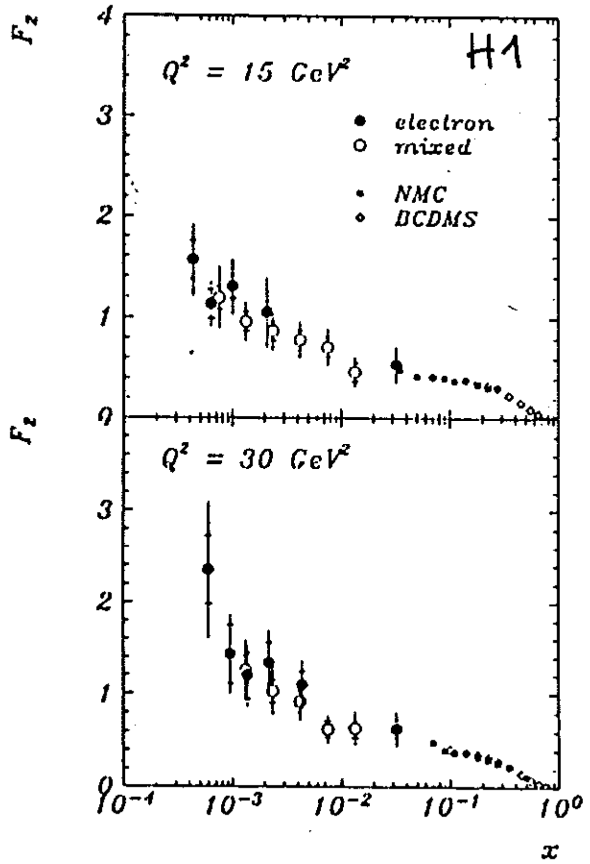
CONFIDENCE IN THE RUNNING OF $\alpha_s(Q)$.

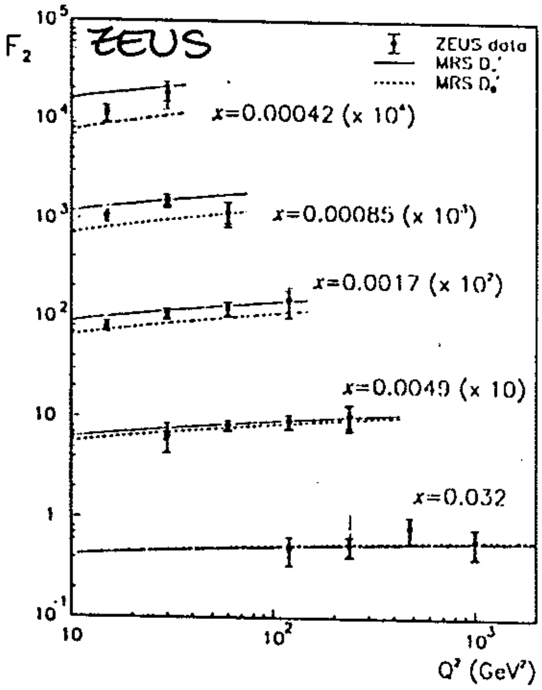
(BETHKE '92

NMC 1993:

AN EXAMPLE FOR VARIOUS PRECISE MEASUREMENTS OF SCALING VIOLATIONS

RECENT HERA RESULTS: (AUG. '93)





$F_2 \propto 1/x^{0.5}$

$\frac{\partial F_2}{\partial \ln Q^2} \approx C(x)$!?

WHY WE BELIEVE IN QUARKS

BOUND STATES: MESONS $|q\bar{q}\rangle$

$q = u, d, s$

$$3 \otimes \bar{3} = 1 \oplus 8$$

BARYONS $|qqq\rangle$

$$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$$

SPIN OF QUARKS : $s_q = \frac{1}{2}$

$S(B) = \frac{1}{2}, \frac{3}{2}$

$S(M) = 0, 1$

COLOR NEUTRALITY OF HADRONS:

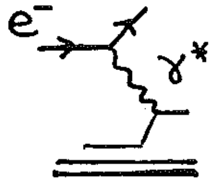
$$B = |q_r q_b q_g\rangle$$
$$M = |q\bar{q}\rangle$$

QUARKS ARE CONFINED.

SO FAR : EXPTL. SEARCHES FOR FREE QUARKS HAVE BEEN NEGATIVE;

(1 EXCEPT. : LARUE . et al. 1977
SUBTLE MAGNETIC EFFECT ?)

- QUARK SPIN $\frac{1}{2}$:



$$\boxed{\frac{\sigma_L}{\sigma_T} = 0} \qquad (\mathcal{O}(\alpha_s^0))$$

CALLEN, GROSS

- FRACTIONAL CHARGES :

- ratio of $M_V^2 \Gamma(V^0 \to f\bar{f}) \sim \underline{e_q^2} \, |\psi(0)|^2$

$$|\rho_0\rangle = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d}) \qquad e_q^2 = \frac{1}{2}$$

$$|\omega_0\rangle = \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) \qquad e_q^2 = \frac{1}{18}$$

$$|\phi\rangle = s\bar{s} \qquad e_q^2 = \frac{1}{9}$$

- $$\frac{F_2^{ed}}{W_2^{\nu d} + W_2^{\bar{\nu} d}} = \frac{\frac{5}{18}\Sigma + \frac{1}{6}(c-s)}{\Sigma} \approx \frac{5}{18}$$

- & COLOR :

- $$R = \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)} \approx \sum_f e_{q_f}^2 \underset{\uparrow \atop 3}{N_c} \, \theta(s - 4m$$

$$R_3 = 3 \times \left(\frac{4}{9} + 2 \cdot \frac{1}{9}\right) = 2$$

$$R_4 = 3 \times \left(\frac{8}{9} + \frac{2}{9}\right) = \frac{10}{3}$$

$$R_5 = \qquad \frac{11}{3} \text{ etc.}$$

- $$\mathrm{Br}\,(\tau^- \to e^- \bar{\nu}_e \nu_\tau) = \frac{\Gamma(\tau \to e^- \bar{\nu}_e \nu_\tau)}{\Gamma(\tau \to \text{all})}$$

$$\approx \frac{1}{1_e + 1_\mu + \underline{N_c} \cdot 1_{\bar{u}d}} \approx \frac{1}{5}$$

$$= (17.44 \pm 0.85)\,\%$$

- $$\Gamma(\pi^0 \to \gamma\gamma) = \left(\frac{\alpha}{2\pi}\right)^2 \left[N_c\,(e_u^2 - e_d^2)\right]^2 \frac{m_\pi^2}{8\pi f_\pi}$$

$$= \begin{cases} 0.86\ \text{eV} & N_c = 1 \\ 7.75\ \text{eV} & N_c = 3 \end{cases}$$

$$(\text{exp}:\ 7.86 \pm 0.54\ \text{eV})$$

FUNDAMENTAL PARTICLES

MATTER FIELDS		GAUGE FIELDS		
		W, Z	γ	g
LEPTONS	NEUTRINOS ν_e, ν_μ, ν_τ	✓		
	CHARGED LEPTONS e, μ, τ	✓	✓	
QUARKS	UP u c t	✓	✓	✓
	DOWN d s b	✓	✓	✓

INDIRECT EVIDENCE ONLY: ν_τ, t

FUDAMENTAL SCALAR: H^0

COUPLES TO ALL PARTICLES EXCEPT OF:

$\gamma, g, \nu_i \; (m_{\nu_i} \equiv 0)$.

SYMMETRIES AND CONSERVATION LAWS

NOETHER'S THEOREM (1918)

SYMMETRIES OF SPACE TIME CORRESPOND TO CONSERVATION LAWS.

e.g.: INVARIANCE OF $\mathcal{L}$ UNDER THE POINCARE-GROUP

$\Longleftrightarrow$ MOMENTUM, ENERGY, ANGULAR MOMENTUM CONSERVATION

(CF. SCHMUTZER, 1973)

INVARIANCE AGAINST	CONSERVATION OF	
SPATIAL TRANSLATION	3-MOMENTUM	} 4-MOM.
TEMPORAL TRANSLATION	ENERGY	
(HOMOGENEITY OF SPACE-TIME)		
SPATIAL ROTATIONS	ANGULAR MOMENTUM	
STEADY MOTION	CENTER OF MASS	
(ISOTROPY OF SPACE-TIME)		

SYMMETRIES OF CLASSICAL SPACE-TIME

HERE WE ARE INTERESTED IN THE SO-CALLED

$$\boxed{\text{INTERNAL SYMMETRIES}}.$$

I.E. THOSE OF $\mathcal{L}$ WHICH ARE NOT CONSEQUENCES OF CLASSICAL SPACE TIME.

- EXAMPE : ELECTRIC CHARGE CONSERVATION.

$$\phi_i(x) \to e^{-ie\theta}\,\phi_i(x)$$

$$\delta\phi_i = -ie\varepsilon\,\phi_i$$

$$0 = \delta\mathcal{L} = \frac{\delta\mathcal{L}}{\delta\phi_i}\delta\phi_i + \frac{\delta\mathcal{L}}{\delta\phi_{i|\mu}}\delta(\phi_{i|\mu}) = -i\varepsilon\frac{\partial}{\partial x_\mu}\left[\frac{\delta\mathcal{L}}{\delta(\partial_\mu\phi_i)}e\phi_i\right]$$

$$J^\mu = i\frac{\delta\mathcal{L}}{\delta(\partial_\mu\phi_i)}e\phi_i \curvearrowright \partial_\mu J^\mu = 0$$

$$Q = \int d^3x\, J_0 \quad \text{- CHARGE OPERATOR}$$

GENERATES THE 1-dim. REPRESENTATION $e^{-ie\theta}$ OF $U(1)$.

ELECTRODYNAMICS OF A SCALAR FIELD:

$$\mathcal{L} = (\mathcal{D}_\mu\phi)^\dagger(\mathcal{D}^\mu\phi) - m^2\phi^\dagger\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\mathcal{D}_\mu = \partial_\mu - ieA_\mu$$

CONSIDER NOW THE INFINITESIMAL TRANSFORMATION

$$\phi(x) \to \phi'(x) = \exp[-ie\theta(x)]\,\phi(x)$$

$$\mathcal{L}' = (\mathcal{D}'_\mu \phi')^\dagger (\mathcal{D}^{\mu\prime}\phi) - m^2 \phi'^\dagger \phi' - \frac{1}{2} F'_{\mu\nu} F^{\mu\nu\prime}$$

$$\mathcal{D}'_\mu = \mathcal{D}_\mu + \frac{1}{e}\partial_\mu \theta(x)$$

$$F'_{\mu\nu} \equiv F_{\mu\nu} \quad , \quad \phi'^\dagger \phi' = \phi^\dagger \phi$$

$$\boxed{\left[\phi(x) \to e^{-ie\theta(x)}\phi(x)\right] \Leftrightarrow \left[A_\mu(x) \to A_\mu(x) - \frac{1}{e}\partial_\mu \theta(x)\right]}$$

GAUGE – PHASE TRANSFORMATION.

PHASE TRANSFORMATION GAUGE TRANSFORMATION

ANALOGOUSLY FOR:

FERMI FIELDS & OTHER GAUGE FIELDS.

YANG - MILLS FIELDS

- NON-ABELIAN GAUGE THEORIES.

YANG, MILLS 195?

$$\phi(x) \longrightarrow \phi'(x) = \mathcal{U}(\theta)\,\phi(x) \equiv \exp\left[-iL_j\theta^j(x)\right]\phi(x)$$

$$\boxed{[L_i, L_j] \neq 0}$$

- CONSIDER LIE GROUPS :

$$\boxed{[L_i, L_j] = i\, c_{ijk} L_k}$$

$$\mathcal{D}_\mu \phi(x) = (\partial_\mu - i g L_j A^j_\mu)\,\phi(x)$$

$$A'^j_\mu L_j = \mathcal{U}(\theta)\left\{ A^j_\mu L_j - \frac{i}{g}\, \mathcal{U}^{-1}(\theta)\,\partial_\mu \mathcal{U}(\theta)\right\} \mathcal{U}^{-1}(\theta)$$

$$\delta A^i_\mu = -\frac{1}{g}\partial_\mu \theta^i + c_{ijk}\,\theta^j A^k_\mu$$

$$\left(\text{QED}: \quad \delta A_\mu = -\frac{1}{g}\partial_\mu \theta \qquad\qquad \right)$$

$\hat{F}^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu$ IS NOT GAUGE INVARIANT !

DEF :

$$\boxed{F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\, c^{ijk} A^j_\mu A^k_\nu}$$

$\delta F^i_{\mu\nu} = c^{ijk}\,\theta_j\, F_{k\,\mu\nu}$. $\qquad \delta(F^i_{\mu\nu} F^{\mu\nu}_i) \equiv 0$.

SPONTANEOUS SYMMETRY BREAKING

UNBROKEN GAUGE SYMMETRIES $\widehat{=}$ MASSLESS GAUGE BOSONS

- SHORT-RANGE (UNCONFINED) INTERACTIONS REQUIRE SYMMETRY BREAKING.

$$\psi_B \approx \frac{1}{r} e^{-r/M_B}$$

- THE THEORY SHALL REMAIN RENORMALIZABLE UNDER SYMMETRY BREAKING.

  ↳ NO A PRIORI MASS TERMS $\sim \frac{1}{2} m^2 A_\mu A^\mu$.

- T'HOOFT 1971 :

  > SPONTANEOUS BROKEN YANG-MILLS THEORIES ARE RENORMALIZABLE.

LET $\mathcal{L}$ INVARIANT UNDER $G \in \mathcal{G}$. IF THE GROUND-STATE Ω_0 IS UNIQUE IT IS INVARIANT AGAINST $\mathcal{G}$. IF Ω_0 IS DEGENERATE $G \in \mathcal{G}$ MAPS THE RESPECTIVE STATES $\omega \in \Omega_0$ INSIDE Ω_0.
THE CHOICE OF $\omega_0 \in \Omega_0$ AS THE GROUNDSTATE **BREAKS $\mathcal{G}$ SPONTANEOUSLY.**

GOLDSTONE'S THEOREM

$\phi = (\phi_i)_{i=1}^n$ n real scalar fields

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\,\partial^\mu\phi - V(\phi)$$

$\mathbf{G}$ - THE MAXIMAL GROUP LEAVING $\mathcal{L}$ INVARIANT; N GENERATORS T_j

$$\phi \to \exp[-i\theta_\alpha L_\alpha]\,\phi$$

$$0 = \delta V = \frac{\partial V}{\partial\phi_j}\delta\phi_j = -i\,\frac{\partial V}{\partial\phi_j}\underline{\theta_\alpha}\,L_\alpha^{jk}\,\phi_j$$

$$\curvearrowright \quad \frac{\partial^2 V}{\partial\phi_i\,\partial\phi_k}L_\alpha^{ij}\phi_j + \frac{\partial V}{\partial\phi_i}L_\alpha^{ik} = 0 \qquad \forall\alpha$$

$$V = -\frac{1}{2}M_{ij}^2(\phi-v)_i(\phi-v)_j + O(\phi^3)$$

$$\boxed{(M^2)^{ij}L_{jk}^{\alpha}v^k = 0\,,\ \forall\alpha} \qquad (*)$$

IF $\mathbf{S} \subset \mathbf{G}$ OBEYS $L_\alpha v = 0$ FOR ALL GENERATORS, THEN $(*)$ ENFORCES $M^2 = 0$ FOR ALL GENERATORS IN $\mathbf{G}\setminus\mathbf{S}$.

This result is GOLDSTONE's theorem : (1961)

> **Theorem.** Let $\mathcal{G}$ be the symmetry group of rank N of the Lagrangian of a self-interacting scalar field Φ and $\mathcal{S}$ a subgroup of $\mathcal{S}$ of rank M. If $\mathcal{G}$ is sponateously broken and $\mathcal{S}$ remains as a symmetry of the vacuum, then $N-M$ massless scalar bosons are contained in the field theory, whose quantum numbers are those of the broken generators.

THE HIGGS MECHANISM

HIGGS,
ENGLERT, BROUT,
GURALNIK, HAGEN
KIBBLE
1964 /67

EXAMPLE: ABELIAN HIGGS MODEL

$$\mathcal{L} = |\mathcal{D}^\mu \phi|^2 - \mu^2 |\phi|^2 - \lambda |\phi^* \phi|^2 - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$\phi = \frac{1}{\sqrt{2}} (\phi_1 \pm i \phi_2)$$

$$\mathcal{D}_\mu = \partial_\mu + ieA_\mu \quad , \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\lambda > 0$$

$\mathcal{L}$ IS INVARIANT UNDER THE GAUGE TRANSFORM.:

$$\phi \to \phi' = e^{ie\alpha(x)} \phi$$

$$A_\mu(x) \to A'_\mu(x) = A_\mu(x) - \partial_\mu \alpha(x)$$

THE MINIMUM OF THE POTENTIAL

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi^* \phi|^2 \qquad \text{IS:}$$

FOR $\mu^2 > 0$: $\phi^* = \phi \equiv 0$

$\mu^2 < 0$: $\langle |\phi|^2 \rangle_0 = -\frac{\mu^2}{2|\lambda|} \equiv \frac{v^2}{2}$

$$\langle \phi \rangle_0 = \frac{v}{\sqrt{2}} \quad , \quad v > 0 .$$

IN THE VINCINITY OF THE GROUND STATE ONE CAN REPARAMETRIZE THE LAGRANGEAN:

$$\phi = e^{i\frac{\xi}{v}}(v+\eta)\frac{1}{\sqrt{2}}$$
$$\simeq (v+\eta+i\xi)\frac{1}{\sqrt{2}}$$

$$\mathcal{L} = \underbrace{\frac{1}{2}\left[(\partial_\mu\eta)(\partial^\mu\eta) + 2\mu^2\eta^2\right]}_{\text{MASSIVE SCALAR}} + \overbrace{\frac{1}{2}(\partial^\mu\xi)(\partial_\mu\xi)}^{\text{APPARENTLY MASSLESS SCALAR}}$$
$$\underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{FREE ABELIAN FIELD}} + \underbrace{ev A_\mu(\partial^\mu\xi)}_{?} + \underbrace{\frac{e^2v^2}{2}A_\mu A^\mu}_{A_\mu\text{'s MASS TERM}} + \dots$$

WHAT IS THE ? - TERM INTERPRETATION?

CHOOSE ANOTHER GAUGE!

$$\boxed{A_\mu \to A'_\mu = A_\mu + \frac{1}{ev}\partial_\mu\xi}$$

$$\boxed{\mathcal{L} = \underbrace{\left[\frac{1}{2}(\partial_\mu\eta)(\partial^\mu\eta) + 2\mu^2\eta^2\right]}_{\text{MASSIVE SCALAR}} \underbrace{- \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2v^2}{2}A'_\mu A'^\mu}_{\text{MASSIVE U(1) FIELD}}}$$

THE APPARENTLY MASSLESS SCALAR IS 'EATEN UP', I.E. ABSORBED INTO THE LONGITUDINAL COMPONENT OF THE GAUGE FIELD. THE 'WOULD BE' GOLDSTONE BOSON DISAPPEARED.

A SIMILAR MECHANISM:

$$\boxed{\text{GINZBURG – LANDAU MODEL OF SUPERCONDUCTIVITY}}$$

GINZBURG, LANDAU, 1950

$$F_n(T,H) = F_n(T,0) - \frac{H^2}{8\pi}$$

$$F_s(T,H) = F_s(T,0) \qquad \text{(Meissner - effect)}$$

$$\curvearrowright \quad F_s(T,0) = F_n(T,0) - \frac{H_c^2}{8\pi}$$

$$F_s = F_{n,0} + a|\psi|^2 + \frac{1}{2}b|\psi|^4 + \frac{1}{2m^*}\left|(\nabla_\mu + ie\vec{A})\psi\right|^2 + \frac{\vec{H}^2}{8\pi}$$

GINZBURG, LANDAU 1950

$$\frac{\partial F_s}{\partial|\psi|^2} = 0 \qquad 1^\circ: |\psi|^2 = -\frac{a}{b} \qquad 2^\circ: |\psi|^2 \equiv 0 \qquad , (\nabla\psi \approx 0.)$$

$$F_s = F_{n,0} - \frac{a^2}{2b} \quad \curvearrowright \quad \boxed{\frac{a^2}{b} = \frac{H_c^2(T)}{4\pi}}$$

$$a = a'(T - T_c) \quad \begin{cases} < 0, & T < T_c \\ > 0, & T > T_c \end{cases}$$

$$\left|\frac{H_c^2(T)}{4\pi a'(T-T_c)}\right| \cong v^2$$

GL $\qquad$ HIGGS

PHEN. GINZBURG–LANDAU THEORY $\longleftarrow$ MICROSCOPIC BCS – THEORY

WHAT ARE THE <u>PHONONS</u> OF THE STANDARD MODEL ?

THE ELECTROWEAK THEORY

1933 FERMI'S THEORY OF β-DECAY

~1957 (V−A) THEORY

(1938: O. KLEIN : CC & NC GAUGE BOSONS !)

→ GOAL : RENORMALIZABLE QFT CONTAINING MASSIVE GAUGE BOSONS.

(→ HE-BEHAVIOUR).

GWS THEORY :

1967	LEPTONS	: WEINBERG, SALAM
1970	GIM Mechanism	GLASHOW, ILIOPOULOS, MAIANI
1971	RENORMALIZIBILITY	't HOOFT
1973	KM-MATRIX	KOBAYASHI, MASKAWA.

THE GLASHOW – WEINBERG – SALAM MODEL: ONLY LEPTONS

FIRST FAMILY: ν_e, e

LEFTHANDED & RIGHTHANDED STATES:

$$\nu_L = \frac{1}{2}(1-\gamma_5)\nu \qquad \nu_R = \frac{1}{2}(1+\gamma_5)\nu$$

$$e_L = \frac{1}{2}(1-\gamma_5)e \qquad e_R = \frac{1}{2}(1+\gamma_5)e$$

	STATES	$SU(2)_L$	Y
	ν_R	$\mathbf{1}$	0
$\psi_L \equiv$	$\begin{pmatrix}\nu\\ e\end{pmatrix}_L$	$\mathbf{2}$	-1
	e_R	$\mathbf{1}$	-2

$$\boxed{Q = T_L^3 + \frac{1}{2}Y}$$

(GELL-MANN, NISHIJIMA)

$Y \equiv$ EW. HYPERCHARGE

GAUGE GROUP: $SU(2)_L \times U(1)_Y$.

$$[T_L^i, Y] = 0$$

THE GAUGE FIELDS

A^i_μ : $SU(2)_L$

B_μ : $U(1)_Y$

$$\mathcal{L}_{gauge} = -\frac{1}{4} F^i_{\mu\nu} F^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$F^i_{\mu\nu} = \partial_\mu A^i_\nu - \partial_\nu A^i_\mu + g\, \varepsilon^{ijk} A^j_\mu A^k_\nu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

FERMION - GAUGE BOSON INTERACTION

COVARIANT DERIVATIVE: $\mathcal{D}^{L,R}_\mu$

$$\mathcal{D}^L_\mu = \underbrace{\partial_\mu}_{\text{free fermions}} - \underbrace{\frac{i}{2} Y g' B_\mu}_{U(1)_Y} - \underbrace{\frac{i}{2} g \tau^i A^i_\mu}_{SU(2)_L}$$

τ^i : SU(2) MATRICES (PAULI MATRICES)

$$\mathcal{D}^R_\mu = \partial_\mu - \frac{i}{2} Y g' B_\mu$$

$$\mathcal{L}_{FB} = \bar{\nu}_R i \gamma^\mu \mathcal{D}^R_\mu \nu_R + \bar{e}_R i \gamma^\mu \mathcal{D}^R_\mu e_R$$
$$+ \bar{\psi}_L i \gamma^\mu \mathcal{D}^L_\mu \psi_L$$

SO FAR, NO MASS TERMS ARE PRESENT.

BOTH BOSON & FERMION MASS TERMS

e.g. $\mathcal{L}_{BM} = \frac{1}{2} m_B^2 A^\mu A_\mu$, $\mathcal{L}_{FM} = m_f \bar{\psi}\psi$

WOULD VIOLATE GAUGE INVARIANCE.

$\therefore \quad A^\mu A_\mu \rightarrow (A^\mu - \partial^\mu \alpha)(A_\mu - \partial_\mu \alpha) \neq A^\mu A_\mu$

$$m_f \bar{\psi}\psi \equiv m_f [\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R]$$

IS NOT $SU(2)_L$ INVARIANT.

$\boxed{\text{MASSES ARE GENERATED VIA THE HIGGS MECHANISM.}}$

INTRODUCE A DOUBLET OF COMPLEX HIGGS SCALARS.
$(SU(2)_L)$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad ; \quad Y = +1.$$

FOR LATER USE ALSO ITS CONJUGATE

$$\tilde{\phi} = i\sigma_2 \phi^* \equiv \begin{pmatrix} \phi^0 \\ -\phi^- \end{pmatrix} \quad ; \quad Y = -1$$

IS NEEDED. $\quad \left(\sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \right).$

TWO INTERACTION TERMS ARISE:

$$\mathcal{L}_{SB} = (\mathcal{D}^L_\mu \phi)^\dagger (\mathcal{D}^{\mu L} \phi) - \underbrace{V(\phi^\dagger\phi)}_{\text{HIGGS POTENTIAL}}$$

$$\mathcal{L}_{SF} = -G_e\left[\bar{e}_R \phi^\dagger \psi_L + \bar{\psi}_L \phi e_R\right] - G_{\nu_e}\left[\bar{\nu}_R \tilde{\phi}^\dagger \psi_L + \bar{\psi}_L \tilde{\phi} \nu_R\right]$$

THE COUPLINGS G_{e,ν_e} WILL BE RELATED TO m_e, m_{ν_e} LATER.

THE HIGGS POTENTIAL IS:

$$V(\phi^\dagger\phi) = \mu^2 \phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2 .$$

- THE LAGRANGEAN

  $$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{FB} + \mathcal{L}_{SB} + \mathcal{L}_{SF}$$

  OBEYS $SU(2)_L \times U(1)_Y$ GAUGE INVARIANCE.

- ν_R'S INTERACT VIA THE HIGGS FIELD ONLY.

SPONTANEOUS SYMMETRY BREAKING OF $SU(2)_L \times U(1)_Y \to U(1)_{em}$

RE-PARAMETRIZE: $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ BY

$$\phi = \mathcal{U}^{-1}(\vec{\xi}(x)) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+\eta(x) \end{pmatrix}$$

WITH $\mathcal{U}(\vec{\xi}) = \exp\left[i \vec{\xi}(x) \cdot \vec{\tau} \frac{1}{2v} \right]$

TRANSFORM:

$$\phi \to \phi' = \mathcal{U}(\vec{\xi})\, \phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+\eta(x) \end{pmatrix}$$

$$\psi_L \to \psi_L' = \mathcal{U}(\vec{\xi})\, \psi_L$$

$A^i_\mu \to A^{i\,\prime}_\mu$ WITH

$$\underline{\vec{\tau} \cdot \vec{A}'_\mu} = \mathcal{U}(\vec{\xi}) \left[\underline{\vec{\tau} \vec{A}_\mu} - \frac{i}{g} \mathcal{U}^{-1}(\vec{\xi})\, \partial_\mu \mathcal{U}(\vec{\xi}) \right] \mathcal{U}^{-1}(\vec{\xi})$$

CHANGES IN :

a) $$\mathcal{L}_{SF} = -\frac{G_e v}{\sqrt{2}} (\bar{e}_R e_L + \bar{e}_L e_R) + \dots$$
$$(\equiv \bar{e} e \;)$$
$$- \frac{G_{\nu_e} v}{\sqrt{2}} \bar{\nu} \nu$$

$$\boxed{\begin{aligned} m_e &= G_e v / \sqrt{2} \\ m_{\nu_e} &= G_{\nu_e} v / \sqrt{2} \end{aligned}}$$

b) $\mathcal{L}_{SB}$.

$$\mathcal{L}_{SB} = \underbrace{\tfrac{1}{2}\partial^\mu \eta \, \partial_\mu \eta}_{\text{FREE HIGGS FIELD}} - V\left[\left(\frac{v+\eta}{\sqrt{2}}\right)^2\right]$$

$$+ \frac{(v+\eta)^2}{8} \chi_-^{+} \left\{ (g'B_\mu + gT^i A^i_\mu)(g'B_\mu + gT^i A^{i\mu}) \right\} \cdot \chi_-$$

$$\chi_- = \binom{0}{1}$$

THE BOSON MASS TERMS IN $\mathcal{L}_{SB}$ ARE:

$$-2\mu^2 \eta^2 \equiv -m_H^2 \eta^2 \qquad (\lambda = -\mu^2/v^2)$$

$$\frac{v^2}{8}\Big[(g'B_\mu - g A^3_\mu)(g'B^\mu - g A^{\mu 3})$$
$$+ g^2 ((A^{\mu 1})^2 + (A^2_\mu)^2)\Big]$$

THE LAST TERM STILL NEEDS A TRANSFORMATION INTO MASS EIGENSTATES.

DEFINE:

$$\boxed{\begin{aligned} W^{\pm}_{\mu} &= \frac{1}{\sqrt{2}}\left(A^1_\mu \mp i A^2_\mu\right) \\ \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} &= \frac{1}{\sqrt{g^2+g'^2}} \begin{pmatrix} -g & g' \\ g' & g \end{pmatrix} \begin{pmatrix} A^3_\mu \\ B_\mu \end{pmatrix} \end{aligned}}$$

CHARGED

NEUTRAL GAUGE BOSONS

$$M_W = \frac{1}{2} g v \qquad M_\gamma = 0 \quad (A_\mu)$$

$$M_Z = \frac{1}{2}\sqrt{g^2+g'^2}\, v.$$

THE MIXING BETWEEN NC GAUGE BOSONS CAN BE PARAMETRIZED BY:

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

θ_W – WEAK MIXING ANGLE.

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

$g \equiv$ weak coupling constant.

FURTHERMORE ONE HAS:

$$\boxed{\frac{M_W}{M_Z} = \frac{e}{g'} = \cos\theta_W}$$

SEQUENTIAL FAMILIES

$$\begin{array}{ccc} \nu_R^e & \nu_R^\mu & \nu_R^\tau \\ \begin{pmatrix} \nu^e \\ e \end{pmatrix}_L & \begin{pmatrix} \nu^\mu \\ \mu \end{pmatrix}_L & \begin{pmatrix} \nu^\tau \\ \tau \end{pmatrix}_L \\ e_R & \mu_R & \tau_R \end{array}$$

$$\mathcal{L} \longrightarrow \mathcal{L}_{(e)} + \mathcal{L}_{(\mu)} + \mathcal{L}_{(\tau)}$$

- e, μ & τ ARE MASS EIGENSTATES
- ν_e, ν_μ, ν_τ ?

IN GENERAL MIXING IS ALLOWED FOR ν_i's.
(HERE WE CONSIDER DIRAC NEUTRINOS ONLY.)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathbf{U} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

↑ flavour ↑ mass
eigenstates

$\mathbf{U}$: 3×3 unitary matrix $(N-1)^2$ parameters
[$N(N-1)/2$ 'EULER' ANGLES
$(N-1)(N-2)/2$ remaining PHASES]

e.g. $(\theta_1^\nu, \theta_2^\nu, \theta_3^\nu ; \delta^\nu)$

$$U = R_2 \widetilde{U} R_1 R_3$$

$$\widetilde{U} = e^{-i\frac{\delta}{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

$$R_1 = \begin{pmatrix} c_1 & s_1 & 0 \\ -s_1 & c_1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad R_2 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_2 & s_2 \\ 0 & -s_2 & c_2 \end{pmatrix} \qquad R_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_3 & s_3 \\ 0 & -s_3 & c_3 \end{pmatrix}$$

$\therefore$ $|\nu_\mu\rangle \simeq |\nu_2\rangle$, mixing only between $|\nu_1\rangle, |\nu_3\rangle$:

$$\begin{pmatrix} \nu_e \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_3 \end{pmatrix}$$

$$|\nu_e(t)\rangle = -\sin\theta\, e^{-iE_1 t}\, |\nu_1\rangle + \cos\theta\, e^{-iE_2 t}\, |\nu_2\rangle$$

OSCILLATION AMPL.^{2} :

$$\left|\langle \nu_e(0) | \nu_e(t)\rangle\right|^2 = \sin^4\theta + \cos^4\theta + 2\sin^2\theta\cos^2\theta\cos t(E_2-E$$

$$t|E_2 - E_1| \approx \frac{t}{2p_\nu}\, |m_{\nu_1}^2 - m_{\nu_2}^2|$$

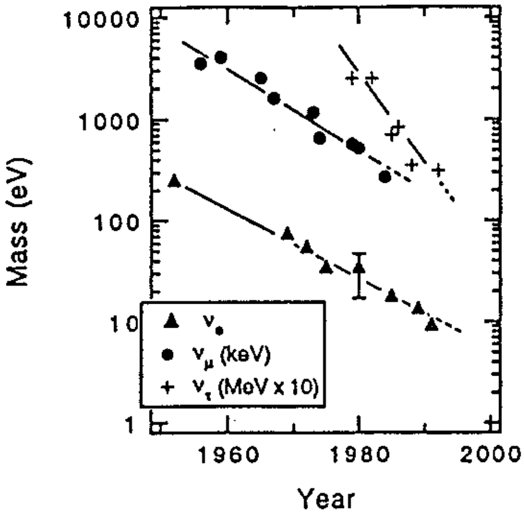


Figure 1. Experimental upper limits on neutrino mass.

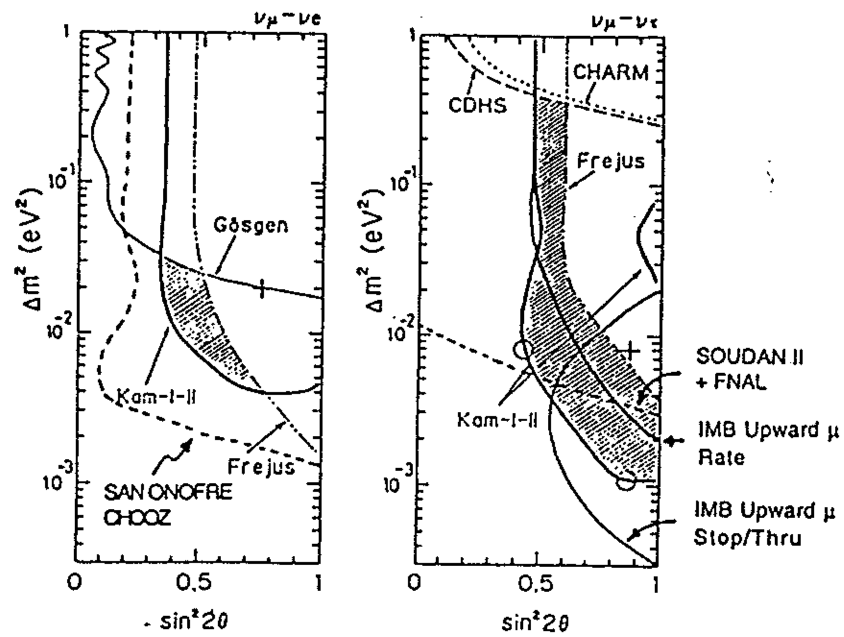
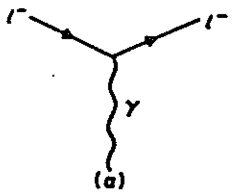
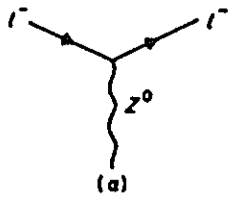


Figure 3. Oscillation parameters in the $\nu_\mu - \nu_e$ and ν_μ disappearance channels. The dotted lines indicate limits to be obtained from future experiments. The crosses are the best fit values from Kamiokande.[24]

BOSON - FERMION VERTICES

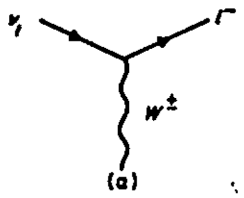


$i e \gamma^\mu$

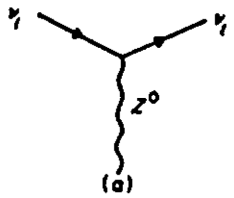


$$\frac{ig\gamma^\mu}{4\cos\theta_W}(1 - 4\sin^2\theta_W - \gamma_5)$$
$$= \frac{-ig\gamma^\mu}{2\cos\theta_W}(g_V - g_A\gamma_5)$$

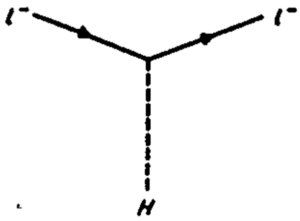
$$g_V = 2\sin^2\theta_W - \tfrac{1}{2}, \qquad g_A = -\tfrac{1}{2}$$



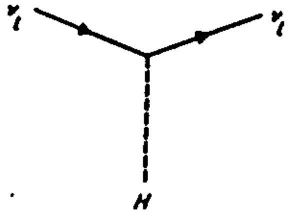
$$\frac{-ig}{2\sqrt{2}}\gamma^\mu(1-\gamma_5)$$



$$\frac{-ig}{4\cos\theta_W}\gamma^\mu(1-\gamma_5)$$

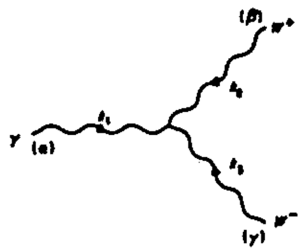


$$\frac{-i}{v}m_l$$

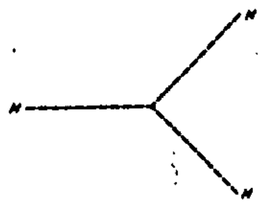


$$\frac{-i}{v}m_{\nu_l}$$

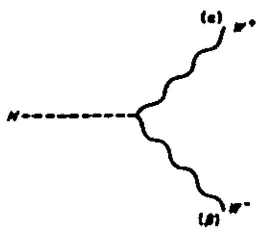
TRIPLE - BOSON COUPLINGS



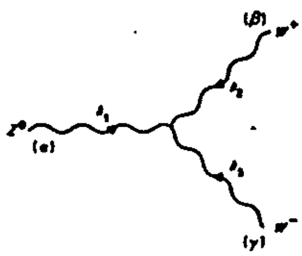
$$ie[g^{\alpha\beta}(k_1-k_2)^\gamma + g^{\beta\gamma}(k_2-k_3)^\alpha + g^{\gamma\alpha}(k_3-k_1)^\beta]$$



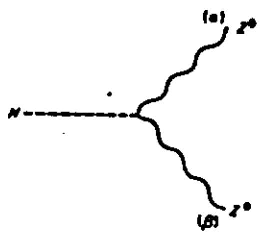
$$-6i\lambda v$$



$$\tfrac{1}{2}ivg^2g^{\alpha\beta}$$

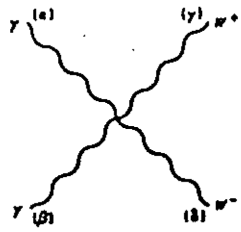


$$ig\cos\theta_W[g^{\alpha\beta}(k_1-k_2)^\gamma + g^{\beta\gamma}(k_2-k_3)^\alpha + g^{\gamma\alpha}(k_3-k_1)^\beta]$$

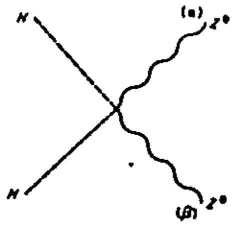


$$\frac{ivg^2}{2\cos^2\theta_W}g^{\alpha\beta}$$

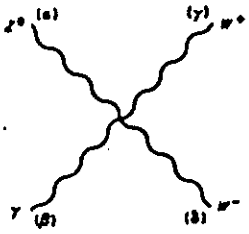
QUARTIC COUPLINGS



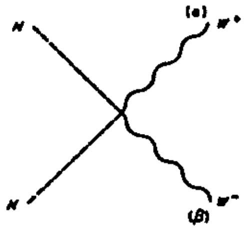
$ie^2[g^{\alpha\gamma}g^{\beta\delta} + g^{\alpha\delta}g^{\beta\gamma} - 2g^{\alpha\beta}g^{\gamma\delta}]$



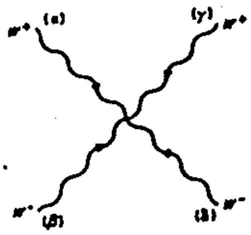
$\frac{ig^2}{2\cos^2\theta_W}g^{\alpha\beta}$



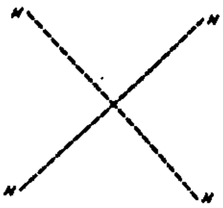
$ieg\cos\theta_W[g^{\alpha\gamma}g^{\beta\delta} + g^{\alpha\delta}g^{\beta\gamma} - 2g^{\alpha\beta}g^{\gamma\delta}]$



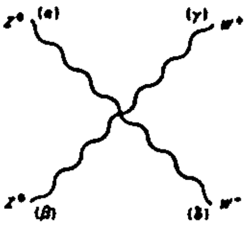
$\frac{1}{2}ig^2g^{\alpha\beta}$



$ig^2[2g^{\alpha\gamma}g^{\beta\delta} - g^{\alpha\beta}g^{\gamma\delta} - g^{\alpha\delta}g^{\beta\gamma}]$



$-6i\lambda$



$ig^2\cos^2\theta_W[g^{\alpha\gamma}g^{\beta\delta} + g^{\alpha\delta}g^{\beta\gamma} - 2g^{\alpha\beta}g^{\gamma\delta}]$

STANDARD-MODEL PARAMETERS
THY. vs. EXP.

(PDG '92)

	EXP	THY
Quantity	Value	Standard Model
M_Z (GeV)	91.173 ± 0.020	input
Γ_Z (GeV)	2.487 ± 0.010	$2.488 \pm 0.002 \pm 0.006$
Γ_{ll} (MeV)	83.0 ± 0.6	$83.7 \pm 0.1 \pm 0.2$
Γ_{had} (MeV)	1736 ± 11	$1737 \pm 2 \pm 4$
Γ_{inv} (MeV)	502 ± 9	$501 \pm 0.3 \pm 1$
$\bar{g}_A^2$	0.2492 ± 0.0012	$0.2513 \pm 0.0002 \pm 0.0004$
$\bar{g}_V^2$	0.0012 ± 0.0003	$0.0011 \pm 0 \pm 0.0001$
P_τ	0.134 ± 0.035	$0.136 \pm 0.003 \pm 0.006$
$A_{FB}(b)$	0.126 ± 0.022	$0.091 \pm 0.002 \pm 0.004$
M_W (GeV)	80.22 ± 0.26	$80.21 \pm 0.03 \pm 0.16$
M_W/M_Z	0.8798 ± 0.0028	$0.8798 \pm 0.0002 \pm 0.0017$
Q_W [16,17]	$-71.04 \pm 1.58 \pm 0.88$	$-73.21 \pm 0.03 \pm 0.03$

$$\Gamma(Z \to \nu\bar{\nu}) \simeq 2\, \Gamma(Z \to \ell\bar{\ell}) \qquad (\sin^2\theta_W \approx .23)$$

$$\curvearrowright \quad N_\nu = 3.02 \pm .13 \; !$$

(cf. D. HAIDT'S LECTURE)

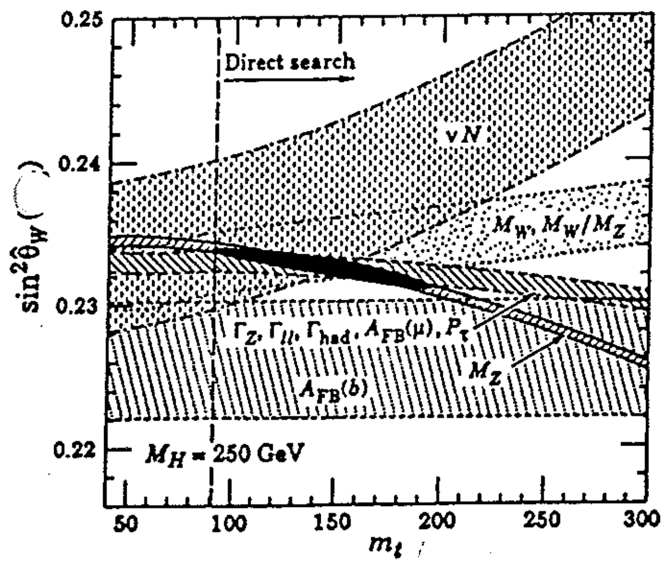


Fig. 1. One standard deviation uncertainties in $\sin^2\hat{\theta}_W$ as a function of m_t, the direct constraint $m_t > 91$ GeV [30], and the 90% CL region in $\sin^2\hat{\theta}_W - m_t$ allowed by all data, assuming $M_H = 250$ GeV.

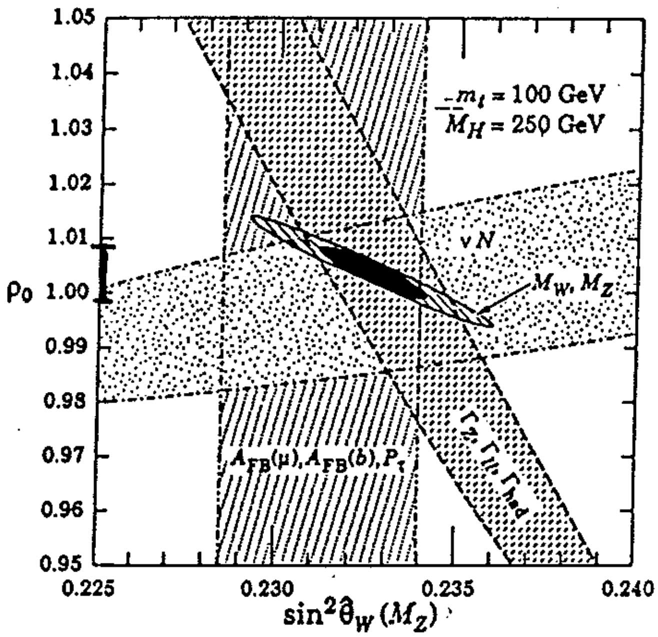
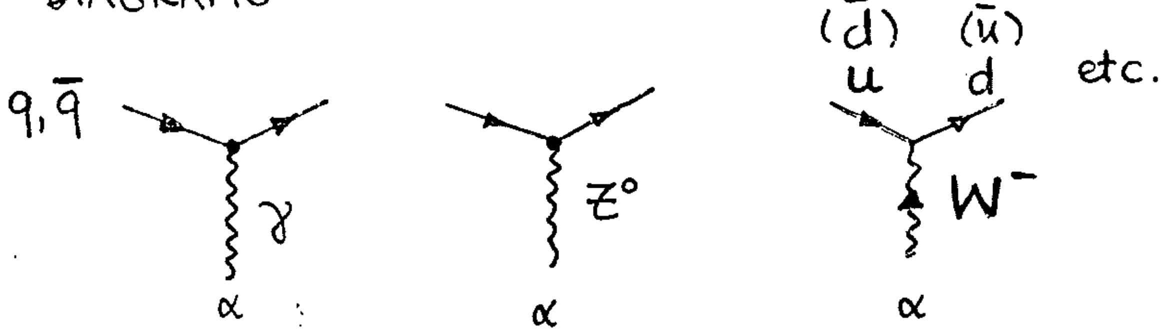


Fig. 2. The allowed regions in $\sin^2\hat{\theta}_W - \rho_0$ at 90% CL for various reactions for $m_t = 100$ GeV.

$$\rho \equiv \frac{M_Z^2 \cos^2\theta_W}{M_W^2 \cancel{\sin^2\theta_W}} = \frac{\sum v_i^2 \frac{1}{2} Y_i^2}{\sum v_i^2 \left(T_i(T_i+1) - \frac{1}{4} Y_i^2\right)} = \begin{cases} 1: & T_i = \frac{1}{2},\ Y_i = 1 \\ 0: & Y_i = 0 \\ 2: & T_i = 1,\ Y_i = 2 \end{cases}$$

ELECTROWEAK INTERACTIONS OF QUARKS

DIAGRAMS :



$$-ie_q \gamma^\alpha \qquad -\frac{ig\gamma^\alpha}{2\cos\theta_W}(g_V - g_A\gamma_5) \qquad -\frac{ig}{2\sqrt{2}}\gamma^\alpha(1-\gamma_5)$$

$$g_V = -\frac{1}{2} - 2e_q \sin^2\theta_W$$

$$g_A = \pm\frac{1}{2} \quad \begin{cases} u, \ldots \\ d, \ldots \end{cases}$$

STATES	$SU(2)_L$	Y
u_R	1	4/3
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	2	1/3
d_R	1	−2/3

SEQUENTIAL FAMILIES

IF THERE WOULD ONLY EXIST THE LIGHT QUARKS u, d, AND s THE HADRONIC CHARGED CURRENT WOULD BE:

$$J_\lambda^{(+)} = \bar{u}\gamma_\lambda(1-\gamma_5)d\cos\theta_c + \bar{u}\gamma_\lambda(1-\gamma_5)s\sin\theta_c$$

$\not\exists$ $s\cos\theta_c - d\sin\theta_c$. , θ_c THE CABIBBO ANGLE.

THE NEUTRAL CURRENT IS:

$$\begin{aligned}
J_\lambda^{(0)} &= J_\lambda^{(3)} - 2\sin^2\theta_W J_\lambda^{(em)} \\
&= \frac{1}{2}\Big[\bar{u}\gamma_\lambda(1-\gamma_5)u - \bar{d}\gamma_\lambda(1-\gamma_5)d\cos^2\theta_c \\
&\qquad - \bar{s}\gamma_\lambda(1-\gamma_5)s\sin^2\theta_c \\
&\qquad - \left[\bar{s}\gamma_\lambda(1-\gamma_5)d + \bar{d}\gamma_\lambda(1-\gamma_5)s\right]\sin\theta_c\cos\theta_c\Big] \\
&\qquad - 2\sin^2\theta_W\left[\frac{2}{3}\bar{u}\gamma_\lambda u - \frac{1}{3}\bar{d}\gamma_\lambda d - \frac{1}{3}\bar{s}\gamma_\lambda s\right].
\end{aligned}$$

i.e. IT CONTAINS FLAVOUR CHANGING NEUTRAL CURRENTS!

(CONTRARY TO OBSERVATION.)

FCNC's ARE PREVENTED IN THE

GIM - MECHANISM

GLASHOW, ILIOPOULOS, MAIANI.

$$\begin{pmatrix} u \\ d_\theta \end{pmatrix}_L \text{ HAS TO BE SUPPLEMENTED BY } \begin{pmatrix} c \\ s_\theta \end{pmatrix}_L$$

$$d_\theta = d\cos\theta_c + s\sin\theta_c$$

$$s_\theta = s\cos\theta_c - d\sin\theta_c$$

$J_\lambda^{(3)}$ IS THEN :

$$J_\lambda^{(3)} = (\bar{u}\,\bar{d}_\theta)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\Gamma\begin{pmatrix} u \\ d_\theta \end{pmatrix} + (\bar{c}\,\bar{s}_\theta)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\Gamma\begin{pmatrix} c \\ s_\theta \end{pmatrix}$$

$$= \bar{u}\Gamma u - \bar{d}\Gamma d\cos^2\theta_c - \bar{s}\Gamma s\sin^2\theta_c - (\bar{s}\Gamma d + \bar{d}\Gamma s)s_\theta c_\theta$$
$$+ \bar{c}\Gamma c - \bar{d}\Gamma d\sin^2\theta_c - \bar{s}\Gamma s\cos^2\theta_c + \underbrace{(\bar{s}\Gamma d + \bar{d}\Gamma s)s_\theta c_\theta}_{\equiv 0.}$$

$$\underline{J_\lambda^{(3)} = \bar{u}\Gamma u + \bar{c}\Gamma c - \bar{d}\Gamma d - \bar{s}\Gamma s}$$

NO MIXING IN THE NC-SECTOR.
NO FCNC's. (SO FAR IN ACCORD WITH OBSERVATION.)

THE DOWN QUARK STATES IN THE LH-DOUBLETS MIX:

$$\underset{\text{flavour}}{\begin{pmatrix} d' \\ s' \end{pmatrix}} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}\underset{\text{mass}}{\begin{pmatrix} d \\ s \end{pmatrix}}$$

eigenstates.

MORE THAN 2 FAMILIES :

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \mathbf{U}_{KM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

AS DISCUSSED FOR ν's ALREADY : 4 MIXING PARAMETERS

e.g. $\theta_1, \theta_2, \theta_3$ + 1 PHASE δ

$\boxed{\text{FIG.}}$

- THE PHASE δ ALLOWS TO DESCRIBE CP-VIOLATING PROCESSES.
- $SU(2)_L \times U(1)_Y$ WITH ONLY **2** FAMILIES DO NOT OBEY THIS DEGREE OF FREEDOM !

$$J_{CP} = \mathrm{Im}\,(V_{cb} V_{us} V_{ub}^{*} V_{cs}^{*})$$

$$= s_1^2 s_2 s_3 c_2 c_3 \sin\delta \qquad \text{(KM-Matrix)}$$

ALL CP-viol. QUANTITIES ARE $\sim J_{CP}$ (JARLSKOG).

$$V = \begin{pmatrix} c_1 & -s_1c_3 & -s_1s_3 \\ s_1c_2 & c_1c_2c_3 - s_2s_3e^{i\phi} & c_1c_2s_3 + s_2c_3e^{i\phi} \\ s_1s_2 & c_1s_2c_3 + c_2s_3e^{i\phi} & c_1s_2s_3 - c_2c_3e^{i\phi} \end{pmatrix}$$ KOBAYASHI, MASKAWA

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -s_{23}c_{12} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$ PDG

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\varrho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\varrho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$ WOLFENSTEIN

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\sigma e^{-i\delta} \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\sigma e^{i\delta}) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$ PECCEI et al.

....

$$J^{+\alpha} = (\bar{u}\ \bar{c}\ \bar{t}) \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \gamma^\alpha (1 + \gamma_5) \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

Table 4.1.3. *Elements of 3 × 3 quark mixing matrix* V_{ik} *from fit of experimental constraints (90 percent C.L. allowed ranges)*

	d	*s*	*b*
u	0.9743–0.9757	0.219–0.225	0.000–0.008
c	0.219–0.225	0.9733–0.9748	0.039–0.050
t	0.002–0.017	0.037–0.048	0.9987–0.9993

(KLEINKNECHT)

CP-VIOLATION FROM THE CKM-MATRIX:

CONSIDER CC:

$$g\left[V_{ij}\,\bar{u}_i\,\gamma_\mu W^{\mu +}(1-\gamma_5)\,d_j + V_{ij}^*\,\bar{d}_j\,\gamma_\mu W^{\mu -}(1-\gamma_5)\,u_i\right] \qquad \text{(CC)}$$

$$\mathcal{V}_{ij} = \bar{u}_i\,\gamma_\mu\,d_j \qquad \mathcal{A}_{ij} = \bar{u}_i\,\gamma_\mu\gamma_5\,d_j$$

$$\mathcal{CP}\,\mathcal{V}_{ij} = -\mathcal{V}_{ji} \qquad \mathcal{CP}\,\mathcal{A}_{ij} = -\mathcal{A}_{ji}$$

$$\mathcal{CP}\,W^{\pm\mu} = -W^{\mp\mu}$$

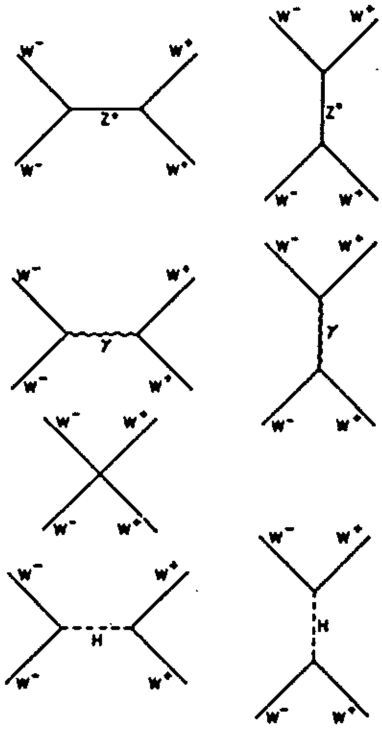
$$\mathcal{CP}\,\bar{\psi}_i\psi_j = \bar{\psi}_j\psi_i$$

$\Downarrow$ (CC) AND MASS TERMS ARE CP INVARIANT, IF THEY ARE <u>REAL</u>.

THE HIGH-ENERGY BEHAVIOUR OF THE GWS-THEORY

1

- $W^+W^- \longrightarrow W^+W^-$



$T(s,t) \sim \frac{s}{M_W^2}$;

$\left(\frac{s}{M_W^2}\right)^2$ TERMS CANCLE DUE TO THE W^4 TERM

CANCLE THE $\sim s/M_W^2$ TERMS!

FIG. 1. Feynman graphs (in the unitary gauge) for the reaction $W^+W^- \to W^+W^-$.

M. VELTMAN 1977

B.W. LEE, C. QUIGG, H.B. THACKER, 1977

HIGGS BOSON NEEDED!

THIS EXAMPLE REFERS TO BOSON COUPLINGS ONLY.

② • $e^+e^- \to W^+W^-$

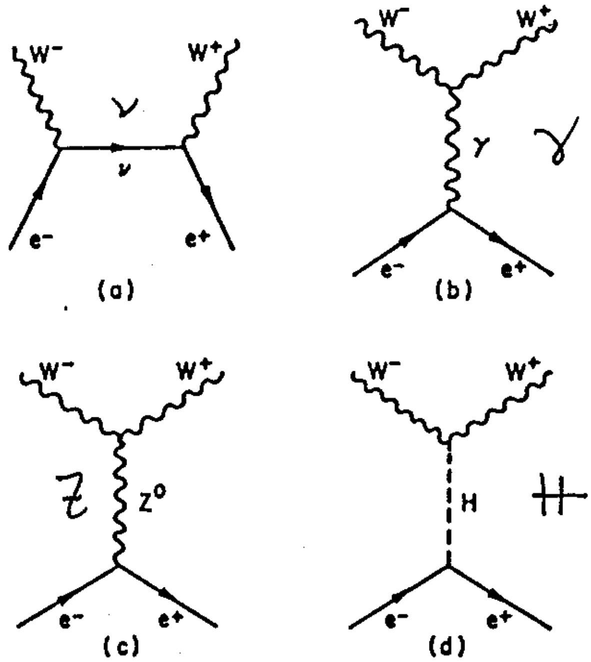
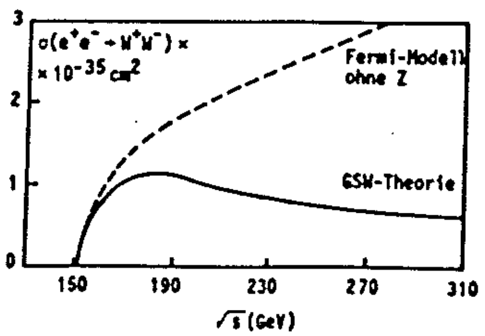


FIG. 6-22. Lowest-order contributions to the reaction $e^+e^- \to W^+W^-$, in the Weinberg-Salam model.

- HE UNITARITY ENFORCES THE GWS RELATION BETWEEN BF- & 3B COUPLINGS.
- FOR $m_e^2 \neq 0$ THE HIGGS TERM IS NEEDED FOR HE UNITARITY!

$$\sigma^{div}_{\substack{e^+e^- \to W^+W^- \\ m_e \equiv 0}} \propto \frac{\pi\alpha^2}{8 s_\theta^4} \beta^3 \frac{s}{M_W^4} \cdot \Big\{ \overset{\nu\nu}{\frac{1}{12}} + \overset{\gamma\gamma}{\frac{2}{3} s_\theta^4} + \overset{ZZ}{\frac{2}{3}\left(s_\theta^4 - \frac{1}{2}s_\theta^2 + \frac{1}{8}\right)} + \overset{Z\gamma}{\frac{4}{3}\left(\frac{1}{4} - s_\theta^2\right)s_\theta^2} + \overset{\nu Z}{\frac{1}{3}\left(s_\theta^2 - \frac{1}{2}\right)} - \overset{\gamma\nu}{\frac{1}{3} s_\theta^2} \Big\}$$

$$\equiv \sigma.$$



e.g.
W. ALLES, C. BOYER
A. BURAS, 1977.

Fig. 3.4: Wirkungsquerschnitt für die Produktion von W^+W^--Paaren in der e^+e^--Vernichtung im Fermi-Modell (---) und in der GSW-Theorie (——).

REMARKS ON RENORMALIZIBILITY

QUANTIZATION: GAUGE FIXING NEEDED.

∴ ABELIAN HIGGS MODEL:

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \eta)(\partial^\mu \eta) + 2\mu^2\eta^2\right] + \frac{1}{2}(\partial_\mu \zeta)(\partial^\mu \zeta) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + MA_\mu(\partial^\mu \zeta) + \frac{1}{2}M^2 A_\mu A^\mu.$$

$$\mathcal{L}_{gf} = -\frac{1}{2}\frac{1}{\xi}\left(\partial^\mu A_\mu + \xi M \zeta\right)^2$$

ghost propagator: $D_G = \dfrac{i}{q^2 - \xi M^2}$

gauge boson propagator: $\dfrac{-i\left[g_{\mu\nu} - (1-\xi)q_\mu q_\nu/(q^2 - \xi M^2)\right]}{q^2 - M^2 + i\varepsilon}.$

$$\xi = \begin{cases} 0 & \text{LANDAU} \\ 1 & \text{FEYNMAN} \\ \infty & \text{UNITARY} \end{cases} \quad \text{GAUGE}$$

$\lim\limits_{\xi \to \infty} D_G = 0$ (GHOST FREE).

$$D_A^{unit}(q) = (-i)\,\frac{\left[g_{\mu\nu} - q_\mu q_\nu/M^2\right]}{q^2 - M^2 + i\varepsilon}.$$

PROOF OF RENORMALIZIBILITY: t' HOOFT, 1971.

ANOMALIES

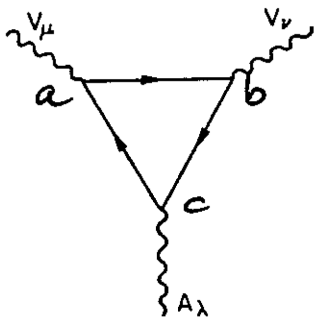


FIG. 6-23. Triangle anomaly for the axial-vector current.

- OCCUR ONLY IN 1-LOOP DIAGRAMS, CONTAINING FERMION LINES. (ADLER, BARDEEN 1969; GROSS, JACKIW 1972; t' HOOFT, VELTMAN, 1972)

- IT IS SUFFICIENT TO ANALYZE THE CASE OF:

  VVA-TRIANGLES

  (BARDEEN, 1969; WESS, 1971; AVIV & ZEE 1972)

CONDITION:

$$\boxed{\mathrm{tr}\,\{\Lambda^L_a,\Lambda^L_b\}\Lambda^L_c - \mathrm{tr}\,\{\Lambda^R_a,\Lambda^R_b\}\Lambda^R_c = 0} \qquad (*)$$

NOT A PRIORI FULLFILLED FOR $SU(2)_L \times U(1)_Y$ AND $SU(3)$!

QCD: q_L, q_R TRANSFORM AS TRIPLETS : (*) OK.

$SU_{2L} \times U_{1Y}$:

$$(*):\quad \mathrm{tr}\left[\{\tau_a,\tau_b\}Y\right] = \left(\mathrm{tr}\,\{\tau_a,\tau_b\}\right)Y \propto \sum_{\substack{\text{fermion}\\ \text{doublets}}} Y$$

$$\boxed{\sum_{\substack{\text{fermion}\\ \text{doublets}}} Y \;=\; \underset{\binom{\nu}{\ell}_L}{-1} \;+\; \underset{\binom{u}{d}_L^R}{\frac{1}{3}} \;+\; \underset{\binom{u}{d}_L^B}{\frac{1}{3}} \;+\; \underset{\binom{u}{d}_L^G}{\frac{1}{3}} \equiv 0}$$

FAMILY BY FAMILY.

QUANTUM CHROMODYNAMICS

QUARKS EMERGE IN THREE COLORS: R B G

BINDING FORCE : GAUGE INTERACTION

- COMPACT SIMPLE LIE GROUP
  - WITH 3-DIMENSIONAL IRREDUCIBLE REPRESENTATION.

$SU(N+1)$, $SO(2N)$, $Sp(N)$, $SO(2N)$, E_6, E_7, E_8, F_4, G_2

3-DIM. REP. : $SU(3)$; $SO(3) \simeq SU(2) \simeq Sp(1)$.

NO DISTINCTION BETWEEN COLOR & ANTICOLOR.

$\exists (q\bar{q}) \Rightarrow \exists (qq)$

(NOT OBSERVED !)

$$\boxed{SU_3^c}$$

$$\boxed{\mathcal{L}_{QCD} = \bar{\psi}\,(i\gamma_\mu \mathcal{D}^\mu - m)\,\psi - \frac{1}{2}\,\mathrm{Tr}\,(G_{\mu\nu}\,G^{\mu\nu})}$$

$$\psi = \begin{pmatrix} q_R \\ q_B \\ q_G \end{pmatrix} \qquad \mathcal{D}_\mu = \partial_\mu + i g_s B_\mu$$

$$B_\mu = \frac{1}{2} \lambda_a \mathcal{A}^a_\mu$$

$$G_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu + i g \left[B_\nu, B_\mu \right]$$

λ's:

$$\mathrm{tr}\left[\lambda^a\right] = 0 , \quad \mathrm{tr}\left[\lambda^a \lambda^b\right] = 2\,\delta^{ab} , \quad \left[\lambda^a, \lambda^b\right] = 2 i f^{abc} \lambda_c$$

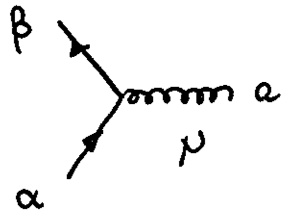
$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \qquad \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \qquad \lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix} \qquad \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

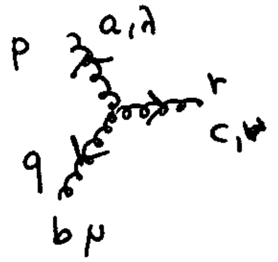
$$\lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix} \qquad \lambda_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} .$$

GELL-MANN matrices.

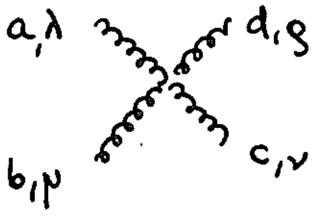
Vertices:



$$-\frac{ig}{2} \lambda^a_{\alpha\beta} \gamma_\mu$$



$$- g_s f^{abc} \left[(p-q)_\nu g_{\lambda\mu} + (q-r)_\lambda g_{\mu\nu} + (r-p)_\mu g_{\lambda\nu} \right]$$



$$\hat{=}\ i g_s^2 \Big[f^{abe} f^{cde} \left(g_{\lambda\nu} g_{\mu\rho} - g_{\lambda\rho} g_{\mu\nu}\right) + f^{ace} f^{bde} \left(g_{\lambda\mu} g_{\nu\rho} - g_{\lambda\rho} g_{\mu\nu}\right) + f^{ade} f^{bce} \left(g_{\lambda\mu} g_{\nu\rho} - g_{\lambda\nu} g_{\mu\rho}\right) \Big]$$

GAUGE FIXING:

- NO ADDITIONAL FEYNMAN RULES IN QED.

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x)$$

PROPAGATOR: (R_ξ gauges):

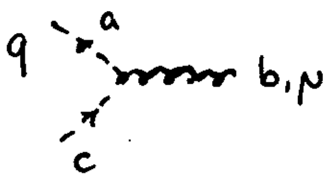
$$-\frac{i}{q^2+i\varepsilon}\left[g^{\mu\nu} + (\xi-1)\, q^\mu q^\nu/(q^2+i\varepsilon)\right]\delta_{ab}$$

e.g.

$\xi = 1$ LORENTZ- FEYNMAN GAUGE

$\xi = 0$ LANDAU GAUGE

- QCD: $\mathcal{A}_\mu^a \to \mathcal{A}_\mu^{a'} = \mathcal{A}_\mu^a - \frac{1}{g}\partial_\mu \alpha^a - f_{bca}\,\alpha^b \mathcal{A}_\mu^c$.



$g_s f^{abc} q_\mu$ GHOST- GLUON VERTEX.

THE 'RUNNING' COUPLING CONSTANT

LET : $G^{(N_\psi, N_G)} = \langle 0 | T(\psi_1 \dots \psi_{N_\psi} G_1 \dots G_{N_G}) | 0 \rangle$

N_ψ NUMBER OF EXTERNAL FERMIONS

N_G NUMBER OF EXTERNAL GLUONS

$$\Gamma_R^{(N_\psi, N_G)} = \frac{G_R^{(N_\psi, N_G)}}{\prod G_R^{(0,2)} \prod G_R^{(2,0)}}$$

$$\Gamma_R^{(N_\psi, N_G)}(p_j, g_s, \mu) = Z_\psi^{N_\psi/2} Z_G^{N_G/2} \Gamma_u^{(N_\psi, N_G)}(p_j, g_s)$$

RGE: $$\boxed{\mu \frac{d}{d\mu} \Gamma_u^{(N_\psi, N_G)} = 0}$$

CALLEN, SYMANZIK.

$$\left[\mu \frac{\partial}{\partial \mu} + \beta(g_s) \frac{\partial}{\partial g_s} - N_\psi \gamma_\psi(g_s) - N_G \gamma_G(g_s) \right] \Gamma_R^{(N_\psi, N_G)} = 0$$

$$\gamma_\psi(g_s) = \frac{\mu}{2} \frac{\partial}{\partial \mu} \ln Z_\psi$$

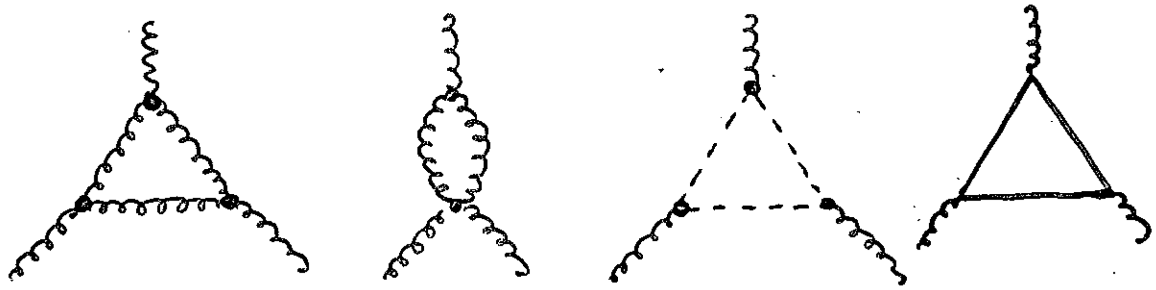
$$\gamma_g(g_s) = \frac{\mu}{2} \frac{\partial}{\partial \mu} \ln Z_g$$

$$\beta(g_s) = \mu \frac{\partial g_s}{\partial \mu}.$$

defines the 'running' of g_s.

THE RENORMALISATION OF g_s:

e.g. Γ_{VVV} :



$$\Gamma_u^{VVV} = Z_1^{-1}\,\Gamma_R^{VVV} \equiv \Gamma_u^{(0,3)}$$

$$G_u^{(0,2)} = Z_3\, G_R^{(0,2)}$$

()

$$g_{s,R} = Z_g\, g_{s,u} = \left(\frac{Z_3^{3/2}}{Z_1}\right) g_{s,u}$$

$G^{(0,2)}$:

$$Z_1 = 1 + \left[\left(\frac{17}{12} - \frac{3}{4}\xi\right) C_G - \frac{4}{6} N_f\right] \frac{g_u^2}{16\pi^2} \ln\left(\frac{\Lambda^2}{\mu^2}\right)$$

$$Z_3 = 1 + \left[\left(\frac{13}{6} - \frac{\xi}{2}\right) C_G - \frac{4}{6} N_f\right] \frac{g_u^2}{16\pi^2} \ln\left(\frac{\Lambda^2}{\mu^2}\right)$$

$$\curvearrowright\; Z_g^{(\mathcal{O}(\alpha_s))} = \left(1 + \left(\frac{11}{6} C_G - \frac{1}{3} N_f\right) \frac{g_u^2}{16\pi^2} \ln\left(\frac{\Lambda^2}{\mu^2}\right)\right)$$

$$\beta(g) = \left(\mu \frac{\partial Z_g}{\partial \mu}\right) g_u = -\left(\frac{11}{3} C_G - \frac{2}{3} N_f\right) \frac{g_u^3}{16\pi^2}$$

$$\beta(g) = \left[-\beta_0 \frac{g^2}{16\pi^2} - \beta_1 \frac{g^4}{(16\pi^2)^2} - \beta_2 \frac{g^6}{(16\pi^2)^3} + \dots \right] g$$

$$2 \frac{\partial g}{\partial \ln \mu^2} \approx -\beta_0 \frac{g^3}{16\pi^2}$$

$$\frac{\partial g^2}{g^4} \cdot 4\pi = -\frac{\beta_0}{4\pi} \partial \mu^2$$

$$\frac{1}{\alpha_s(\mu^2)} \equiv \frac{4\pi}{g^2} = \frac{\beta_0}{4\pi}\left[\ln\left(\frac{\mu^2}{\Lambda^2}\right)\right] - \frac{1}{\alpha_s(\Lambda^2)} \quad N_f \equiv 0$$

$$\boxed{\begin{array}{l} \alpha_s^{LO} = \dfrac{4\pi}{\beta_0} \dfrac{1}{\ln\left(\frac{Q^2}{\Lambda^2}\right)} \\[2ex] \alpha_s^{NTLO} = \alpha_s^{LO} \cdot \left[1 - \dfrac{\beta_0}{\beta_1^2} \dfrac{\ln \ln (Q^2/\Lambda^2)}{\ln (Q^2/\Lambda^2)} \right] \end{array}}$$

$\beta_0^{QCD} = 11 - \frac{2}{3} N_f$ POLITZER, GROSS, WILCZEK 1973

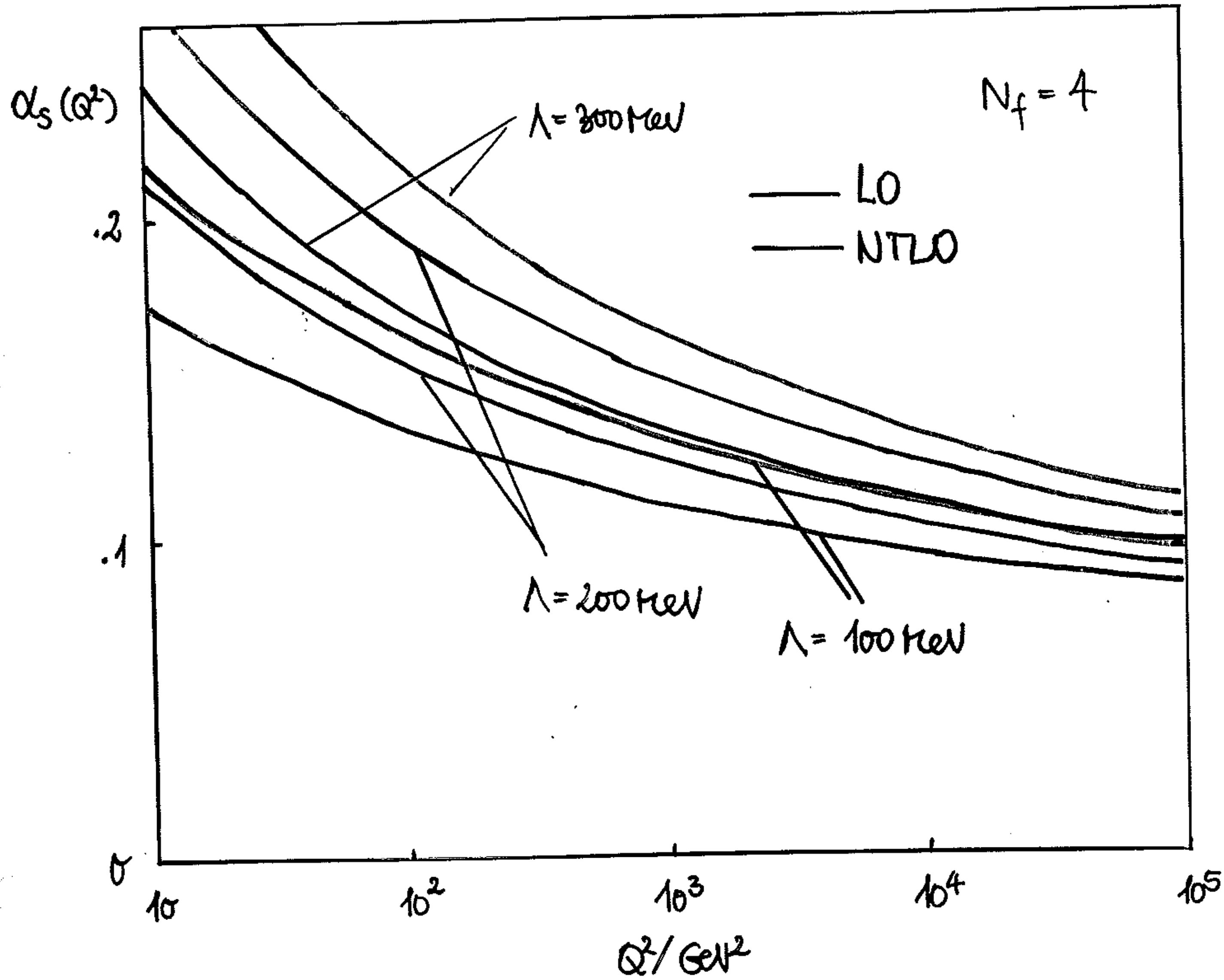
$\beta_1^{QCD} = 102 - \frac{38}{3} N_f$ CASWELL, JONES 1974

$\beta_2^{QCD} = \frac{2857}{2} - \frac{5033}{18} N_f + \frac{325}{54} N_f^2$

TARASOV, VLADIMIROV, ZHARKOV 1980.

$$\boxed{\alpha_{QED}^{LO} = \frac{\alpha(m^2)}{1 - \frac{\alpha(m^2)}{3\pi} \ln\left(\frac{Q^2}{m^2}\right)}}$$

'ONLY FERMIONS!

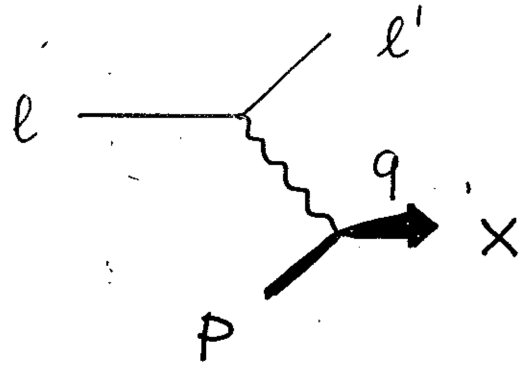


COLEMAN, GROSS: (1973)

ONLY NON-ABELIAN FIELD THEORIES ARE ASYMPTOTIC FREE IN 4 DIMENSIONS !

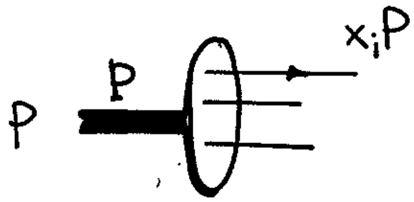
THE PARTON PICTURE OF NUCLEONS

DEEP INELASTIC SCATTERING:



$-q^2 = Q^2 \gg M_p^2$

$\sqrt{Q^2} \sim 1/\Delta x_T$ SPATIAL RESOLUTION OF THE PROTON STRUCTURE.



FEYNMAN :

PARTONS

LATER (1975) IDENTIFIED BY :
- QUARKS
- ANTIQUARKS
- GLUONS

POINTLIKE SCATTERING:

$$W_2(Q^2, \nu, x) = \sum_i \int_0^1 dx_i \, f(x_i) \, W_2^{(i)}(Q^2, \nu, x_i)$$

$$W_2^{(i)}(Q^2, \nu, x_i) = x_i e_i^2 \, \delta\left(\frac{p_i \cdot q}{M} - \frac{Q^2}{2M}\right)$$

$$\boxed{\nu W_2(Q^2, \nu) = \sum_i e_i^2 f_i(x) \cdot x}$$

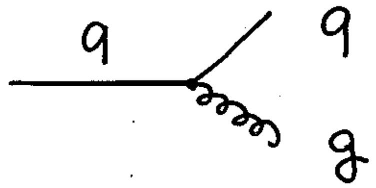
(SCALING)

$x = \frac{Q^2}{2M\nu}$; $\nu = qP/M$.

SCALING VIOLATIONS OF STRUCTURE FUNCTIONS

COLLINEAR RADIATION OFF PARTONS:

(WEIZSÄCKER - WILLIAMS PICTURE)

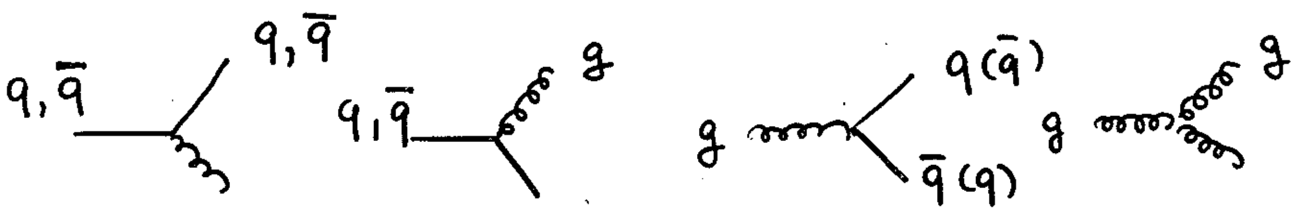


$$\frac{\partial q_{NS}(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} P_{NS}(x) \otimes q_{NS}(x,Q^2)$$

$$\frac{\partial}{\partial \ln Q^2}\begin{pmatrix}\Sigma(x,Q^2)\\ G(x,Q^2)\end{pmatrix} = \frac{\alpha_s(Q^2)}{2\pi}\begin{pmatrix}P_{qq} & P_{qG}\\ P_{Gq} & P_{GG}\end{pmatrix} \otimes \begin{pmatrix}\Sigma\\ G\end{pmatrix}(x,Q^2)$$

GLAP - equs. 1972, 1977.

$$F_2^{ep}(x,Q^2) = \sum e_q^2\,\left(q(x,Q^2) + \bar{q}(x,Q^2)\right)$$



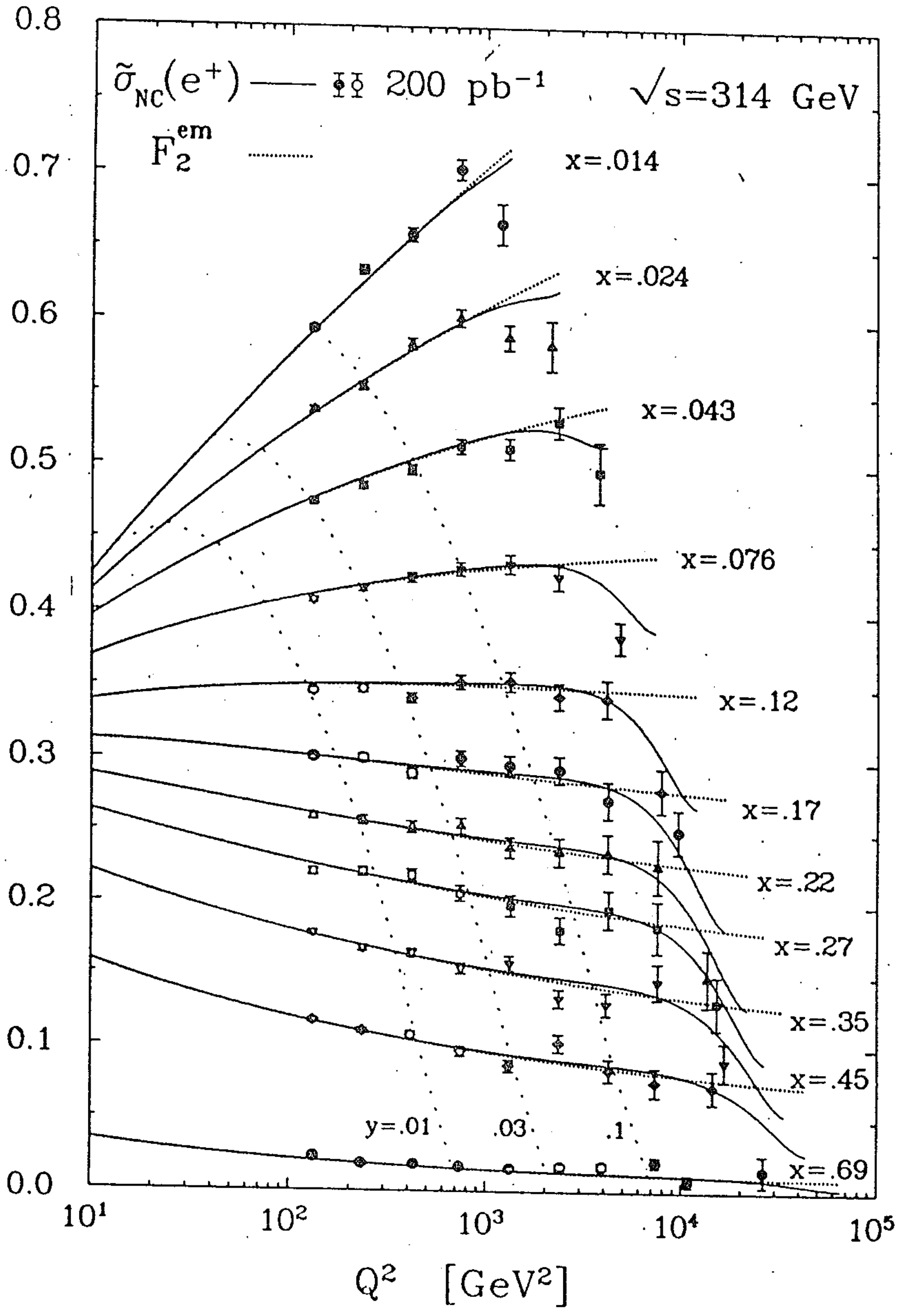

$\tilde{\sigma}_{NC}(e^+)$ —— 200 pb^{-1}
$\sqrt{s}$=314 GeV
F_2^{em}
x=.014
x=.024
x=.043
x=.076
x=.12
x=.17
x=.22
x=.27
x=.35
x=.45
x=.69
y=.01
.03
.1
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
10^1
10^2
10^3
10^4
10^5
Q^2 [GeV^2]

Fig. 3

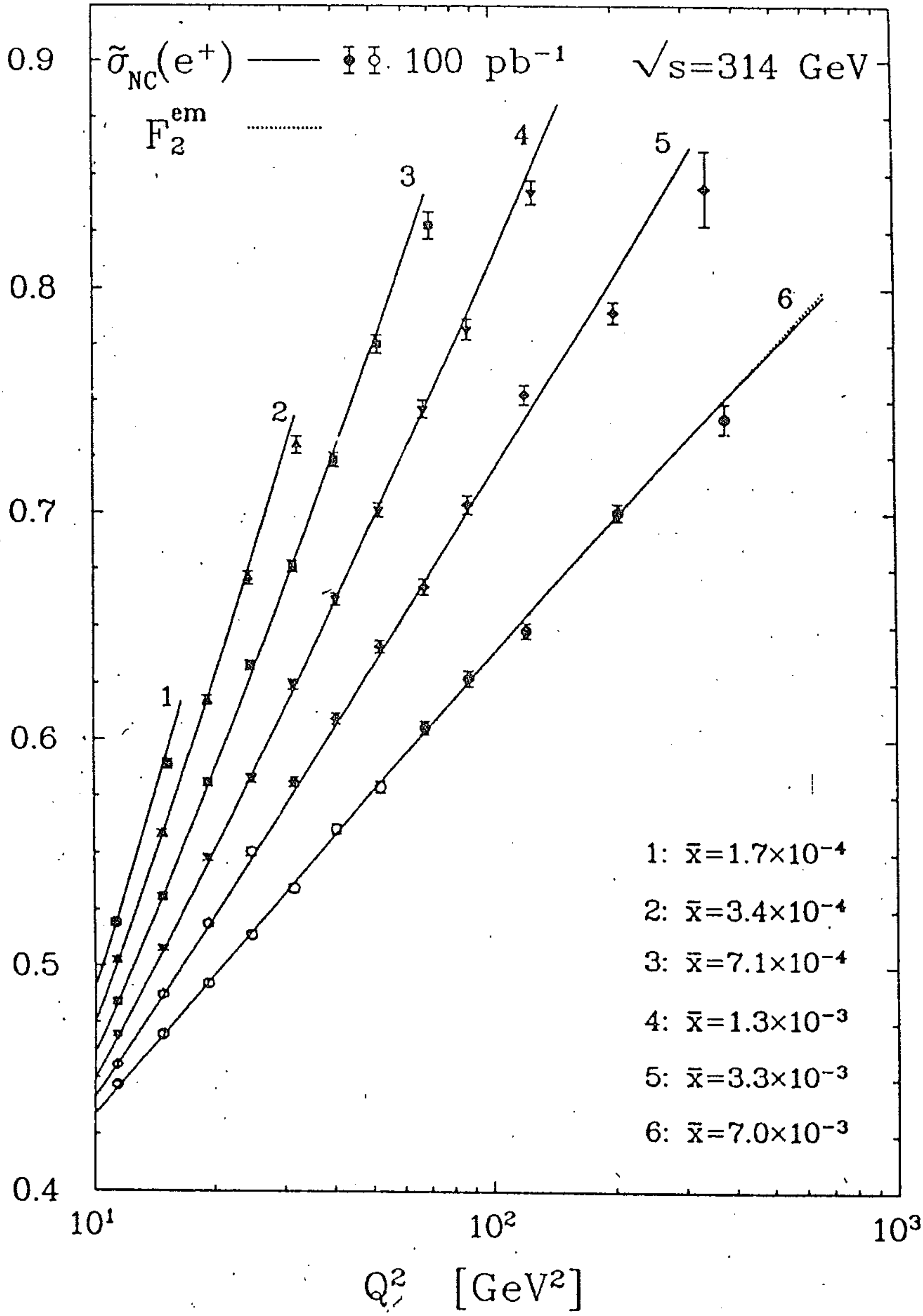
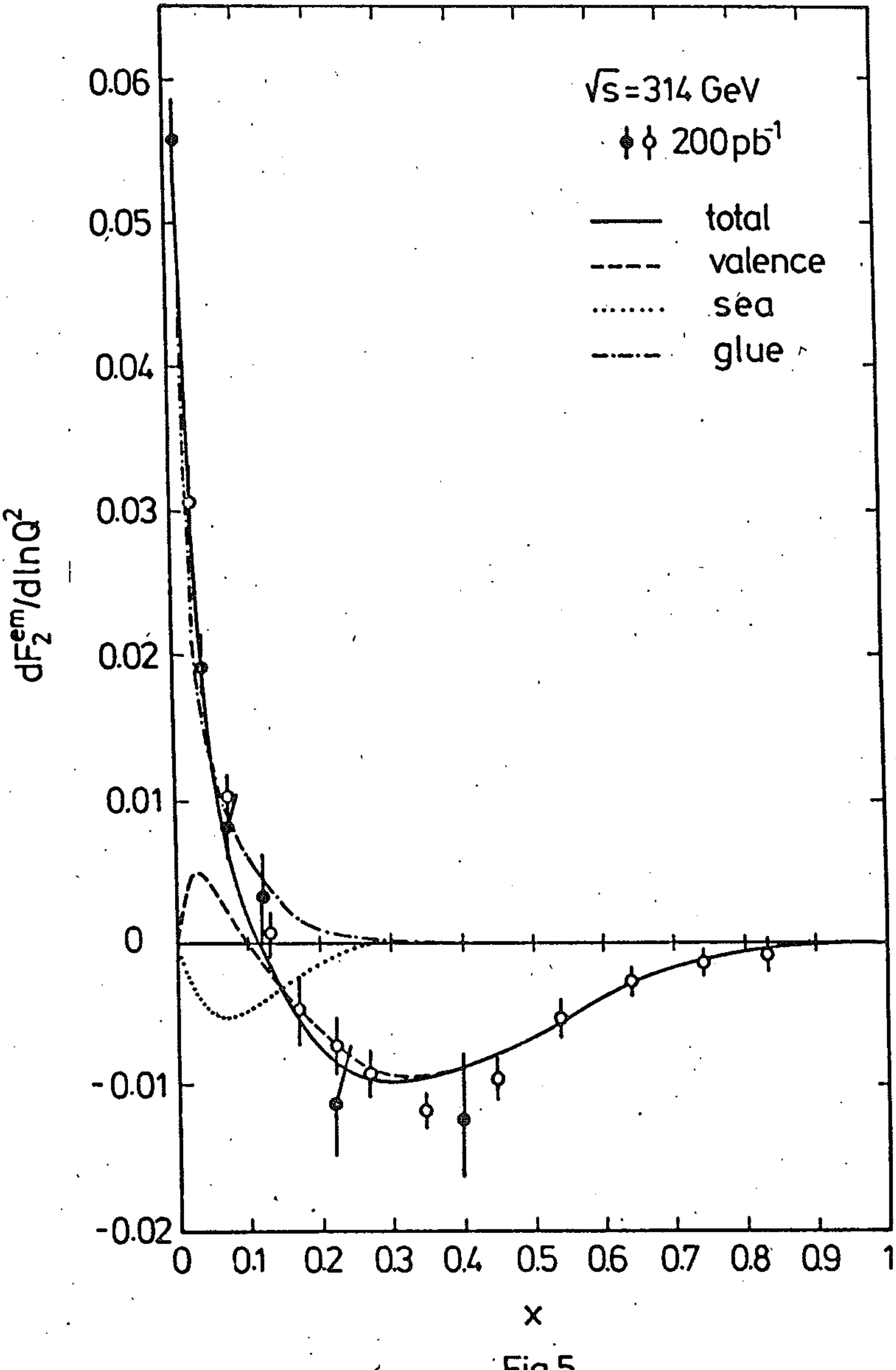

$\tilde{\sigma}_{NC}(e^+)$ —— 100 pb^{-1}
$\sqrt{s}$=314 GeV
F_2^{em}
1
2
3
4
5
6
0.9
0.8
0.7
0.6
0.5
0.4
10^1
10^2
10^3
Q^2 [GeV^2]
1: $\bar{x}=1.7\times10^{-4}$
2: $\bar{x}=3.4\times10^{-4}$
3: $\bar{x}=7.1\times10^{-4}$
4: $\bar{x}=1.3\times10^{-3}$
5: $\bar{x}=3.3\times10^{-3}$
6: $\bar{x}=7.0\times10^{-3}$

Fig. 6



$\sqrt{s}=314$ GeV
200 pb^{-1}
total
valence
sea
glue
$dF_2^{em}/d\ln Q^2$
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x

Fig.5

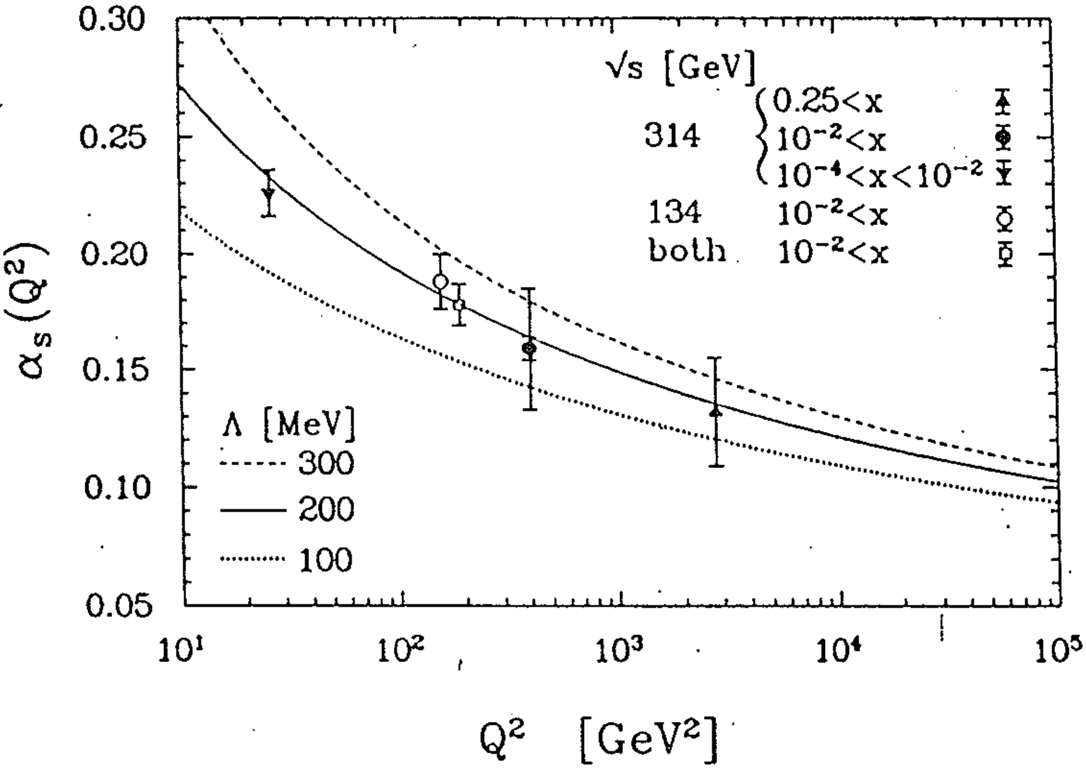


Fig. 8

Ag.-Nr. 521/683/89
Rg.-Nr. I/12/6

THE STRONG CP - PROBLEM

CONSIDER YM-FIELD CONFIGURATIONS IN EUKLIDEAN SPACE.

$$\nu = \frac{1}{32\pi^2} \int d^4x \; F^a_{\mu\nu}(x) \tilde{F}^{\mu\nu}_a(x)$$

$$\tilde{F}^{\mu\nu}_a(x) = \frac{1}{2} \varepsilon^{\mu\nu\rho\sigma} F_{a\rho\sigma}(x)$$

$\nu[A^a]$ - PONTRYAGIN INDEX

$$\frac{\delta \nu[A^a]}{\delta A^a} = 0$$

ν DEFINES THE HOMOTOPY CLASS OF THE RESPECTIVE GAUGE TRANSFORMATION

$\nu \simeq |\nu\rangle$ VACUUM

$$|\theta\rangle = \sum_{\nu=-\infty}^{+\infty} e^{i\nu\theta} |\nu\rangle$$

θ - vacuum.

$\curvearrowright$ $$\mathcal{L}_\theta = \frac{\theta}{32\pi^2} F^a_{\mu\nu}(x) \tilde{F}^{\mu\nu}_a(x)$$

CP- violating term.

OBSERVABLE:

$$d_n = 2.7 \cdot 10^{-16} \, \theta \; e\,cm$$

(BALUNI)

$$|d_n^{exp}| < 6 \cdot 10^{-25} \; e\,cm$$

$$\theta < 10^{-8} \ldots 10^{-9}$$

is $\theta \neq 0$?

∴ CHIRAL SOLUTIONS : 'INVISIBLE' AXION

$$m_A < 10^{-3}\ eV$$

OPEN PROBLEMS AND THE WAY BEYOND

- THE SUCCESS OF THE STANDARD MODEL:
  - RENORMALIZABLE QUANTUM FIELD THEORY
  - DESCRIBES TO A WIDE EXTENT THE EXPERIMENTAL DATA (NO REAL CONFLICTS YET).
  - EMPHASIS:
    - GAUGE BOSON – FERMION
    - GAUGE BOSON – GAUGE BOSON INTERACTIONS.

- PARAMETRIZES ONLY:

m_f :	$\underset{q}{6} + \underset{\ell}{3} + \ldots \underset{\nu}{3}$	PARAMETERS
CKM_q:	4	PARAMETERS
CKM_ℓ:	... 4	PARAMETERS

$$\left.\begin{array}{l} \alpha_{QED} \\ \sin^2\theta_W \\ \Lambda_{QCD} \\ M_Z \end{array}\right\} \text{4 PARAMETERS}$$

$(N_{family} = 3)$

18 ... 24 PARAMETERS
+1

NOT YET UNDERSTOOD!

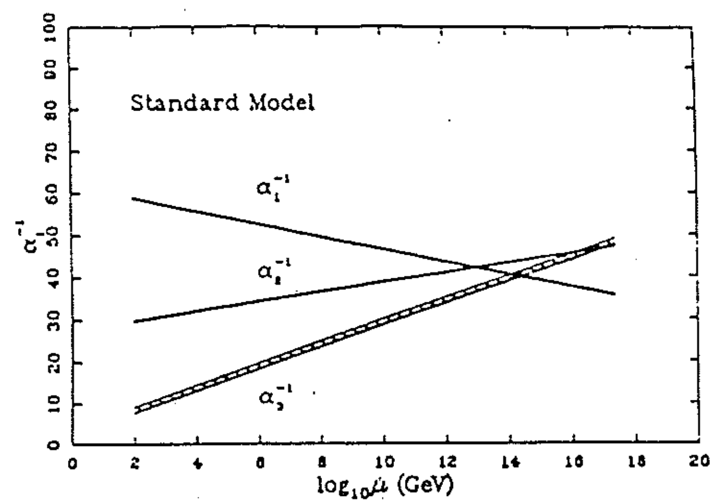
- THE HIGGS MECHANISM NICELY DECOUPLES THE FERMION MASS PROBLEM.

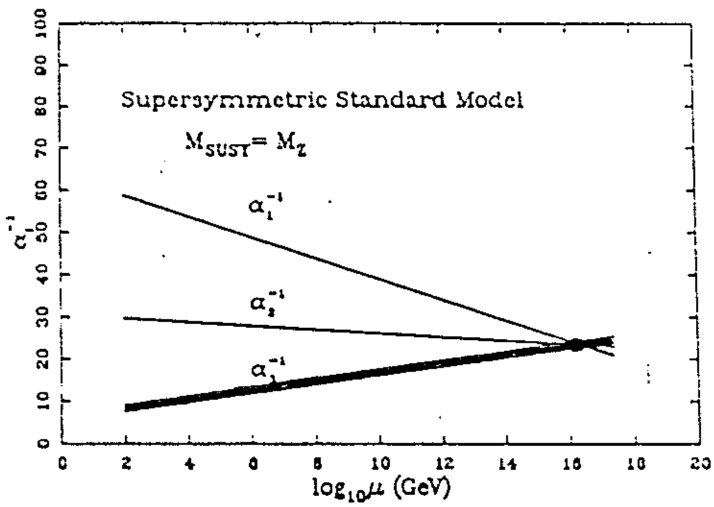
  → CAN IT BE SOLVED INVOKING GAUGE THEORIES ?

  - PREON STRUCTURES ?
  - WHAT ARE THE PHONONS IN THE STANDARD THEORY ?
  - WHY FAMILY REPLICATION ?
    WHY 3 OF THEM ?

- WHAT IS THE REASON FOR CKM - MIXING ?
- DO ν'S MIX AS WELL AND IS $m_{\nu_i} > 0$?
- DO, AND IF HOW, DO THE FUNDAMENTAL FORCES UNIFY?

THE CASE FOR SUSY ?





LANGACKER '93

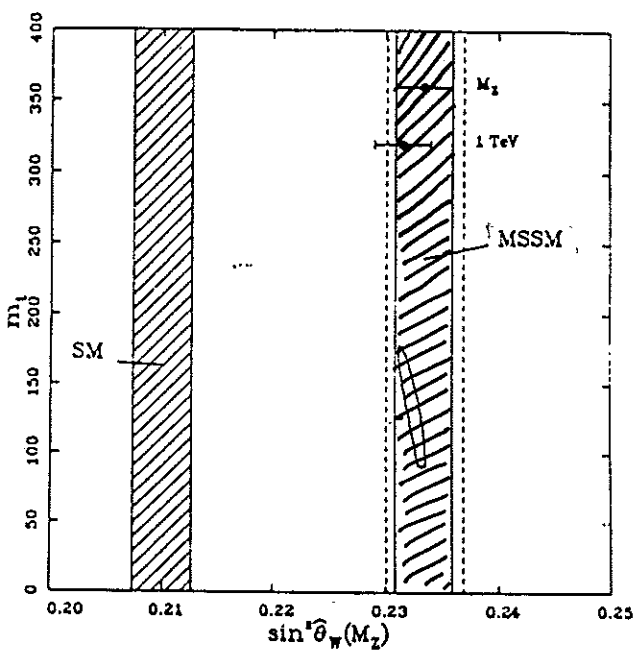


Figure 16: Predictions of the ordinary and supersymmetric grand unified theories for $\sin^2\theta_W$, compared with the experimental value, from [24].

$\alpha_S(M_Z^2)$

Table 2
Evolution of the strong coupling constant $\alpha_s(Q)$ for $N_{\tilde{g}} = 0$ and 1 starting from the value at 91.2 GeV down to 5 GeV. The experimental values are taken from ref. [2].

Q (GeV)	$N_{\tilde{g}}$		Experiment
	0	1	
91.2	0.124 ± 0.005	0.124 ± 0.005	0.124 ± 0.005
58.0	0.134 ± 0.006	0.130 ± 0.006	0.130 ± 0.008
34.0	0.147 ± 0.007	0.139 ± 0.006	0.140 ± 0.020
20.0	0.164 ± 0.009	0.148 ± 0.007	$0.138^{+0.028}_{-0.019}$
10.0	0.193 ± 0.013	0.164 ± 0.009	$0.167^{+0.015}_{-0.011}$
7.1	0.212 ± 0.015	0.172 ± 0.010	0.180 ± 0.014
5.0	0.235 ± 0.019	0.182 ± 0.011	0.193 ± 0.019 0.174 ± 0.012

JEŁABEK, KÜHN

LIGHT GLUINO ?

- THE STANDARD THEORY DELIVERS A GOOD DESCRIPTION FOR MANY EXPERIMENTAL EFFECTS, AND A GOOD PARAMETRIZATION FOR VARIOUS OTHERS.

- A LARGE NUMBER OF QUESTIONS (24+1) IS OPEN

  AND REQUIRES NEW THEORETICAL EFFORTS.