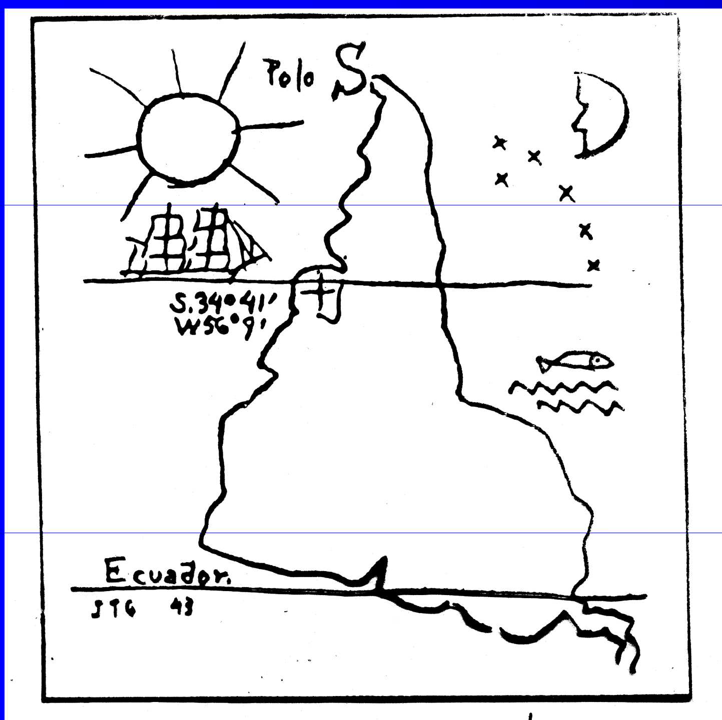
Standard Model and beyond: particles & interactions



Gabriel González Sprinberg
Instituto de Física, Facultad de Ciencias
Montevideo - Uruguay

gabrielg@fisica.edu.uy

ECOS-SUD

Mar 8, 14 h – Ven 11, 14 h – Mar 15, 10 h – Ven 18, 10 h

OUTLINE

- ✓ Particles: matter and gauge bosons
- ✓ Interactions (low and high energies regimes)
- ✓ Symmetries: internal, external, continuous, discrete
- ✓ Lagrangians and Feynman diagrams (quantum field theory by drawing)
- ✓ Some processes
- ✓ A closer look to some examples
- ✓ SM: experimental status and tests
- ✓ Beyond the forest: models and phenomenology
- ✓ Some extensions: grand unification, supersymmetry, ...
- ✓ And their observables: proton decay, sparticles, neutrino masses and oscillations...

SOME HISTORY

before '30

- e, p, γ; nucleus ($A \longrightarrow p$, $A - Z \longrightarrow e$)
- 1925/6 Heisenberg/Schrödinger QM
  Pauli exclusion principle
- 1927/8 Dirac's electron relativistic wave equation
  Quantum electrodynamics
  Magnetic moment for the electron
- β decay in nuclei: a total mess
  - → 1914, e with continuous spectrum
  - → missing energy (34% !!)
  - → N. Bohr: energy-momentum not conserved (non-invariance under translations of Poincare group)
  - → 1930, Pauli was not so radical: a new particle must exist $\longrightarrow$ neutrinos

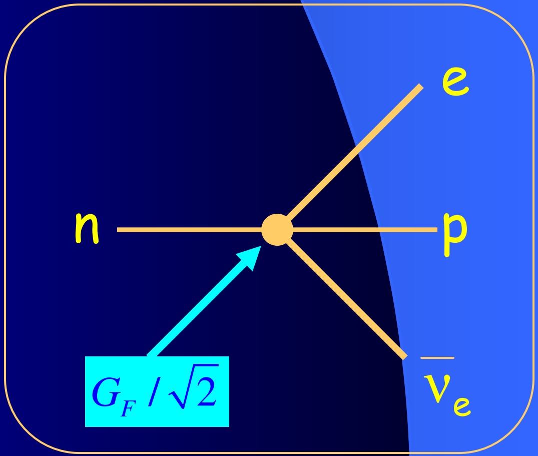
SOME HISTORY

after '30

- 1931 Dirac prediction of positron and antiproton
- 1932
  - → Anderson: positron
  - → Chadwick: neutron (α + Be $\longrightarrow$ C + n)
  - → Heisenberg nuclei: protons and neutrons
    spin-statistics accomodates
- 1934
  - → Pauli explanation of β decay: $n \rightarrow p + e^{-} + \overline{\nu}_e$
  - → Fermi theory of weak interactions

$$\mathrm{N}_{\mathrm{i}}^{\mathrm{Z}} \rightarrow \mathrm{N}_{\mathrm{f}}^{\mathrm{Z+1}} + \mathrm{e} + \overline{\nu}_e$$

$$H_{\mathrm{int}} = \frac{G_F}{\sqrt{2}} \left(\overline{p} \gamma_\mu n \right) \left(\overline{e} \gamma^\mu \nu_e \right)$$



SOME HISTORY

- 1935 Yukawa predicts π
- 1936 Gamow-Teller extension of Fermi theory
- 1937 Majorana neutrino theory; μ discovered
- 1947 Pontecorvo universality of weak interactions in decay and capture processes; π discovered
- 1949 Universality of weak interactions for hadrons and leptons; QED is a renormalizable theory
- 1950- Hundreds of particles/resonances are found
- 1954 Yang-Mills gauge theories
- 1956/7 Parity violation proposal and evidence
- 1957 Neutrino two component theory; intermediate vector boson for weak interactions
- 1958 Feynman and Gell-Mann; Marshak and Sudarshan; Sakurai: universal V-A weak interactions
- 1959 Detection of anti-neutrino

SOME HISTORY

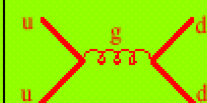
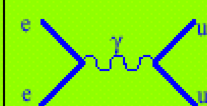
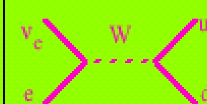
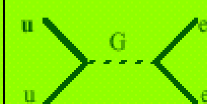
- 1961 SSB; Glashow neutral boson
- 1964 Gell-Mann/Zweig quark model; proposal of charm; CP violation in K^0 mesons decays; Higgs mechanism; color QN
- 1967 Weinberg EW model
- 1970 GIM lepton-quark symmetry and charmed quarks (FCNC)
- 1971 Renormalization of SSB gauge theories
- 1973 Kobayashi-Maskawa CP model; evidence of the predicted neutral current; Gross, Wilczek, Politzer asymtotic freedom; Fritzsch, Gell-Mann, Leutwyler QCD
- 1974-5 SLAC J/ψ, τ
- 1977 Fermilab Υ
- 1979 Gluon jets
- 1983 Charged W and neutral Z bosons
- 1995 Top quark
- 1998-9 Neutrino oscillations @ SuperKamiokande

PARTICLES & INTERACTIONS
(matter and gauge bosons)

QUARKS S=1/2		LEPTONS S=1/2		GAUGE BOSONS S=1
Q = –2/3	Q = –1/3	Q = –1	Q = 0	quanta
u u u m=(1-4) 10^{-3}	d d d m=(5-8) 10^{-3}	e m=5.11 10^{-4}	ν_e m<3 10^{-9}	g_1 …… g_8 m< a few 10^{-3}
c c c m=1.0-1.4	s s s m=0.08-0.15	μ m=0.10566	ν_μ m<1.9 10^{-4}	γ m<2 10^{-25}
t t t m=174.3±5.1	b b b m=4.0-4.5	τ m=1.7770	ν_τ m<18.2 10^{-3}	$W^{\pm}$, Z^0 m_W=80.432 ±0.39, m_Z=91.1876 ±0.0021

(mass in Gev/c^2)

(plus antiparticles!)

Interaction	exchanged boson	relative strength	example
Strong	Gluon (g)	1	
Electromagnet.	Photon (γ)	$\frac{1}{137}$	
Weak	W^+, W^-, Z^0	10^{-14}	
Gravitation	Graviton (G) ?	10^{-40}	

PARTICLES & INTERACTIONS

Besides, there are hadrons, atoms, molecules…

HADRONS: Mesons ($q\bar{q}$) $\pi^{\pm}$ π^{0} K ρ … ϕ … J/ψ …

Baryons (qqq states- fermions) p n $\Delta^{\pm}$ … Λ … Λ_b …

Pentaquarks…?

Is there any order in the list?

1. Matter particles are not the same as the messengers of the interactions, the gauge bosons
2. Particles are sensitive to different forces:
   quarks couple directly to gluons, photons, weak bosons
   leptons only to photons and weak bosons
3. There is some order in mass in leptons, not so evident in quarks

Other way to find some order:

Relate: SYMMETRY $\Leftrightarrow$ INTERACTIONS

"QUARKS, NEUTRONS,MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM !! "

SYMMETRIES

In classical physics:

Symmetry	$\rightarrow$	Conservation laws
space translation	$\rightarrow$	momentum
time translation	$\rightarrow$	energy
rotation	$\rightarrow$	angular momentum

These are continuous and external symmetries.
Some others may also be discrete:

space inversion $\rightarrow$ parity

High energy physics : Relativistic (Lorentz invariant)
Quantum
Field theory

Is there any other symmetry principle?

Is there any other guide in order to construct our theories?

SYMMETRIES AND GAUGE THEORIES

Relativistic quantum field theory (as QED) is not enough, we need a GAUGE THEORY

WHY?

Nice features about GAUGE THEORIES:

➔once the symmetry is chosen (internal symmetry group) the interactions are fixed!

➔quantum corrections can be computed and are finite

➔consistency of the theory motivate for the seach of new particles and interactions

➔the theory is full of predictions…

It is a gauge, Lorentz invariant, quantum field theory what is needed

TWO SLIDES GAUGE THEORY PRIMER (I)

Electrodynamics as an example:

$$H = \frac{1}{2m}\left(\vec{p} - q\vec{A}\right)^2 + q\Phi$$

gives the Lorentz force for a particle in an electromagnetic field

Electric and magnetic fields are described by

$$A^\mu = (\Phi, \vec{A})$$

$$\vec{E} = -\vec{\nabla}\Phi - \frac{\partial \vec{A}}{\partial t}; \quad \vec{B} = \vec{\nabla}\times\vec{A}$$

Fields remain the same with the gauge transformation (G):

$$\Phi \to \Phi' = \Phi - \frac{\partial \aleph}{\partial t}; \quad \vec{A} \to \vec{A}' = \vec{A} + \vec{\nabla}\aleph$$

$$\aleph = \aleph(x, t) \quad !!!$$

Now, what happens in quantum mechanics?

We quantize the Hamiltonian with the prescription $\vec{p} \to -i\vec{\nabla}$

TWO SLIDES GAUGE THEORY PRIMER (II)

The Schrödinger equation for a particle in an electromagnetic field is

$$\left[\frac{1}{2m}\left(-i\vec{\nabla}-q\vec{A}\right)^2+q\Phi\right]\Psi(x,t)=i\frac{\partial\Psi(x,t)}{\partial t}$$

If we make a gauge transformation: $(\Phi,\vec{A})\xrightarrow{G}(\Phi',\vec{A}')$

and, at the same time, we transform the wave function as

$$\Psi(x,t)\xrightarrow{G}\Psi'(x,t)=\exp(iq\aleph(x,t))\Psi(x,t)$$

we obtain the same equation and the same physics, described either by the original field and wave function or the transformed ones

$$(\Phi,\vec{A},\Psi)\xrightarrow{G}(\Phi',\vec{A}',\Psi')$$

A particle in interaction with the EM field has a whole class of "equivalent" potentials and wave functions related by the gauge group G, and only one generator in the group (only one function $\aleph$)

QUANTUM ELECTRODYNAMICS AS A GAUGE THEORY

QED

Gauge theory with only one freedom in the gauge function; this means in the group language U(1) abelian-symmetry and we end up with one gauge boson, the photon, and one coupling constant e that couples matter and radiation.

Free electron Lagrangian has a global phase invariance:

$$L = \bar{\Psi}(i\partial_\mu \gamma^\mu)\Psi - m\bar{\Psi}\Psi \qquad \Psi \rightarrow \exp(i\alpha)\Psi$$

Introducing a gauge field A_μ (photon field) with the above transformation rules, we have an invariant lagrangian with interactions:

$$L = \bar{\Psi}(i\partial_\mu - eA_\mu)\gamma^\mu\Psi - m\bar{\Psi}\Psi$$

kinetic term

interaction term

mass term

ELECTRODYNAMICS AS A GAUGE THEORY

Up to know, the EM field has no dynamics. This is introduced in a natural way by the gauge invariant field EM tensor

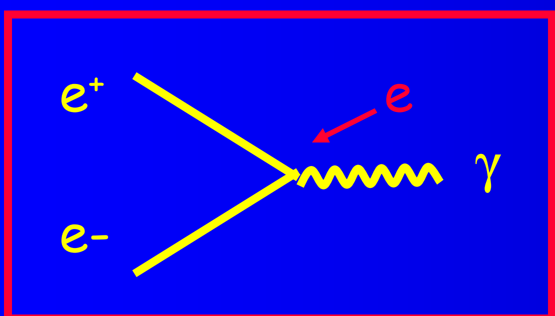
$$\boxed{F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu}$$

$$\boxed{L_A = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}}$$

Finally, the Lagrangian is

$$\boxed{L = \overline{\Psi}(i\partial_\mu - eA_\mu)\gamma^\mu \Psi - m\overline{\Psi}\Psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}}$$

kinetic interaction mass kinetic



represents the interaction term

coupling: $\boxed{\alpha = e^2/4\pi \sim 1/137}$

A photon mass term $\boxed{L_A^m = -\frac{1}{2} m_\gamma^2 A_\mu A^\mu}$ is not gauge invariant !!!!

ELECTRODYNAMICS: Feynman diagrams

All physical observables can be obtained with the Feynman diagrams:

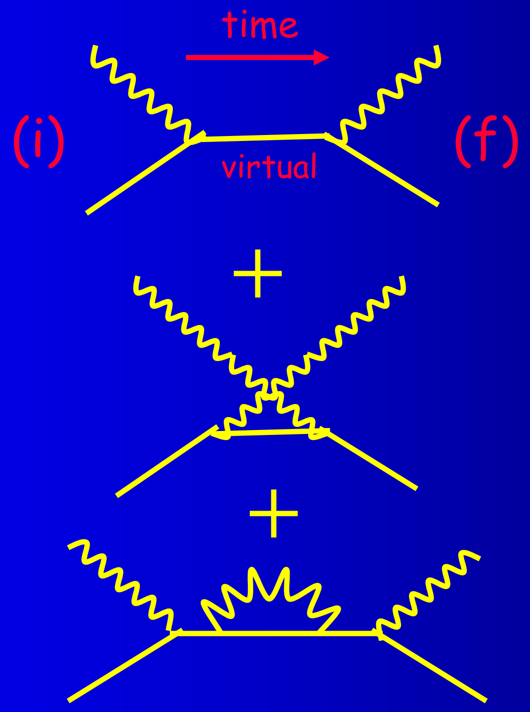
$d\sigma \sim |M|^2 \, d\,(P.S.)$ $\qquad$ $d\Gamma \sim |M|^2 \, d\,(P.S.)$

The amplitude M is computed with all the possible Feynmann diagram that contribute to the reaction.

For example:

$e^- \gamma \rightarrow e^- \gamma$

Compton Effect

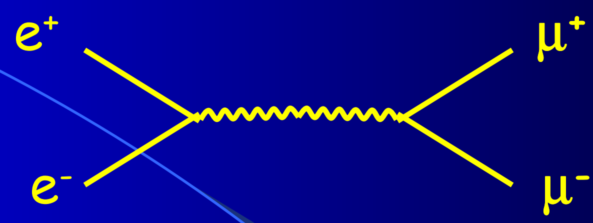


$+ \cdots$

ELECTRODYNAMICS: some processes

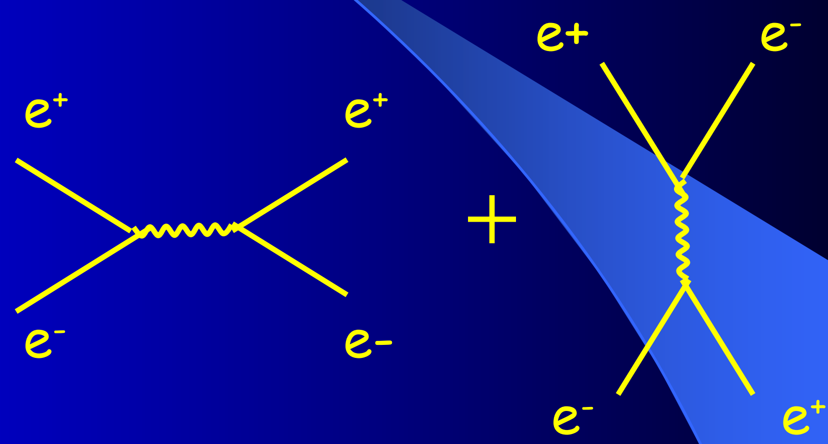
$e^+ e^- \longrightarrow \mu^+ \mu^-$

(tree level)



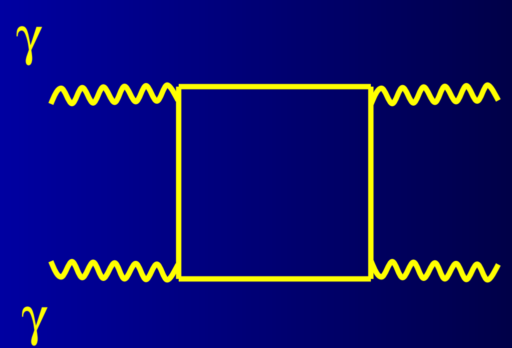
Bhabha $e^+ e^- \longrightarrow e^+ e^-$

(tree level)



$\gamma\gamma \longrightarrow \gamma\gamma$

(first order)



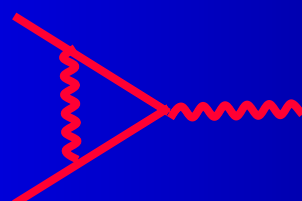
ELECTRODYNAMICS: e magnetic moment

One of the best known quantities in physics
One of the best predictions of the physical theories

$$\mu_e = (\,1.001\ 159\ 652\ 187 \pm 0.000\ 000\ 000\ 004\,)\quad 2\,\mu_B$$

Dirac's equation prediction: gyromagnetic factor

Anomalous magnetic moment = $\mu_e / 2\mu_B - 1 = a_e$

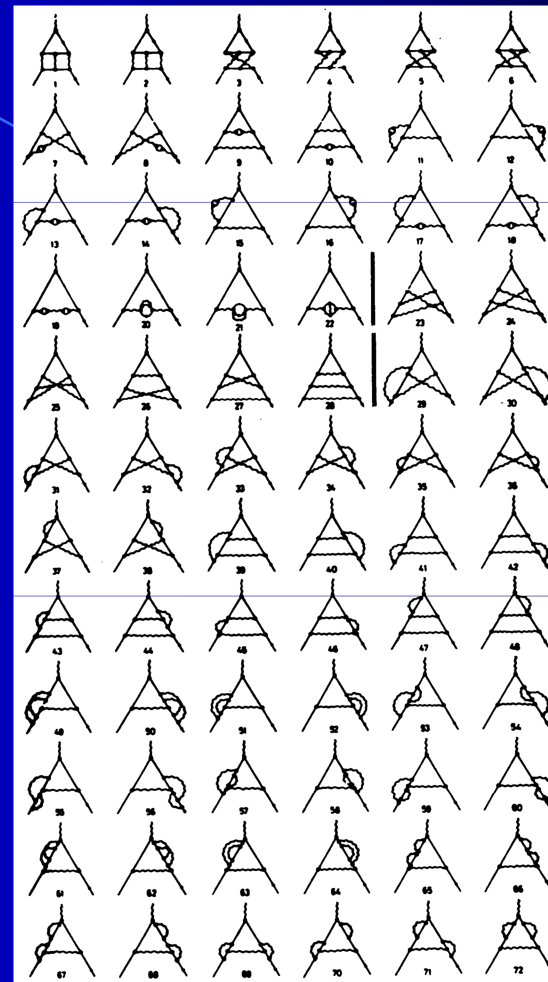
Computed to first order:  $= \alpha/2\pi \approx 0.0011623$

Schwinger

One can also compute to higher orders; for example:

ELECTRODYNAMICS: e magnetic moment

Third order diagrams...



$$a_e = \frac{\alpha}{2\pi} - 0.328\ 478\ 965\text{K}\left(\frac{\alpha}{\pi}\right)^2 + 1.181\ 241\ 456\text{K}\left(\frac{\alpha}{\pi}\right)^3 - 1.509\ 8(384)\left(\frac{\alpha}{\pi}\right)^4 + 4.393(27)\times 10^{-12}$$

weak and hadronic contributions

ELECTRODYNAMICS: some comments

Gauge invariance ⟶ minimal coupling interaction term $" - eA_\mu \bar{\Psi} \gamma^\mu \Psi "$

Other terms:

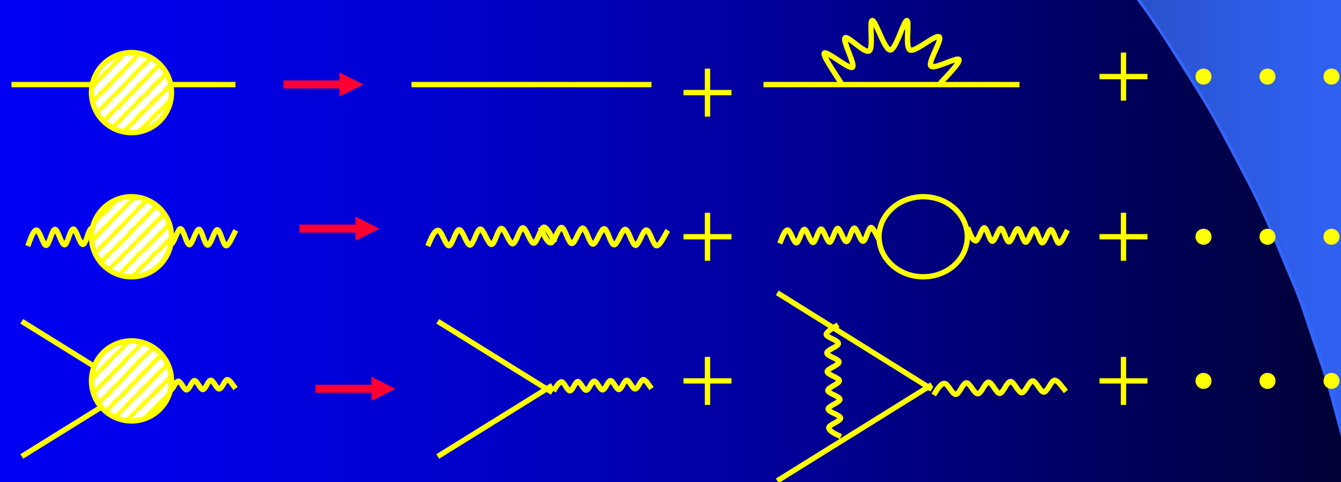
- boson mass $" m_\gamma^2 A_\mu A^\mu "$ spoils not only gauge invariance but also renormalizability
- higher order terms $" \bar{\Psi} \sigma^{\mu\nu} \Psi F_{\mu\nu} ; \bar{\Psi} \Psi F_{\mu\nu} F^{\mu\nu} \ldots "$ are forbidden by causality or renormalizability
- only exception is $" \varepsilon^{\mu\nu\sigma\delta} F_{\mu\nu} F_{\sigma\delta} "$, a CP-odd one but it is a divergence, i.e. a surface term that can be eliminated in QED (it is "$-8 \vec{E} \times \vec{B}$ ")
- only D≤4 terms respect renormalization

ELECTRODYNAMICS: some comments

Renormalization:

all the quantum corrections to the processes can be taken into account by renormalizing the fields (A,ψ) and constants (m,e) in the lagrangian plus some finite contributions; in this way no infinite quantities appear in the physical results

In diagrams: tree level + one loop + higher orders



This also means:

$e_0 \rightarrow e \quad A_0 \rightarrow A \quad m_0 \rightarrow m \quad \Psi_0 \rightarrow \Psi$

ELECTRODYNAMICS: some comments

The coupling constant is renormalized and depends on the scale !!
(running coupling constant)

electron charge $\equiv e(Q^2=0)$

the coupling constant $\alpha(Q^2)=e^2(Q^2)/4\,\pi$ runs with the scale

$$\alpha(Q^2=0) = e^2(0)/4\,\pi = 1/137.03599976(50)$$

$$\alpha(Q^2=M_Z^{\,2}) = e^2(M_Z^{\,2})/4\,\pi = 1/127.934(27)$$

Allright Ruth, I about got this one renormalized

ELECTRODYNAMICS as a tool

Quarks have, besides flavour, a new quantum number

COLOUR

$$\sigma\left(e^+e^- \to \mu^+\mu^-\right) = \frac{4\pi}{3}\frac{\alpha^2}{q^2}$$

$$\sigma\left(e^+e^- \to q\bar{q}\right) = \frac{4\pi}{3}\frac{\alpha^2}{q^2}e_q^2$$

e_q=1/3, 2/3

At a given energy:

$$\sigma\left(e^+e^- \to X \;\; hadrons\right) = \frac{4\pi}{3}\frac{\alpha^2}{q^2}\sum_{all\, q} e_q^2$$

at lowest order

$$R_{had} = \frac{\sigma\left(e^+e^- \to X\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = \sum_{all\, q} e_q^2 = \begin{cases} 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = 2 \\ 3\left[\left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{1}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{1}{3}\right)^2\right] = \frac{11}{3} \end{cases}$$

below charm

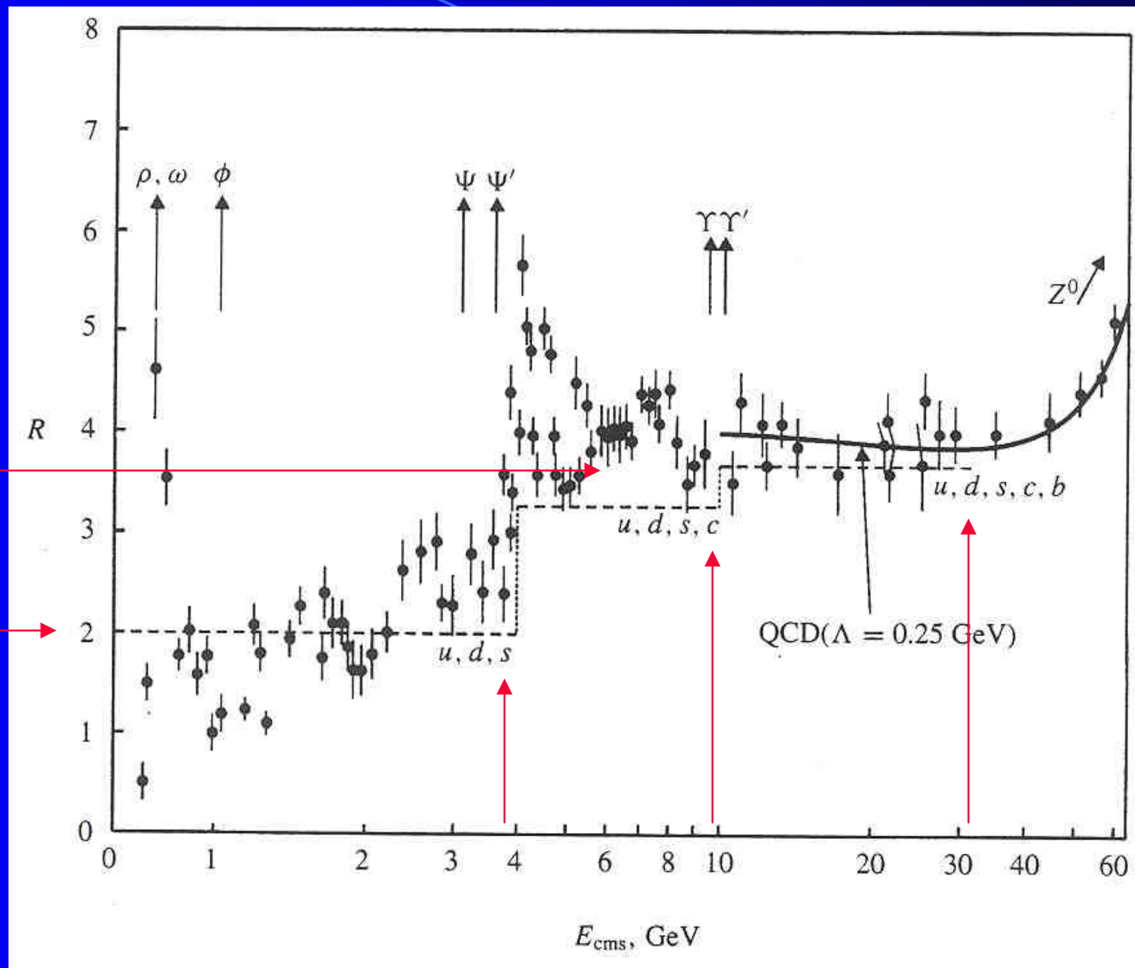
above bottom

ELECTRODYNAMICS as a tool

R

bottom

charm



CM ENERGY in GeV

QUANTUM CROMODYNAMICS: SU(3) GAUGE THEORY

$U(1)_{QED}$ ✸ $SU(3)_{Color}$ with **eight** generators

$$eA \to g_s \sum_{c=1}^{8} \frac{\lambda^c}{2} G^c ; \quad c = 1,\ldots 8$$

3 means that we have ② ② ② for the quark colors

$$q = \begin{pmatrix} q \\ q \\ q \end{pmatrix}$$

$$L' = \bar{q}\left(i\partial_\mu - g_s \sum_{c=1}^{8} \frac{\lambda^c}{2} G_\mu^{\ c} \right)\gamma^\mu q - m\,\bar{q}q ; \quad q = u, d, s, c, b, t$$

we sum in all flavors (u,d,s…) and also in colour

$$L_G = -\frac{1}{4}\sum_{c=1}^{8} G^c_{\ \mu\nu} G^{c\,\mu\nu}$$

$$G^c_{\ \mu\nu} = \partial_\mu G^c_{\ \nu} - \partial_\nu G^c_{\ \mu} + \underbrace{g_s f^{cab} G^a_{\ \mu} G^b_{\ \nu}}$$

$$L_{QCD} = L' + L_G$$

THESE NON ABELIAN TERMS ARE THE MAIN DIFFERENCE WITH QED

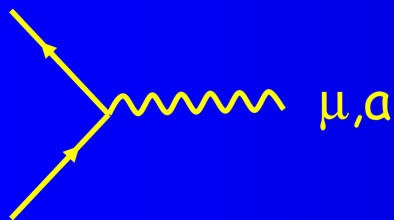
QUANTUM CROMODYNAMICS: SU(3) GAUGE THEORY

$$L_{QCD} = \bar{q}\left(i\partial_\mu - g_s \sum_{c=1}^{8} \frac{\lambda^c}{2} G_\mu^c\right)\gamma^\mu q - m_q \bar{q} q - \frac{1}{4}\sum_{c=1}^{8} G^c_{\mu\nu} G^{c\,\mu\nu}$$

INTERACTIONS

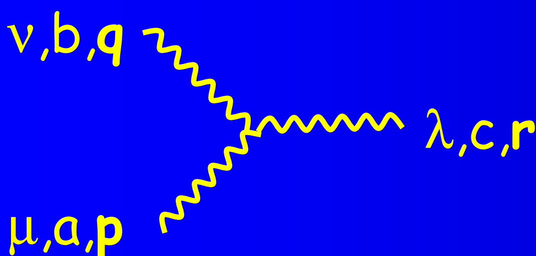
DIAGRAM

COUPLING



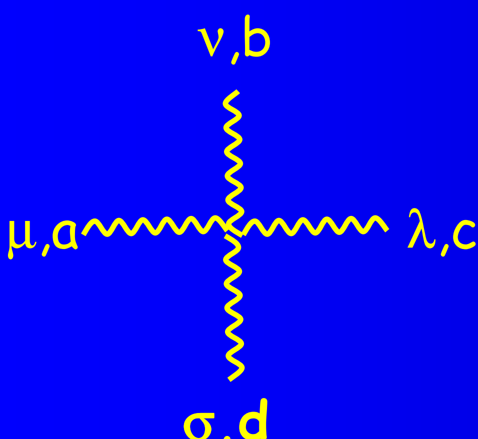
$$-g_s \frac{\lambda^a}{2}\gamma^\mu$$

this index says which of the 8 gluon is



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

group structure factor



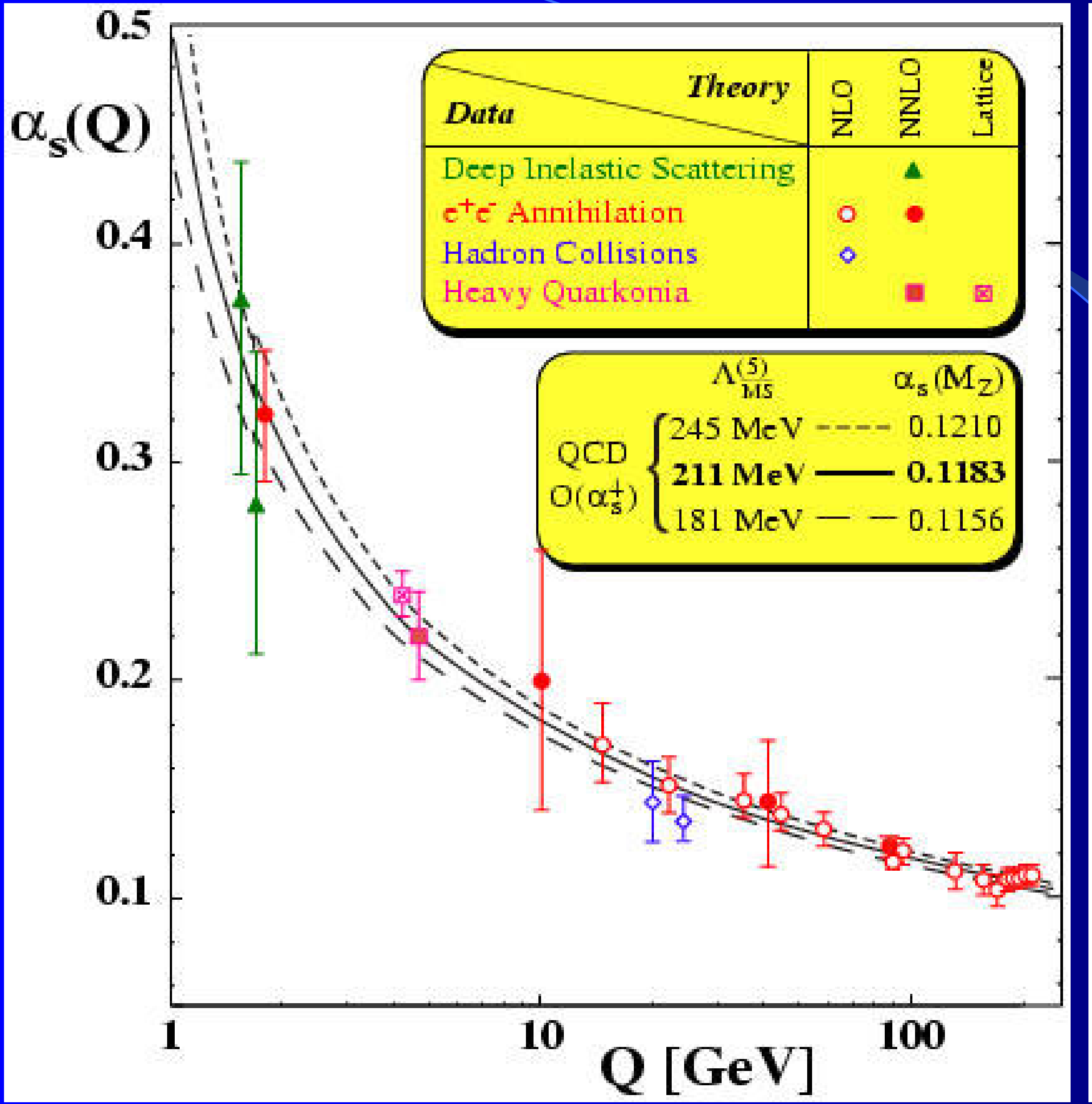
$$\begin{aligned}-g_s^2\Big[&f^{abe} f^{cde}(g_{\mu\lambda}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\lambda}) + \\ &f^{ace} f^{bde}(g_{\mu\nu}g_{\lambda\sigma} - g_{\mu\sigma}g_{\nu\lambda}) + \\ &f^{ade} f^{cbe}(g_{\mu\lambda}g_{\nu\sigma} - g_{\mu\nu}g_{\lambda\sigma})\Big]\end{aligned}$$

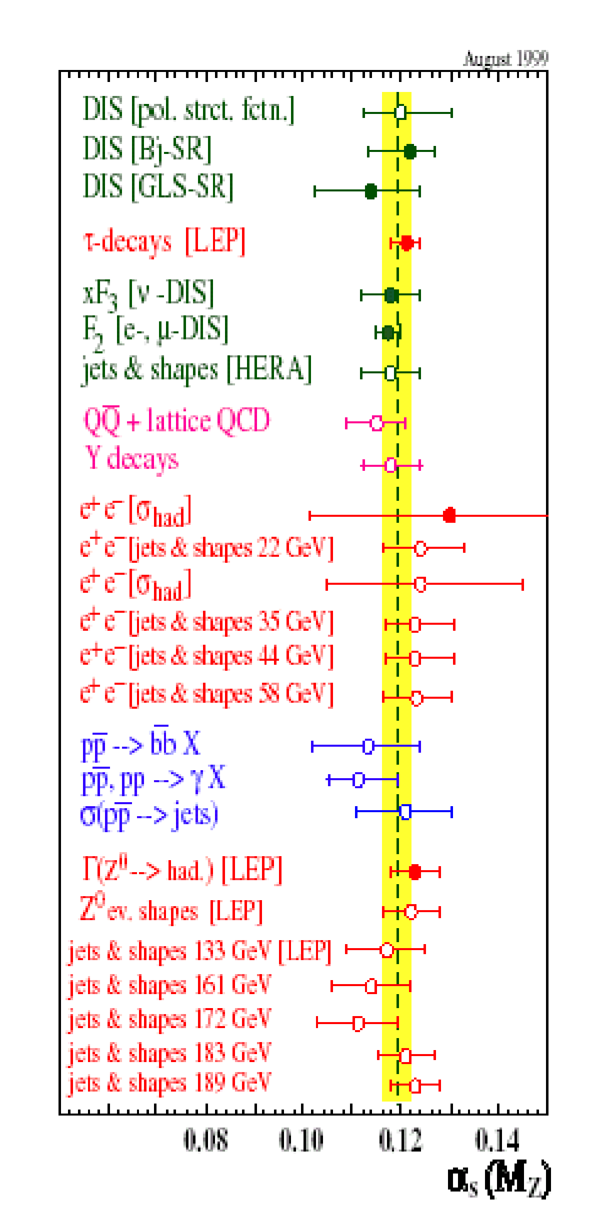
QUANTUM CROMODYNAMICS: SU(3) GAUGE THEORY

$$L_{QCD} = \bar{q}\left(i\partial_{\mu} - g_s \sum_{c=1}^{8} \frac{\lambda^c}{2} G_{\mu}^{c} \right)\gamma^{\mu} q - m_q \bar{q} q - \frac{1}{4}\sum_{c=1}^{8} G^{c}{}_{\mu\nu} G^{c\,\mu\nu}$$

- Quark-gluon interactions are flavour independent
- Physical states are believed to be colorless (confinement)
- QCD exhibits asymtotic freedom: the coupling constant decreases at high energies (short distances) and, as contrary as QED has an anti-screening property
- The low energy regime is no perturbative (alternatives: lattice gauge theory, large number of colours limit, chiral perturbation theory,....)
- Low up-down masses define a regime where QCD has a new symmetry, chiral symmetry, softly broken by up and down masses (isospin is understood as the m_u=m_d limit)
- The CP-odd term "$\theta \varepsilon^{\mu\nu\sigma\delta} F^{a}{}_{\mu\nu} F^{a}{}_{\sigma\delta}$" is not forbidden but a limit can be obtained from the neutron EDM: $\theta < 10^{-10}$

QUANTUM CROMODYNAMICS: running coupling constant





MORE ON SYMMETRIES

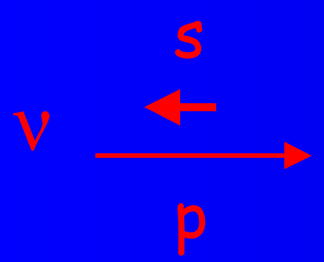
- "EXACT": $U(1)_{EM}$, $SU(3)_{QCD}$,...
- "ANOMALIES": a classical symmetry of the hamiltonian can be violated by quantum efects
- "ALMOST SYMMETRY": isospin, broken by $m_u \neq m_d$ and by electromagnetism
- "HIDDEN SYMMETRY": in invariance of the lagrangian it is not necessarily an invariance of the ground state; the symmetry is not realized in the physical states.

  1. spontaneously broken

  2. broken by quantum dynamical effects

WEAK INTERACTIONS (ν are left)

HELICITY, PARITY VIOLATION AND NEUTRINOS



$$h = \hat{p} \cdot \vec{s}$$

For massless neutrinos (left-) handedness (helicity h = -1/2) is a relativistic invariant

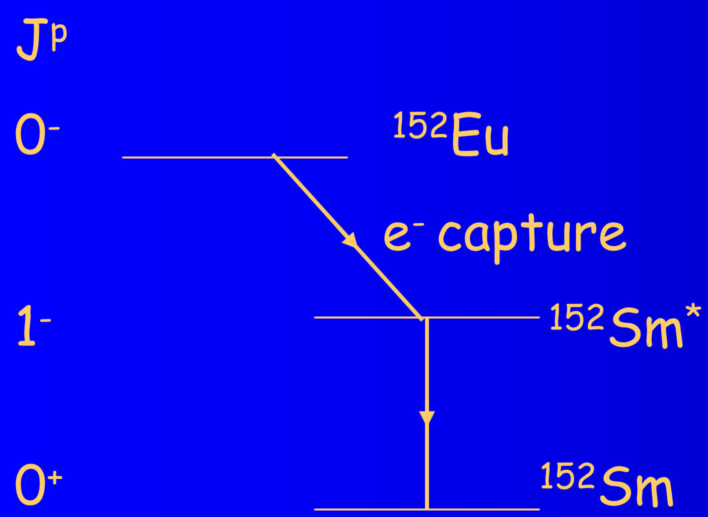
Are neutrinos left? In that case WI are parity violating

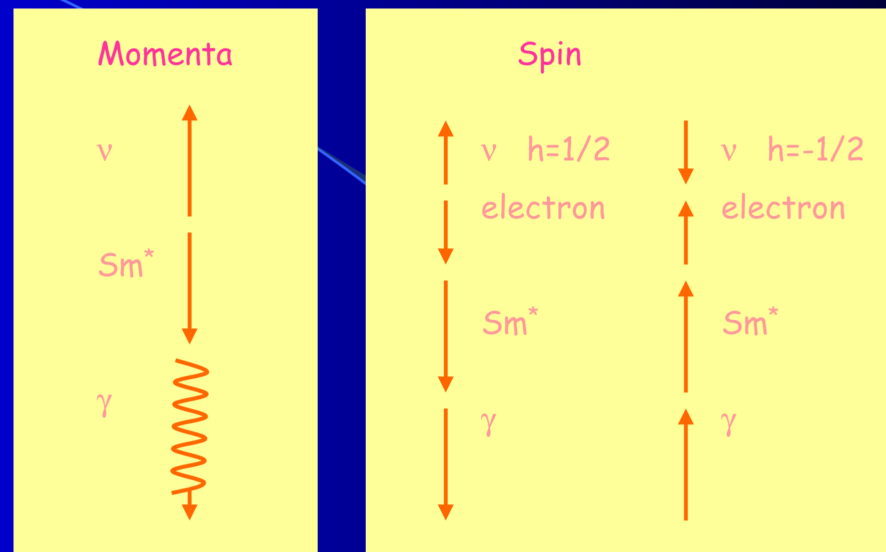
GOLDHABER etal experiment : within this experiment the photon helicity is the neutrino helicity

$$e^- + {}^{152}Eu \longrightarrow {}^{152}Sm^* + \nu_e$$
$$\hookrightarrow {}^{152}Sm + \gamma$$

WEAK INTERACTIONS (ν are left)

$e^- + {}^{152}Eu \rightarrow {}^{152}Sm^* + \nu_e$





Only γ along the recoiling $^{152}Sm^*$ selected

Helicities of the γ and the ν are the same !!

It was found that h=-1 always

THE ν IS ALWAYS LEFT-HANDED

WEAK INTERACTIONS (helicity and handedness)

Left and right particles in field theory:

$$\boxed{\psi_L = \frac{(1-\gamma^5)}{2}\psi}$$ left handed particle

$$\boxed{\psi_R = \frac{(1+\gamma^5)}{2}\psi}$$ right handed particle

(helicity and handedness are equal only in the m=0 limit)

Parity is not violated in a theory with a symmetric treatment of L and R

mass terms $\bar{\psi}\psi = \bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R$

QED interaction $\bar{\psi}\gamma^\mu\psi = \bar{\psi}_L\gamma^\mu\psi_L + \bar{\psi}_R\gamma^\mu\psi_R$

WI are parity violating, so L and R fields are treated in a different way

WEAK INTERACTIONS (V-A)

The Fermi model for lepton/hadron interactions has to be extended to explicitely include

1. parity violation
2. only left neutrinos

$$\boxed{H_{\text{int}} = \frac{G_F}{\sqrt{2}}\left(\bar{e}\gamma_\mu \nu_e\right)\left(\bar{\nu}_\mu \gamma^\mu \mu\right)} \longrightarrow \boxed{H_{\text{int}} = \frac{G_F}{\sqrt{2}}\left(\bar{e}\gamma_\mu (1-\gamma_5)\nu_e\right)\left(\bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\mu\right)}$$

$$\boxed{2\bar{e}_L\gamma^\mu \nu_L} \qquad \boxed{2\bar{\nu}_L\gamma^\mu \mu_L}$$

We may also have neutral currents, such as a combination of the terms:

$$\boxed{\bar{\nu}_L\gamma^\mu \nu_L \; ; \qquad \bar{l}_L\gamma^\mu l_L \; ; \qquad \bar{l}_R\gamma^\mu l_R}$$

WI also imposes other constraints to the lagrangian.

WEAK INTERACTIONS (ν flavours, leptons are left)

We do not observe $\boxed{\mu^- \to e^- \gamma}$ Br < 1.2×10^{-11}; if the two neutrinos in the decay $\boxed{\mu^- \to e^- \bar{\nu}_e \nu_\mu}$ had the same "lepton flavour" this decay would be possible: but we have different neutrinos!

We measure that in the process $\boxed{\pi^- \to f^- \bar{\nu}_f ;\ f = e, \mu}$

the lepton is always right handed, then the anti-neutrino is also right handed. If one assumes that only left-handed leptons participate in the WI then this decay should be forbidden in the zero-mass limit (where helicity is identical with handedness). The extended Fermi model

$$H_{\text{int}} = \frac{G}{\sqrt{2}} \left(\bar{u} \gamma^\mu (1-\gamma_5) d \right) \left(\bar{e} \gamma_\mu (1-\gamma_5) \nu_e \right)$$

gives

$$R_{e/\mu} = \frac{\Gamma\left(\pi^- \to e^- \bar{\nu}_e\right)}{\Gamma\left(\pi^- \to \mu^- \bar{\nu}_\mu\right)} = \frac{m_e^2 \left(1 - m_e^2 / m_\pi^2\right)}{m_\mu^2 \left(1 - m_\mu^2 / m_\pi^2\right)} \left(1 + \delta_{QED}\right) = (1.2352 \pm 0.0005) \times 10^{-4}$$

in agreement with experiment: $\boxed{R_{e/\mu} = (1.230 \pm 0.004) \times 10^{-4}}$

WEAK INTERACTIONS (IVB)

Intermediate vector boson:

the extended V-A Fermi Model is not renormalizable and at high energies predicts

$$\sigma\left(\nu_\mu e^- \to \mu^- \nu_e\right) \approx \frac{G_F^2 q^2}{\pi}$$

that violates the unitarity bound

$$\sigma < \frac{2\pi}{q^2}$$

The extended Fermi hamiltonian:

$$\mathrm{H}_{\mathrm{int}} = \frac{\mathrm{G}}{\sqrt{2}} J^\alpha J_\alpha^\dagger$$

$$J^\alpha = \left[\bar{u}\gamma^\alpha(1-\gamma^5)d\right] + \left[\bar{\nu}_e\gamma^\alpha(1-\gamma^5)e\right] + \left[\bar{\nu}_\mu\gamma^\alpha(1-\gamma^5)\mu\right] + \ldots$$

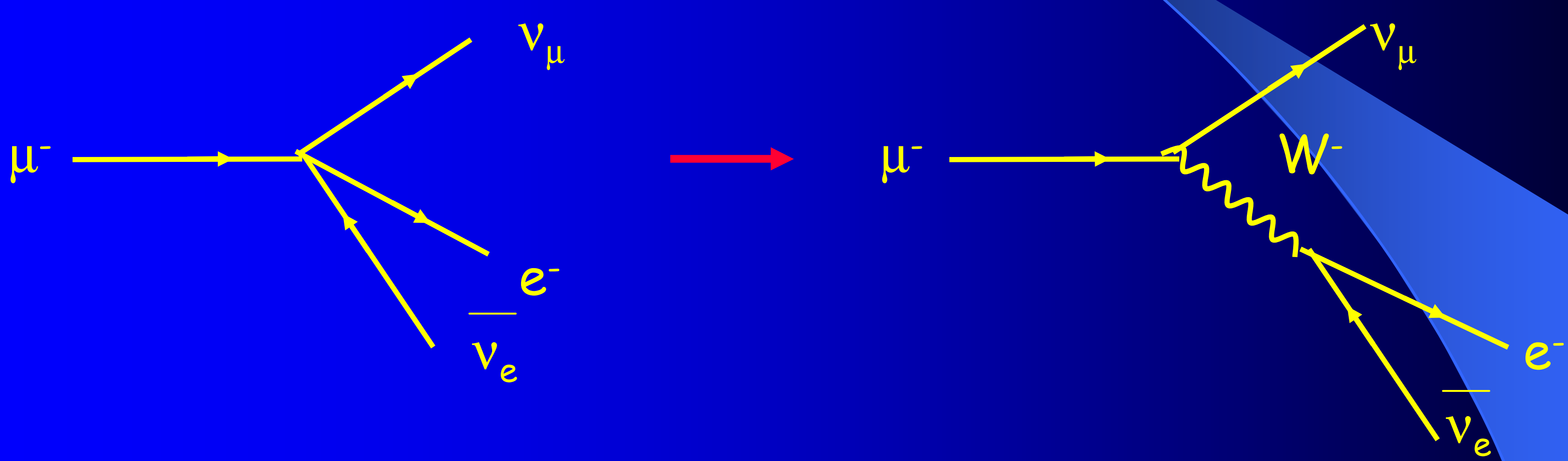
is only correct at low energies.

WEAK INTERACTIONS (IVB)

We assume that the charged current couples to a charged massive vector boson:

$$\boxed{H_{int} = \frac{g}{2\sqrt{2}}\left(J^{\alpha} W_{\alpha}^{\dagger} + h.c.\right)}$$

The V-A interaction is generated through W-exchange:



In the limit $M_W \to \infty$ $$\boxed{\frac{-1}{q^2 - M_W^2} \to \frac{1}{M_W^2}}$$

we find $$\boxed{\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}}$$ ($g < 1$ implies $M_W < 123$ GeV)

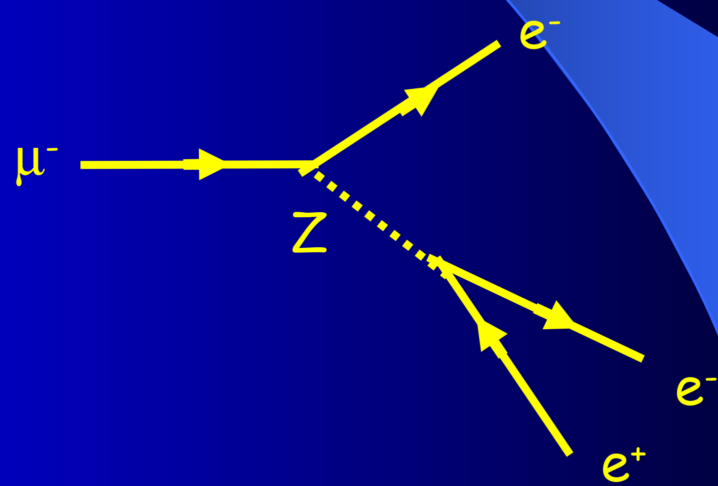
WEAK INTERACTIONS (neutral currents)

Neutral currents:

in 1973 the elastic scattering $\nu_\mu e^- \to \nu_\mu e^-$ confirms their existence

Extensively analyzed in many experiments; in contrast to charged interactions one finds that flavour changing neutral-currents (FCNC) are very suppressed: the Z couplings are flavour diagonal

$$\frac{\Gamma\left(\mu^- \to e^- e^+ e^-\right)}{\Gamma\left(\mu^- \to e^- \bar{\nu}_e \nu_\mu\right)} \le 10^{-12}$$



(this diagram does not exist)

What are all the ingredients for a theory of WI?

WEAK INTERACTIONS (ingredients)

- intermediate spin-1 massive bosons Z^0, W^+ ,W^- and γ (4 of them)
- electroweak unification $\boxed{\frac{g_W}{2\sqrt{2}} \approx \frac{g_Z}{2\sqrt{2}} \approx e}$

  that together with $\boxed{\frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}}}$ imply $\boxed{M_W \approx 100\,GeV}$

- The W field couples only to left handed doublets

$$\boxed{\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L}$$

- The Z only with flavour diagonal couplings (FCNC)
- Lepton number conservation
- Renormalizability

WEAK INTERACTIONS (the group)

Schwinger 1957 tried O(3); Bludman 1958 tried SU(2); finally Glashow in 1960 proposed SU(2)⊗U(1); Salam and Ward did something similar in 1964.

$$G = SU(2)_L \otimes U(1)_Y$$

L: only left fields are transformed by the gauge group

Y: hyphercharge

A total consistent theory can be written in this way for each family:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad e_R \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad u_R \quad d_R$$

$$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \mu_R \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad s_R \quad c_R$$

$$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \tau_R \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \quad t_R \quad b_R$$

A CLOSER LOOK TO THE WI GAUGE GROUP

$$\psi_1 = \begin{pmatrix} u \\ d \end{pmatrix}_L \qquad \psi_2 = u_R \qquad \psi_3 = d_R$$

$$\psi_j \xrightarrow{G} \psi'_j = \exp\left\{i\vec{\tau}\cdot\vec{\alpha}\,\delta_{j1}\right\}\exp\left\{iY_j\beta\right\}\psi_j$$

$SU(2)_L \rightarrow$ 3 generators $\rightarrow$ 3 bosons $W_1\ W_2\ W_3$

$U(1)_Y \rightarrow$ 1 generator $\rightarrow$ 1 bosons B

Physical bosons $W^{\pm}$ Z γ are linear combinations of these fields:

$W^3 = \cos\theta_W\, Z + \sin\theta_W\, A$

$B = -\sin\theta_W\, Z + \cos\theta_W\, A$

The kinetic terms for the gauge fields, the interaction terms obtained from the gauge invariance give us all the terms that define the weak interactions:

A CLOSER LOOK TO THE WI GAUGE GROUP

$$L_{kin.gauge} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \vec{W}_{\mu\nu} \vec{W}^{\mu\nu}$$

$$L = \sum_{j=1}^{3} \overline{\Psi}_j i D_\mu \gamma^\mu \Psi_j ; \quad D_\mu \psi_j = (\partial_\mu - ig \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - ig' Y_j B_\mu) \Psi_j$$

What do we have here?

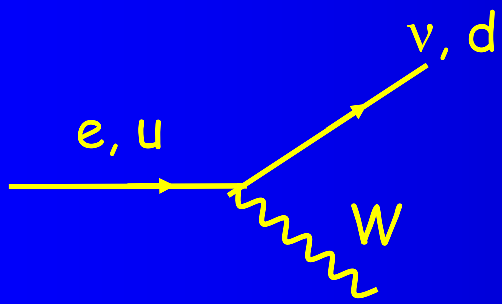
1. charged current interactions
2. neutral current interaction
3. QED
4. Gauge self interactions

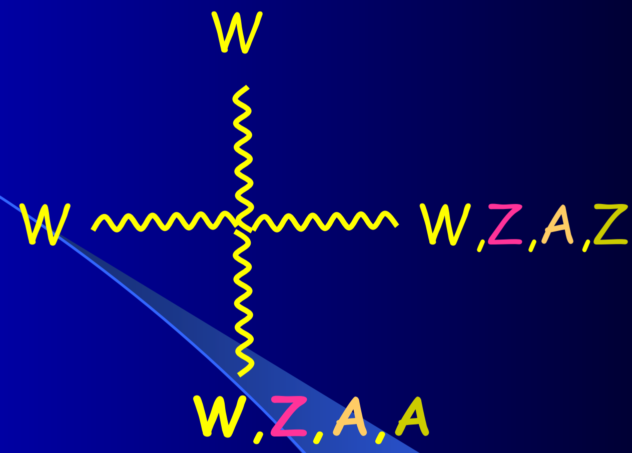
What we do not have here!

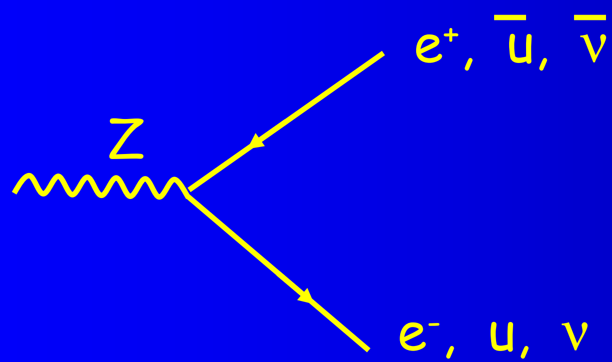
1. fermion masses
2. gauge boson masses

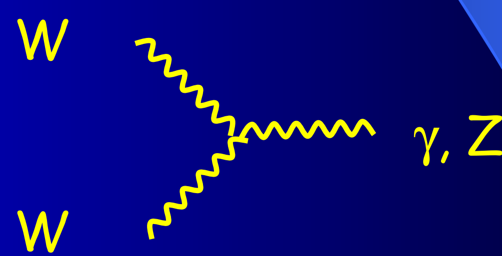
How do we generate mass without breaking gauge invariance and renormalizability?

WEAK INTERACTIONS (some diagrams)









STANDARD MODEL (group, mass)

$$G_{SM} = SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

$$G_{EW} = SU(2)_L \otimes U(1)_Y$$

In the G_{EW} structure we have 6 different quark flavour (u, d, s, c, b,t), 3 different leptons (e, μ, τ) with their neutrinos (ν_e, ν_μ, ν_τ).

These are organized in 3 identical copies (families) with masses as the only difference.

Mass in a gauge renormalizable theory

1. Fermion masses: $\bar{\psi}\psi = \bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R$ L and R are mixed, so gauge inv., but also renormalizability are spoiled by these terms.

2. Boson masses: no gauge invariance neither renormalizability with a mass term.

A way out is provided by the Goldstone/Higgs mechanism

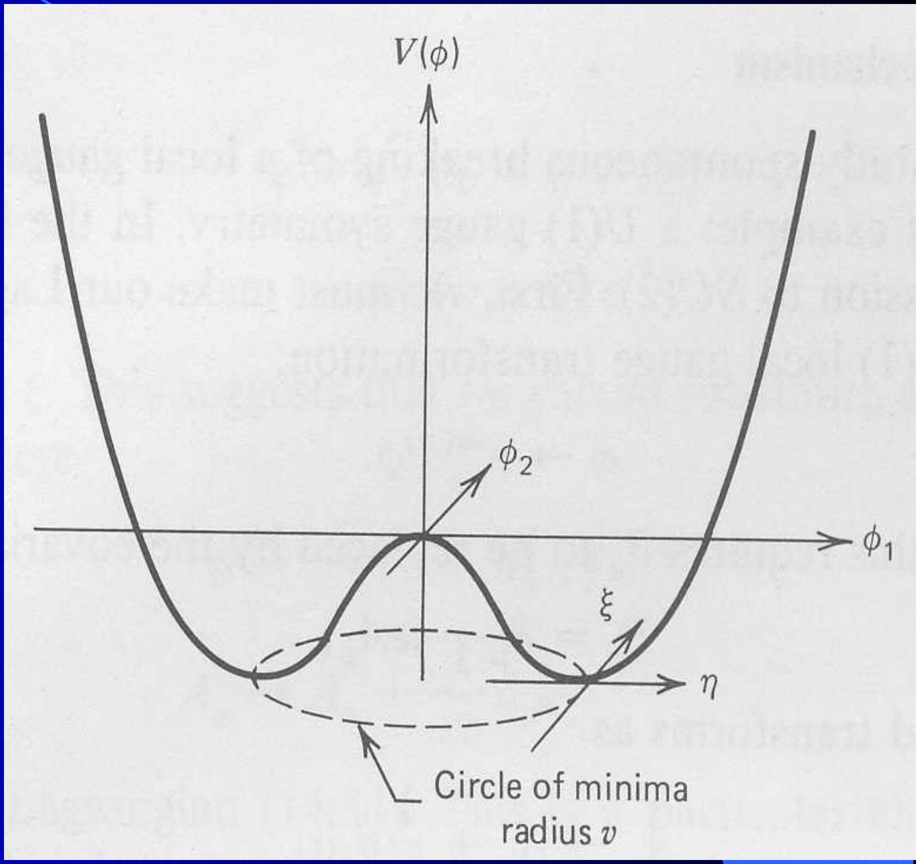
STANDARD MODEL (Higgs)

Complex scalar field with a spontaneously broken symmetry:

1. this is the case with quadratic plus quartic terms in the lagrangian (Mexican hat)

2. there are infinite states with the minimum energy, and by choosing a particular solution the symmetry gets spontaneously broken

3. fluctuations around this ground state (ϕ_1=v, ϕ_2=0) defines a massless and a massive excitation (**Goldstone theorem**: if a lagrangian is invariant unader a continuous symmetry group G, but the vacuum is only invariant under a subgroup H $\subset$ G, then there must exist as many massless spin-0 particles (Goldstone bosons) as broken generators (i.e. generators of G which do not belong to H)



STANDARD MODEL (Higgs)

4. What happens if the scalar field is in interaction with the gauge bosons by means of a local gauge symmetry?

$$D_\mu \phi = (\partial_\mu - ig \frac{\vec{\tau}}{2} \cdot \vec{W}_\mu - ig' Y_\phi B_\mu)\phi$$

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \to \begin{pmatrix} 0 \\ v + H \end{pmatrix}$$

$$(D_\mu \phi)^\dagger D^\mu \phi \to \frac{1}{2}\partial_\mu H \partial^\mu H + (v + H)^2 \left\{ \frac{g^2}{4} W_\mu^\dagger W^\mu + \frac{g^2}{8\cos^2\theta_W} Z_\mu Z^\mu \right\}$$

And we have a mass term for the W and the Z:

$$M_Z \cos\theta_W = M_W = {vg}/{2}$$

5. The same idea for the fermions, where the interaction term is the most general gauge invariant interaction between the fermions and the Higgs doublet ("Yukawa term"):

$$\mathcal{L}_{Yukawa} = \frac{1}{\sqrt{2}}(v + H)\left\{ c_1 \bar{e} e + c_2 \bar{u} u + c_3 \bar{d} d + \ldots \right\}$$

$$m_e = -c_1 v/2\,; \; m_u = -c_2 v/2\,; \; m_d = -c_3 v/2$$

STANDARD MODEL (Higgs)

Using the equations

$$e = g \sin\theta_W \qquad \frac{g^2}{8M_W^2} = \frac{G_F}{\sqrt{2}} \qquad M_Z \cos\theta_W = M_W = vg/2$$

we have

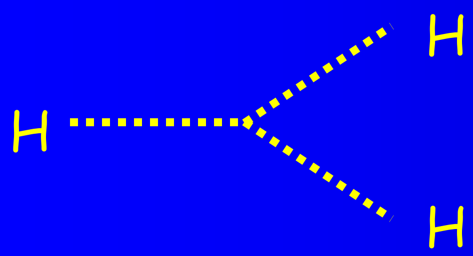
vacuum expectation value of the Higgs field

$$M_W = \left(\frac{\pi\alpha}{G_F\sqrt{2}}\right)^{1/2} \frac{1}{\sin\theta_W} = \frac{37.28GeV}{\sin\theta_W}; \qquad v = \left(\sqrt{2}G_F\right)^{1/2} = 246GeV$$

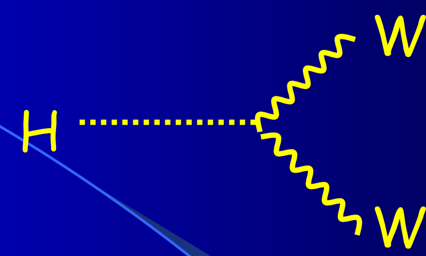
Measuring the weak angle (or the Z mass) we have a prediction for the masses, but what about M_H? It is a free parameter...

We have also generated interaction terms for the Higgs particle with the bosons and the fermions of the SM....

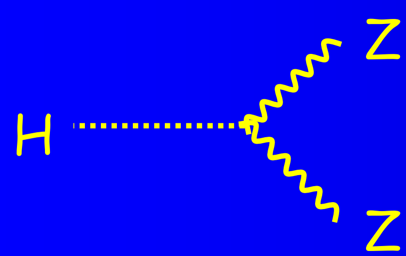
STANDARD MODEL (Higgs)



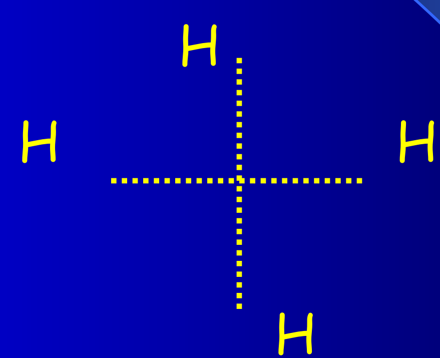
$$\approx \frac{M_H^2}{246 GeV}$$

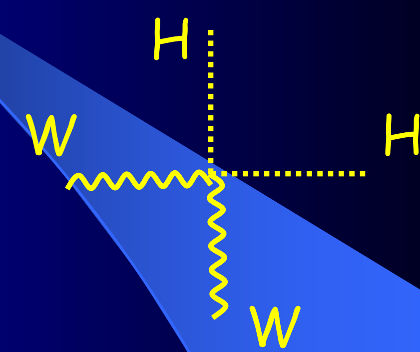


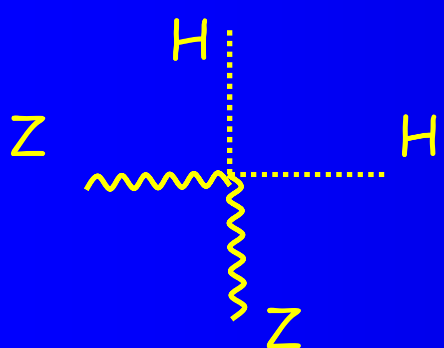
$$\approx \frac{M_W^2}{246 GeV}$$

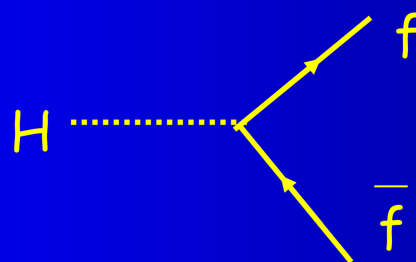


$$\approx \frac{M_Z^2}{246 GeV}$$









$$\approx \frac{m_f}{246 GeV}$$

Note: Higgs physics remains perturbative and also $\Gamma < M_H$ iff $M_H \approx 10^{2\text{-}3}$ GeV

STANDARD MODEL (mixing)

- The weak eigenstates (the ones that transforms with the EW group) are linear combinations of the mass eigenstates (physical states)

- This enters in the Yukawa coupling terms that generate the fermion masses.

- For 3 families we need 3 angles and 1 phase in order to parametrize this in the most general way: Cabibbo-Kobayashi-Maskawa (CKM) unitary matrix.

- This imaginary component is the only responsible for CP violation in the SM.

STANDARD MODEL (mixing)

Weak eigenstates

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix}_L = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

Mass eigenstates

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

c_{12} = cos $\theta_{12} \geq 0$, etc...

$$V = \begin{pmatrix} 0.9742 - 0.9757 & 0.219 - 0226 & 0.002 - 0.005 \\ 0.219 - 0.225 & 0.9734 - 09749 & 0.037 - 0.043 \\ 0.004 - 0.014 & 0.035 - 0.043 & 0.9990 - 0.9993 \end{pmatrix}$$

Values obtained from weak quark decays and deep inelastic neutrino scattering

STANDARD MODEL (parameters,status)

FREE PARAMETERS

Gauge and scalar sector:

α, M_Z, G_F, M_H (most precisely known)

Other, like M_W, θ_W, g, g', Higgs self-coupling, are determined from these ones

$G_F = (1.166\,39 \pm 0.000\,02) \times 10^{-5}\ GeV^2$

$\alpha^{-1} = 137.035\,999\,76 \pm 0.000\,000\,50$

$M_Z = 91.1876 \pm 0.0021\ GeV^2$

Yukawa sector:

9 masses (6 quarks, 3 leptons)
3 angles
1 phase

QCD:

$\alpha_S(M_Z^2)$
(θ ???)

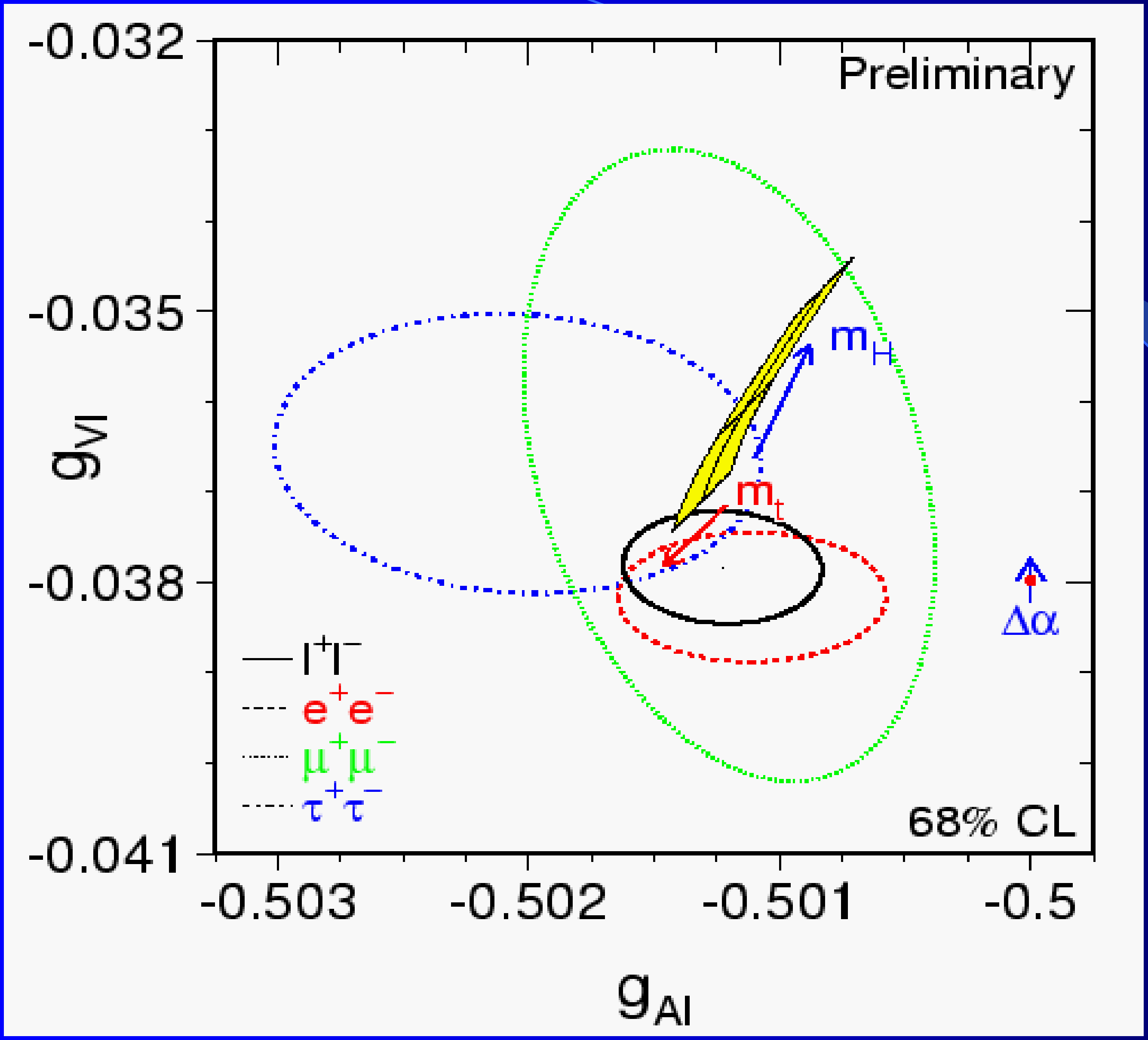
Total: 18

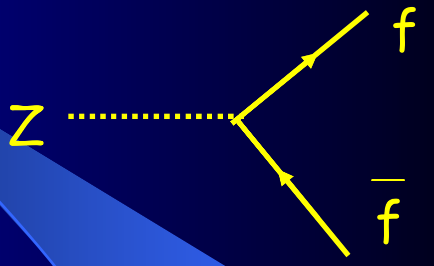
STANDARD MODEL (status)

There is a huge amount of data to support the SM:
cross sections, decay widths, branching ratios, asymmetries, polarization measurements, ...

Many of them at the 1/1000 level.

Z-LEPTON COUPLINGS (M_t , M_H)

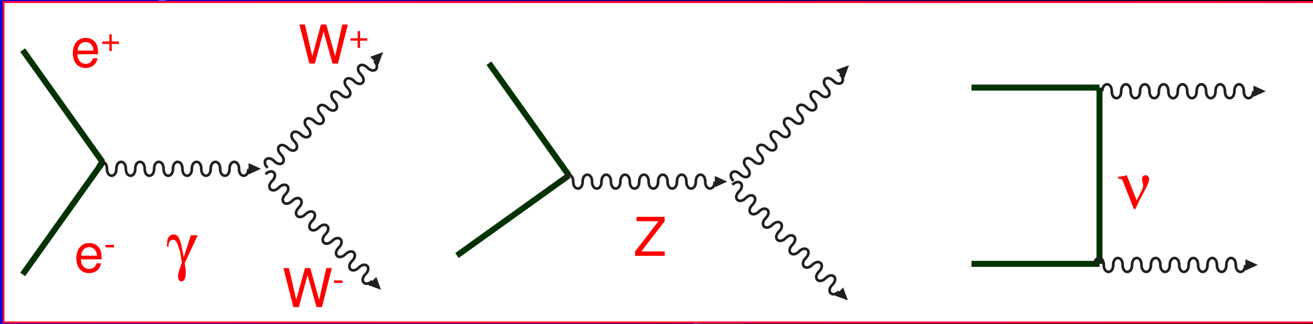


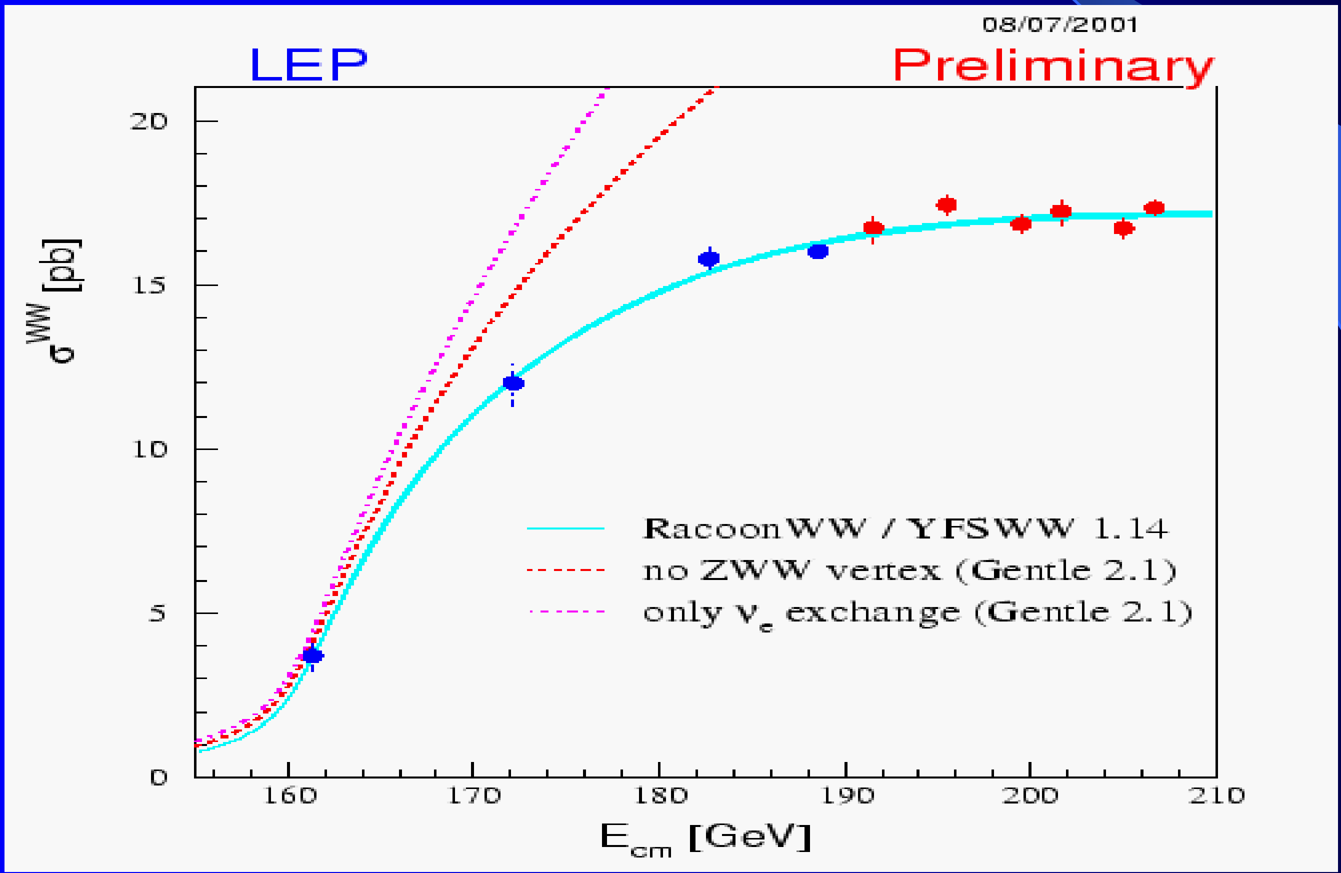


$$\approx \frac{e}{\sin 2\theta_W} \gamma^\mu \left(g_V - g_A \gamma^5 \right)$$

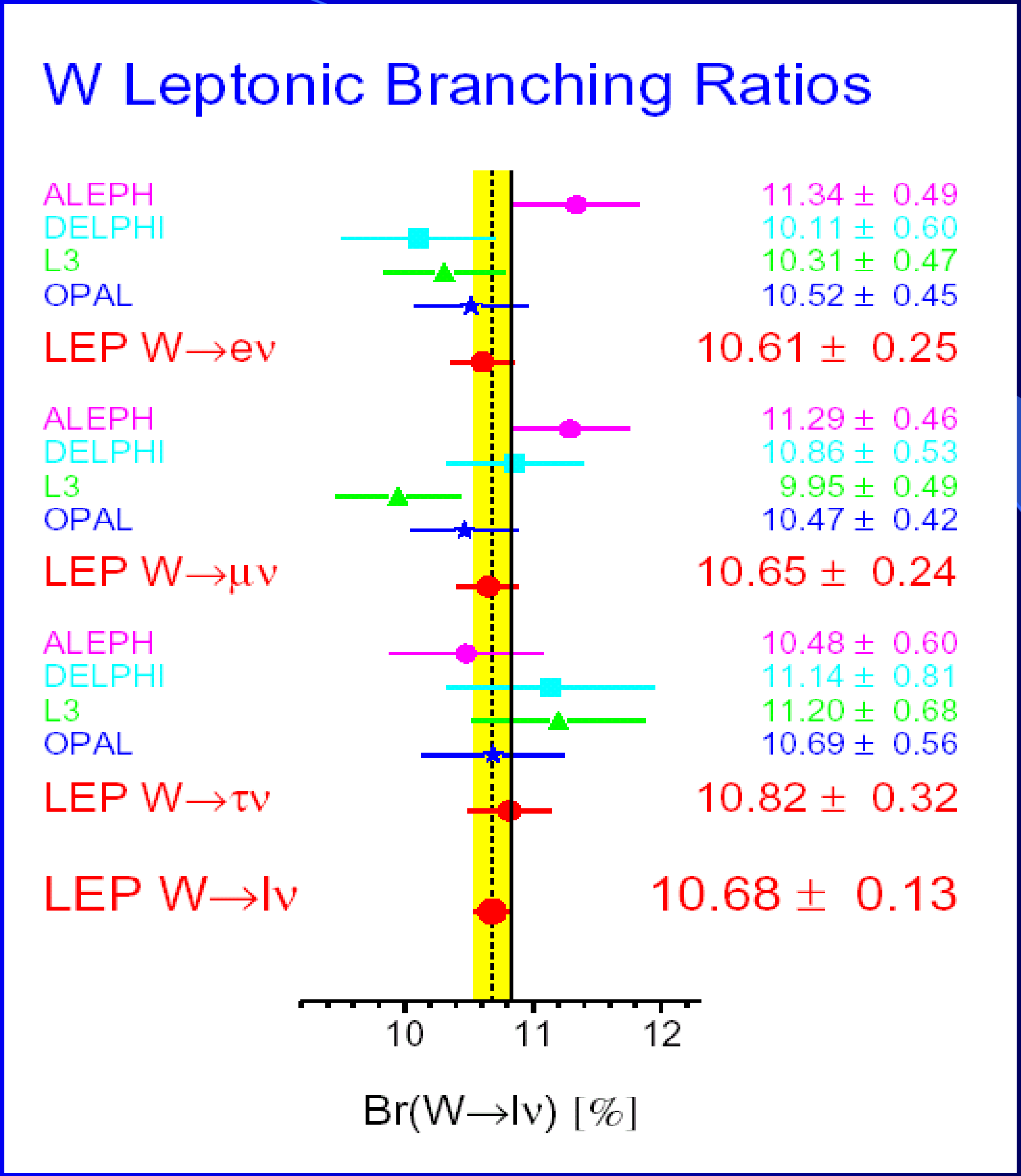
WW PRODUCTION AT LEP2

$\sigma(e^+ e^- \rightarrow W^+ W^-)$





W TO LEPTONS



W Leptonic Branching Ratios
ALEPH
DELPHI
L3
OPAL
LEP W→eν
ALEPH
DELPHI
L3
OPAL
LEP W→μν
ALEPH
DELPHI
L3
OPAL
LEP W→τν
LEP W→lν
11.34 ± 0.49
10.11 ± 0.60
10.31 ± 0.47
10.52 ± 0.45
10.61 ± 0.25
11.29 ± 0.46
10.86 ± 0.53
9.95 ± 0.49
10.47 ± 0.42
10.65 ± 0.24
10.48 ± 0.60
11.14 ± 0.81
11.20 ± 0.68
10.69 ± 0.56
10.82 ± 0.32
10.68 ± 0.13
10
11
12
Br(W→lν) [%]

TOP FROM LEP

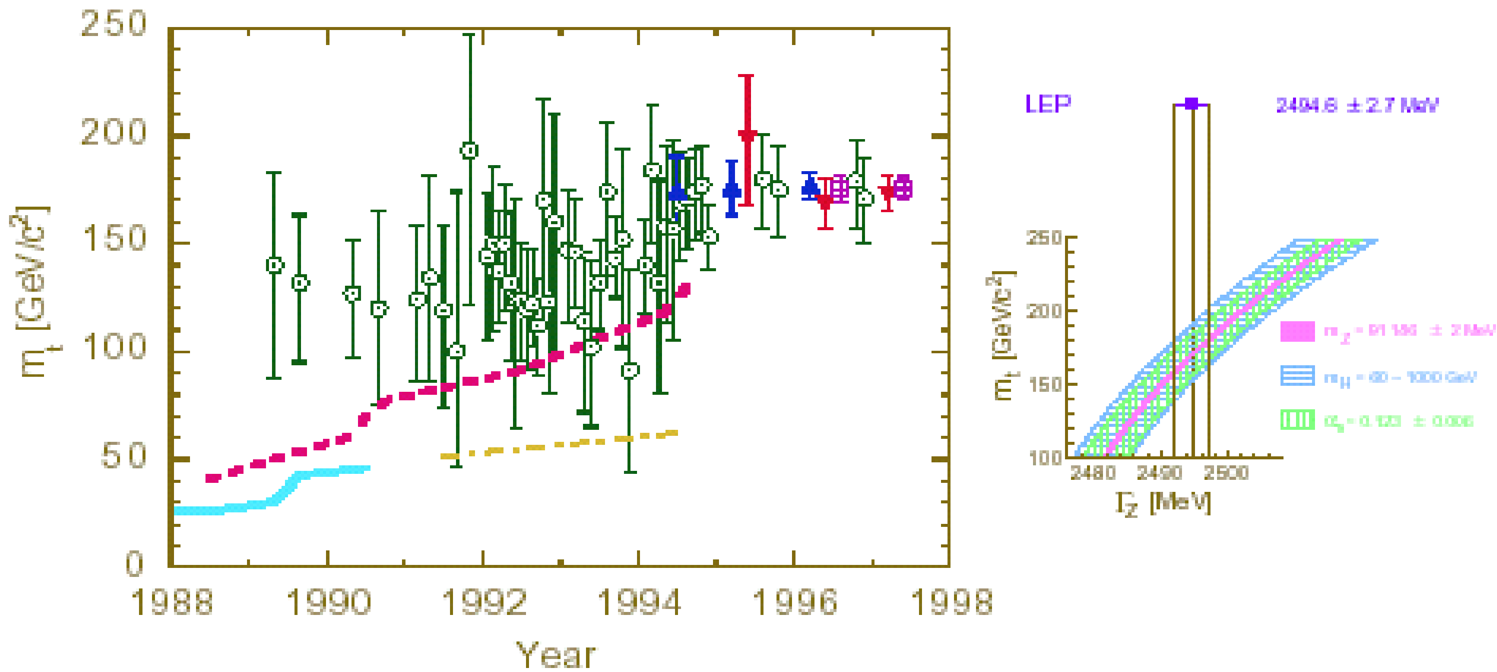
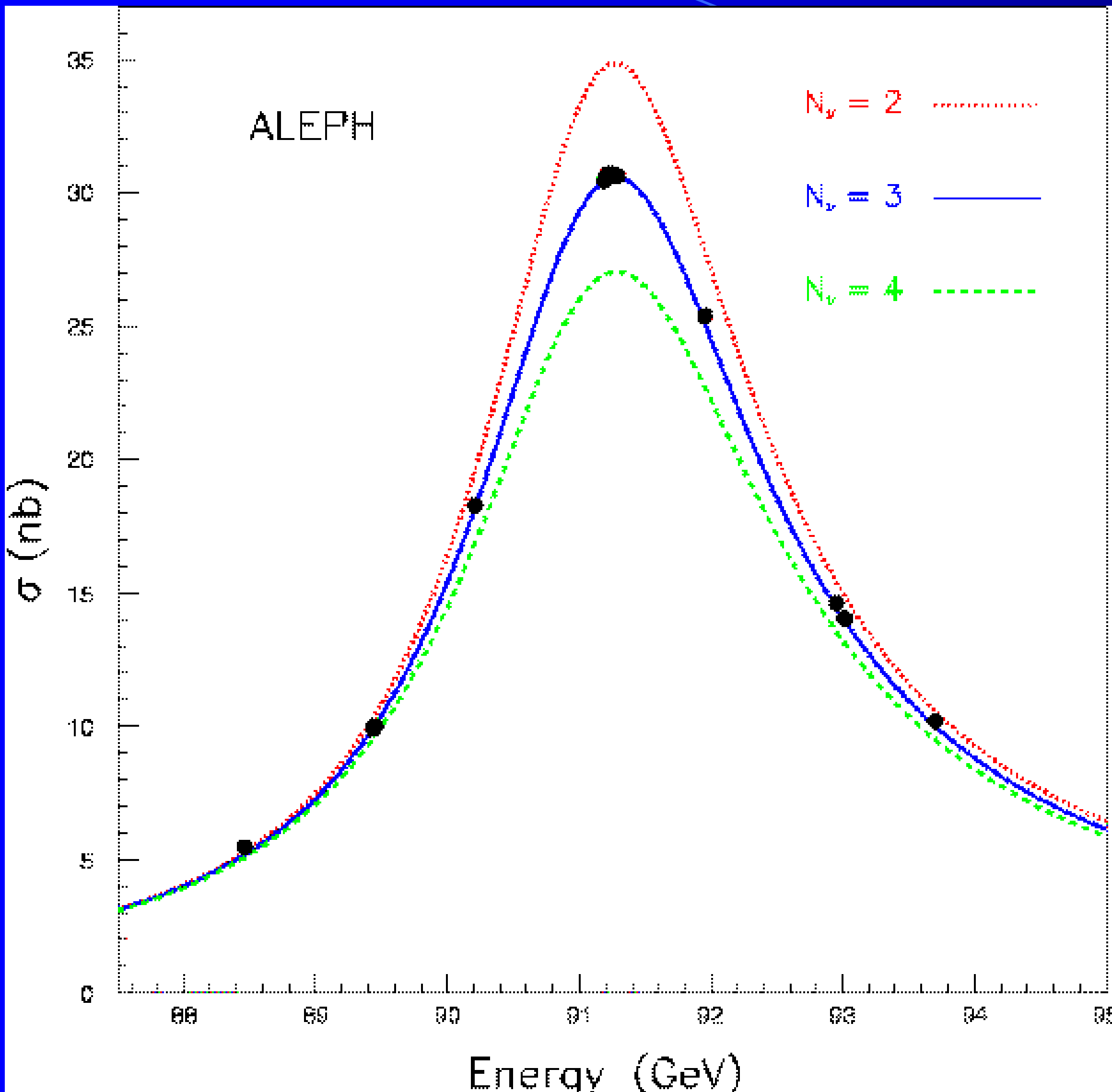


FIGURE 6. Indirect determinations of the top-quark mass from fits to electroweak observables (open circles) and 95% confidence-level lower bounds on the top-quark mass inferred from direct searches in e^+e^- annihilations (solid line) and in $\bar{p}p$ collisions, assuming that standard decay modes dominate (broken line). An indirect lower bound, derived from the W-boson width inferred from $\bar{p}p \to (W \text{ or } Z) +$ anything, is shown as the dot-dashed line. Direct measurements of m_t by the CDF (triangles) and DØ (inverted triangles) Collaborations are shown at the time of initial evidence, discovery claim, and at the conclusion of Run 1. The world average from direct observations is shown as the crossed box. For sources of data, see Ref. [11]. *Inset:* Electroweak theory predictions for the width of the Z^0 boson as a function of the top-quark mass, compared with the width measured in LEP experiments. (From Ref. [18]).

NEUTRINO AND FAMILIES (number of l and q)



Number of light neutrinos (m < 45 GeV)

For the Z:

$\Gamma_{inv} = \Gamma_Z - 3\,\Gamma_l - \Gamma_{had}$

$\Gamma_{inv} = 500.1 \pm 1.9$ GeV

$\Gamma_{inv} / \Gamma_l = 5.961 \pm 0.023$

$\Gamma_{inv} = N_\upsilon \Gamma_\upsilon$

$(\Gamma_\upsilon / \Gamma_l)_{SM} = 1.991 \pm 0.001$

N = 2.9841 ± 0.0083

SM fits to data

Z-LEPTON WIDTH AND WEAK ANGLE

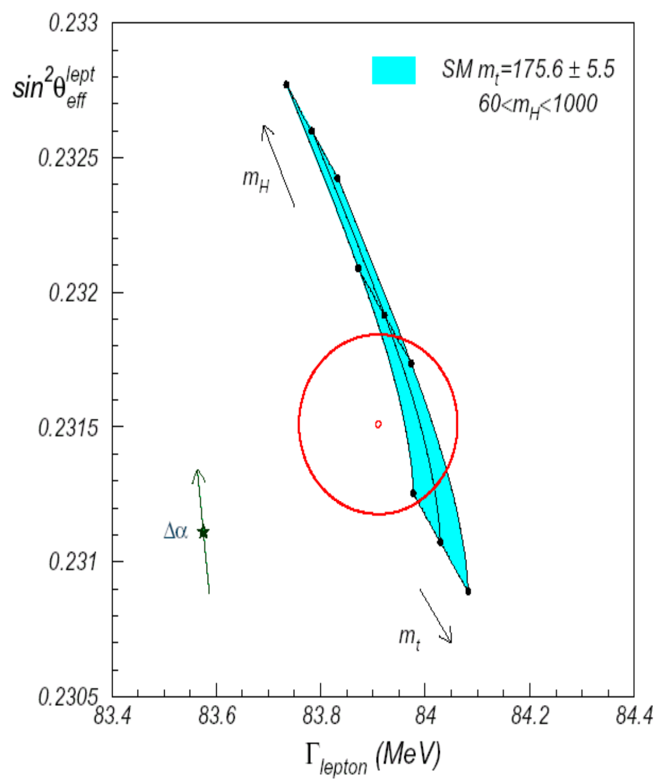
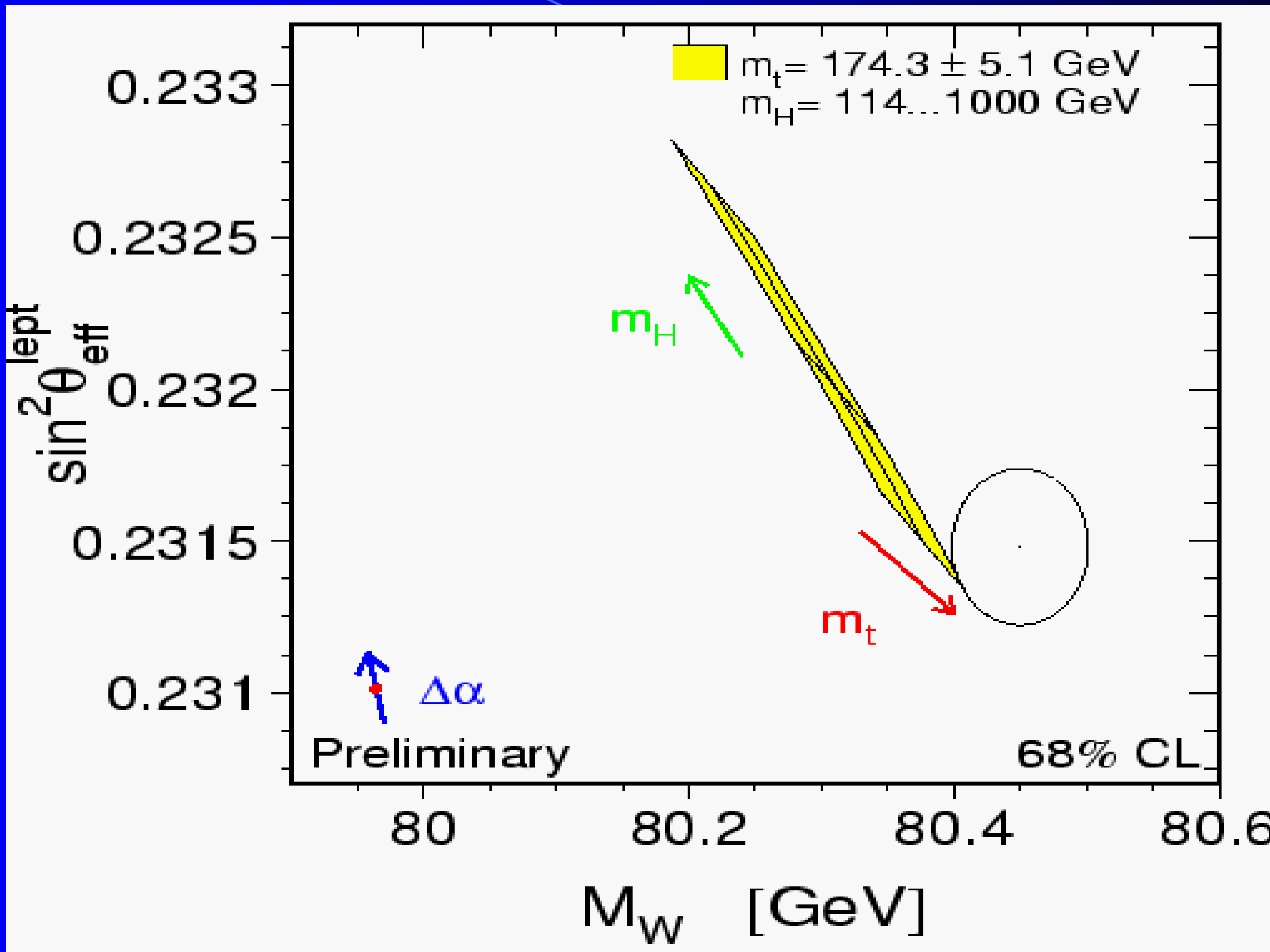
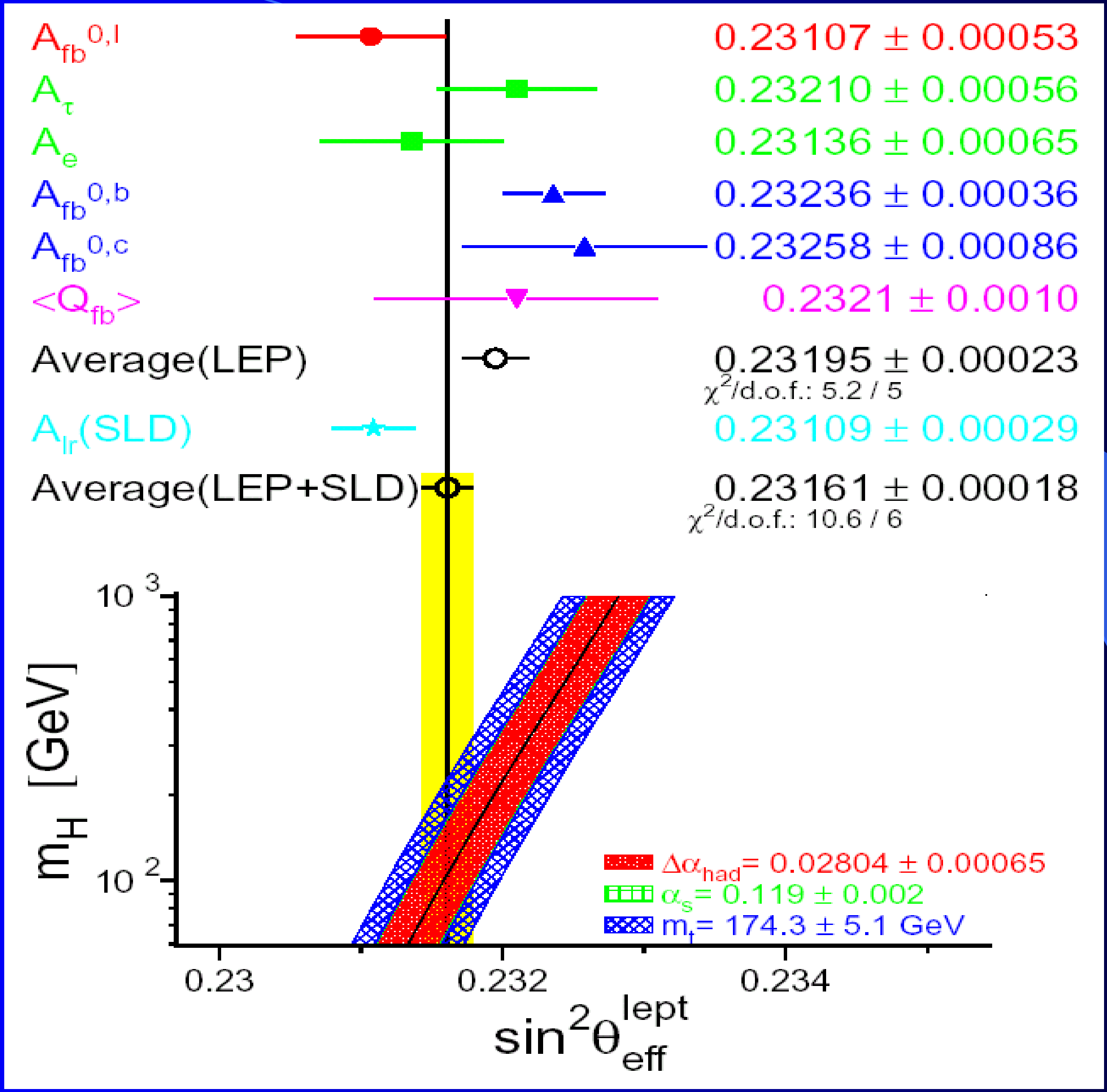


FIG. 11. The allowed region for $\sin^2\theta_w$ vs. $\Gamma_{\rm lepton}$ in the context of the SM, showing the need for the higher order EW corrections. The region within the ellipse is allowed (at 1 standard deviation) by the many precision measurements at the LEP and SLC ee colliders and the FNAL $p\overline{p}$ collider; the shaded region comes from the measurements of the top mass at FNAL, for a range of possible Higgs masses. The star, well outside the allowed region, gives the expected value in the SM without the higher order EW corrections.

W MASS AND WEAK ANGLE



H MASS AND WEAK ANGLE



HIGGS MASS (M_t , M_W)

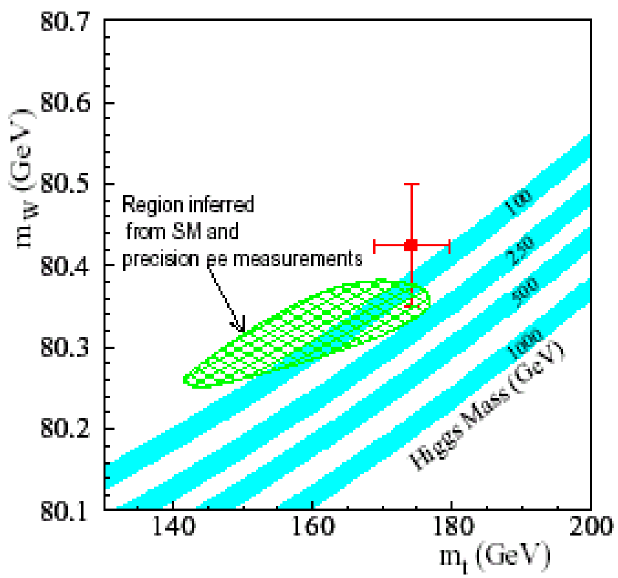


FIG. 13. W boson mass vs. top quark mass. The data point is the average of FNAL data for the top quark mass and FNAL and CERN data for the W boson mass. The shaded bands give the expected values for specific conventional Higgs boson mass values in the context of the minimal SM. The cross-hatched region shows the predictions for m_W and m_{top}, at 68% confidence level, from precision electroweak measurements of Z boson properties.

HIGGS MASS

For the Higgs physics to remain perturbative and also $\Gamma < M_H$ we need

$$M_H \approx 10^{2\text{-}3}\ \mathrm{GeV}$$

But:

1. From radiative corrections $M_H < 190$ GeV
2. No Higgs observation at LEP2 $M_H > 113$ GeV

STANDARD MODEL (pull)

$$\text{PULL} = \frac{\text{data point} - \text{fit value}}{\text{error on data point}}$$

Stanford 1999

	Measurement	Pull
m_Z [GeV]	91.1871 ± 0.0021	.08
Γ_Z [GeV]	2.4944 ± 0.0024	-.56
σ^0_{hadr} [nb]	41.544 ± 0.037	1.75
R_e	20.768 ± 0.024	1.16
$A^{0,e}_{fb}$	0.01701 ± 0.00095	.80
A_e	0.1483 ± 0.0051	.21
A_τ	0.1425 ± 0.0044	-1.07
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.60
m_W [GeV]	80.350 ± 0.056	-.62
R_b	0.21642 ± 0.00073	.81
R_c	0.1674 ± 0.0038	-1.27
$A^{0,b}_{fb}$	0.0988 ± 0.0020	-2.20
$A^{0,c}_{fb}$	0.0692 ± 0.0037	-1.23
A_b	0.911 ± 0.025	-.95
A_c	0.630 ± 0.026	-1.46
$\sin^2\theta^{lept}_{eff}$	0.23099 ± 0.00026	-1.95
$\sin^2\theta_W$	0.2255 ± 0.0021	1.13
m_W [GeV]	80.448 ± 0.062	1.02
m_t [GeV]	174.3 ± 5.1	.22
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02804 ± 0.00065	-.05

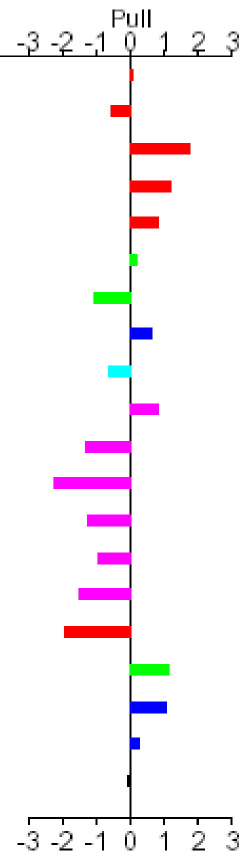
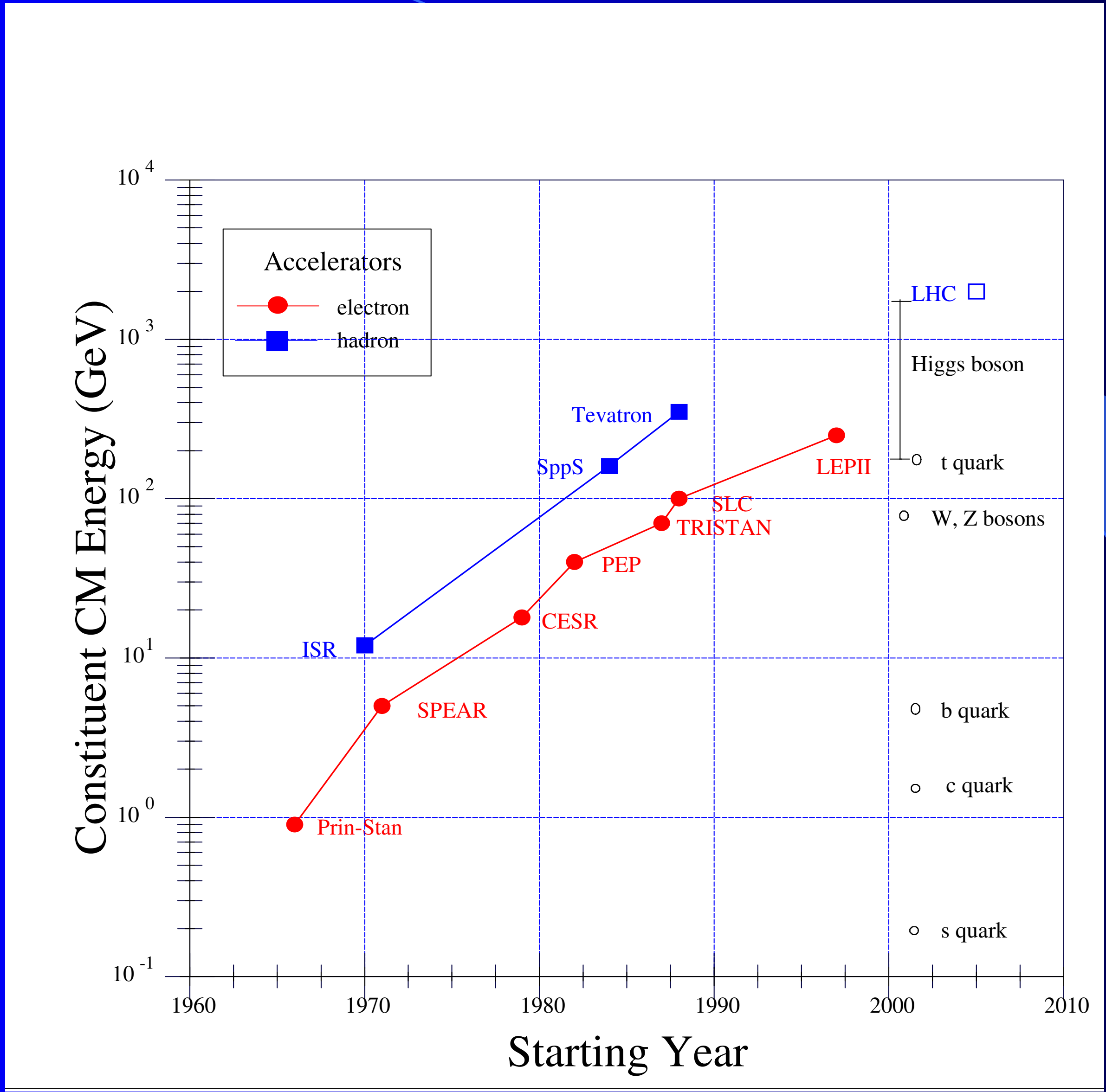


FIGURE 7. Precision electroweak measurements and the pulls they exert on a global fit to the standard model, from Ref. [19].

HIGH ENERGY ACCELERATORS (mass)



SM CONCEPTUAL PROBLEMS

Why we just find the Higgs and declare the game is over?
(we did not find it yet!!!)

- Too many parameters
- Why such an strange EW group
- Why 3 families
- What is the origin of the masses ($M_{EW} \approx G_F^{-1/2} \approx 200$ GeV)
- Why is the origin of the electric charge quantization

....

From theory: hierarchy problem

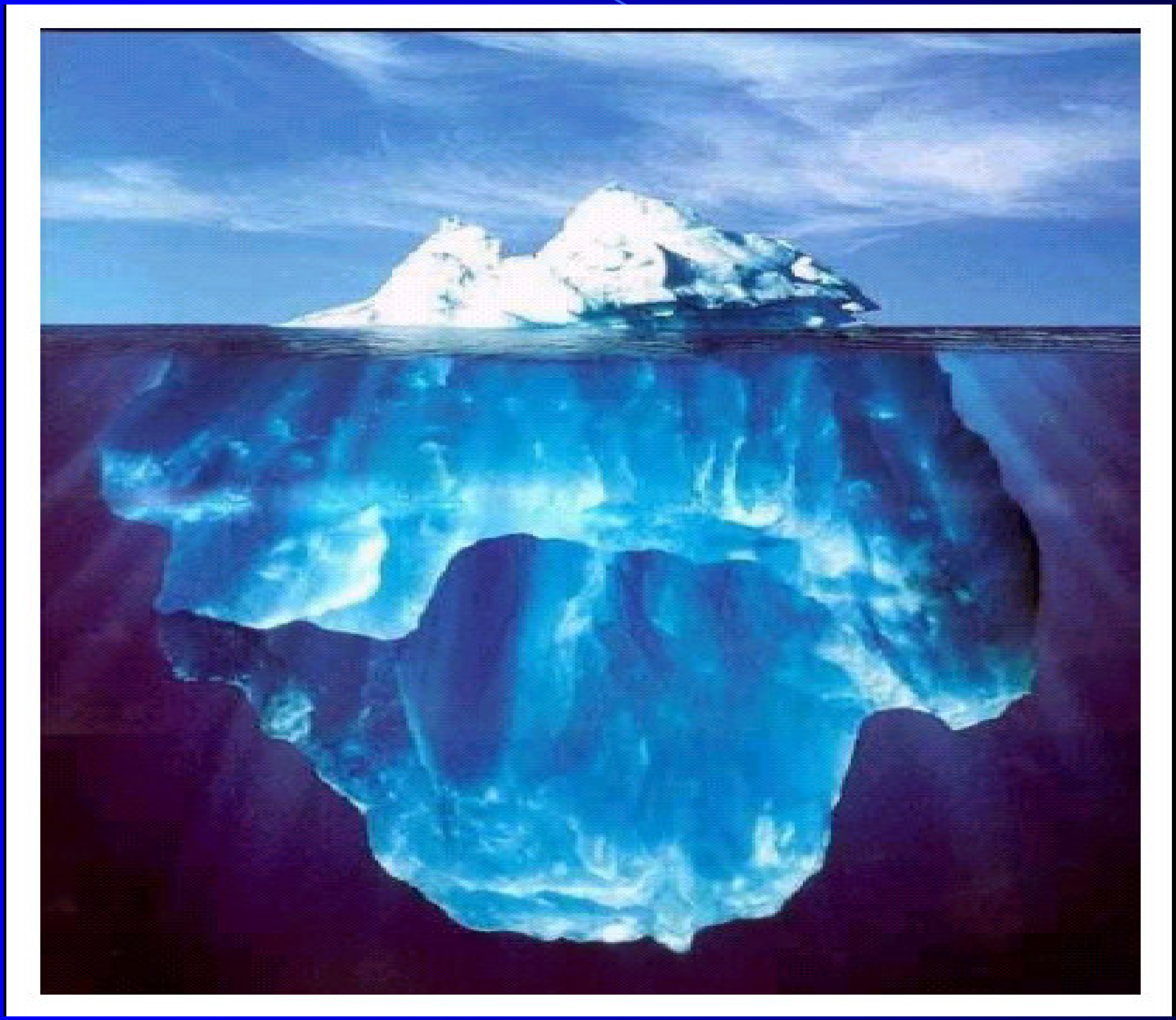
From "experiment":

- Coupling unification
- Neutrino masses
- Dark matter
- Baryogenesis

...

BEYOND THE SM

WHAT WE SEE IS JUST A SMALL PART OF WHAT IS POSSIBLE !!!



BEYOND THE SM

First priority in particle physics:

Test by experiment the physics of the EW symmetry breaking sector of the SM

Search for new physics beyond the SM: there are strong arguments to expect new phenomena not far from the Fermi scale (at ≤ few TeV).

LHC has been designed for that.

$2E_{COM}$~14 TeV

Start in 2007

SUPERSYMMETRY (hierarchy problem)

The low energy theory must be renormalisable as a necessary condition for insensitivity to physics at higher scale Λ:

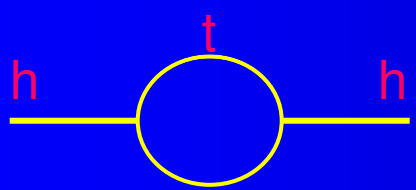
[the cutoff Λ can be seen as a parametrisation of our ignorance of physics at higher scales]

But, as this scale Λ is so large, in addition the dependence of renormalized masses and couplings on this scale must be reasonable: e.g. a mass of order m_W cannot be linear in the new scale ☹

But in SM indeed m_h, m_W... are linear in Λ !!!!!!
(the scale of new physics beyond the SM)

SUPERSYMMETRY (hierarchy problem)

e.g. the top loop:



$m_h^2 = m^2_{bare} + \delta m_h^2$

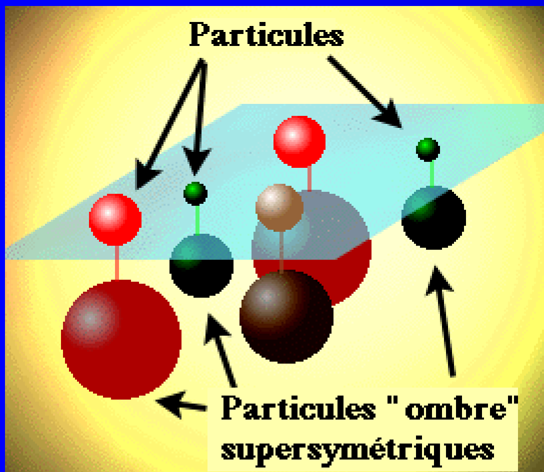
$$\boxed{\delta M_H^2 \Big|_{top} = \frac{3G_F}{\sqrt{2}\pi^2} m_t^2 \Lambda^2 \approx (0.3\Lambda)^2}$$

The hierarchy problem demands new physics near the weak scale

- $\Lambda \gg m_Z$: the SM is so good at LEP
- $\Lambda \sim$ few times $G_F^{-1/2} \sim o(1\text{TeV})$ for a natural explanation of M_H or M_W

Other conceptual problems (why 3 families, why such masses...) has to be posponed to the time where the high energy theory will be known

SUPERSYMMETRY (hierarchy problem)



Extra boson-fermion symmetry and then the quadratic divergence is exactly cancelled

particle	Lower limit (GeV)	Source
chargino	45	Zwidth
Higgsino	89	LEP2
neutralino	32	LEP2
$\tilde{e}_R$	89	LEP2
$\tilde{\mu}_R$	71	LEP2
$\tilde{\tau}_R$	71	LEP2
$\tilde{\nu}$	43	Zwidth
$\tilde{q}$	260	D0
	230	CDF
$\tilde{g}$	190	D0
	180	CDF

GRAND UNIFICATION (GUT's and supersymmetry)

Is there a bigger group that naturally includes all the SM groups without a direct product? If this is possible we have a grand unification theory (EM,Weak,Strong). Quarks and lepton are then organized in multiplets, and "weak" transition between them becomes possible: proton decay ($p \rightarrow \pi^0 + e+$, ...)

From $\alpha_{QED}(m_Z)$, $\sin^2\theta_W$ measured at LEP predict $\alpha_s(m_Z)$ for unification (assuming desert)

EXP: $\alpha_s(m_Z) = 0.119 \pm 0.003$
Present world average

Non SUSY GUT's

$\alpha_s(m_Z)=0.073\pm0.002$

SUSY GUT's

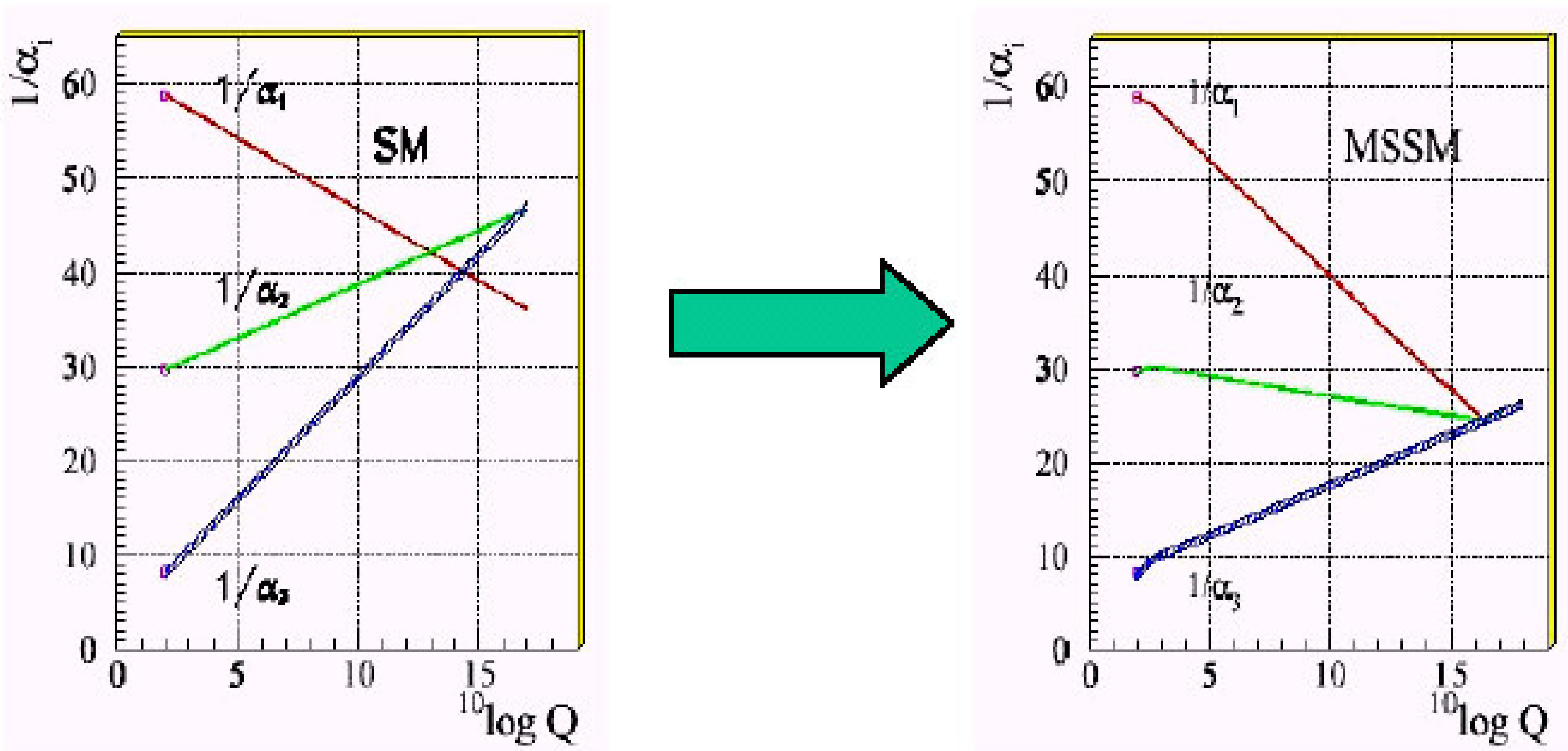
$\alpha_s(m_Z)=0.130\pm0.010$

Proton decay: Far too fast without SUSY

GRAND UNIFCATION (supersymmetry)

Coupling unification: Precise matching of gauge couplings at M_{GUT} fails in SM and is well compatible in SUSY

SUSY is important for GUT's



BEYOND THE SM

WHAT WE SEE IS JUST A SMALL PART OF WHAT IS POSSIBLE !!!

TO GO BEYOND THIS LECTURES

Elementary level:

more stress in phenomenology

D.H.Perkins, Intr. to high energy physics

F.Halzen, A.D.Martin, Quarks and leptons

more stress in theory

Leite Lopes, Gauge field theory, an introduction

I.J.R.Aitchison, Gauge theories in particle physics

Higher level:

more stress in phenomenology

E.D.Commins, P.H.Bucksbaum, Weak interactions

T.P.Cheng, L.F:Li, Gauge theories of elem. part. phys.

more stress in theory

Chanfray, Smajda, Les particules et leurs symetries

M.E.Peskin, D.V.Schroeder, Quantum Field Theory