Searching for the unknown in Particle Physics:

past discoveries

and

present challenges

QuarkNet 2002, FSU
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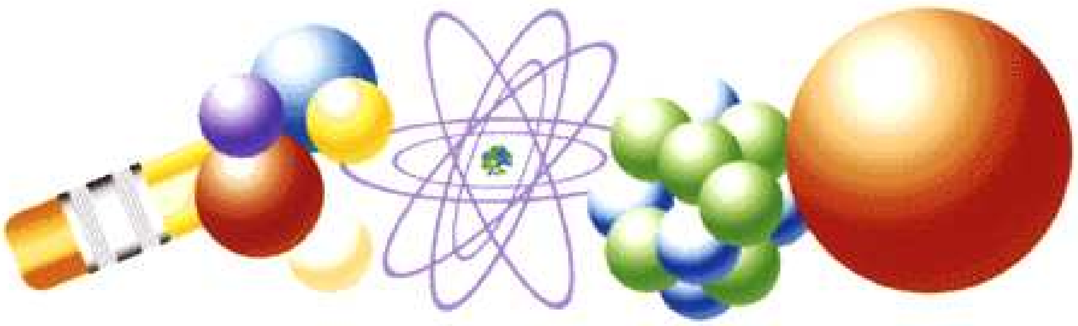


Outline

- What is Particle Physics?
- The origins of Particle Physics:
  - $\longrightarrow$ the atom (p,e^-), radioactivity, and the discovery of the neutron (n). (1895-1932)
  - $\longrightarrow$ Cosmic Rays: the positron (e^+), the muon ($\mu^\pm$), the pion ($\pi^\pm, \pi^0$), and the Kaon ($K^\pm, K^0$). (1932-1959)
- The advent of Colliders: more and more particles discovered, patterns emerge (1960's and on):
  - $\longrightarrow$ leptons and hadrons
  - $\longrightarrow$ electromagnetic, weak, and strong interactions
- The present scenario: the Standard Model of Electroweak and Strong interactions
  - $\longrightarrow$ formulation and discovery (1960's-1980's)
  - $\longrightarrow$ precision experimental tests (1990's and on)
  - $\longrightarrow$ very accurate theoretical predictions needed
- The quest for New Physics: Going beyond the Standard Model
  - $\longrightarrow$ open problems and possible strategies
  - $\longrightarrow$ present and future experimental facilities
  - $\longrightarrow$ example: the search for the Higgs particle

What is Particle Physics?

it is explaining the physical world, from the smallest atomic scale to the astronomical scales, in terms of the same

$\to$ fundamental constituents of matter ("building blocks")

$\to$ fundamental forces between them ("interactions").

$$\Downarrow$$

- Are there irreducible building blocks?

$\to$ how many?

$\to$ properties? (mass, charge, flavor, ...)

- How do they interact?

$\to$ how many forces?

$\to$ differences/similarities?

- What is mass?

- What is charge?

...

The Origins of Particle Physics

In school text books we learn that

• All matter is composed of atoms, which themselves form aggregates called molecules.
• An atom contains a nucleus of positive charge $+Z$ and Z electrons.
• If the atomic mass is A, the nucleus contains Z protons and $A - Z$ neutrons.

This picture did not exist in 1895 ...

• atoms creation of chemists
• electron, proton and neutron were yet to be discovered
• atomic spectra were known but not understood
• "*cathode rays*" discovered: look like particles with negative charge.

... when Röntgen discovers x-rays!

• 1896-97 : "*cathode rays*" are negatively charged particles of charge e and mass m, s.t. e/m is 2000 times larger than H

$$\Downarrow$$

Thomson's Model of the atom

• 1896-1900: enormous effort in study of radioactive elements (Becquerel, Curie's, Rutherford)
• 1906-1911: Geiger, Marsden and Rutherford's scattering experiments

$$\Downarrow$$

Rutherford's Model of the atom

But:

$\rightarrow$ electron orbiting around the nucleus accelerates and therefore (Maxwell) radiates
$\rightarrow$ electron looses energy by radiation: orbit decays
$\rightarrow$ continuum spectrum and unstable atoms.

Answers:

1924-1927 Quantum Mechanics

(Planck,Bohr,De Broglie,Heisenberg,Schrödinger,Dirac,...)

- 1932 : Chadwick discovers the neutron

$$He_2^4 + Be_4^9 \rightarrow C_6^{12} + n_0^1$$

$$\Downarrow$$

The modern atom is complete

However ... Most is still to come!

The Development of Particle Physics

- Evidence of very light neutral particle in β decay: the electron neutrino (predicted by Pauli in 1930, discovered by Cowan and Reines in 1956-58)

$$n \to p + e^- + \bar{\nu}_e$$

- Cosmic Rays: atmospheric nuclear collision of incoming high energy protons produce new particles

$\to$ 1932: positron (e^+) (Anderson), as predicted by Dirac (1928)

$\to$ 1936-1951: the muon ($\mu^\pm$) and the pion ($\pi^\pm, \pi^0$)

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^0 \to \gamma\gamma$$

$\to$ 1943-1959: the discovery of "*strange particles*", the Kaon ($K^\pm, K^0, \bar{K}^0$)

$$K^0 \to \pi^+ + \pi^-$$

$$K^+ \to \mu^+ + \nu_\mu \quad \cdots$$

1940's $\rightarrow$ 1950's

A plethora of particles is discovered

(mainly in cosmic rays)

e^-, p, n, ν_e, μ^-, ($\pi^\pm$, π^0), e^+

plus

($K^\pm$, K^0, $\bar{K}^0$), Λ^0, $\bar{p}$, (Σ^+, Σ^0), Ξ, ...

NATURE CANNOT BE SO MESSY!

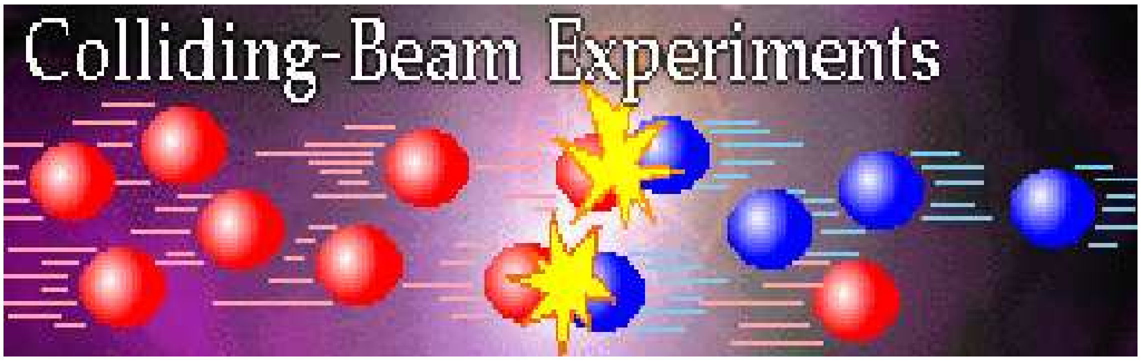
$\Downarrow$

- Are all these particle intrinsically different?

OR

- Can we recognize patterns or symmetries in their nature (charge,mass,flavor) or the way they behave (decays)?

1950's $\rightarrow$ .....
A new era for particle physics



We can convert energy into particles

$$E^2 = p^2c^2 + m^2c^4$$

and reproduce the primordial stages of our universe (almost...)

$\Downarrow$

Collider Physics

$$e^+e^- \ , \ p\bar{p} \ , \ \ldots.$$

With High Energies we can:

$\rightarrow$ make objects of large mass
$\rightarrow$ resolve structure at small distances

First Great Discoveries....

• $e^{\pm}, \mu^{\pm}, \tau^{\pm}$ and their neutrinos (we call them *Leptons*) are fundamental particles and interact electromagnetically and "*weakly*"

while

• p, n, $(\pi^{\pm}, \pi^0)$, $(K^{\pm},\ K^0,\ \bar{K}^0)$, Λ^0, (Σ^+, Σ^0), Ξ, ... (we call them *Hadrons*) are not fundamental particles!

$\Downarrow$

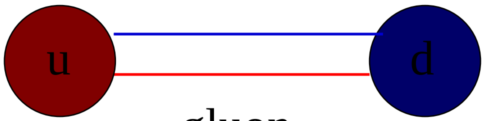
They are made of QUARKS!
named up, down, and strange

and they interact electromagnetically, "*weakly*", and "*strongly*".

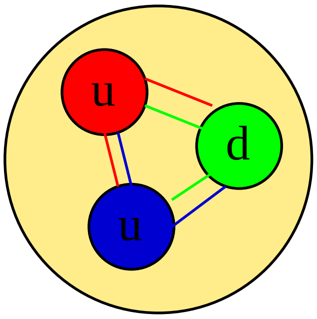
Quarks carry a COLOR charge

$$\text{un UP quark can be} \begin{cases} up & (green) \\ up & (red) \\ up & (blue) \end{cases}$$

and interact exchanging GLUONS, the carriers of the STRONG FORCE



gluon



proton

Barions	Mesons
(qqq)	$(\bar{q}q)$
$p \rightarrow uud$	$\pi^{\pm} \rightarrow u\bar{d}(\bar{u}d)$
$n \rightarrow ddu$	$\pi^{0} \rightarrow u\bar{u} + d\bar{d}$
$\Sigma^{+} \rightarrow uus$	$K^{\pm} \rightarrow u\bar{s}(\bar{u}s)$
$\Sigma^{0}, \Lambda^{0} \rightarrow uds$	$K^{0}(\bar{K}^{0}) \rightarrow \bar{s}d(s\bar{d})$
$\Xi^{0} \rightarrow uss$	$\rho \rightarrow u\bar{d}$
$\ldots$	$\ldots$

Both Leptons and Quarks carry a Weak Charge

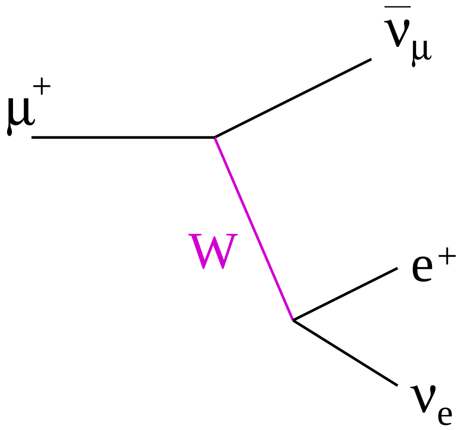
as well as the usual electric charge

and also interact exchanging:

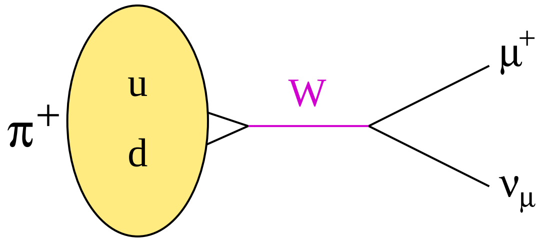
- Neutral EW force carriers : γ (photon), Z^0 ($M_\gamma = 0, M_Z = 91$ GeV)

- Charged EW force carriers : $W^\pm$ ($M_W = 80$ GeV)

$$\mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$$



$$\pi^+ \to \mu^+ + \nu_\mu$$



Some Milestones...

$\rightarrow$ Quantum Electrodynamics (QED) (1950's), (Feynman,Schwinger,Tomonaga)

$\rightarrow$ Electroweak unification: the Standard Model (1960's) (Glashow,Weinberg,Salam)

$\rightarrow$ SLAC/MIT elastic/inelastic scattering from nucleons (1956-1973)

$\rightarrow$ Quark Model (1964) (Gell-Mann,Zweig)

$\rightarrow$ Quantum Chromodynamics (QCD) (1970's) (Gross, Wilceck, Politzer,...)

More Quarks coming along .....

1974 $\rightarrow$ Discovery of the charm quark ($\psi = c\bar{c}$, D mesons) (BNL, SLAC)

1977 $\rightarrow$ Discovery of the bottom quark ($Y = b\bar{b}$, B mesons) (FERMILAB, DESY)

1995 $\rightarrow$ Discovery of the top quark (no bound state) (FERMILAB)

And more Forces .....

1983 $\rightarrow$ Discovery of the $W^{\pm}$ and Z^{0} bosons, carriers of the WEAK FORCE (CERN)

$$\Downarrow$$

As the Standard Model predicts

1990's $\rightarrow$ Precision tests of the Standard Model (CERN,SLAC,FERMILAB)

Present Scenario and future Developments

- Most of the particle the world is made of are : electrons, protons, and neutrons (e^+, u, and d quarks).

- This is because our world lives at very low energy.

- All other particles were created at the high energies of the very early stages of our universe and we can nowadays recreate some of them in our laboratories, even if for very short time

  $\rightarrow$ LEP (e^+e^-),CERN (Geneva, CH) (done)
  $\rightarrow$ Tevatron ($p\bar{p}$), Fermilab (Chicago) (2001)
  $\rightarrow$ B-factories (SLAC, KEK) (e^+e^-)(1999)
  $\rightarrow$ LHC (pp), CERN (Geneva,CH) ($\sim$ 2006)
  $\rightarrow$ NLC/Tesla (e^+e^-) ($\sim$ 2020?)

- This allows us to study their nature, test the Standard Model, and discover direct or indirect signals of new physics.

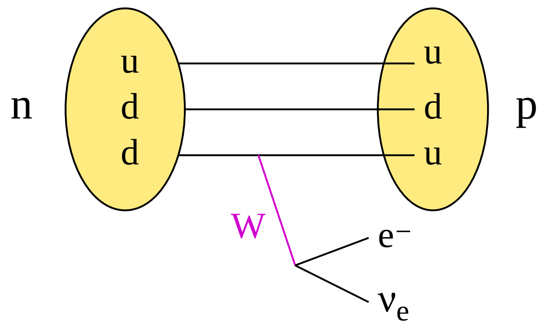
Direct vs Indirect Evidence

- Either you produce a new particle: Direct Evidence or Discovery

- Or you see it in a "virtual state": Indirect Evidence

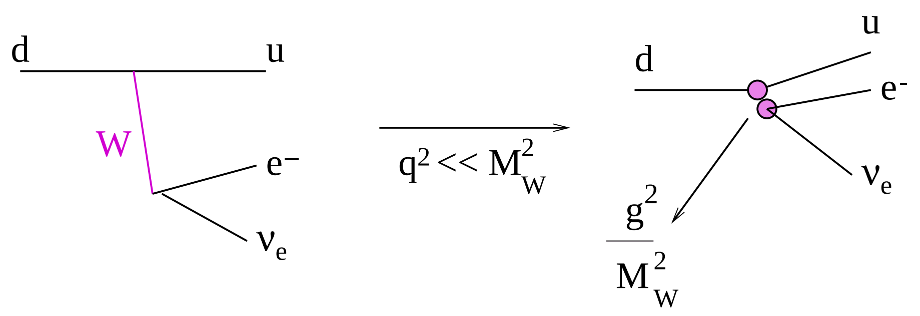
  Very famous example: β decay

$$n \to p + e^- + \bar{\nu}_e$$

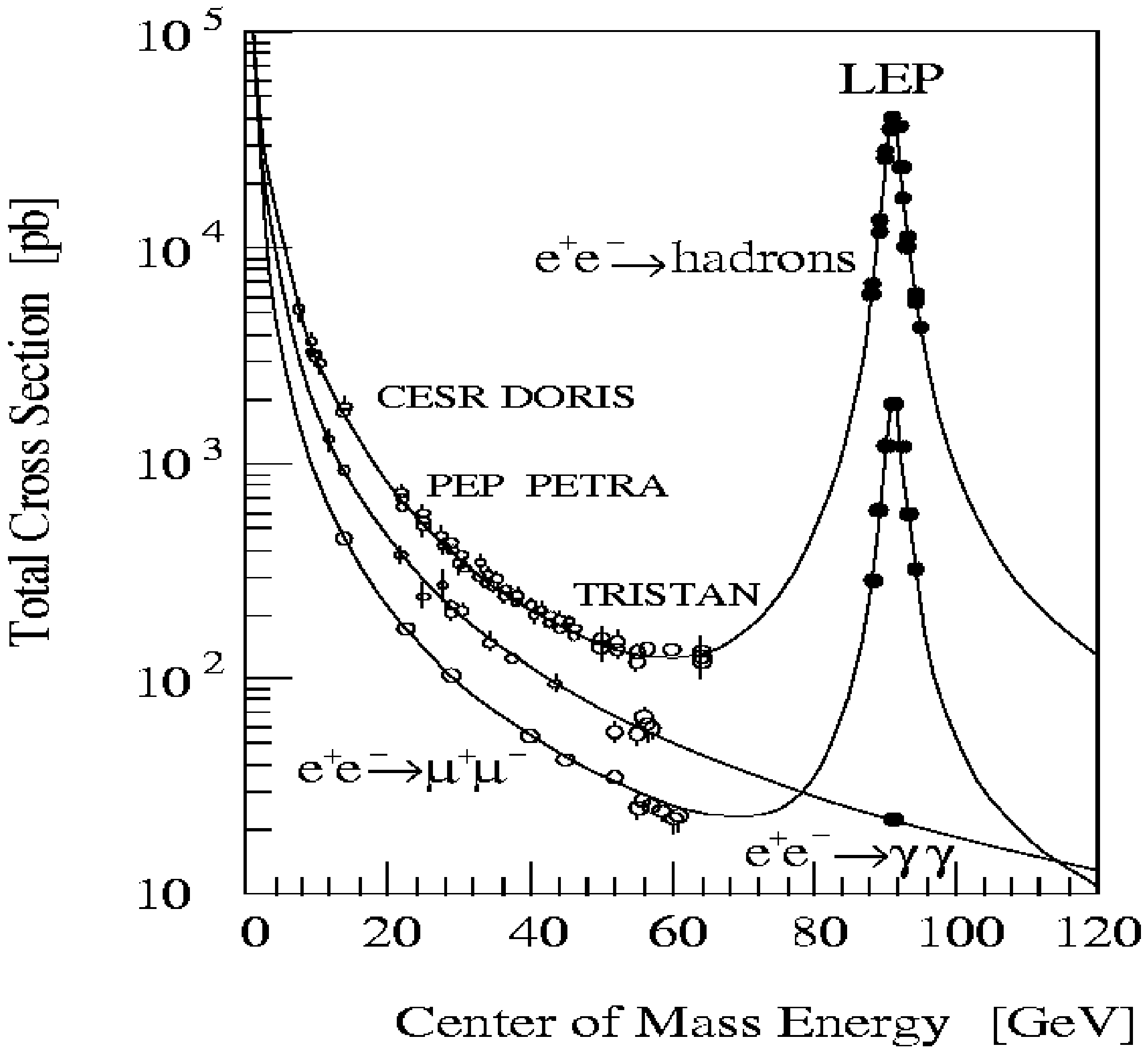


Fermi's Theory: pointlike interaction

$$\text{decay rate} \propto G = \frac{g^2}{M_W^2}$$



First Precision Studies: LEP 1 (CERN)

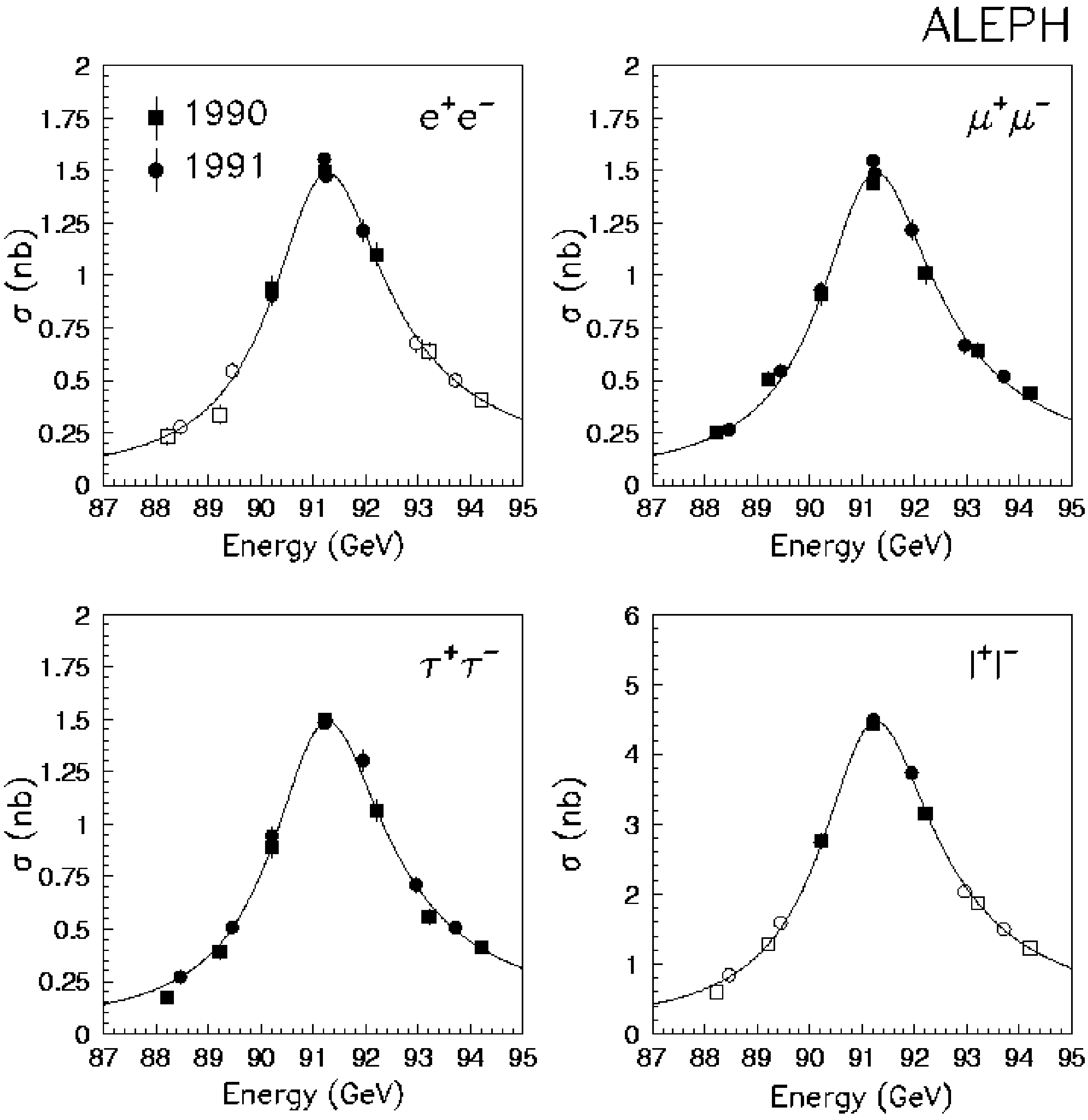


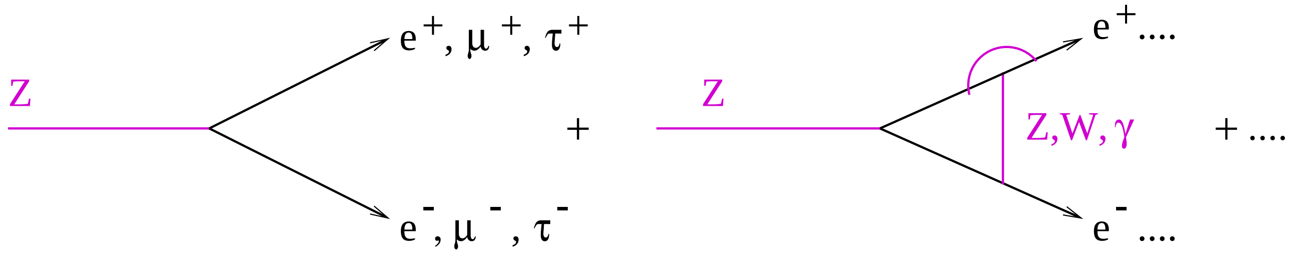
cross section	$\longrightarrow$	probability for a process to happen ($a + b \to c + d + \ldots$) (units barn=10^{-28} m^2)

resonance $\leftrightarrow$ bound state produced

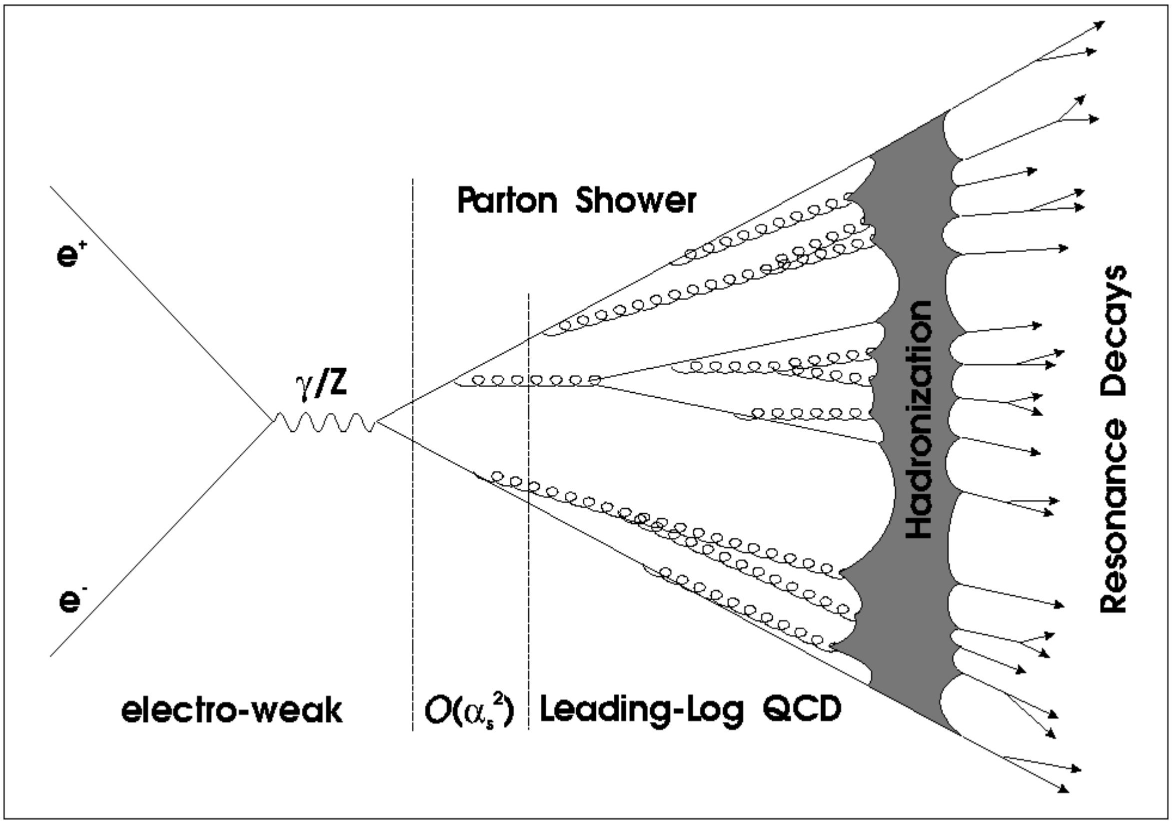
LEP 1	$\longrightarrow$	3.5 Millions Z^0 produced: precision measurements

$$e^+e^- \to \gamma, Z^0 \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$





$$e^+e^- \to \gamma, Z \to q\bar{q} \to \text{hadrons}$$



Higher order calculations need

- powerful algorithms (ex.:integration,resummation techniques)
- algebraic manipulators (Maple,Mathematica,...)
- Monte Carlo techniques (to generate final state particles)

Why need high precision?

Z pole observables

Quantity	Group(s)	Value	Standard Model	pull
M_Z [GeV]	LEP	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	LEP	2.4952 ± 0.0023	2.4966 ± 0.0016	-0.6
$\Gamma(\text{had})$ [GeV]	LEP	1.7444 ± 0.0020	1.7429 ± 0.0015	—
$\Gamma(\text{inv})$ [MeV]	LEP	499.0 ± 1.5	501.76 ± 0.14	—
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	83.984 ± 0.086	84.019 ± 0.027	—
σ_{had} [nb]	LEP	41.541 ± 0.037	41.477 ± 0.014	1.7
R_e	LEP	20.804 ± 0.050	20.744 ± 0.018	1.2
R_μ	LEP	20.785 ± 0.033	20.745 ± 0.018	1.2
R_τ	LEP	20.764 ± 0.045	20.790 ± 0.018	-0.6
$A_{FB}(e)$	LEP	0.0145 ± 0.0025	0.01636 ± 0.00025	-0.7
$A_{FB}(\mu)$	LEP	0.0169 ± 0.0013		0.4
$A_{FB}(\tau)$	LEP	0.0188 ± 0.0017		1.4
R_b	LEP + SLD	0.21664 ± 0.00068	0.21569 ± 0.00016	1.4
R_c	LEP + SLD	0.1729 ± 0.0032	0.17230 ± 0.00007	0.2
$R_{s,d}/R_{(d+u+s)}$	OPAL	0.371 ± 0.023	0.35920 ± 0.00005	0.5
$A_{FB}(b)$	LEP	0.0982 ± 0.0017	0.1035 ± 0.0008	-3.1
$A_{FB}(c)$	LEP	0.0689 ± 0.0035	0.0740 ± 0.0006	-1.5
$A_{FB}(s)$	DELPHI + OPAL	0.0976 ± 0.0114	0.1036 ± 0.0008	-0.5
A_b	SLD	0.921 ± 0.020	0.93474 ± 0.00011	-0.7
A_c	SLD	0.667 ± 0.026	0.6680 ± 0.0005	0.0
A_s	SLD	0.895 ± 0.091	0.93570 ± 0.00009	-0.4
A_{LR} (hadrons)	SLD	0.15138 ± 0.00216	0.1477 ± 0.0011	1.7
A_{LR} (leptons)	SLD	0.1544 ± 0.0060		1.1
A_μ	SLD	0.142 ± 0.015		-0.4
A_τ	SLD	0.136 ± 0.015		-0.8
$A_e(Q_{LR})$	SLD	0.162 ± 0.043		0.3
$A_\tau(\mathcal{P}_\tau)$	LEP	0.1439 ± 0.0041		-1.0
$A_e(\mathcal{P}_\tau)$	LEP	0.1498 ± 0.0048		0.3
Q_{FB}	LEP	0.0407 ± 0.0022	0.0424 ± 0.0003	-0.8

Many open problems .....

- What is the origin of mass??

$$\Downarrow$$

the Higgs boson story

a very elusive particle.....

$\rightarrow$ no direct evidence yet
$\rightarrow$ many indirect pieces of evidence

- Do forces unify?? (a hint for larger symmetries, like SuperSymmetry)

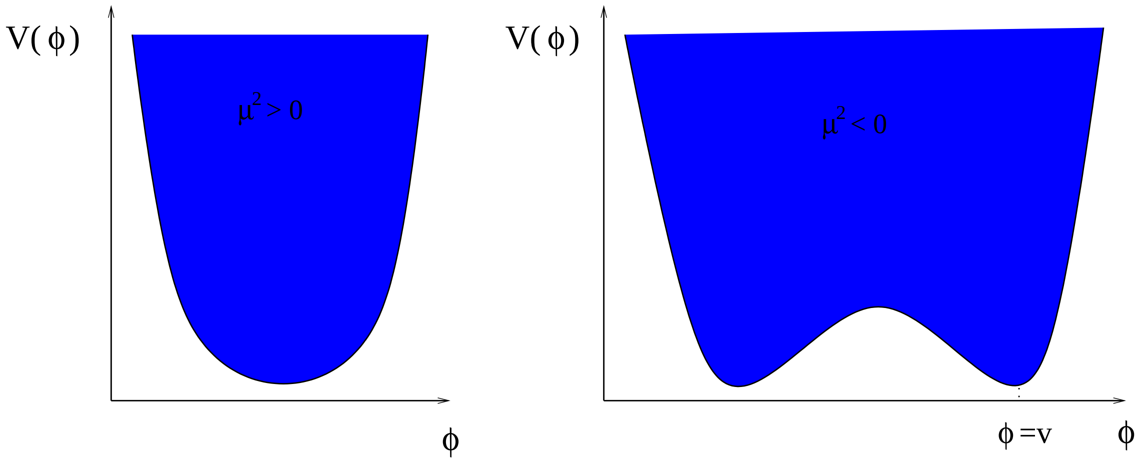
- Are there more fundamental objects than just leptons and quarks??

- What about the gravitational force? Can it be naturally part of the picture??

- Are there extra dimensions?? does this explain the magnitude of the gravitational force/scale??

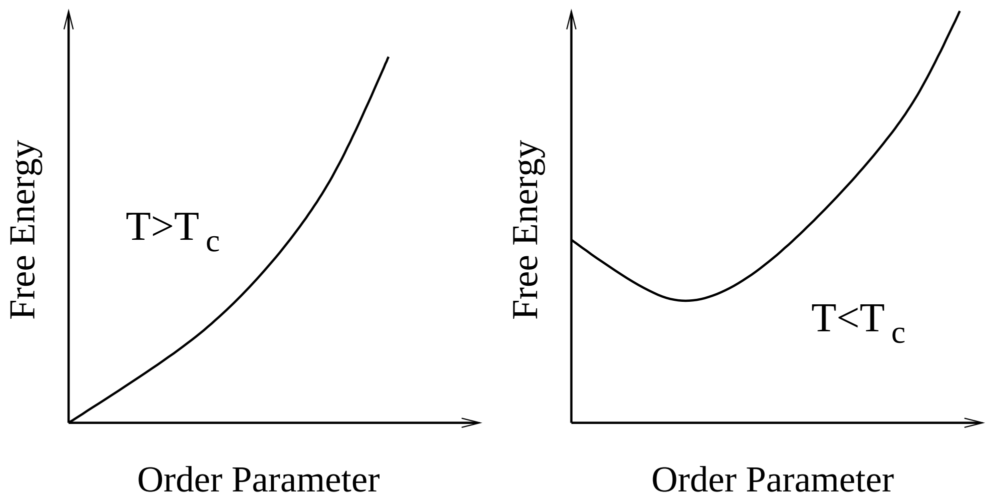
and more .....

The Higgs-Kibble Mechanism



$$V(\phi) = \mu^2\phi^2 + \lambda\phi^4$$

analogously to Superconductivity



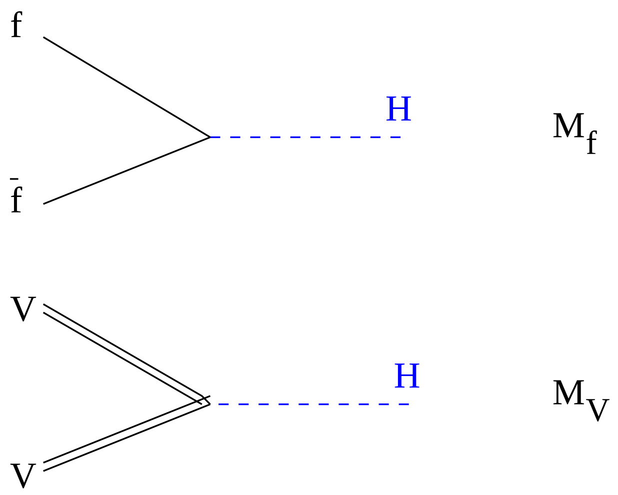
we talk of

Spontaneous Symmetry Breaking

After which....

- $\rightarrow$ leptons and quarks (f) get mass
- $\rightarrow$ the $W^{\pm}$ and Z^0 particles (V) get mass
- $\rightarrow$ the Higgs particle (H) gets mass

and new interactions arise



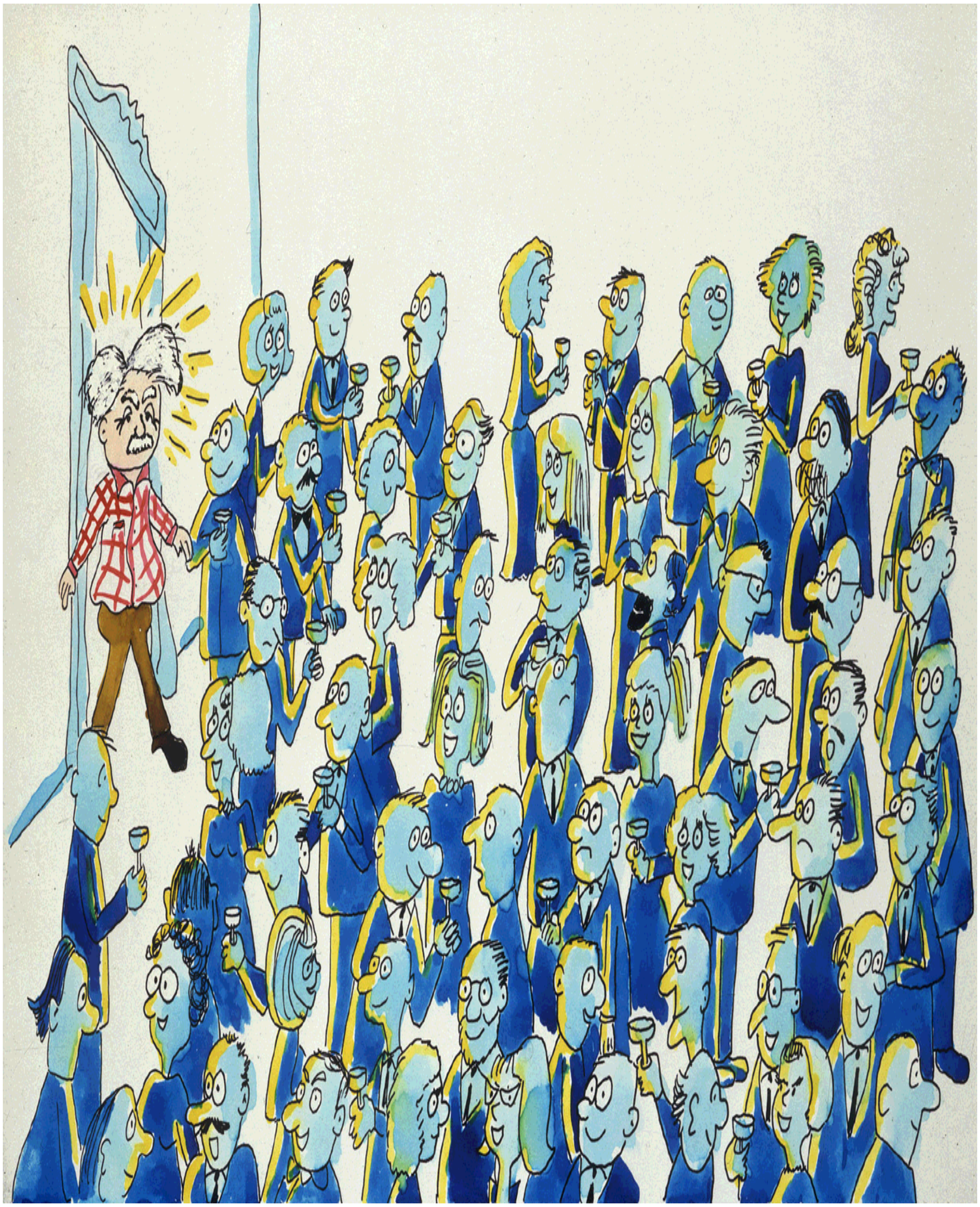
Our **Program** is to

- $\rightarrow$ discover the Higgs particle (one? many?)
- $\rightarrow$ measure its properties (mass,couplings)

Success depends on extreme precision from both theory and experiments.

From The Large Hadron Collider, by C Llewvellyn Smith, Scientific American, July 2000

A room full of physicists quietly chattering....



... a well known physicist walks in ...

... he attracts a cluster of admirers with each step, which makes difficult for him to move ... he acquires a mass!

... if a rumor crosses the room ...

... it creates some kind of clustering, but this time among physicists themselves ...

The Standard Model Higgs story

$\rightarrow$ Indirect limits from EW precision fits

$$M_{h_{SM}} < 196 - 222\,\text{GeV} \quad (95\%\,\text{cl})$$

$\rightarrow$ Direct bounds from LEP2 (192-202 GeV):

$$M_{h_{SM}} \geq 114.1\,\text{GeV} \quad (95\%\,\text{cl})$$

$$\Downarrow$$

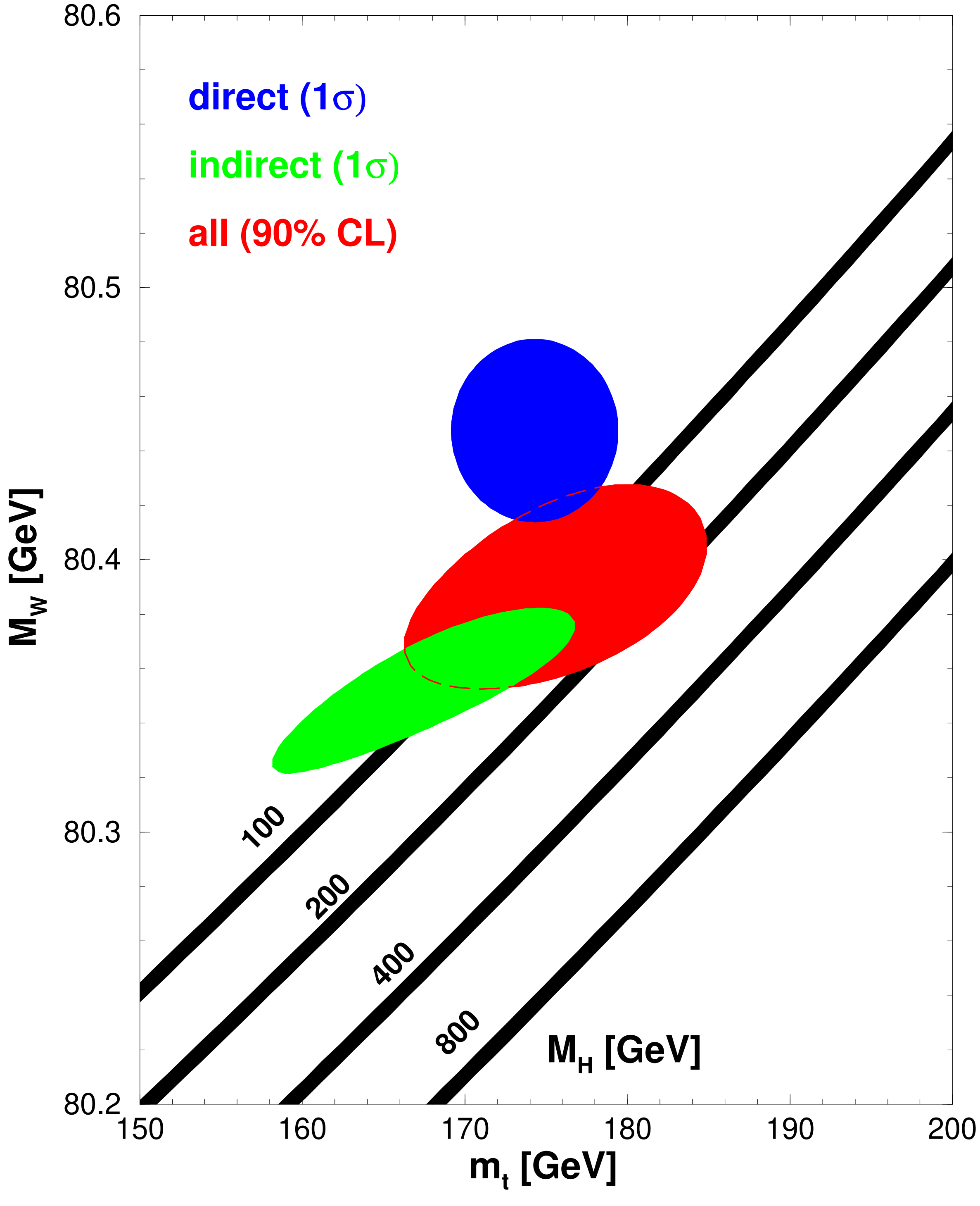
The window is getting tighter!

The future looks really exciting!

- Present/Close Future $\rightarrow$ Tevatron
  ($p\bar{p}$-collider, $\sqrt{s}=2$ TeV)

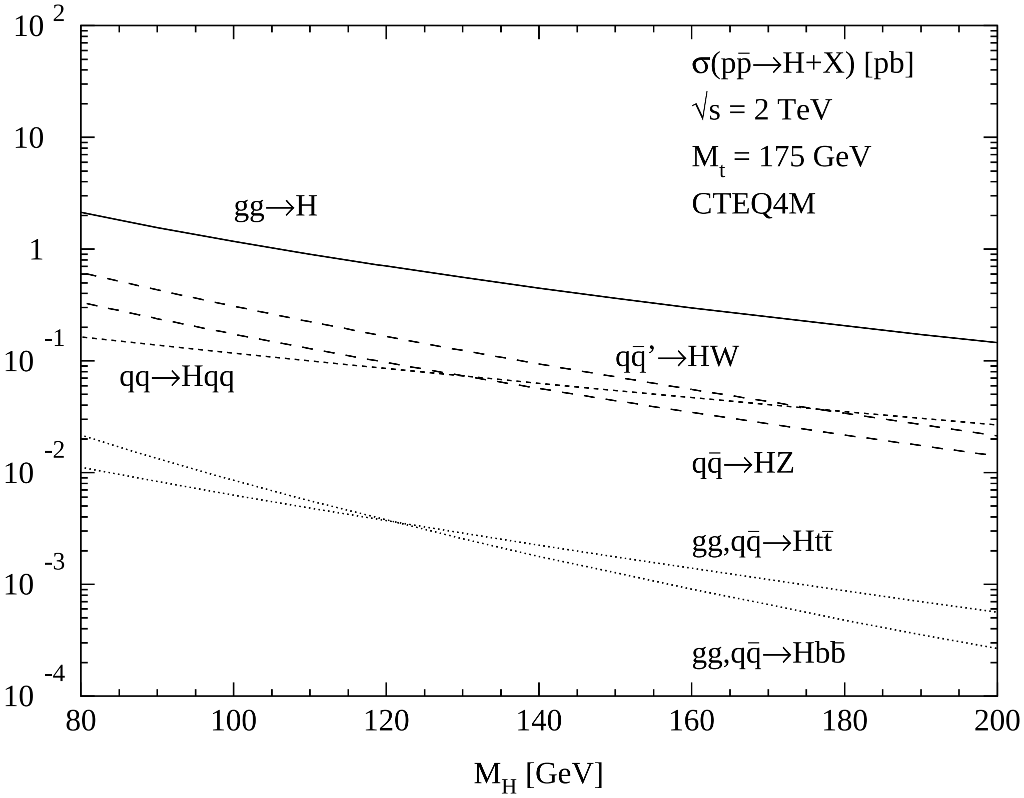
- Future $\rightarrow$ LHC (due by 2006)
  (pp-collider, $\sqrt{s}=14$ TeV)

$M_W - m_t$

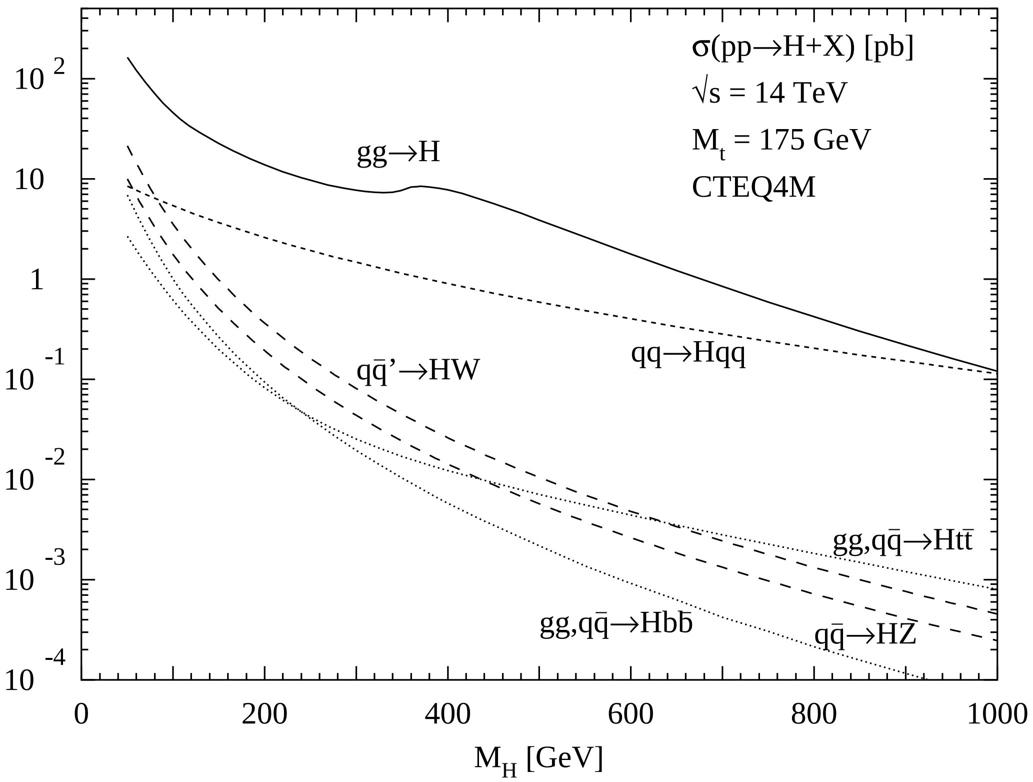


direct (1σ)
indirect (1σ)
all (90% CL)
100
200
400
800
M_H [GeV]
80.6
80.5
80.4
80.3
80.2
150
160
170
180
190
200
m_t [GeV]
M_W [GeV]

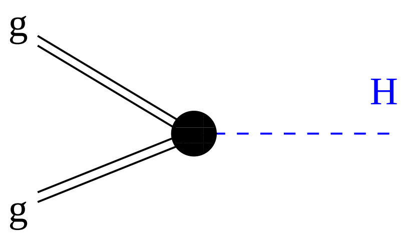
Tevatron, SM Higgs



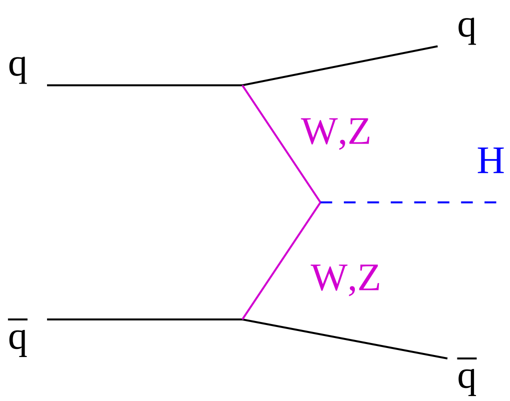
LHC, SM Higgs



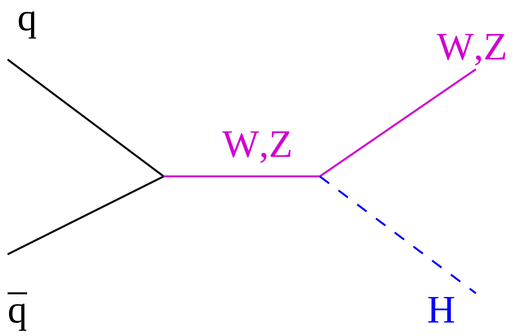
Higgs produced via ....



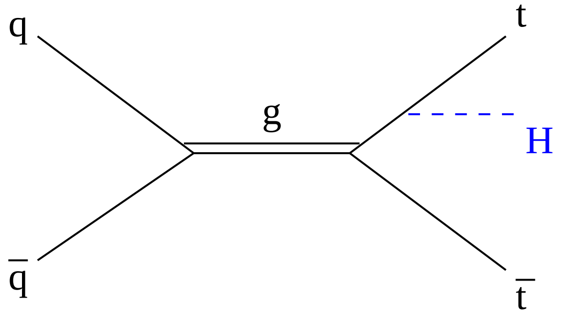
gg -> H

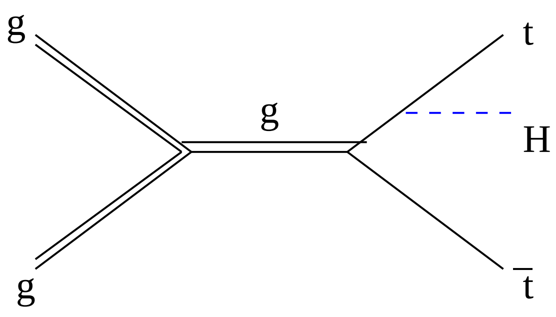


$q\bar{q}$ -> $q\bar{q}$ H



$q\bar{q}$ -> WH
$q\bar{q}$ -> Z H





$q\bar{q}$ -> $t\bar{t}$ H

gg -> $t\bar{t}$ H

In conclusion ...

- Particle physics was born during the last century and has witnessed an incredible development, due to revolutionary ideas in both theory and experiments.

- The excitement is not over: the physics of the present and future accelerators will confirm existing theories and/or give us dramatically new hints of yet unknown physics.

- The success of this program once again relies on a healthy dialog between theorists and experimentalists...

- ... and between different disciplines, like particle physics, nuclear physics and astrophysics.

- New revolutionary ideas are arising in Particle Physics. We may understand the missing links that prevent Gravitation from being part of the Standard Model yet and ....

..... we may have to look back at the universe to know more and try to unify the very large with the very small!