The two infinities and their connections

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1) Elementary particles and fundamental interactions
2) Content of the Universe and evolution

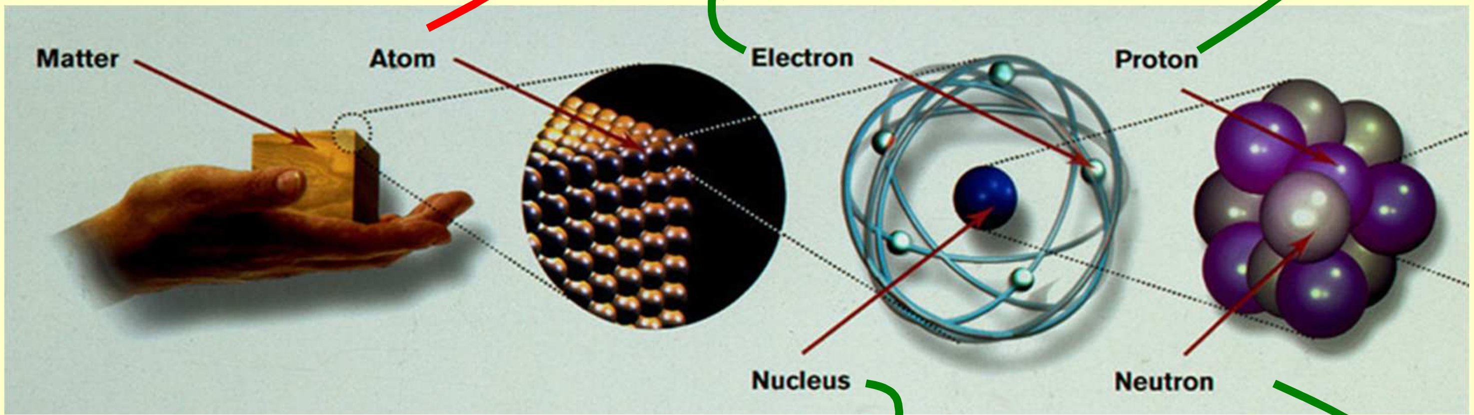
Elementary particles
and
fundamental interactions

The starting point: atomic structure

1913: N.Bohr,
quantum theory
of atoms

1897, J.J.Thomson

1919, E.Rutherford



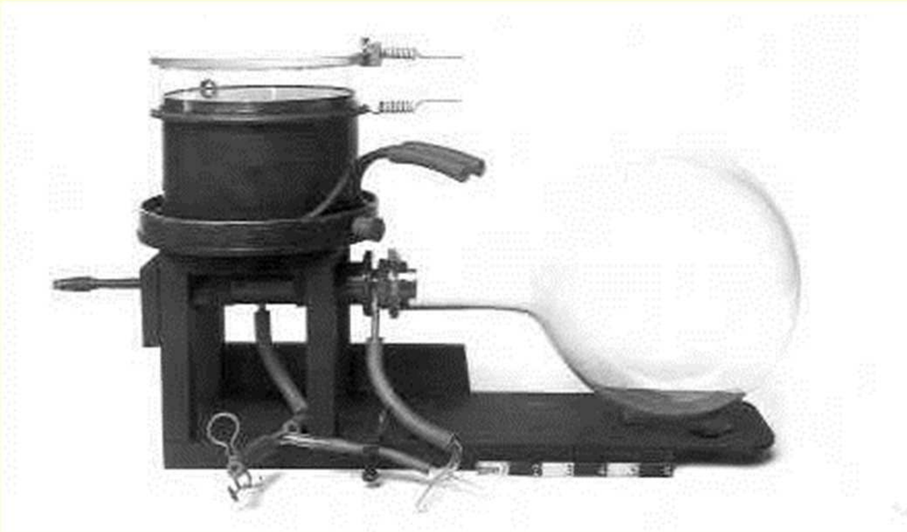
. . . .

1911, E.Rutherford, H.Geiger & E.Marsden

1932, J.Chadwick

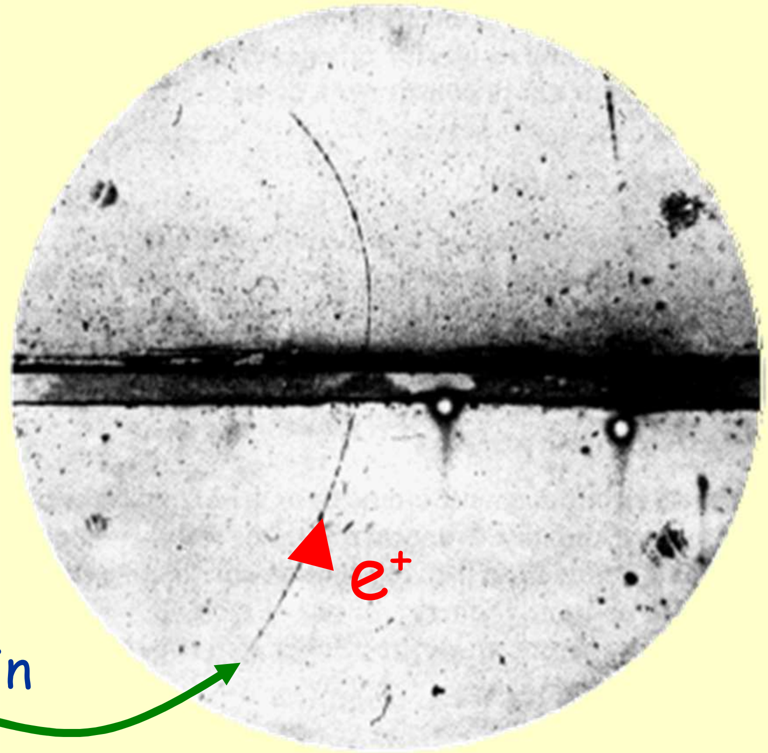
1931, P. Dirac : e^+ is predicted

Antimatter exists !



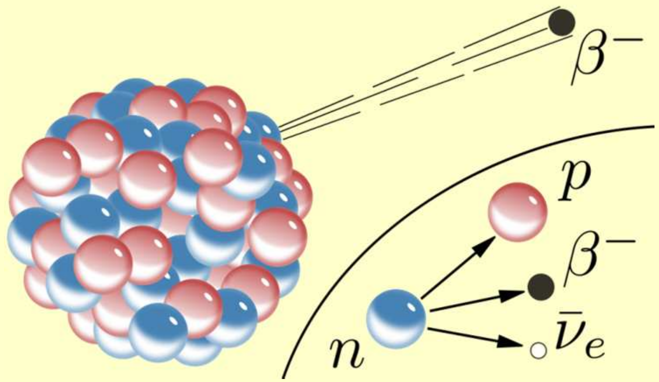
cloud chamber

1932, C. Anderson : positron discovery in cosmic rays



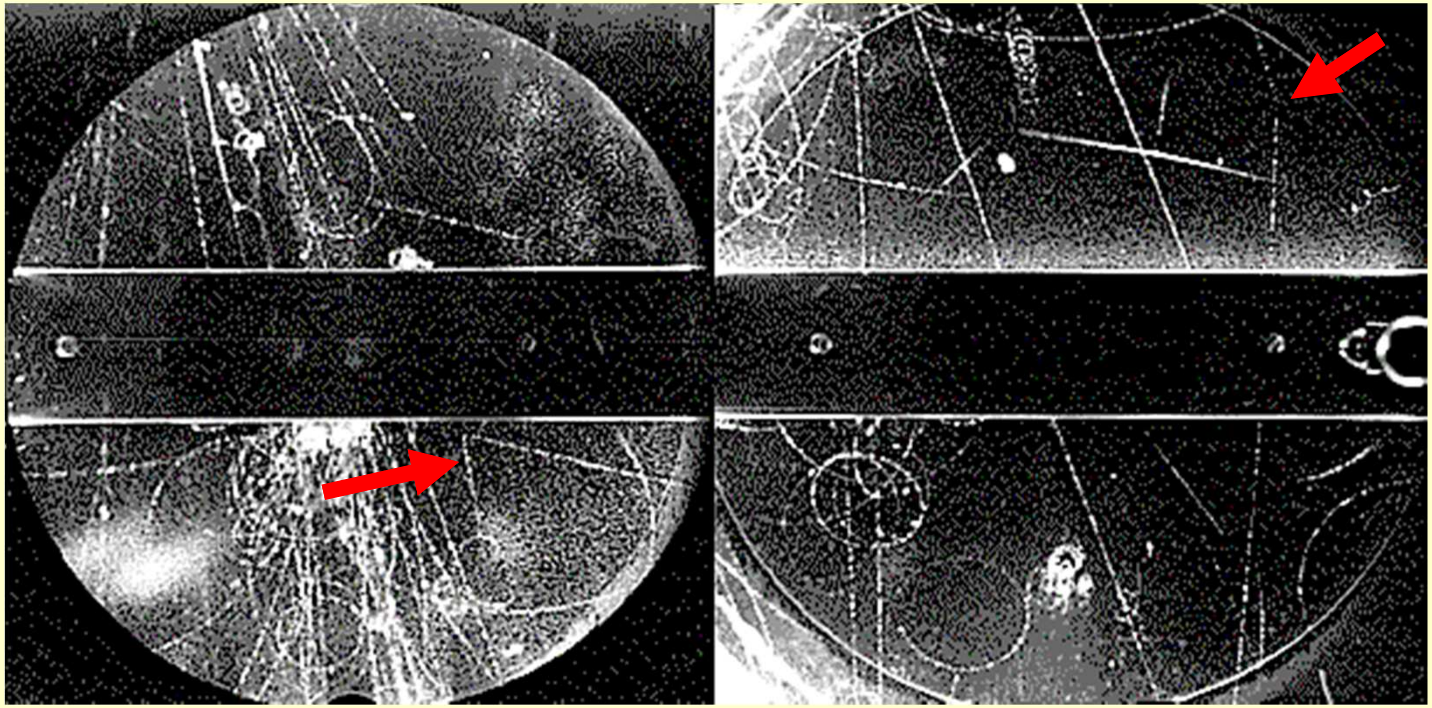
Neutrinos are predicted

1930, W.Pauli : ν is postulated to preserve energy conservation in β decays



Beyond ordinary matter …

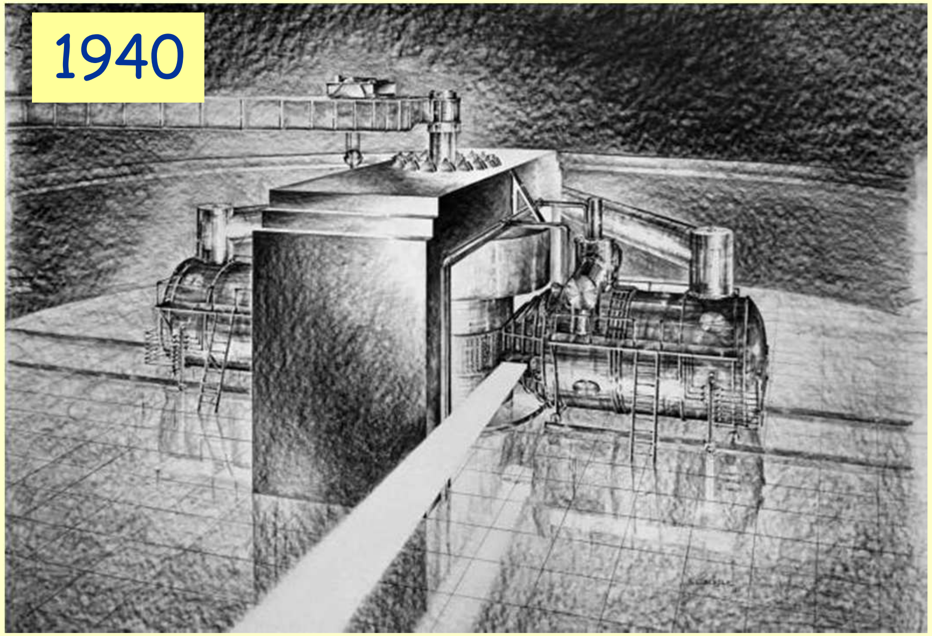
1937, muon discovery (C. Anderson & S. Neddermeyer)
1947, pion discovery (C. Powell)
1947 discovery of neutral and charged kaons (G. Rochester & C. Butler)



$K^0 \rightarrow \pi^+ \pi^-$ $K^\pm \rightarrow \mu^\pm \nu$

Photographs of cloud chamber exposed to cosmic rays

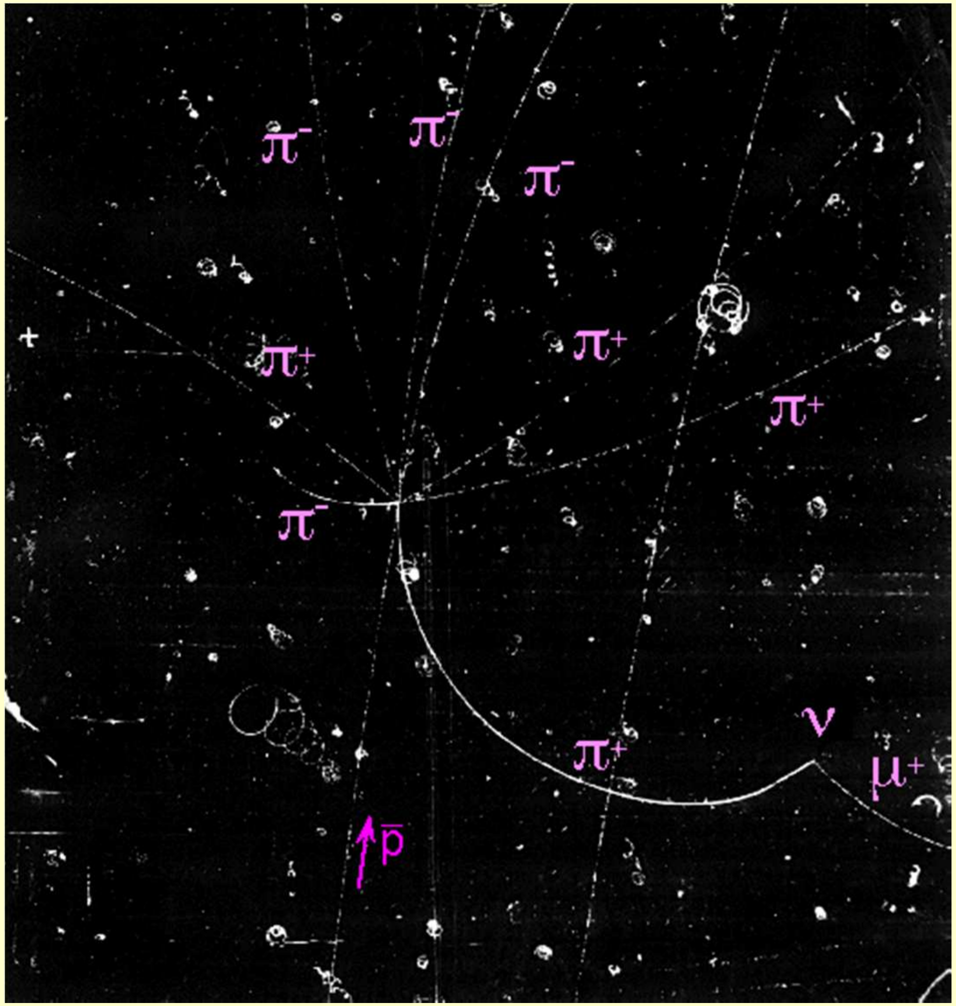
Accelerators come on stage



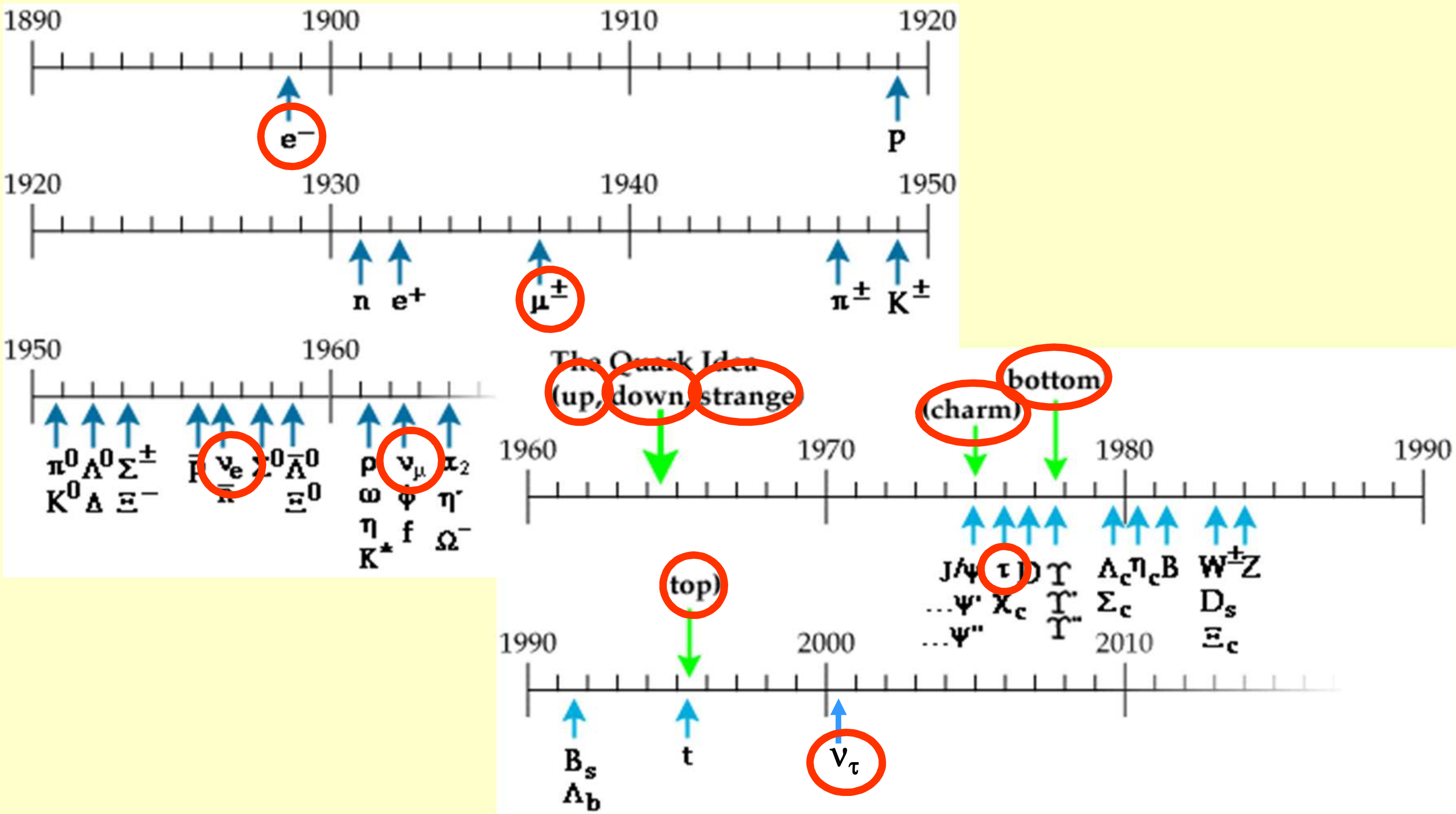
1948, Berkeley cyclotron at 95MeV/nucleon: first π production in laboratory (E.Gardner, G.Lattes)

note: 1 MeV = 10^6 eV, 1 GeV=10^9 eV

Bubble chamber photograph: antiproton proton interaction

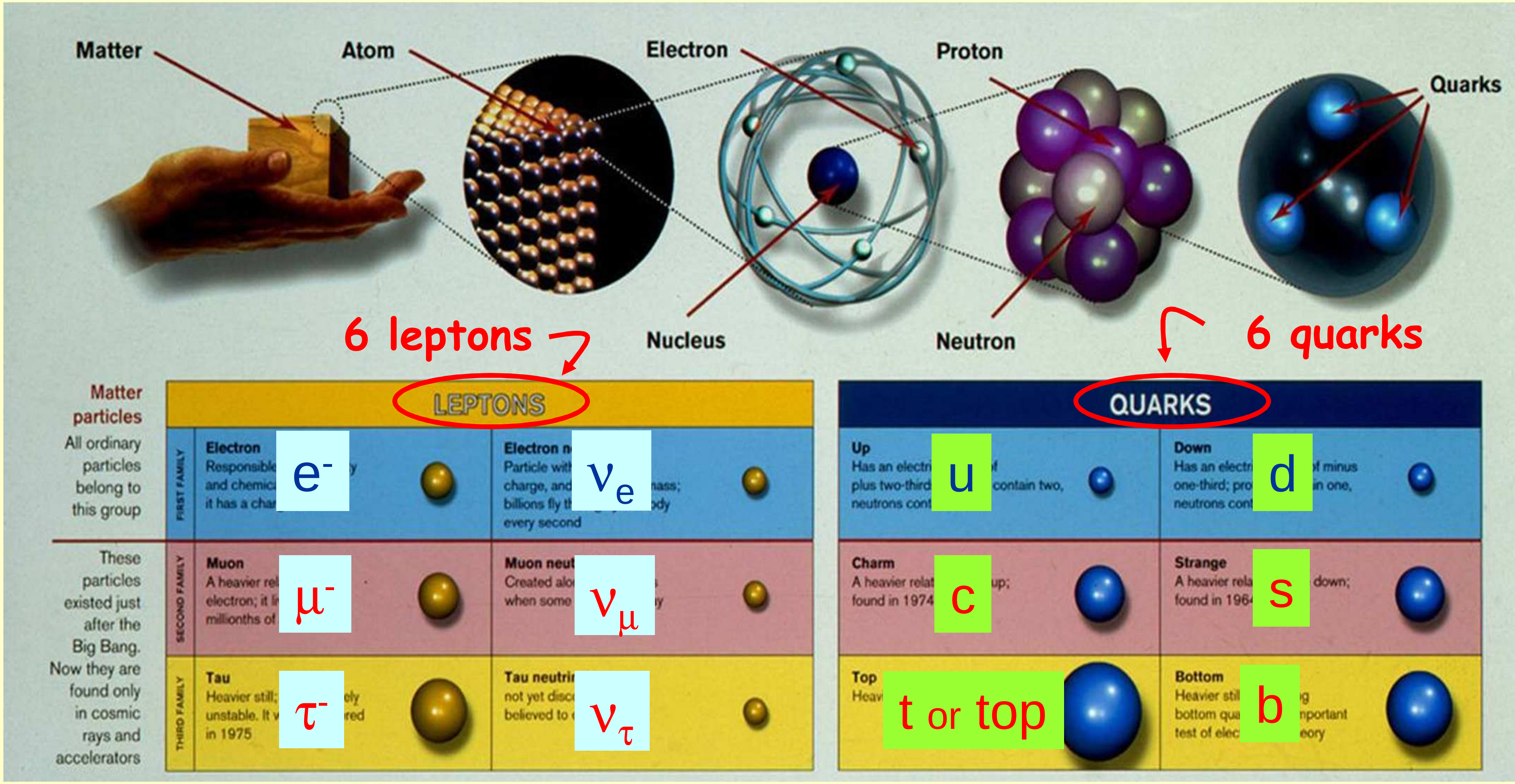


More and more particles !



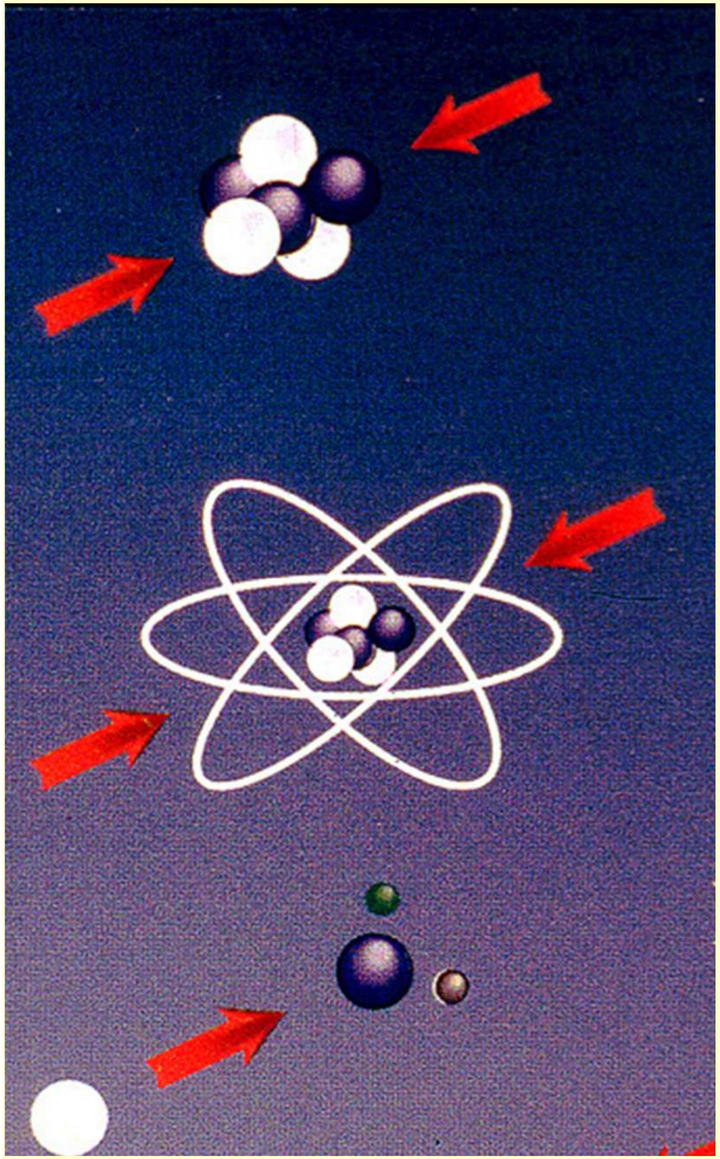
… but only 12 elementary constituants
governed by 3 fundamental interactions
in a quantic, relativistic and unified framework:
the Standard Model of particle physics

The 12 elementary constituants



All constituants observed experimentally: from e^- (1897) to top quark (1995) and ν_τ(2000). So far, no internal structure detected.

The 3 fundamental interactions



Strong interaction:

- Binding force in nucleons and atomic nuclei; nuclear reactions in stars
- range: 1fm = 10^{-15}m
- mediated by **gluons**

Electromagnetic interaction:

- Binding force in atoms, molecules and cristals; electricity, magnetism
- range: infinite
- mediated by the **photon**

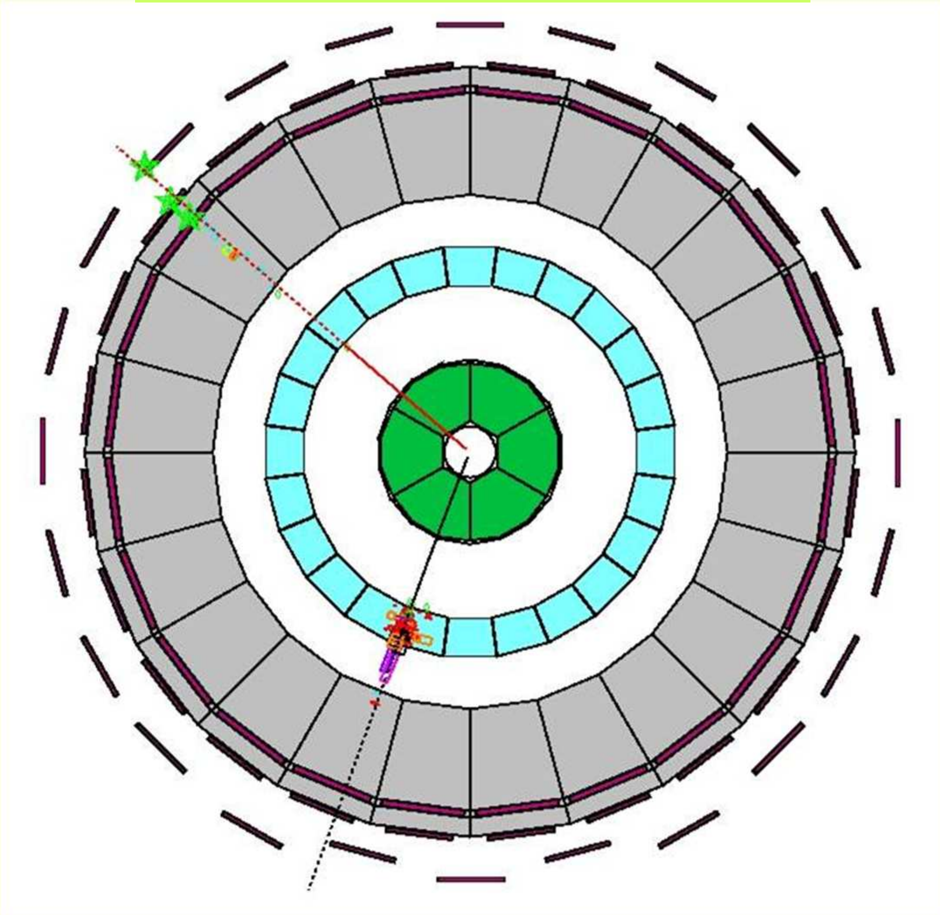
Electroweak interaction

Weak interaction:

- Radioactive decays; nuclear reactions in stars
- range: 10^{-18} m
- mediated by the **W and Z bosons**

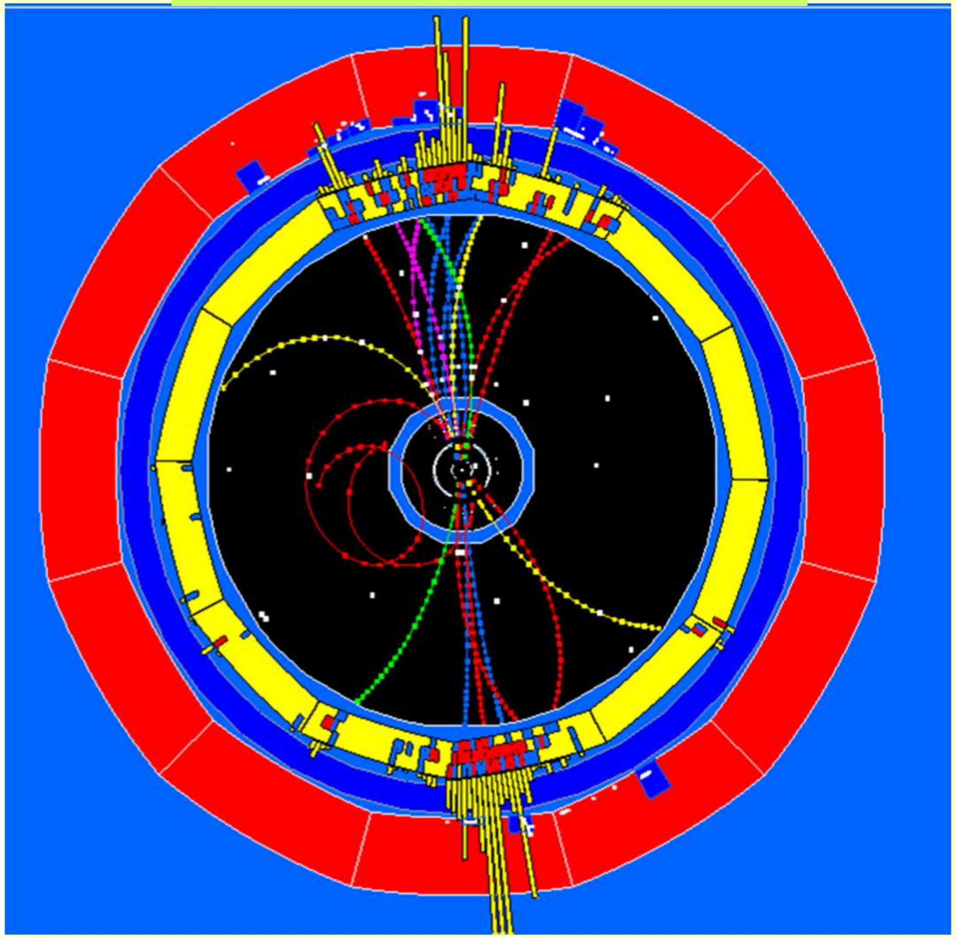
Events in particle detectors

$e^+e^- \to W^+ W^- \to e^+\nu\mu^-\bar{\nu}$



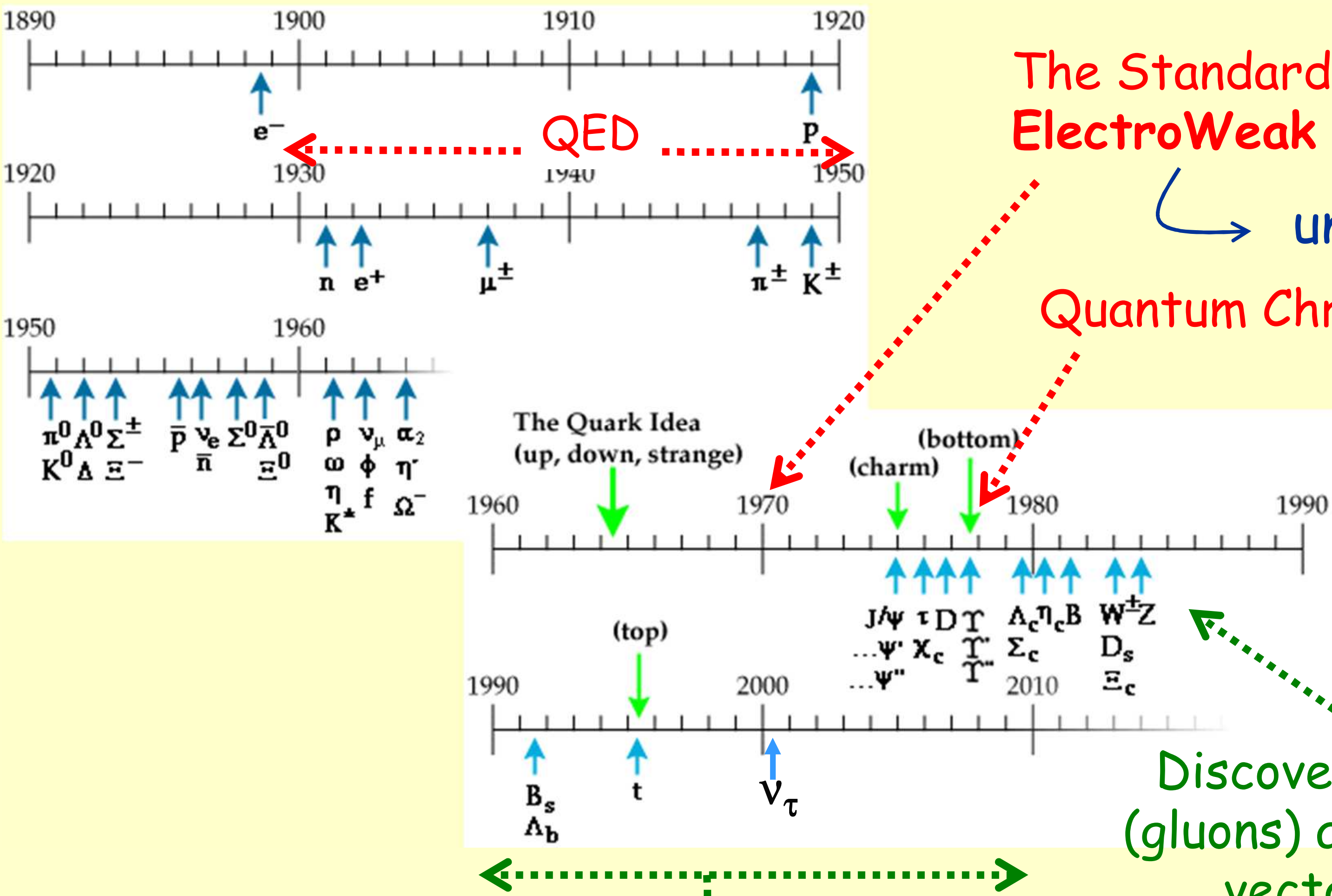
final-state: two charged leptons

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



final-state: two jets of hadrons !

The emergence of the Standard Model



The Standard Model of the **ElectroWeak** interaction

unification

Quantum ChromoDynamics

Discovery of strong (gluons) and EW (W,Z) vector bosons

Precise tests of the electroweak theory, tests of QCD

Main topics in particle physics

EW symmetry breaking

- SM confirmed down to quantum corrections
- Higgs mechanism ? New physics ?

Tevatron (US), LHC (CERN)

CP violation in the quark sector

- SM agree with data (K,B)
- Extend measurements

Belle (Japan), LHC (CERN)

Strong interaction

- Proton deep structure
- Interaction intensity
- Quark-gluon plasma ?

RHIC (US), LHC (CERN)

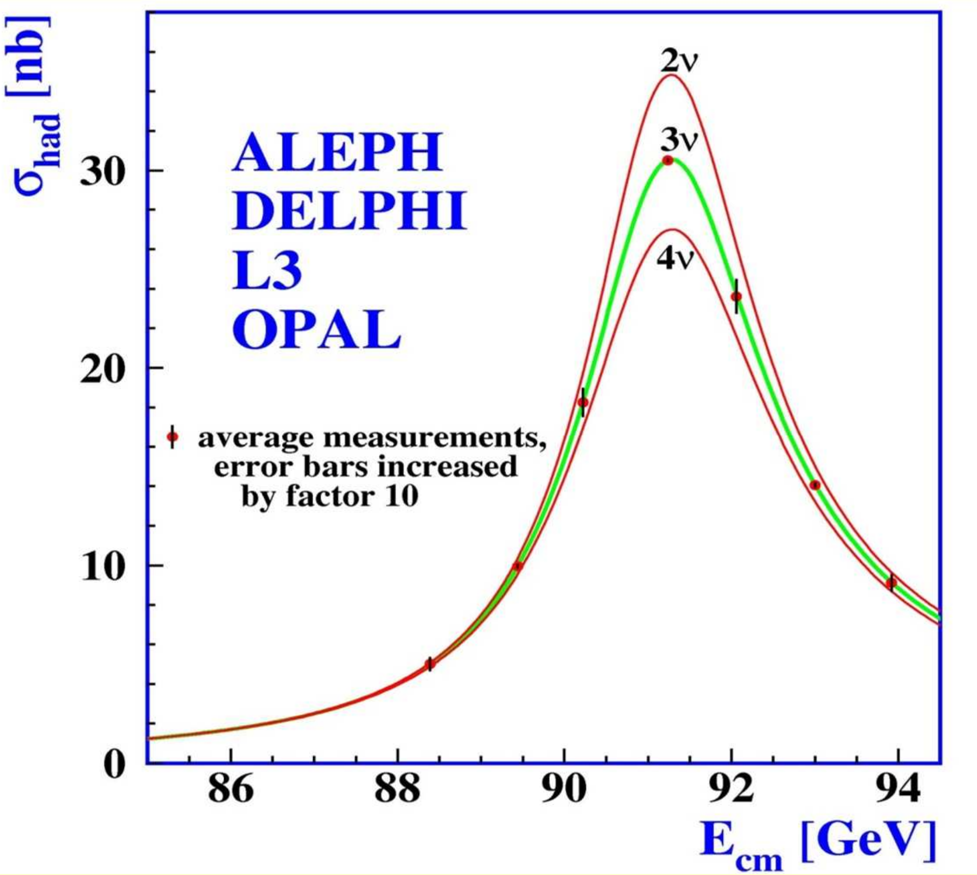
Neutrinos

- Oscillations confirmed
- Masses ? $\nu = \overline{\nu}$ or $\nu \neq \overline{\nu}$?
- CP violation ?

Japan, US, Europe…

Number of light neutrinos

$e^+ e^- \to Z \to$ hadrons



- tree-level SM prediction:

$$\sigma_f(\sqrt{s}) = \frac{s\Gamma_Z^2}{(s - M_Z^2)^2 + \Gamma_Z^2 M_Z^2}\sigma_f^0$$

$$\sigma_f^0 = \frac{12\pi}{M_Z^2}\frac{\Gamma_{e\bar{e}}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$$

$\Rightarrow$ total width, and hence normalization, depend on N_ν

- data best agree with $N_\nu=3$ neutrinos coupled to the Z

$N_\nu = 2.9840 \pm 0.0082$

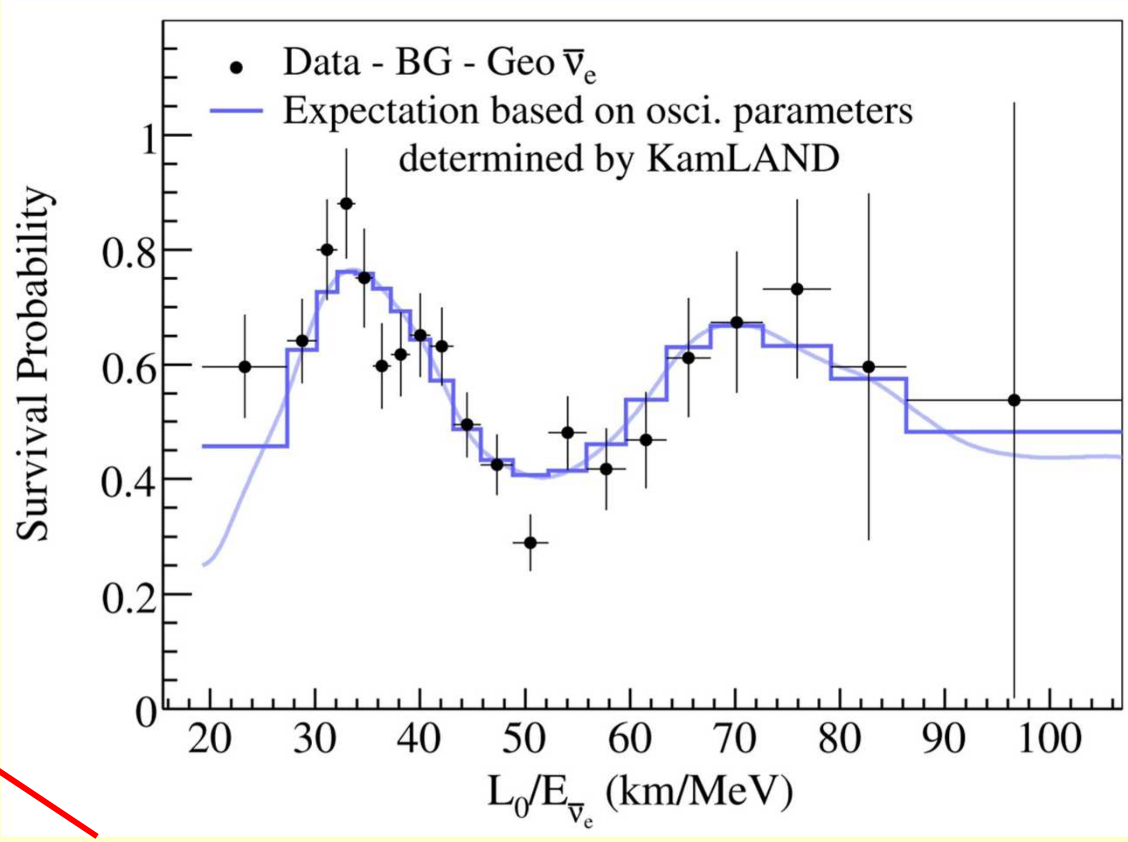
- Cosmology: $N_{eff} = 4.34^{+0.86}_{-0.88}$ effective number of relativistic ν's in the early Universe

Neutrino oscillations

- Multiple evidence for ν flavour conversion: solar, atmospheric & reactor ν's

⇒ $m_\nu \neq 0$, ν mixing

$P(\bar{\nu}_e \rightarrow \bar{\nu}_e, t)$



$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

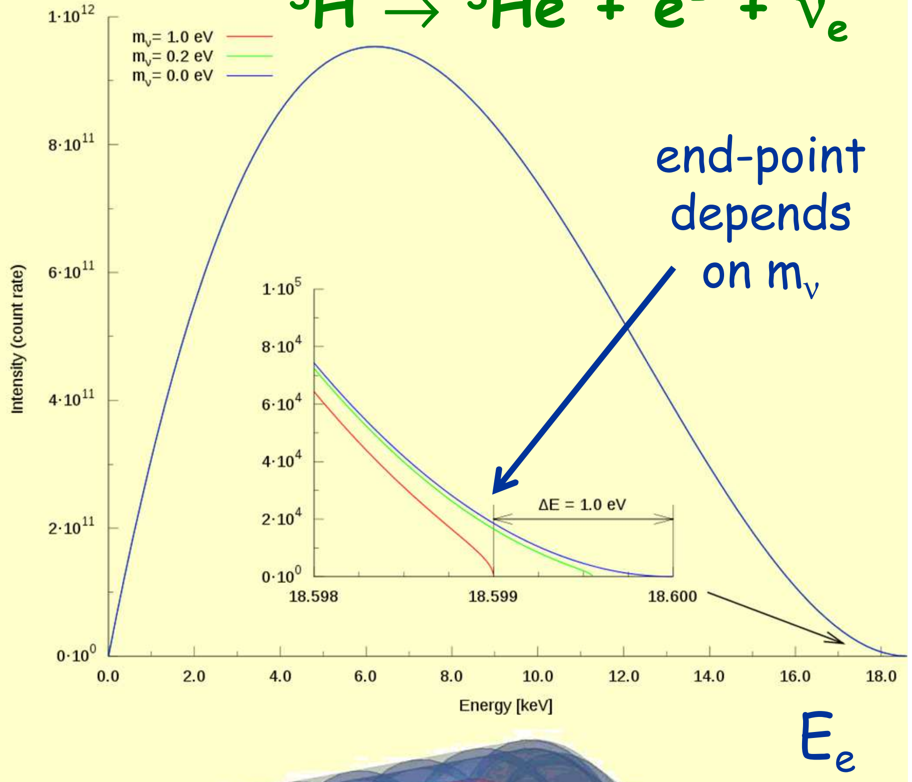
flavour ν's produced in weak processes (e.g. β decays)

mass eigenstates, $m_{\nu_{1,2,3}} < 1\,eV$, $\exists i$, $0.05\,eV < m_i$: responsible for oscillations

- Consequences: $m_\nu \neq 0 \leftrightarrow$ generation of the baryon asymmetry of the Universe (if CP violation in ν mixing) & role in structure formation

Neutrino masses

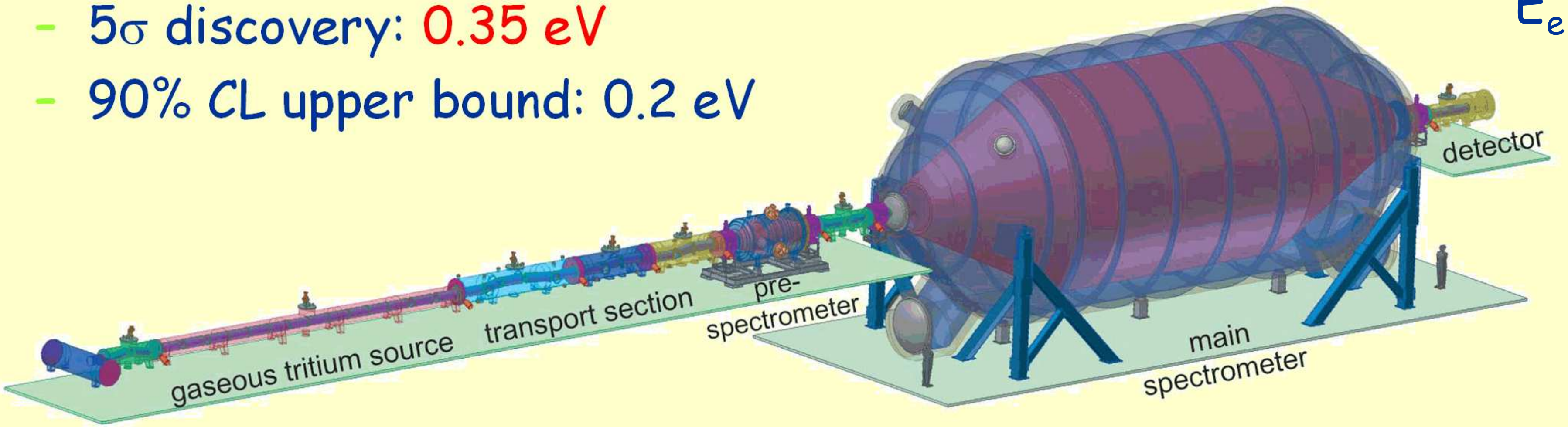
$^3H \rightarrow {}^3He + e^- + \bar{\nu}_e$



- most sensitive method:
  tritium β–decay spectrum
- current status (95% CL):

$$\langle m_\beta^2 \rangle \equiv \sum_i |U_{ei}|^2 m_{\nu_i}^2 \quad \sqrt{\langle m_\beta^2 \rangle} \leq 2eV$$

- future: KATRIN
  - 5σ discovery: 0.35 eV
  - 90% CL upper bound: 0.2 eV



- Cosmology (95% CL): $\sum_i m_{\nu_i} \leq 0.91\, eV$

CP violation and quark mixing

- 1950-1960: C and P are not conserved in weak processes
- 1964: CP is also violated in (rare) weak processes

$$\frac{|A(K_L^0 \to \pi\pi)|}{|A(K_S^0 \to \pi\pi)|} = (2.2 \pm 0.01)\, 10^{-3} \qquad \neq \mathbf{0}\,! \quad \text{CP not conserved}$$

- SM interpretation:

weak eigenstates, coupled to $W^{\pm}$ →

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

← mass eigenstates

CKM mixing matrix: contains a physical phase, responsible of CP violation

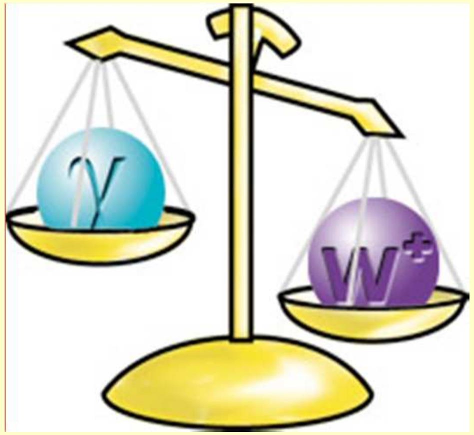
- Status: all CP-violation measurements (K & B hadrons) agree with SM predictions

But the effect is not large enough to explain the matter-antimatter asymmetry observed in the Universe : $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$

Symmetry and symmetry breaking

- **Electroweak symmetry** : the electromagnetic and weak interactions are **unified at high energy**
- **Electroweak symmetry breaking** : at low energy the symmetry is **spontaneously broken**

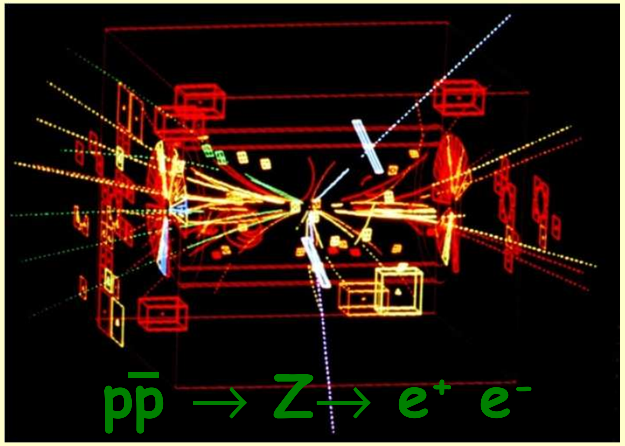
Generation of particle masses



$m_\gamma=0$ $m_Z\sim 91\,GeV$ $m_W\sim 80\,GeV$

note: $m_{proton} = 1\,GeV$

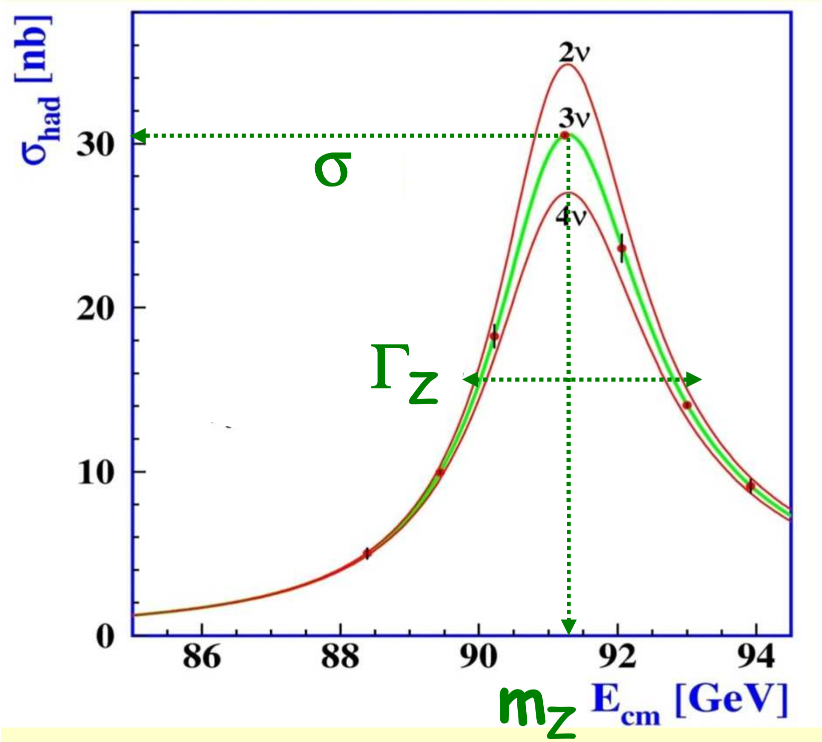
experimentally confirmed with the W, Z discovery at CERN ('80)



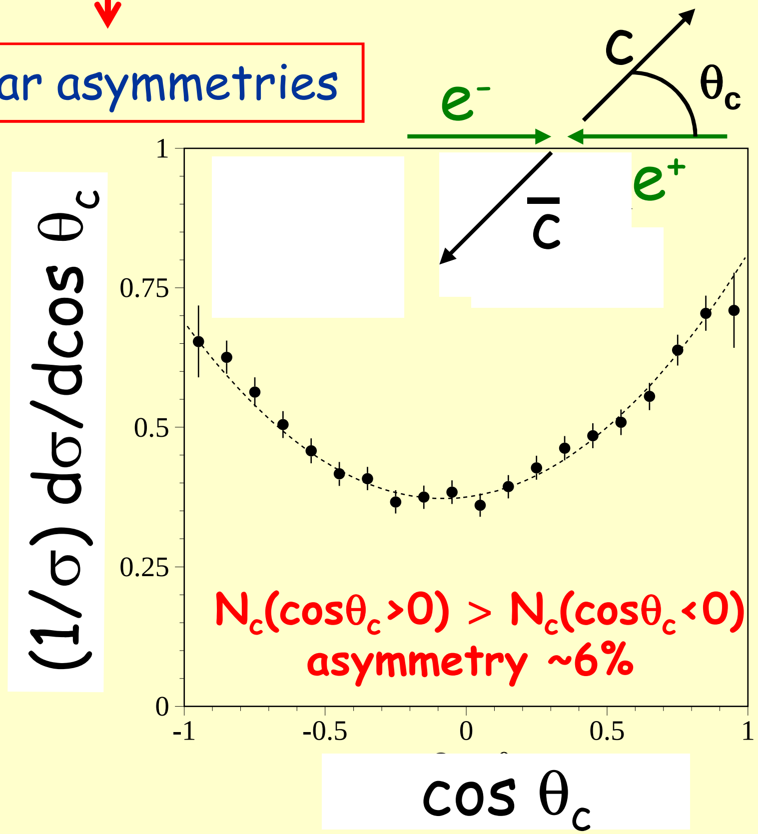
Precision tests of the Standard Model

- Precise measurements of :
  - the **W** and the **top** quark masses
  - the **Z** properties (mass, width, asymmetries)

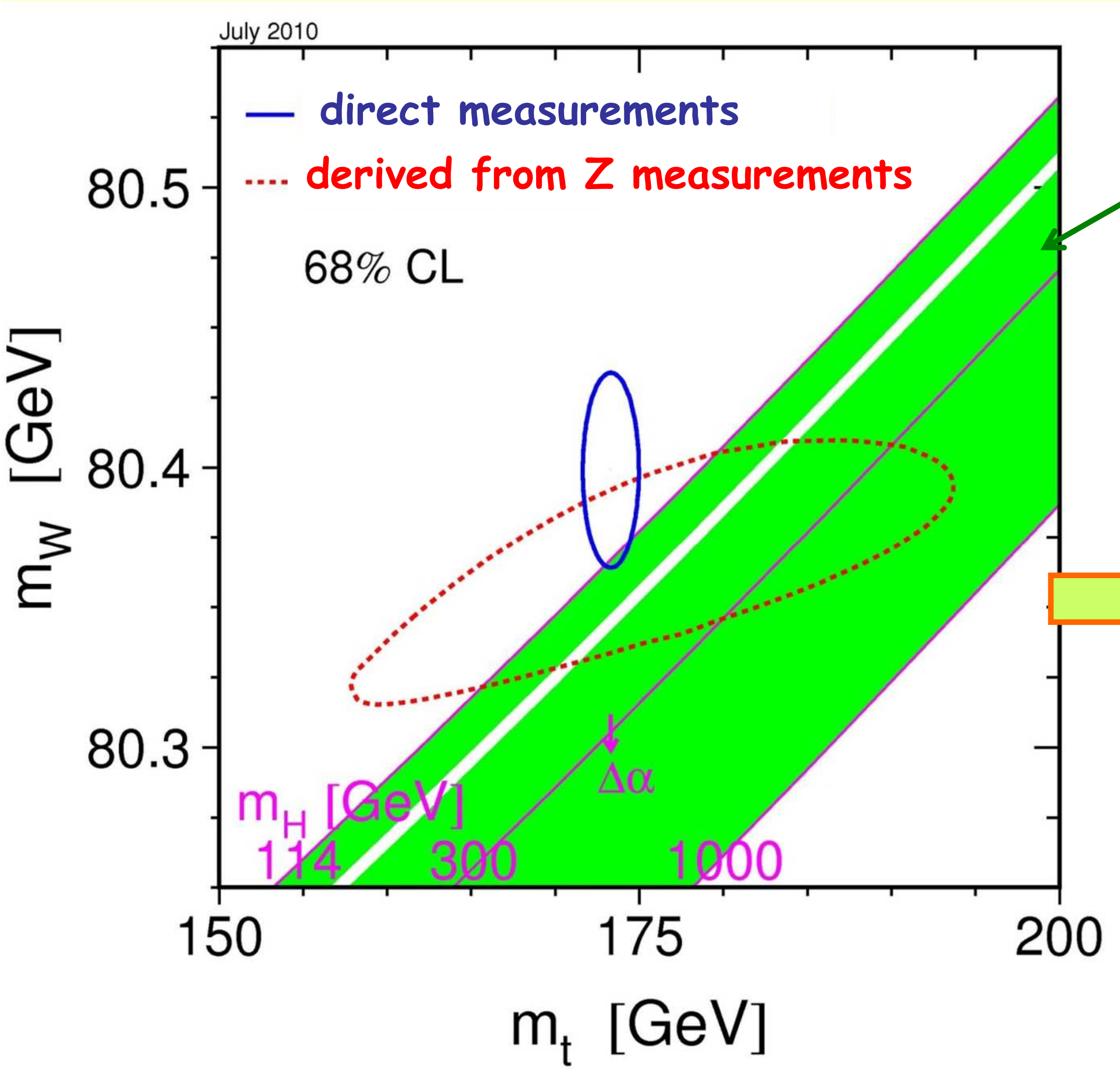
Resonance curve



Angular asymmetries



to be compared with precise predictions of the Standard Model



m_W vs m_{top} **if** EW symmetry breaking via the Higgs mechanism with only one Higgs boson

- The Standard Model agrees with data
- If it exists, the Higgs boson must be light

114GeV<m_H<158GeV

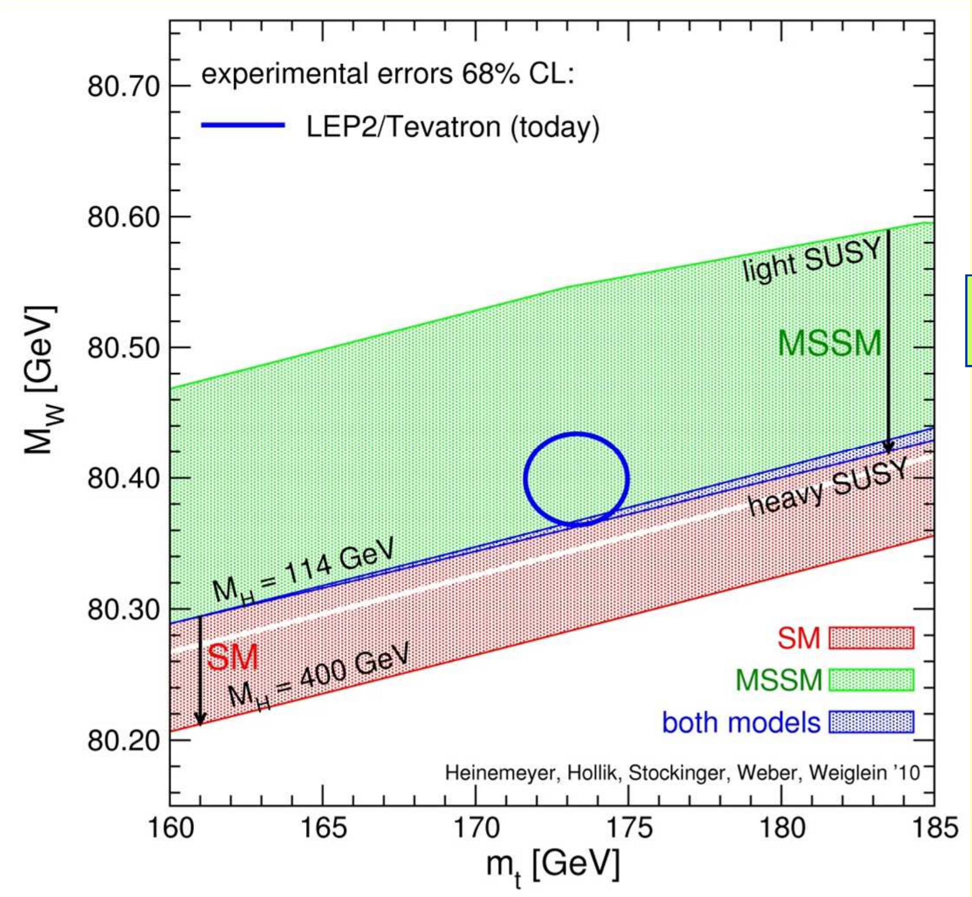
main topic at LHC !

- Link with cosmology: EW symmetry spontaneous breaking means non zero vacuum energy, an explanation of the accelerated expansion of the Universe ? Not the right order of magnitude !

Beyond Standard Model

- The Standard Model does not answer all questions: parameter values (e.g. masses, mixing matrix elements …), Higgs sector calculations diverge at high energy…

  ⇨ Standard Model: an effective theory valid at low energy



- Many extensions beyond SM: supersymmetry, extra dimensions, superstrings….

New particle searches at LHC !

- Link with cosmology: dark matter candidate (e.g. lightest supersymmetric particle)

Basic lectures

- The Standard Model of particle physics and beyond
- Particle detectors and large HEP-experiments

EW symmetry breaking

Lecture

- Physics at LHC, first results

CP violation in the quark sector

Lecture

- CP-violation and matter anti-matter asymmetry

Main topics in particle physics

Strong interaction

Lecture

- Heavy Ion collisions and the quark-gluon plasma

Neutrinos

Lectures

- Physics of neutrino oscillations
- Neutrino masses, experiment KATRIN