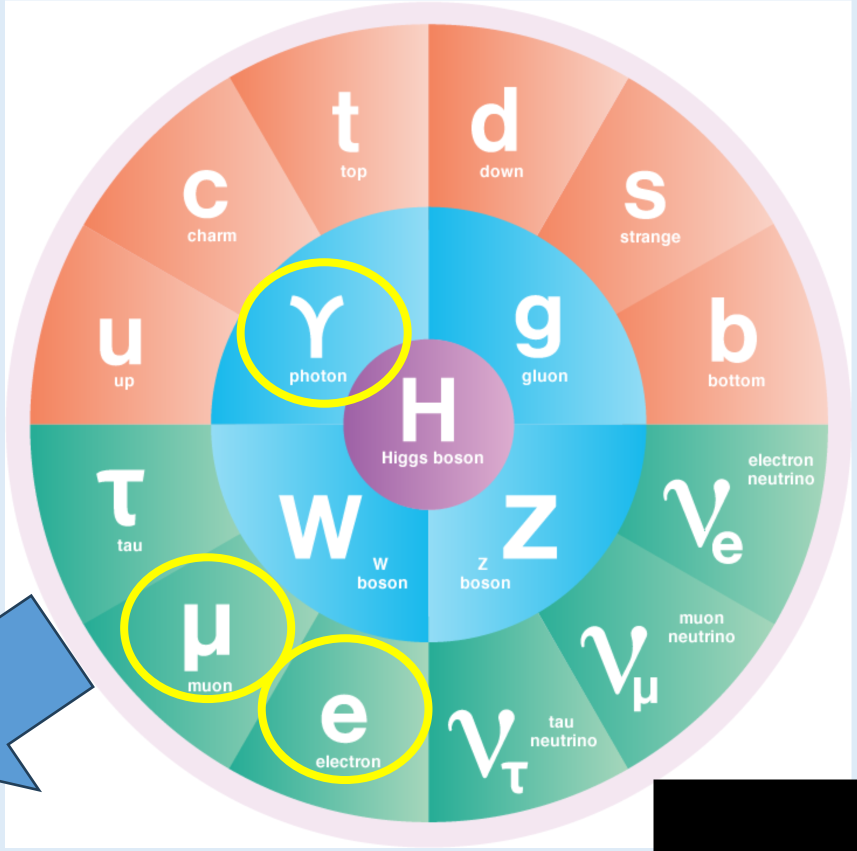
1954-2024

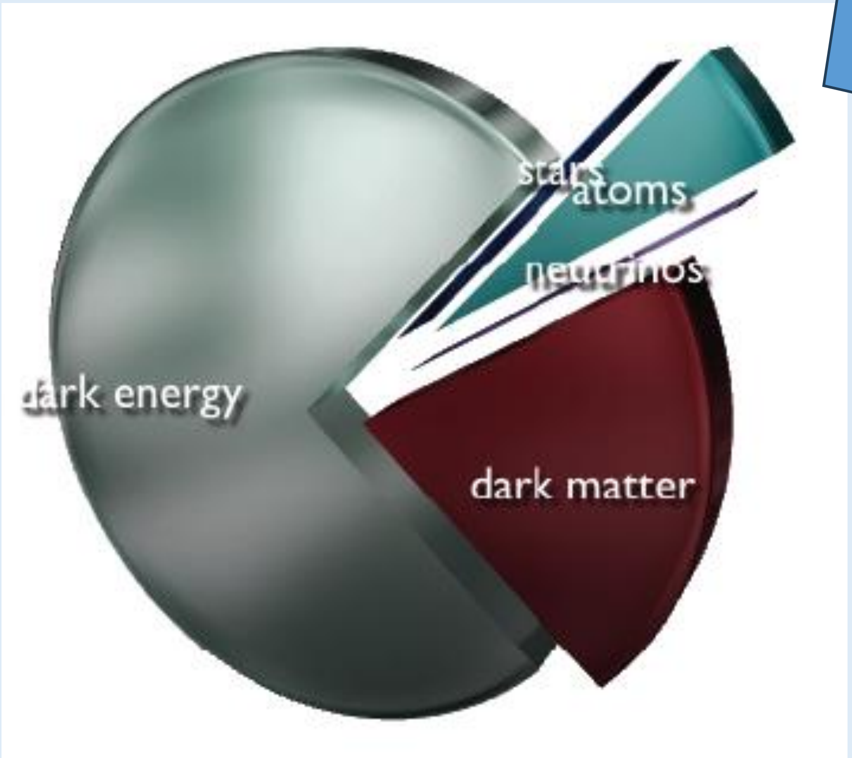
YEARS / ANS CERN

A subjective stroll with CERN through the ‘discovery’ of the Standard Model

Standard Model of Particle Physics

discovered before 1954





$$\begin{aligned}\mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\ & + i \bar{\psi} \not{D} \psi + h.c. \\ & + \psi_i y_{ij} \psi_j \phi + h.c. \\ & + |D_\mu \phi|^2 - V(\phi)\end{aligned}$$

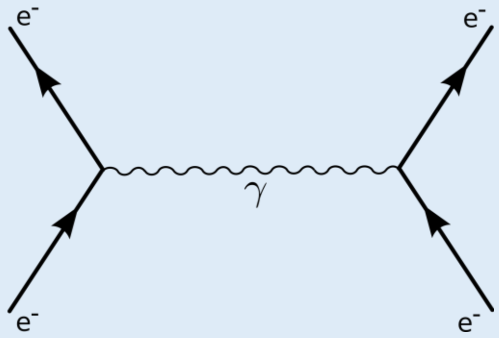
Status of particle physics before ~1954

Elementary particles and forces

1948: First Quantum Field Theory

- QED (Feynman, Schwinger, Tomonaga)

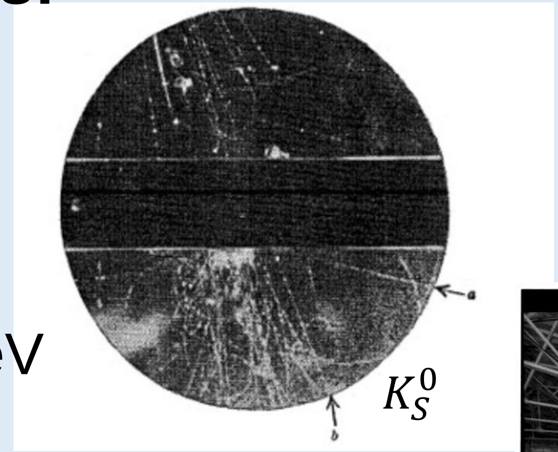
Nobel prize 1965



Sin-Itiro Tomonaga Julian Schwinger Richard P. Feynman

1945-1950s many new particles in cosmic rays:

- enabled by Cloud Chamber



1950+: Accelerator physics

- Berkeley: Bevatron proton accelerator: E=6.2 GeV
- Stanford: Mark III, E>188 MeV
- Cornell: Electron synchrotron E=1.3 GeV

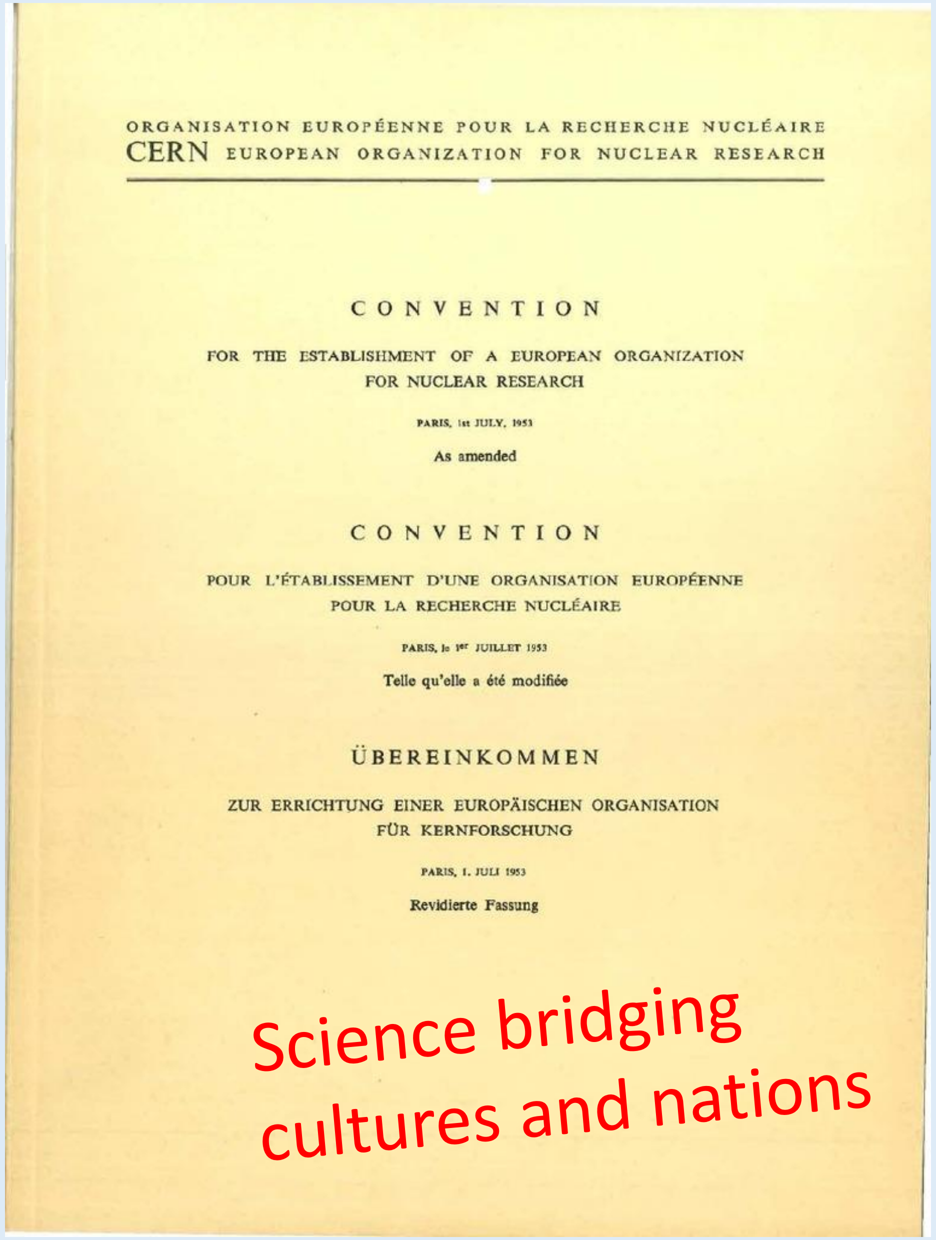
Bevatron, Berkeley 1954

CERN’s Origins

- 1945: Europe is in ruins after WWII
- 1946: French proposal to the UN
- 1949: European Cultural Conference, Lausanne

Louis de Broglie proposed:
 "the creation of a laboratory or institution where it would be possible to do scientific work, but somehow beyond the framework of the different participating states [Endowed with more resources than national facilities, such a laboratory could] undertake tasks, which, by virtue of their size and cost, were beyond the scope of individual countries".

CERN's governance


ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CONVENTION

FOR THE ESTABLISHMENT OF A EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PARIS, 1st JULY, 1953

As amended

CONVENTION

POUR L'ÉTABLISSEMENT D'UNE ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

PARIS, le 1er JUILLET 1953

Telle qu'elle a été modifiée

ÜBEREINKOMMEN

ZUR ERRICHTUNG EINER EUROPÄISCHEN ORGANISATION FÜR KERNFORSCHUNG

PARIS, 1. JULI 1953

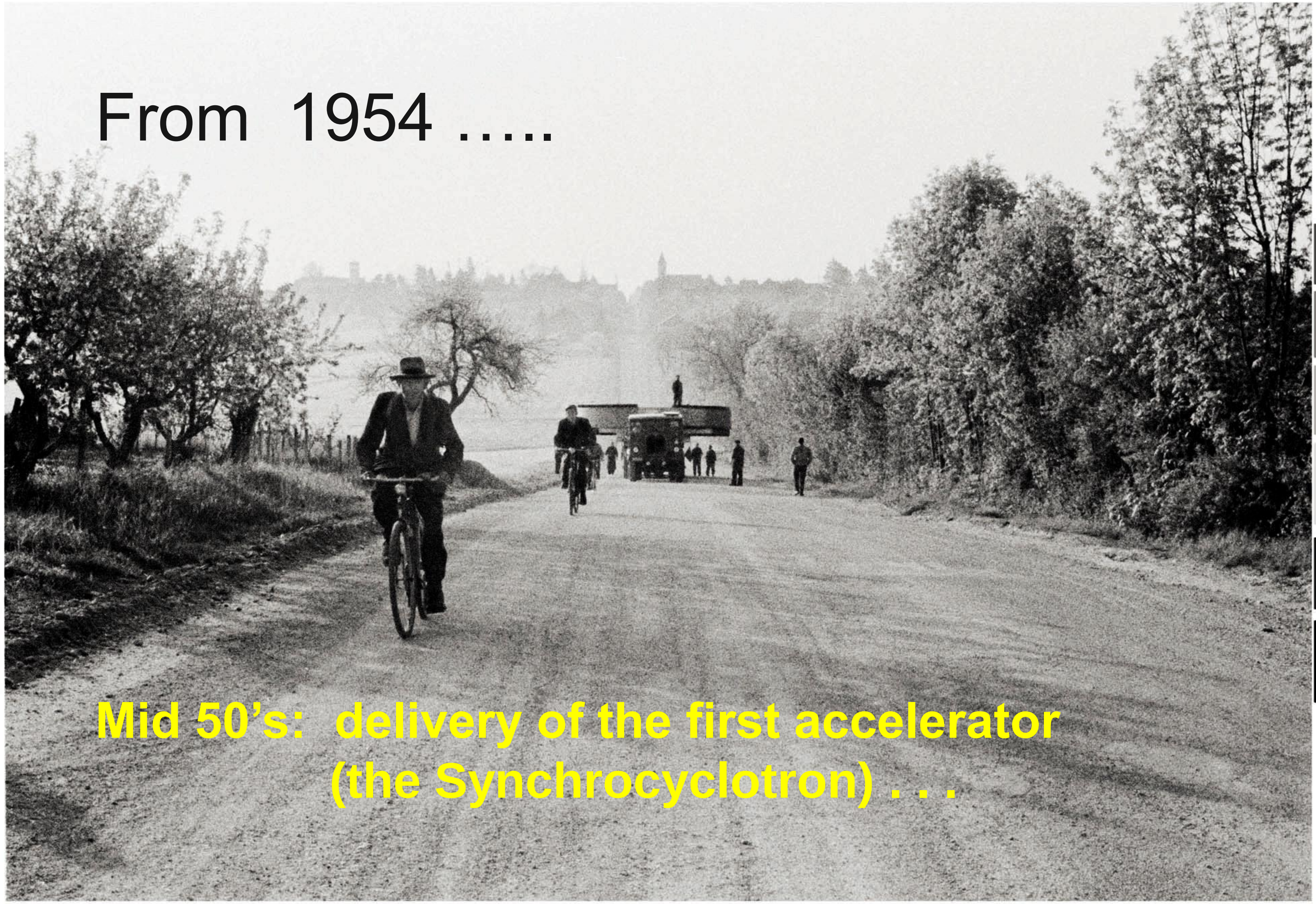
Revidierte Fassung

"The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character, and in research essentially related thereto. The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available."

"Each Member State shall have one vote in the Council."

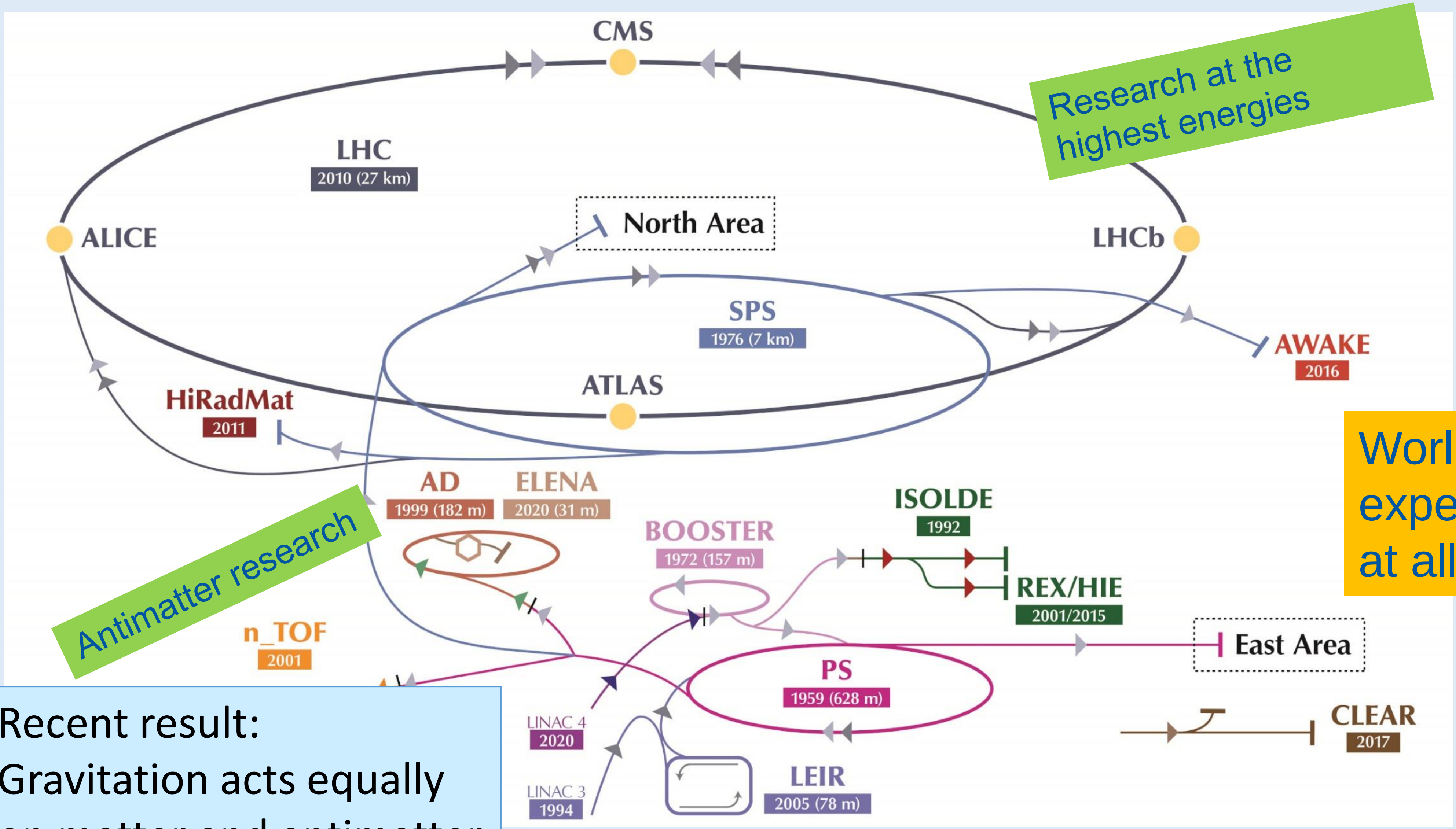
"Each Member State shall contribute both to the capital expenditure and to the current operating expenses of the Organization….based on the average net national income …"

From 1954 …..



Mid 50’s: delivery of the first accelerator (the Synchrocyclotron) . . .

. . . to today: CERN accelerator complex



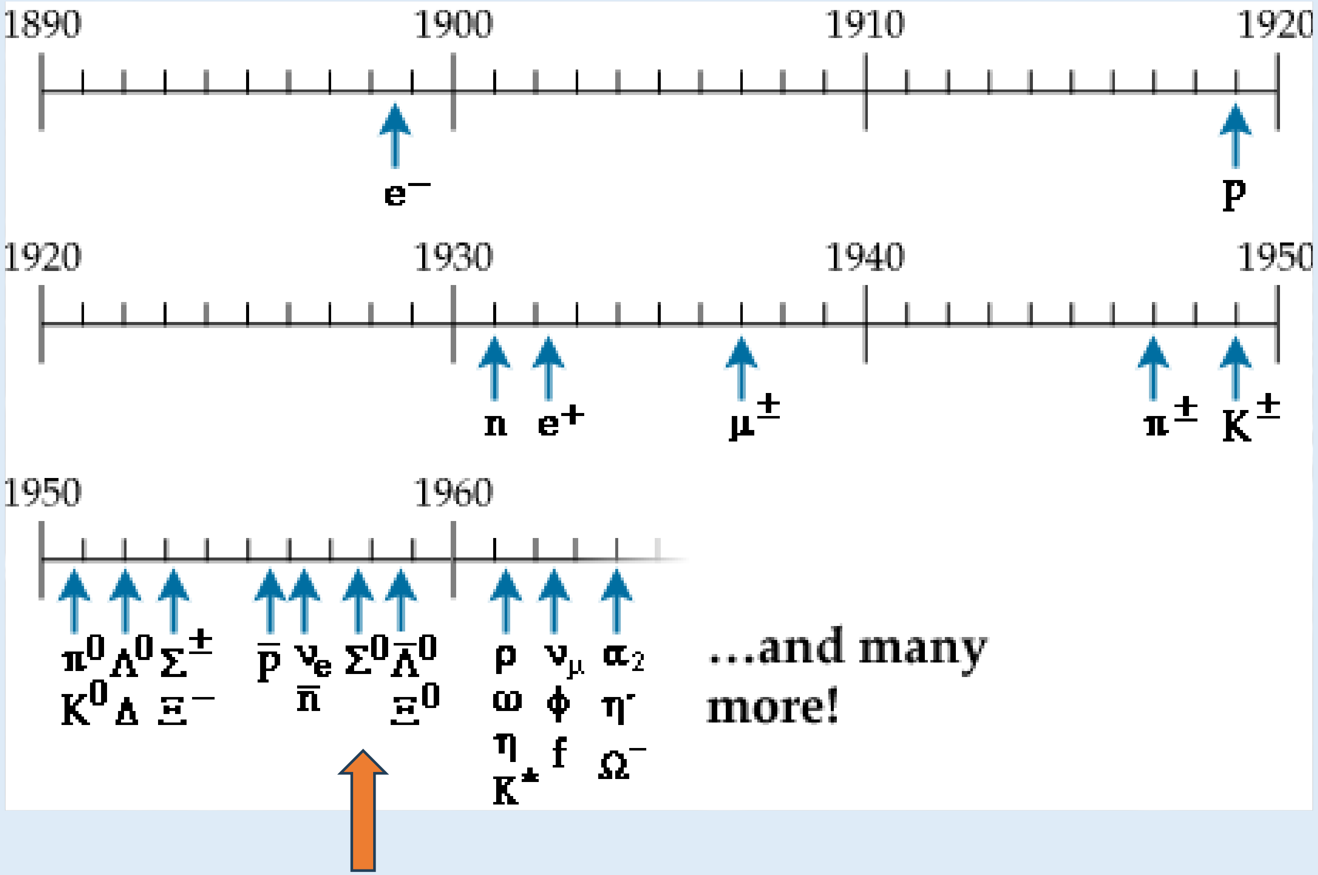
Research at the highest energies

Worldwide unique experiments at all accelerators

Antimatter research

Recent result:
Gravitation acts equally on matter and antimatter

Status mid 1960 ies



start of the synchrocyclotron

A plethora of particles

1961

Gell-Mann introduced the concept of quarks as the fundamental building blocks of strongly interacting particles

Nobel prize 1969

late 60ies, early 70ies: electroweak theory

Requires massive gauge bosons for the weak interaction

formulation of the electroweak theory

- applying current ideas to $SU(2) \times U(1)$ gauge theory

  Weinberg 1967, Salam 1968 (formulated for leptons)

- extension to hadrons

  assuming two quark generations: *c-quark postulated*

  Glashow, Iliopoulos, Maiani 1970

- assuming three quark generations: *t, b-quarks postulated*

  Kobayashi, Maskawa 1973

  embedding of CP-violation *(discovered 1964)*

Result: unified electroweak theory at the classical level

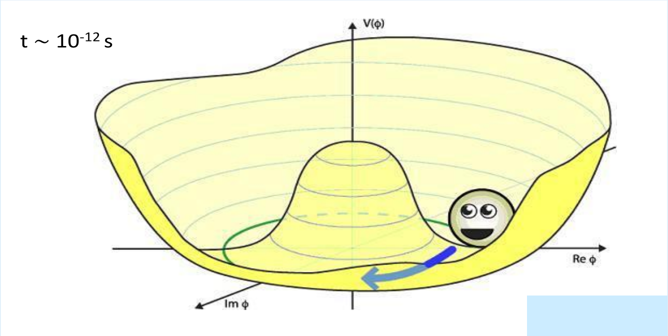
W. HOLLIK

Electroweak Symmetry Breaking

1964-1969:towards the Standard Model

$$V(\phi)=\frac{\lambda}{2}\left[|\phi|^2-\frac{v^2}{2}\right]$$

gauge group
and a scalar field



This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

S. Weinberg, A Model of Leptons, Phys.Rev.Lett. 19 (1967) 1264-1266

Veltman, t'Hooft
Nucl.Phys.B 44 (1972) 189-213

(Brout), Englert, Higgs

Nobel prize 1999: 't Hooft, Veltman

Nobel prize: Englert, Higgs 2013

1973: Discovery of Weak Neutral Currents at CERN

first direct evidence of the existence of a neutral particle to carry the weak fundamental force

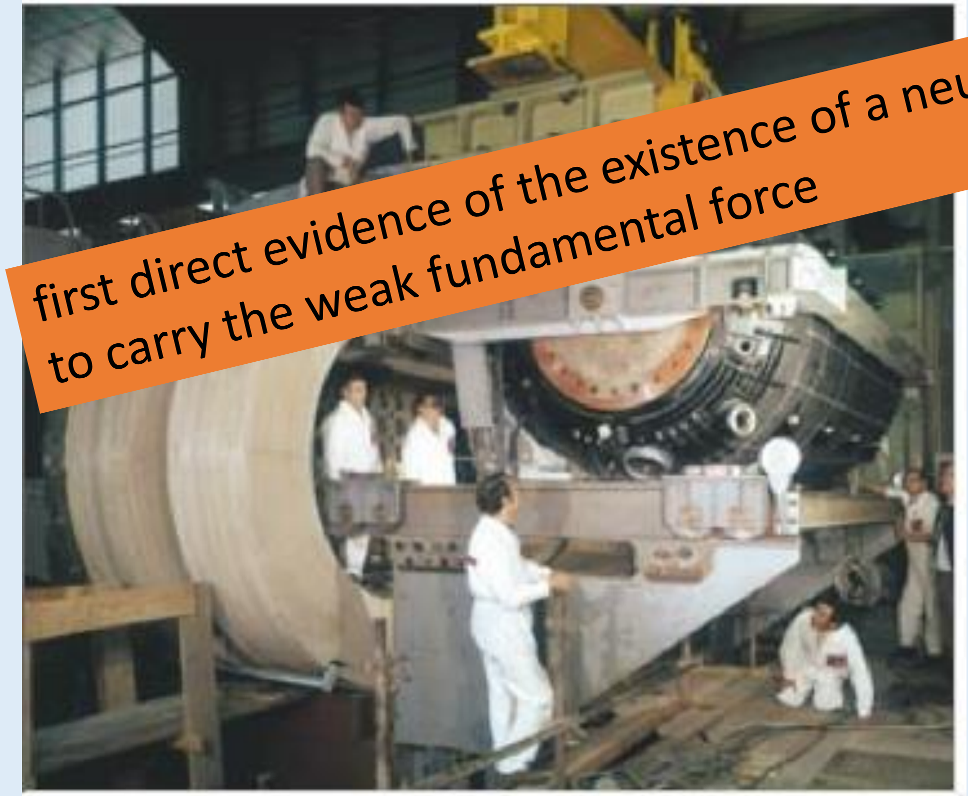
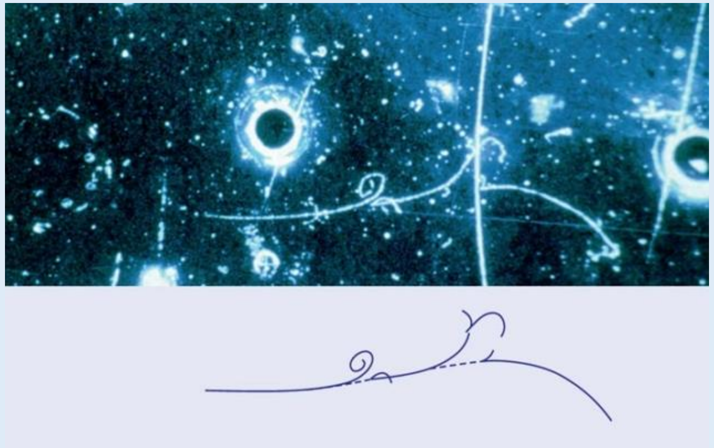
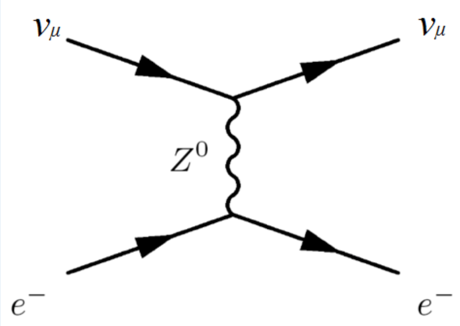


Fig. 1. The Gargamelle heavy-liquid bubble chamber, installed into the magnet coils, at CERN in 1970.

m_W=60-80 GeV, m_Z=75-92 GeV





Nobel prize: Glashow, Salam, Weinberg 1979

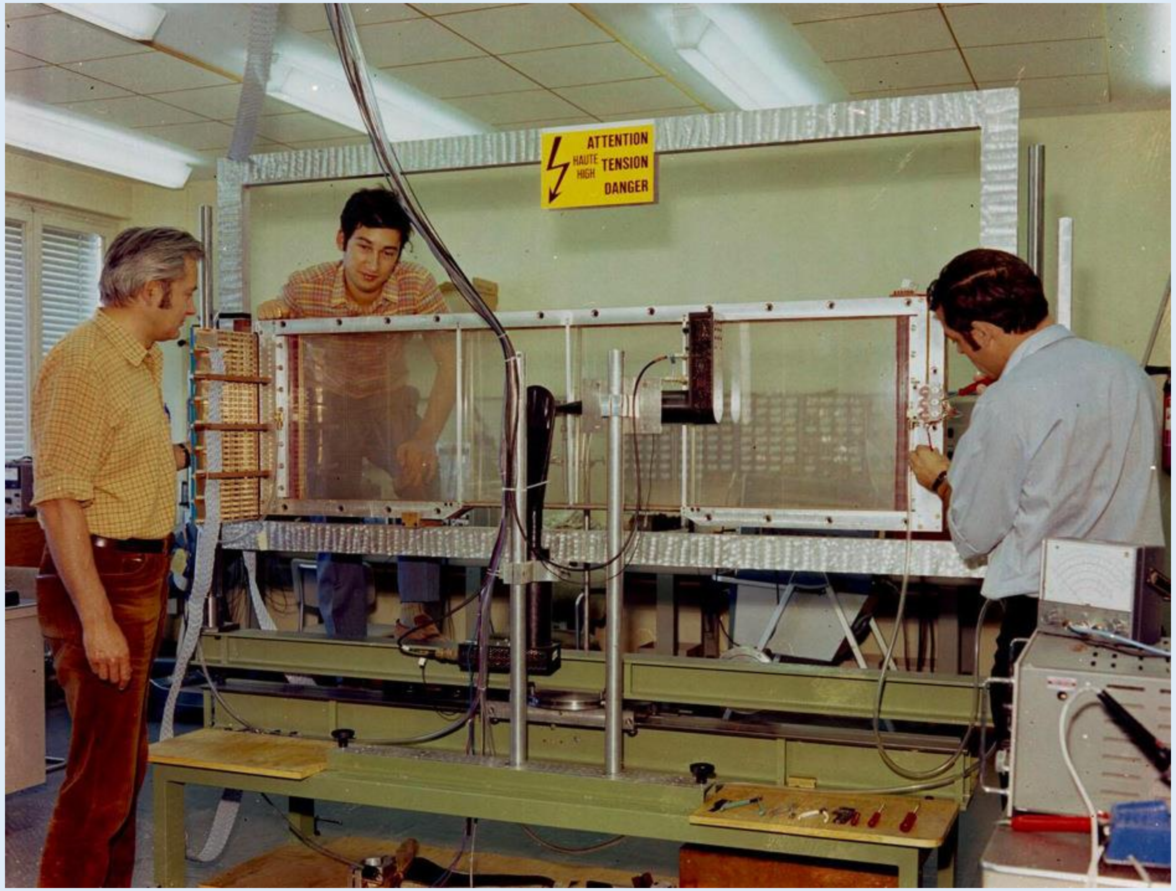
Further advances needed progress
in **experimental techniques**
as well as in theory

1968: Multiwire Proportional Chamber

Gas-filled box with a large number of parallel detector wires running through it. Each wire was connected to individual amplifiers, so acted as an independent proportional counter. When linked to a computer, this could achieve a counting rate a thousand times better than any existing detectors.

The invention revolutionised particle detection, pushing it into the electronic era.

Few years later:
multiwire proportional chamber → Drift Chamber

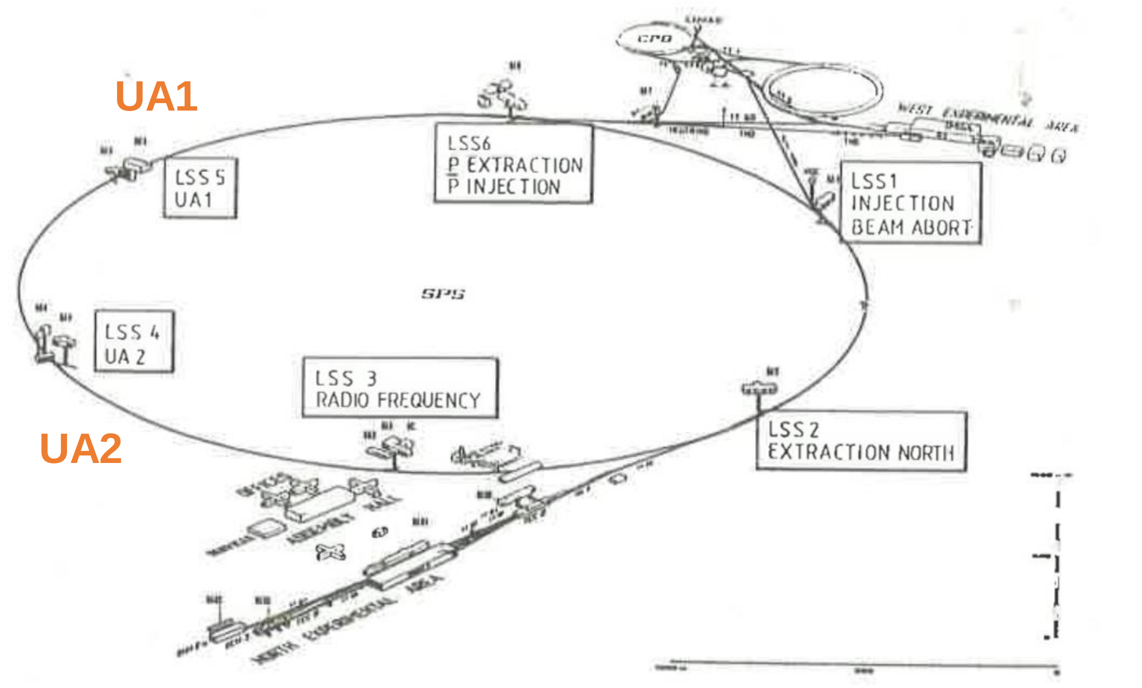


Nobel prize: Charpak 1992

W and Z boson discoveries

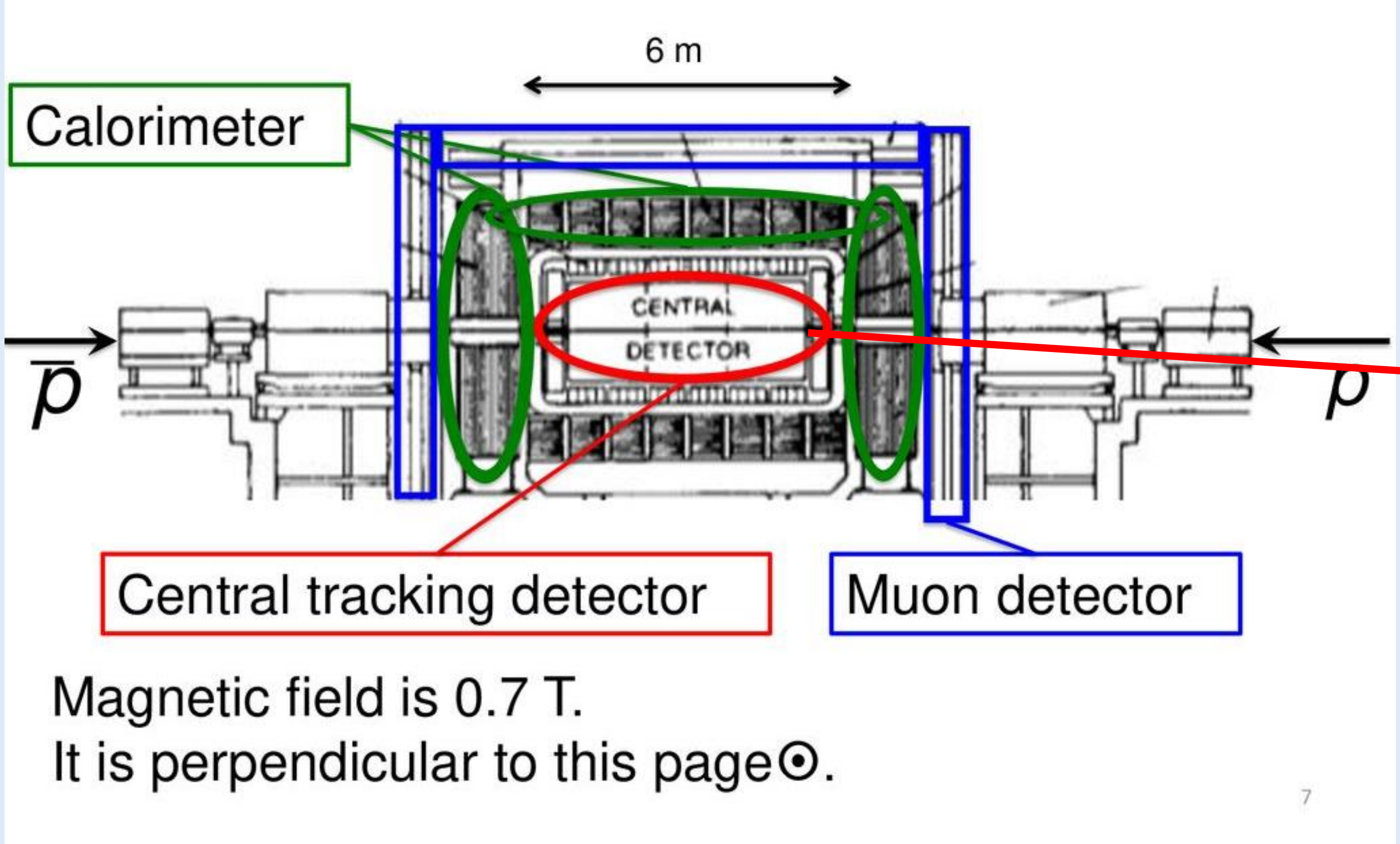
SppbarS

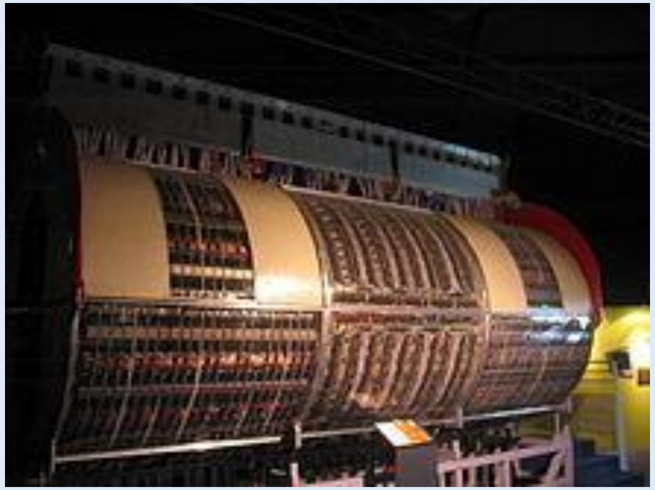
- 1976: C. Rubbia, D. Cline & P. McIntire propose **to build accelerator at CERN and FNAL to find W and Z boson**
  - accelerator at 900 GeV
  - Enabled by **stochastic cooling** (S. van der Meer, demonstrated 1974)
- **Approval 1978**
- **First collisions 1981**



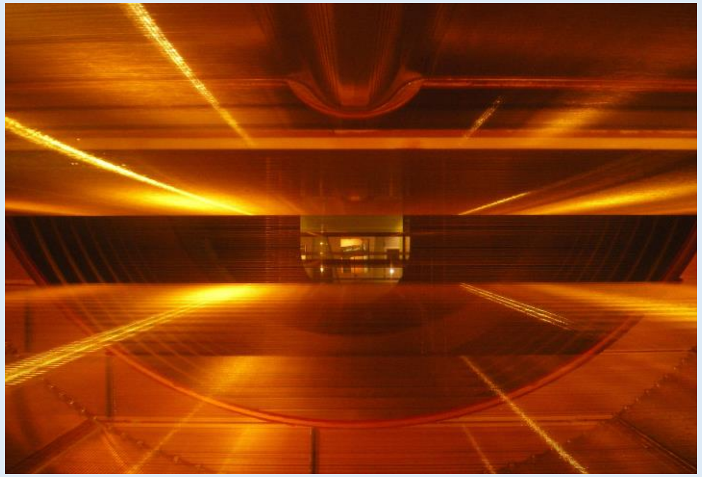
The UA1 Experiment

SppbarS



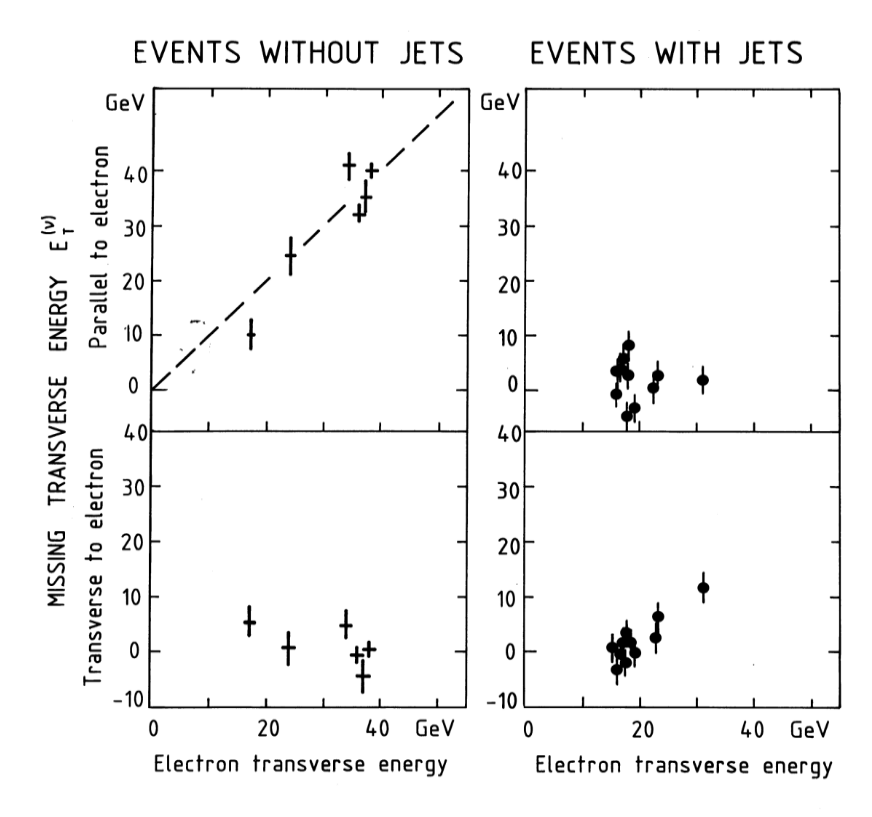


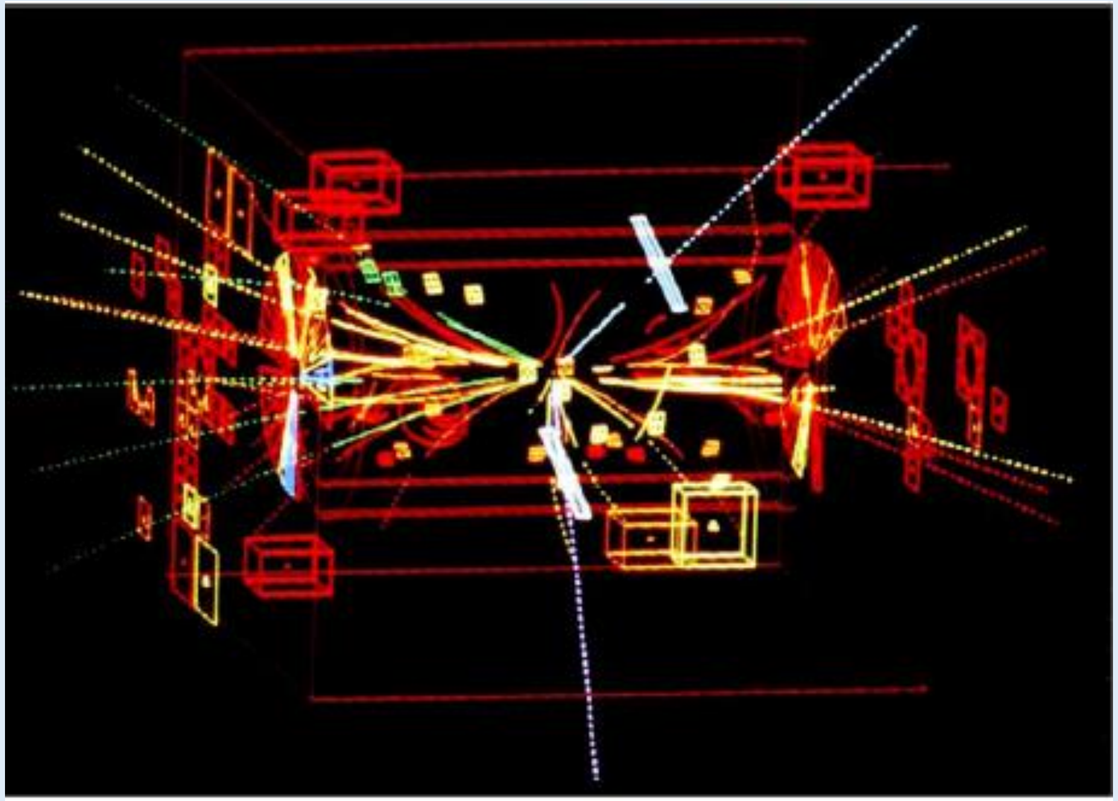
Drift Chamber



W and Z boson discoveries

SppbarS collider at CERN





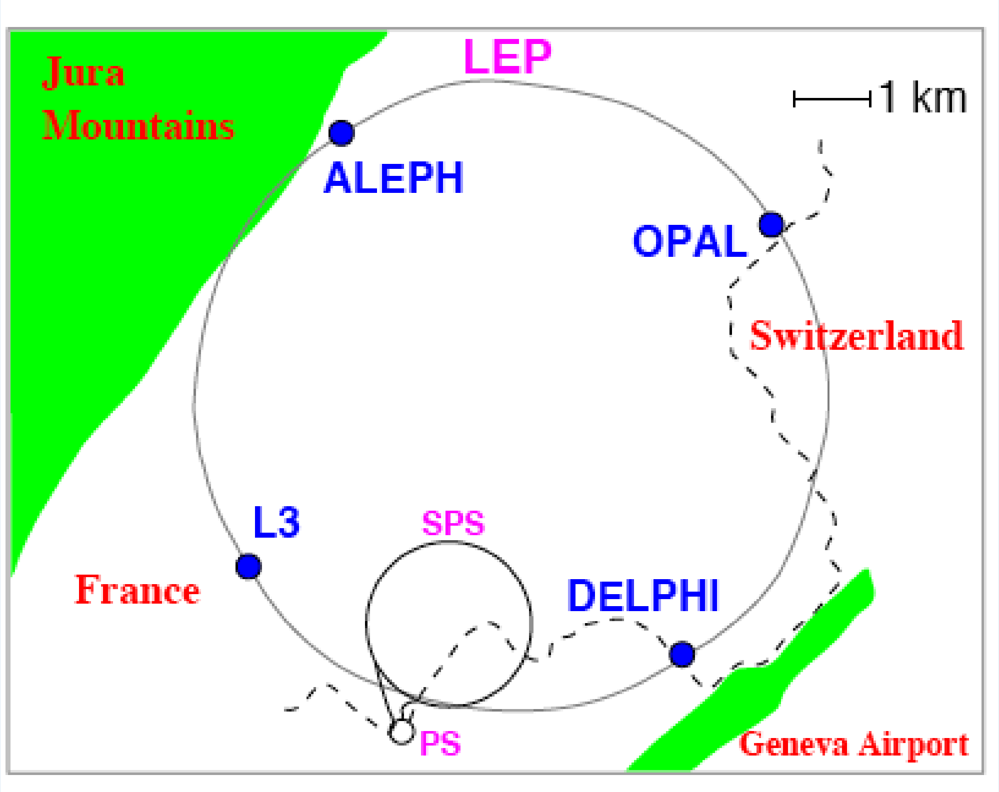
Z-boson candidate event at UA1: 1983

m_W=81 ± 5 GeV

Nobel prize: Rubbia, van der Meer 1984

1980s: LEP

- Goals: study the weak interaction via Z-boson and W-boson pair production
- Needed: 100 GeV beams, Luminosity = $10^{32}/cm^2/s$
- 27 km ring, partially under Jura mountains



Oct. 1981: approved but on tight budget;
Two stages:
LEP1 up to ~95 GeV
LEP2 up to 209 GeV

Z metrology: original expectations

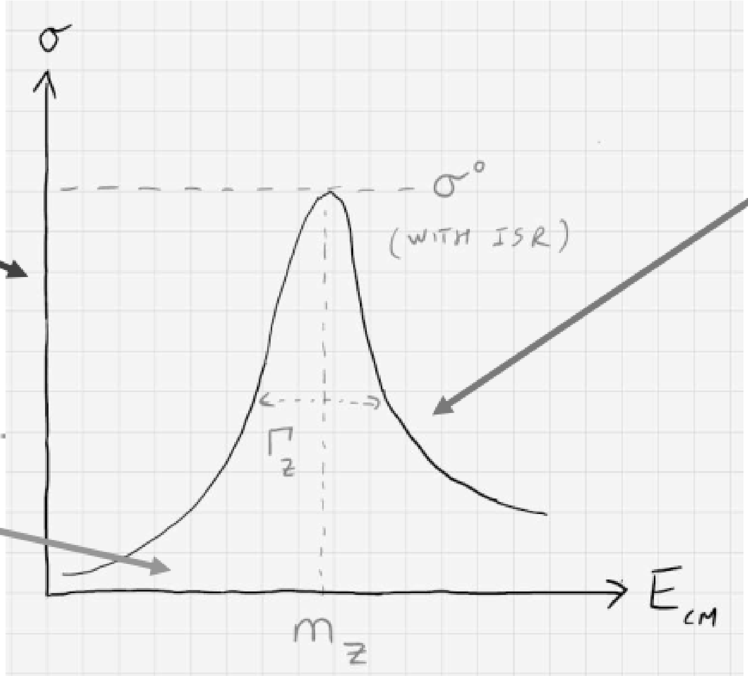
Outlook shortly before LEP turn on: *"The overall conclusion is that at LEP the Z^0 mass and width can be measured with relative ease down to … +/- 50 MeV. A factor of 2-3 improvement can be reached with a determined effort…"* CERN 86-02 'Physics at LEP', ed. Ellis and Peccei.

Vertical-scale uncertainty dominated by luminosity, largely correlated between experiments.

It was assumed this could be done to ~2%.

Horizontal-scale uncertainty set by knowledge of collision energy, also common between experiments.

It was guessed that ~10 MeV uncertainty *might* be possible.



Also vital Is understanding of shape, in particular effect of QED radiative corrections.

Important, but not discussed further today.

LEP 1:

LEP knowledge of line-shape parameters largely derived from two three-point scans in 1993 and 1995, with final precision on mass and width of:

$$\sigma_{M_Z} = 2.1 \text{ MeV}$$

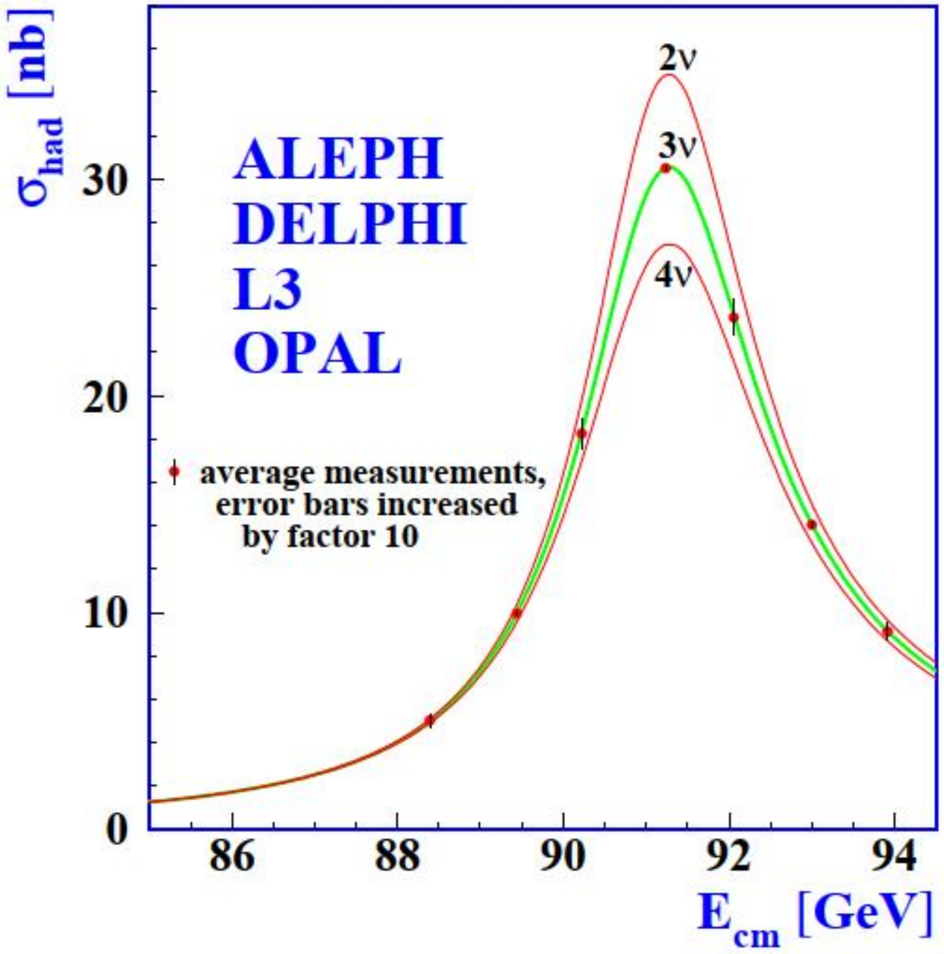
$$\sigma_{\Gamma_Z} = 2.3 \text{ MeV}$$

<<50 MeV !!! How did that happen

Another noteworthy output of scans

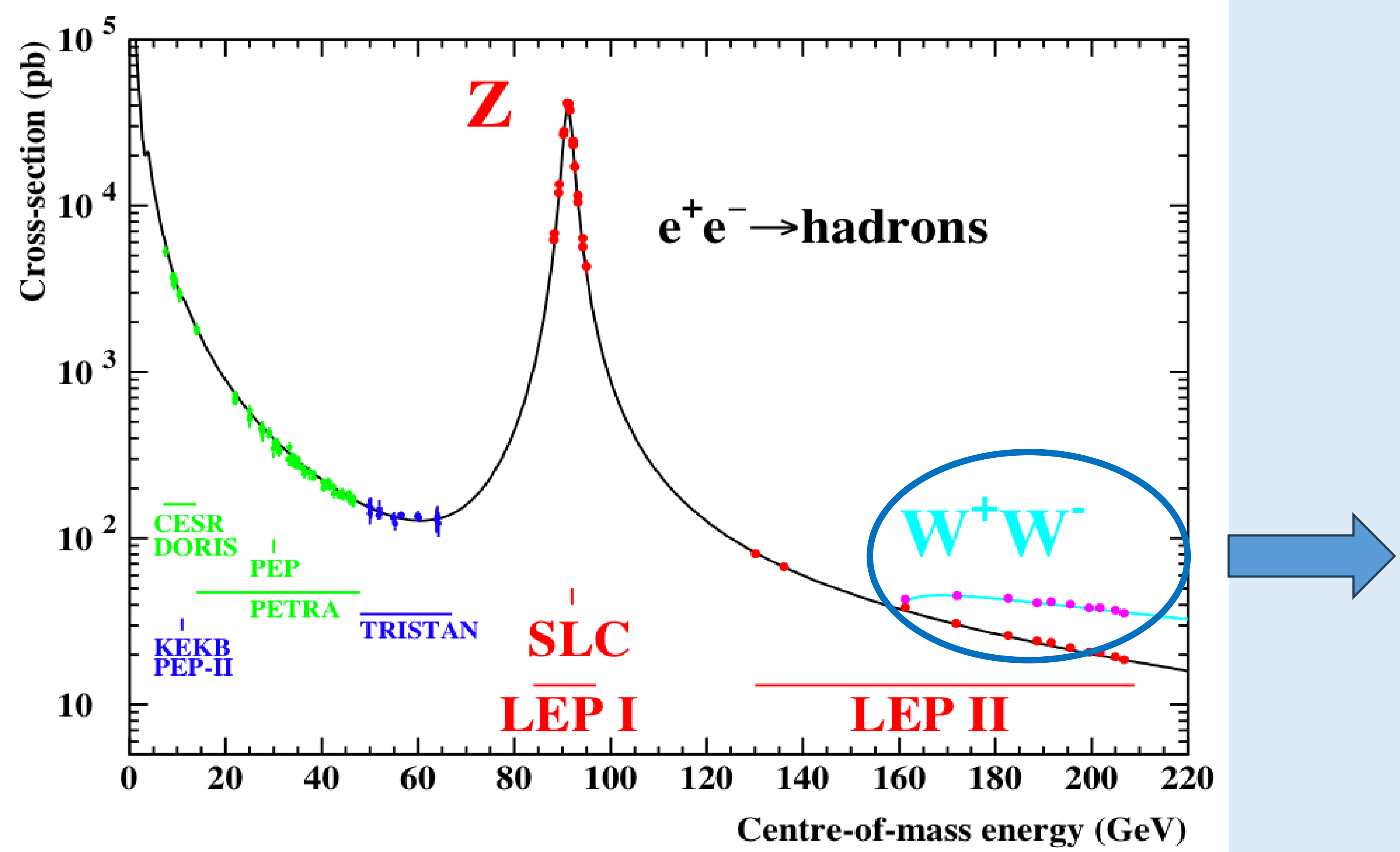
$$N_\nu = 2.9840 \pm 0.0082$$

There are only
3 light neutrinos
and therefore
3 generations



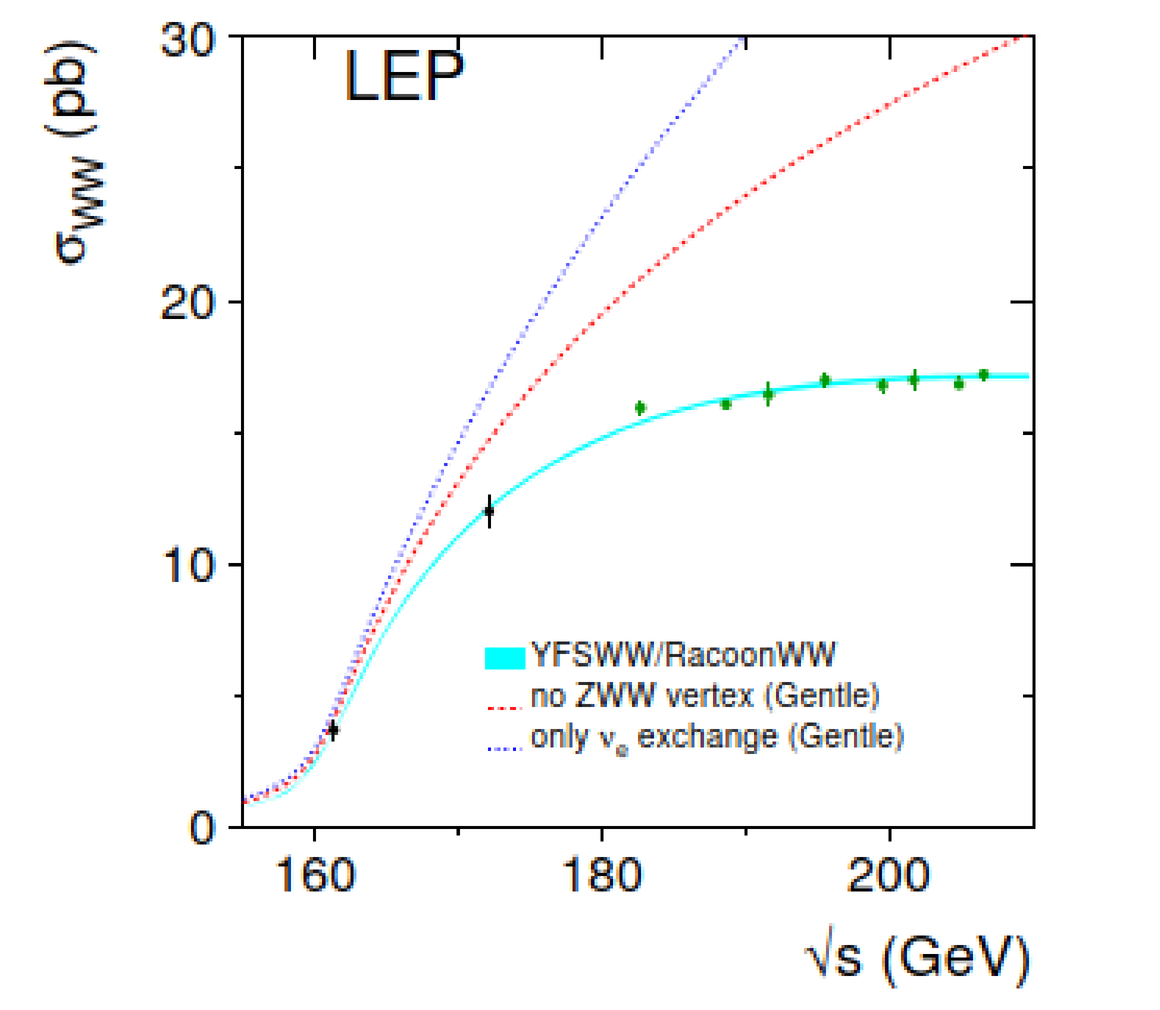
m_Z = (91.1875 +/- 0.0021) GeV

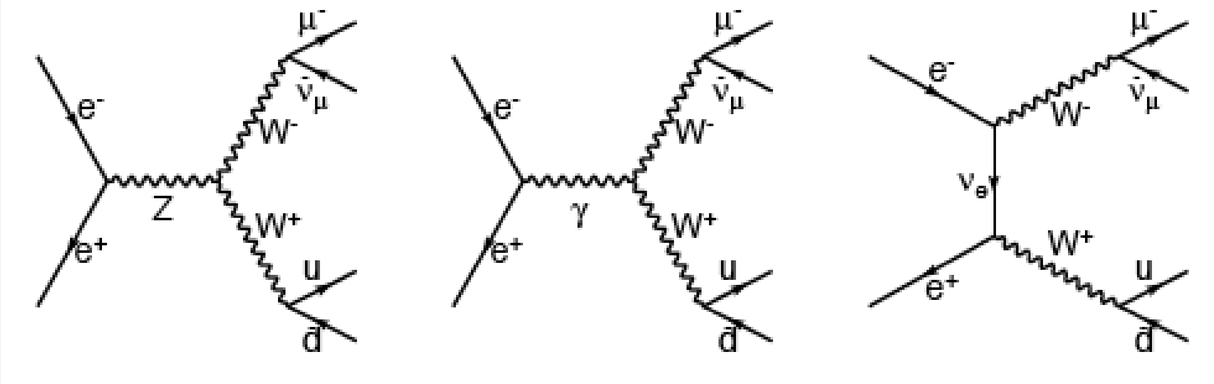
LEP 1 & 2:



Cross-section (pb)
10^5
10^4
10^3
10^2
10
Z
$e^+e^- \rightarrow$ hadrons
W^+W^-
CESR
DORIS
PEP
PETRA
TRISTAN
KEKB
PEP-II
SLC
LEP I
LEP II
0
20
40
60
80
100
120
140
160
180
200
220
Centre-of-mass energy (GeV)

LEP 2: W boson pair production





- Direct demonstration of non-abelian gauge interactions: SU(2) group
- Measurement of W boson mass

m_W=80.376±0.033 GeV

Confirmation of the Gauge Boson self-coupling

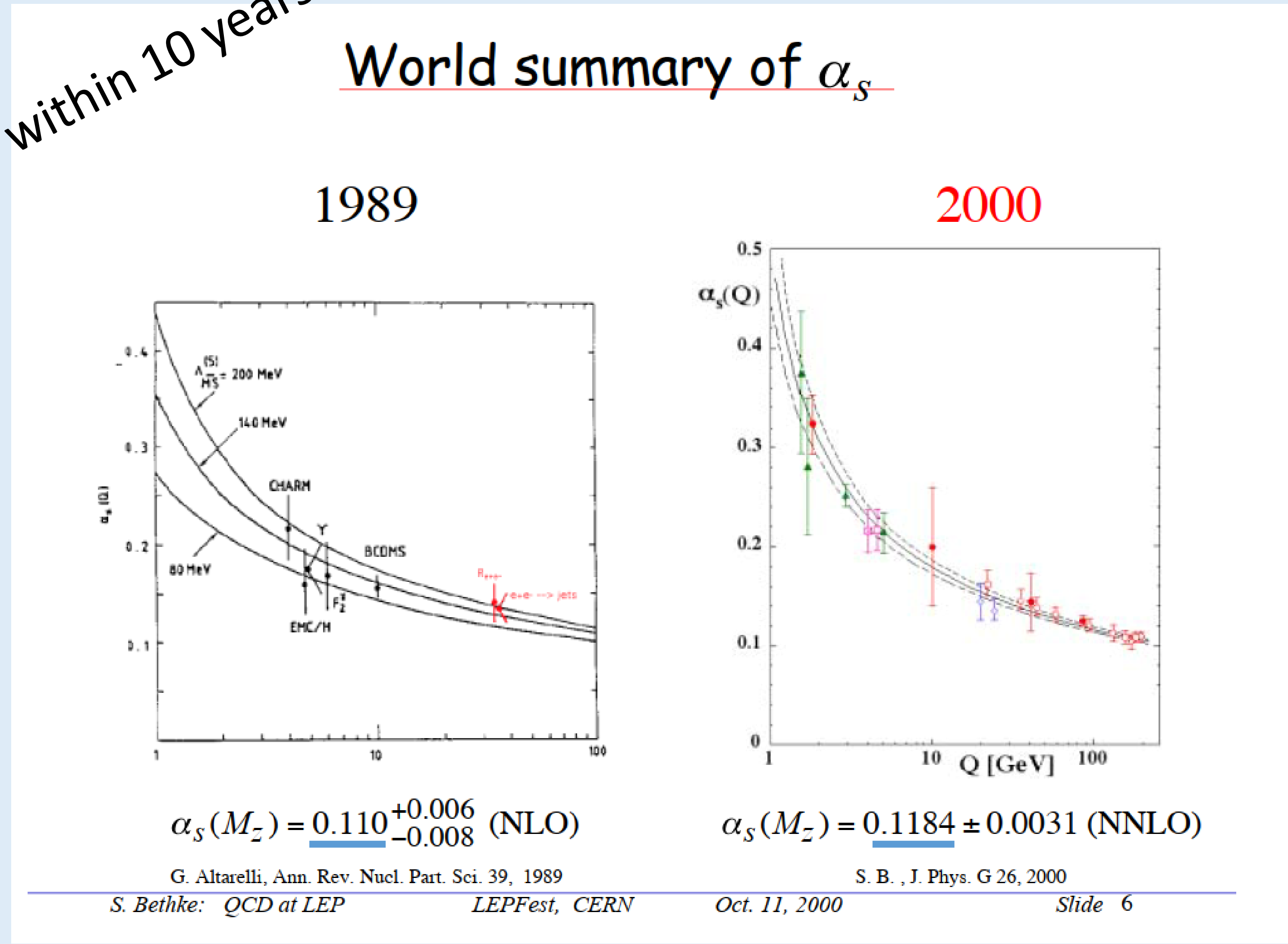
LEP besides the e-w interaction:

Study of the strong interaction (QCD)

Measuring the strong coupling:

The running constant

Progress within 10 years

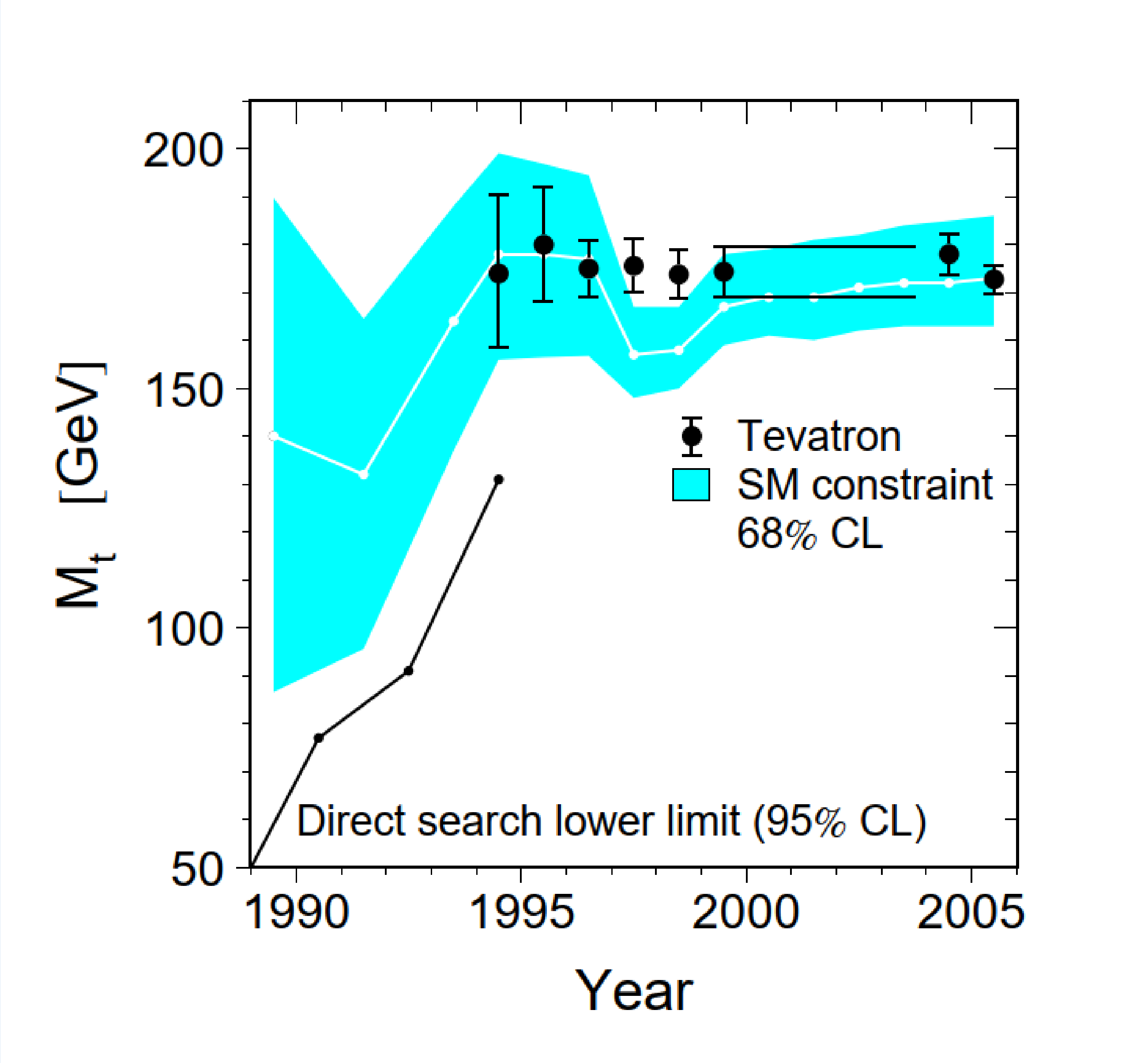


What about

top quark ? → Tevatron

Higgs Boson ? → LHC

Search for the Top quark at LEP



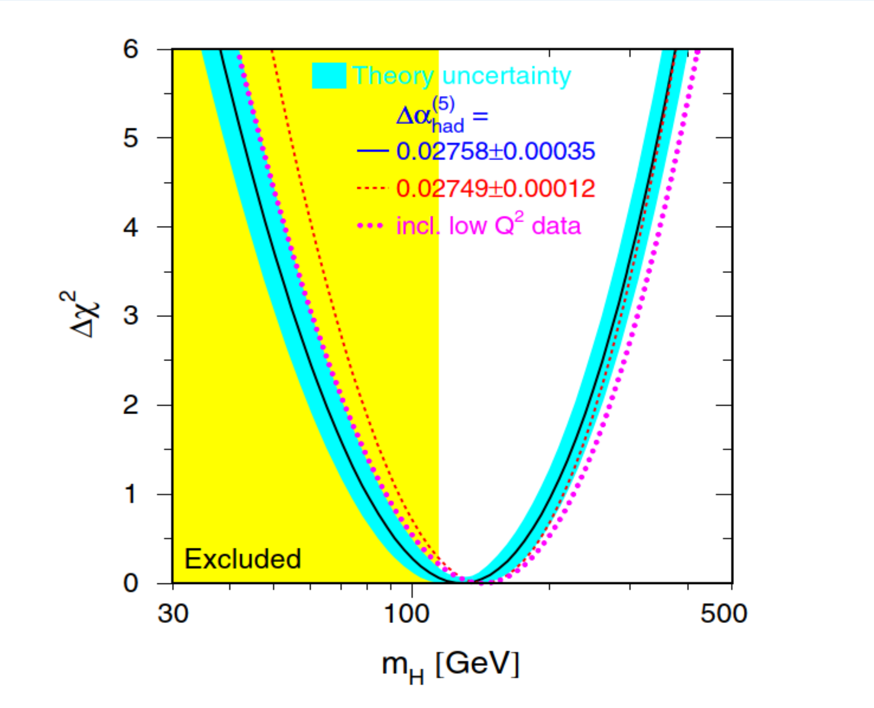
LEP and SLD data indicated the value of the top mass well before discovery

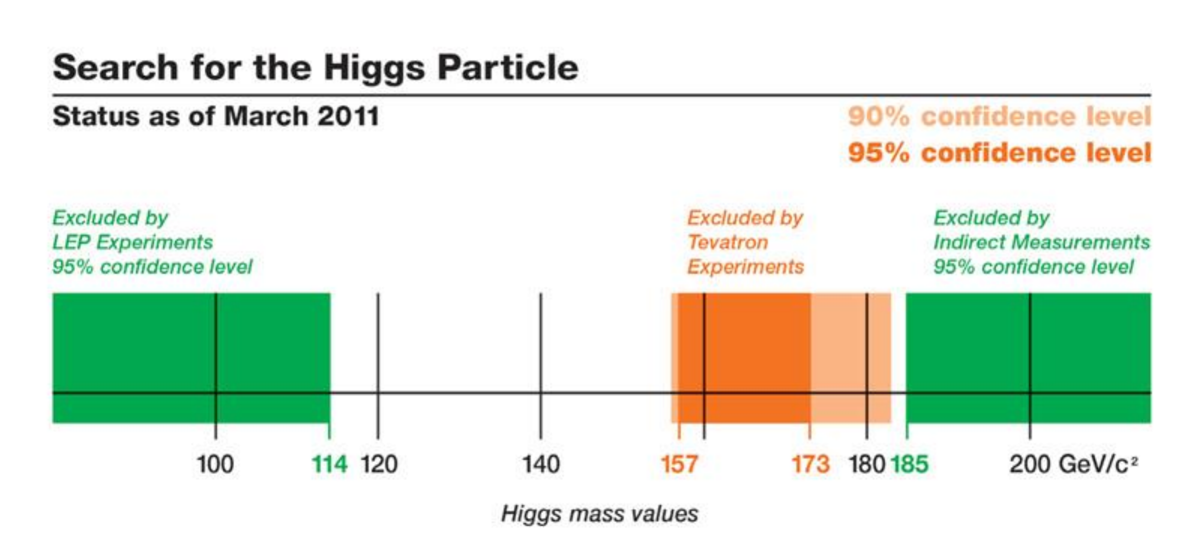
Precision measurements (SM constraints) and direct measurements agree and complement each other well

Status of the search for the Higgs-Boson March 2011

LEP1 1989 - 2000

Precision tests of the Standard Model



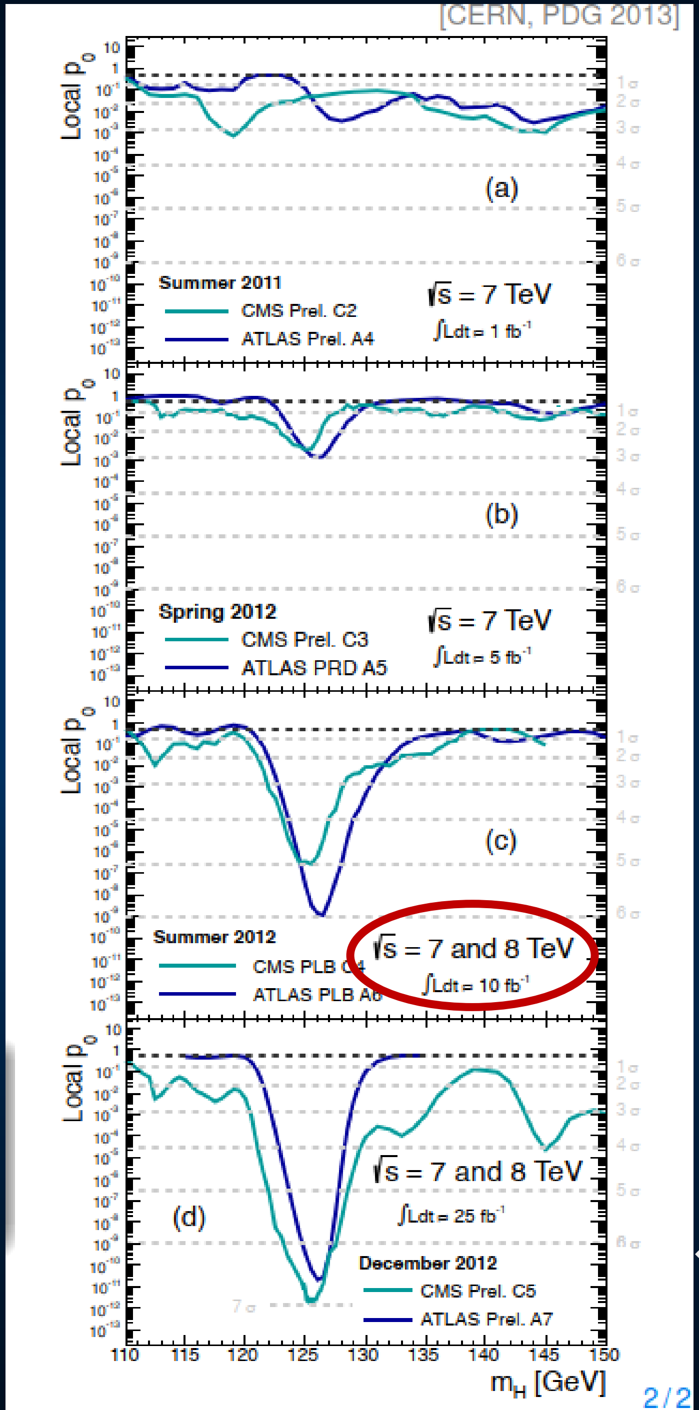


LEP1 + LEP2 and Tevatron

LHC: 12 months to the discovery……….

Signal Development

during the 12 months before the announcement

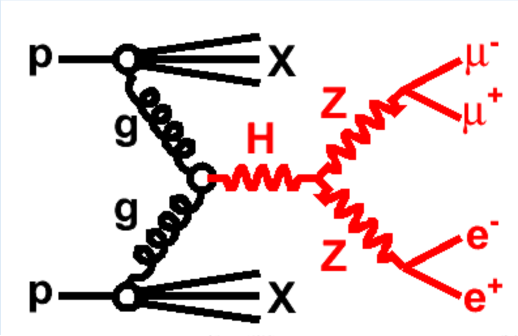


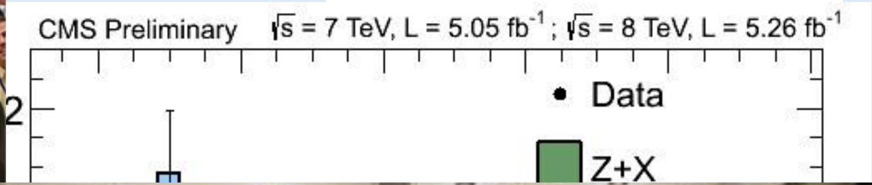
← 3 sigma

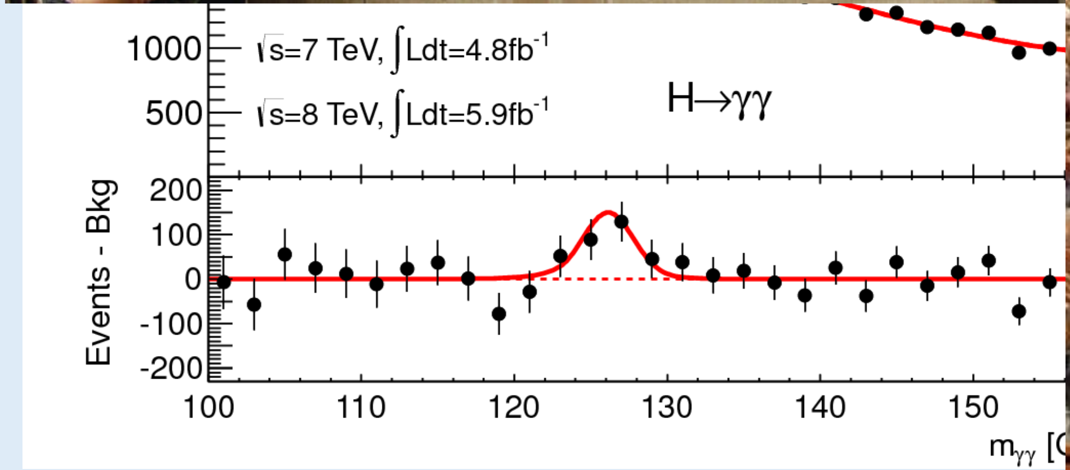
← 5 sigma

← 6 sigma

Higgs Boson Discovery (2012)







Higgs is Really New Physics!

* We've never seen anything like it
* Harbinger of Profound New Principles at work in quantum vacuum

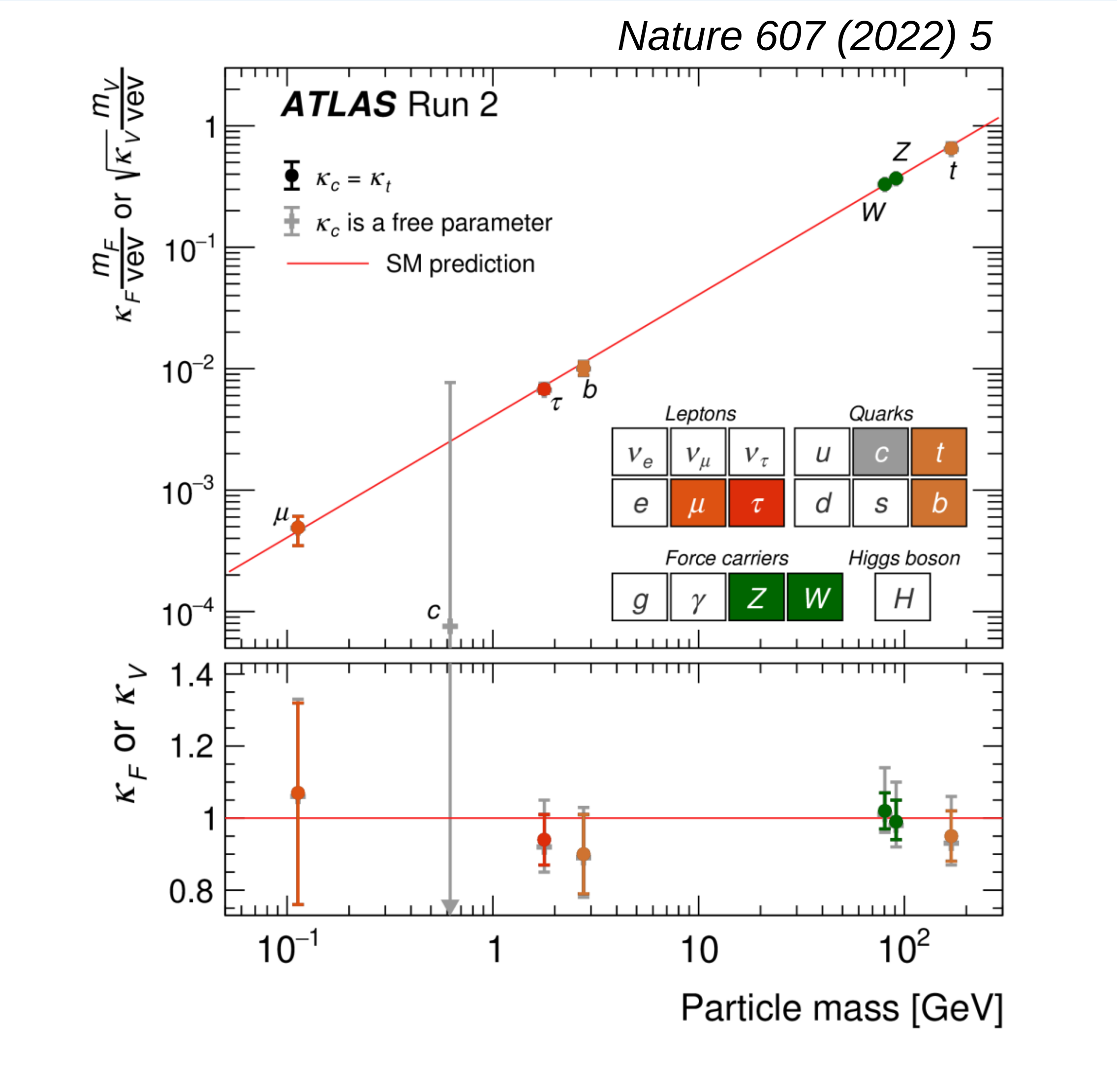
PUT IT UNDER MICROSCOPE

STUDY IT TO DEATH

Nima Arkani-Hamed

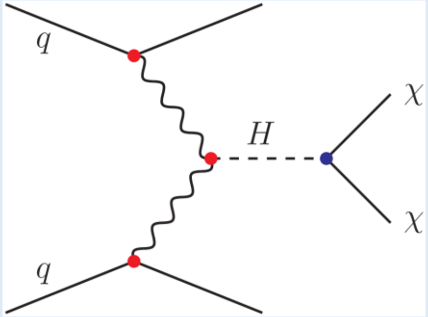
Higgs Boson: recent experimental results

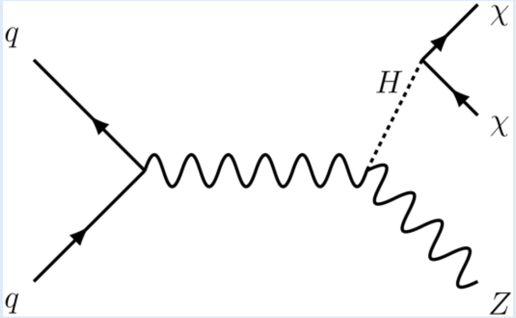
LHC Run 2



Higgs boson gives mass to gauge bosons and fermions of 2nd and 3rd generation

No anomalous H decays detected e.g. to dark matter candidates





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