The scientific contributions of Mohammad Abdus Salam

Carlo Rubbia

GSSI-INFN, GranSasso Science Institute

L'Aquila, Italy

IASS, Institute for Advanced Sustainability Studies

Potsdam, Germany

Forward

- Modern science is based on the well known principle of Natural Philosophy, initiated in Italy with Galileo Galilei, priming objective experimental discoveries over philosophical considerations and the human behaviour.
- Most major discoveries in the last centuries have been characterized by the interplay between theories and ultimate experiments, in periods whenever experimentalists and theorists were really interested in what each other had to say and made great discoveries through their mutual exchanges.
- In the specific field of electro-weak particle unification these crucial periods were characterized by the remarkable theoretical progress in the seventies and eighties crowned by the experimental discovery of the W and Z bosons, followed by a period of relative pause in the three subsequent decades, returning again today with the discovery of the Higgs particle and with the consequent completion of the Standard Model.

“CERN made” colliders

- Experimental progress toward an Electro-Weak unification has been widely pursued at CERN with the development and the successful operation of a chain of unique and innovative colliding beam machines, first with the conversion of the SPS into the pbar-p Collider, later with LEP and then finally with the LHC.
- No doubt, **Abdus Salam** would have been proud of seeing today the last step in the Electro-Weak unification of the Standard Model with the experimental observation of the Higgs scalar, a subject to which he had initially contributed so greatly.
- He would have been equally proud of the progressive emergence of Developing Countries in the new, remarkable and world-wide developments of Science and Technology, to which he had so intensively anticipated from the early times when these concepts were still vastly unknown to most.

Not being a theorist…..

- The scientific achievements of **Abdus Salam** will be briefly reviewed in my short presentation, primarily to the attention of the many non-specialists here present today.
- **Salam** however was responsible not only for major developments and contributions in theoretical and particle physics, but as well for promoting scientific and human developments to the highest level in his own country and elsewhere.
- **Salam** had a prolific research career in theoretical high-energy physics and in the unification of the four fundamental forces of nature: the gravitational force, the strong and weak nuclear forces, and the electromagnetic force.
- **Salam** had worked on the unification of electro-weak forces from 1959 with Glashow and Weinberg. **Salam** successfully showed with them that weak nuclear forces are not really different from electromagnetic forces and could inter-convert.

- Following the publication the Symmetry Breaking papers by Peter Higgs and François Englert in 1964, Steven Weinberg and **Salam** were the first to apply the Higgs mechanism to electroweak symmetry breaking for the interaction between a scalar boson and the electroweak symmetry theory.
- They provided a theory that predicted the unification of two fundamental forces of nature, weak nuclear forces and the electromagnetic forces, one into another. For this achievement, Salam, Glashow, and Weinberg were awarded the Nobel Prize in Physics in 1979.
- The Nobel Prize Foundation paid tribute to the scientists :
- *"For their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current".*
- The theory (and the Nobel Prize) required also one new, massive neutral scalar particle, the Higgs— to be found in the laboratory.

From a model to a complete theoretical description

- During the following years, two very fundamental developments took place after the idea of **Salam** and Weinberg, one theoretical the second experimental:
- Veltman and t'Hooft in 1971 defined in the Weinberg-Salam Model a "gauge" which had a property that in all orders of perturbation theory there are only a finite number of infinities which then might be absorbed into a re-definition of parameters, essential to any true (renormalizabile) Theory. The Nobel Prize in Physics 1999 was jointly awarded to them: *"for elucidating the quantum structure of electroweak interactions in physics"* .
- However the importance of the renormalizability of the electroweak theory was not so much that infinities could be removed by renormalization, but rather that the theory might describe the weak and electromagnetic interactions even at energies much greater than 300 GeV, and maybe all the way up to $\approx 10^{19}$ GeV, the so called Planck mass scale (the initial big Bang)

The discovery of the neutral currents in neutrino interations

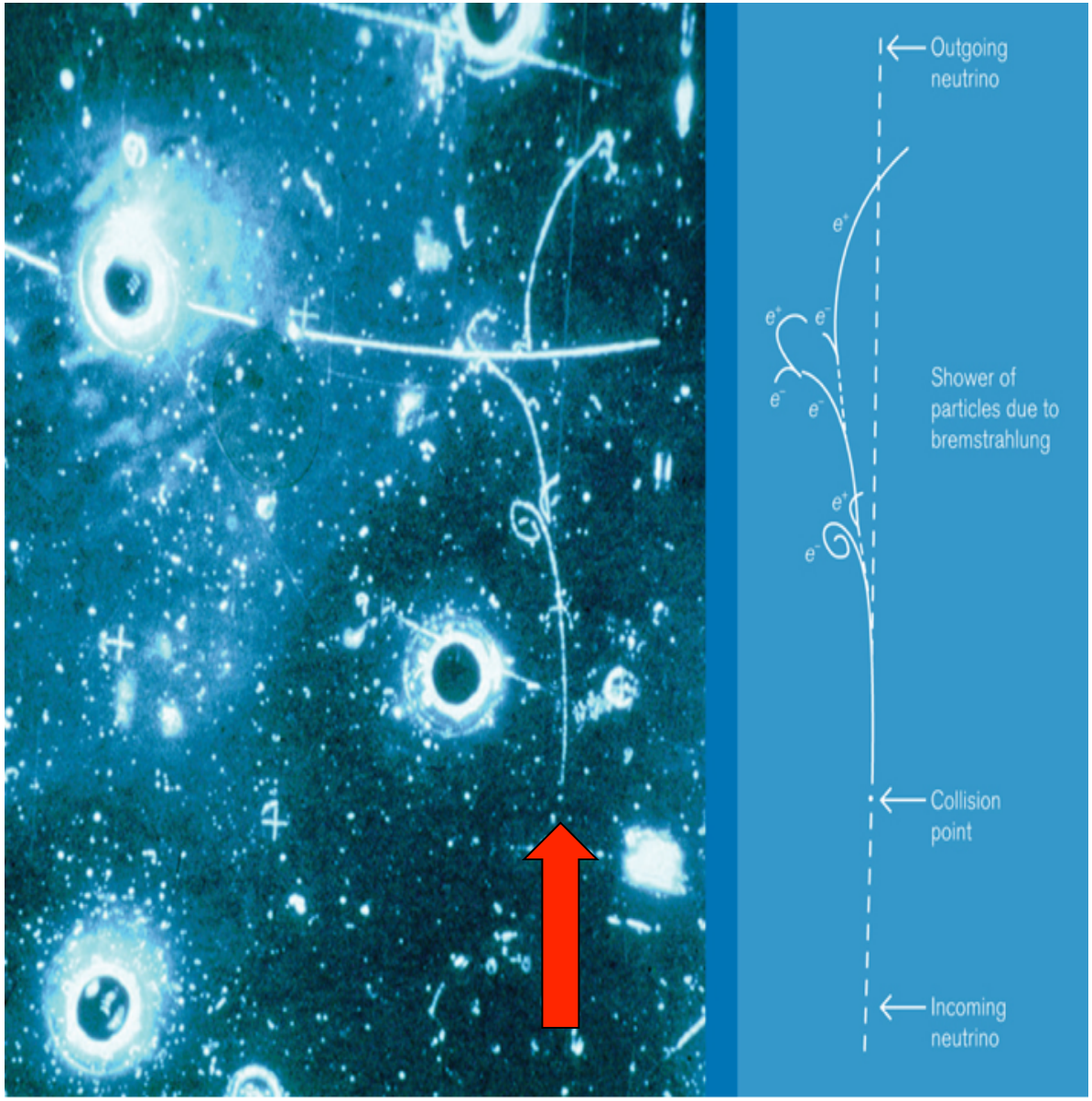
- The second breakthrough was experimental. Indeed these attractive developments did not mean that their theory was true.—*that was an ultimate matter for the experiments*.
- In 1973the so-called Neutral Currents were discovered in the neutrino reactions at CERN and promptly confirmed at FermiLab.
- Experimental observations in neutrino interactions indicated that beside the (then hypothetical] weak interaction mediated by the charged bosons $W^{\pm}$ there was the need of a neutral electroweak partner, the Z^{o}.
- This was, no doubt, another "Nobel Prize class" discovery which was however never recognized, in my view, because of the early death of Andre Lagarrigue.

The first example of a neutrino induced neutral current

- Neutrinos interacted at CERN in a 1200 litres bubble chamber, "Gargamelle".
- A muon neutrino (the vertical going line) interacts with an electron and leaves the volume unseen.

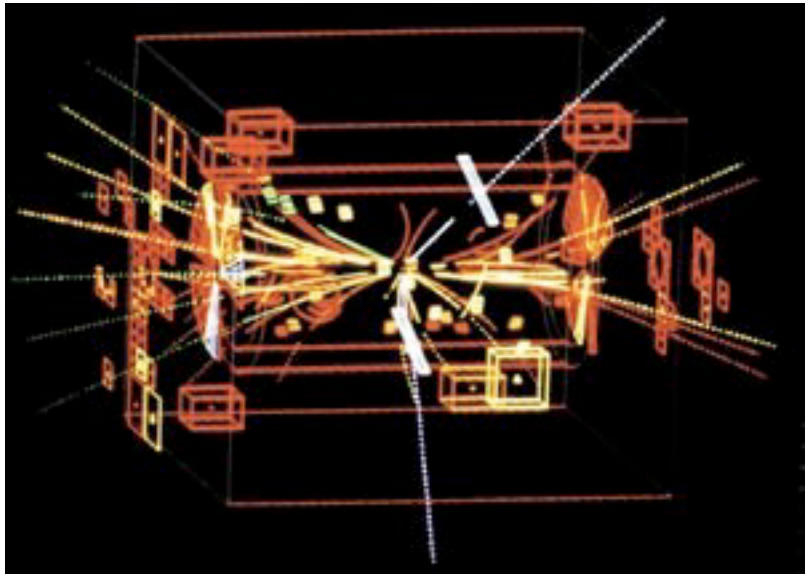
$$\nu + e \rightarrow \nu + e$$

- Observed an Aachen in 1973 this has been the first observation of a neutral current event.

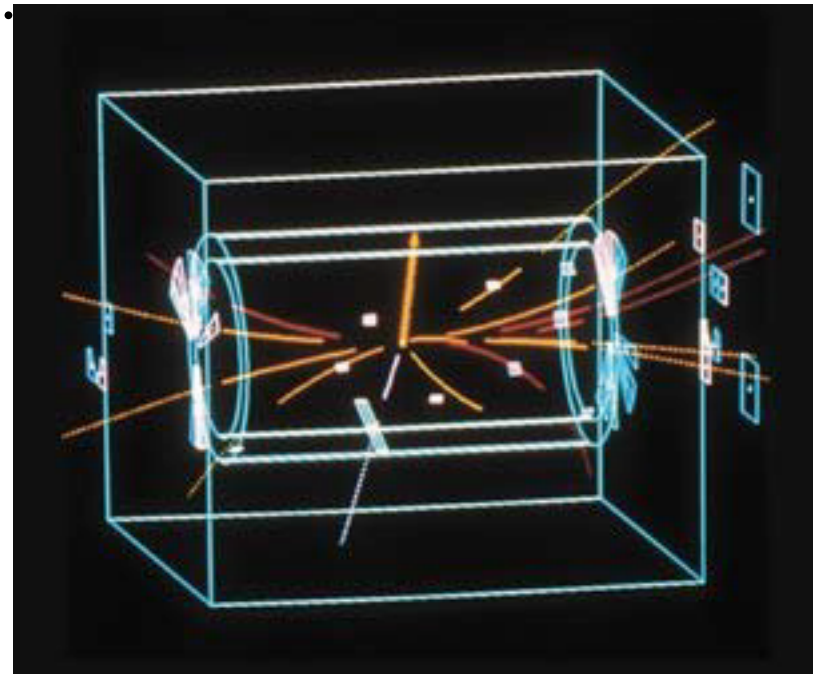


The discovery of the charged and neutral Itermediate bosons

- In the subsequent decade, the WSG theory became progressively more and more consistent. The next major experimental step has been in 1983 with the discovery of the W and Z bosons with the p-pbar collider at the CERN-SPS and the UA1 and UA2 experiments.



$Z \longrightarrow e^+ + e^-$



$W \longrightarrow e\,\nu$

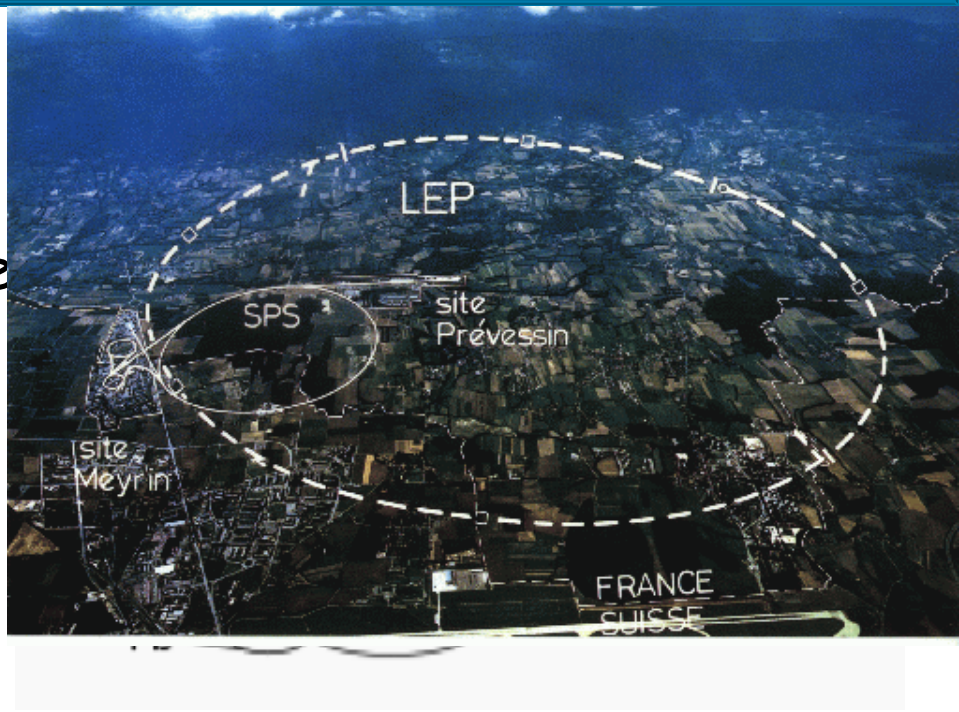
Nobel Prize in Physics to Rubbia and Van der Meer (1984)

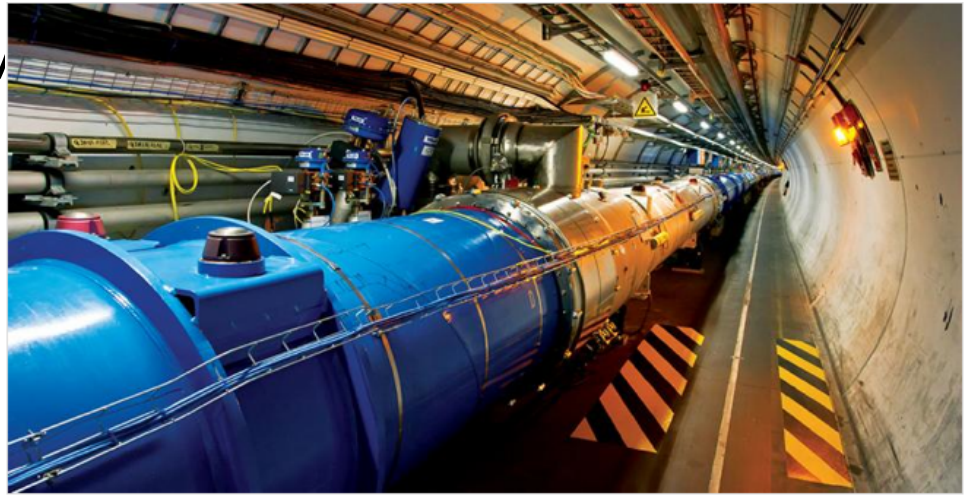
Theorists and experimentalists joining at the Nobel Cerimony

C. Rubbia and S. van der Meer, in the first raw, receiving the Prize with in thesecond raw A. Salam (1, with the turban), S. Glashow (2) and S. Weinberg (3) celebrating at the 1984 Nobel Prize Ceremony

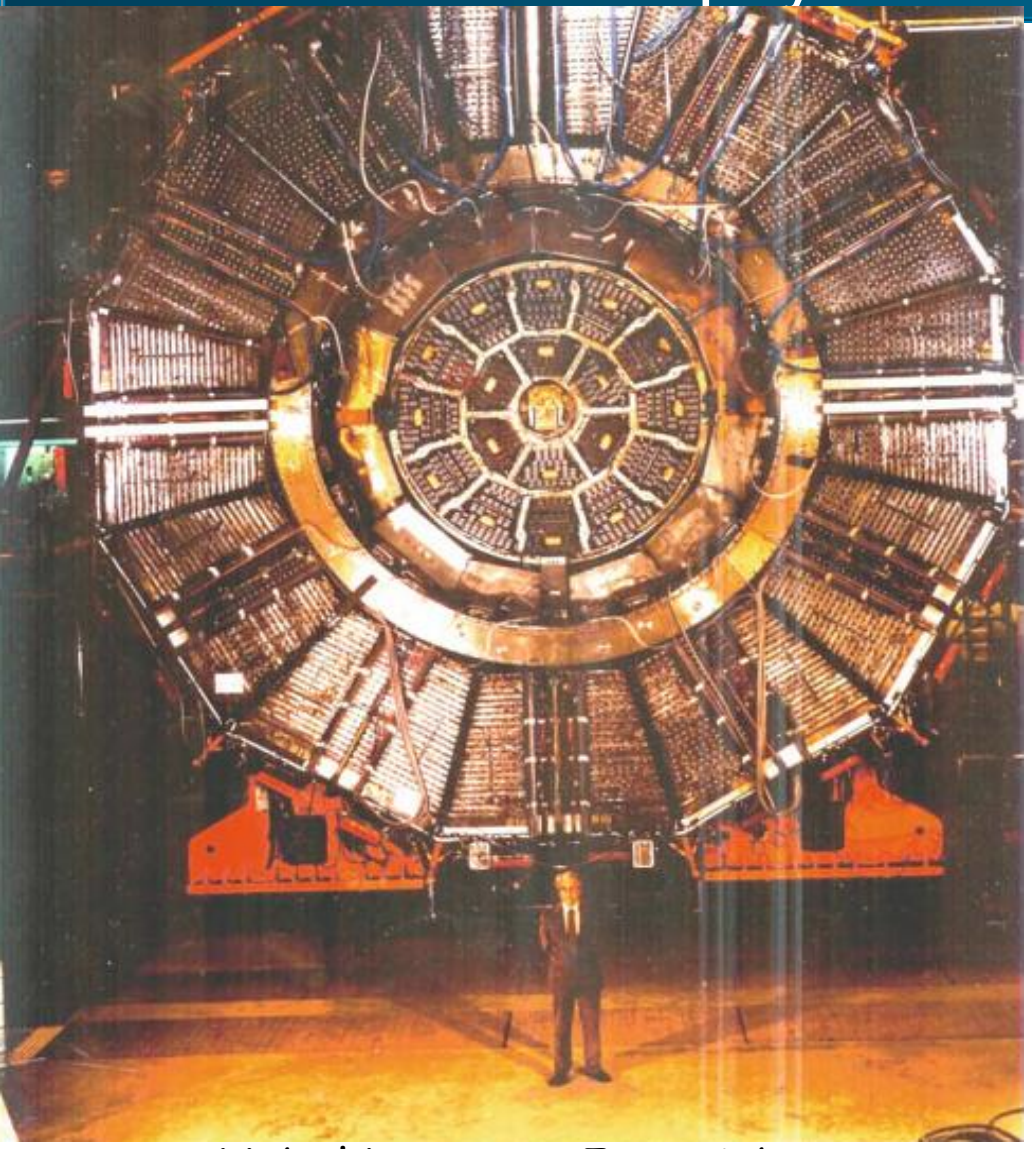
CERN accelerator programmes toward the Standard Model

- The final confirmation of the initial Glashow, **Salam** and Weinberg theory came from the new 27 km long accelerator at CERN first housing the 4 LEP experiments (ALEPH, DELPHI, L3 and OPAL) and later the LHC, a huge superconducting hadron collider installed in the same tunnel.
- LEP1 (1989-1995) with ≈ 4.5 Million Z events/experiment
- LEP2 (1996-2000) with ≈ 10'000 WW events/experiment
- LHC (2009-2012) A new particle has been observed at 125 GeV that is in agreement with a Higgs boson in two experiments (ATLAS and CMS).



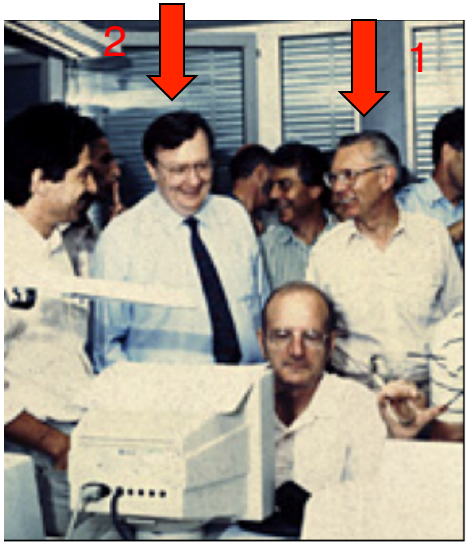


Thousands of physicists have participated to LEP



- Nobel Laureate J. Steinberger in charge the ALEPH experiment

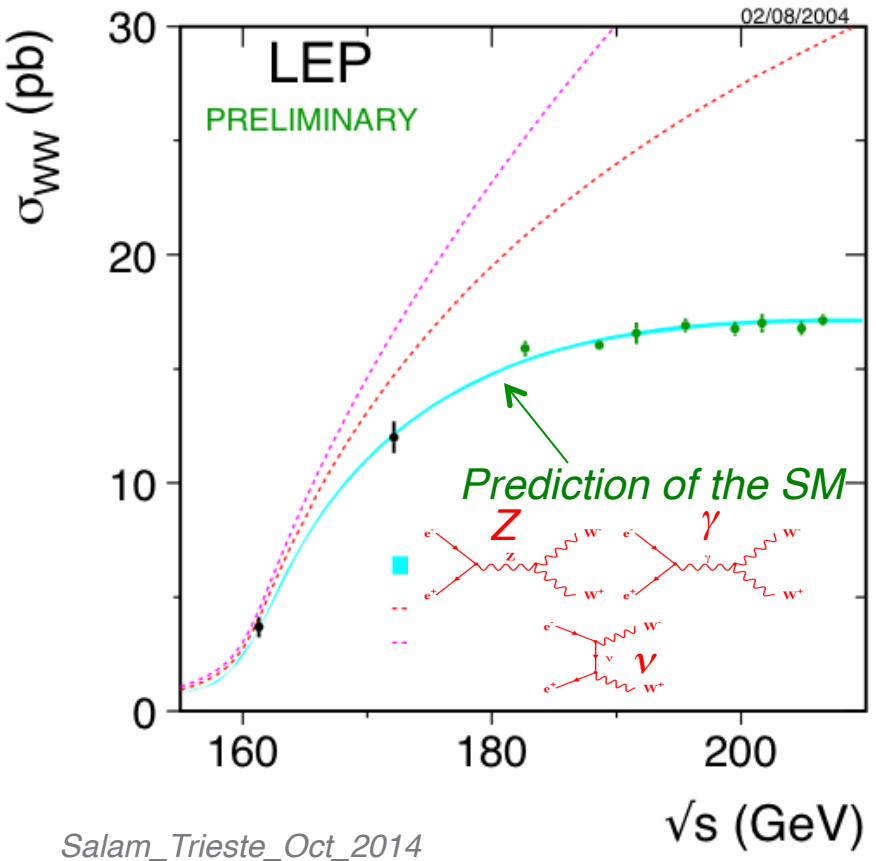
3 Nobel Laureates: S. Ting (1) in charge of the L3 experiment with C. Rubbia (2) and G. Charpak (3)

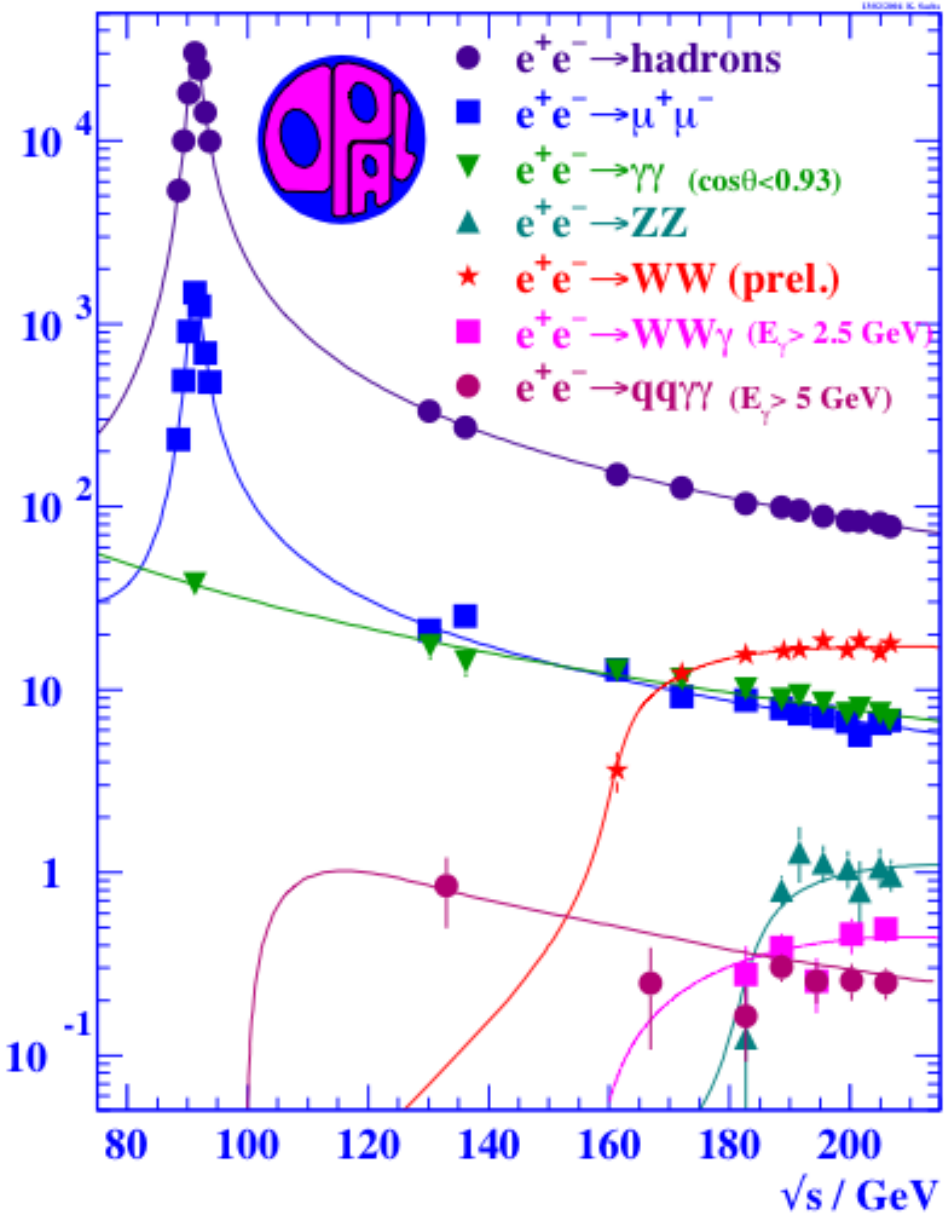


H. Schopper (1) and C. Rubbia (2), the CERN Directors during the construction of LEP, on the day of the first successful collisions

Some of the confirmations of the SM with LEP

- The very impressive coverage of the e^+- e^- cross sections with CERN-LEP, a tremendous success of the Glashow, **Salam** and Weinberg predictions.

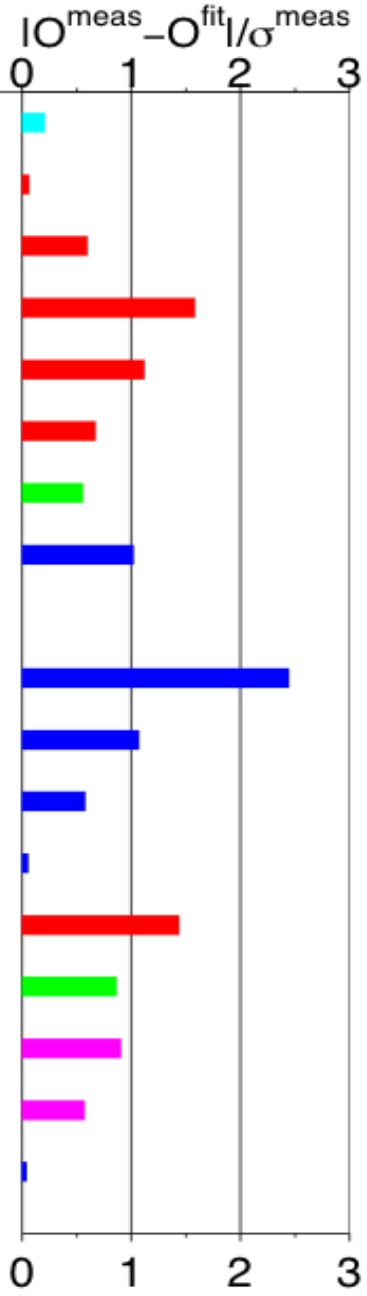




Some of the LEP findings

- Main observations of Electro-Weak parameters
- Note the very high accuracy of measurements and the splendid agreement of data with SM's fit

	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02769
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4966
σ^0_{had} [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01650
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1483
R_b	0.21630 ± 0.00066	0.21562
R_c	0.1723 ± 0.0031	0.1723
$A^{0,b}_{fb}$	0.0998 ± 0.0017	0.1040
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0744
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1483
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.394
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.2

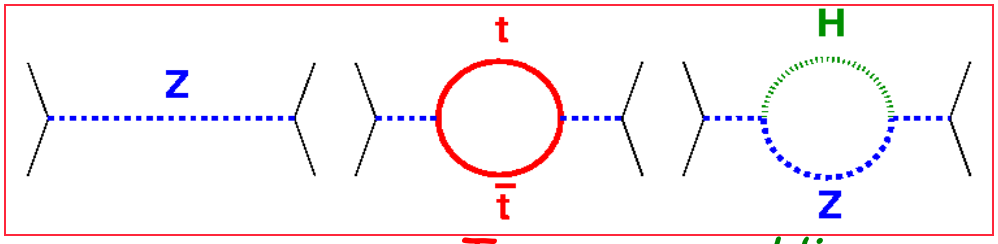


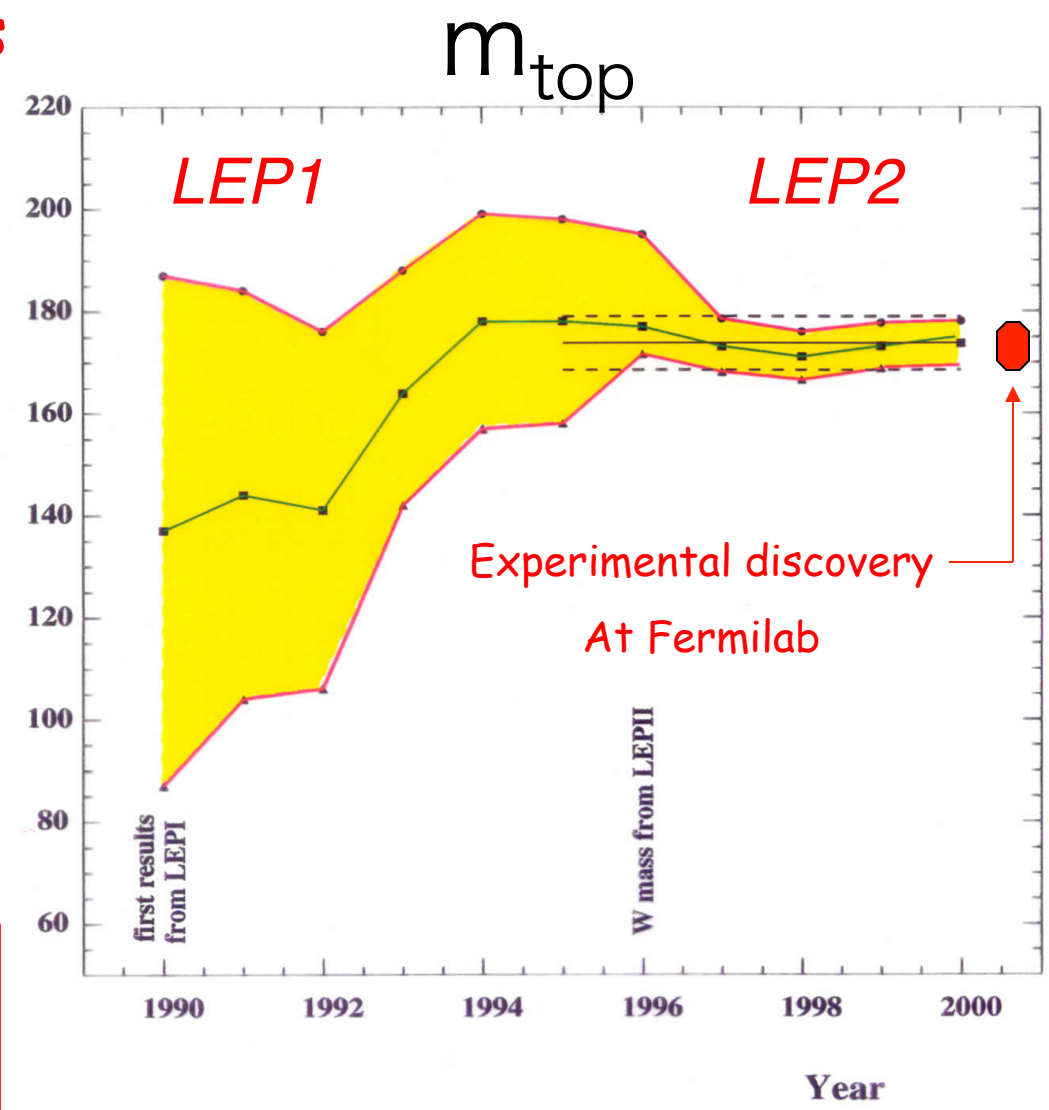
Predictive power of the theory

From theoretical SM predictions to the experimental observation

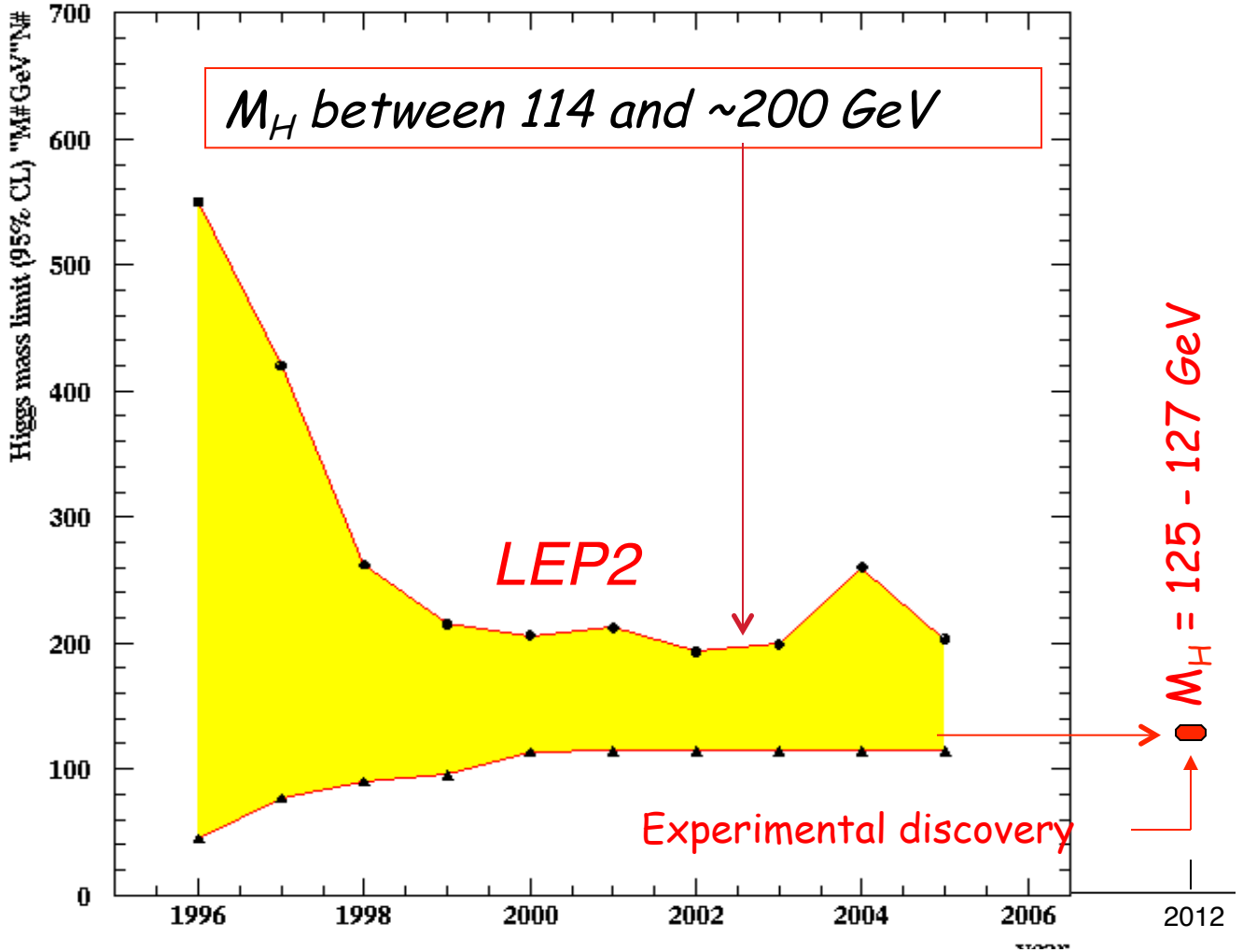
Extremely precise predictions of the SM from electromagnetism, mainly from LEP, g-2 etc.

Higher order, renormalizable experimental corrections of electro-weak interactions are used to predict a mass beyond data (virtual graphs).



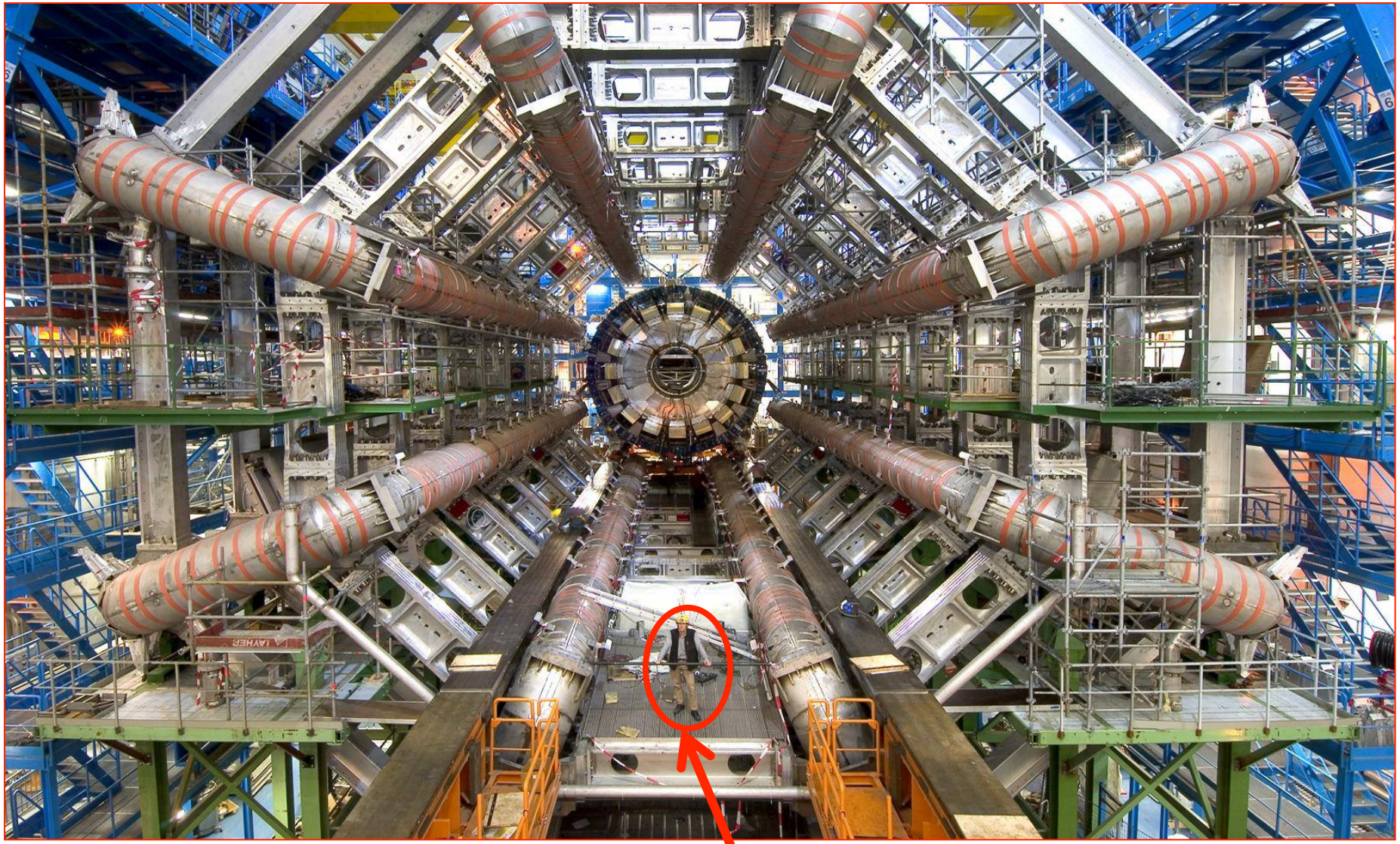


The similar higher order evidence for the Higgs particle

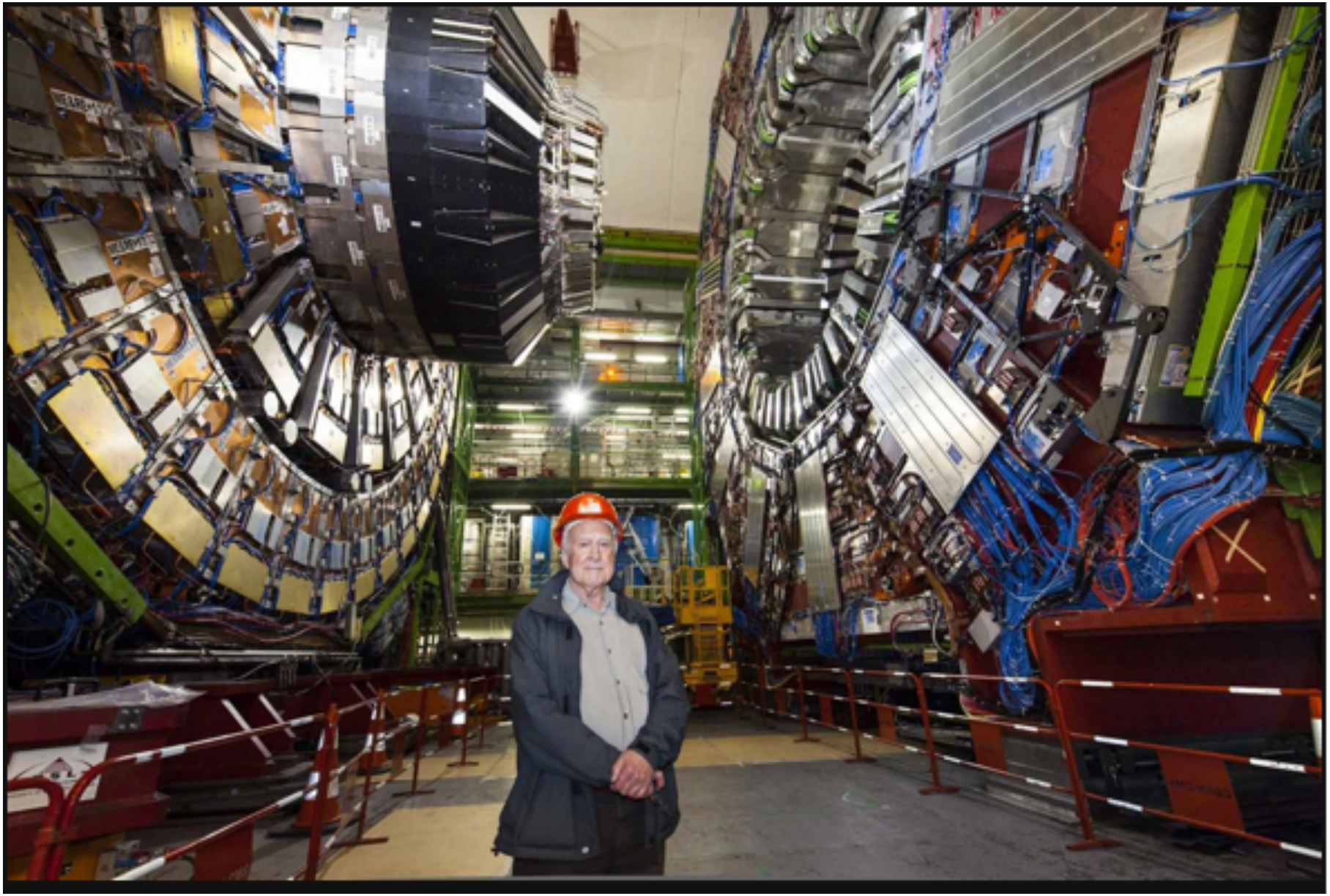


Predictions of the range of the Higgs mass and actual observation

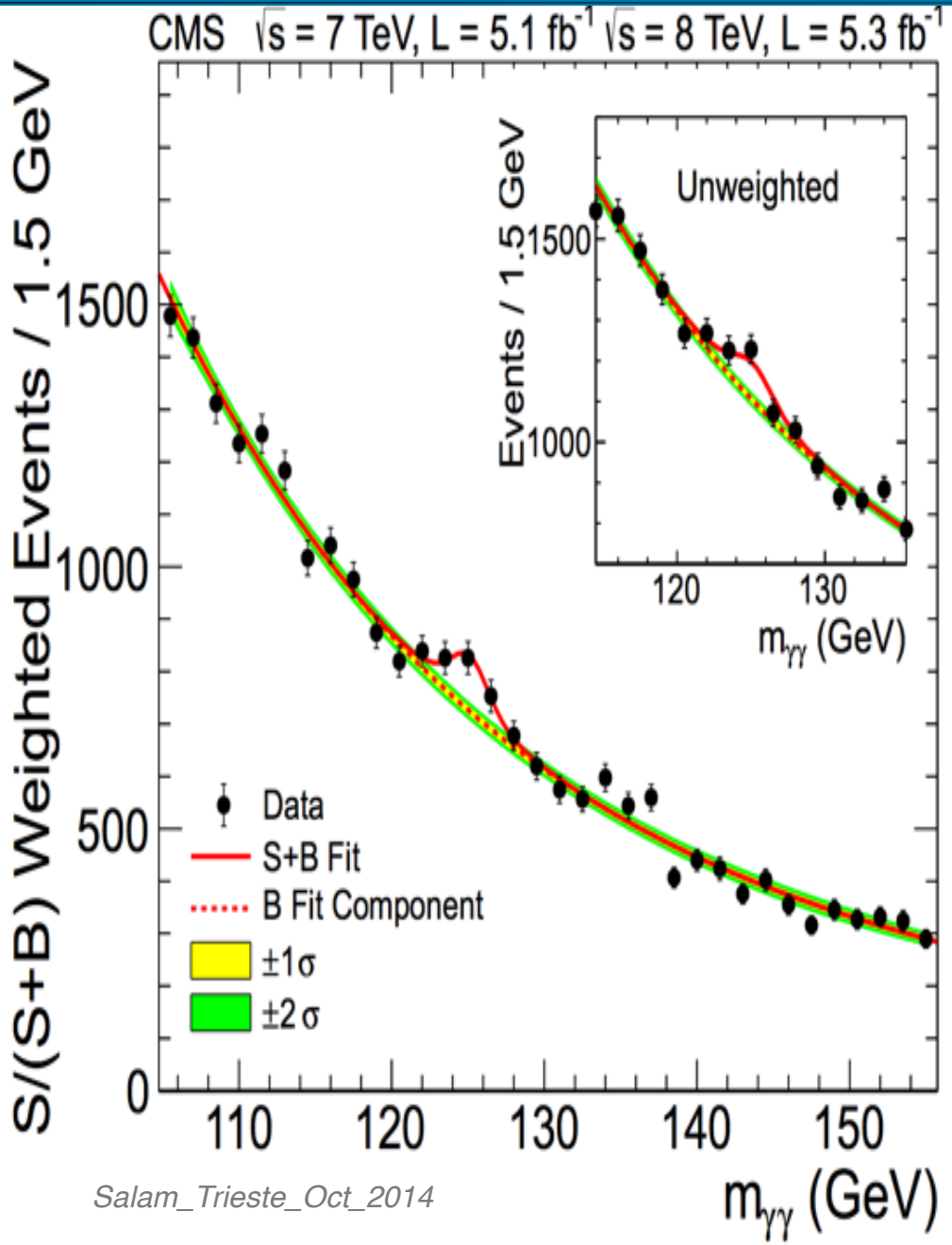
The ATLAS detector at CERN

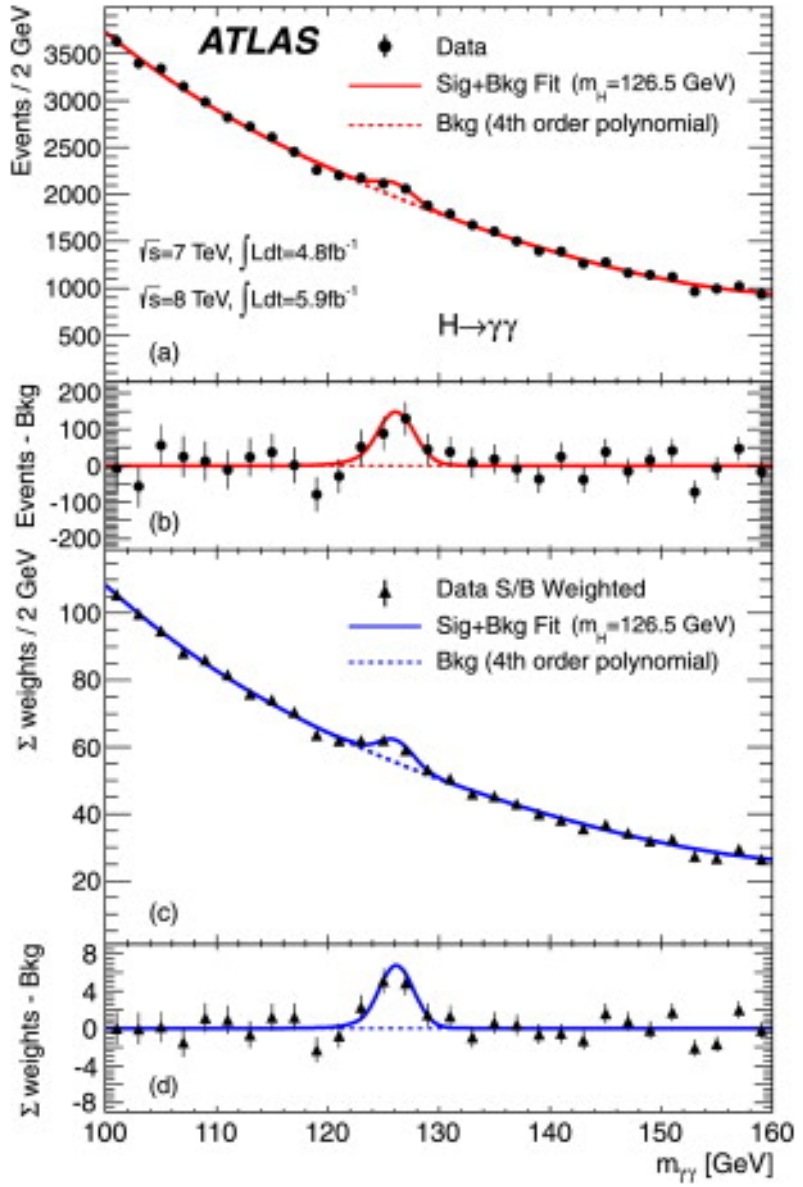


A quiet man making a big bang: Peter Higgs at CMS



The H_o -> $\gamma\gamma$ channel



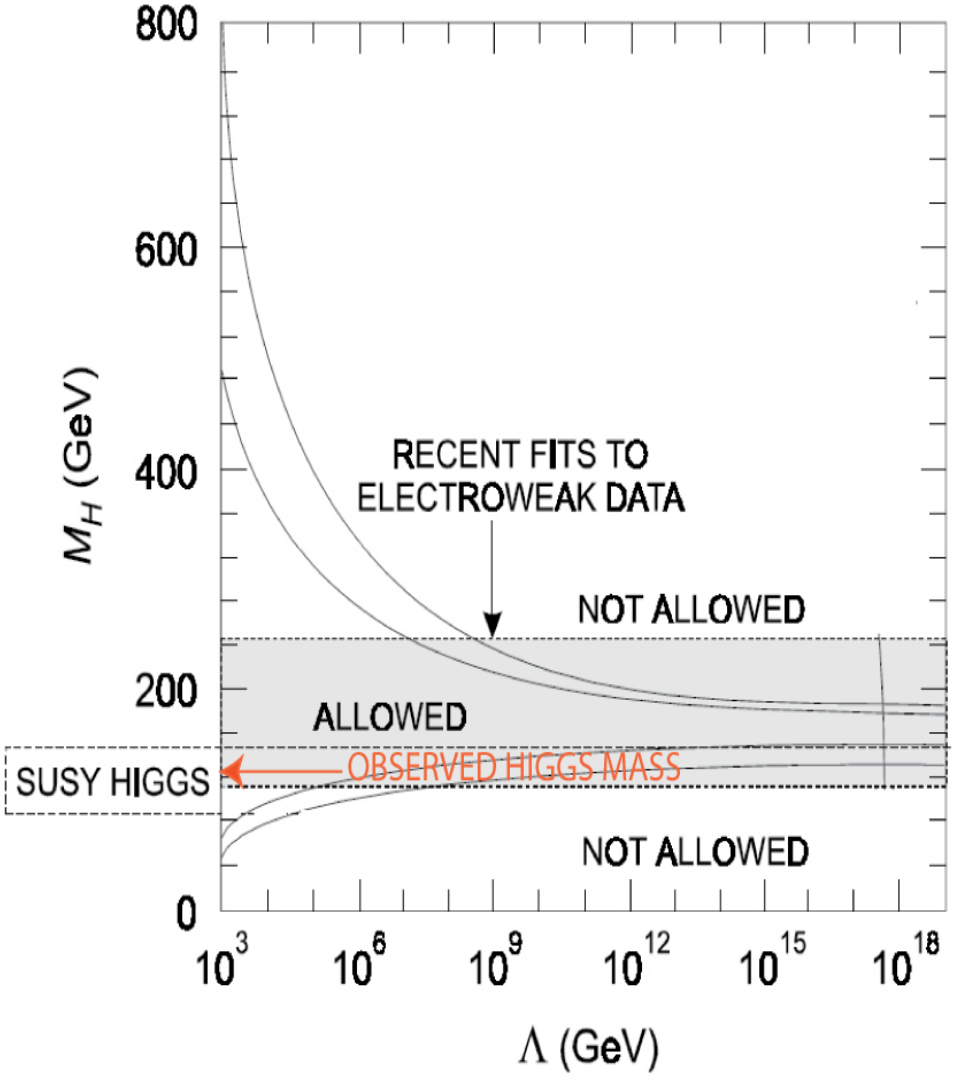


Final confirmation of new particle as a Higgs boson

- On 14 March 2013 CERN confirmed that:
- CMS and ATLAS have compared a number of options for the spin-parity of this particle, and these all prefer no spin and positive parity [two fundamental criteria of a Higgs boson consistent with the Standard Model].
- This, coupled with the measured interactions of the new particle with other particles, strongly indicates that it is a Higgs boson.
- This also makes this particle the first elementary scalar particle discovered in nature.
- The experimental results are entirely consistent with the original Glashow, **Salam** and Weinberg description

What about the so called “no fail theorem” ?

- The otherwise divergent self-interaction of the Higgs sector may require a cutoff at the TeV scale, like for instance with SUSY .
- However, this does not apply for the recently observed Higgs mass of 125 GeV, since now stability conditions allow without novelties a legitimate cutoff maybe up to the Planck Mass.
- Thus, there may be only one standard Higgs and no near by SUSY



Concluding remarks: 5 Nobel awards +….

- Nobel Prize in Physics (1979) – Glashow, Salam and Weinberg, *"for their contributions to the unified weak and electromagnetic interaction between elementary particles, including, inter alia, the prediction of the weak neutral current"*
- Nobel Prize in Physics (1984) - Rubbia and Van der Meer, *"for their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of weak interaction"*
- Nobel Prize in Physics (1999) –'t Hooft and Veltman *"for elucidating the quantum structure of electroweak interactions in physics"*
- Nobel Prize in Physics (2008) –Nambu (shared), *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*
- Nobel Prize in Physics (2013) –Higgs and Englert, *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

+ + thousands of experimental physicists working during many decades

A Salam's dream: from here to infinity (the Planck mass)

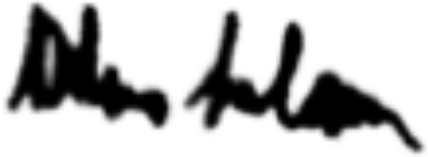
- Salam's major and notable other achievements include also many other domains like the Pati-Salam model, magnetic photon, vector meson, Grand Unified Theory, Super-symmetry (SUSY).
- As much as many others, he was deeply convinced that some new physics was to be found at energies much higher than those that any accelerator could ever be capable to provide, but in which Nature has evolved from the initial "big Bang" presumably from $\approx 10^{19}$ GeV to the now explored LHC energy domain of $\approx 10^{3}$ GeV.
- Many of these alternatives have so far failed to correspond to proven experimental discoveries, like for instance:
  - Super-symmetry, a new realm of "symmetric" particles with the "Grand Unification" of three of the main forces
  - The decay of the proton ("diamonds are not for ever")
  - The true nature of neutrinos and universality of CP violation.
- Because of his premature death, **Abdus Salam** has unfortunately missed two extraordinary cosmic discoveries, which no doubt would have fashinated him, the Dark Mass and the Dark Energy.

One of my dearest, hardly missed personal fiends….

Mohammad Abdus Salam
محمد عبد السلام

Abdus Salam in 1987

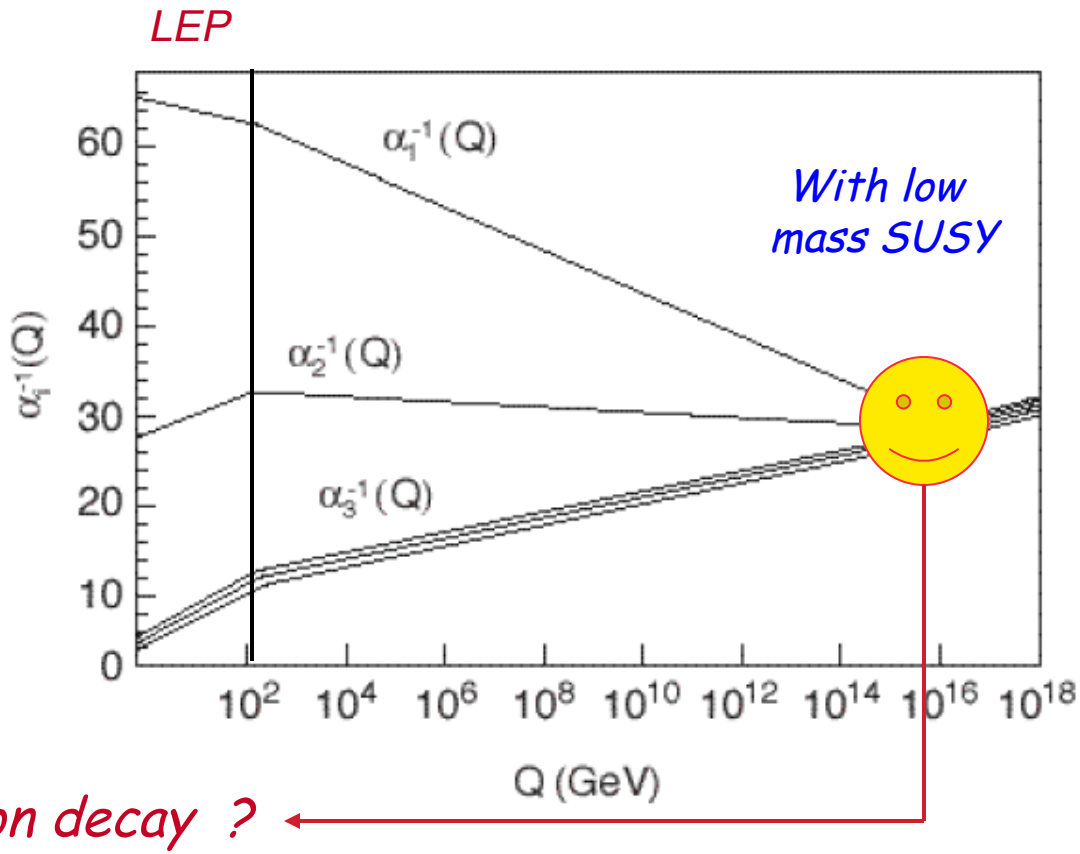
Born	29 January 1926 Santokdas, Sahiwal District, Punjab, British India (now Punjab, Pakistan)
Died	21 November 1996 (aged 70) Oxford, United Kingdom
Nationality	Pakistani[1]
Fields	Theoretical physics
Institutions	PAEC · SUPARCO · PINSTECH · Punjab University · Imperial College London · Government College University · University of Cambridge · ICTP · COMSATS · TWAS · Edward Bouchet Abdus Salam Institute



Thank you !

An other dream of Abdus Salam: the Grand Unification

- Running coupling constants may be modified in the case of a low mass SUSY –like threshold, and the three main interactions converge to a common Grand Unified Theory, provided that for instance SUSY is there wth not too high masses (the graph is indicative)



- No doubt the convergence of all the three running coupling constants to a common value with lepton-quark unification is probably inevitable.
- However the mechanism of this change and mass values of its occurrence are vastly unknown (Pati-Salam, Giorgi, Glashow, etc.)