Luciano Maiani:
. Lezione Fermi 18
Tutto quello che ... 2
Il bosone nella teoria elettrodebole

1. Da Glashow (1961) a Weinberg-Salam (1967-1968)
2. Doppietto scalare e la massa dei bosoni intermedi
3. Estensione ai quark e completamento dello SM
4. La ricerca del bosone di Higgs al LEP
5. Le Roy est mort-Vive le Roy

1, Da Glashow a Weinberg-Salam

- Il messaggio di Brout-Englert-Higgs e' stato prontamente raccolto
- nel 1967, S. Weinberg e A. Salam, indipendentemente, arrivano alla stessa soluzione.
- Lo schema era quello delineato da S. Glashow nel 1961 (in post-doc a Copenhagen) a partire dalla teoria di Yang-Mills del 1954.
- Per dare una massa ai campi di gauge e all'elettrone, Glashow aggiungeva all'Azione di Y-M dei termini (di massa) ad hoc, che violano la simmetria (e che, ora sappiamo, non sono consistenti con la rinormalizzazione).
- Nello schema di Weinberg e Salam, il gruppo di simmetria e' lo stesso di Glashow, ma l'Azione e' perfettamente simmetrica
- sono presenti dei campi scalari aggiuntivi, il cui condensato rompe la simmetria e provvede alle masse richieste.

Towards a unified theory: Threads in a tapestry"

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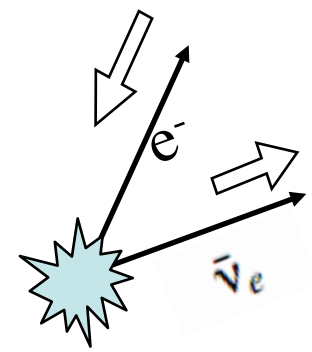
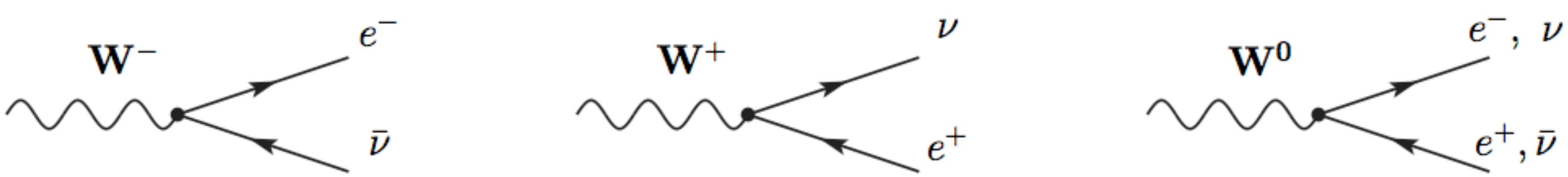
We come to my own work (Glashow, 1961), done in Copenhagen in 1960, and done independently by Salam and Ward (Salam and Ward, 1964). We finally saw that a gauge group larger than SU(2) was necessary to describe the electroweak interactions. Salam and Ward were motivated by the compelling beauty of gauge theory. I thought I saw a way to a renormalizable scheme. I was led to the group $SU(2) \times U(1)$ by analogy with the approximate isospin-hypercharge group which characterizes strong interactions. In this model there were two electrically neutral intermediaries: the massless photon and a massive neutral vector meson which I called B but which is now known as Z. The weak mixing angle determined to what linear combination of $SU(2) \times U(1)$ generators B would correspond. The precise form of the predicted neutral current interaction has been verified by recent experimental data. However, the strength of the neutral current was not prescribed, and the model was not in fact renormalizable. These glaring omissions were to be rectified by the work of Salam and Weinberg and the subsequent proof of renormalizability. Furthermore, the model was a model of leptons—it could not evidently be extended to deal with hadrons.

Composizione della teoria EW

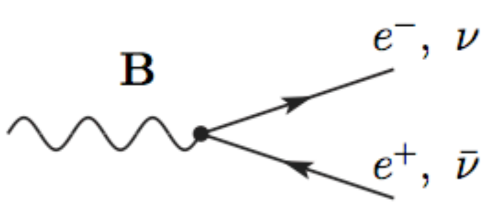
$SU(2) \otimes U(1)$ doppietto e singoletto :

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \; e_R$$

- Campi di gauge e vertici, a partire da 



SU(2)



U(1)

2. Doppietto scalare e massa dei Bosoni intermedi

Doppietto di Higgs:
= 4 campi reali

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \frac{\phi_1 + i\phi_2}{\sqrt{2}} \\ \frac{\phi_3 + i\phi_4}{\sqrt{2}} \end{pmatrix}$$

(S. Weinberg, Nobel lecture)

.... The spontaneous breakdown of SU(2) ⊗ U(1) to the U(1) of ordinary electromagnetic gauge invariance would give masses to three of the four vector gauge bosons: the charged bosons $W^{\pm}$, and a neutral boson that I called the Z^0.

The fourth boson would automatically remain massless, and could be identified as the photon.

Knowing the strength of the ordinary charged current weak interactions like beta decay which are mediated by $W^{\pm}$, the mass of the $W^{\pm}$ was then determined as about 40 GeV/sinθ, where θ is the γ-Z^0 mixing angle.

To go further, one had to make some hypothesis about the mechanism for the breakdown of SU (2) ⊗ U (1).

The only kind of field in a renormalizable SU(2) ⊗ U(1) theory whose vacuum expectation values could give the electron a mass is a spin zero SU(2) doublet (φ^+, φ^0), so for simplicity I assumed that these were the only scalar fields in the theory.

The mass of the Z^0 was then determined as about 80 GeV/sin 2θ.

Nota: $\sin^2\theta \approx 0.231; M_W \approx 83 \text{ GeV}; \; M_Z \approx 95 \text{ GeV}$

Rottura spontanea della simmetria

Doppietto di Higgs:
= 4 campi reali

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \frac{\phi_1 + i\phi_2}{\sqrt{2}} \\ \frac{\phi_3 + i\phi_4}{\sqrt{2}} \end{pmatrix}$$

- possiamo sempre fare in modo che il condensato sia in φ_3
- i campi $\varphi_1, \varphi_2, \varphi_4$ sarebbero i campi di Goldstone, ma spariscono con una trasformazione di gauge
- resta solo un campo fisico, φ_3
- i quanti di φ_{3quant} , sono delle particelle neutre di spin zero: il Bosone di Higgs ,
- la particella da cercare a conferma che e' proprio il meccanismo di B-E-H a dare la massa all'elettrone e ai bosoni intermedi.

dall'articolo di S. Weinberg (1967)

Is this model renormalizable?

We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our **A** *and B mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning.*

Indeed, the model Lagrangian we start from is probably renormalizable, so the question is whether this renormalizability is lost in the reordering of the perturbation theory implied by our redefinition of the fields.

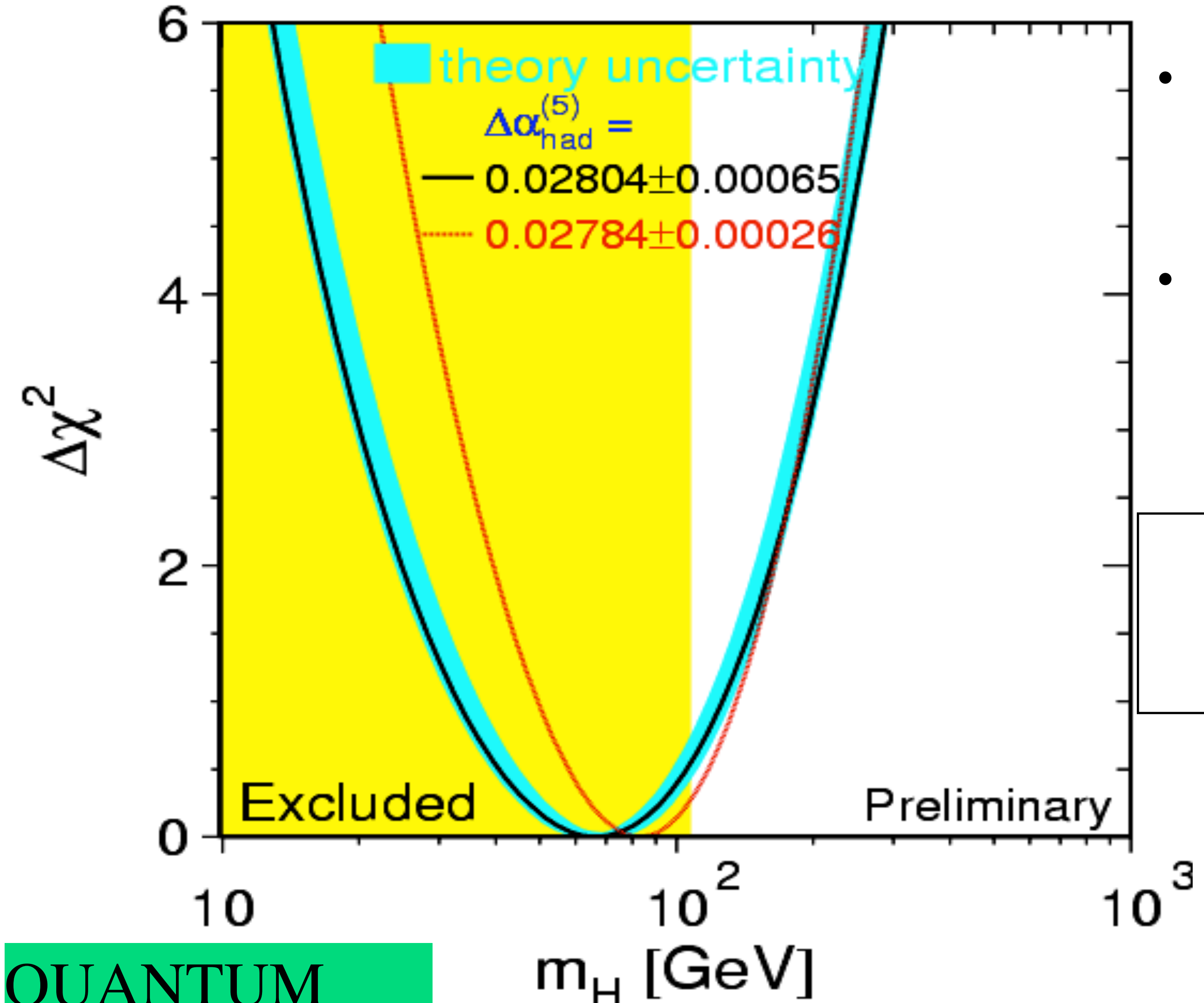
And if this model is renormalizable, then what happens when we extend it to include the couplings of **A** *and B to the hadrons?*

Renormalizability of the BEH mechanism for a non- abelian gauge theory
A first proof was given in 1972, by Gerhardt 't-Hooft and Martinus Veltman.
The final proof of the cancellation of the Adler-Bell-Jackiw anomalies among quarks and leptons of each generation was obtained by Claude Bouchiat, John Iliopoulos and Philippe Meyer in 1973.

3. Estensione ai quark e completamento dello SM

- If one tried to extend the theory to the hadrons using the three quarks introduced by Gell- Mann and the Cabibbo description of the weak currents, the exchange of Z^0 would produce strangeness-changing neutral current processess to a level firmly excluded by the then available experiments.
- In 1970, Sheldon Glashow, John Iliopoulos and Luciano Maiani showed that the introduction of a fourth quark, coupled to the superposition of down and strange quarks orthogonal to the Cabibbo, would produce, in lowest order, only strangeness-conserving neutral current processes, in agreement with data.
- The Standard Model was essentially completed in 1973, with
  - the discovery of asymptotic freedom
  - the proposal af a third generation, by Makoto Kobayashi and Toshihide Maskawa, to describe CP violation
- A season opened of great experimental discoveries, which have made SM into one of the greatest and better controlled constructions of modern physics:
  - neutral current neutrino processes (CERN, 1973),
  - the observation of the charm quark (Brookhaven and SLAC, 1974),
  - the observation of the first particles of the third generation with the τ lepton (SLAC, 1976) and the b quark (FermiLab, 1976),
  - the $W^{\pm}$ and Z^0 bosons (CERN, 1982) and the t quark (FermiLab, 1994).
- After that, the long Higgs boson hunting at LEP, Tevatron and finally at the LHC.

M_H prediction from precision Electroweak Measurements:



- Includes all electroweak precision measurements;
- Constrained by direct m_W and m_{top} determinations;

$$m_H = (77^{+69}_{-39})\ \mathrm{GeV}/c^2$$

QUANTUM STABILITY
135-170 GeV $\Lambda = 10^{19}$

$$m_H < 188\ \mathrm{GeV}/c^2 \text{ at } 95\%\text{C.L.}$$

4. La ricerca del bosone di Higgs al LEP

Una campagna di ricerca al LEP II per osservare un bosone di Higgs con massa fino a circa 115 GeV

$$e+e- \longrightarrow Z+H$$

$$Z \longrightarrow q+\bar{q}, l+\bar{l}, \nu+\bar{\nu}$$

$$H \longrightarrow b+\bar{b}$$

Canali studiati:

1. 4 jets, com massa invariante di due jet = M_Z
2. 2 jet+ energia mancante (corrispondente a Z–>nu+nu)
3. 2jet + 2 leptoni (corrispondente a Z–>l+l-bar)
4. Nei jet, si applicava per quanto possibile il b tagging, per esaltare gli eventi con un possibile H

Eventi interessanti raccolti da ALEPH nell' estate 2000, nel canale 4 jets con b-tagging, massa 114 GeV;
Alla fine, sui 4 esperimenti, l' evidenza per un Higgs di 114 GeV e' di circa 2 standard deviations
Per arrivare a questo, sono state fatte analisi statistiche molto raffinate

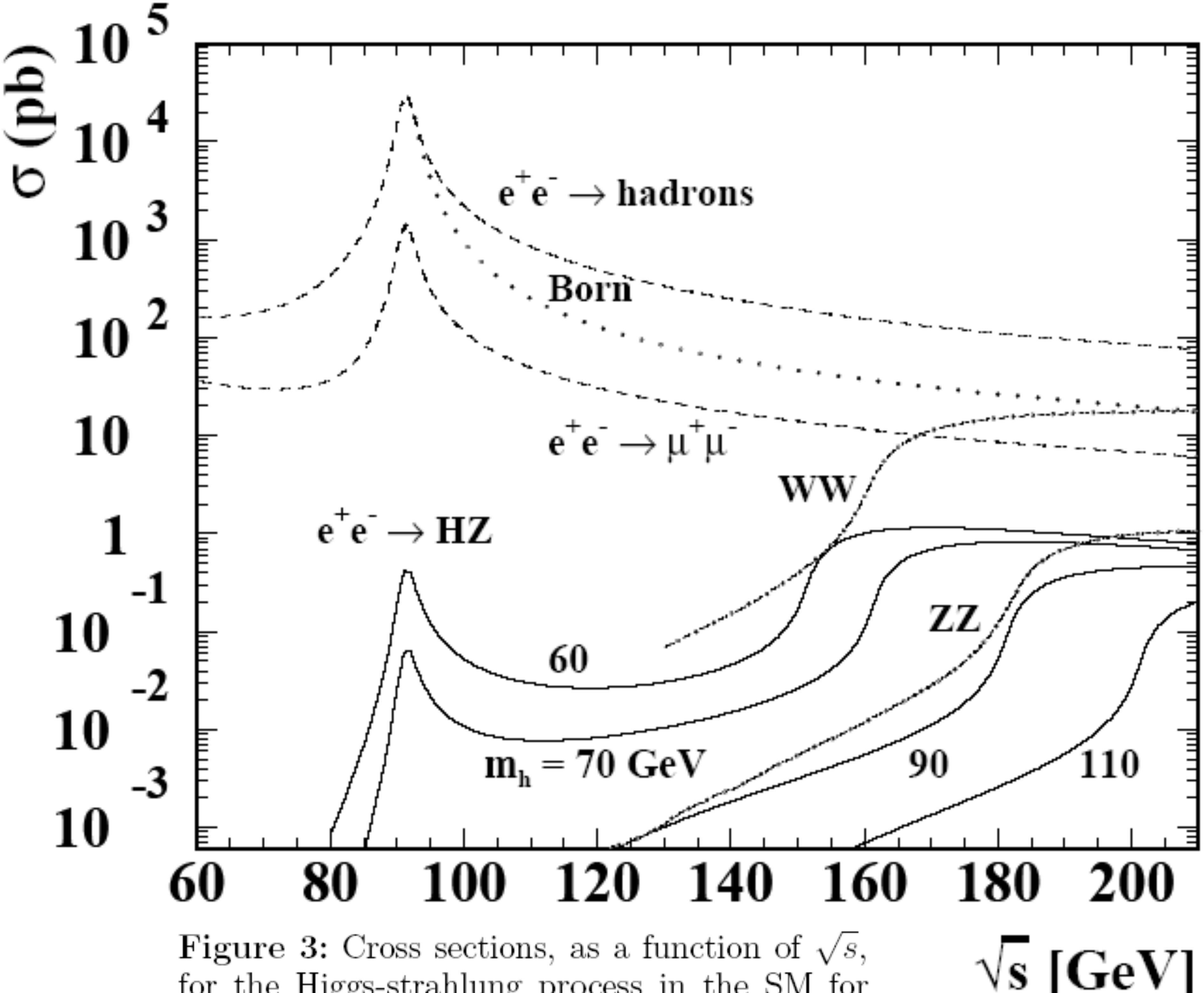
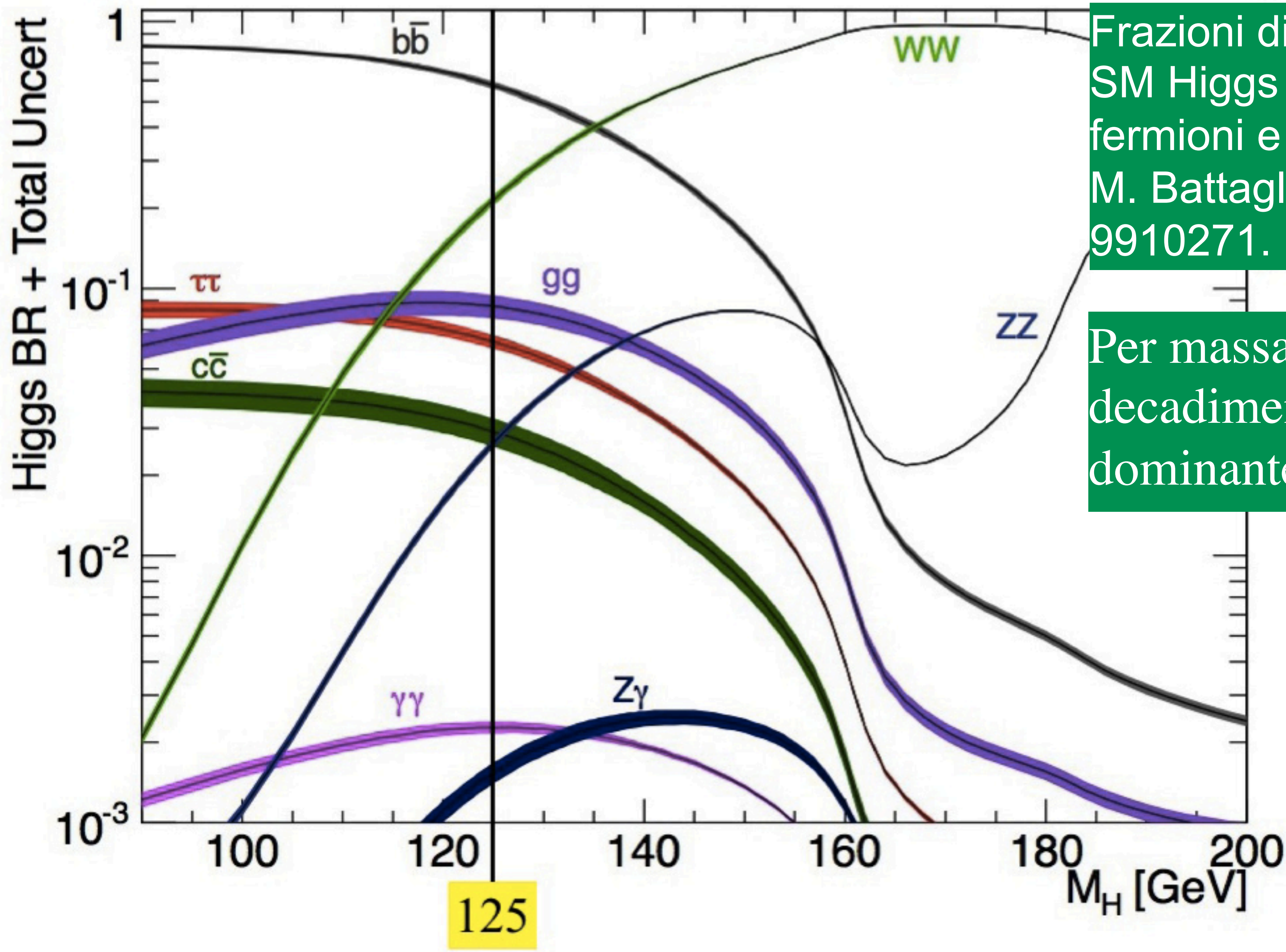


Figure 3: Cross sections, as a function of $\sqrt{s}$, for the Higgs-strahlung process in the SM for fixed values of m_{H^0} (full lines), and for other SM processes which contribute to the background.

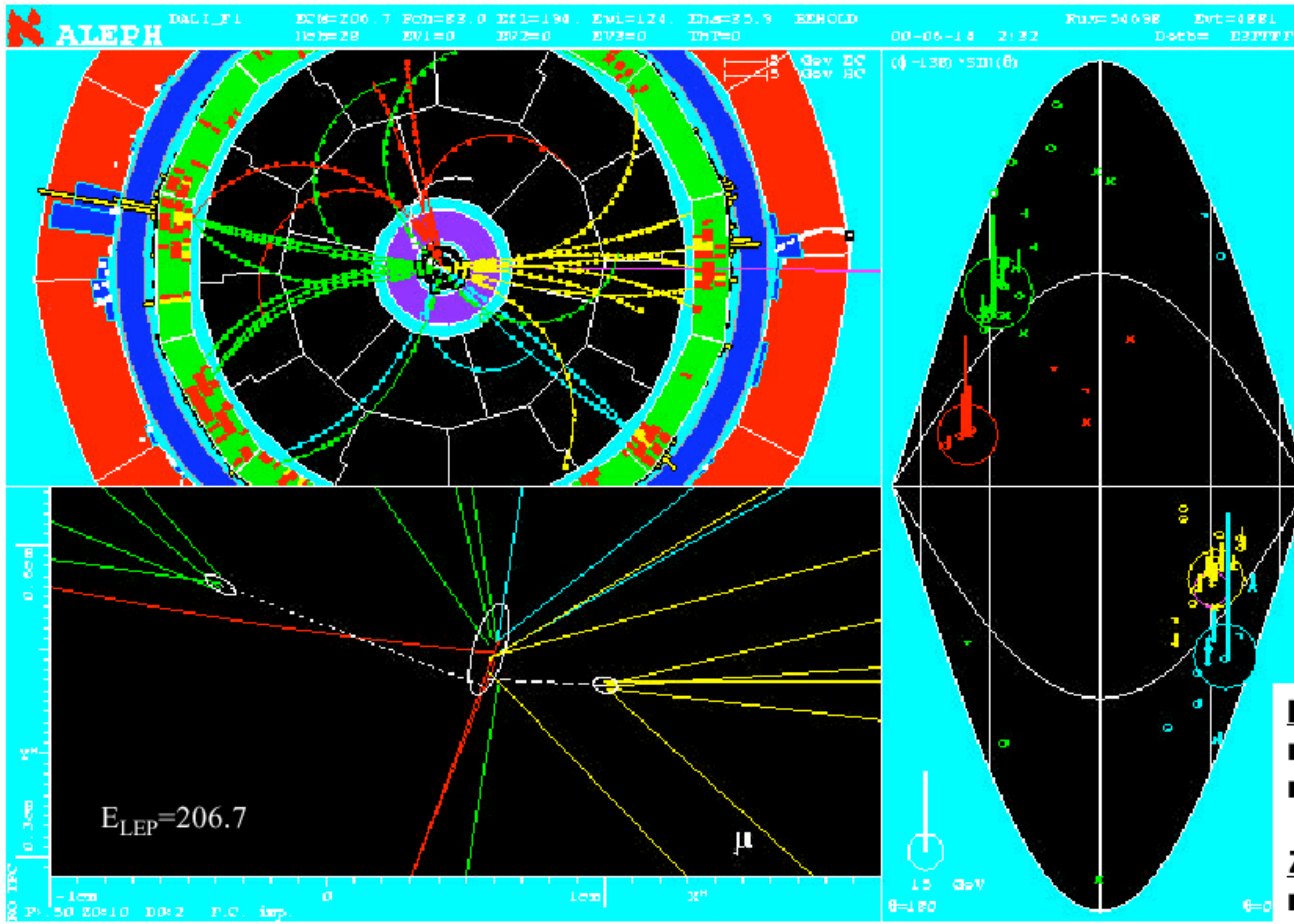
Rapporti di decadimento del bosone di Higgs



Frazioni di decadimento dello SM Higgs in coppie di fermioni e VV.
M. Battaglia, hep-ph/ 9910271.

Per massa <130 GeV, il decadimento in b b-bar e' dominante

ALEPH: candidate for e+e-→Z+H (Summer 2000)



2 b cand.

HZ hyp.
m_H=114 GeV
±3 GeV

NN = 0.996

jet	b-tag:
Z	
1	0.14
2	0.01
H	
3	0.99
4	0.99

kin. mass fit
m_H=112.4GeV
m_Z=93.3GeV

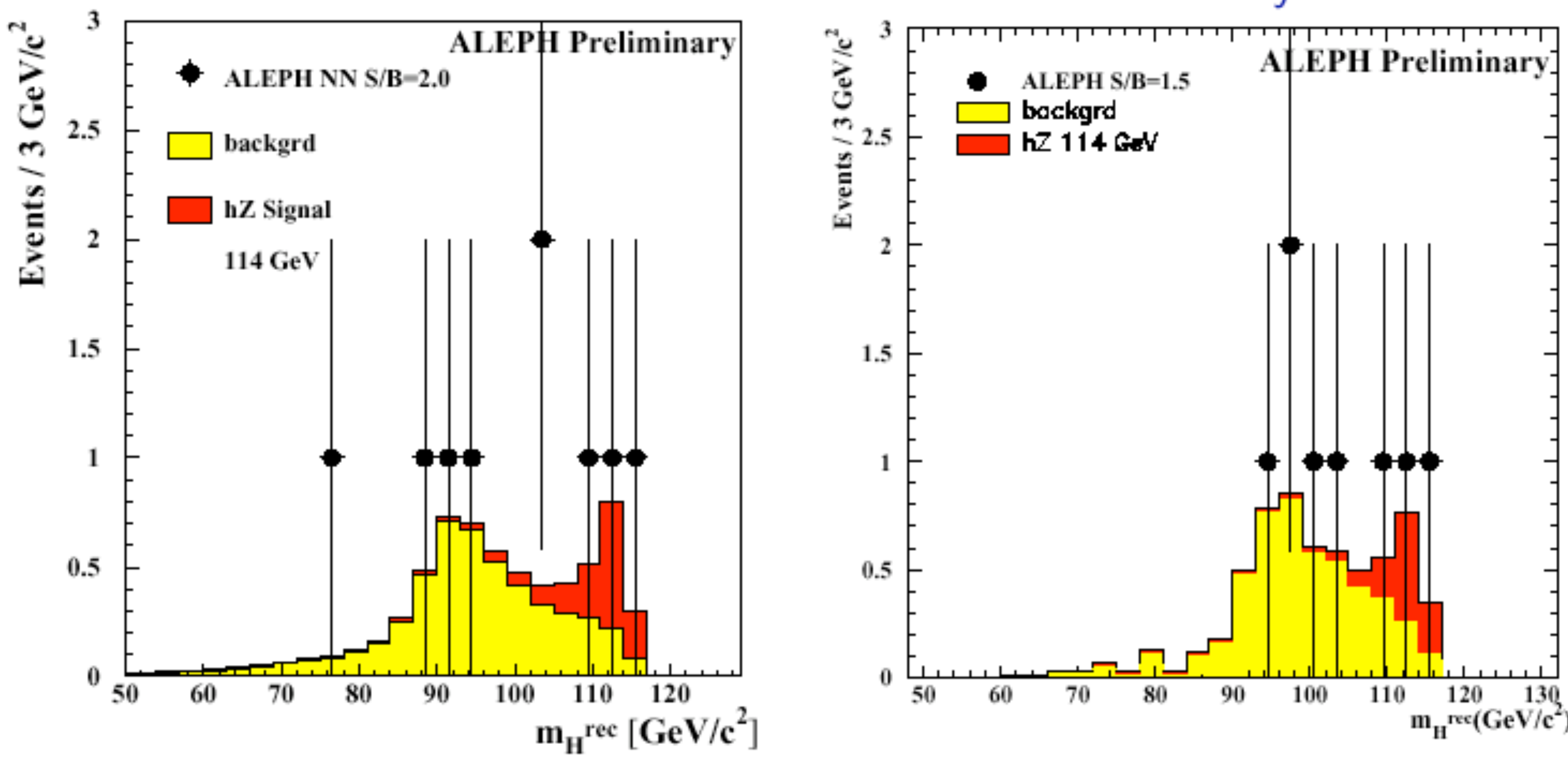
ZZ hyp.
m_Z=102 GeV
m_Z=91.7GeV

Mass plot by ALEPH (Sept. 2000)

Mass Plot - Tight Cuts

NN Analysis

CUT Analysis



When cuts are tightened, both accept the same three four jet events with M_H >109 GeV/c^2

The survival of these three candidates indicates that they are indeed quite signal-like

Peter McNamara　　Status of the Higgs Search at Aleph　　November 3, 2000

LEP in Year 2000

- LEP has obtained important results in the last months of operation in the year 2000
- evidence for a Higgs particle at about 115 GeV/c^2.
- LEP Collaborations requested a further run in 2001(from May to October) in order to consolidate the data.

Agreement with SM Higgs cross-sect. for

$$m_H = 115.0^{+1.3}_{-0.9}\ \text{GeV}$$

P. Igo-Kemenes - LEP Seminar - Nov. 3, 2000

Statistical Significance

2.2	September 5
2.3	LEP fest
2.9	November 2

- Run in September and October has been very beneficial: significance increased, better understanding of background

LHC project

Orders are leaving on schedule and within budget; ≈ 1.7 BCHF committed (CERN money+ special contributions)

The civil engineerings have gone through a difficult phase, with comparatively little damage (≈ 6 months delay)

The superconducting dipoles of the pre-series perform brilliantly

One cryoline prototype is qualified, other two are being tested, contracts next year

ALL LHC COMPONENTS HAVE BEEN TESTED (MAC, Nov.15)

Detector construction is taking off

LHC-C agrees they will fit in this schedule (but manpower problems)

The updated estimate of the LHC schedule, which takes into account further delays in LEP dismantling was reported to CC of Nov. 17 and included in the LHC status report. It foresees:

commissioning in 2005;

a physics run at limited luminosity (~1-2 fb^{-1}) in 2006;

a higher luminosity run (~10 fb^{-1}) in 2007.

Higgs Boson at the LHC

- SM Higgs boson can be discovered at ≈ 5 σ after ≈1 year of operation (10 fb^{-1}/ experiment) for $m_H \approx 150$ GeV
- Discovery faster for larger masses
- Whole mass range can be excluded at 95% CL after ~1 month of running at 10^{33} cm^{-2} s^{-1}.

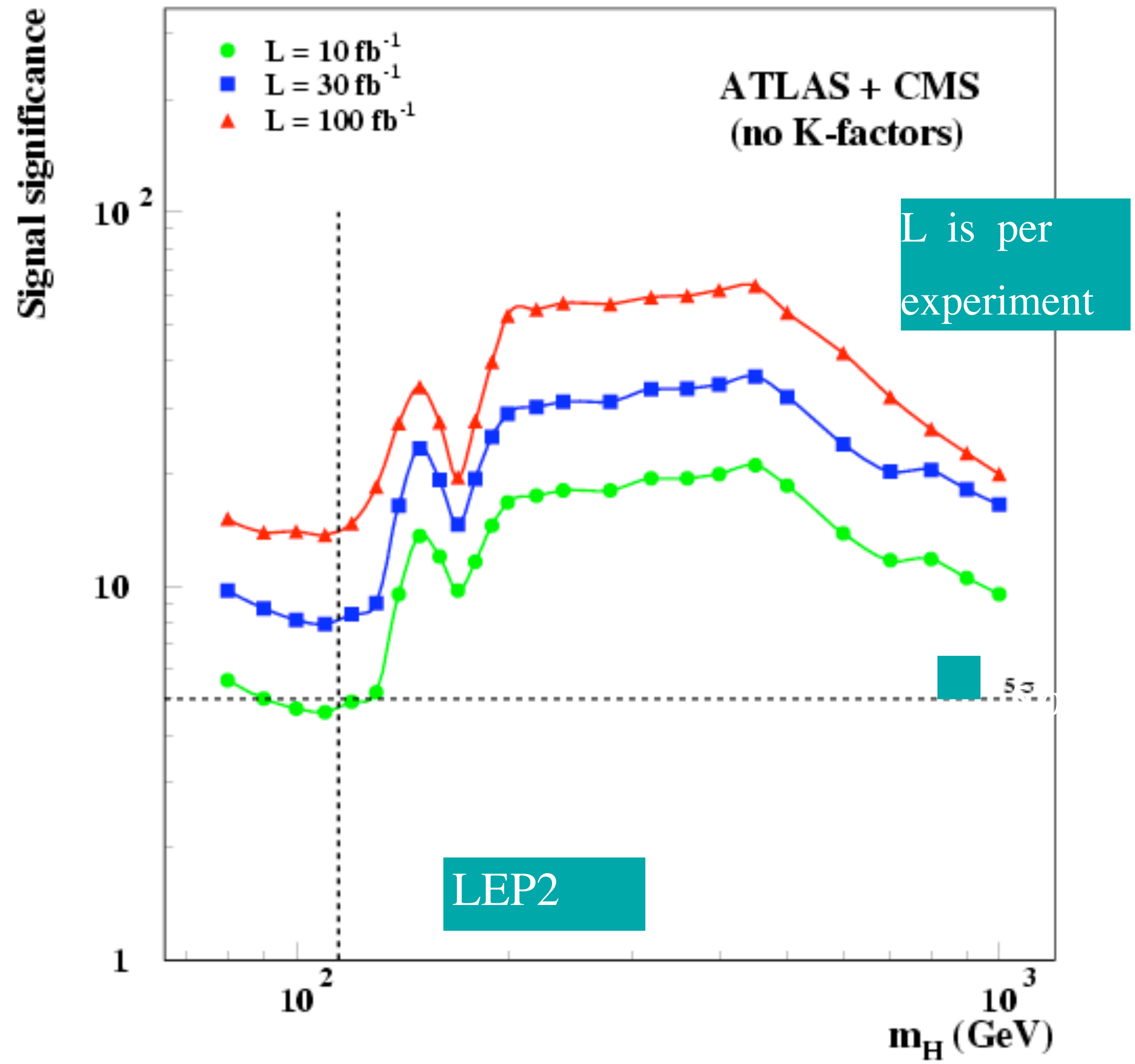
<u>results are conservative:</u>

-- no k-factors

-- simple cut-based analyses

-- conservative assumptions on detecto performance

-- channels where background control is difficult not included, e.g. $WH \perp l \, b\bar{b}$



LEP RUNNING A FULL YEAR IN 2001: OBJECTIVES AND CONSEQUENCES

- beam energy of 104.1 GeV (+1.5GeV), integrated luminosity of 200 pb^{-1}

M_H= 115: 2.9σ –> 5.3±0.5σ
M_H= 116: 2.6σ –> 4.3±0.5σ

may be inconclusive !!

- Additional cost: 110 MCHF (40 LEP running, 70 penalities, rescheduling...)
- Delay to the LHC ≈ 1 year
- CERN manpower is decreasing: $\Delta_{manpower}$≈ -100 FTE/year:

Works reported by one year will find less manpower to be executed

- Agreements with CERN Non- Member States on the LHC ?

The future of CERN is in the LHC !!!

CC Statement

"On 17th November 2000, the CERN Committee of Council held a meeting to examine a proposal by the Director-General concerning the continuation of the existing CERN programme, which foresees the decommissioning of the LEP accelerator at the end of the year 2000.

The Committee has expressed its recognition and gratitude for the outstanding work done by the LEP accelerator and experimental teams.

It has taken note of the request by many members of the CERN Scientific Community to continue LEP running into 2001 and also noted the divided views expressed in the Scientific Committees consulted on this subject.

On the basis of these considerations and in the absence of a consensus to change the existing programme, the Committee of Council supports the Director-General in pursuing the existing CERN programme."

This decision moves us definitely into the LHC era
A powerful complex, machine and detectors, to f
explore the Higgs and SUSY region

Le Roi est mort
Vive le Roi !!

January 2001: the excavation of the tunnel from SPS to LHC hits the LEP/LHC tunnel: the LHC era begins