# Luciano Maiani:
# . Lezione Fermi 23
# L'idea di Touschek al limite: il collisore elettrone-positrone del CERN

1. LEP: un balzo in avanti
2. I parametri di LEP
3. La rivoluzione nei computer degli anni ’90 e la Web
4. I risultati di LEP, in breve
5. Il panorama delle macchine nel 2004: risultati e promesse

# 1. LEP: un balzo in avanti

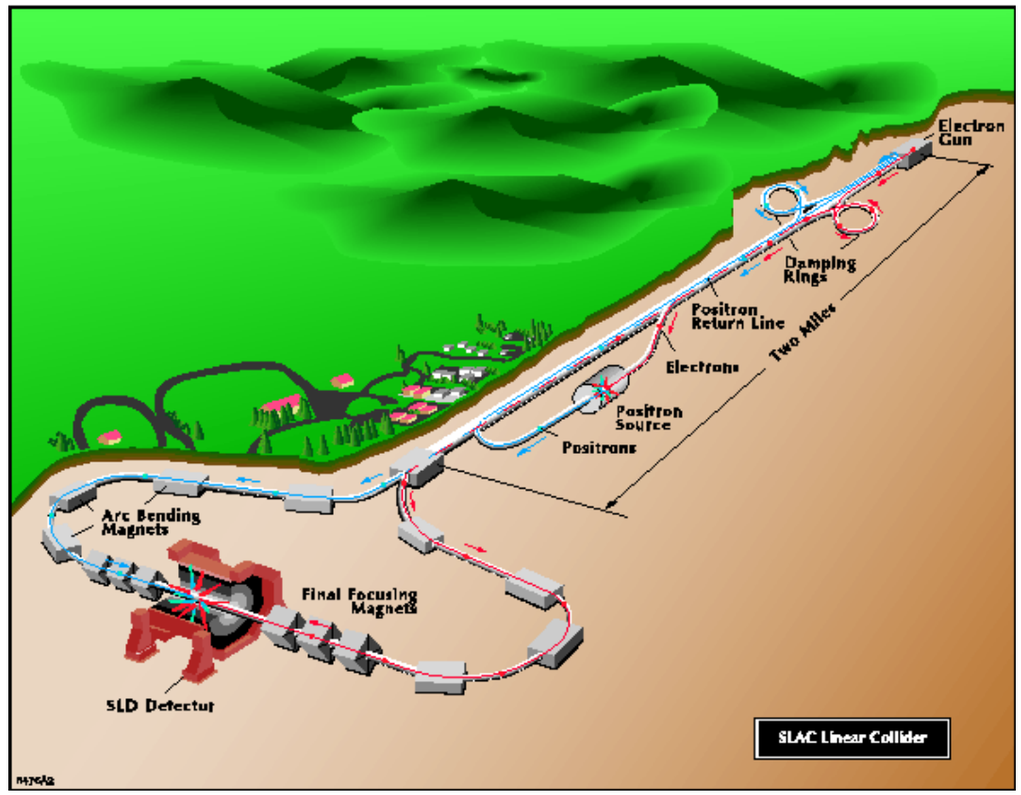
- La scoperta delle correnti neutre aveva indicato i valori delle masse degli ipotetici bosoni intermedi, W e Z, circa 80 e 90 volte la massa del protone
- la sfida di entrare nel nuovo modo delle energie “elettrodeboli” fu raccolta dalla comunita’ scientifica europea e dal CERN con la proposta di una macchina di precisione che portava al limite l’idea di Bruno Touschek: un anello di collisione gigantesco, LEP (Large Electron Positron ring)
- le dimensioni erano dettate  dalla necessita’ di limitare la perdita di energia degli elettroni per emissione di luce di sincrotrone, che cresce rapidamente con l’energia ma inversamente al raggio dell’orbita

# LEP time-line

- **1976 Richter at CERN, Study of parameters of a big e+e- circular at CERN.** Tra i primi ad affrontare il problema, Burton Richter, "on leave" al CERN nel 1976, aveva calcolato le dimensioni ottimali di una simile macchina, rispetto alla luminosita' necessaria, ai costi del tunnel ed a quelli richiesti per compensare l' energia perduta per la radiazione di sincrotrone. Il risultato era una macchina con un raggio di 5-6 km, che si sarebbe adattata molto bene nella pianura di Gex.
- **1978.** ECFA (European Committee for Future Accelerators) commissiona un gruppo di studio sull' argomento.
- **1981.** Il Consiglio del CERN approva il progetto finale del LEP. Prevede la costruzione: (i) di una macchina convenzionale con energia fino a 50 GeV/fascio (LEP1) (ii) l' aumento dell' energia fino a 100 GeV/fascio con l' inserzione di cavita' a radiofrequenza superconduttive (LEP2), e conseguente aumento di luminosita', per studiare la produzione di coppie di bosoni intermedi. La direzione del progetto fu affidata ad Emilio Picasso, che ha portato a compimento la prima fase nel 1989.
- **1981** SppbarS in operazione: jets
- **1982** Scoperta di W&Z
- **1989** Prime collisioni a LEP (14 Luglio).

# La competizione con gli USA

- Nel 1983 parte a Stanford, la costruzione dello SLAC Linear Collider (SLC) diretta dal Premio Nobel Burton Richter, basato su un nuovo principio.
- Due fasci indipendenti e paralleli, uno di elettroni e uno di positroni, accelerati dalla stessa struttura lineare per circa due miglia, fino a raggiungere ciascuno l'energia di circa metá della massa dello $Z^0$. I due fasci, separati su due archi opposti, collidono frontalmente per produrre lo $Z^0$ (single pass collider).




- SLC apre la strada ai futuri collisori lineari per elettroni, ad energie non raggiungibili con gli anelli di collisione, a causa dell'eccessiva radiazione di sincrotrone degli elettroni su orbite circolari. Picasso e Richter si conoscono bene, come le rispettive mogli Mariella e Laurose, e competono sportivamente.
- 12 Aprile 1989, SLC taglia il traguardo e produce il primo $Z^0$.
- 23 Agosto 1989, il primo $Z^0$ a LEP. L'anello del CERN entra in campo e ben presto si impone come macchina di punta per la sua luminosita'.

# 2. I parametri di LEP

*Caccia al Bosone di Higgs*, L. Maiani, R. Bassoli (Mondadori, 2013)

- Il gruppo di lavoro di ECFA, formato da fisici europei esterni al CERN e presieduto da A. Zichichi, doveva rivedere il “Libro Rosa” preparato dal CERN per caratterizzare la macchina
- una forte partecipazione italiana: Cabibbo partecipa alla definizione dei parametri dell’acceleratore (non per niente, studente di Touschek)
- scontro sul diametro del tunnel: il gruppo appoggia la proposta di un diametro abbastanza grande da prevedere una futura macchina a protoni con magneti superconduttori, il partito anti-CERN non vede bene un futuro cosi’ lungo e vuole la larghezza strettamente indispensabile per gli elettroni di LEP, e’ in gioco l’approvazione della macchina.
- Il compromesso: ci stara’ una macchina superconduttiva a protoni, ma con un solo anello: assurdo? grande sfida?
- per avere l’ energia piu‘ alta possibile il tunnel aveva una circonferenza di 30 km ed entrava ben sotto il Jura.
- Il contemporaneo scavo della galleria del Gran Sasso, gravemente ostacolato dall’acqua a pressione, consiglia di portare il tunnel fuori dalla montagna, Schopper e Picasso riducono la circonferenza a 27 km.

Francois Mitterand alla cerimonia di apertura dei lavori di scavo di LEP, con Erwig Schopper, Direttore Generale del CERN (destra) e Emilio Picasso, Direttore del progetto (sinistra), settembre 1983.

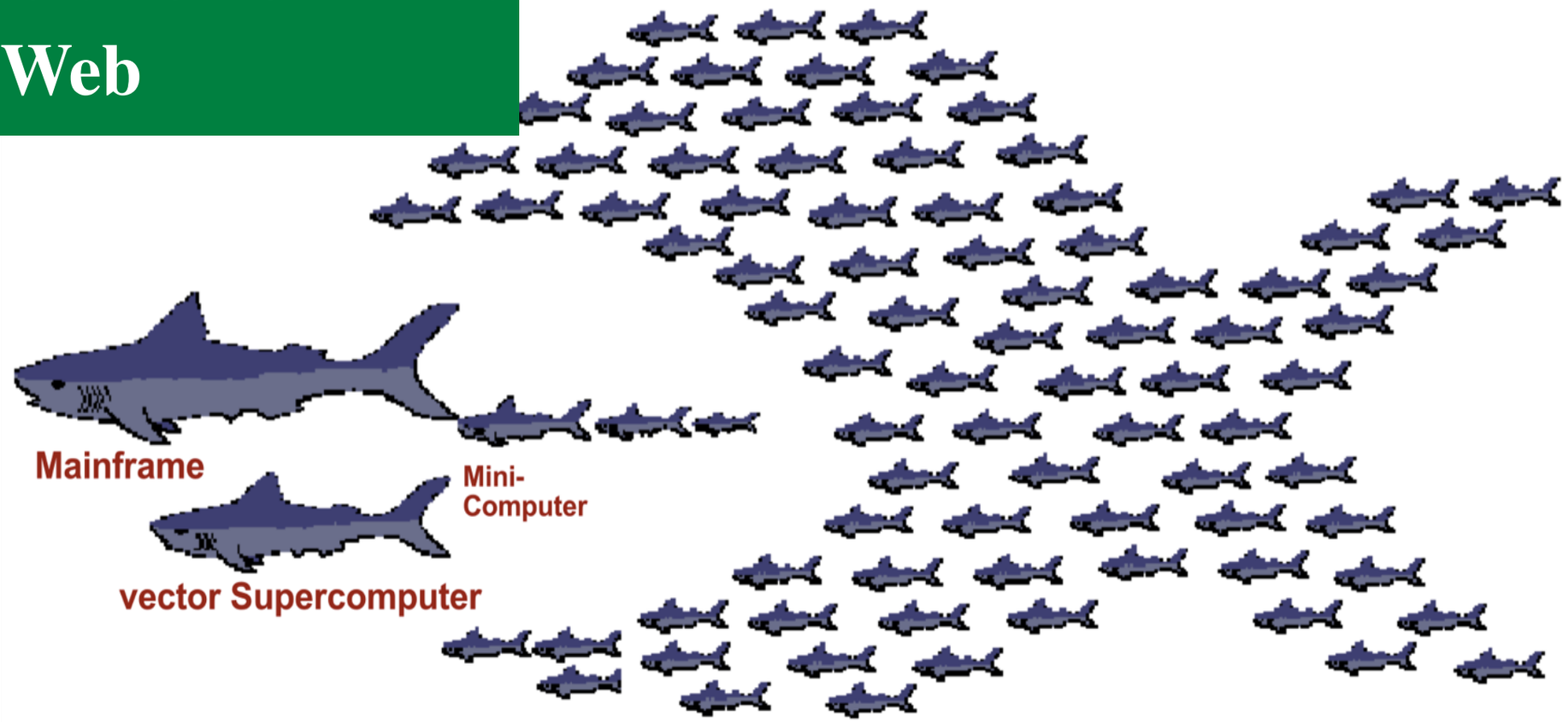
Emilio Picasso all'inaugurazione di LEP, alla presenza dei rappresentanti degli Stati Membri, per la Francia il presidente Mitterand, novembre 1989.

Primi fasci a LEP, con Carlo Rubbia e Erwig Schopper.
In primo piano a destra, Steve Meyers

# LEP performance

- from *The History of CERN*
- For seven years, the accelerator operated at 100 GeV, producing 17 million Z particles, uncharged carriers of the weak force.
- LEP was then upgraded for a second operation phase, with as many as 288 superconducting accelerating cavities added to double the energy and produce W bosons, also carriers of the weak force. LEP collider energy eventually topped 209 GeV in the year 2000.
- The Large Electron-Positron collider was shut down for the last time at 8 am on 2 November 2000. Members of government from around the world gathered at CERN on 9 October to celebrate the achievements of LEP and its 11 years of operational life.
- With the tunnel now  available for work, teams began excavating the caverns to house the four big detectors on the Large Hadron Collider.

# 3. The computer revolution of 1990s and the Web




## NOW

Found at the NOW project (http://now.cs.berkeley.edu)

- PC+Linux: the new supercomputer for scientific applications

obswww.unige.ch/~pfennige/gravitor/gravitor_e.html

www.cs.sandia.gov/cplant/

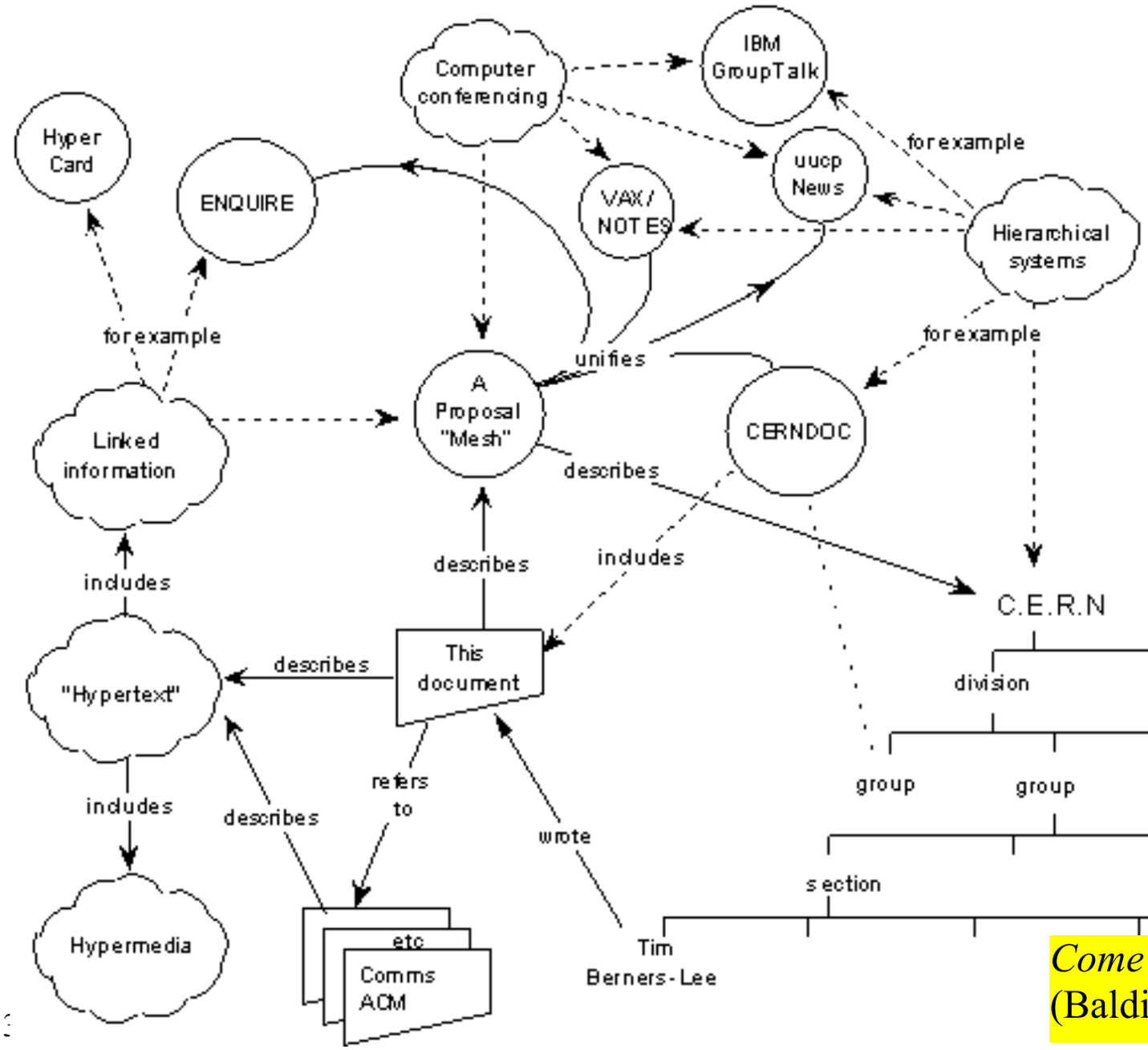
- Principle well established; farm examples abound

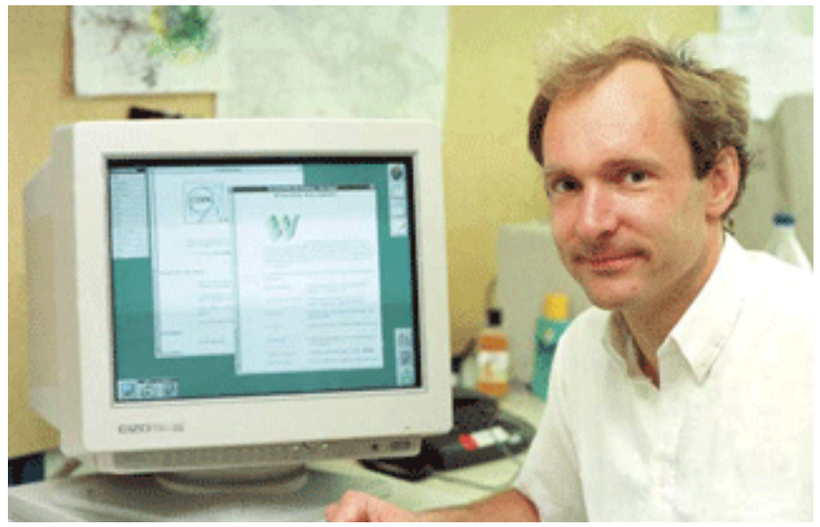
now.cs.berkeley.edu

www.ncsa.uiuc.edu/General/CC/ntcluster/

# World Wide Web (1989)

- Copertina della proposta di Tim Berners-Lee che illustra la struttura della futura World Wide Web (Marzo 1989)
- il suo capo, Mike Sendall, annota: *vague but exciting*...



*Come e' nato il Web*, J. Gillies, R. Cailliau (Baldini&Castoldi, 2000)

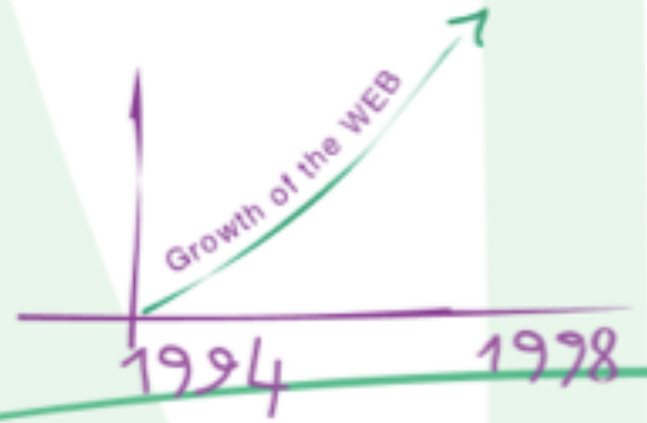
EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN

# World-Wide Web :

## Invented at CERN

Everyone knows the World-Wide Web, but not everyone knows that it was invented at CERN. Conceived to give particle physicists easy access to their data wherever they happened to be, the Web has grown into a telecommunications revolution.



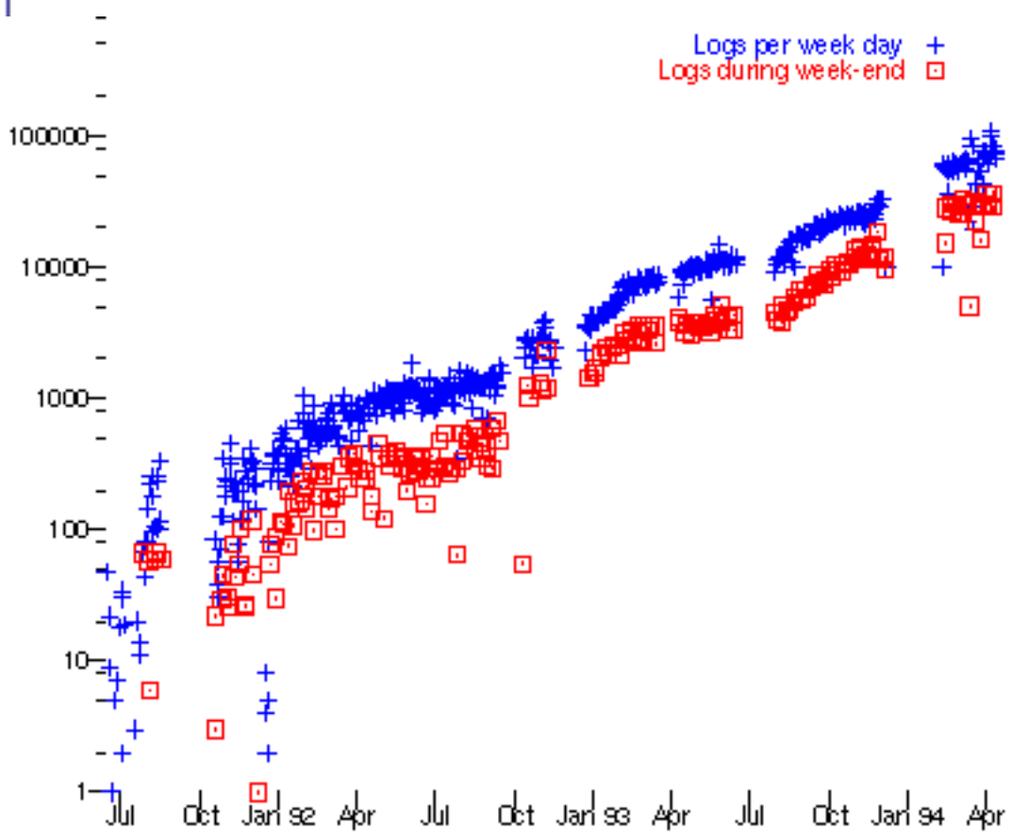

### What is the Web ?

But what is the Web ? In short, it is a world of information at the click of a mouse. To use it, you need a computer, a connection to the Internet, and a browser programme. When you run your browser, it displays a page of information which might be held on your own computer or fetched from somewhere else, you needn't know or even care where it comes from. Certain words, phrases, or images are highlighted, and clicking on them causes the browser to go off and find another page, which probably contains more highlighted items, and so on. The Web knows no geographical boundaries. For example, starting from the CERN 'Welcome page' in Switzerland, your next click might take you to the other side of the world. All the information seems to be in the little box in front of you, and in a sense it is. When you click on a piece of highlighted text your browser connects to another computer, asks it for the requested information, and displays it on your screen. You are then free to browse the new page at leisure, the computers have finished their 'conversation'.

### How did it start ?

It all began in 1989, when Tim Berners-Lee proposed a distributed information system for CERN based on hypertext. By hiding network addresses behind highlighted items on the screen, information could be linked between several computers. This system became the Web, with the world as its library.

I siti web (1 nel 1989) aumentano vertiginosamente nel tempo




In tre anni, le connessioni alla Web passano da 10 a 1000 al giorno

# 1993. Il CERN rinuncia a tutti i diritti sulla Web

*CERN's decision to make the Web foundations and protocols available on a royalty free basis, and without additional impediments, was crucial to the Web's existence. Without this commitment, the enormous individual and corporate investment in Web technology simply would never have happened, and we wouldn't have the Web today* (Tim Berners Lee, 2003)

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
**CERN** EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

STATEMENT CONCERNING CERN W3 SOFTWARE RELEASE INTO PUBLIC DOMAIN

TO WHOM IT MAY CONCERN

**Introduction**

The World Wide Web, hereafter referred to as W3, is a global computer networked information system.

The W3 project provides a collaborative information system independent of hardware and software platform, and physical location. The project spans technical design notes, documentation, news, discussion, educational material, personal notes, publicity, bulletin boards, live status information and numerical data as a uniform continuum, seamlessly intergated with similar information in other disciplines.

The information is presented to the user as a web of interlinked documents .

Acces to information through W3 is:

- via a hypertext model;
- network based, world wide;
- information format independent;
- highly platform/operating system independent;
- scalable from local notes to distributed data bases.

Webs can be independent, subsets or supersets of each other. They can be local, regional or worldwide. The documents available on a web may reside on any computer supported by that web.





**Declaration**

The following CERN software is hereby put into the public domain:

- W 3 basic ("line-mode") client
- W 3 basic server
- W 3 library of common code.

CERN's intention in this is to further compatibility, common practices, and standards in networking and computer supported collaboration. This does not constitute a precedent to be applied to any other CERN copyright software.

CERN relinquishes all intellectual property rights to this code, both source and binary form and permission is granted for anyone to use, duplicate, modify and redistribute it.

CERN provides absolutely NO WARRANTY OF ANY KIND with respect to this software. The entire risk as to the quality and performance of this software is with the user. IN NO EVENT WILL CERN BE LIABLE TO ANYONE FOR ANY DAMAGES ARISING OUT THE USE OF THIS SOFTWARE, INCLUDING, WITHOUT LIMITATION, DAMAGES RESULTING FROM LOST DATA OR LOST PROFITS, OR FOR ANY SPECIAL, INCIDENTAL OR CONSEQUENTIAL DAMAGES.

Geneva, 30 April 1993

W. Hoogland
Director of Research

H. Weber
Director of Administration

ORGANISATION EUROPEENNE POUR LA RECHERCHE NUCLEAIRE
DIVISION DES FINANCES

# I risultati di LEP, in breve

W. Adam, *Review of 10 years of LEP,* Four Seas Conference, Thessaloniki, 2004

**1976** **B.Richter: $e^+e^-$ machine needed to study weak interactions at high energy; $\sqrt{s}$~200GeV at R~6km seems feasible**

**1st physics study**

**1978** **"Blue Book"**

**Les Houches summer study: baseline 140GeV (200GeV with SC cavities) at $2R\pi$=22.2km**

**What to expect? E.g. possibility of an "invisible" Z for high $N_\nu$!**

**Glashow quotes 4 scenarios; considers the assumption of a correct extra-polation of the 17 parameter model as "arrogant".**

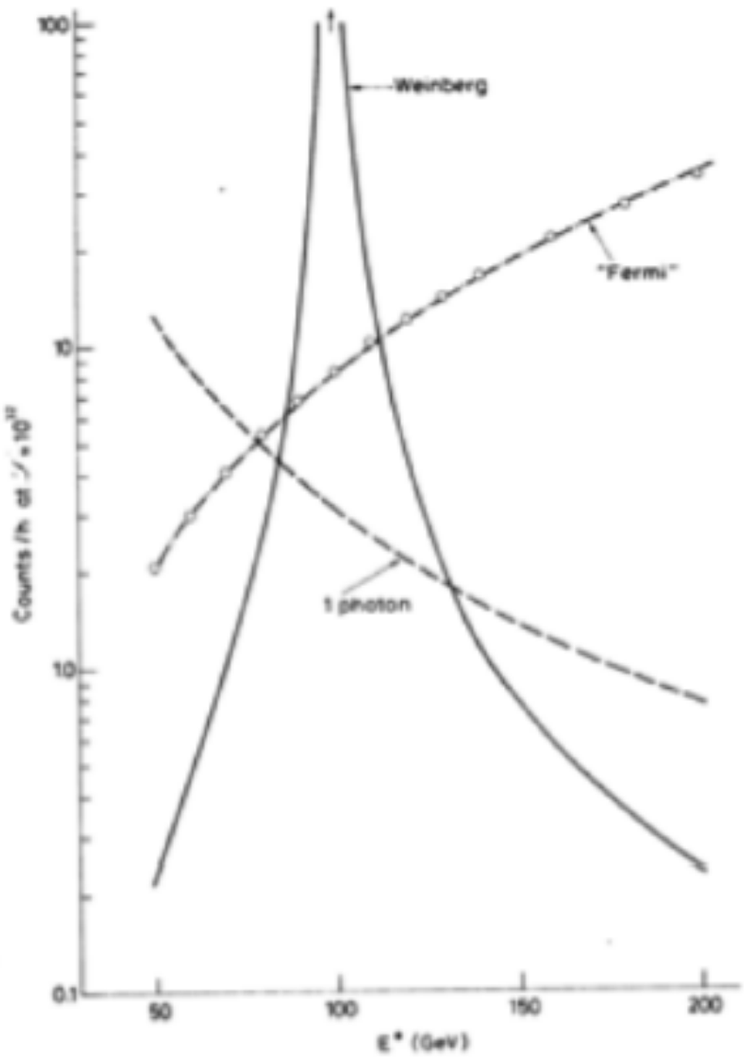



Fig. 2

# Un po' di storia…

**1979** — **"Pink Book": 2Rπ~30km**

**1983** — **Discovery of W and Z**

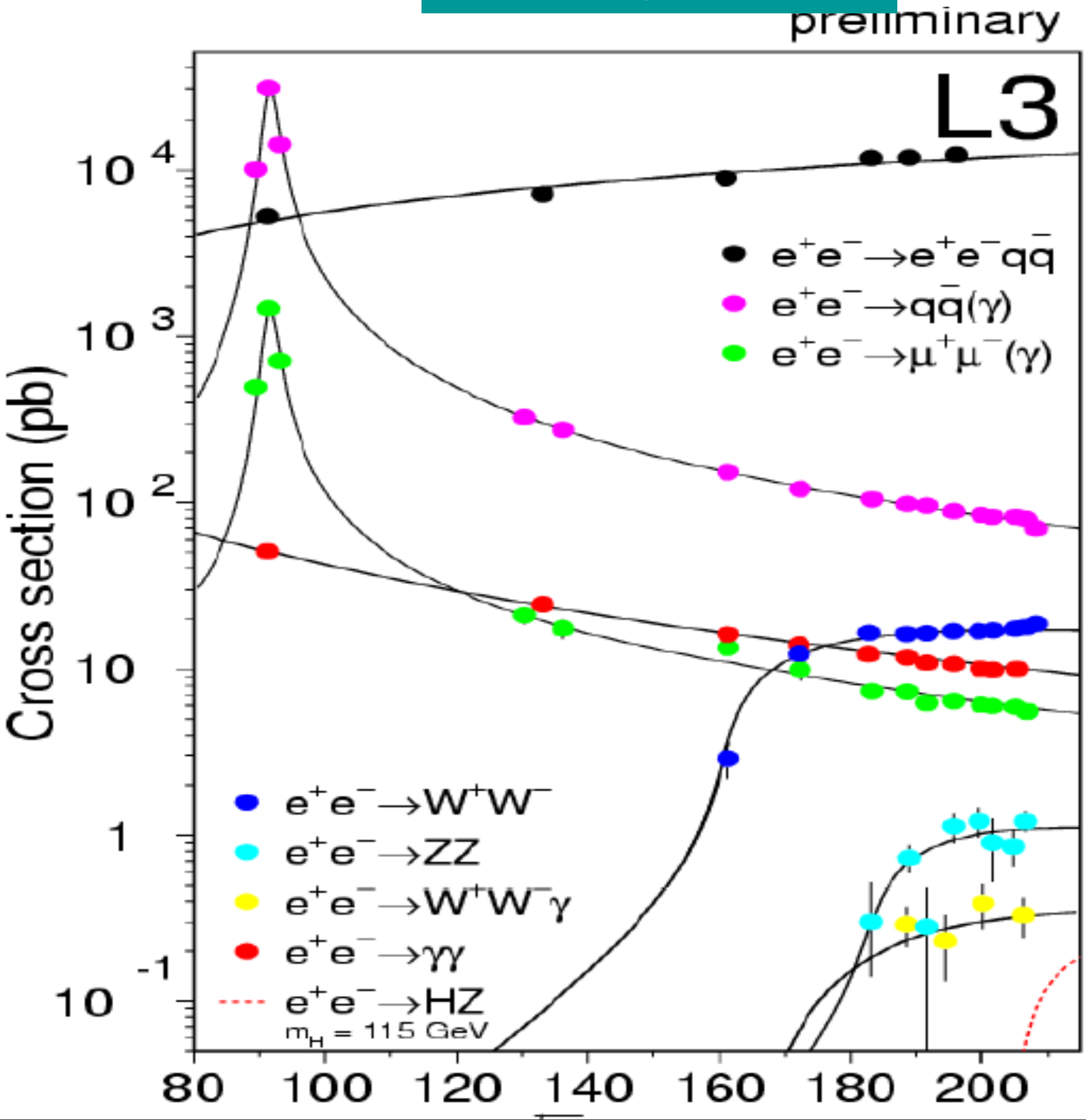
**1984** — **LEP Design Report: 2Rπ=26.7km**

**1986** — **"Physics at LEP": detailed study of the physics scenario**

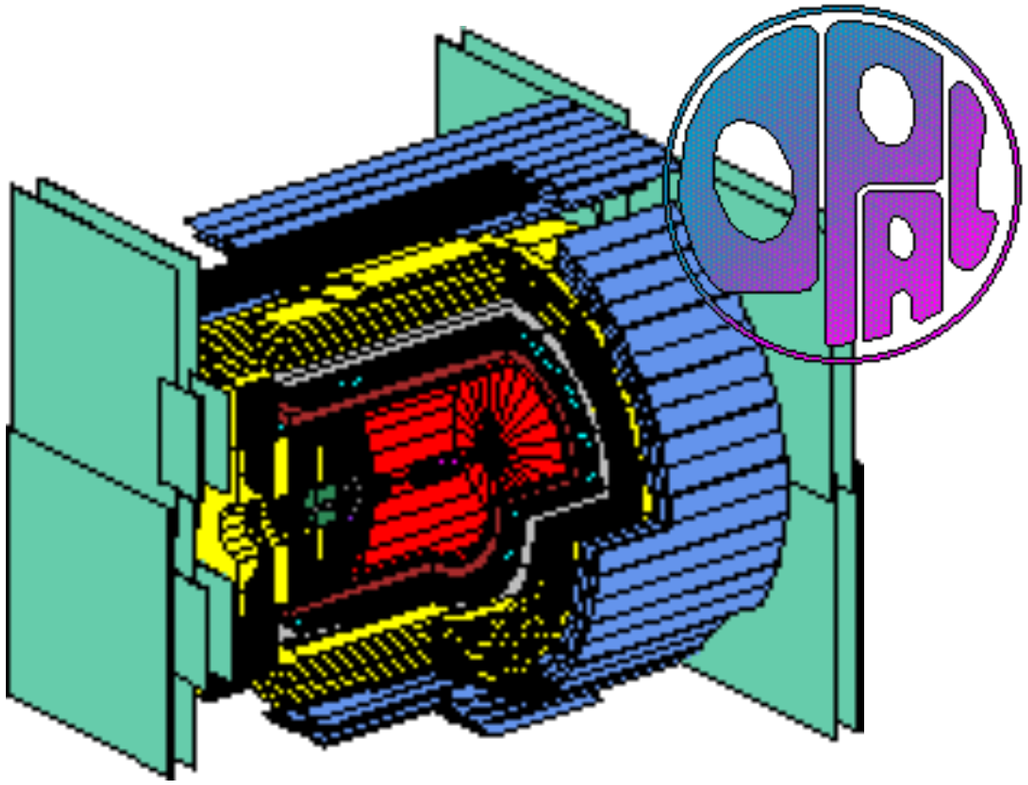
- **Discusses effects of radiative corrections**
- **Treats SUSY (~neglected in first study)**
- **Full chapter on toponium!**

**1989** — **"Z physics at LEP1"**
**Start of LEP operations**

# LEP1, LEP2


preliminary
L3
$e^+e^- \to e^+e^- q\bar{q}$
$e^+e^- \to q\bar{q}(\gamma)$
$e^+e^- \to \mu^+\mu^-(\gamma)$
$e^+e^- \to W^+W^-$
$e^+e^- \to ZZ$
$e^+e^- \to W^+W^-\gamma$
$e^+e^- \to \gamma\gamma$
$e^+e^- \to HZ$
$m_H$ = 115 GeV
Cross section (pb)
$10^4$
$10^3$
$10^2$
10
1
$10^{-1}$
80
100
120
140
160
180
200

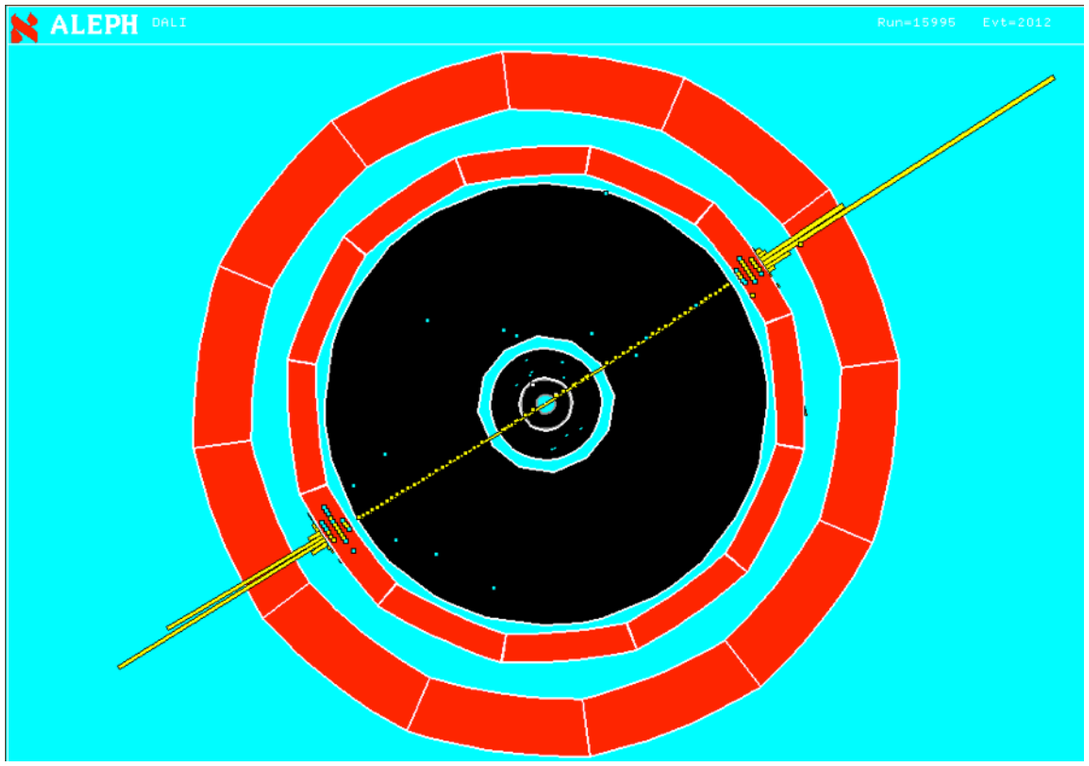
# Gli esperimenti al LEP

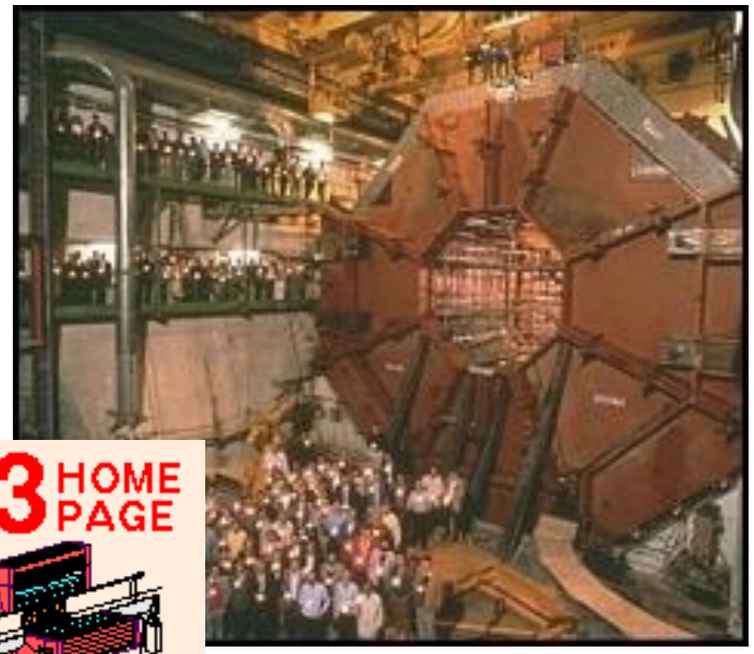



*OPAL*

*DELPHI*

*ALEPH*

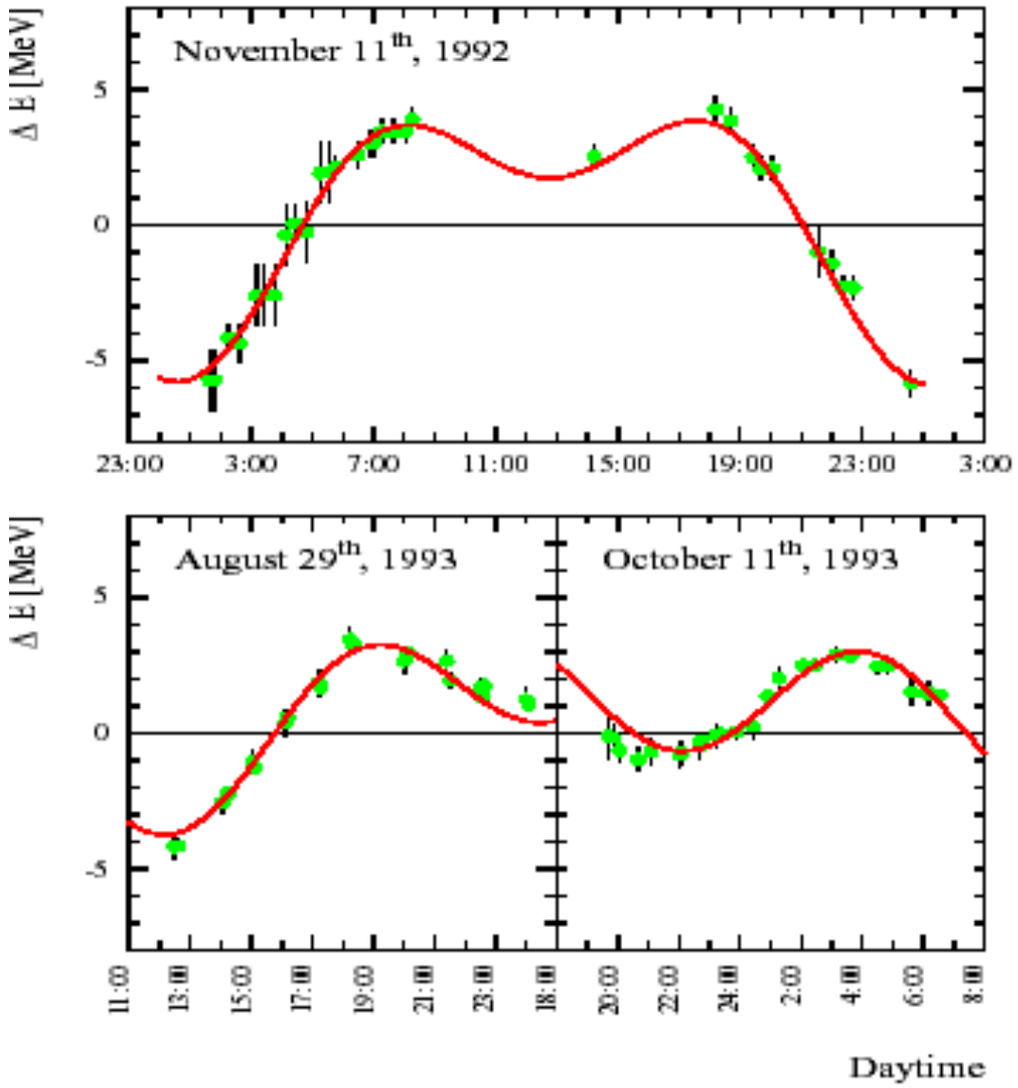


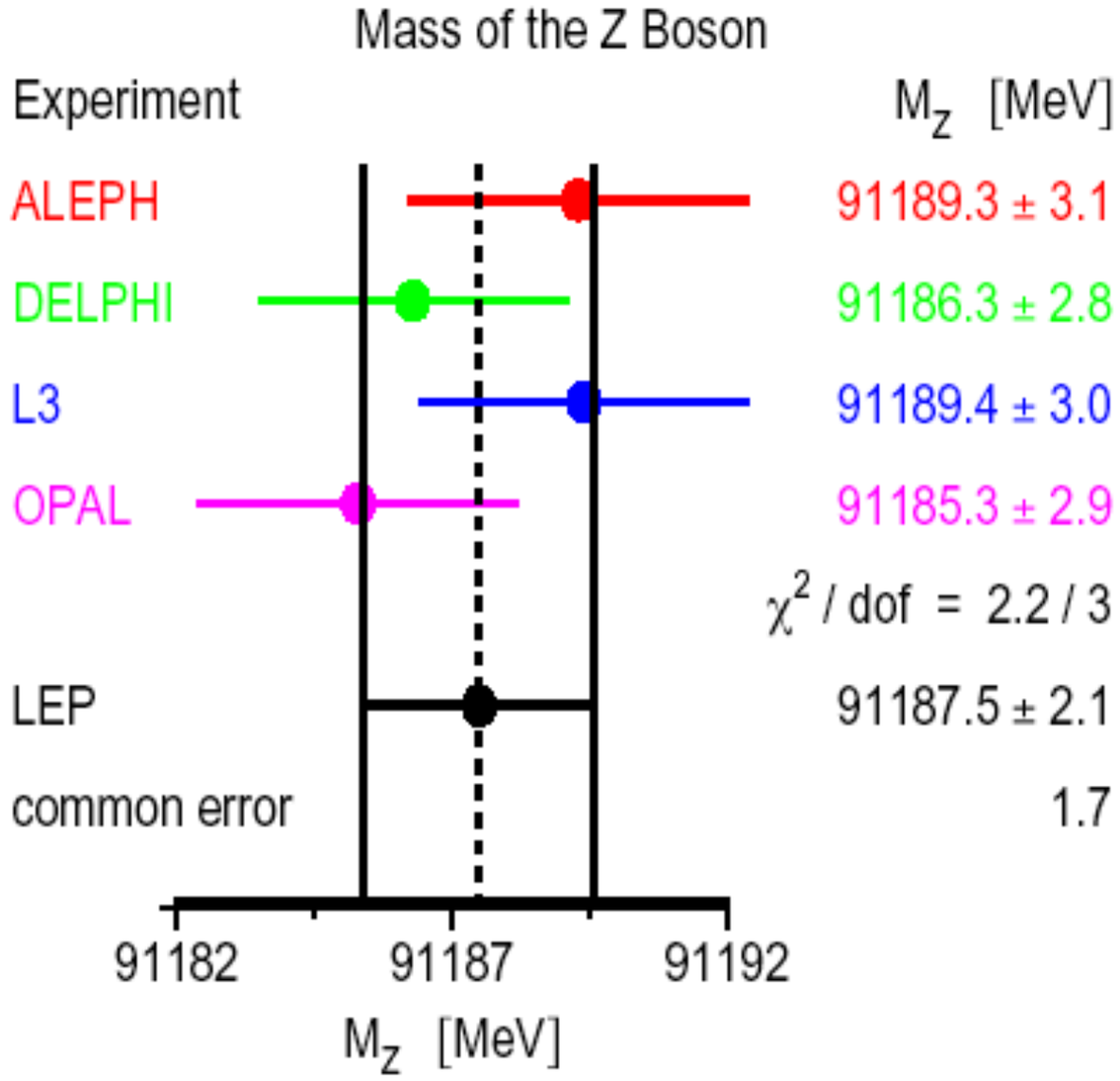



L3 HOME PAGE

# A MODERN EPIC: THE MEASUREMENT OF THE $Z^0$ MASS AT LEP WITH AN ACCURACY OF 20 PPM.

**ONE HAD TO TAKE INTO ACCOUNT THE TIDAL FORCE FROM THE MOON**
**THE LEVEL OF WATER IN THE LAKE AND THE TIMETABLE OF THE TGV!**



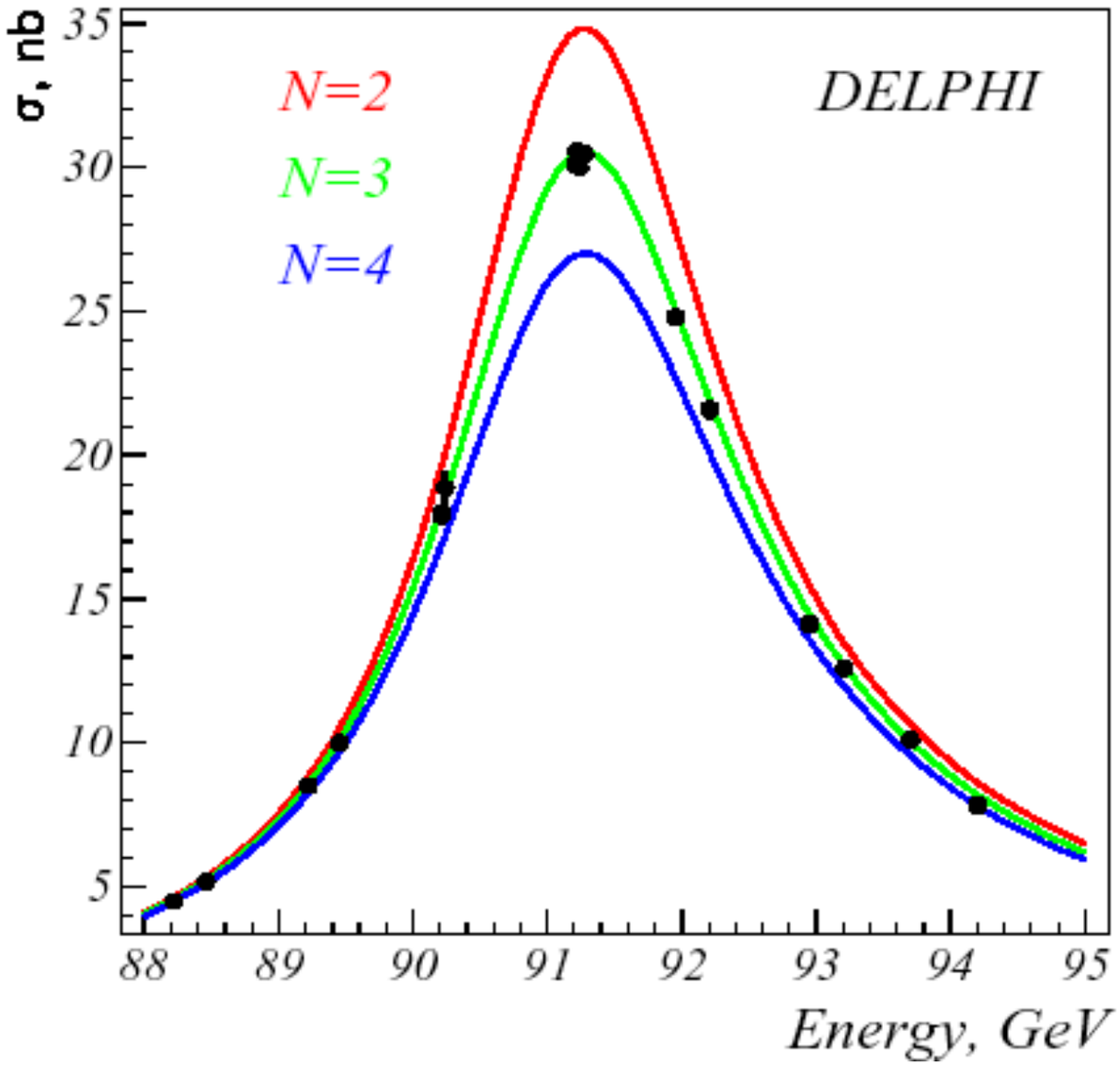
# Tre risultati straordinari

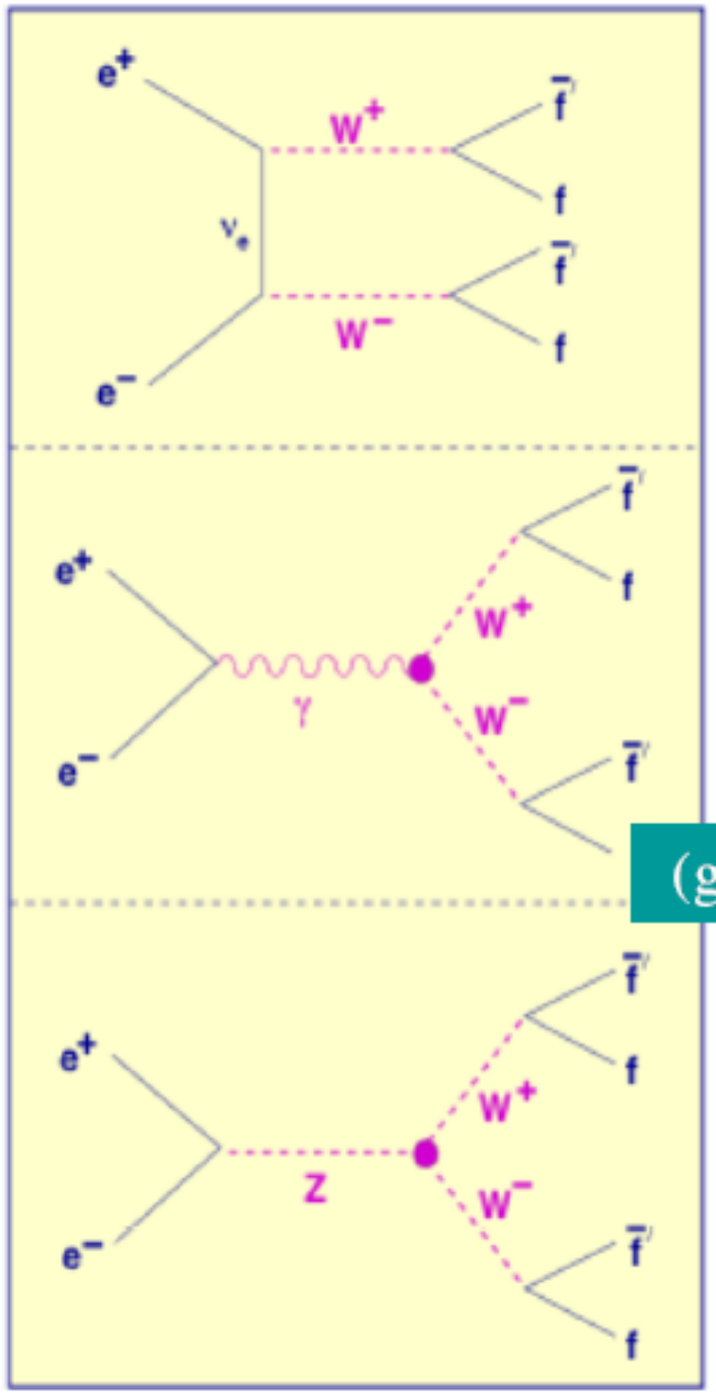
- Solo 3 neutrini!
- Le forze elettrodeboli sono di Yang-Mills
- Il bosone di Higgs pesa piu' di 114 GeV … e meno di 200 GeV

# A VERY EARLY AND CLEAR ANSWER FROM LEP:

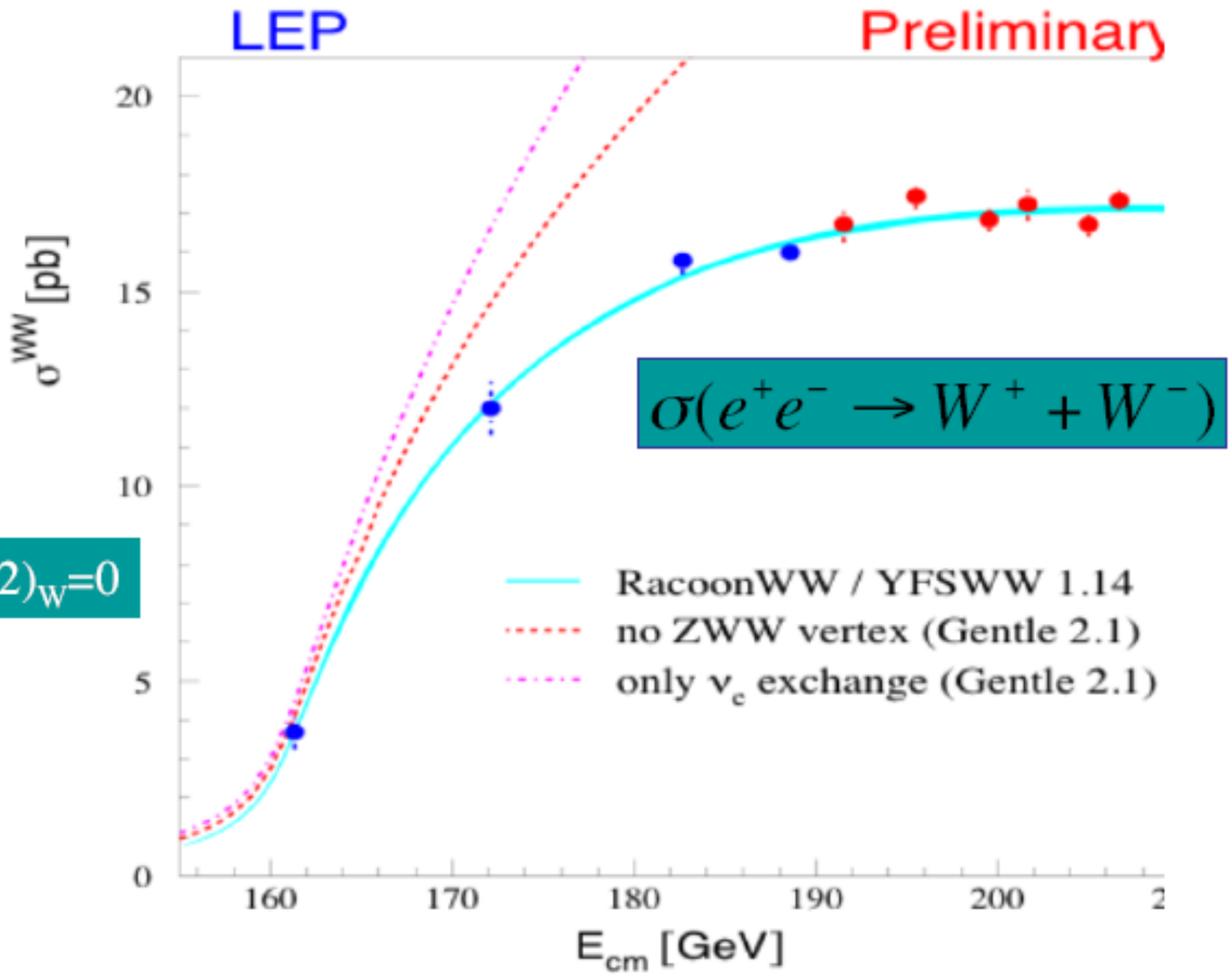
## THERE EXIST THREE FAMILIES OF FERMIONS AND ONLY THREE, AT LEAST WITH A VERY LIGHT NEUTRINO.

## INTRODUCED IN THE BIG BANG MODEL THIS RESULT LEADS TO PREDICT 24 PERCENT OF PRIMORDIAL HELIUM IN THE UNIVERSE, WHICH IS THE OBSERVED VALUE.

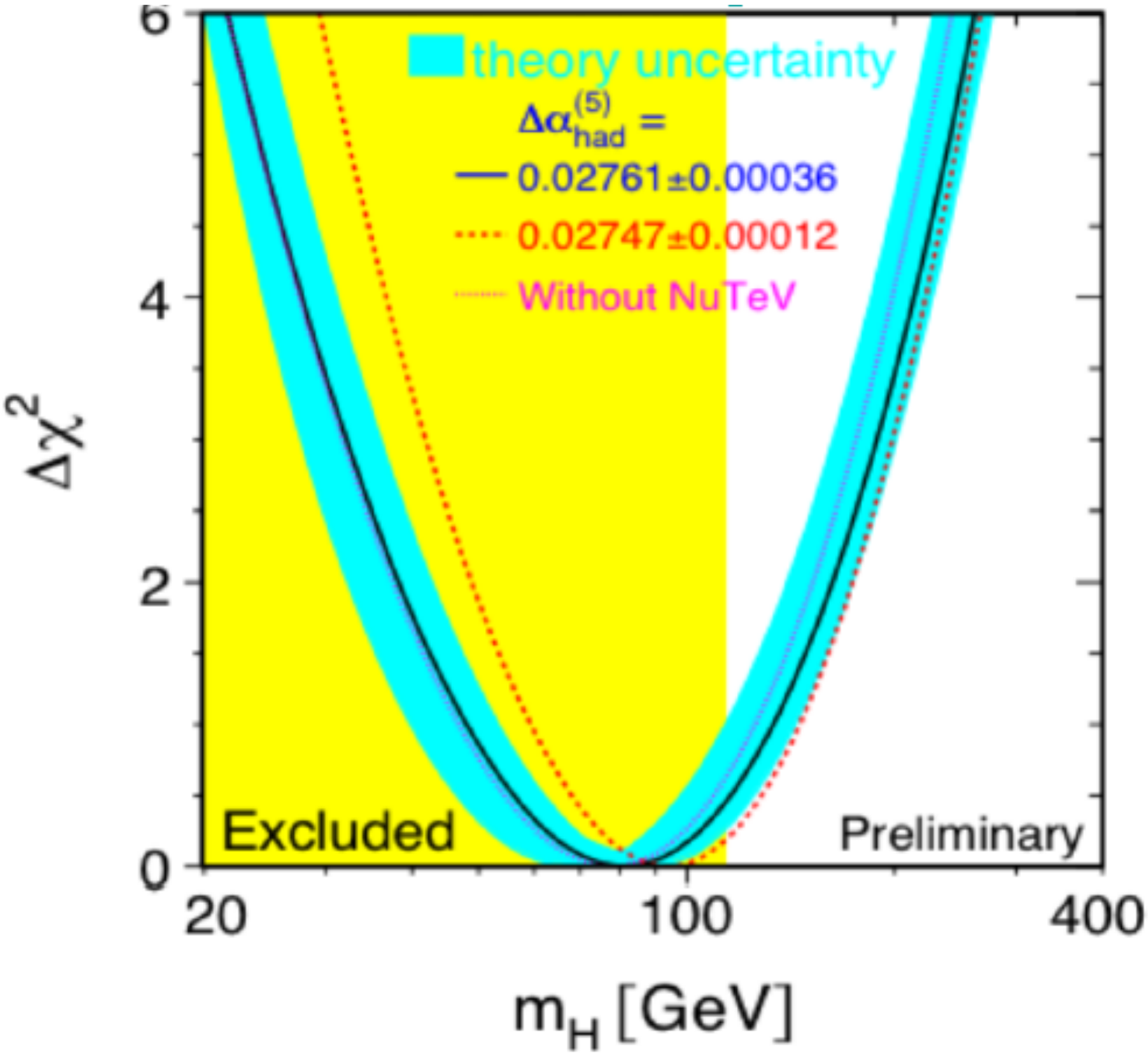



e+
e−
W+
W−
νe
f̄
f
γ
Z

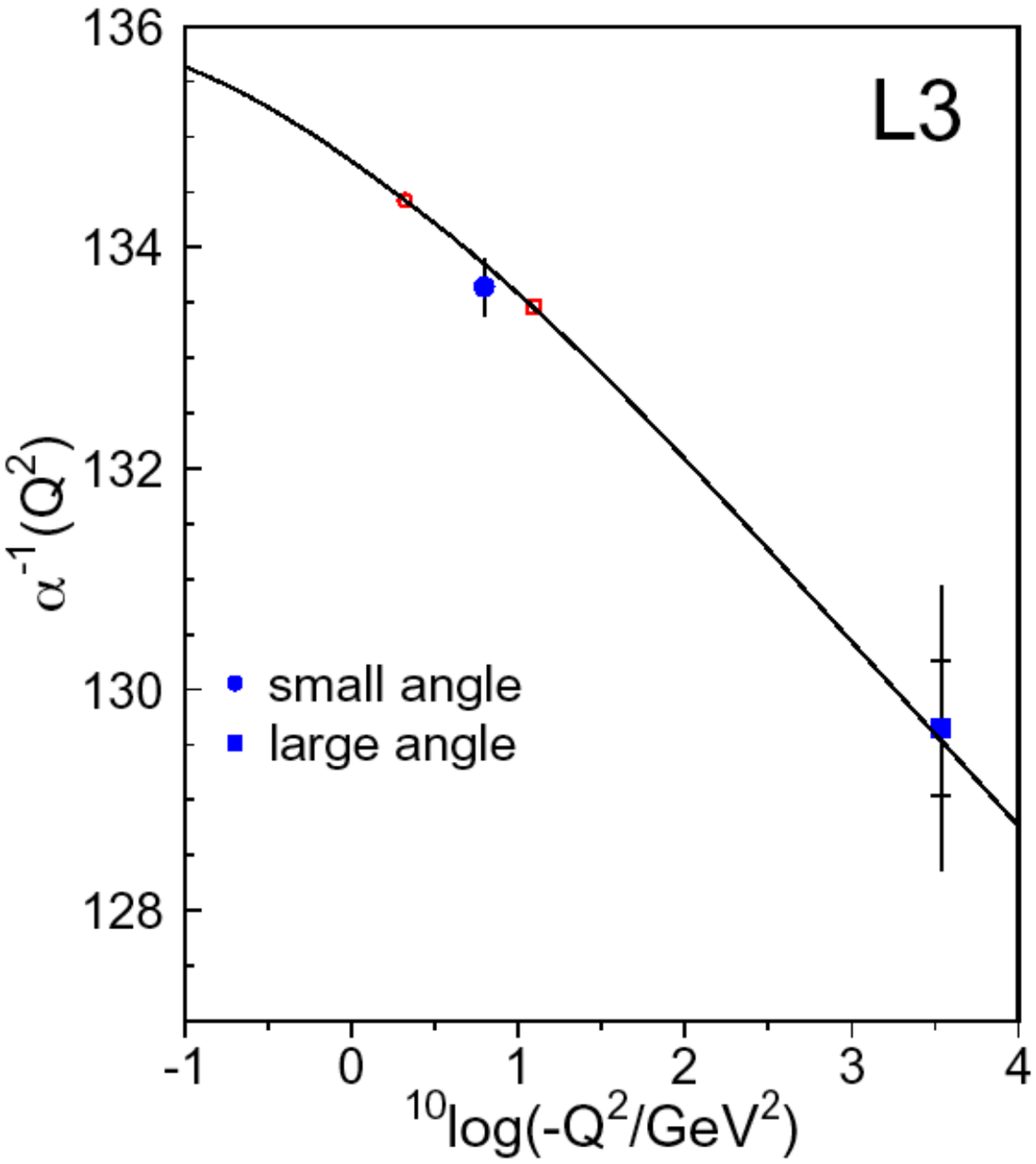
$(g-2)_W=0$

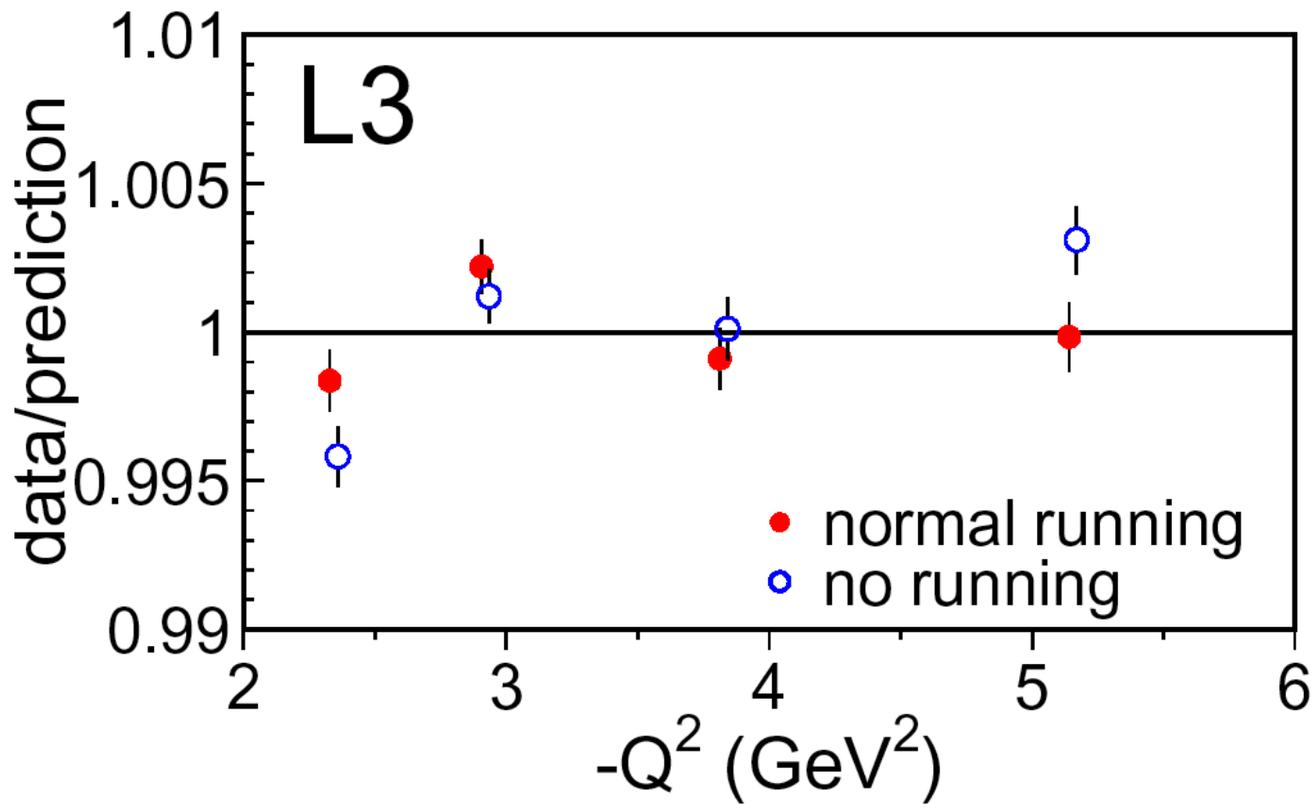

LEP
Preliminary
$\sigma^{WW}$ [pb]
20
15
10
5
0
160
170
180
190
200
$E_{cm}$ [GeV]
$\sigma(e^+e^- \rightarrow W^+ + W^-)$
RacoonWW / YFSWW 1.14
no ZWW vertex (Gentle 2.1)
only $\nu_e$ exchange (Gentle 2.1)

Escluso dagli esperimenti LEP

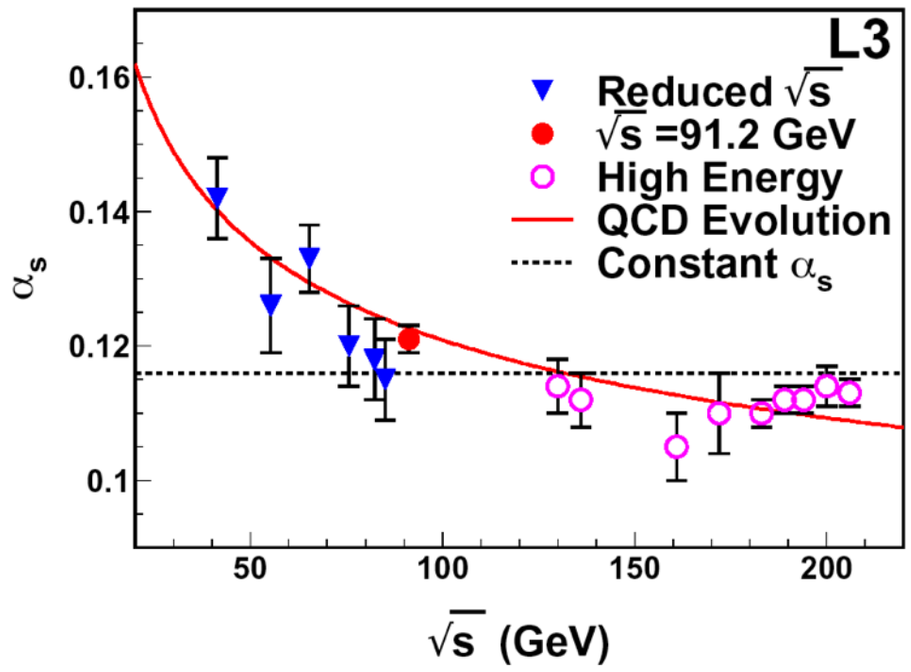


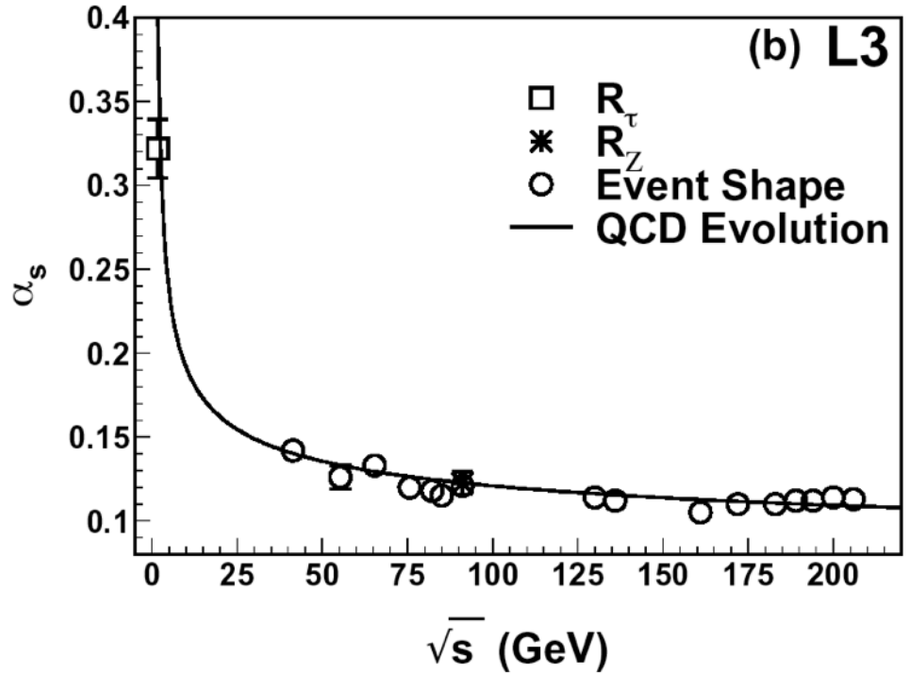
# QED: la costante di struttura fina “running” dalla diffusione Bahba

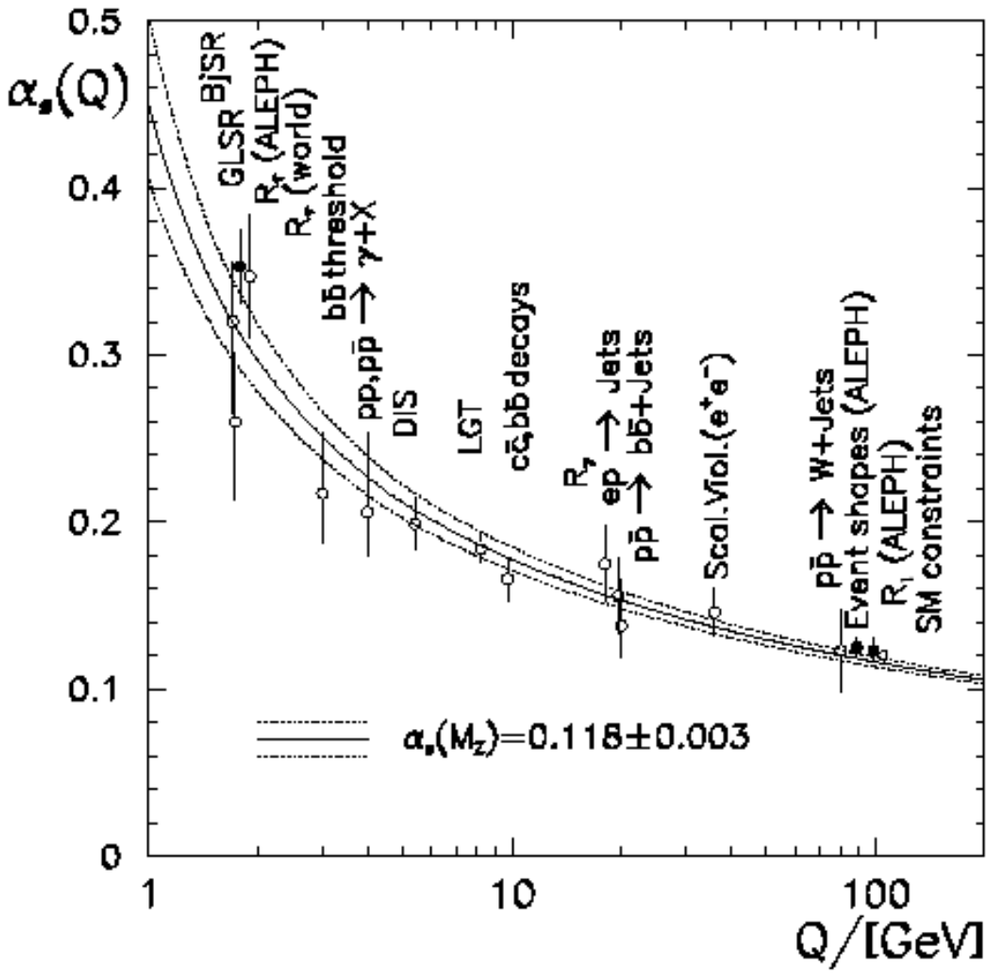


# QCD: la costante "running" dallo studio dei jets

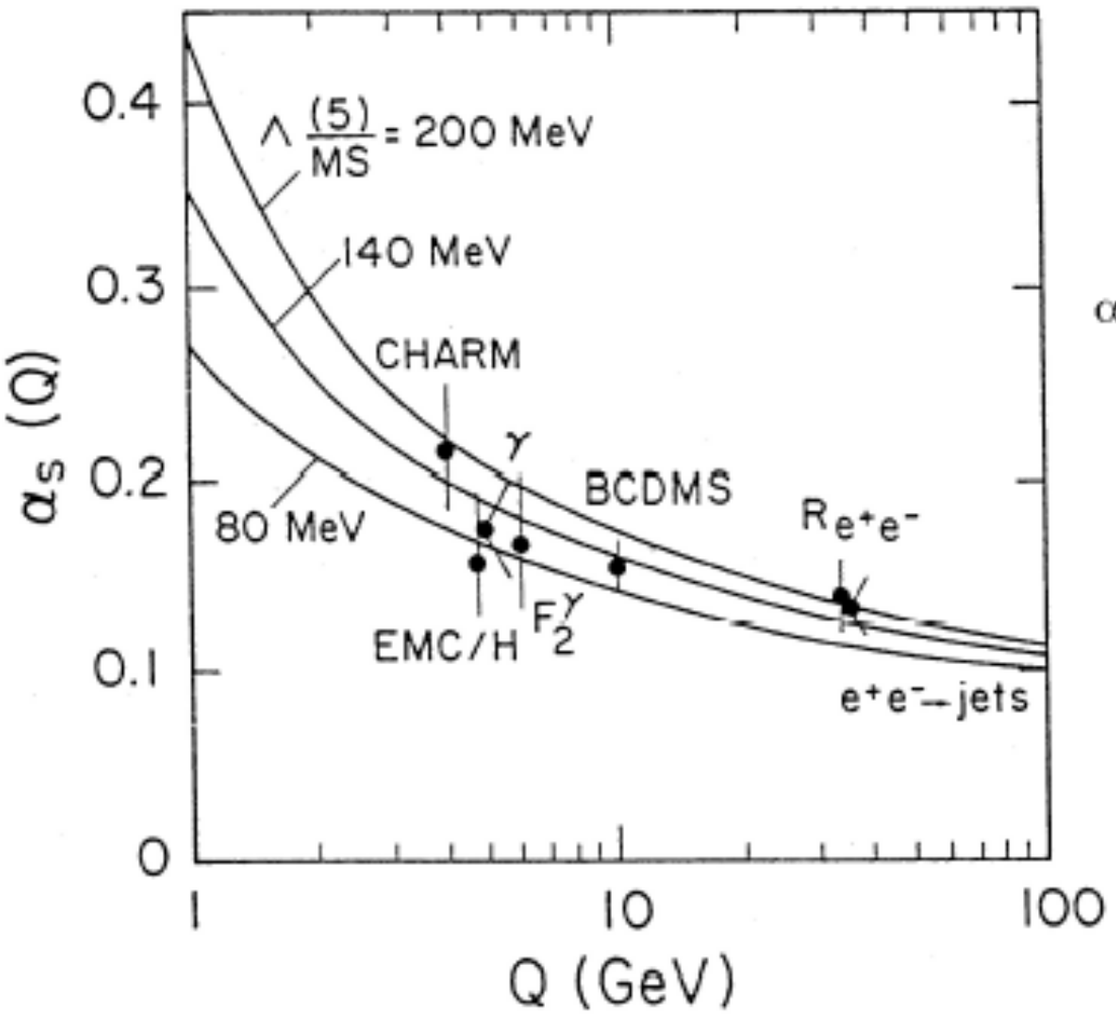


# QCD: la costante "running" dallo studio dei jets

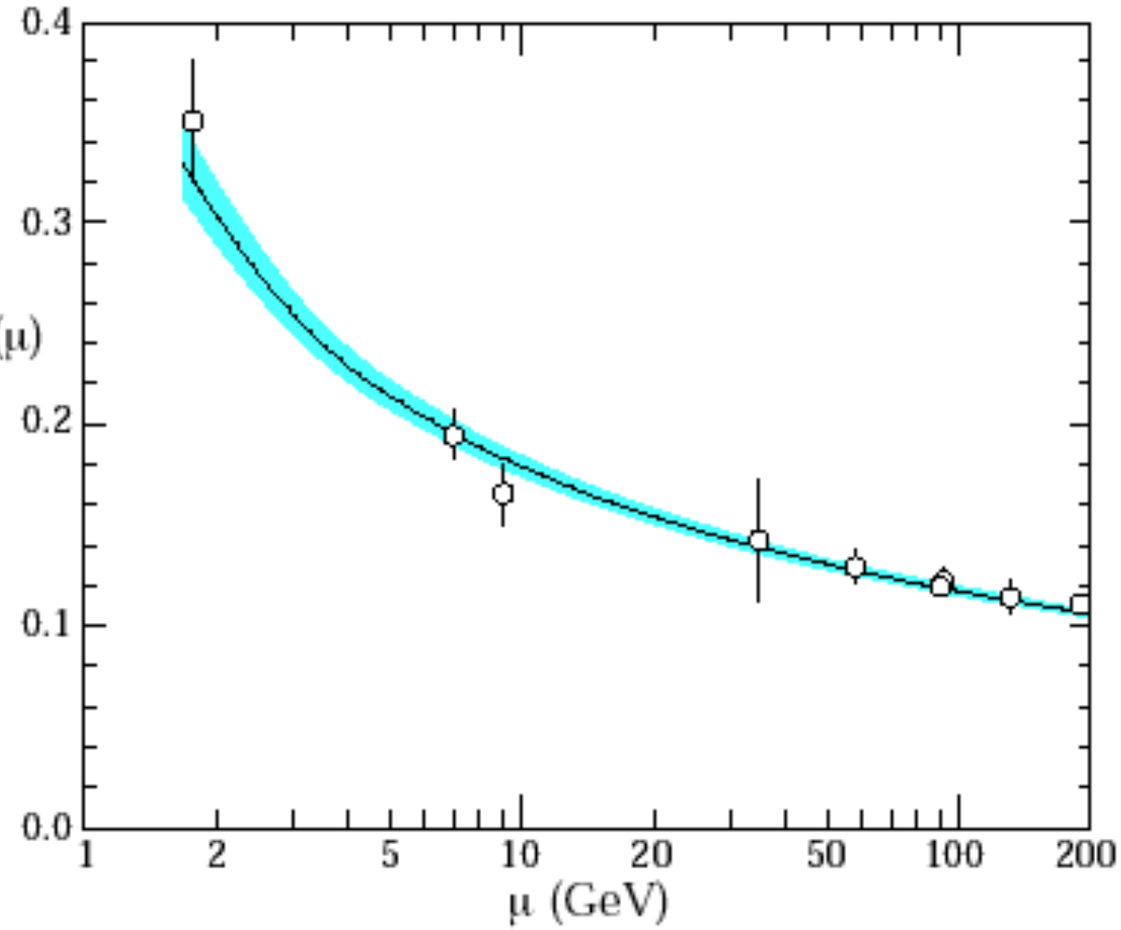
1989




$$\alpha_s(M_Z) = 0.11 \pm 0.01$$

Physics at LEPI (after Altarelli)

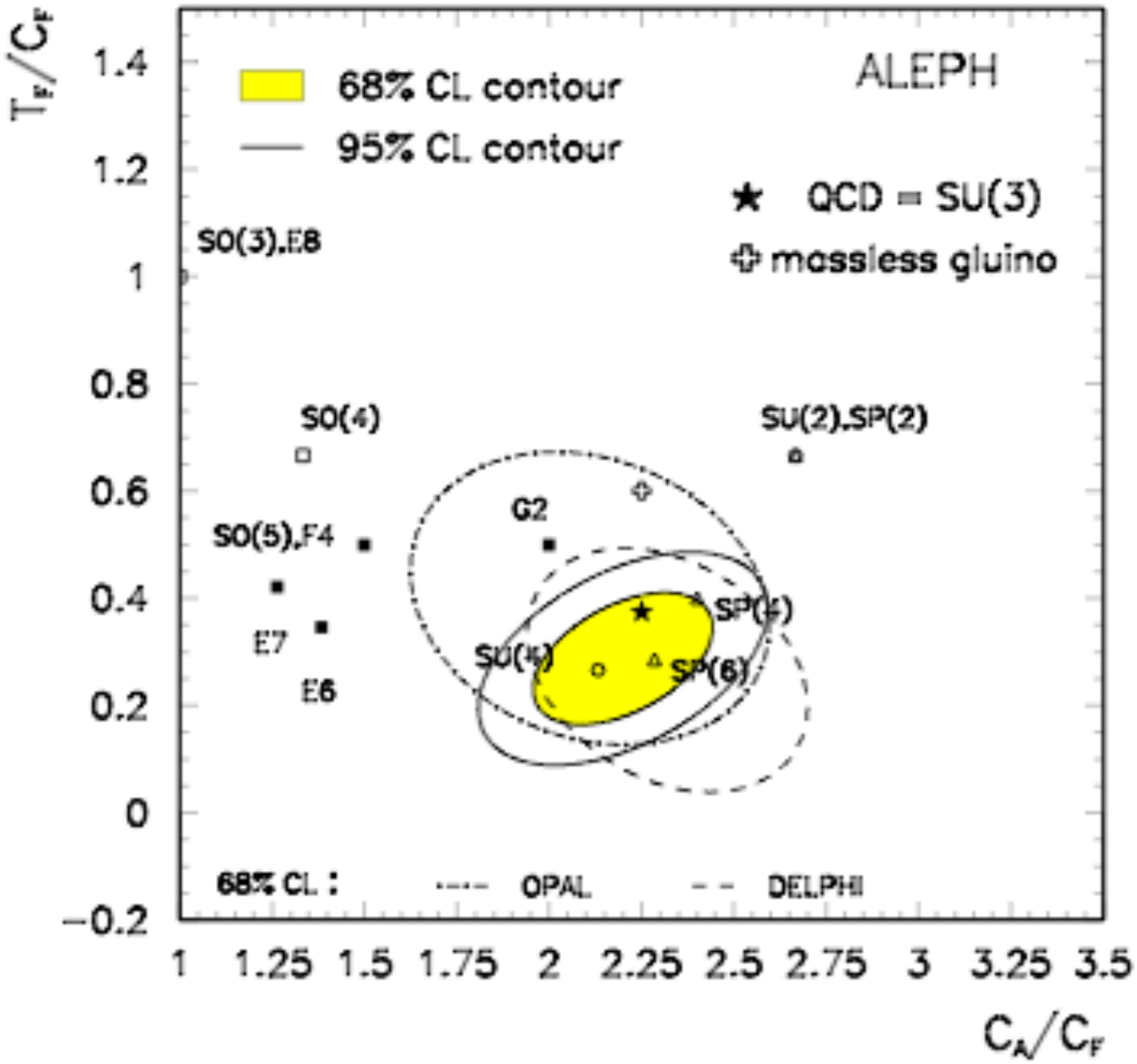
2000

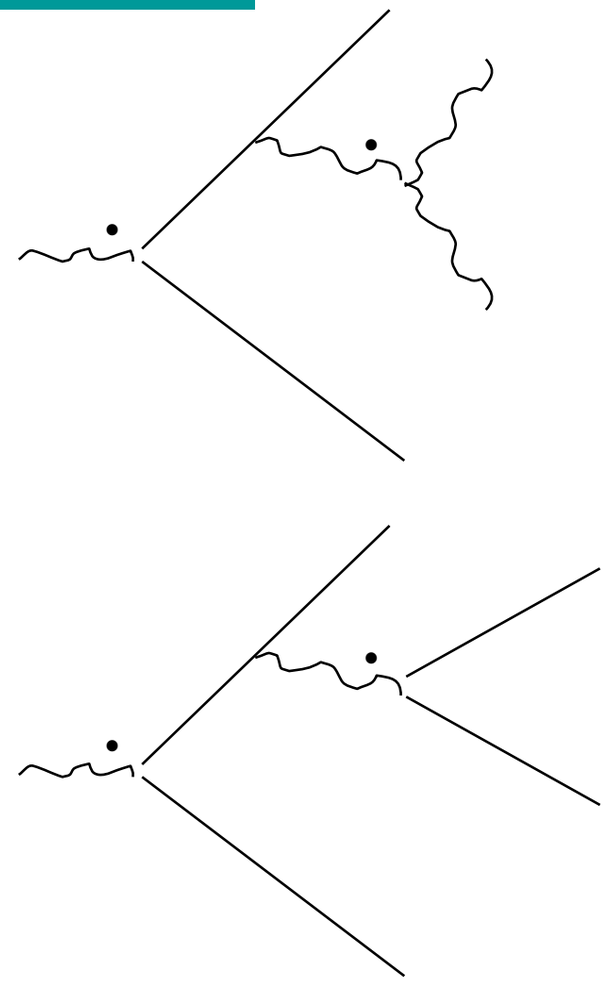



$$\alpha_s(M_Z) = 0.118 \pm 0.002$$

Particle Data Group 2000

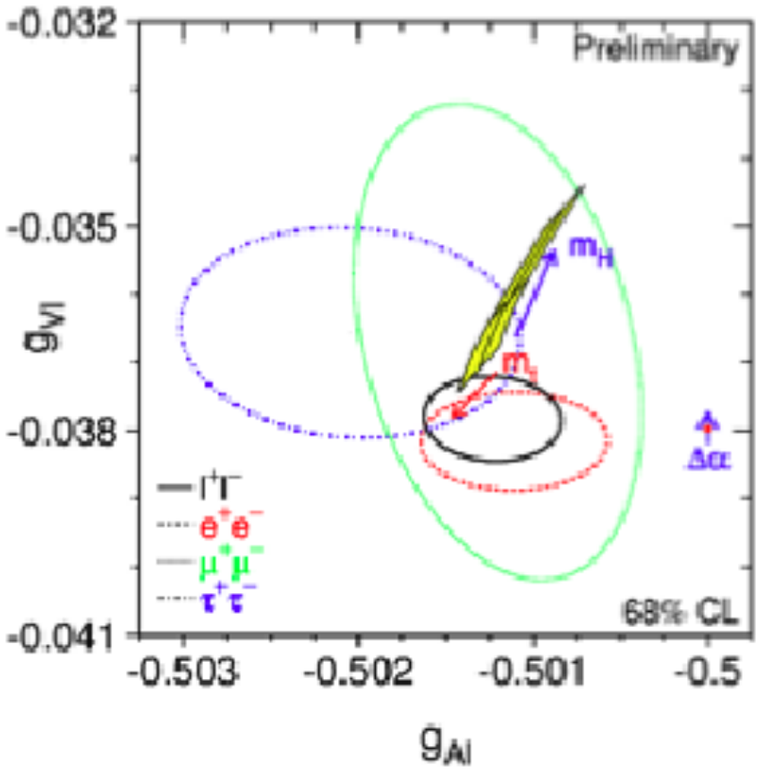
# Il gruppo di colore dagli esperimenti!



La sezione d' urto per 4 jet e' sensibile alla natura del gruppo di colore

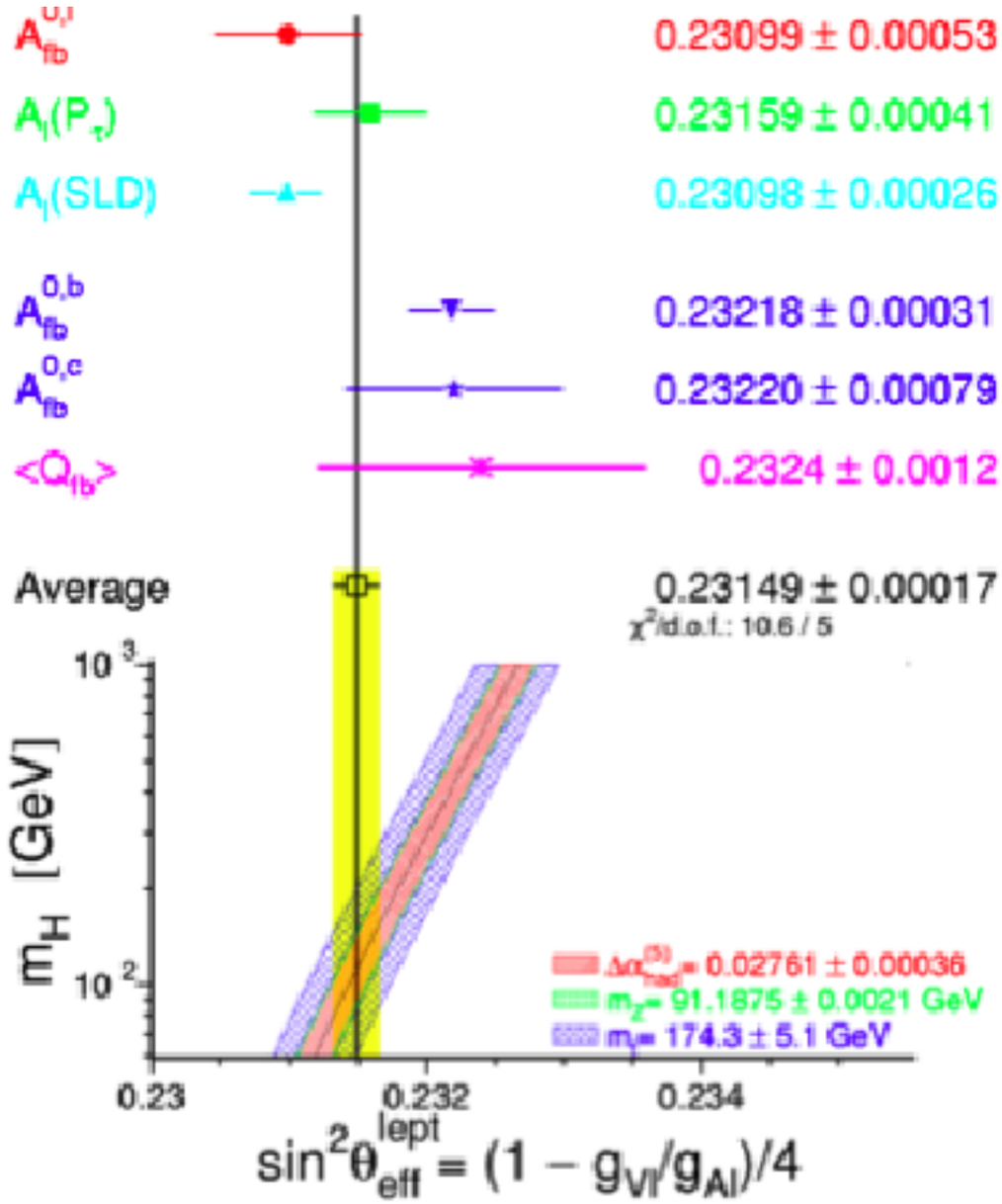
# L' angolo elettrodebole




**Different definitions of $\sin^2\theta$ used:**

$$\sin^2\bar{\vartheta}_l = \frac{1}{4}\left(1-\frac{\bar{g}_{Vl}}{\bar{g}_{Al}}\right) \quad (Z-\text{pole})$$

$$\sin^2\vartheta_W = 1-\frac{m_W}{m_Z^2} \quad (p\bar{p})$$




**and others**

# Riassumendo…

- I valori delle costanti running di SU(3)xSU(2)xU(1), alla scala $\mu=M_Z$ sono state determinate al LEP con notevole precisione

$$\alpha_S(M_Z) = 0.118 \pm 0.004$$

$$\alpha_{QED}(M_Z) = (128.93)^{-1}$$

$$\sin^2\theta_{eff} = 0.23149 \pm 0.00017$$

- Da cui:

$$\alpha_3(M_Z) \equiv \alpha_S(M_Z) = (8.47)^{-1}$$

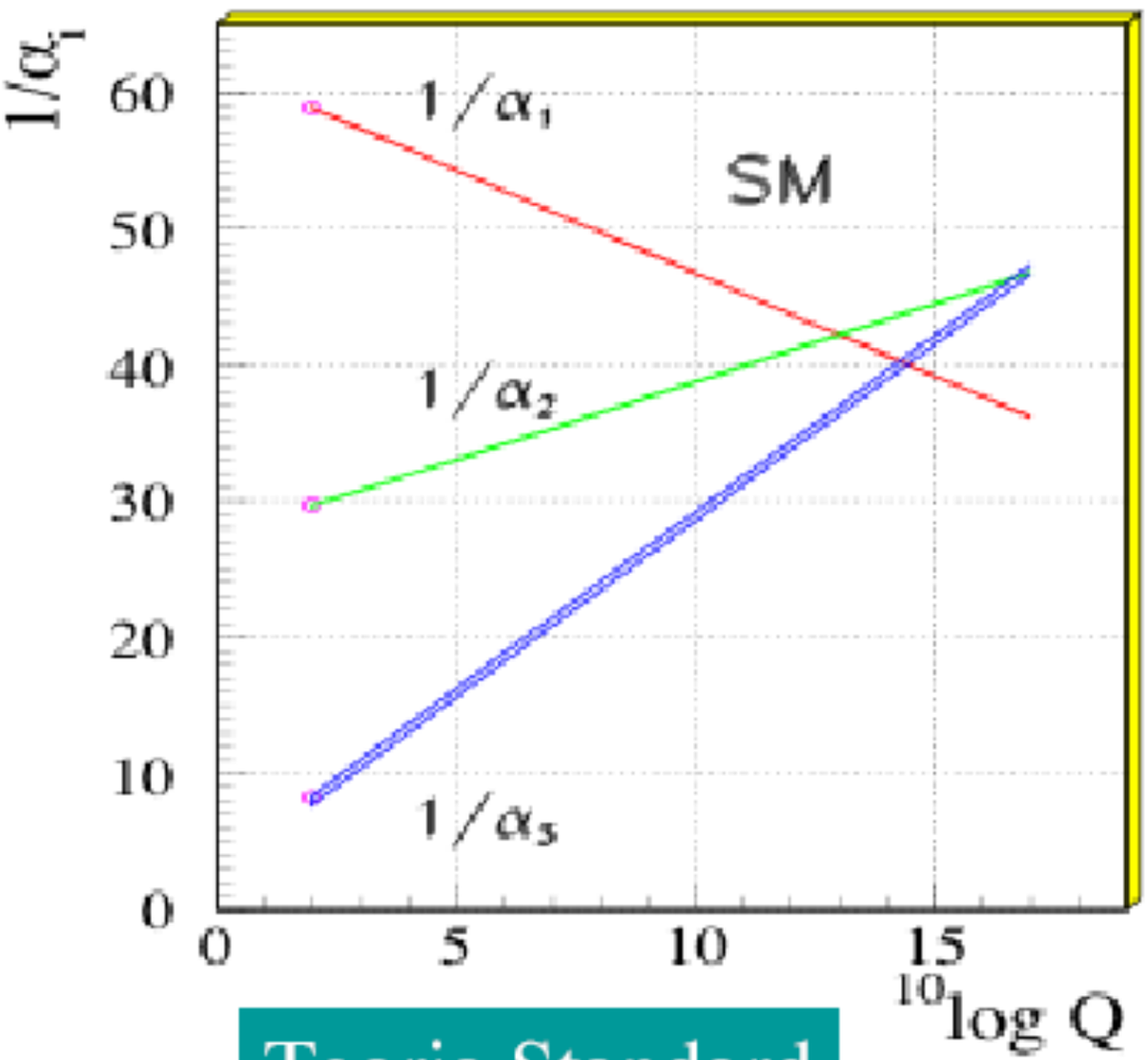
$$\alpha_2(M_Z) \equiv \frac{\alpha_{QED}(M_Z)}{\sin^2\theta_{eff}} = (29.85)^{-1}$$

$$\alpha_1(M_Z) \equiv \frac{\alpha_{QED}(M_Z)}{\cos^2\theta_{eff}} = (99.08)^{-1}$$

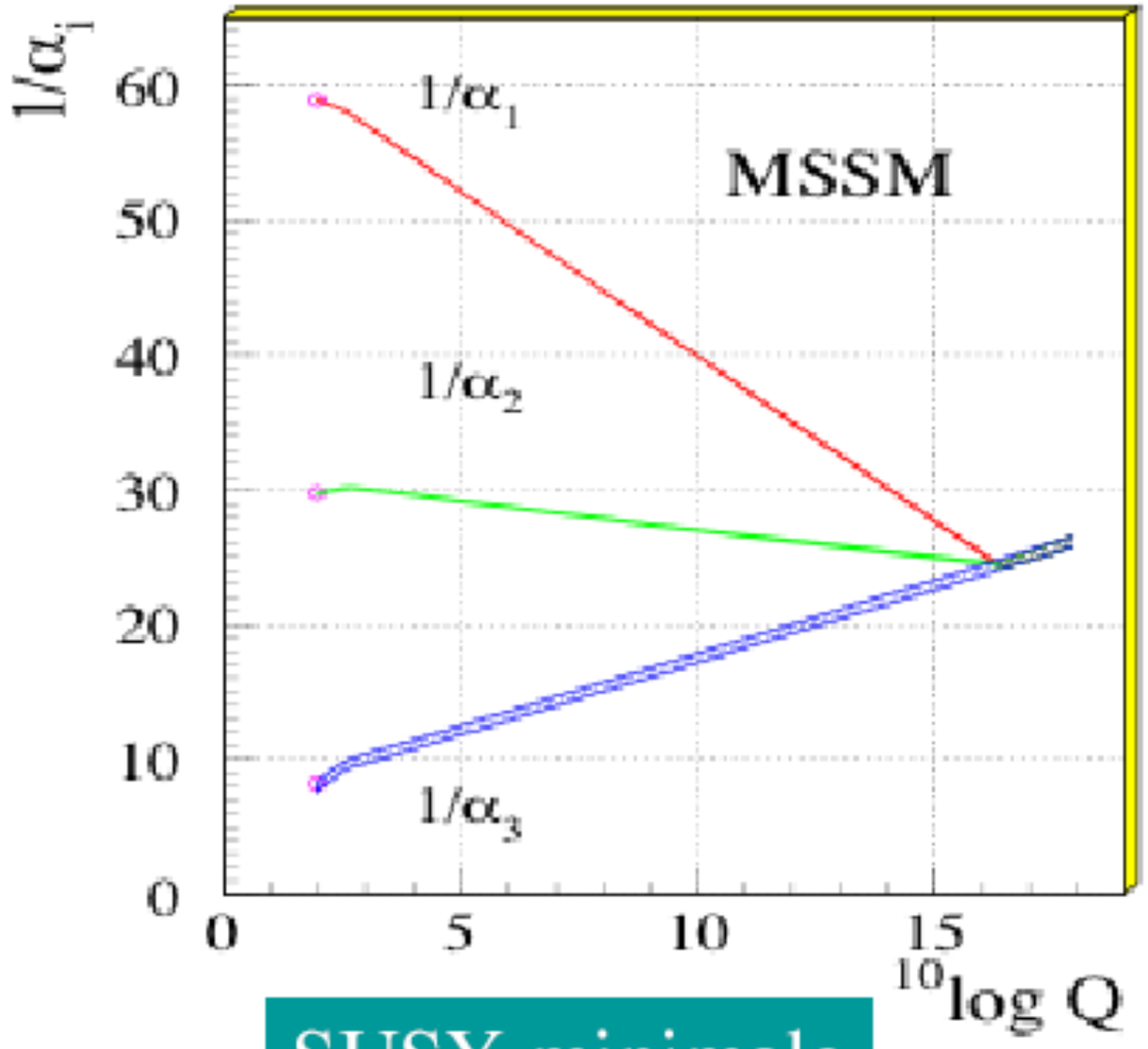
- In una teoria grande-unificata, $\alpha_2$ e $\alpha_3$ convergono ad uno stesso valore mentre $\alpha_1$ converge a $(\tan^2\theta)_{GUT}$ $(\alpha_2)_{GUT.}$. In SU(5) $(\tan^2\theta)_{GUT} = 3/5$ , quindi normalmente viene considerata la costante $(\alpha_1 (M_Z))_{normalizz} = 3/5 \cdot \alpha_1 (M_Z) = (5/3 \cdot 99.08)^{-1} = (59.4)^{-1}$.

# Convergenza delle costanti di accoppiamento di $SU(2)xU(1)xS(3)_{color}$ ?

**Nota**: $(\alpha_1)_{graf.} = 5/3\ (\alpha_1)_{nostro} = (3/5 \cdot 99.08)^{-1} = (59.4)^{-1}$;




Teoria Standard




SUSY minimale

# Il panorama delle macchine nel 2004: grandi risultati e grandi promesse

*LEP : Large Electron Positron Collider at CERN (1989–2000)*

*SLC : SLAC Linear Collider ($e^+$–$e^-$) in Stanford, now stopped*

*TEVATRON : proton–antiproton collider in FERMIL. in operation (2 TeV)*

*LHC : proton–proton collider at CERN (14 TeV), planned for 2007*