

# Guido Altarelli Memorial Symposium

## The LEP era

Riccardo Barbieri  
CERN, June 10, 2106

(a story starting in the summer of 1990)

# The interest in LEP precision

1. See the “genuine” ElectroWeak loops
2. Constrain the SM parameters  $m_t, m_H$
3. See early indirect signs of BSM physics

# The ante-LEP knowledge

## Experiments:

eD asymmetry,  $R_\nu, R_{\bar{\nu}}$ , W-mass, APV

$\Rightarrow \rho \approx 1, \sin^2 \theta_W \approx 0.22$  within few %

## Theory:

$$\Delta\rho = 3x \quad \delta V_\mu(Z \rightarrow b\bar{b}) = -\frac{g}{\cos\theta_W} x \quad x = \frac{G_F m_t^2}{8\pi^2 \sqrt{2}}$$

$$\Delta\rho = -\frac{3\alpha}{8\pi \cos^2 \theta_W} \log \frac{m_H}{M_Z} + \frac{\sqrt{2} G_F M_W^2}{\pi \alpha} \left(1 - \frac{M_W^2}{M_Z^2}\right) \equiv 1 + \Delta r = 1 + \frac{11\alpha}{24\pi \sin^2 \theta_W} \log \frac{m_H}{M_Z}$$

$\Rightarrow$  at summer conferences in 1989:

$40 \text{ GeV} < m_t < 210 \text{ GeV}$  (90% C.L.) for  $m_H < 1 \text{ TeV}$

(including the very fresh  $m_Z = 91.17 \pm 0.18 \text{ GeV}$  by SLC)

# The observables at the Z-pole

Assuming quark-lepton and flavour universality,

3 effective observables only

$$g_A^f = T_{3L}^f \left(1 + \frac{\epsilon_1}{2}\right) \quad \frac{g_V^f}{g_A^f} = 1 - 4|Q_f|s^2 \left(1 + \frac{\epsilon_3 - c^2\epsilon_1}{c^2 - s^2}\right)$$

$$\Delta r = \frac{1}{s^2} \left(-c^2\epsilon_1 + (c^2 - s^2)\epsilon_2 + 2s^2\epsilon_3\right) \quad s^2c^2 = \frac{\pi\alpha(M_Z)}{\sqrt{2}G_F M_Z^2}$$

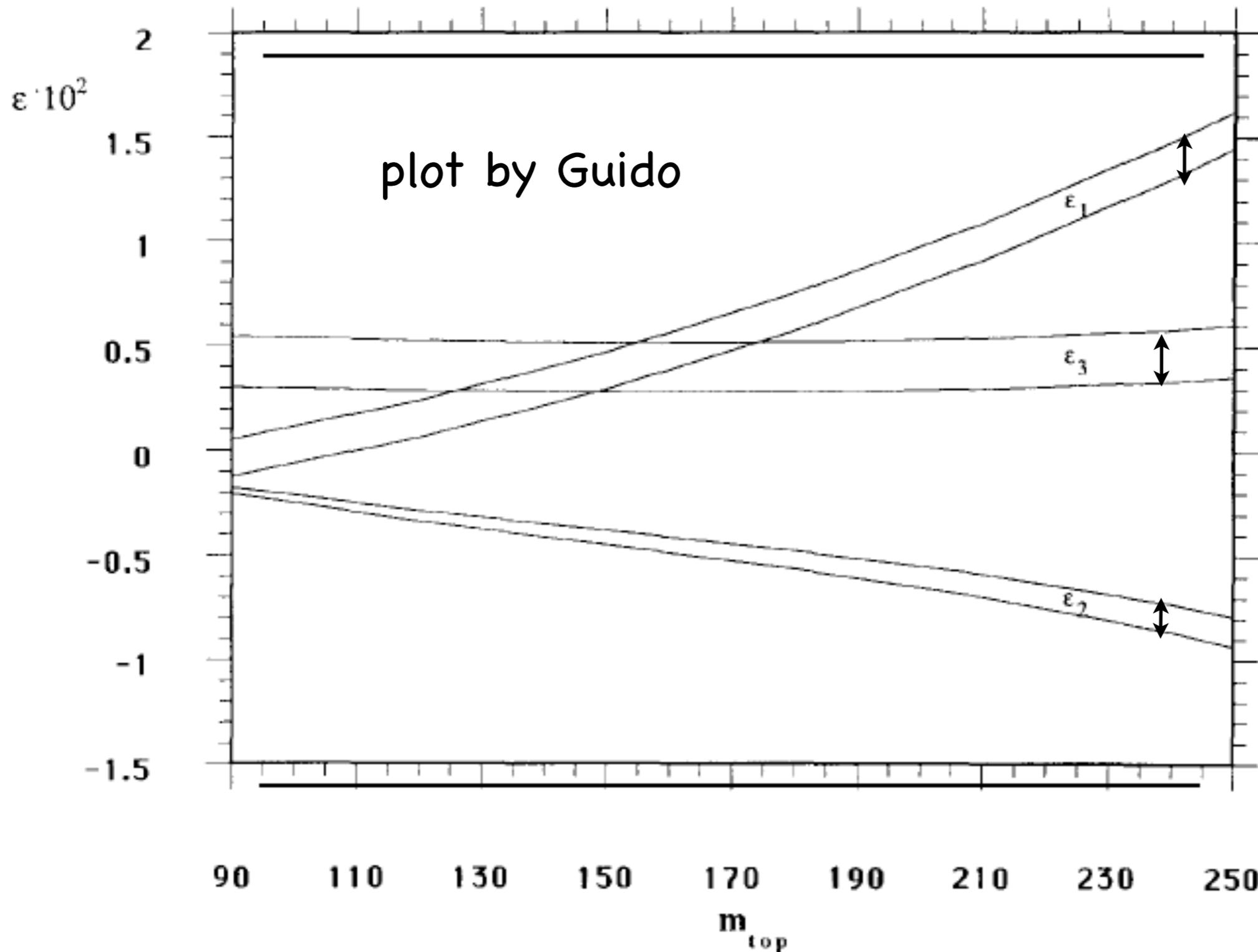
+1 including flavour breaking in  $Z \rightarrow b\bar{b}$

$$g_A^b = -\frac{1}{2} \left(1 + \frac{\epsilon_1}{2}\right) \left(1 + \epsilon_b\right) \quad \frac{g_V^b}{g_A^b} = \frac{1}{1 + \epsilon_b} \left(1 - \frac{4}{3}s^2 \left(1 + \frac{\epsilon_3 - c^2\epsilon_1}{c^2 - s^2}\right) + \epsilon_b\right)$$

(Peskin, Takeuchi 1990)

Altarelli, B 1990  
Altarelli, B, Jadach 1991

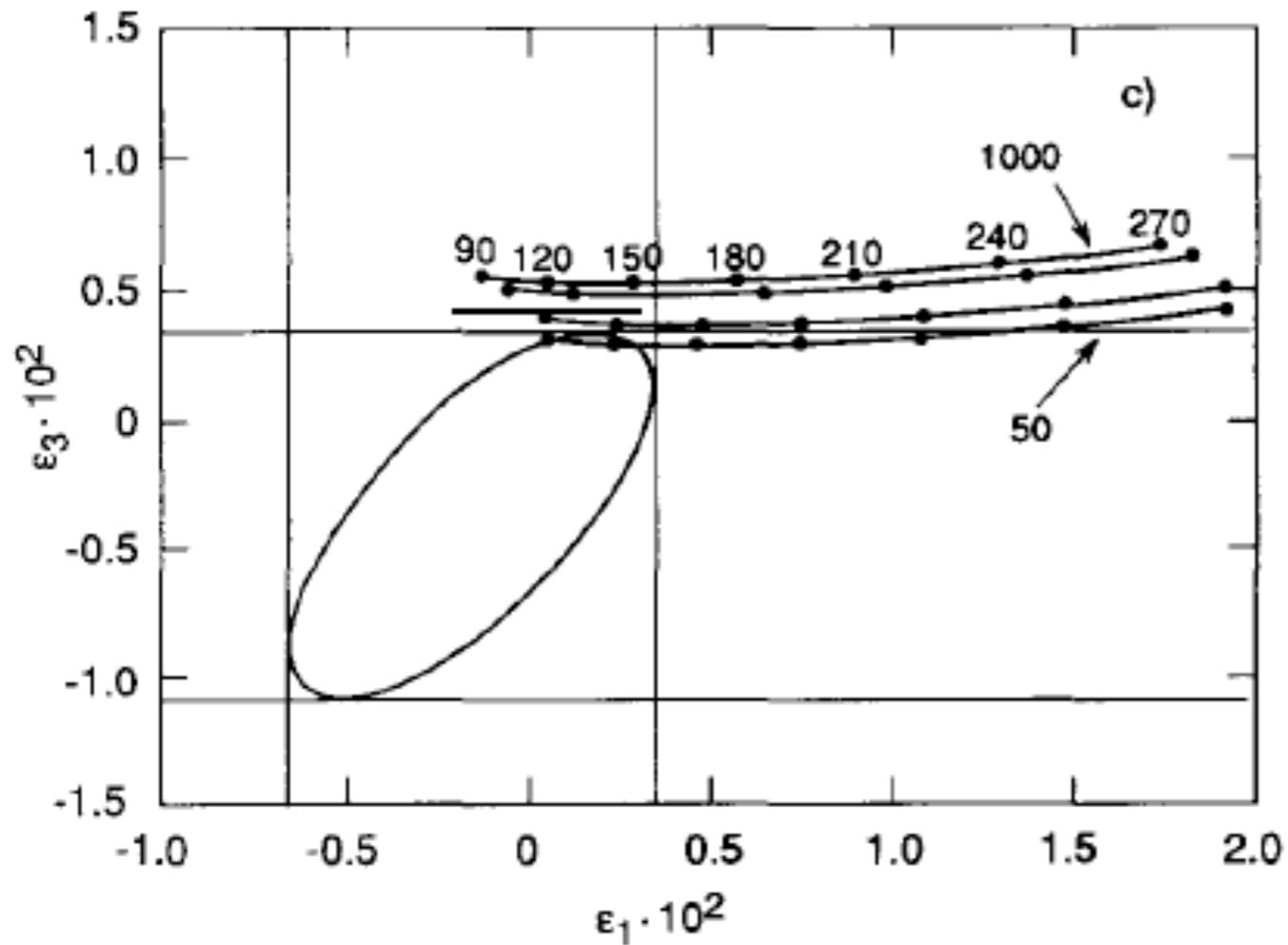
# $\epsilon_i(m_t, m_H)$ predicted in the SM



$m_H = 50 \div 1000$  GeV

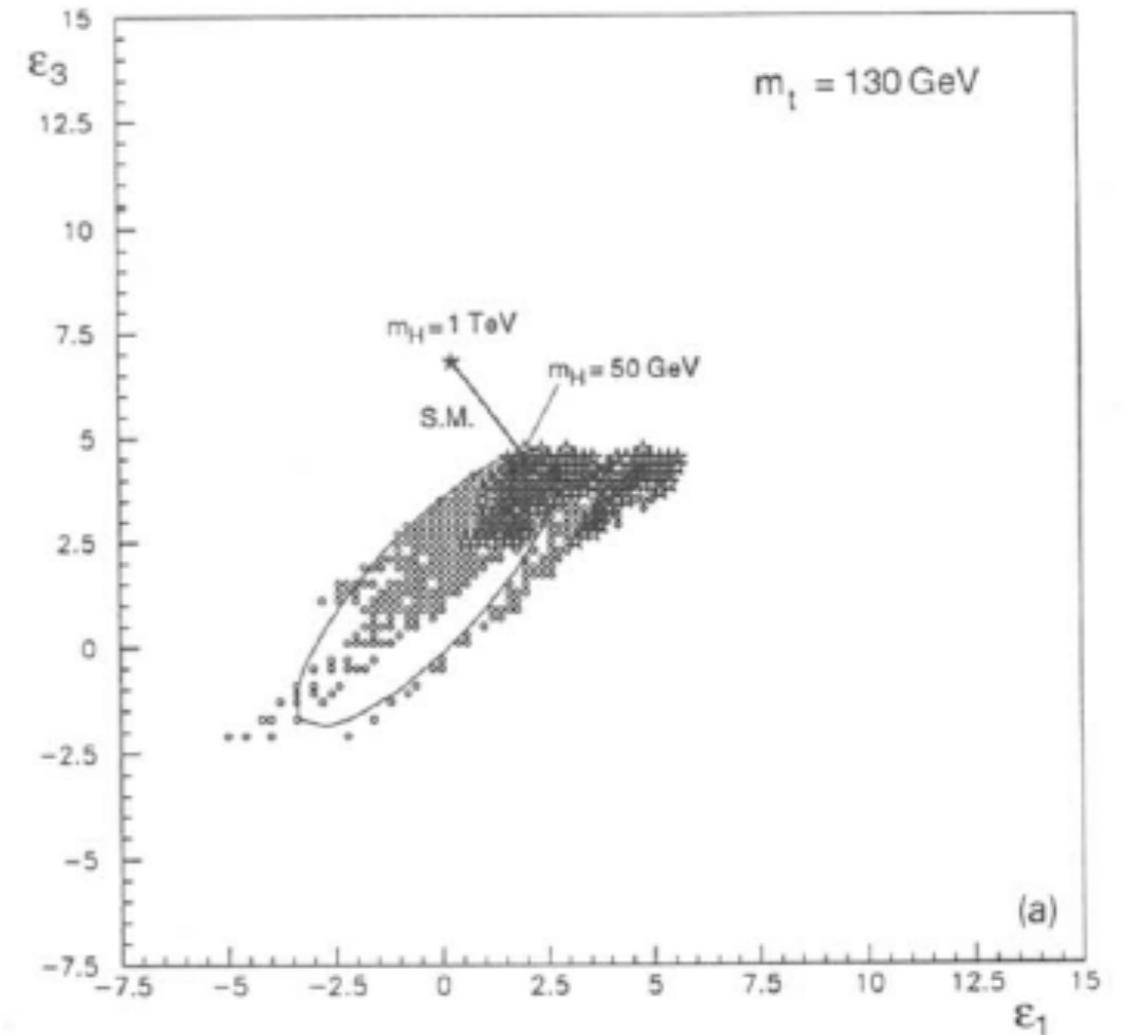
# From LEP data in 1991-1993

plots by Guido



**SM 1991**

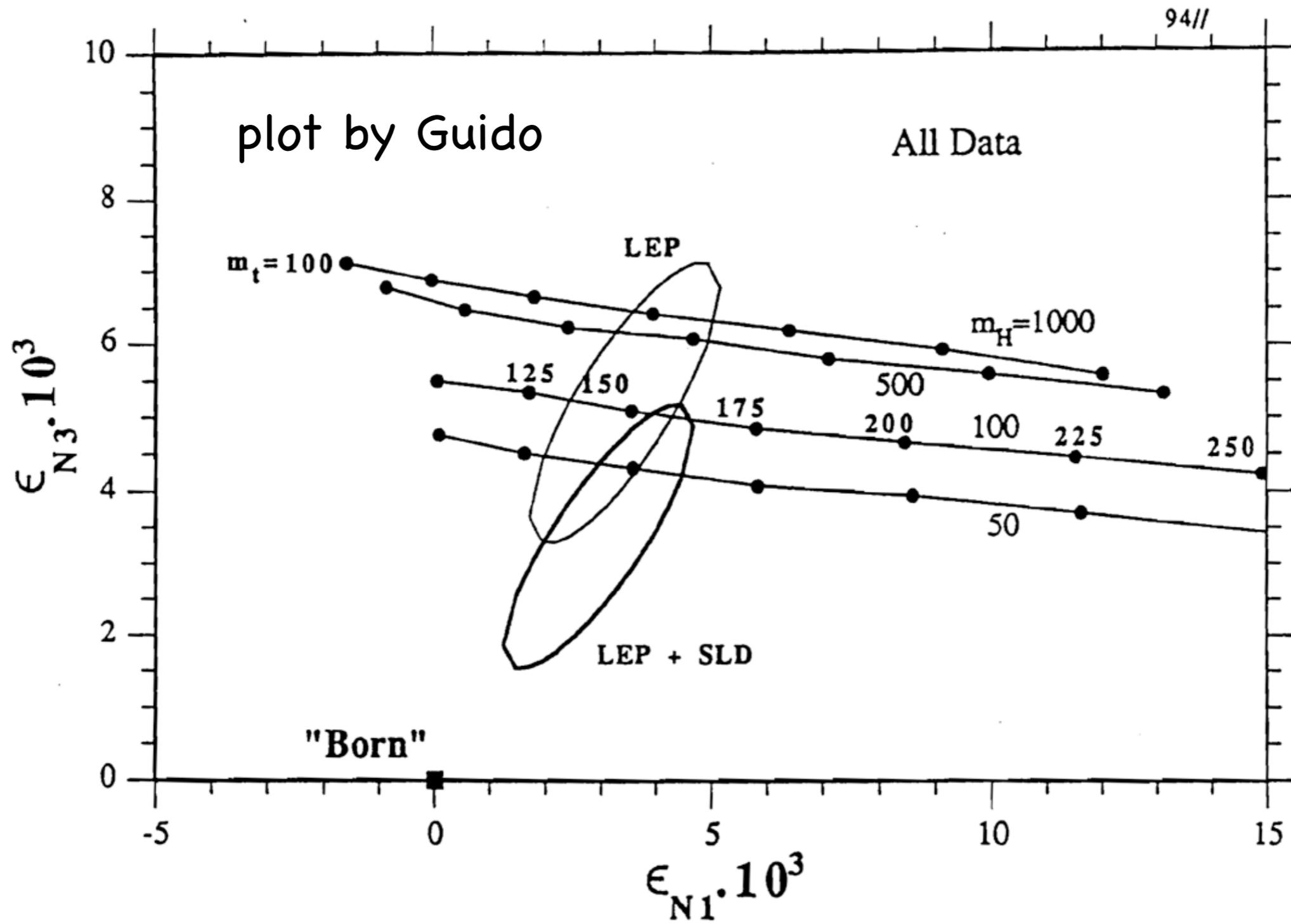
Altarelli, B, Jadach



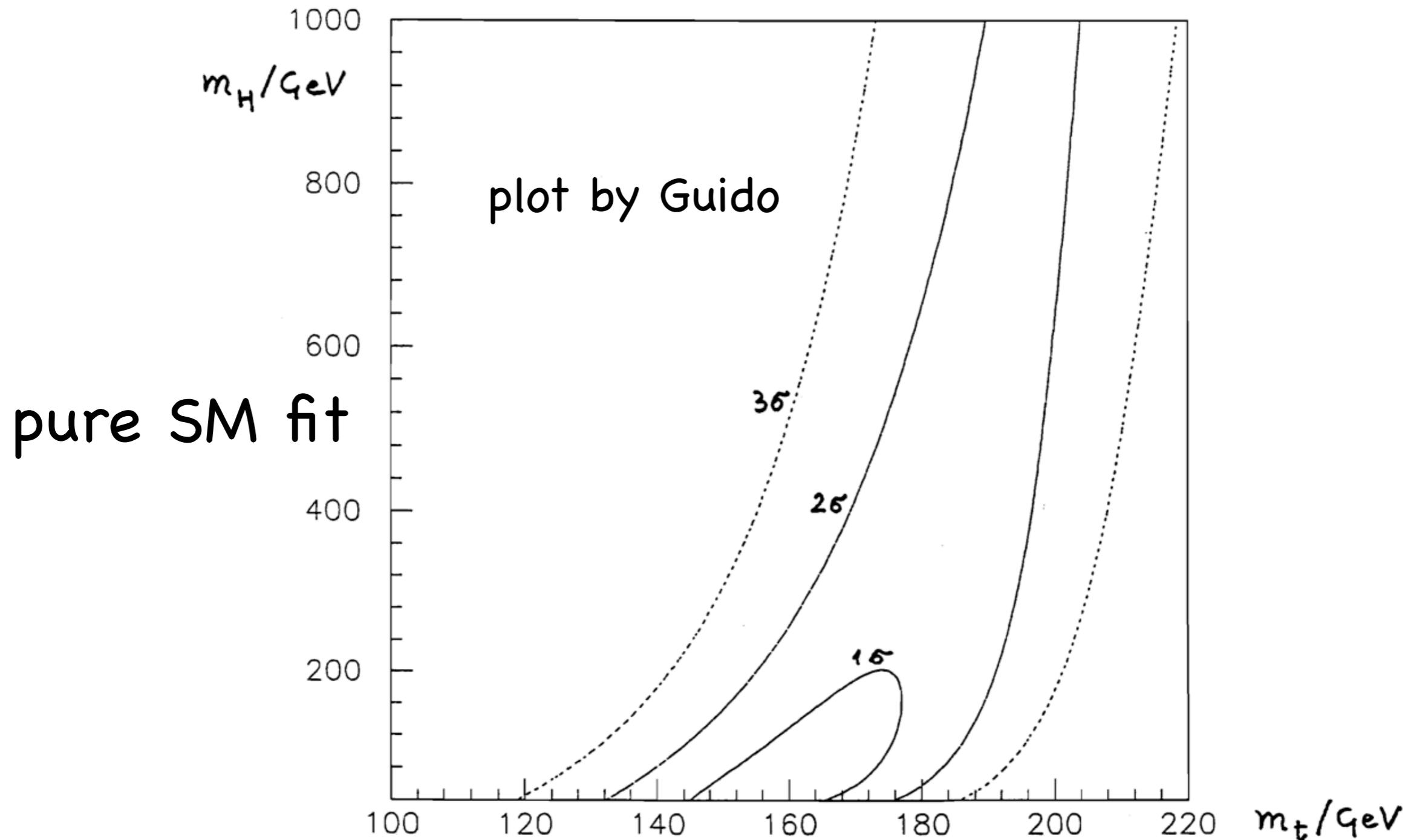
**light SUSY 1993**

Altarelli, B, Caravaglios

# La Thuile, April 1994



# La Thuile, April 1994

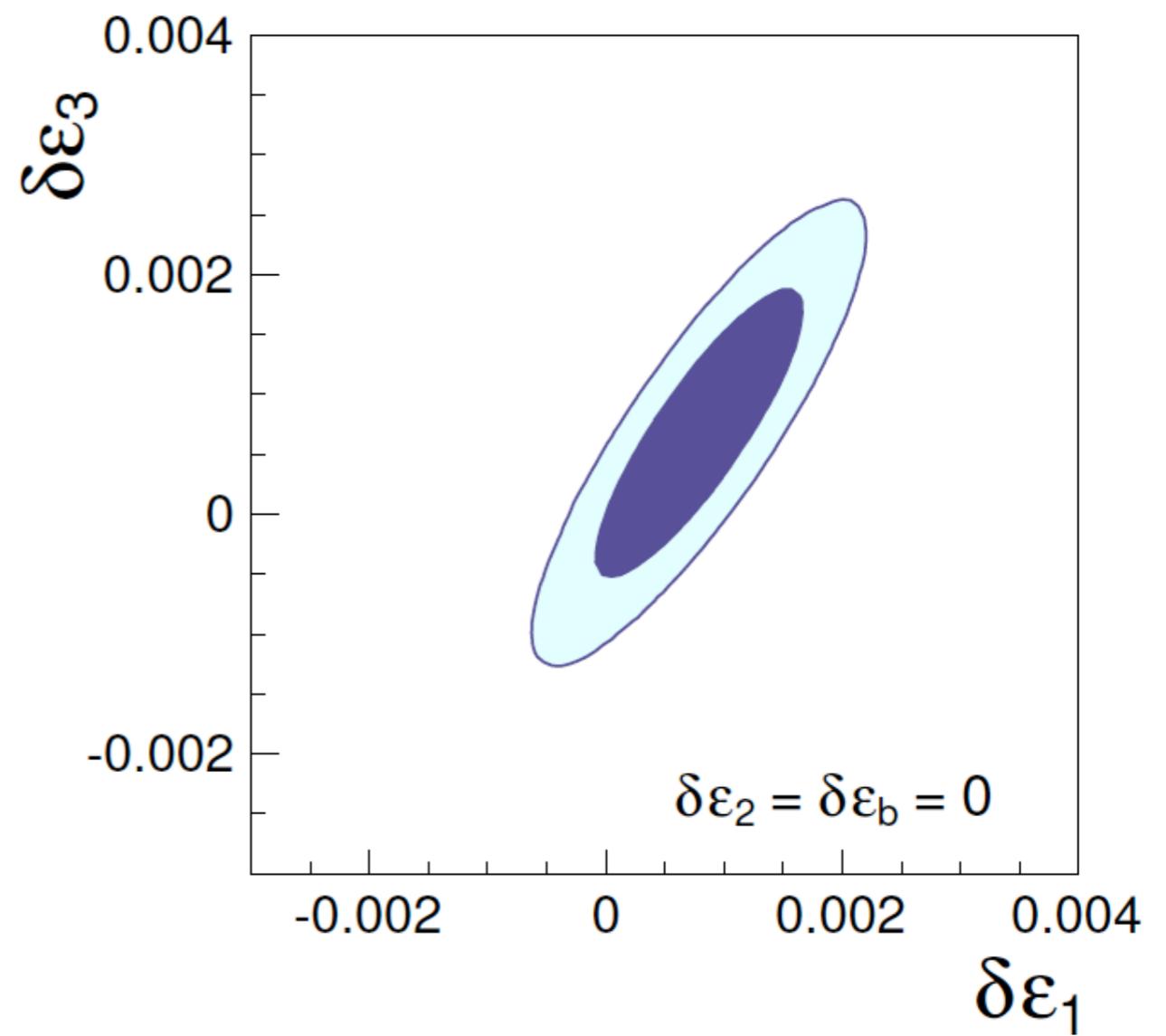
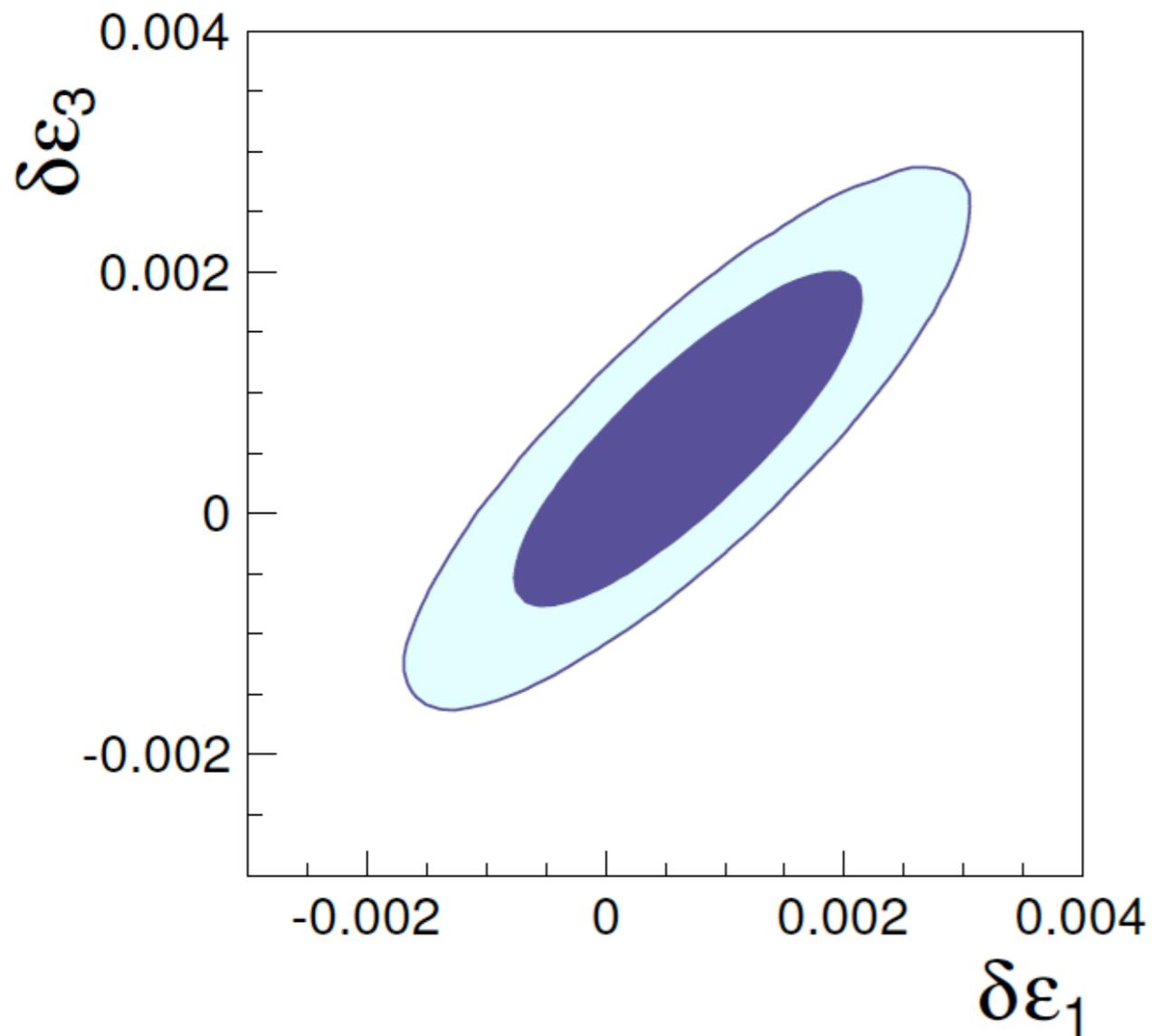


compared with  $m_t = 174 \pm 10^{+13}_{-12} \text{ GeV}$  in the first CDF paper that appeared in PRD in Sept 1994

# Currently

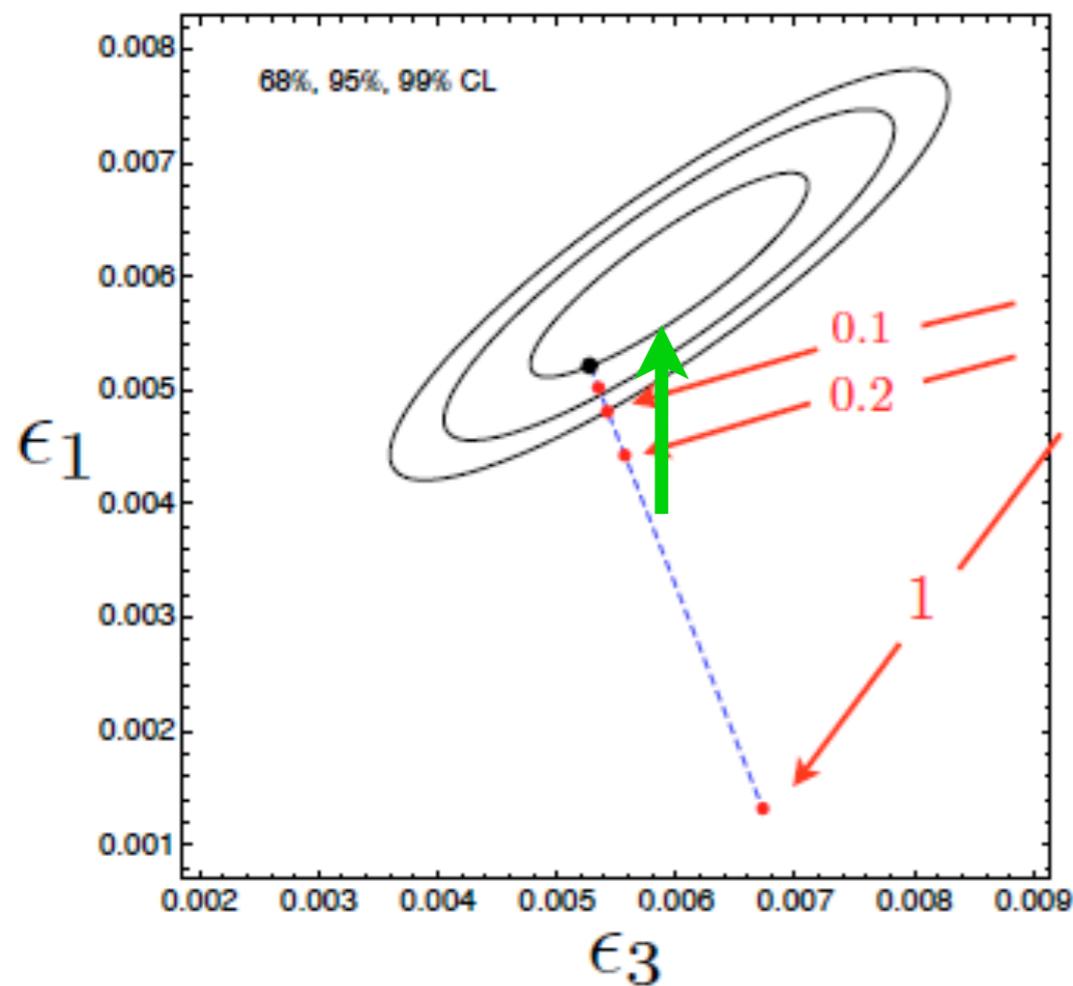
$$\epsilon_1^{SM} = 5.21 \cdot 10^{-3}, \quad \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$$

$$\delta\epsilon_i = \epsilon_i - \epsilon_i^{SM}$$

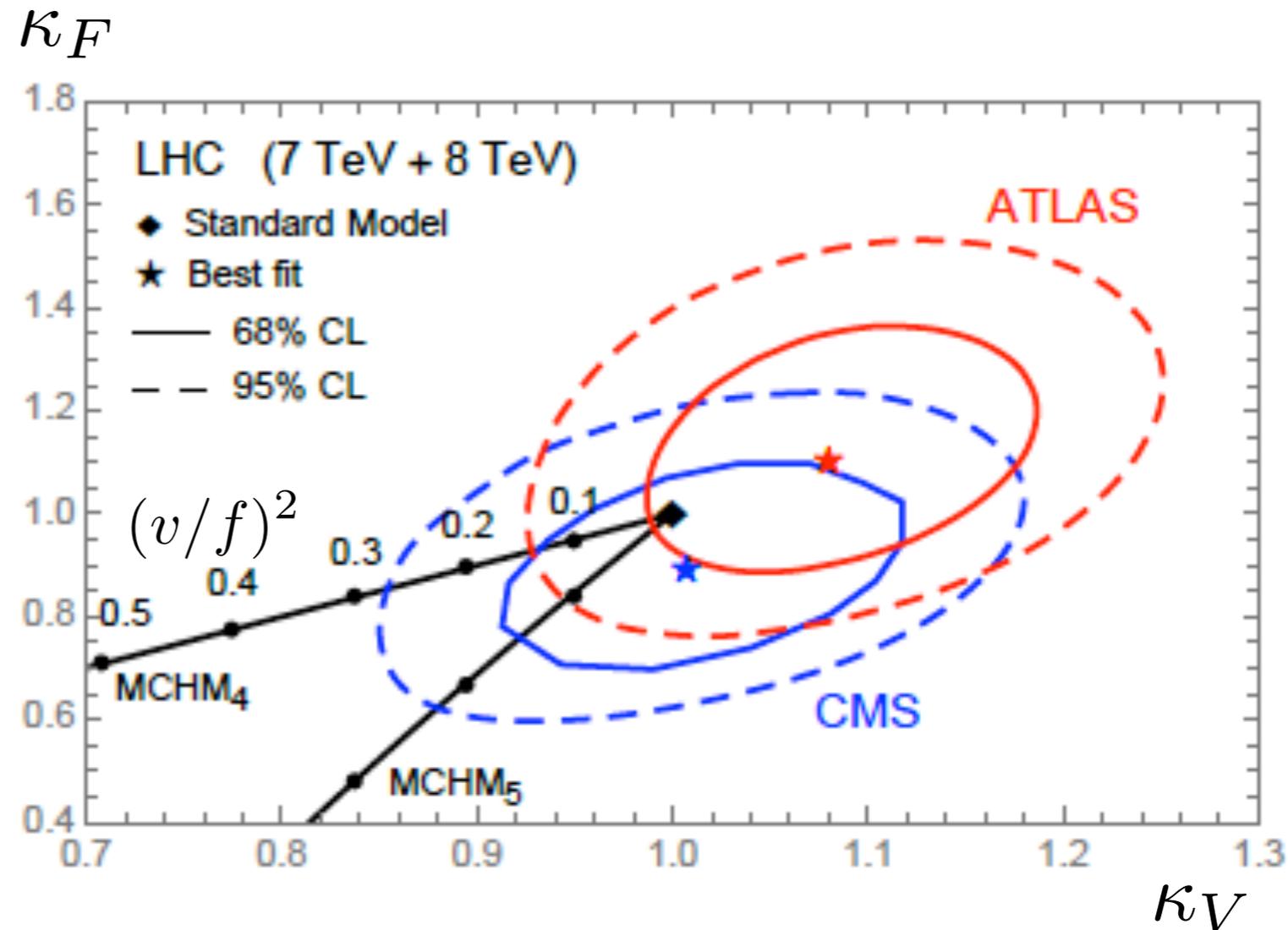


Ciuchini et al, 2013

# The epsilon-parameters constraining the scale $f$ of a composite Higgs boson picture



EWPT



Higgs precision

(from a stop-sbottom  $\delta\epsilon_1 = \frac{G_F m_t^4}{\sqrt{2} 8\pi^2 m_{\tilde{Q}_3}^2} \approx 10^{-3} \left( \frac{300 \text{ GeV}}{m_{\tilde{Q}_3}} \right)^2$  )

# LEP precision with effective operators

(often discussed with Guido)

$$\mathcal{L}_{eff}(E < \Lambda) = \mathcal{L}_{SM} + \sum_{i,p>0} \frac{c_{i,p}}{\Lambda^p} \mathcal{O}_i^{(4+p)}$$

95% lower bounds on  $\Lambda$  /TeV on one operator at a time

|  | $c_i = -1$ | $c_i = +1$ | $c_i = -1$ | $c_i = +1$ |
|--|------------|------------|------------|------------|
| $(H^+ \tau^a H) W_{\mu\nu}^a B_{\mu\nu}$             | 9.7        | 10         | 11.1       | 18.4       |
| $ H^+ D_\mu H ^2$                                    | 4.6        | 5.6        | 6.3        | 15.4       |
| $i(H^+ D_\mu \tau^a H)(\bar{L} \gamma_\mu \tau^a L)$ | 8.4        | 8.8        | 9.8        | 14.8       |
| $i(H^+ D_\mu \tau^a H)(\bar{Q} \gamma_\mu \tau^a Q)$ | 6.6        | 6.8        | 9.6        | 8.7        |
| $i(H^+ D_\mu H)(\bar{L} \gamma_\mu L)$               | 7.3        | 9.2        | 14.8       | 9.2        |

B, Strumia 2000

deBlas et al 2014

# The SM as an emerging iceberg



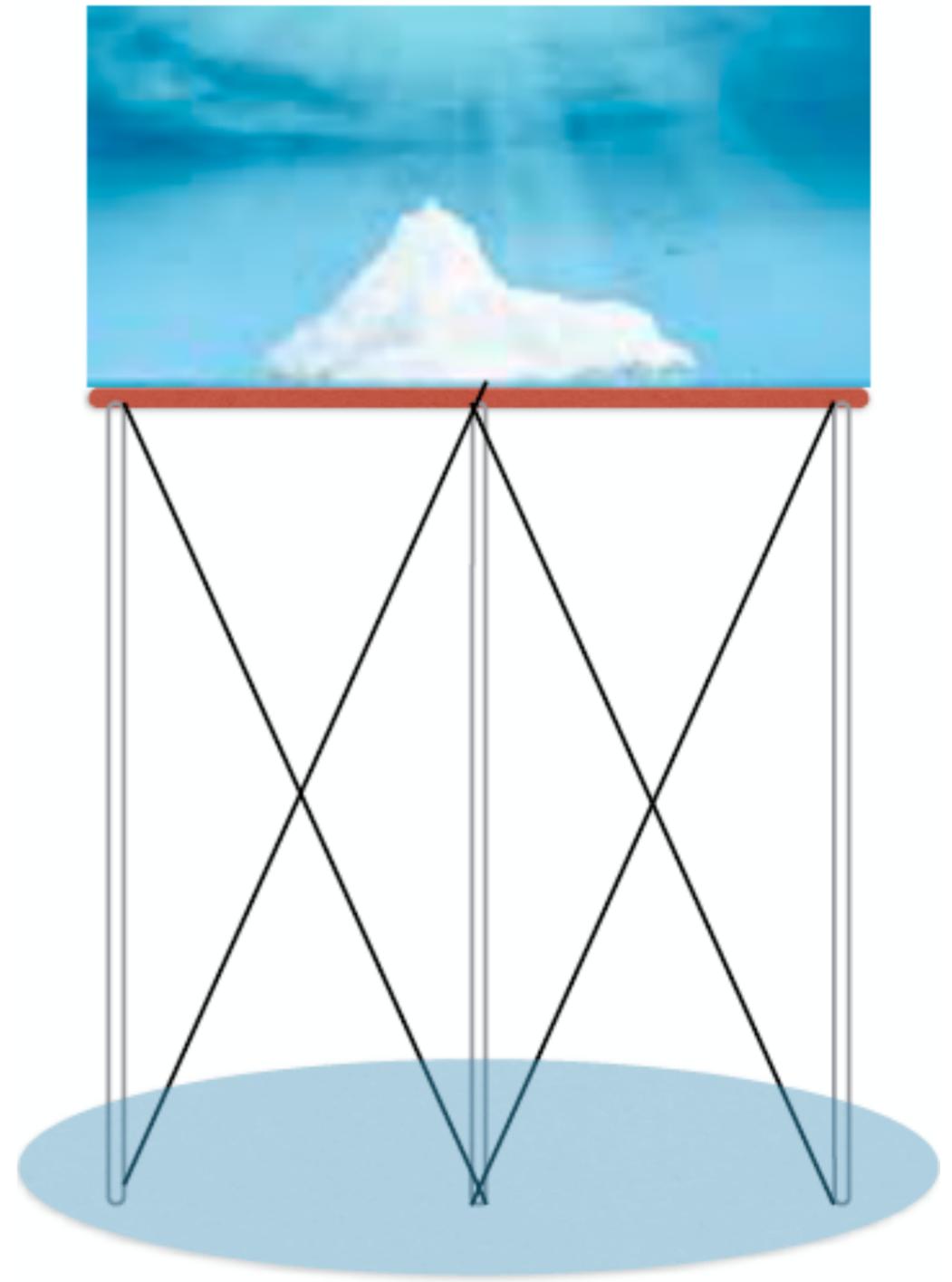
What there is under the water?

(out of a conversation with Lawrence Hall)

# BSM in the multi TeV region...



# BSM in the multi TeV region...



... or the SM extended up to  $E \gg \text{TeV}$ s?

Guido was a wise man  
who had a strong influence  
on particle physics at large  
and in particular at CERN and in Italy

A kind of "older brother" for me,  
in spite of having about the same age