The importance of precision in ElectroWeak Physics

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Four lectures on particle physics phenomenology
Rome, December 19, 2016

(recalling Guido Altarelli)

The 3 ways to judge a physical theory

1. Its aesthetics and its synthesis

2. Its discovery signals

3. Its precise numerical consequences

(in the order one prefers and the weight one wants to give}

The Lagrangian of the SM
(since 1973 in its full content)

$$\mathcal{L}_{\sim SM} = -\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + i\bar{\psi}\not{D}\psi \qquad (\sim 1975\text{-}2000)$$

$$+|D_\mu h|^2 - V(h) \qquad (\sim 1990\text{- } 2012)$$

$$+\psi_i\lambda_{ij}\psi_j h + h.c. \qquad (\sim 2000\text{- now})$$

	APV	$(g-2)_e$	$(g-2)_\mu$	W, Z	m_{top}
$\Delta\mathcal{O}/\mathcal{O}$	10^{-3}	10^{-8}	10^{-6}	$10^{-(3\div5)}$	10^{-2}
d(cm)	10^{-5}	10^{-11}	10^{-13}	10^{-16}	10^{-16}

precision at work at many different scales

Precision in ElectroWeak Physics

(with a focus on my collaboration with Guido, from 1990 on,
even though the story starts much earlier and is at the route of
the making of the Standard Model)

1. Constrain the SM parameters m_t, m_H
   (now mostly of historic interest)

2. See the "genuine" ElectroWeak loops
   (an important numerical test of the SM)

3. See early indirect signs of BSM physics
   (of persistent high interest even today)

The ante-LEP knowledge

(about 1970 - 1990)

Experiments:

polarized eN scattering at $q^2 = O(1) GeV^2$

Atomic Parity violation

$$R_\nu = \frac{\sigma(\nu_\mu\ N \to \nu_\mu\ X)}{\sigma(\nu_\mu\ N \to \mu\ X)} \qquad R_{\bar\nu} = \frac{\sigma(\bar\nu_\mu\ N \to \bar\nu_\mu\ X)}{\sigma(\bar\nu_\mu\ N \to \mu\ X)}$$

$\sigma(\nu_\mu\ e),\ \sigma(\bar\nu_\mu\ e)$ elastic

$e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$ at low q^2

W-mass measurements

Defining:

$$\mathcal{L}^{NC}_{q^2<<M_Z^2} = 4\frac{G_F}{\sqrt{2}}\rho J^{NC}_\mu J^{\mu NC} \qquad J^{NC}_\mu = J^3_\mu - \sin^2\theta_W J^{em}_\mu$$

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

The ante-LEP knowledge

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

Theory:

- at tree level $\rho = 1$ from Higgs being a doublet

Veltman 1977 +...

$$V(H) = |H_1|^2 + |H_2|^2 + |H_3|^2 + |H_4|^2$$

$$SO(4) = SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$$

"custodial symmetry"

Sikivie et al 1980

- at 1 loop two types of contributions:

1. top-bottom-Goldstone bosons

2. Only 2 $\log m_h$ dependent (see below)

The ante-LEP knowledge

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

Theory:

- at 1 loop two types of contributions:

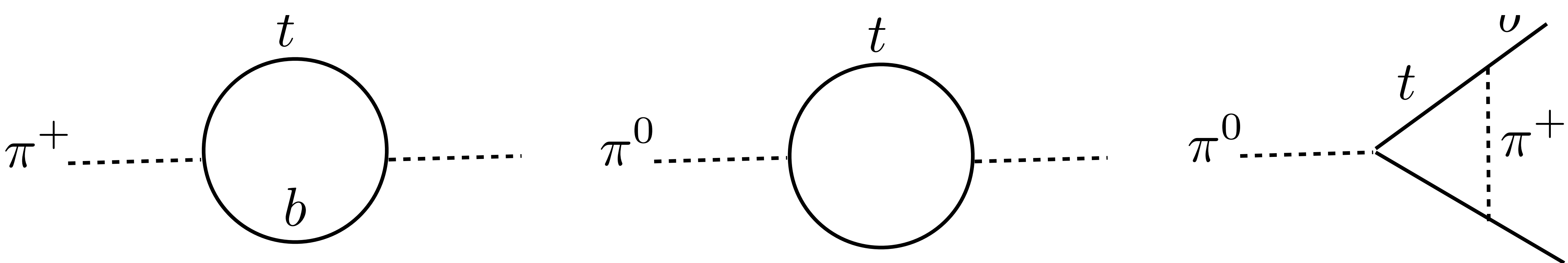
    1. top-bottom-Goldstone bosons

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

the "gaugeless" limit of the SM

$$\phi(x) = e^{i\pi_i(x)\sigma_i/v} \begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$

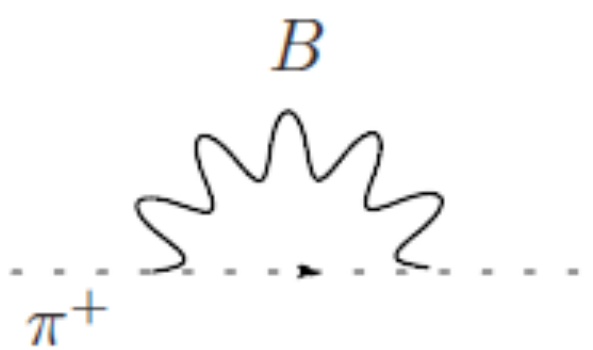
$$\mathcal{L}_{kin}(\pi_i) = Z_2^{(+)} \left| \partial_\mu \pi^+ - g\frac{v}{\sqrt{2}} W_\mu^+ \right|^2 + \frac{Z_2^{(0)}}{2} \left(\partial_\mu \pi^0 - \frac{gv}{2\cos\theta} Z_\mu \right)^2$$

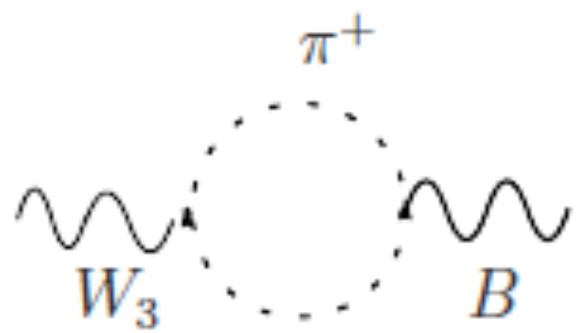


The ante-LEP knowledge

- at 1 loop two types of contributions:

2. Only 2 $\log m_h$ dependent (see below)





Passarino, Veltman 1979

Antonelli et al 1980

Sirlin 1980

$$\Delta\rho = -\frac{3\alpha}{8\pi\cos^2\theta_W}\log\frac{m_H}{M_Z}$$

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

Out of all this

⇒ at summer conferences in 1989:

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

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

LEP (and not only LEP) at work

(from 1990 on)

The observables at the Z-pole and the W-mass

Assuming quark-lepton and flavour universality,

3 effective observables only

In terms of the vector/axial couplings of the Z to the fermion f

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

and the W-mass

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

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

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

Altarelli, B 1990 — Altarelli, B, Jadach 1991

Why this peculiar definition of the ϵ_i ?

"Oblique" or non-"oblique"

$$\Pi_{ij}^{\mu\nu}(q^2) = -i\left[A_{ij}(0) + q^2 F_{ij}(q^2)\right]\eta^{\mu\nu} + (q^\mu q^\nu - \text{terms})$$

with $i,j = W, Z, \gamma$ or $i,j = 0,3$ for B, W^3

Defining:

Peskin, Takeuchi 1990

$$\hat{T} = \frac{1}{m_W^2}(A_{33}(0) - A_{WW}(0)); \quad \hat{S} = \frac{c}{s}F_{30}(0); \quad \hat{U} = F_{WW}(0) - F_{33}(0)$$

$\epsilon_1 = \hat{T}$ + smaller oblique + non oblique

$\epsilon_2 = \hat{U}$ + smaller oblique + non oblique

$\epsilon_3 = \hat{S}$ + smaller oblique + non oblique

non-oblique = vertices, boxes

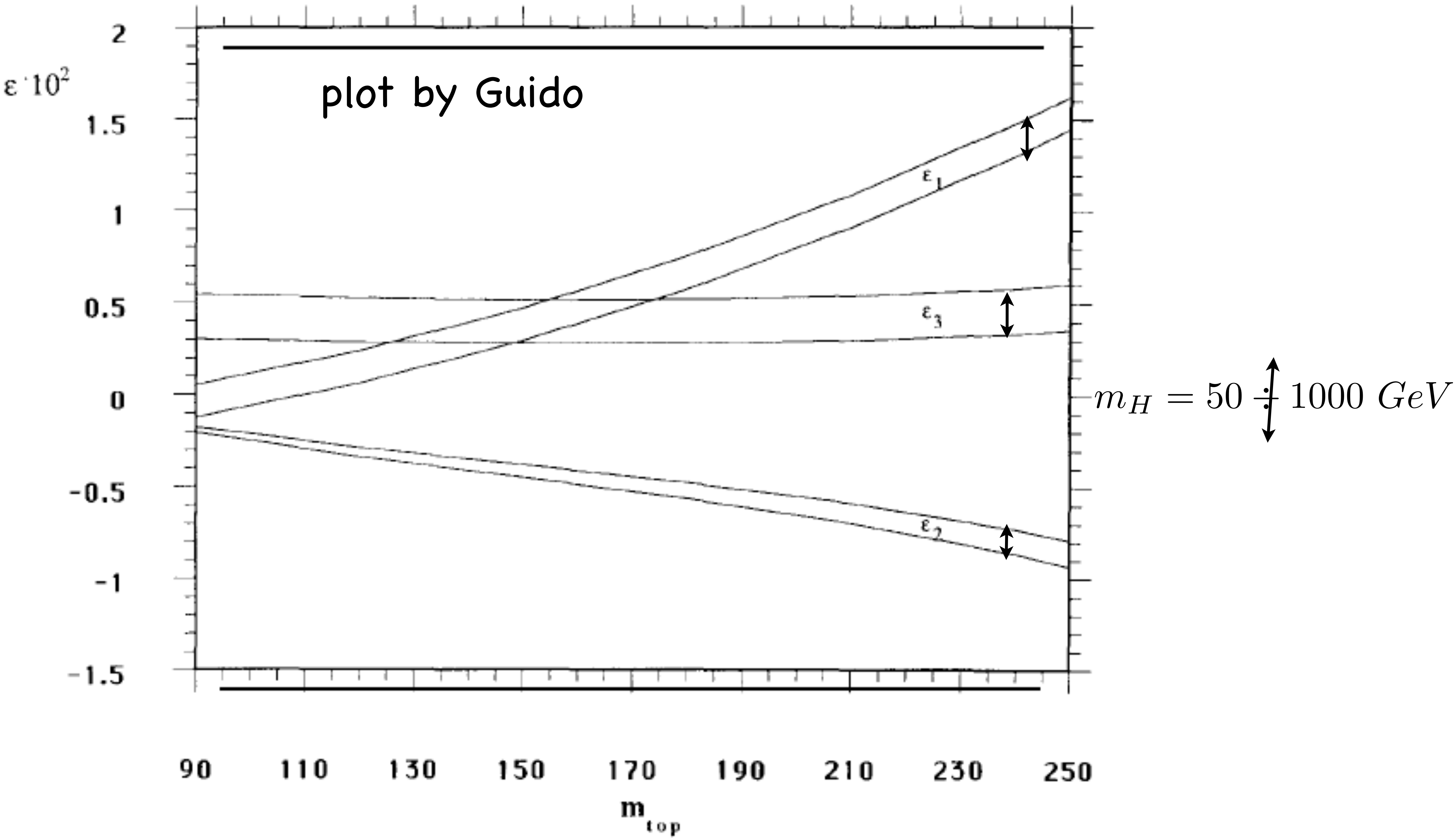
$$\Pi_{WW}, \Pi_{33}, \Pi_{30}, \Pi_{00} \Rightarrow 8 \ (\Pi(0), \Pi'(0))$$

$$8 = 2 \ (\Pi_{\gamma\gamma}(0) = \Pi_{\gamma Z}(0) = 0) + 3 \ (g, g', v) + 3 \ (\hat{S}, \hat{T}, \hat{U})$$

U less UV-sensitive than S and T $\Rightarrow$ only 2 independent $\log m_h$ terms

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

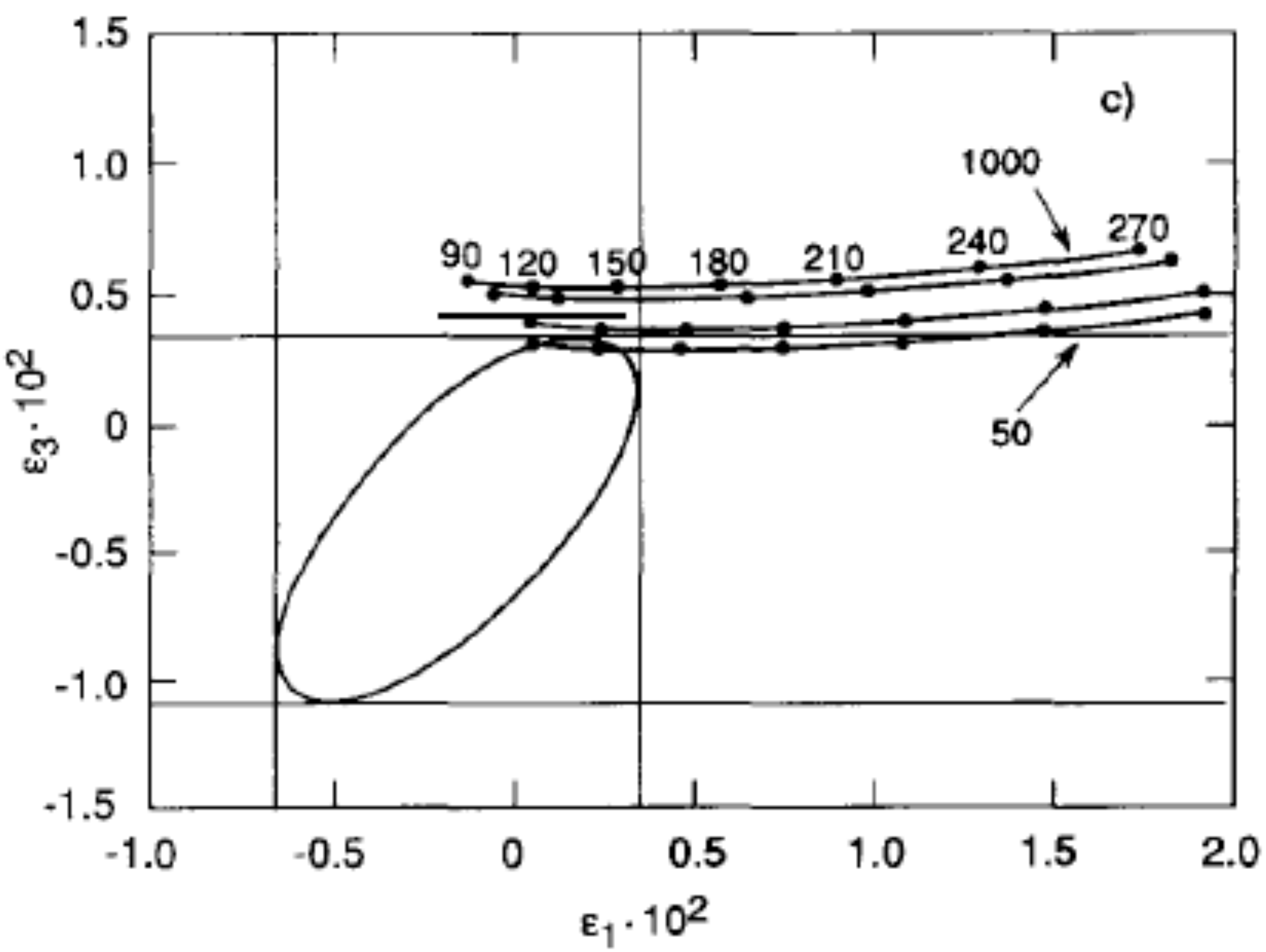
(with a simple dependence on m_t and m_h)

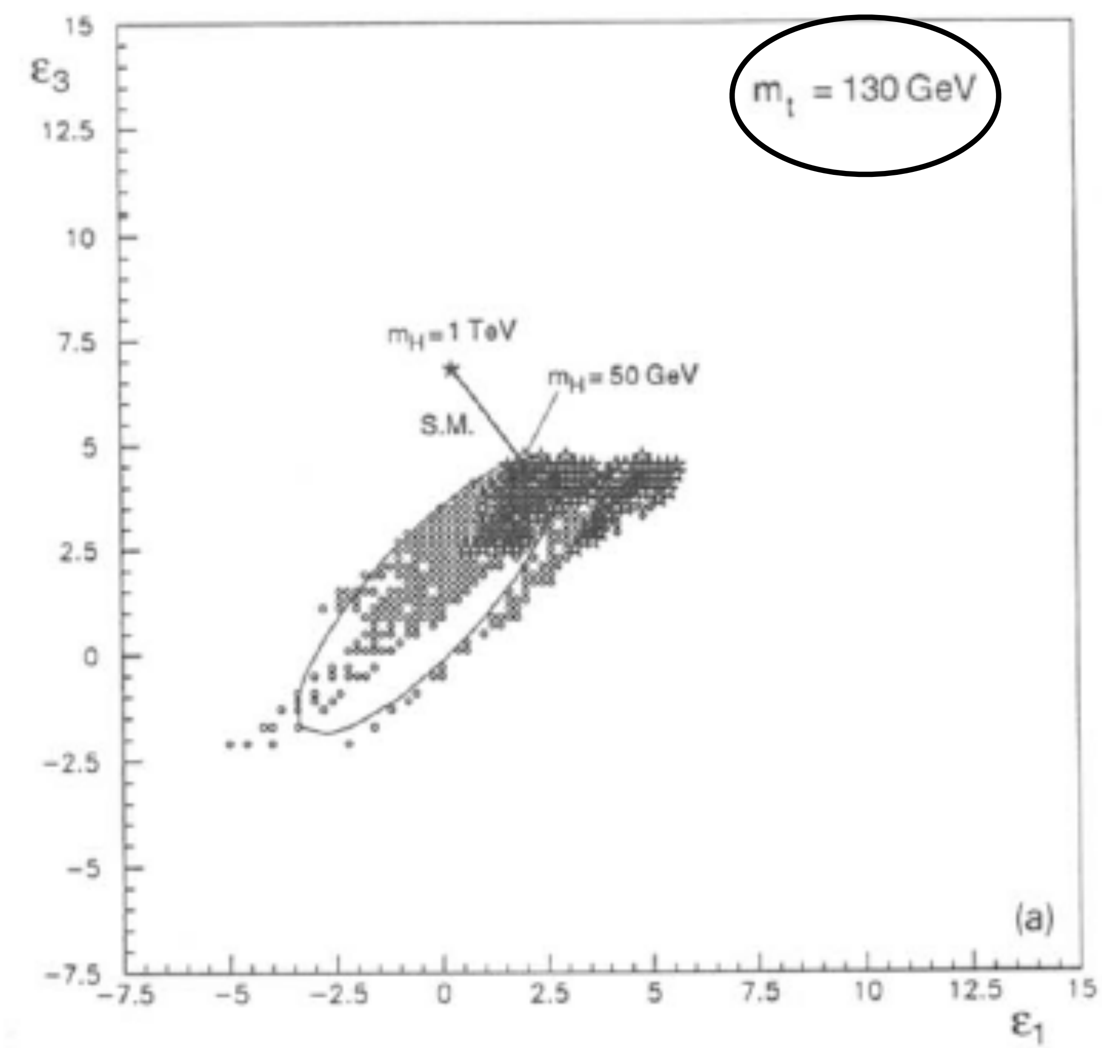


Altarelli, B, Jadach 1991

From LEP data in 1991-1993

Two different theories compared with observations:





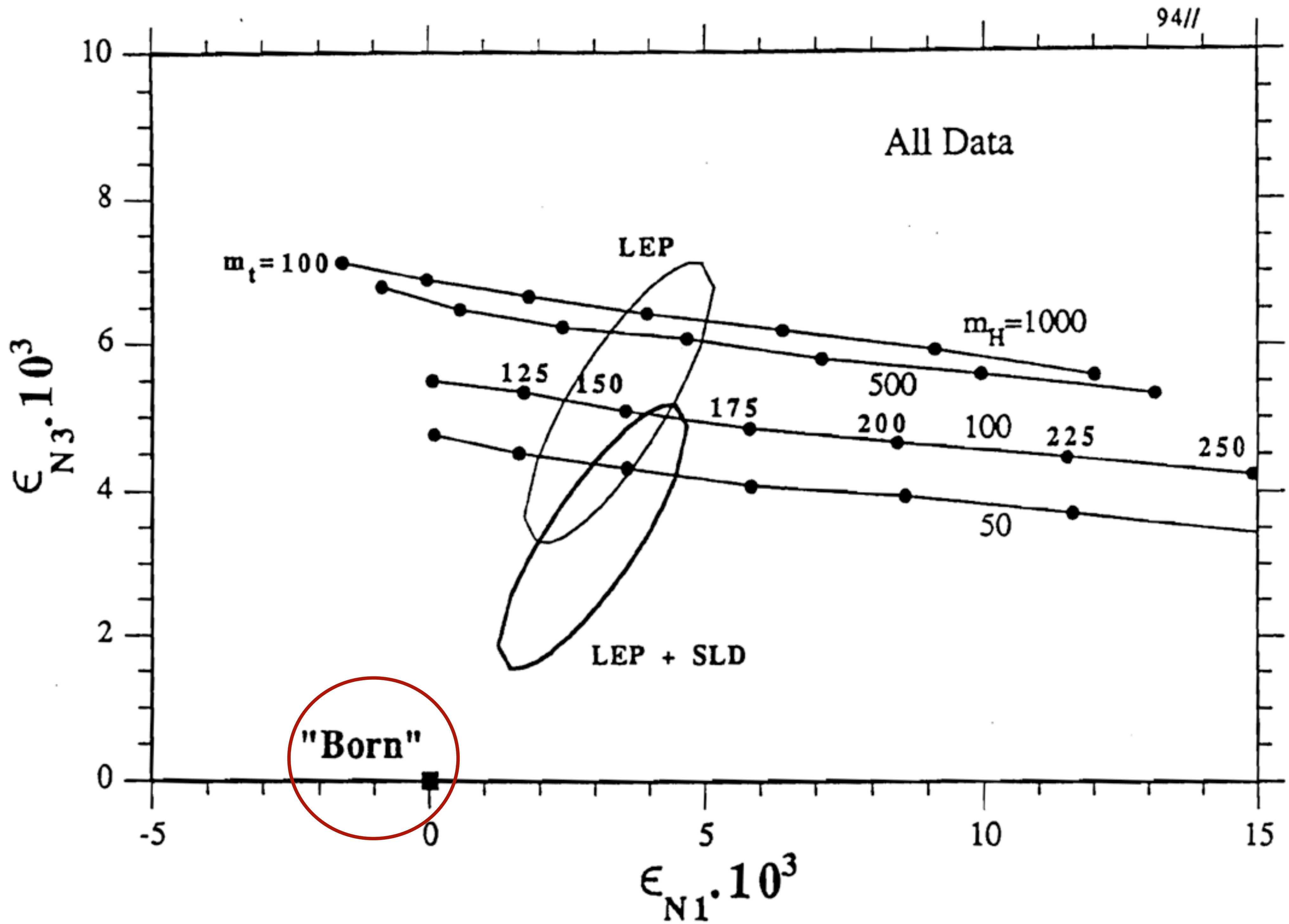
SM 1991

Altarelli, B, Jadach

light SUSY 1993

Altarelli, B, Caravaglios

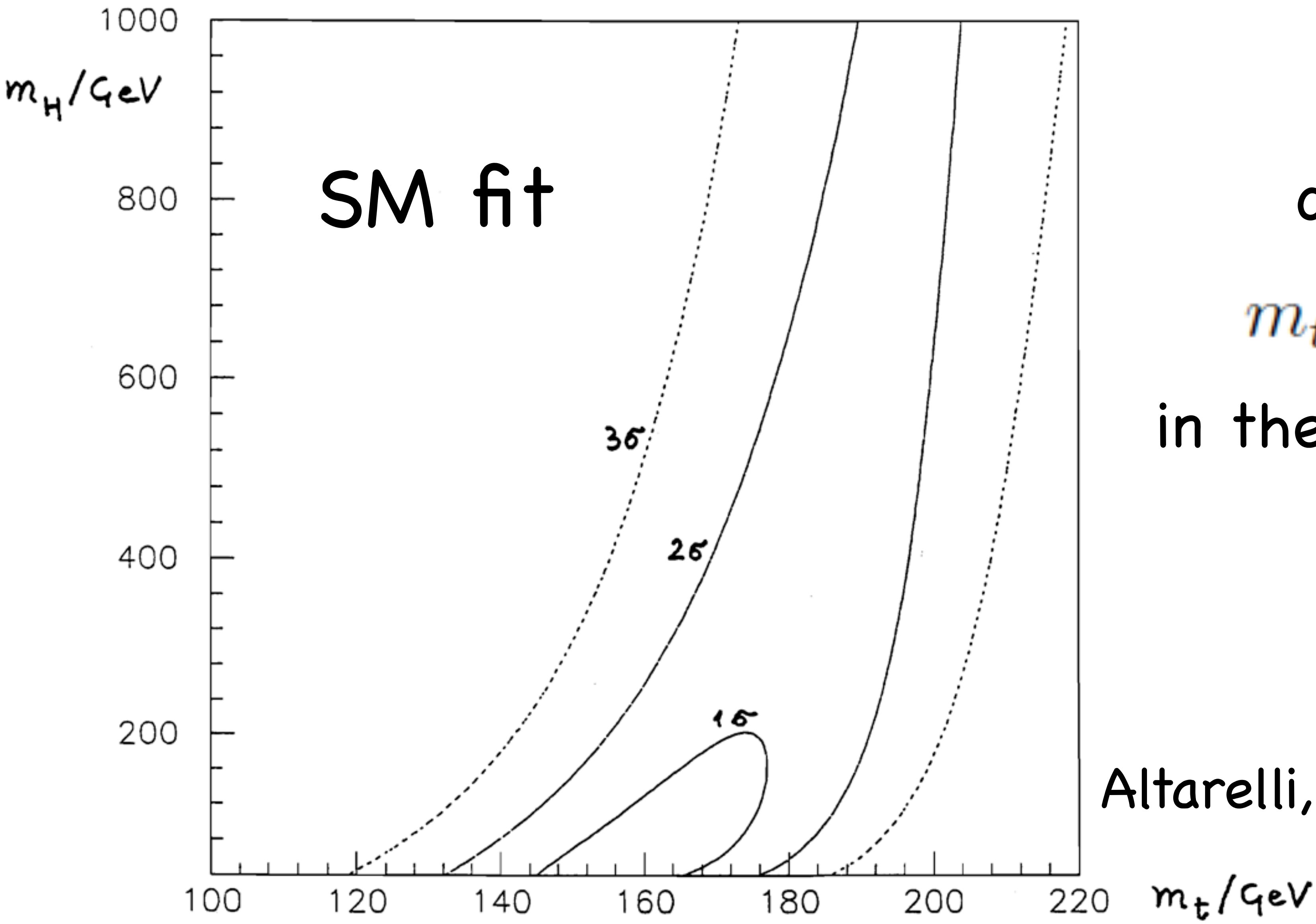
Constraining the top mass



Altarelli, B

La Thuile, April 1994

La Thuile, April 1994



compared with

$$m_t = 174 \pm 10^{+13}_{-12}\ GeV$$

in the CDF paper of Sept 1994

Altarelli, B

For the Higgs boson a similar story in July 2012

EW precision	ATLAS	CMS
$m_h/GeV = 97^{+23}_{-17}$	$126.0 \pm 0.4 \pm 0.4$	$125.3 \pm 0.4 \pm 0.5$

Current SM predictions (all OK with exp)

$$g,\ g',\ v \quad + \quad g_S, m_t, m_h, \Delta\alpha_{had}$$

$$G_\mu = 1.1663787 \times 10^{-5}\ \text{GeV}^{-2} \qquad \alpha = 1/137.035999139$$

		Prediction	α_s	$\Delta\alpha^{(5)}_{\rm had}$	M_Z	m_t
80.385 ± 0.015	M_W [GeV]	80.3618 ± 0.0080	± 0.0008	± 0.0060	± 0.0026	± 0.0046
	Γ_W [GeV]	2.08849 ± 0.00079	± 0.00048	± 0.00047	± 0.00021	± 0.00036
	Γ_Z [GeV]	2.49403 ± 0.00073	± 0.00059	± 0.00031	± 0.00021	± 0.00017
	σ_h^0 [nb]	41.4910 ± 0.0062	± 0.0059	± 0.0005	± 0.0020	± 0.0005
0.23146 ± 0.00012	$\sin^2\theta_{\rm eff}^{\rm lept}$	0.23148 ± 0.00012	± 0.00000	± 0.00012	± 0.00002	± 0.00002
	$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.14731 ± 0.00093	± 0.00003	± 0.00091	± 0.00012	± 0.00019
	$\mathcal{A}_c$	0.66802 ± 0.00041	± 0.00001	± 0.00040	± 0.00005	± 0.00008
	$\mathcal{A}_b$	0.934643 ± 0.000076	± 0.000003	± 0.000075	± 0.000010	± 0.000005
	$A_{\rm FB}^{0,\ell}$	0.01627 ± 0.00021	± 0.00001	± 0.00020	± 0.00003	± 0.00004
	$A_{\rm FB}^{0,c}$	0.07381 ± 0.00052	± 0.00002	± 0.00050	± 0.00007	± 0.00010
	$A_{\rm FB}^{0,b}$	0.10326 ± 0.00067	± 0.00002	± 0.00065	± 0.00008	± 0.00013
	R_ℓ^0	20.7478 ± 0.0077	± 0.0074	± 0.0020	± 0.0003	± 0.0003
	R_c^0	0.172222 ± 0.000026	± 0.000023	± 0.000007	± 0.000001	± 0.000009
	R_b^0	0.215800 ± 0.000030	± 0.000013	± 0.000004	± 0.000000	± 0.000026

(negligible uncertainty from m_h variations)

de Blas et al, 2016

The state of the art on 2 most precisely known quantities

$$M_W, \qquad \sin^2\theta^l_{eff} \equiv \frac{1}{4}(1 - \frac{g^l_V}{g^l_A})$$

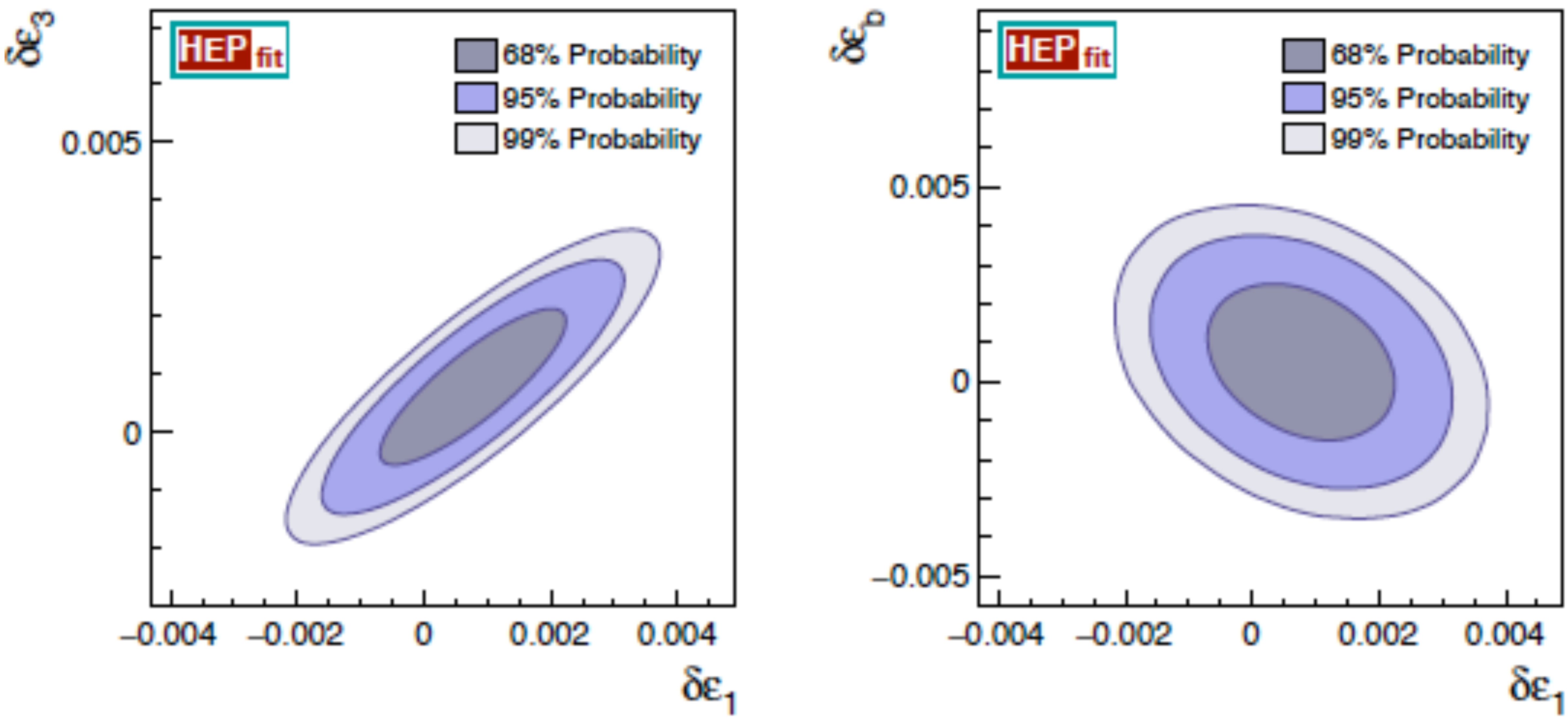
	$\delta M_W/MeV$	$\delta \sin^2\theta^l_{eff}/10^{-5}$
higher orders	5	5
parametric	9	12
exp. current	15	16
exp. FCC-ee	0.5	0.3

"parametric": $\Delta m_t = 1\ GeV$, $\Delta\alpha^{(5)}_{had} = 3.3 \cdot 10^{-4}$, $\Delta\alpha_S(M_Z) = 7 \cdot 10^{-4}$

Degrassi, Gambino, Giardino 2014

general current fit

de Blas et al, 2016

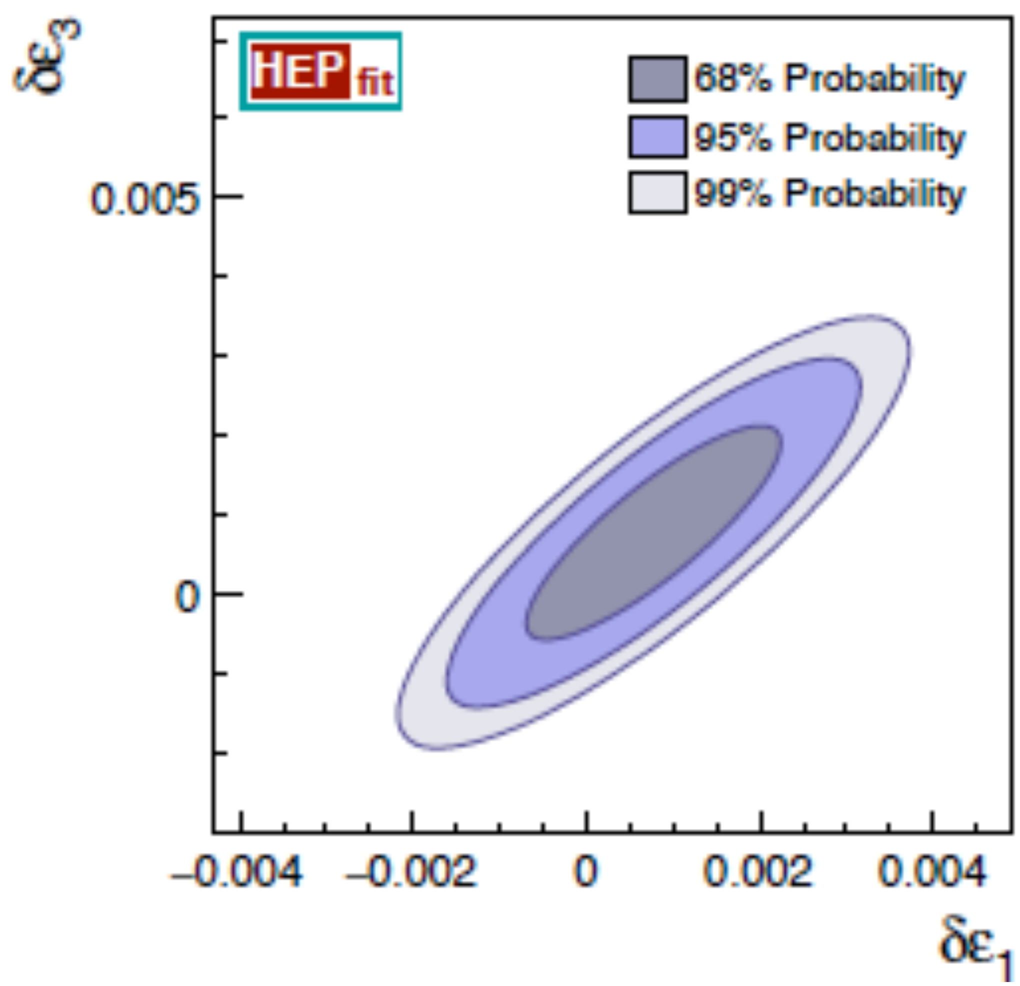


$$\delta\epsilon_i = \epsilon_i - \epsilon_i^{SM} \qquad \epsilon_1^{SM} = 5.21 \cdot 10^{-3},\ \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$$

SM EW loops seen with about 20% precision

A significant comparison

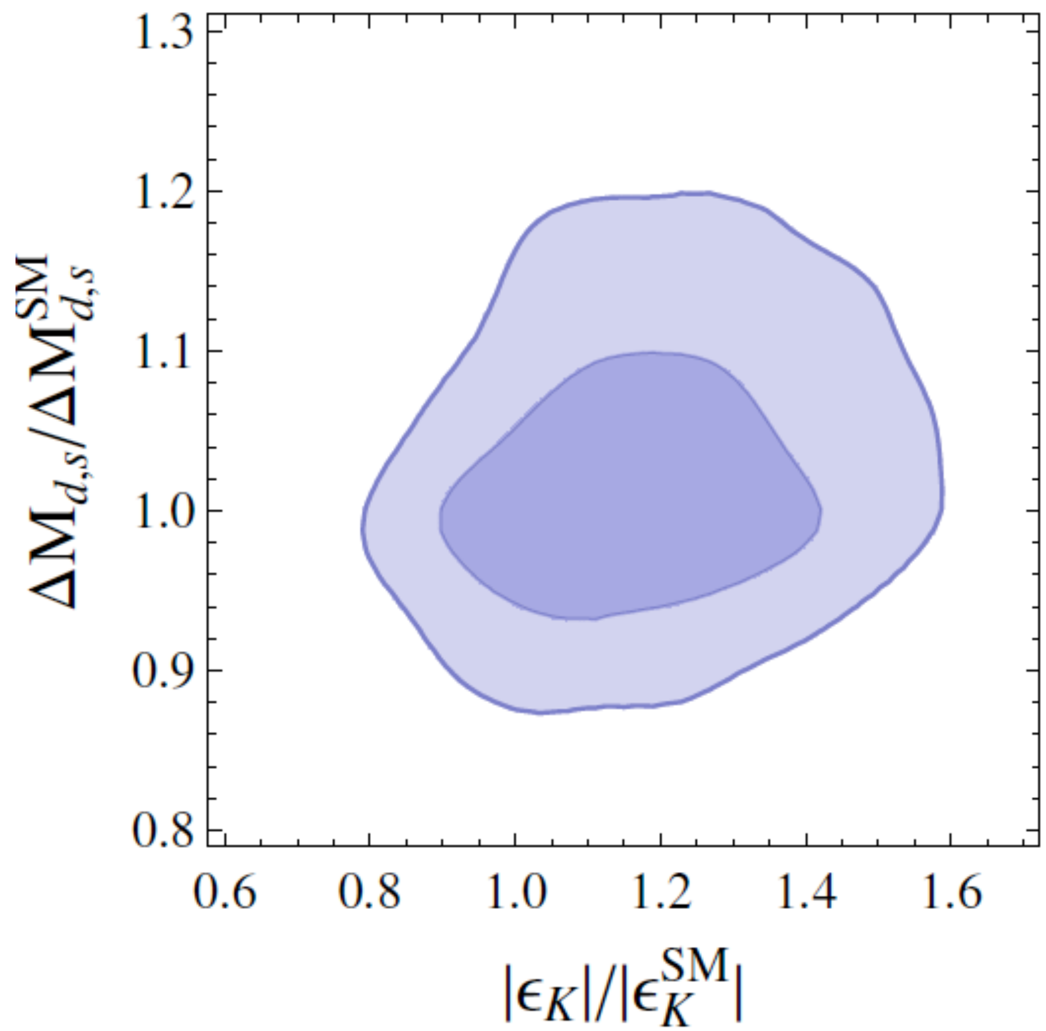
$\epsilon_1^{SM} = 5.21 \cdot 10^{-3}, \ \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$



measures EW loops
at about 20% level

A future facility (FCCee, ...)
could go to 2% level

B, Buttazzo, Sala, Straub 2014



measures FCNC loops
at about 20% level

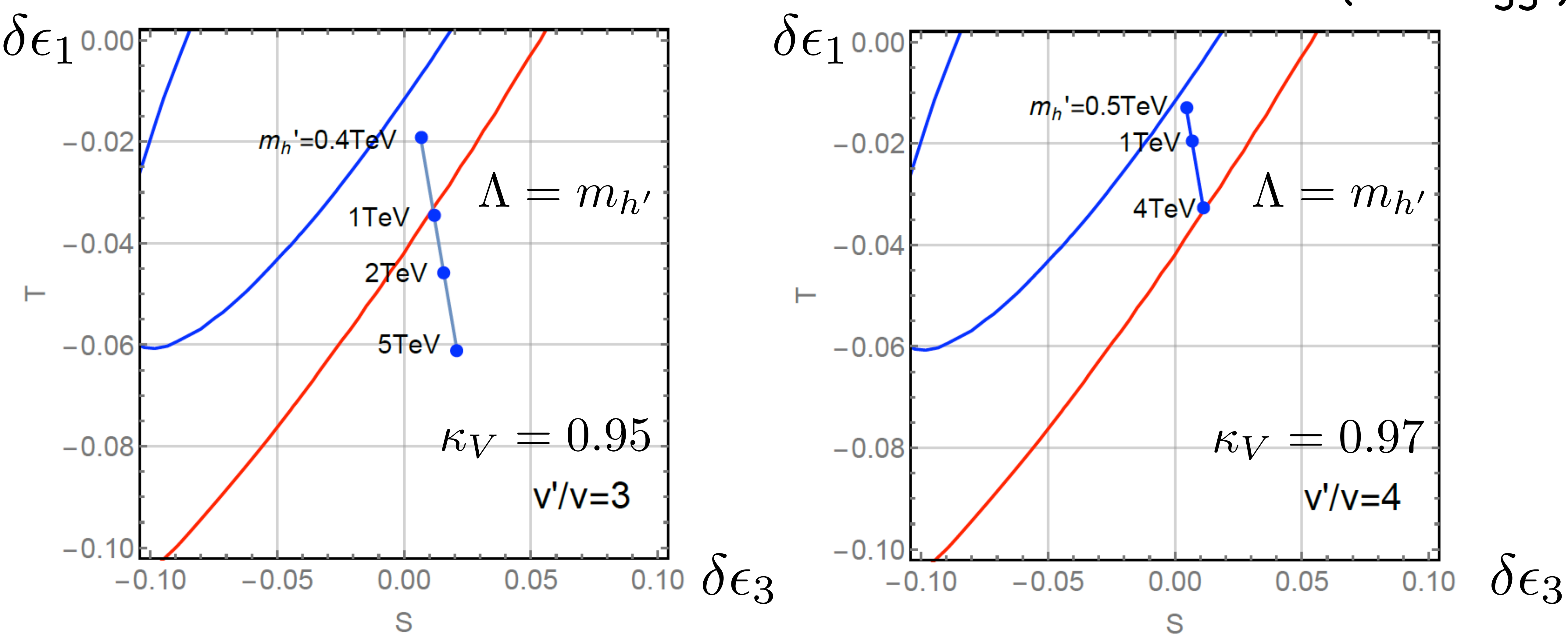
An "aggressive" flavour program
could go to 2% level

A relevant example of BSM constraint from EW precision

Consider any theory where the hVV-coupling κ_V deviates from the SM

$$\delta\epsilon_1 = -\frac{3\alpha}{8\pi c^2}(1-k_V^2)\log\frac{\Lambda}{m_h}, \qquad \delta\epsilon_3 = \frac{\alpha}{24\pi s^2}(1-k_V^2)\log\frac{\Lambda}{m_h}$$

(twin Higgs)



$$k_V = \frac{g_{HVV}}{g_{HVV}^{SM}} = (1-(v/v')^2)^{1/2}$$

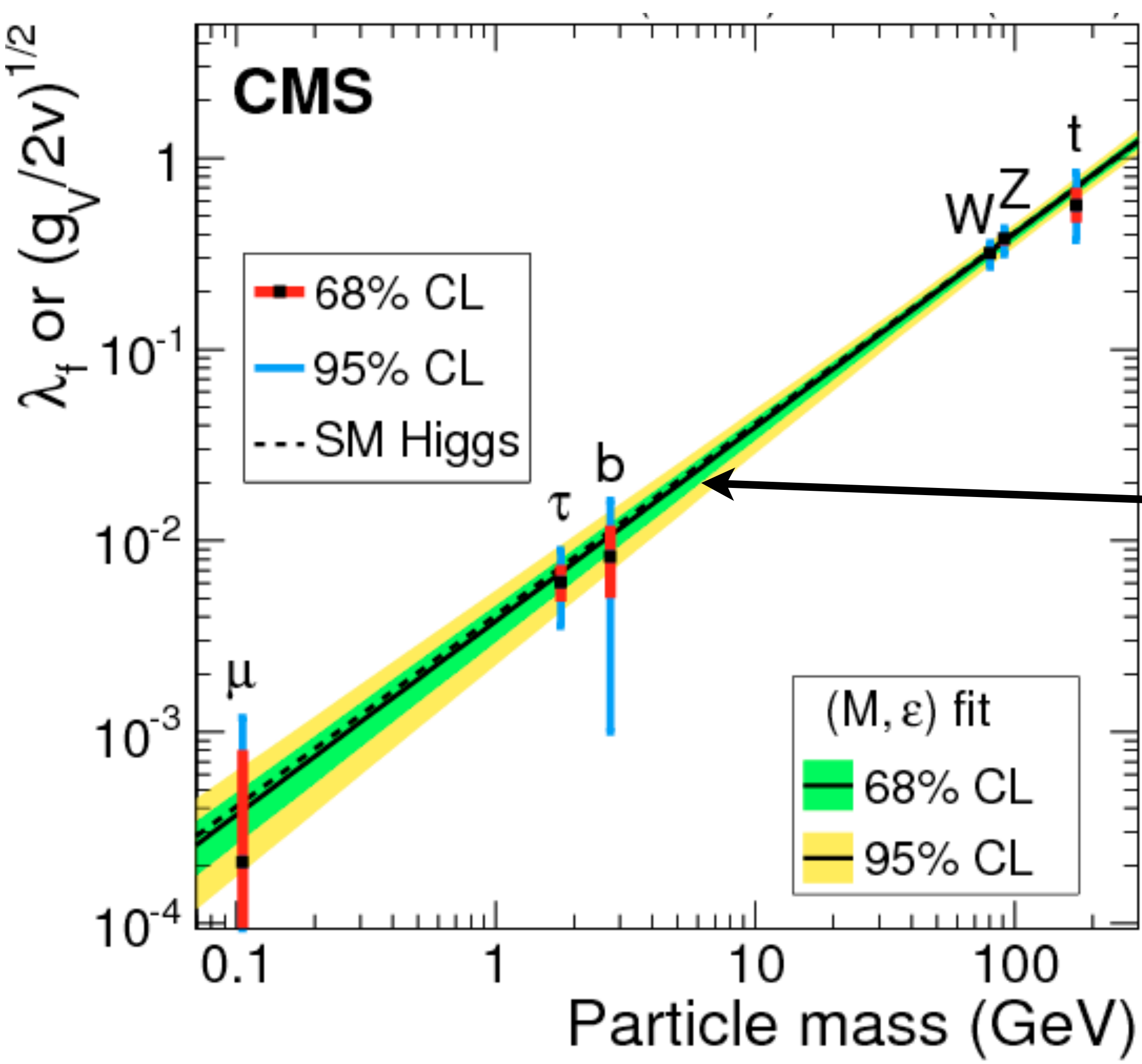
Any other contribution?

Two other complementary directions in (the use of) precision data

1. The SM as an effective low-energy theory

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

2. Precision in Higgs couplings



the slope of the line is the only parameter (v)

(not only ElectroWeak)

EW precision with effective operators

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

95% lower bounds on Λ/TeV on one operator at a time

	$c_i = -1$	$c_1 = +1$	$c_i = -1$	$c_i = +1$
$(H^+\tau^a H)W^a_{\mu\nu}B_{\mu\nu}$	9.7	10	11.1	18.4
$\lvert H^+D_\mu H\rvert^2$	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

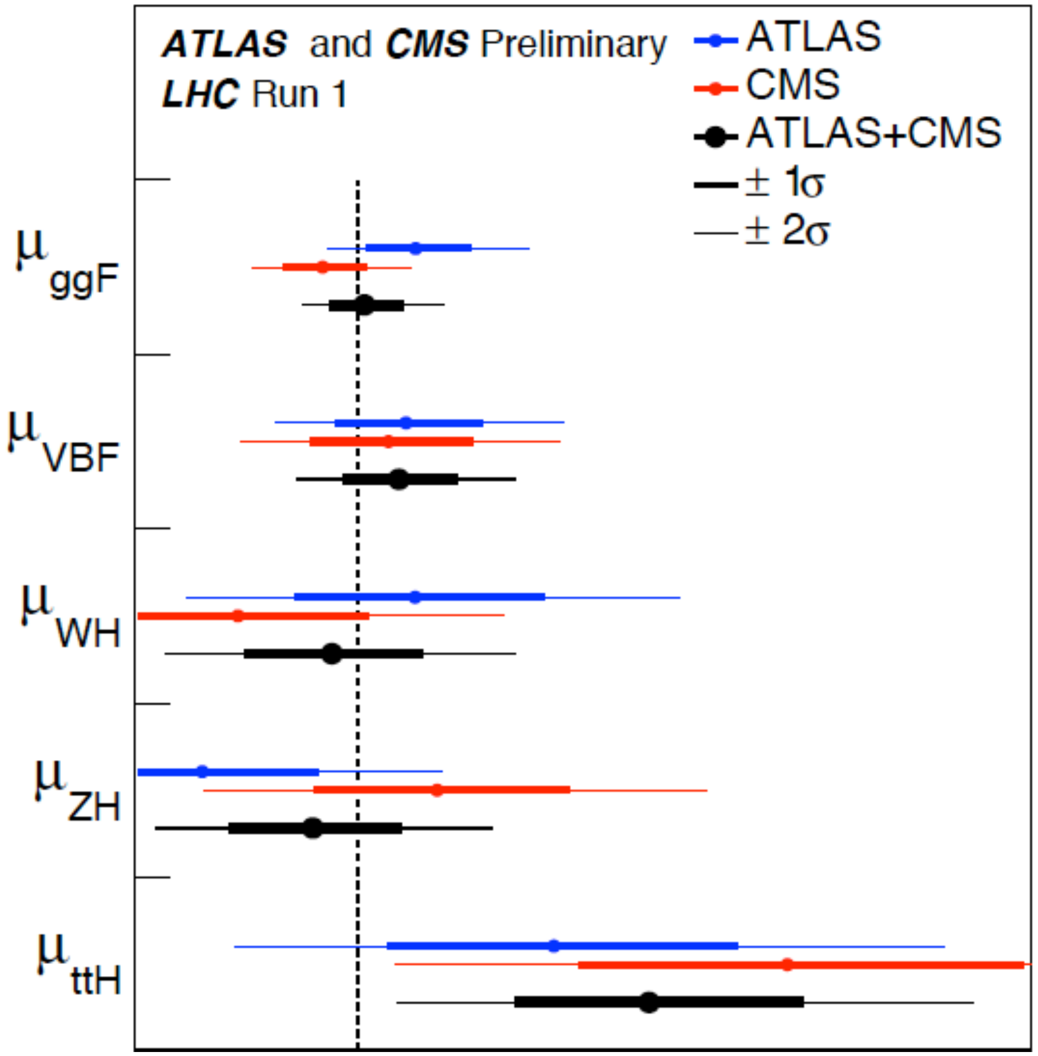
caveats:

In general many more operators already at dim=6

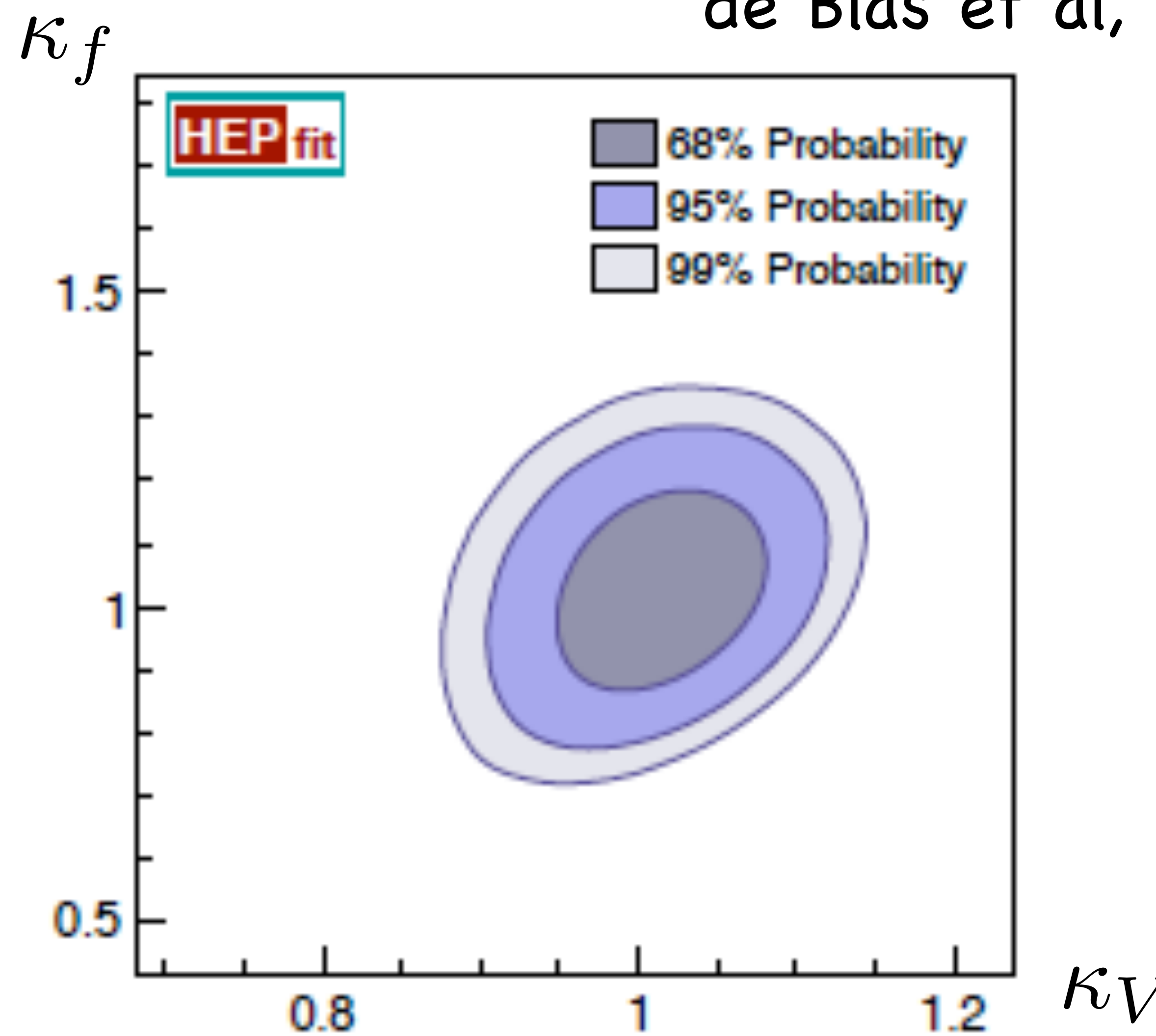
Correlations lost

What is the "true" meaning of this bounds?

Precision in Higgs couplings



de Blas et al, 2016



EW precision in principle more constraining on κ_V

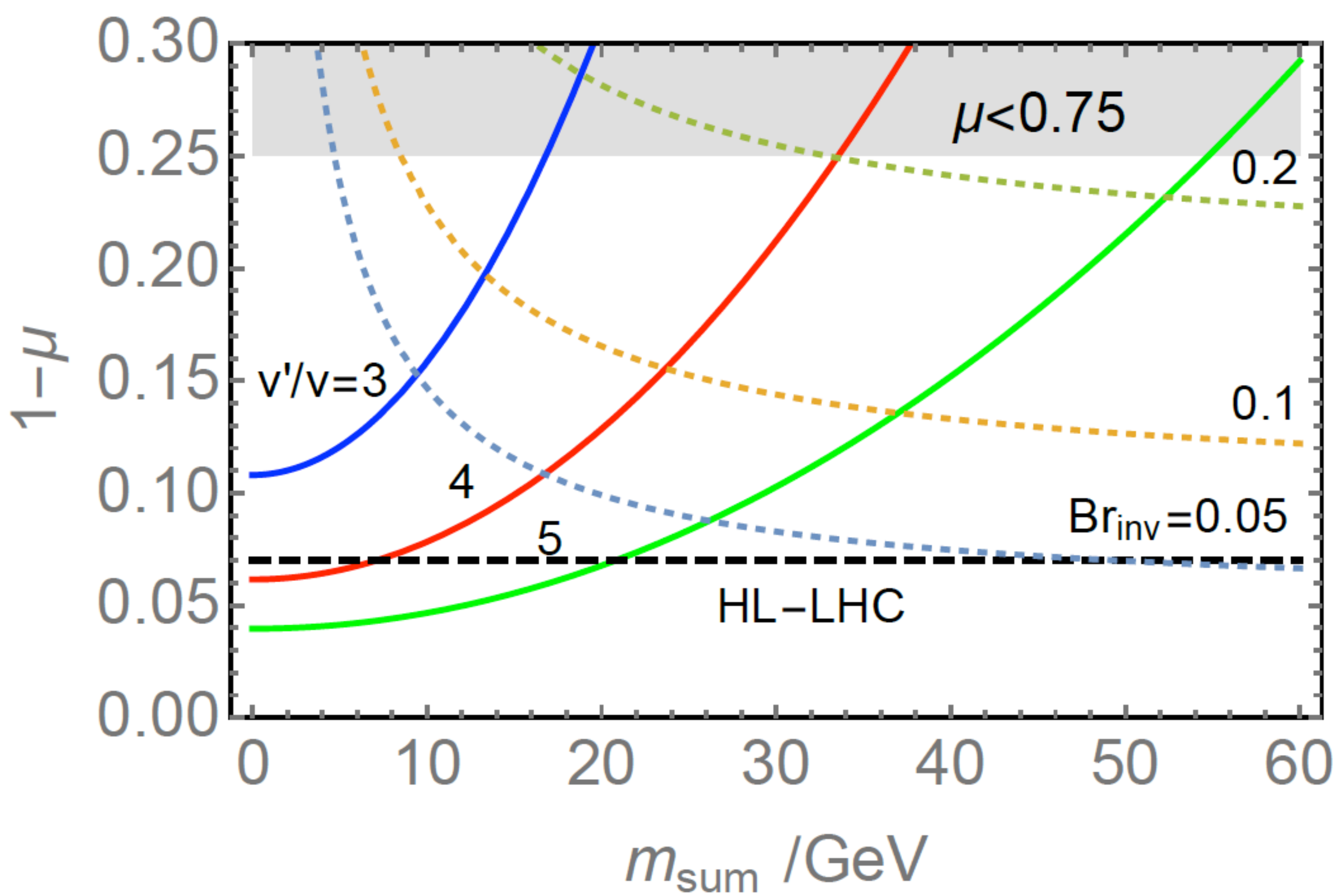
caveats:

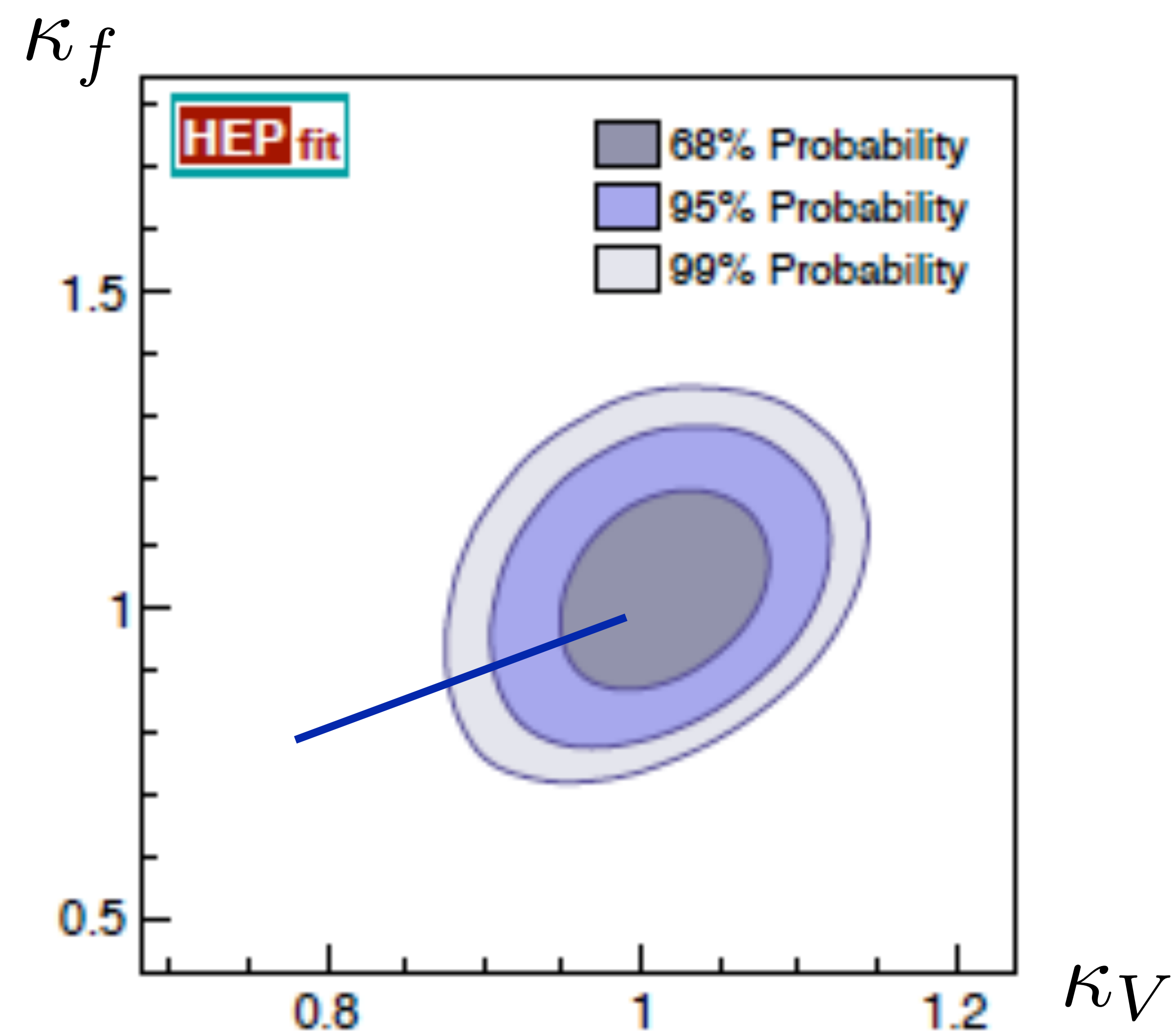
Need to specify the cutoff and be sure of no other contribution

A model example (twin Higgs)

$$h = cos\theta H + sin\theta H' \qquad tan\theta \approx \frac{v}{v'} \qquad h \rightarrow i_{SM}, f'\bar{f}'$$

$$\mu(i_{SM}) \equiv \frac{\sigma^{TH}(pp \rightarrow i_{SM})}{\sigma^{SM}(pp \rightarrow i_{SM})} = \mu = cos^2\theta(1 - Br_{inv}) \approx 1 - (\sin^2\theta + Br_{inv})$$





$$BR_{inv} = f(v'/v, m_{sum})$$

B, Hall, Harigaya 2016

Precision and SM vacuum stability

$$V(\varphi) = \mu^2|\varphi|^2 + \lambda|\varphi|^4$$

$$\frac{d\lambda}{d\log Q} = \frac{3}{2\pi^2}\left[\lambda^2 + \frac{1}{2}\lambda y_t^2 - \frac{1}{4}y_t^4 + \cdots\right]$$

$$m_W = gv/\sqrt{2}$$
$$m_H = 2\sqrt{\lambda}v$$
$$m_t = y_t v$$

With current values of $m_H,\ m_t,\ \alpha_S, \ldots$

$$\lambda(\approx 10^{11}\ GeV) < 0$$

⇒ A second minimum of V at $\phi \gtrsim 10^{11}\ GeV$
to which v should tunnel in a very long time (>> t_{Univ})

Degrassi et al, 2013

- Is there a real meta-stability at $\phi < M_{Pl}$?
- Any experimental implication?
- Connection to inflation?
- Is it a problem?

The 3 ways to judge a physical theory

1. Its aesthetics and its synthesis

2. Its discovery signals

3. Its precise numerical consequences

Guido and I both liked precision in physical theories
I advocate that this be kept as a key criterium