The Standard Model and (some of) its extensions

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GGI, Florence, January 9-27, 2017

Program

I. The SM and its status, as of 2016

II. Problems of (questions for) the SM

III. Minimal Mirror Twin Higgs (2 lectures)

IV. Anomalies in B-decays

V. Axion searches by way of their coupling to the spin

I. The Standard Model and its status summarized

The SM Lagrangian
(since 1973 in its full content)

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

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

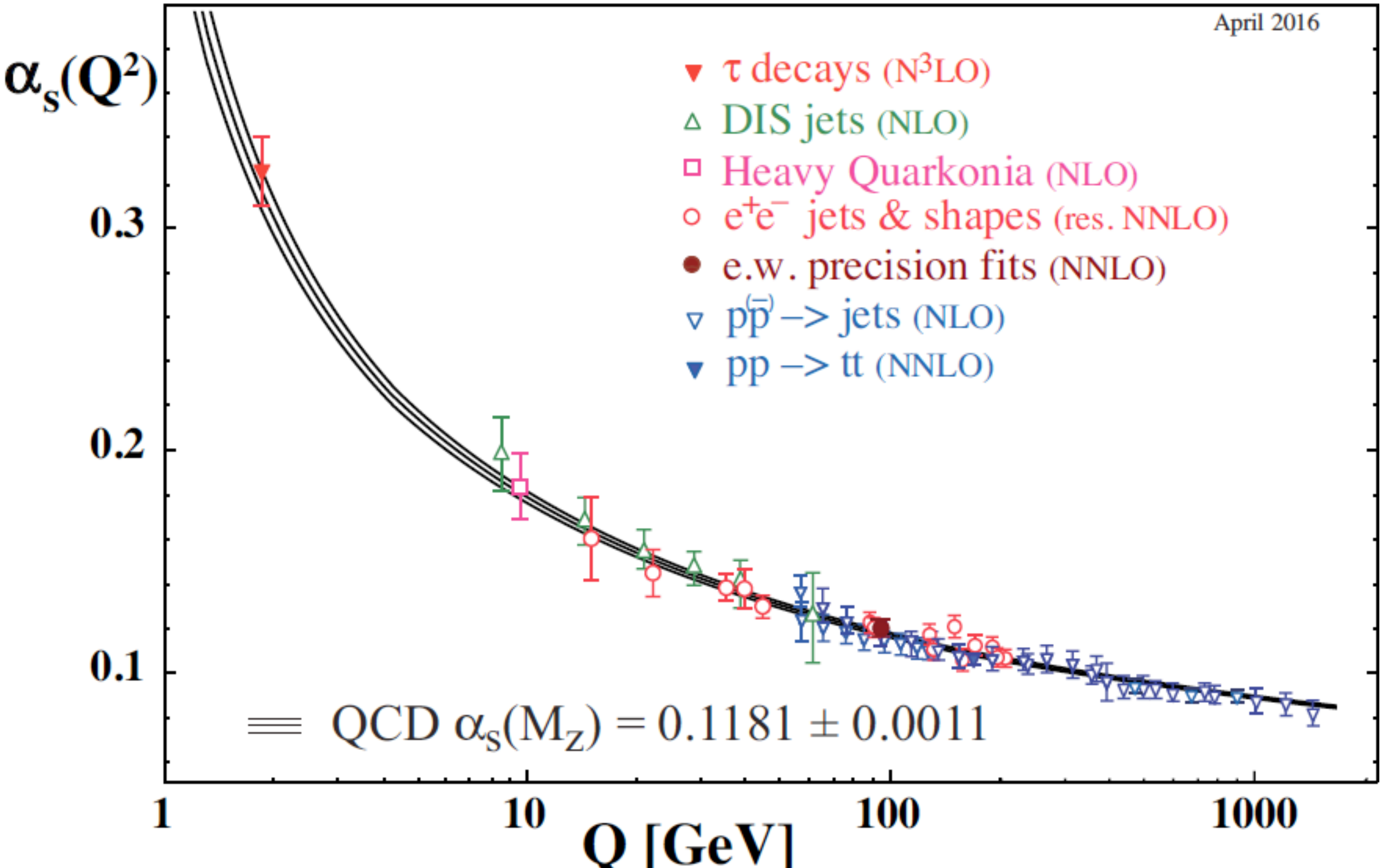
$$+ \psi_i \lambda_{ij} \psi_j h + h.c. \qquad (\sim 2000\text{- now})$$

In () the approximate dates of the experimental shining of the various lines (at different levels)

The synthetic nature of PP exhibited

QCD in full strength

(see Maltoni's lectures)



G. Dissertori 2016

even though in the strong coupling regime...

Precision in ElectroWeak Physics

(a story that goes on from about 1970 on

and still keeps its relevance)

	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

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

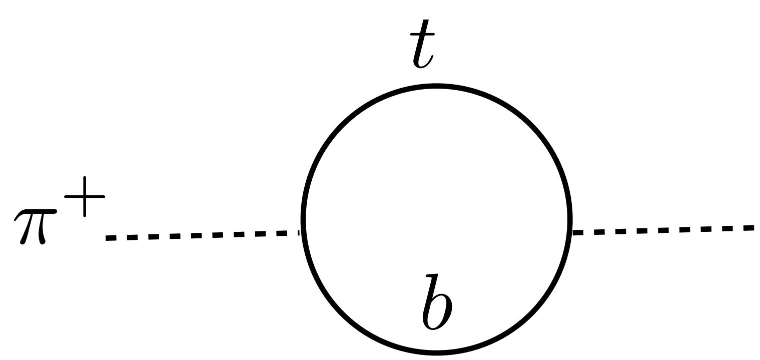
the "gaugeless" limit of the SM

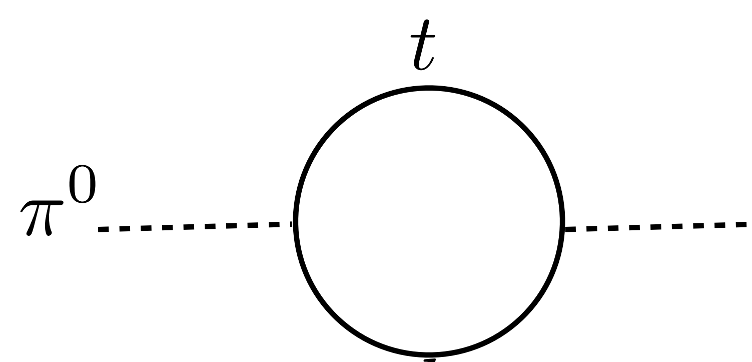
$$\phi(x) = e^{i\pi_i(x)\sigma_i/v} \begin{pmatrix} 0 \\ v + \frac{h(x)}{\sqrt{2}} \end{pmatrix}$$

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

$$\Delta\rho = 3x$$

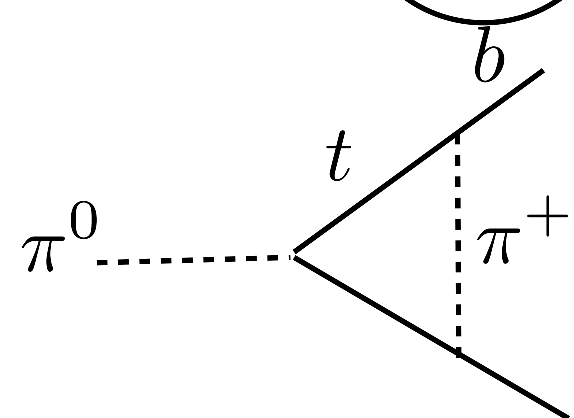
$$x = \frac{G_F m_t^2}{8\pi^2\sqrt{2}}$$





?

$$\delta V_\mu(Z \to b\bar{b}) = -\frac{g}{cos\theta_W} x \bar{b}_L \gamma_\mu b_L$$

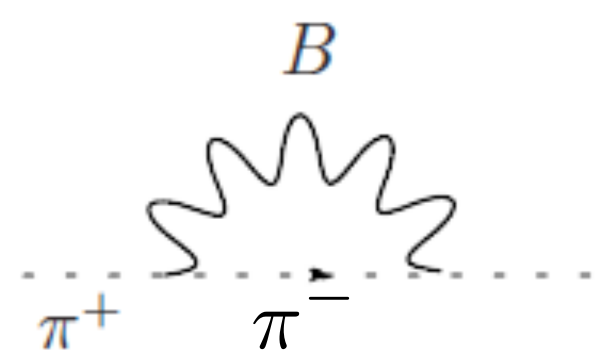


The ante-LEP knowledge

- at 1 loop two types of contributions:

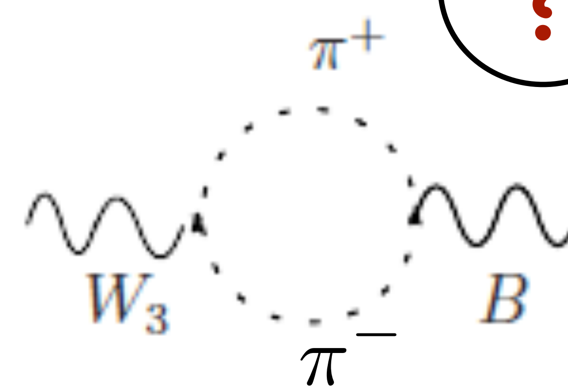
  2. Only 2 $\log m_h$ dependent (see below)

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



(B in the Landau gauge)

?



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

Passarino, Veltman 1979

Antonelli et al 1980

Sirlin 1980

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

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

and the W-mass

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

Why this peculiar definition of the ϵ_i ?

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

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

?

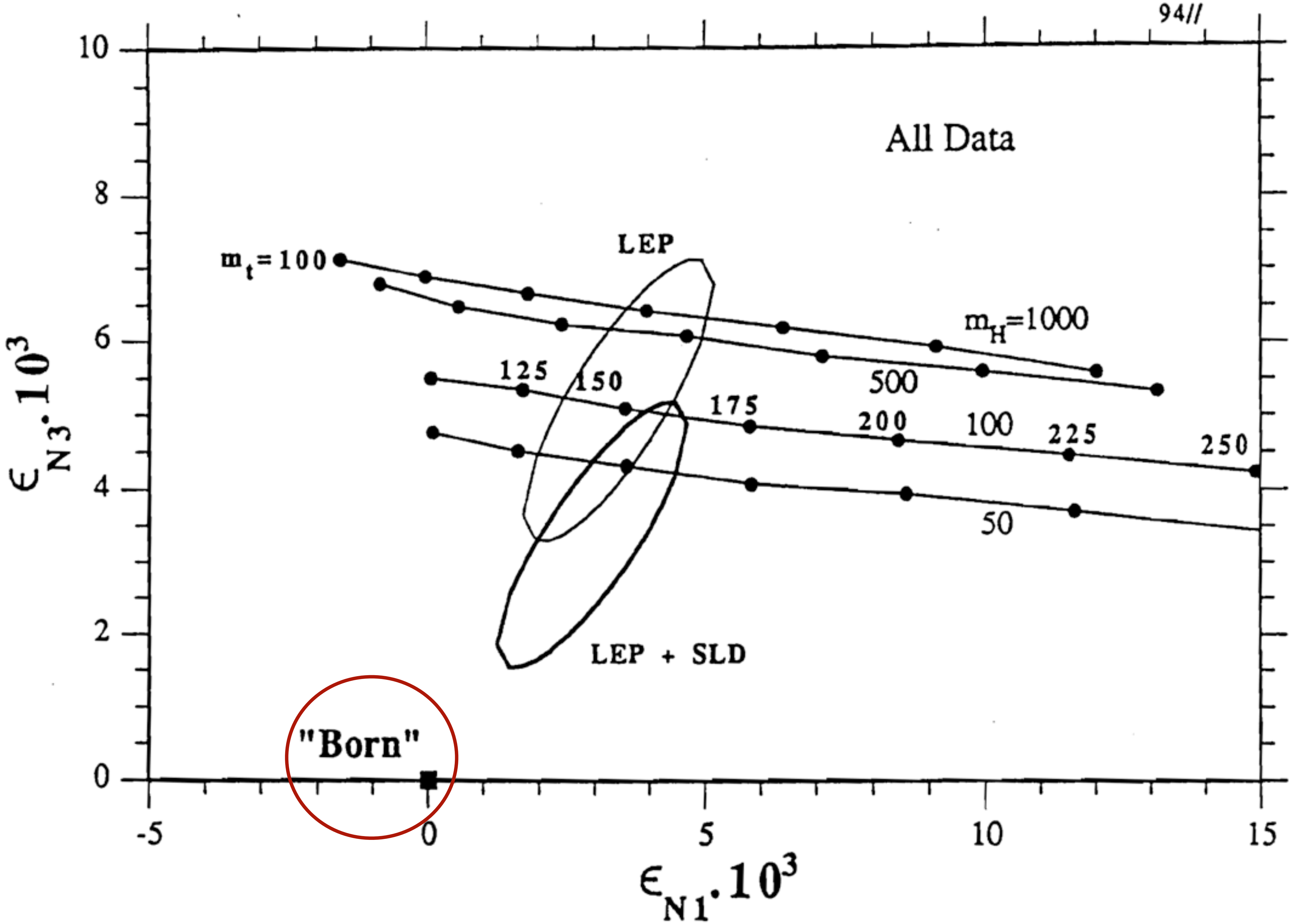
non-oblique = vertices, boxes

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

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

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

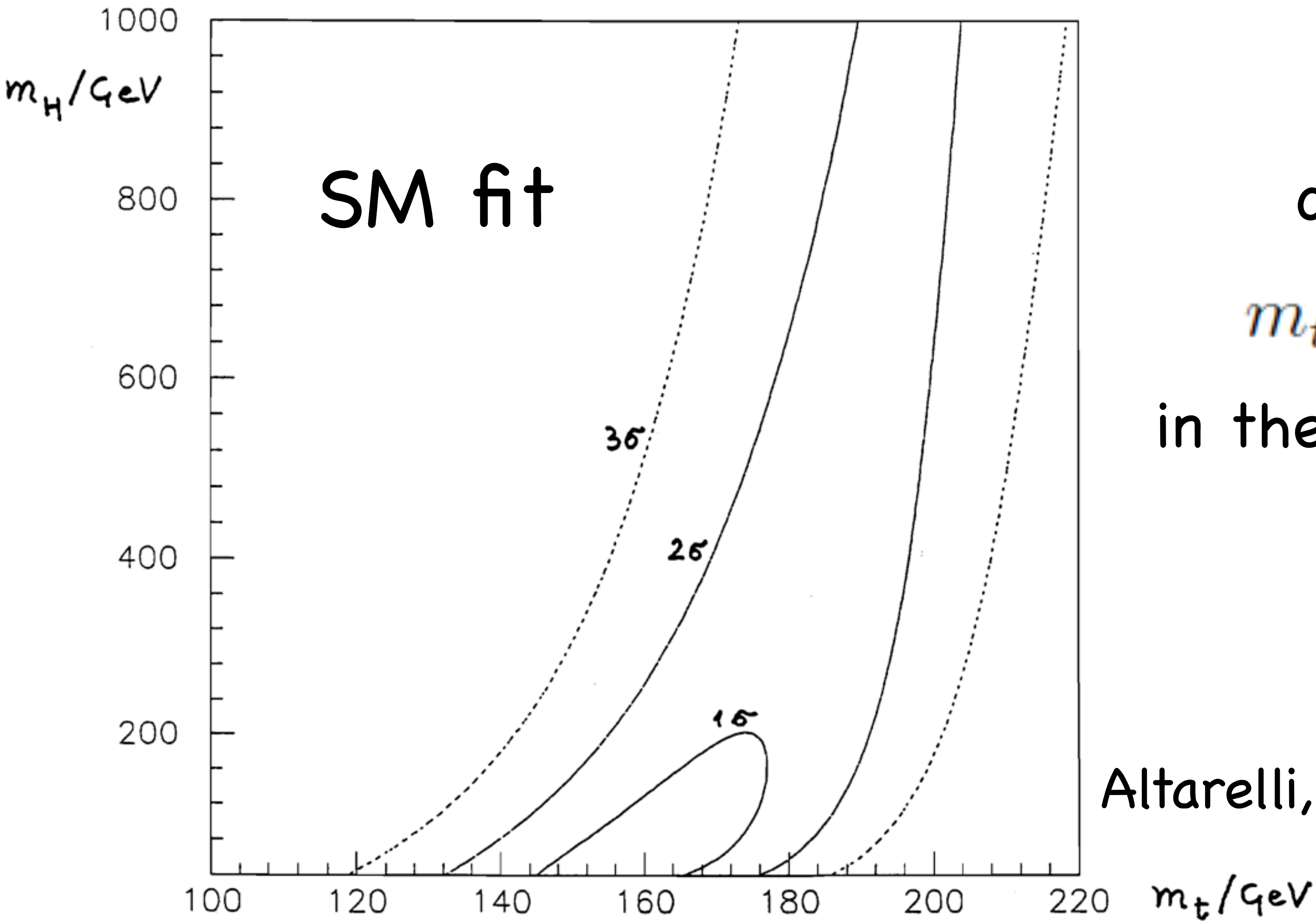
Constraining the top mass



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)

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

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

		Prediction	α_s	$\Delta\alpha_{\rm had}^{(5)}$	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

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

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

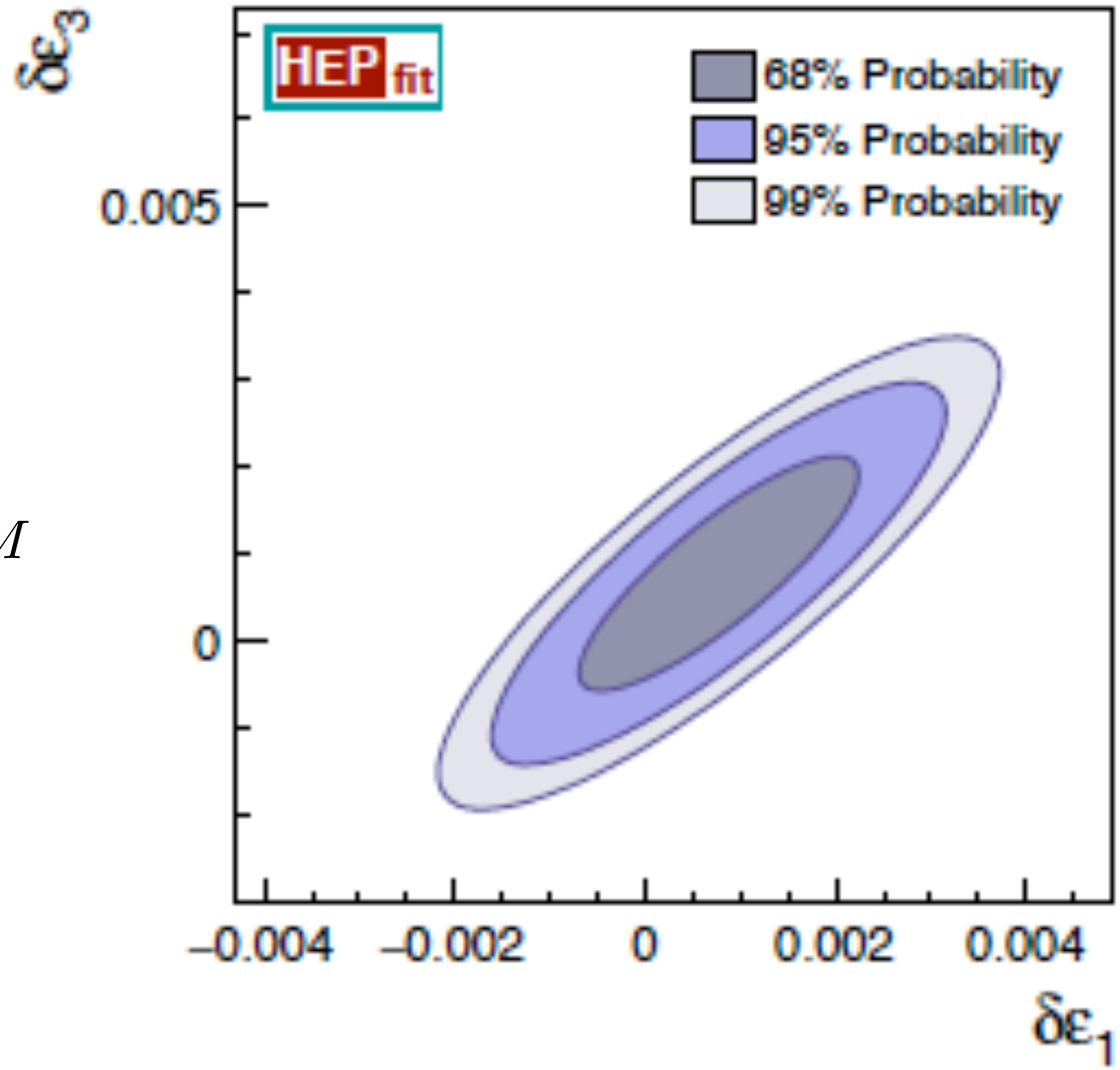
"parametric": $\Delta m_t = 1\ GeV$, $\Delta\alpha^{(5)}_{had} = 3.3\cdot 10^{-4}$, $\Delta\alpha_S(M_Z) = 7\cdot 10^{-4}$

Degrassi, Gambino, Giardino 2014

general current fit

de Blas et al, 2016

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



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

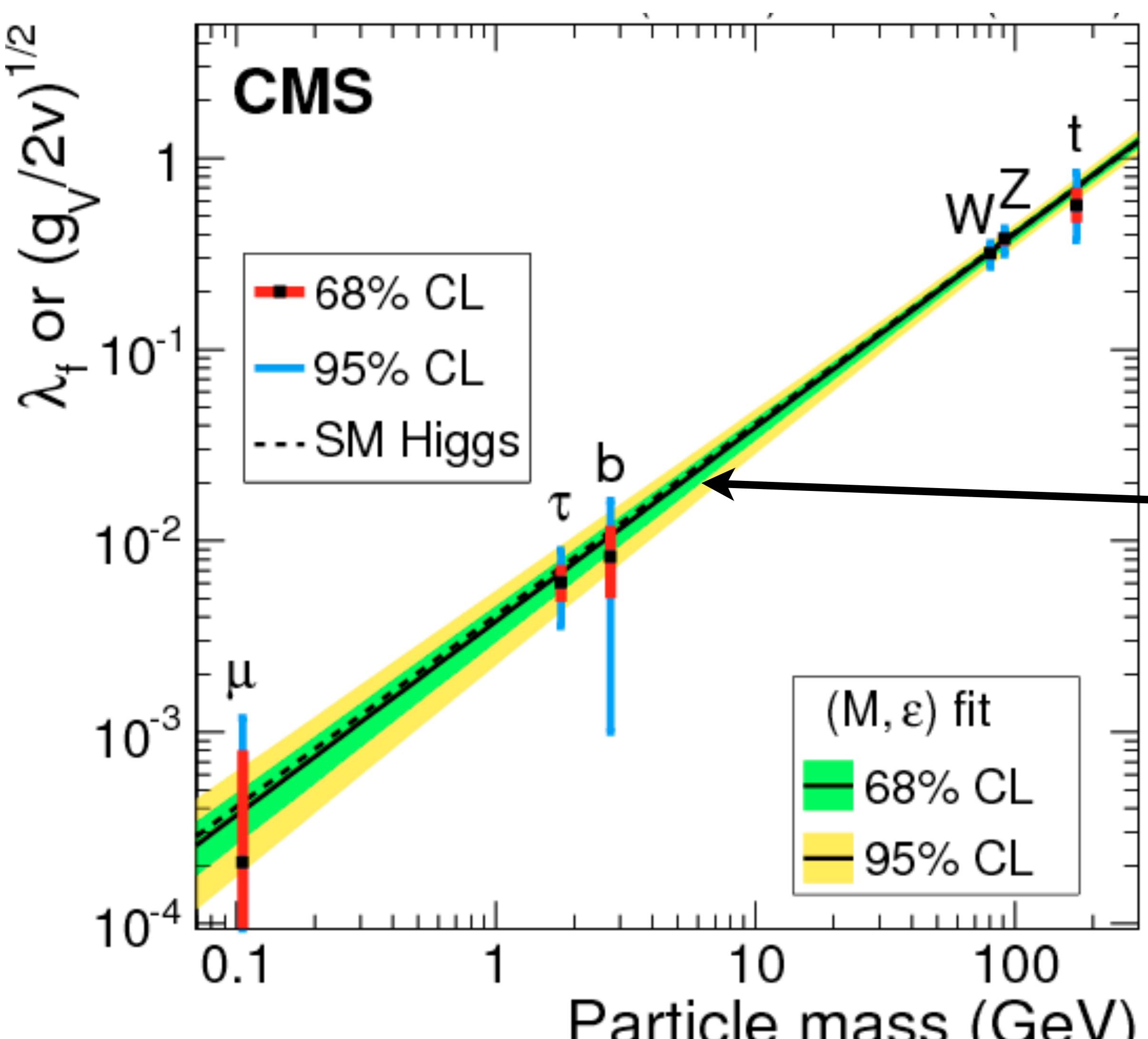
SM EW loops seen with about 20% precision

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
$\vert H^+D_\mu H\vert^2$	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

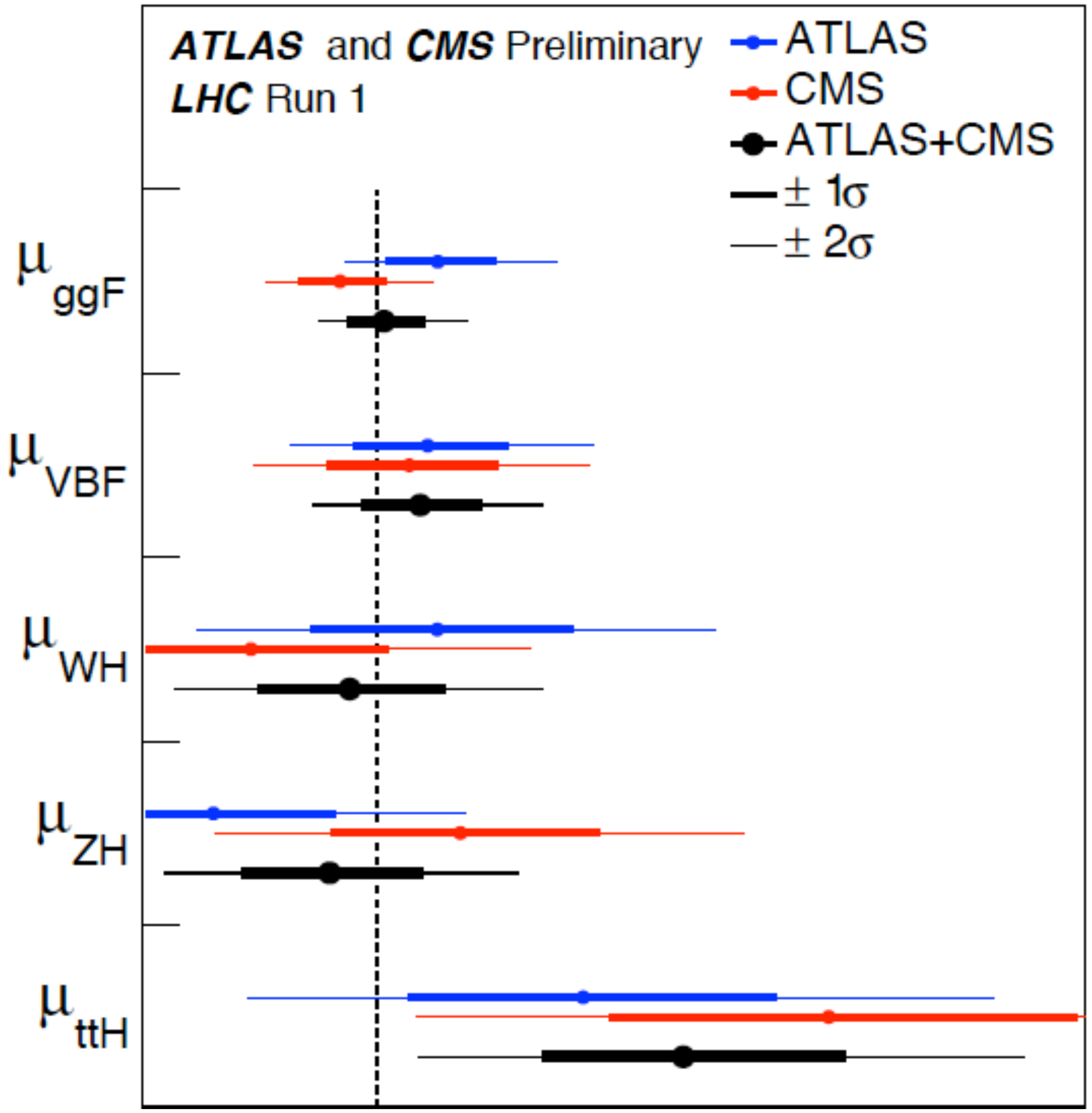
caveats:

In general many more operators already at dim=6

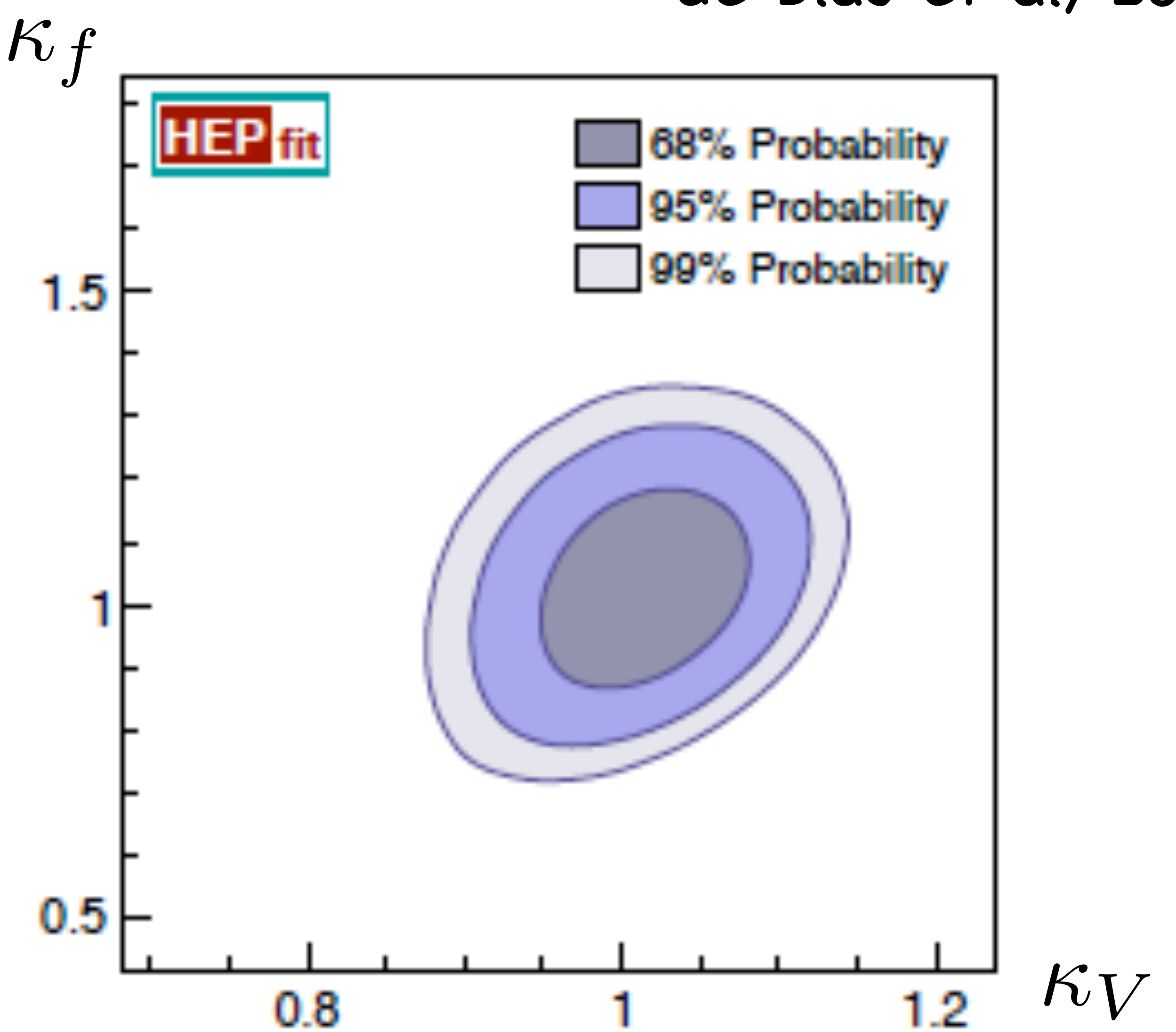
Correlations lost

What is the “true” meaning of these bounds?

Precision in Higgs couplings



de Blas et al, 2016



$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}} \qquad \kappa_f = \frac{g_{hf_if_i}}{(g_{hf_if_i})_{SM}} \qquad \kappa_V = \frac{g_{hVV}}{(g_{hVV})_{SM}}$$

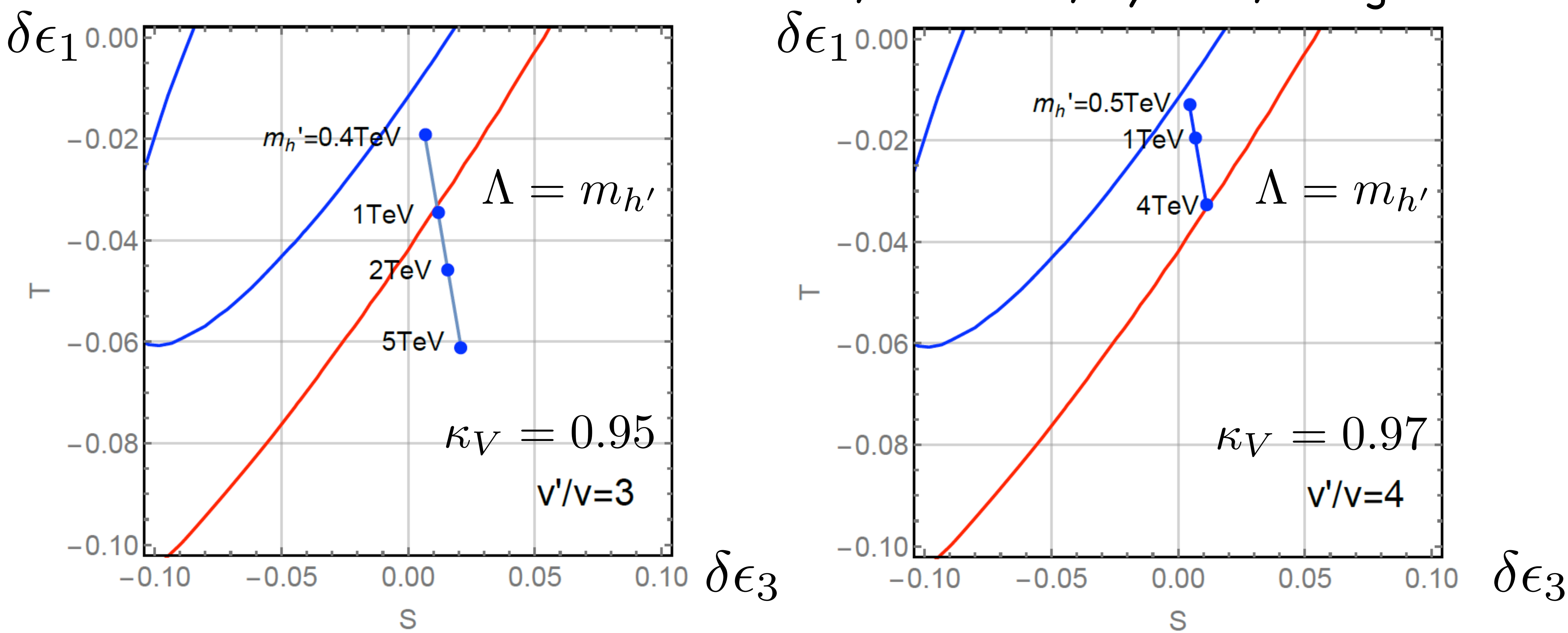
comparing Higgs with EW precision

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

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

?

B, Bellazzini, Rychkov, Varagnolo 2007



EW precision in principle more constraining on κ_V

however:

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

The single prediction of the SM in quark flavour physics

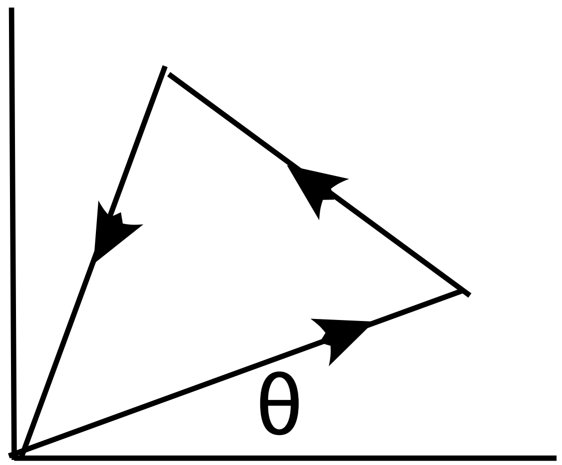
$$J^{\mu}_{W}|_{\text{quarks}} = \bar{u}^i_L \gamma^\mu d^i_L \quad \xrightarrow{u,d \text{ mass-basis}} \quad \bar{u}^i_L V_{ij} \gamma^\mu d^j_L$$

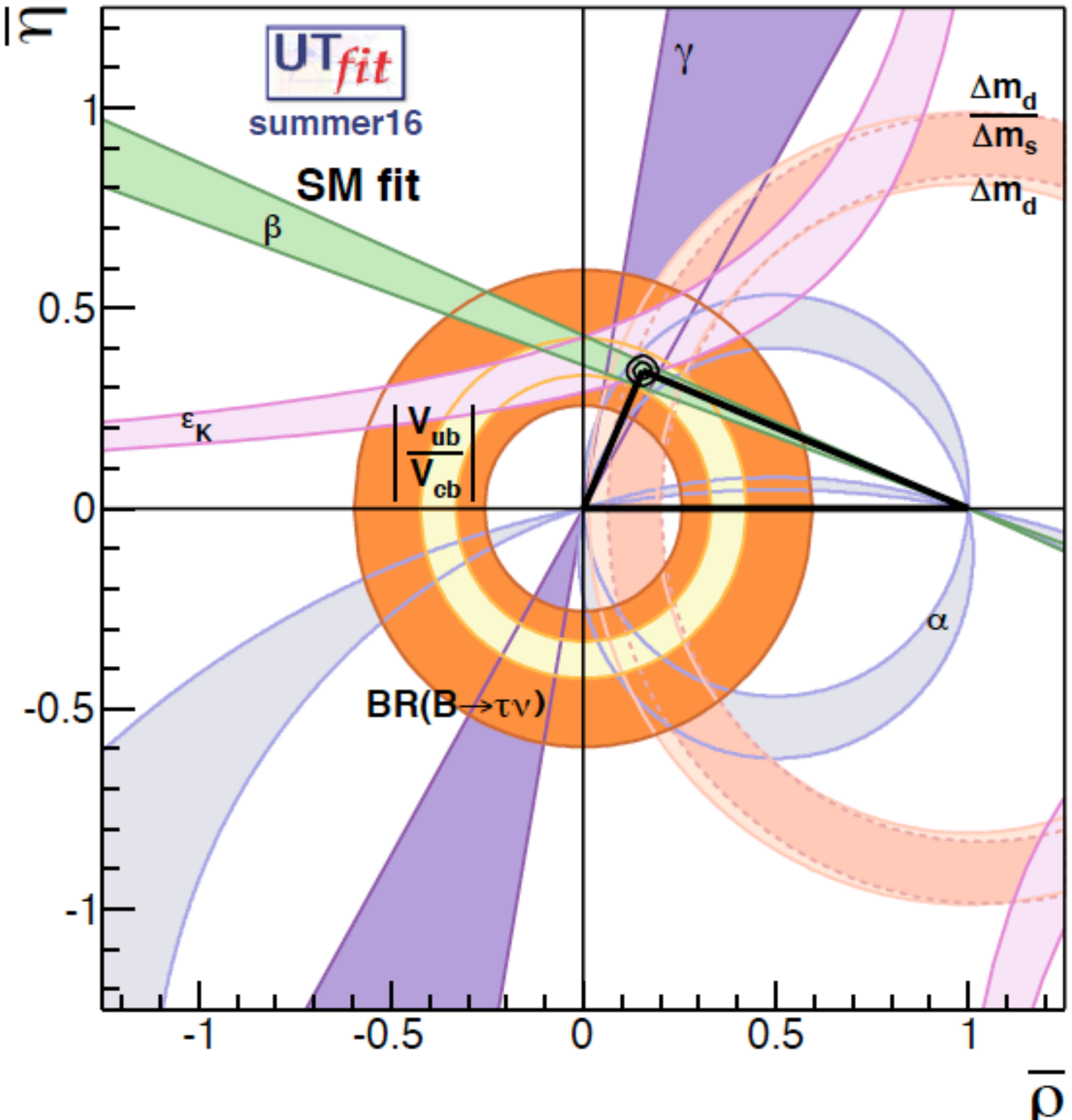
?

the only FV interaction with $VV^+ = 1$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

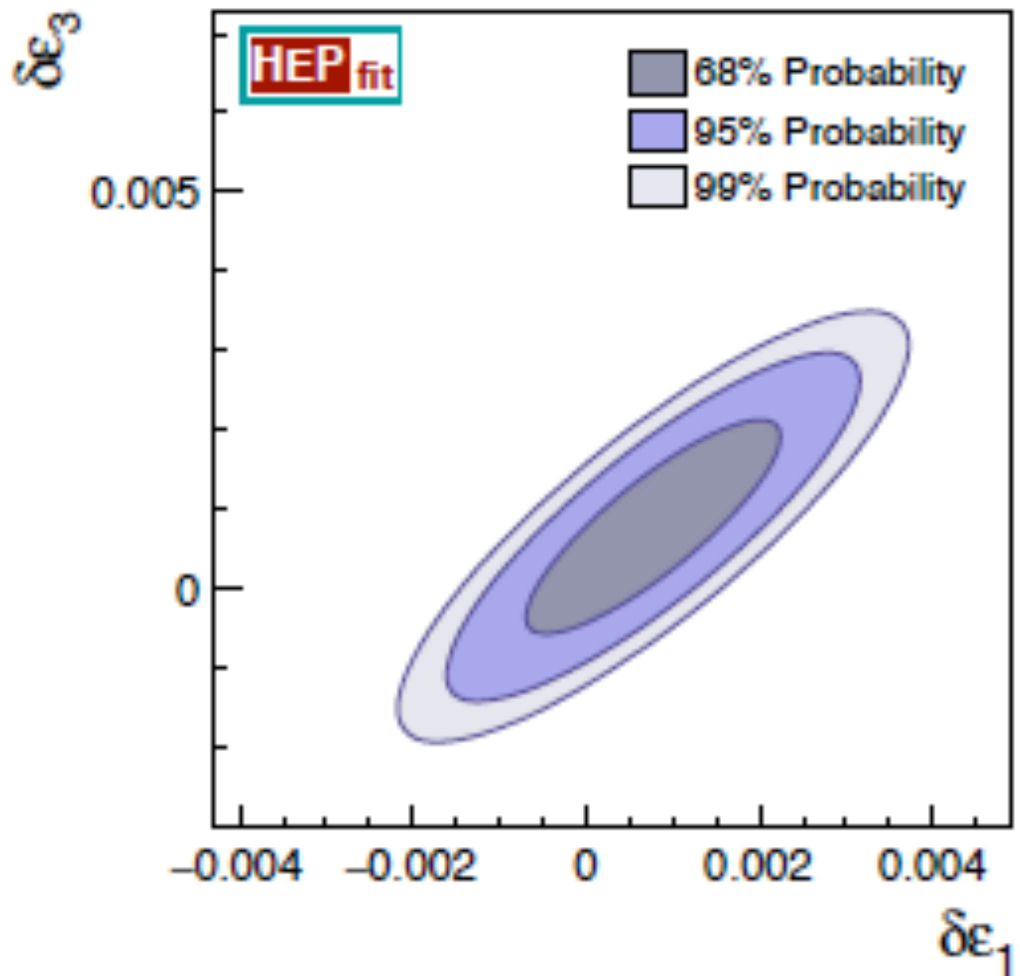
$$V_{ud}V^*_{ub} + V_{cd}V^*_{cb} + V_{td}V^*_{tb} = 0$$





A significant comparison

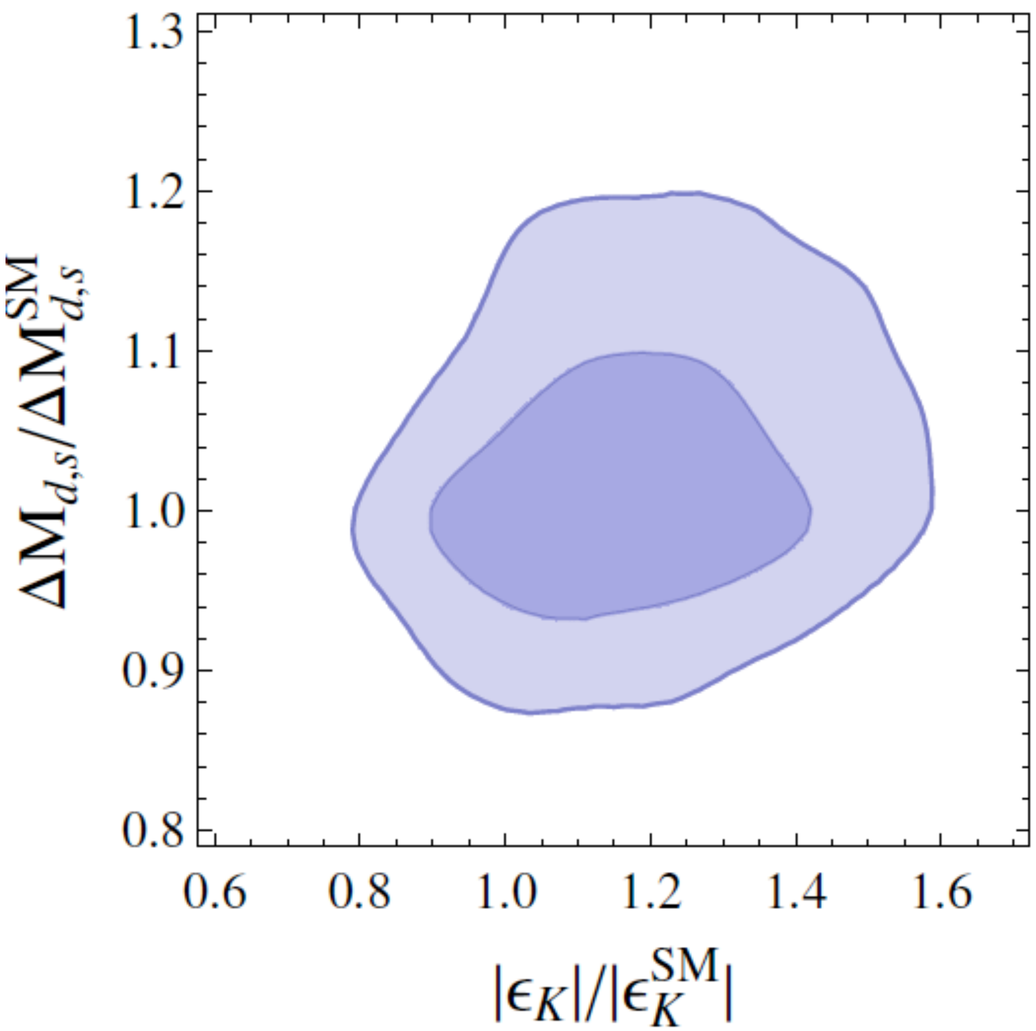
$$\epsilon_1^{SM} = 5.21 \cdot 10^{-3},\ \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$$



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

An alternative definition of the SM (equally precise!)

1. Symmetry group $\mathcal{L} \times \mathcal{G}$

$\mathcal{L}$ = Lorentz (rigid, exact)

$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local, spontaneously broken)

2. Particle content (rep.s of $\mathcal{L} \times \mathcal{G}$) - See below

3. All "operators" (products of $\Phi, \partial_\mu \Phi$) in $\mathcal{L}$ of dimension ≤ 4 with a single exception $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

$$\hbar = c = 1 \Rightarrow [A_\mu] = [\phi] = [\partial_\mu] = M, \quad [\Psi] = M^{3/2}, \quad [\mathcal{L}] = M^4$$

The particles of the Standard Model (SM)

$J = 0$

$h(2012)$

$i =$

$\Psi_i =$

$J = 1/2$

$u(1968)$	$d(1968)$	$e(1897)$	$\nu_e(1956)$	$\leftarrow$ 1
$c(1974)$	$s(1968)$	$\mu(1937)$	$\nu_\mu(1962)$	$\leftarrow$ 2
$t(1994)$ *	$b(1977)$	$\tau(1975)$	$\nu_\tau(2000)$ *	$\leftarrow$ 3

$H = (pe)$ $\quad p = (uud)$ $\quad n = (udd)$

$J = 1$

$G^a_\mu(1978)$ *	$A_\mu(1905)$	$W_\mu(1984)$	$Z_\mu(1984)$

A complete story? A single scalar?

Representation content and accidental symmetries

$$\Psi = Q(3,2)_{1/6} \;\; u(\bar{3},1)_{-2/3} \;\; d(\bar{3},1)_{1/3} \;\; L(1,2)_{-1/2} \;\; e(1,1)_1$$

(An important hint for "algebraic" Unification?)

From $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$

?

$$\Rightarrow B, \;\; L_e, L_\mu, L_\tau$$

and $U(3)^3 \equiv U(3)_Q \times U(3)_u \times U(3)_d$ only broken by Y_u, Y_d

An interesting story about symmetries

∞'s $\Rightarrow$ renormalizable th.s $\mathcal{O}_d(\Phi, \partial_\mu \Phi)\ d \leq 4$ $\Rightarrow d > 4$

30's 40's - 50's 70's

$\Downarrow$

Accidental symmetries (approximate)

Parity in the electromagnetic interactions

?

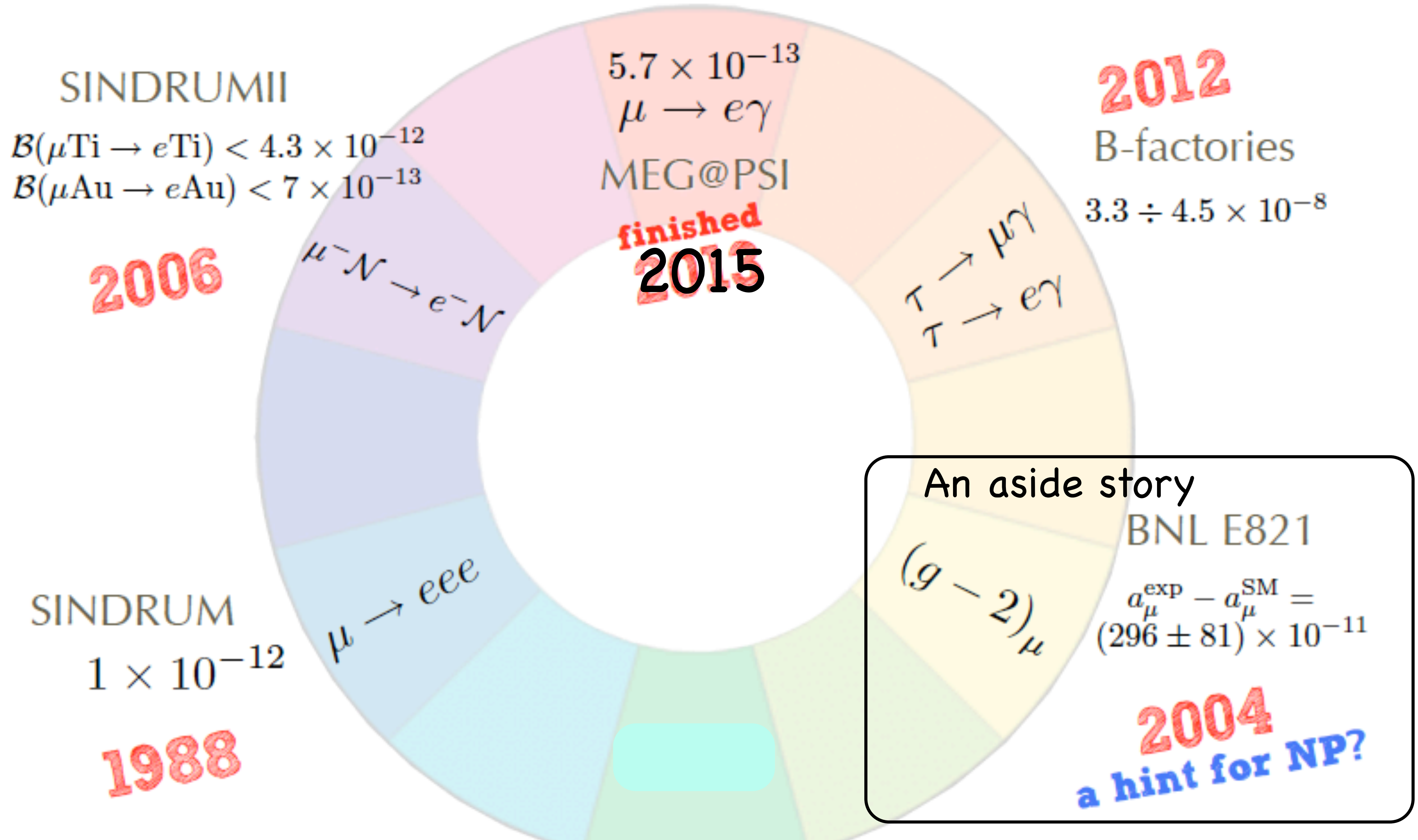
Isospin, $SU(3)$, chiral symmetry in strong interactions

Barion (B) and Lepton (L_i) numbers in the full SM

$$B = N_q - N_{\bar{q}} \qquad L_i = N_{l_i} - N_{\bar{l}_i}$$

$$\cancel{p \to e^+ + \pi^0}$$

Lepton Flavour Violation is absent in the SM



Conclusions postponed to end

end of lecture II

For question time

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})

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

Landau poles

$$\frac{dg_1^2}{dt} = \frac{41}{40} g_1^4 \quad \Rightarrow \text{a Landau pole at } \Lambda_1$$

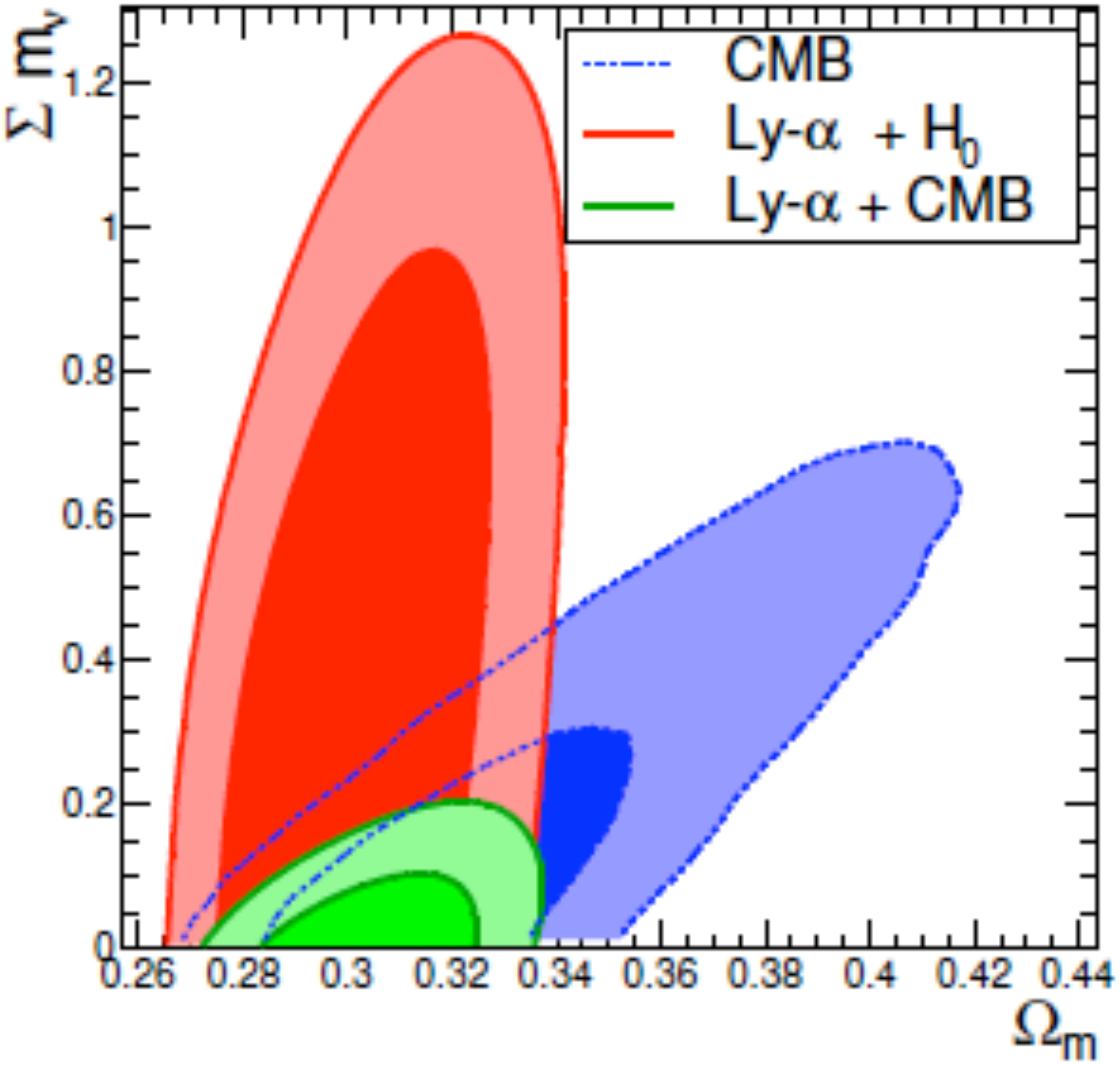
- the problem not cured by including other couplings
- can it be cured by gravity? Yes, since $\Lambda_1 > M_{Pl}$, if gravity important at $E \lesssim M_{Pl}$
- what if gravity softened enough, so that it becomes irrelevant? (How is hard to tell, but...)
- need $SU(3) \times SU(2) \times U(1)$ fully immersed in a non-abelian group

$$SU(4)_{PS} \times SU(2)_L \times SU(2)_R$$

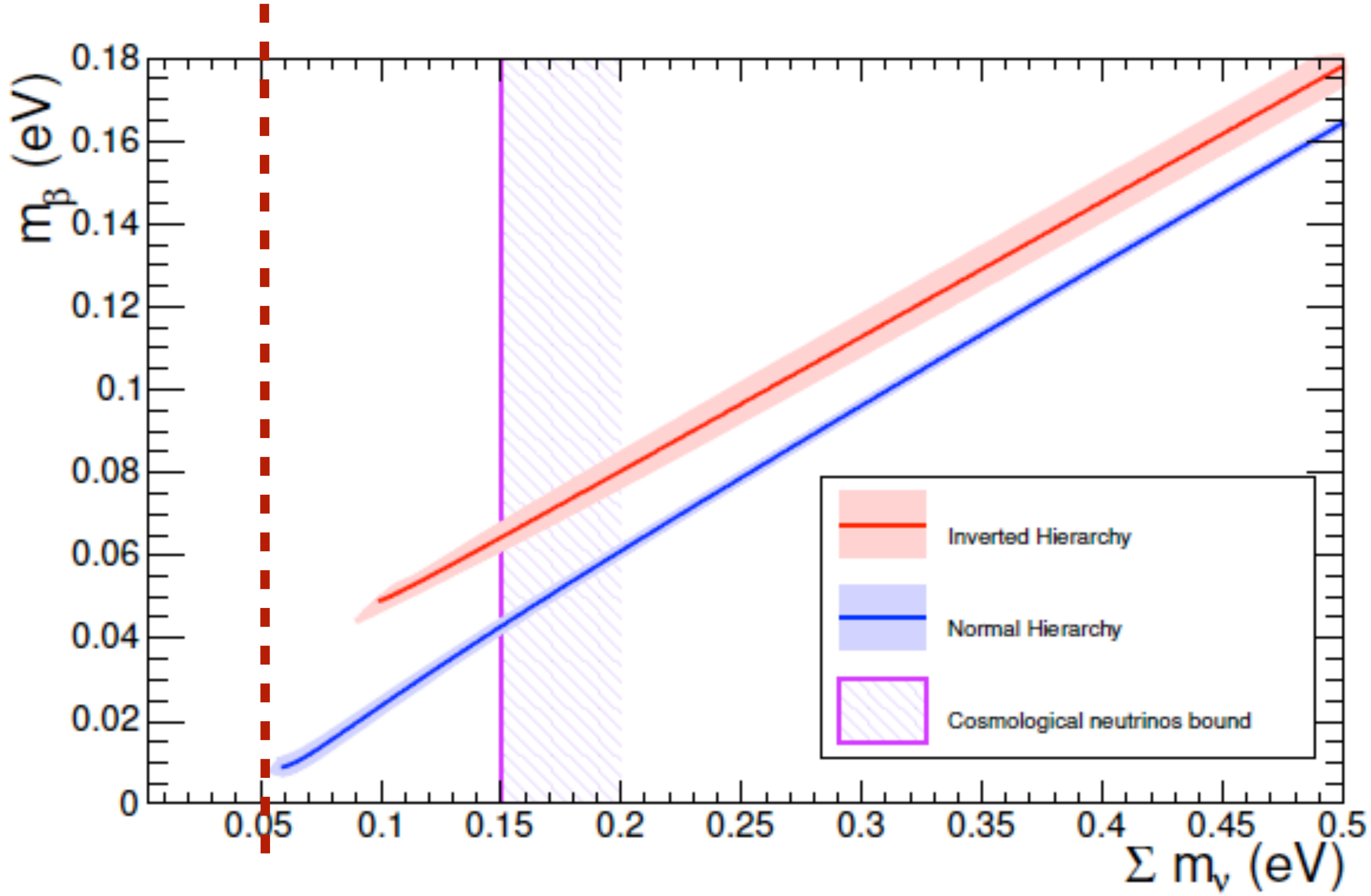
$$SU(3)_c \times SU(3)_L \times SU(3)_R$$

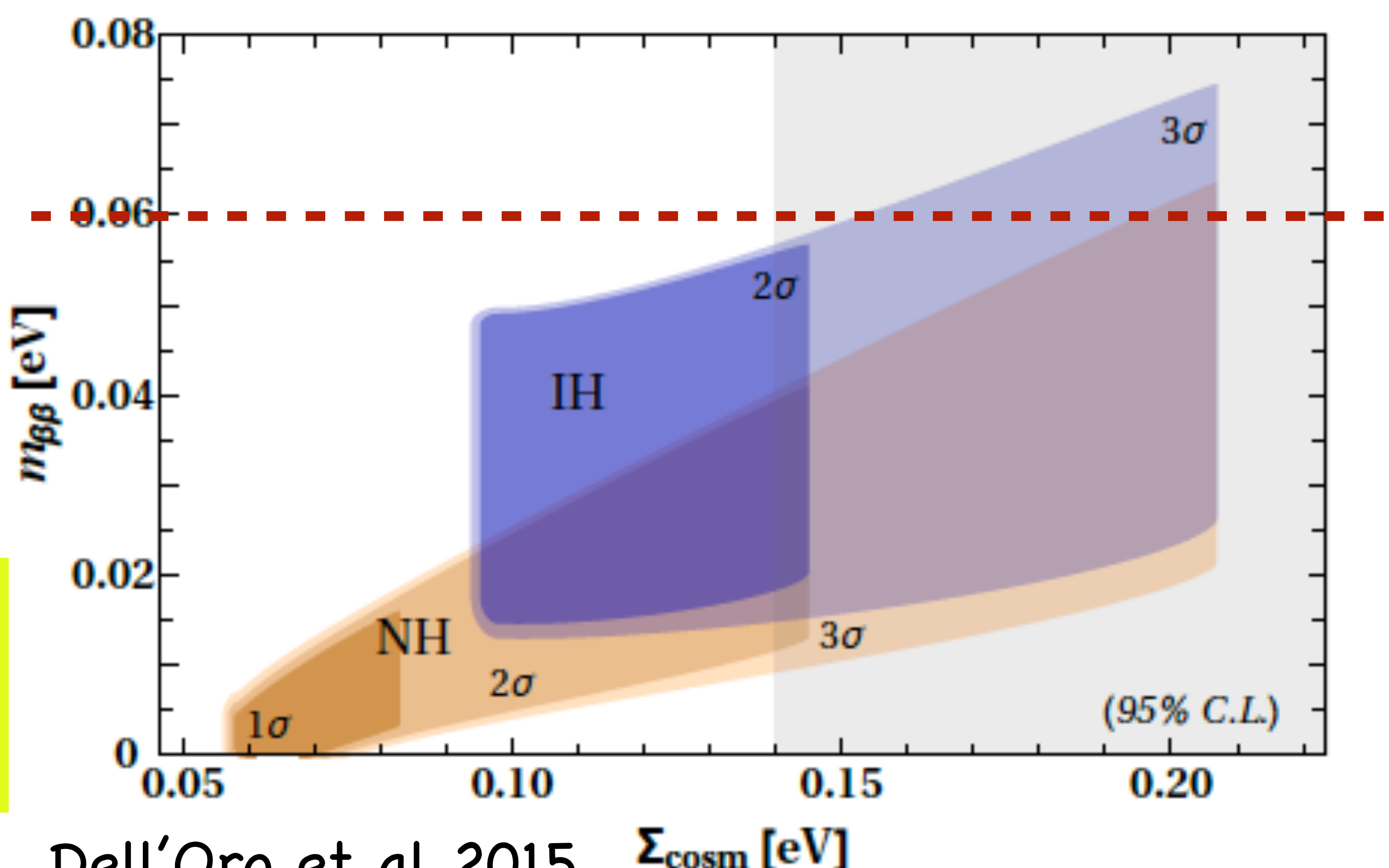
which requires heavier scales than v

Σm_ν determination



Palanque-Delabroullle et al 2015





Dell'Oro et al 2015

(a recent result from KamLAND)

$$m_{\beta\beta} < 0.06 \div 0.16\ eV$$