Particle Physics after the discovery of the Higgs boson

R. Barbieri

From the Vacuum to the Universe

Kitzbuhel, June 26-July 01, 2016

I. The SM Lagrangian
(since 1973 in its full content)

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

$$+|D_\mu h|^2 - V(h)$$ (∿1990- 2012)

$$+\Psi_i\lambda_{ij}\Psi_j h + h.c.$$ (∿2000- now)

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

The synthetic nature of Particle Physics

The particles of the Standard Model (SM)

$J = 0$

$h(2012)$

$J = 1/2$

$\Psi_i =$

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

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

$J = 1$

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

A complete story? A single scalar?

Problems of (questions for) the SM

0. Which rationale for matter quantum numbers?

$$|Q_p + Q_e| < 10^{-21} e$$

1. Phenomena unaccounted for

neutrino masses
Dark matter

matter-antimatter asymmetry
inflation?

2. Why $\theta \lesssim 10^{-10}$?

$$\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$$

Axions

3. $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ only?

neutrino masses
Gravity

Are the protons forever?

4. Lack of calculability (a euphemism)

the hierarchy problem
the flavour paradox

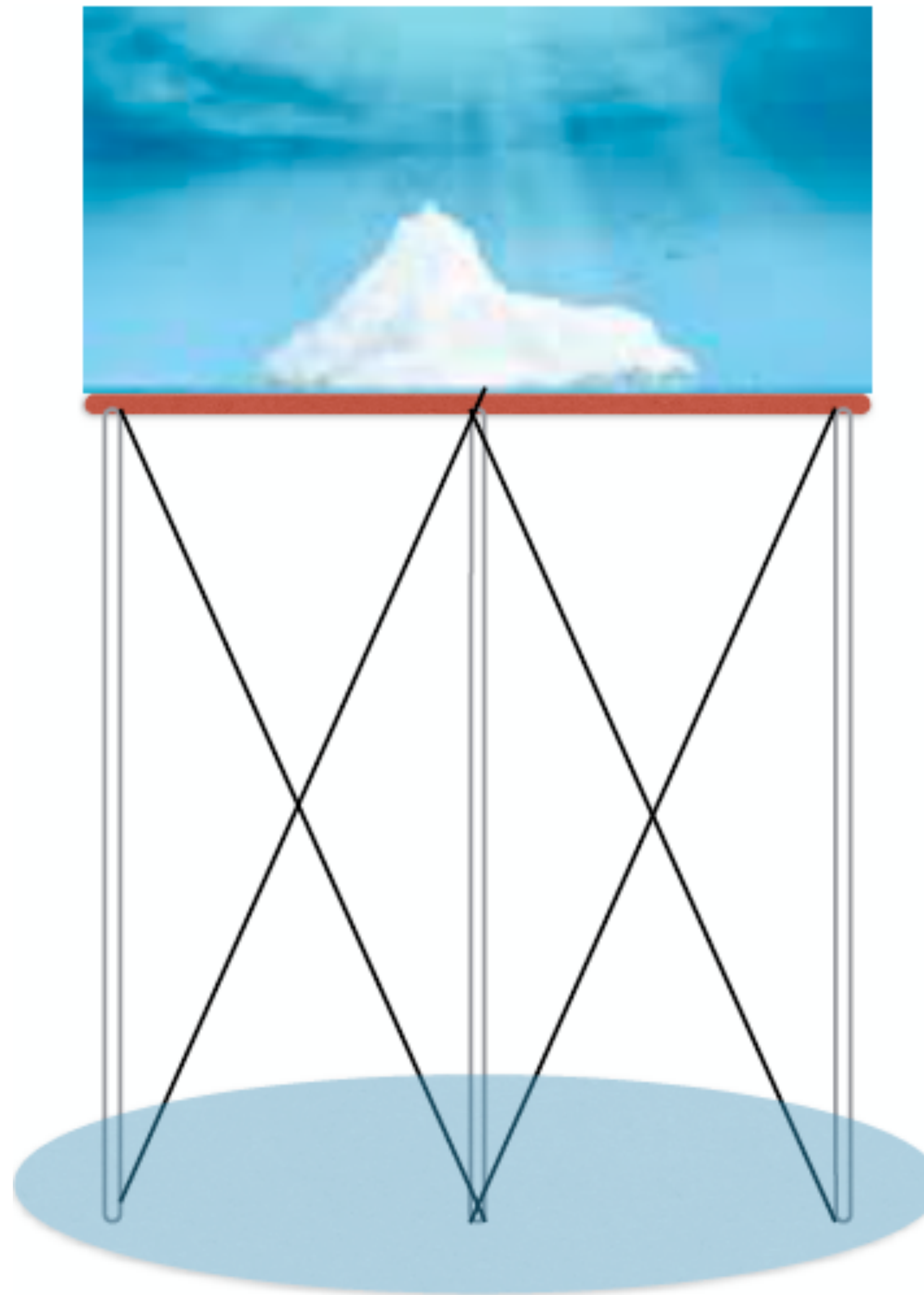
The SM as an emerging iceberg

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 >> TeVs?

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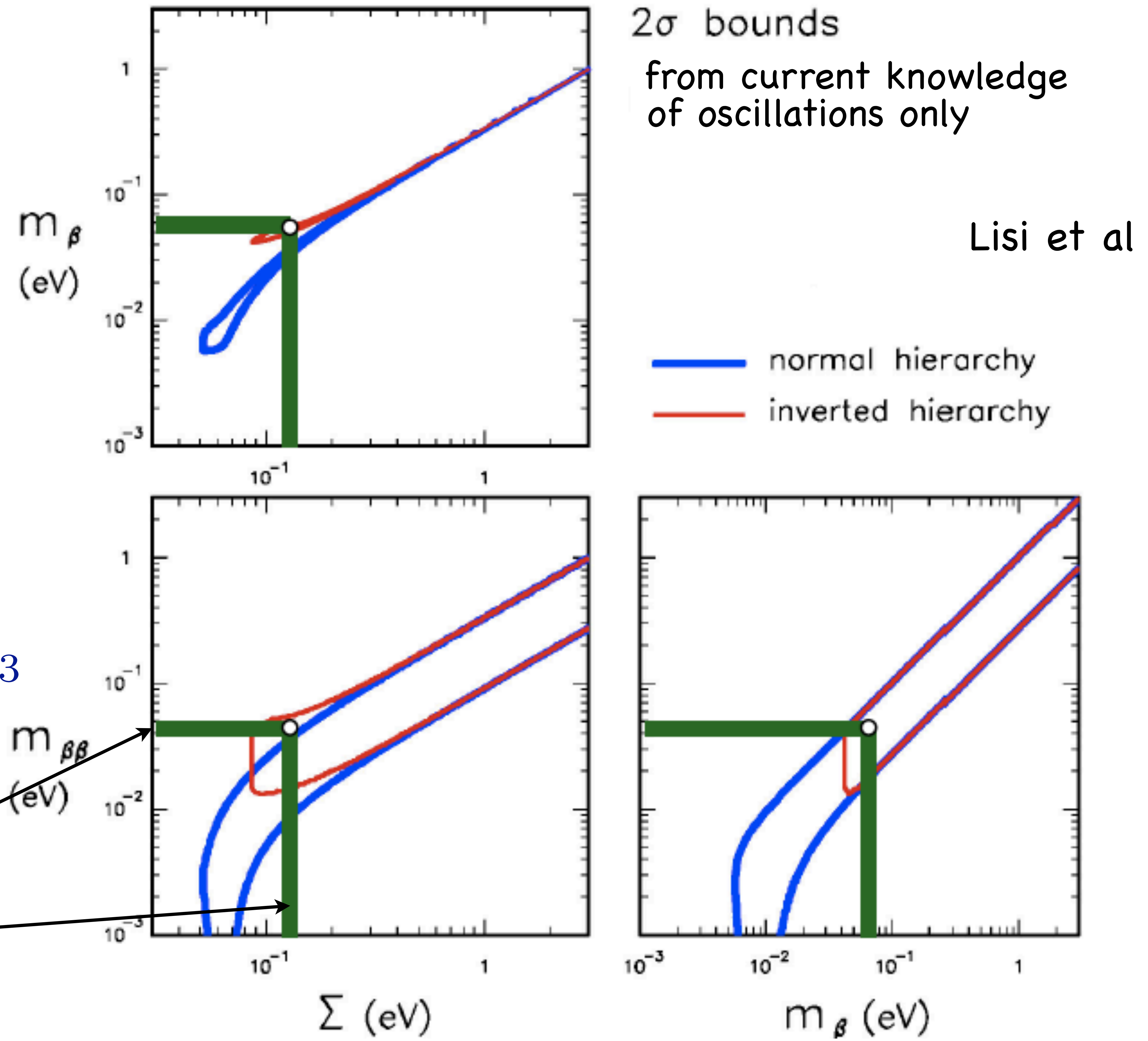
1 Key neutrino measurements

m_β
beta-decay endpoint

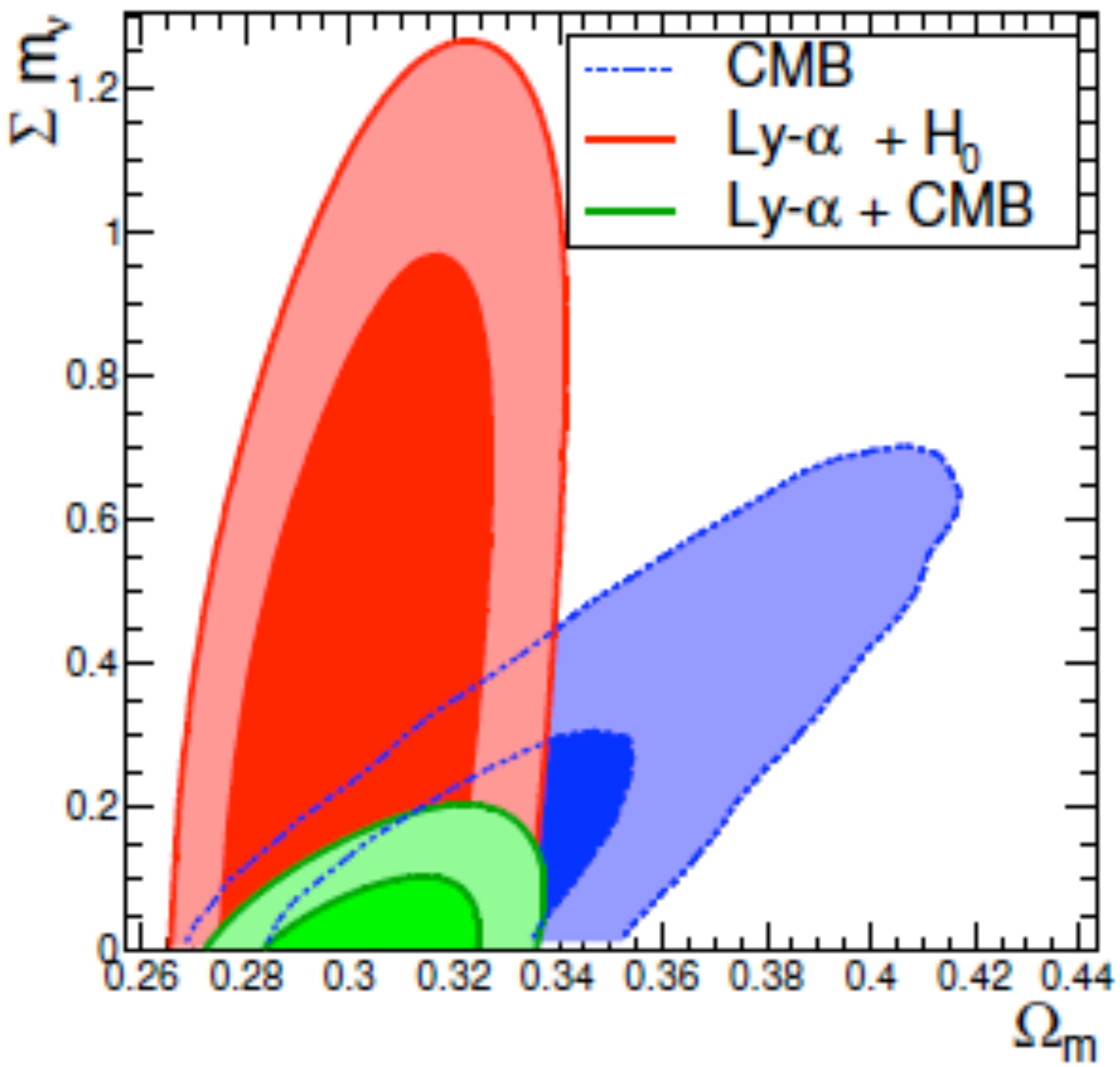
$m_{\beta\beta}$
neutrino-less $\beta\beta$ decay

$\Sigma = m_1 + m_2 + m_3$
large scale structures

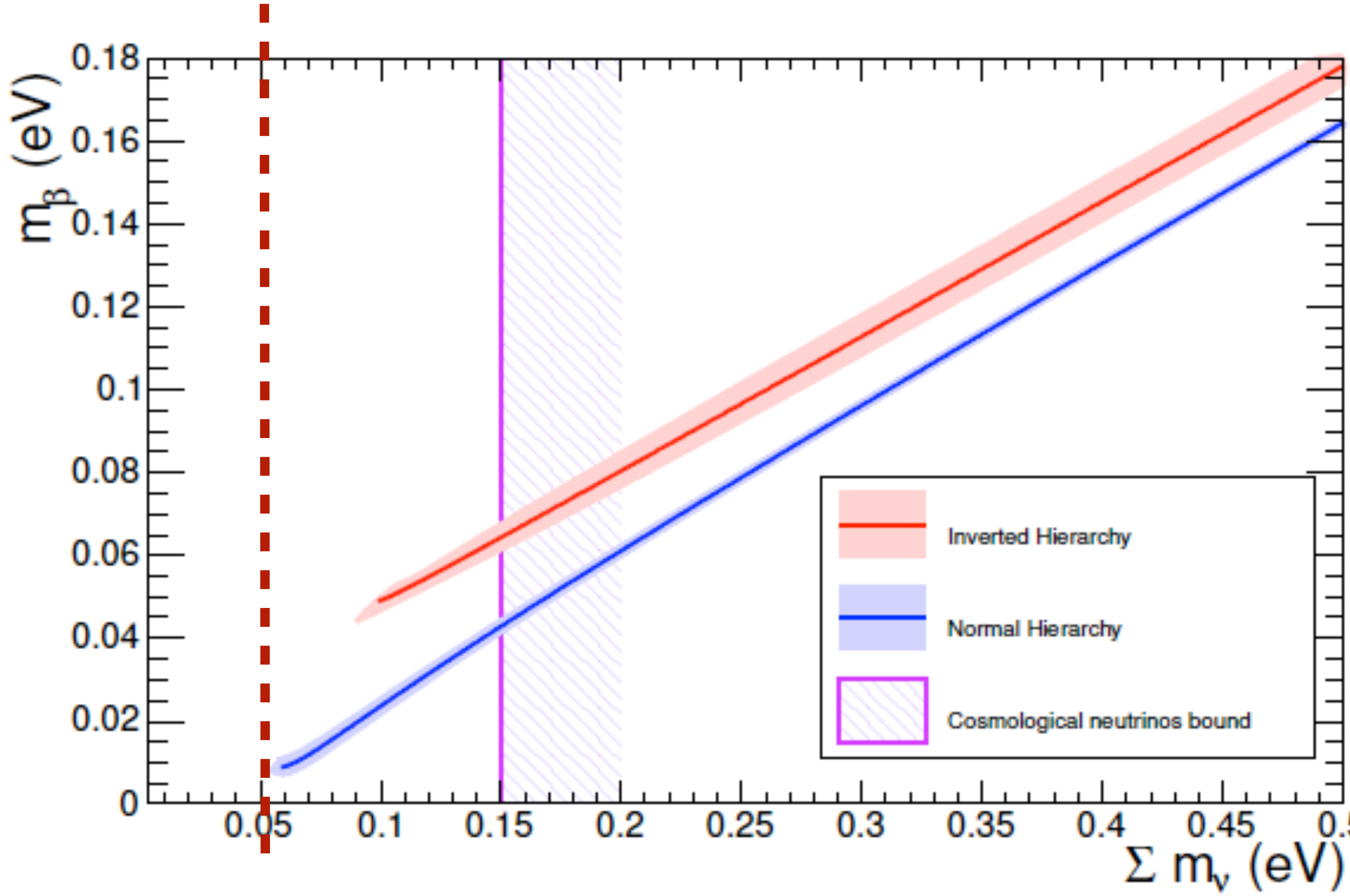


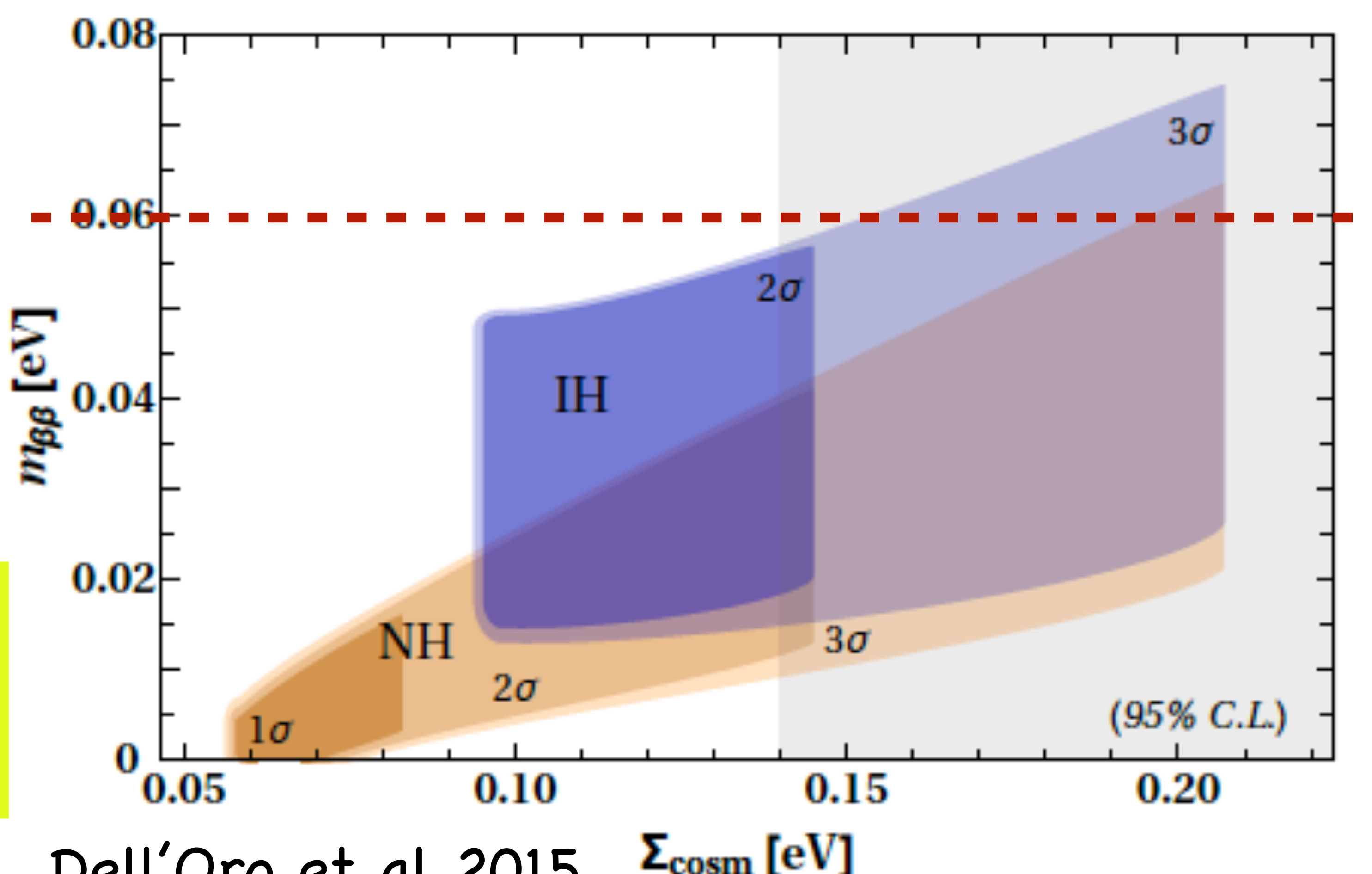
hypothetical measurements

Σm_ν determination



Palanque-Delabroullle et al 2015





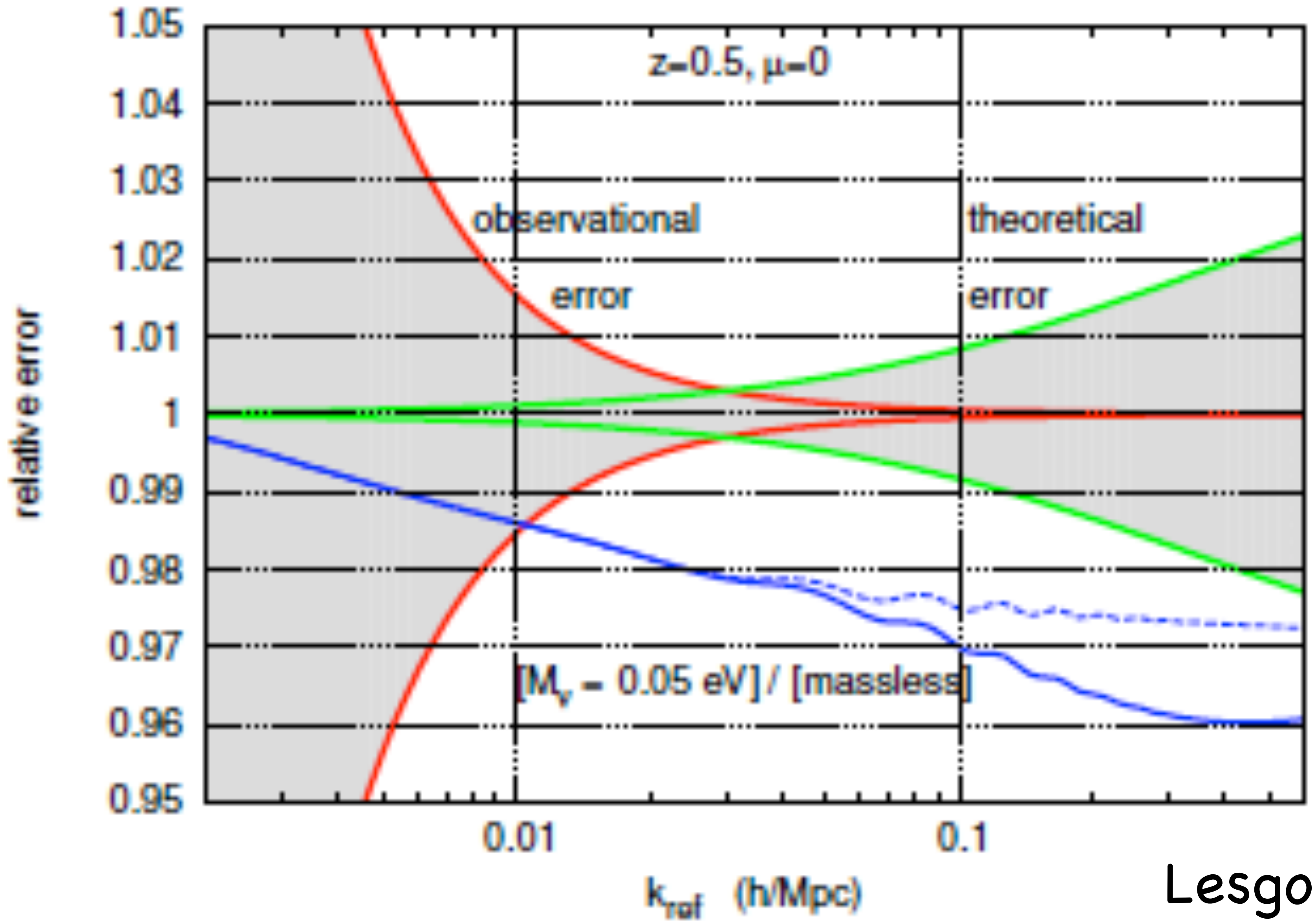
Dell'Oro et al 2015

(a recent result from KamLAND)

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

- Determination with future large-scale structure observations (Euclid) at $2-5\sigma$ depending on control of (mildy) non-linear physics

Power spectrum $P(k)/P_{massless\ \nu}(k)$



Lesgourgues et al, 2103

- Not independent on "priors" but still highly significant

2

2. Why $\theta \lesssim 10^{-10}$? $\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$

How do we know that $\theta \lesssim 10^{-10}$?

$\theta G_{\mu\nu}\tilde{G}^{\mu\nu}$ is T-odd and (almost) the only source of T-violation in the SM

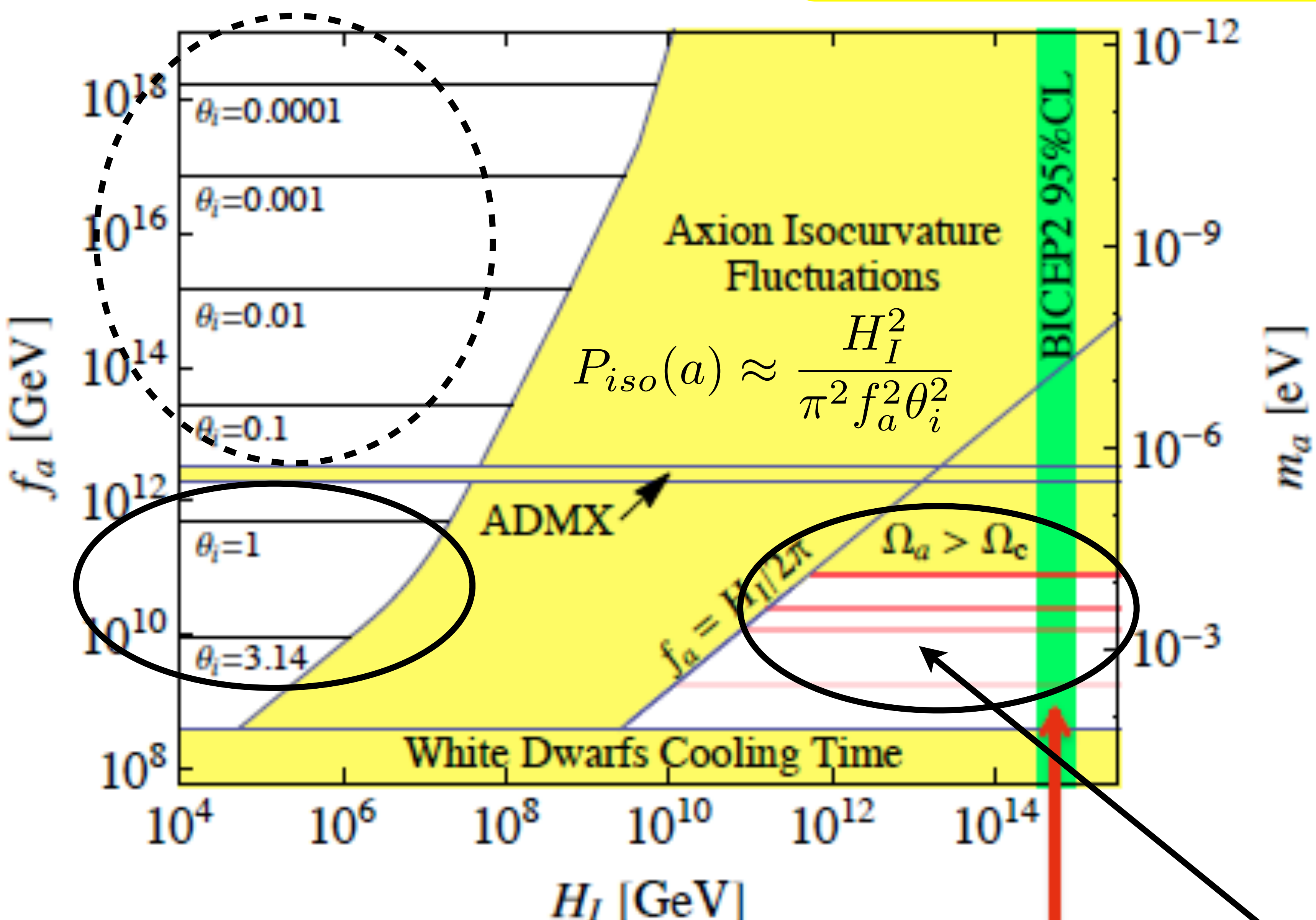
	$\vec{\mu}\cdot\vec{B}$	$\vec{d}\cdot\vec{E}$
T	$+$	$-$

$$|\vec{\mu_N}| = 2\cdot 10^{-14} e\cdot cm$$
$$|\vec{d_N}| \approx \theta\cdot 10^{-15} e\cdot cm$$
$$|\vec{d_N}|_{exp} < 3\cdot 10^{-26} e\cdot cm$$

$\Rightarrow$ Make θ a dynamical field forced in its cosmological history to relax to 0 (almost) and (possibly) appear as DM

QCD Axions in cosmology

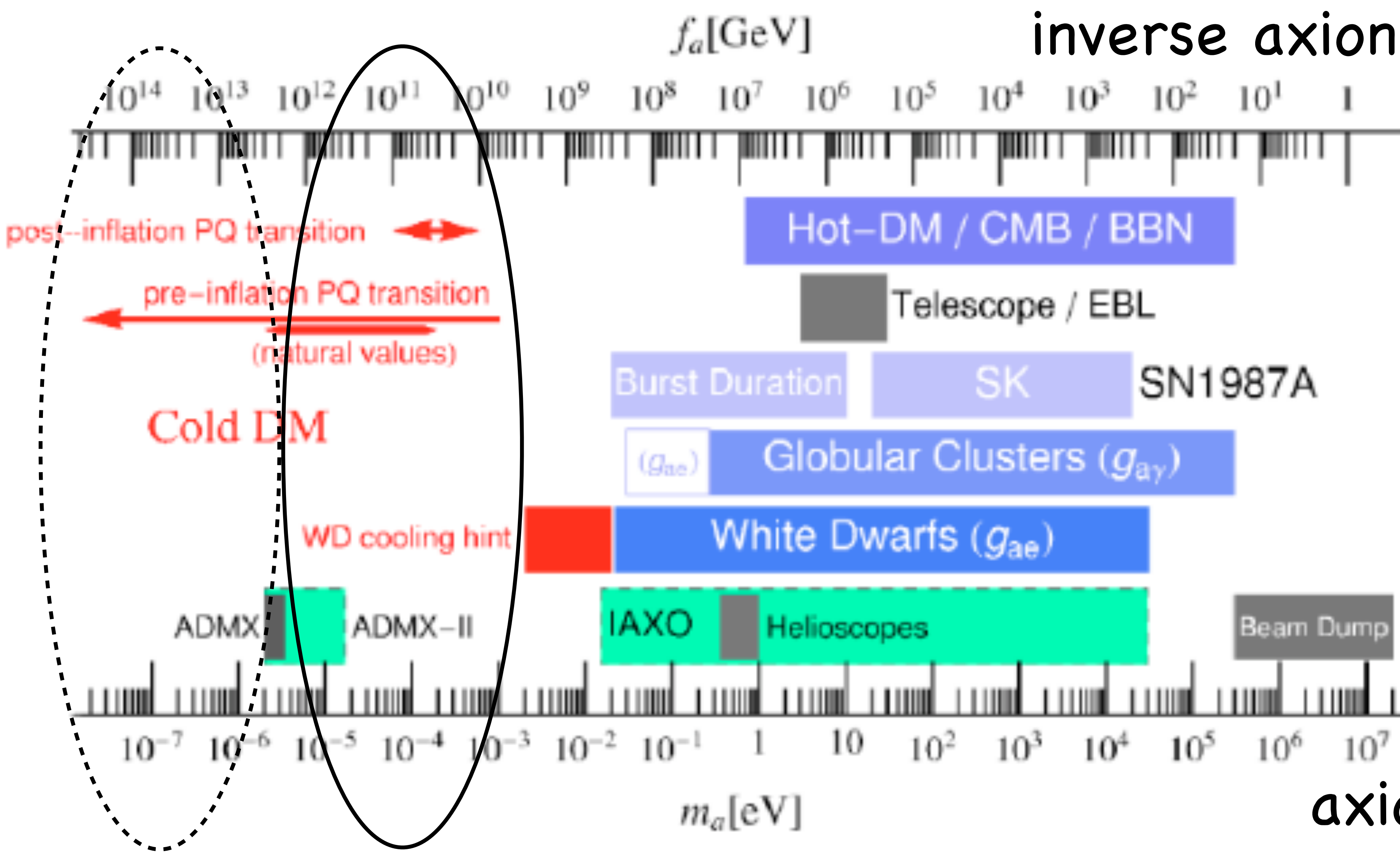
$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$



$$\Omega_a h^2 \approx 0.16\left(\frac{m_a}{10^{-5} eV}\right)^{-1.18} \theta_i^2 \qquad \theta_i = \frac{a_i}{f_a} \qquad \theta_i^2 = \frac{\pi^2}{3}$$

(Axion Like Particles: m and f unrelated)

The dynamical field, a, is the "axion"



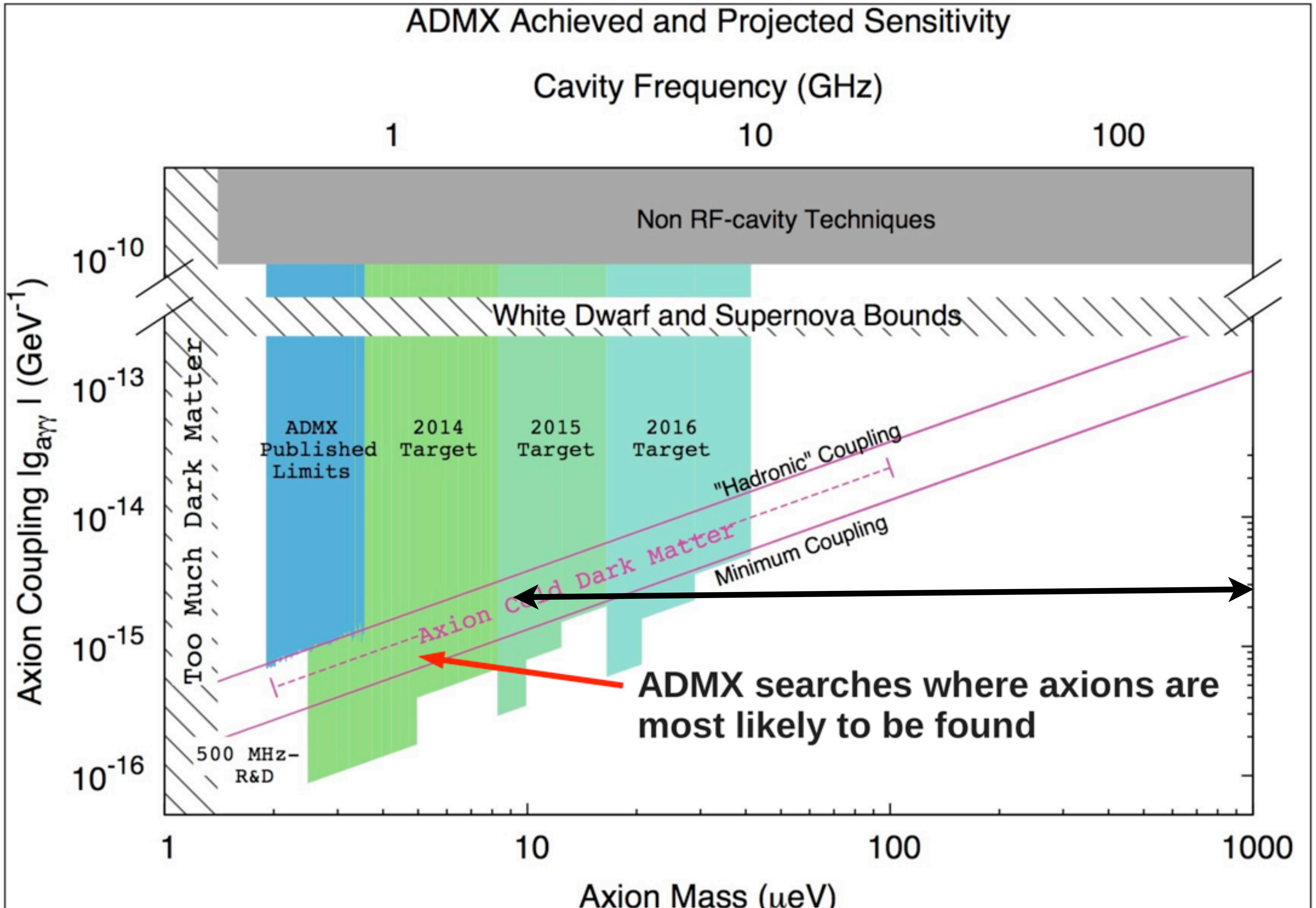
Olive et al, 2104

and is very intensively searched for

(with the most interesting region still unaccessible)

The classic search

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$



Not easy to explore the most relevant region

$10^{-5} \lesssim m_a/eV \lesssim 10^{-3}$

Rybka ADMX

The coupling of the axion to spin

$$L = \bar{\psi}(x)(i\hbar\partial\!\!\!/_x - mc)\psi(x) - a(x)\bar{\psi}(x)(g_s + ig_p\gamma_5)\psi(x)$$

$$g_p \approx \frac{m}{f_a} \qquad (g_s = 10^{-(12\div17)} g_p \frac{GeV}{m})$$

DFSZ

NRL: $$-\hbar\frac{\partial\phi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + g_s c a - \frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla} a\right]\phi$$

$$\gamma \boldsymbol{B}_{eff}\cdot\boldsymbol{\sigma} \qquad \gamma = \frac{e}{m}$$

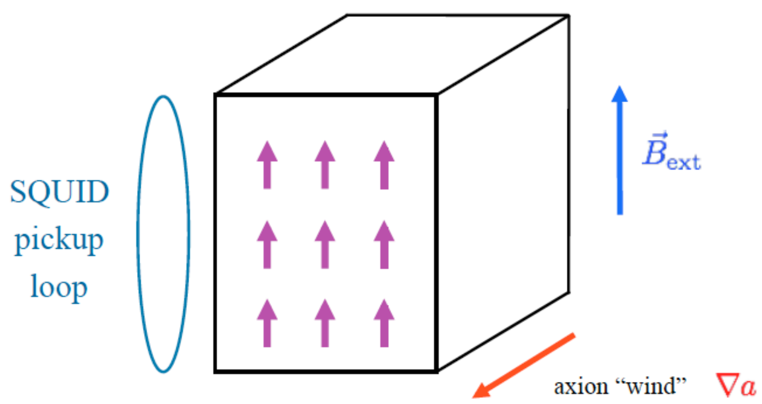
$$\mathbf{B}_{eff} = \frac{g_p}{2e}\left(\frac{n_a\hbar}{m_a c}\right)^{1/2} \boldsymbol{p}_E \sin\left(\frac{p^0 ct - \boldsymbol{p}_E\cdot\boldsymbol{x}}{\hbar}\right)$$

$$\mathbf{B}_{eff} = 10^{-22}\left(\frac{m_a}{10^{-4}\mathrm{eV}}\right)\ T \qquad \frac{\omega_a}{2\pi} = 24\left(\frac{m_a}{10^{-4}\mathrm{eV}}\right) GHz$$

$$\lambda_d \simeq h/(m_a v_a) \simeq 13.8\left(10^{-4}\mathrm{eV}/m_a\right)\mathrm{m} \qquad \Delta\omega_a/\omega_a \simeq 5.2\times10^{-7}$$

$$< \boldsymbol{p}_E >= m_a(\boldsymbol{v}_S + \boldsymbol{v}_O + \boldsymbol{v}_R)$$

Proposed experiments using NMR/EMR

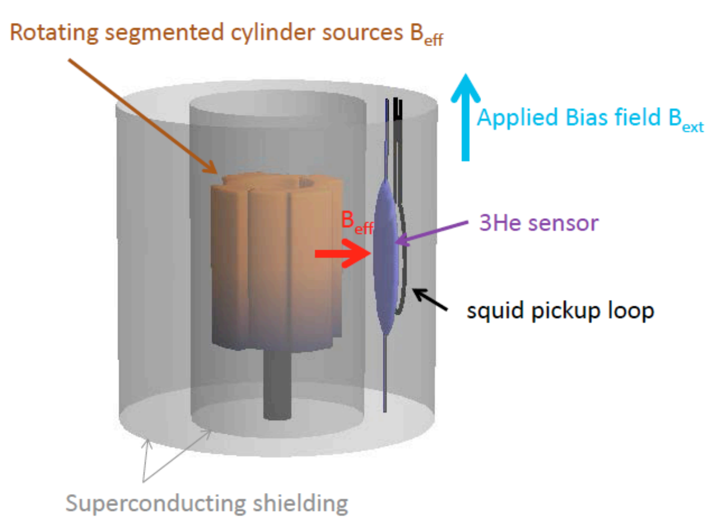


CASPEr axion wind/NMR

limited in frequency (mass)
but size of the effect OK

$$(m_a/eV = 10^{-7},\ \tau = 0.1sec)$$

$$B_{eff}/T \approx 10^{-22} \qquad M_T/T \approx 10^{-19}$$

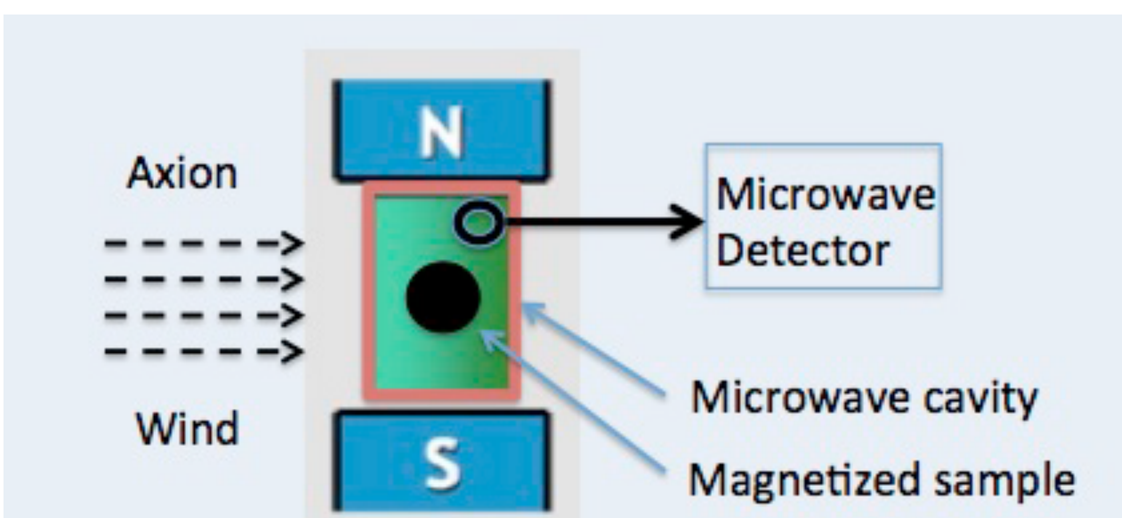


static source NMR

not limited in frequency
but size of the effect smaller

$$(m_a/eV = 10^{-4},\ \tau = 0.1sec)$$

$$B_{eff}/T \lesssim 10^{-23} \qquad M_T/T \lesssim 10^{-20}$$



QUAX axion wind/EMR

frequency OK

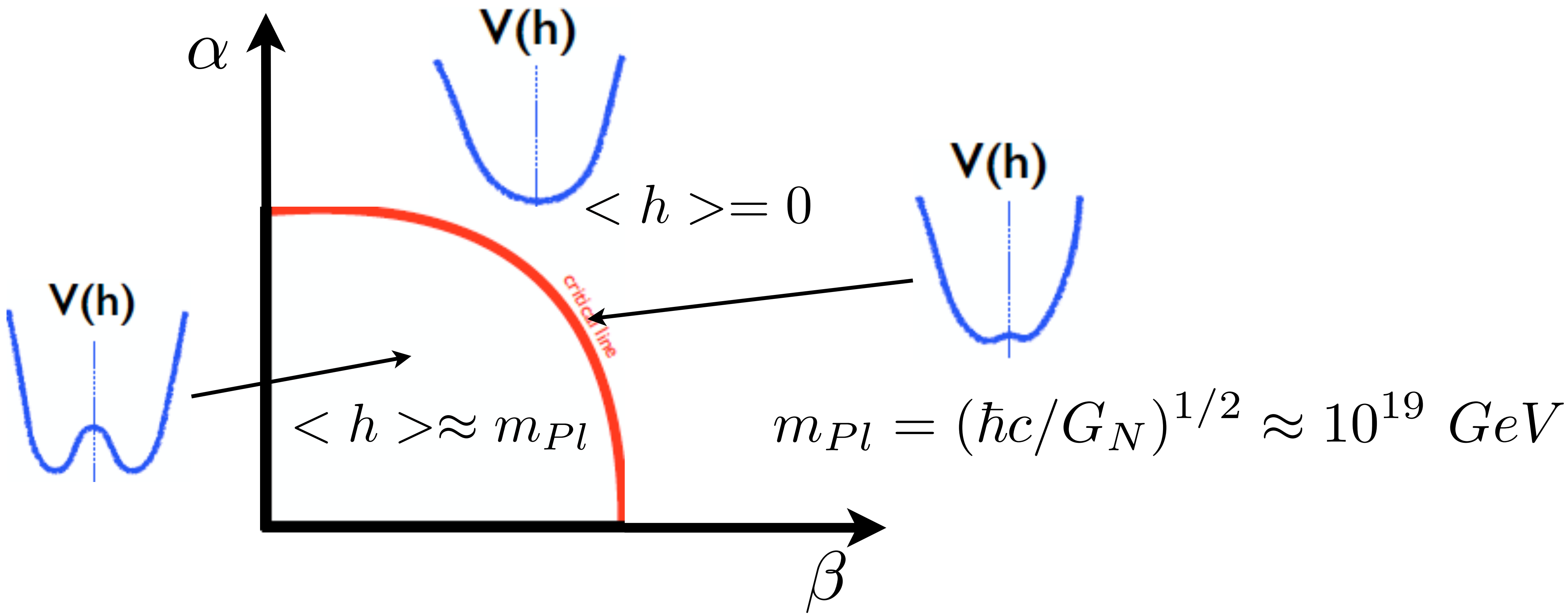
$$(m_a/eV = 10^{-4},\ \tau = 10^{-6}sec)$$

$$B_{eff}/T \approx 10^{-22} \qquad M_T/T \approx 10^{-21}$$

3 The "hierarchy" problem

Can we calculate the Higgs mass? NOT in the SM

If we try: $V(h) = m^2(\alpha,\beta)|h|^2 + \lambda|h|^4$



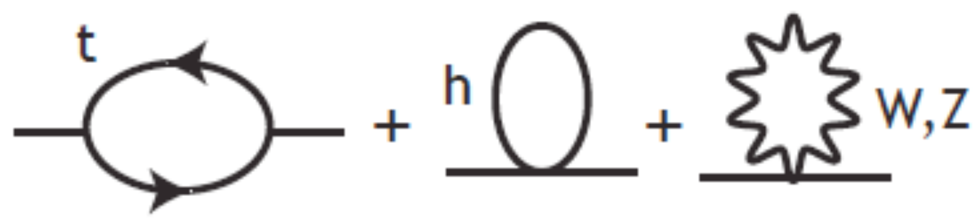
To get <h> = 175 GeV, as observed, we have to live very very close to the critical line

But we don't have knobs!

The hierarchy problem, once again

Can we compute the Higgs mass/vev in terms of some fundamental dynamics?

NOT in the SM



$$\delta m_h^2 = \frac{3y_t^2}{4\pi^2}\Lambda_t^2 - \frac{9g^2}{32\pi^2}\Lambda_g^2 - \frac{3g'^2}{32\pi^2}\Lambda_{g'}^2 + \ldots$$

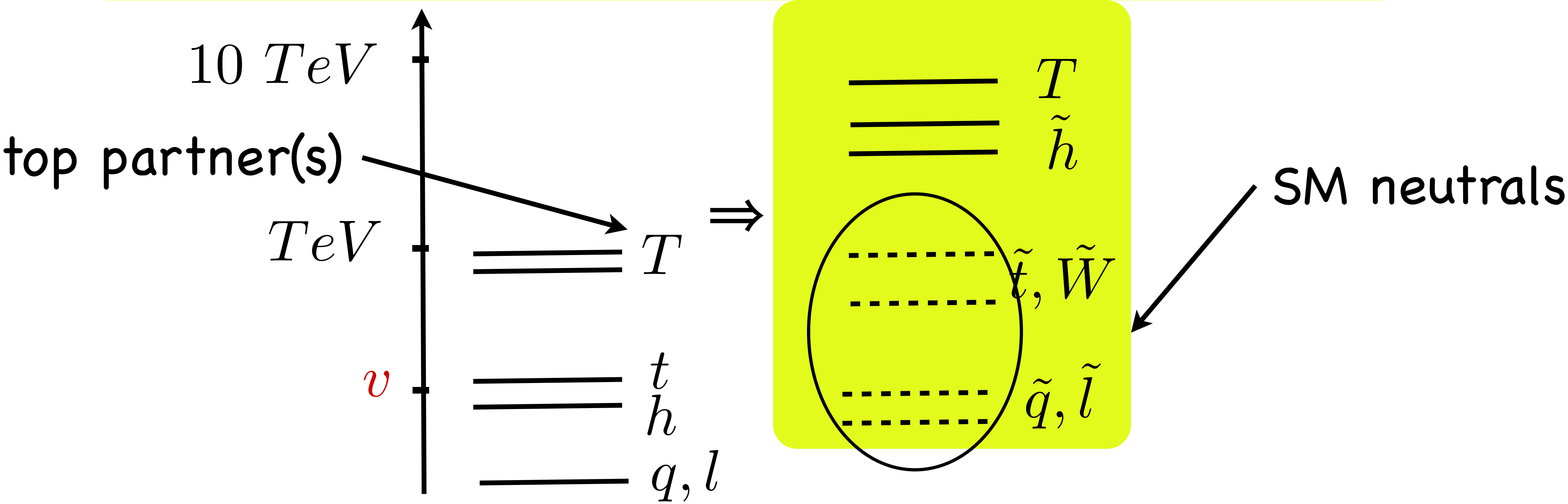
$\Lambda_t \lesssim 0.4\sqrt{\Delta}\ TeV$ $\Lambda_g \lesssim 1.1\sqrt{\Delta}\ TeV$ $\Lambda_{g'} \lesssim 3.7\sqrt{\Delta}\ TeV$

$1/\Delta$ = amount of tuning

$\Rightarrow$ Look for a top "partner" (coloured, S=0 or 1/2) with a mass not far from 1 TeV

Are there any "strictly natural" theory compatible with current data?

- Not anymore
- Searching for "top partners" remains the key
- However, if one is willing to accept a doubling of the SM ("Twin Higgs") can conceive a situation like this one



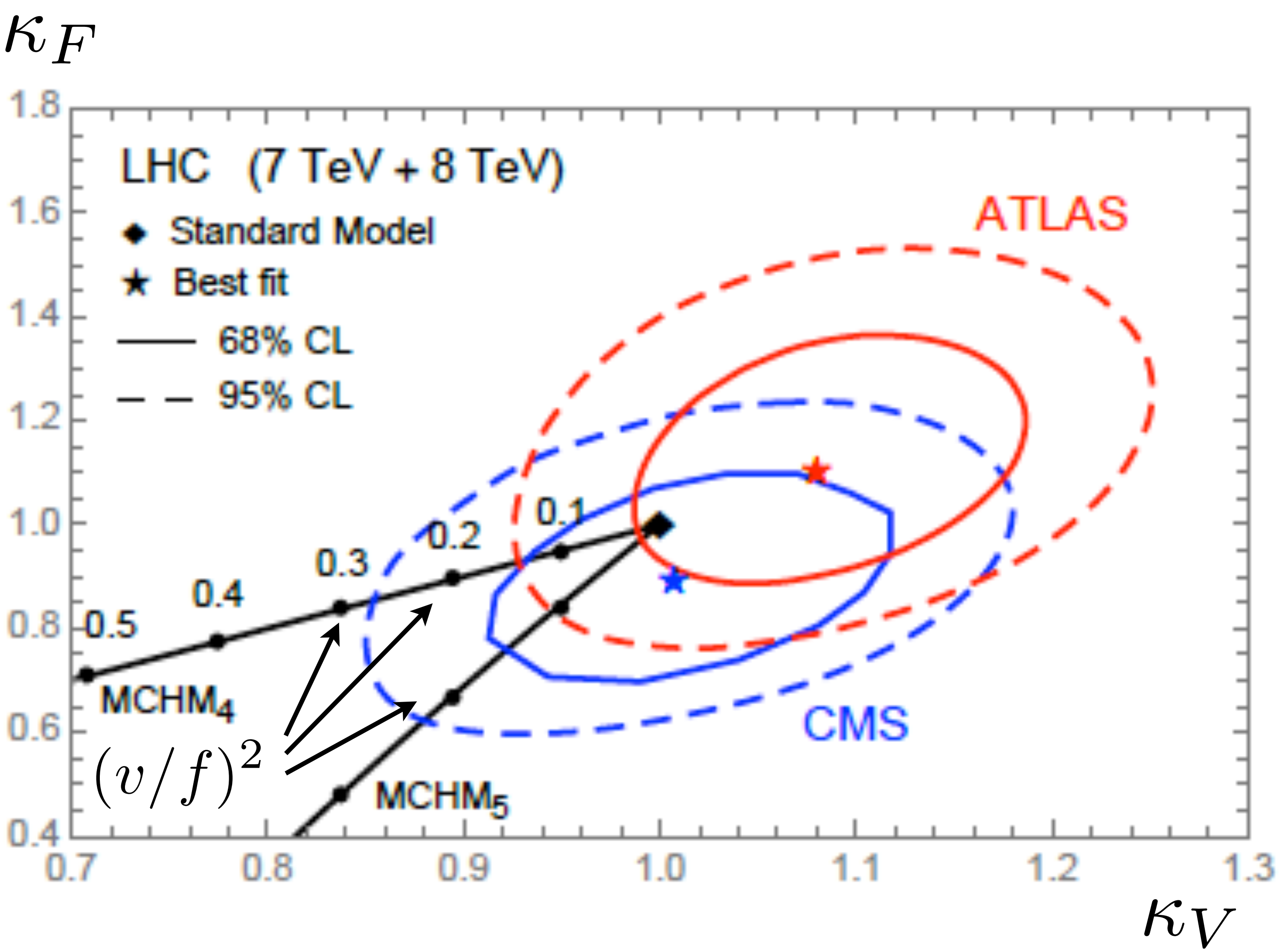
Chacko, Goh, Harnik 2005

$v \longrightarrow f$

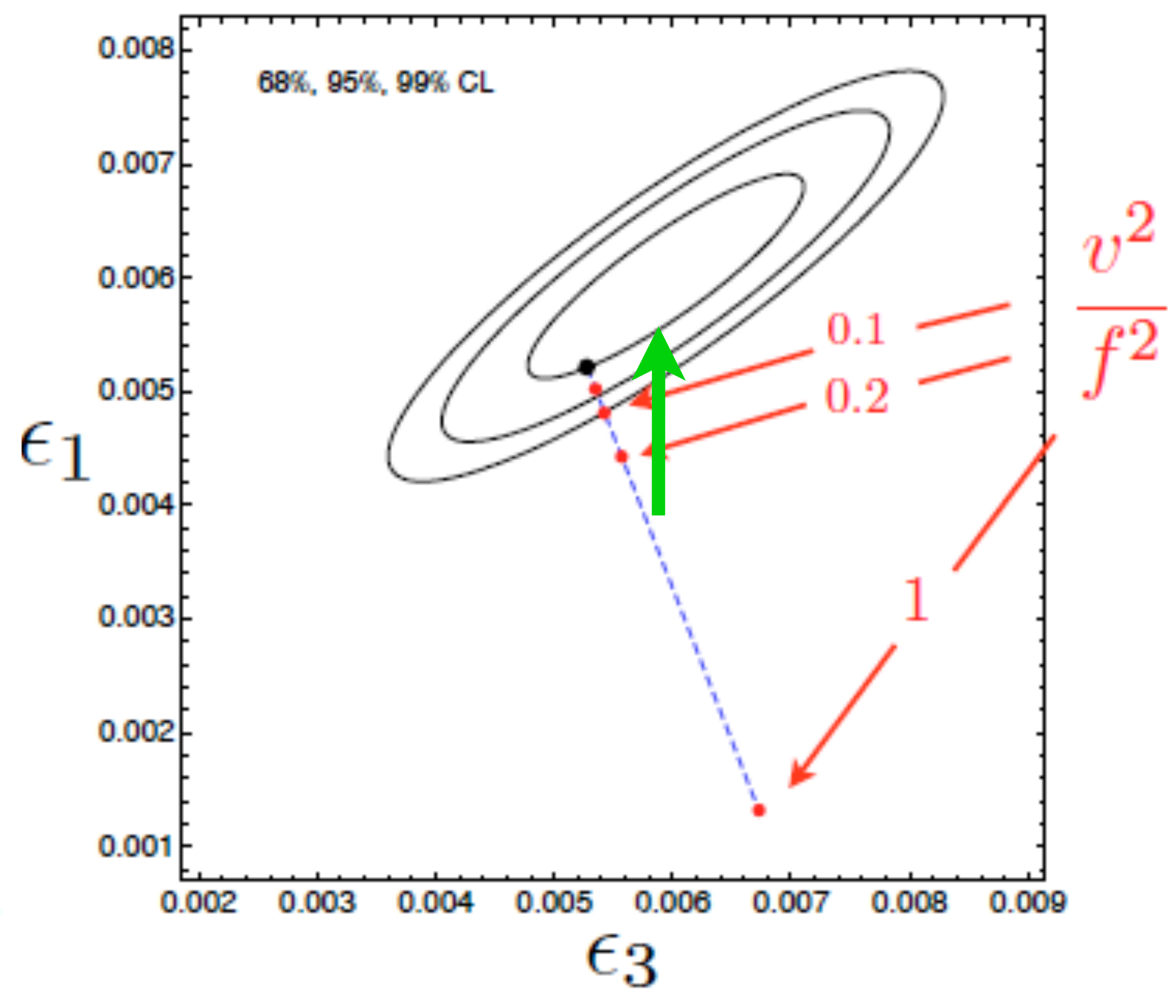
$$\Delta_{v/f} = (f/v)^2$$

Precision can be the only signal

generic of a composite (Twin) Higgs



Higgs precision

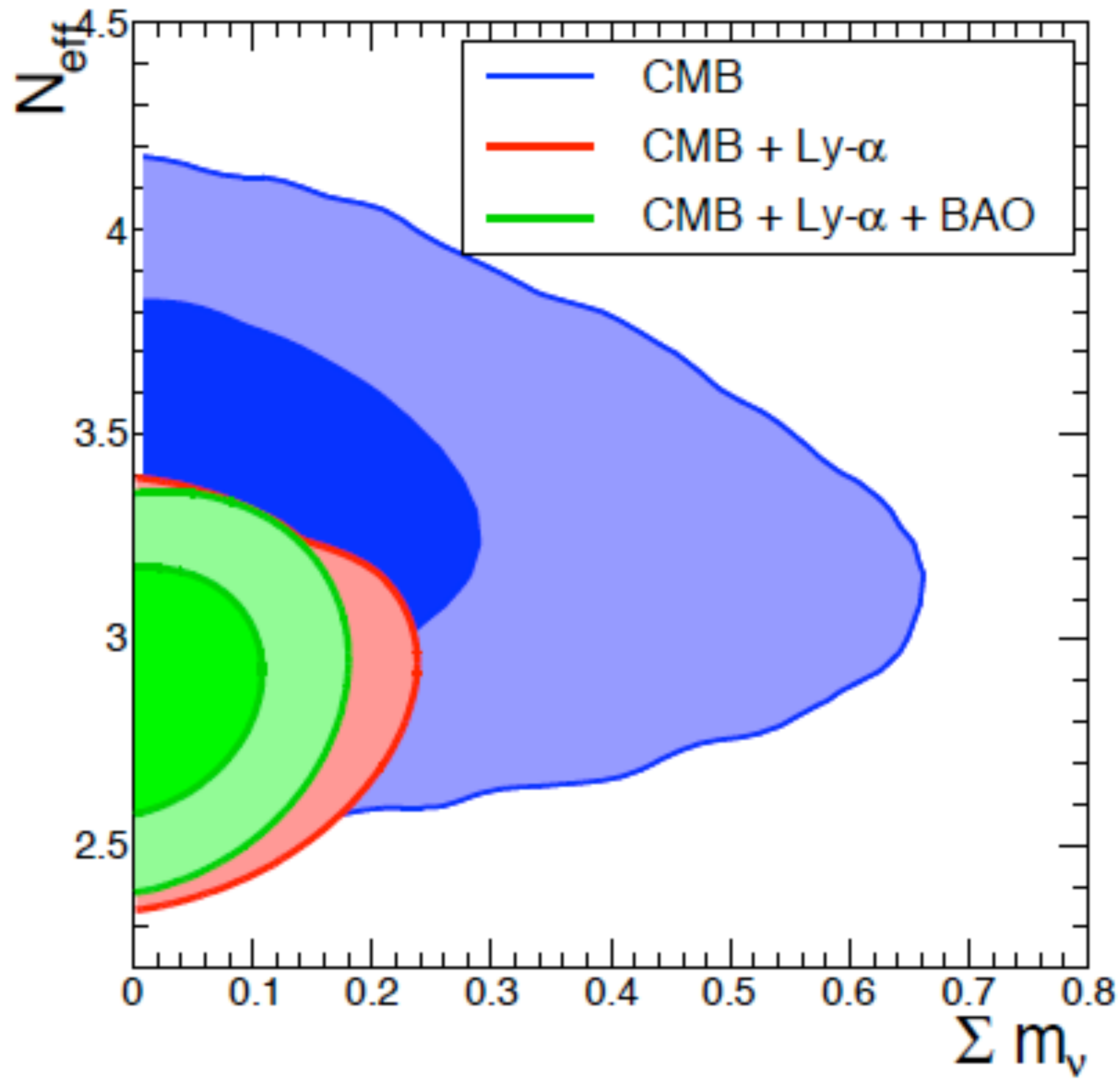


EWPT

B, Hall, Gregoire 2005

A problem for twin Higgs

Where is the twin radiation: $\tilde{\nu}, \tilde{\gamma}$?

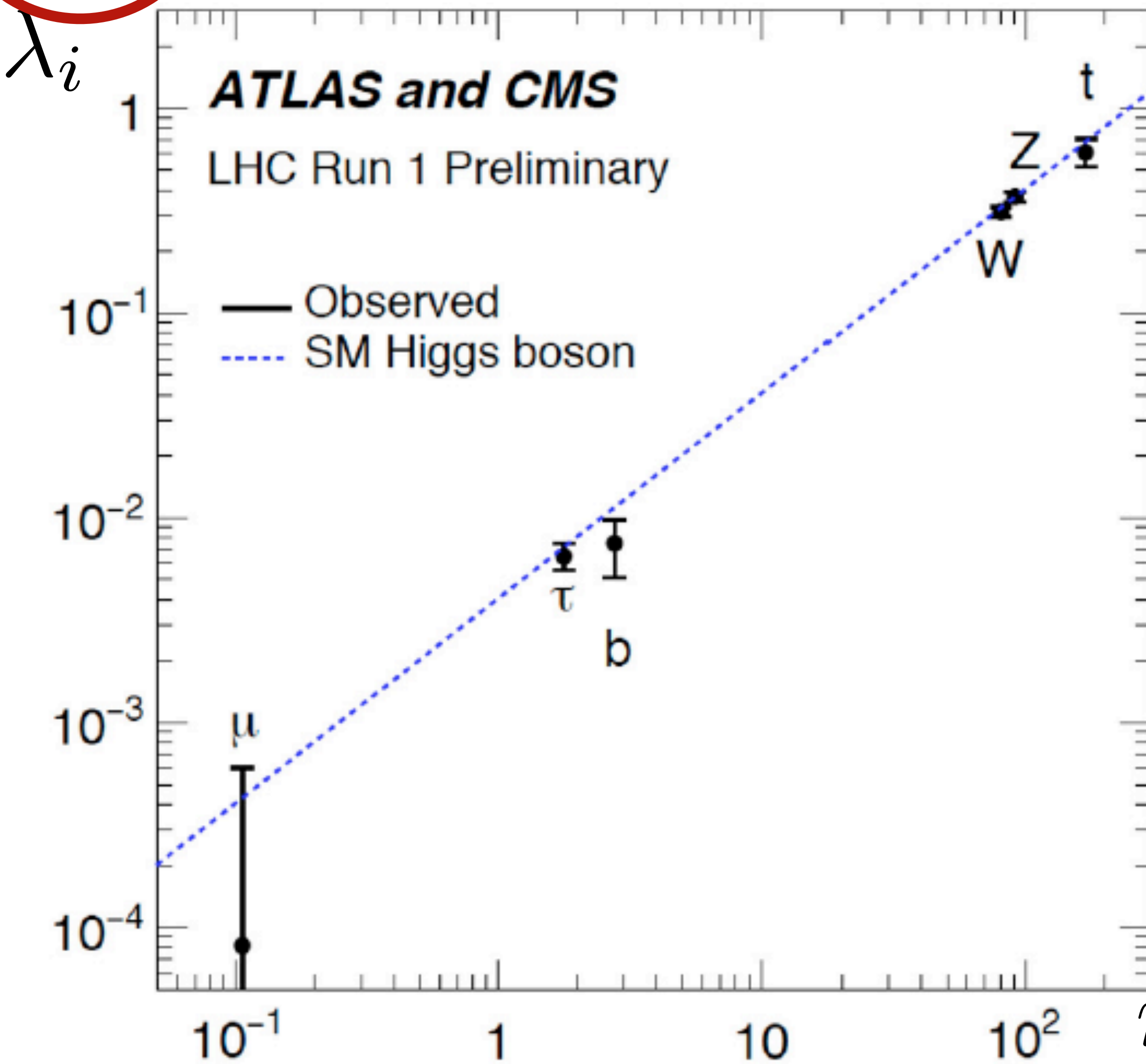


Rossi et al 2015

Need a reheating of the SM sector below $T_{dec} = 1 \div 5 \ GeV$
or some suitable Z_2 breaking

B, Hall, Gregoire 2005

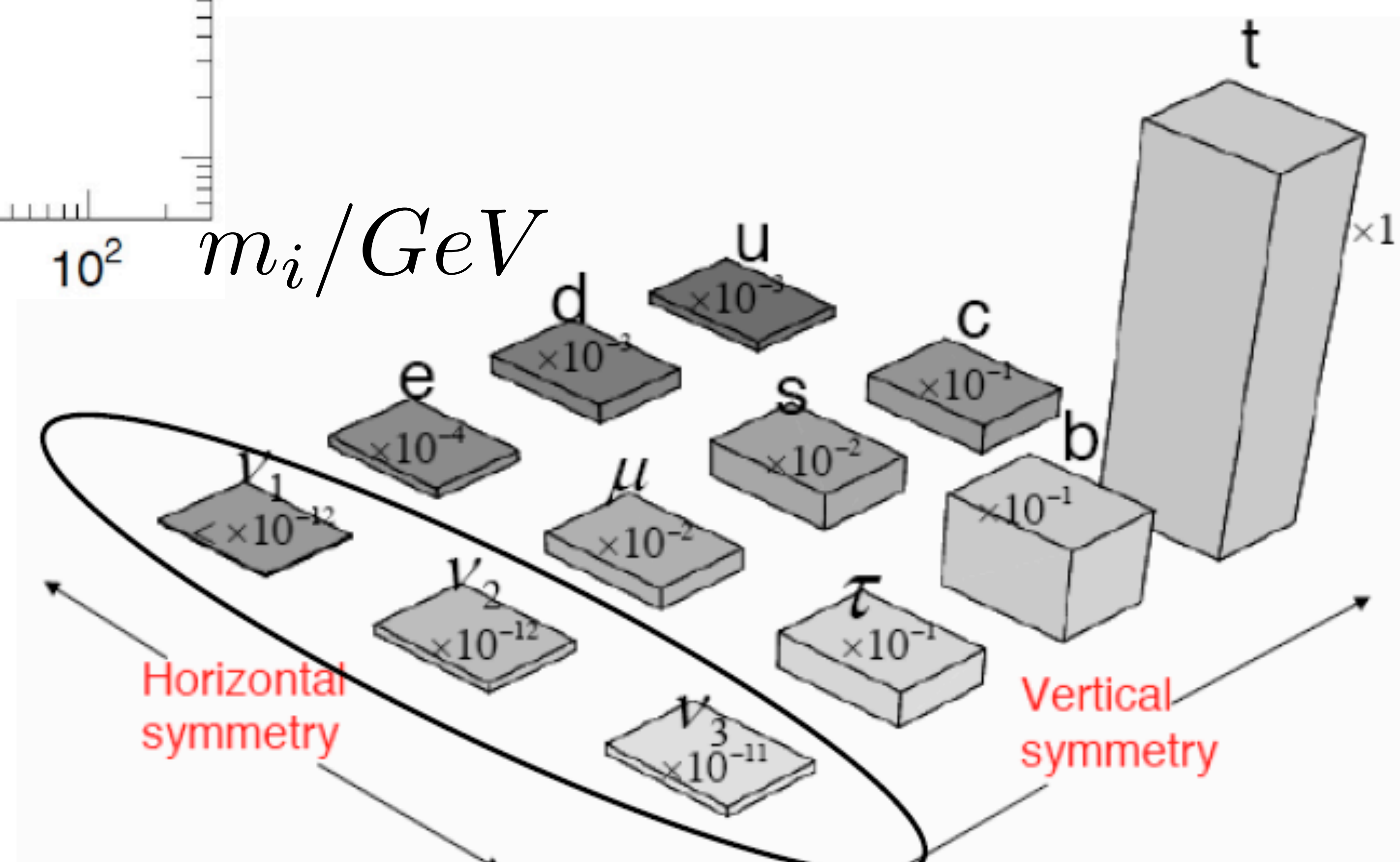
4 The flavour paradox $\lambda_{ij}\Psi_i\Psi_j h$



$$m_i = \lambda_i < h >$$

a piece of physical reality since 2012 (at least)

as opposed to:



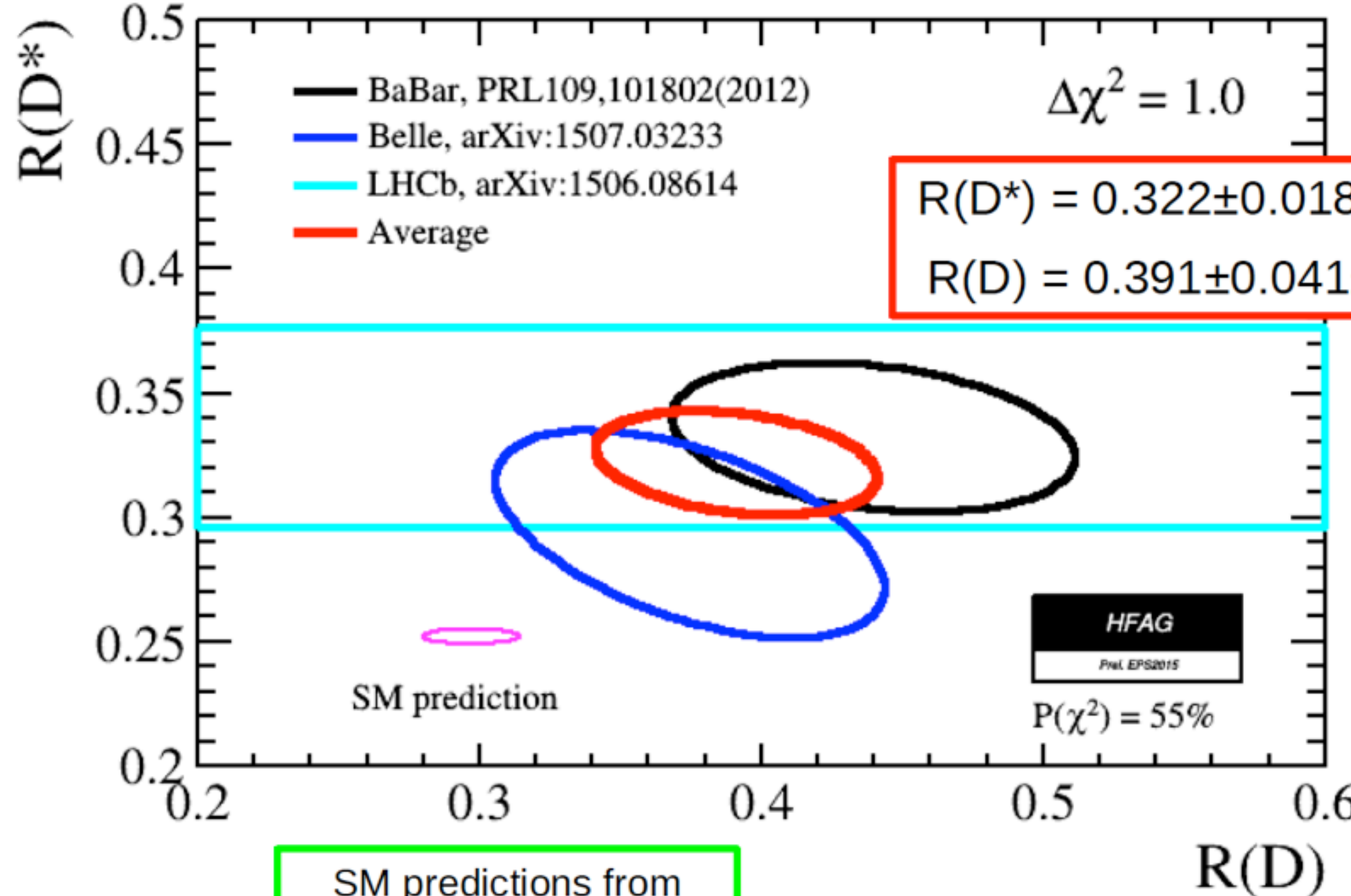
?!?!?

Not easy to improve without observed deviations from the SM

A deviation from the SM in flavour, finally?

$B \to D^{(*)}\tau\nu$

Tension with SM at 3.9σ



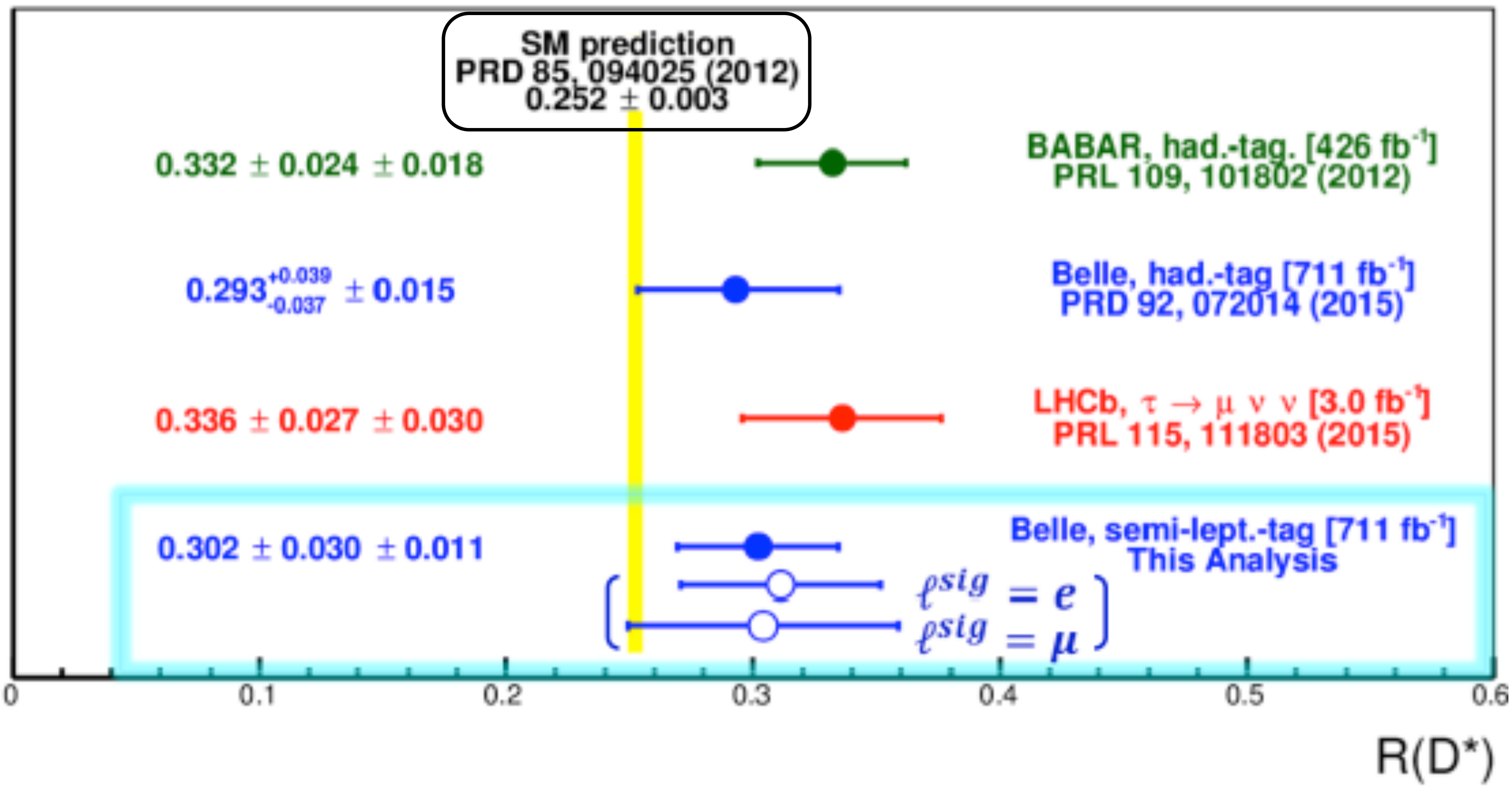
R(D*) = 0.322±0.018±0.012

R(D) = 0.391±0.041±0.028

SM predictions from PRD 85 (2012) 094025

A deviation from the SM in flavour, finally?

$$B \to D^* \tau \nu \quad (b \to c + \tau + \nu)$$



P. Goldenzwieg, 2016

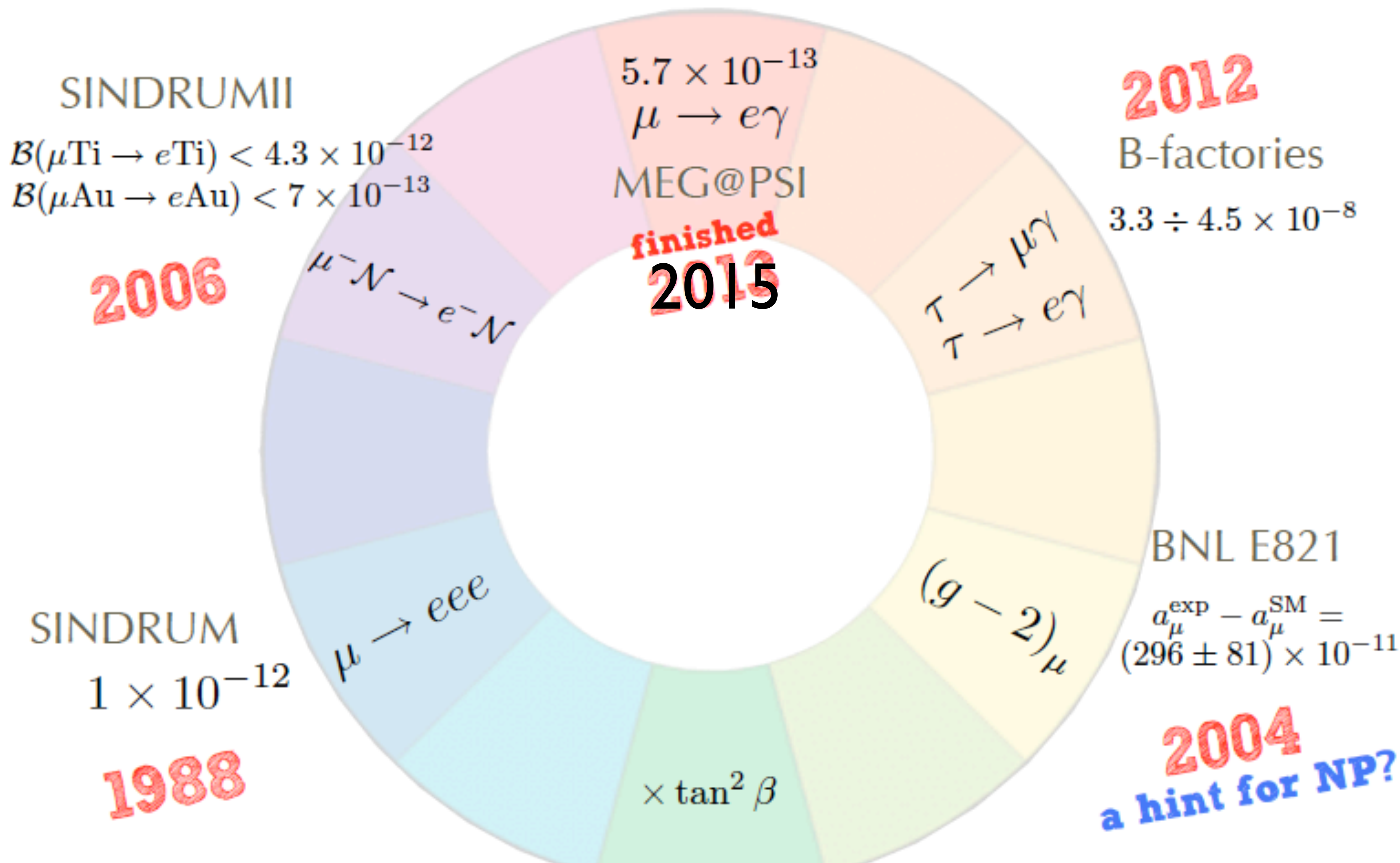
An “Extreme Flavour” experiment?

Vagnoni - SNS, 7-10 Dec 2014

- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events and hadronic final states, but limited in luminosity, 50 fb^{-1} vs 3000 fb^{-1}
- Would an experiment capable of exploiting the full HL-LHC luminosity for flavour physics be conceivable?
  - Aiming at collecting O(100) times the LHCb upgrade luminosity → 10^{14} b and 10^{15} c hadrons in acceptance at $L=10^{35}$ $cm^{-2}s^{-1}$

Motivation: test CKM (FCNC loops) from ≃ 20% to ≲ 1%

Lepton Flavour Violation



Motivation: extra degrees of freedom + unification

Summary

The Standard Model is NOT a complete story

Pictures that go Beyond the SM are not lacking, but - fair to say - we don't know which one is right

The very nature of Particle Physics and the current uncertain situation REQUIRE highly diverse frontiers of research

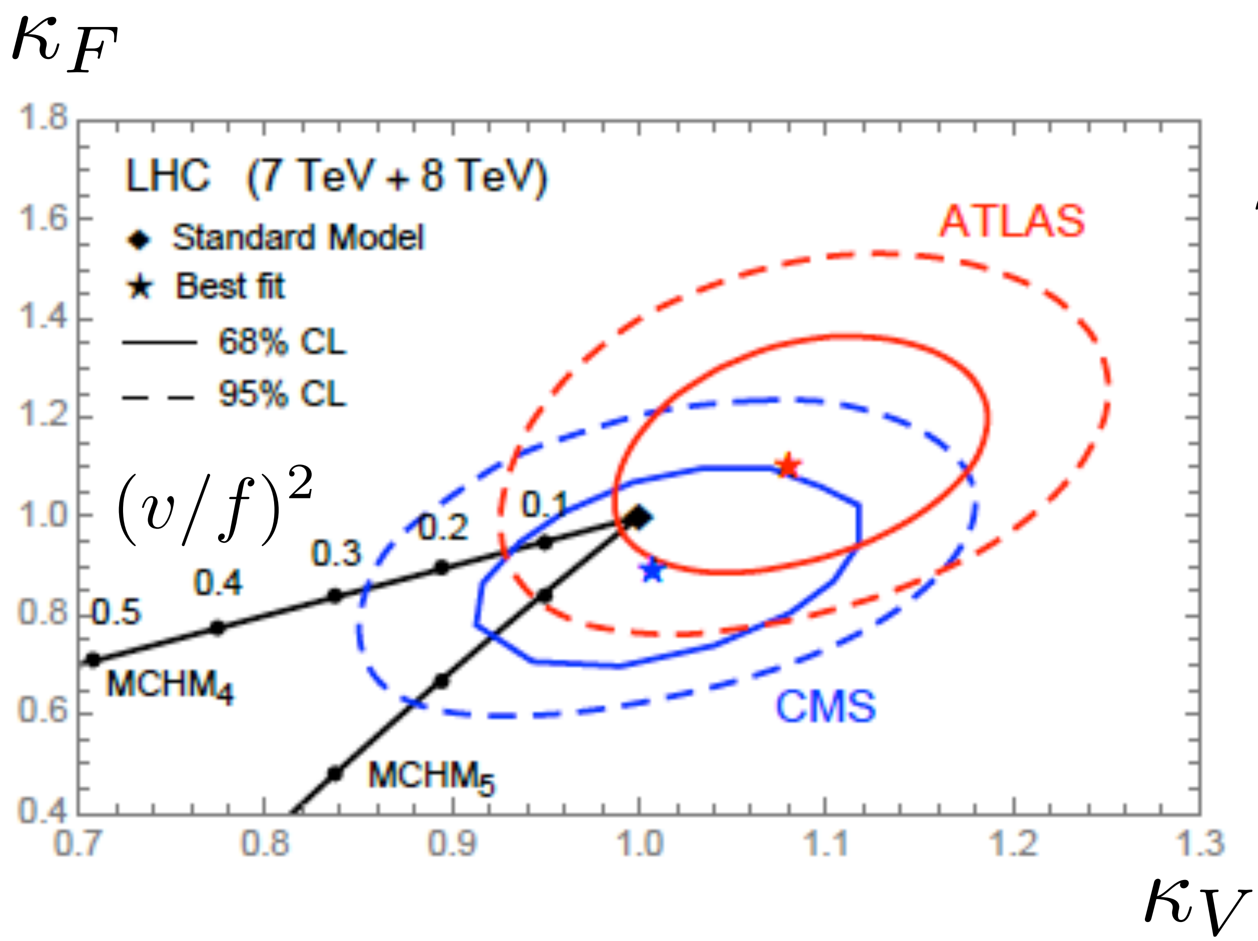
(Not in contradiction with above) the SM is going TO STAY as an accurate and very economic description/explanation of fundamental physics at short scales

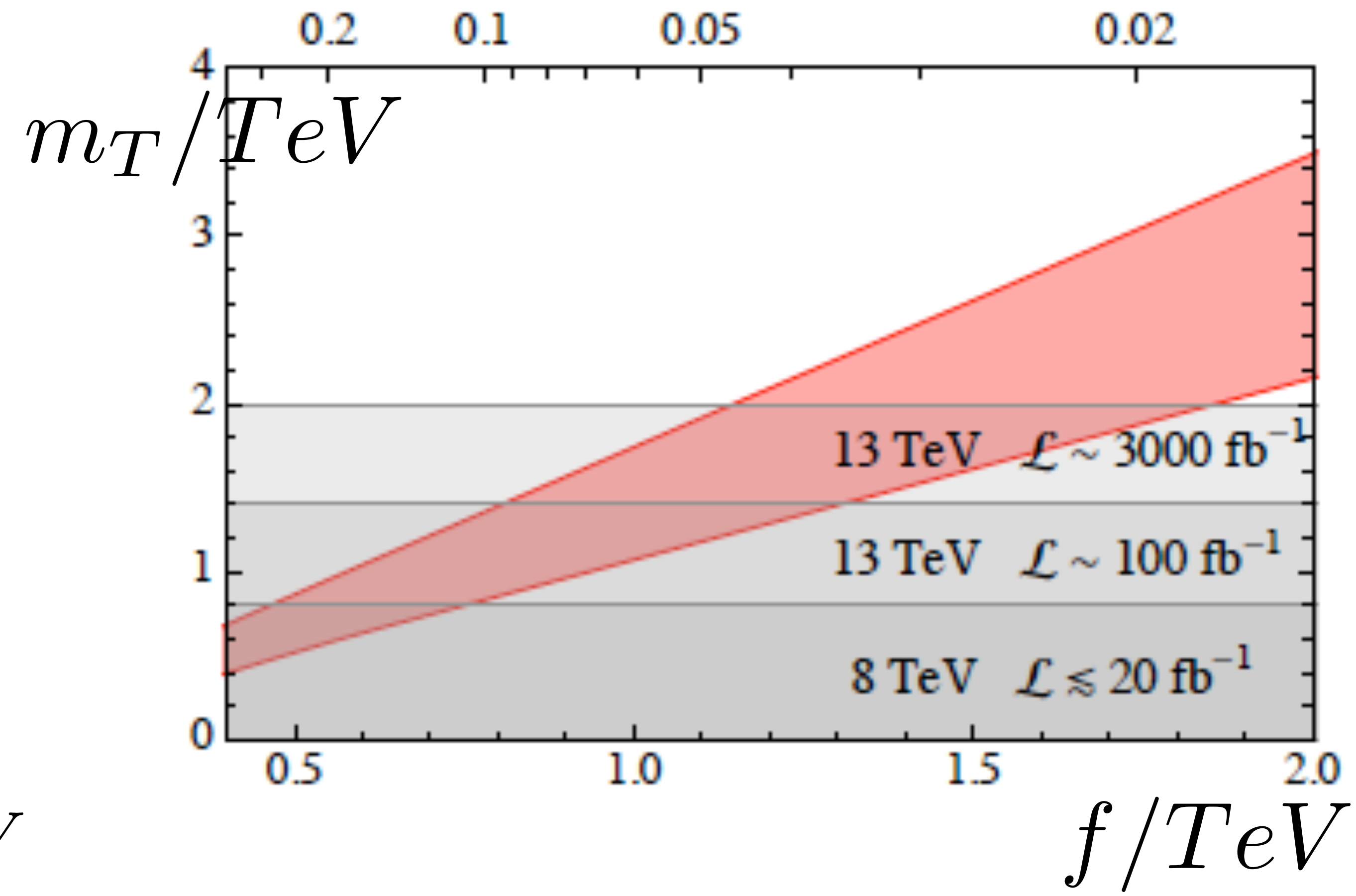
For possible questions

Composite Higgs $(G \xrightarrow{f} H \xrightarrow{v} U(1)_{em})$

$$\Delta_{v/f} = (f/v)^2 \qquad \Delta_{m_h^2} = \frac{g_E^2}{\lambda_t^2}\left(\frac{m_T}{500GeV}\right)^2$$

$$\Delta_{tot} = \Delta_{v/f}\Delta_{m_h^2}$$





Higgs precision (left) and

direct searches (right, single and double T prod.)

explore $\Delta_v = 10 \div 100$

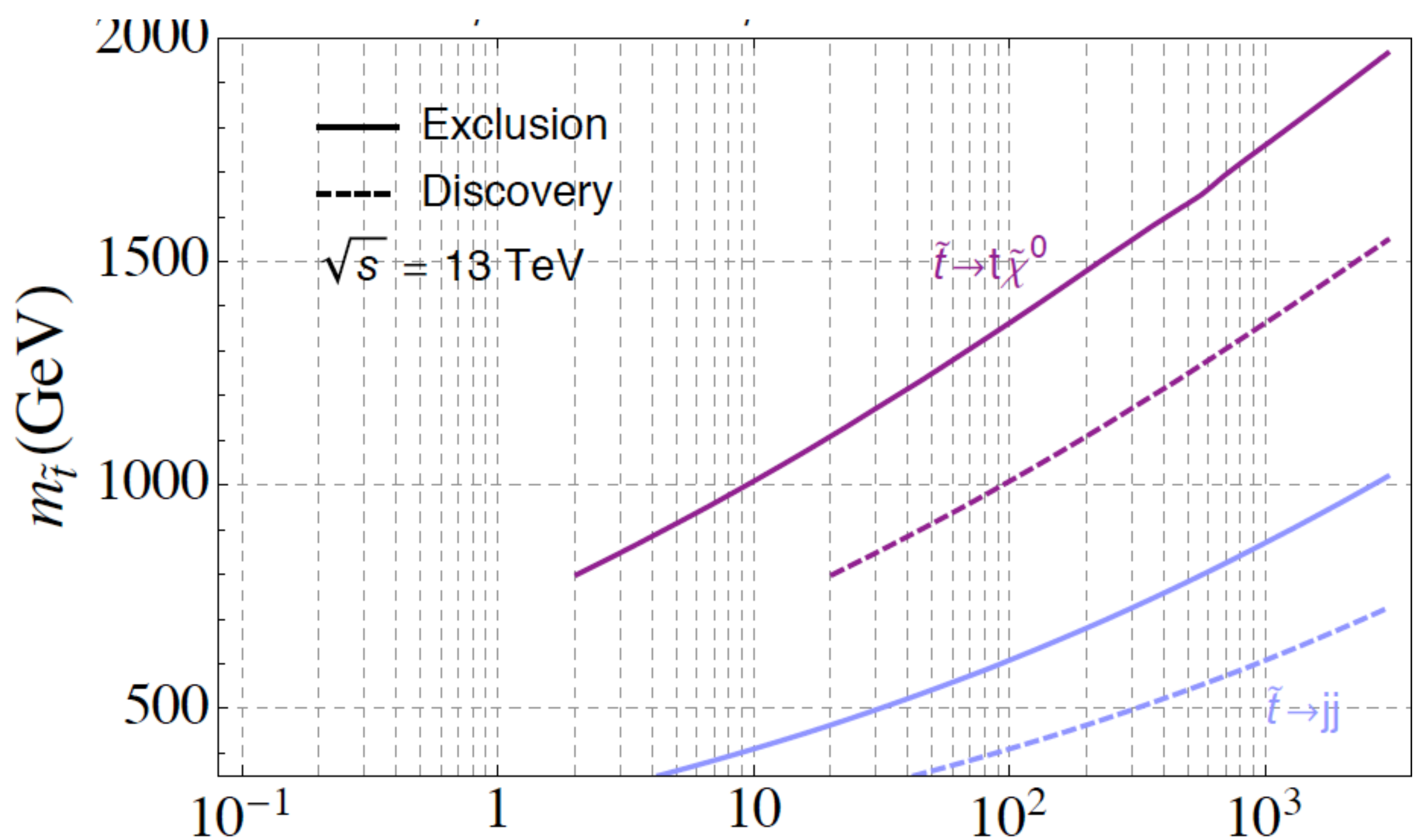
Matsedonsky et al 2015

MSSM

$$\Delta_v = \frac{\delta v^2}{v^2} = \frac{4c_W^2}{g^2}\frac{\delta m_{H_u}^2}{v^2} \qquad \delta m_{H_u}^2 = \frac{3}{4\pi^2}\frac{m_t^2}{v^2 s_\beta^2} m_{\tilde{t}}^2 \log\left(\Lambda^2/m_{\tilde{t}}^2\right)$$

$$m_h^2 < M_Z^2 c_{2\beta}^2 + \Delta m_h^2(\log m_{\tilde{t}}, A_t)$$

$m_h = 125\ GeV$ **requires** $m_{\tilde{t}} \gtrsim 1\ TeV$**, large** $A_t \Rightarrow \Delta_v > 100 \div 1000$



$L(fb^{-1})$

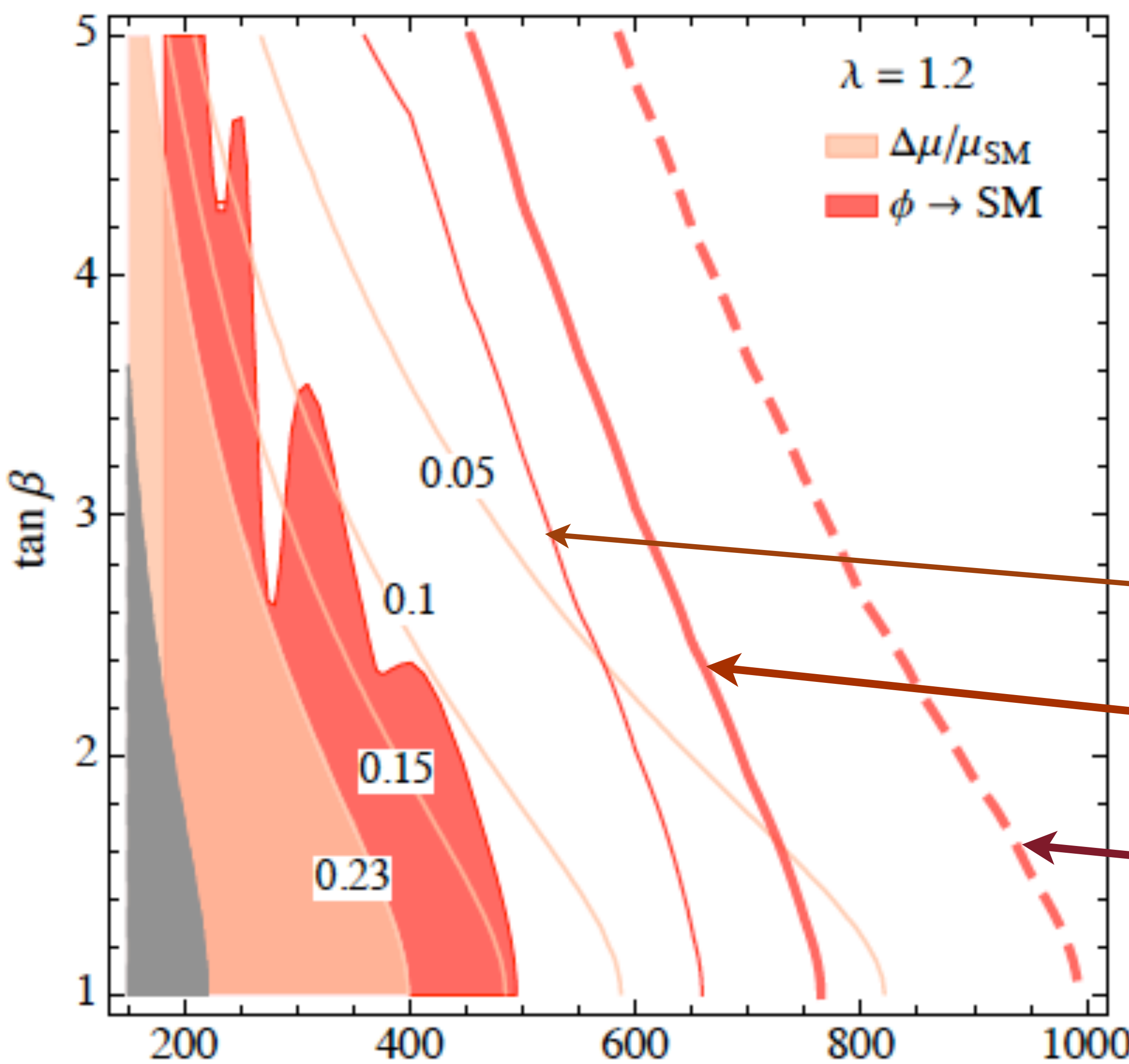
D'Agnolo

Direct searches explore $\Delta_v \gtrsim 100 \div 1000$

NMSSM $(\lambda S H_u H_d)$

$$\Delta_v = \frac{\delta m^2_{H_u}}{\lambda^2 v^2} \approx \frac{g^2}{4\lambda^2}\Delta_v^{MSSM} \qquad m_h^2 \leq M_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2$$

$m_h = 125\ GeV$ in the right ballpark for $\lambda \approx 1$ and $t_\beta \lesssim 3 \div 4$ without the need of a heavy stop



m_S/GeV

Direct searches, including extra scalars explore $\Delta_v = 10 \div 100$

$LHC13, 100 fb^{-1}$

$LHC14, 300 fb^{-1}$

$LHC14, 3000 fb^{-1}$

Buttazzo et al 2015

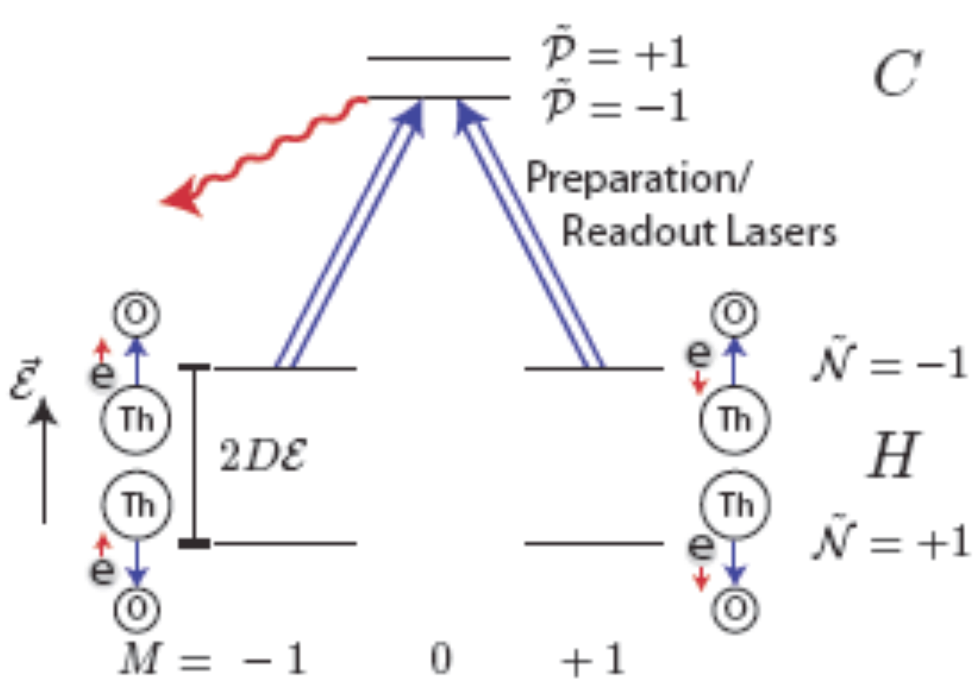
②

Electric Dipole Moments

in absence of other CPV operators

	limit (e cm)	year	SM (e cm)
electron	$8.7 \cdot 10^{-29}$	2013	$\sim 10^{-38}$
neutron	$2.9 \cdot 10^{-26}$	2006	$\sim 10^{-31}$ (*)

(*) if $\theta \lesssim 10^{-21}$



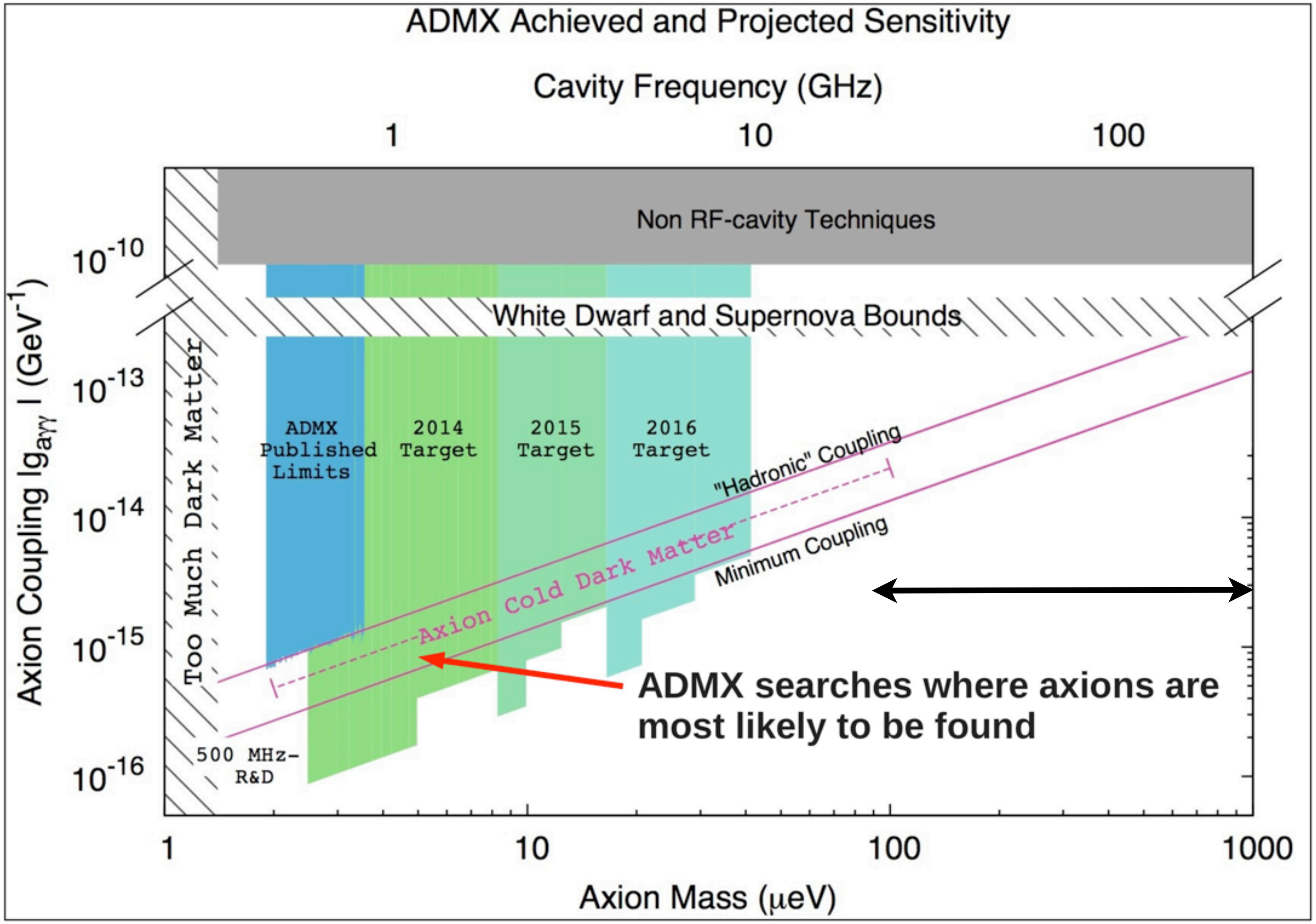
ACME Collaboration

Gabrielse (Harvard), DeMille (Yale) et al

using a polarized ThO molecule

The classic search

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

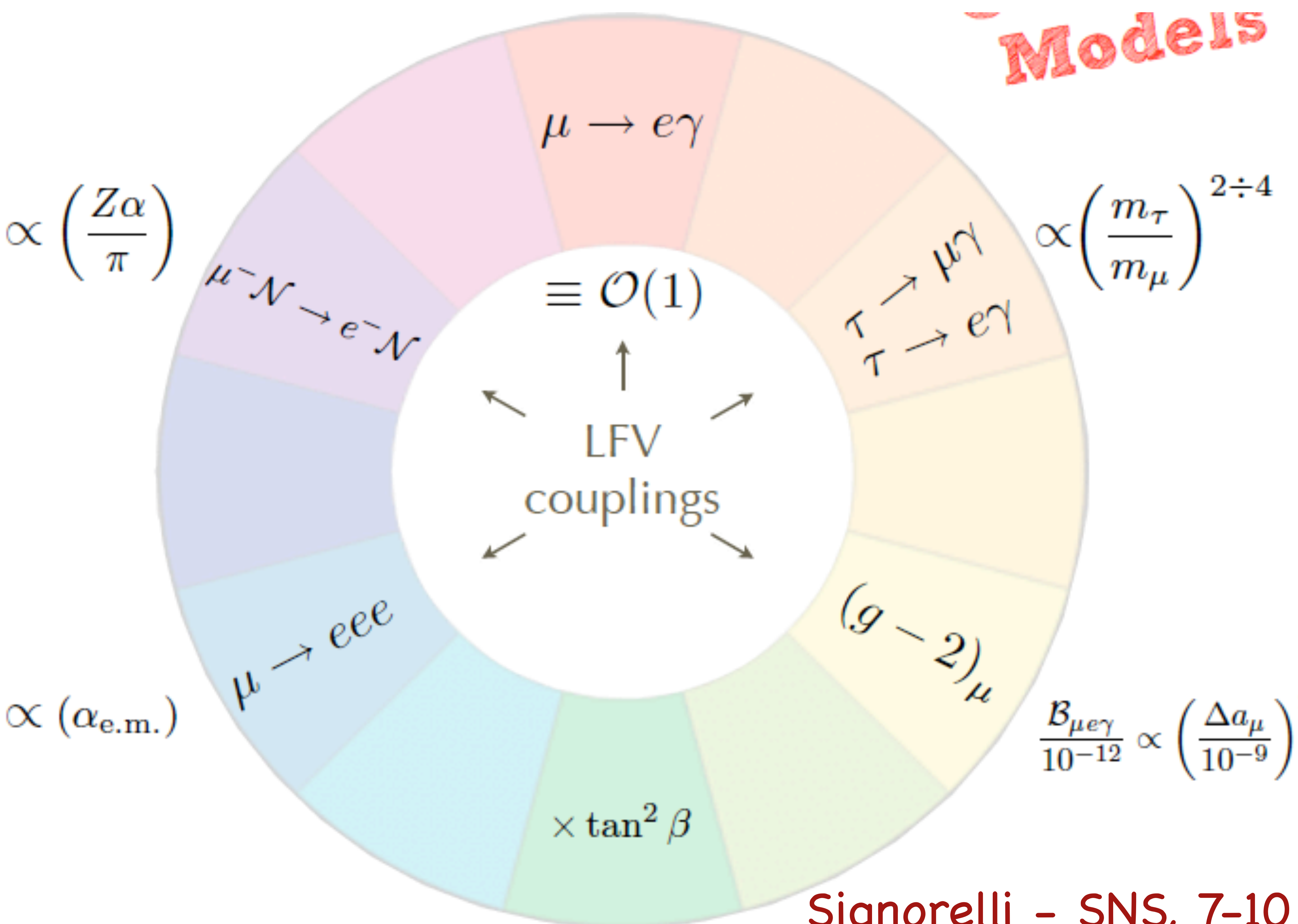


Not easy to explore the most relevant region

$m_a = 10^{-5} \div 10^{-3}\ eV$

ADMX

Lepton Flavour Violation



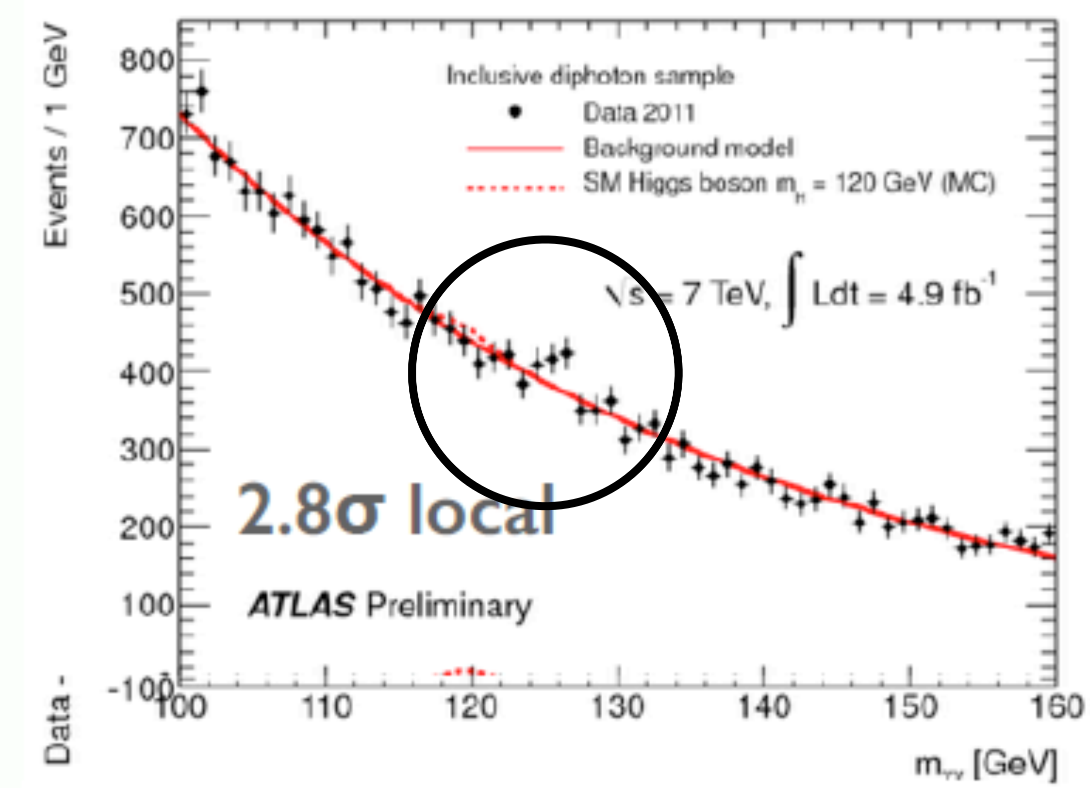
Signorelli - SNS, 7-10 Dec 2014

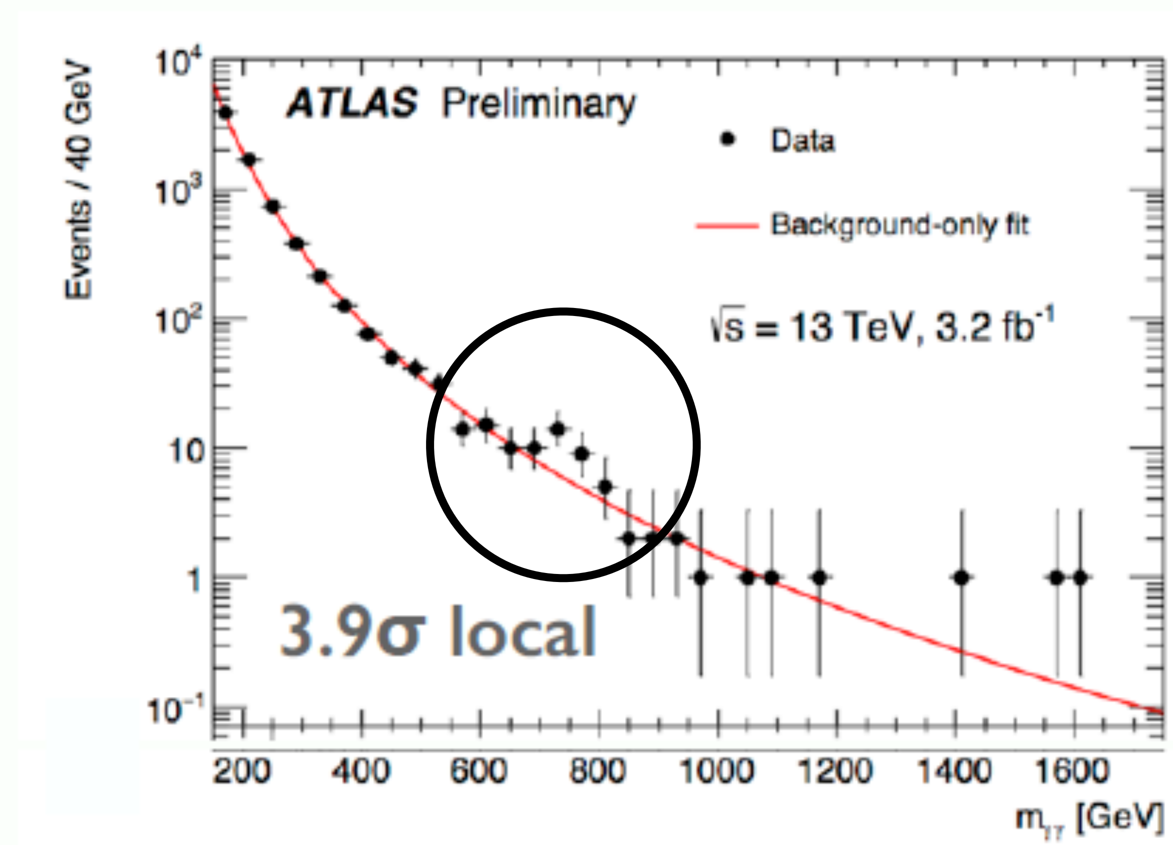
Motivation: extra degrees of freedom + unification

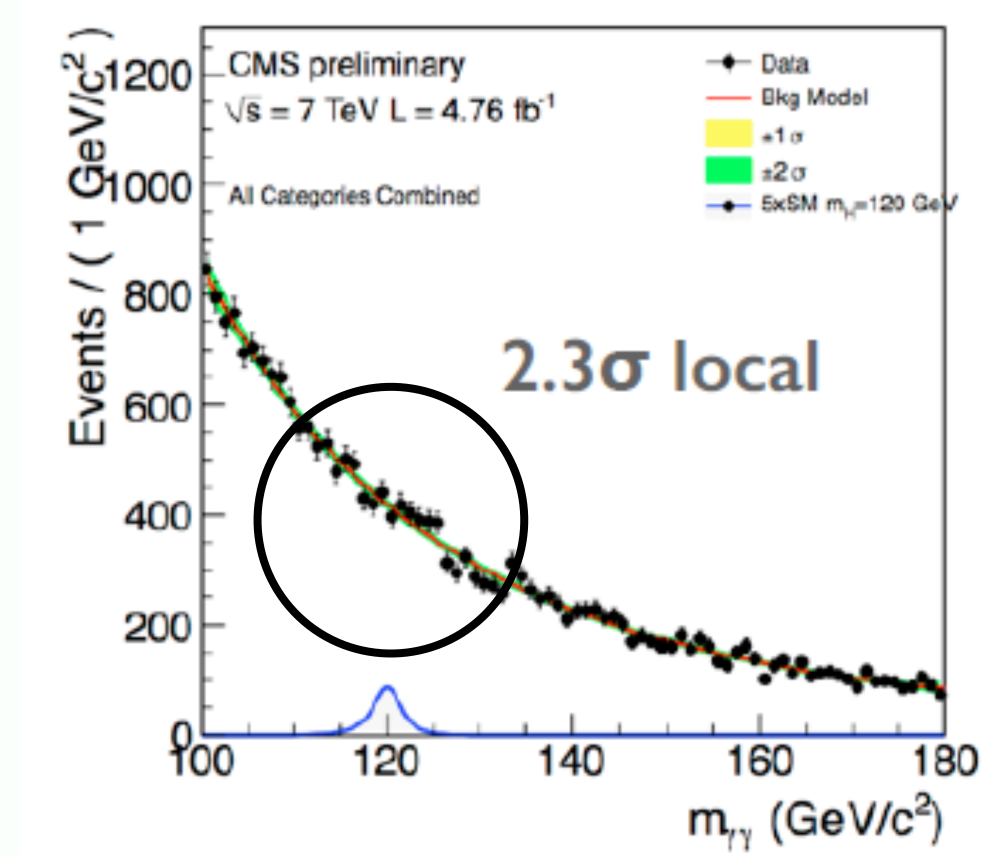
Only one scalar: the Higgs boson?

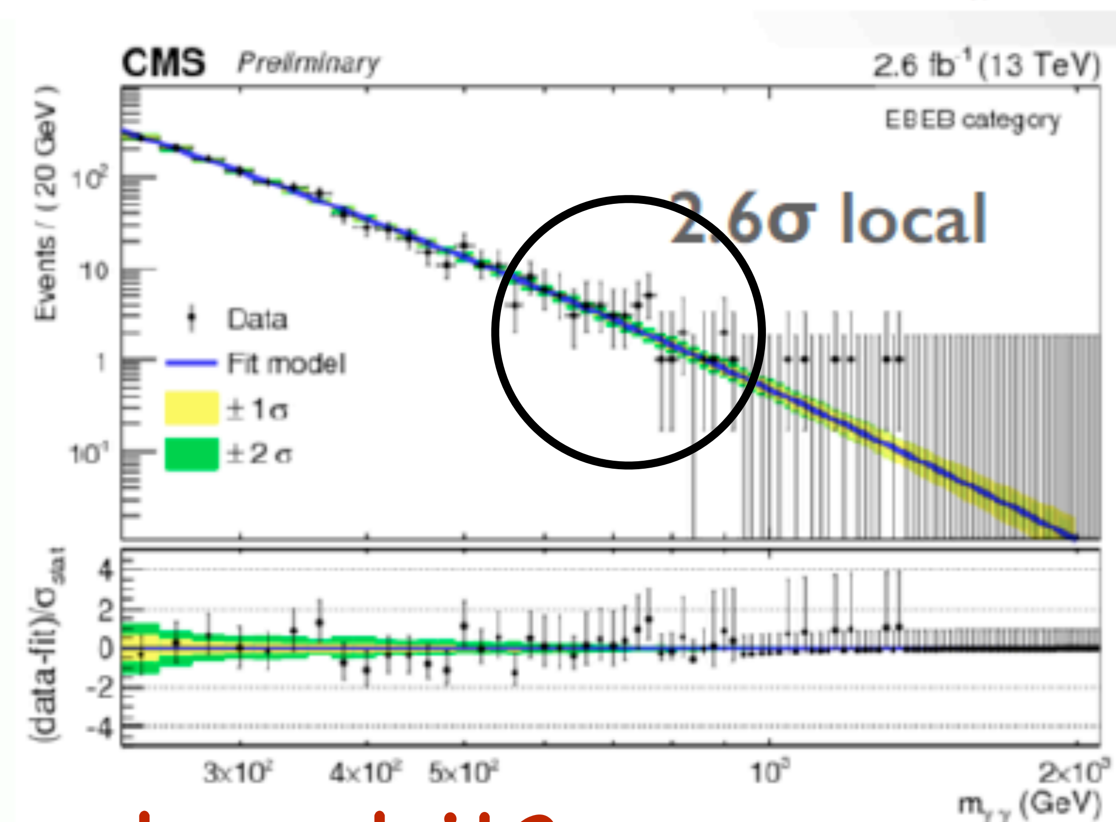
Dec 2011

Dec 2015



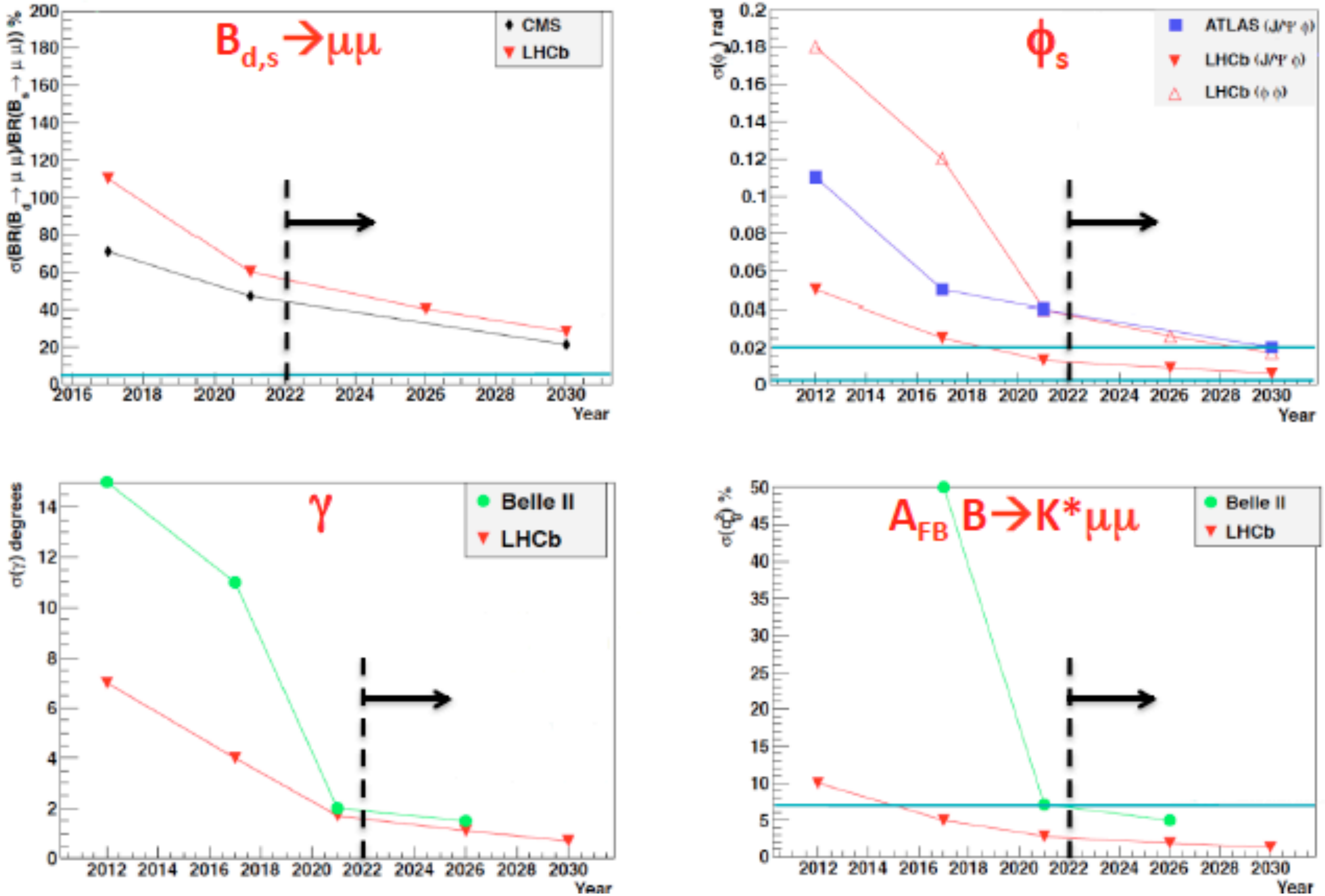






If real, who ordered it?

Nice prospects in the quark sector …



…but flattening out after ~2022

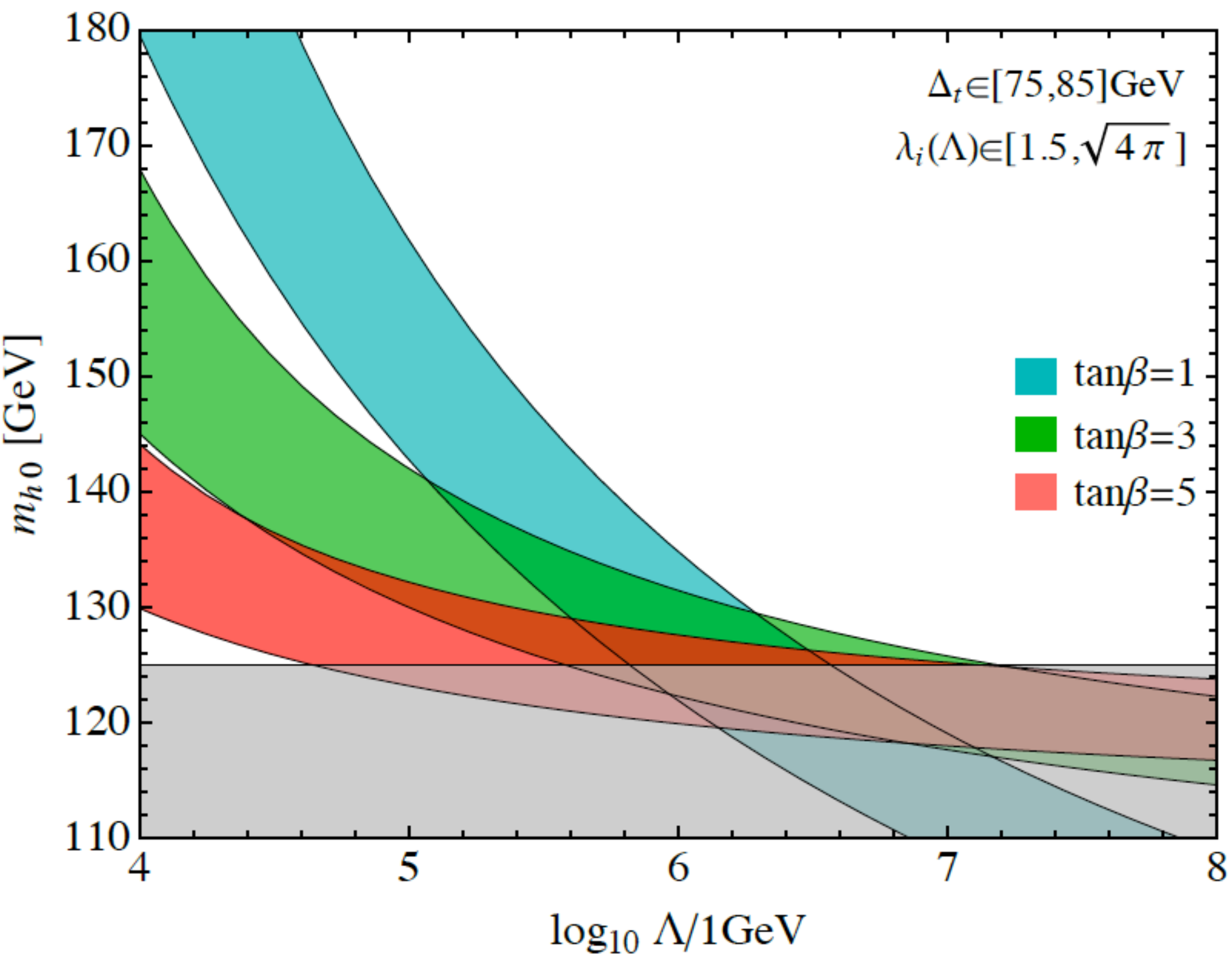
My favorite explanation

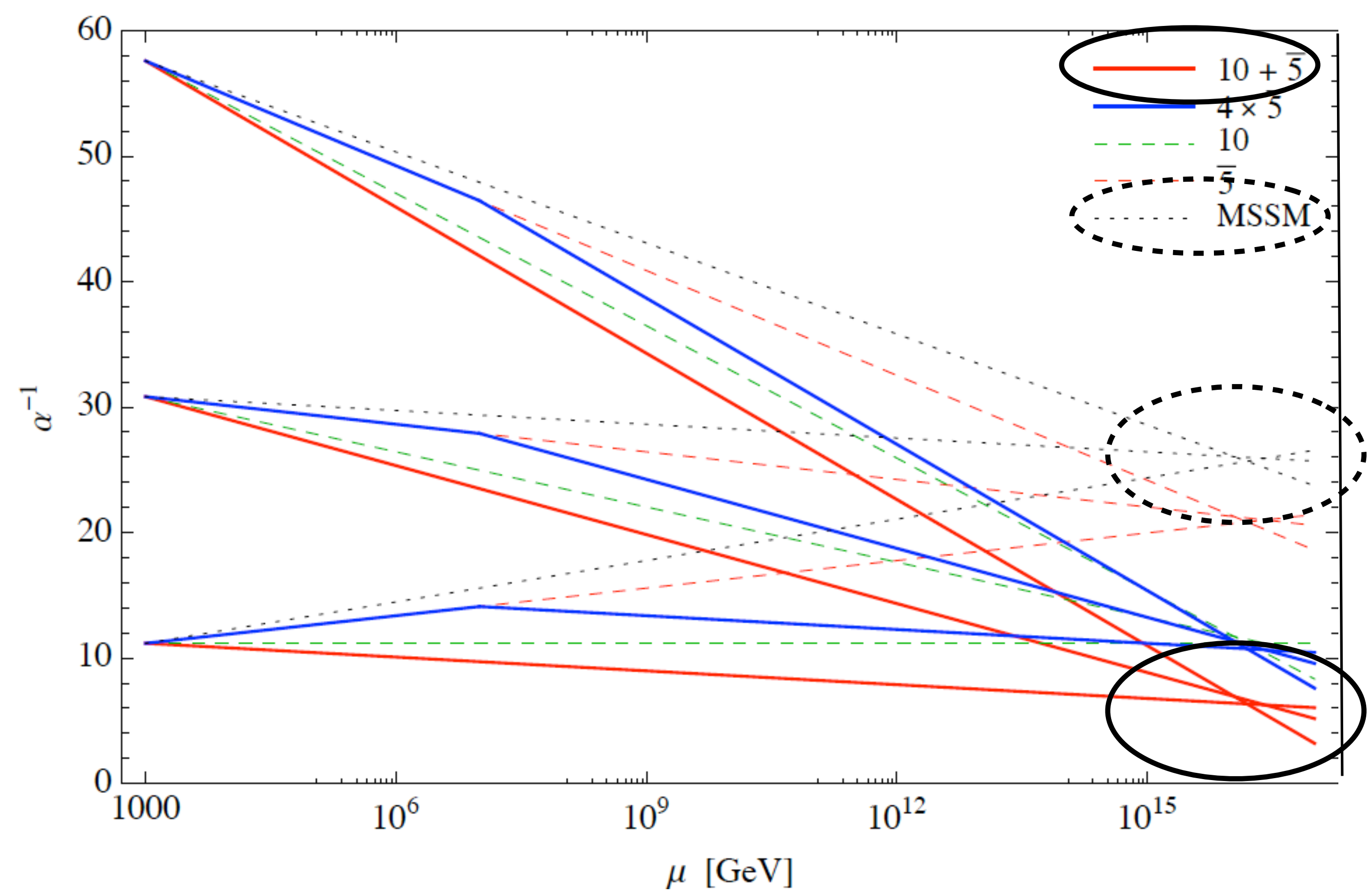
$\Rightarrow \quad m_h \leq M_Z \cos 2\beta \longrightarrow$ 125 GeV. How?

$\Rightarrow$ Why 3 generations?

Answer: the NMSSM with a unified coupling $\alpha_G \approx 1$
as provided by one vector-like extra generation $N_g = 3 + 2$

$$W_{eff} = W_{Yuk} + \lambda_H S H_u H_d + \lambda_i S \bar{\Phi}_i \Phi_i + \frac{\kappa}{3} S^3$$





$$m_{h0}^2 = M_Z^2 \cos^2 2\beta + \lambda_H^2 v^2 \sin^2 2\beta + \Delta_t^2$$

B, Buttazzo, Hall, Marzocca 2016

My favorite explanation

A vector lepto-quark $U_\mu^{2/3}$

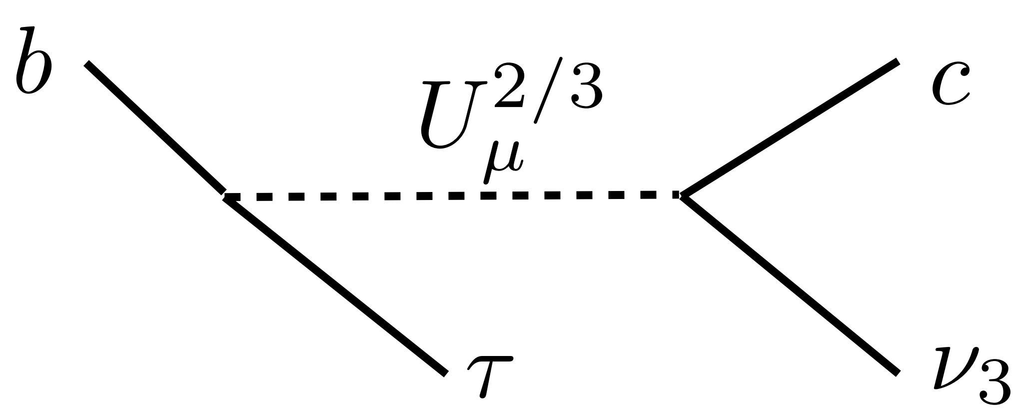
singlet under a flavour $U(2)_Q \times U(2)_L$

$$\mathcal{L} = g_U U_\mu^{2/3} (\bar{Q}_3 \gamma_\mu L_3) + h.c.$$

\+ $U(2)_Q \times U(2)_L$ - breaking as in MFV

$$\Rightarrow \quad g_U U_\mu^{2/3} (\bar{u}_{Li} \gamma^\mu F_{ij}^U \nu_{Lj} + \bar{d}_{Li} \gamma^\mu F_{ij}^D e_{Lj}) + \mathrm{h.c}$$

$$F_{ij}^{U,D} \approx \delta_{i3} \delta_{j3}$$



need $$\frac{4 g_U^2 M_W^2}{g^2 M_U^2} \approx 0.25 \div 0.35$$

B, Isidori, Pattori, Senia 2015