

Beyond the Standard Model: the big picture

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SWHEPPS 2016, 7-9 June, Aegerisee

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

$$\begin{aligned}\mathcal{L}_{\sim SM} = & -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + i\bar{\Psi} \not{D}\Psi & (\sim 1975-2000) \\ & + |D_\mu h|^2 - V(h) & (\sim 1990- 2012) \\ & + \Psi_i \lambda_{ij} \Psi_j h + h.c. & (\sim 2000- now)\end{aligned}$$

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

The synthetic nature of Particle Physics

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



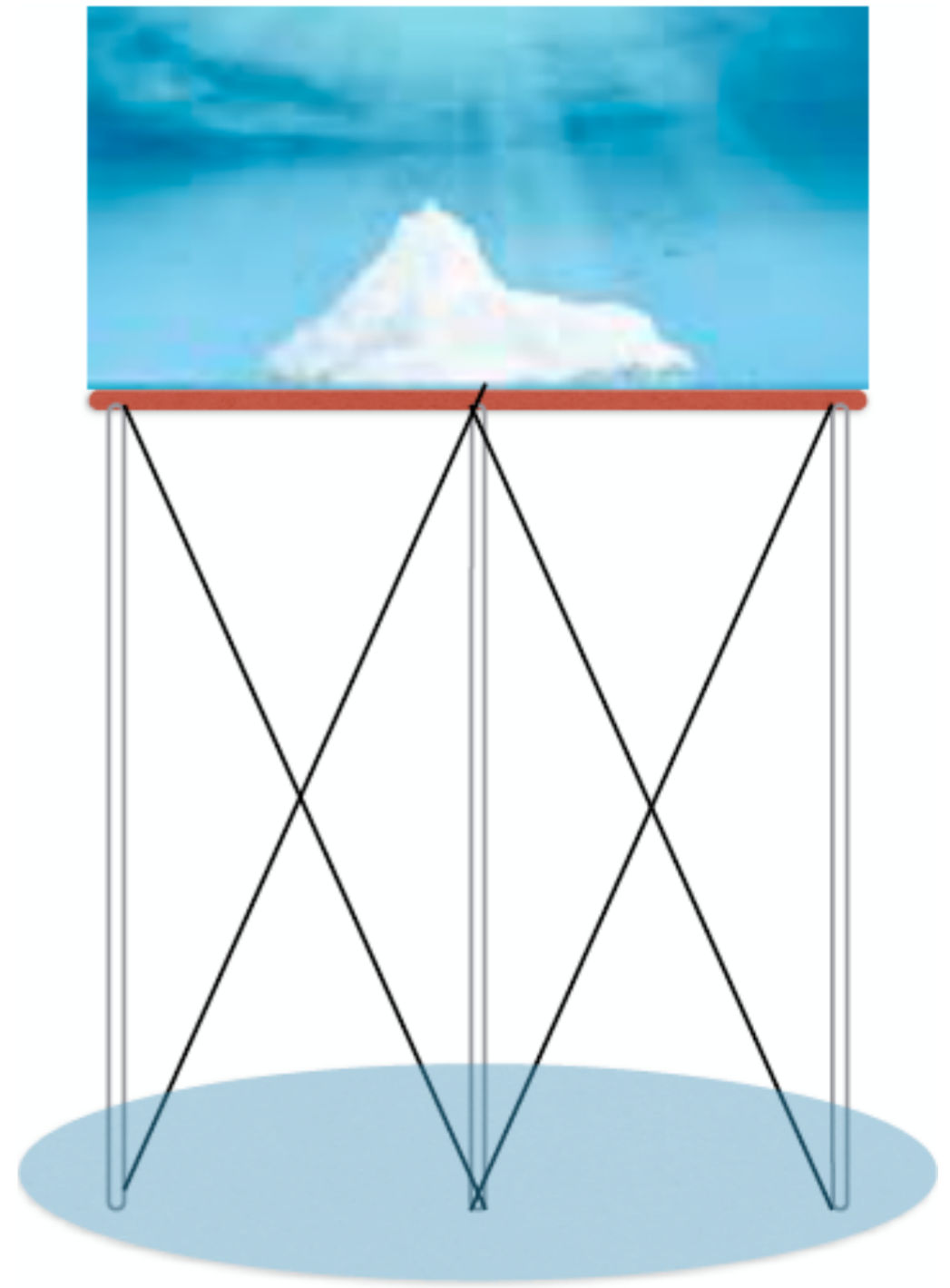
What there is under the water?

(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 $E \gg \text{TeV}$ s?

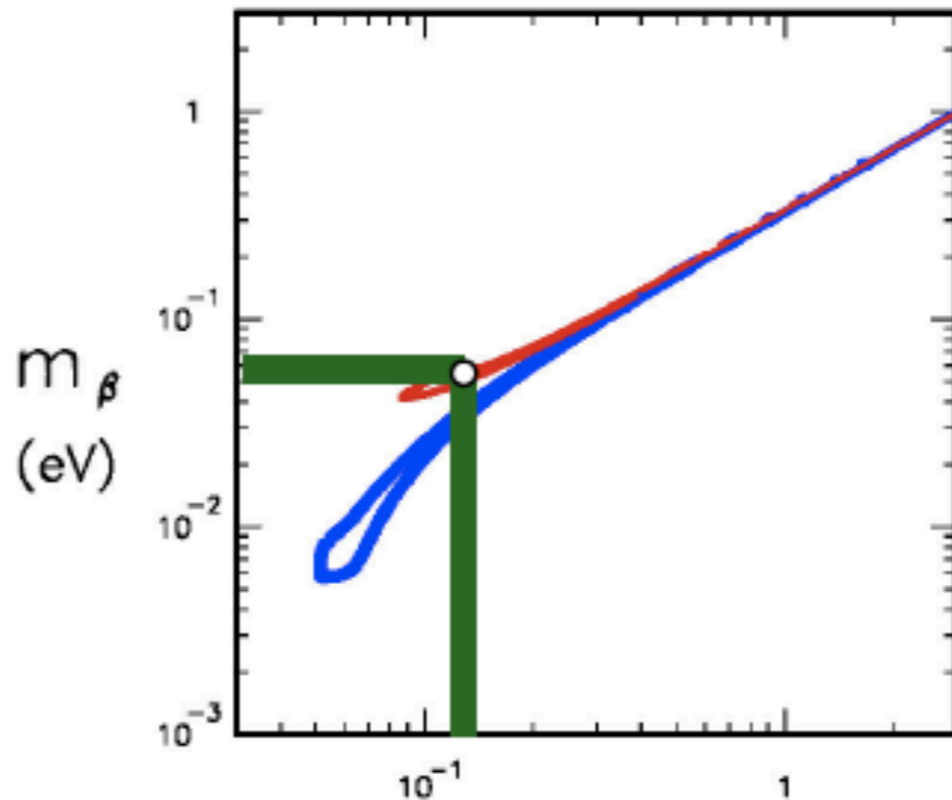
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Key neutrino measurements

m_β
beta-decay
endpoint

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

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

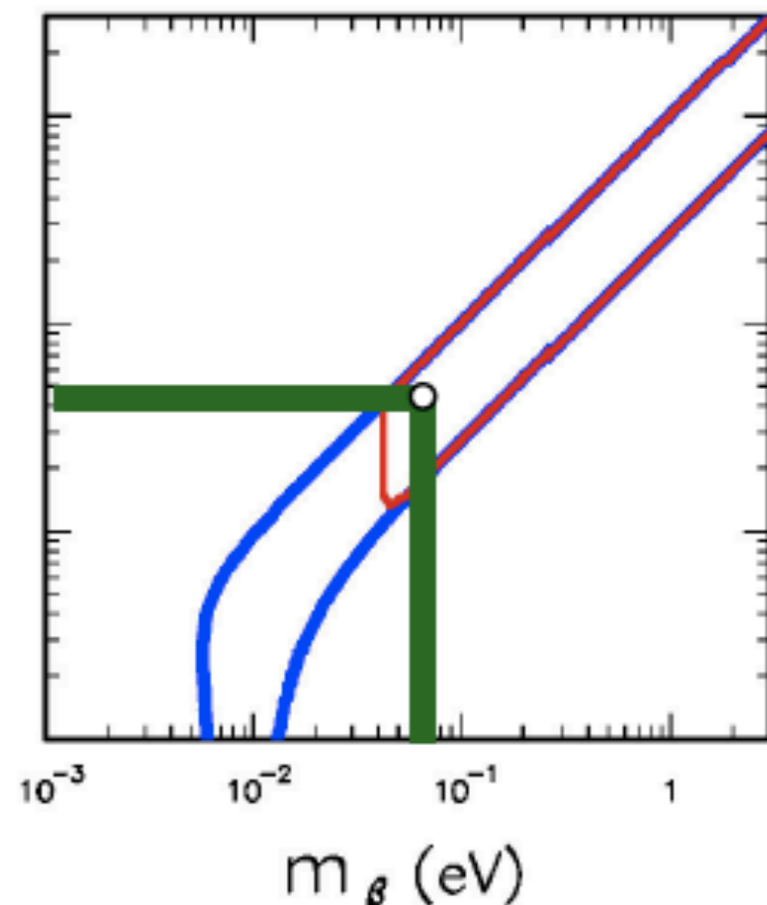
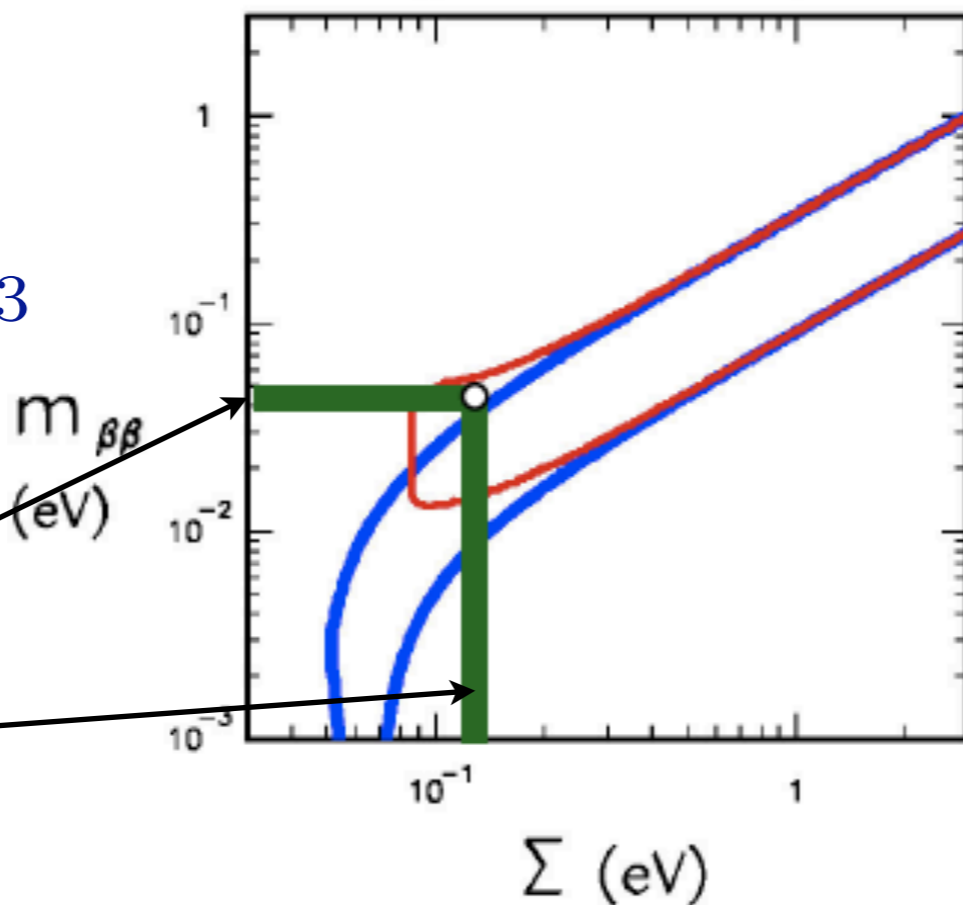


2σ bounds

from current knowledge
of oscillations only

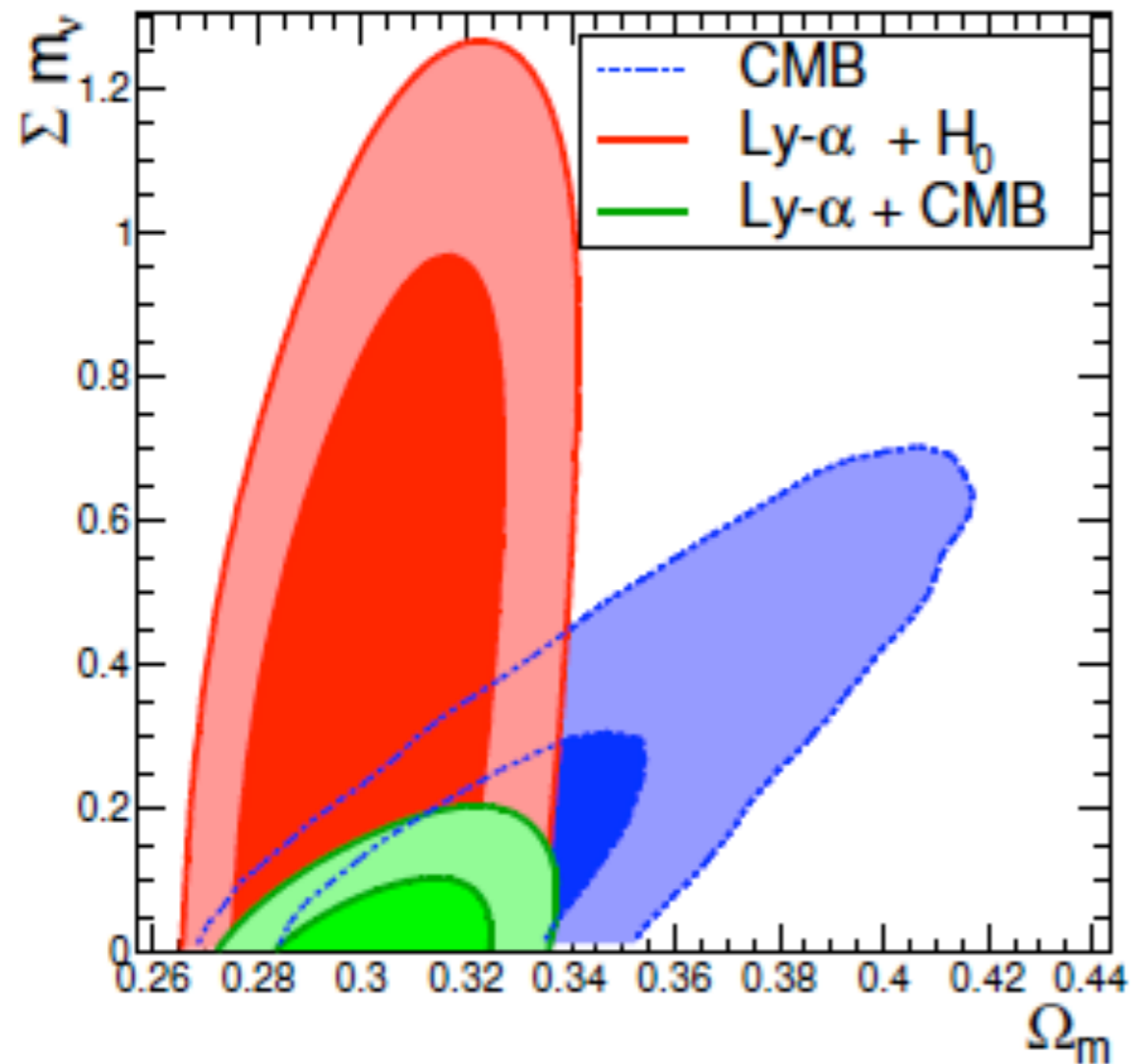
Lisi et al

— normal hierarchy
— inverted hierarchy



hypothetical measurements

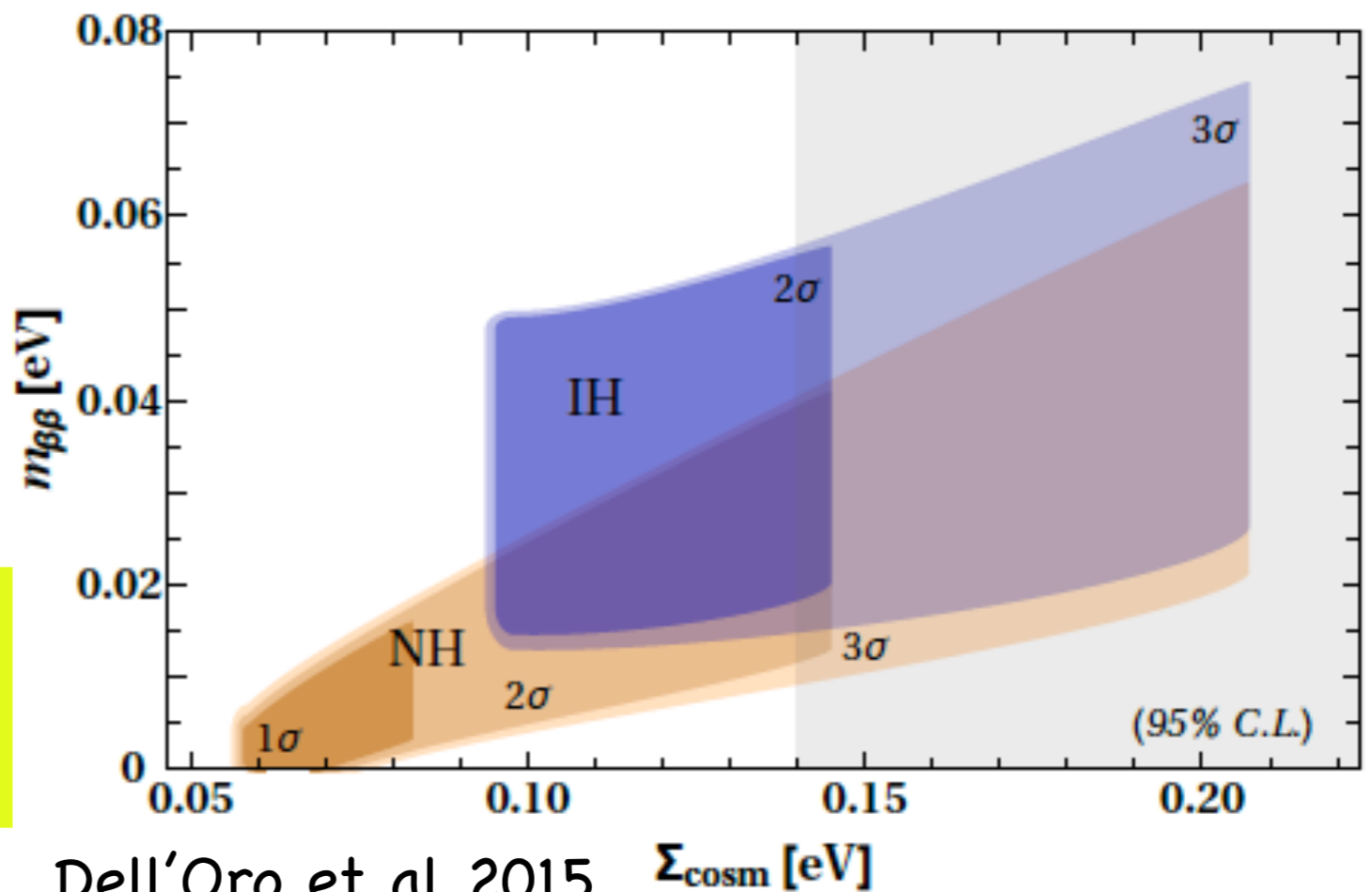
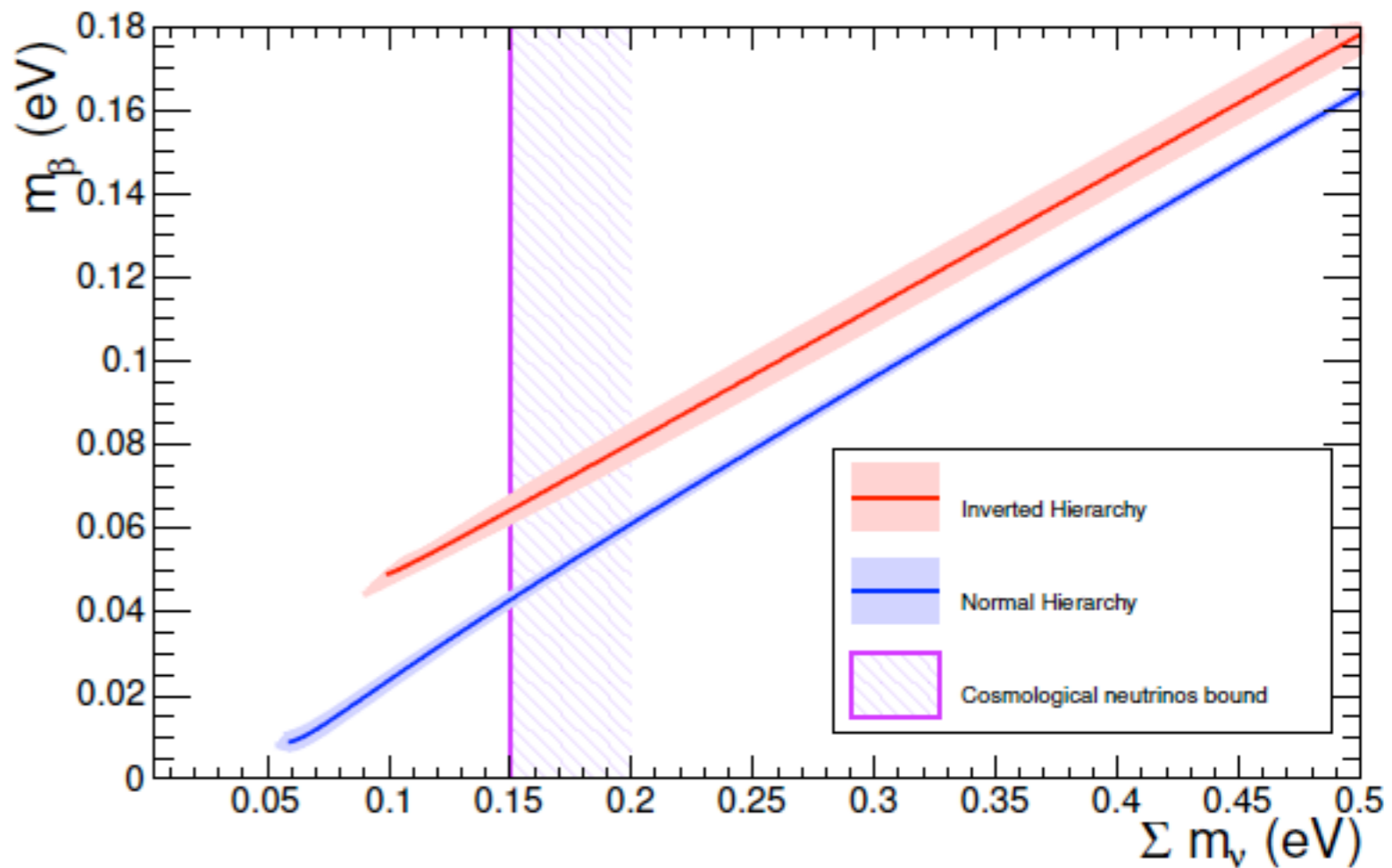
Σm_ν determination



Palanque-Delabrouille et al 2015

(a recent result from KamLAND)

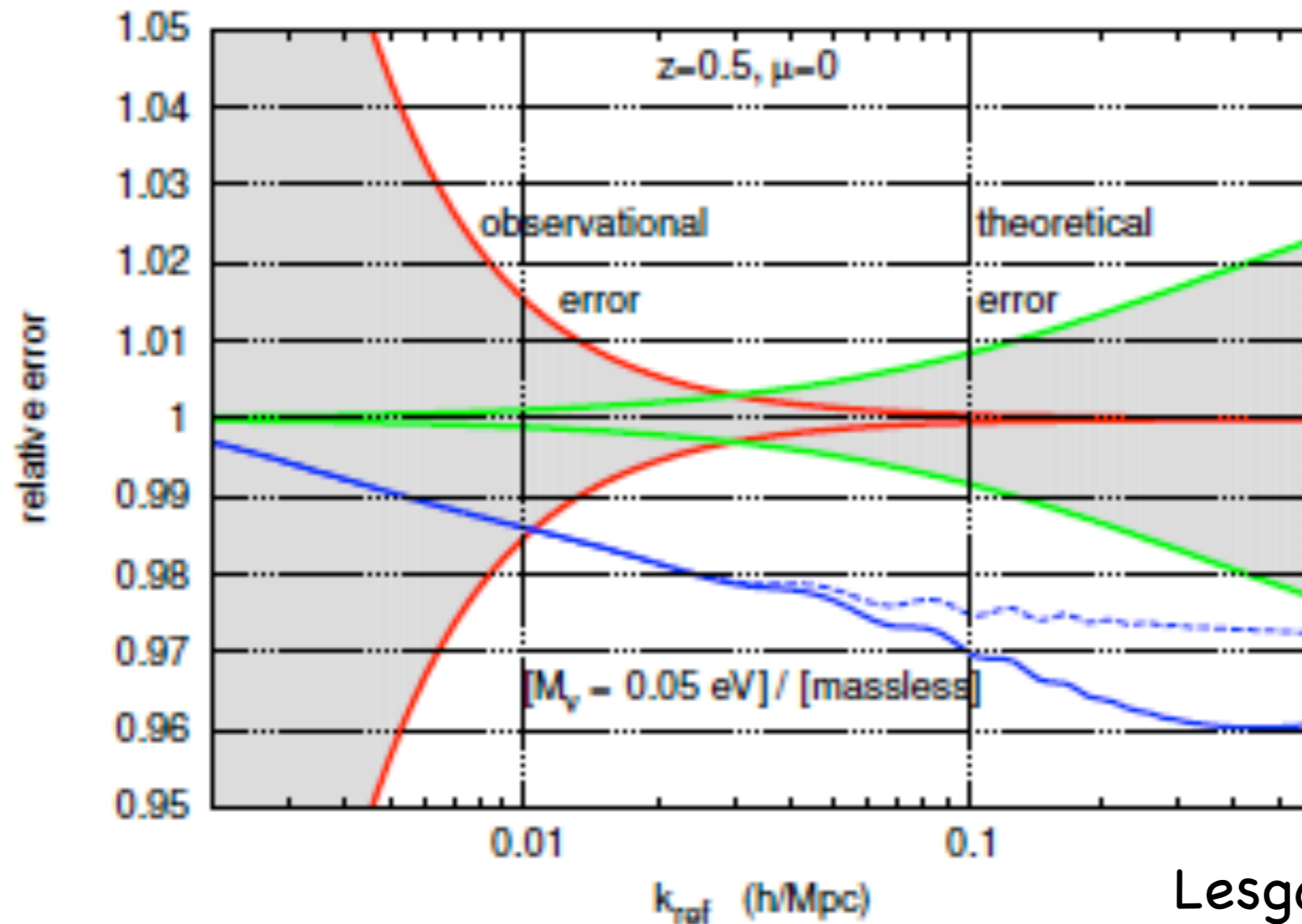
$$m_{\beta\beta} < 0.06 \div 0.16 \text{ eV}$$



Dell'Oro et al 2015

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

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



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	+	-

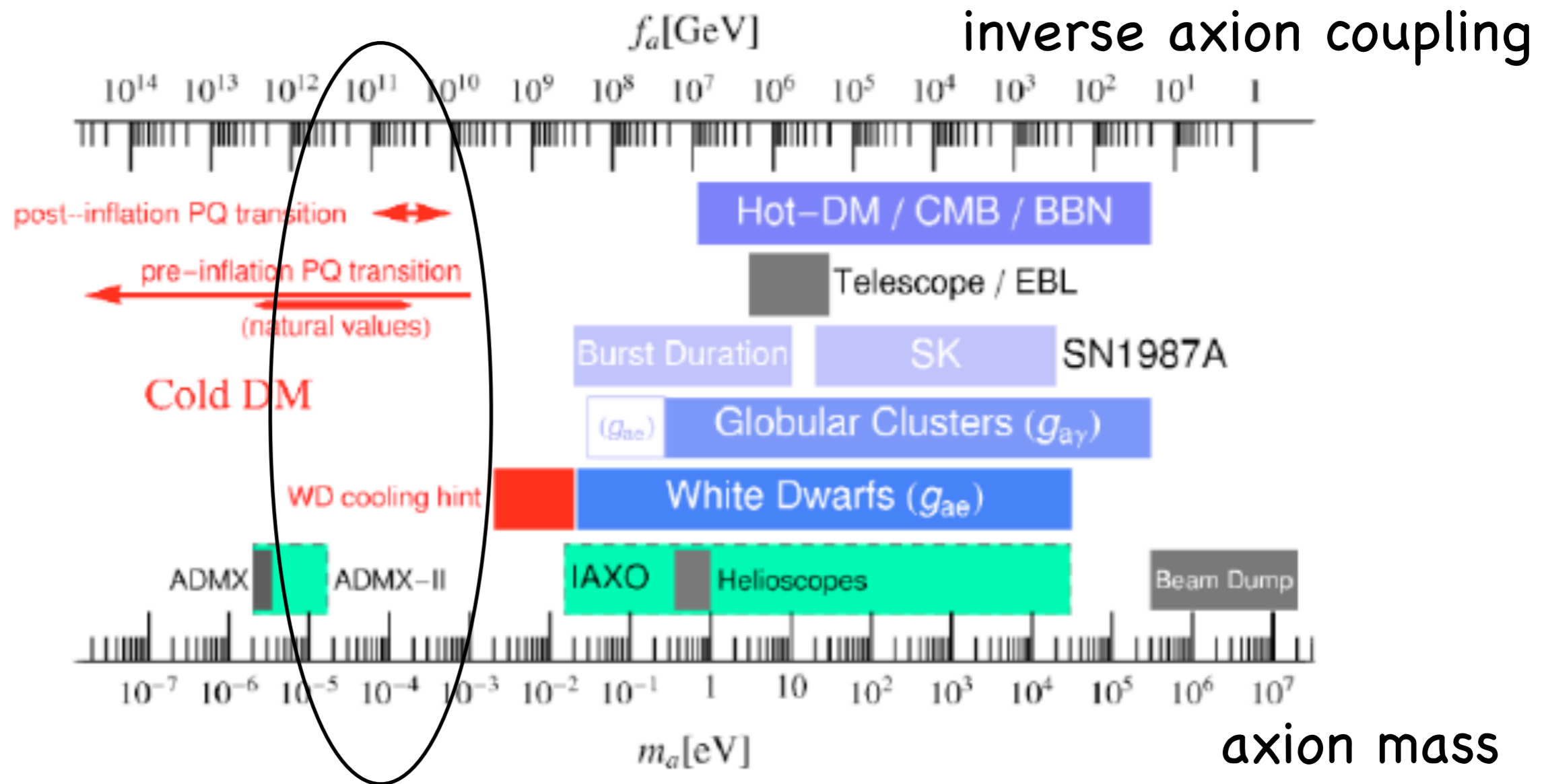
$$|\mu_N^{\vec{N}}| = 2 \cdot 10^{-14} e \cdot cm$$

$$|d_N^{\vec{N}}| \approx \theta \cdot 10^{-15} e \cdot cm$$

$$|d_N^{\vec{N}}|_{exp} < 3 \cdot 10^{-26} e \cdot cm$$

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

The dynamical field, a , is the "axion"



Olive et al, 2104

and is very intensively searched for
(with the most interesting region still inaccessible)

The coupling of the axion to spin

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

$$g_p \approx \frac{m}{f_a} \quad \left(g_s = 10^{-(12 \div 17)} g_p \frac{GeV}{m} \right) \quad \text{DFSZ}$$

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

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

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

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

$$\lambda_d \simeq h/(m_a v_a) \simeq 13.8 (10^{-4} \text{eV}/m_a) \text{ m} \quad \Delta\omega_a/\omega_a \simeq 5.2 \times 10^{-7}$$

$$\langle \mathbf{p}_E \rangle = m_a (\mathbf{v}_S + \mathbf{v}_O + \mathbf{v}_R)$$

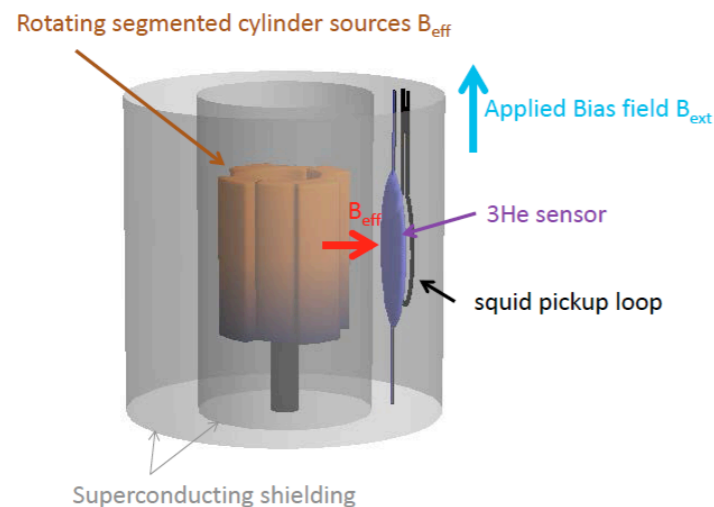
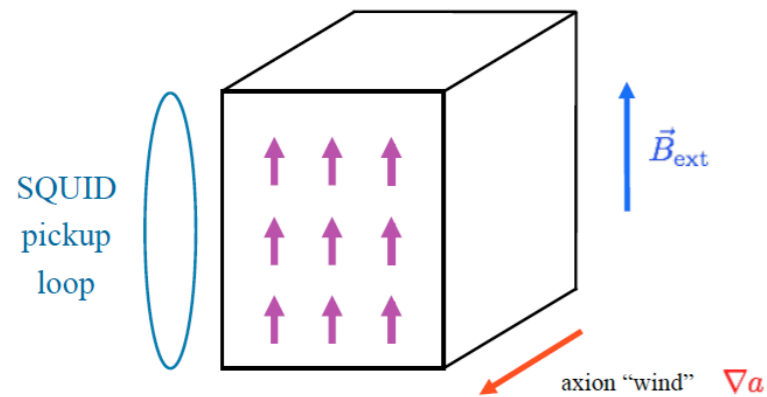
Proposed experiments using NMR/EMR

CASPER axion wind/NMR

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

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

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



static source NMR

not limited in frequency
but size of the effect smaller

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

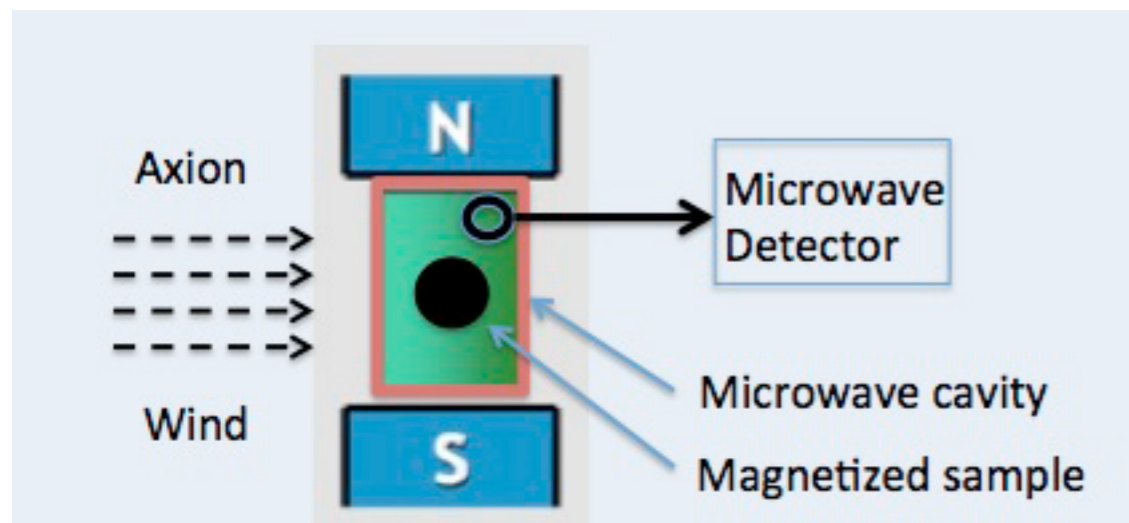
$$B_{eff}/T \lesssim 10^{-23} \quad M_T/T \lesssim 10^{-20}$$

QUAX axion wind/EMR

frequency OK

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

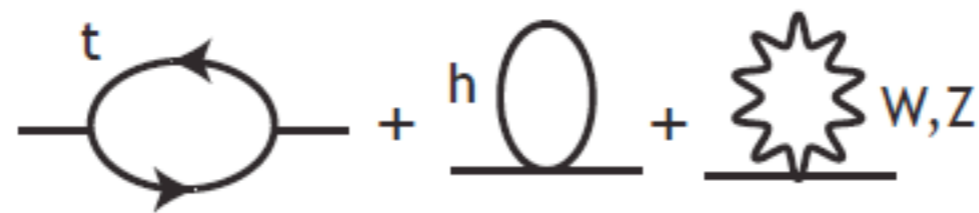
$$B_{eff}/T \approx 10^{-22} \quad M_T/T \approx 10^{-21}$$



3 The hierarchy problem, once again

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

NOT in the SM



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

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

$1/\Delta$ = amount of tuning

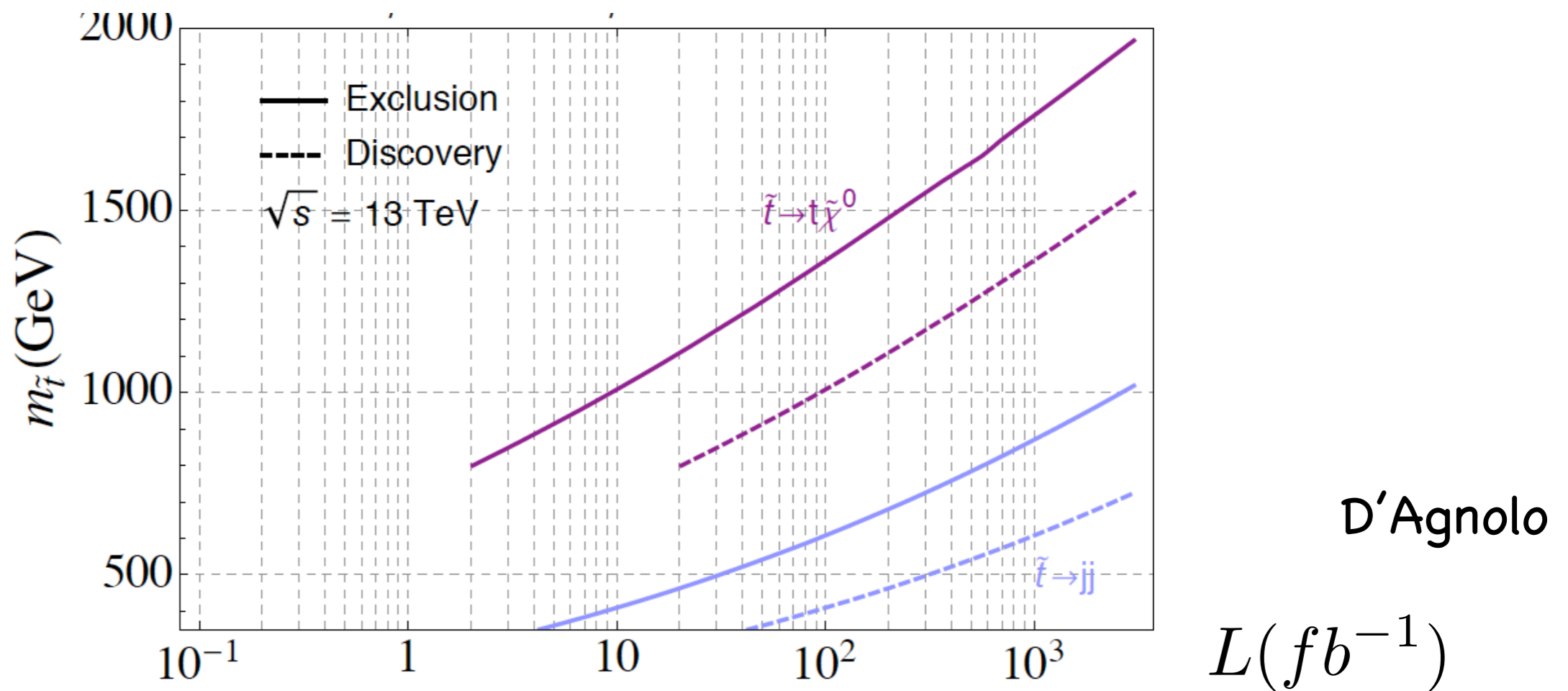
⇒ Look for a top "partner" (coloured, $S=0$ or $1/2$) with a mass not far from 1 TeV

MSSM

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

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

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

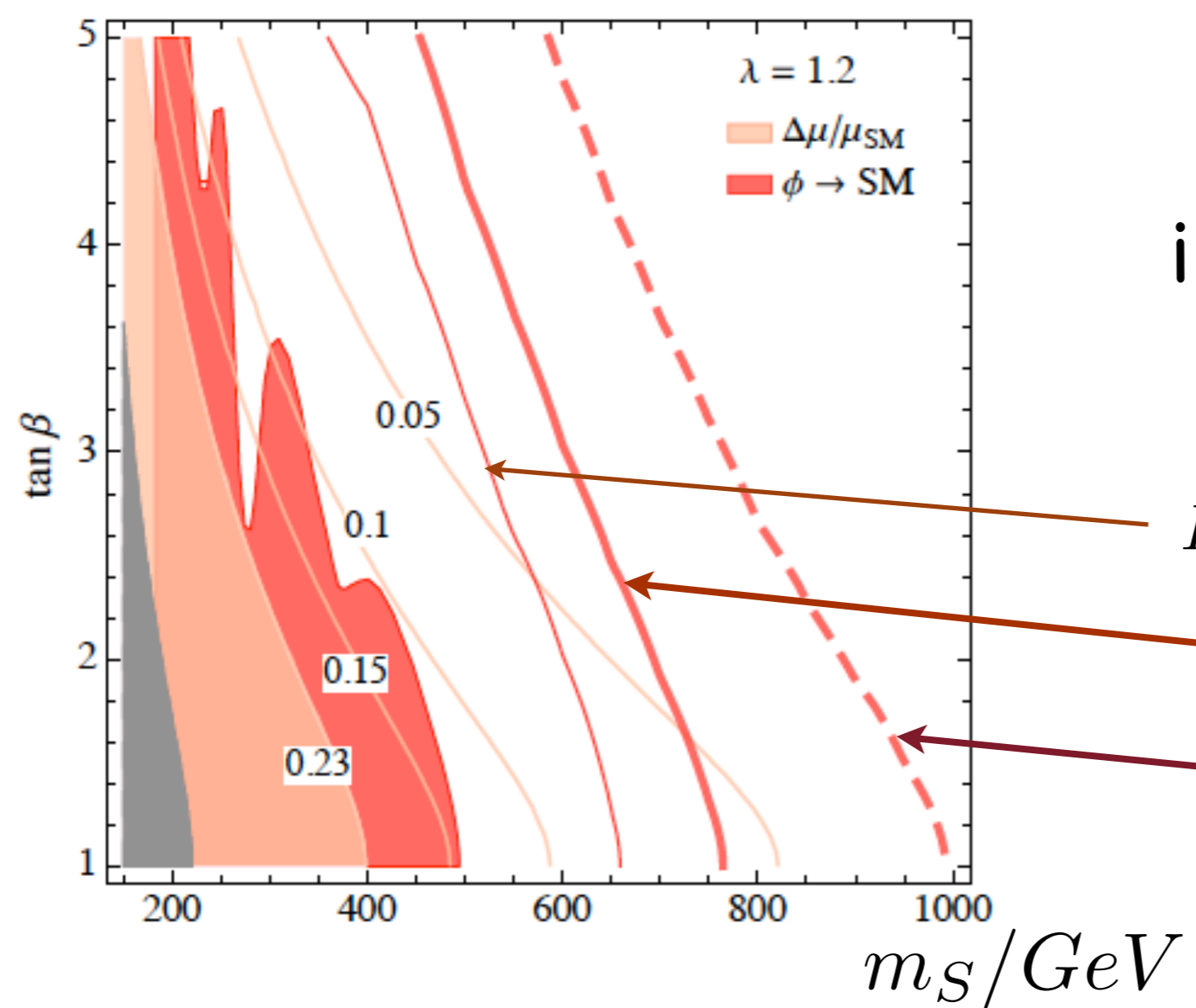


Direct searches explore $\Delta_v \gtrsim 100 \div 1000$

NMSSM ($\lambda S H_u H_d$)

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

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

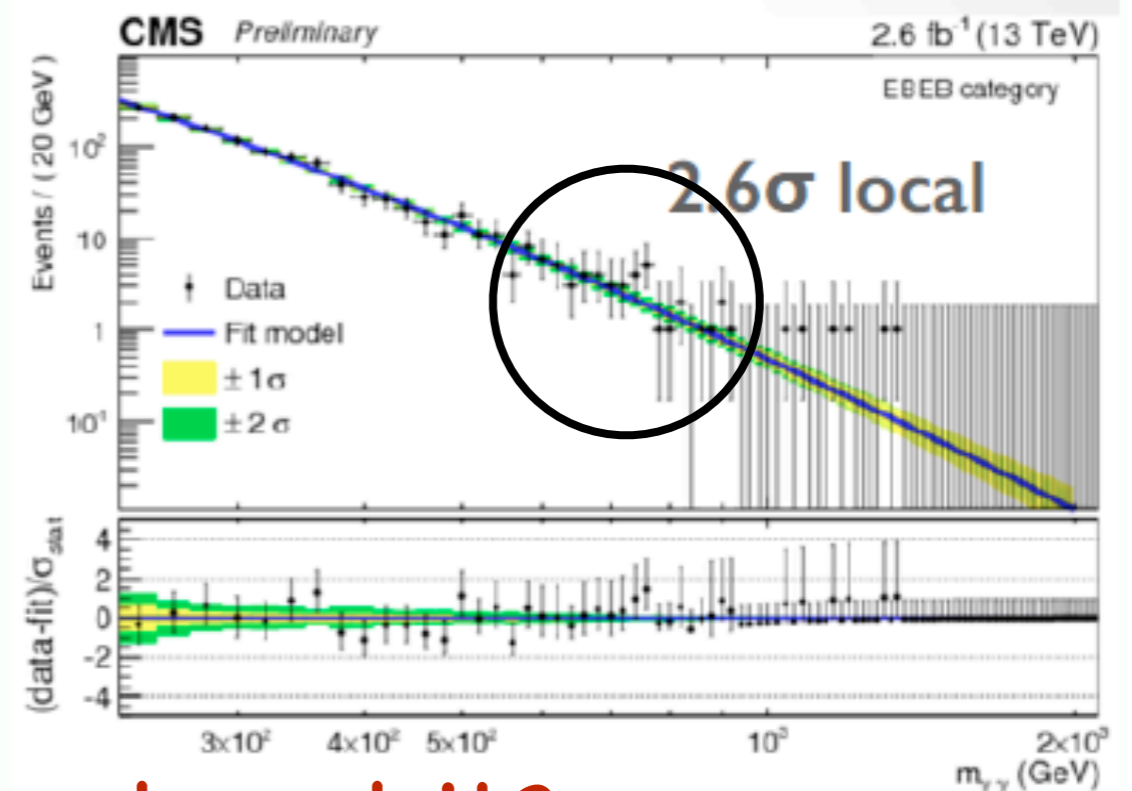
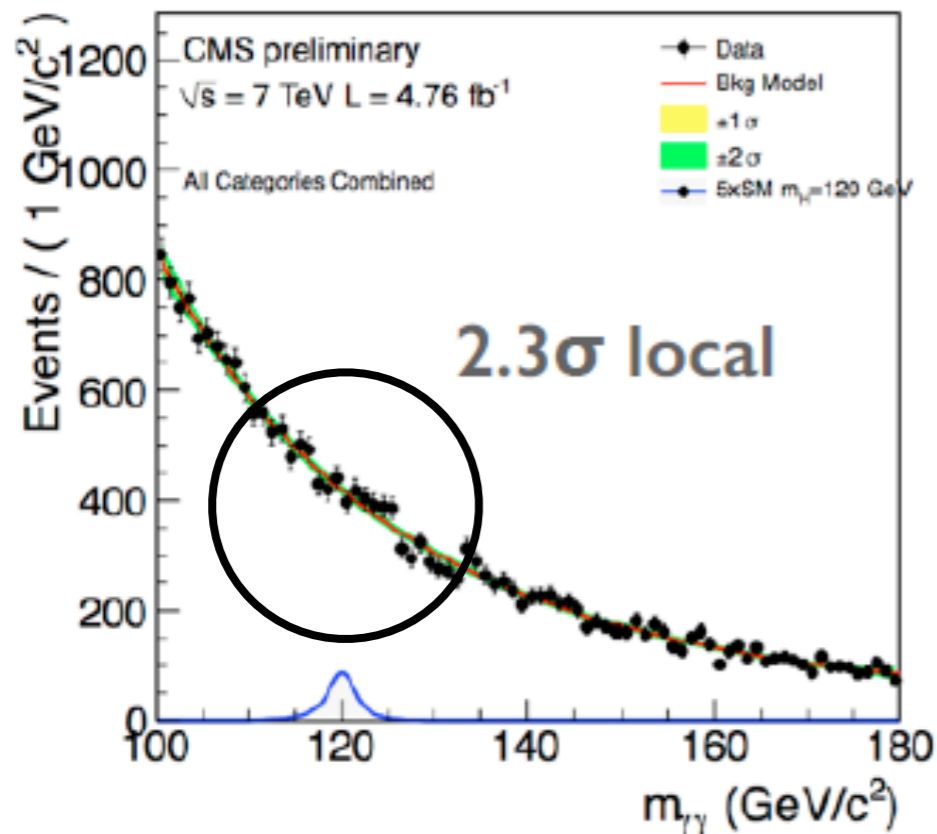
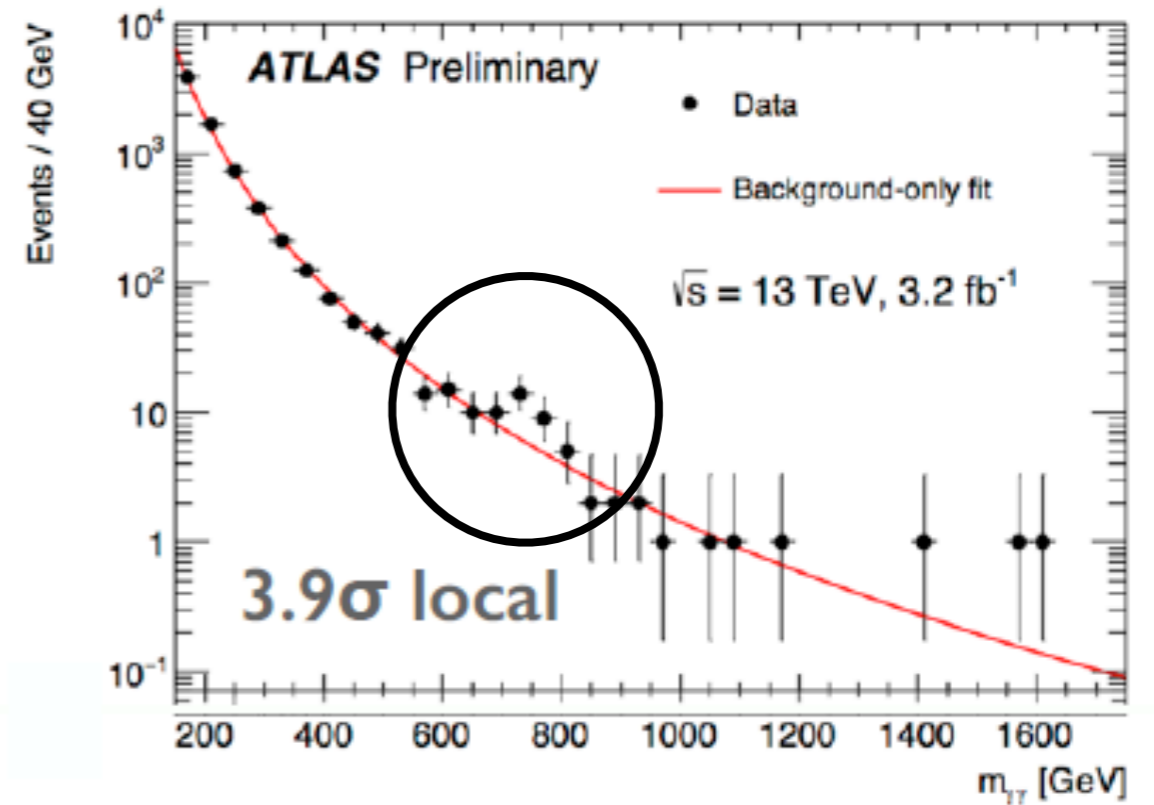
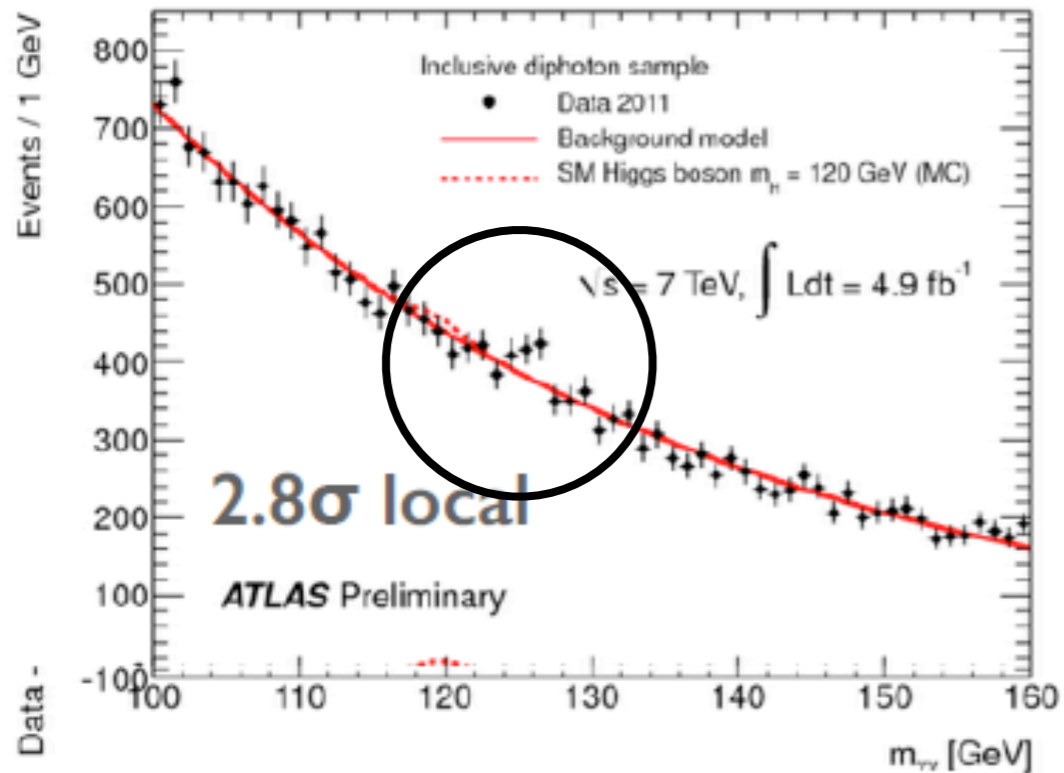


Direct searches, including extra scalars explore $\Delta_v = 10 \div 100$

Only one scalar: the Higgs boson?

Dec 2011

Dec 2015



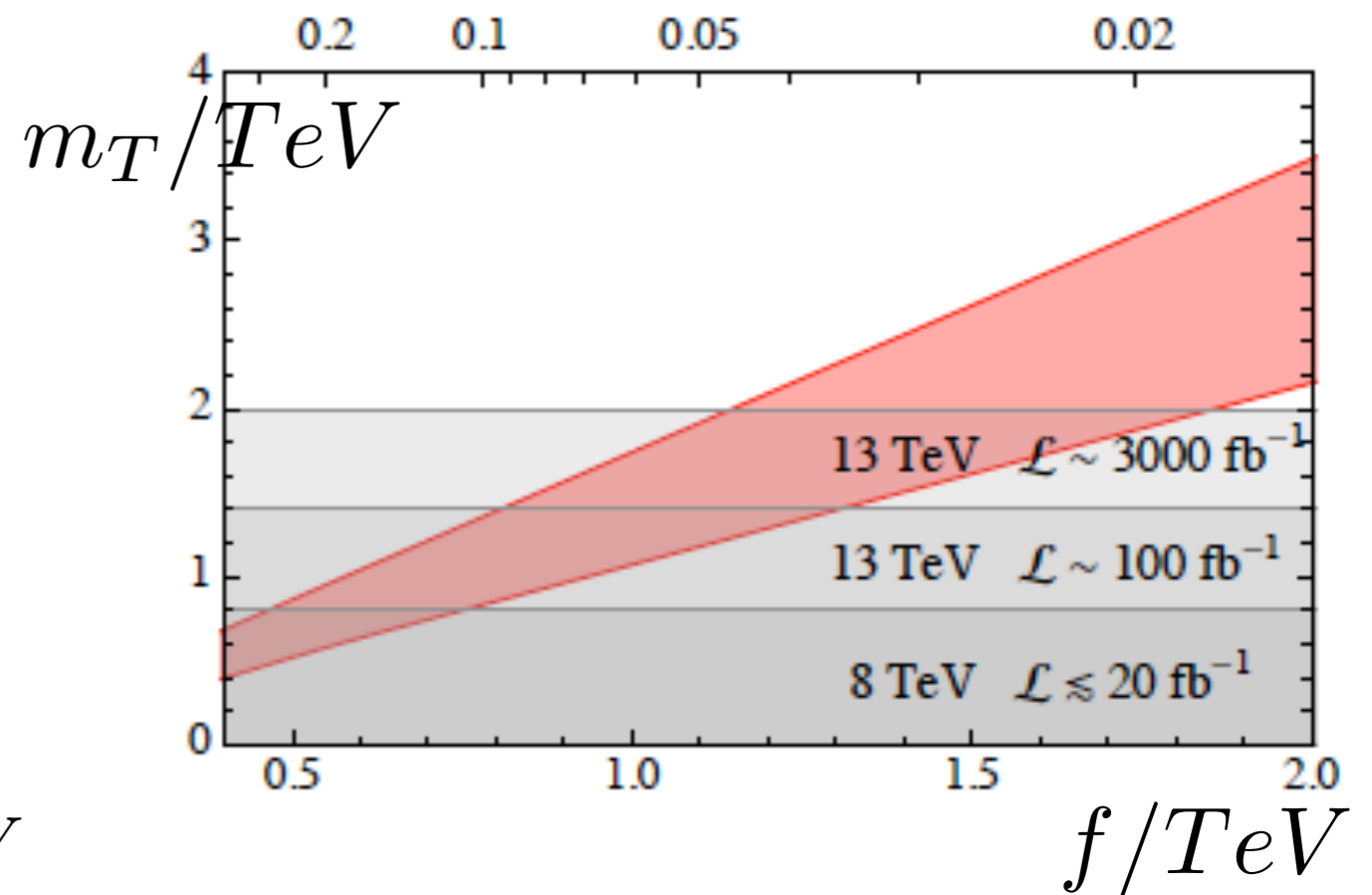
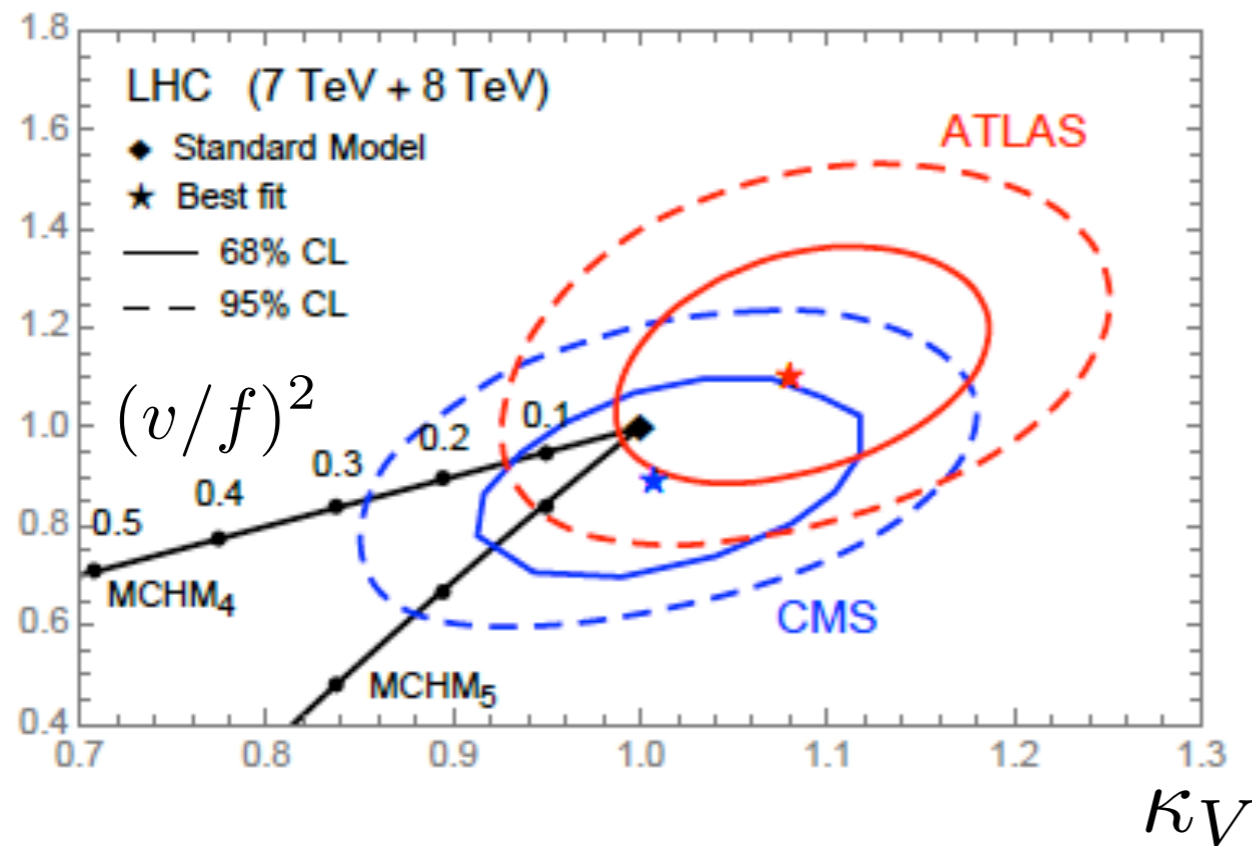
If real, who ordered it?

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

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

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

κ_F

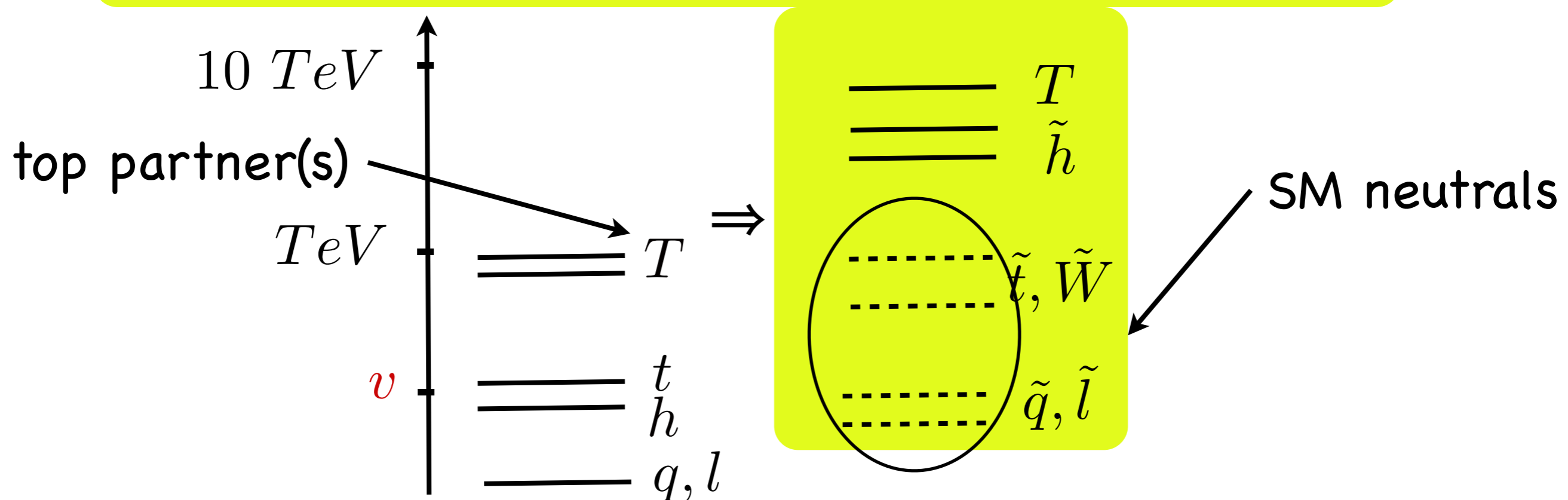


Higgs precision (left) and direct searches (right, single and double T prod.)

explore $\Delta_v = 10 \div 100$

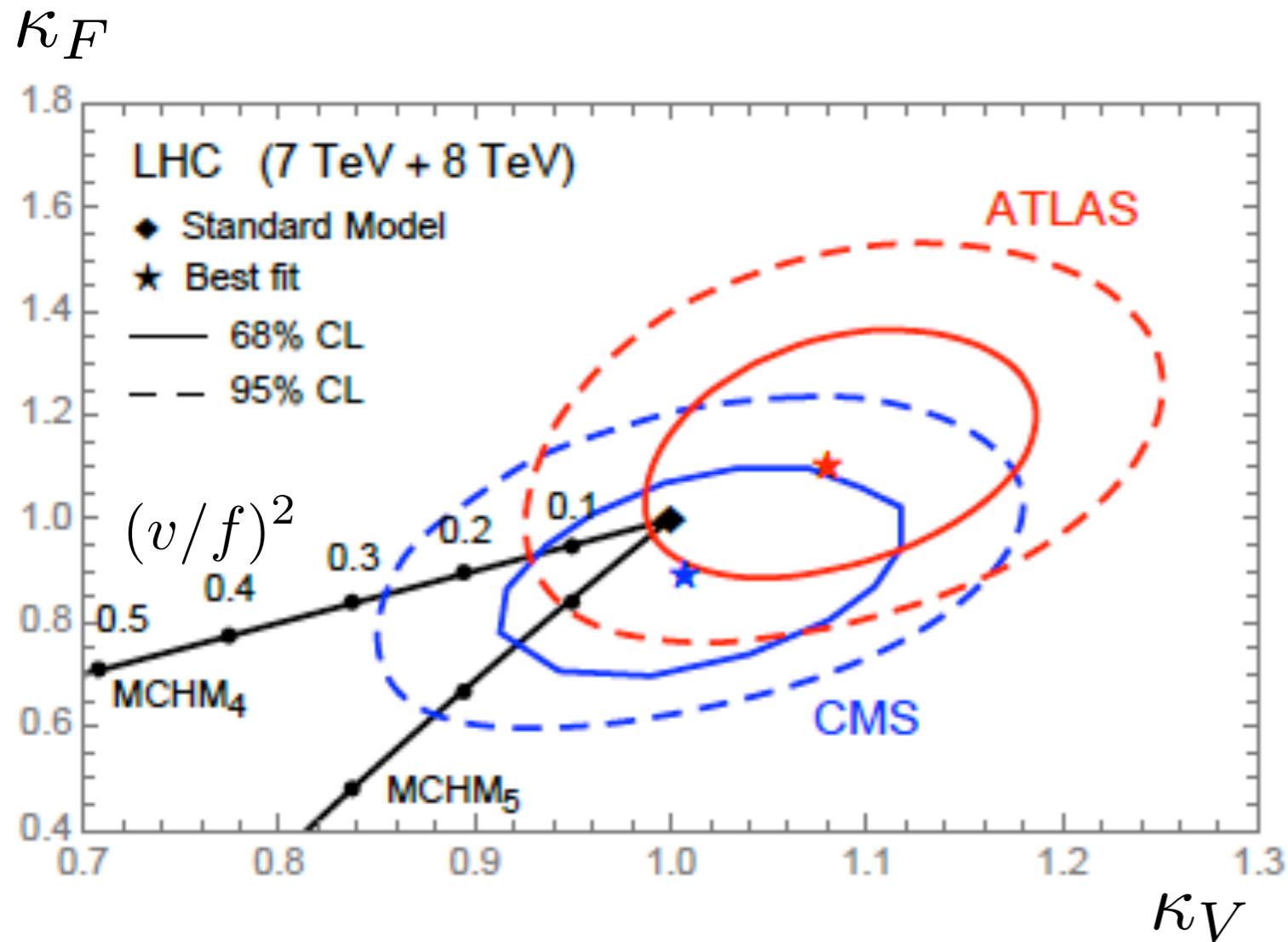
Are there any “strictly natural” theory compatible with current data?

- 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

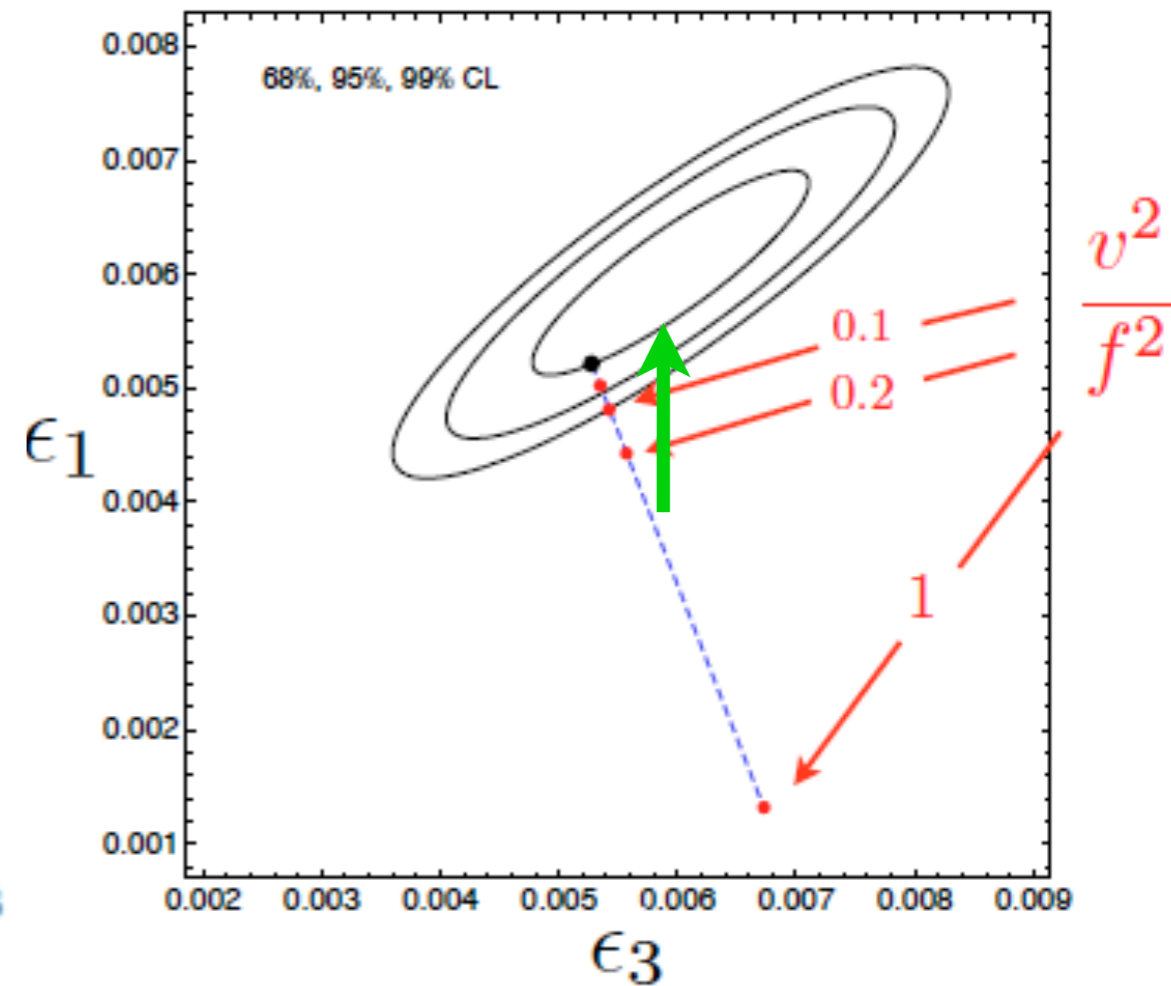


$$v \longrightarrow f \quad \Delta_{v/f} = (f/v)^2$$

Precision can be the only signal generic of a composite (Twin) Higgs



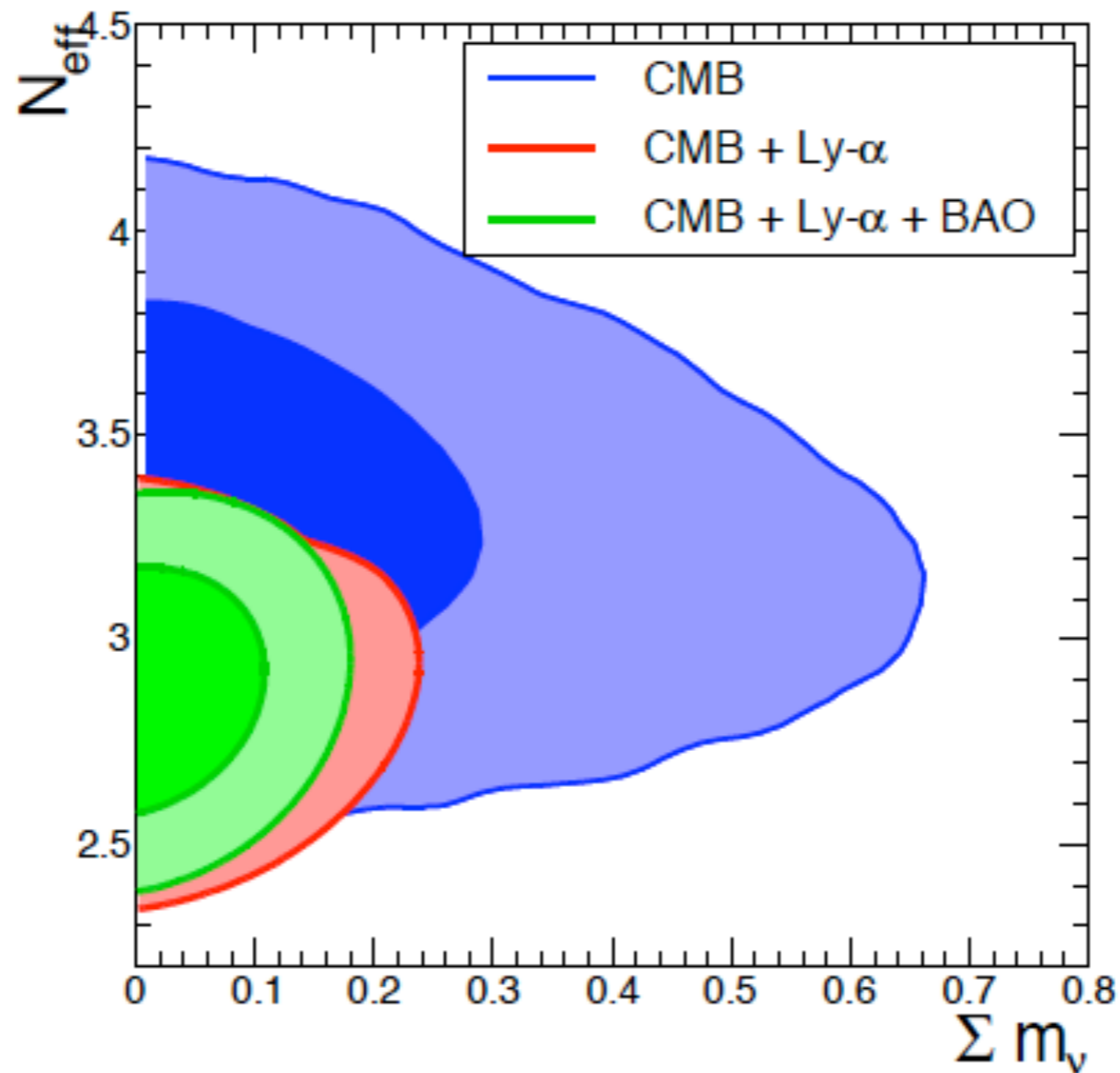
Higgs precision



EWPT

A problem for twin Higgs

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



Rossi et al 2015

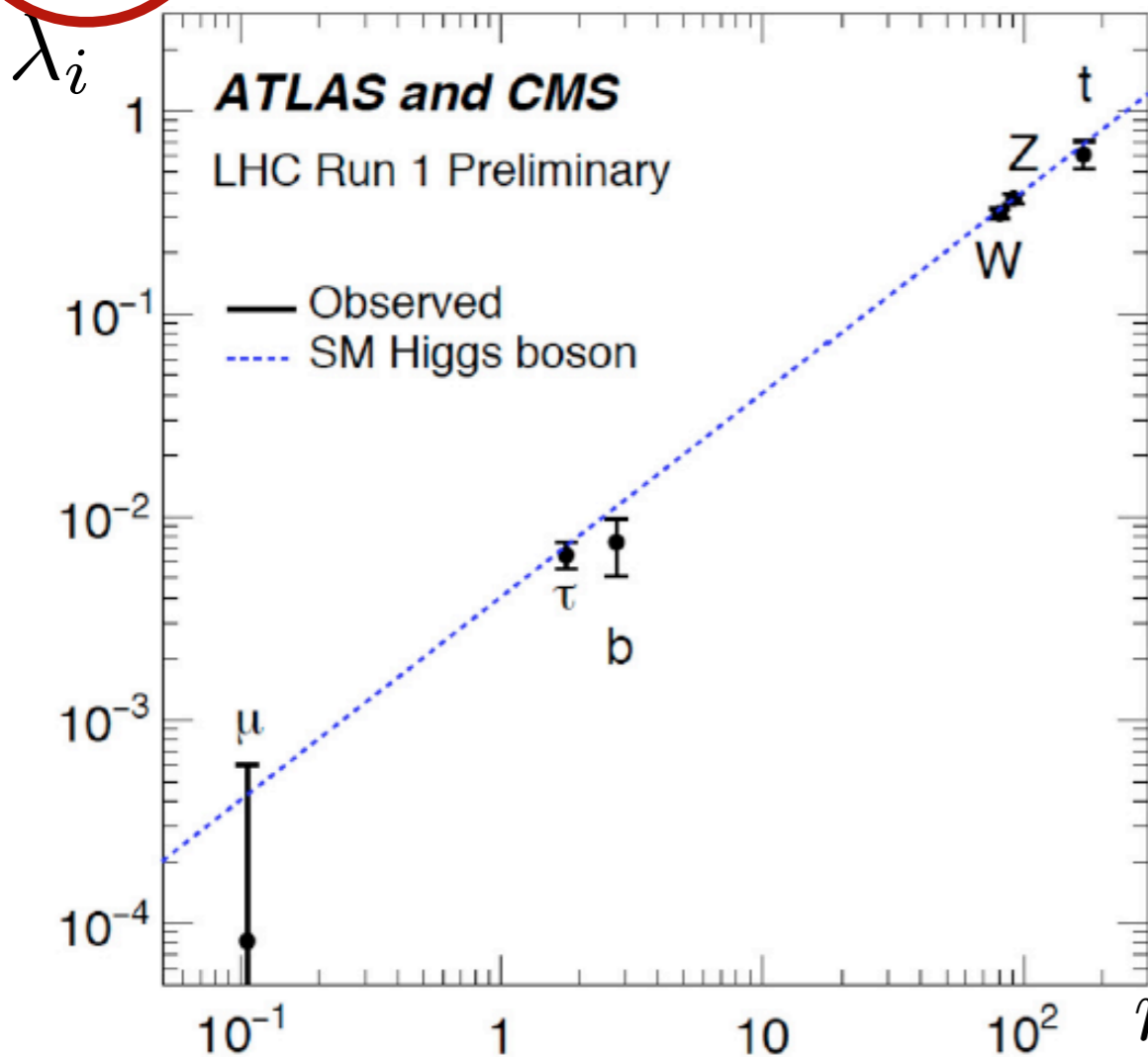
Need a reheating of the SM sector below $T_{dec} = 1 \div 5 \text{ GeV}$

B, Hall, Gregoire 2005

4

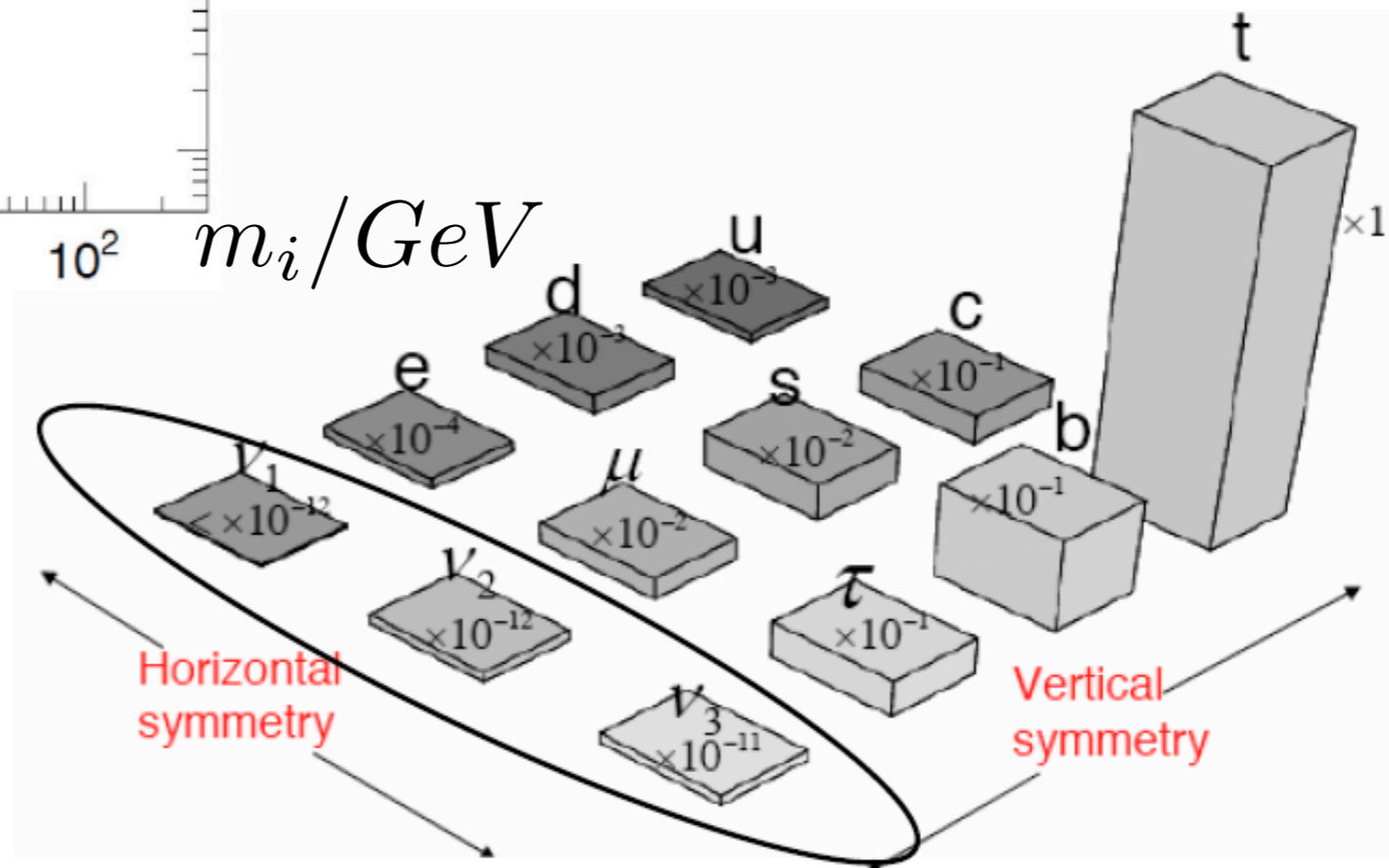
The flavour paradox

$$\lambda_{ij} \Psi_i \Psi_j h$$



$$m_i = \lambda_i \langle h \rangle$$

a piece of physical reality since 2012 (at least)



as opposed to:

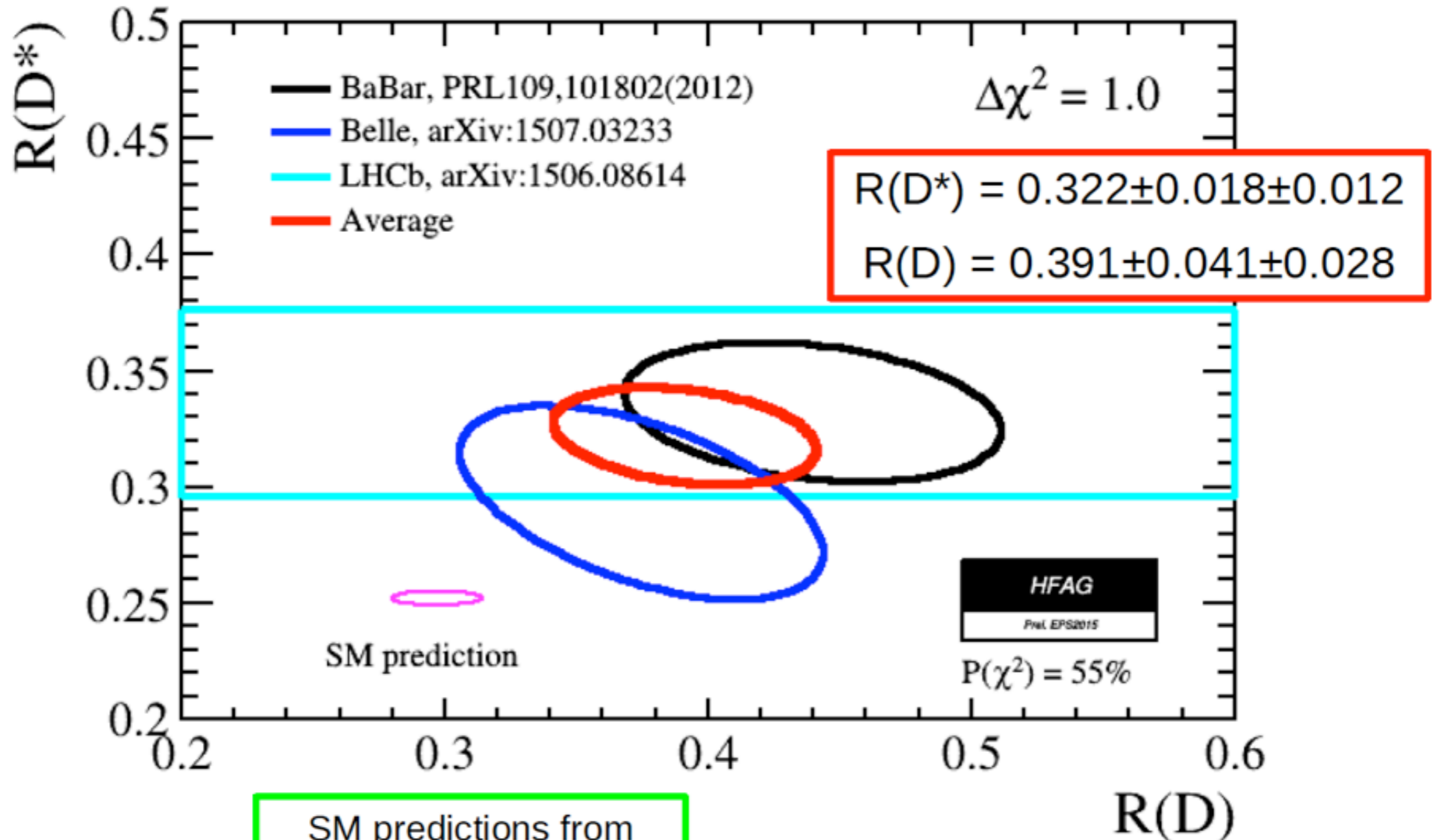
?!?!?

Not easy to improve without observed deviations from the SM

A deviation from the SM in flavour, finally?



Tension with SM at 3.9σ



SM predictions from
PRD 85 (2012) 094025

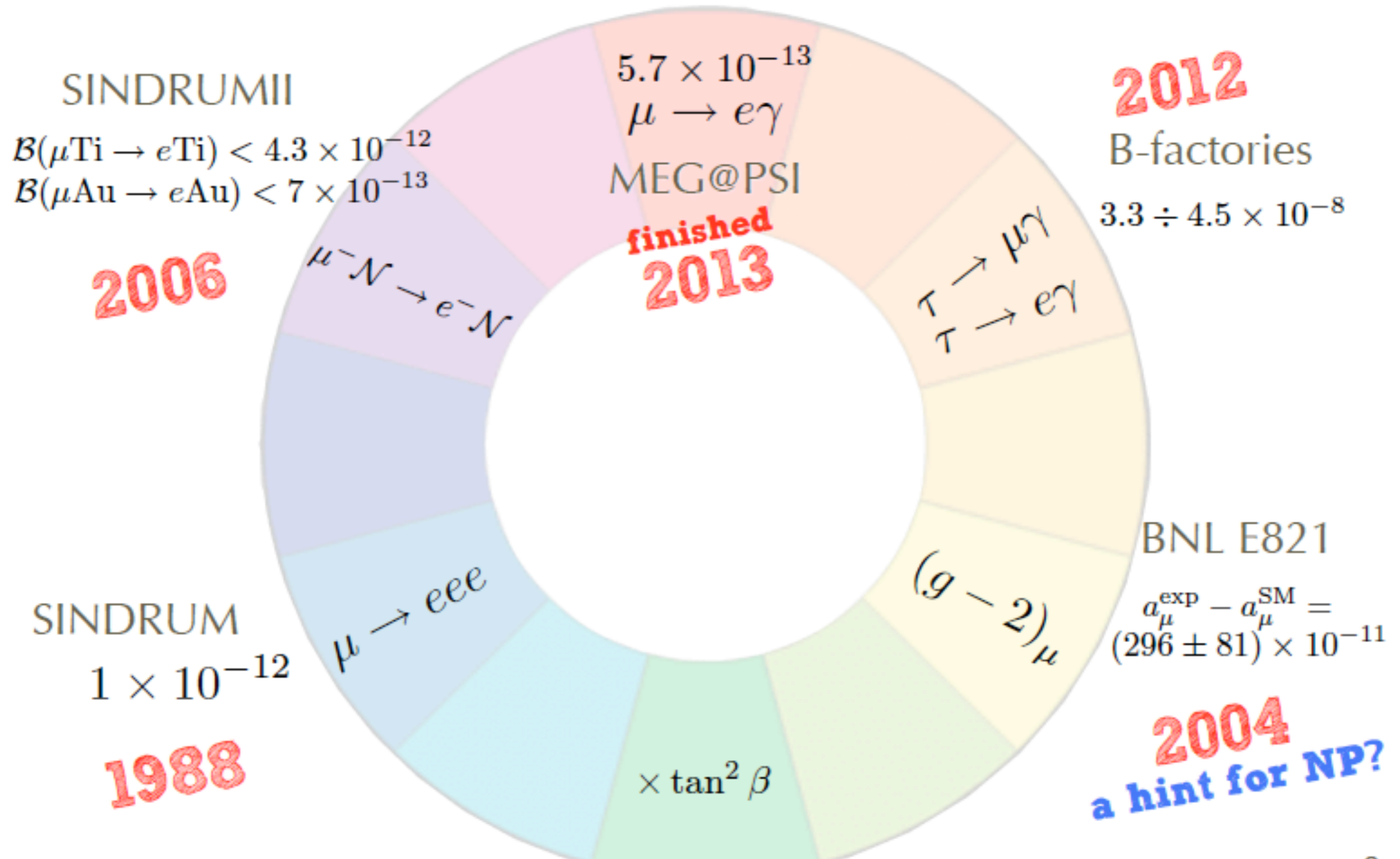
An “Extreme Flavour” experiment?

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 $L=10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Motivation: test CKM (FCNC loops)
from $\approx 20\%$ to $\approx 1\%$

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

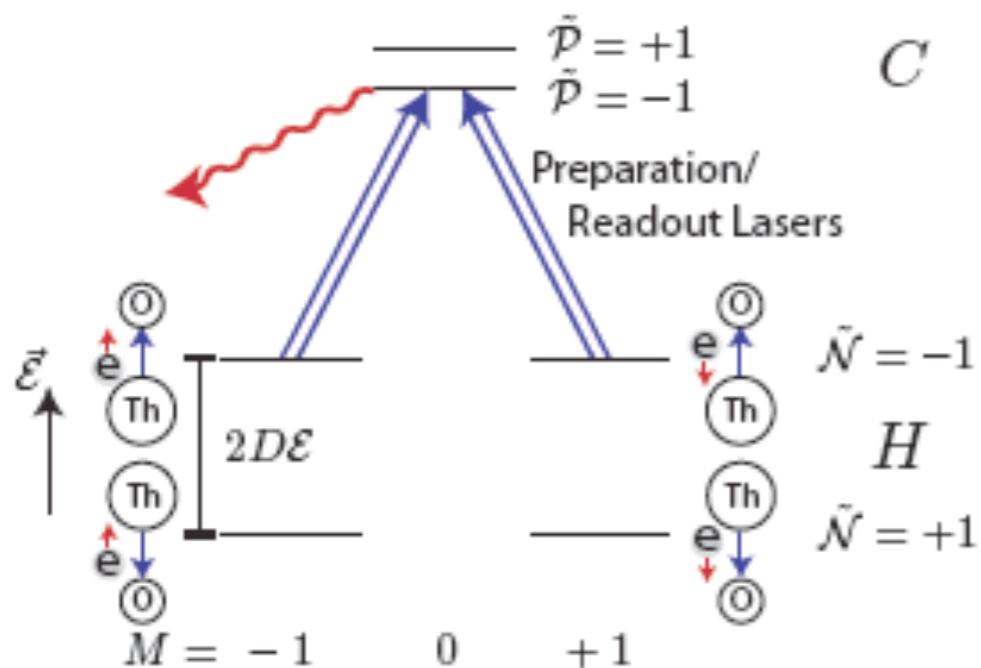
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Electric Dipole Moments

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	$\sim 10^{-31}$ (*)

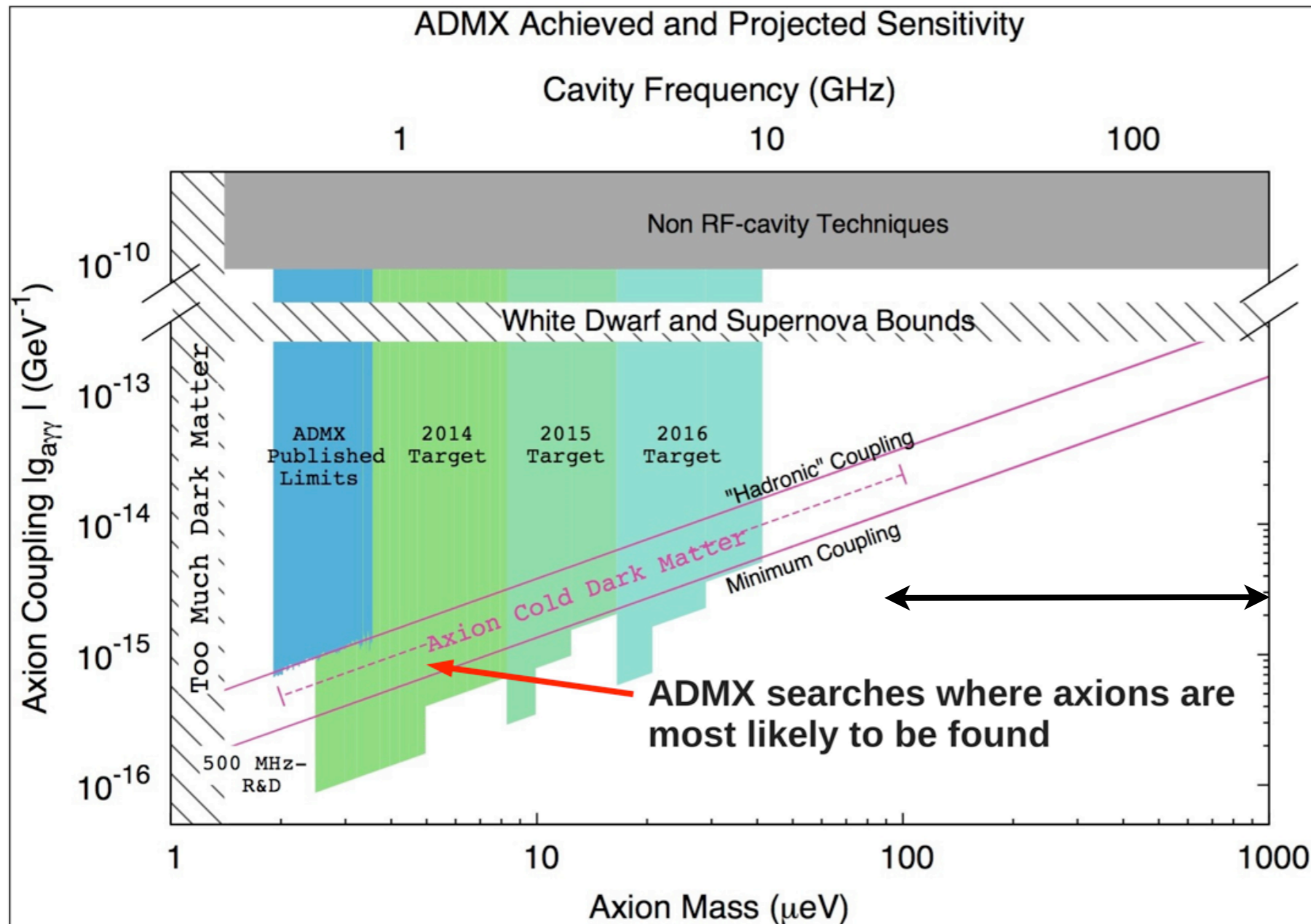
(*) if $\theta \lesssim 10^{-21}$



ACME Collaboration
 Gabrielse (Harvard), DeMille (Yale) et al
 using a polarized ThO molecule

The classic search

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

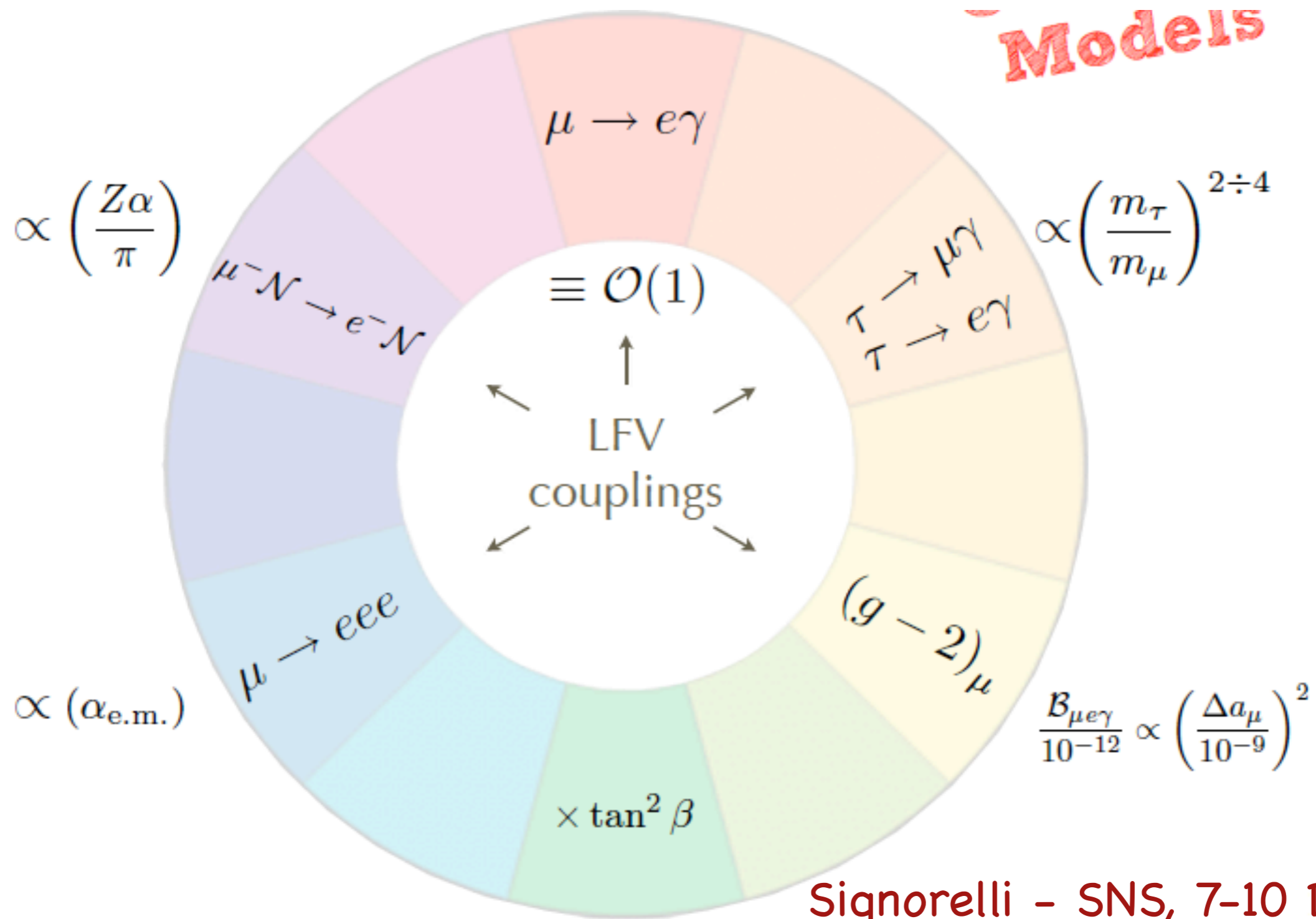


Not easy to explore the most relevant region

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

ADMX

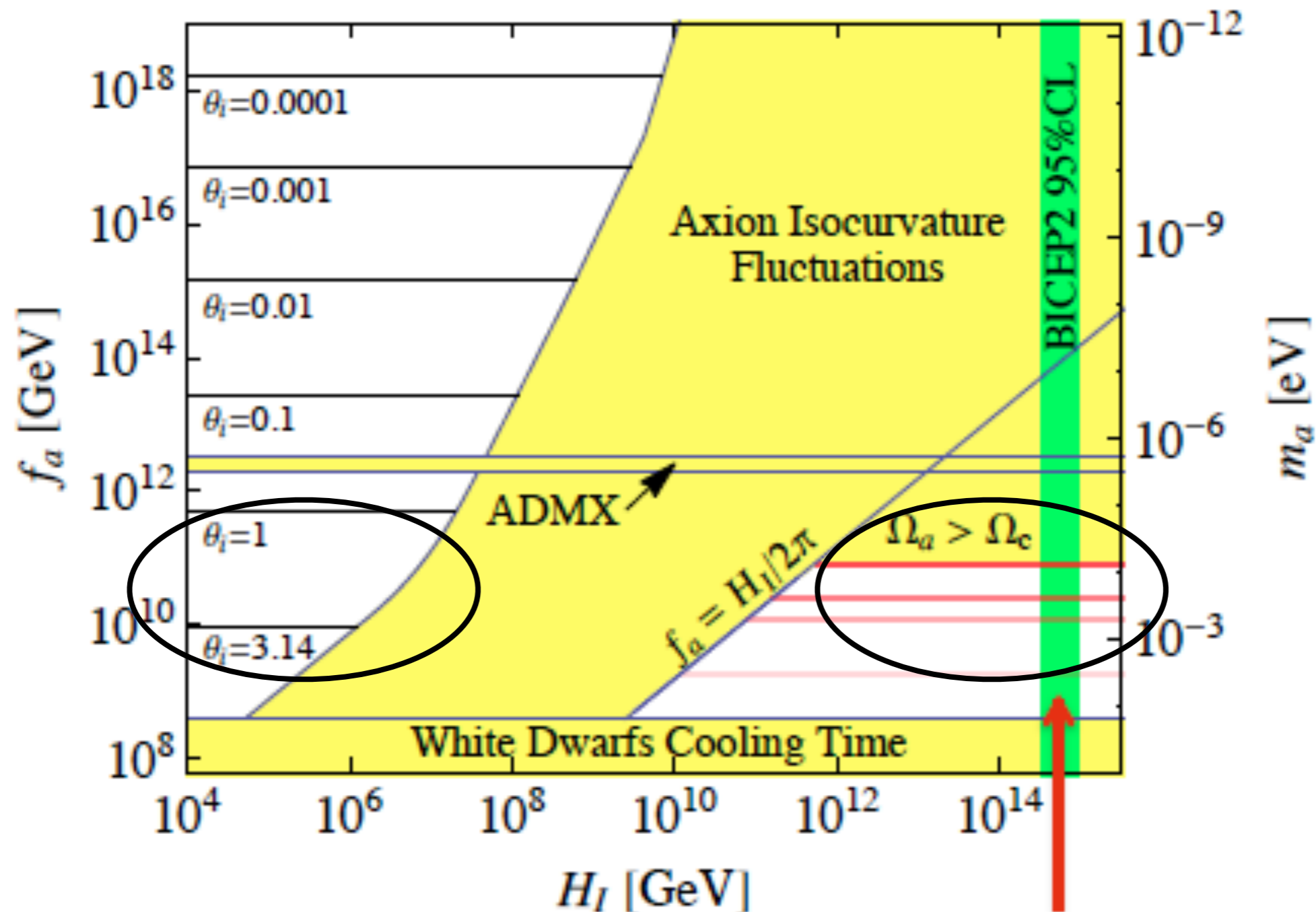
Lepton Flavour Violation



Motivation: extra degrees of freedom + unification

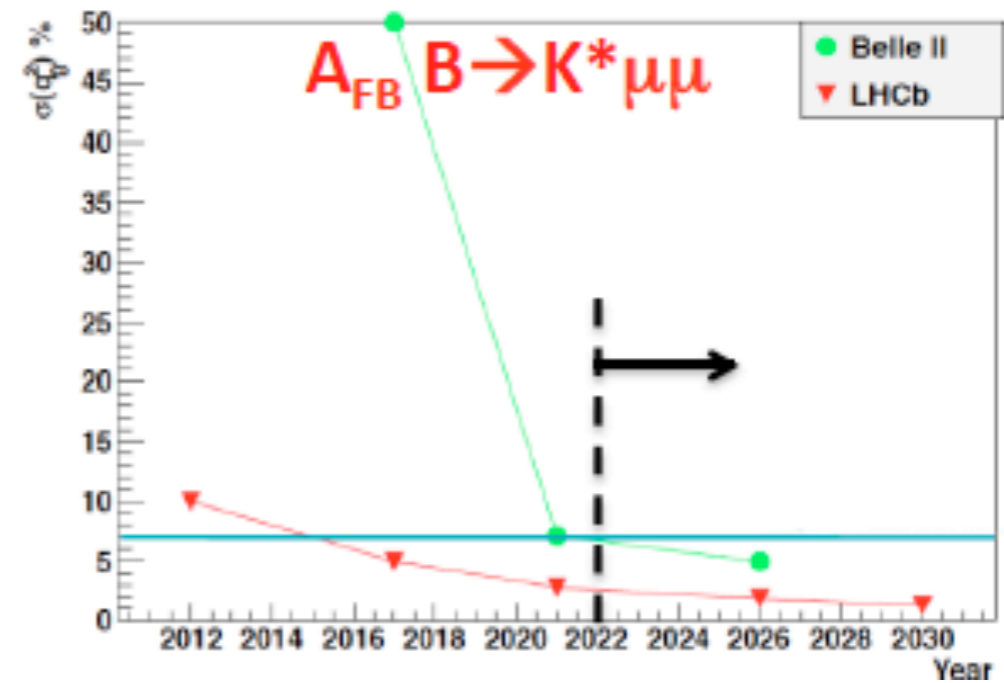
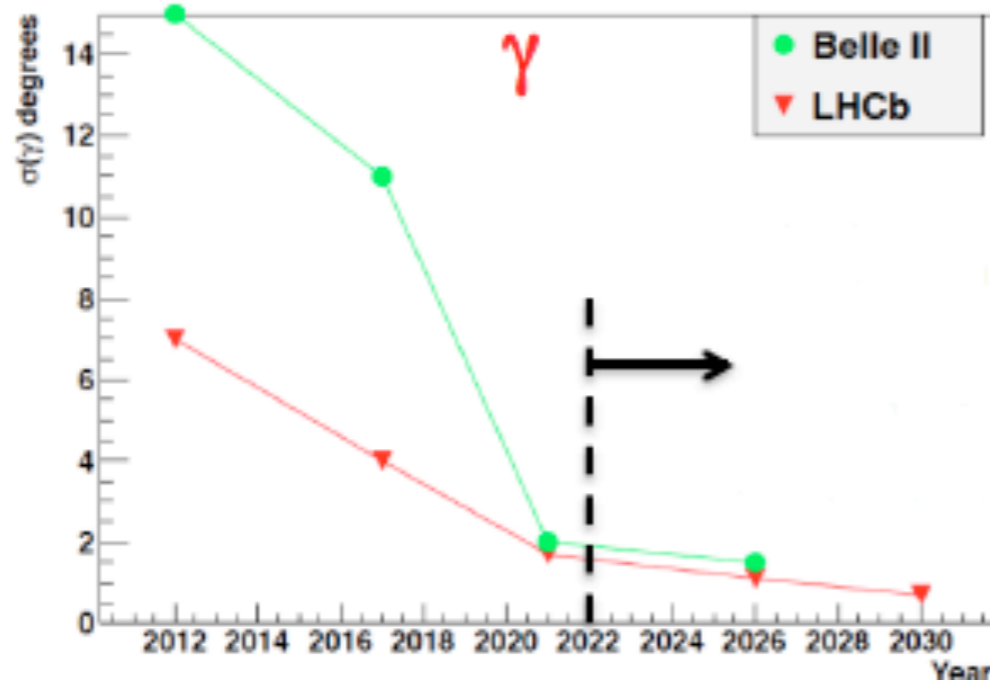
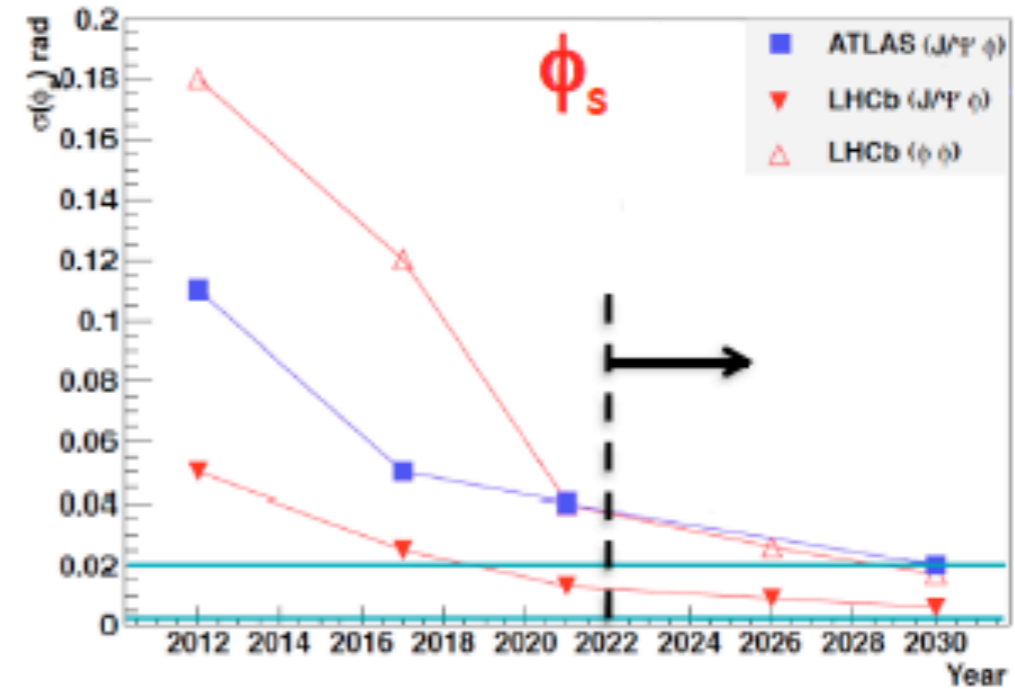
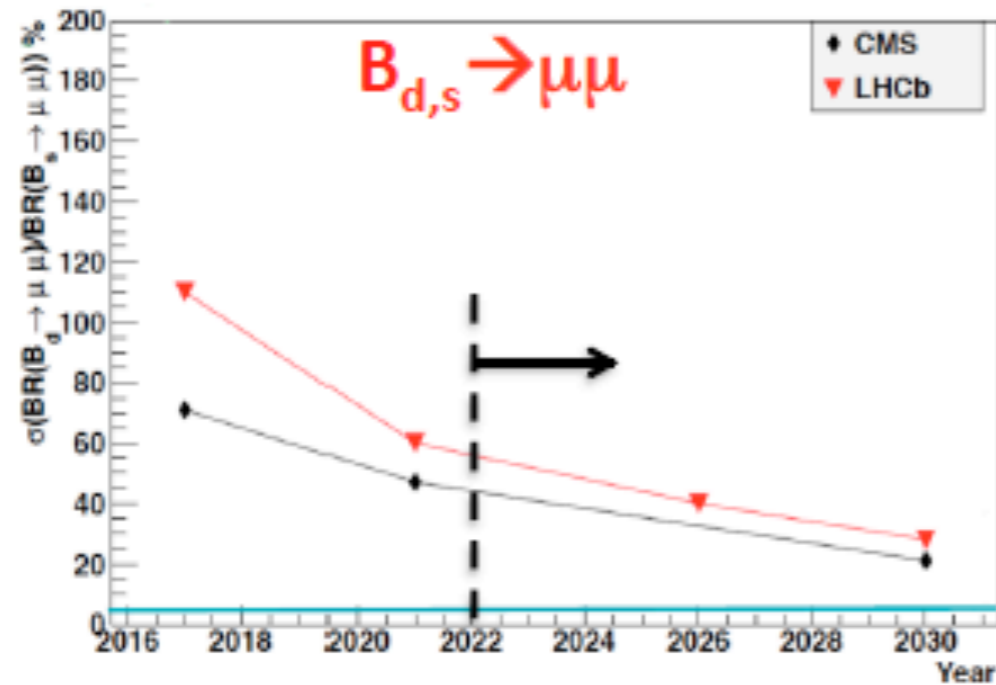
Dark Matter: QCD Axions

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



$m_a = 10^{-5} \div 10^{-3} \text{ eV}$ as the most interesting region

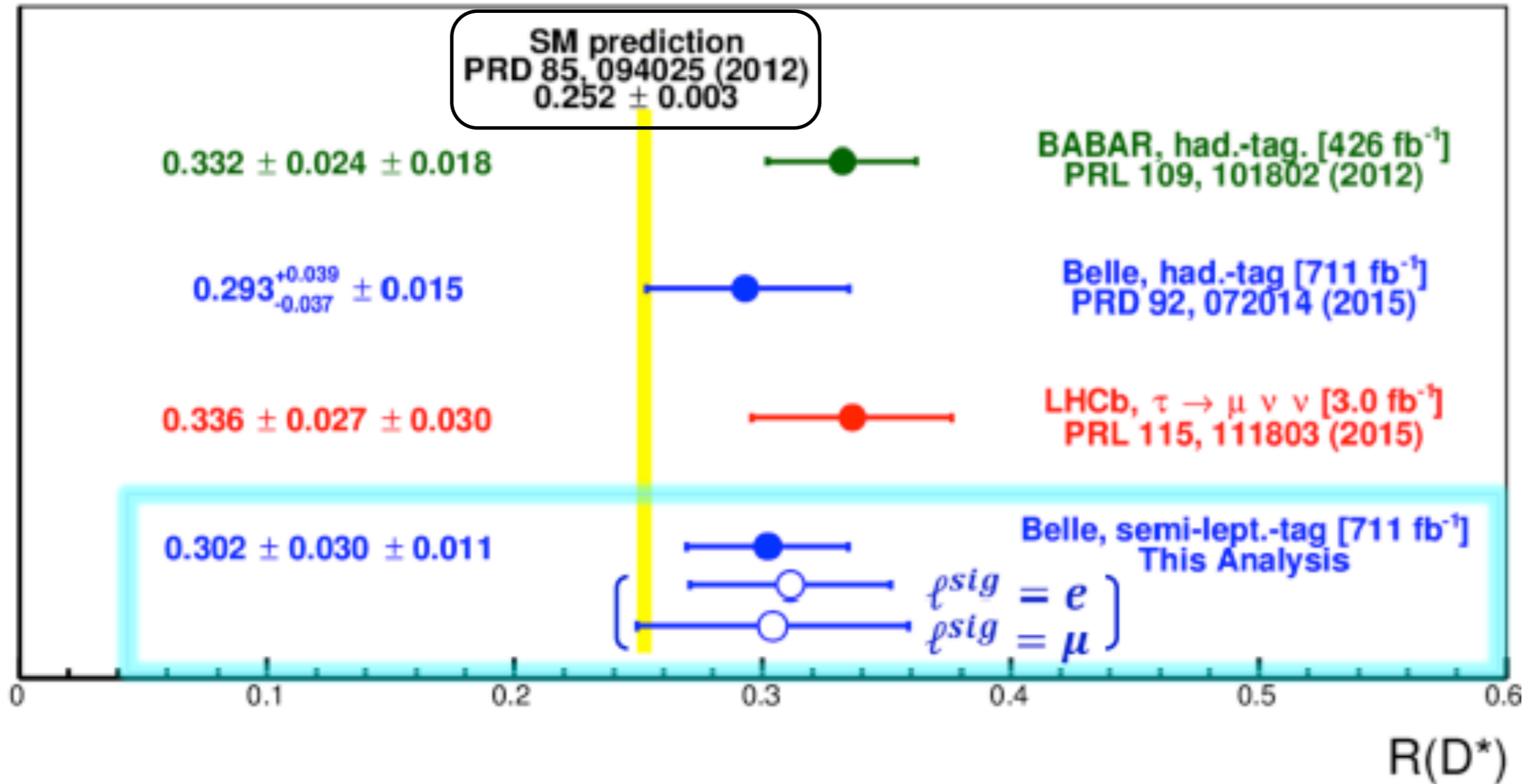
Nice prospects in the quark sector ...



...but flattening out after ~ 2022

A deviation from the SM in flavour, finally?

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

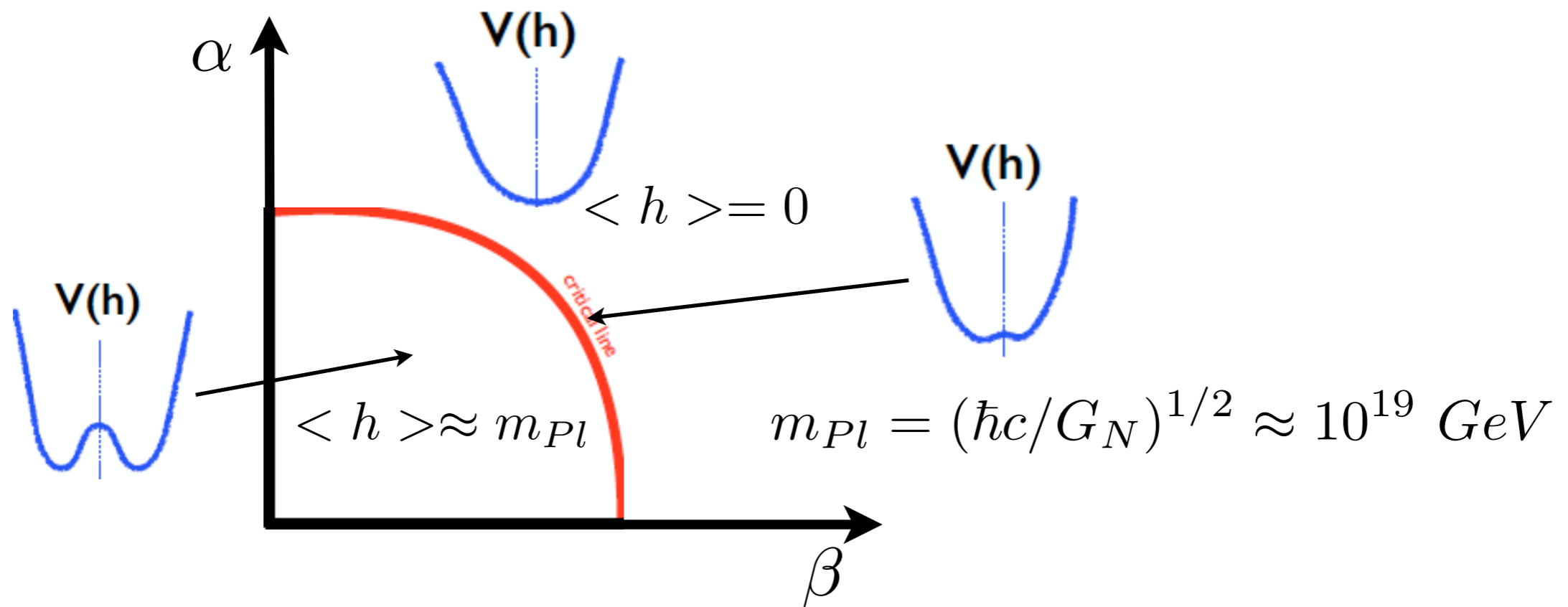


3

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 $\langle h \rangle = 175 \text{ GeV}$, as observed, we have to live very very close to the critical line

But we don't have knobs!

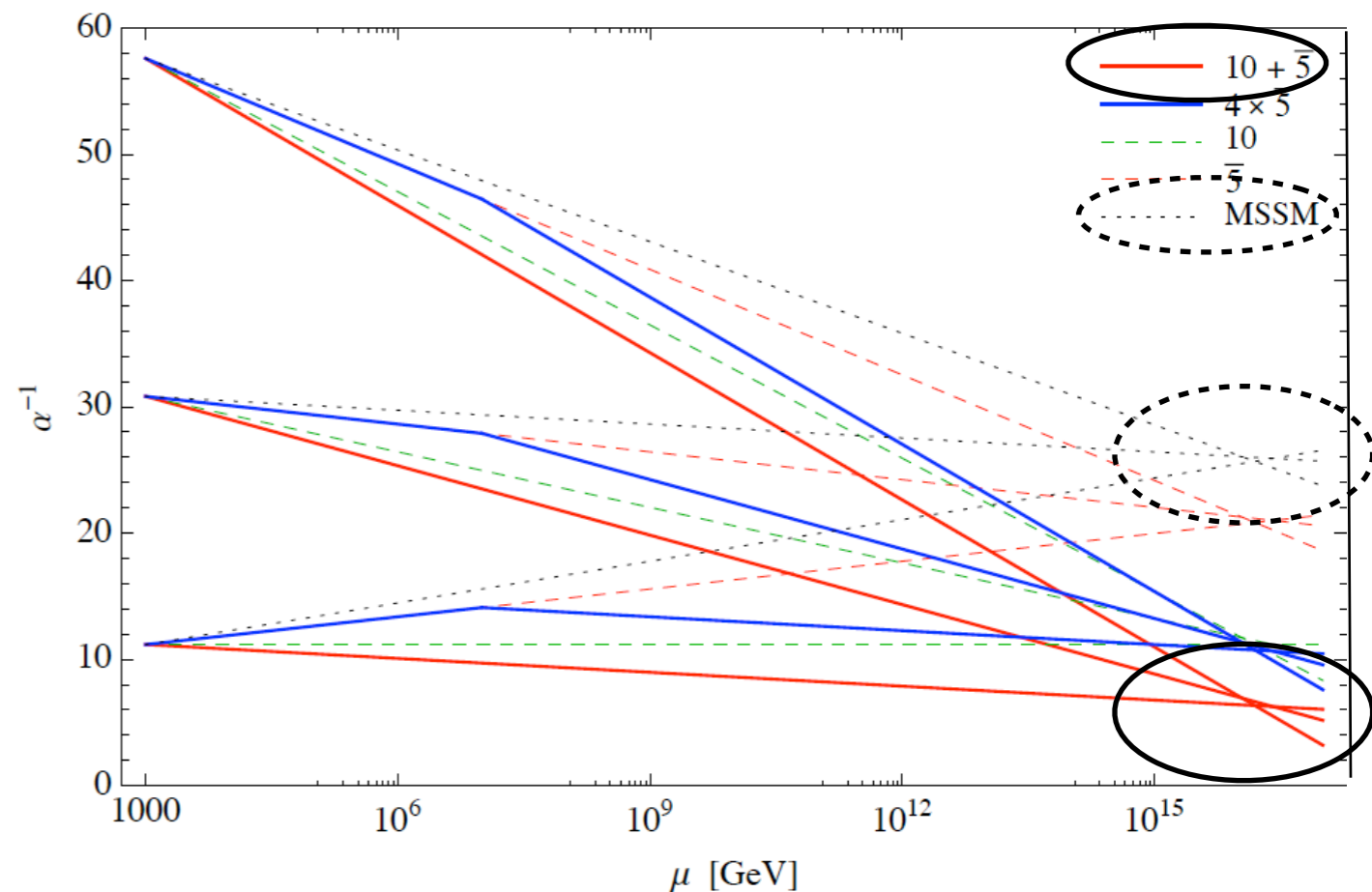
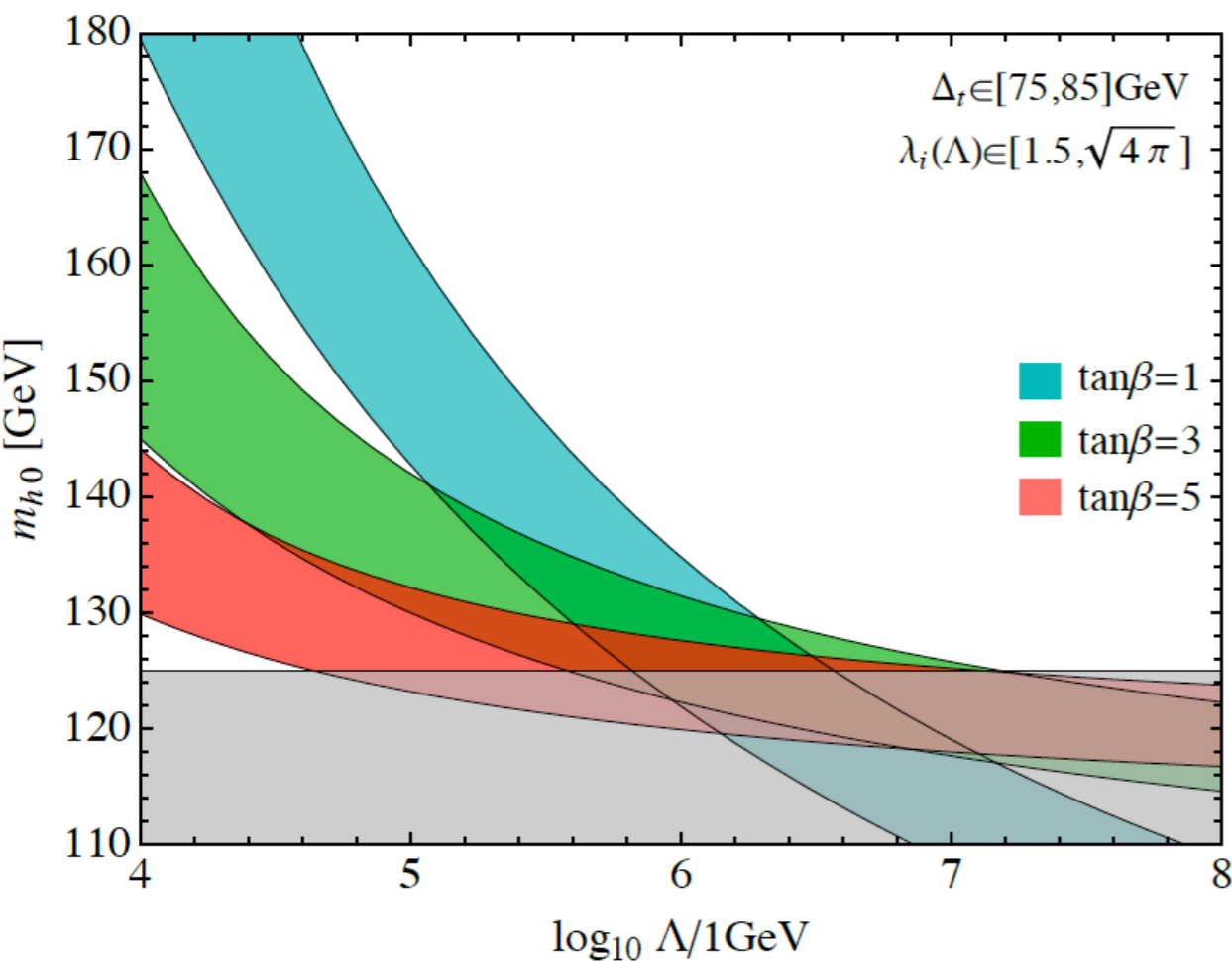
My favorite explanation

$\Rightarrow m_h \leq M_Z \cos 2\beta \longrightarrow 125 \text{ GeV. How?}$

\Rightarrow Why 3 generations?

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

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



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

My favorite explanation

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

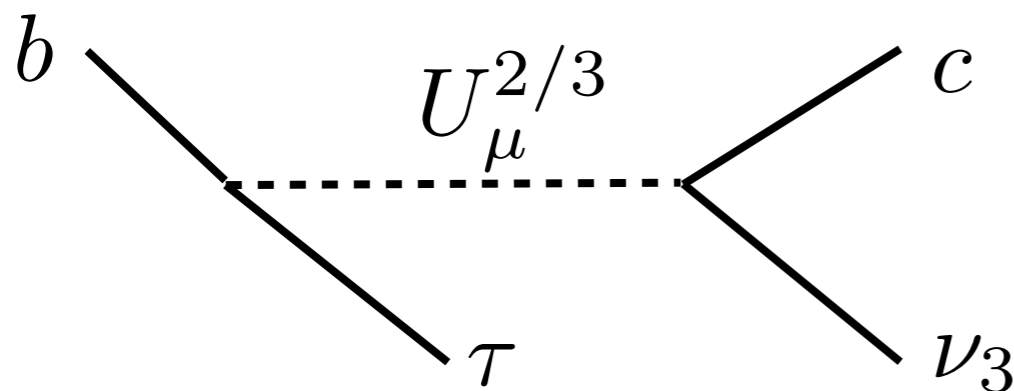
singlet under a flavour $U(2)_Q \times U(2)_L$

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

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

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

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



need

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