Particle Physics after the discovery of the Higgs boson

An outlook

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PSI, February 9, 2015

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

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

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

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

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

The synthetic nature of Particle Physics

An alternative definition of the SM (equally precise!)

1. Gauge group $\mathcal{G} = SU(3) \times SU(2) \times U(1)$

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

3. All $\mathcal{O}_i : d(\mathcal{O}_i) \leq 4$ except for $\theta F_{\mu\nu}\tilde{F}^{\mu\nu}$

(In spite of $F_{\mu\nu}\tilde{F}^{\mu\nu} = \partial_\mu J_\mu$, neutron EDM $\approx 10^{-16}\theta \ e \cdot cm$)

The particles of the Standard Model

$\Psi_i =$ ($J = 1/2$)

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

$J = 1$

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

$J = 0$

$h(2012)$

A complete story?

A single scalar?

Problems of (questions for) the SM

1. Unaccounted phenomena

neutrino masses $\Leftarrow$ 1
Dark matter
Baryon asymmetry

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

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

unaccounted phenomena (?)
vacuum stability $\Leftarrow$ 3
Landau poles
Gravity

4. Lack of calculability

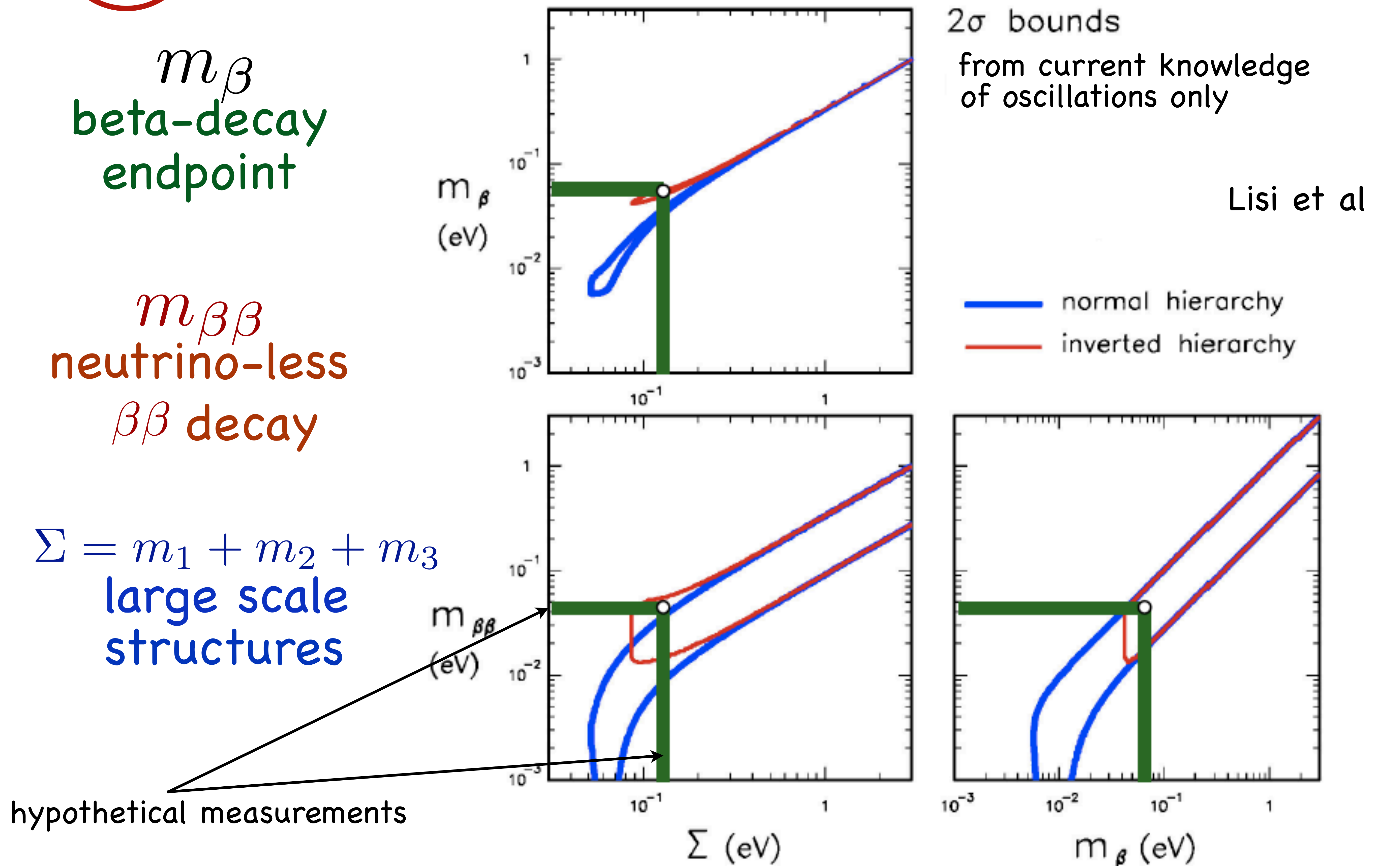
the hierarchy problem $\Leftarrow$ 4
the flavour paradox $\Leftarrow$ 5

1 Key neutrino measurements

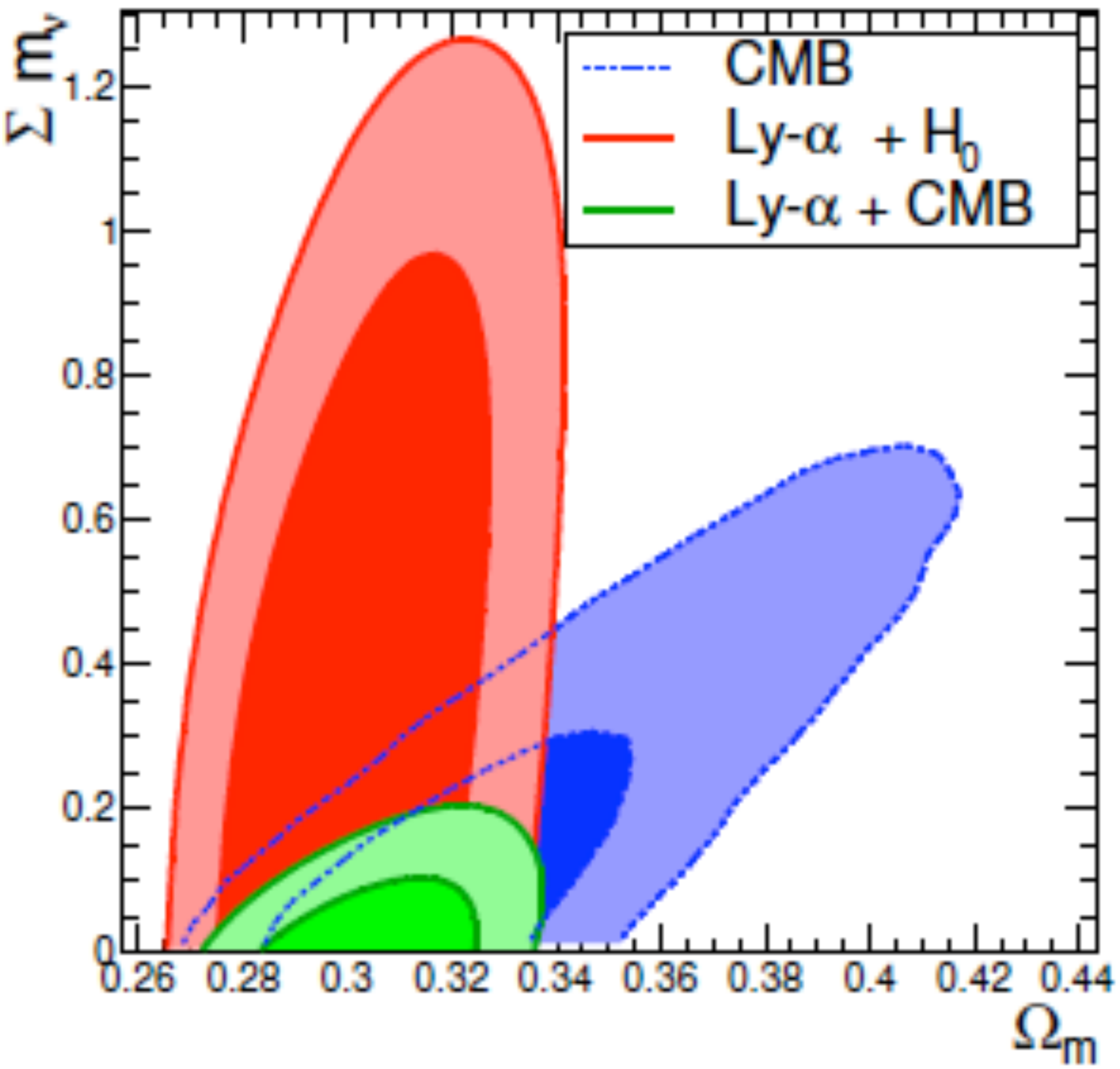
m_β
beta-decay endpoint

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

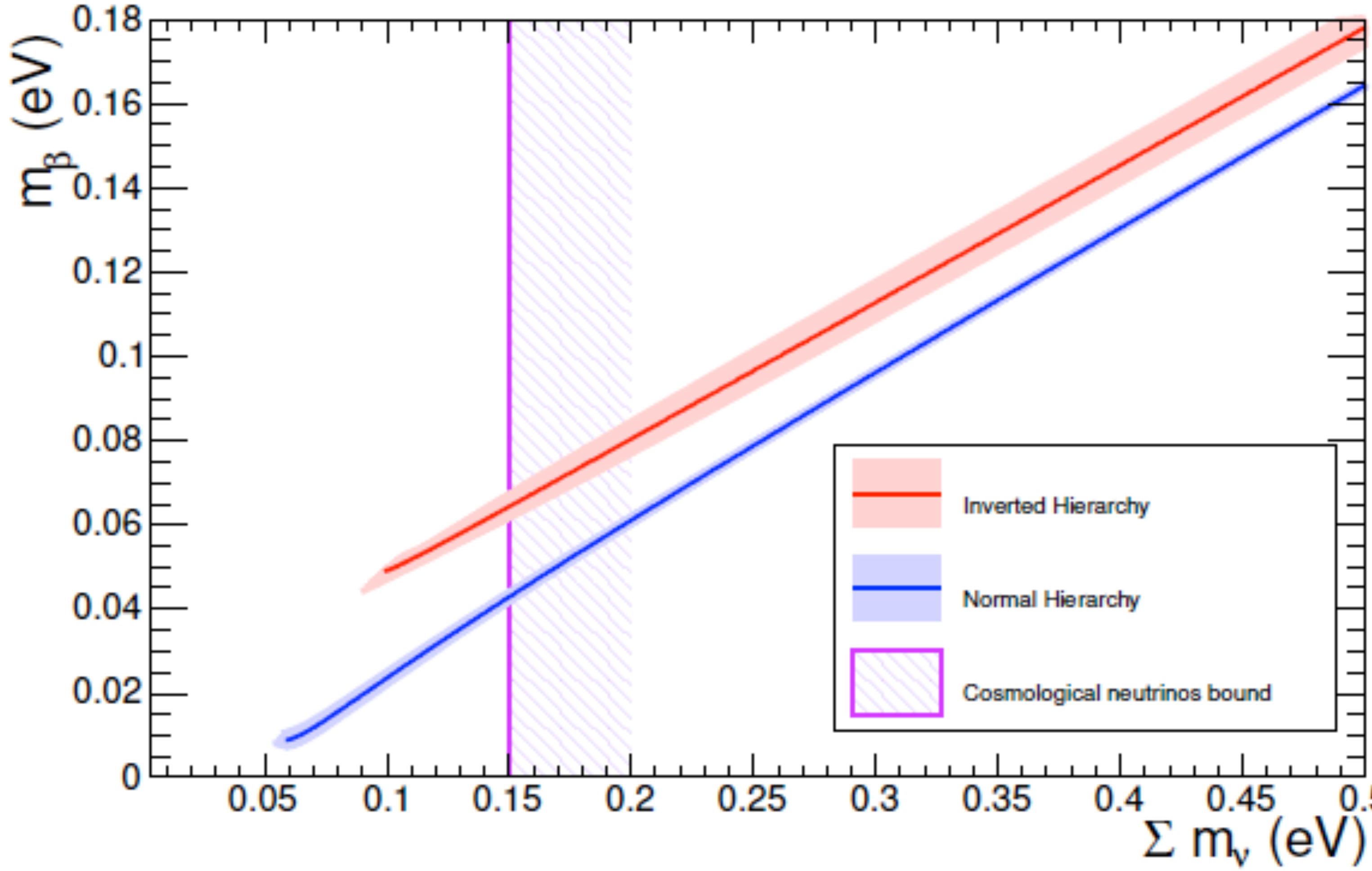
$\Sigma = m_1 + m_2 + m_3$
large scale structures

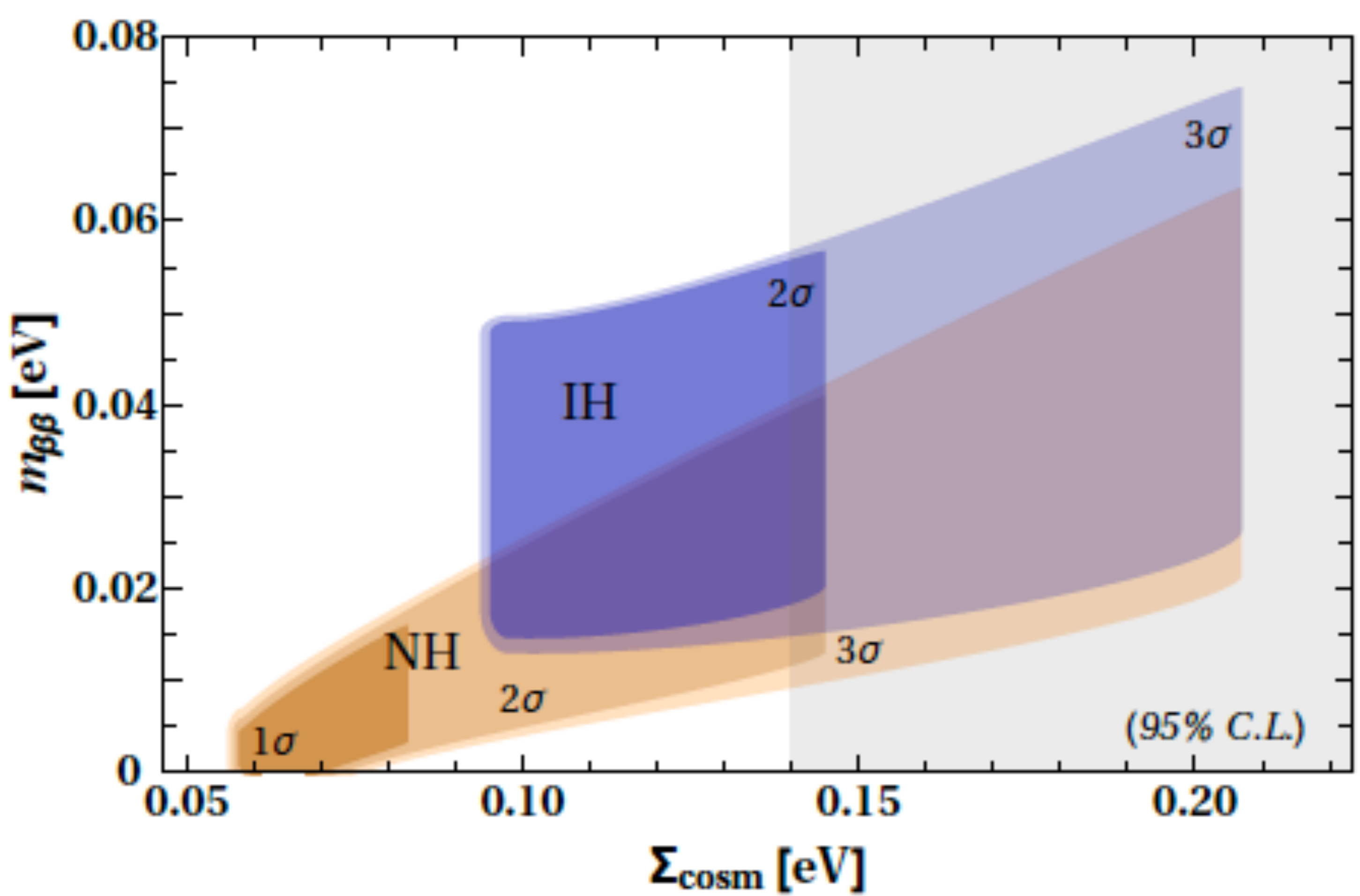


Σm_ν determination



Palanque-Delabroullle et al 2015

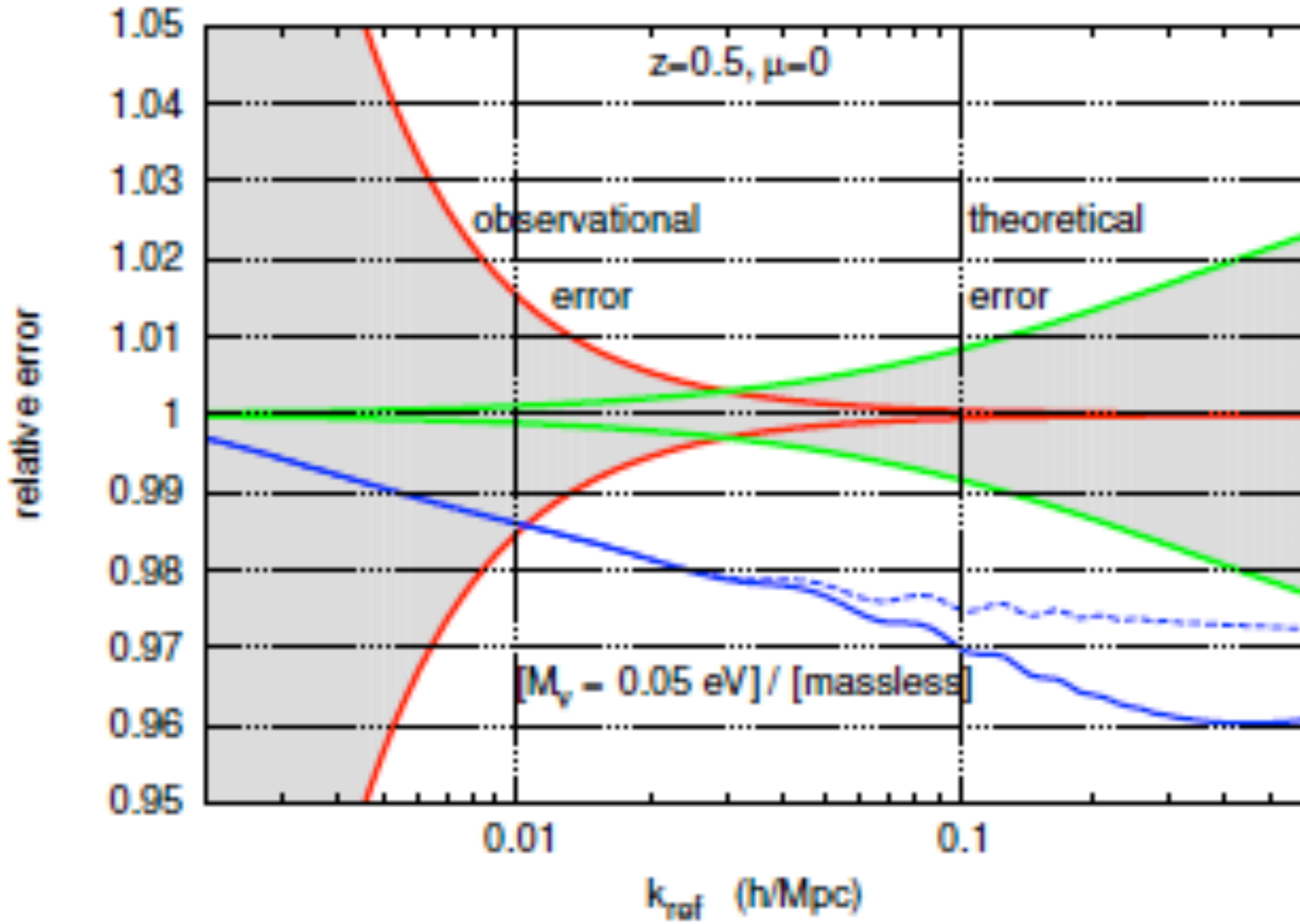




Dell'Oro et al 2015

- 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

- Not independent on "priors" but still highly significant

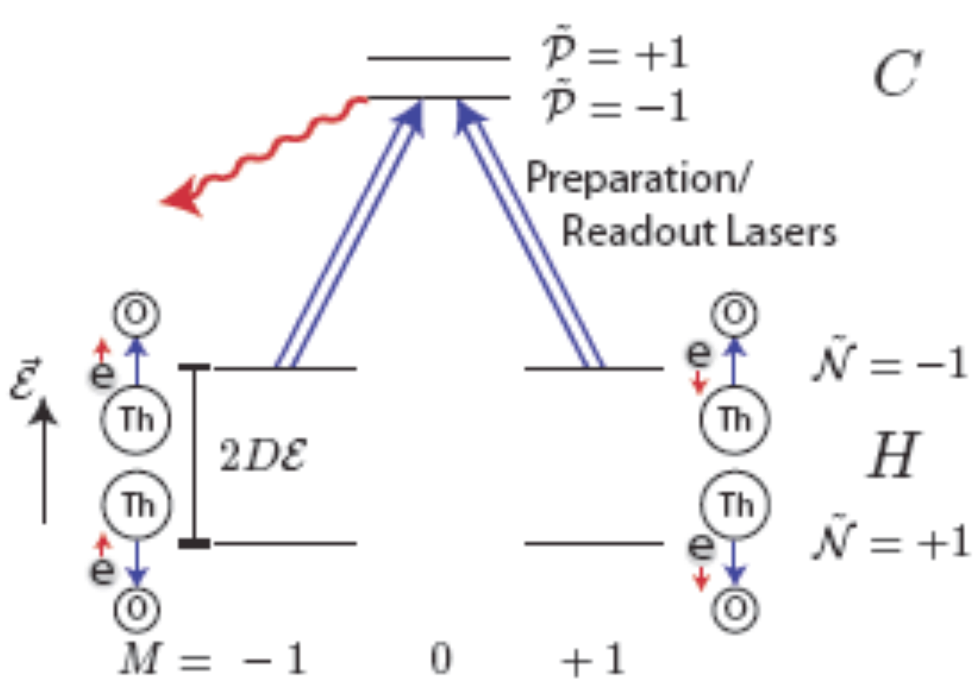
2

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 $\theta \lesssim 10^{-21}$

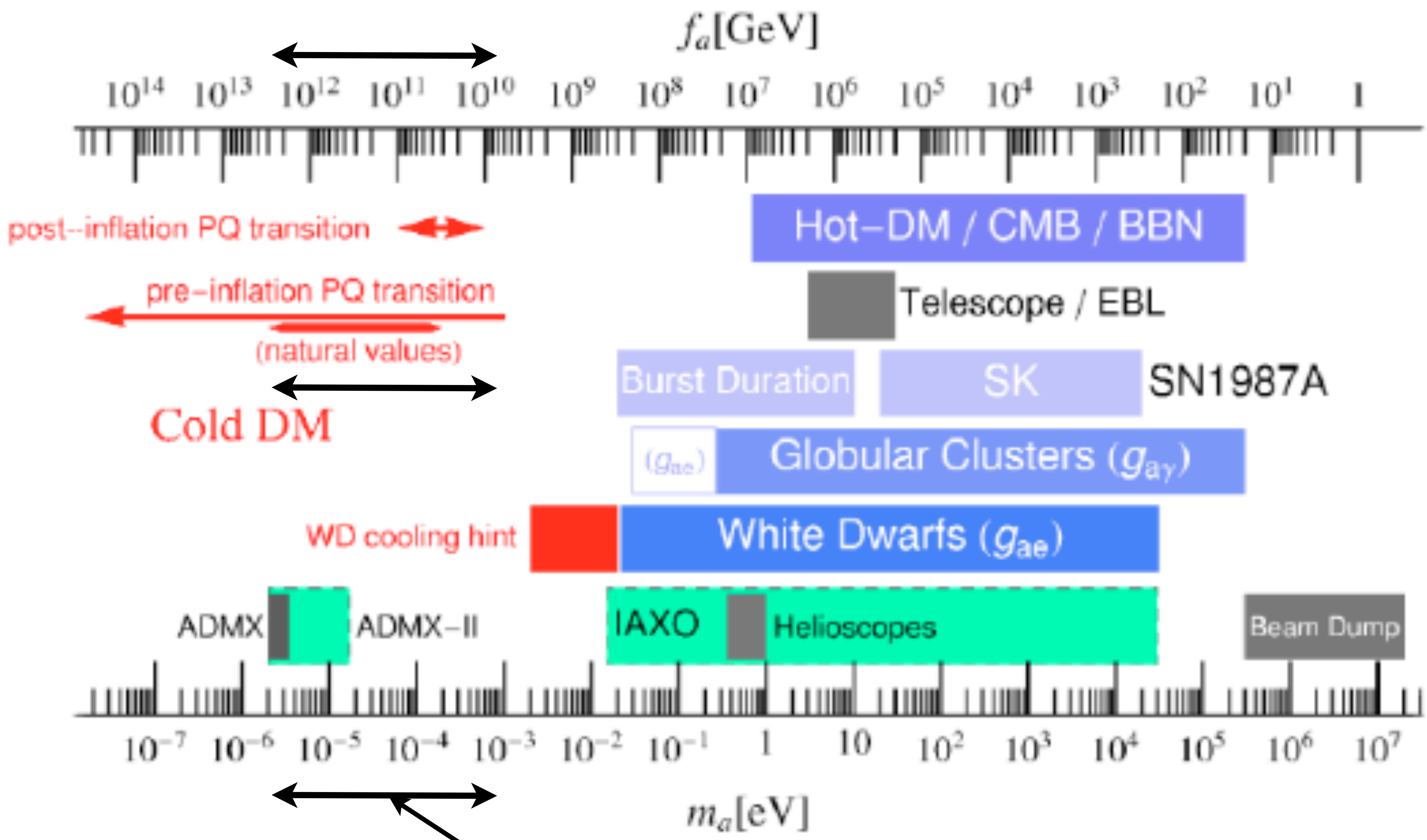


ACME Collaboration

Gabrielse (Harvard), DeMille (Yale) et al

using a polarized ThO molecule

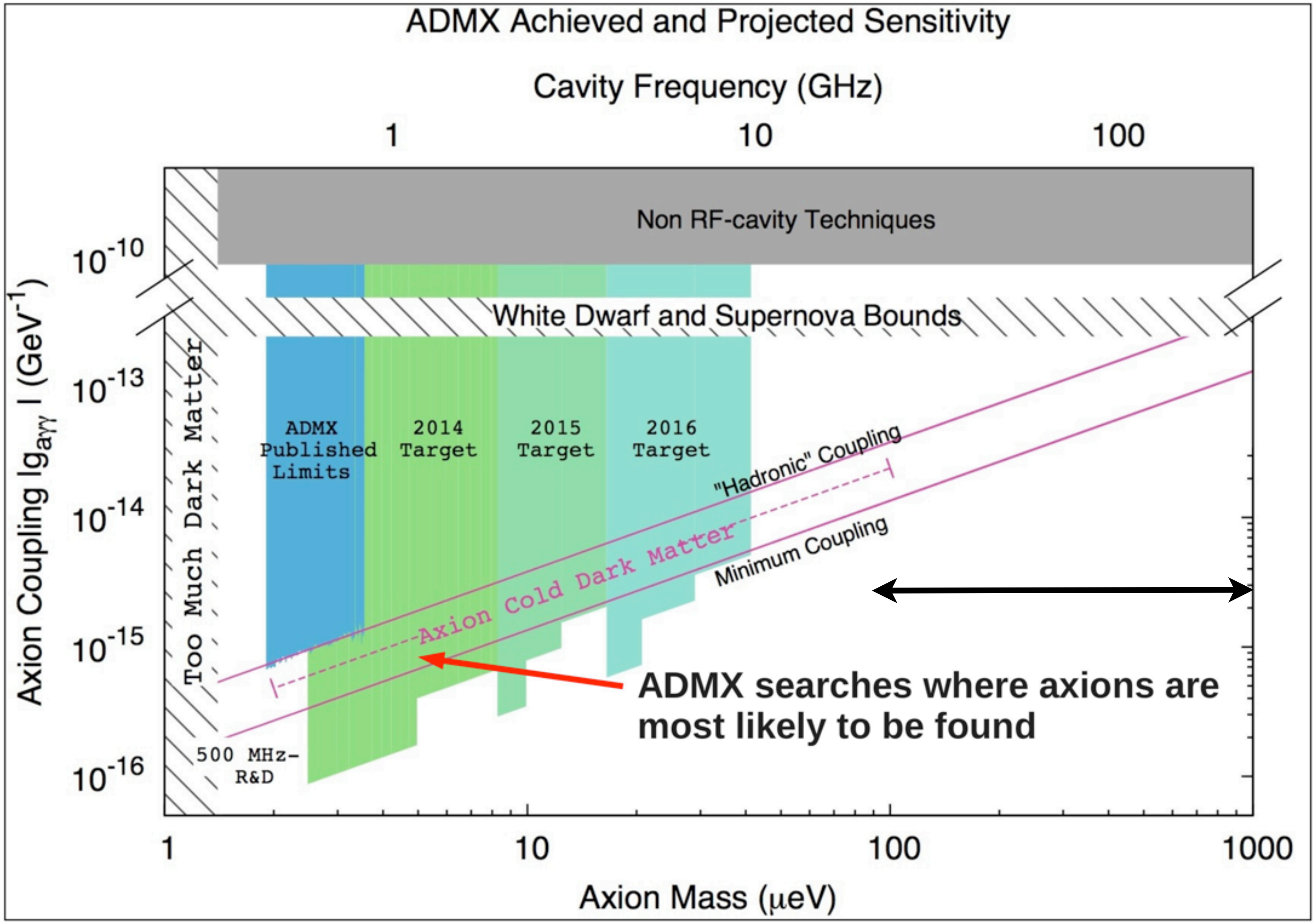
$\theta < 10^{-16}$ ⇔ axions ⇔ Cold DM



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

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

The coupling of the axion to spin

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

$$g_p = A_\Psi \frac{m_\Psi}{f_a} \qquad (g_s = 10^{-(12\div17)} g_p \frac{GeV}{m_\Psi})$$

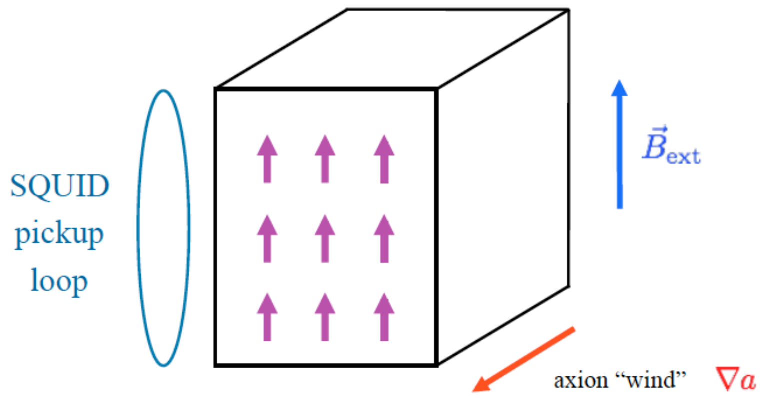
DFSZ
KSVZ

NRL: $$i\hbar\frac{\partial\varphi}{c\partial t} = \left[-\frac{\hbar^2\nabla^2}{2m} + g_s ca - i\frac{g_p}{2m}\vec{\sigma}\cdot(-i\hbar\vec{\nabla}a)\right]\varphi$$

$$\gamma\vec{B}_{eff}\cdot\vec{\sigma}$$

$$\gamma = \frac{e}{2m_\Psi}$$

Summary on proposed exp.s using NMR/EMR

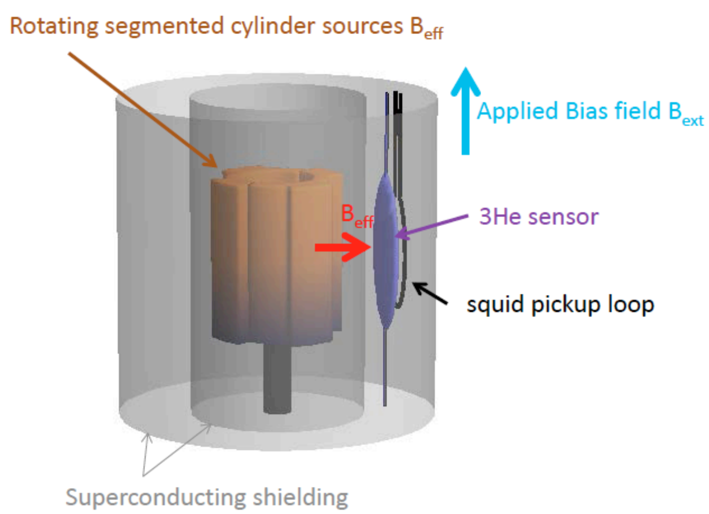


CASPEr axion wind/NMR

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

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

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

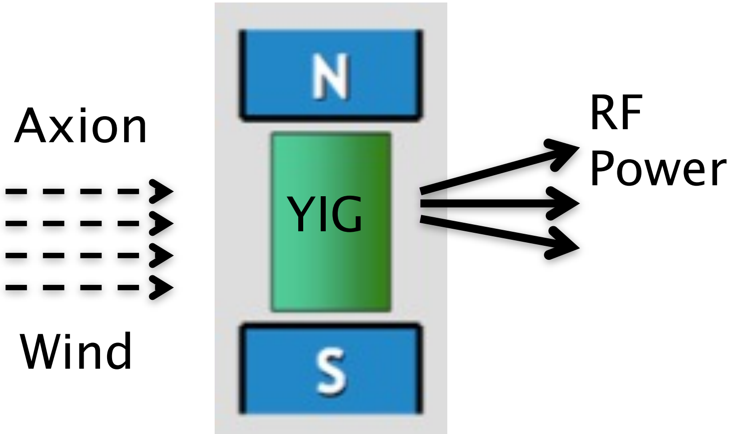


static source NMR

not limited in frequency
but size of the effect smaller

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

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



QUAX axion wind/EMR

frequency OK
detection method still under scrutiny

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

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

3

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 $m_H,\ m_t,\ \alpha_S, \ldots$

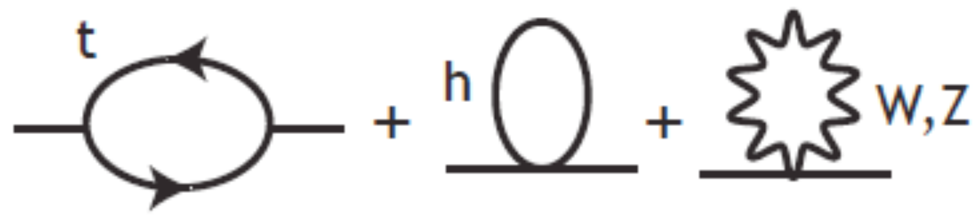
$$\lambda(\approx 10^{11}\ GeV) < 0$$

⇒ 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?

4 The hierarchy problem, once again

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



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

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

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

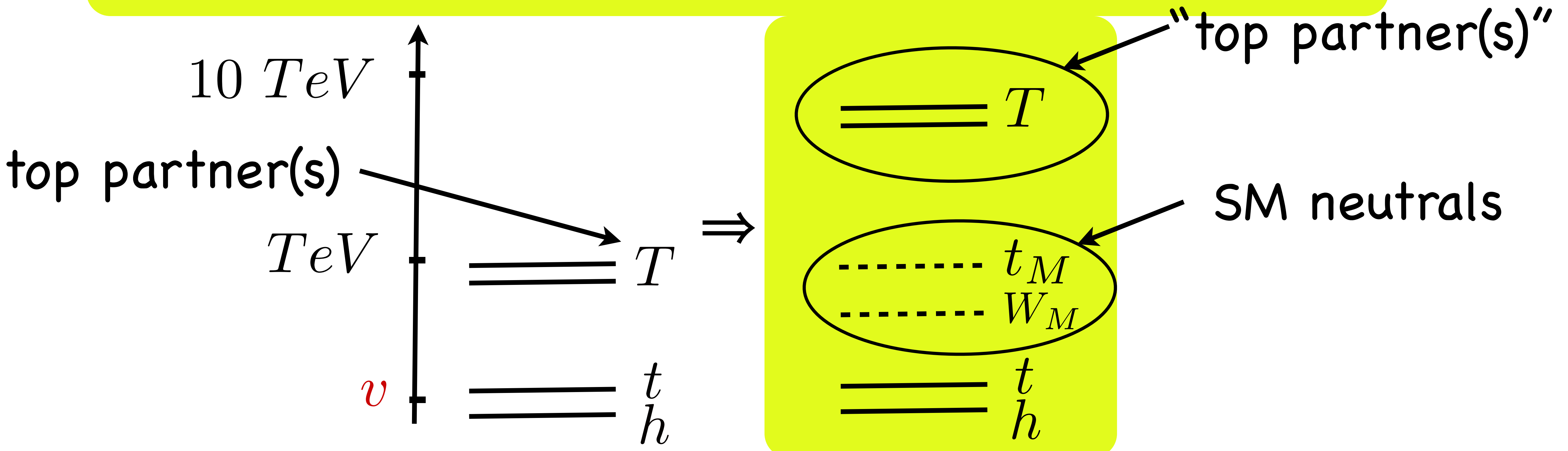
(we have become more prudent!)

Are there any strictly natural theory compatible with current data?

- Not in my view
- Searching for "top partners" remains the key
- However, if one is willing to accept a (partial) doubling of the SM ("Twin Higgs")

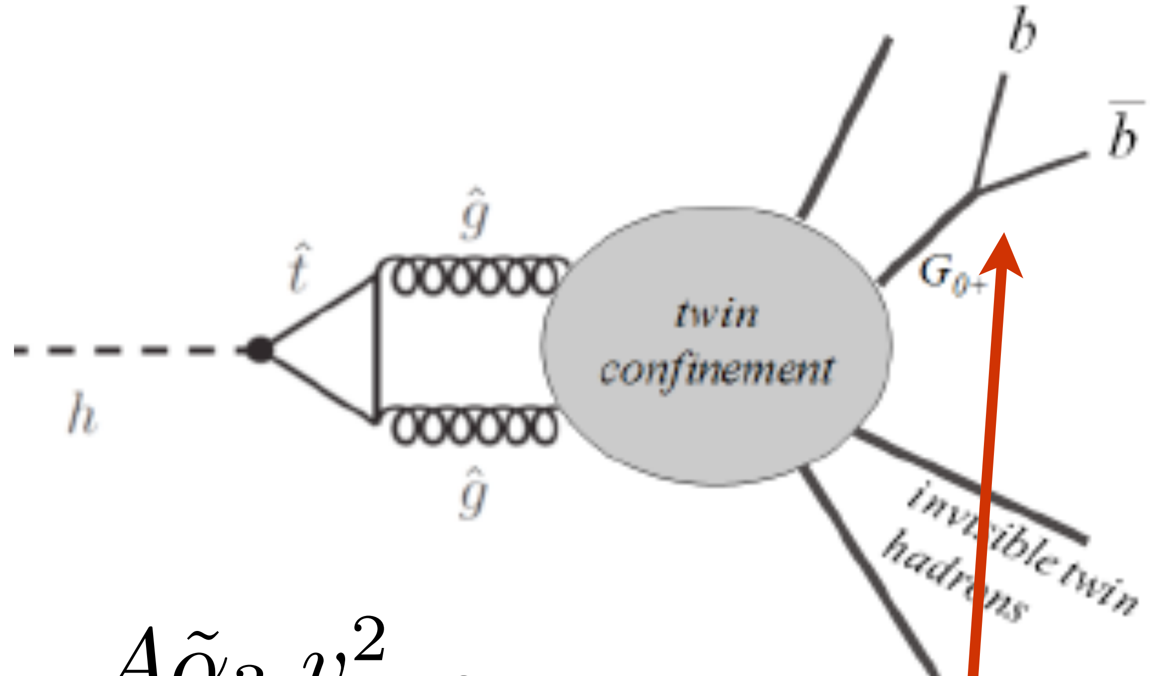
$$SU(3) \times SU(2) \times U(1) \Rightarrow (SU(3) \times SU(2) \times U(1))^2$$

can conceive a situation like



LHC signatures of light mirror glueballs

important parameters: $\tilde{\Lambda}_{QCD},\ m_{\tilde{b}},\ f$



$$\frac{\Gamma(h \to \tilde{g}\tilde{g})}{\Gamma(h \to gg)} = \left(\frac{A\tilde{\alpha}_3}{\alpha_3}\frac{v^2}{f^2}\right)^2$$

$$A = 1 \div 6$$

$$BR(h \to \tilde{g}\tilde{g}) = 3\%\left(\frac{3}{f/v}\right)^4$$

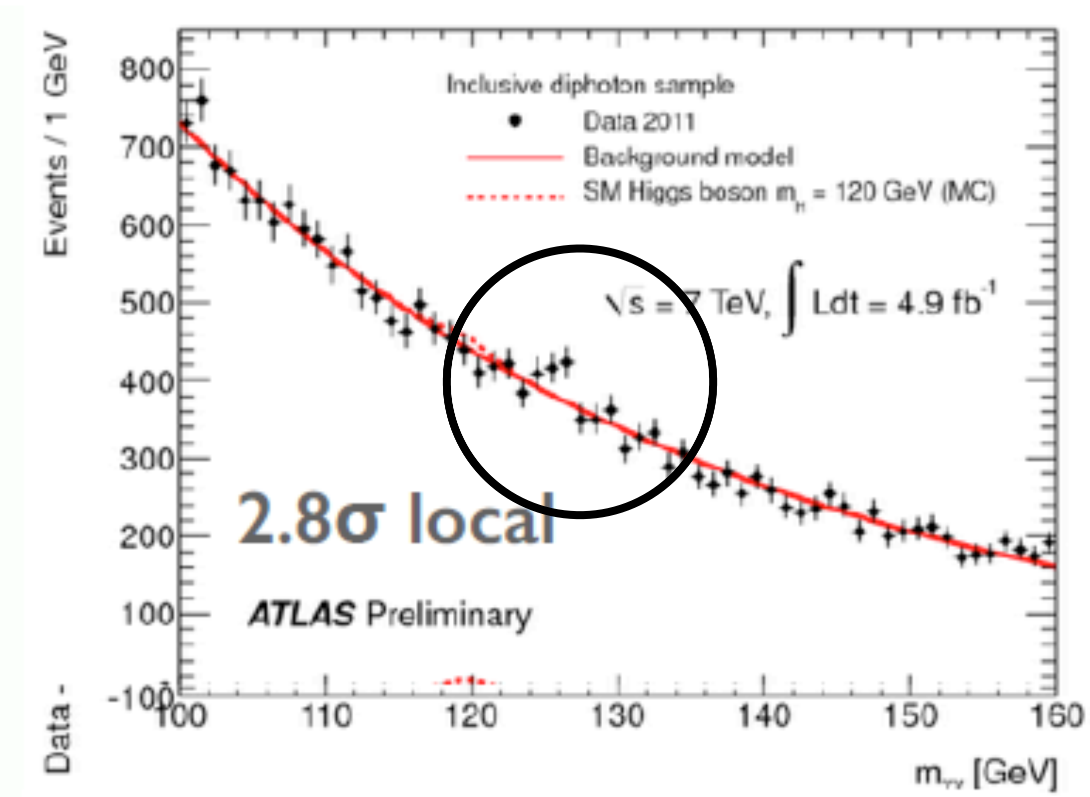
$\tilde{G}_{0+} \longrightarrow$ SM via Higgs mixing

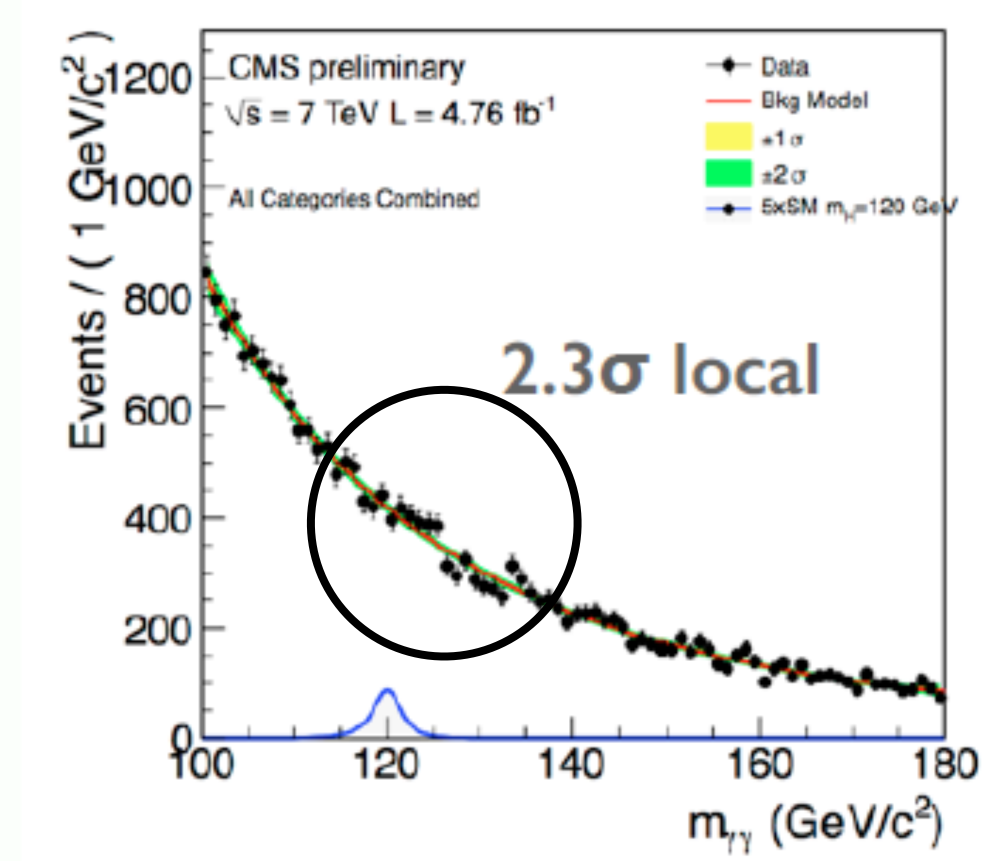
$$c\tau(\tilde{G}_{0+}) \approx 3m\left(\frac{8\ GeV}{m(\tilde{G}_{0+})}\right)^7\left(\frac{f/v}{3}\right)^4$$

Craig, Katz, Strassler, Sundrum

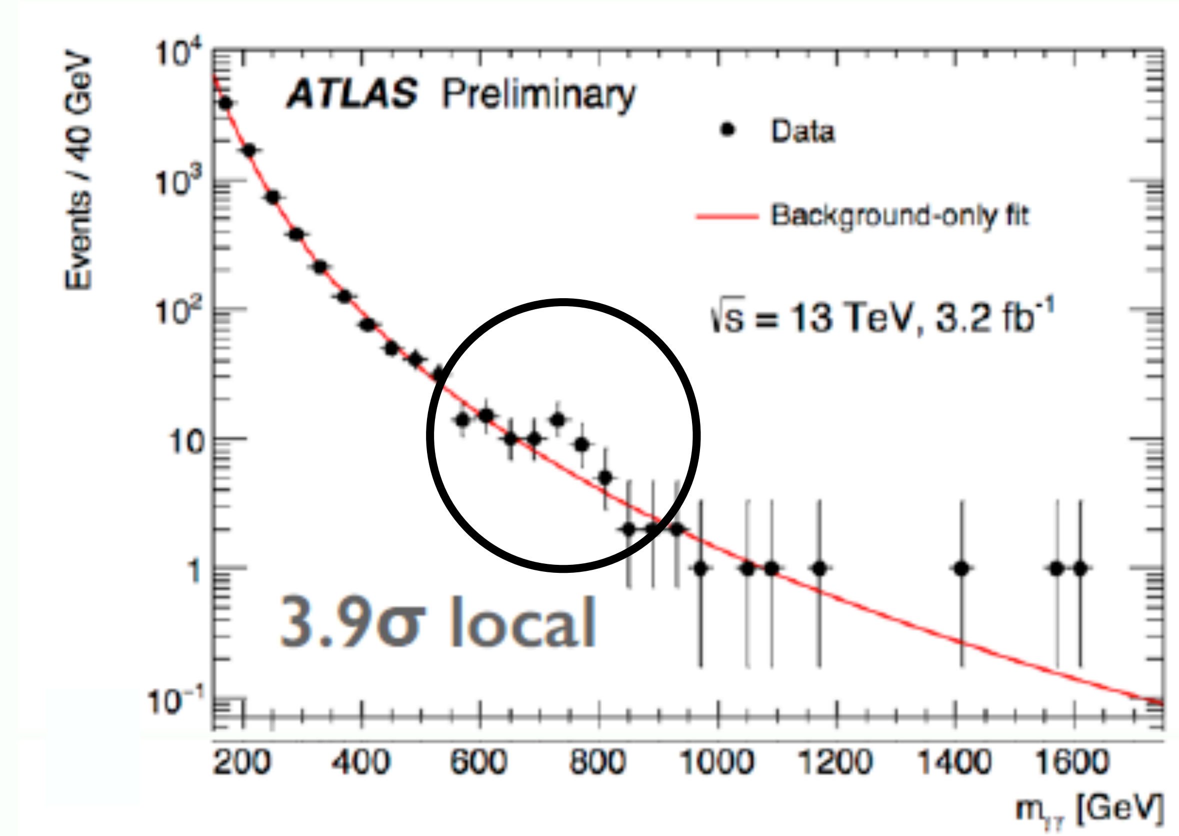
Only one scalar: the Higgs boson?

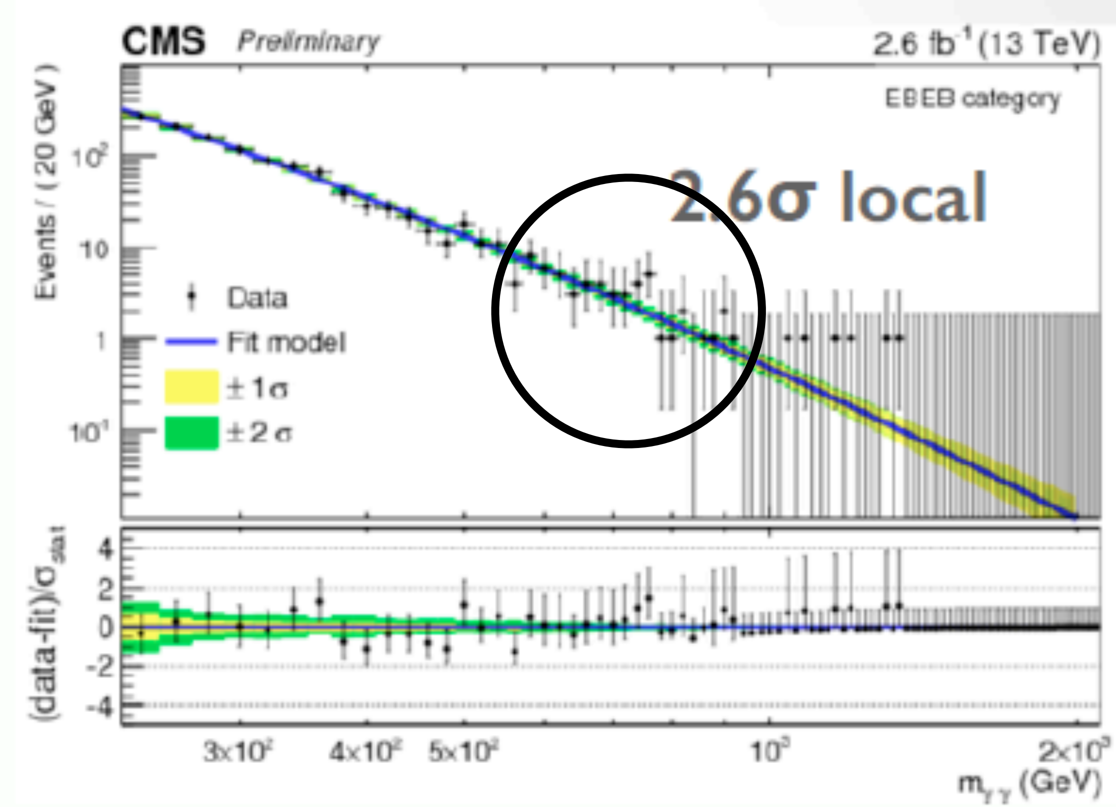
Dec 2011





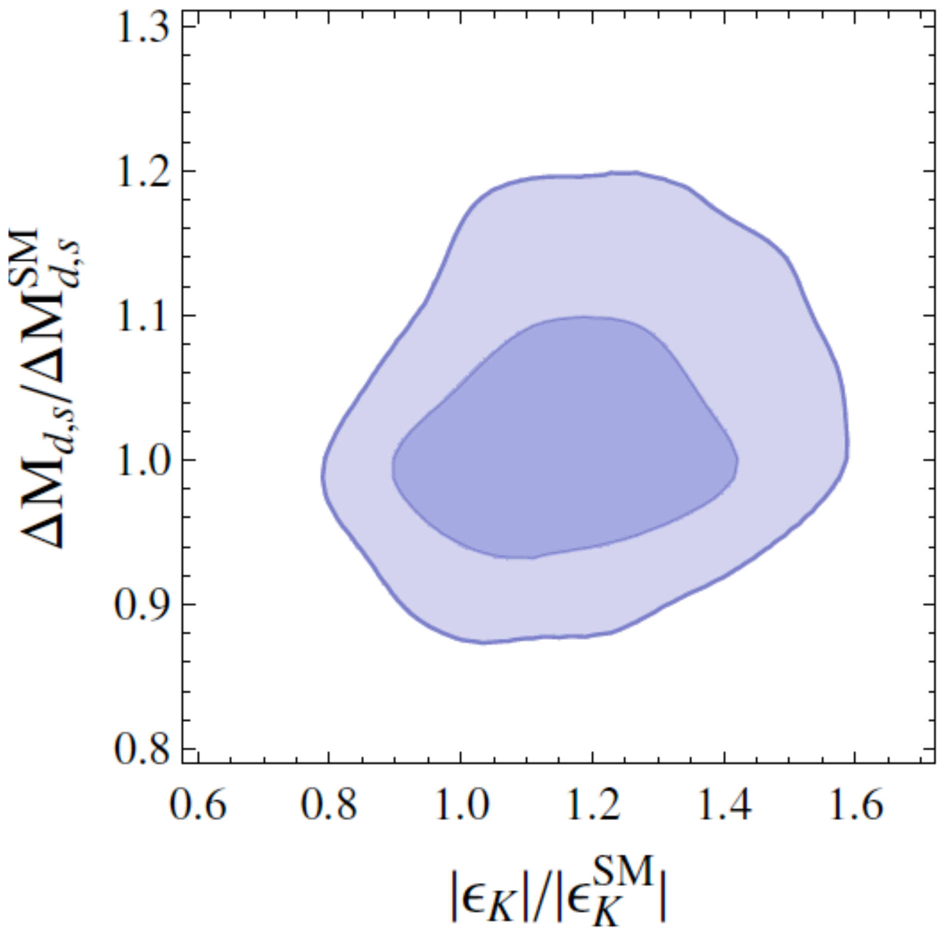
Dec 2015

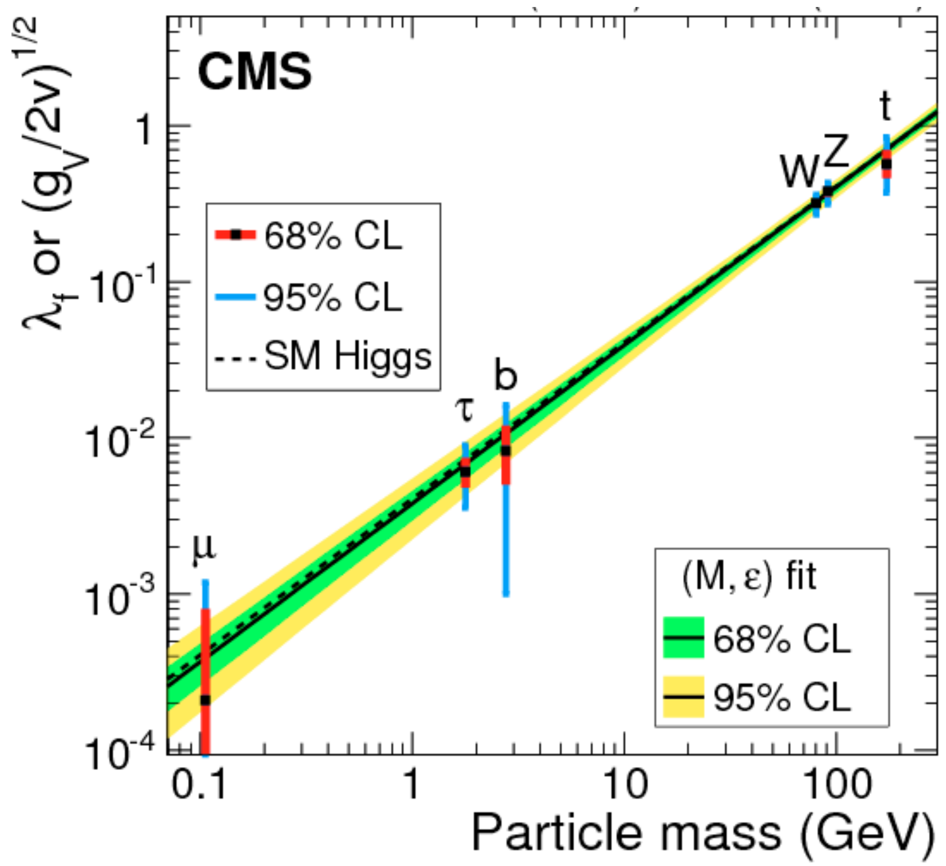




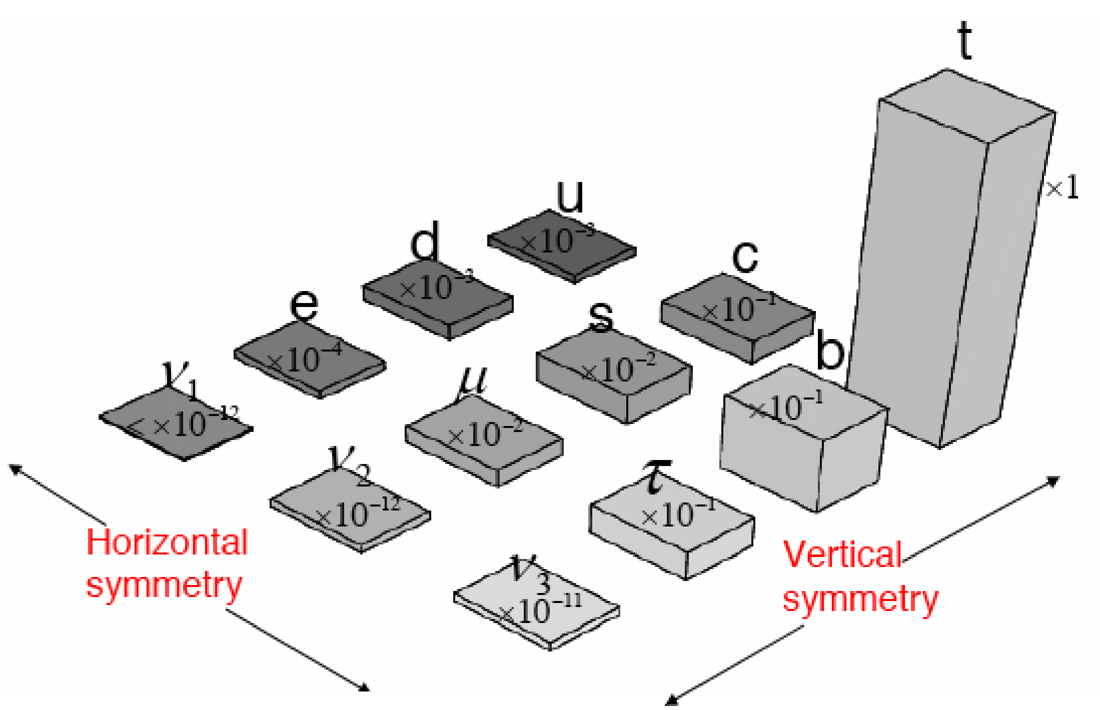
5 The flavour paradox

Yukawa couplings: a piece of physical reality





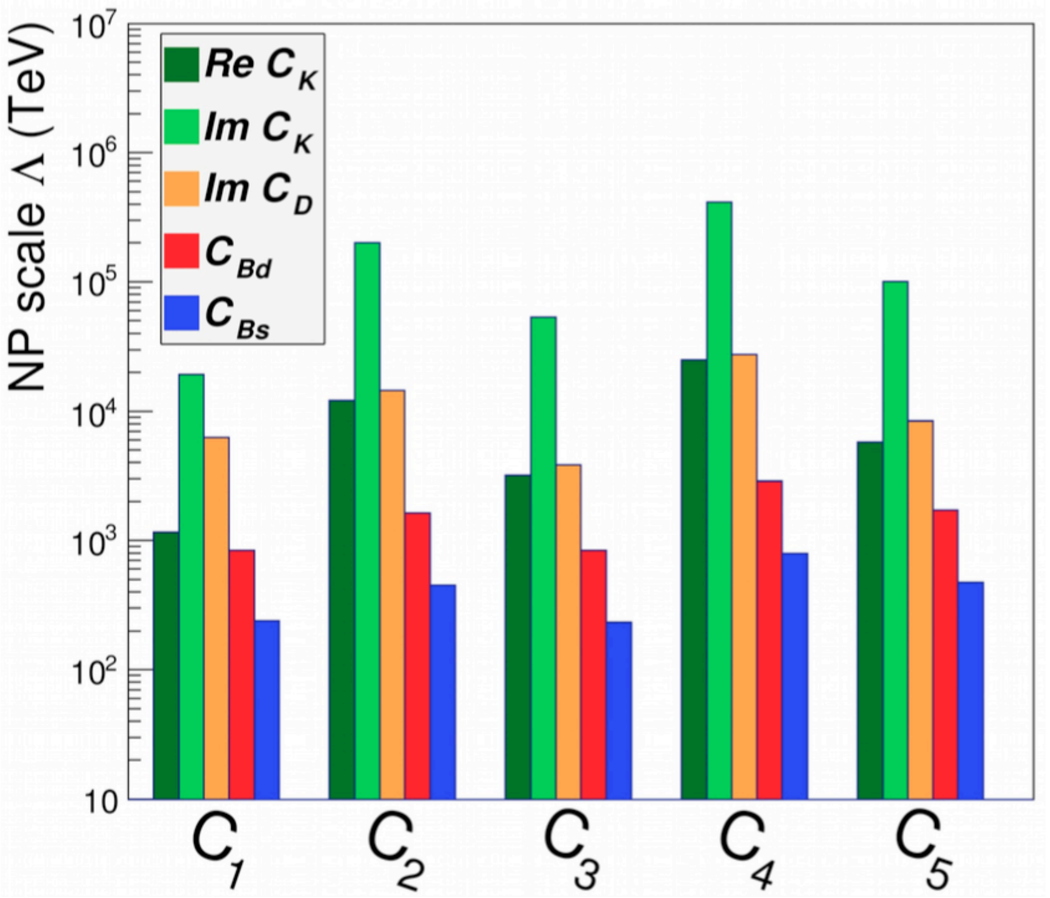
as opposed to:



?!?!?

Which direction to take in flavour physics?

1. High energy exploration



2. Indirect signals of new physics at the TeV scale

3. Putative anomalies in B-decays

$$V_{ub}\ exc/inc \quad B \to D(D^*)\tau\nu \quad B \to K\mu^+\mu^-/e^+e^- \ P_5'(B \to K^*\mu^+\mu^-)$$

B-physics "anomalies"

1. $b \rightarrow c\tau\nu$

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^*\tau\nu)_{\rm exp}/\mathcal{B}(B \to D^*\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D^*\ell\nu)_{\rm exp}/\mathcal{B}(B \to D^*\ell\nu)_{\rm SM}} = 1.28 \pm 0.08$$

$$R_{D}^{\tau/\ell} = \frac{\mathcal{B}(B \to D\tau\nu)_{\rm exp}/\mathcal{B}(B \to D\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D\ell\nu)_{\rm exp}/\mathcal{B}(B \to D\ell\nu)_{\rm SM}} = 1.37 \pm 0.18 \,,$$

2. $b \rightarrow s l^+ l^-$

$$R_K^{\mu/e} = \left.\frac{\mathcal{B}(B \to K\mu^+\mu^-)_{\rm exp}}{\mathcal{B}(B \to Ke^+e^-)_{\rm exp}}\right|_{q^2\in[1,6]{\rm GeV}} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

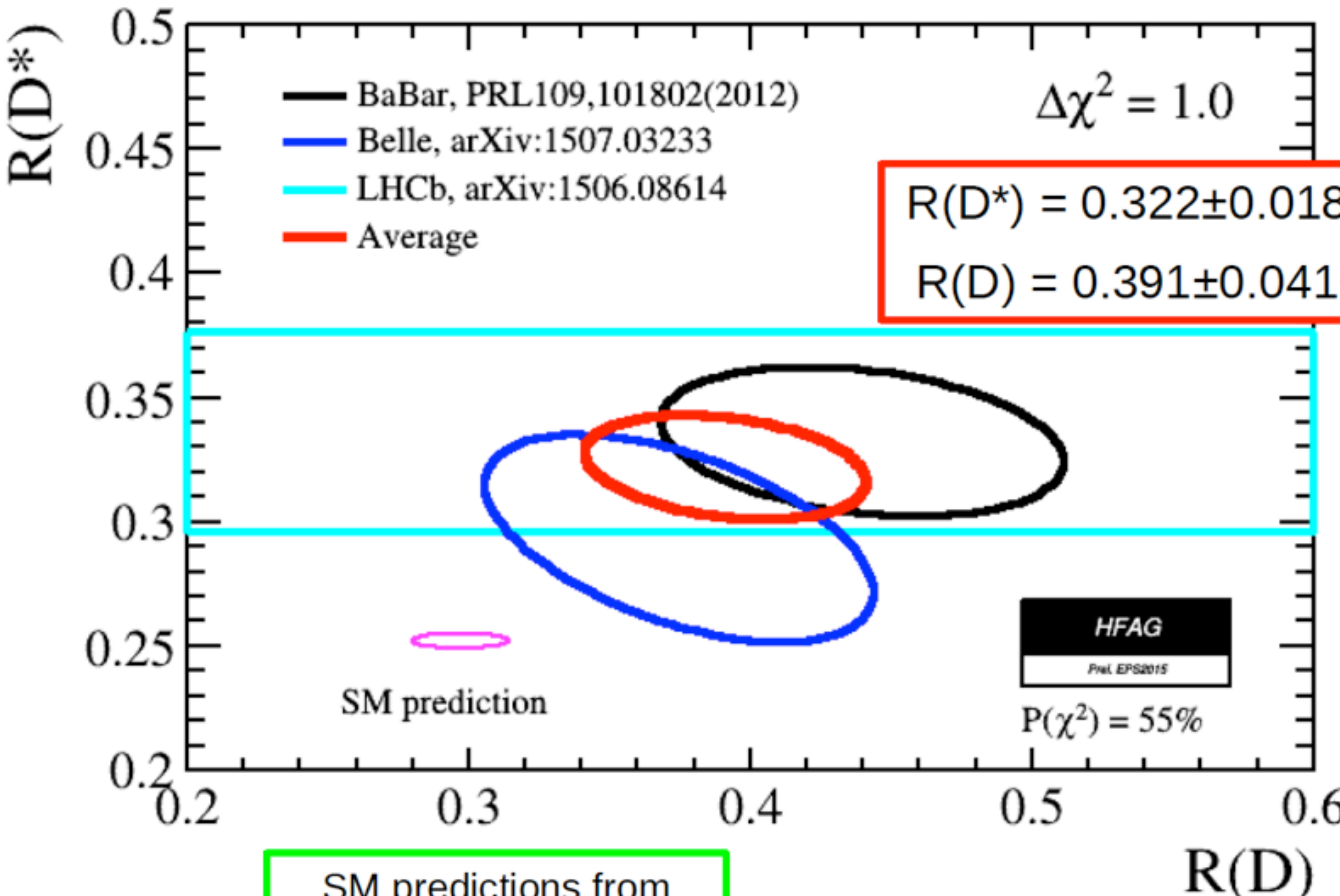
(could be related to the P_5' anomaly in the q^2distribution)

Both a $20 \div 30\%$ deviation from the SM

However tree (1) versus loop level (2)!

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

Tension with SM at 3.9σ



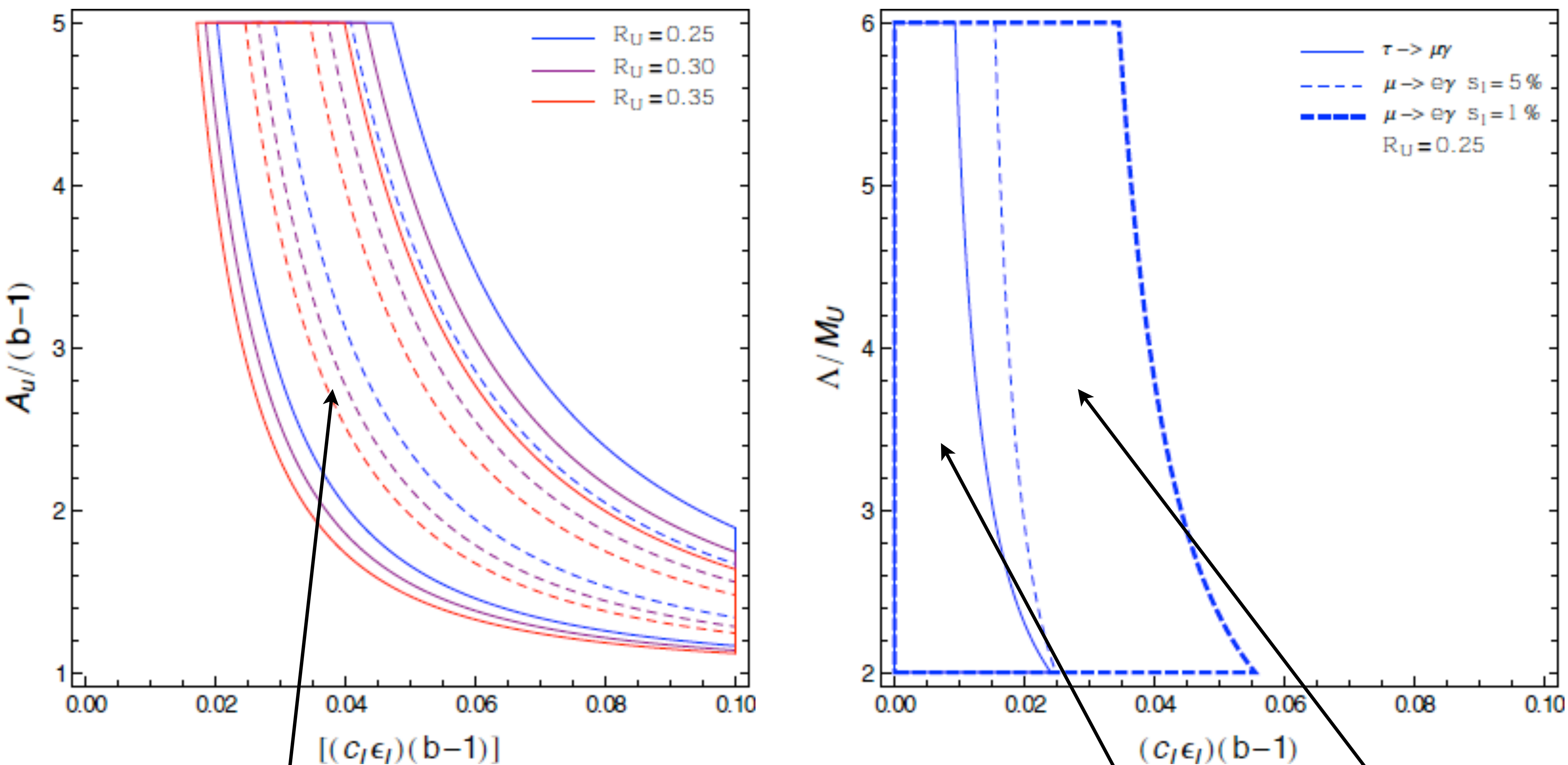
$R(D^*) = 0.322 \pm 0.018 \pm 0.012$

$R(D) = 0.391 \pm 0.041 \pm 0.028$

SM predictions from
PRD 85 (2012) 094025

Consistency with data (and expected signals)

$b \to s\mu\bar{\mu}$ and correlated processes

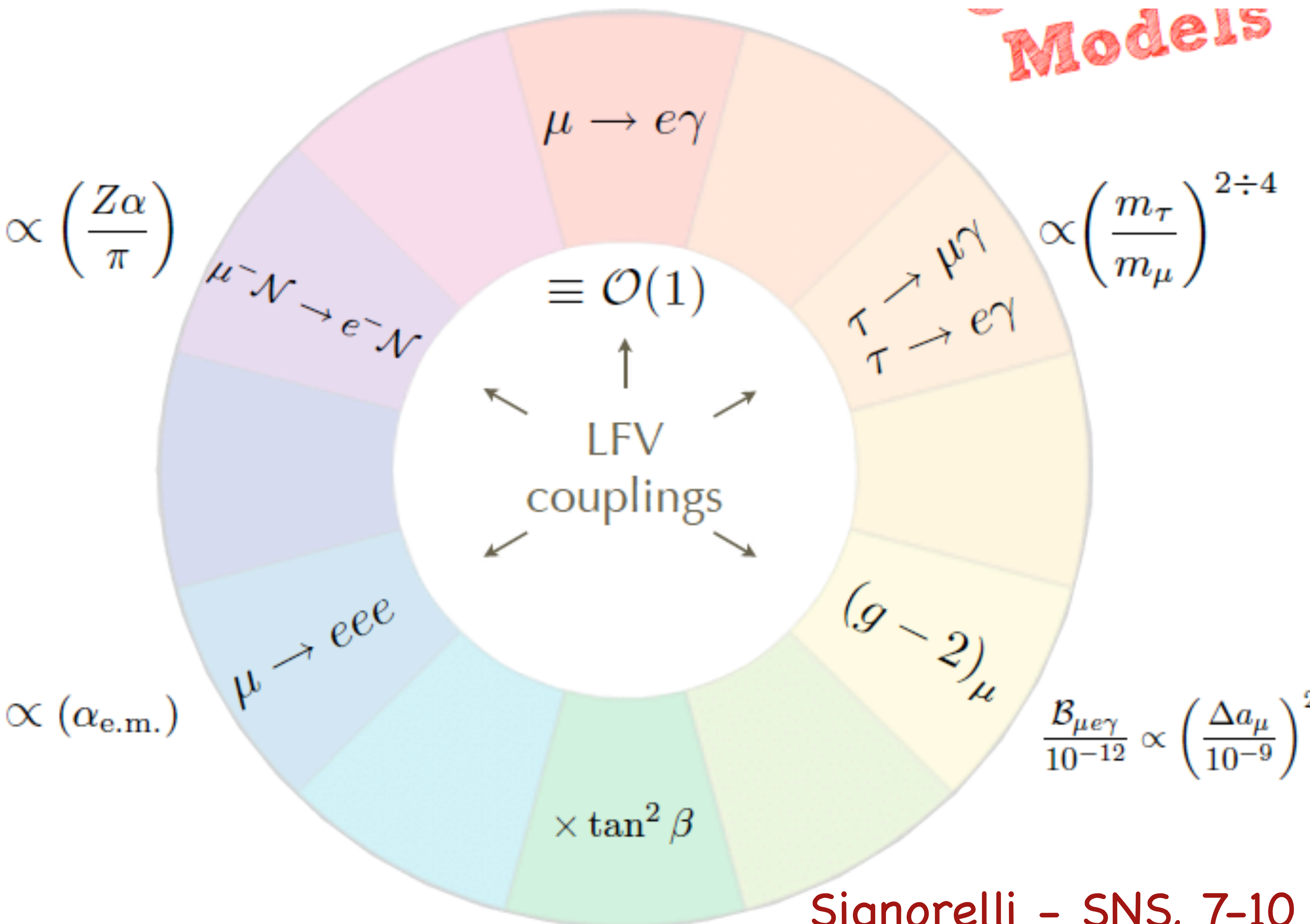


required by $R_K^{\mu/e}$

allowed by $\tau \to \mu\gamma$ $\mu \to e\gamma$

B, Isidori, Pattori, Senia

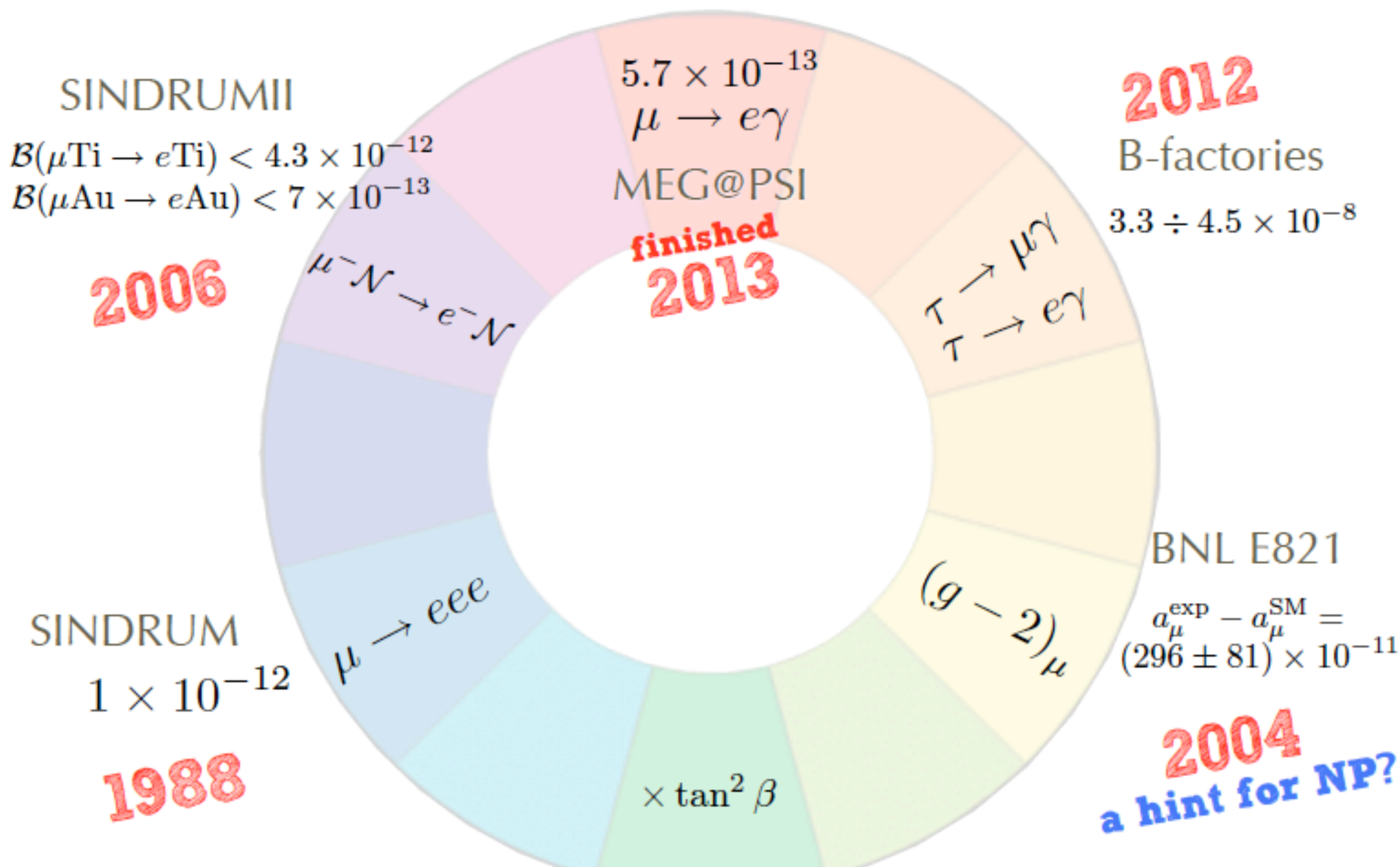
Lepton Flavour Violation



Signorelli - SNS, 7-10 Dec 2014

Motivation: extra degrees of freedom + unification

Current limits



time for improvement

Outlook of the Outlook

While the exploration of the energy frontier remains
a main task of particle physics,
in the current uncertain state of particle physics
(not the first nor the last such situation)
useful/necessary to have a diversified program
(LHC, precision, flavour, astro-cosmo-particle, DM)

An "Extreme Flavour" experiment?

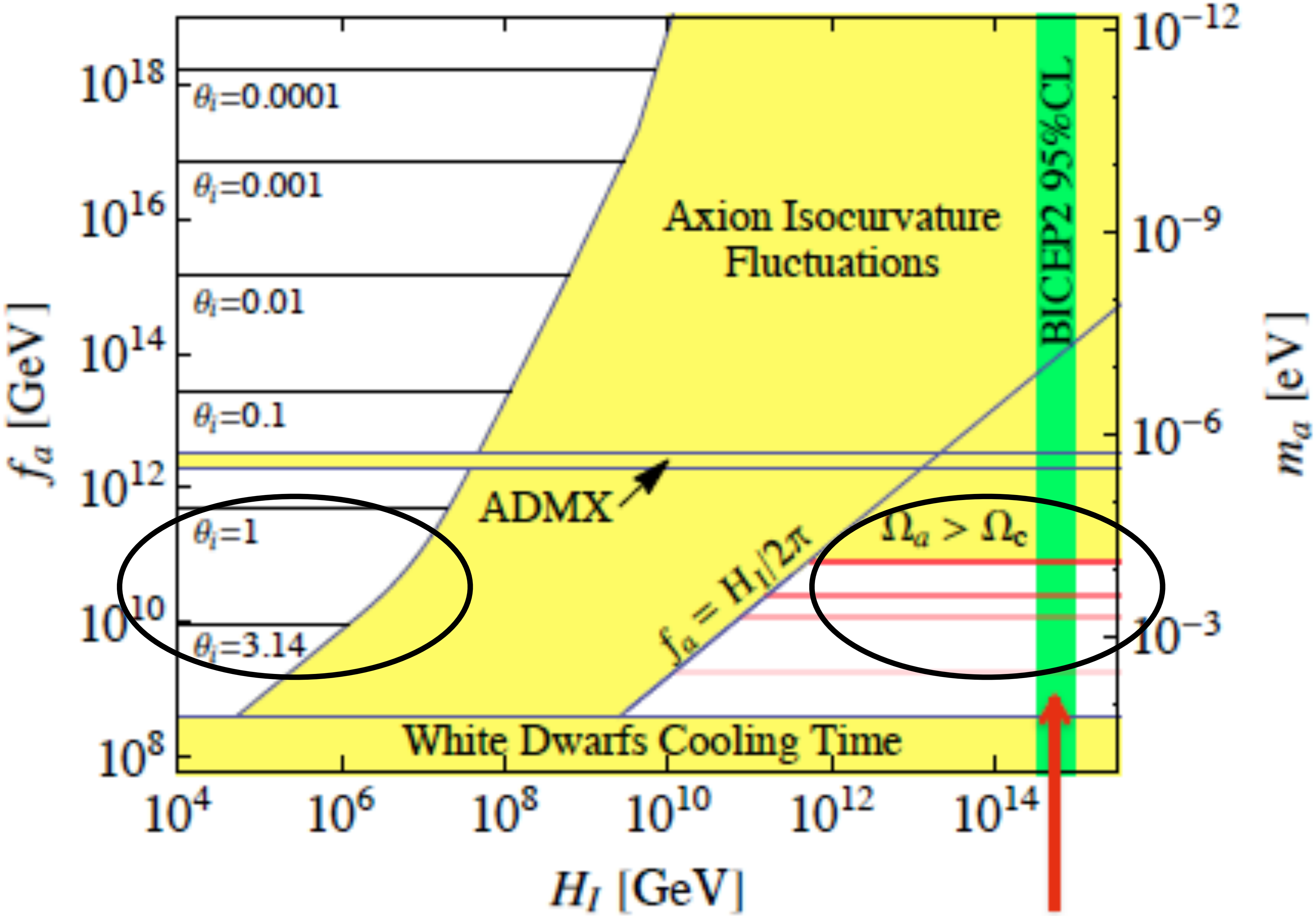
Vagnoni - SNS, 7-10 Dec 2014

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

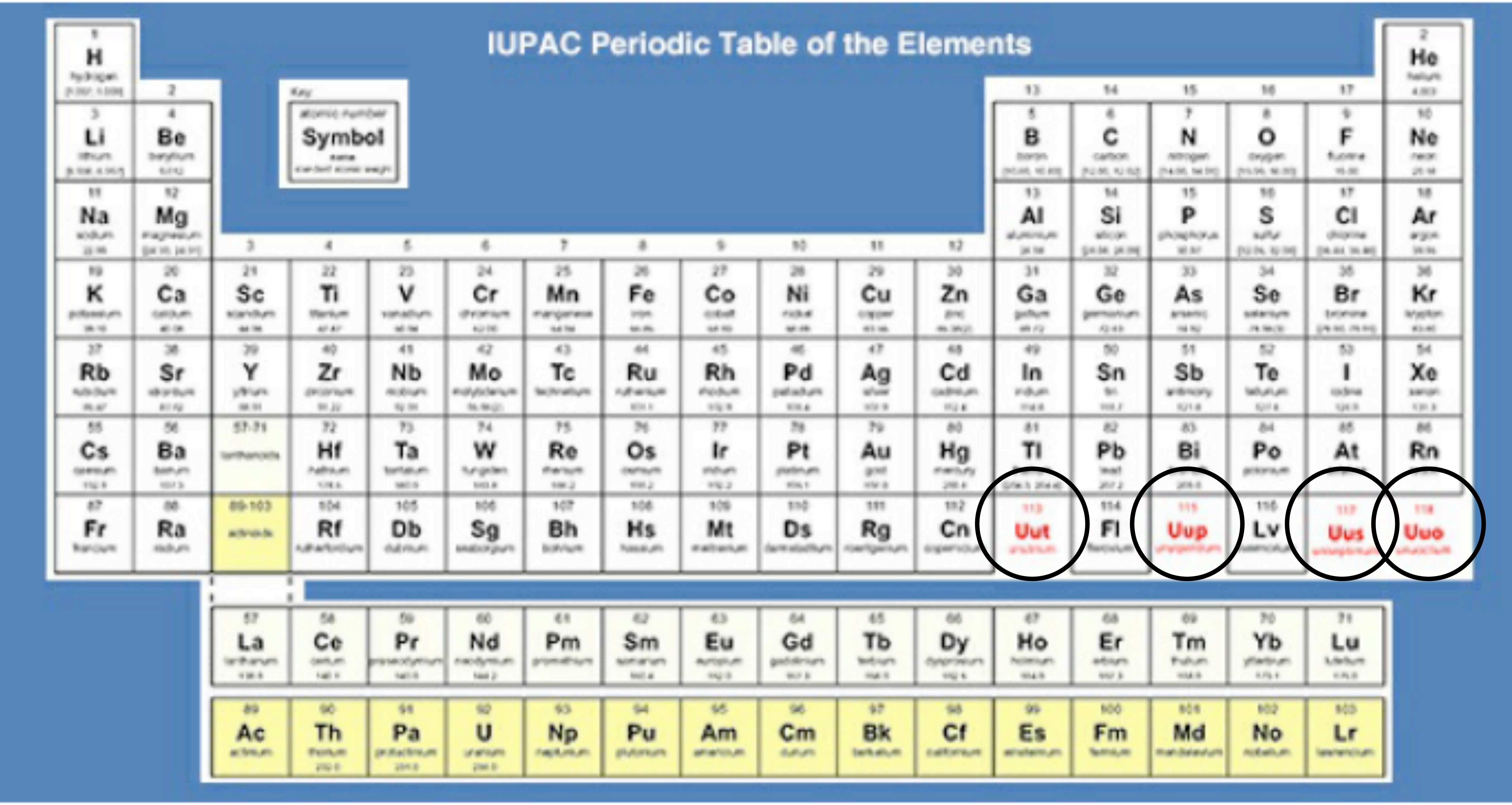
Motivation: test CKM (FCNC loops) from $\simeq$ 20% to $\lesssim$ 1%

Dark Matter: QCD Axions

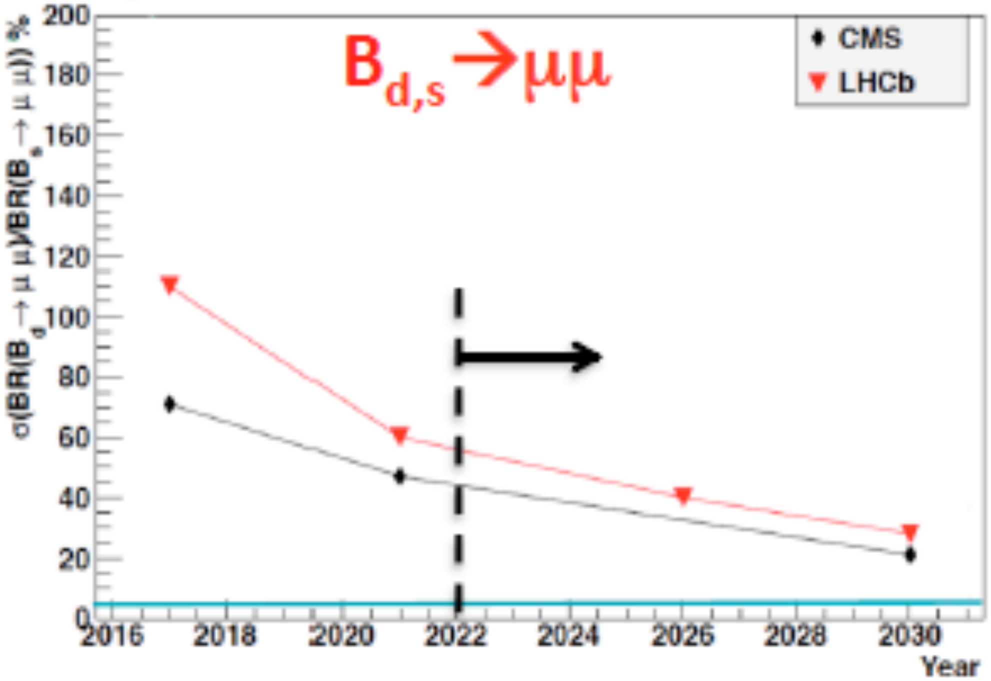
$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$

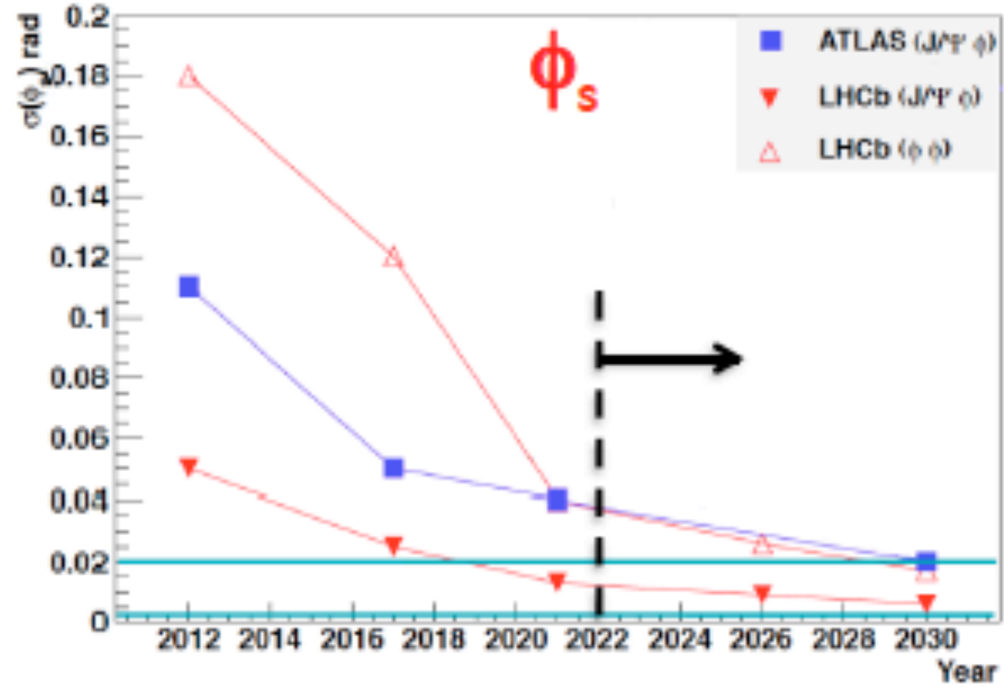


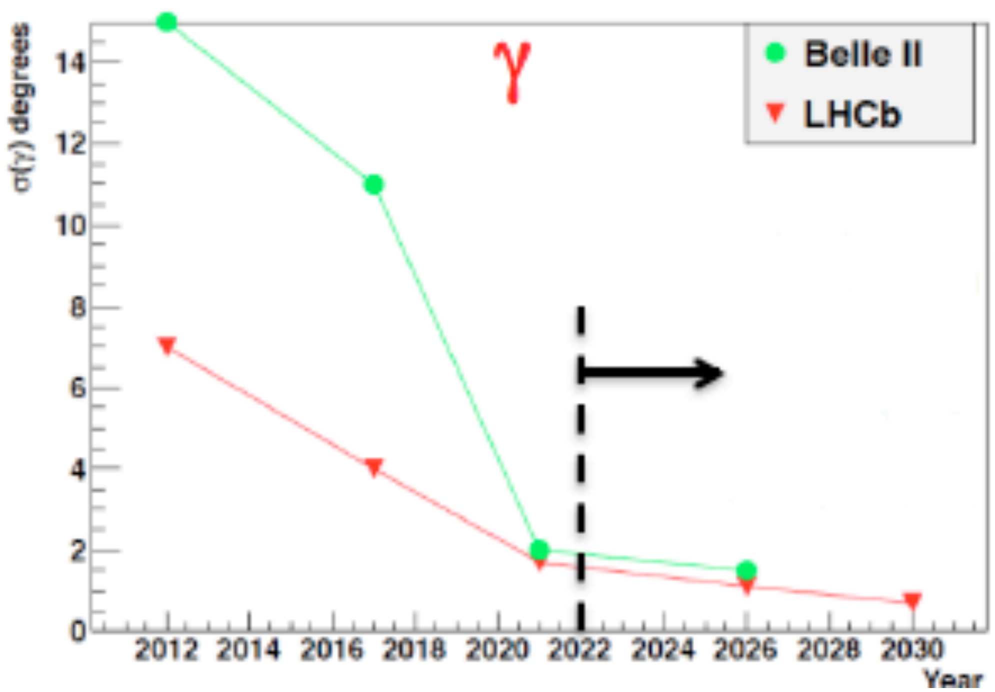
$m_a = 10^{-5} \div 10^{-3}\ eV$ as the most interesting region

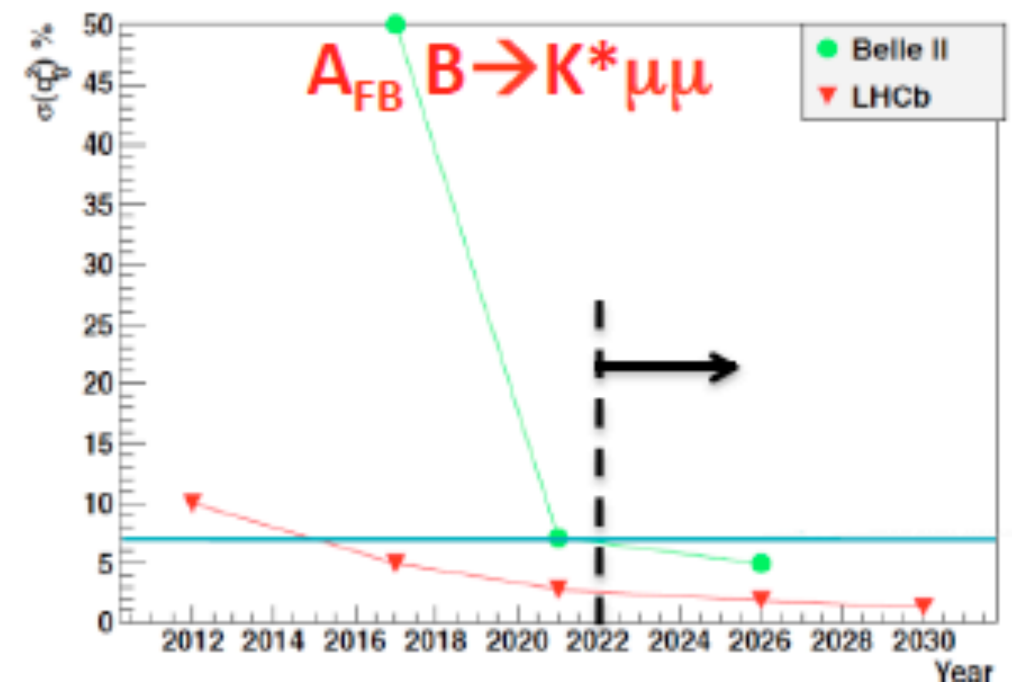

IUPAC Periodic Table of the Elements
Key
Symbol
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Uut Fl Uup Lv Uus Uuo
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr

Nice prospects in the quark sector …

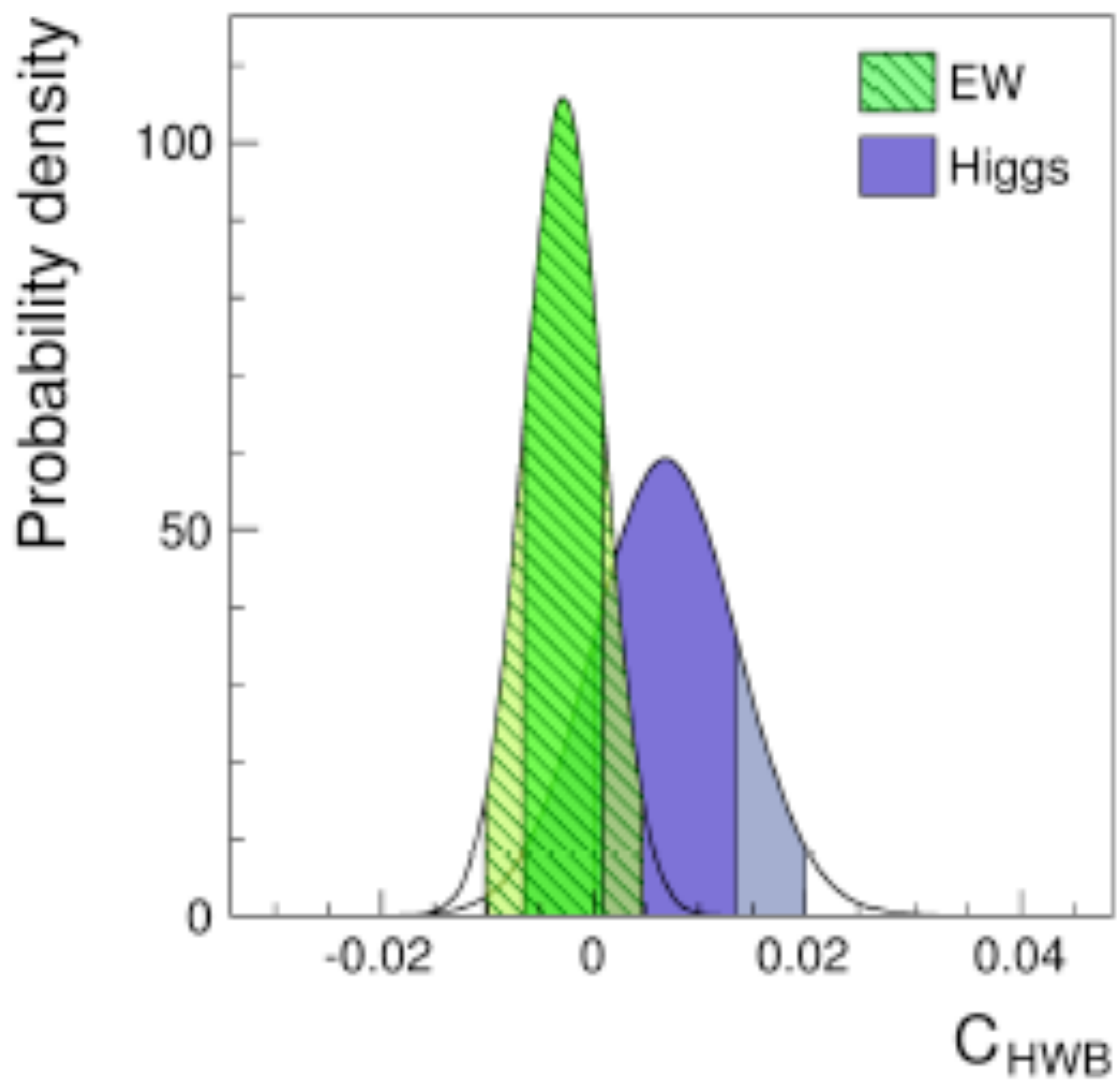






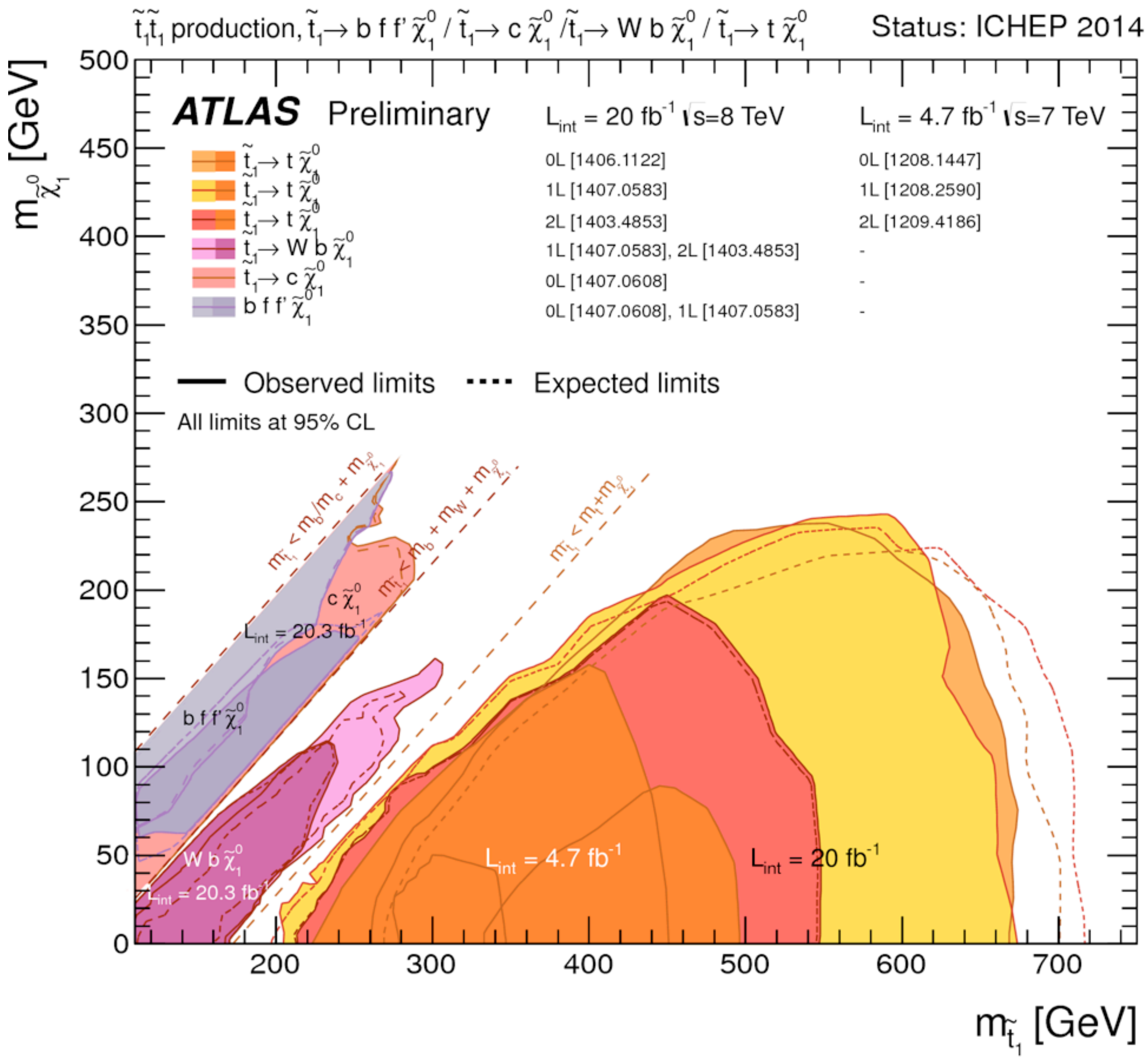


…but flattening out after ~2022



Probability density
100
50
0
-0.02
0
0.02
0.04
C_{HWB}
EW
Higgs

1. How solid are the "current" lower bounds on top-partner masses?

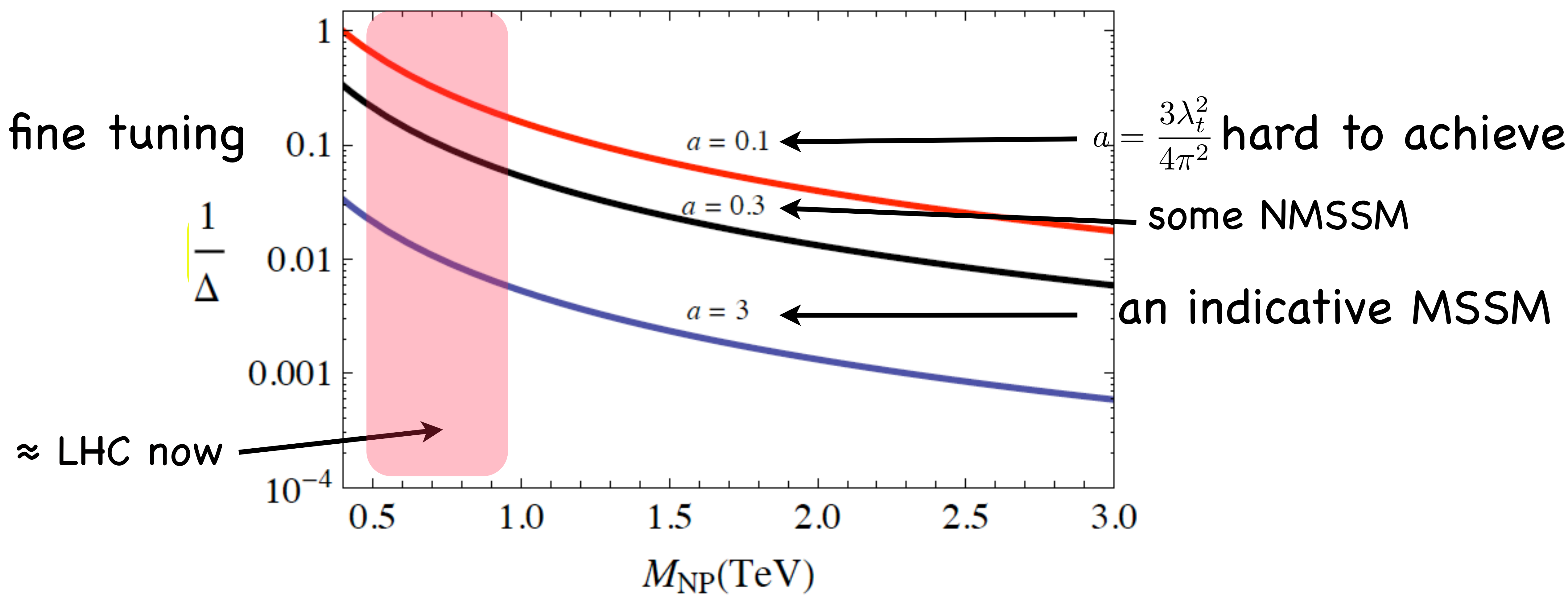


Holes that must be covered

2. How dramatic is the "little hierarchy problem"?

$$\Delta \equiv \frac{\delta m_h^2}{m_h^2} \approx a \frac{M_{NP}^2}{m_h^2}$$

model dependent

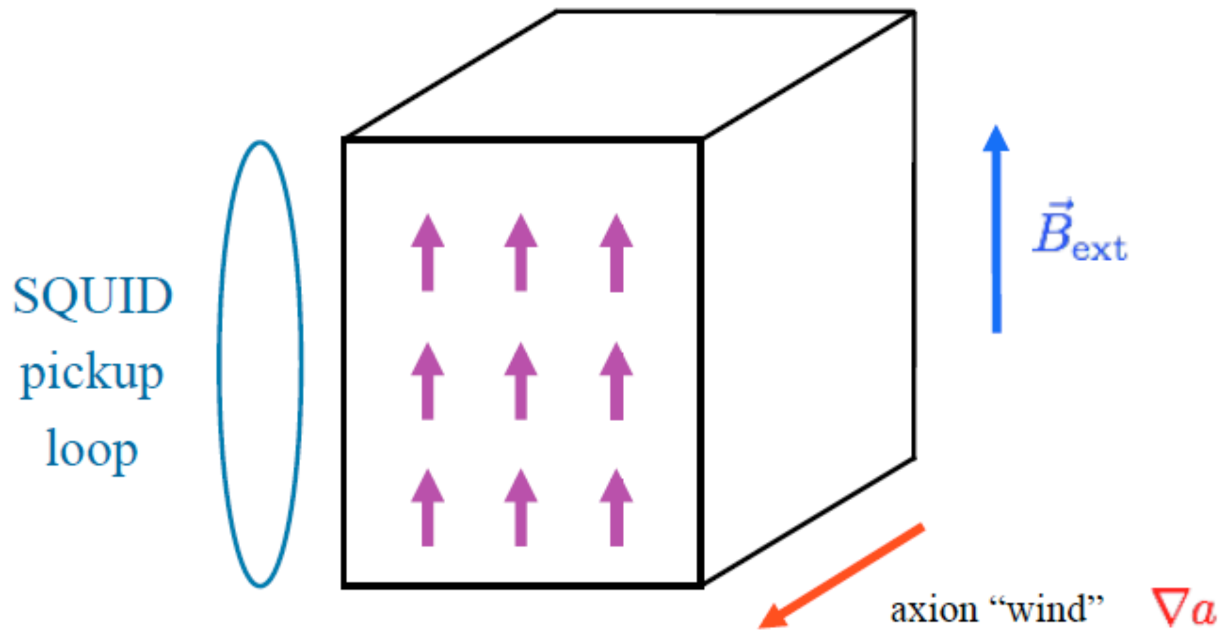


- Things do not work the way they were originally thought
- Not a serious problem at a fundamental level

LHC-13 TeV

In any way FCC-hh a must

Proposal 1 (axion DM wind)



on electron spins
B, Cerdonio, Fiorentini, Vitale 1989

on nucleon spins
Graham, Rajendram 2010
CASPEr 2014

Solving Block eq.s, at resonance $m_a =$

$$\xrightarrow{e}\ 2\gamma_e B^{ext} \approx 10^{-4}\ eV \frac{B^{ext}}{T}$$

$$\xrightarrow{N}\ 2\gamma_N B^{ext} \approx 10^{-7}\ eV \frac{B^{ext}}{T}$$

$$M_T = \gamma^2_{e,N} B^{eff}_{e,N} n_S \tau \cos{(m_a t)}$$

$$\xrightarrow{N}\ 10^{-19} T\ (m_a = 10^{-7}\ eV,\ \tau = 0.1\ sec)$$

$$\xrightarrow{e}\ 10^{-21} T\ (m_a = 10^{-4}\ eV,\ \tau = 10^{-6}\ sec)$$

$$\tau = min(\tau_a, \tau_{rel}, \tau_R)$$

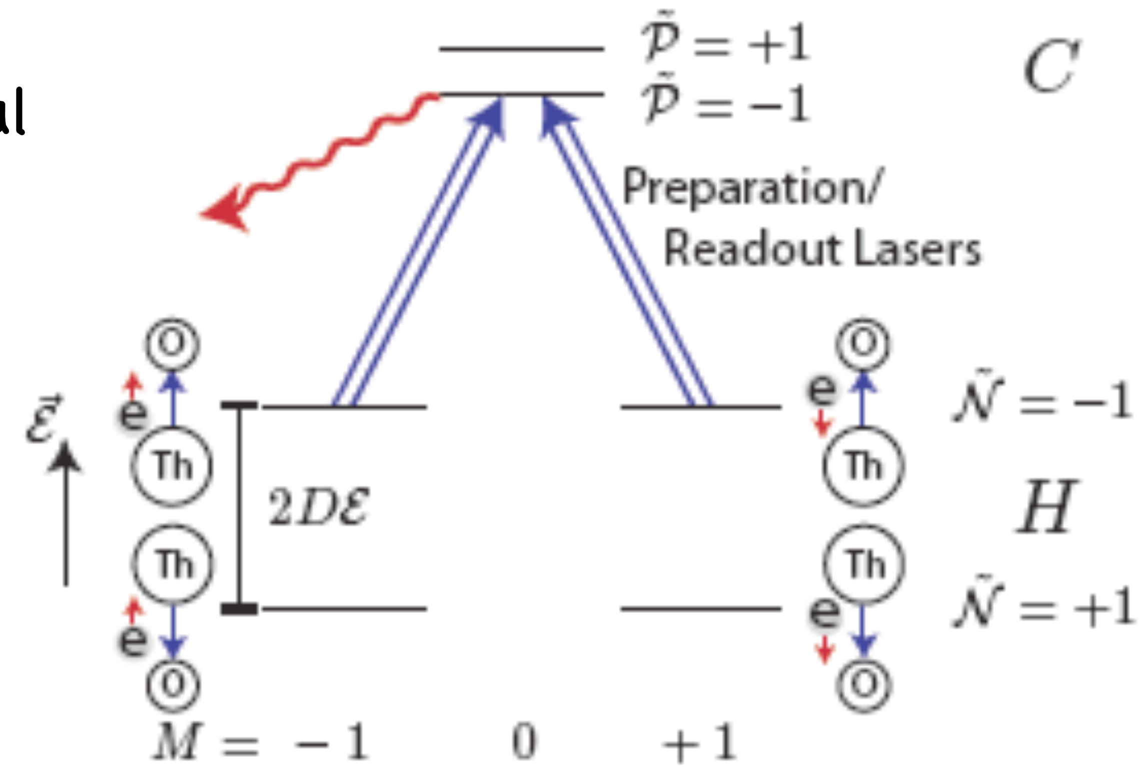
$$n_S = 10^{22}/cm^3$$

Electron Electric Dipole Moment

$$\vec{d}_e \xrightarrow{CP} -\vec{d}_e$$

C = charge conjugation P = parity

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



$$U = -\vec{d}_e \cdot \mathcal{E}_{eff}$$

$$\mathcal{E}_{eff} = 84\ GV/cm$$

$$d_e = (-2.1 \pm 3.7 \pm 2.5) \cdot 19^{-29}\ e \cdot cm$$