

# 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)

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

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

The synthetic nature of Particle Physics

# 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

$\Psi_i =$

$J = 1/2$

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

$i =$

$J = 1$

$G_\mu^a(1978)$	$A_\mu(1905)$	$W_\mu(1984)$	$Z_\mu(1984)$
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$J = 0$

$h(2012)$
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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  $\Leftarrow 5$

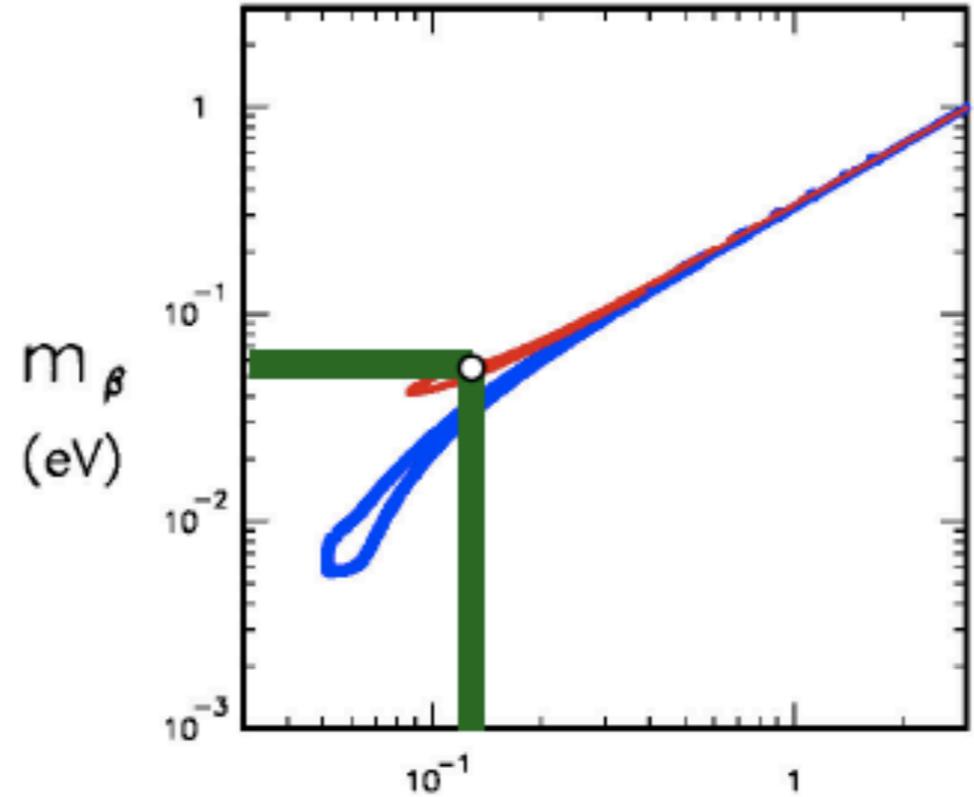
# 1

## Key neutrino measurements

$m_\beta$   
beta-decay  
endpoint

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

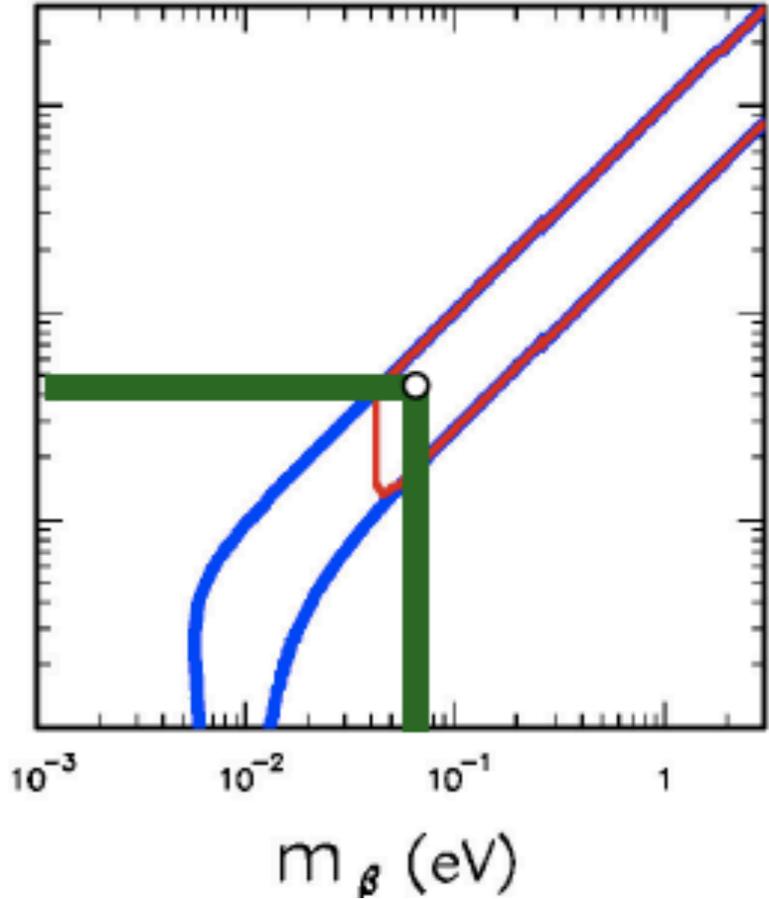
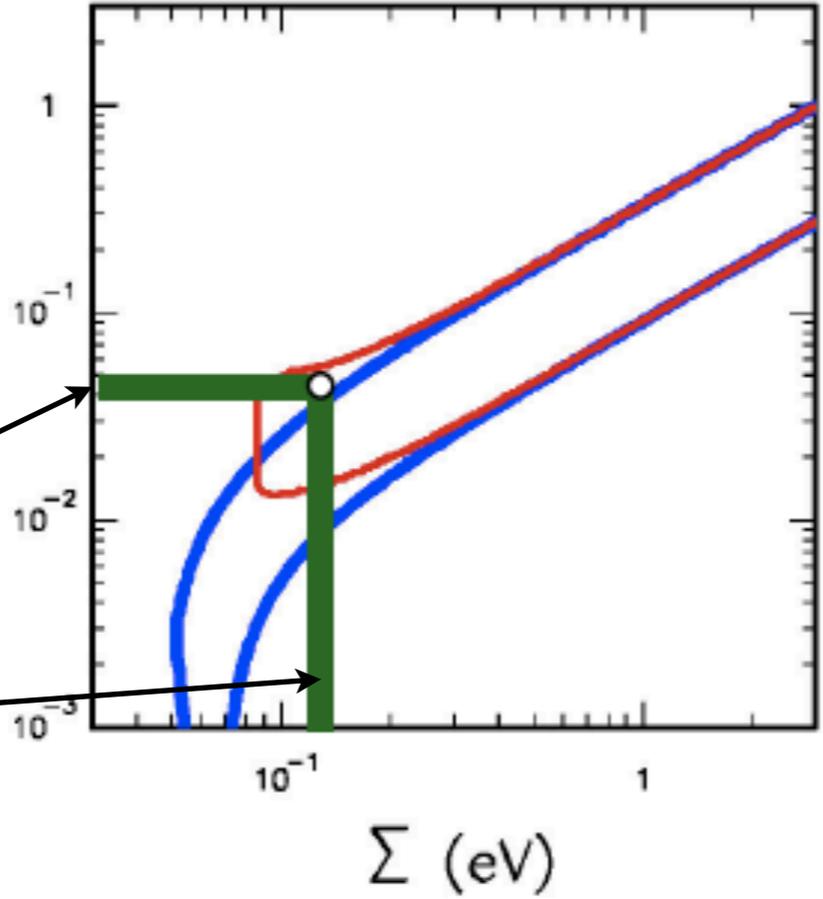
$\Sigma = m_1 + m_2 + m_3$   
large scale  
structures



$2\sigma$  bounds  
from current knowledge  
of oscillations only

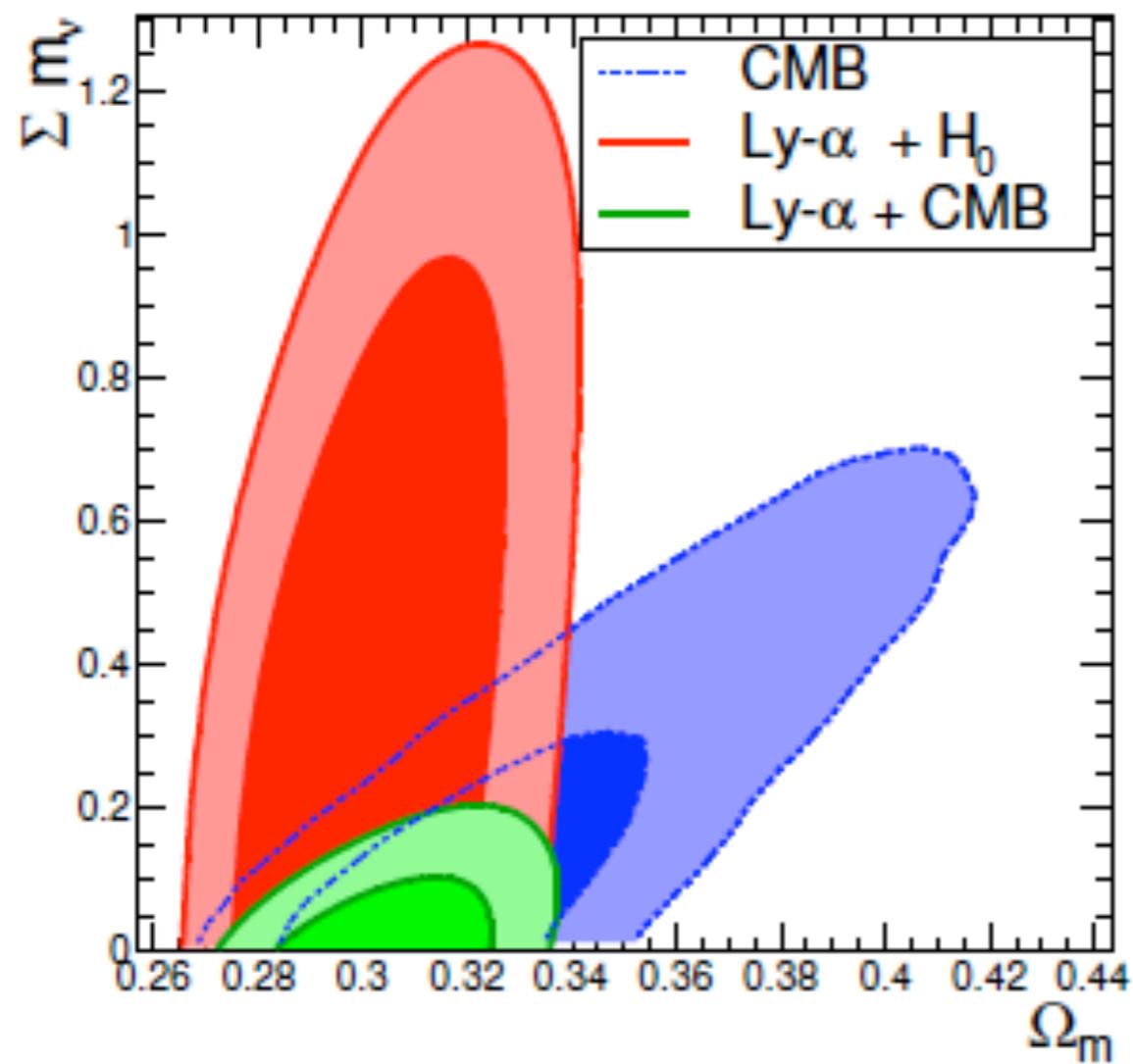
Lisi et al

— normal hierarchy  
— inverted hierarchy

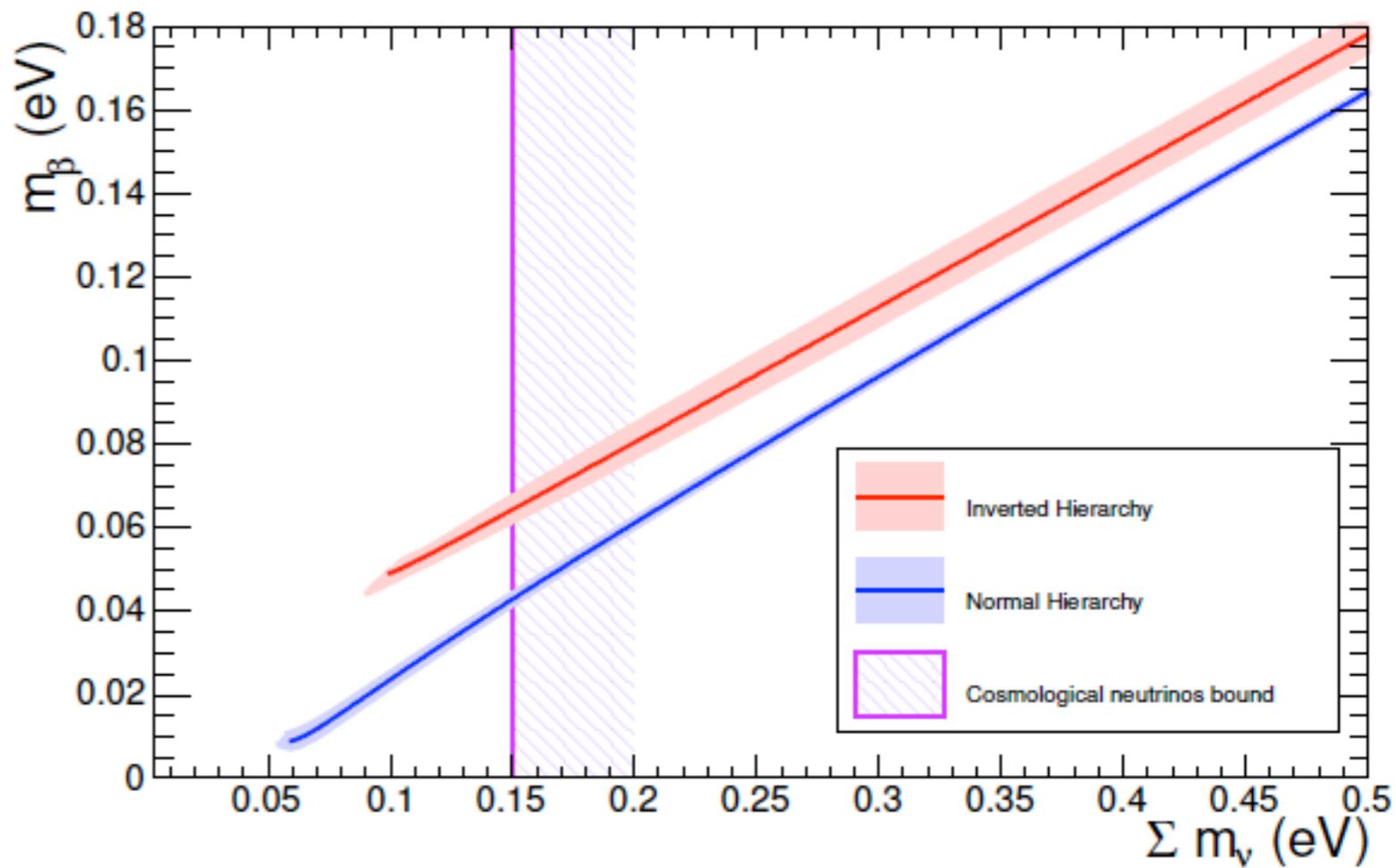


hypothetical measurements

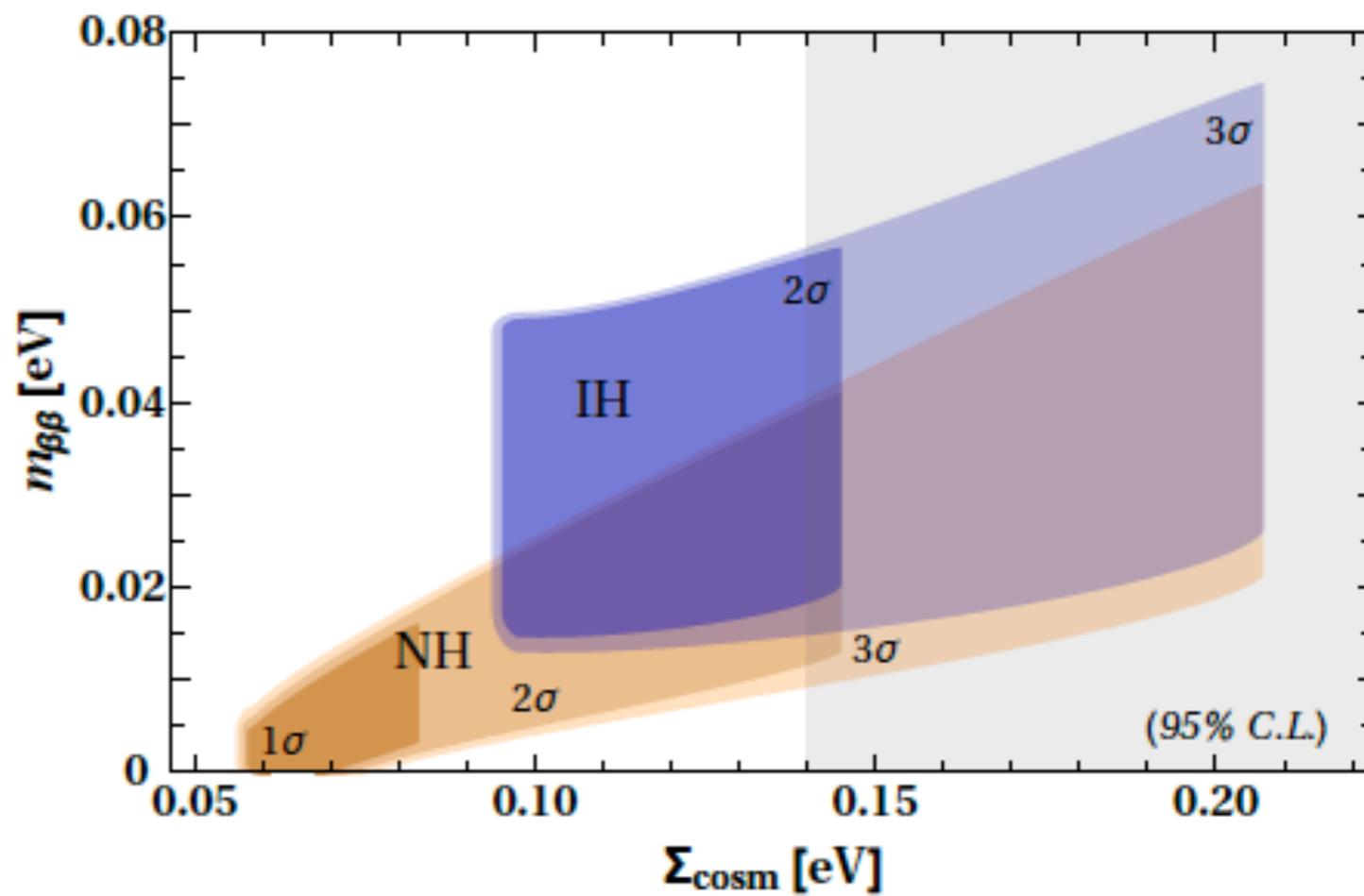
# $\Sigma m_\nu$ determination



Palanque-Delabrouille et al 2015

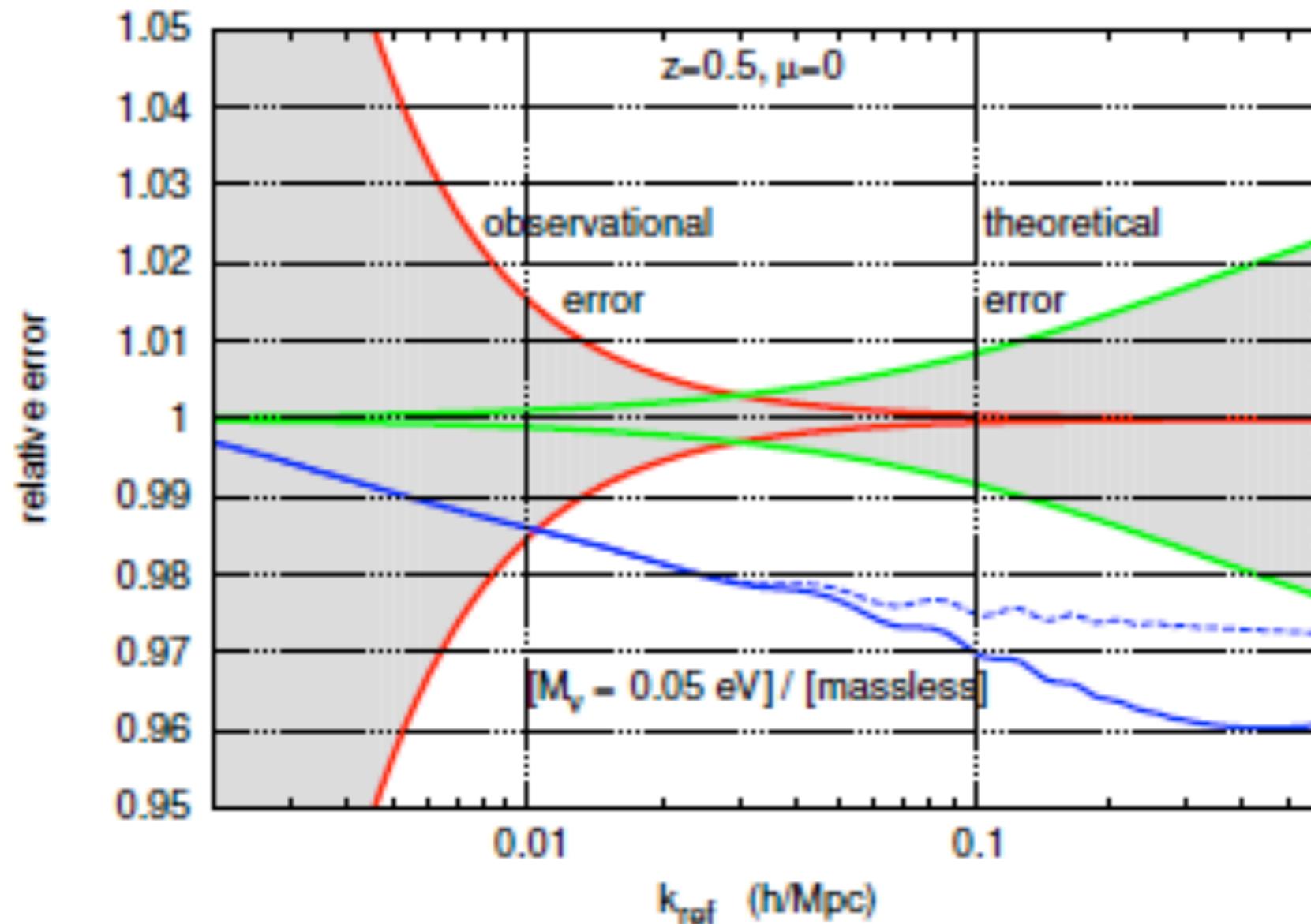


Dell'Oro et al 2015



- 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

- Not independent on “priors” but still highly significant

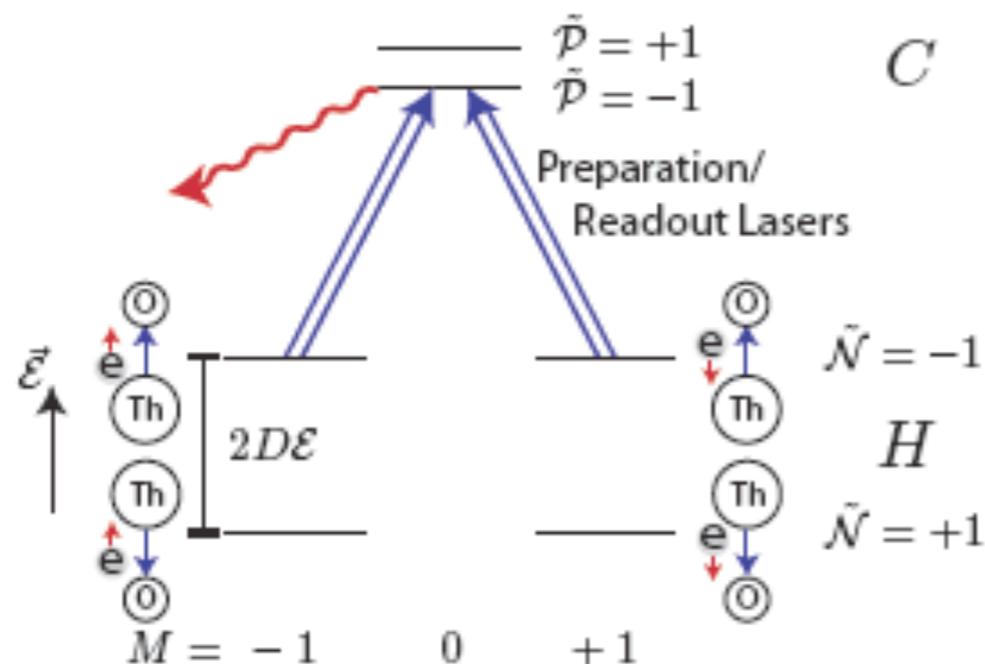
# 2

## Electric Dipole Moments

in absence of other CPV operators

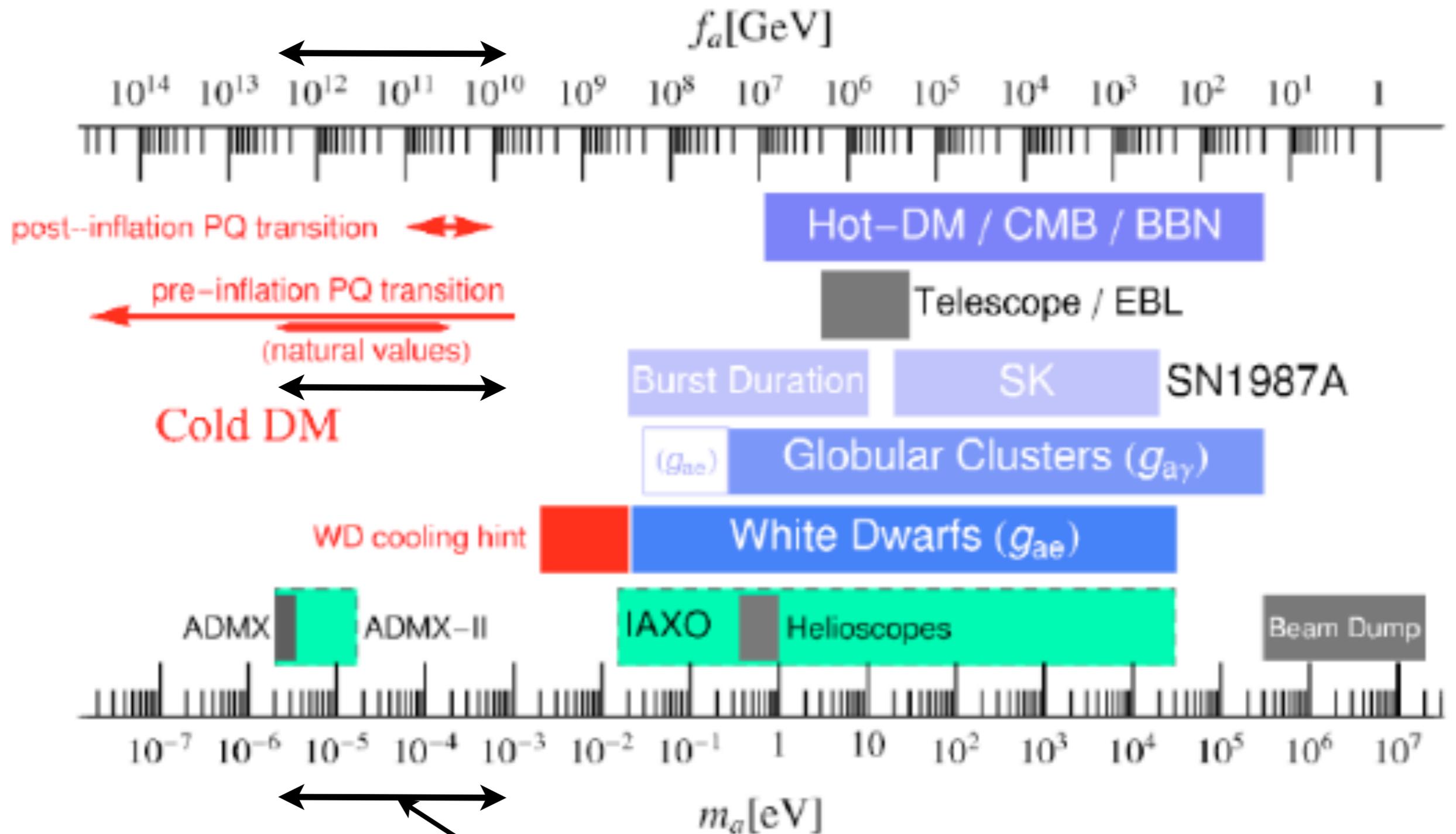
	limit (e cm)	year	SM (e cm)
electron	$8.7 \cdot 10^{-29}$	2013	$\sim 10^{-38}$
neutron	$2.9 \cdot 10^{-26}$	2006	$\sim 10^{-31}$ (*)

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



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

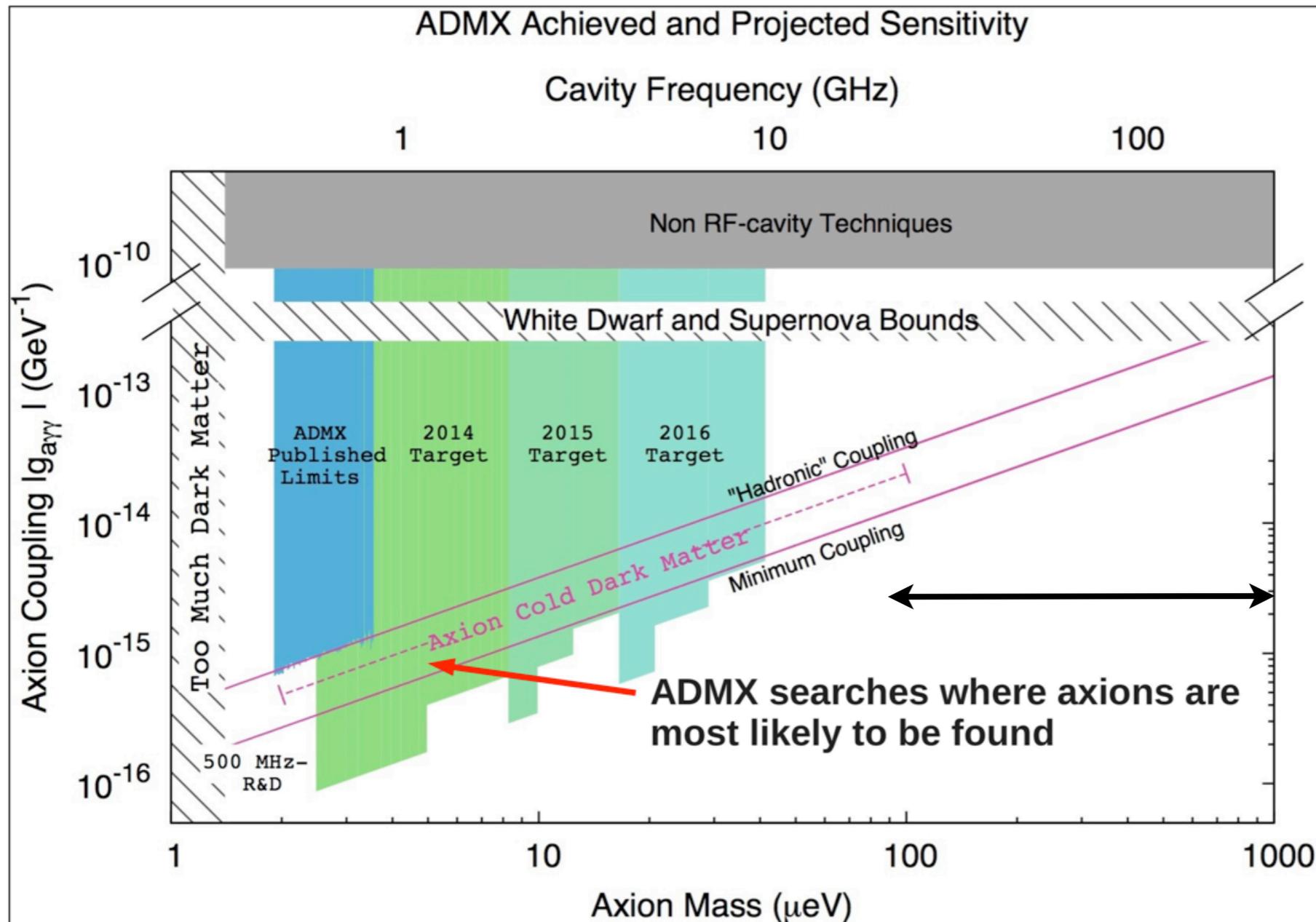
$\theta < 10^{-16}$   $\Leftrightarrow$  axions  $\Leftrightarrow$  Cold DM



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

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

$$g_p = A_\Psi \frac{m_\Psi}{f_a} \quad \left( g_s = 10^{-(12 \div 17)} g_p \frac{GeV}{m_\Psi} \right) \quad \begin{array}{l} \text{DFSZ} \\ \text{KSVZ} \end{array}$$

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

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

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

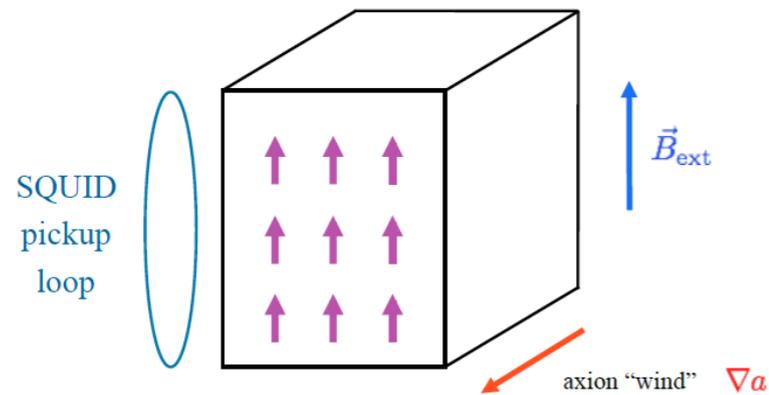
# Summary on proposed exp.s using NMR/EMR

## CASPER axion wind/NMR

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

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

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

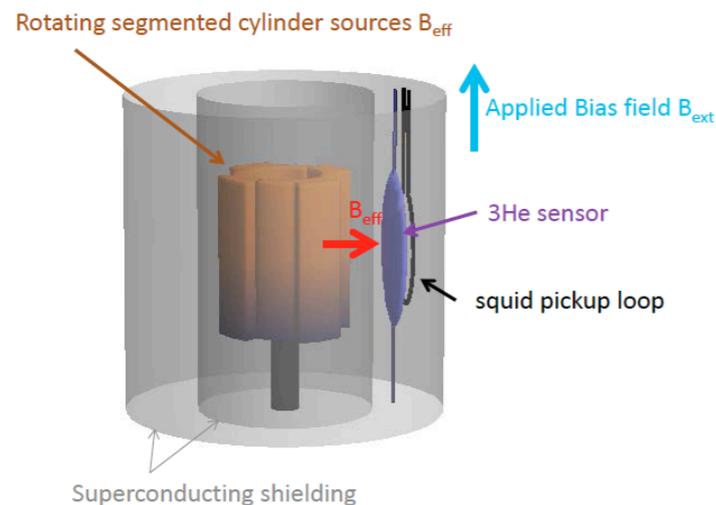


## static source NMR

not limited in frequency  
but size of the effect smaller

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

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



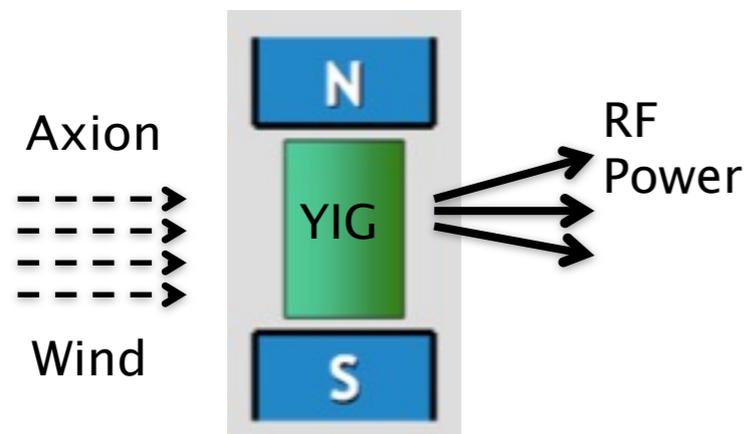
## QUAX axion wind/EMR

frequency OK

detection method still under scrutiny

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

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



3

## vacuum stability

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

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

$$m_W = gv/\sqrt{2}$$

$$m_H = 2\sqrt{\lambda}v$$

$$m_t = y_t v$$

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

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

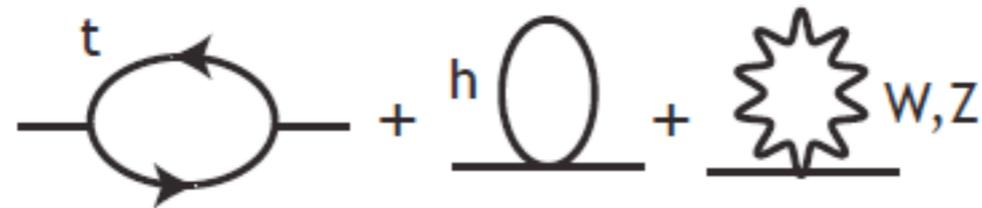
$\Rightarrow$  A second minimum of  $V$  at  $\phi \gtrsim 10^{11} \text{ GeV}$   
to which  $v$  should tunnel in a very long time ( $\gg t_{Univ}$ )

- 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?



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

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

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

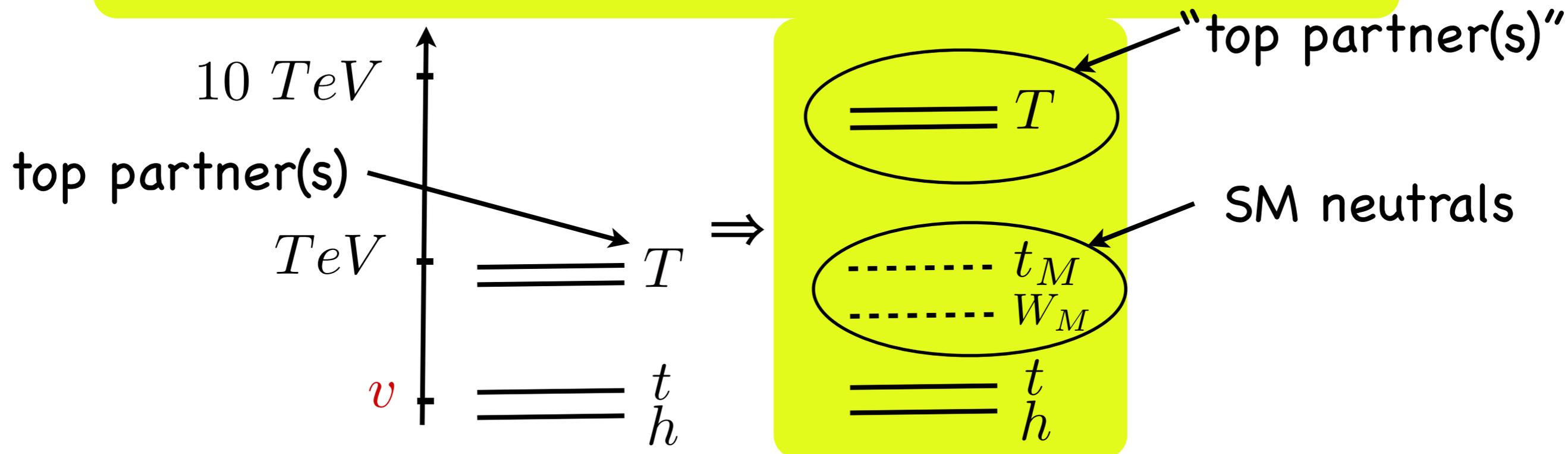
(we have become more prudent!)

# 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")

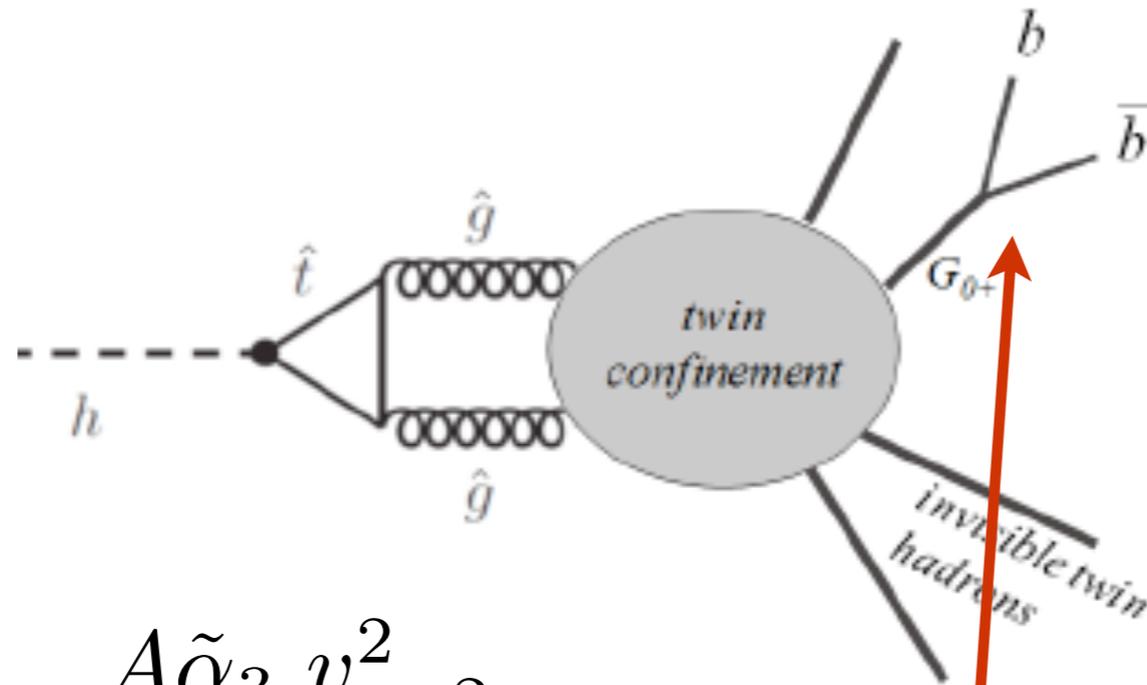
$$SU(3) \times SU(2) \times U(1) \Rightarrow (SU(3) \times SU(2) \times U(1))^2$$

can conceive a situation like



# LHC signatures of light mirror glueballs

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



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

$A = 1 \div 6$

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

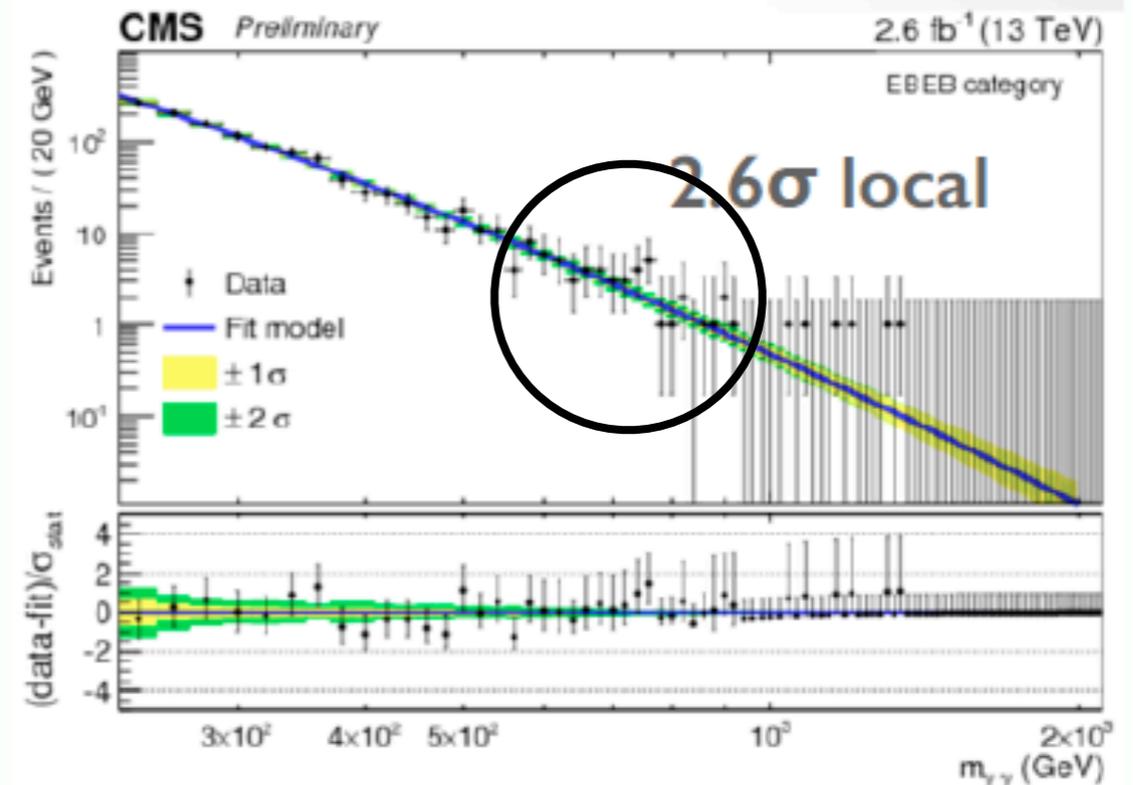
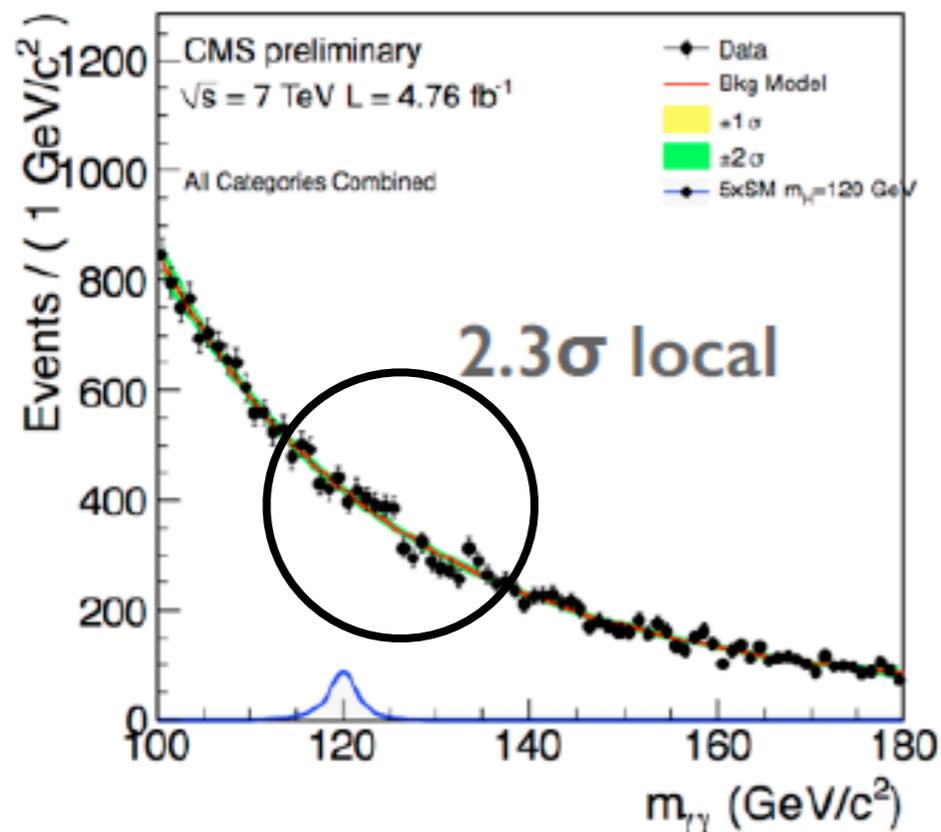
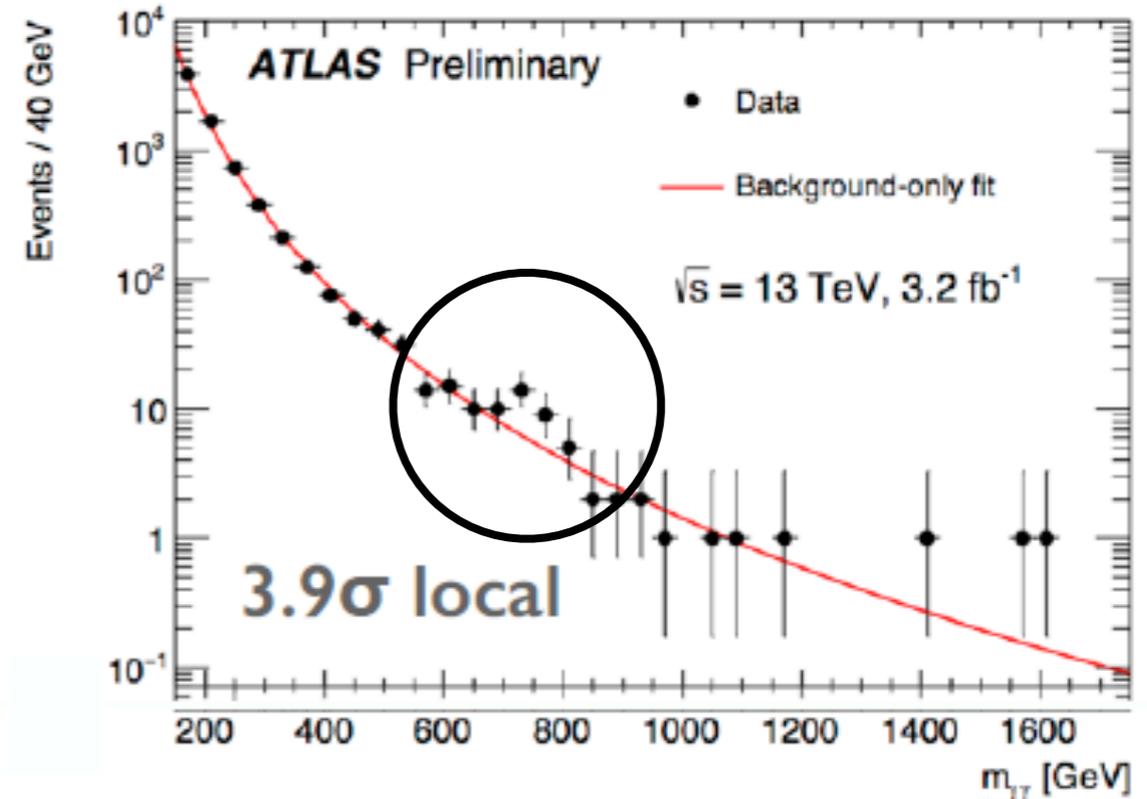
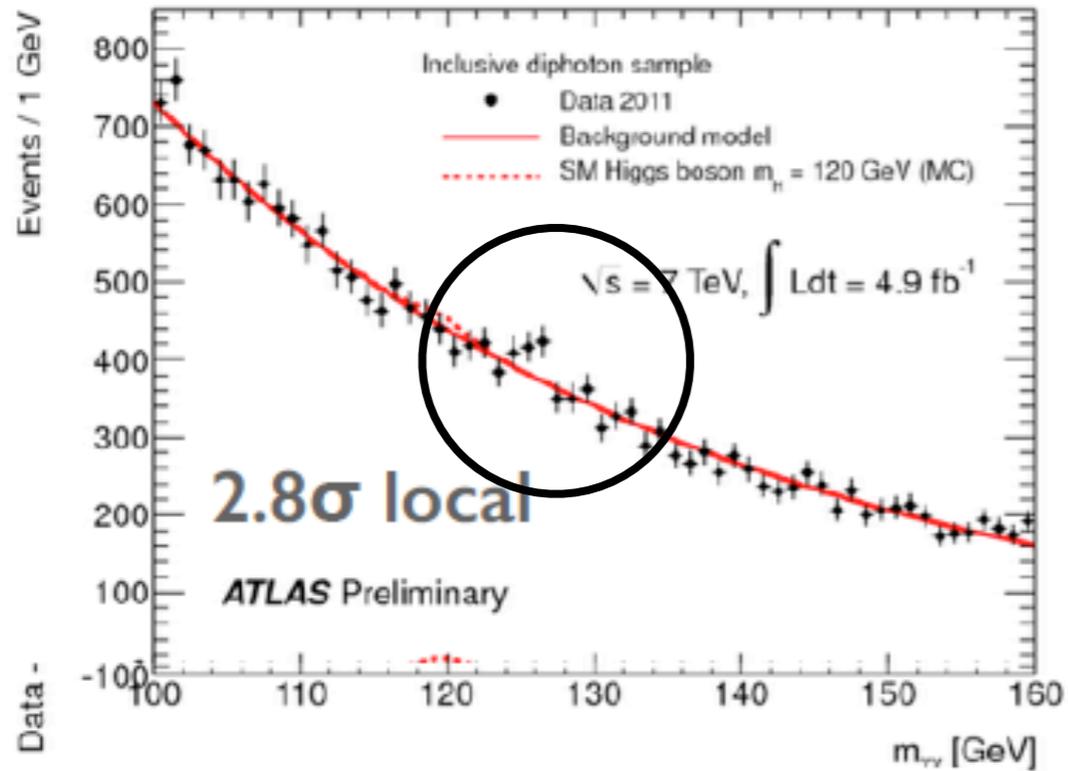
$\tilde{G}_{0+} \rightarrow$  SM via Higgs mixing

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

# Only one scalar: the Higgs boson?

Dec 2011

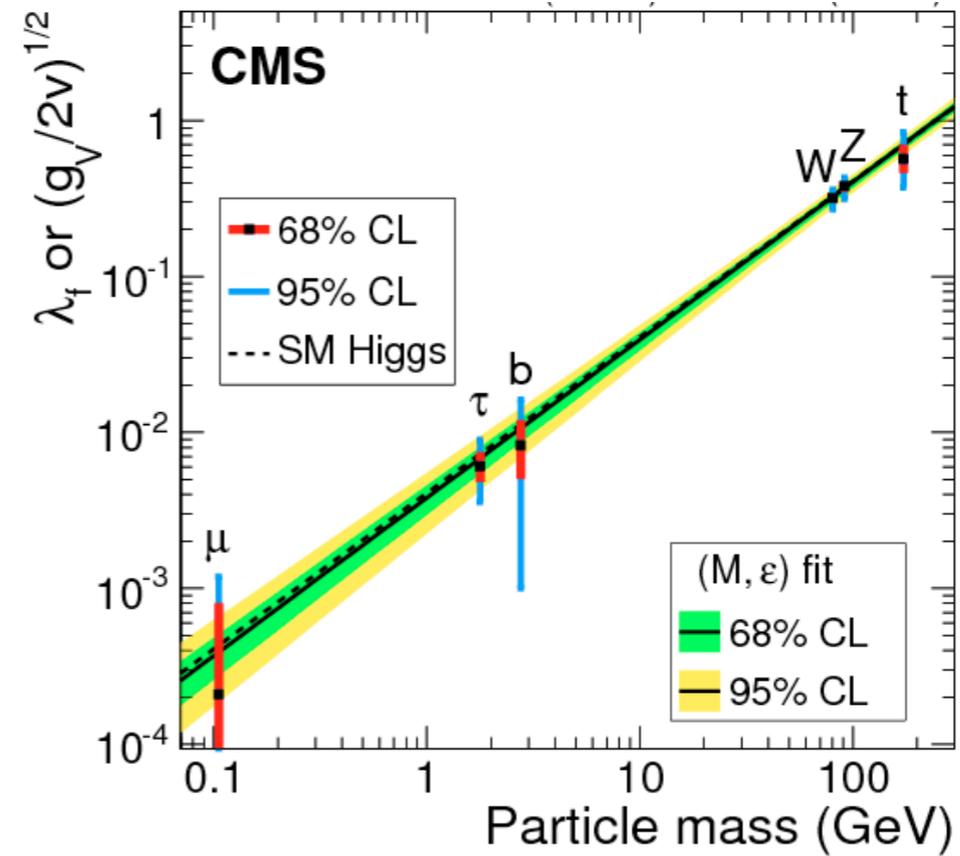
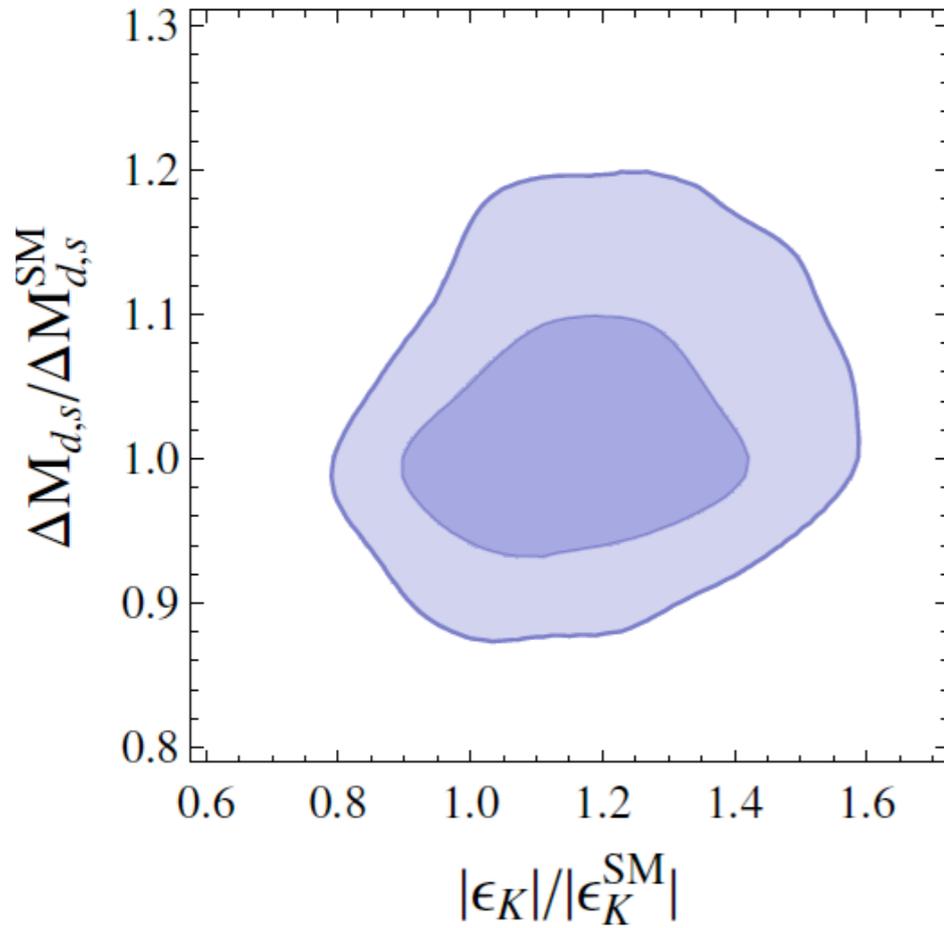
Dec 2015



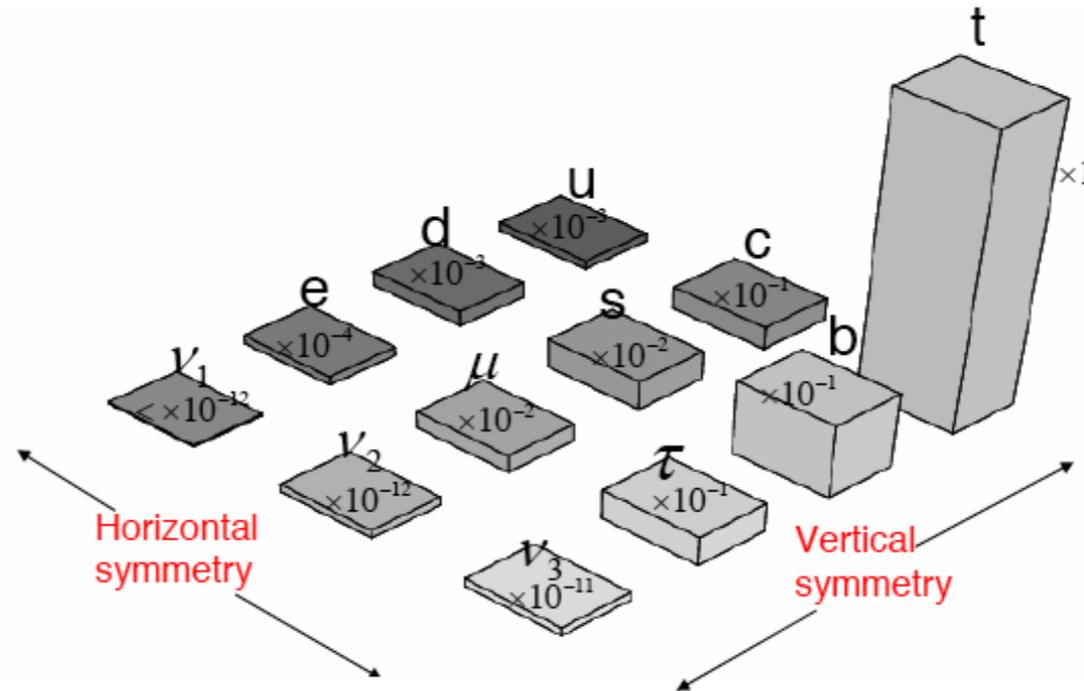
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# The flavour paradox

Yukawa couplings: a piece of physical reality



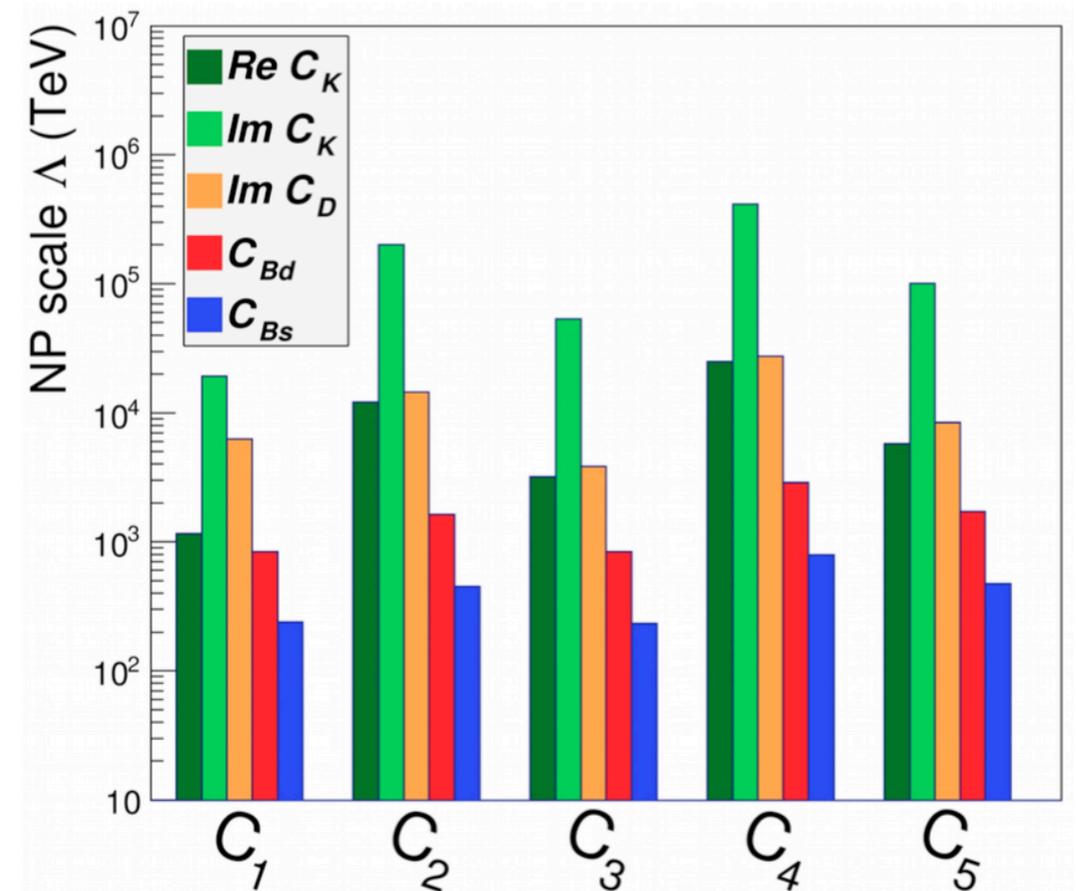
as opposed to:



?!?!?

# 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*  $B \rightarrow D(D^*)\tau\nu$   $B \rightarrow K\mu^+\mu^-/e^+e^-$   $P'_5(B \rightarrow K^*\mu^+\mu^-)$

# B-physics "anomalies"

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

$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \rightarrow D^* \tau \nu)_{\text{exp}} / \mathcal{B}(B \rightarrow D^* \tau \nu)_{\text{SM}}}{\mathcal{B}(B \rightarrow D^* \ell \nu)_{\text{exp}} / \mathcal{B}(B \rightarrow D^* \ell \nu)_{\text{SM}}} = 1.28 \pm 0.08$$
$$R_D^{\tau/\ell} = \frac{\mathcal{B}(B \rightarrow D \tau \nu)_{\text{exp}} / \mathcal{B}(B \rightarrow D \tau \nu)_{\text{SM}}}{\mathcal{B}(B \rightarrow D \ell \nu)_{\text{exp}} / \mathcal{B}(B \rightarrow D \ell \nu)_{\text{SM}}} = 1.37 \pm 0.18 ,$$

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

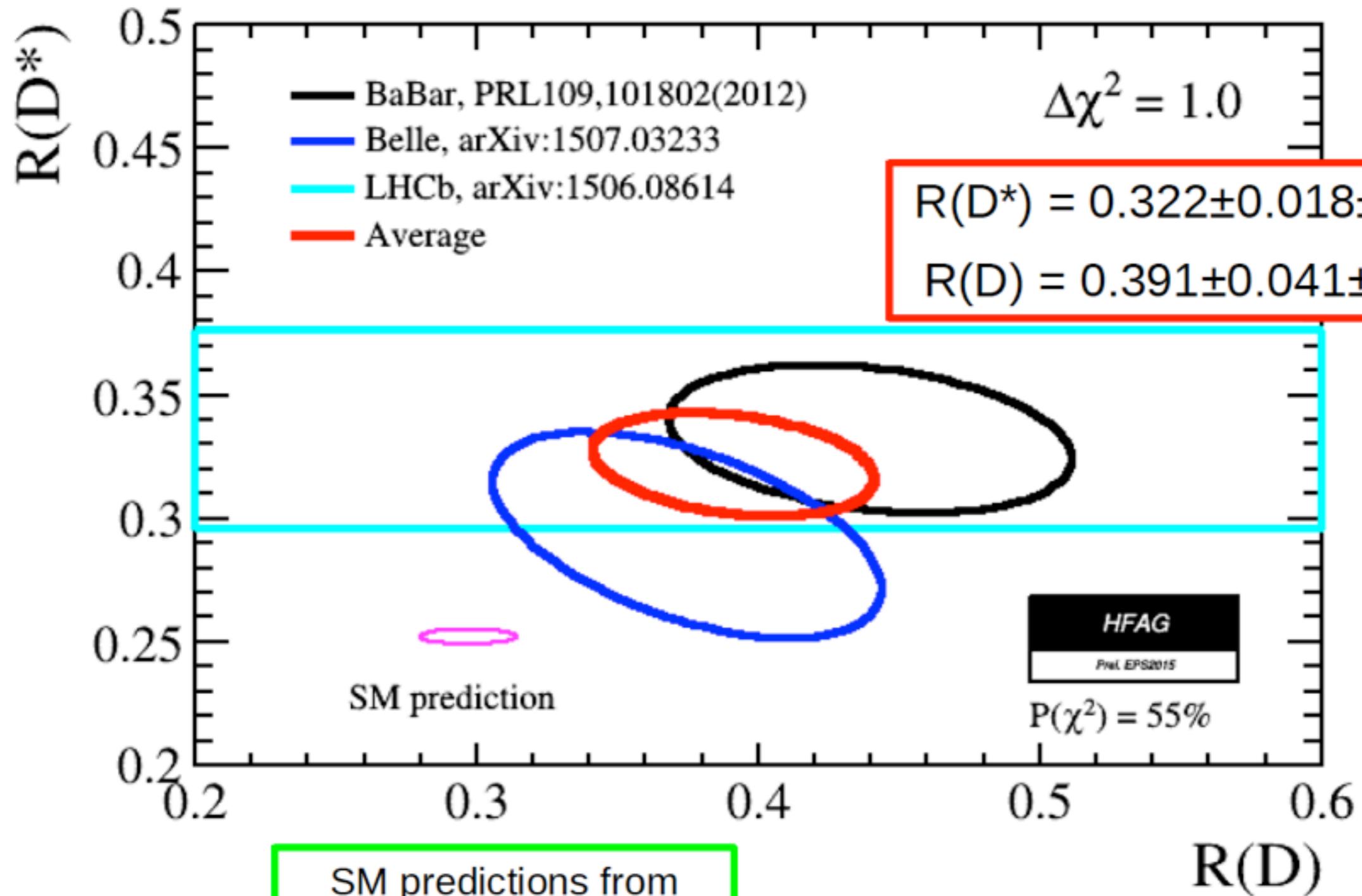
$$R_K^{\mu/e} = \frac{\mathcal{B}(B \rightarrow K \mu^+ \mu^-)_{\text{exp}}}{\mathcal{B}(B \rightarrow K e^+ e^-)_{\text{exp}}} \Big|_{q^2 \in [1,6] \text{ GeV}} = 0.745_{-0.074}^{+0.090} \pm 0.036$$

(could be related to the  $P'_5$  anomaly in the  $q^2$  distribution)

Both a 20 ÷ 30% deviation from the SM  
However tree (1) versus loop level (2)!

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

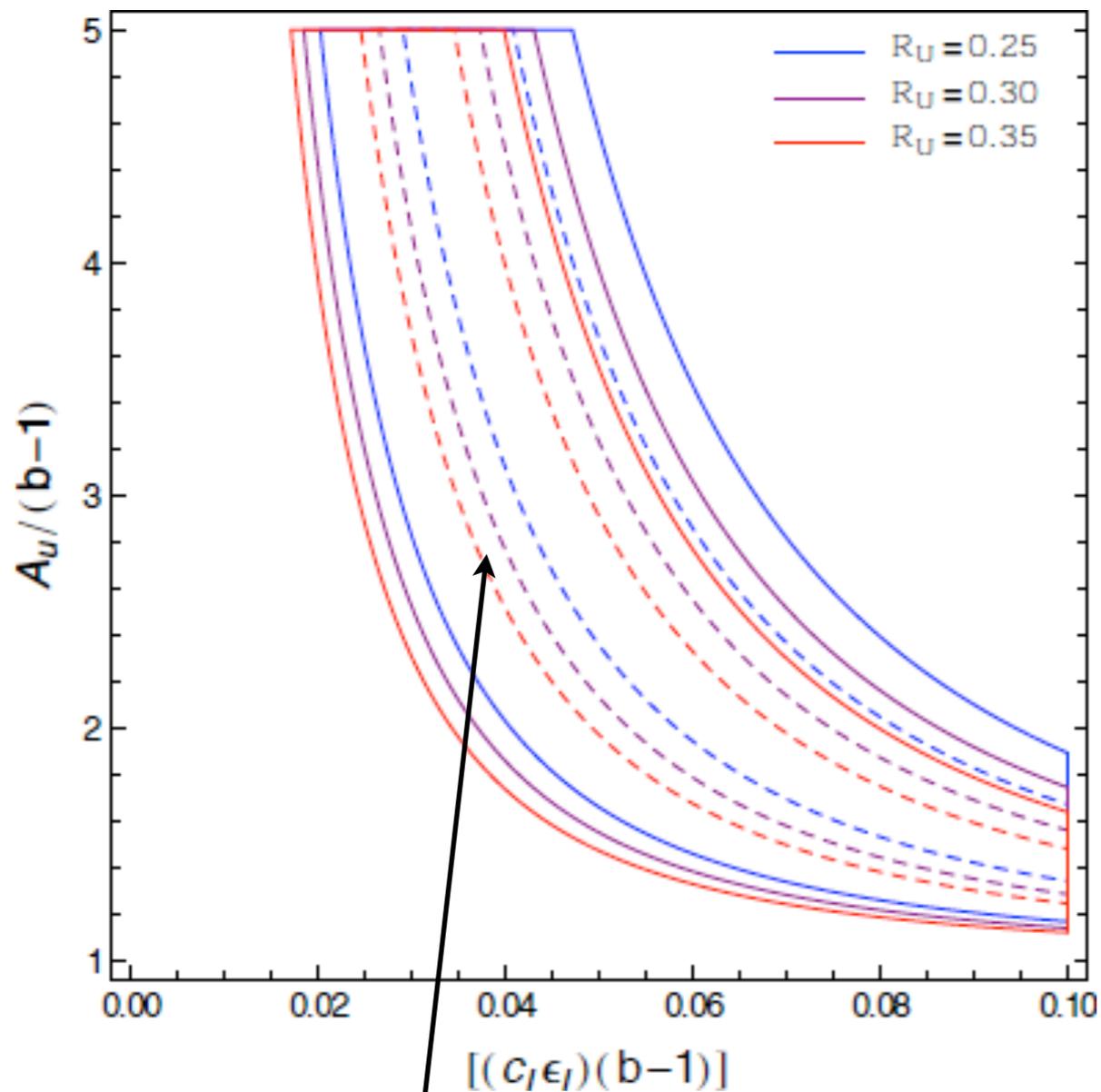
Tension with SM at  $3.9\sigma$



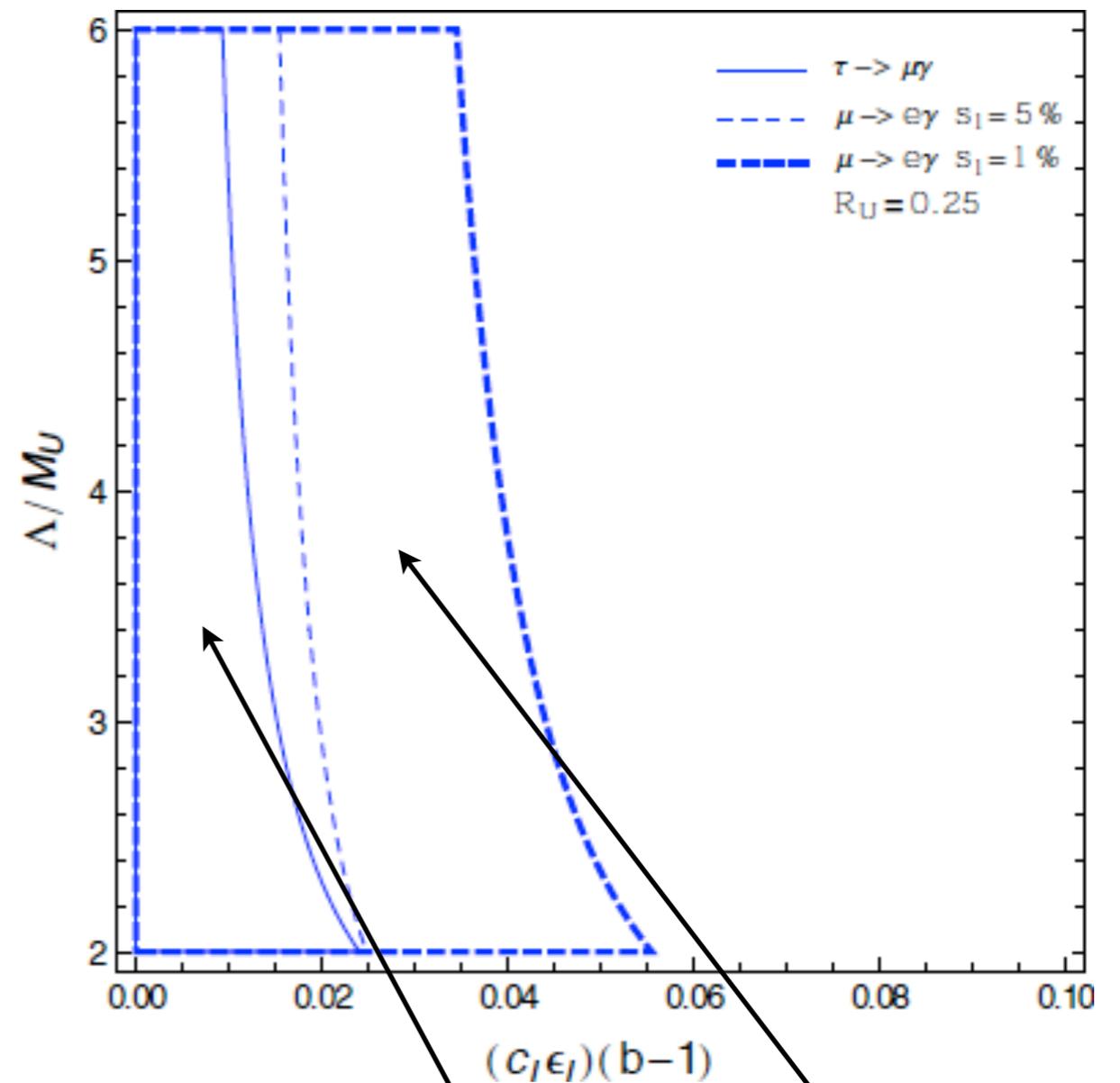
SM predictions from  
PRD 85 (2012) 094025

# Consistency with data (and expected signals)

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

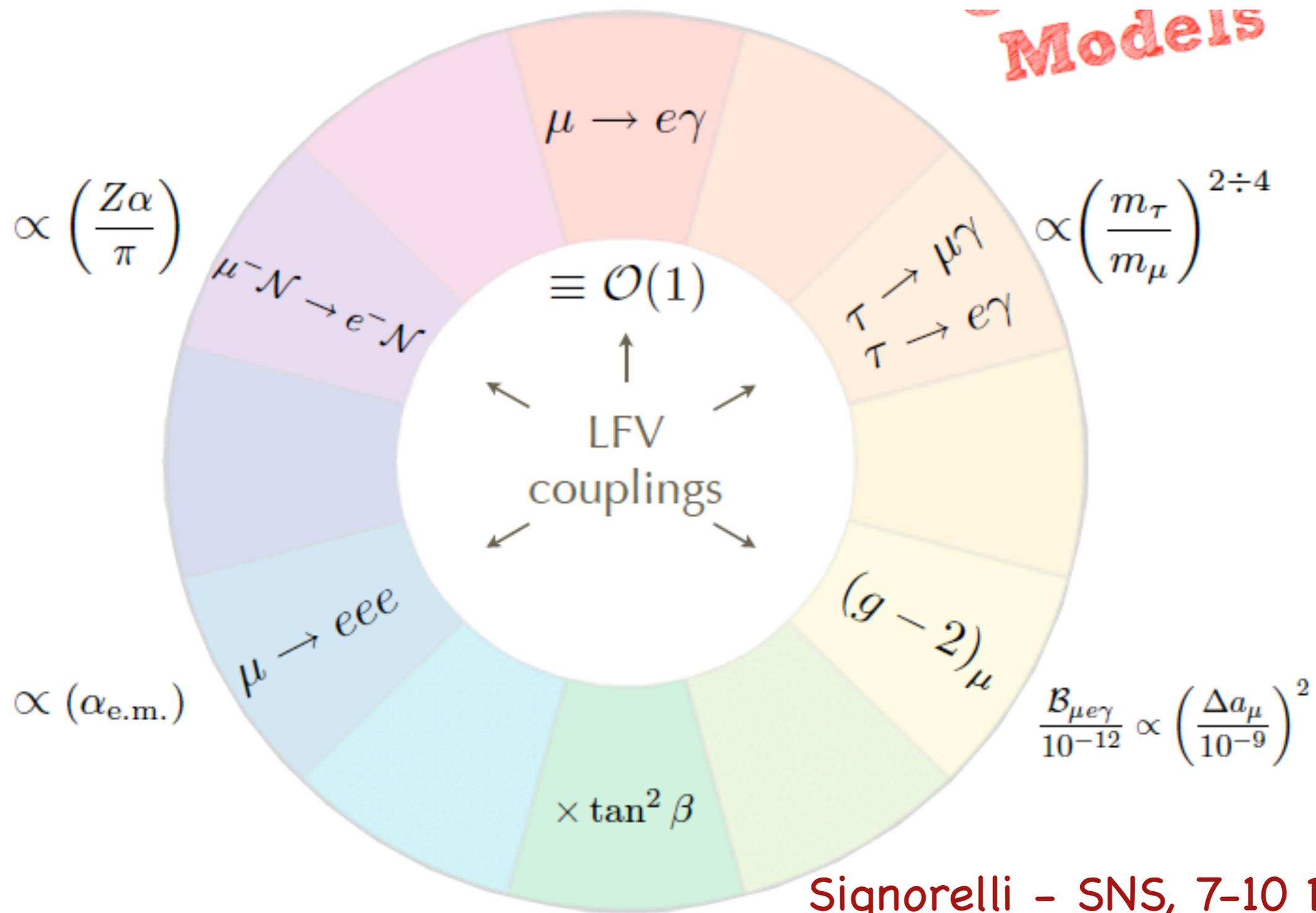


required by  $R_K^{\mu/e}$



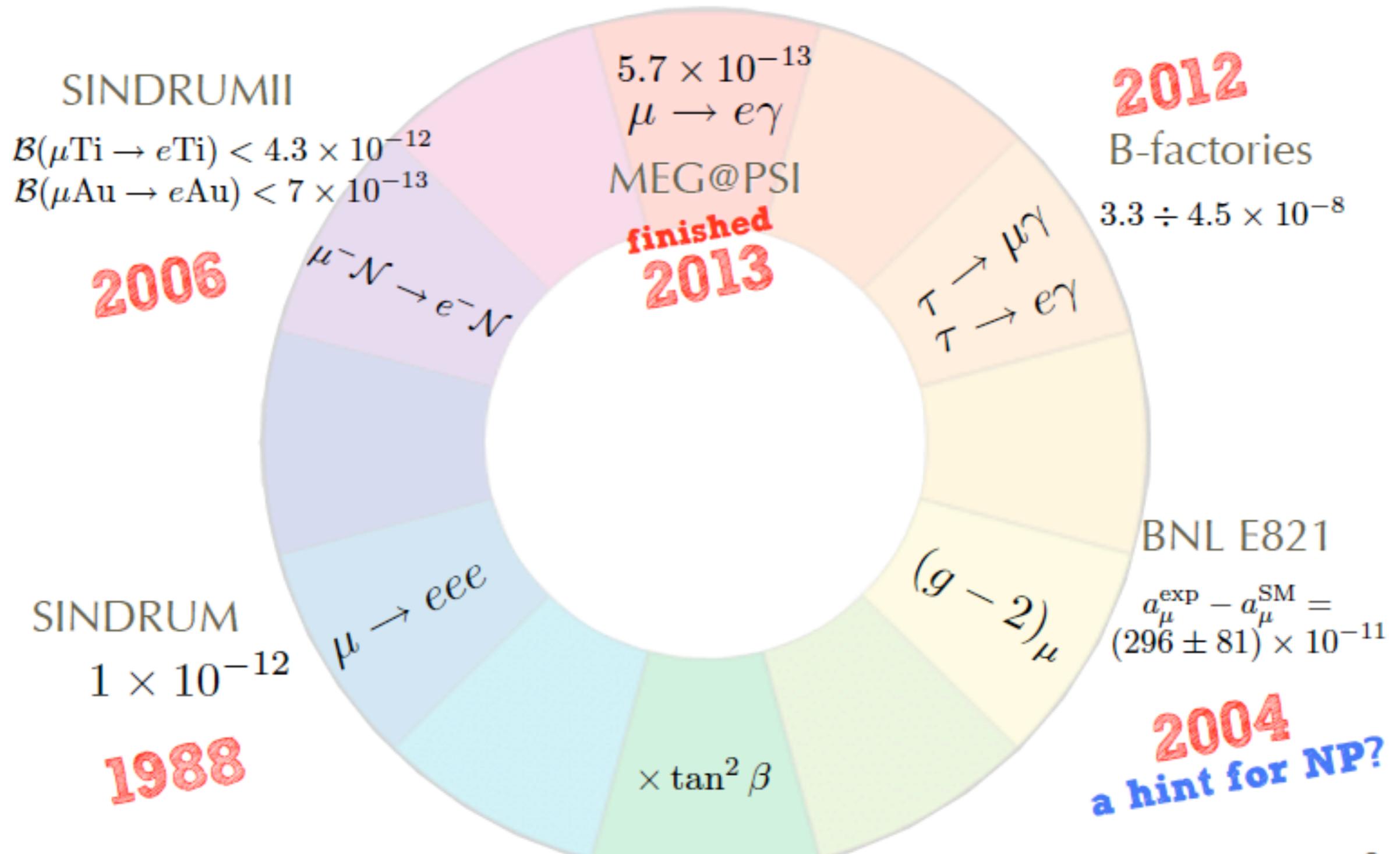
allowed by  $\tau \rightarrow \mu\gamma$   $\mu \rightarrow e\gamma$

# Lepton Flavour Violation



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?

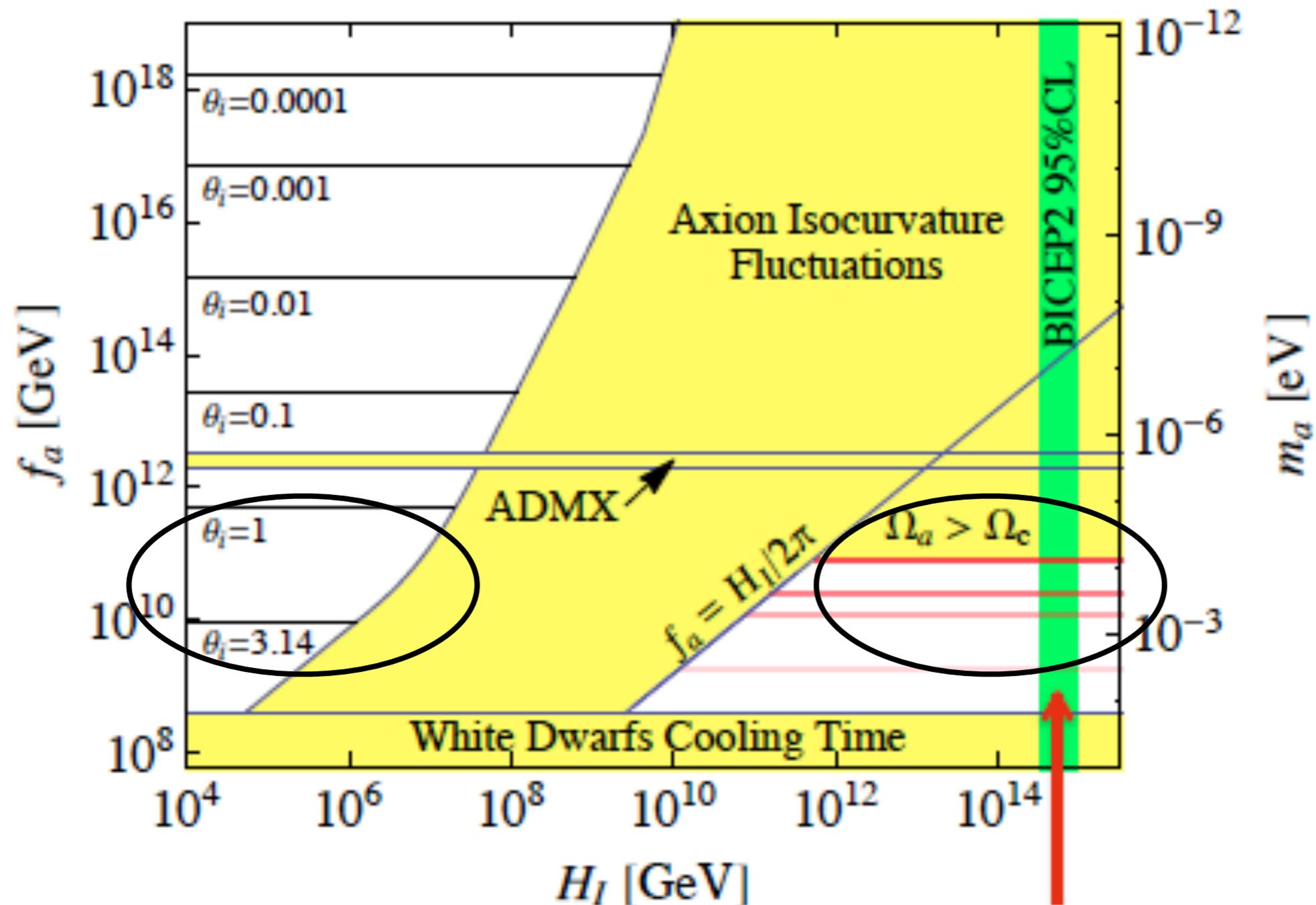
Vagnoni - SNS, 7-10 Dec 2014

- 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  $3000 \text{ fb}^{-1}$ , 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,  $50 \text{ fb}^{-1}$  vs  $3000 \text{ fb}^{-1}$
- 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  $\approx 1\%$

# Dark Matter: QCD Axions

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



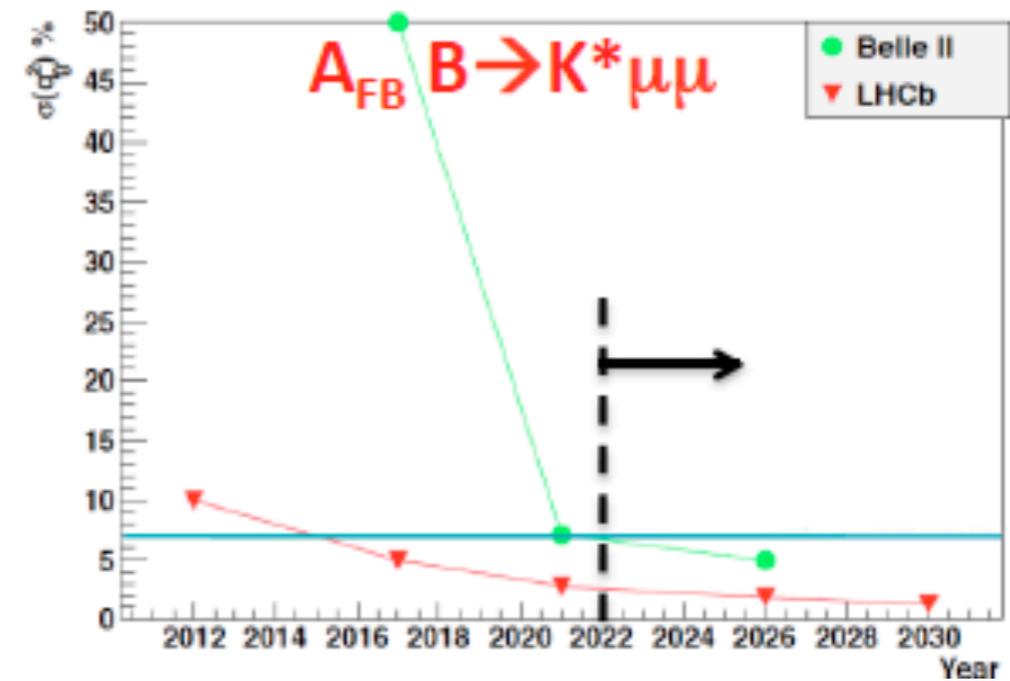
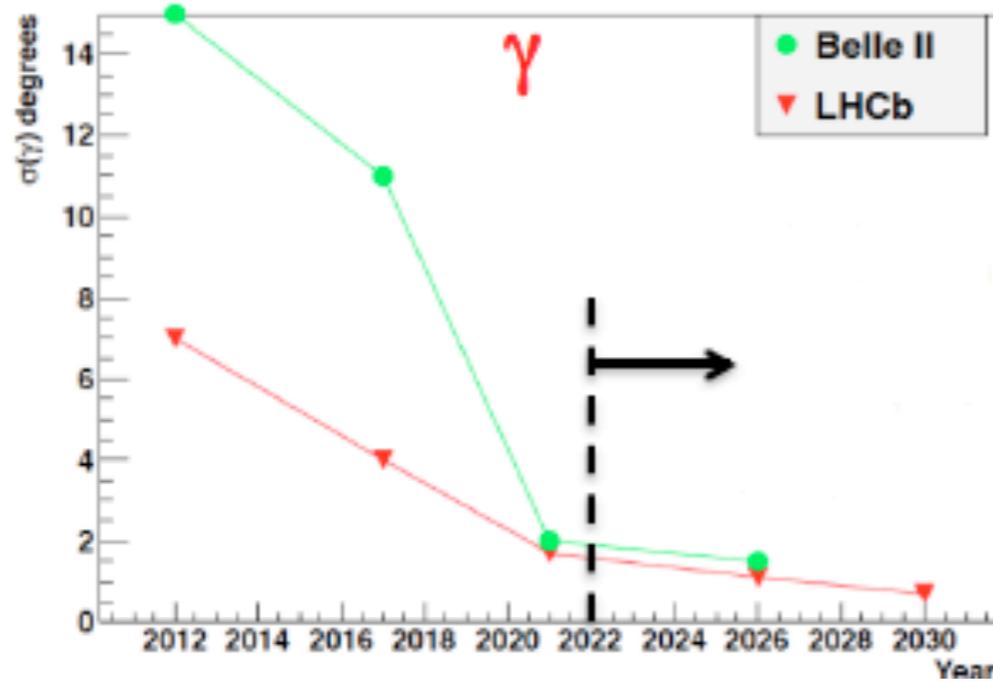
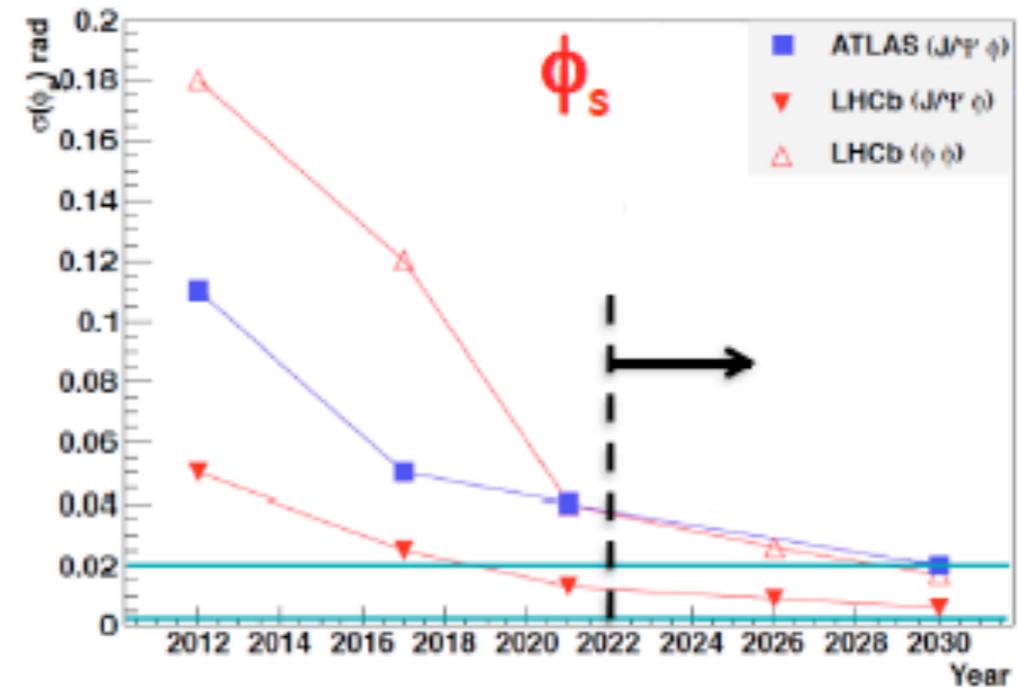
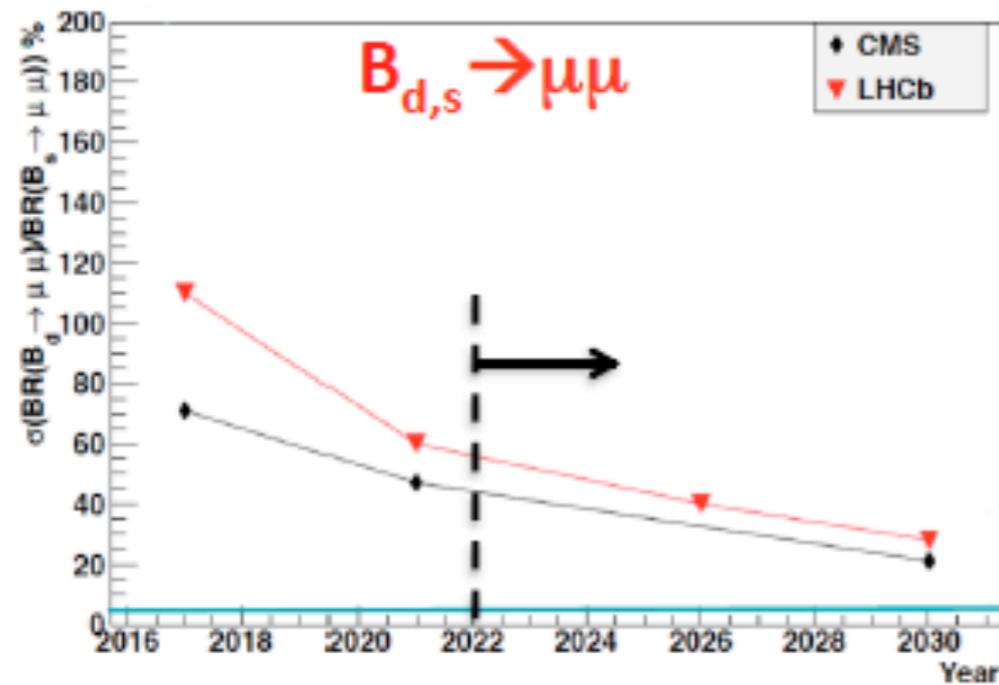
$m_a = 10^{-5} \div 10^{-3} \text{ eV}$  as the most interesting region

# IUPAC Periodic Table of the Elements

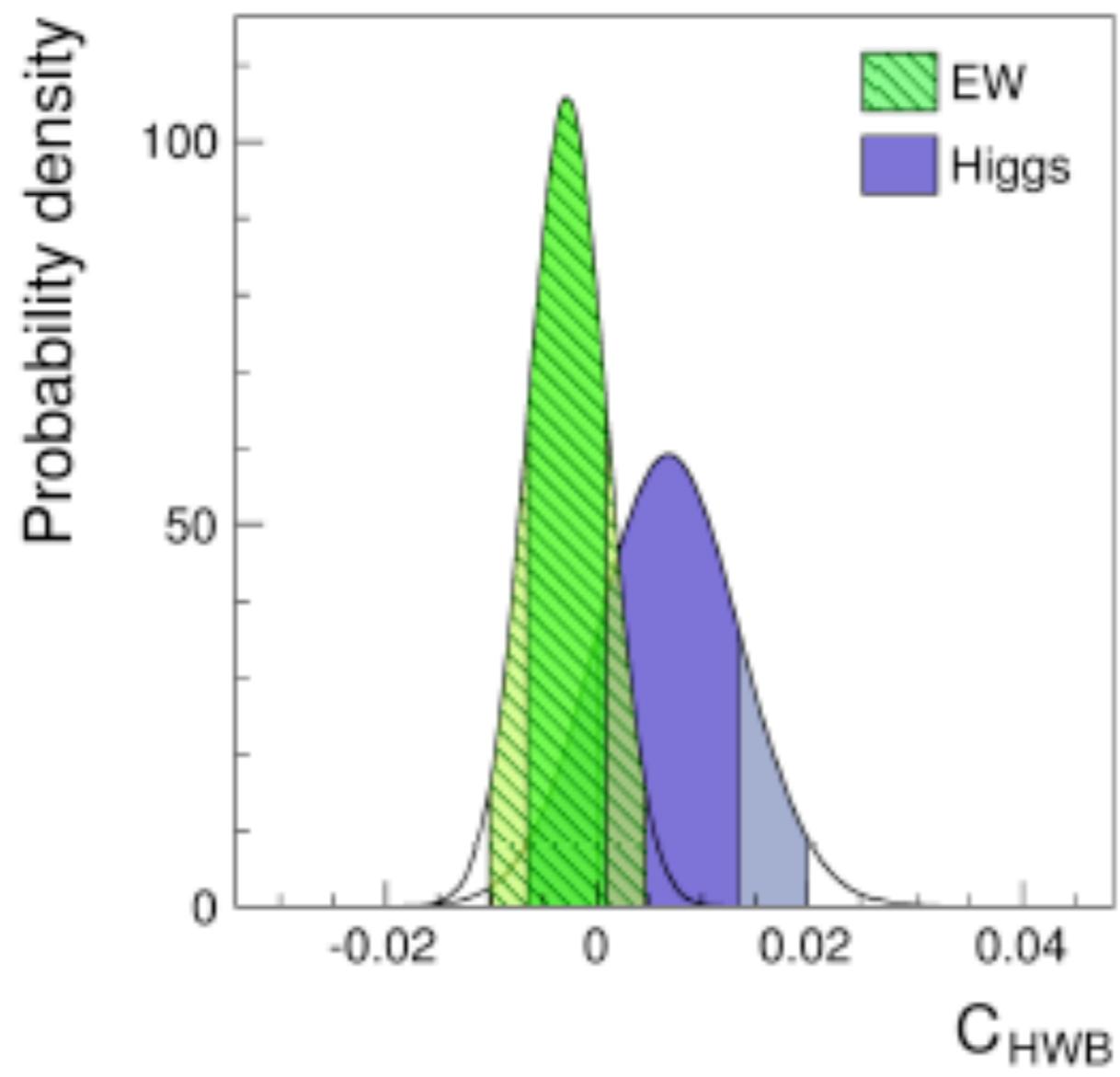
1		Key										13						18
1 <b>H</b> Hydrogen (1.007 9404)	2 <b>He</b> Helium (4.002 603)											5 <b>B</b> Boron (10.811)	6 <b>C</b> Carbon (12.010 7)	7 <b>N</b> Nitrogen (14.006 4)	8 <b>O</b> Oxygen (15.999 4)	9 <b>F</b> Fluorine (18.998 4)	10 <b>Ne</b> Neon (20.179 7)	
3 <b>Li</b> Lithium (6.941)	4 <b>Be</b> Beryllium (9.012 2)											11 <b>Al</b> Aluminum (26.981 5)	12 <b>Si</b> Silicon (28.085 5)	13 <b>P</b> Phosphorus (30.973 8)	14 <b>S</b> Sulfur (32.06)	15 <b>Cl</b> Chlorine (35.453)	16 <b>Ar</b> Argon (39.948)	
19 <b>K</b> Potassium (39.098 3)	20 <b>Ca</b> Calcium (40.078)	21 <b>Sc</b> Scandium (44.955 9)	22 <b>Ti</b> Titanium (47.88)	23 <b>V</b> Vanadium (50.941 5)	24 <b>Cr</b> Chromium (51.996 1)	25 <b>Mn</b> Manganese (54.938 0)	26 <b>Fe</b> Iron (55.845)	27 <b>Co</b> Cobalt (58.933 2)	28 <b>Ni</b> Nickel (58.693 4)	29 <b>Cu</b> Copper (63.546)	30 <b>Zn</b> Zinc (65.38)	31 <b>Ga</b> Gallium (69.723)	32 <b>Ge</b> Germanium (72.630 8)	33 <b>As</b> Arsenic (74.921 6)	34 <b>Se</b> Selenium (78.96)	35 <b>Br</b> Bromine (79.904)	36 <b>Kr</b> Krypton (83.80)	
37 <b>Rb</b> Rubidium (85.467 8)	38 <b>Sr</b> Strontium (87.62)	39 <b>Y</b> Yttrium (88.905 8)	40 <b>Zr</b> Zirconium (91.224)	41 <b>Nb</b> Niobium (92.906 4)	42 <b>Mo</b> Molybdenum (95.94)	43 <b>Tc</b> Technetium	44 <b>Ru</b> Ruthenium (101.07)	45 <b>Rh</b> Rhodium (101.07)	46 <b>Pd</b> Palladium (106.36)	47 <b>Ag</b> Silver (107.868 2)	48 <b>Cd</b> Cadmium (112.414)	49 <b>In</b> Indium (114.818)	50 <b>Sn</b> Tin (118.710)	51 <b>Sb</b> Antimony (121.757)	52 <b>Te</b> Tellurium (127.6)	53 <b>I</b> Iodine (126.905)	54 <b>Xe</b> Xenon (131.29)	
55 <b>Cs</b> Cesium (132.905)	56 <b>Ba</b> Barium (137.327)	57-71 Lanthanoids	72 <b>Hf</b> Hafnium (178.49)	73 <b>Ta</b> Tantalum (180.948)	74 <b>W</b> Tungsten (183.84)	75 <b>Re</b> Rhenium (186.207)	76 <b>Os</b> Osmium (190.23)	77 <b>Ir</b> Iridium (192.22)	78 <b>Pt</b> Platinum (195.084)	79 <b>Au</b> Gold (196.967)	80 <b>Hg</b> Mercury (200.59)	81 <b>Tl</b> Thallium (204.38)	82 <b>Pb</b> Lead (207.2)	83 <b>Bi</b> Bismuth (208.98)	84 <b>Po</b> Polonium	85 <b>At</b> Astatine	86 <b>Rn</b> Radon	
87 <b>Fr</b> Francium	88 <b>Ra</b> Radium	89-103 Actinoids	104 <b>Rf</b> Rutherfordium	105 <b>Db</b> Dubnium	106 <b>Sg</b> Seaborgium	107 <b>Bh</b> Bohrium	108 <b>Hs</b> Hassium	109 <b>Mt</b> Meitnerium	110 <b>Ds</b> Darmstadtium	111 <b>Rg</b> Roentgenium	112 <b>Cn</b> Copernicium	113 <b>Uut</b> Ununtrium	114 <b>F1</b> Flerovium	115 <b>Uup</b> Ununpentium	116 <b>Lv</b> Livermorium	117 <b>Uus</b> Ununseptium	118 <b>Uuo</b> Ununoctium	

57 <b>La</b> Lanthanum (138.905)	58 <b>Ce</b> Cerium (140.12)	59 <b>Pr</b> Praseodymium (140.908)	60 <b>Nd</b> Neodymium (144.24)	61 <b>Pm</b> Promethium	62 <b>Sm</b> Samarium (150.36)	63 <b>Eu</b> Europium (151.964)	64 <b>Gd</b> Gadolinium (157.25)	65 <b>Tb</b> Terbium (158.925)	66 <b>Dy</b> Dysprosium (162.50)	67 <b>Ho</b> Holmium (164.930)	68 <b>Er</b> Erbium (167.259)	69 <b>Tm</b> Thulium (168.934)	70 <b>Yb</b> Ytterbium (173.054)	71 <b>Lu</b> Lutetium (174.967)
89 <b>Ac</b> Actinium	90 <b>Th</b> Thorium (232.037)	91 <b>Pa</b> Protactinium (231.036)	92 <b>U</b> Uranium (238.029)	93 <b>Np</b> Neptunium	94 <b>Pu</b> Plutonium	95 <b>Am</b> Americium	96 <b>Cm</b> Curium	97 <b>Bk</b> Berkelium	98 <b>Cf</b> Californium	99 <b>Es</b> Einsteinium	100 <b>Fm</b> Fermium	101 <b>Md</b> Mendelevium	102 <b>No</b> Nobelium	103 <b>Lr</b> Lawrencium

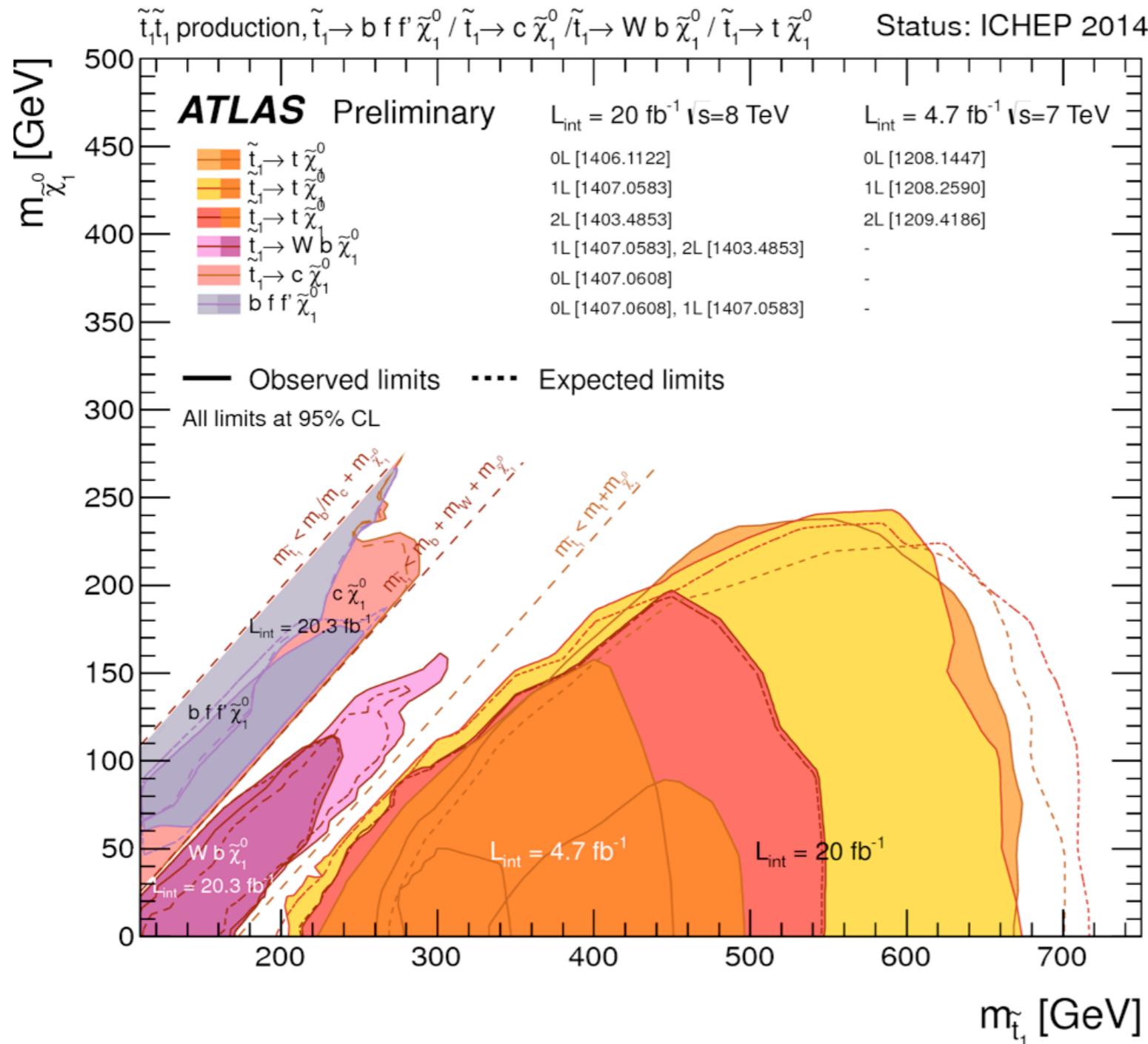
# Nice prospects in the quark sector ...



...but flattening out after  $\sim 2022$



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

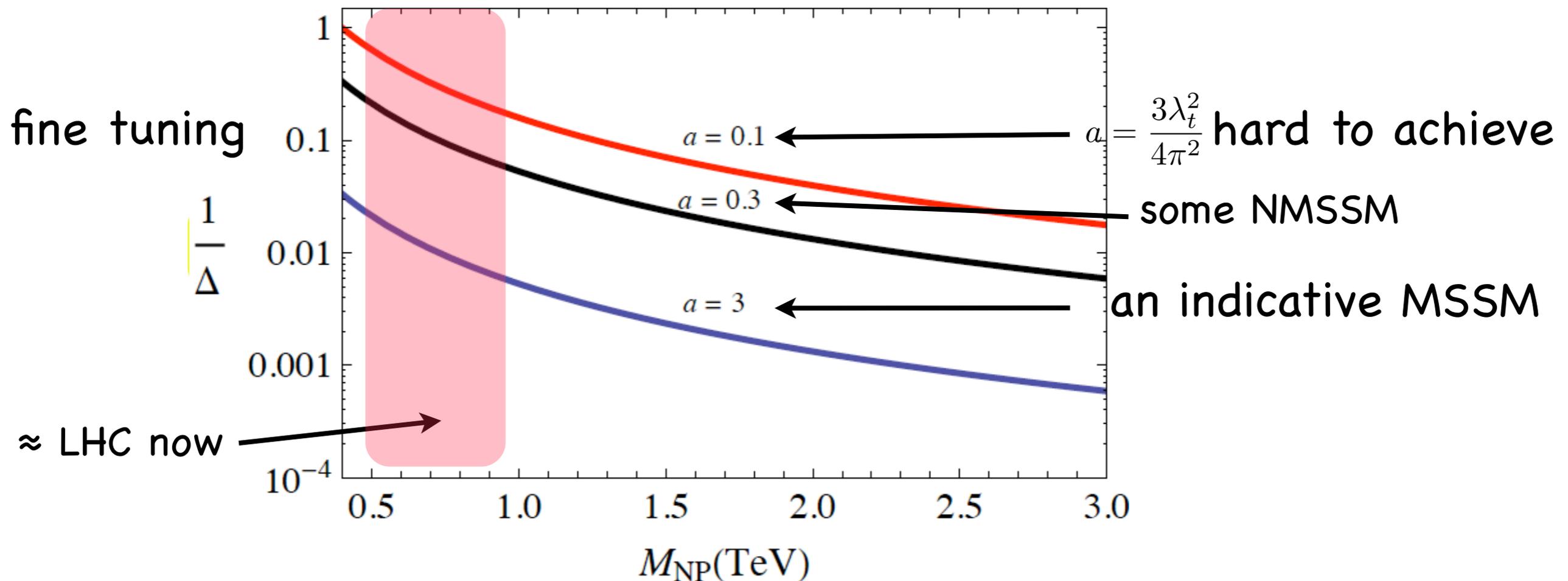


Holes that must be covered

## 2. How dramatic is the “little hierarchy problem”?

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

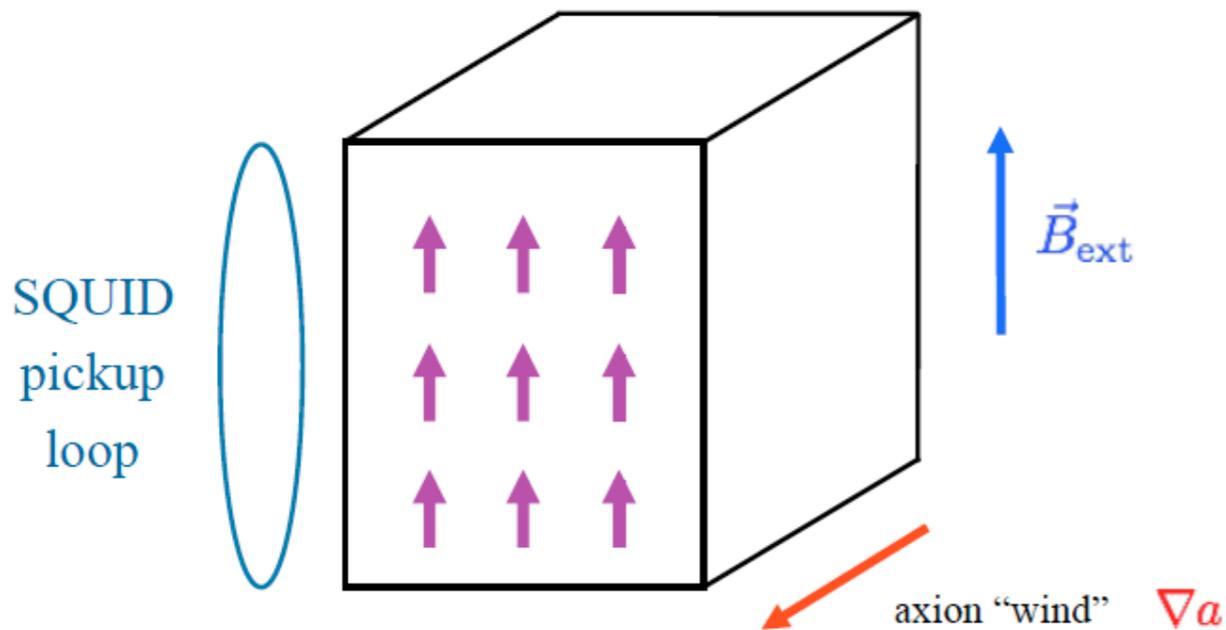
model dependent



- 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 Bloch eq.s, at resonance

$$m_a =$$

e  
N

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

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

$$M_T = \gamma_{e,N}^2 B_{e,N}^{eff} n_S \tau \cos(m_a t)$$

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

N  
e

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

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

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

# Electron Electric Dipole Moment

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

C = charge conjugation

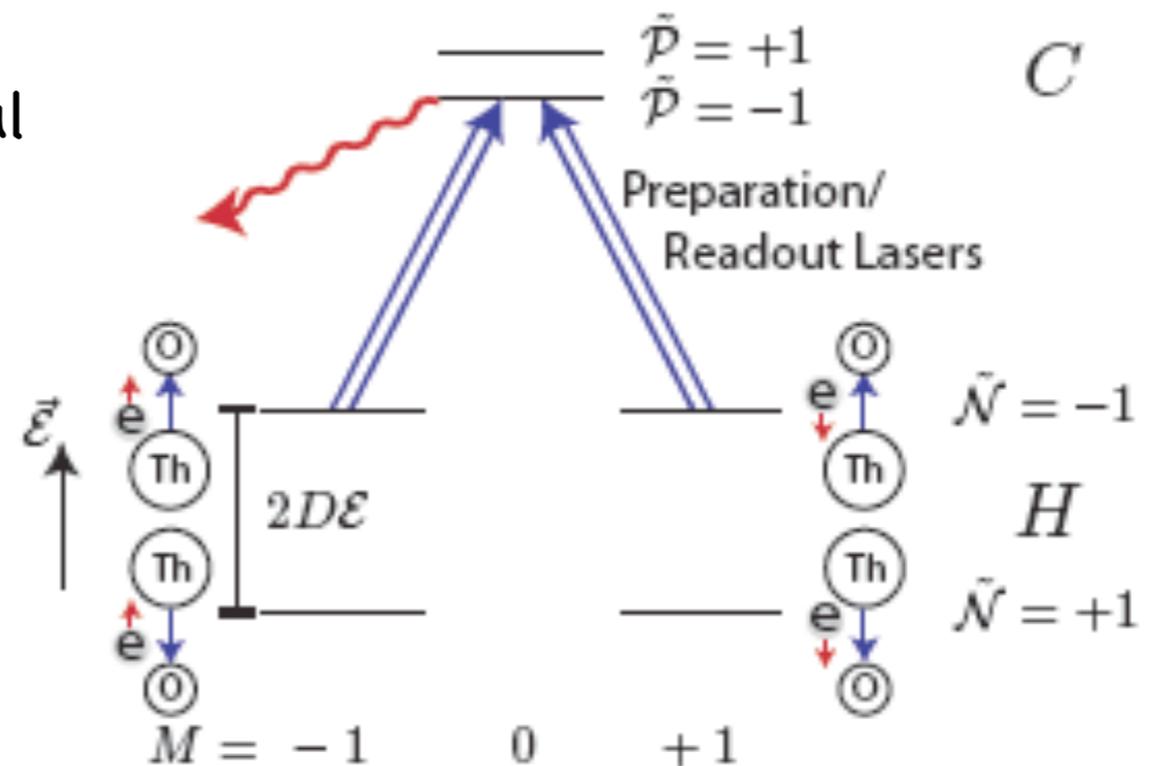
P = parity

## ACME Collaboration

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

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

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



$$d_e = (-2.1 \pm 3.7 \pm 2.5) \cdot 10^{-29} \text{ e} \cdot \text{cm}$$