Beyond the Standard Model as of 2015

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I. The SM as of 2015

II. Problems of (questions for) the SM

III. New (revisited) ideas to address these problems

IV. What if the hierarchy problem were a dead end?

III. New (revisited) ideas to address these problems/questions

- Neutral top "partners" (fermionic or even bosonic)
- Mirror Dark Matter
- Self-criticality of the Higgs vev
- Axion (light scalar) detection
- Putative anomalies in B-decays

A self-critical Higgs vev

1. A Goldstone boson ϕ of a U(1) broken at a scale f
2. A U(1)-breaking coupling of ϕ to H (that keeps $\phi \to \phi + 2n\pi f$)
3. A breaking of $\phi \to \phi + 2n\pi f$ controlled by a small mass parameter m entering the Higgs mass term

$$V = -f^2|S|^2 + |S|^4 + \rho(H)\frac{S+S^+}{f} + (\Lambda^2 - m\phi)|H|^2 + \lambda|H|^4 + m\Lambda^2\phi$$

$S = se^{-i\phi/f}$

Λ = UV cutoff

V is a natural potential

Minimizing $V(H,\phi)$

$$V = \rho(H)\cos\phi/f + (\Lambda^2 - m\phi)|H|^2 + \lambda|H|^4 + m\Lambda^2\phi$$

$$\rho(H) = \cancel{\rho_0} + \rho_1 \frac{H}{v_F} + \rho_2 (\frac{H}{v_F})^2 + \ldots \qquad v_F^4 > \rho_{1,2}$$

(non trivial)

$$\frac{\partial V}{\partial h} = 0 \;\Rightarrow h^2 \approx \frac{\Lambda^2 - m\phi}{\lambda} > 0$$

$$\frac{\partial V}{\partial \phi} = 0 \;\Rightarrow h \approx v_F \frac{\Lambda^2 m f}{\rho_1}$$

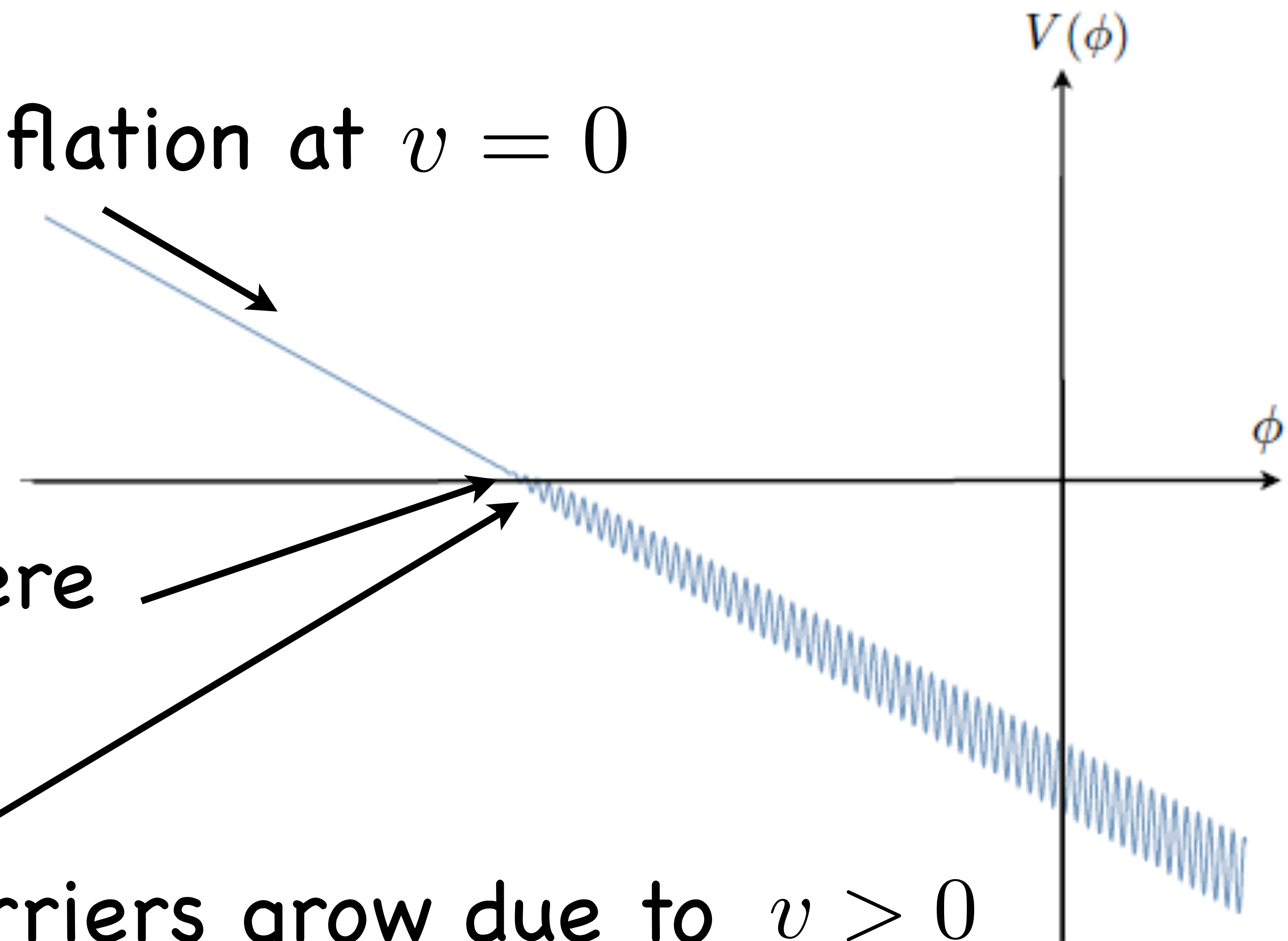
$h = v_F$ natural = moving Λ, m, f, ρ_1 by O(1)
h changes by O(1)

$$m = \frac{\rho_1}{\Lambda^2 f} \lesssim \frac{v_F^4}{\Lambda^2 f} \qquad \phi \approx \frac{\Lambda^2}{m} \gtrsim \frac{\Lambda^4 f}{v_F^4}$$

historical evolution of ϕ (and of v)

(under suitable conditions: e.g. a very very long inflation period)

ϕ slow-rolls during inflation at $v = 0$



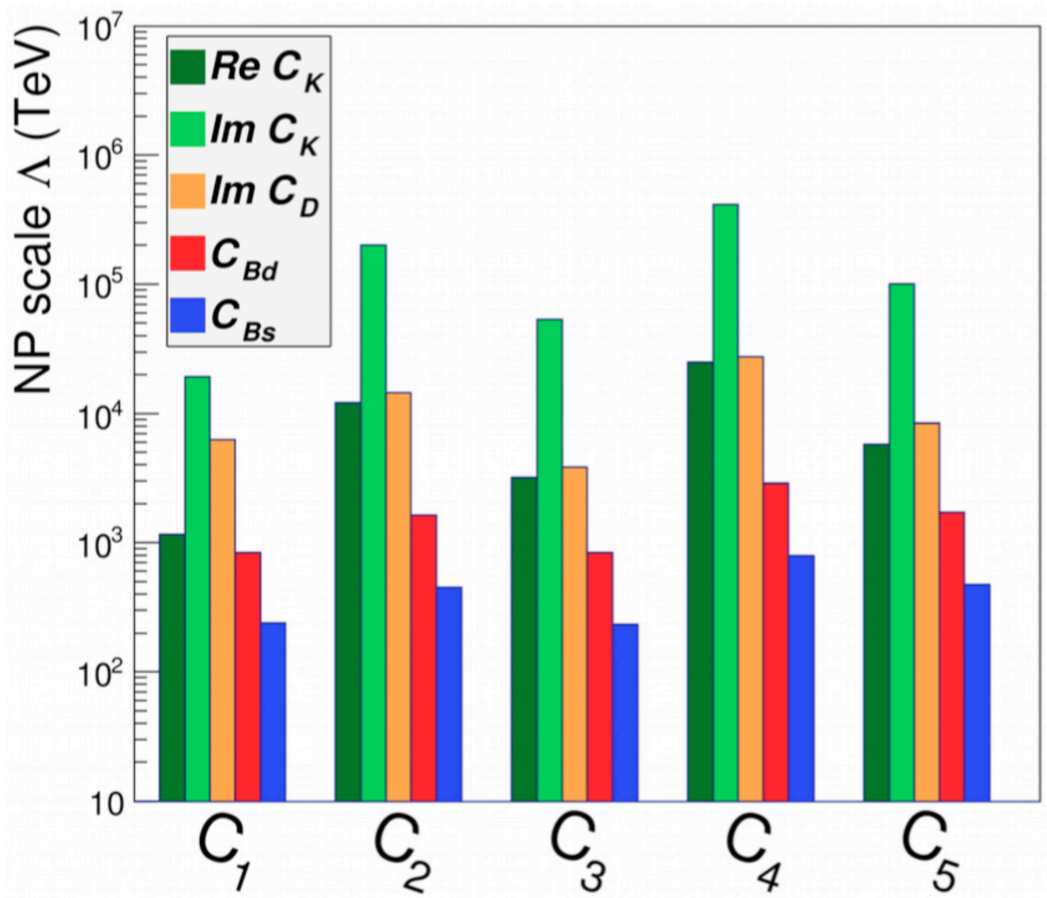
until it hits value where m_h^2 crosses zero

rolling stops when barriers grow due to $v > 0$

experimental consequences:??

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"

$b \to c\tau\nu$

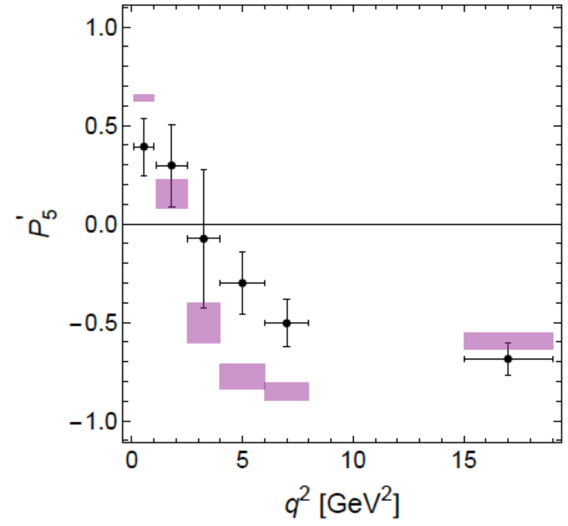
$$R_{D^*}^{\tau/\ell} = \frac{\mathcal{B}(B \to D^*\tau\nu)_{\rm exp}/\mathcal{B}(B \to D^*\tau\nu)_{\rm SM}}{\mathcal{B}(B \to D^*\ell\nu)_{\rm exp}/\mathcal{B}(B \to D^*\ell\nu)_{\rm SM}} = 1.28 \pm 0.08$$

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

$b \to s l^+ l^-$

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

P_5' anomaly in the q^2 distribution



$V_{ub}(V_{cb})\ exc/inc$

$$|V_{ub}|_{\rm incl} = (4.40 \pm 0.25)\cdot 10^{-3}, \qquad |V_{cb}|_{\rm incl} = (42.21 \pm 0.78)\cdot 10^{-3}$$

$$|V_{ub}|_{\rm excl} = (3.72 \pm 0.14)\cdot 10^{-3}, \qquad |V_{cb}|_{\rm excl} = (39.36 \pm 0.75)\cdot 10^{-3}$$

(An interlude)
Minimal Flavour Violation in the quark sector

Phenomenological Definition:

In EFT the only relevant op.s correspond to the FCNC loops of the SM, weighted by a single scale Λ and by the standard CKM factors (up to $O(1)$ coeff.s)

Strong MFV $U(3)_Q \times U(3)_u \times U(3)_d$

$$Y_u = (3, \bar{3}, 1) \to Y_u^D \qquad Y_d = (3, 1, \bar{3}) \to V Y_d^D$$

$$\Rightarrow \quad A(d_i \to d_j) = V_{tj} V_{ti}^* A_{SM}^{\Delta F=1} (1 + a_1 (\frac{4\pi M_W}{\Lambda})^2)$$

$$M_{ij} = (V_{tj} V_{ti}^*)^2 A_{SM}^{\Delta F=2} (1 + a_2 (\frac{4\pi M_W}{\Lambda})^2)$$

Weak MFV

$$U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$

$$y_b = (1,1,1)_{-1} \quad \lambda_u = (2,\bar{2},1)_0 \quad \lambda_d = (2,1,\bar{2})_0 \quad \mathbf{V} = (2,1,1)_0$$

$$\Rightarrow \quad Y_u = \left(\begin{array}{c|c} \lambda_u & y_t x_t \mathbf{V} \\ \hline 0 & y_t. \end{array}\right) \qquad Y_d = \left(\begin{array}{c|c} \lambda_d & y_b x_b \mathbf{V} \\ \hline 0 & y_b \end{array}\right) \quad \mathbf{V} = \begin{pmatrix} 0 \\ \epsilon \end{pmatrix} \quad \lambda_{u,d} = U^{(12)}_{u,d} \lambda^D_{u,d}$$

$$Y_u \approx U_u Y_u^D \qquad Y_d \approx U_d Y_d^D \qquad U_{u,d} \approx U^{(23)}_{u,d}(x_{t,b}\epsilon) U^{(12)}_{u,d}(s_L^{u,d})$$

$$V_{CKM} = U_u^+ U_d = \begin{pmatrix} c_L^u c_L^d & \lambda & s_L^u s\, e^{-i\delta} \\ -\lambda & c_L^u c_L^d & c_L^u s \\ -s_L^d s\, e^{i(\delta+\phi)} & -c_L^d s & 1 \end{pmatrix} \qquad \begin{aligned} s &\sim O(\epsilon) \\ s_L^u c_L^d - s_L^d c_L^u e^{i\phi} &= \lambda e^{i\delta} \end{aligned}$$

$$A(d_i \to d_j) = V_{tj} V_{ti}^* A_{SM}^{\Delta F=1} (1 + (a_{1b}, a_{1s}) (\frac{4\pi M_W}{\Lambda})^2)$$

$$M_{ij} = (V_{tj} V_{ti}^*)^2 A_{SM}^{\Delta F=2} (1 + (a_{2b}, a_{2s}) (\frac{4\pi M_W}{\Lambda})^2)$$

Question

Is there a flavour group $\mathcal{G}_F$ and a tree level exchange Φ such that:

1. With unbroken $\mathcal{G}_F$, Φ couples to the third generation of quarks and leptons only;

2. After small $\mathcal{G}_F$ breaking, the needed operators:

$$(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma_\mu \nu_L)$$
$$(\bar{b}_L \gamma_\mu s_L)(\bar{\mu} \gamma_\mu \mu)$$

are generated.

Answer

$\mathcal{G}_F = \mathcal{G}_F^q \times \mathcal{G}_F^l$ broken as above

$$\mathcal{G}_F^q = U(2)_Q \times U(2)_u \times U(2)_d \times U(1)_{d3}$$
$$\mathcal{G}_F^l = U(2)_L \times U(2)_e \times U(1)_{e3}$$

$\Phi = (3,3)_{-1/3}$ Lorentz scalar, $\mathcal{G}_F$ singlet

$V_\mu = (3,1)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet

$\mathbf{V}_\mu = (3,3)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet

~~$\tilde{V}_\mu = (1,3)_{2/3}$ Lorentz vector, $\mathcal{G}_F$ singlet~~

(vectors have Λ^2-divergent loops)

Greljo, Isidori, Marzocca
Alonso, Grinstein, Camalich
Freytsis, Ligeti, Ruderman
Calibbi, Crivellin, Ota

Parameters after $\mathcal{G}_F$ breaking

e.g. in the scalar case (but all similar)

$$\mathcal{L} = g_\Phi \Phi_a (\bar{Q}_i \sigma^a i\sigma_2 F_{ij} L_j^c)$$

$$F_{ij} = \delta_{i3}\delta_{j3} + aV_{Qi}\delta_{j3} + b\delta_{i3}V_{Lj}^* + cV_{Qi}V_{Lj}^*$$

$$V_{Q,Li} = \delta_{i2}\epsilon_{Q,L}$$

$$M_{23}^{U,D,L} = \epsilon_Q, \; d\epsilon_Q, \epsilon_L \qquad V_{cb} = -V_{ts} = \epsilon_Q(d-1)$$

$\Rightarrow$ parameters:

$$\frac{g_\Phi^2}{M_\Phi^2}, \; \epsilon_L$$

$a, \; b, \; c, \; d$ of order unity

Main effects (under investigation)

in the vector $SU(2)$-singlet case

tree level

$b \to c\ \tau\nu$

$b \to s\ \mu\bar{\mu}$ ($b \to s\ \tau\bar{\mu}$ $b \to s\ \tau\bar{\tau}$)

$t \to c\ \nu\nu$

loop level (Λ^2-divergent; $\Lambda \approx 4\pi M_V / g_V$)

$b \to s\ \nu\nu$

$\tau \to 3\mu$

$b\bar{s} \to \bar{b}s$

pair production

$gg \to V_{2/3}V_{-2/3}$ → $t\nu$ $\bar{t}\nu$ / $b\bar{\tau}$ $\bar{b}\tau$ $(m_V \gtrsim 500\ GeV)$

IV. What if the hierarchy problem were a dead end?

1. Precision physics
2. The flavour puzzle
3. The astro-cosmo-particle connection
4. Dark Matter

The synthetic nature of PP at full work

Precision physics: 2 ways to go

"Micro-precision": Which possible deviations from the SM are less constrained?

effective operators (many) and so on

"Macro-precision": How competitive with direct searches of NP?

Higgs couplings

LHC14 at $300\ fb^{-1}$
HighIntensity-LHC14
ILC
TLEP

versus

the EWPT
at a Z-factory

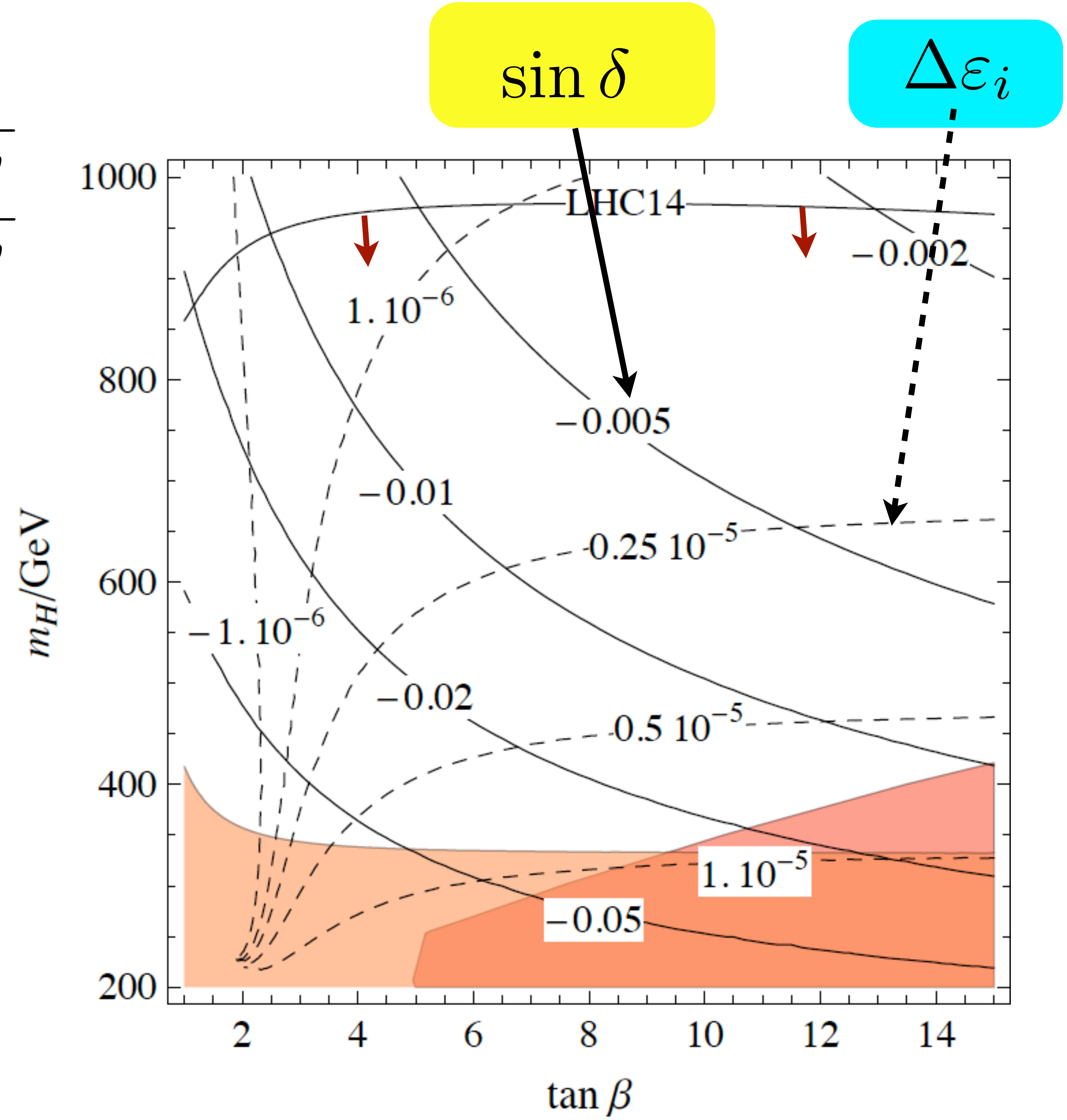
ILC
TLEP

E.g.: MSSM with s-particles "decoupled" but not H

$$h = \cos\delta\ h_v - \sin\delta\ h_v^\perp$$
$$H = \sin\delta\ h_v + \cos\delta\ h_v^\perp$$

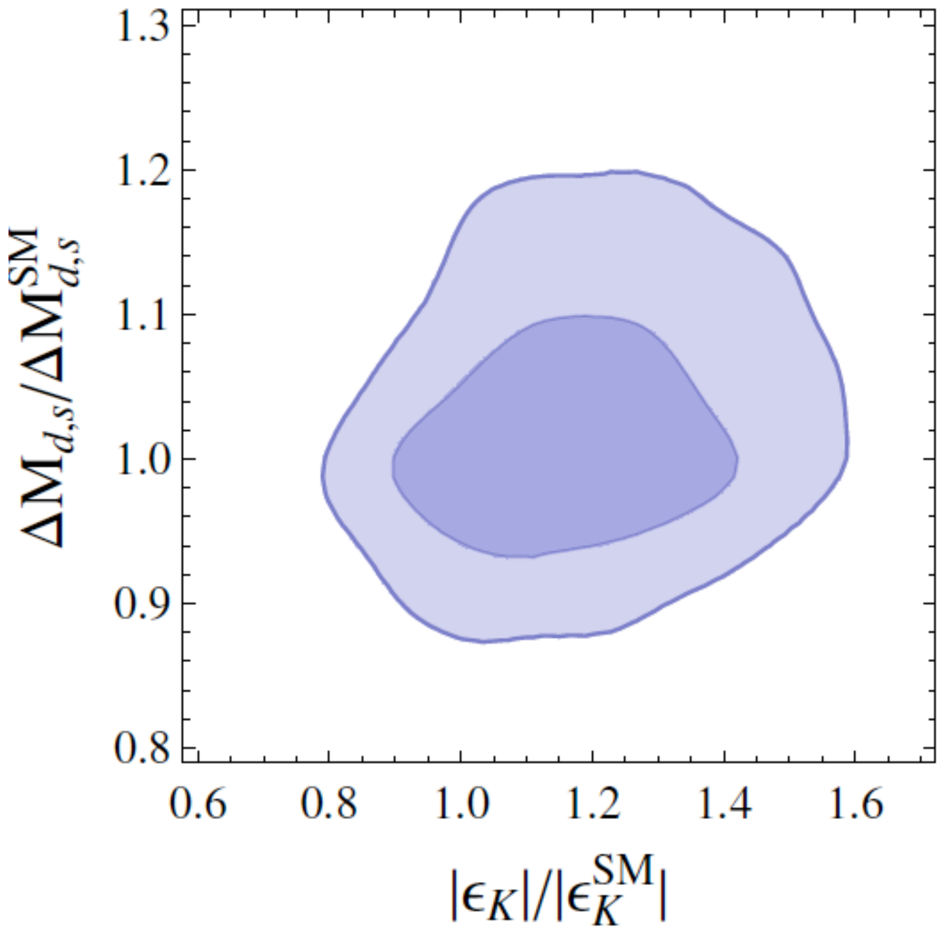
	ATLAS	CMS
$h \to \gamma\gamma$	0.16	0.15
$h \to ZZ$	0.15	0.11
$h \to WW$	0.30	0.14
$Vh \to Vb\bar{b}$	–	0.17
$h \to \tau\tau$	0.24	0.11
$h \to \mu\mu$	0.52	–

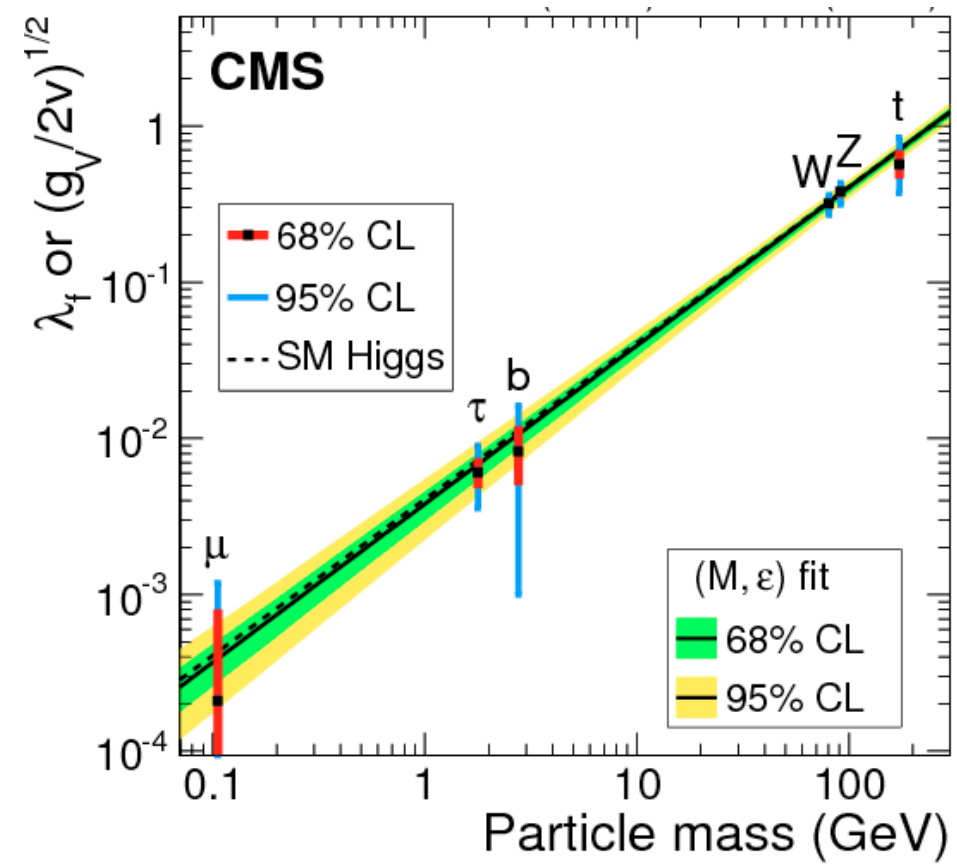
At TLEP
$\delta\varepsilon_i < 10^{-4}$

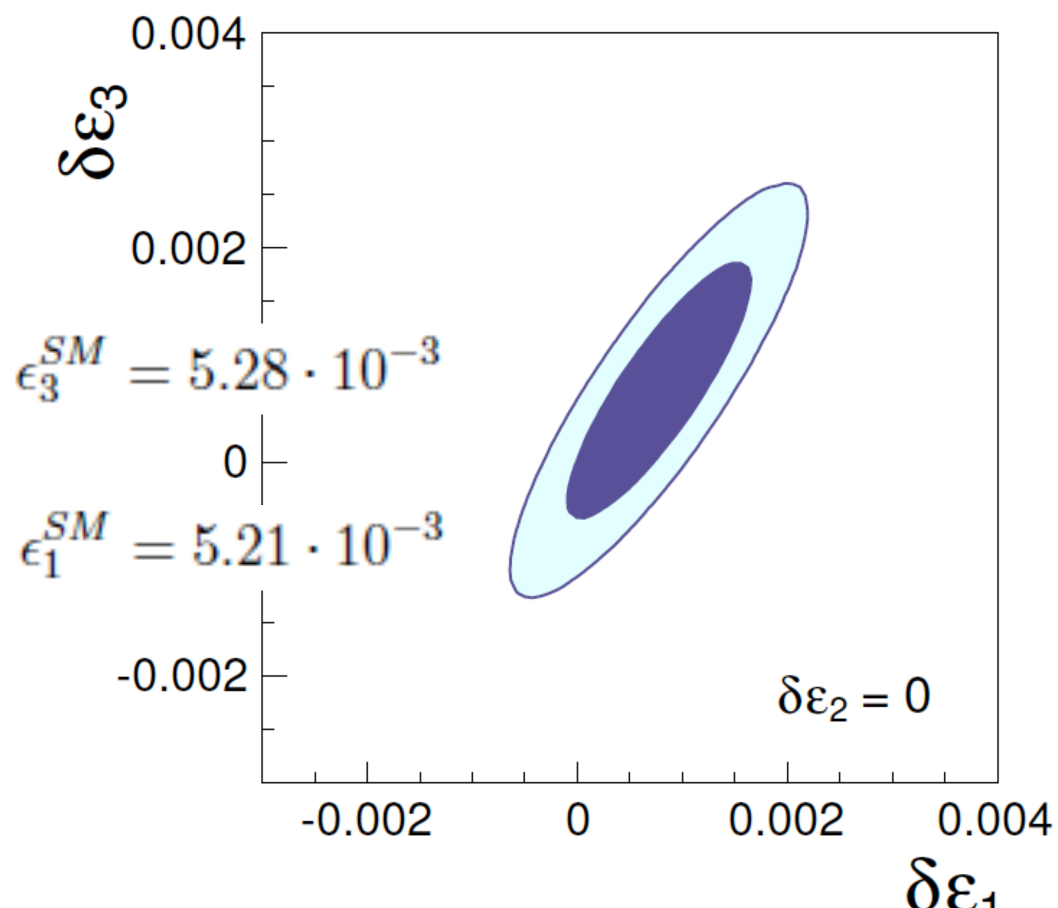


Are there extra Higgs scalars?

The flavour paradox







To make progress, new flavour signals badly needed

A suitable flavour program can reduce errors on CKM tests from about 20% (now, similar to $\delta\epsilon_i/\epsilon_i^{SM}$) to $\lesssim$ 1%

An "Extreme Flavour" experiment?

Vagnoni – SNS, 7-10 Dec 2014

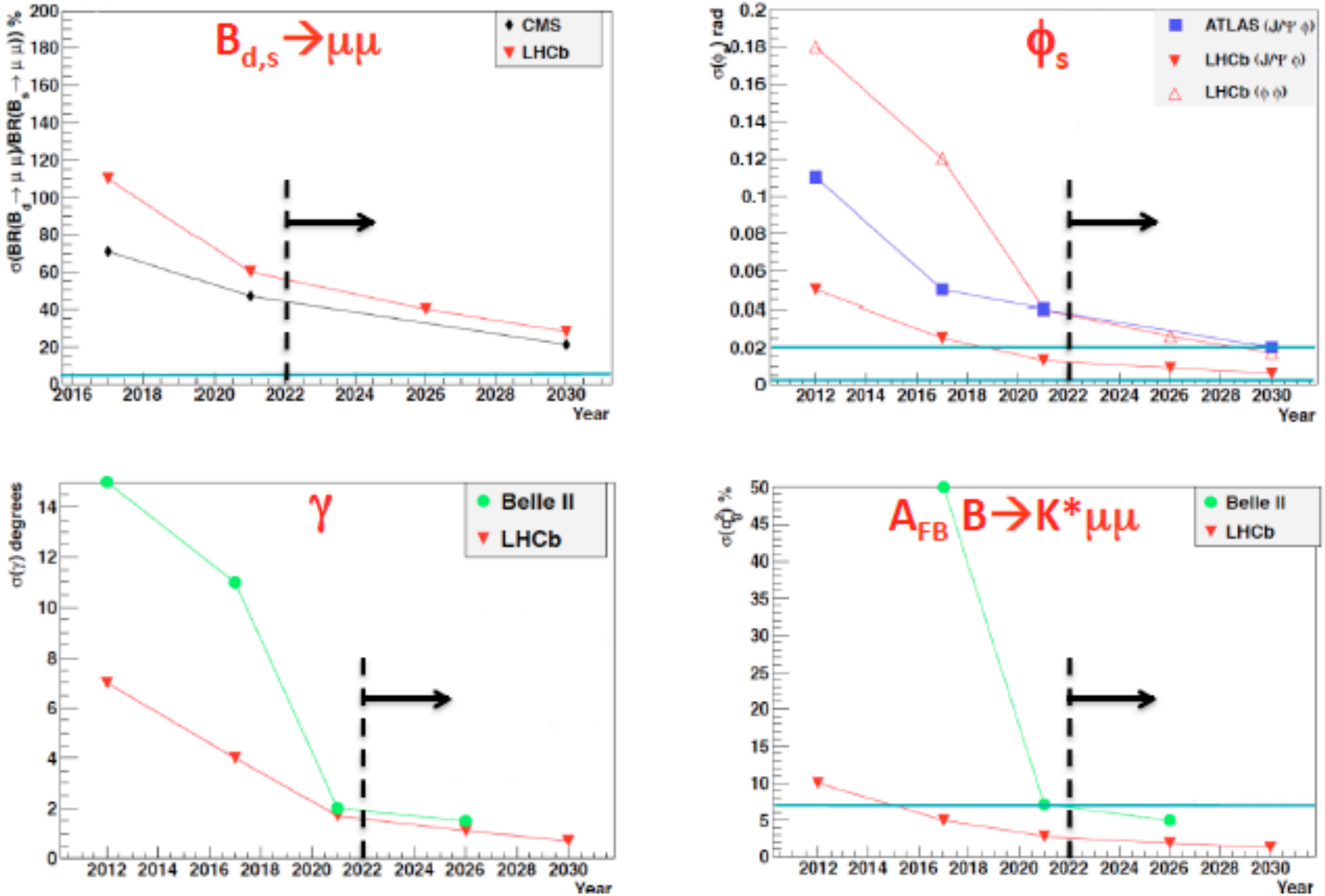
- Currently planned experiments at the HL-LHC will only exploit a small fraction of the huge rate of heavy-flavoured hadrons produced
  - ATLAS/CMS: full LHC integrated luminosity of 3000 fb^{-1}, but limited efficiency due to lepton high p_T requirements
  - LHCb: high efficiency, also on charm events 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%

A minimal list of key observables in QFV to be improved and not yet TH-error dominated

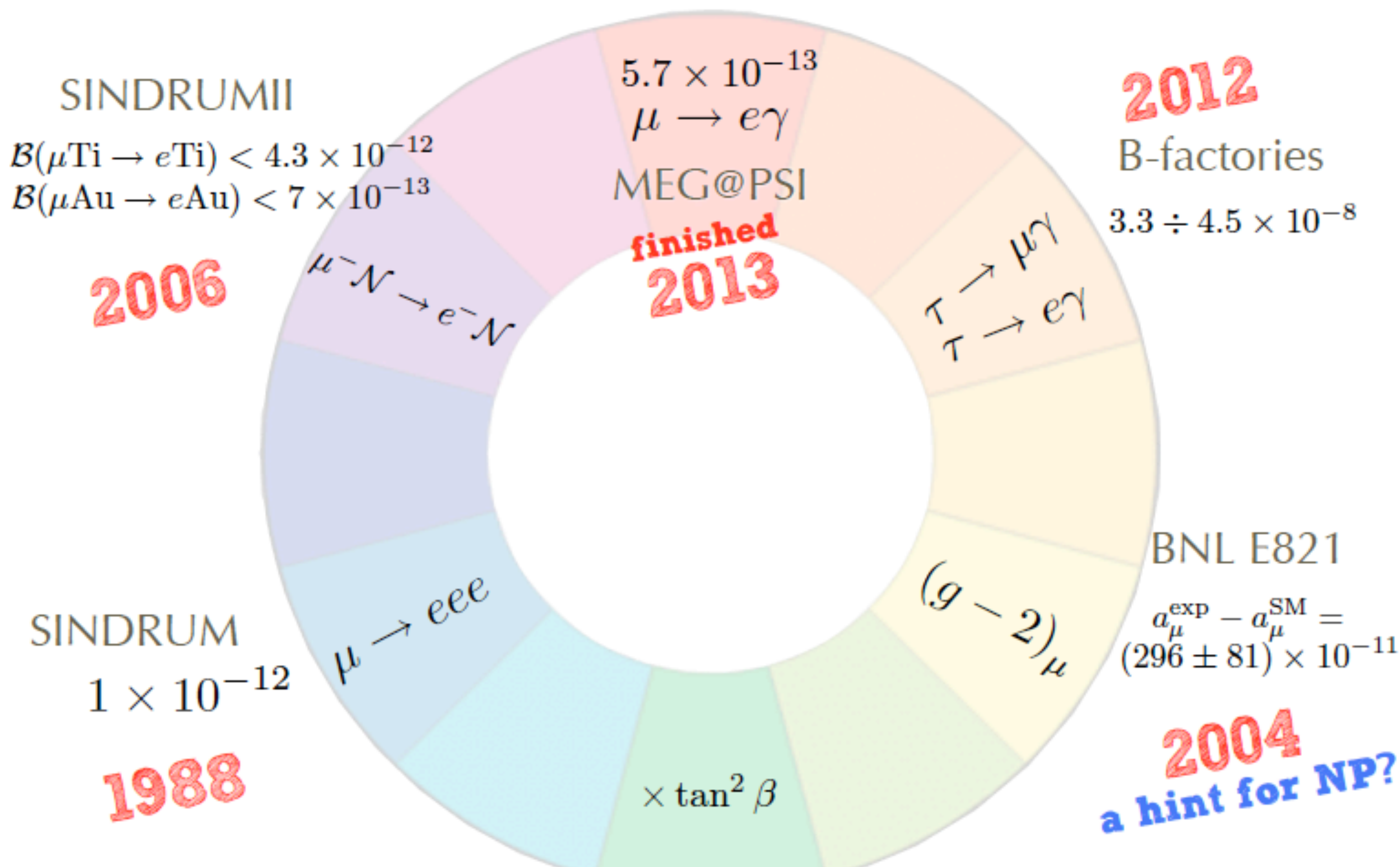
- γ from tree: $B \to DK$, etc (now better from loops)
- $|V_{ub}|, |V_{cb}|$
- $B \to \tau\nu, \mu\nu \ (+D^{(*)})$
- $B \to K^{(*)} \ l^+l^-, \nu\nu$ (in suitable observables?)
- $K_S, D, B_{s,d} \to l^+l^-$ ("Higgs penguins")
- $\phi^{\Delta}_{d,s}$ (CPV in $\Delta B_{d,s} = 2$)
- $K^+, K_L \to \pi\nu\nu$
- ΔA_{CP} in selected D modes

Nice prospects in the quark sector …



…but flattening out after ~2022

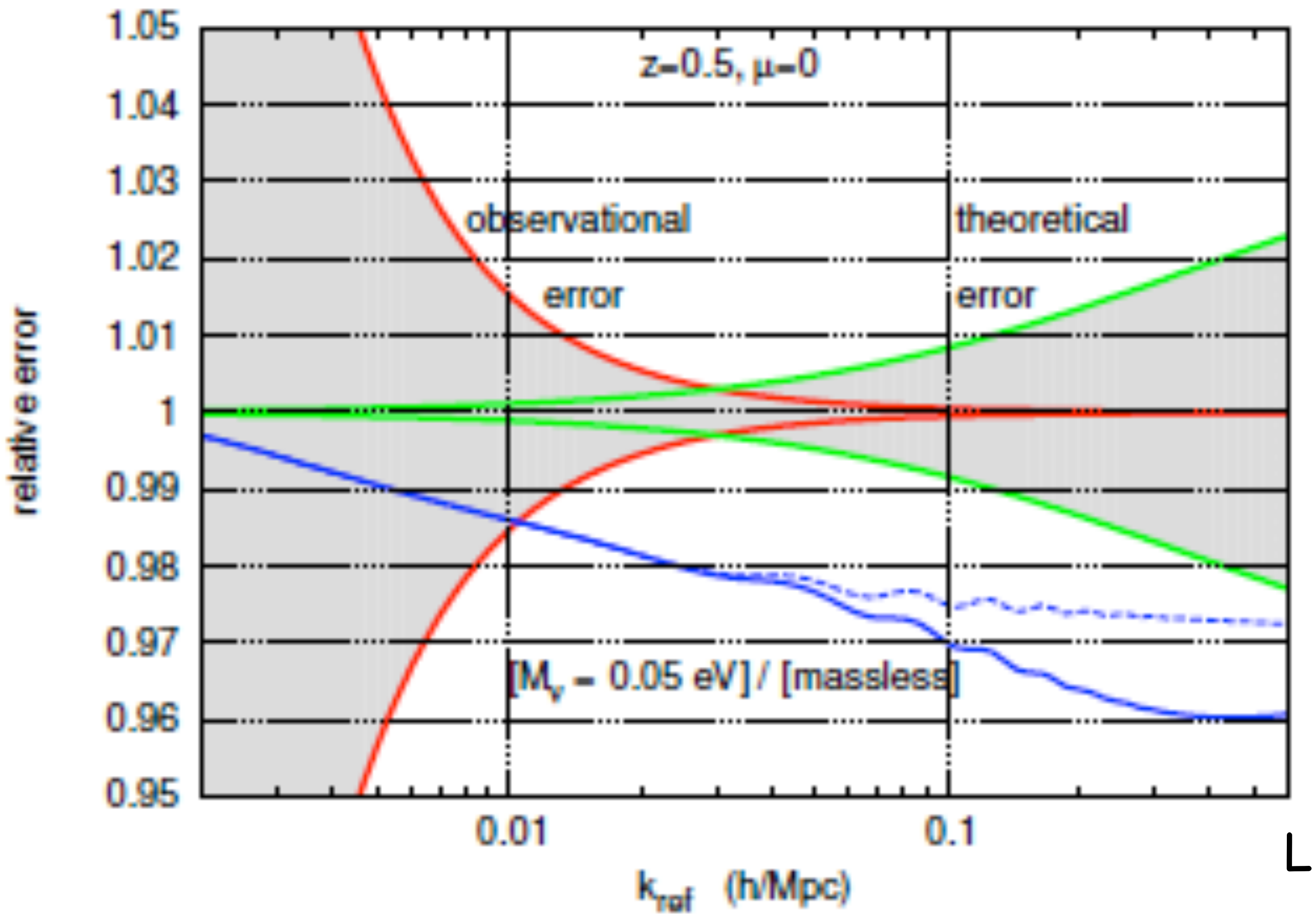
Current limits



time for improvement

The astro-cosmo-particle connection

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



Lesgourgues et al

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

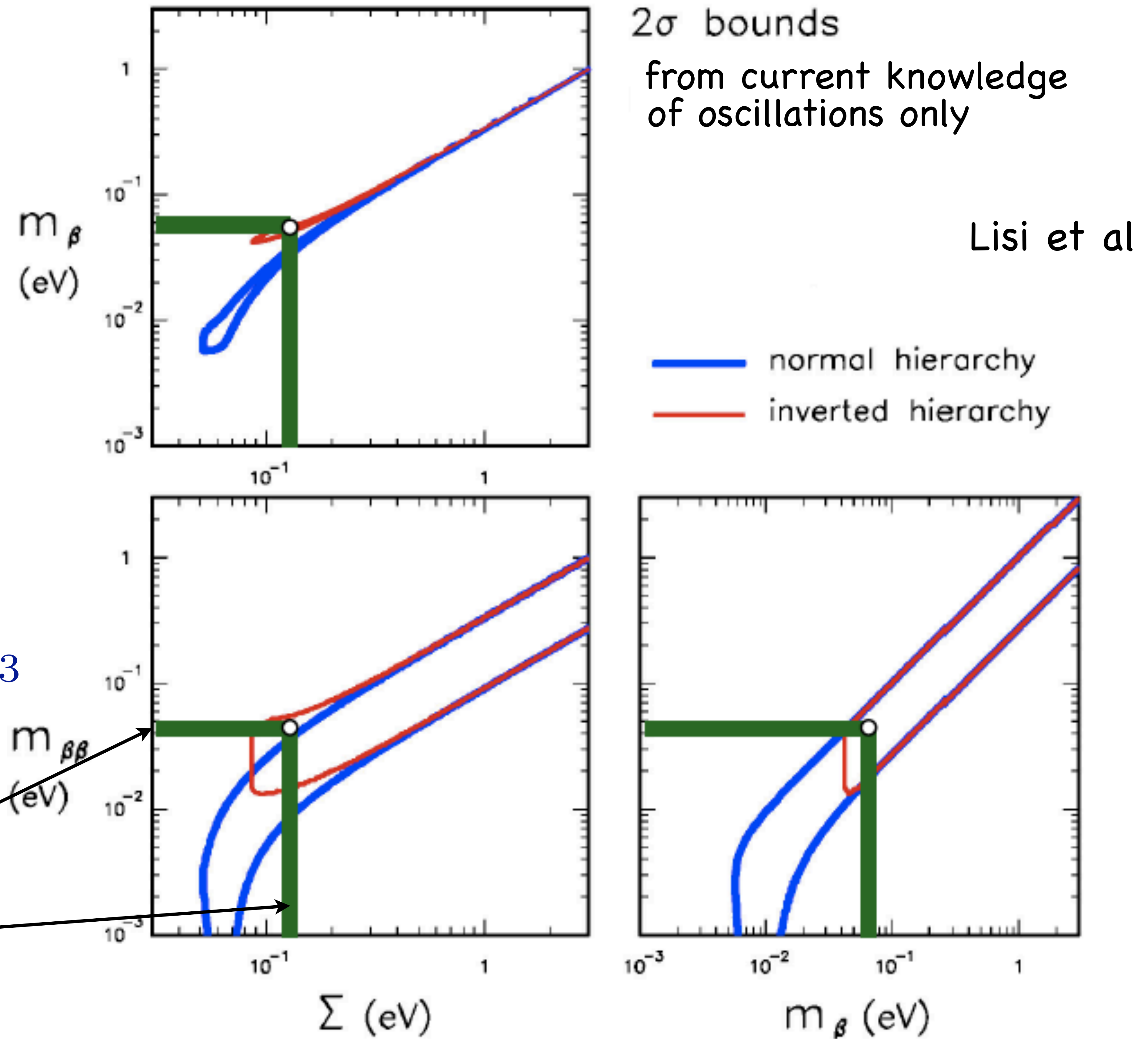
▶ Not independent on "priors" but still highly significant

Key/dream neutrino measurements

m_β
beta-decay endpoint

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

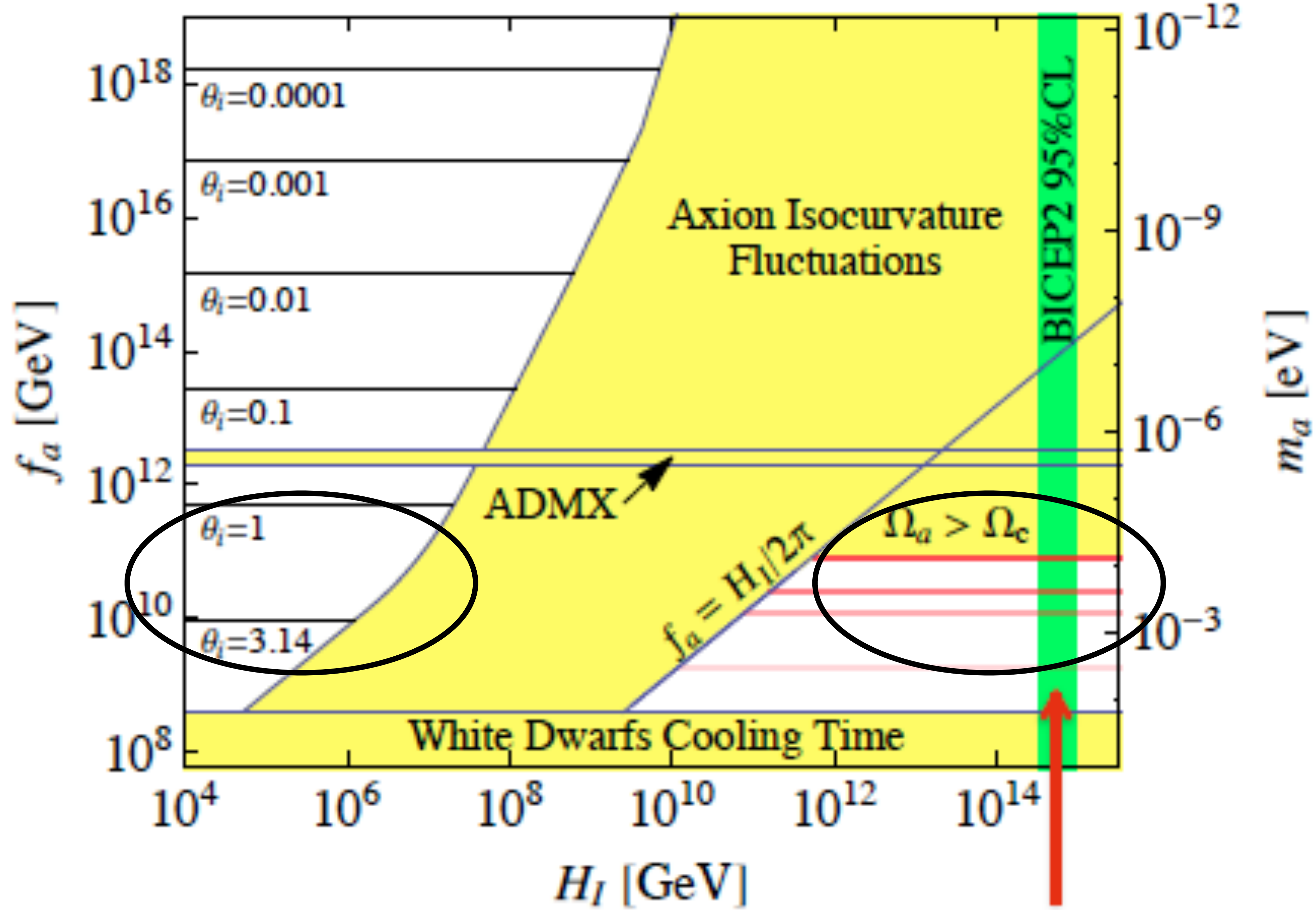
$\Sigma = m_1 + m_2 + m_3$
large scale structures



hypothetical measurements

Dark Matter: QCD Axions

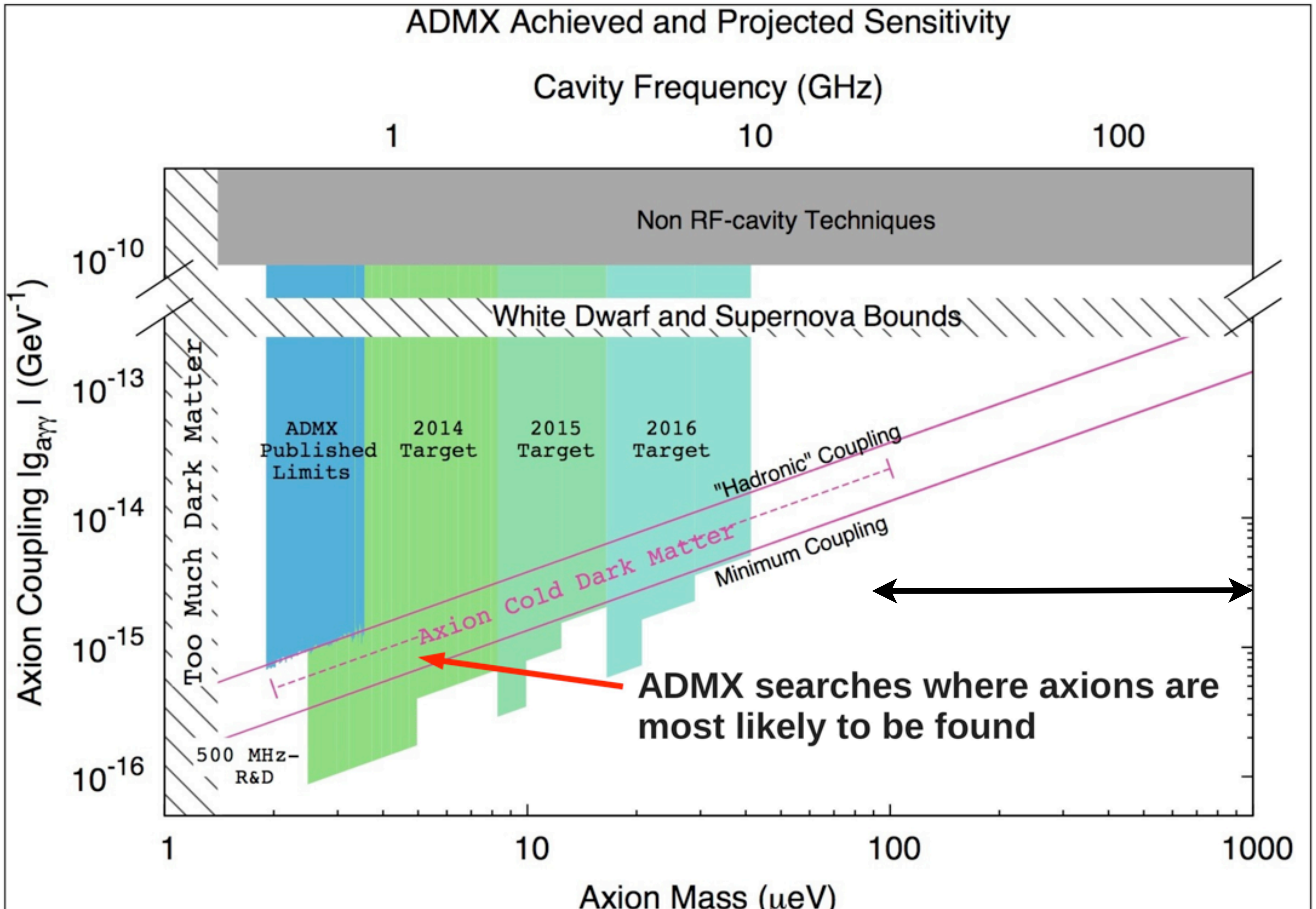
$$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$$



$m_a = 10^{-4} \div 10^{-3}\ eV$ 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

$10^{-4} \lesssim m_a/eV \lesssim 10^{-3}$

Rybka ADMX

The coupling of the axion to spin

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

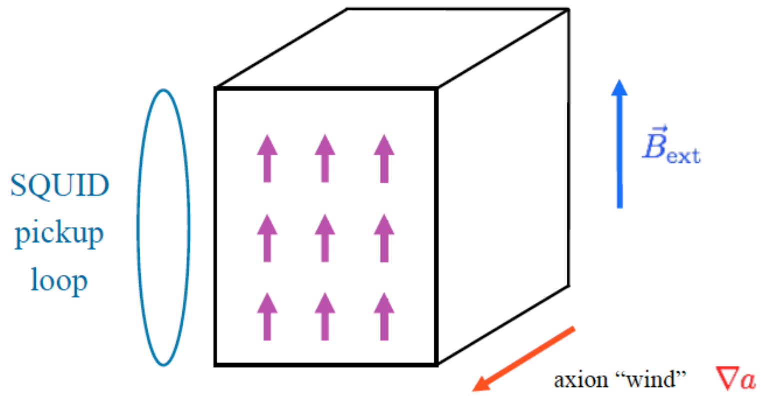
$$g_p = A_\Psi \frac{m_\Psi}{f_a} \qquad \left(g_s = 10^{-(12\div17)} g_p \frac{GeV}{m_\Psi}\right)$$

DFSZ
KSVZ

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

$$\gamma\vec{B}_{eff}\cdot\vec{\sigma} \qquad \gamma = \frac{e}{2m_\Psi}$$

Summary on proposed exp.s using NMR/EMR

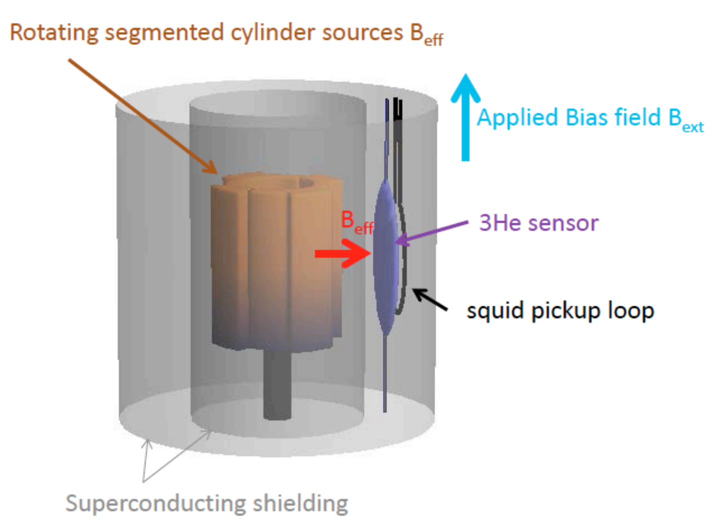


CASPEr axion wind/NMR

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

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

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

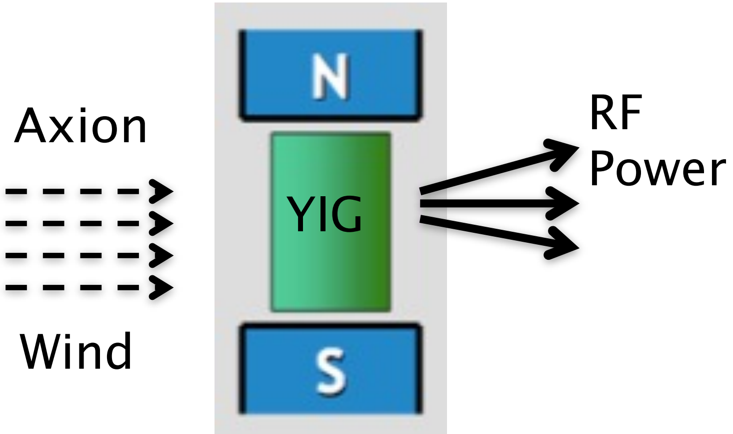


static source NMR

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

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

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

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)