Outlook ($\neq$ Summary)

Oxford Dictionary:

1. A person's point of view
2. The prospect for the future

A contribution to the discussion in a time of

healthy uncertainty

The Standard Model paradox

R. Barbieri

Pisa, June 8, 2017

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)

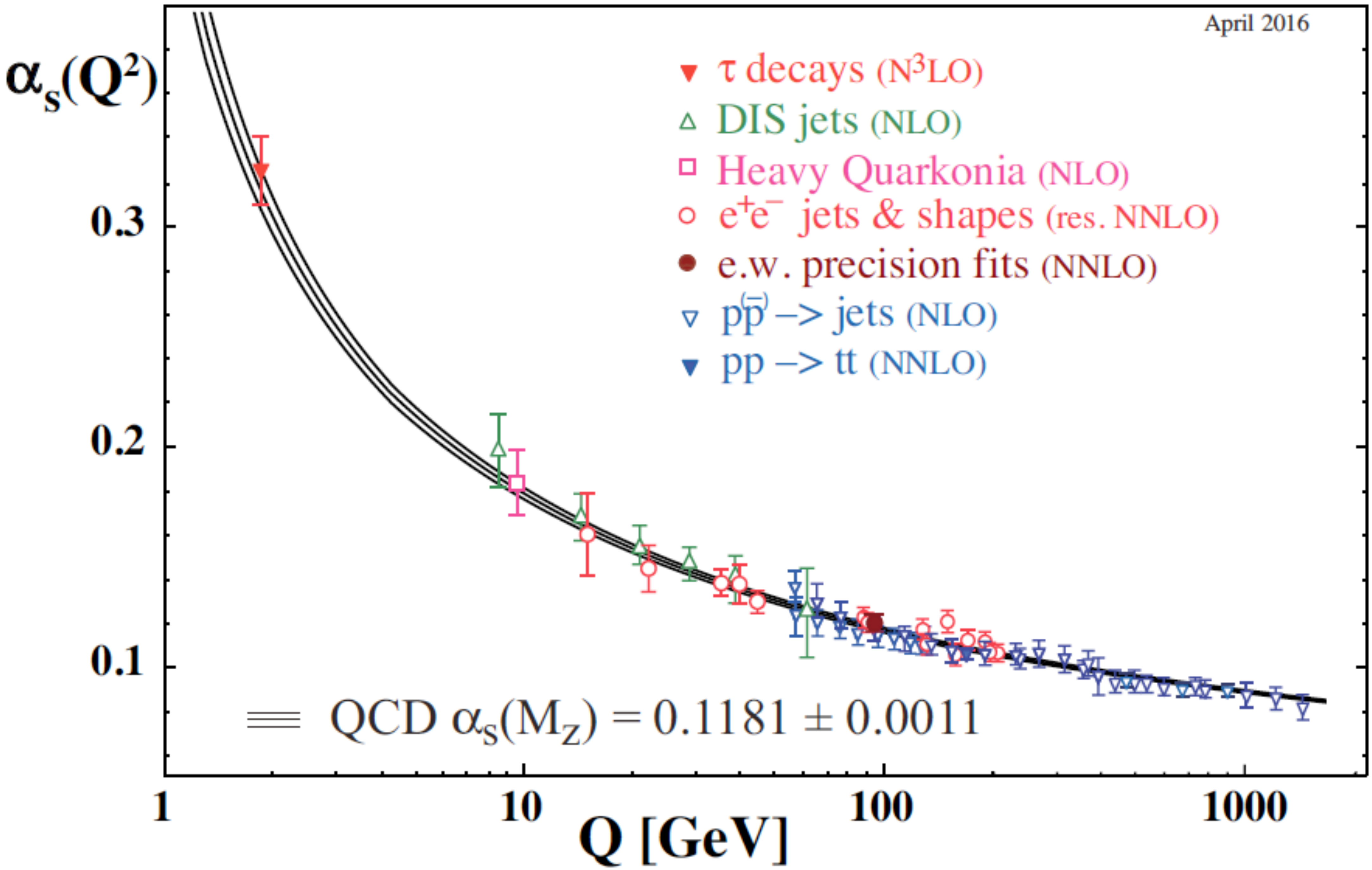
$$+ |D_\mu h|^2 - V(h)$$ (∼1990 -2012- now)

$$+ \psi_i \lambda_{ij} \psi_j h + h.c.$$ (∼2000 - now)

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

The synthetic nature of PP exhibited

QCD in full strength



Dissertori 2016

Precision in ElectroWeak Physics

(a story that goes on from about 1970 on

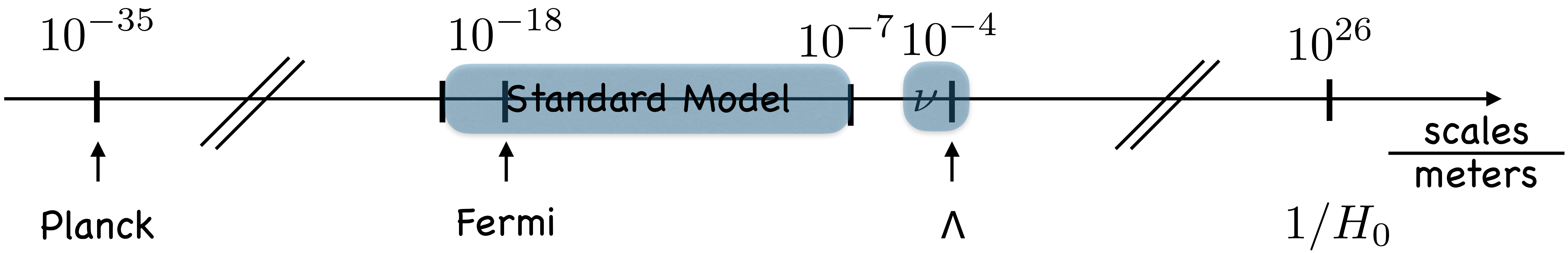
and still keeps its relevance)

	APV	$(g-2)_e$	$(g-2)_\mu$	W, Z	m_{top}
$\Delta\mathcal{O}/\mathcal{O}$	10^{-3}	10^{-8}	10^{-6}	$10^{-(3\div4)}$	10^{-2}
d(cm)	10^{-5}	10^{-11}	10^{-13}	10^{-16}	10^{-16}

precision at work at many different scales

a key to understanding

The Standard Model or not the SM?



Question:

1: Give the SM for granted and “look elsewhere”

or ?

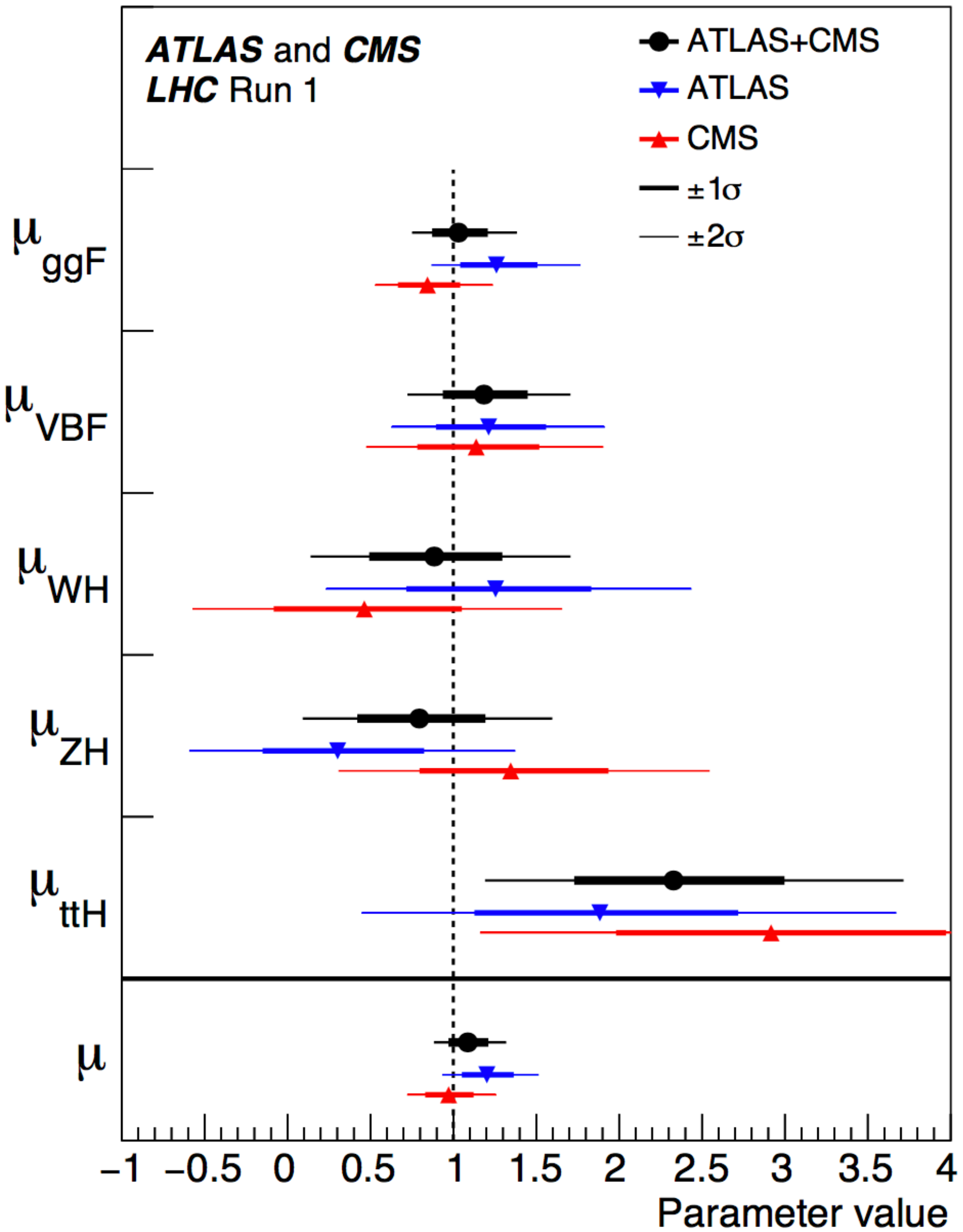
2: Keep testing the SM to learn how to complete it

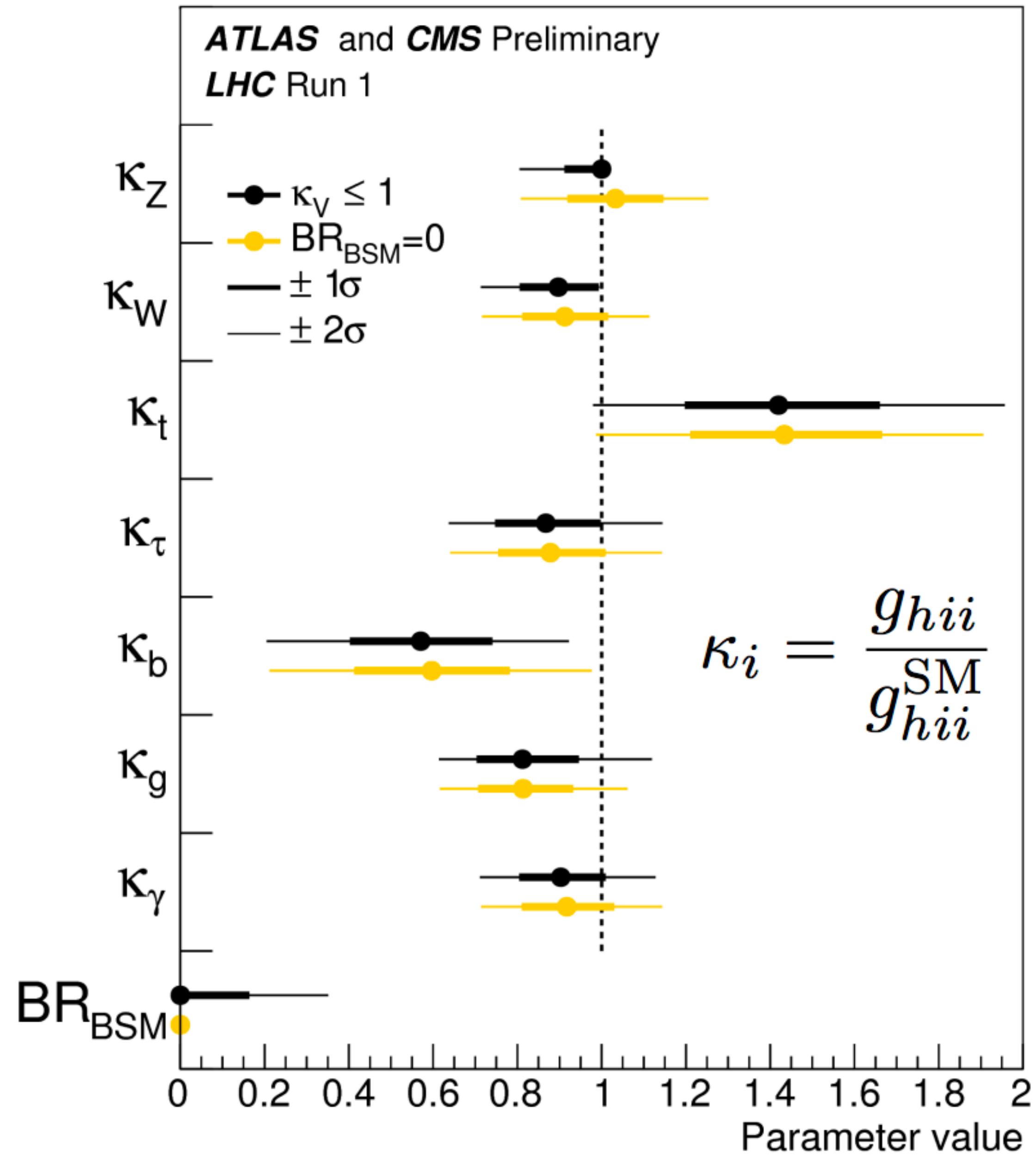
Answer:

the “or” is the problem

reasons of poor understanding and reasons of incompleteness

Precision in Higgs couplings





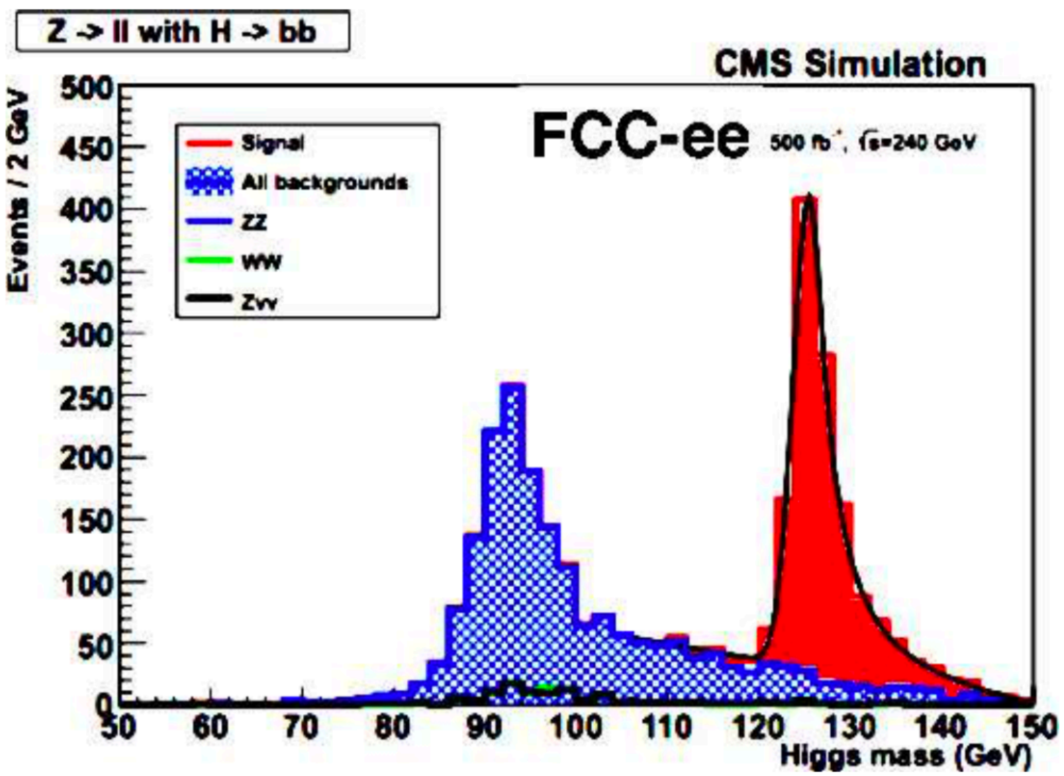
$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}} \qquad \kappa_f = \frac{g_{hf_if_i}}{(g_{hf_if_i})_{SM}} \qquad \kappa_V = \frac{g_{hVV}}{(g_{hVV})_{SM}}$$

at best, currently, a 20% precision

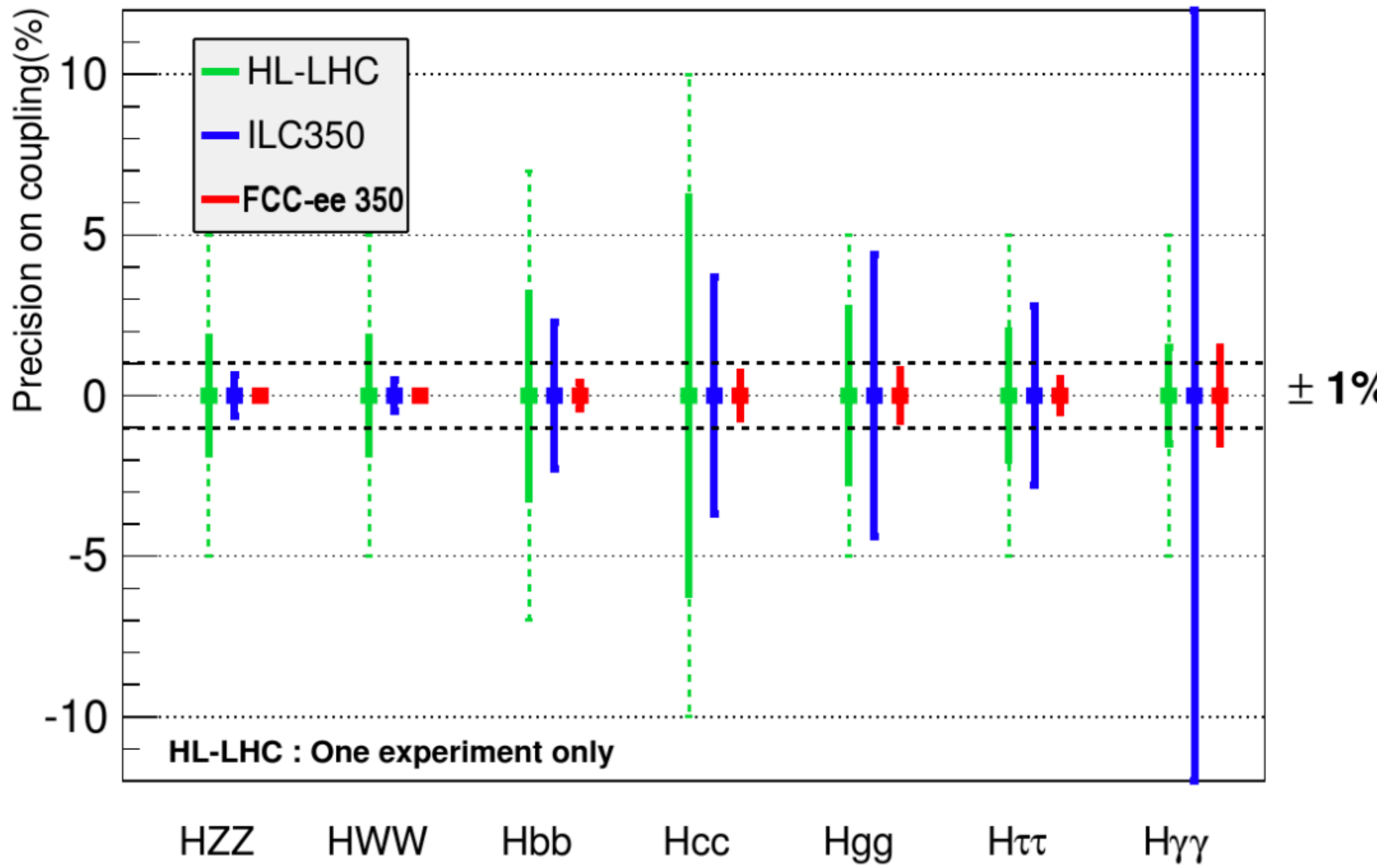
no measurement, so far, of triple or quartic self-coupling

The Higgs boson is the least "understood" particle in the SM

It cannot be the one that is less precisely measured



Bicer et al, 2014



$\sigma(Br_{inv}) = 0.2\%$

$\delta\sigma_{Zh}/\sigma_{Zh} < 1\%$ achievable in an e+e- collider

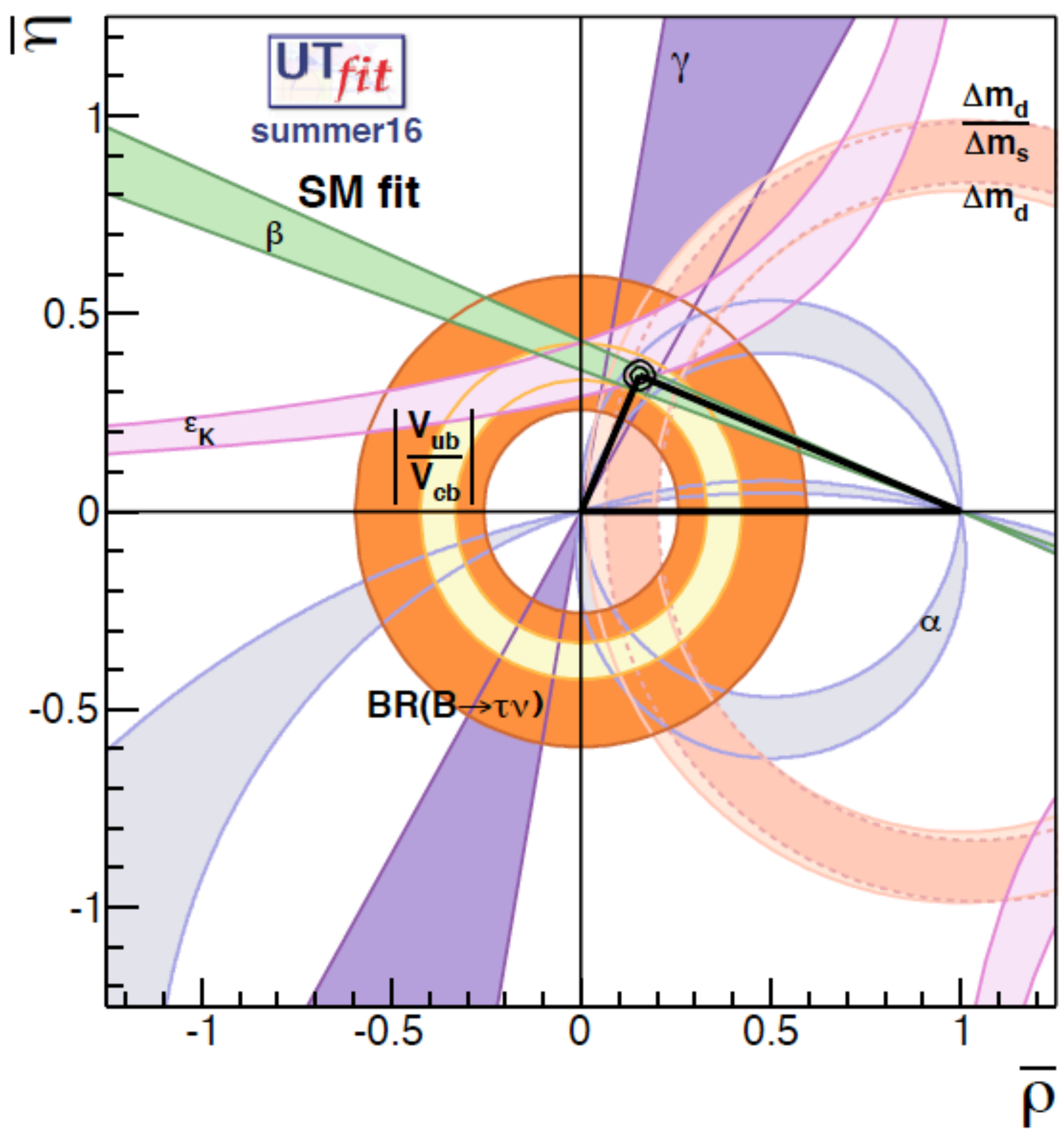
ILC: about 30% in Higgs self-coupling

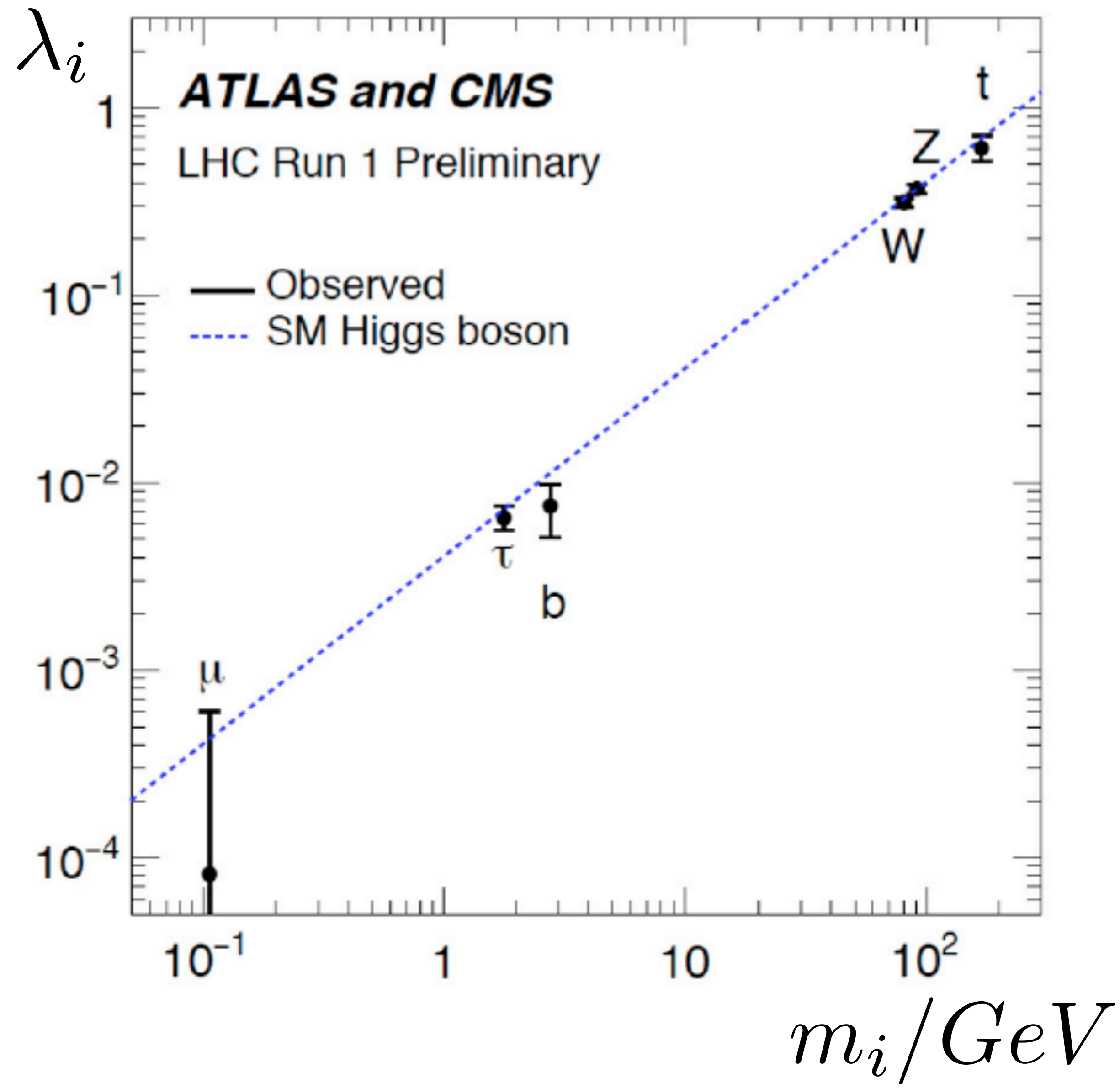
CEPC

CLIC

muon collider

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



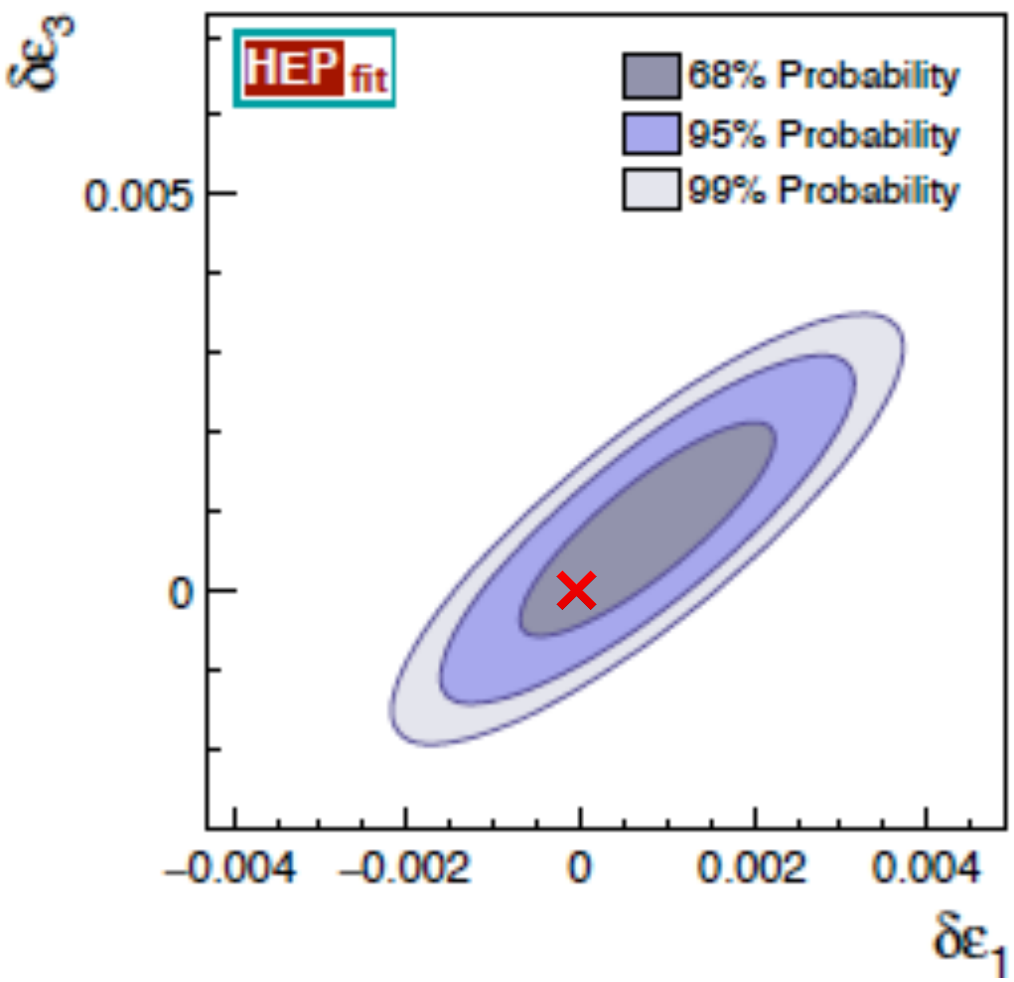


as opposed to the hard time we have in trying to describe spectrum and mixings of quarks and leptons

Not easy to improve without observed deviations from the SM

A significant comparison

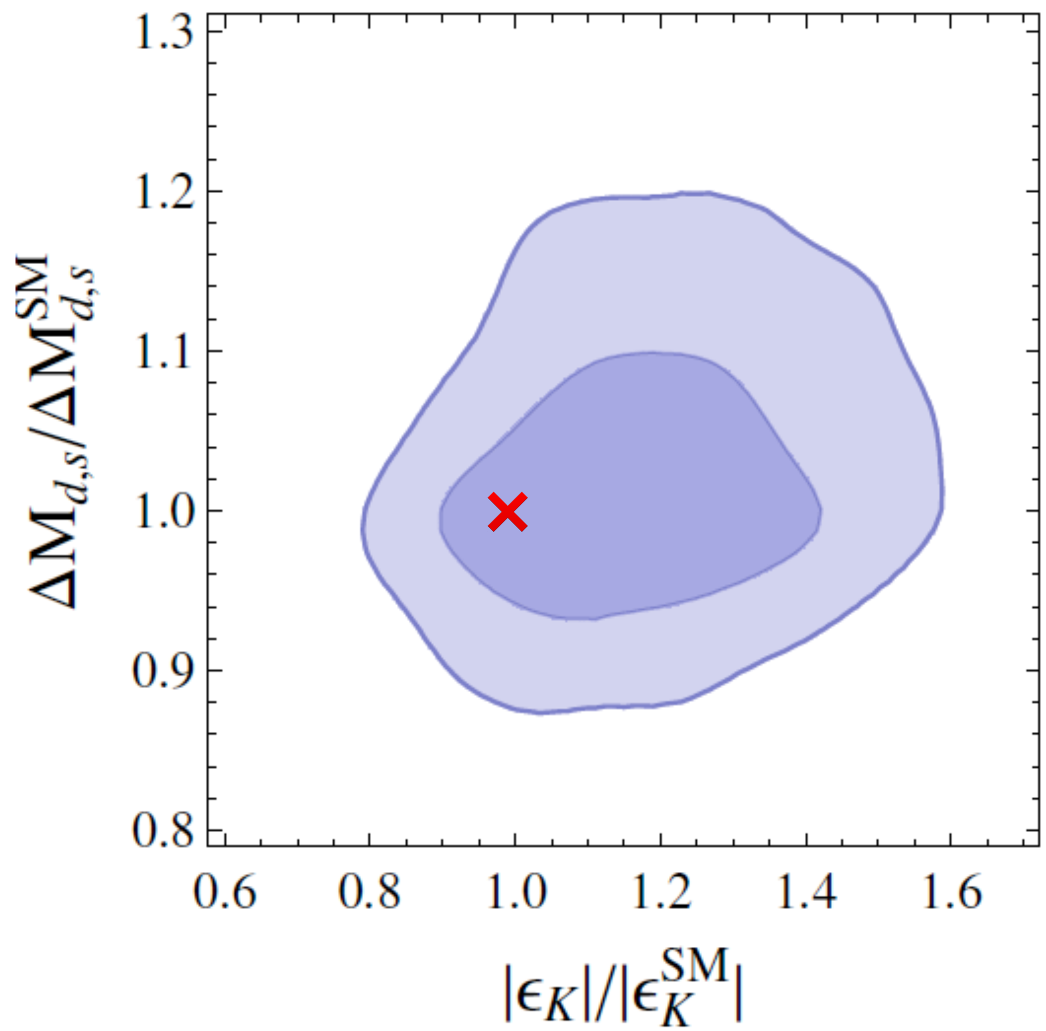
$\epsilon_1^{SM} = 5.21 \cdot 10^{-3}, \ \epsilon_3^{SM} = 5.28 \cdot 10^{-3}$



measures EW loops
at about 20% level

A future facility (FCCee, ...)
could go to 2% level

B, Buttazzo, Sala, Straub 2014



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An “aggressive” flavour program
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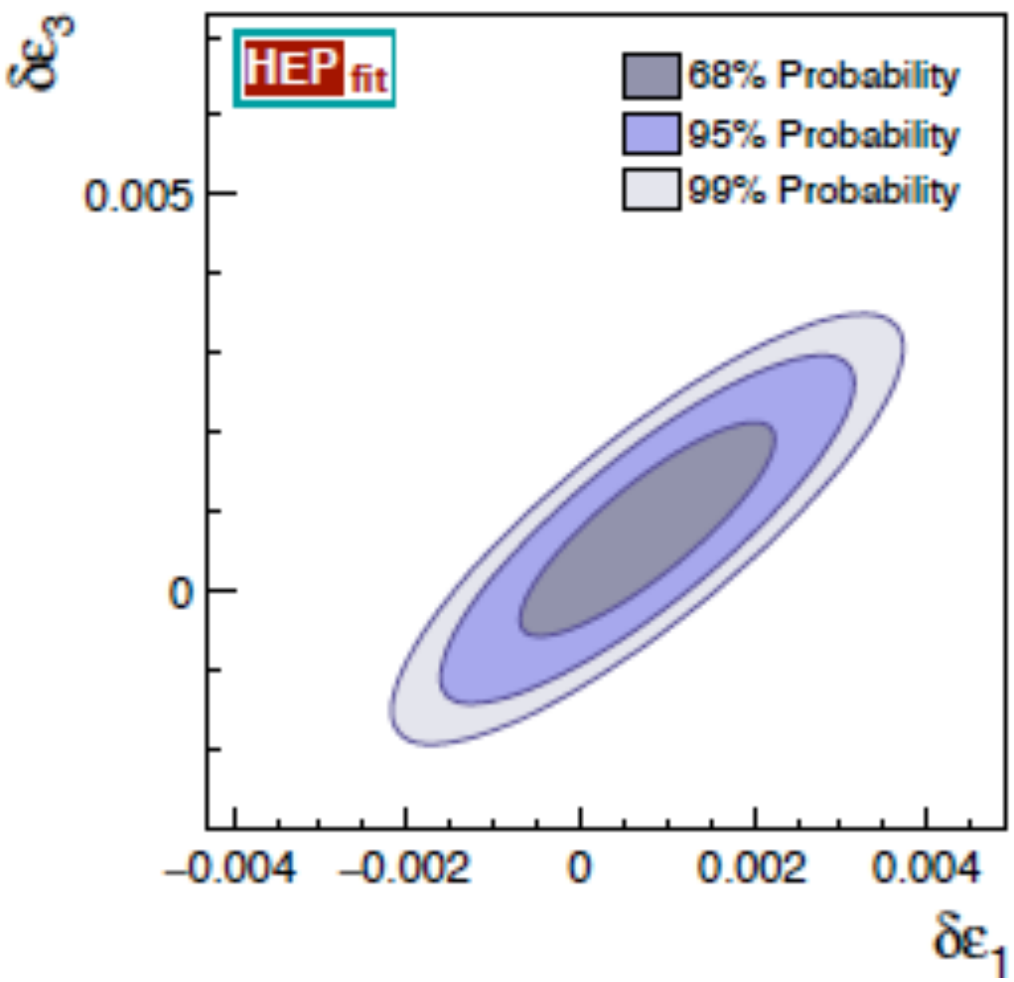

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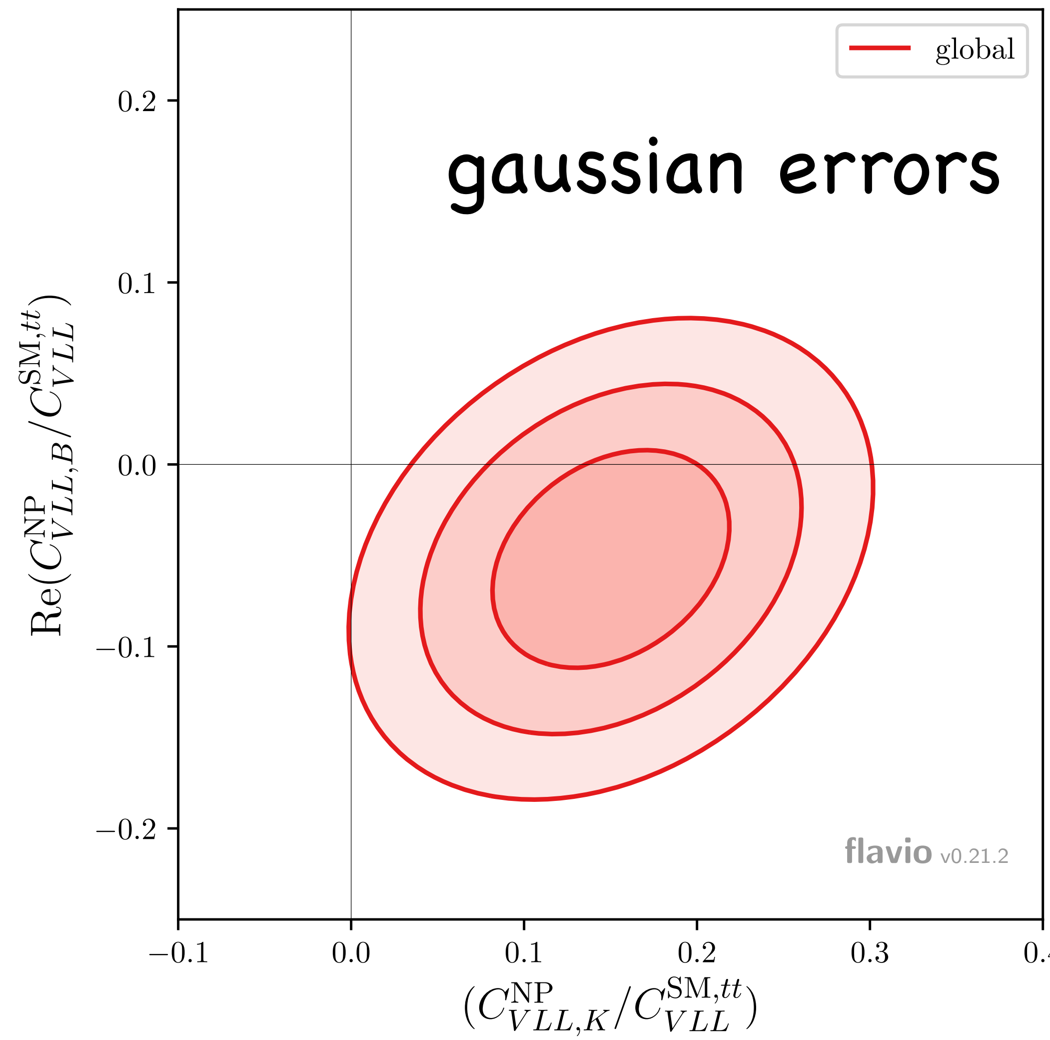
Straub 2016



measures FCNC loops
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An “aggressive” flavour program
could go to 2% level

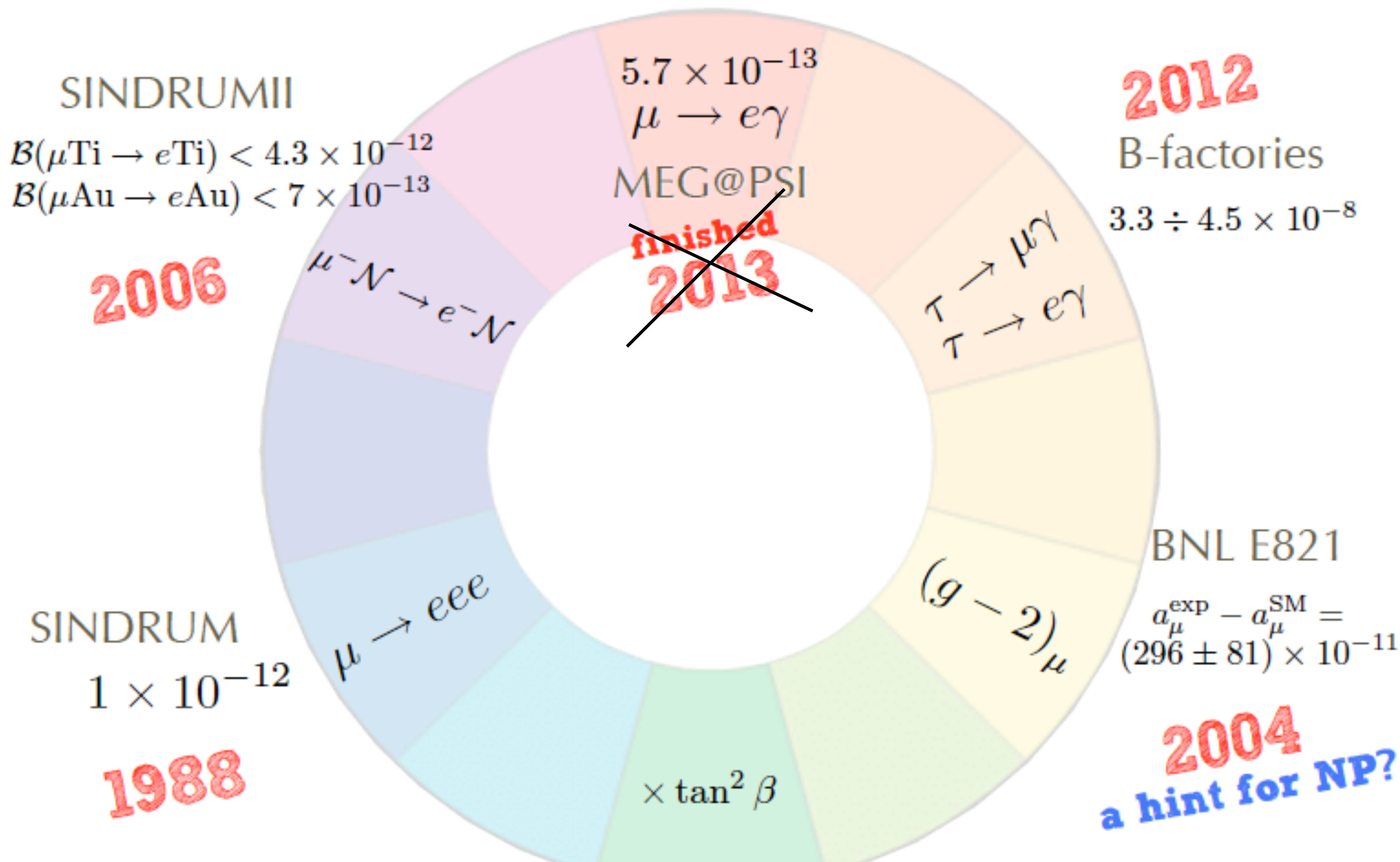
An "Extreme Flavour" experiment?

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

a recent <Phase-II LHCb Upgrade>
submitted to the LHCC

Lepton Flavour Violation



Motivation: extra degrees of freedom + unification

The incompleteness of 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)

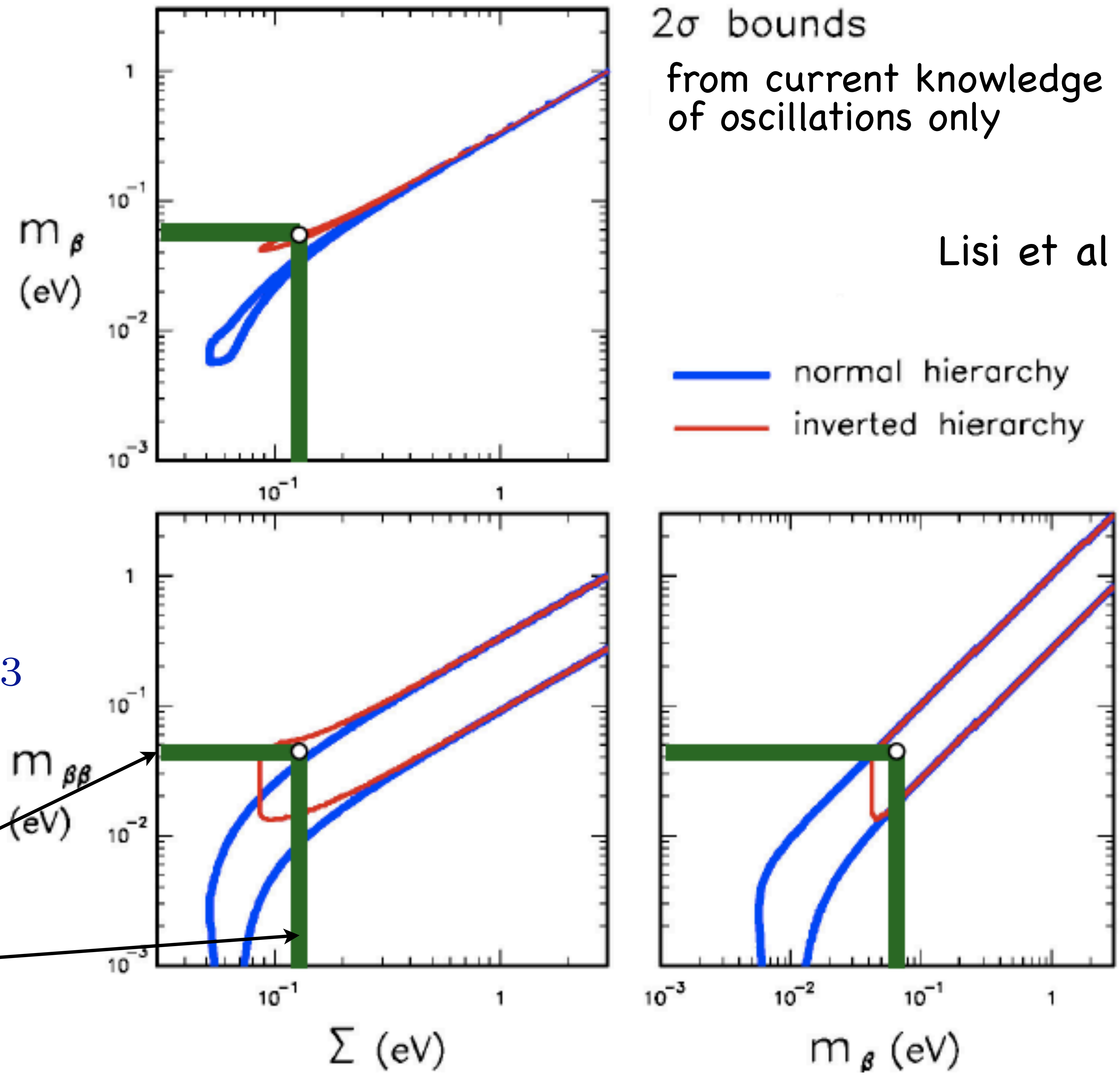
$\Rightarrow$ the hierarchy problem
the flavour paradox $\Leftarrow$

Key neutrino measurements

m_β
beta-decay endpoint

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

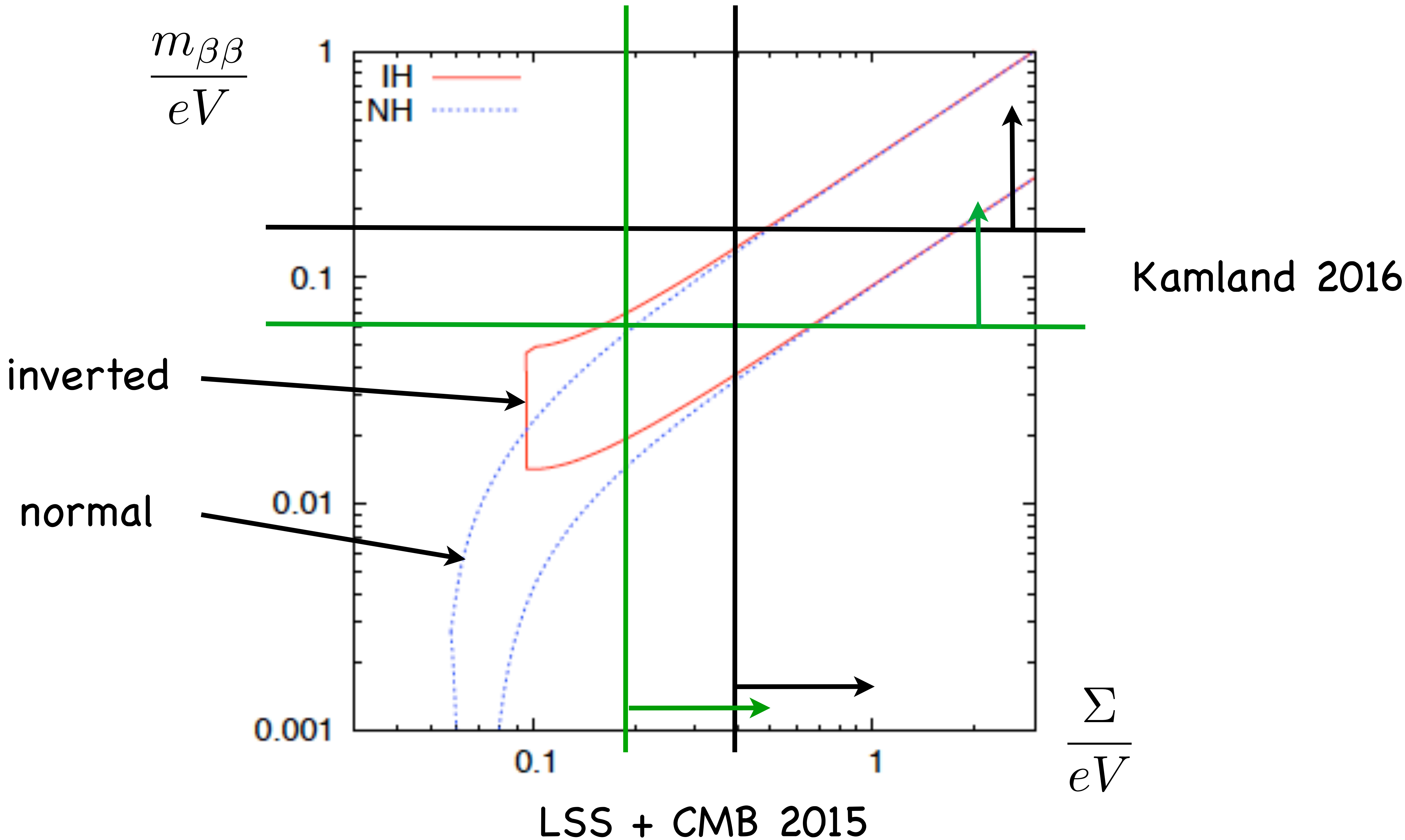
$\Sigma = m_1 + m_2 + m_3$
CMB
large scale structures



hypothetical measurements

Where progression is most likely

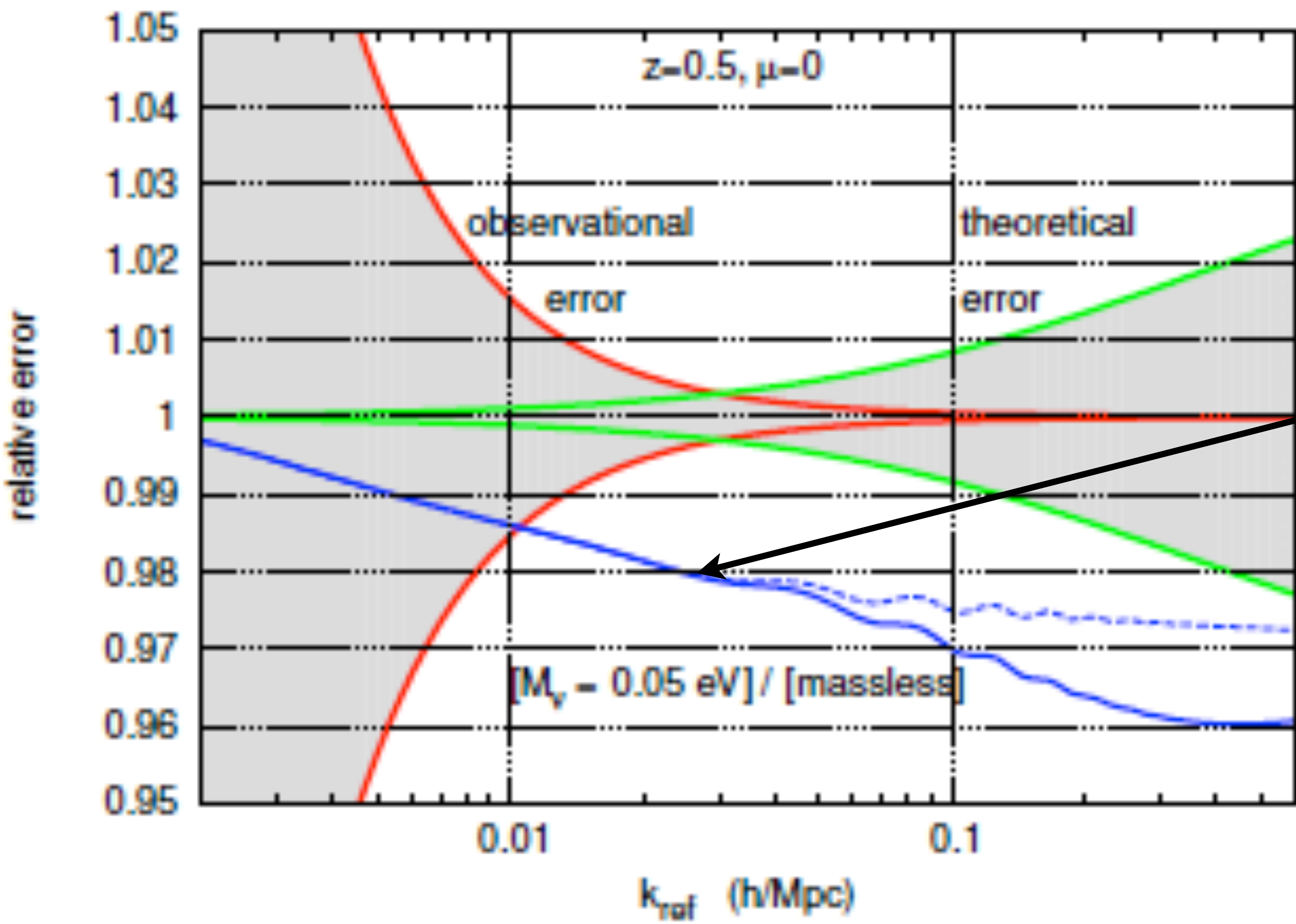
current bounds (with uncertainties)



black = realistic/conservative
green = optimistic

Power spectrum of large scale structures

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

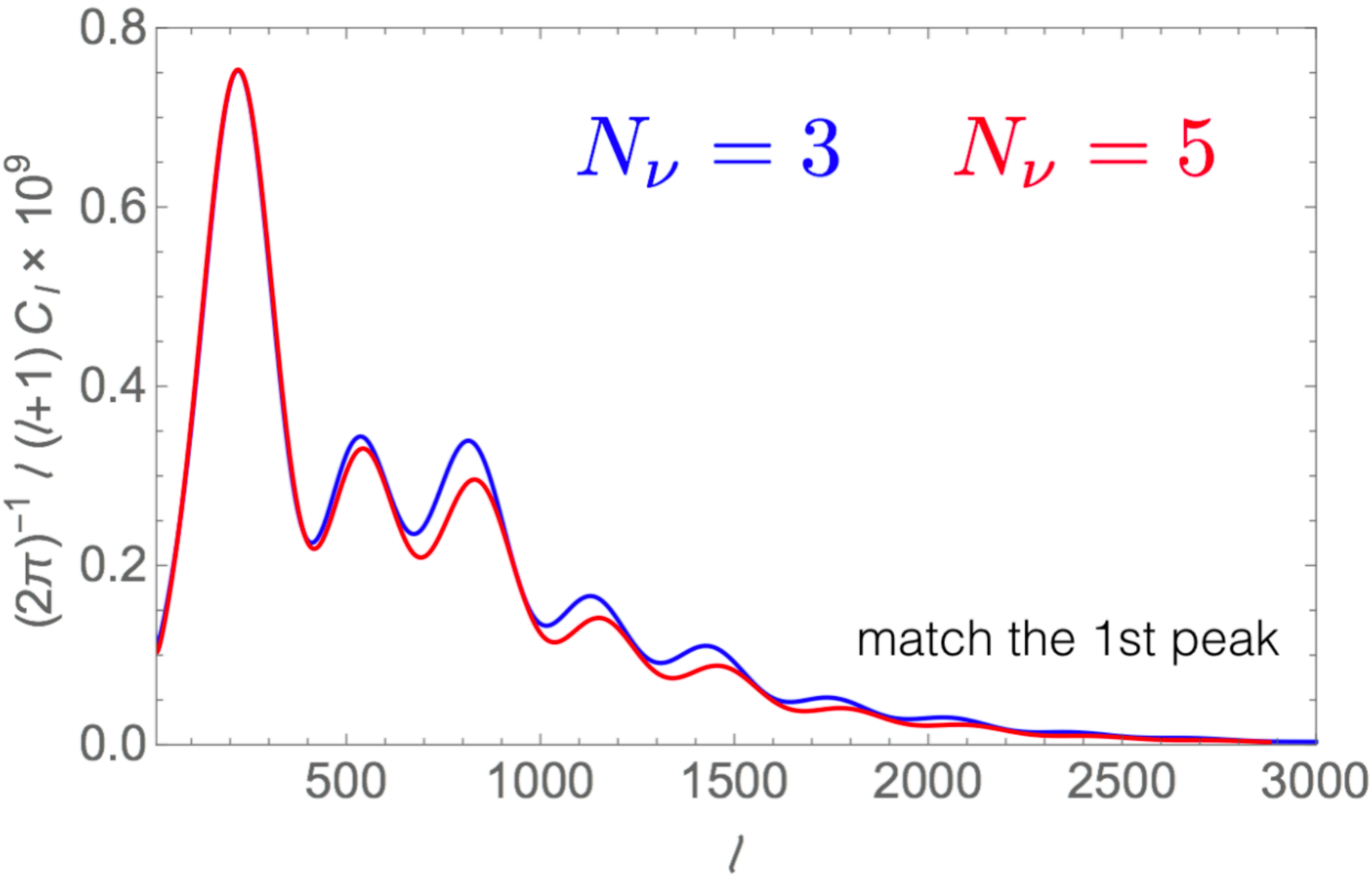


ratio between with (ν massive) and without (ν massless) "free streaming"

Lesgourgues et al, 2103

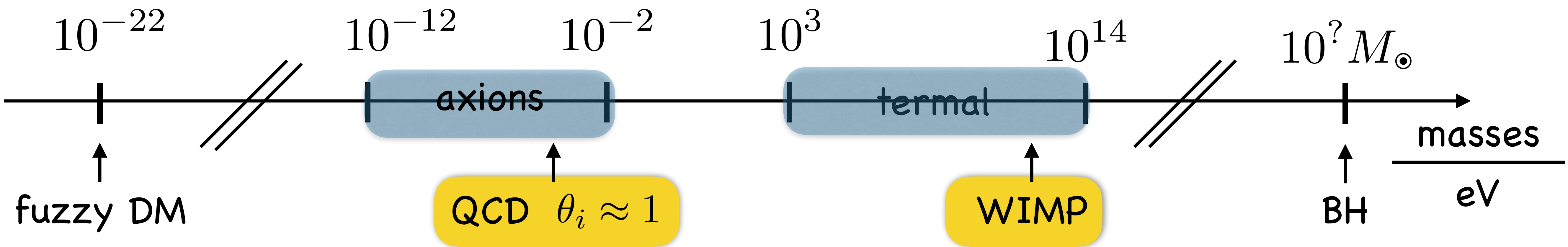
- Determination with future large-scale structure observations (Euclid) at $2-5\sigma$ depending on control of (mildy) non-linear physics

▶ Not independent on "priors" but still highly significant



$\Delta N^{\nu}_{eff} \lesssim 0.6$ now, expected to improve in sensitivity by about one order of magnitude

Dark Matter



$$\Omega_{WIMP} \sim 0.1 \frac{\sigma v}{(20\ TeV)^2}$$

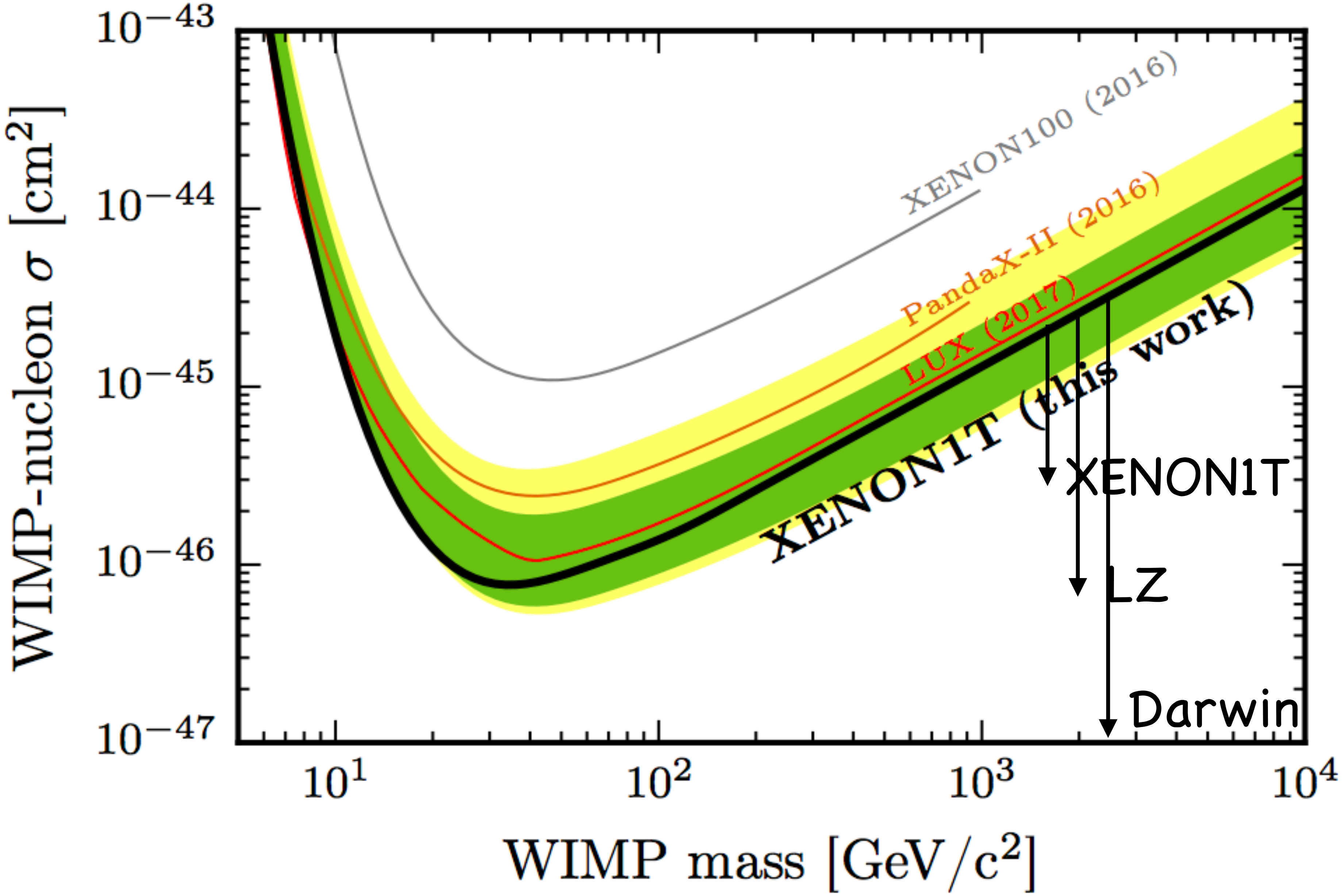
$$\Omega_a \sim 0.1 \left(\frac{10^{-5} eV}{m_a}\right)^2 \theta_i^2 \qquad m_a \sim 10^{-(4\div5)} eV \frac{10^{11\div12} GeV}{f_a}$$

makes sense to look also elsewhere

independent motivations valuable

(almost)
a forgotten question: Why Ω_b and Ω_{DM} comparable?

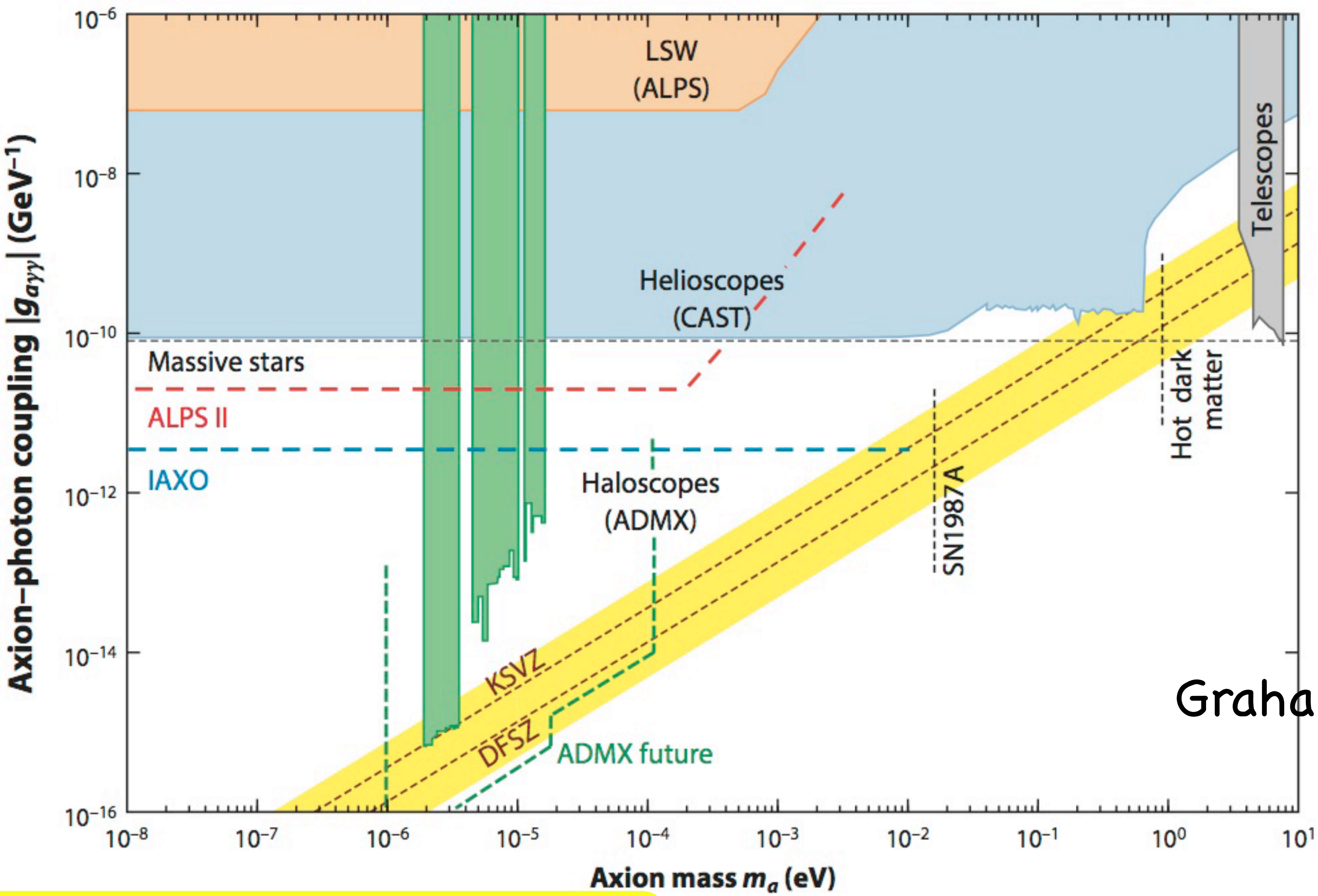
WIMP direct searches



well in place, quite relevant already now

$\lambda h \bar{\chi}\chi$ $\qquad\qquad$ $\sigma_{\chi N} \approx 10^{-44}(\lambda/0.1)^2 cm^2$

Axion/ALP searches



Graham et al, 2106

$$\frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} \qquad a \xrightarrow{\vec{B}} \gamma$$

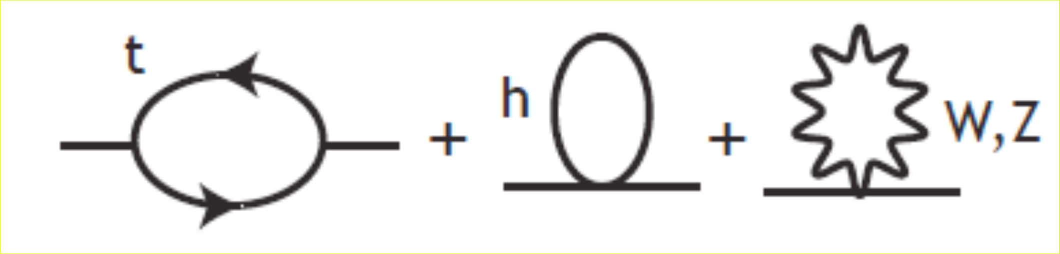
Good to look for other couplings:

$$\vec{\nabla} a \cdot \vec{\sigma},\ a\vec{\sigma} \cdot \vec{E},\ \dot{a}\mathcal{O}_{SM}\ (a\mathcal{O}_{SM})$$

The hierarchy problem, once again

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

NOT in the SM

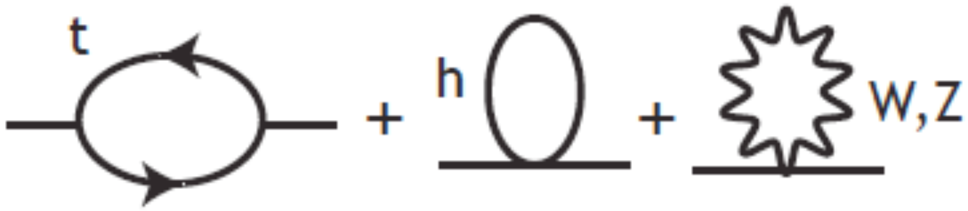


$$\delta m_h^2 \propto \Lambda^2$$

We have seen $\log\Lambda$ divergences everywhere: running of gauge couplings, scaling violations, anomalies

Power law divergences prevent us from calculating or even estimating the Fermi scale nor the cosmological constant

The standard reaction



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

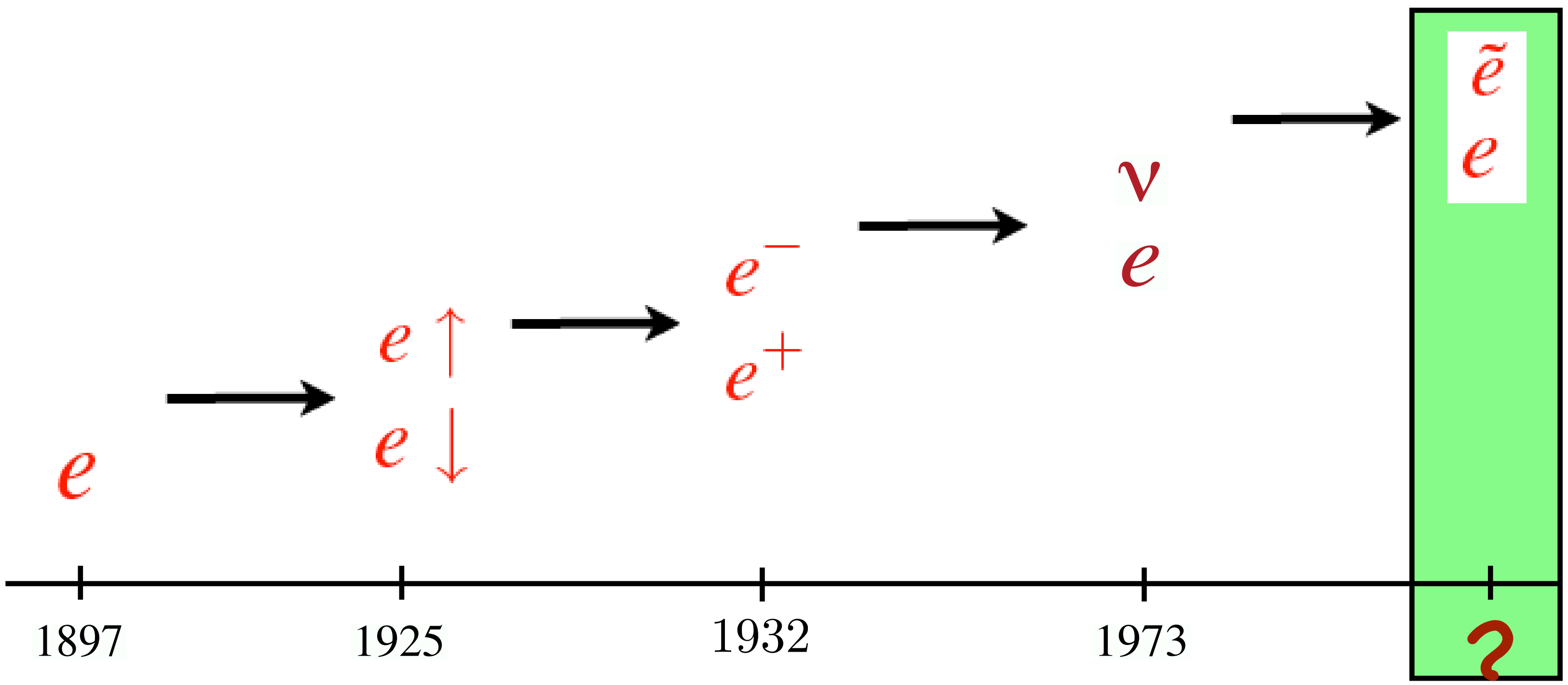
$$\Lambda_t \lesssim 0.4\sqrt{\Delta}\ TeV \qquad \Lambda_g \lesssim 1.1\sqrt{\Delta}\ TeV \qquad \Lambda_{g'} \lesssim 3.7\sqrt{\Delta}\ TeV$$

$1/\Delta$ = amount of tuning

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

SUSY as the best option

(among others)



$$< h > \approx m_{\tilde{e}} \approx m_{SUSY\ \ particles}$$

But this is a quantitative relation only
if one bars accidental cancellations

Not a problem for SUSY but for knowing if true in nature

Where are the superpartners?

Define an "inverse fine-tuning" measure

$$\Delta = \frac{\delta m_h^2}{m_h^2}, \quad Max_{a_i} \frac{dm_h^2/m_h^2}{da_i/a_i}, \ldots$$

G. Ross (sept 2016) Is low energy SUSY alive ?

$\Delta^{CMSSM} > 350$ ✗ $\Delta^{(C)MSSM} > 40\,(200)^{SUSY\ DM}$

$\Delta^{CGMSSM} > 60$ ✗ $\Delta^{(C)GNMMS} > 20$ ✔8TEV 13TEV?

$\Delta^{(C)MSSM+\mu'} > 20\,(40)^{SUSY\,DM}$

Cute more natural models available (JMR) Too cute?

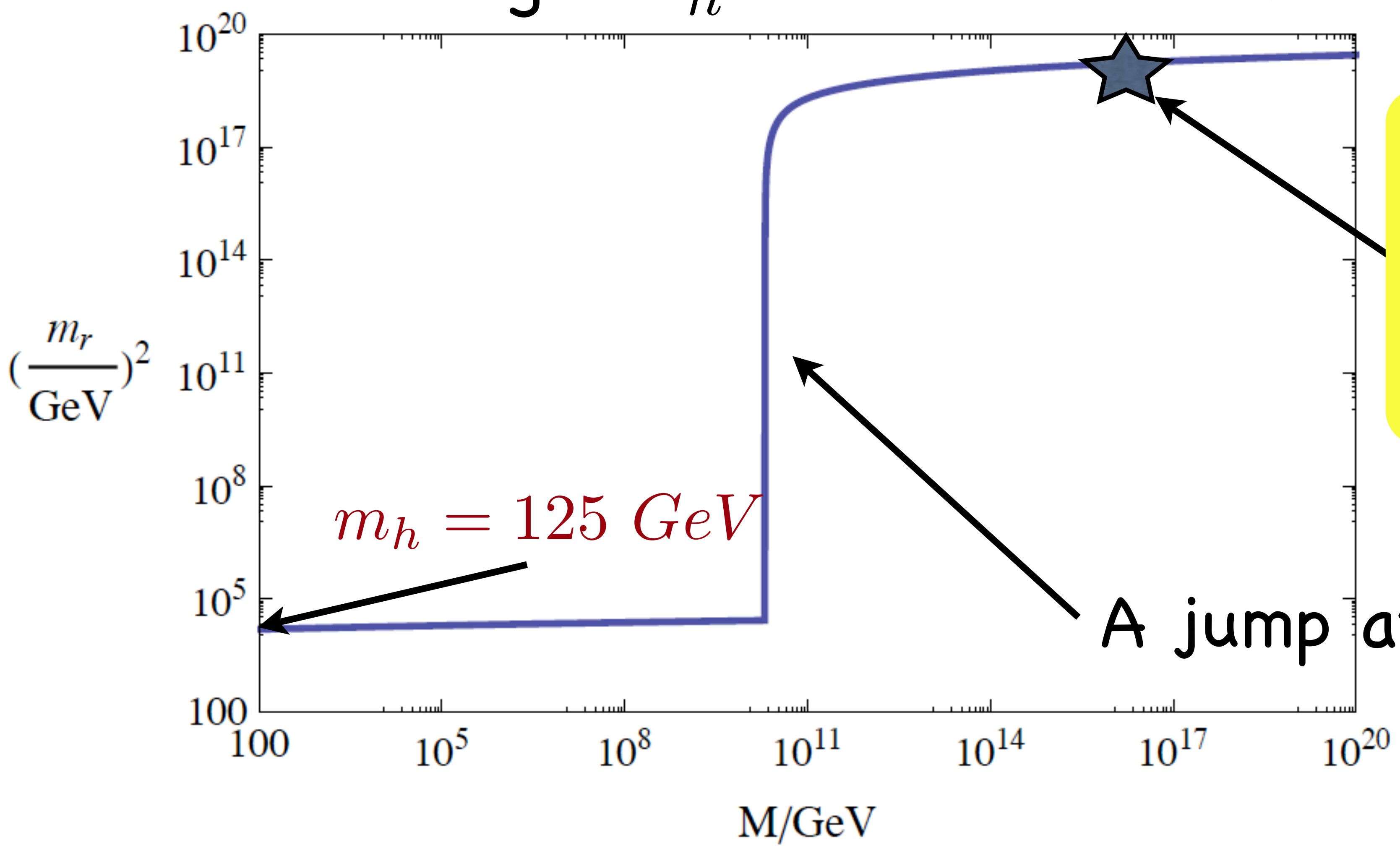
Peculiar configurations $(m_i^{susy} >?)$

The judgement suspended, reasons of concern

Other signals than from standard sparticles (R-axions, S-axions, ...)?

Λ^2-divergences as a signal of the problem

The running m_h^2 versus the scale M



"fine tuning"

m_h depends on a very precise initial condition of order $O(m_h^2/m_H^2)$ at some short distance

A jump at M_H of size $\frac{(\lambda_H M_H)^2}{16\pi^2}$

Pending questions to avoid a "low energy" explanation of the hierarchy:

- gravity?
- Non-asymptotically free couplings?
- No higher physical scale?

Can we lack a clever IR-UV connection?

Frequently asked questions about "naturalness"

especially after the (temporary) blank of LHC in BSM

Is the quest for "naturalness" still relevant?

More than ever

How about: "naturalness" = "low energy" New Physics?

Not a "theorem" anymore

Which are the good "naturalness" solutions?

The ones that lead to testable predictions,
the more quantitative the better

For completeness

$$\mathcal{L}_{SMGR} = \frac{\sqrt{-g}}{16\pi G_N}(-R(g) + 2\Lambda)$$

Classically well tested

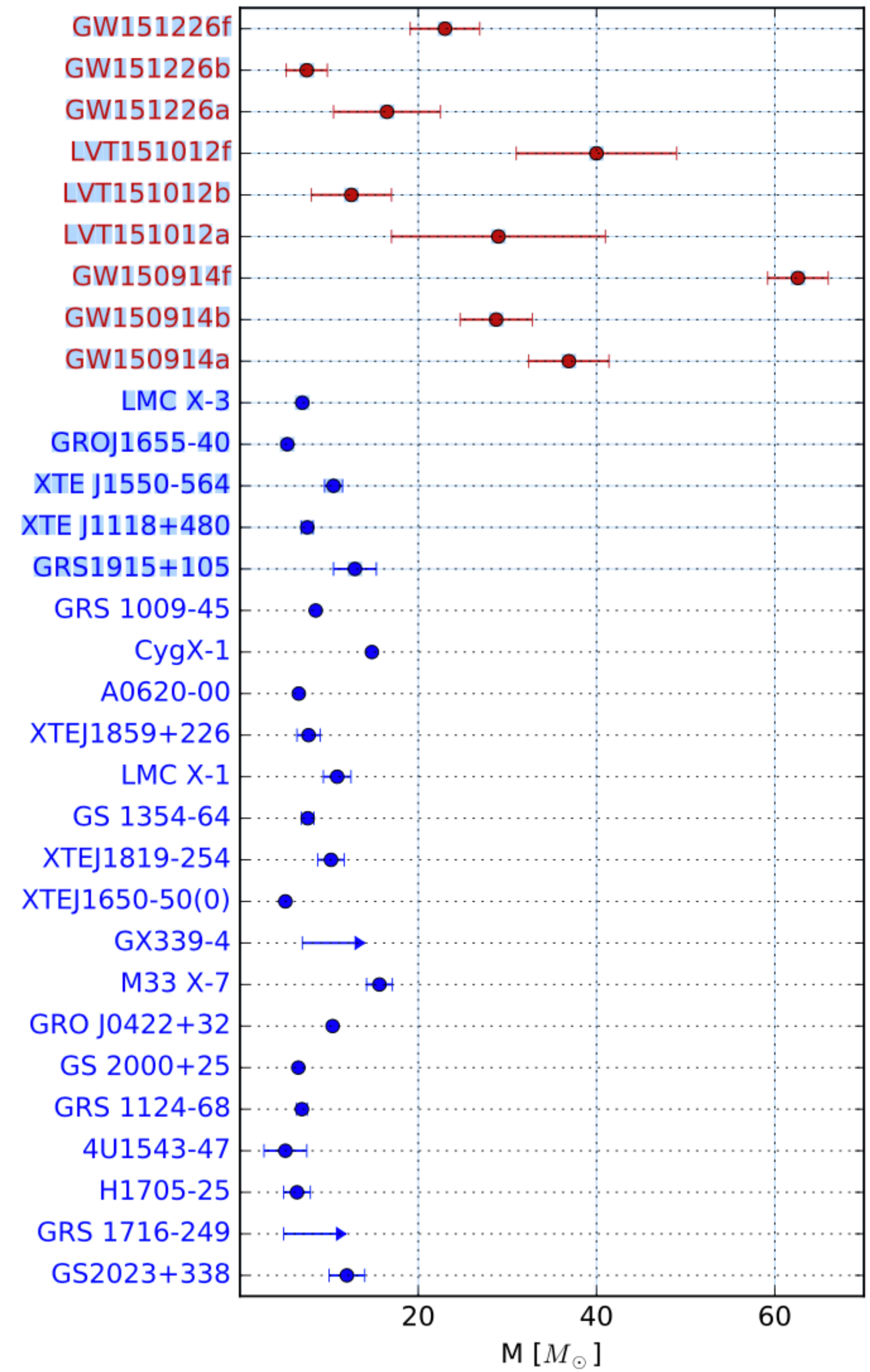
BH, GW, cosmology

Resists quantisation

No successful renormalisation recipe so far

No way to calculate or even estimate $\Lambda \ (\approx (10^{-3}eV)^4)$

The boundaries between PP, AP and cosmology fading away



Vitale 2017

Among the many reactions to the (temporary) blank of LHC in BSM

Twin Higgs

Chacko, Goh, Harnik 2005

$V(H, H') \to V(\mathcal{H}), \quad |\mathcal{H}|^2 = |H|^2 + |H'|^2$ is $SO(8)$-symmetric

$$\Downarrow$$

$V(\mathcal{H}) : SO(8) \to SO(7) \Rightarrow 7\ PGBs, \ SU(2)' \times U(1)' \to U(1)'_{em}$

+ $SU(2) \times U(1)$ unbroken

and 1 massless Higgs doublet, a pseudo-Goldstone

Craig et at 2015

Fraternal

minimise extra " ' "

rely on many initial conditions

No problem with (1)

need Parity broken to get $v/v' \neq 0, 1$

(1)

Lee, Yang 1956

Mirror World

Dark baryons/atoms? (2)

Dark radiation? (3)

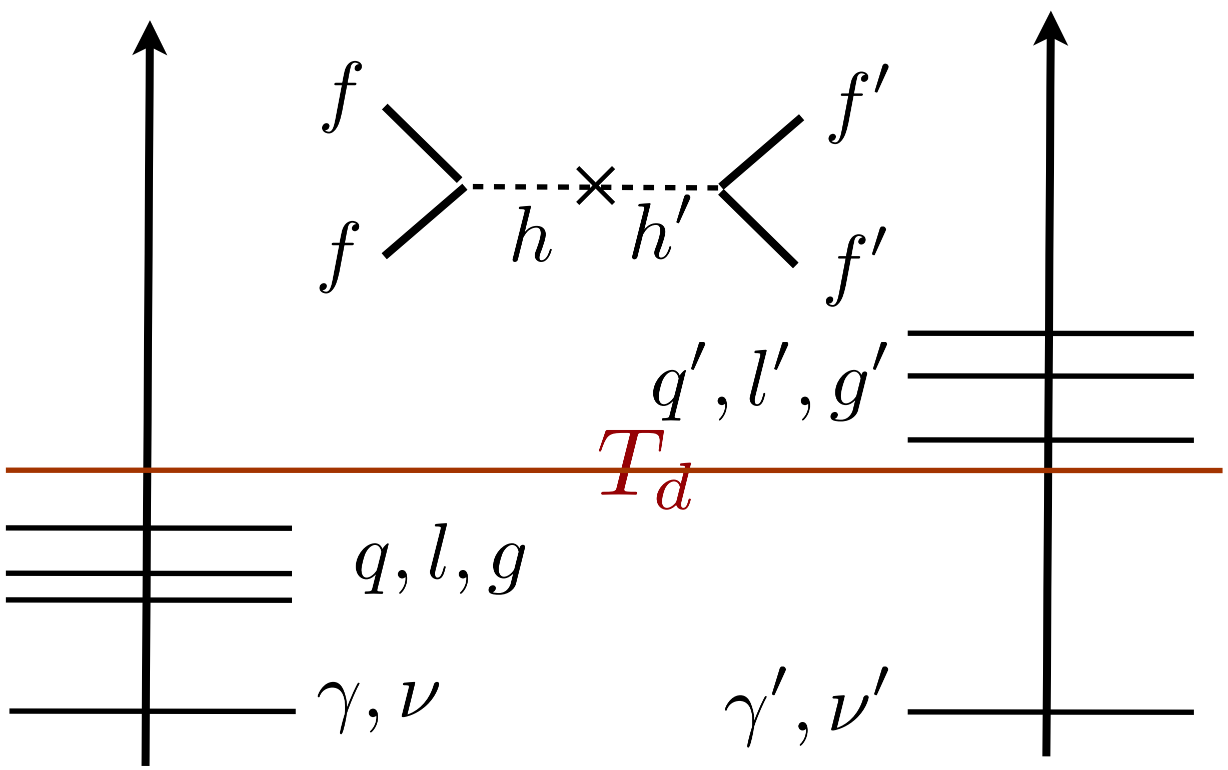
(very annoying since seems make you loose $\Omega_B \sim \Omega_{DM}$!)

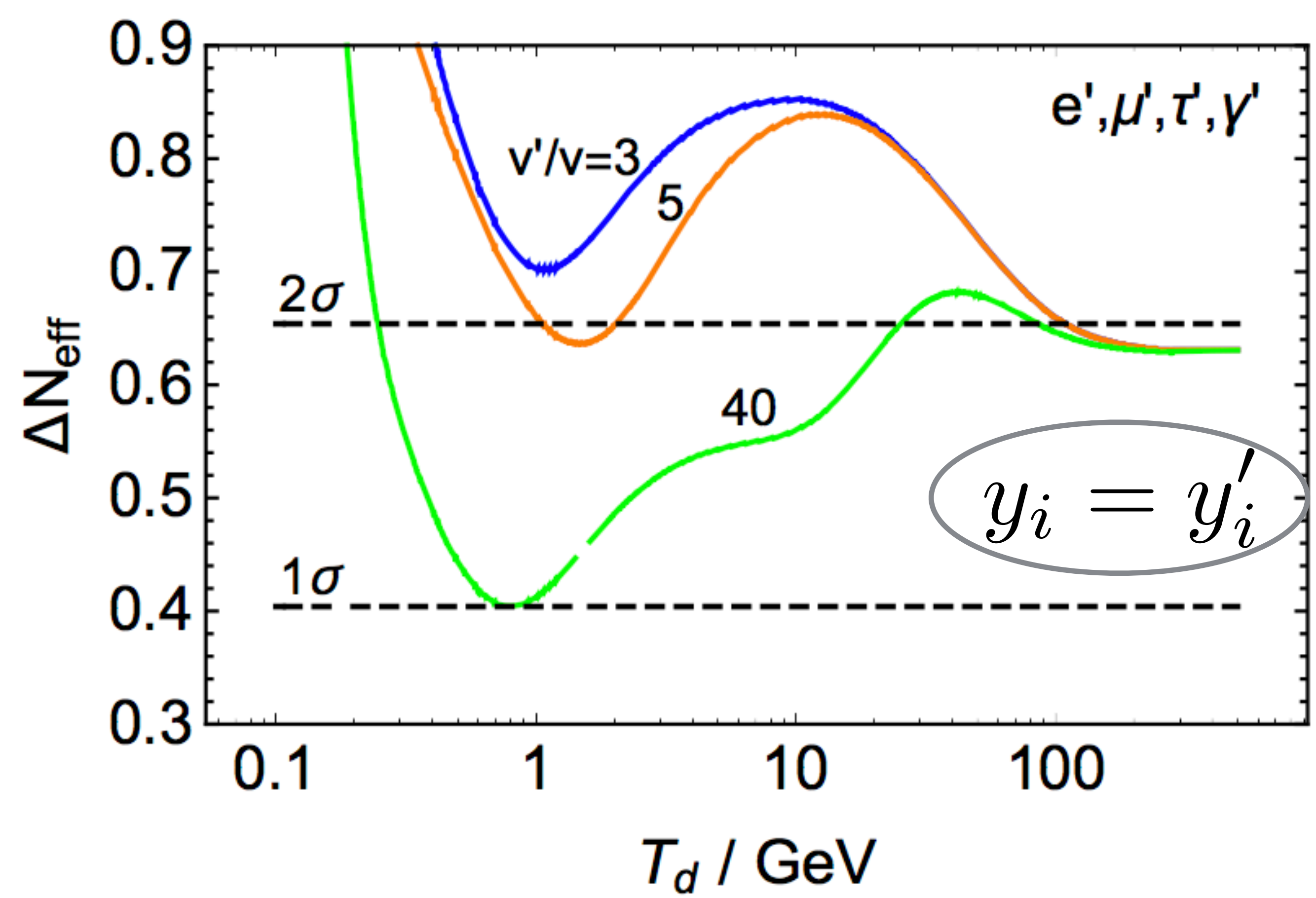
If mirror, is there a way to solve (1) (2) (3) ?

First guided by the Dark Radiation:

$m'_i = y'_i v'$

T_d = decoupling temperature





look for P-breaking in light Yukawa's $y'_i > y_i$

Enough? Need a theory of flavour?

B, Hall, Gregoire 2005

If mirror, is there a way to solve (1) (2) (3) ?

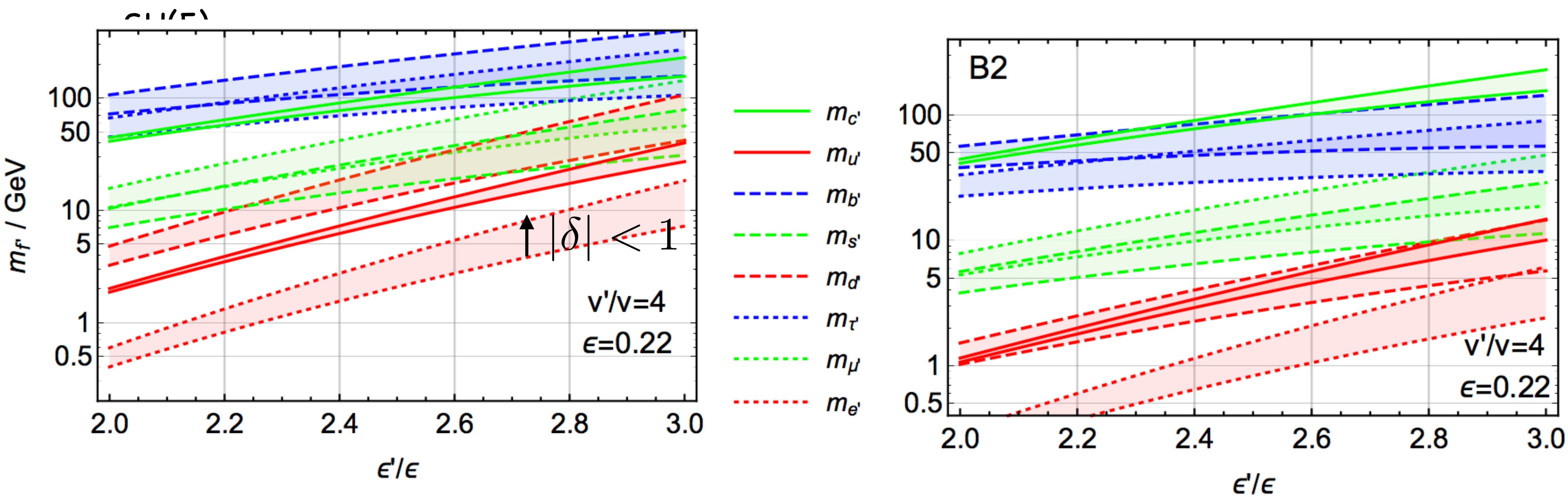
The only breaking of Parity in a single parameter

$$\epsilon \neq \epsilon'$$

from where the fermion hierarchies (standard and mirror) arise

$$y_{ij} = \epsilon^{n_i} \lambda_{ij} \epsilon^{\bar{n}_j} \qquad\qquad y'_{ij} = \epsilon'^{n_i} \lambda_{ij} \epsilon'^{\bar{n}_j}$$

$$\frac{y'_f}{y_f} = (\frac{\epsilon'}{\epsilon})^{n_f} (1 + \delta_f (\epsilon'^{m_f} - \epsilon^{m_f}))$$

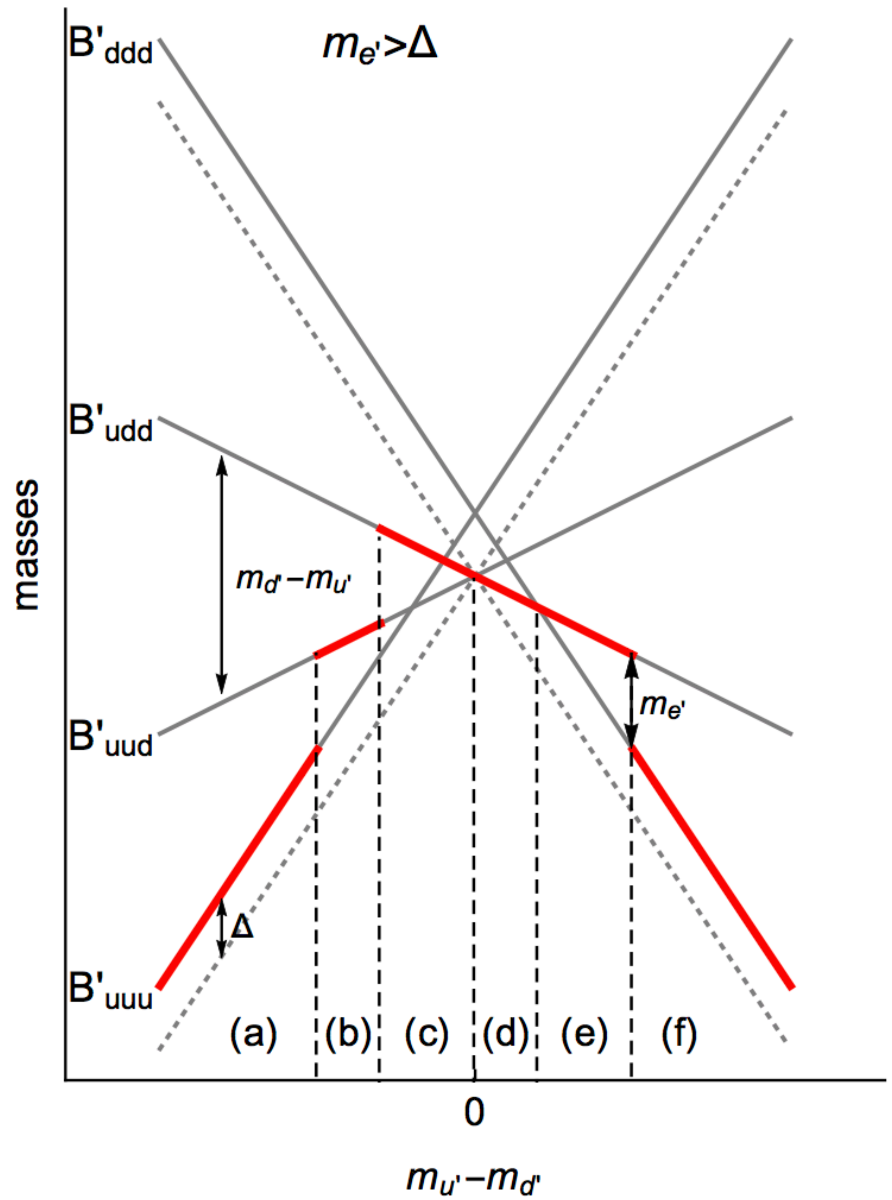


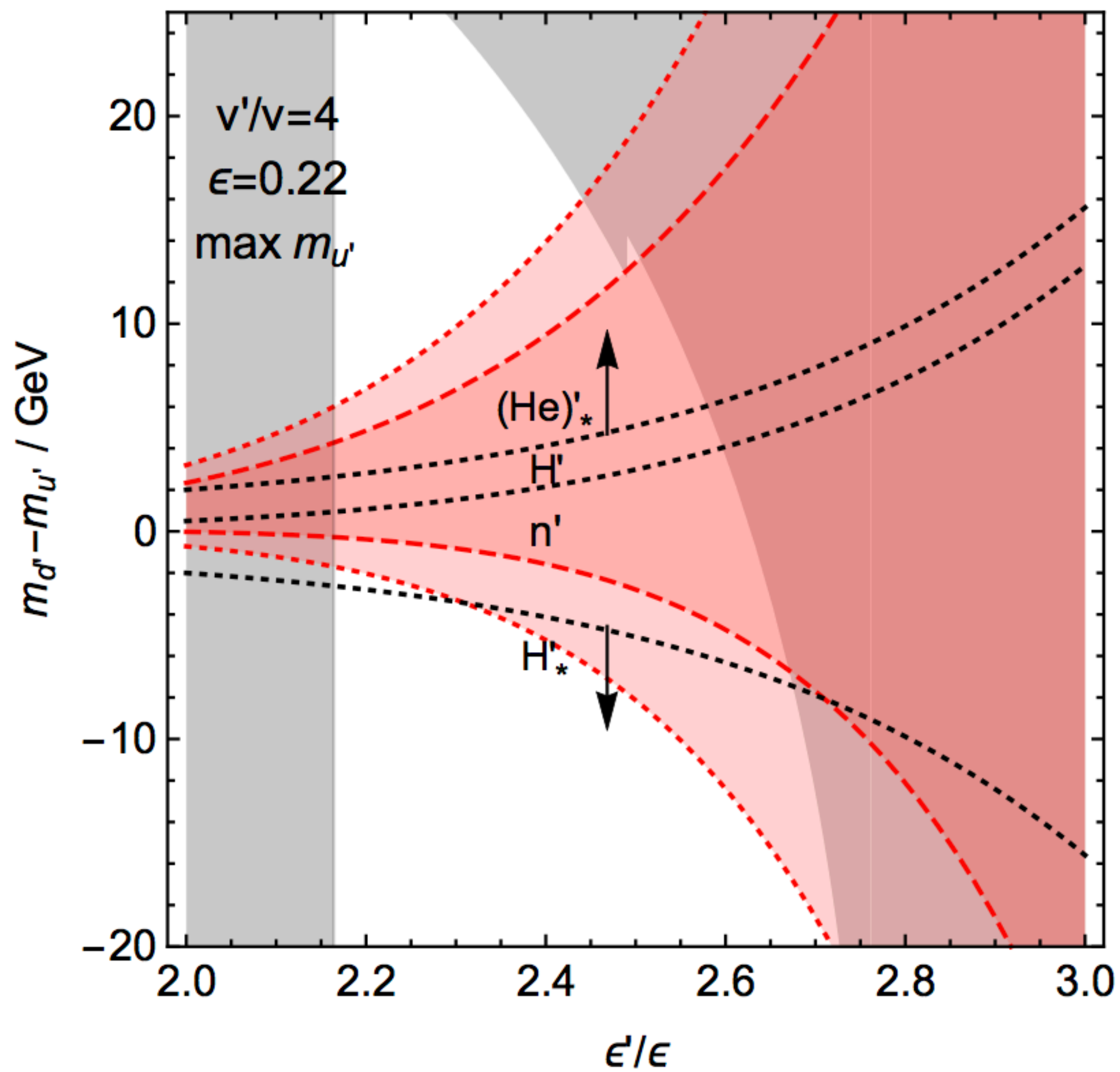
$m_f \geq 2$ Typically $\epsilon \sim 0.2$

B, Hall, Harigaya 2017

Dark Matter

Mirror matter asymmetry stored in $B'_{uuu},\ B'_{uud},\ B'_{udd},\ B'_{ddd},\ e'$

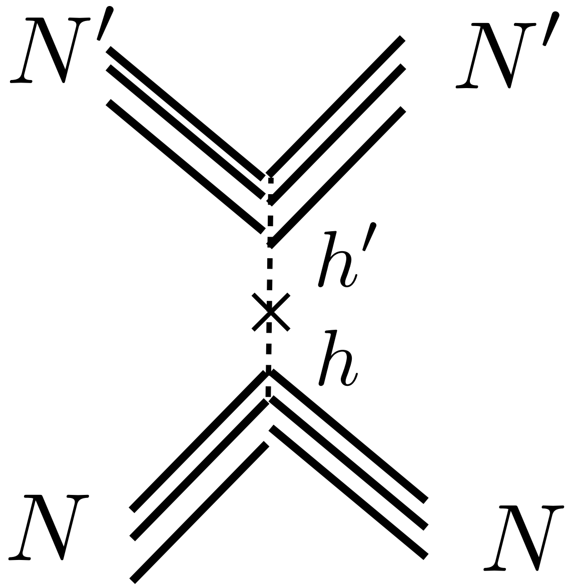




DM = the lightest among:

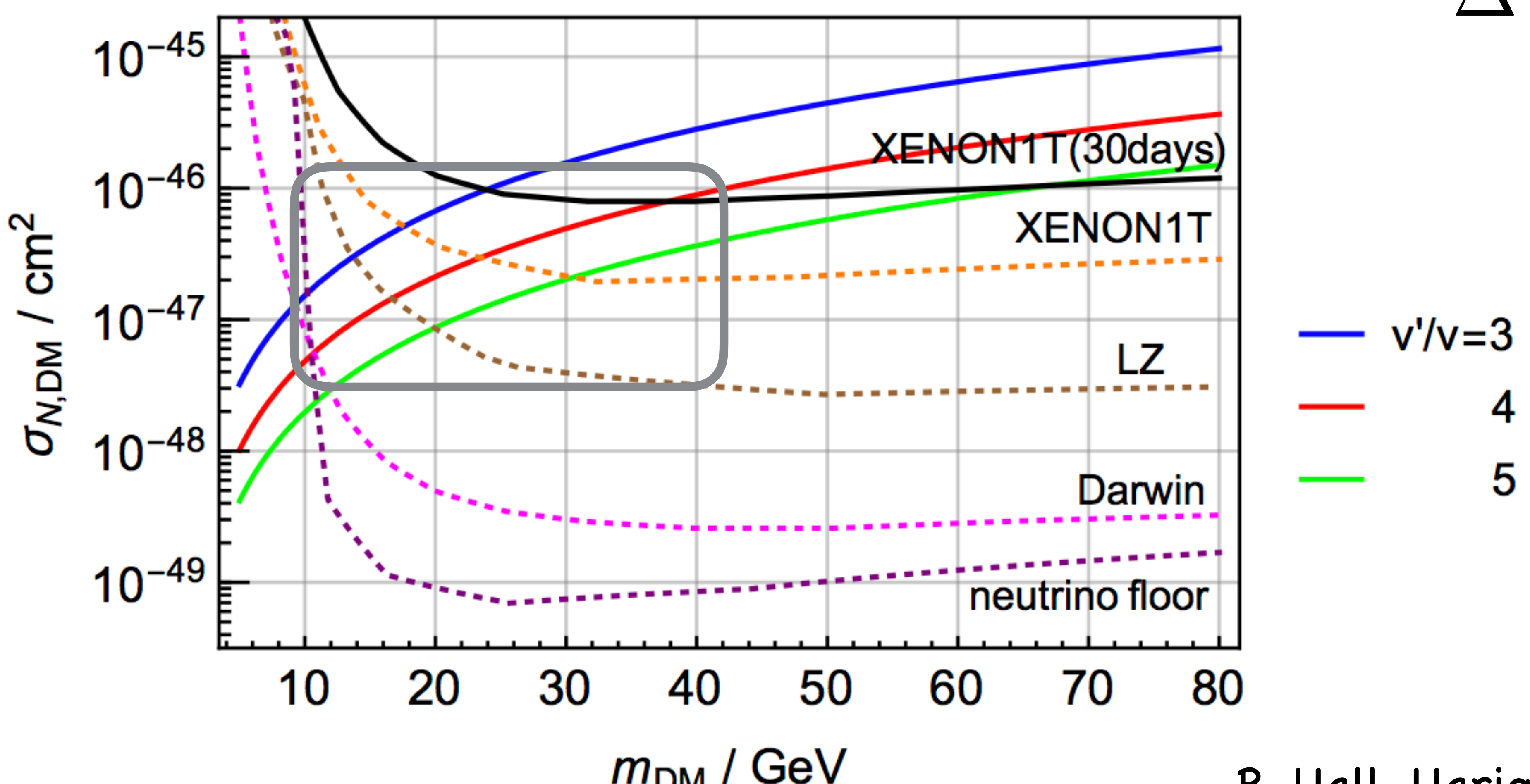
$$He'_* = B'_{uuu} + 2e' \quad H' = B'_{uud} + e' \quad n' = B'_{udd} \quad H'_* = B'_{ddd} + \bar{e}'$$

Dark Matter direct detection



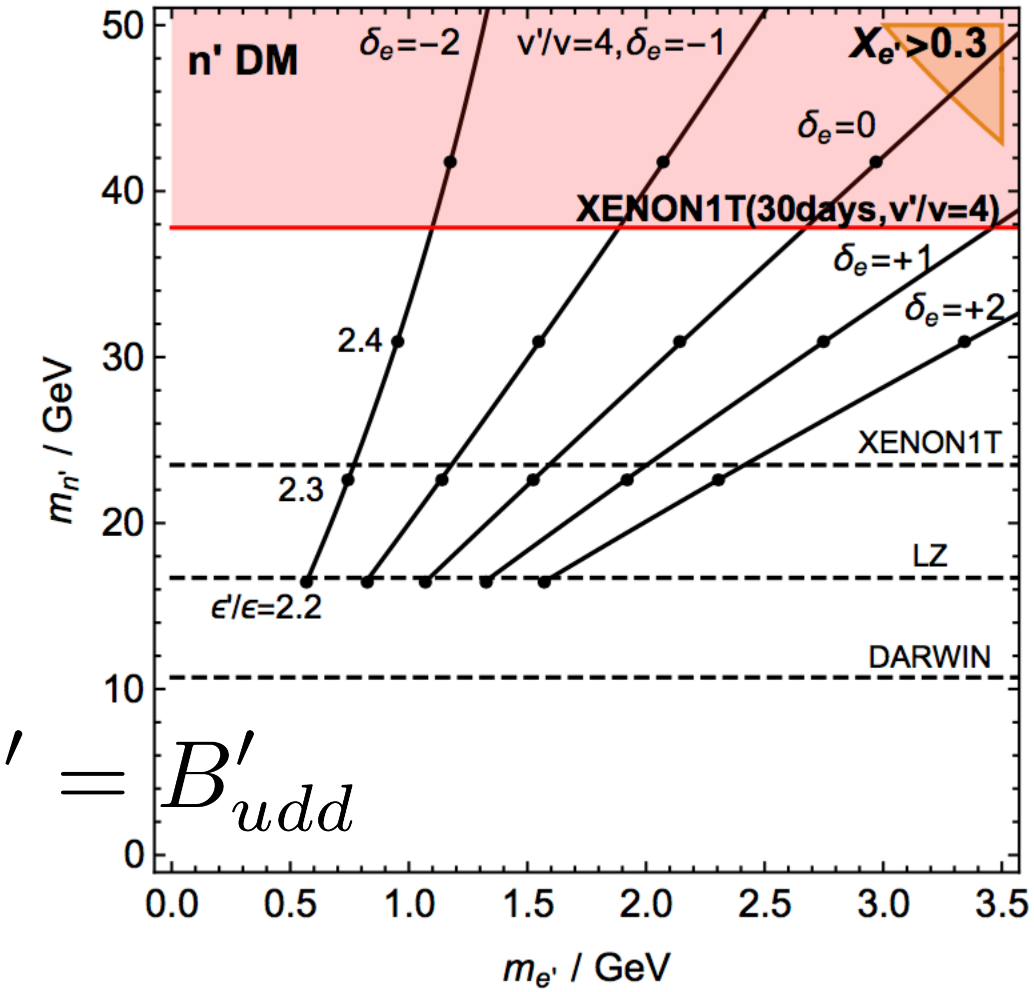
$$\sigma_{NN'} = \frac{0.028}{\pi} \frac{m_{N'}^2 m_N^2}{v'^4 m_h^4} \left(\frac{m_N m_{N'}}{m_N + m_{N'}} \right)^2$$

$$\frac{1}{\Delta} = 2(\frac{v}{v'})^2$$

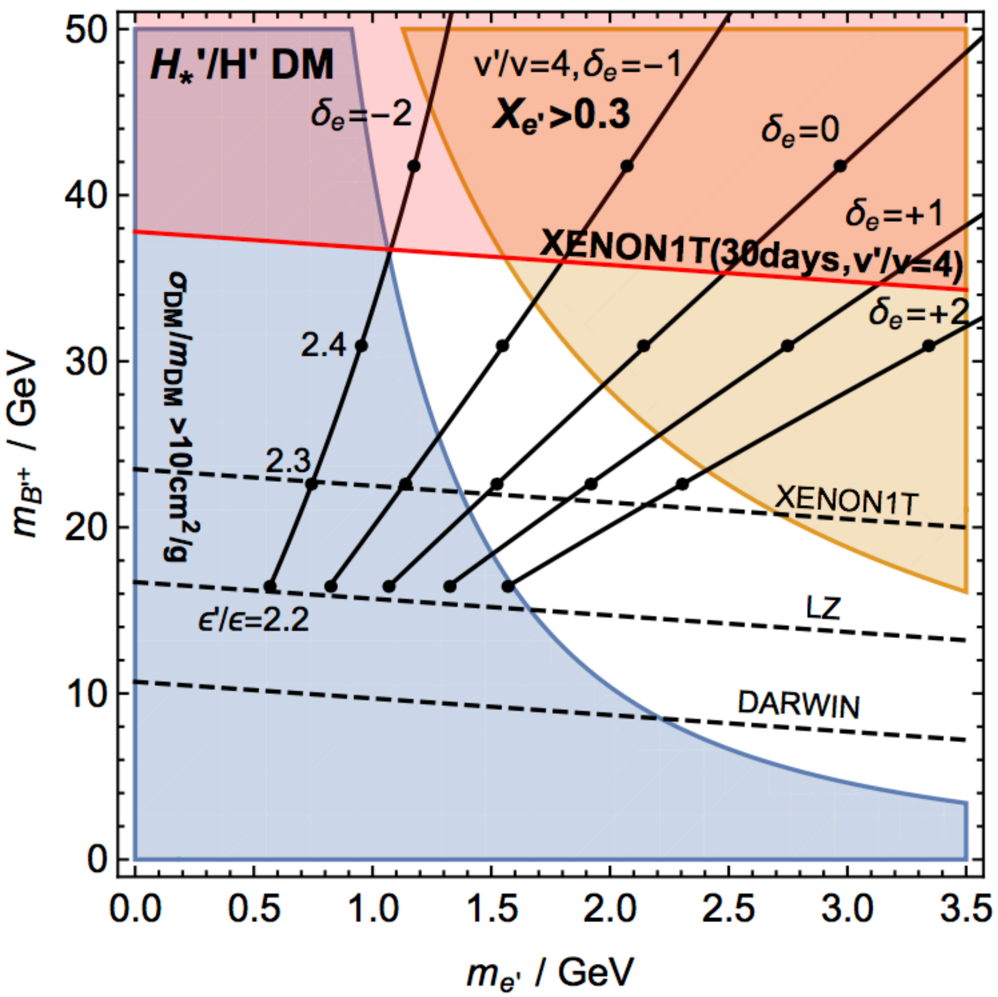


B, Hall, Harigaya 2016

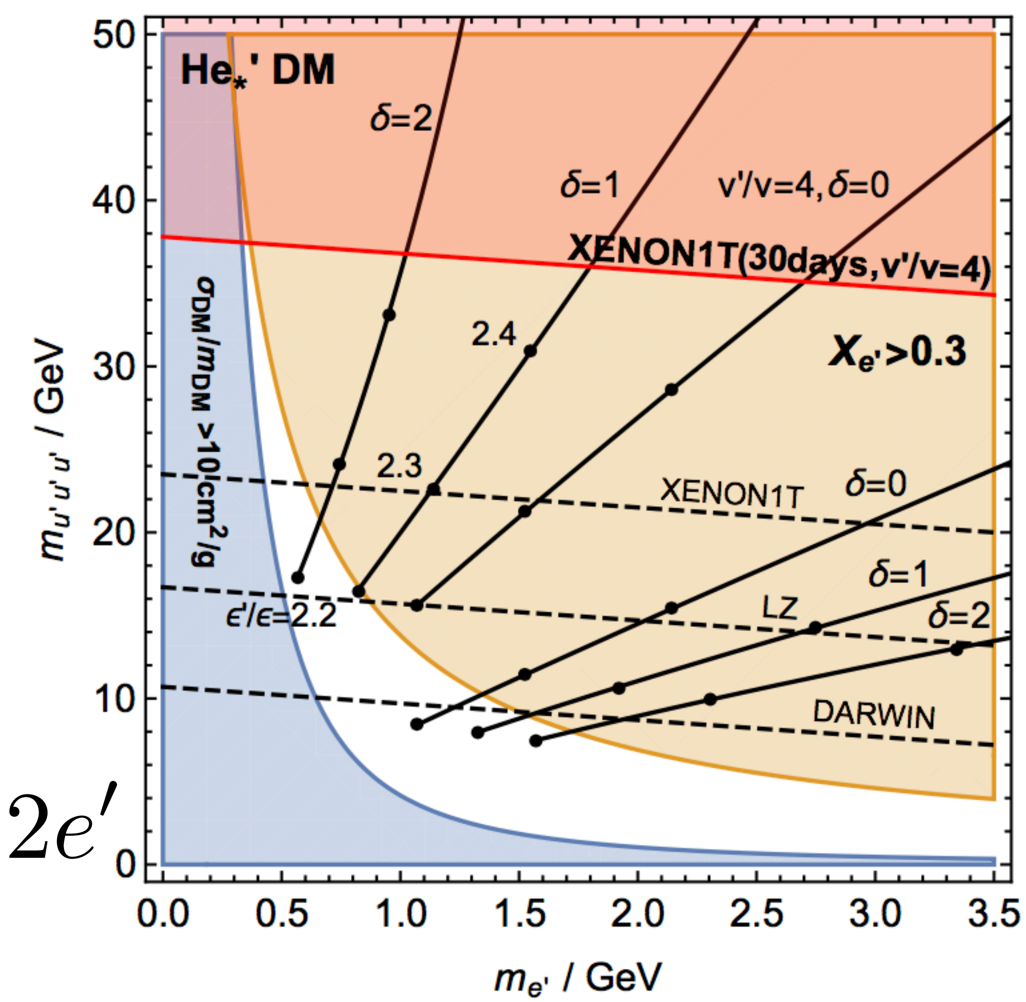
Astro/Cosmo phase space



$$n' = B'_{udd}$$

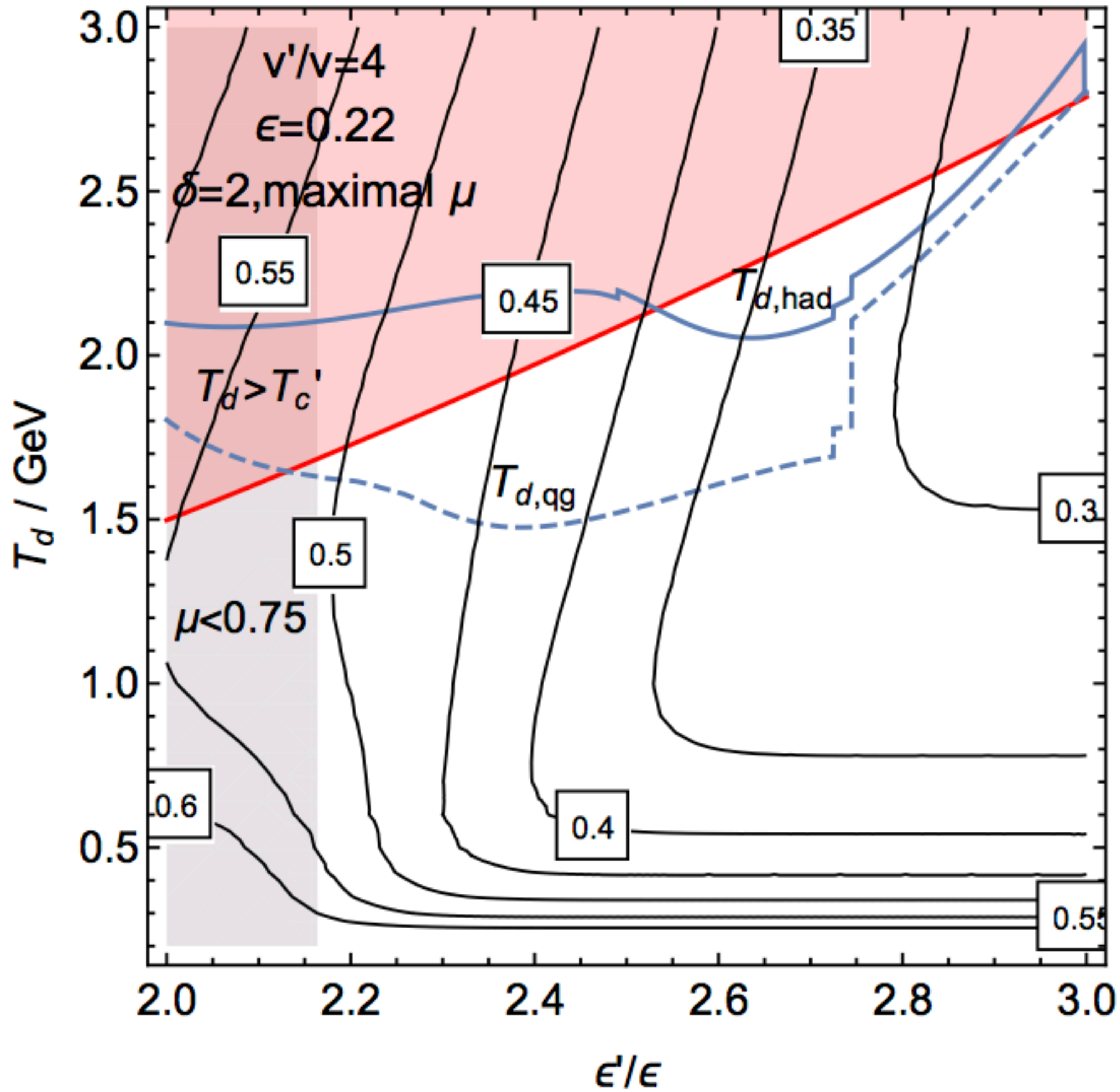


$$H'_*/H' = B'_{ddd} + \bar{e}'/B'_{bud} + e'$$



$$He'_* = B'_{uuu} + 2e'$$

Dark Radiation $\Delta N_{eff} = \frac{\rho_{\gamma',\nu',f'}}{\rho_{1\nu}}|_{now}$



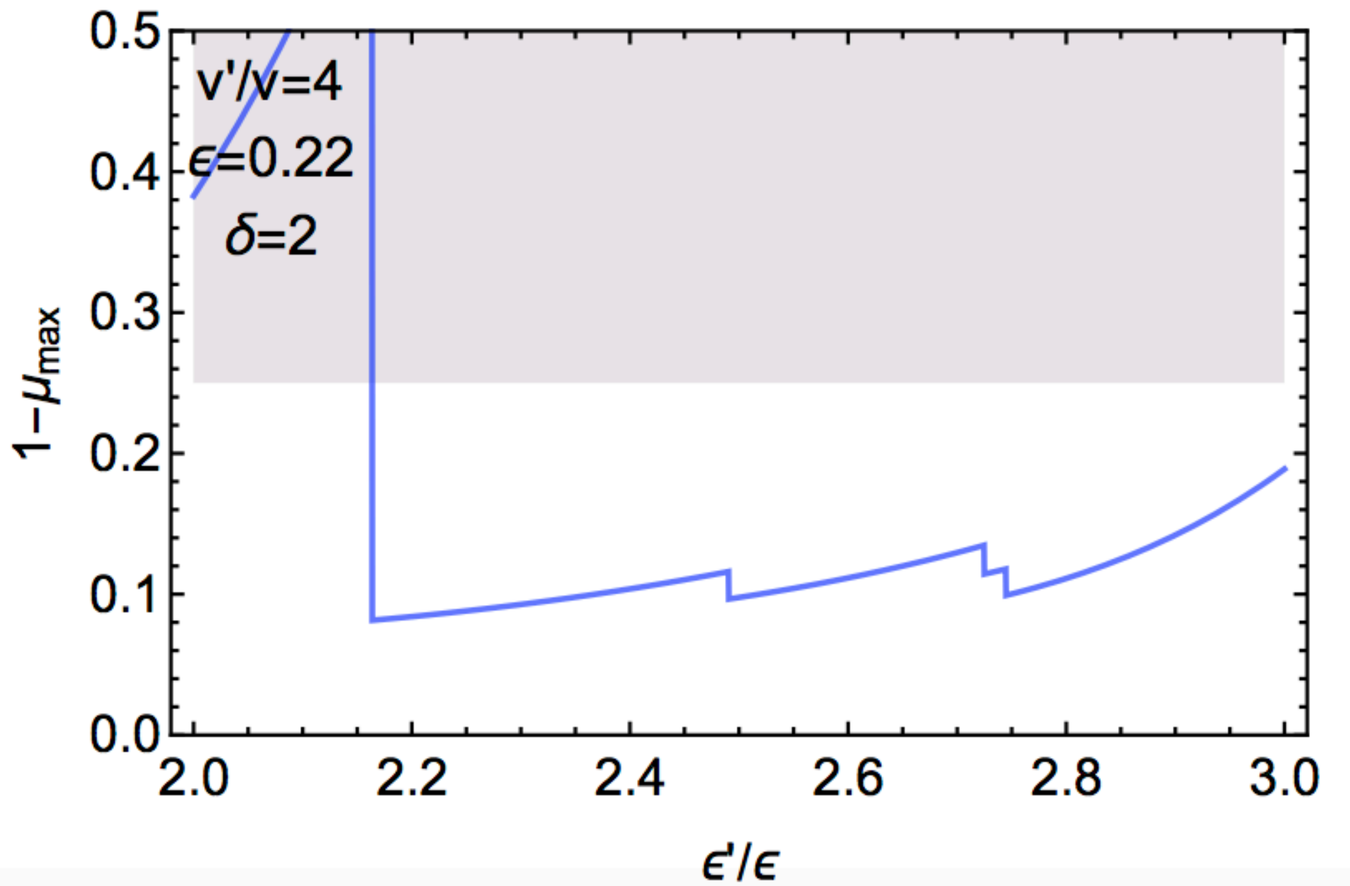
Now

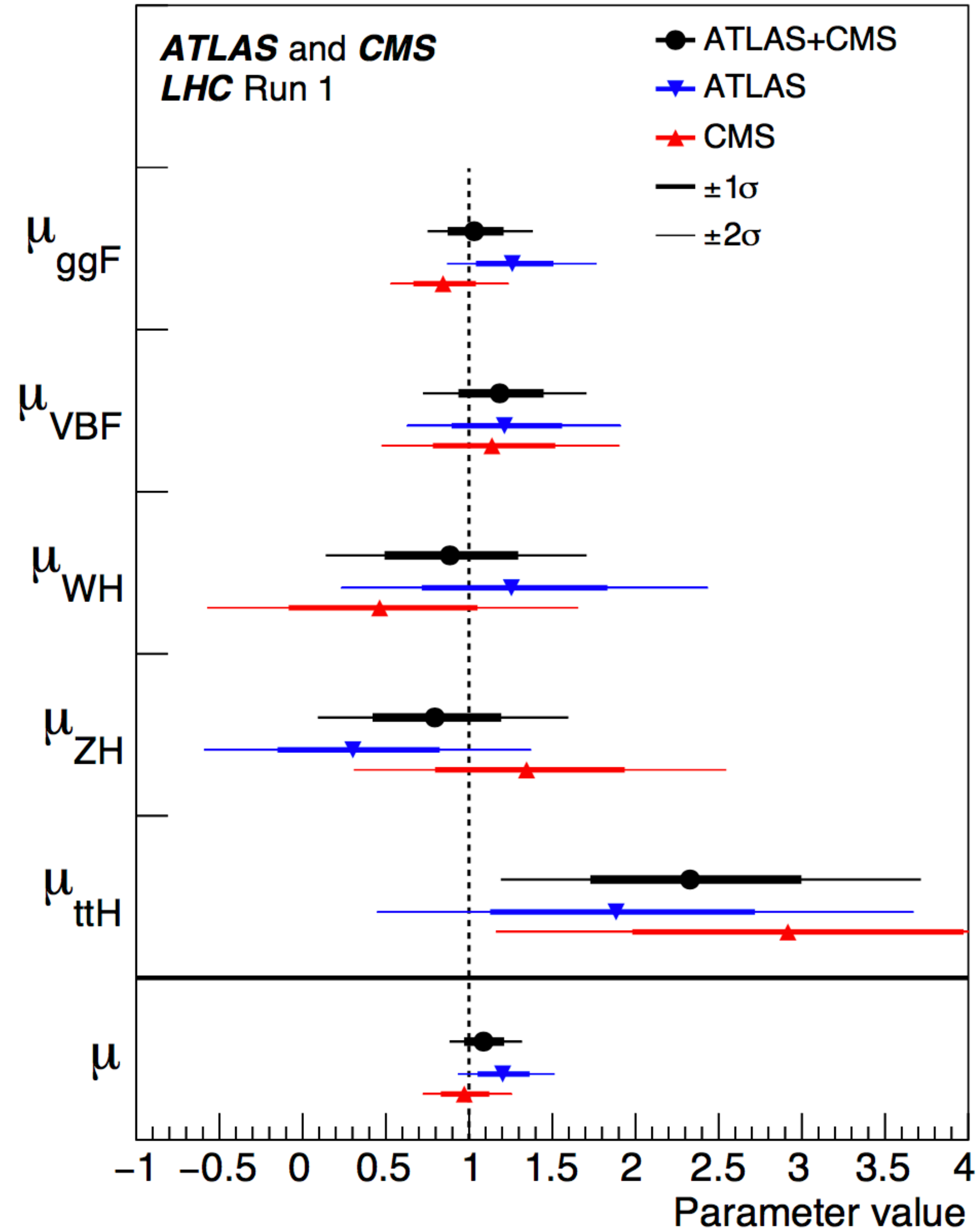
$\Delta N^{\nu}_{eff} \lesssim 0.6$

Precision on Higgs couplings

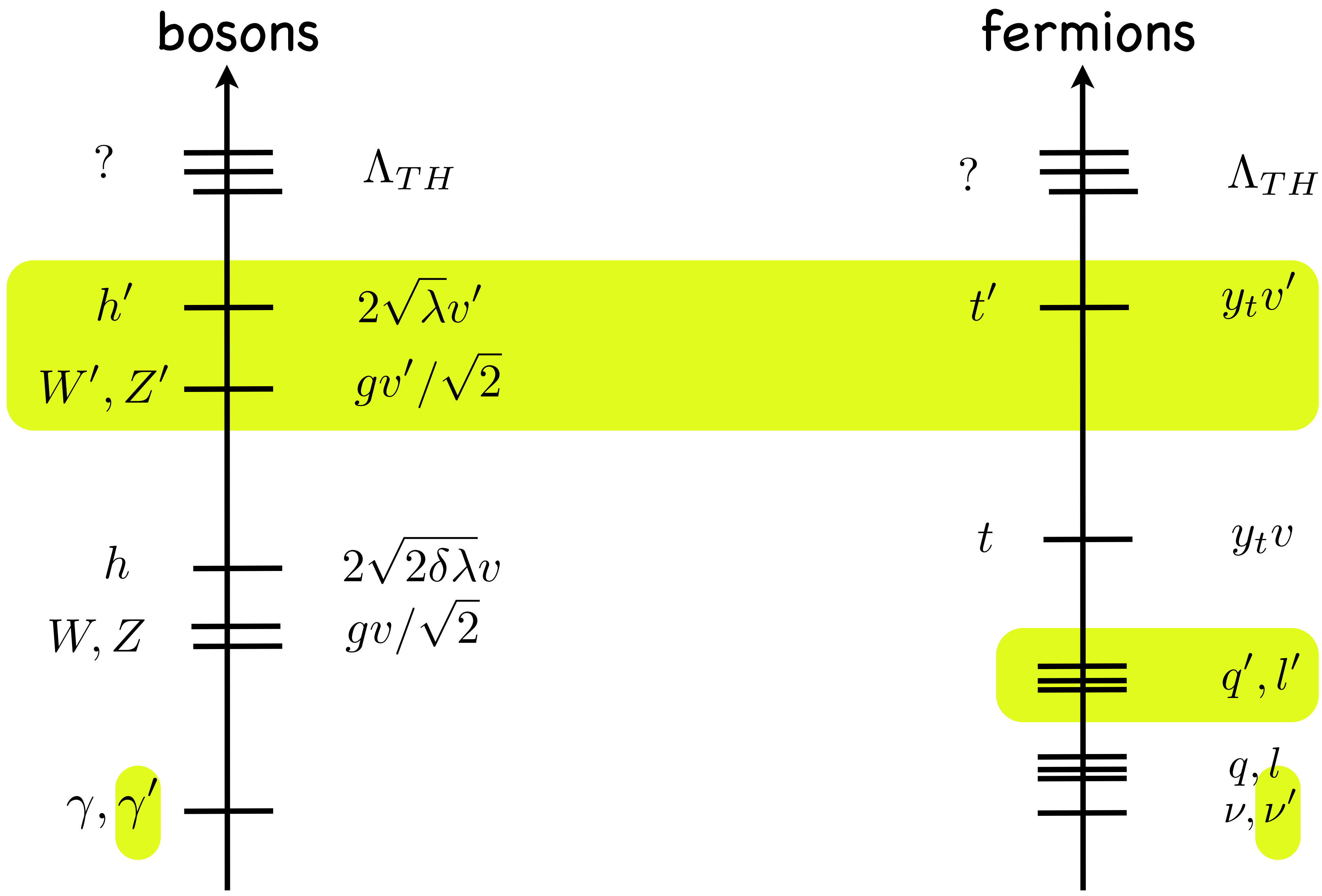
$$h = cos\theta H + sin\theta H' \qquad tan\theta \approx \frac{v}{v'} \qquad h \to i_{SM}, f'\bar{f}'$$

$$\mu_i^f = \frac{\sigma_i \cdot BR^f}{(\sigma_i)_{SM} \cdot (BR^f)_{SM}} \approx 1 - \sin^2\theta - BR_{inv} \equiv \mu$$





The Minimal Mirror Twin Higgs spectrum



Physics at Λ_{TH} (SUSY, composite, extra-dim.s, etc.?) affects $m_{h'}$ (1 TeV?) but not m_h

Is this why nothing new has been seen so far at LHC?

A deviation from the SM, finally?

Babar
Belle
LHCb

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)} l\nu, l = \mu, e)}$$

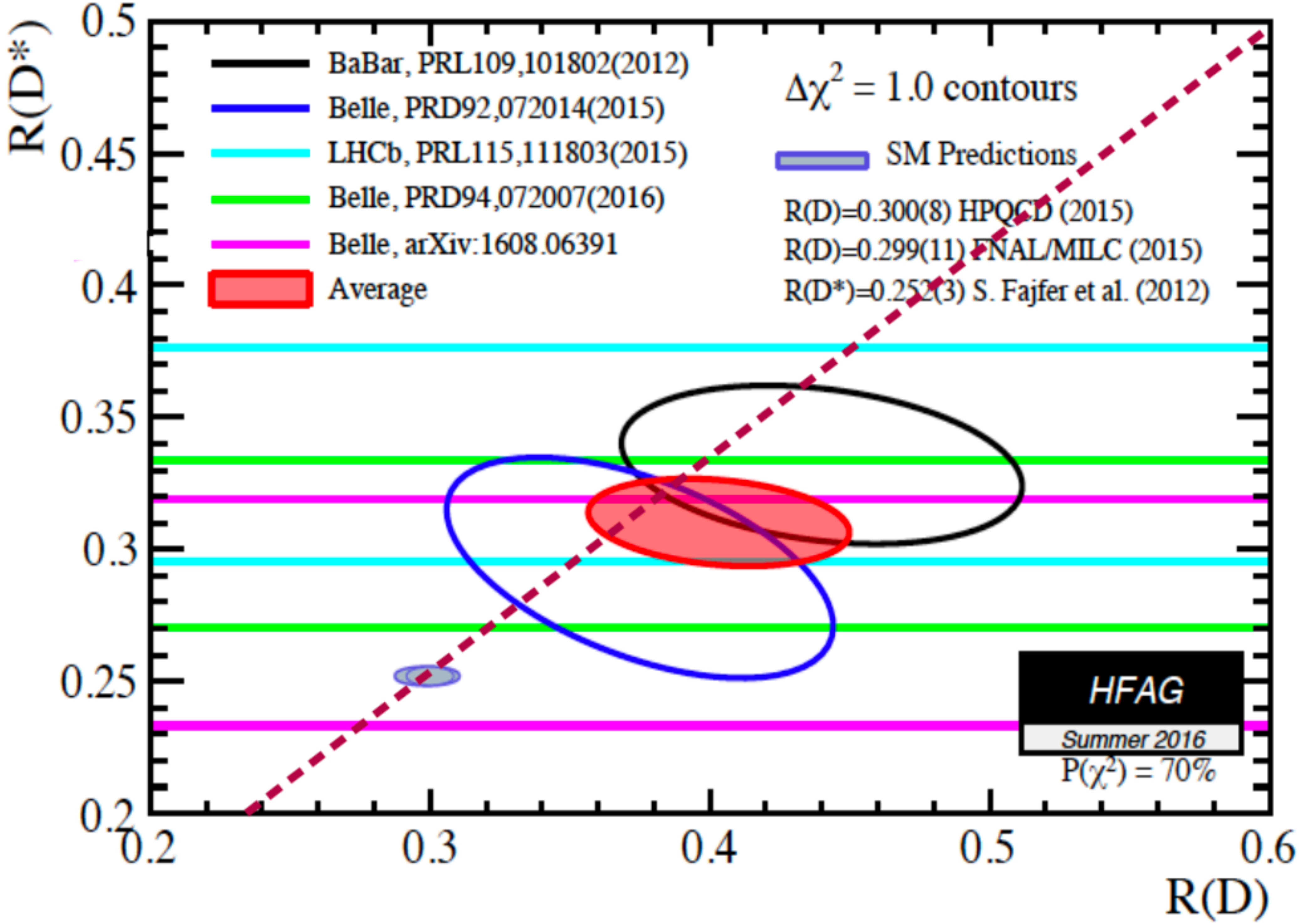
	exp	SM	Pull
$R_D^{\tau/l}$	0.403 ± 0.047	$0.300(8)$	$2\ \sigma$
$R_{D^*}^{\tau/l}$	0.310 ± 0.017	$0.252(3)$	$3.4\ \sigma$

$$R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)} ee)}$$

	exp	SM	Pull
$R_K^{\mu/e}$	$0.745^{+0.090}_{-0.074} \pm 0.036$	1.00 ± 0.01	$2.6\ \sigma$
$R_{K^*(low\ q^2)}^{\mu/e}$	$0.660^{+0.110}_{-0.070} \pm 0.024$	0.906 ± 0.028	$2.3\ \sigma$
$R_{K^*(high\ q^2)}^{\mu/e}$	$0.685^{+0.113}_{-0.069} \pm 0.047$	1.00 ± 0.01	$2.4\ \sigma$

LHCb 2017

$$P_5'(B \to K^*\mu\mu);\ BR(B \to \phi\mu\mu)$$



3.9σ if D and D* combined

general caveats

$$R_{D^{(*)}} = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)} l\nu, l = \mu, e)} \qquad R_{K^{(*)}} = \frac{BR(B \to K^{(*)}\mu\mu)}{BR(B \to K^{(*)}ee)}$$

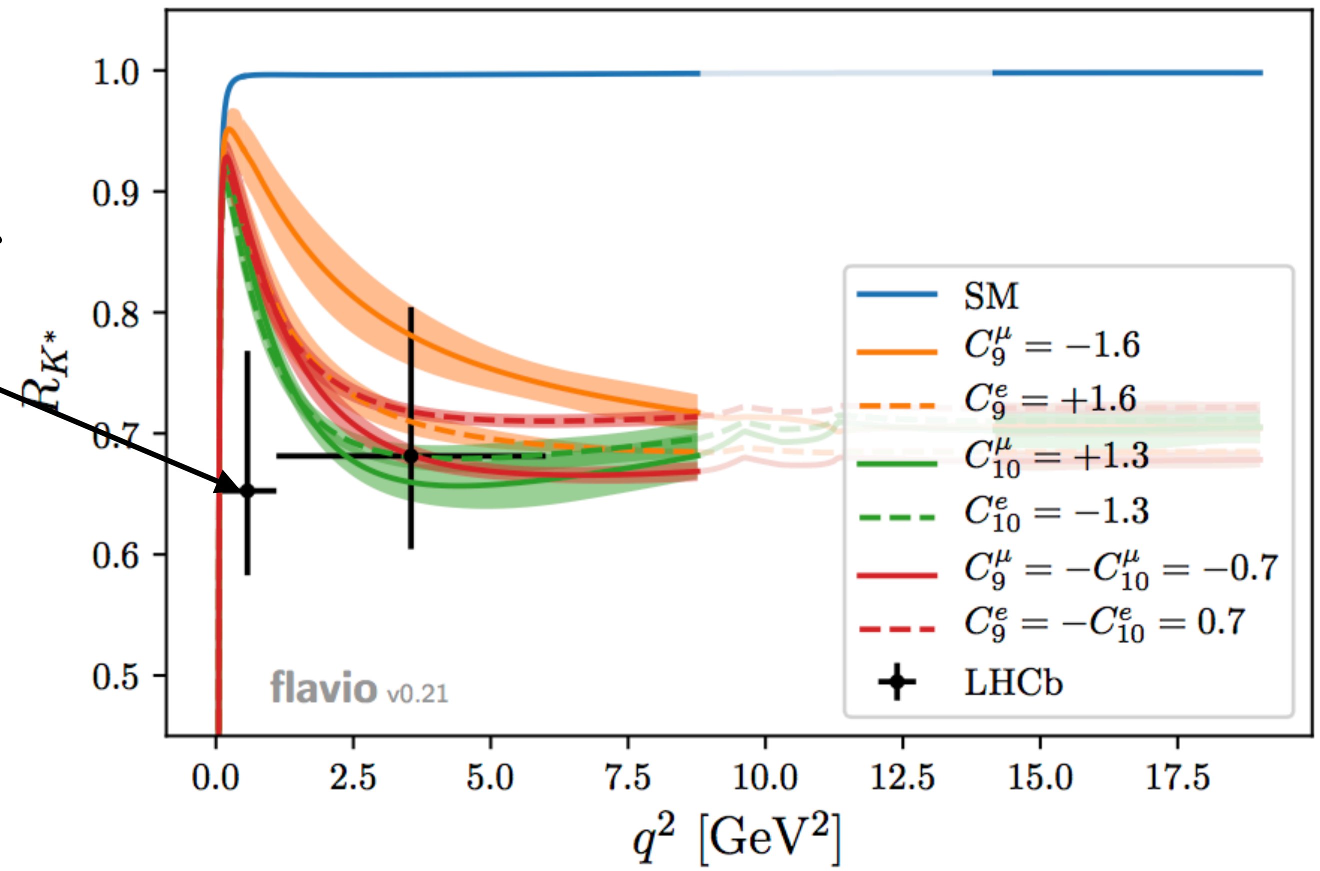
Difficult experiments

Lepton Flavour Violation never seen before
in charged leptons

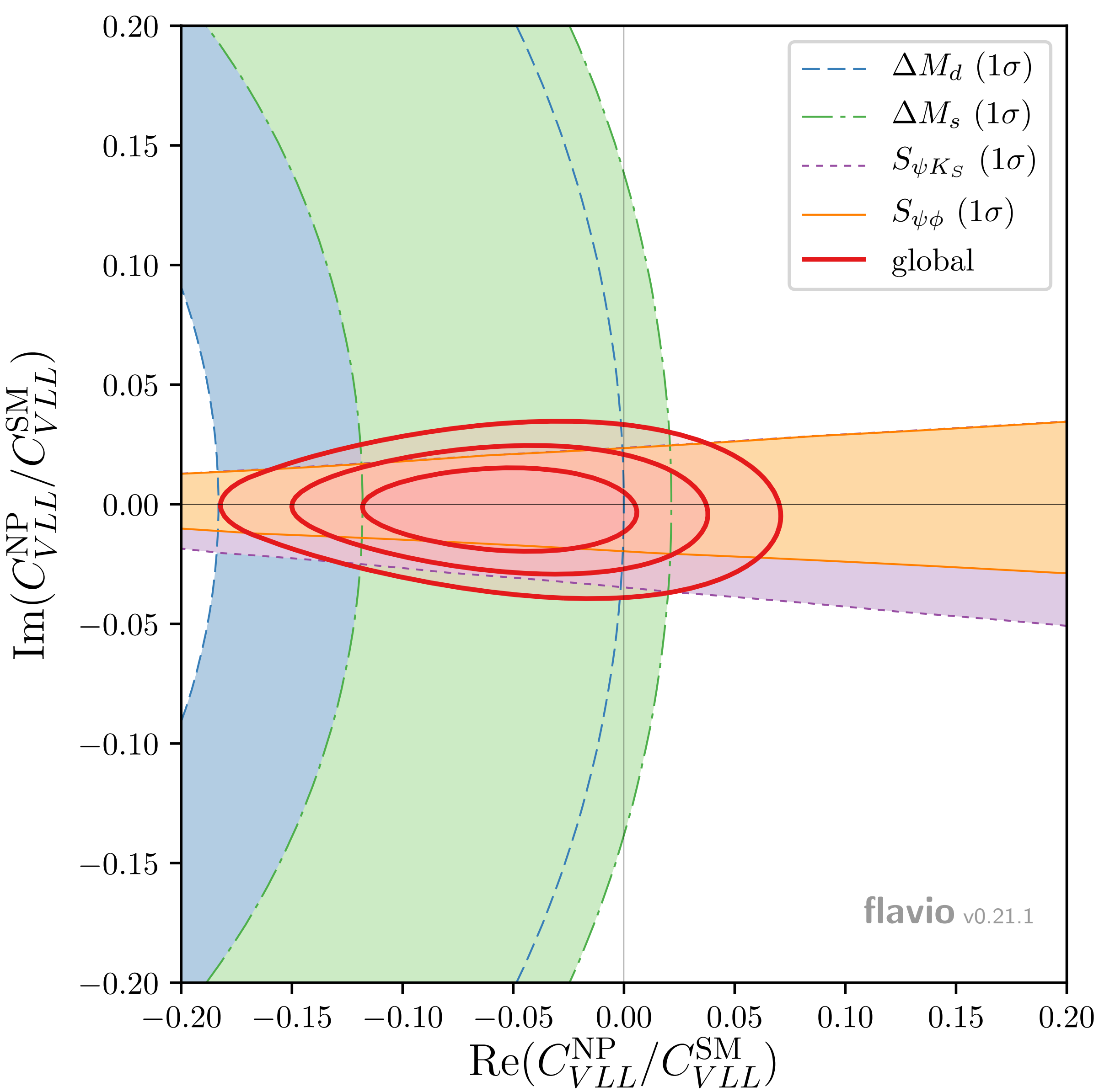
In case one wants to see them correlated:
$b \to c\, l\nu$ tree level, $b \to s\, ll$ loop level

more specific slight caveats

One would have preferred a smaller deviation from the SM at low q^2



Altmannshofer, Straub 2017



Straub 2017

No significant deviation seen so far in $\Delta B = 2$

$$L^{NP} = \frac{(V_{tb}V_{tq}^*)^2}{\Lambda^2}(\bar{b}_L\gamma_\mu q_L)^2; \quad \Lambda \gtrsim 10\ TeV$$

against

$$L^{NP} \approx \frac{V_{cb}}{(1TeV)^2}(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$$

Why I like them

1. A $U(2)^n$ flavour symmetry
as approximately observed in the
quarks (spectrum and mixings) and in the charged leptons
basically distinguish
the $q_3,\ l_3$ singlets from the $(q_1, q_2),\ (l_1, l_2)$ doublets

2. If due to a leptoquark exchange, singlet under $U(2)^n$
$U_\mu(\bar{q}_3\gamma_\mu l_3),\ S(\bar{q}_3 l_3)$ only allowed by exact $U(2)^n$

3. After (small) $U(2)^n$-breaking, mixing gives
$b \to c\ \tau\nu$ (once suppressed)
$b \to s\ \mu\mu$ (3 times suppressed)

▶ *EFT-type considerations* [$U(2)^n$ flavor symmetry]

This coherent picture leads to several testable predictions in other low-energy observables:

- $b \to c(u)\, l\nu$ — $BR(B \to D^* \tau\nu)/BR_{SM} = BR(B \to D\tau\nu)/BR_{SM} = BR(\Lambda_b \to \Lambda_c \tau\nu)/BR_{SM}$
$= BR(B \to \pi\, \tau\nu)/BR_{SM} = BR(\Lambda_b \to p\, \tau\nu)/BR_{SM} = BR(B_u \to \tau\nu)/BR_{SM}$

- $b \to s\, \mu\mu$ — $\Delta C_9^\mu = -\Delta C_{10}^\mu$ (→ to be checked in several other modes...)
- $b \to s\, \tau\tau$ — $|NP| \sim |SM|$ → large enhancement (easily 10×SM)
- $b \to s\, \nu\nu$ — ~ O(1) deviation from SM in the rate

- $K \to \pi\, \nu\nu$ — ~ O(1) deviation from SM in the rate

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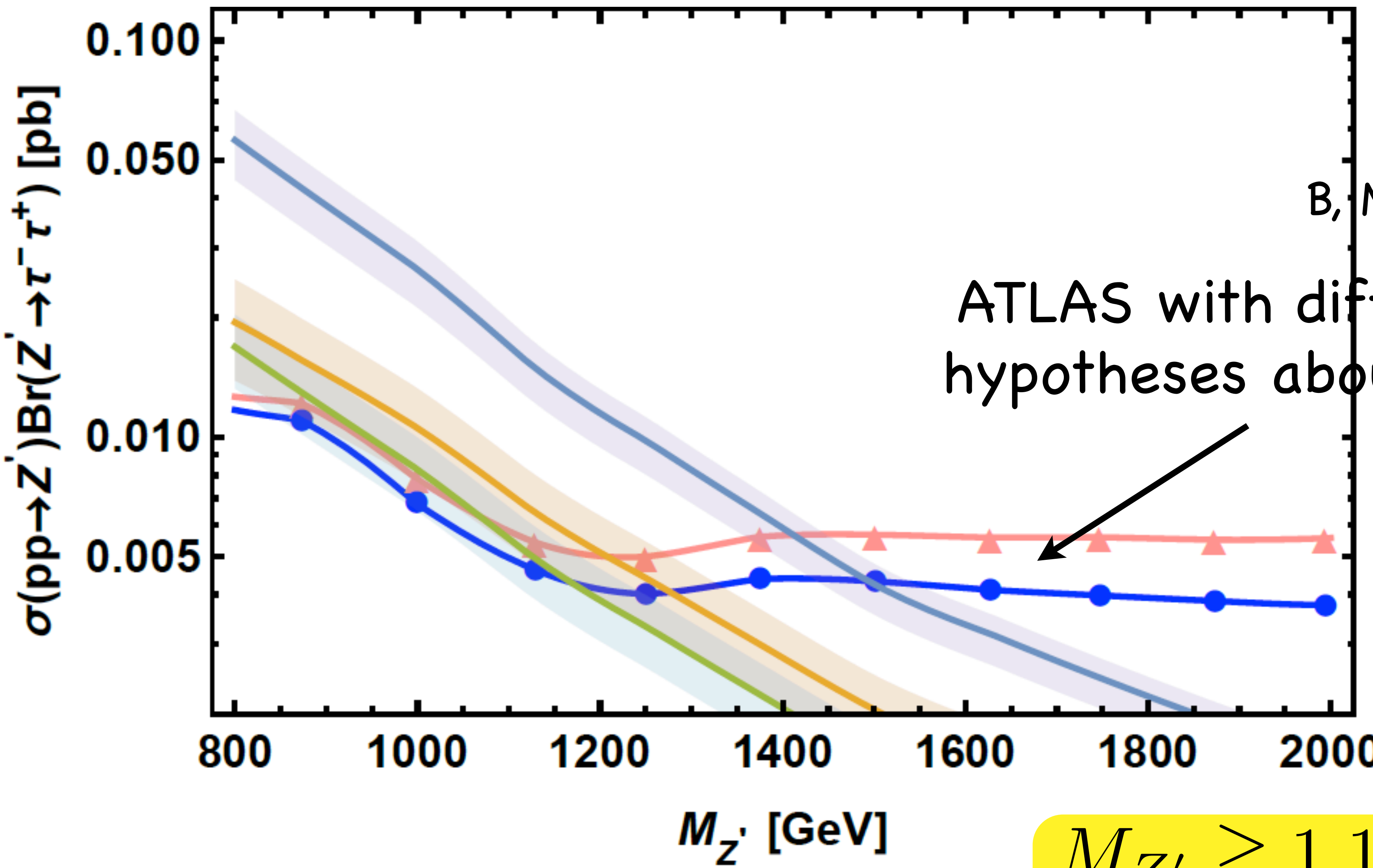
- Meson mixing — ~ 10% deviations from SM both in ΔM_{Bs} & ΔM_{Bd}
- τ decays — $\tau \to 3\mu$ not far from present exp. Bound ($BR \sim 10^{-9}$)

Signals

LFV in many other channels

Buttazzo, Greljo, Isidori, Marzocca 2016

Anomalous $\sigma(pp \to (b\bar{b}) \to \tau\tau)$



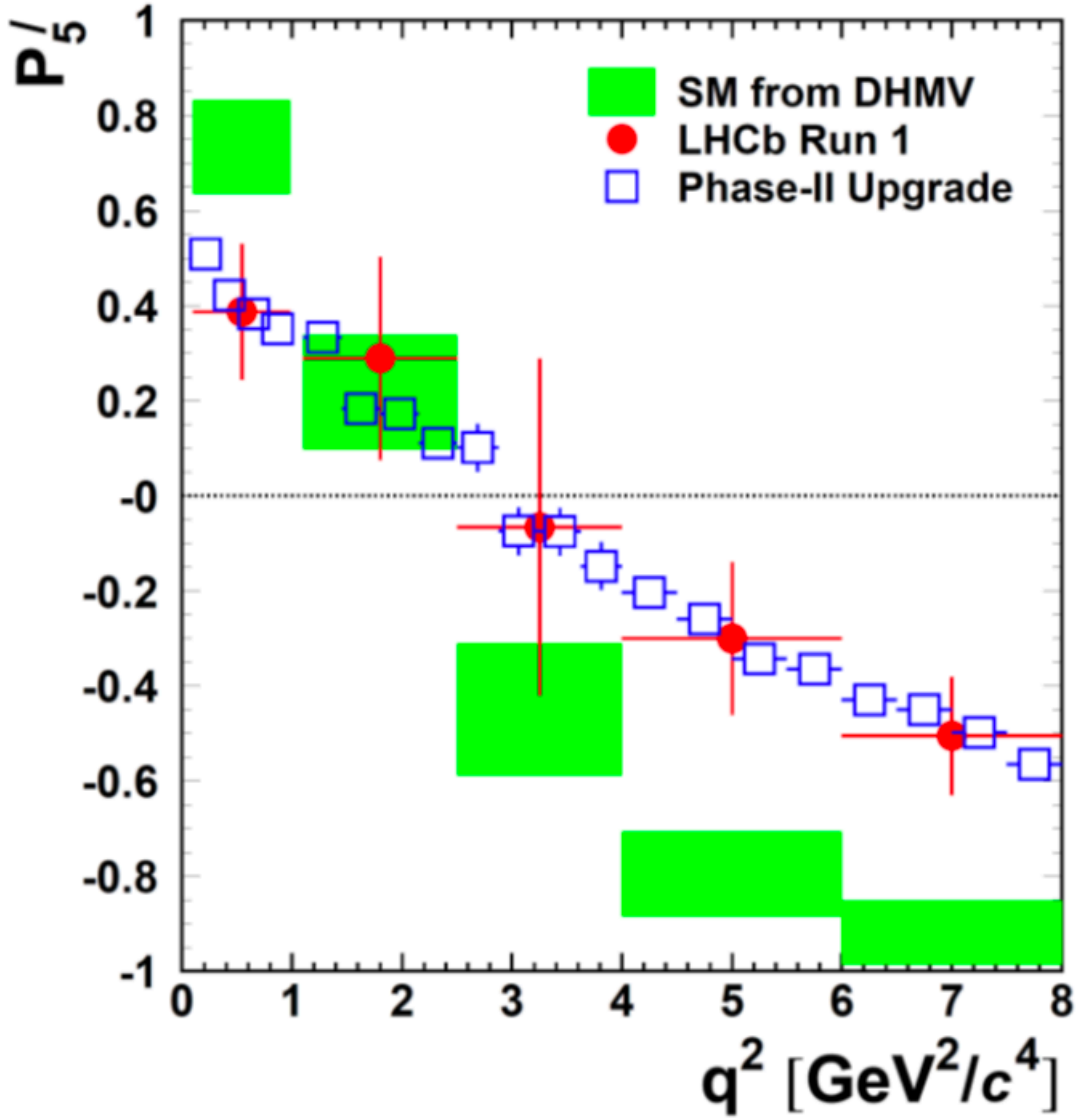
B, Murphy, Senia 2016

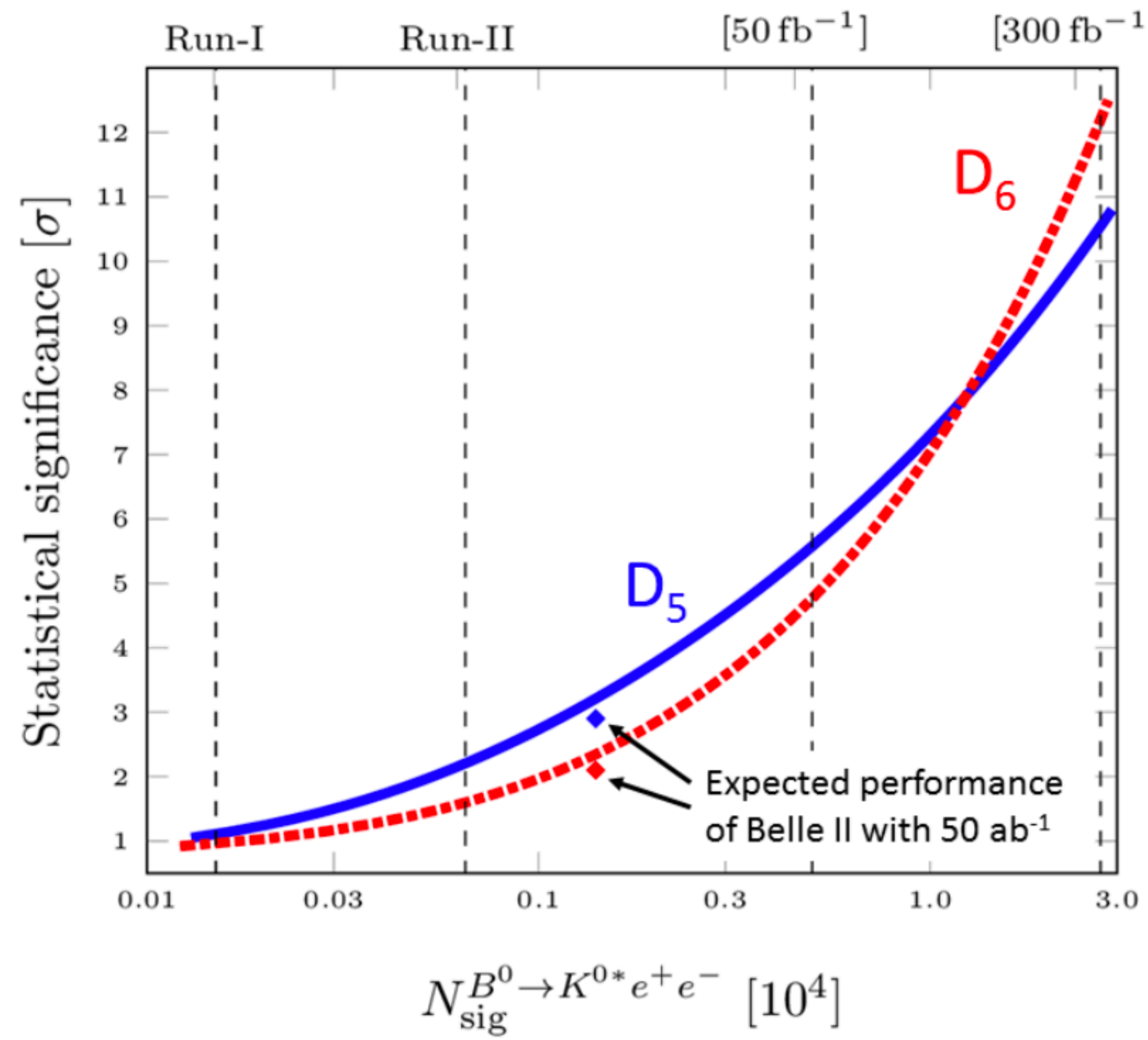
ATLAS with different hypotheses about Γ_{tot}/M

$M_{Z'} \gtrsim 1.1 \div 1.5\ TeV$

$g* \gtrsim 2$

from the <Phase-II LHCb Upgrade>





CERN-LHCC-2017-003

Conclusions

The Standard Model is NOT a complete story (although any deeper theory will include it as a relevant limit)

Precision in Higgs and flavour physics is a must

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

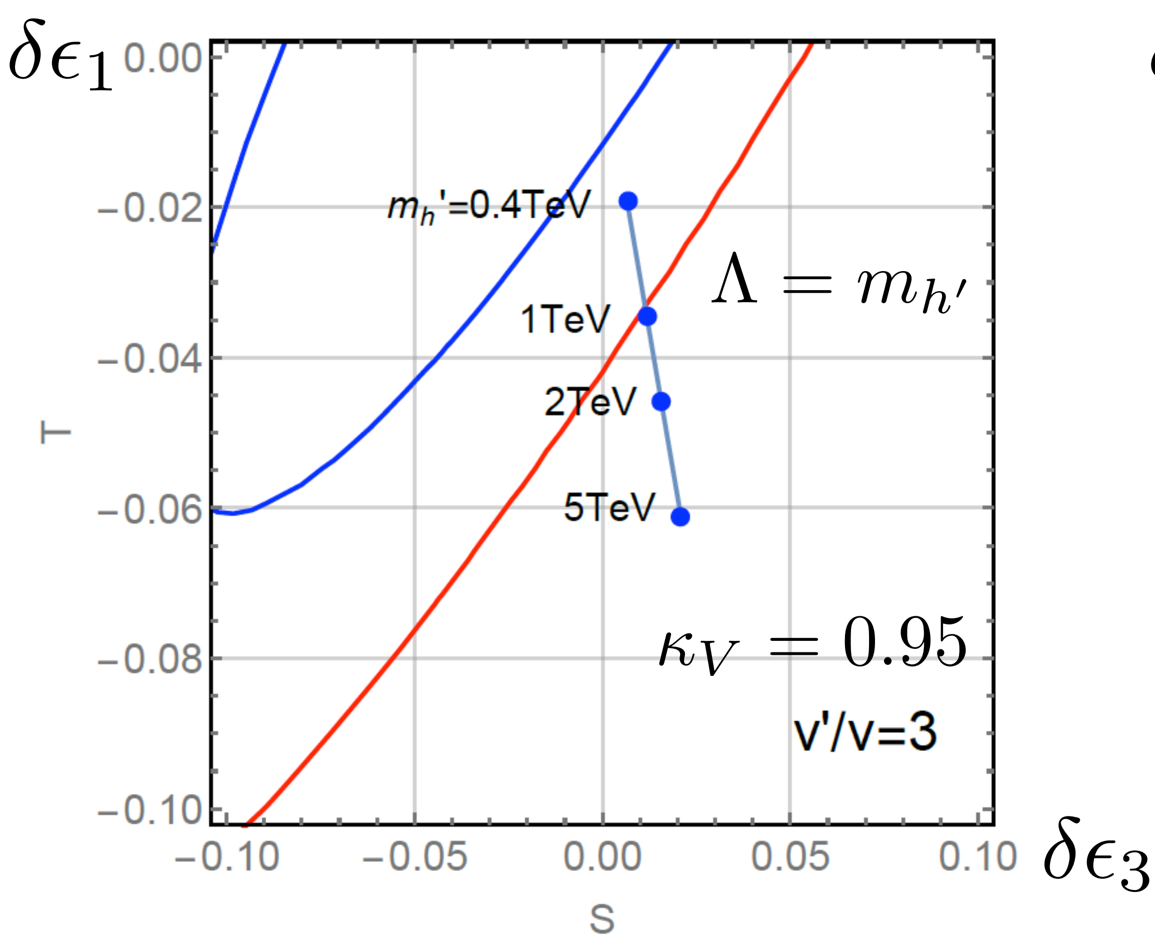
The very nature of Particle Physics and the current uncertain situation REQUIRE highly diverse frontiers of research

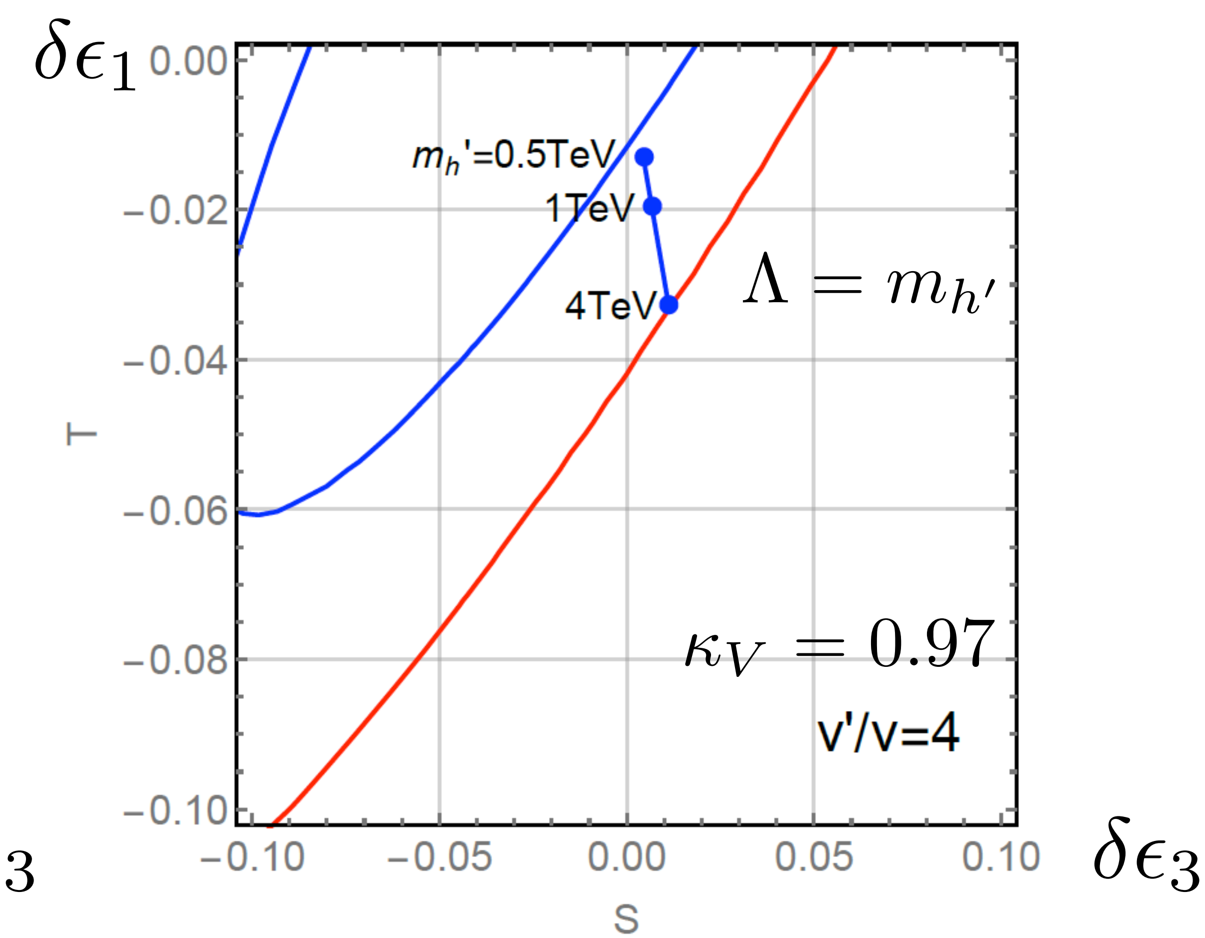
For question time

comparing Higgs with EW precision

Consider any theory where the hVV-coupling κ_V deviates from the SM

$$\delta\epsilon_1 = -\frac{3\alpha}{8\pi c^2}(1-k_V^2)\log\frac{\Lambda}{m_h}, \qquad \delta\epsilon_3 = \frac{\alpha}{24\pi s^2}(1-k_V^2)\log\frac{\Lambda}{m_h}$$





EW precision in principle more constraining on κ_V

however:

1. Need to specify the cutoff
2. Be sure of no other contribution

Successful FN models

SU(5) $Q, \bar{u}, \bar{e}: \; (4,2,0), \quad \bar{d}, L: \; (4,3,3).$

B1 $Q:(3,2,0), \; \bar{u}:(4,2,0), \; \bar{e}:(4,2,0), \; \bar{d}, L: \; (4,3,3)$

B2 $Q:(3,2,0), \; \bar{u}:(4,2,0), \; \bar{e}:(4,2,0), \; \bar{d}, L: \; (3,2,2)$

model	$\frac{m_b}{m_t}$	$\frac{m_\tau}{m_t}$	$\frac{m_c}{m_t}$	$\frac{m_s}{m_t}$	$\frac{m_\mu}{m_t}$	$\frac{m_u}{m_t}$	$\frac{m_d}{m_t}$	$\frac{m_e}{m_t}$
$SU(5)$	$1.6\epsilon^3$	$1.1\epsilon^3$	$1.8\epsilon^4$	$1.0\epsilon^5$	$1.25\epsilon^5$	$2.5\epsilon^8$	$4.5\epsilon^8$	$0.6\epsilon^8$
B1	$1.6\epsilon^3$	$1.1\epsilon^3$	$1.8\epsilon^4$	$1.0\epsilon^5$	$1.25\epsilon^5$	$0.55\epsilon^7$	$1.0\epsilon^7$	$0.6\epsilon^8$
B2	$0.5\epsilon^2$	$0.4\epsilon^2$	$4.0\epsilon^4$	$0.45\epsilon^4$	$0.6\epsilon^4$	$2.2\epsilon^7$	$0.7\epsilon^6$	$0.5\epsilon^7$

V_{us}	V_{cb}	V_{ub}
$4.5\epsilon^2$	$1.0\epsilon^2$	$2.3\epsilon^4$
1.0ϵ	$1.0\epsilon^2$	$0.5\epsilon^3$
1.2ϵ	$1.5\epsilon^2$	$1.8\epsilon^3$

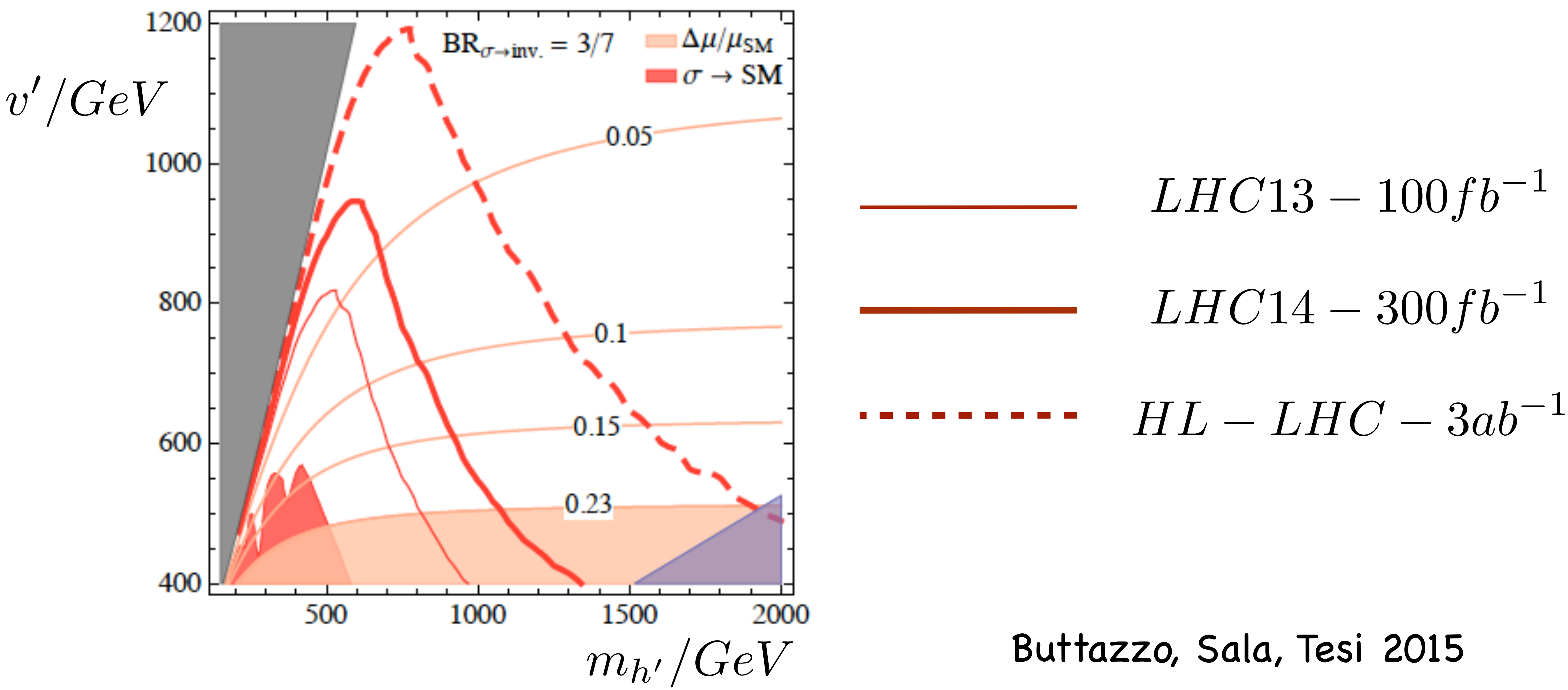
h' production and decays

B, Hall, Gregoire 2005

$$\sigma(pp \to \tilde{h}') \approx (\frac{v}{v'})^2 \sigma(pp \to h_{SM}(m = m_{h'}))$$ via a top loop

Neglecting phase space $$\frac{\Gamma_L}{\Gamma_L + \Gamma_T} \to 1$$

f	ZZ	WW	hh	$W'W'$	$Z'Z'$
$\Gamma(\tilde{h}' \to f)$	1	2	1	2	1



Buttazzo, Sala, Tesi 2015

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

(recall Einstein's lesson from $m_{in} = m_{grav}$)

$$\Psi = Q(3,2)_{1/6} \;\; u(\bar{3},1)_{-2/3} \;\; d(\bar{3},1)_{1/3} \;\; L(1,2)_{-1/2} \;\; e(1,1)_1$$

Ψ = next-to-simplest rep of $\mathcal{G}$:

chiral, anomaly-free, vector-like under $SU(3) \times U(1)_{em}$

However:

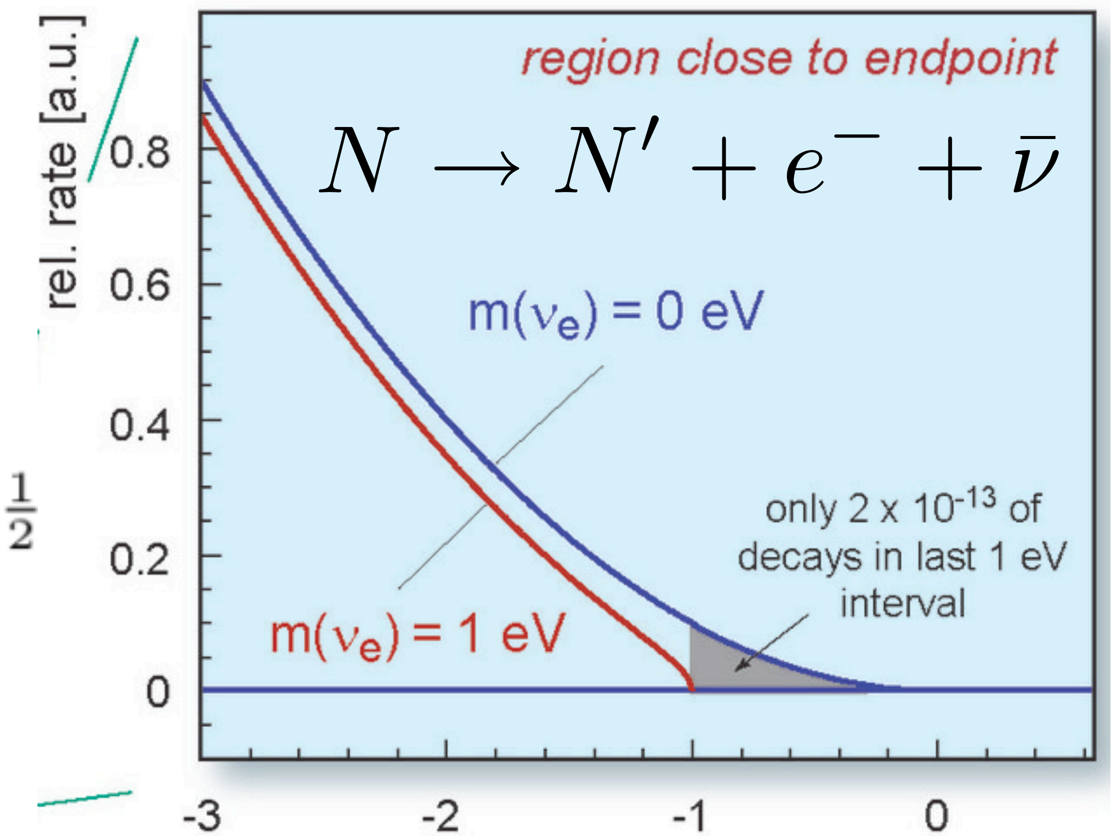
1. A simpler rep: $\Xi = (3,2)_0 \;\; (\bar{3},1)_{1/2} \;\; (\bar{3},1)_{-1/2}$

2. What if ν_R are added?

$$\tilde{\Psi} = Q(3,2)_y \;\; u(\bar{3},1)_{-y-1/2} \;\; d(\bar{3},1)_{-y+1/2} \;\; L(1,2)_{-3y} \;\; e(1,1)_{5y+1/2} \;\; \nu^c(1,1)_{3y-1/2}$$

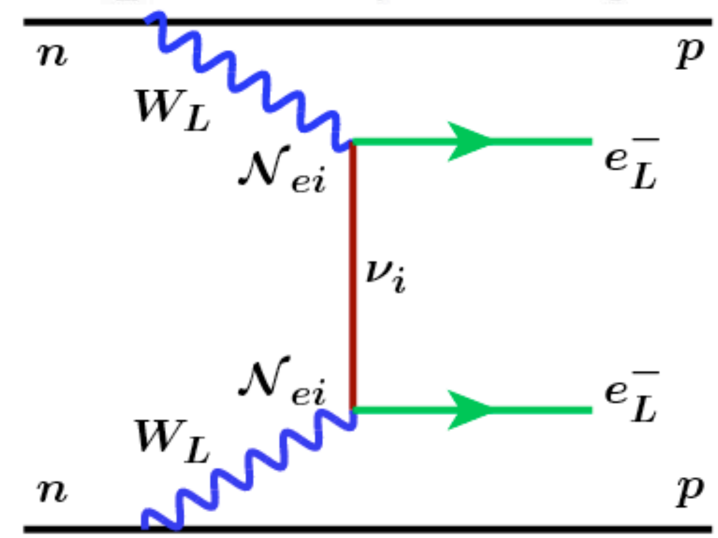
(An important hint for "algebraic" Unification?)

3 ways to be sensitive to the absolute ν-mass scale



1- beta-decay endpoint

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



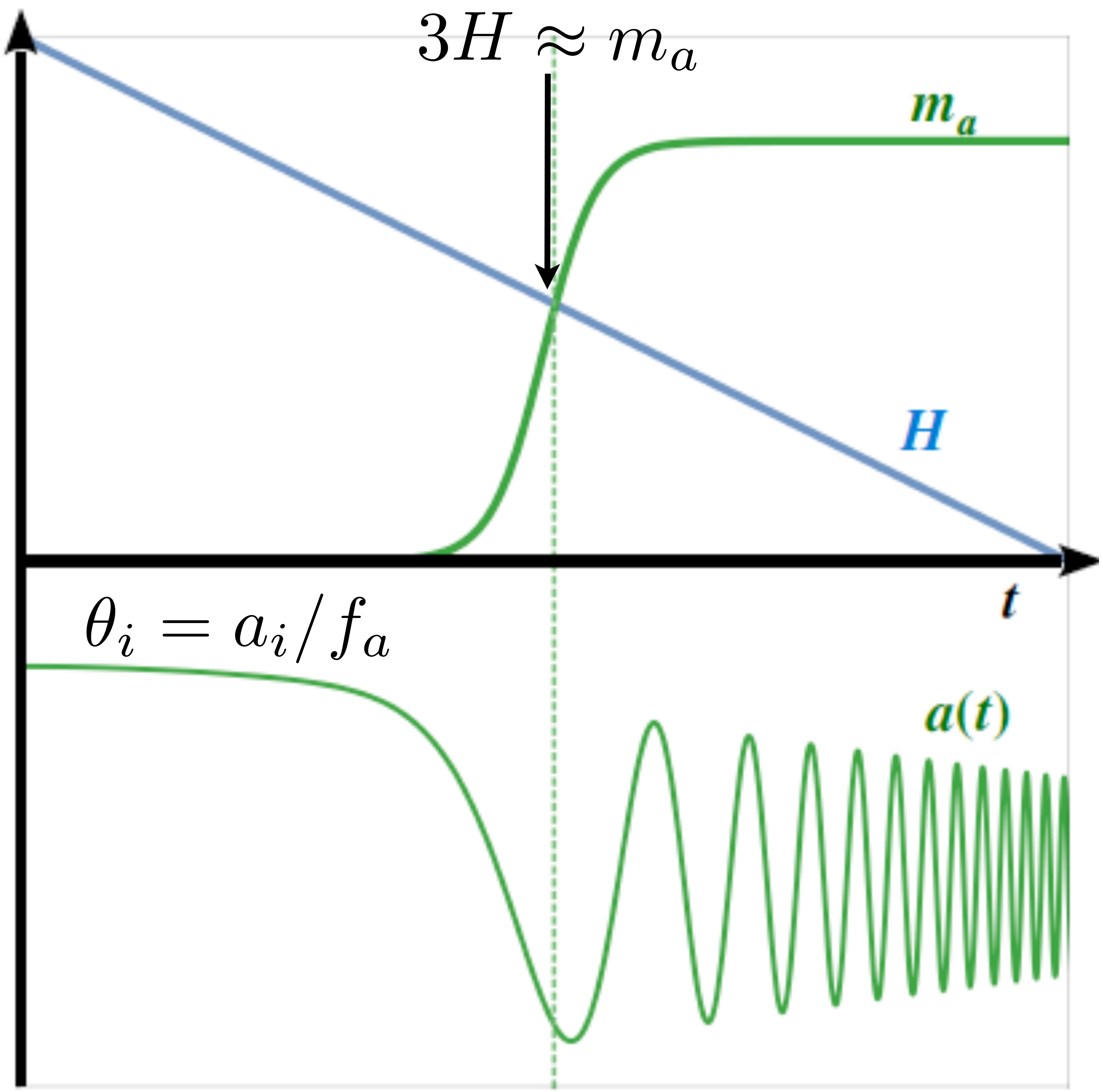
2- neutrino-less ββ-decay

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

3 - cosmology (large scale structures)

$$\Sigma = m_1 + m_2 + m_3$$

Relic abundance of the QCD axion



$$H = T^2/M_{Pl}$$

m_a: for $T > \Lambda_{QCD}$, $\frac{m_\pi^2}{f_a}\left(\frac{\Lambda_{QCD}}{T}\right)^4$; for $T < \Lambda_{QCD}$, $\frac{m_\pi^2}{f_a}$

$$\rho_a = m_a^2 a^2 \propto T^3 \propto 1/R^3$$

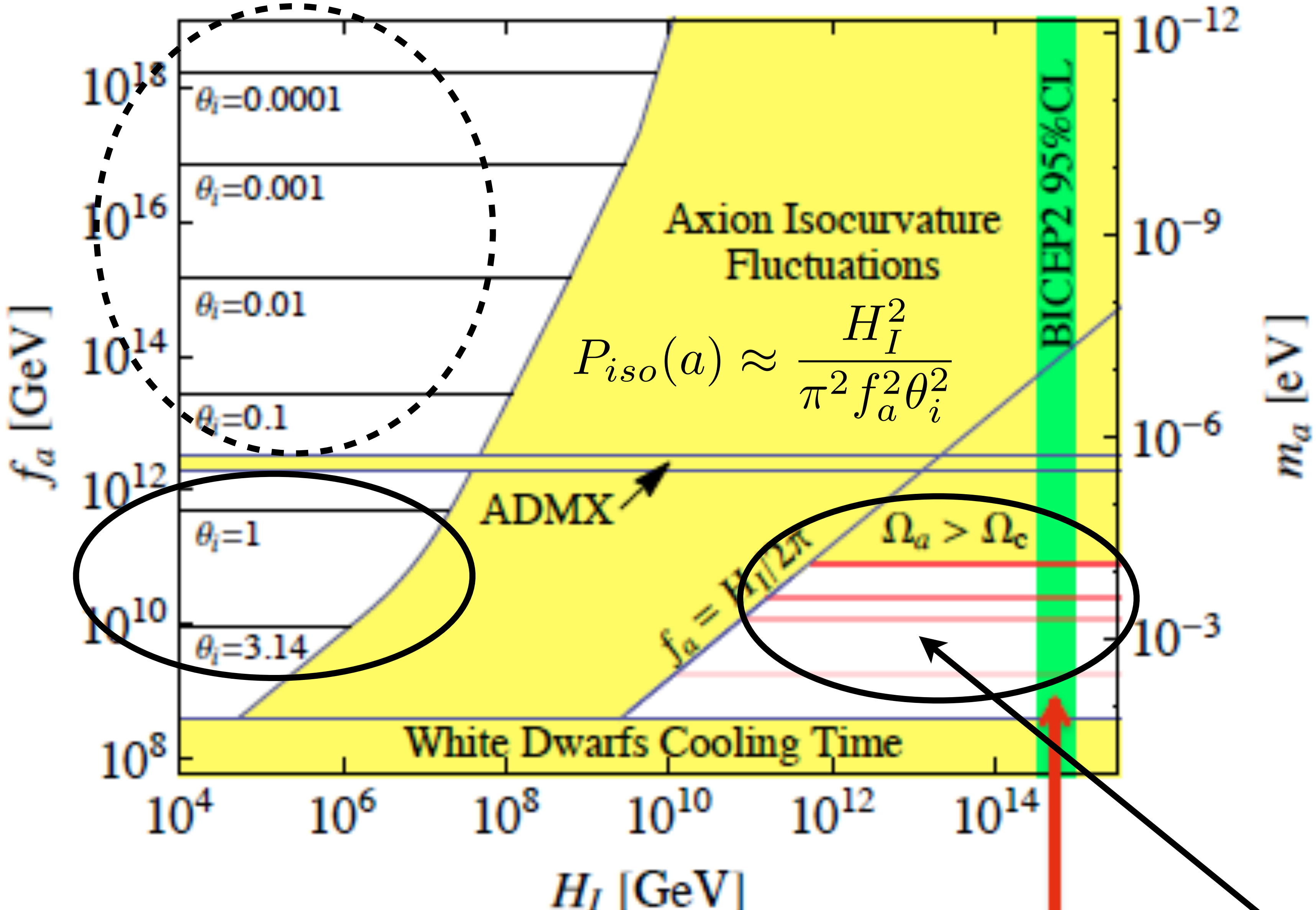
i.e. cold Dark Matter

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

?

QCD Axions in cosmology

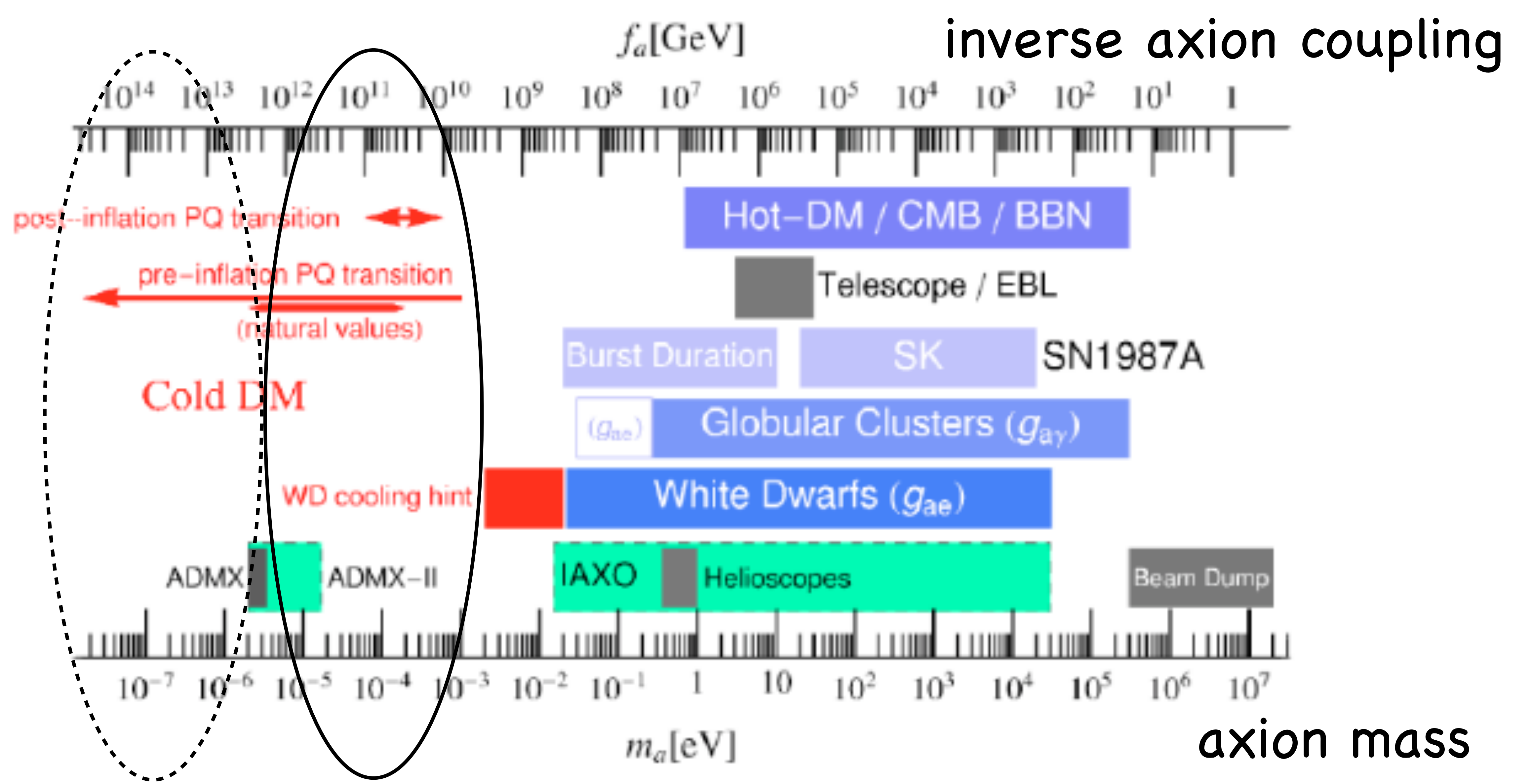
$m_a f_a \approx 10^{-4}\ eV \cdot 10^{11} GeV$



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

(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)

An alternative definition of the SM (equally precise!)

1. Symmetry group $\mathcal{L} \times \mathcal{G}$

$\mathcal{L}$ = Lorentz (rigid, exact)

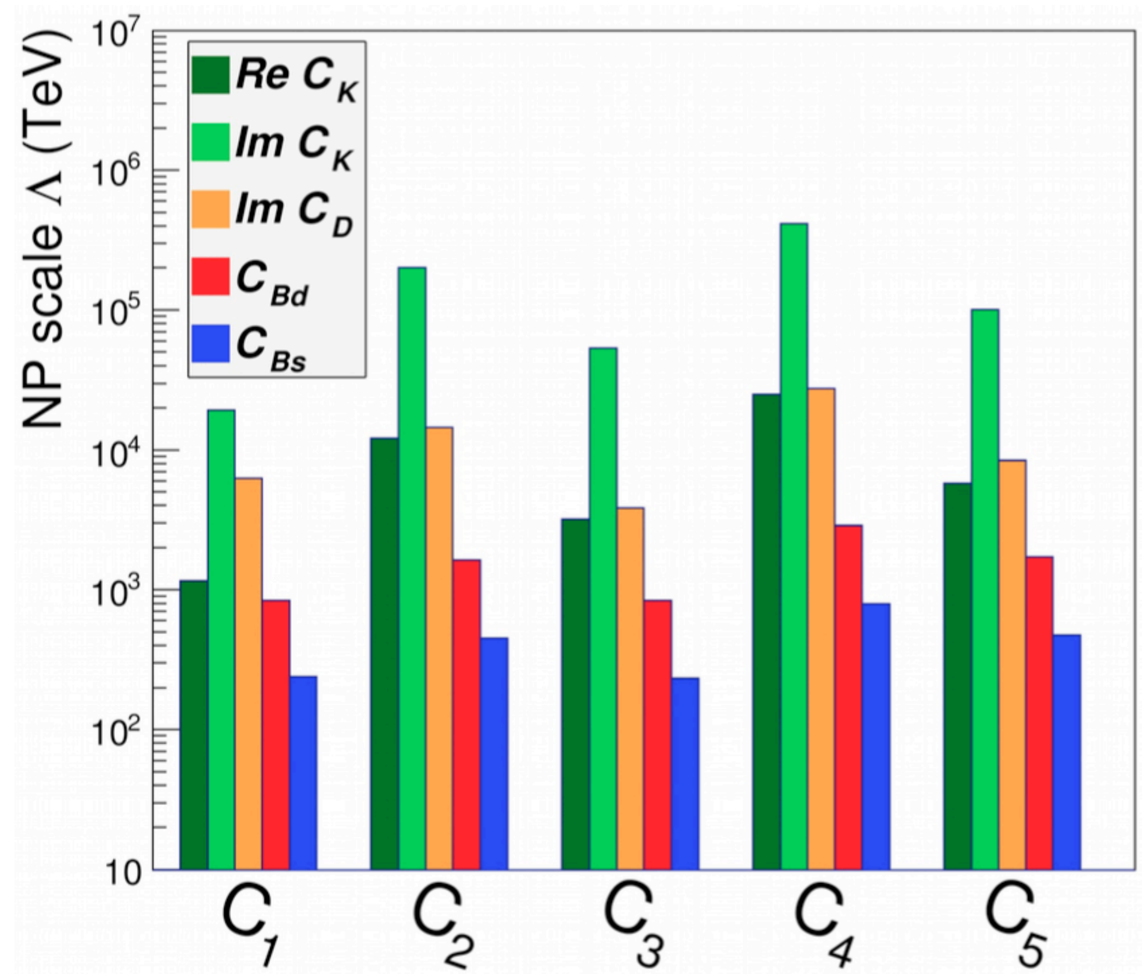
$\mathcal{G} = SU(3) \times SU(2) \times U(1)$ (local, spontaneously broken)

2. Particle content (rep.s of $\mathcal{L} \times \mathcal{G}$)

3. All "operators" (products of $\Phi, \partial_\mu \Phi$) in $\mathcal{L}$ of dimension ≤ 4 with a single exception $\theta G_{\mu\nu} \tilde{G}^{\mu\nu}$

$$\hbar = c = 1 \Rightarrow [A_\mu] = [\phi] = [\partial_\mu] = M, \quad [\Psi] = M^{3/2}, \quad [\mathcal{L}] = M^4$$

Which direction to take in flavour?



1. High energy exploration

$$\mathcal{L} = \mathcal{L}_{SM} + \Sigma_i^\alpha \frac{C_i^\alpha}{\Lambda_i^\alpha} (\bar{f} f \bar{f} f)_i^\alpha$$

$$\alpha = K(\Delta S = 2),\ D(\Delta C = 2),\ B_d(\Delta B = 1),\ B_s(\Delta B = 1)$$

i = 1,...,5 = different Lorentz structures

Lepton Flavour Violation at least equally motivated

2. Indirect signals of new physics at the TeV scale