EW Moriond 2013
Theory Summary

HEP-EX is on the move
The triumph of the SM
Naturalness challenged
Where is BSM physics?

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(ITN-UNILHC + ERC-DaMeSyFla)

Apologies

For theory, I counted 26 "regular" talks and 10 "short" talks by young scientists: it would be impossible (and boring) to give a fair account of all of them

I will use the unwritten privileges of the summary speaker to transmit you my (of course debatable) theorist's viewpoint on the status of the field and its perspectives

The Standard Model of strong and electroweak interactions (effectively coupled to gravity) quantitatively describes most observations

ν oscillations call (so far) for minor modifications

Stronger exceptions with gravity/astro/cosmo: dark matter, dark energy, inflation, baryogenesis

True last year, still true today: what changed?

Let us start from the big question of particle physics to which we are finding answers now:

symmetry breaking in the SM

Symmetry breaking in the SM

$$\mathcal{L}_{gf} = -\frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} + i\overline{\Psi} \not{D} \Psi$$

G_{loc}=SU(3)×SU(2)×U(1) G_{gl}=SU(3)^5×U(1)^4

Spontaneous breaking of the gauge symmetry:

$$\mathcal{L}_S = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

Explicit breaking of the flavour symmetry:

$$\mathcal{L}_{Yuk} = \overline{\Psi}_i Y_{ij} \Psi_j \phi + h.c.$$

H_{loc}=SU(3)$_C$×U(1)$_{em}$ H_{gl}=U(1)^4 [B,L_e,L_μ,L_τ]

The message from EXP to TH

The minimal, weakly-coupled
Standard Model implementation
of the Brout-Englert-Higgs mechanism
with
a single “elementary” scalar doublet
CKM description of flavour change and CPV
a generalised GIM mechanism at work

works far beyond most expectations

Recent experimental milestones (just summarised by Paris Sphicas):

- A new particle compatible with the SM scalar

We have now 5 fundamental forces in Nature, mediated by spin-0, spin-1 and spin-2 bosons!

- New precise flavour and CPV tests

passed with flying colours!

- More stringent bounds on new particles

LHC bounds well above 1 TeV for sizeable couplings to quarks and gluons viable signatures in the LHC environment

SM Flavour

COMPARISON OF ST WITH DATA

	$\lvert\epsilon_K\rvert$	Δm_K	$\lvert\Delta M(B_d^0)\rvert$	$\lvert\Delta M(B_s^0)\rvert$	$\lvert\Delta M(D^0)\rvert$	$\lvert Br(B_s \to \mu^+\mu^-)\rvert$
EW diagr.	$6.34\ 10^{-3}$	$3.12\ 10^{-12}$	$7.51\ 10^{-10}$	$294\ 10^{-10}$	$2.0\ 10^{-13} \cdot (\frac{m_s}{0.15GeV})^2$	$4.0\ 10^{-9}$
QCD corrcts	$2.65\ 10^{-3}$	$3.85\ 10^{-12}$	$4.13\ 10^{-10}$	$119\ 10^{-10}$	??	$(3.53 \pm 0.38)\ 10^{-9}$
expt	$2.228\ 10^{-3}$	$3.483\ 10^{-12}$	$3.34\ 10^{-10}$	$117.0\ 10^{-10}$	$(1.57 \pm 0.39)\ 10^{-11}$	$(3.2 \pm 1.4)\ 10^{-9}$

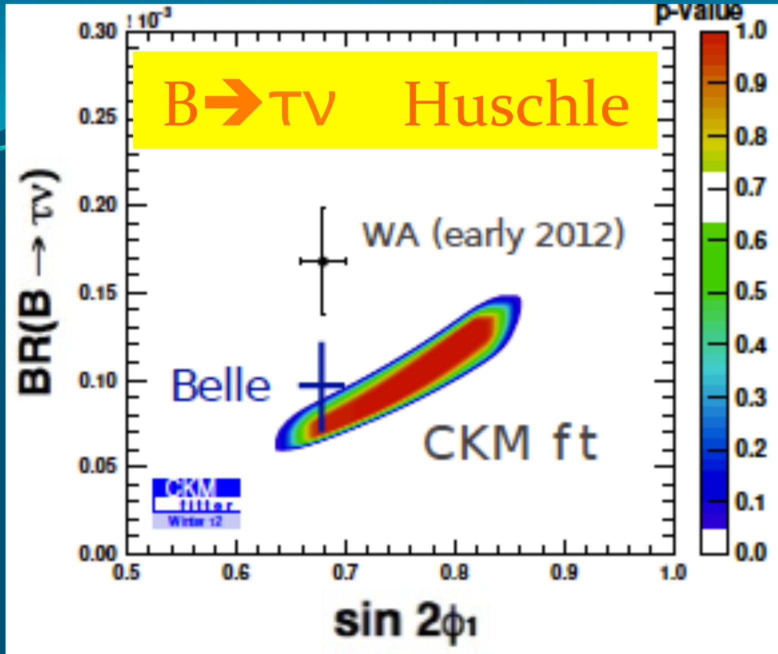
Table 1: Masses in MeV

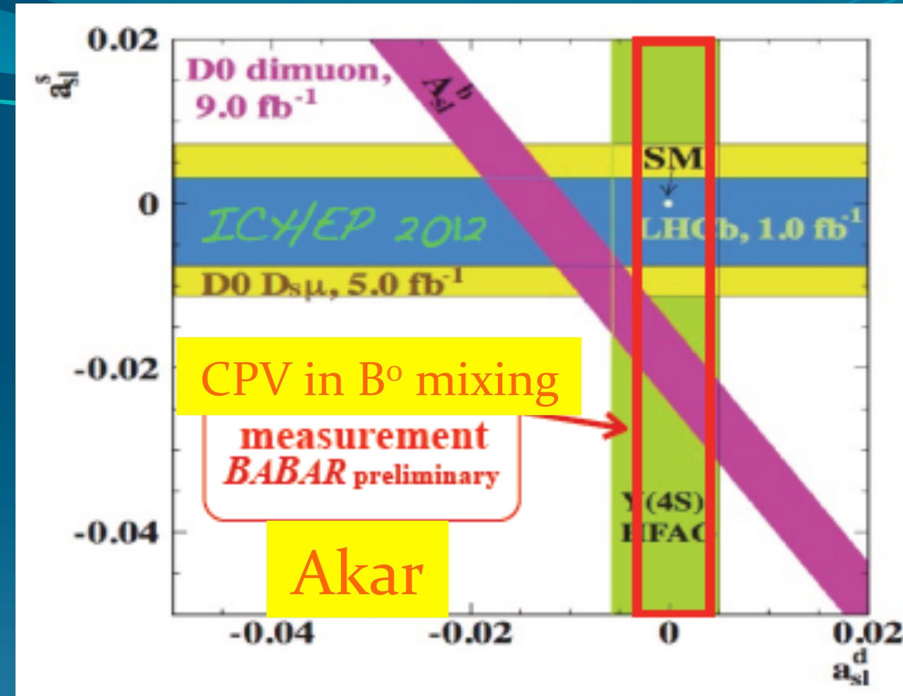
dominated by the t-quark

dominated by the c-quark

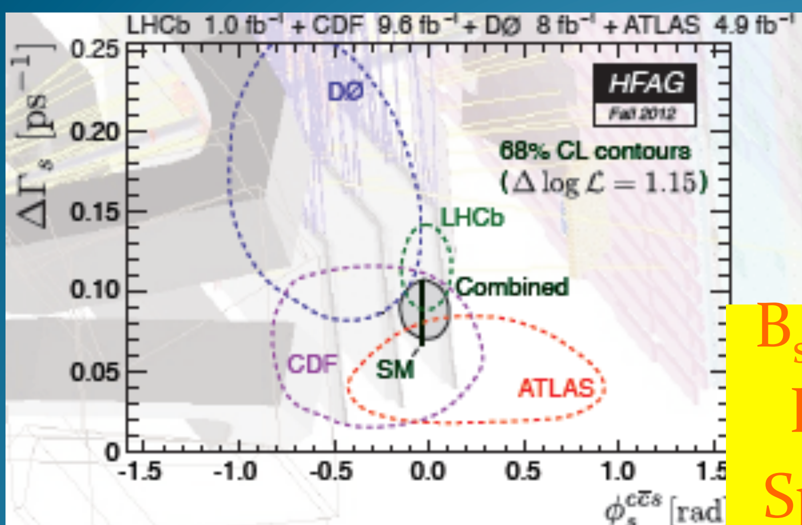
Input data:
CKM coefficients (weak decays of s, c and b)
m_c=1.5, m_t=173, m_s=0.150, m_b=5.0

Maiani



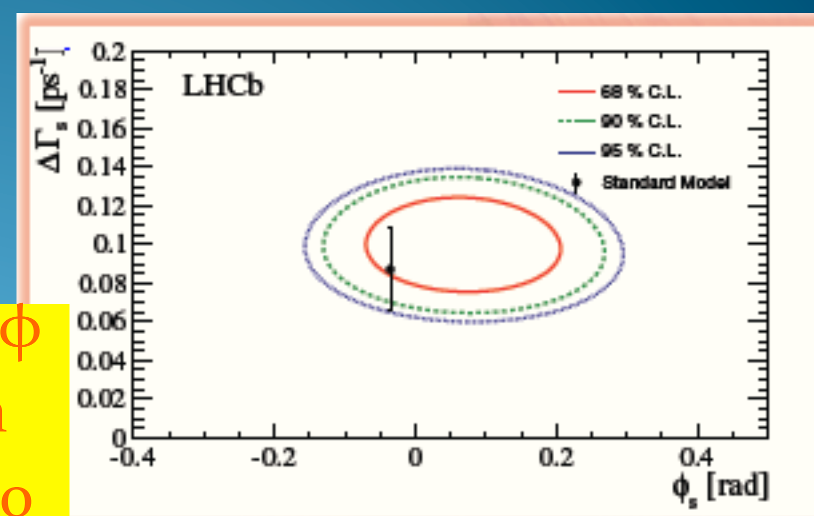


Many small tensions going…



→

B_s→J/ψ φ
Benson
Spagnolo



Some hopes that have not materialised (so far)

- $\mu \rightarrow e\gamma$: new MEG bound BR < 5.7 x 10^{-13} (90%cl)

Ootani

- LHCb 3.5 σ evidence for $B_s \rightarrow \mu\mu$, agrees with SM

Sarti

Other small tensions fading away?

- CDF top FB distribution, 2.1 σ from NLO SM starts being tested at the LHC

Wilson; Battilana

- ΔA_{CP} in D decays (3.5 σ in LHCb), followed by theory reassessment, exp update is imminent

Hampson

Precision flavour physics calls for state-of-the-art phenomenology

A hot example discussed at this meeting:

$b \rightarrow s\, l^+ l^-$ transitions, e.g. $B \rightarrow K^* \mu^+ \mu^-$

Tevatron and LHCb have entered the precision era and started measuring angular distributions

- Predictions for ang distr at low hadronic recoil
  Extraction of hadronic form factors from data

Hiller

- Extract constraints on flavour effective operators with theoretically "clean" observables ➔
  New strong constraints on semil & rad ops

Virto

…as well as for hard SM theory (e.g. lattice)

$\Delta I=1/2$ rule from the lattice

$\Gamma(K_S \rightarrow \pi^+\pi^-)/\Gamma(K^+ \rightarrow \pi^+\pi^0)=670$

$[\mathrm{Re}A_0/\mathrm{Re}A_2 \approx 22.5]$

with implications for ε'/ε

Domain wall quarks
full QCD (no χPT)
physical pion mass

Soni

New strong cancellation found (factor 3-4) in $\mathrm{Re}A_2$. A_0 needs more work but it is under way

Towards solving a long-standing puzzle?

The boson

Impressive progress in the study of its properties
as just described in the experimental summary
And there is more to come from Moriond QCD!

Three comments:

Once more, admiration for ATLAS/CMS colleagues

I was impressed by new direct indications for
SM-like couplings to τ leptons and b quarks

To take deviations from the SM seriously we should
apply the same stringent standards as for discovery!
Difficult to imagine a SM scalar crisis in < 3 years

Is it a spin-0 CP-even particle?

ATLAS/CMS are now testing J^{CP} of the new particle

Important as a consistency check and must be done

However, we should keep in mind what the σ's mean

With M_H known, no free parameter left in the SM to describe all production mechanisms and decay modes: renormalizable theory, passes all precision tests, can be safely extrapolated to (much) higher energies

More complicated to do the same with $J^{CP} \neq 0^+$!
Technically possible to write an effective Lagrangian, but this adds many parameters and "theory sigmas"

Is it the SM scalar?

Several ways to go non-standard:

Rzehak, Carena, Ellwanger, Yamawaki,...

- H mixes with other spin-0 states
  e.g. additional doublets and/or singlets
- H meson of a new strong force, kept light by its pseudo-Goldstone boson nature
- H decays into invisible particles
- Loops for H production (ggH) and decay (Hgg,Hγγ,HZγ) modified by new particles

How to parametrise a non-SM scalar?

Eboli, Jenkins, Azatov, Gavela Merlo, Yamawaki

Compromise between simplicity and completeness, depending on kind of experimental data and purpose

For present book-keeping, under reasonable assumptions (spin-0, CP even, custodial, no FCNC)

$$\mathcal{L}^{eff}_{<m_h} \approx c_V \left(\frac{2m_W^2}{v} W_\mu^+ W_\mu^- + \frac{m_Z^2}{v} Z_\mu^2\right) h + c_b \frac{m_b}{v} \bar{b} b h + c_\tau \frac{m_\tau}{v} \bar{\tau} \tau h$$
$$+ c^\gamma \frac{2\alpha}{9\pi v} F_{\mu\nu}^2 h + c^g \frac{\alpha_S}{12\pi v} G_{\mu\nu}^2 h$$
$$+ \mathcal{L}(h \to inv)$$

$$c^\gamma = c_t + \frac{9}{2}\delta c^\gamma$$
$$c^g = c_t + \delta c^g$$

SM recovered for all five c=1 and L(h→inv)=0

For testing models, use effective Lagrangians

Eboli

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \sum_n \frac{f_n}{\Lambda^2}\mathcal{O}_n + \cdots$$

dimension-6 operators summarizing NP effects

Linear realization for models with elementary H

Non-linear realization for composite H (WTC, PC)

Merlo

$$\mathbf{U}(x) \equiv \mathbf{M}(x)/v = e^{i\sigma_a \pi^a(x)/v} + F_i(H)$$

In both cases, important to identify
a suitable basis of independent operators

Theoretically-motivated fitting strategies being suggested by theorists to experimentalists

Azatov

Correlations between anomalous scalar couplings, EWPT and anomalous vector boson couplings

Jenkins, Eboli

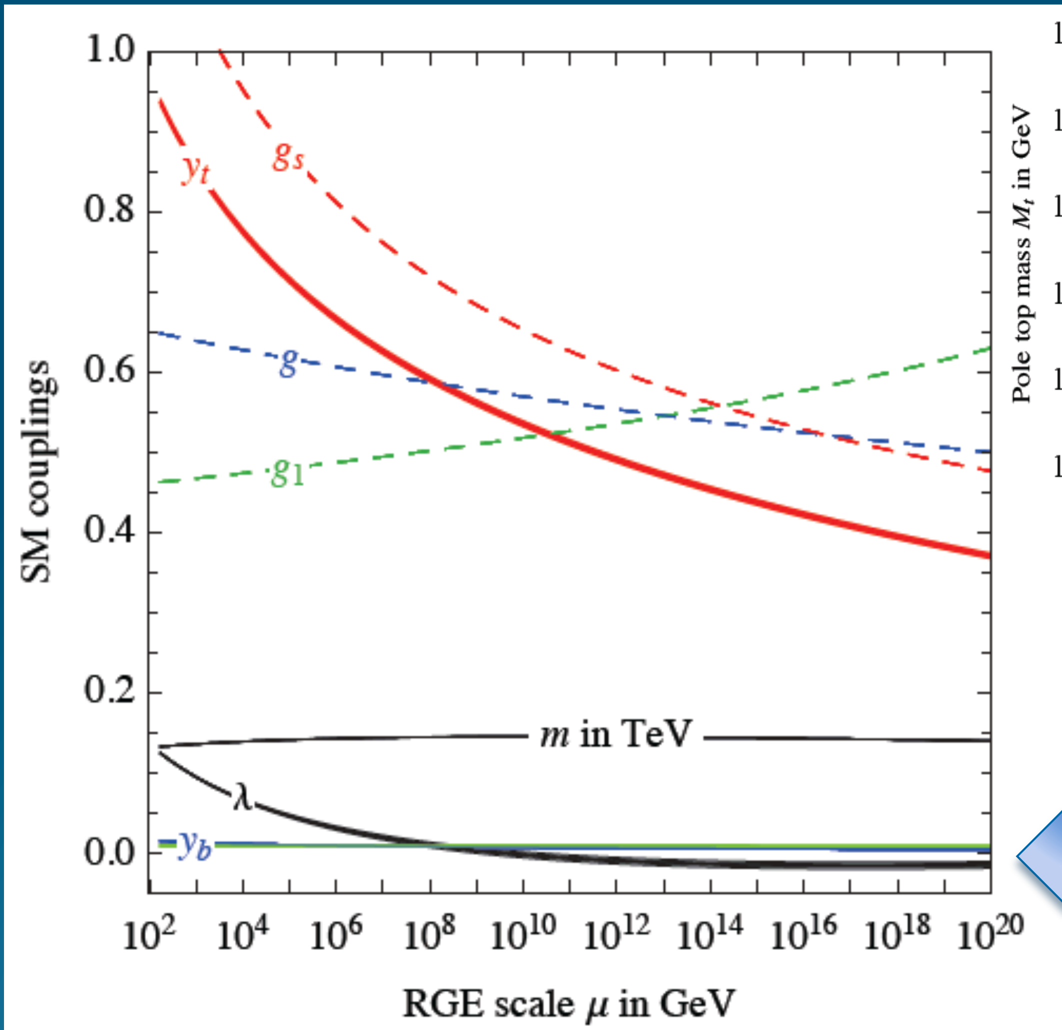
RG evolution from Λ to m_H can give sizable effects

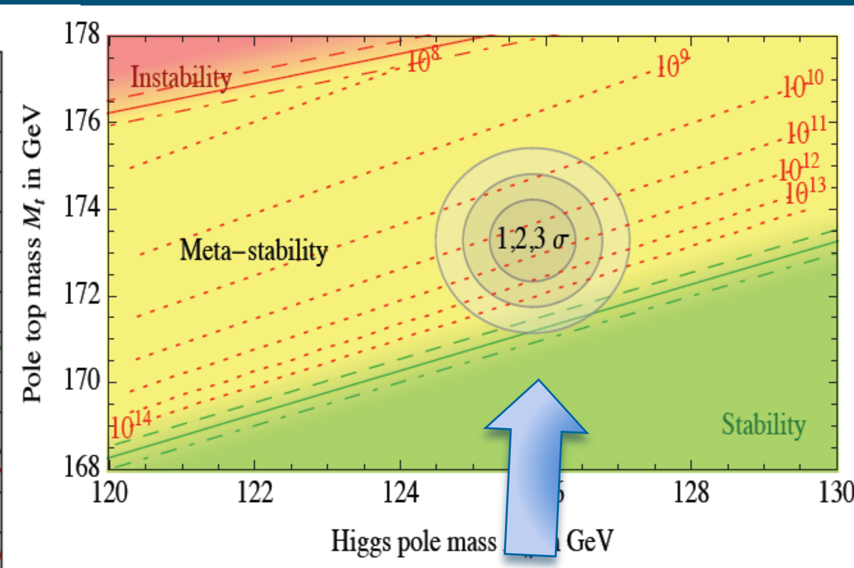
Jenkins

$$\mu_{\gamma\gamma} \simeq 1 - 0.02\, S \log \frac{\Lambda}{M_h} + 0.02 \left(\frac{1\ \mathrm{TeV}}{\Lambda}\right)^2 \left(16\pi^2 c_{\gamma\gamma}(\Lambda)\right)$$

What is m≈125.8 GeV telling us?

Strumia
Elias-Miro





We are safe!

λ & β_λ nearly 0 for $\mu > 10^8$ GeV

- There is nothing forcing us to extend the SM before 10^{10} GeV or so if we ignore naturalness (scales for ν_R & invisible axion can be beyond)
- Is there some meaning in the near vanishing of λ, β_{λ}, m_H/Λ at very high cutoff scales for the SM?
- Precise RG calculations and top mass measurements will become important when/if threshold effects at Λ will be calculable
- Potential implications for cosmology & susy
- A scalar singlet is enough to cure the instability if needed for the consistency of model building

A tribute to SM theory

A theoretical construction essentially completed 40 years ago found recently its coronation and stands as solid as a rock admiration for the vision and insight of the founding theorists

However, we should also pay tribute to the long-term efforts to characterize direct and indirect signals of the SM scalar boson and compute the relevant backgrounds

Are we done now?

No, it js just the start of a major programme that may take several decades for completion

The program for the years to come

1. Study the properties of the new scalar with the highest possible precision, to reveal possible inconsistencies of the SM that would point indirectly to new physics

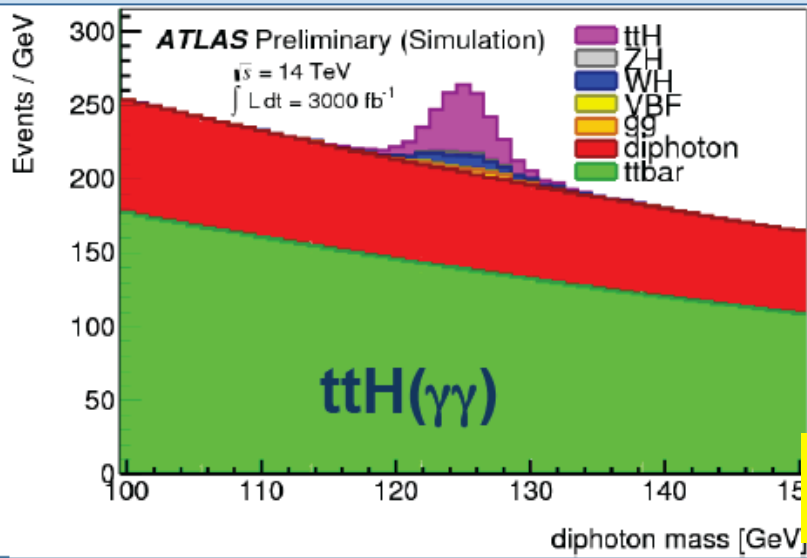
2. Find out whether it is accompanied by other new physics near the TeV scale

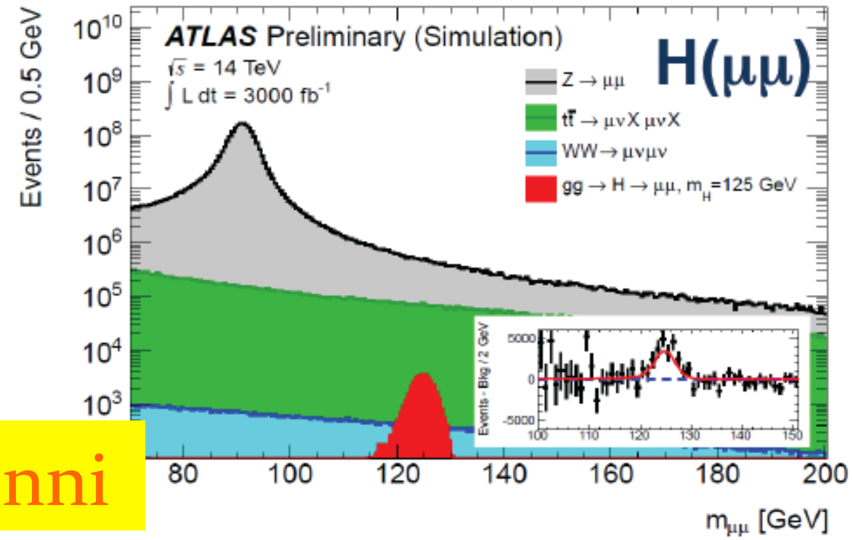
Both missions may require an electron-positron collider to complement the unique information that LHC will collect until ~2030

Physics @ LHC: high luminosity

From 'High Energy Frontier' presented by Marcella Diemoz

HL-LHC: √s ~14 TeV, L=5x10^{34} cm^{-2}s^{-1} and 3000 fb^{-1} ~ 2030





Jenni

CMS ESTIMATE

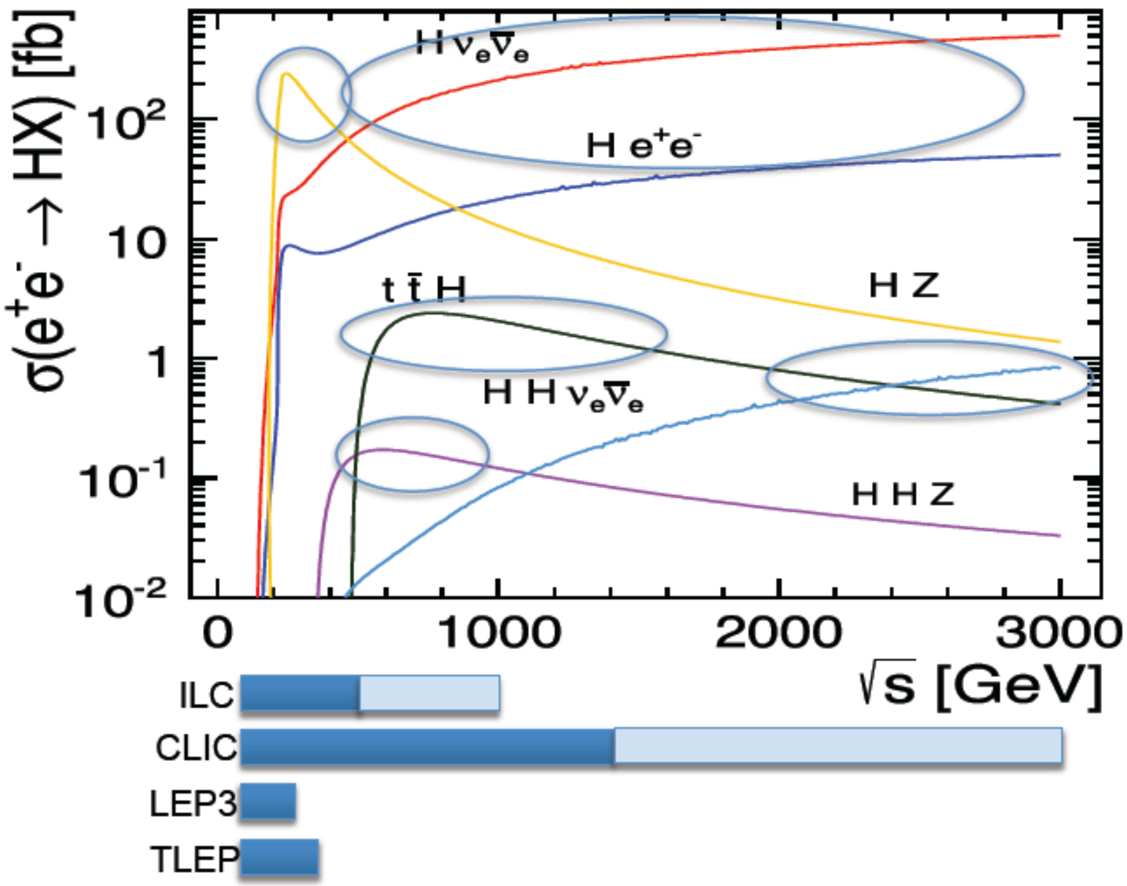
Coupling	300 fb^{-1} syst. (%) actual	300 fb^{-1} syst. (%) scaled	3000 fb^{-1} syst. (%) actual	3000 fb^{-1} syst. (%) scaled
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

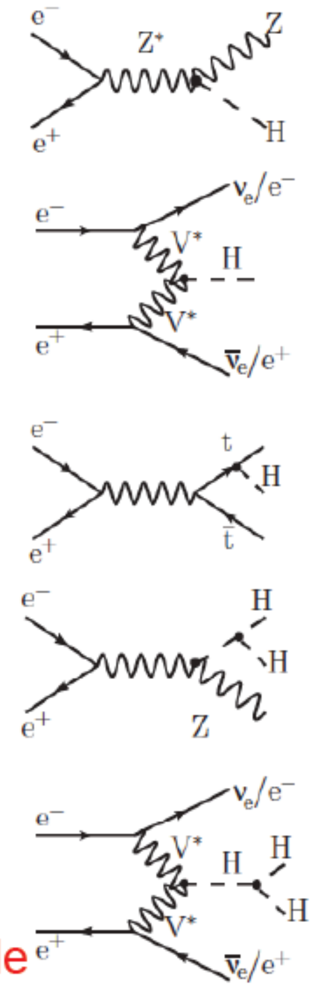
Profit from statistics:

- rare H production channels
- rare H decay channels
- H couplings
- Higgs self coupling (HH detection)
- VBS: dynamics of EWSB (is it SM?)
- New physics with suppressed couplings

Precision Higgs Studies

Jenni





Mass
g_Z (m.i.)
BR´s
(LHC)-invisible

Γ_{tot}

g_t (ILC,CLIC)

g_{HHH} (ILC500)

g_{HHH} (ILC1000, CLIC)

- Many processes at different √s needed & accessible
- HZ (at 250-350 GeV): recoil mass as anchor for model-independence

From 'High Energy Frontier' presented by Marcella Diemoz

What lies Beyond the SM
(with a chance of being at reach)?

LHC-8 relied on a powerful no-lose theorem

either the SMS, or new physics at the TeV scale

We won't be again in such a condition for a long time

Diversify efforts to maximise chances

We are now sailing in uncharted waters

must be persistent as Columbus in his trip to Indies...

The SM as an effective theory

Λ = effective UV cutoff (not necessarily universal)
= the scale of some (unspecified) new physics

$$L_{eff}^{SM} = \Lambda^4 + \Lambda^2\Phi^2 \qquad (\Lambda^{n>0} \Rightarrow \textit{hierarchy problems!})$$

$$+ (D\Phi)^2 + \overline{\Psi}\, \not{D}\Psi + F\cdot F + F\cdot\widetilde{F} + \overline{\Psi}\Psi\Phi + \Phi^4$$

$(controllable\ \log\Lambda\ dependence\ via\ quantum\ corrections)$

$$+\frac{\overline{\Psi}\Psi\Phi^2}{\Lambda} + \frac{\overline{\Psi}\sigma^{\mu\nu}\Psi F_{\mu\nu}}{\Lambda} + \frac{\overline{\Psi}\Psi\overline{\Psi}\Psi}{\Lambda^2} + \frac{\Phi^2 F^{\mu\nu}F_{\mu\nu}}{\Lambda^2} + \dots$$

$(\Lambda^{n<0} \Rightarrow EW\ tests,\ \ flavour\ tests,\ \ \not{B},\ \ \not{L},\ \ \dots)$

Beyond the SM with neutrinos

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \delta\mathcal{L}(m_\nu) + \ldots$$

$\mathcal{L}_{SM}$:

Renormalizable minimal SM Lagrangian

3 families with ν_L but no ν_R

Accidental $(B, L_e, L_{mu}, L_{tau})$ [(B+L) anomalous]

$\delta\mathcal{L}(m_\nu)$: experimentally needed, still undetermined

Simplest solutions

1. Dirac [add 3 right-handed ν_R, assume (B-L)]
2. Majorana [Broken (B-L)], favoured because of

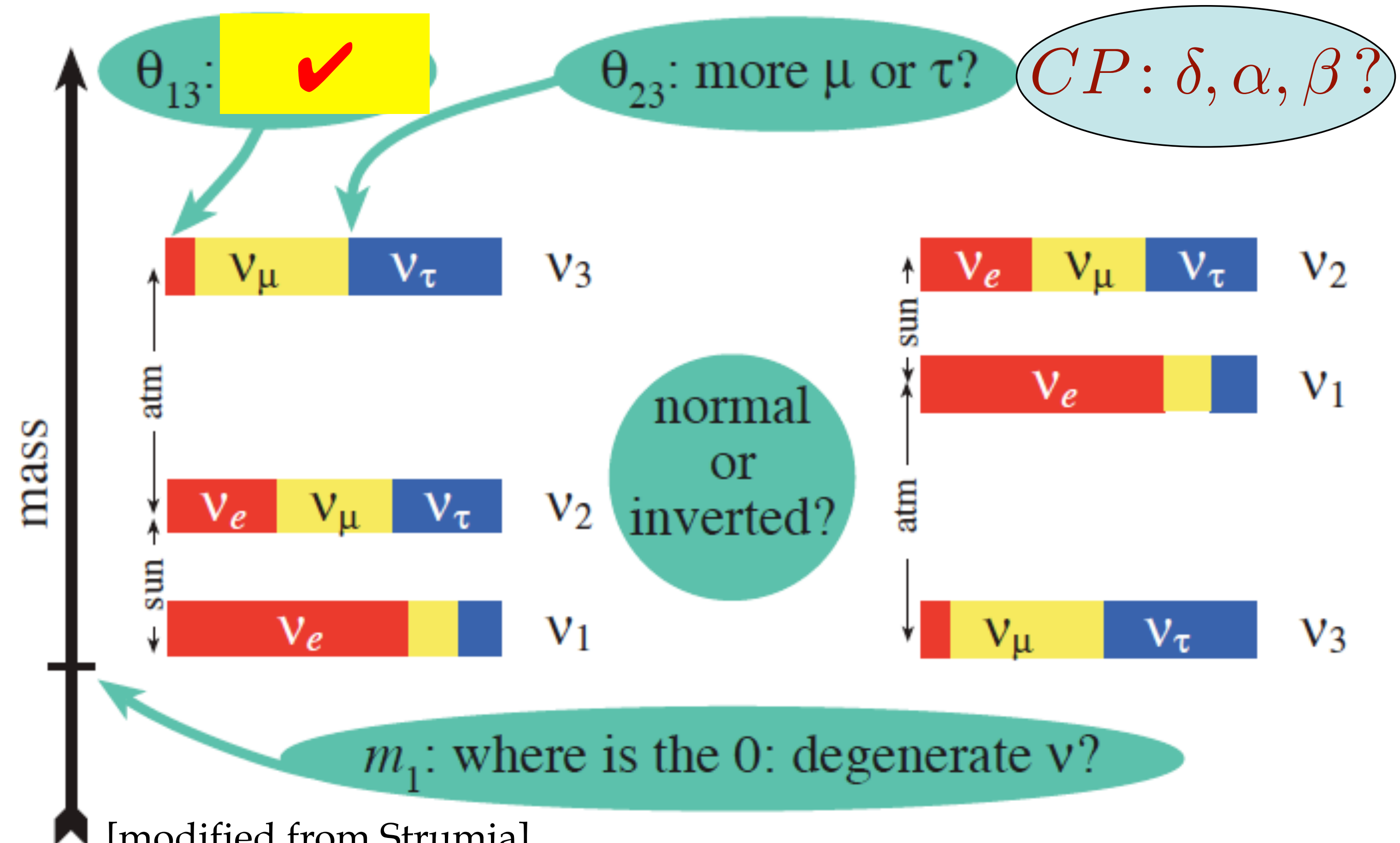
- Unique d=5 op in L_{eff}, Λ as large as almost M_{GUT}
- Simplest see-saw mechanism with heavy ν_R
- Makes possible baryogenesis via leptogenesis

Clear th bias for 2., but exp open question: $(\beta\beta)_{0\nu}$

Neither 1. nor 2. affect the success of L_{SM} until Λ

Known unknowns

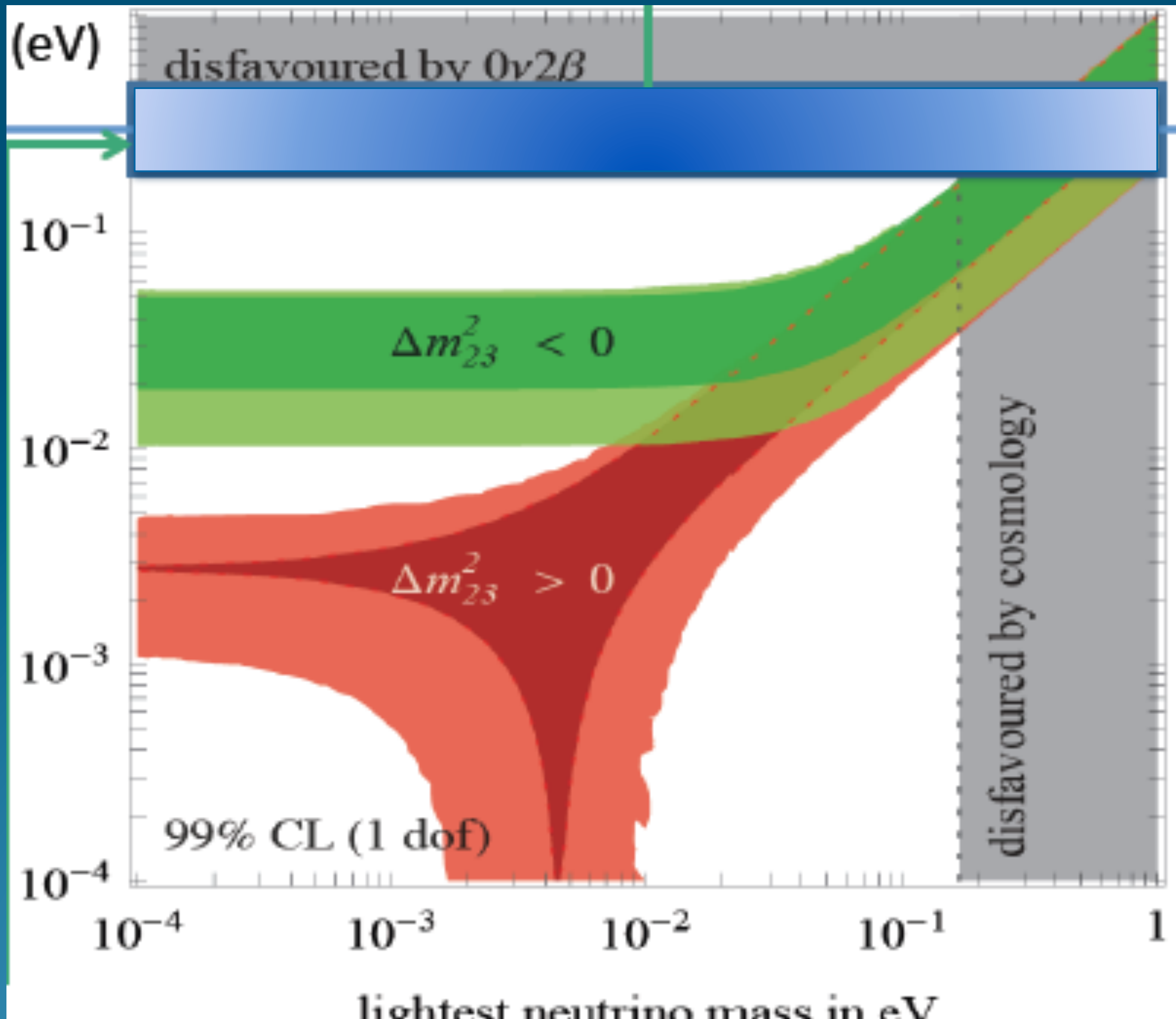
Is L violated?



[modified from Strumia]

3

My n.1 question: is L violated? $(\beta\beta)_{0\nu}$ experiments



Main issues of ν-related theory talks

Gavela, Hernandez, Tamborra, Palomares-Ruiz

- Cosmological constraints/hints for sterile ν's (difficult to draw firm conclusions? Planck?)
- Are we in a better position to study flavour models now that we have 2 flavour sectors? Non-abelian discrete symmetries? Yukawa couplings as dynamical variables? (beware MFV spoiled by higher-dim ops when integrating out heavy fields carrying flavour)
- Can the scale of lepton flavour be low enough to give detectable signals in charged LFV? Y
- Mass hierarchy from atmospheric neutrinos?

Beyond the SM with Dark Matter

WIMP = Weakly Interacting Massive Particle

A good argument for new physics at the TeV scale but not fully compelling: DM could well be axions

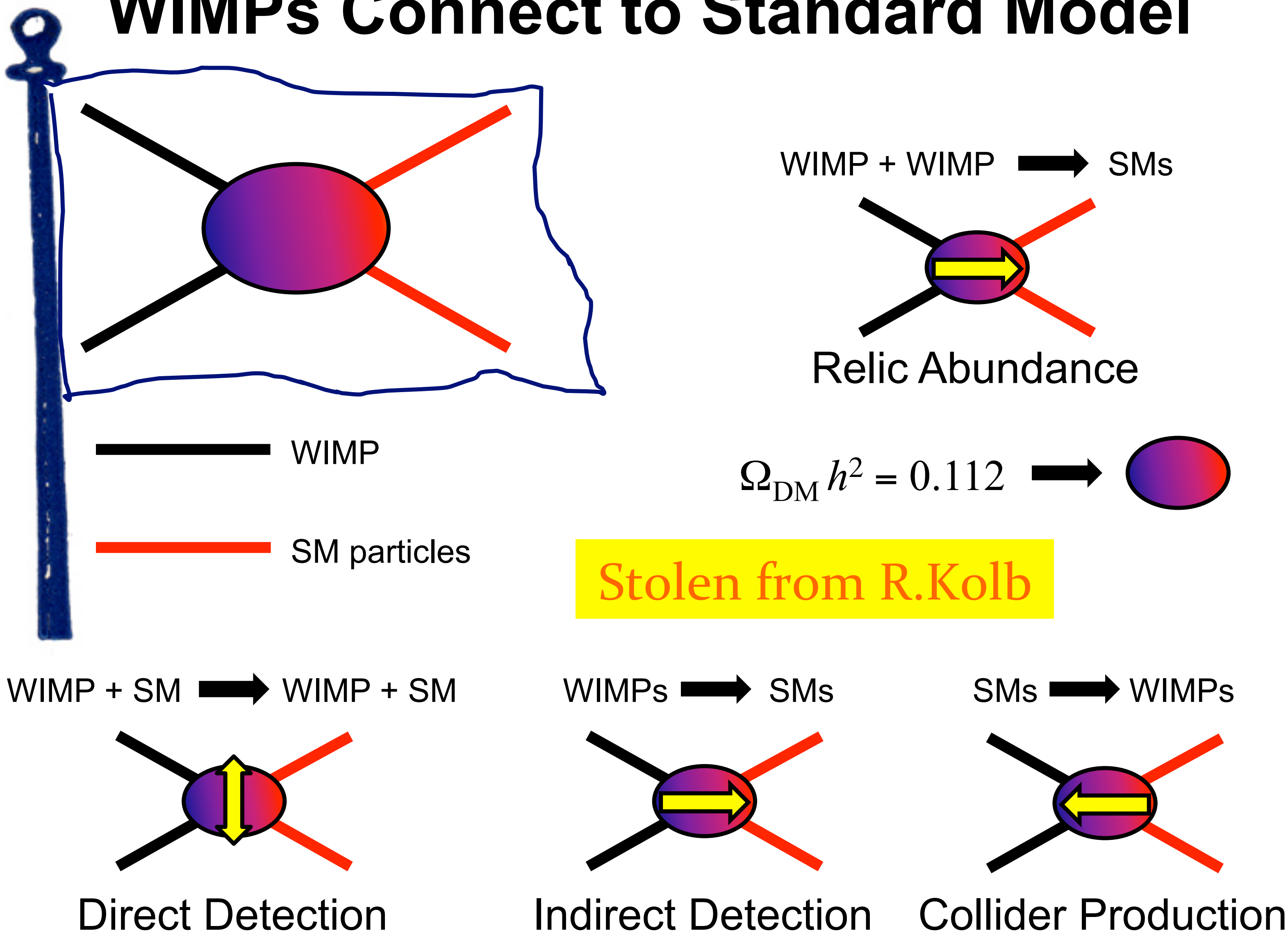
For WIMPs in thermal equilibrium after inflation

$$\langle \sigma_{\rm ann} v \rangle \simeq 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

EW x-section for particle with $M \sim 10^{2-3}$ GeV

The WIMP miracle…

WIMPs Connect to Standard Model



Theory issues with DM

Ibarra, Rydbeck, Tytgat, Lopez-Honorez

Variety of models explored to produce diverse interesting signals in indirect or collider searches

My comments:

LHC results may eventually shift focus from "social" (MSSM, Xdim,…) to "simplified" DM models

Check the consistency of the approximation when using pointlike 4-fermion operators to put bounds on DM at the LHC with monojets or monophotons

Naturalness

coefficients small only because of symmetries

It works in many cases!

- Electron mass in NR QED → positron

$$\delta m_e \sim \alpha\Lambda \quad \rightarrow \quad \delta m_e \sim \alpha m_e \log \ldots$$

- 4-f FCNC box diagram with 3 light q → c

$$G_F^2 \Lambda^2 \sim G_F^2 m_W^2 \ \textit{too large!} \quad \rightarrow \quad G_F^2 m_c^2 \ OK$$

- π^+ - π^0 mass difference in QED → ρ

$$\Delta m_\pi^2 = (3\alpha)/(4\pi)\Lambda^2 \ \rightarrow \ \Lambda \sim m_\rho \, OK$$

It does not seem to work for the dark energy

$\Lambda_{CC} \sim 2.4 \times 10^{-3}$ eV

The naturalness puzzle in the SM

No quantum SM symmetry recovered for $m_H \rightarrow 0$

(scale invariance broken by quantum corrections and UV physics)

SM unnatural unless New Physics at the LHC scale

$$\delta m_H^2 \sim -\frac{3\,h_t^2}{8\,\pi^2}\,\Lambda^2 < O(m_H^2) \quad \rightarrow$$

Λ < O(500) GeV

However, precision tests of the SM suggest:

Λ > O(few) TeV [flavour-ind operators]

Λ > O(1000) TeV [flavour-dep operators]

What is the way out?

Ways out of the naturalness puzzle

Insist on the few viable (almost) natural models

1) Natural supersymmetry
2) Natural composite scalar

They can all be ruled out by the LHC

Have we missed some more subtle possibilities (perhaps in connection with gravity and DE)?

Puzzle might be solved only in the full theory (mysterious IR-UV connection missed by EFT)

Naturalness vs. flavour tests

Sala

Flavour: excellent agreement between data and CKM picture

In other words: $\Delta\mathcal{L} = \sum_i \frac{1}{\Lambda_i^2}\mathcal{O}_i \quad \Rightarrow \quad \Lambda_i \gtrsim 10^3 \div 10^4\ \mathrm{TeV}$

Hierarchy problem: $m_h \approx \Lambda$ $\quad$ [Λ = highest scale h couples to]

Possible way out: $\Delta\mathcal{L} = \sum_i \xi_i \frac{c_i}{\Lambda_i^2}\mathcal{O}_i$

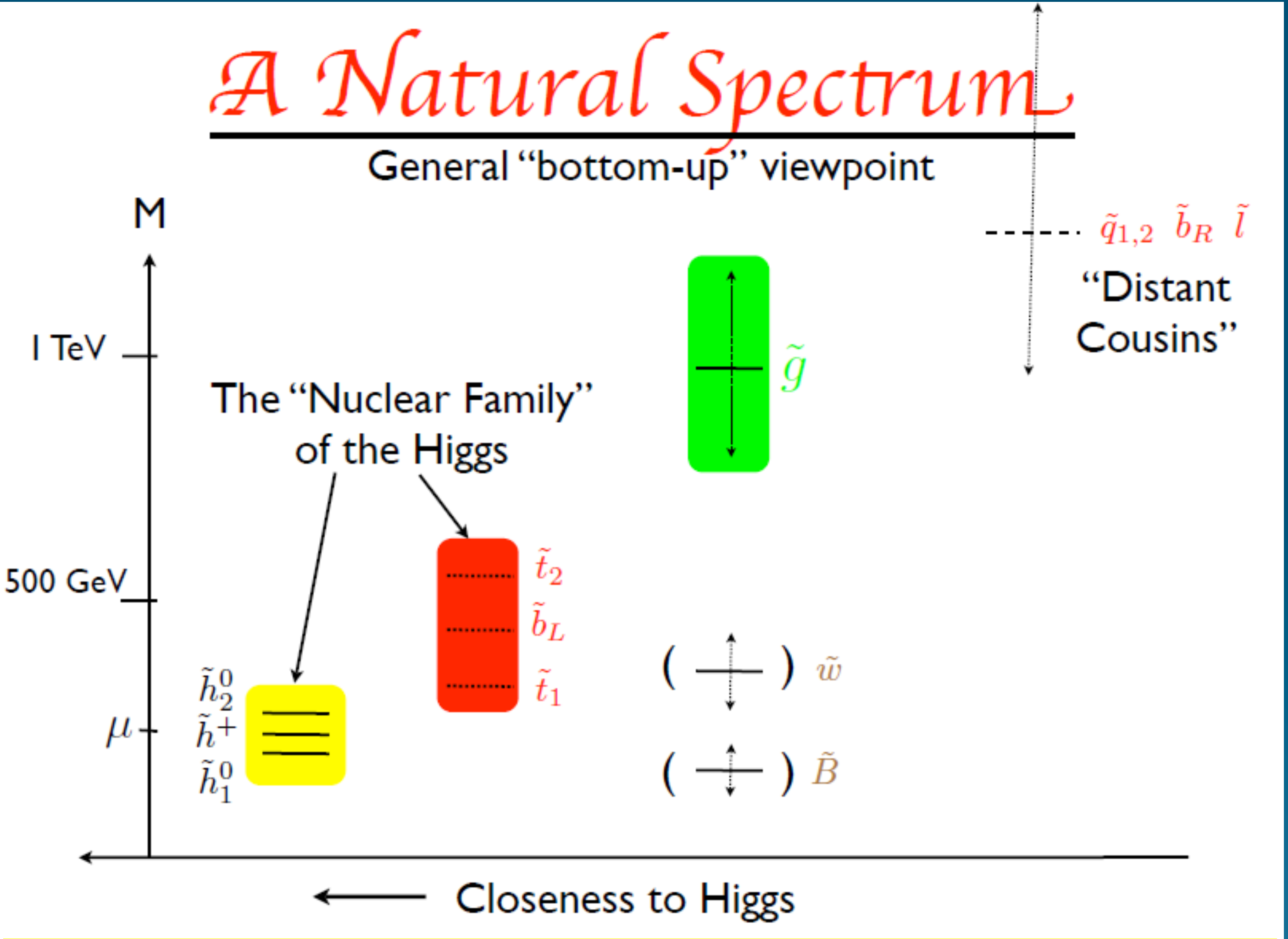
with $c_i \sim O(1)$ and ξ_i small due to some **flavour symmetry**

$U(2)^3 = U(2)_{Q_L} \times U(2)_{U_R} \times U(2)_{D_R}$

- ✓ $\xi \sim V_{CKM}^{2\div 4} \quad \Rightarrow \quad \Lambda \sim$ a few TeV is OK with flavour bounds
- ✓ potentially rich phenomenology behind the corner
- ✓ other virtues...

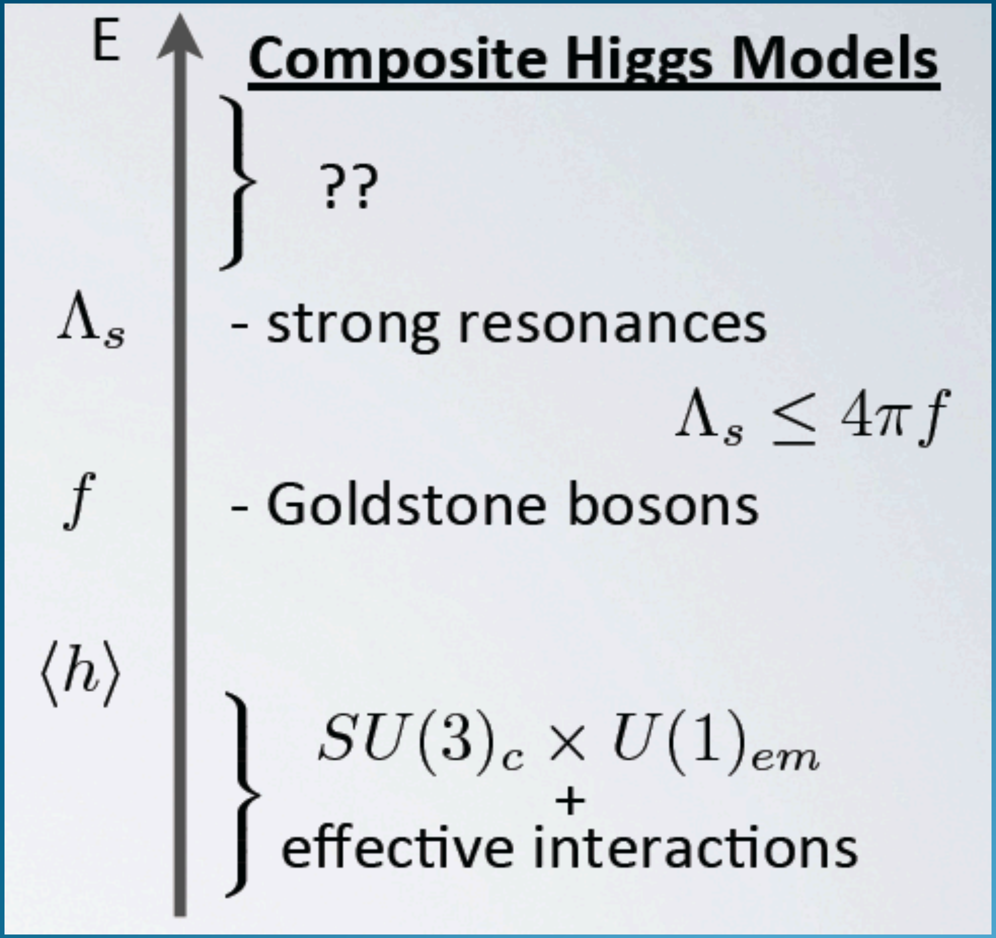
Natural SUSY

Example:



New limits described by Marrouche + Verducci

Natural composite scalar



Partial compositeness:
Light scalar correlates with light top partners

Merlo, Azatov

Walking technicolor with approximate scale invariance: technidilaton with non-SM couplings

Yamawachi

Supersymmetry and ascendants

Kazakov, Carena, Ellwanger, Dudas, Sagnotti

My opinion (after following the experimental searches and contributing to the theory for roughly 30 years):

- Too good an idea to be wasted by Nature (general symmetry of RQFT, role in superstrings, etc)
- Might need to be combined with some additional ingredient to solve the SM naturalness problem
- Conventional susy models (CMSSM, NMSSM,…) do not work as such and should finally rest in peace

SUSY phenomenology

A quote from another summary talk, H.Georgi at a conference in Santa Barbara I attended in the early 90's (giving a talk on susy pheno):

"stop wandering in susy parameter space"

At the moment I was not very happy, but I think we theorists can now be more useful:

- Pointing out to experimentalists possible signals they may have overlooked so far in the searches
- Trying to understand what we are missing within simple controllable (even non-realistic) contexts

Seemingly unnatural SUSY

If we do not insist on naturalness, SUSY with heavy scalars can evade direct searches and flavour constraints while mantaining gauge coupling unification + DM candidate

E.g. mini-split supersymmetry: Dudas

scalars at ~1000 TeV, gauginos 1-2 loop factors lighter (R-symmmetry), higgsinos model-dependent, m_H~125 GeV easy

Conclusions (of Winter 2013)

HEP-EX is on the move

The triumph of the SM

Naturalness challenged

Where is BSM physics?

We must know, we will know

but we must be patient and try hard

We are lucky to live in such exciting times!

Many thanks to:

- The Secretariat: Isabelle Cossin, Vera de Sa-Varanda, Sarodia Vydelingum
- The Computer Support: Gérard Dreneau, Damien Fligiel, Victor Mendoza, Olivier Drevon
- The Organizers: Etienne Augé, Jacques Dumarchez, Jean Tran Thanh Van
- The Scientific Organizers present in La Thuile: Lydia Iconomidou-Fayard, Jean-Marie Frère, Eric Armengaud, Patrick Janot, Jean-Pierre Lees, Sotiris Loucatos, François Montanet, Jean Orloff as well as those who contributed remotely.