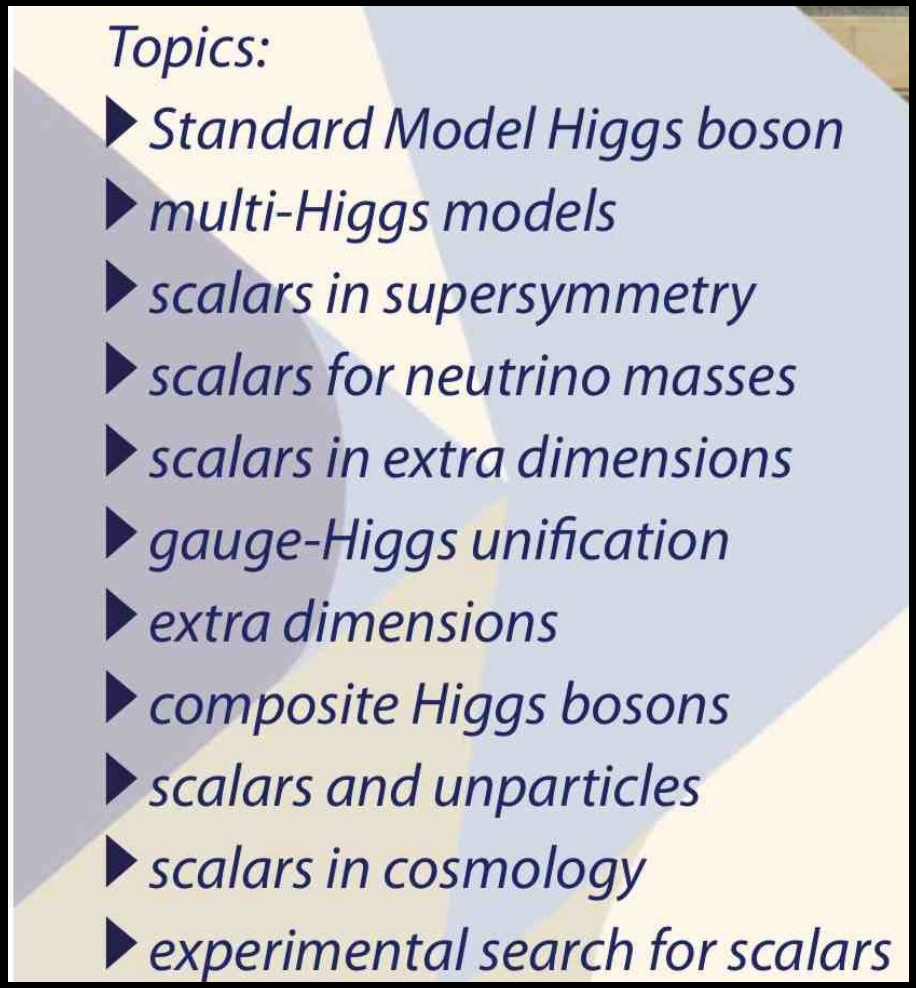
SCALARS 1960-2025 AND BEYOND



SCALARS 2011

Plenty of scalars at this meeting….

so far, Nature does not seem
to like elementary scalars

and the composite ones are never „unnaturally" light, unless they are (pseudo) Nambu- Goldstone bosons, like pions in QCD

A YEAR LATER AN APPARENTLY ELEMENTARY SCALAR HAS BEEN DISCOVERED

1960-1964: FOCUS ON STRONG INTERACTION, THE IDEAS BORROWED FROM CONDENSED MATTER PHYSICS

1960: NAMBU GENERATES PROTON AND NEUTRON MASSES AND A MASSLESS PION (BY SPONTANEOUS BREAKING OF CHIRAL SU(2)xSU(2) SYMMETRY), BY THE VACUUM (GROUND) STATE OF FERMION-ANTIFERMION CONDENSATE

1961: GOLDSTONE INTRODUCES A SCALAR FIELD AS A „SOURCE" OF THE GROUND STATE; FERMION MASSES WOULD THEN BE GENERATED BY A COUPLING TO THAT SCALAR FIELD.

INDEPENDENT QUESTION OF THOSE TIMES:
CAN RHO MESONS BE GAUGE BOSONS OF SOME GAUGE SYMMETRY?
HOW TO GIVE THEM MASSES IN A GAUGE INVARIANT WAY?

BROUT-ENGLERT(1964): GIVE MASS TO A GAUGE BOSON BY COUPLING IT TO A SCALAR FIELD THAT BREAKS SPONTANEOUSLY A GLOBAL SYMMETRY

HIGGS(1964): MOTIVATED BY THE QUESTION HOW TO AVOID MASSLESS N-G BOSONS! BY COUPLING THEM TO GAUGE FIELDS…

MY LIFE AS A BOSON (by PETER HIGGS)

My revised paper was received by Physical Review Letters at the end of August (1964) (…). The referee who, I discovered later, was Nambu, drew my attention to a paper by Englert and Brout which had been received on the 22nd of June,
before I even started my piece of work, and published on the 31st of August.

MY LIFE AS A BOSON (by PETER HIGGS)

The reference to the so-called Higgs boson would never have appeared in print if Physics Letters had accepted the original version. One of the additions was the sentence 'it is worth noting that an essential feature of this type of theory is the prediction of incomplete multiplets of scalar and vector bosons.'

SP: THIS IS THE VERY LAST SENTENCE IN THE PAPER AND THE ONLY ONE THAT MENTIONS THE "HIGGS" BOSON

MY LIFE AS A BOSON (PH)

The only thing that did not really go right was that I did not make any impact in terms of the possible applications.
All of us, Brout, Englert and myself, had been going in the wrong direction, looking at hadron symmetries.
(.....)

So it was left to Weinberg and Salam in 1967, as is well known, to bolt my and Brout and Englert's type of model onto Glashow's SU(2) × U(1) model of leptons, and the rest of the story is well-known to you.

2012: AN APPARENTLY ELEMENTARY HIGGS BOSON HAS BEEN DISCOVERED

Simplest dynamical sector (considered by many as a toy model) with global chiral symmetry (to be spontaneously broken) – self interacting scalar field, a doublet of SU(2)- HAS BEEN PROMOTED TO A REAL THING

$$V = m_H^2 H H^+ + \tfrac{1}{2}\lambda (H H^+)^2$$

$$v^2 = -m_H^2/\lambda$$

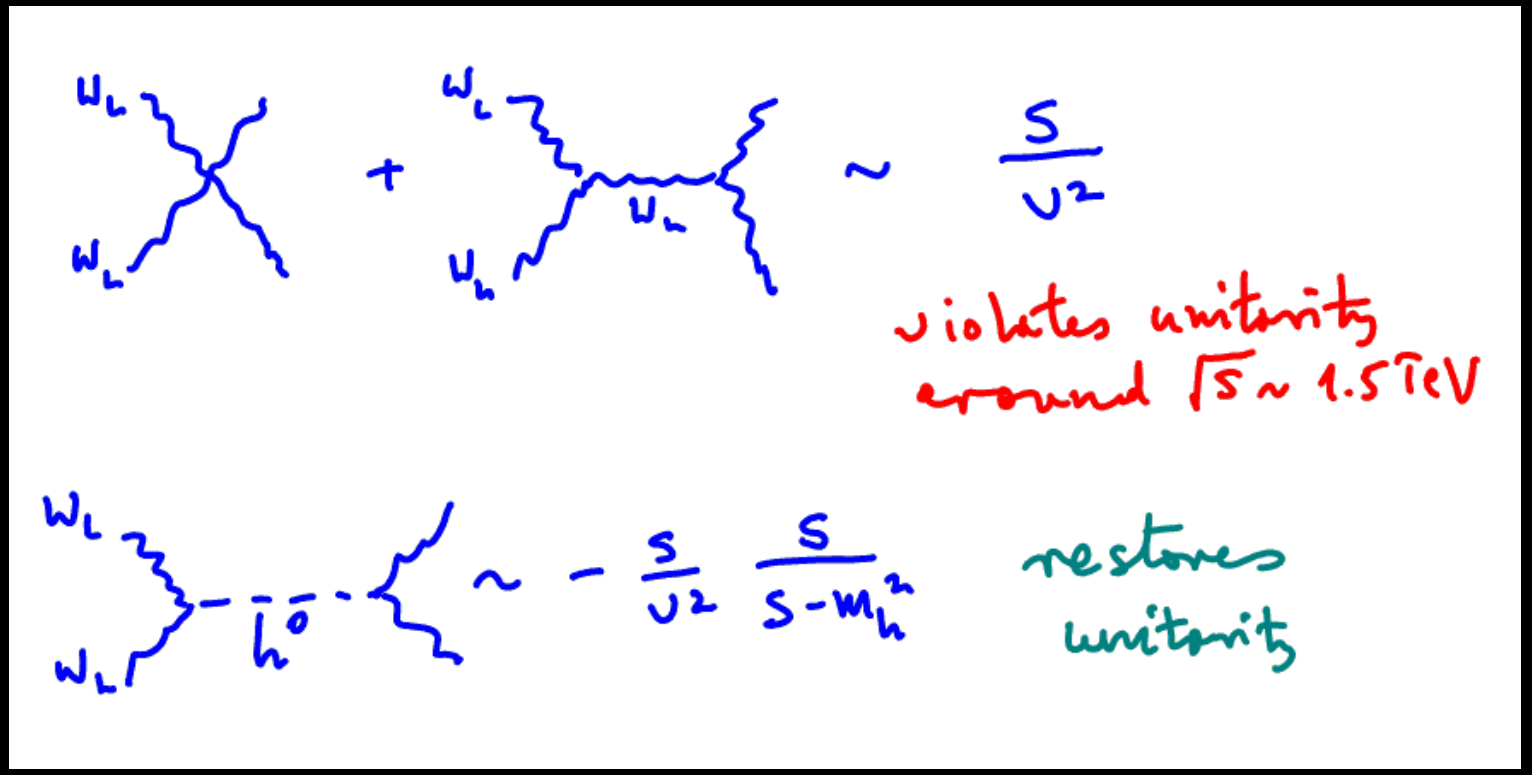
$$m_h^2 = 2\lambda v^2$$

3 Goldstone bosons +
physical elementary scalar

WAS IT TOTALLY UNEXPECTED?

NOT REALLY!

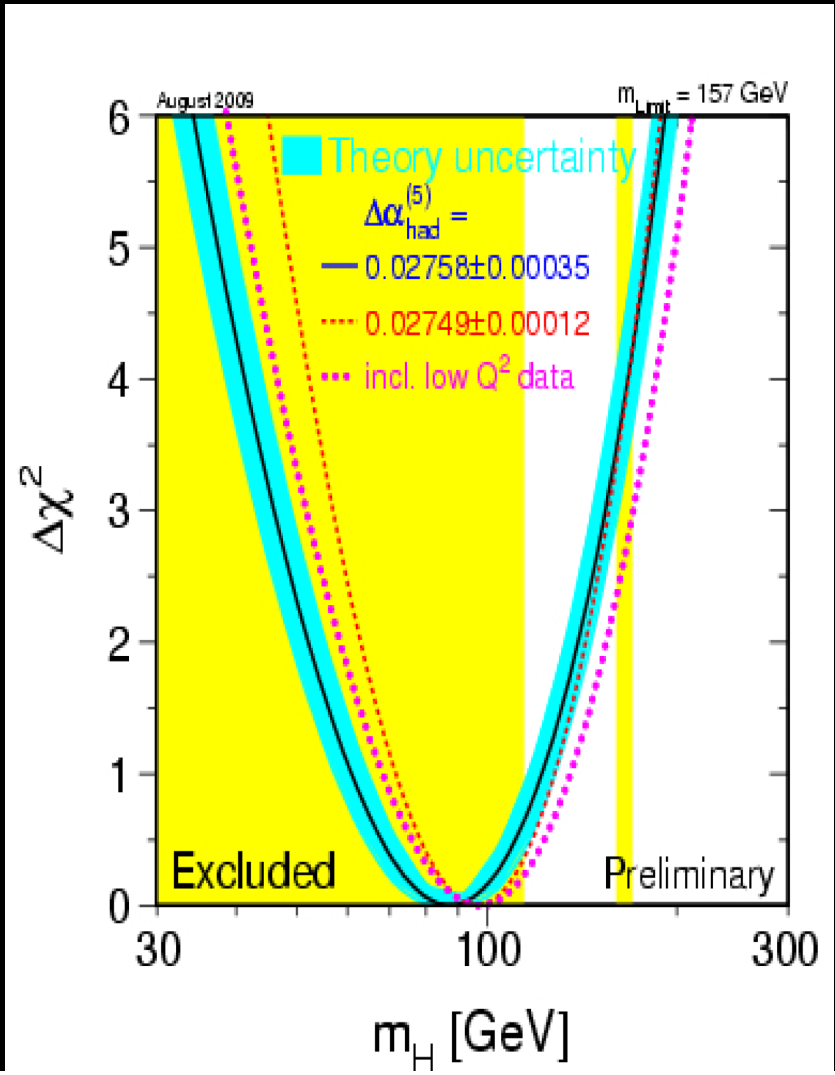
Perturbative unitarity of $W_L W_L (Z_L)$ scattering amplitude : (LEE, THACKER, QUIGG -1977



Tree level amplitudes do not rise with energy and do not violate unitarity at any energy

PRECISION LEP DATA

m_h



IS THE SM A CONSISTENT THEORY UP TO THE PLANCK SCALE ? YES!

RENORMALISABLE

NO LANDAU POLE UP TO Mp

(ALMOST) STABLE VACUUM UP TO Mp

THOSE CONCLUSIONS STRONGLY DEPEND ON

$$m_t = 173GeV, \qquad m_h = 125GeV$$

NEVERTHELESS , THE MAIN PUZZLE OF THE SM IS THAT THERE ARE NO (EXPERIMENTAL) PUZZLES

THE STANDARD MODEL IS INCOMPLETE

- RUNNING SM GAUGE COUPLINGS INTO FAR UV EVENTUALLY GIVES LANDAU POLE IN U(1). WOULD CAUSE FERMIONS TO CONDENSE IN UV.

SO UV COMPLETION OF SM IS UNAVOIDABLE.

- THE SUCCESS OF THE SM DEPENDS NOT ONLY ON THE TOP AND HIGGS MASS TAKEN FROM EXPERIMENT BUT ALSO ON MANY FLAVOUR PARAMETERS

- HIGGS NATURALNESS PROBLEM

MOREOVER (LAST BUT NOT LEAST)

NEUTRINO MASSES AND MIXING

DARK MATTER ?

BARYOGENESIS ?

UNIFICATION ?

CP PROBLEM?

NATURALNESS (HIERARCHY PROBLEM)

IT IS NOT THE PROBLEM OF QUADRATIC DIVERGENCES IN THE SM:

SM IS A RENORMALISABLE THEORY.

Thus if one ignores the hierarchy problem it is completely finite and predictive
If you do not care about fine tuning you are not punished!!

WHEN YOU CARE TO PREDICT M_W , YOU FACE THE QUESTION!

ANY SHORT DISTANCE PHYSICS THAT COUPLES TO THE HIGGS (RH NEUTRINO, GUT PARTICLES..) WOULD INTRODUCE QUADRATIC SENSITIVITY OF M_W TO THOSE SCALES

ALSO E.G. IN DIM. REG. IF YOU CARE ABOUT TUNING OF RENORMALISABLE MASS WITH NEW CONTRIBUTIONS

DON'T UNDERESTIMATE THE NATURALNESS PROBLEM

DIRAC'S QUESTION: WHY IS $M_P \ll M_{PL}$?

18 ORDERS OF MAGNITUDE!

ANSWER: QCD SCALE IS DYNAMICALLY GENERATED BY LOGARITHMIC EVOLUTION OF QCD COUPLING: "DIMENSIONAL TRANSMUTATION"

$$m_p \sim \Lambda_{QCD} = M_{Pl} e^{\frac{2\pi}{b_3} \frac{1}{\alpha_s(M_{Pl})}}$$

THE DIMENSIONLESS COUPLING IS O(1), TOTALLY NATURAL

The original idea of Nambu – a dynamical origin of the order parameter sigma: fermion- antifermion pair condensation („Cooper pairs")

$$< \Omega | \bar{\psi}^a_R \psi^b_L | \Omega > \neq 0$$

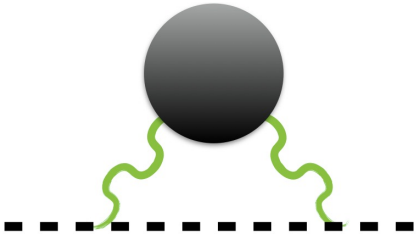
Beautiful mechanism in QCD: condensation scale (confinement scale) is linked to asymptotic freedom of QCD

$$v/Q = exp(-\pi/b\alpha(Q))$$

BUT NATURALNESS HAS OFTEN BEEN A VERY *SUCCESSFUL* STRATEGY.
WE HAVE OTHER SCALARS IN NATURE, THANKS TO QCD.

E.G. CHARGED PIONS

PIONS ARE GOLDSTONES, BUT ELECTROMAGNETISM EXPLICITLY BREAKS GLOBAL SYMMETRY.



ELECTROMAGNETIC CONTRIBUTION TO THE CHARGED PION MASS SENSITIVE TO THE CUTOFF OF THE PION EFT.

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi}\Lambda^2$$

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = (35.5\,\mathrm{MeV})^2 \Rightarrow \Lambda < 850\,\mathrm{MeV}$$

RHO MESON (NEW PHYSICS!) ENTERS AT 770 MEV: $\Delta \sim 1$

OTHER EXAMPLES OF NATURALNESS AT WORK

K-K MASS DIFFERENCE

$$\frac{M_{K_L^0} - M_{K_S^0}}{M_{K_L^0}} = \frac{G_F^2 f_K^2}{6\pi^2}\sin^2\theta_c \Lambda^2$$

INFLATION: SOLVES HORIZON PROBLEM, FLATNESS PROBLEM

A *GUIDEPOST* TO WHERE NEW PHYSICS SHOULD ENTER; IN THE SM WITH A UNIFORM CUTOFF Λ, SM LOOPS UP TO Λ GIVE

$$\delta m_H^2(\mu) = \frac{\Lambda^2}{16\pi^2}\left[6\lambda(\mu) + \frac{9}{4}g_2^2(\mu) + \frac{3}{4}g_Y^2(\mu) - 6\lambda_t^2(\mu)\right]$$

EXPECT NEW PHYSICS TO ENTER AND ALTER SM AT SOME SCALE*

$\Delta \lesssim 1$ (NO TUNING) REQUIRES $\Lambda \lesssim 500$ GEV;

$\Delta \lesssim 10$ (10%-LEVEL TUNING) REQUIRES $\Lambda \lesssim 1.6$ TEV;

$\Delta \lesssim 100$ (1%-LEVEL TUNING) REQUIRES $\Lambda \lesssim 5$ TEV.

*BEST-CASE SCENARIO, NO LARGE LOGS

EFFECTS OF THE SM LOOPS

5 TeV SUSY?

EFFECTS OF NEW HIGGS COUPLINGS, TO BE ALSO CONTROLLED

In particular, the Type-I seesaw entails right-handed neutrinos N with c

$$\mathcal{L} \supset -\frac{M_R^{ij}}{2} N_i N_j - y_{ij} L^i N^j H + \text{h.c.}$$

This provides a very concrete example of new fermions coupling to
The leading one-loop correction to the Higgs mass is

$$\delta m_H^2 = -\frac{1}{4\pi^2} \sum_{ij} |y_{ij}|^2 M_j^2$$

THE HIERARCHY PROBLEM IS SOLVED BY NEW SYMMETRIES ENTERING

NEAR THE WEAK SCALE THAT MAKE THE SCALAR SECTOR INSENSITIVE

TO UV PHYSICS

NEW SYMMETRIES ALSO NEEDED FOR SOLVING THE FLAVOUR PROBLEM.

CAN THE TWO PROBLEMS HAVE ONE SOLUTION?

FLAVOUR HIERARCHIES (INCLUDING NEUTRINO MASSES AND MIXINGS)

PHENOMENOLOGY OF FLAVOUR PHYSICS(FCNC) IN THE SM BASED ON **pattern of quark masses and mixing taken from experiment**

IN THE LIMIT OF MASSLESS NEUTRINOS AND U(2) GLOBAL SYMMETRY FOR THE FIRST TWO GENERATIONS :

1. NO FCNC PROCESSES
2. LEPTON NUMBER CONSERVATION
3. LEPTON FLAVOUR CONSERVATION

BOTH ARE WEAKLY ENOUGH VIOLATED!

SM AS AN EFFECTIVE THEORY (SMEFT)

L_{SM} + $SU(2)$ x U(1) invariant higher dim operators

e.g. dim 6 four fermion operators contributing to

$M - \bar{M}$ Mixing, FCNC decays

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_{ijkl}}{\Lambda^2}(\bar{Q}_i Q_j \bar{Q}_k Q_l) + \dots.$$

$l_j \to l_i \gamma$

$$\mathcal{L}_{eff} = \frac{C_{ij}}{\Lambda^2}(\bar{L}_j \sigma^{\mu\nu} E_i) H B^{\mu\nu}$$

FLAVOUR PRECISION DATA -→

FLAVOUR BLIND SMEFT WOULD REQUIRE

$$\Lambda \propto \mathcal{O}(10^4) TeV$$

TASKS FOR BSM: EXPLAIN THE PHENOMENOLOGICAL APPROXIMATE SYMMETRIES OF FERMION MASSES AND MIXING,

CONTROL BSM PHYSICS
(IN PARTICULAR, CONTROL SMEFT)

SYMMETRIES FOR THE NATURALNESS PROBLEM

SUSY | **HIGGS AS A PSEUDO-GOLDSTONE**

BOTH ARE INTERESTING, BOTH HAVE THEIR STRONG POINTS,
NO EXP TRACE OF ANY..

STRONG POINTS

UNIFICATION, THEORETICAL ATTRACTIVENESS (SUPERGRAVITY, STRING THEORY..) DARK MATTER?

PION DOES EXISTS,
LINK TO NEW STRONG INTERACTIONS,
MORE FLEXIBILITY FOR FLAVOUR

WEAKNESS

FLAVOUR

TOO MANY MODELS

Strongly coupled theories with a scalar doublet as a Golstone boson

A TOY MODEL, TO SEE QUALITATIVE (GENERIC?) PREDICTIONS:

GLOBAL $SO(5) \rightarrow SO(4) = SU_L(2) \times SU_R(2)$
(SPONTANEOUSLY BROKEN)
and doublet H remains as a Goldstone boson;

THE POTENTIAL FOR H obtained from explicit breaking of SO(5) by top quark Yukawa (and SM gauge couplings) (COLEMAN-WEINBERG)

SYMMETRIES FOR FLAVOUR

SU(2)xU(1)x G_F

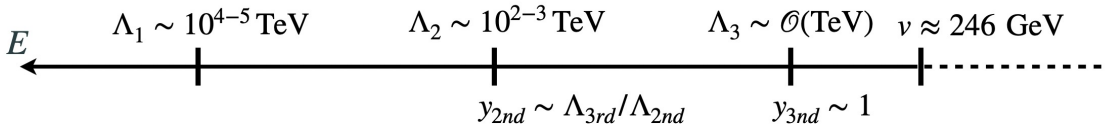
E.G. FROGGATT-NIELSEN $U(1)_F$

CONTINOUS INTEREST IN EXPERIMENTAL SIGNATURES OF HORIZONTAL SYMMETRIES CAPABLE TO ”EXPLAIN” THE PATTERN OF FERMION MASSES AND MIXING

TO CONTROL FCNC, THE SCALE OF UV COMPLETIONS > $\mathcal{O}(100TeV)$

MULITI-SCALE APPROACH TO FERMION MASSES (INVERSE HIERACHY)

- Multiscale picture for flavor:



A DYNAMICAL EXPLANATION OF FLAVOUR HIERARCHIES AS A CONSEQUENCE OF THE EXISTENCE OF SEVERAL NEW SCALES.

THE APPROXIMATE U(2) GLOBAL SYMMETRY WOULD EMERGE **AT TeV** SCALE AS AN ACCIDENTAL SYMMETRY OF A BSM STRUCTURE, WITH THE SM EMBEDDED IN IT.

INVERSE HIERARCHY MODELS: HIGH NEW SCALES RESPONSIBLE FOR LIGHT FERMION MASSES, LOW SCALE PHYSICS RESPONSIBLE FOR THE THIRD GENERATION MASSES.

Z. G. Berezhiani, The Weak Mixing Angles in Gauge Models with Horizontal Symmetry: A New Approach to Quark and Lepton Masses, Phys. Lett. B 129 (1983) 99–102.

Z. G. Berezhiani and R. Rattazzi, Inverse hierarchy approach to fermion masses, Nucl.Phys. B 407 (1993) 249–270, [hep-ph/9212245].

MULTI-SCALE MODELS OFFER A LINK TO THE HIRARCHY PROBLEM (NON-SUPERSYMMETRIC APPROACH?)

NEW VECTOR BOSONS

Generic characteristics of the scalar sector in extensions of the SM with elementary (supersymmetry) or composite scalars:
more scalars, the Higgs couplings are not exactly SM like

OPTIMISTIC VIEW FOR 2050:

HIGGS FACTORY

- SEES DEVIATIONS IN THE HIGGS PROPERTIES FROM THE SM PATTERN
- EXPLORES BSM BELOW THE HIGGS MASS EVEN IF NO COUPLING TO Z (STERILE NEUTRINO, DARK MATTER)

CHARGED LEPTON FLAVOUR WILL BE FINALLY VIOLATED IN MUON CONVERSION INTO ELECTRON IN NUCLEI AND IN MUON DECAY

HEAVY VECTOR BOSONS AND/OR HIGGSINO/WINO WILL BE DISCOVERED IN pp COLLIDERS

HYPER-KAMIOKANDE DISCOVERS PROTON DECAY

SUMMARY

I HOPE YOU ENJOYED MY TALK

BACK UP

ANOTHER POSSIBILITY: AN UNDERLYING DYNAMICAL EXPLANATION OF FLAVOUR HIERARCHIES, AS A CONSEQUENCE OF THE EXISTENCE OF SEVERAL NEW SCALES.
THE APPROXIMATE U(2) GLOBAL SYMMETRY WOULD EMERGE **AT TeV** SCALE AS AN ACCIDENTAL SYMMETRY OF A BSM STRUCTURE, WITH THE SM EMBEDDED IN IT.

INVERTED HIERARCHY MODELS: HIGH NEW SCALES RESPONSIBLE FOR LIGHT FERMION MASSES, LOW SCALE PHYSICS RESPONSIBLE FOR THE THIRD GENERATION MASSES.

PIONEERED BY

A NEW APPROACH TO QUARK AND LEPTON MASSES, Z.G. BEREZHIANI, Phys.Letters. B 129 (1983) 99.
INVERSE HIERARCHY APPROACH TO FERMION MASSES, Z.G. BEREZHIANI, R. RATTAZZI, NUCL.PHYS.B 407(1993) 249
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MOST RECENT IMPLEMENTATION: A REVIVAL OF MODELS BASED ON THE (OLD) IDEA OF DECONSTRUCTION.

COMMON FUTURE OF THOSE FLAVOUR MODELS: NEW MASSIVE VECTOR BOSONS WTH INTERESTING PHENOMENOLOGY

START WITH A 3-SITE MODEL $SU(2)_1 \times SU(2)_2 \times SU(2)_3$

ONE LEFT-HANDED SU(2), FOR EACH FAMILY SEPARATELY

$\Lambda_1 \propto 10^{3-4} TeV$ ⇓ BY THE VEV OF Φ_1

$SU(2)_{12} \times SU(2)_3$

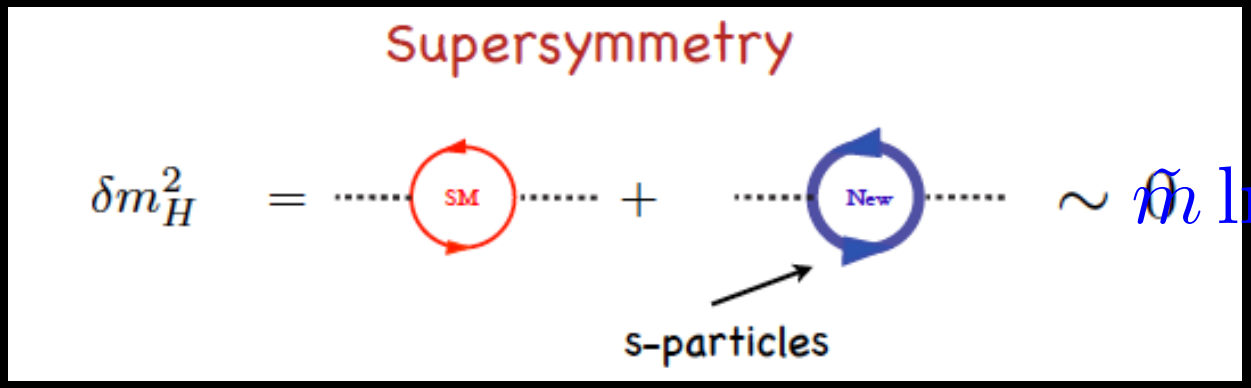
$\Lambda_2 \propto \mathcal{O}(10) TeV$ ⇓ BY THE VEV OF Φ_2

$SU(2)_{SM}$

ONE GETS APPROXIMATE U(2) GLOBAL SYMMETRY FOR THE FIRST TWO FAMILIES (APPROXIMATELY UNIVERSAL SU(2) GAUGE INTERACTIONS) IF, IN ADDITION THE HIGGS CARRIES ONLY $SU(2)_3$ CHARGES

HEAVY VECTOR BOSONS FROM THE FIRST $M_{W''} = \mathcal{O}(\Lambda_1)$

AND SECOND BREAKING $M_{W'} = \mathcal{O}(\Lambda_2)$



UNIQUE FEATURE:
ALSO CANCELLATION OF QUADRATIC SENSITIVITY TO MUCH HIGHER SCALES

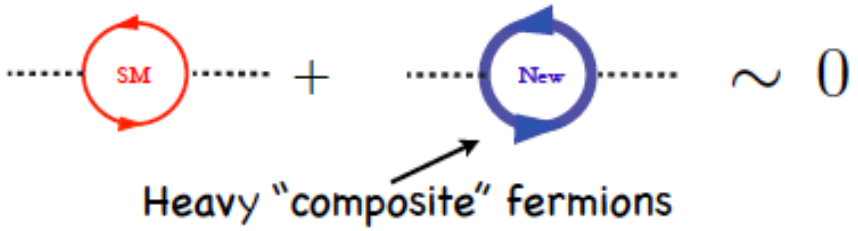
M

$M + \tilde{m}$

$\tilde{m} \ln \Lambda$

The Higgs boson as a pseudoGolsdtone

(like the π in QCD)

δm_H^2 = 

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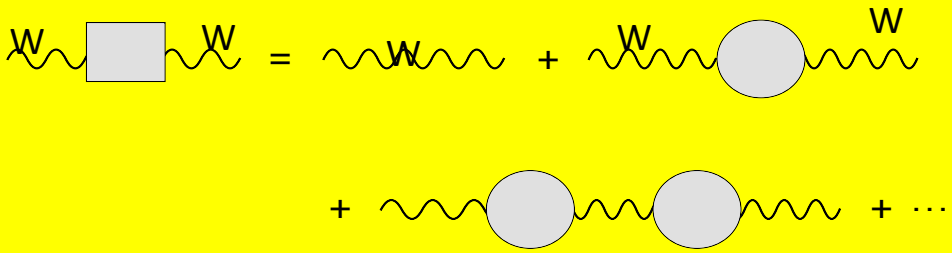
Heavy "composite" fermions

$gW^\mu J_\mu$ AND WAVE FUNCTION RENORMALIZATION OF THE GAUGE BOSON



$$G_{\mu\nu}(q) = \frac{-i}{q^2 - g^2\Pi(q^2)/2}\,(P_T)_{\mu\nu}\,, \qquad (P_T)_{\mu\nu} \equiv \eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\,,$$

where

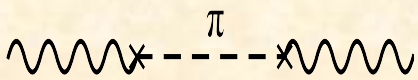
$$i\Pi_{\mu\nu}(q) = -\int d^4x\; e^{-iq\cdot x}\langle 0|T\left(J^+_\mu(x)J^-_\nu(0)\right)|0\rangle$$

$$\Pi_{\mu\nu}(q) = \left(\eta_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)\Pi(q^2)\,.$$

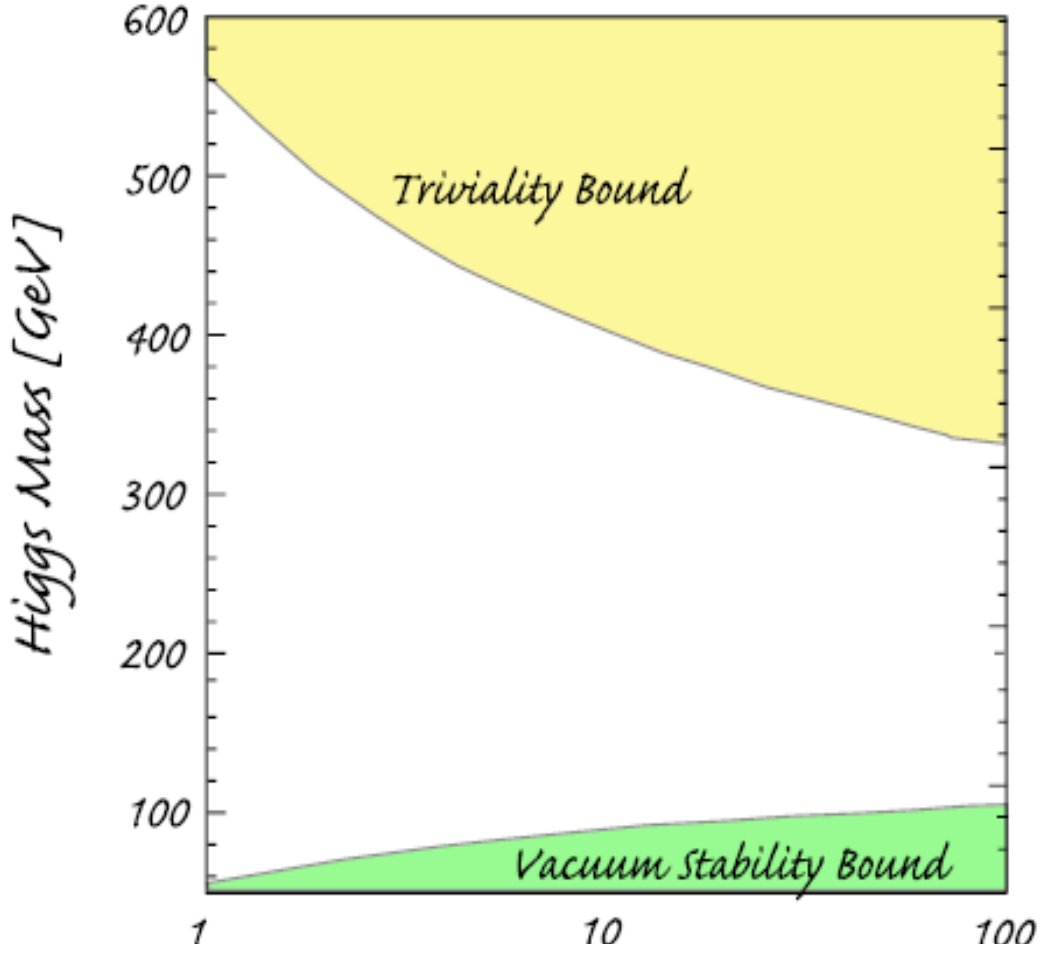
GOLDSTONE BOSON OF SB GLOBAL SYMMETRY OF SOME INTERACTIONS

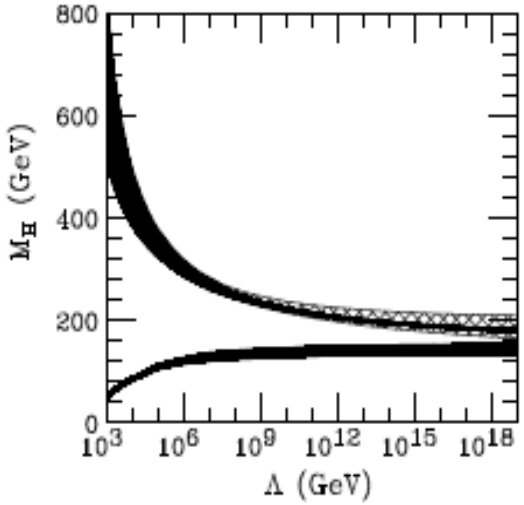
Then, a mass for the W arises if $\Pi_{\mu\nu}(q^2)$ has a pole at $q^2 = 0$. The pole in fact exists as a result of the symmetry breaking, due to the exchange of the "pion:"

$$\langle 0|J_\mu^+|\pi^-(p)\rangle = i\frac{f_\pi}{\sqrt{2}}p_\mu \tag{21}$$



$$\Longrightarrow \qquad \Pi(q^2) = \frac{f_\pi^2}{2}.$$



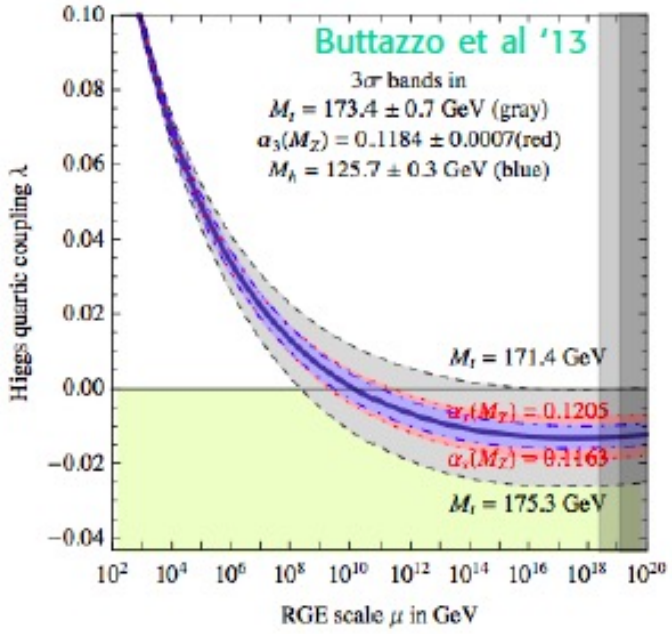


Hambye & Riesselman '97

VACUUM STABILITY IN SM

$$V = \frac{\lambda(\mu)}{4} h^4$$

$$\lambda_0 = \frac{m_h^2}{4v^2}$$



IN THE ABSENCE OF NEW PHYSICS, FOR $m_h = 125 GeV$ THE UNIVERSE BECOMES

METASTABLE AT $\Lambda \approx 10^{10-12} GeV$

BUT WITH SUFFICIENTLY LONG LIFE TIME! SM COULD BE A CONSISTENT THEORY UP TO THE PLANCK SCALE

INTERESTING QUESTIONS:

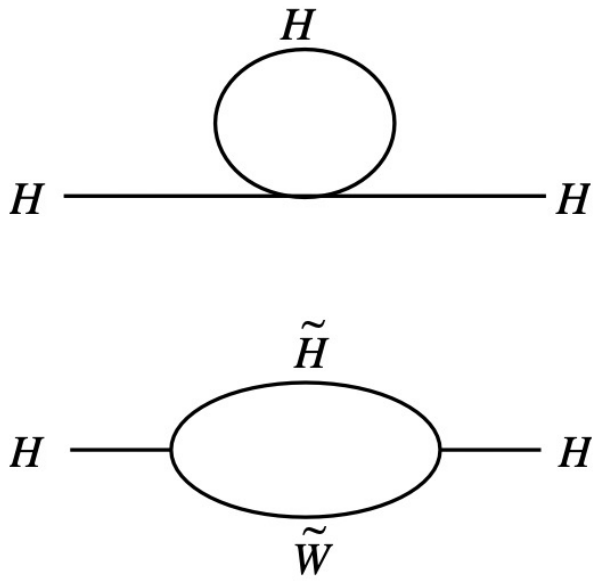
WHAT TO DECONSTRUCT? WHICH PART OF THE SM?

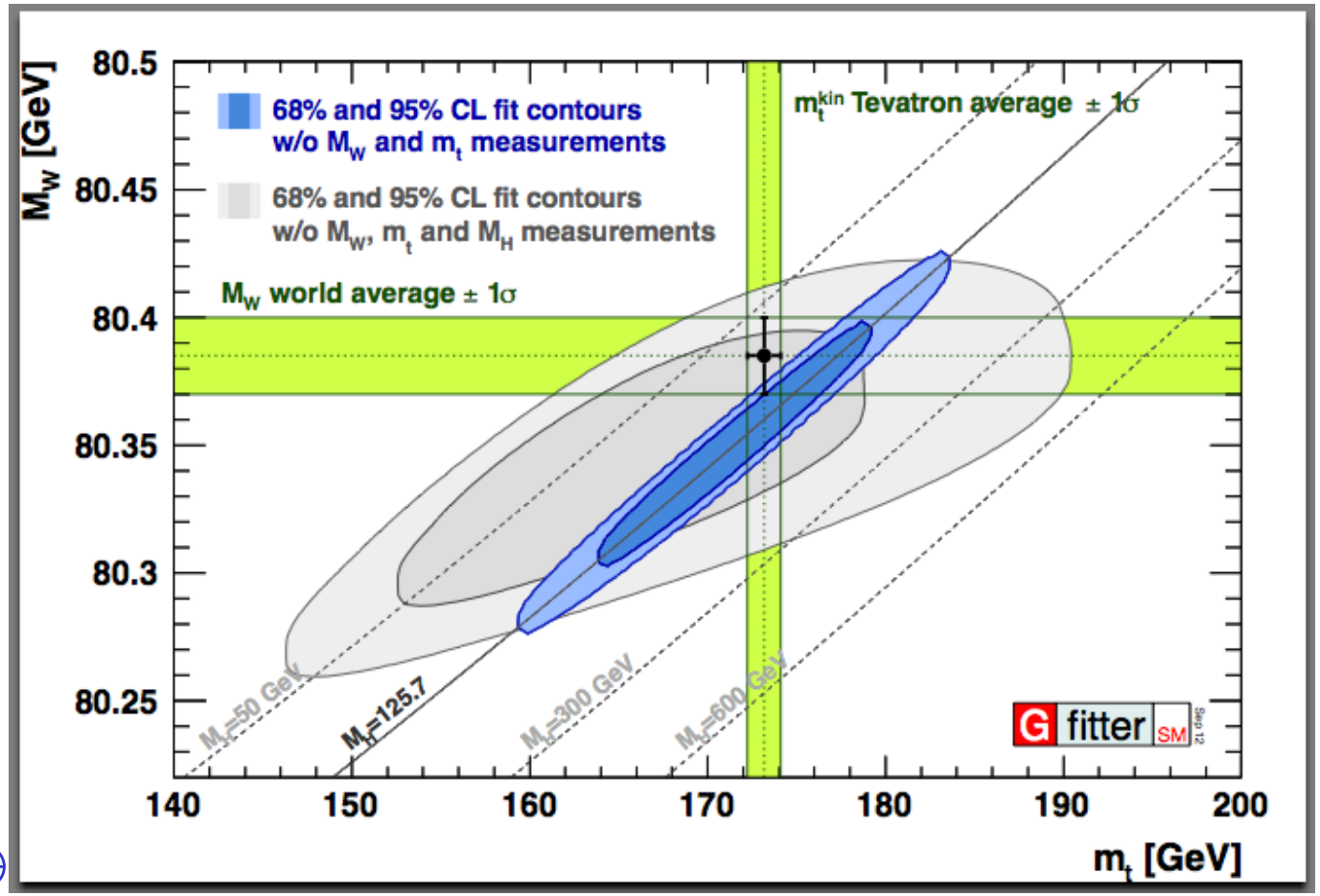
UV COMPLETIONS (MULTI-HIGGS, VECTOR LIKE FERMIONS) FOR BREAKING (SLIGHTLY) U(2)'s

LOCALISATION OF LEPTONS, CHIRAL ANOMALY CANCELATION (NEW FERMIONS –CHIRAL WITH RESPECT TO THE ORIGINAL GAUGE GROUPS BUT VECTOR LIKE IN THE SM (PMNS PATTERN)

UV COMPLETIONS FOR GETTING THE VEV's OF BI-DOUBLET SCALARS FROM RENORMALISABLE THEORIES (ELEMENTARY OR COMPOSITE (JAVIER LIZANA))

LINK TO THE HIERARCHY PROBLEM (THE HIGGS AS A PSEUDO-GOLDSTONE)-LITTLE HIGGS MODELS OR TECHNICOLOUR LIKE MODELS.


H
H
H
$\tilde{H}$
H
H
$\tilde{W}$


80.5
80.45
80.4
80.35
80.3
80.25
M_W [GeV]
140
150
160
170
180
190
200
m_t [GeV]
68% and 95% CL fit contours
w/o M_W and m_t measurements
68% and 95% CL fit contours
w/o M_W, m_t and M_H measurements
M_W world average ± 1σ
m_t^{kin} Tevatron average ± 1σ
M_H=50 GeV
M_H=125.7
M_H=300 GeV
M_H=600 GeV
G fitter SM
Sep 12

2013

On top of this, one should include a bare term, so that the expectation for the
mass in the Standard Model EFT is

$$m_H^2 = c\Lambda^2 + \delta m_H^2$$

PION IS A GOLDSTONE BOSON OF SPONTANEOUSLY BROKEN CHIRAL SU(2)_L SYMMETRY OF THE FIRST GENERATION (u,d) QUARKS.

EVIDENCE: $\pi \to l\nu$ DECAY

LAGRANGIAN $$L = J_\mu(l) J^\mu(h)$$

$$< l\nu|JJ|\pi >=< l\nu|J|0 >< 0|J|\pi >$$

NON-SUPERSYMMETRIC APPROACH:

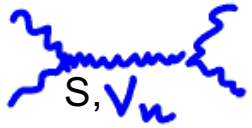
HIGGS DOUBLET AS A (PSEUDO) GOLDSTONE BOSON

KAPLAN, GEORGI (1984)
ARKANI-HAMED, COHEN, GEORGI (2001)
CONTINO, NOMURA, POMAROL (2003)
AGASHE, CONTINO, POMAROL (2005)

USUALLY LINKED TO A NEW STRONGLY INTERACTING SECTOR;

BUT THERE IS ROOM FOR IT IN PERTURBATIVE EXTENSIONS OF SM , IN PARTICULAR IN SUPERSYMMETRIC MODELS AS WELL (THIS TALK)

Partial unitarization of the WW scattering by the lightest scalar

$$A_{WW} \sim \frac{s}{v^2} - (1 - \frac{v^2}{f^2})\frac{s}{v^2}\frac{t}{t-m_h^2} + \sum_n$$ 

$$\approx \frac{s}{f^2} + \sum_n$$

The essence of Brout-Englert-Higgs mechanism:

Gauge bosons are coupled to currents of a spontaneously broken global symmetry of some interactions

Goldstone bosons become longitudinal degrees of freedom of gauge bosons

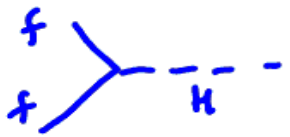
For the weak gauge boson,
one needs a new dynamical sector with at least SU(2)xU(1)→SU(2) spontaneously broken global symmetry

2) Partial unitarization of the WW scattering by the light Higgs boson

$$A_{WW} \sim \frac{s}{v^2} - (1-\frac{v^2}{f^2})\frac{s}{v^2}\frac{t}{t-m_h^2} +$$

$$\approx \frac{s}{f^2} +$$

3) Higgs boson couplings to fermions



$$Y(1-\frac{v^2}{f^2})^{\frac{1}{2}}$$