The Standard Model and Beyond up to 10 TeV

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the theoretical principles behind modern particle physics:

described by local, relativistic, quantum field theory

physics usually changes with scale; thus, at every scale, we have a description in terms of an appropriate

Effective Field Theory (EFT)

naturalness has been, and still is, a major driving force in exploring possible extensions of the Standard Model since the '70s
(until challenged by some, lately...)

EFT and symmetries:

at every scale, organize Lagrangian of QFT with relevant degrees of freedom in terms of

- operator dimensions
- symmetries of operators

thus, for a generic field theory:

$$\mathcal{L} = \mu_0^4 \mathcal{O}_{(0)} + \mu_2^2 \mathcal{O}_{(2)} + c_4 \mathcal{O}_{(4)} + \frac{1}{\mu_5} \mathcal{O}_{(5)} + \frac{1}{\mu_6^2} \mathcal{O}_{(6)} + \quad \ldots$$

$$\mathcal{O}_{(d)} \equiv \text{dim-}d \text{ operator} \quad [h] = 1, \ [\psi] = \frac{3}{2}, [A_\mu] = 1 \ldots$$

operators containing only fields - i.e. degrees of freedom - and
only respecting symmetries that are relevant at the given energy scale

at every scale, organize Lagrangian of QFT with relevant degrees of freedom in terms of

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cosmological constant

$$\mathcal{O}_{(0)} \equiv \mathbb{1}$$

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cosmological constant

``Standard Model (SM) renormalizable lagrangian''

$$\mathcal{O}_{(0)} \equiv \mathbb{1} \qquad \mathcal{O}_{(2)} = H^{+} \cdot H$$

$$\mathcal{O}_{(4)} = F_{\mu\nu} F^{\mu\nu} ; \; \bar{\Psi} \not{D} \Psi ; \ldots$$

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cosmological constant

``Standard Model (SM) renormalizable lagrangian"

no current evidence that such terms have nonzero coeffts

$$\mathcal{O}_{(0)} \equiv \mathbb{1} \qquad \mathcal{O}_{(2)} = H^{+} \cdot H \qquad \mathcal{O}_{(5)} \supset \nu_L^T C h_0^2 \nu_L$$

$$\mathcal{O}_{(4)} = F_{\mu\nu}F^{\mu\nu};\ \bar{\Psi} \not{D} \Psi; \ldots \qquad \ldots$$

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cosmological constant

``Standard Model (SM) renormalizable lagrangian"

no current evidence that such terms have nonzero coeffts

$$\mathcal{O}_{(2)} = H^{+} \cdot H$$

c_4 - dimensionless couplings: $g_1 g_2 g_3$ Yukawa/CKM

$$\mathcal{O}_{(4)} = F_{\mu\nu} F^{\mu\nu};\ \bar{\Psi} \not{D} \Psi;\ \ldots$$

$$\mathcal{O}_{(5)} \supset \nu_L^T C h_0^2 \nu_L$$

$$\ldots$$

But where do scales come from?

Two distinct sources in SM.

But where do scales come from? Two distinct sources in SM.

a.) hadronic scale -

proton mass ~ 1 GeV ~ $\Lambda_{QCD} = \Lambda_{UV}\, e^{-\frac{8\pi^2}{b_0\, g_3^2(\Lambda_{UV})}}$

$$\left(b_0 = \frac{11}{3} N_c - \frac{2}{3} N_f \quad > 0 \right)$$

often referred to as

``dimensional transmutation"

$\Lambda_{UV} \to \infty$

$g_3(\Lambda_{UV}) \to 0$

Λ_{QCD} - fix

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mechanism of generating large scale hierarchies is generic in asymptotically free theories (not just QCD):

small, but O(1), coupling + high scale = very (!) low scale

proton mass ~ 1 GeV while **few TeV <** Λ_{UV} **< 10^{19} GeV**

- understood in terms of strong infrared dynamics
- "naturalness" $\neq$ insensitivity to g_3, rather, there are no unexplained cancellations between contributions to proton mass coming from different scales

But where do scales come from? Two distinct sources in SM.

b.) electroweak scale - $\mu_2^2\, \mathcal{O}_{(2)}$ $\mathcal{O}_{(2)} = H^\dagger \cdot H$

- in SM, put in by hand!

why is the Higgs field so light?

(why is this an issue? light compared to what?) compared to

$$\textbf{few TeV} < \Lambda_{UV} < \mathbf{10^{19}\,GeV}$$

some theory describing physics at high energy scales Λ_{UV} should exist - at least to include gravity in a more complete picture of the four "forces"

``hierarchy problem" -

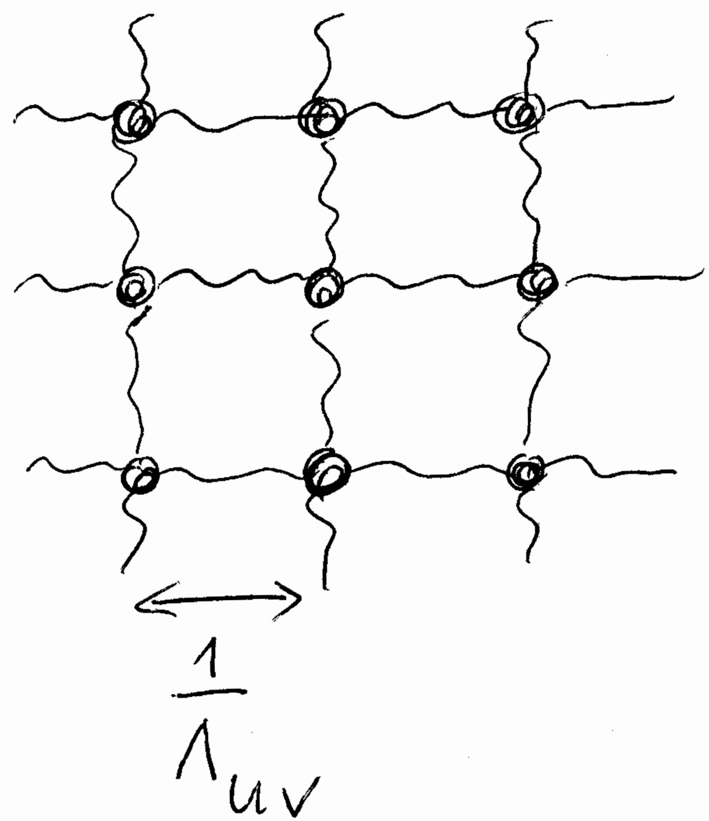
how does the dynamics at this high scale give rise to long-distance (much-longer distance!) **physics?**

But where do scales come from? Two distinct sources in SM.

- e.g., in condensed matter: Λ_{UV} ~ inverse lattice spacing (Debye frequency),

long-distance modes - ``light particles" - exist **always** for a reason...

be it
dynamics and symmetry



like phonons -

- long-distance collective modes:

massless Goldstone bosons of spontaneously broken translation symmetry

Manton; Hosotani; Georgi, Kaplan, ...'79-: **- could the Higgs be "like" them?**

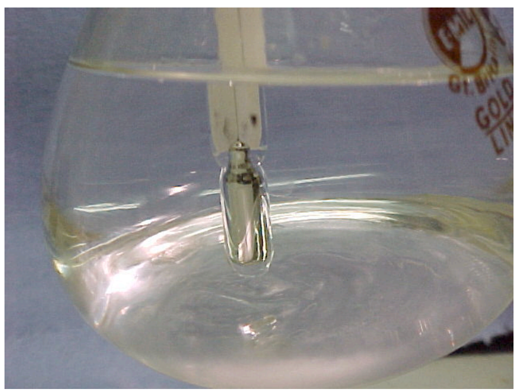
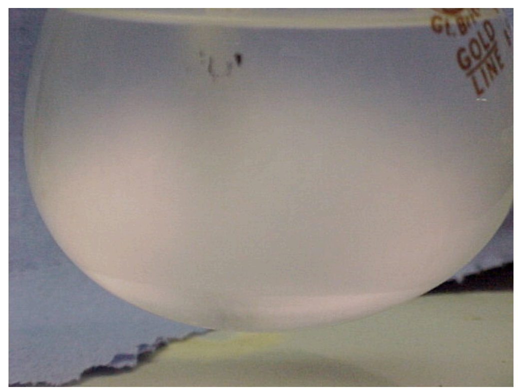
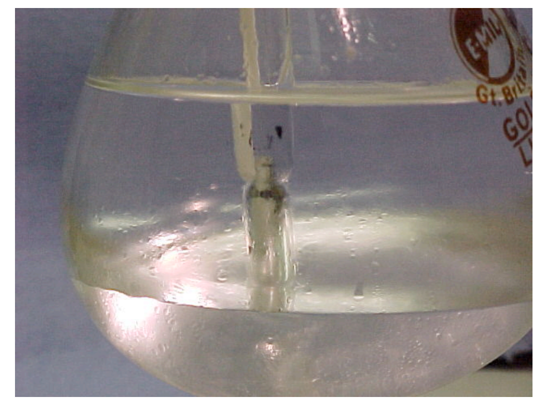
But where do scales come from?

Two distinct sources in SM.

- e.g., in condensed matter: Λ_{UV} ~ typical scale in system ~ distance between molecules

long-distance modes - ``light particles" - exist **always** for a reason...

or **fine tuning,** like long-range (e.g. density) fluctuations
- on large length scales wrt inverse UV cutoff -
which arise when temperature is tuned near critical:

T>Tc
no higgs ("heavy," that is)

T ~ Tc
light higgs

T<Tc
no higgs ("heavy")

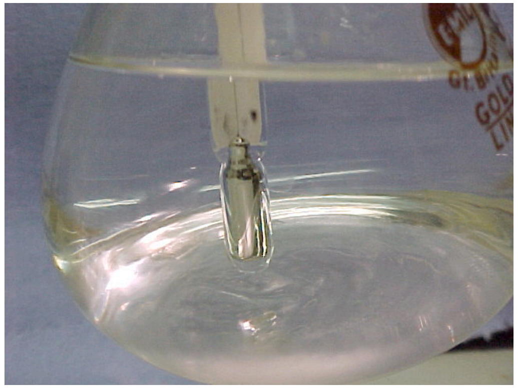
hexane and methanol are mixed, heated above roughly 42 celsius and allowed to cool, $T_c \sim$ 37C

(T- Tc)/Tc - small = long-range fluctuations = light Higgs

But where do scales come from? Two distinct sources in SM.

(T- Tc)/Tc - small = light Higgs

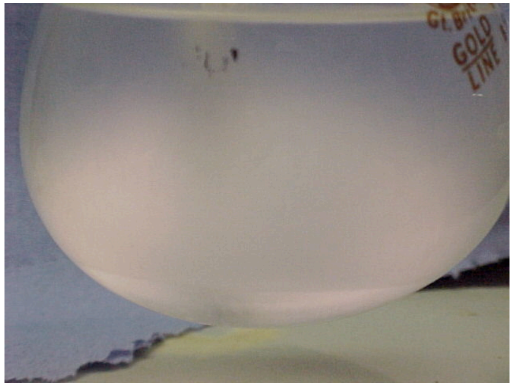
but who tuned T?



T>Tc

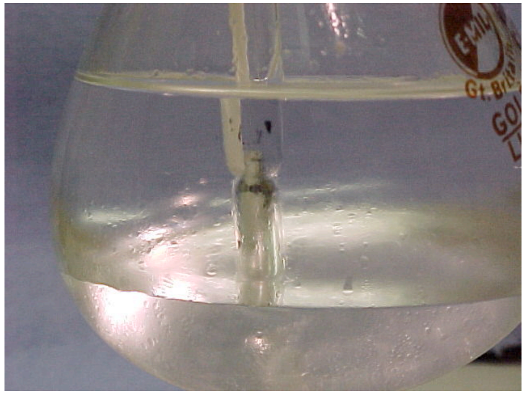
no higgs

(heavy)



T ~ Tc

light higgs



T<Tc

no higgs

But where do scales come from? Two distinct sources in SM.

our current thinking about the origin of the weak scale...

... apart from

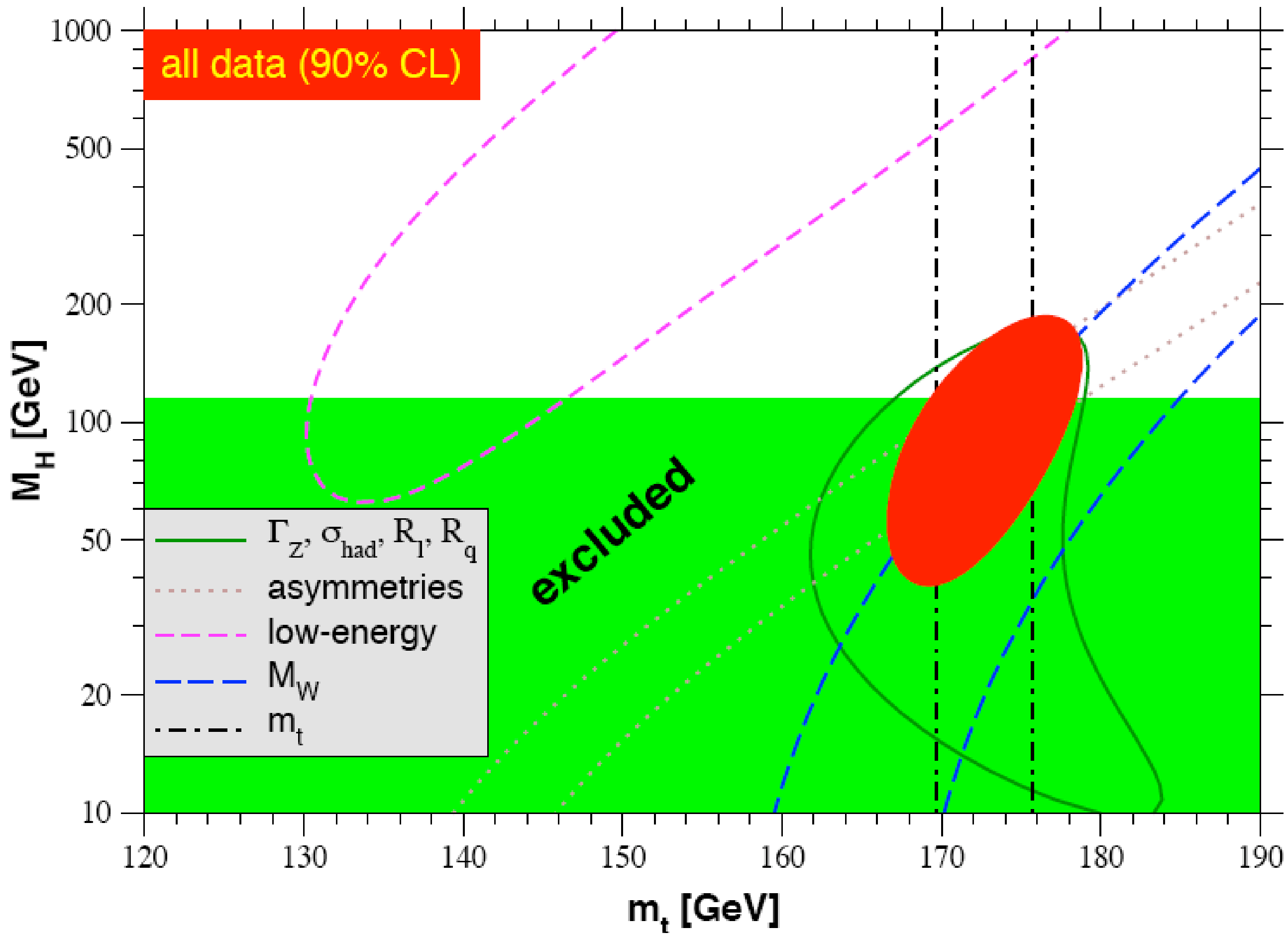
...is that it arises through a mechanism similar to that of the hadronic scale
i.e. "dimensional transmutation" in some gauge theory... except we don't quite know the details...

- in many cases, this mechanism will not directly manifest itself at the LHC, for example in most **supersymmetric**, **little Higgs**, **twin Higgs**, **Randall-Sundrum**, **etc.**, models
(as the corresponding " Λ_{QCD} " scale is too high)

- only in models with strong dynamics at LHC energies will it be directly seen

...or will it?

What do current data have to say about the origin of the electroweak scale?



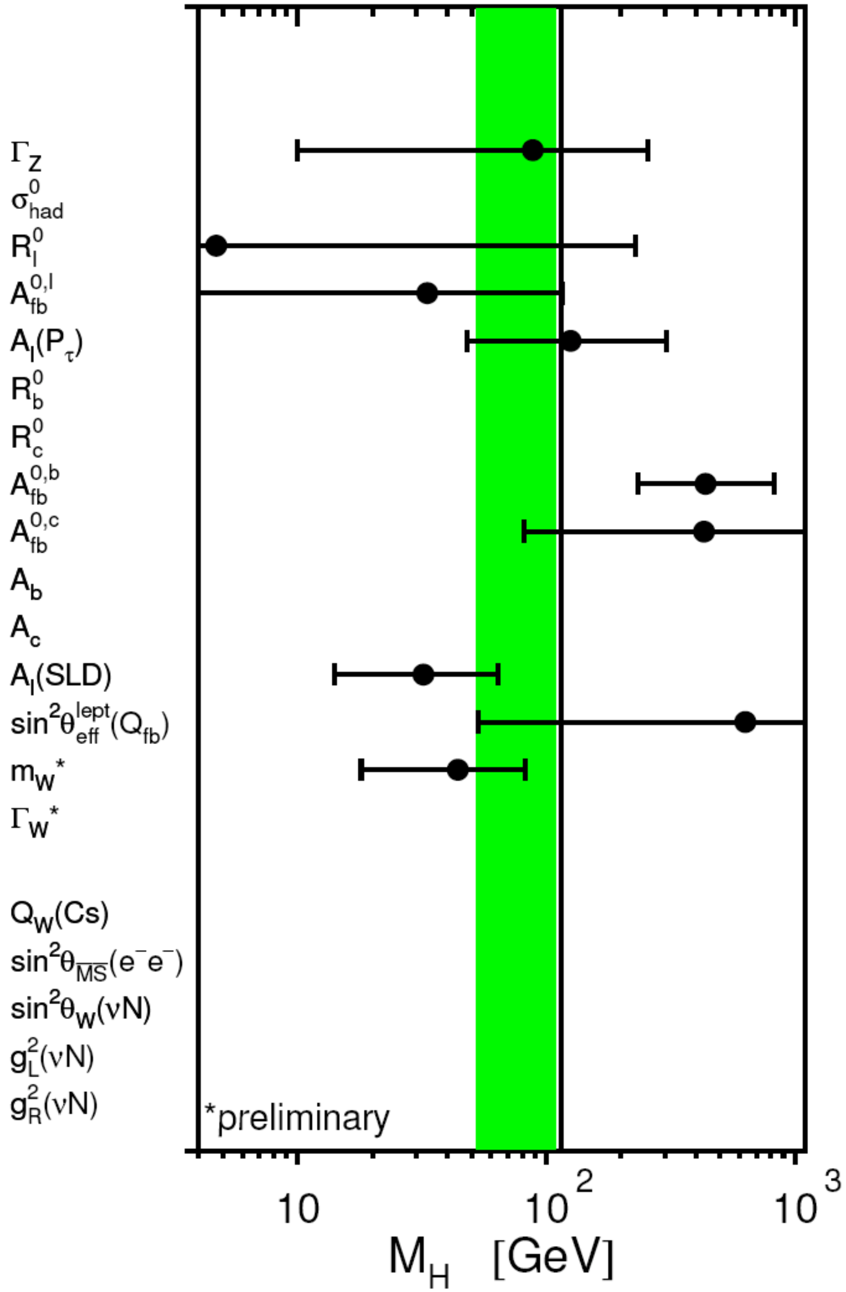
PDG, updated 9/2005

assuming Standard Model - best fit value for m_H is slightly less than LEPII bound

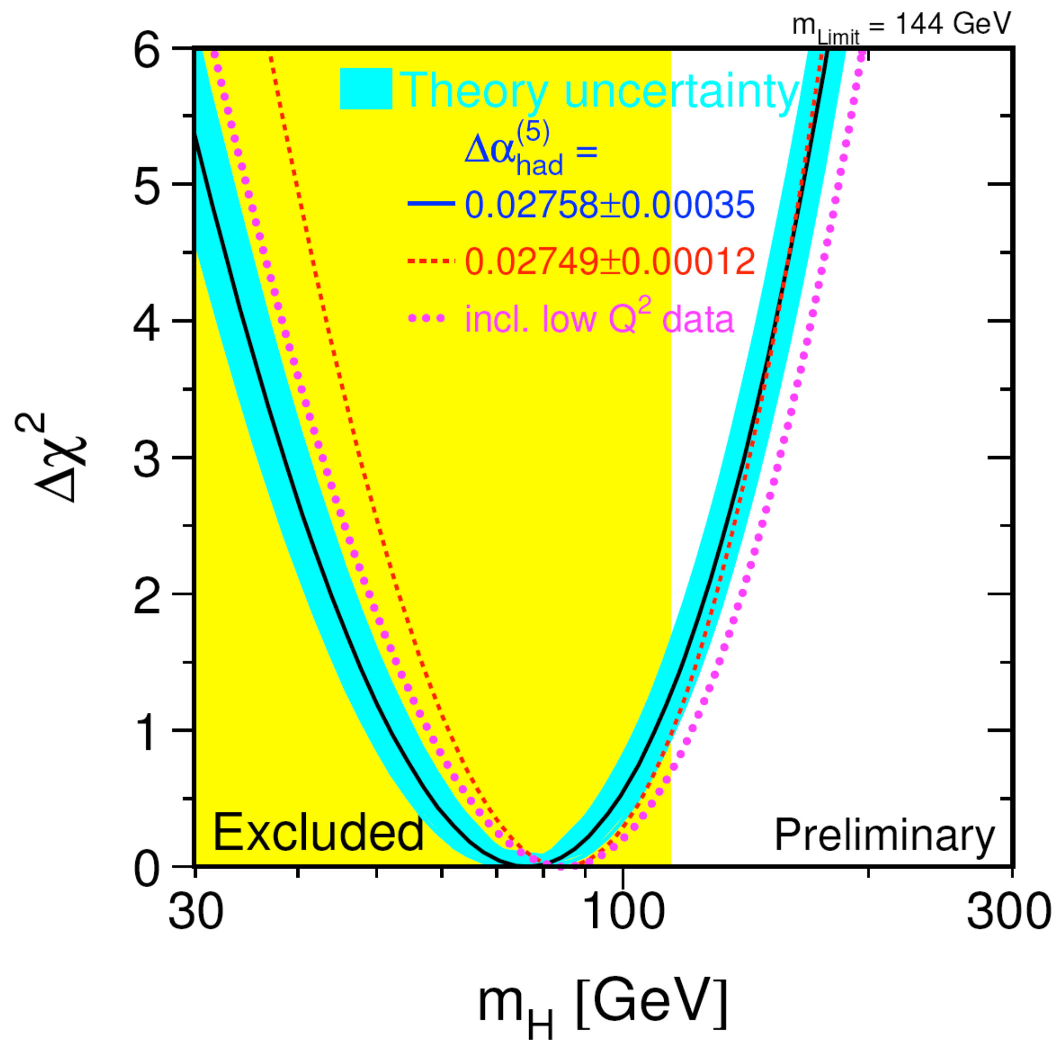
...made somewhat worse with the lighter top...

What do current data have to say about the origin of the electroweak scale?

also seen in latest plots: LEPEWWG/plots/winter2007



still some tension between hadron and lepton asymmetries...?



What do current data have to say about the origin of the electroweak scale?

should we conclude, then, that a light Higgs certainly exists?

- certainly, this is a possible interpretation of the data

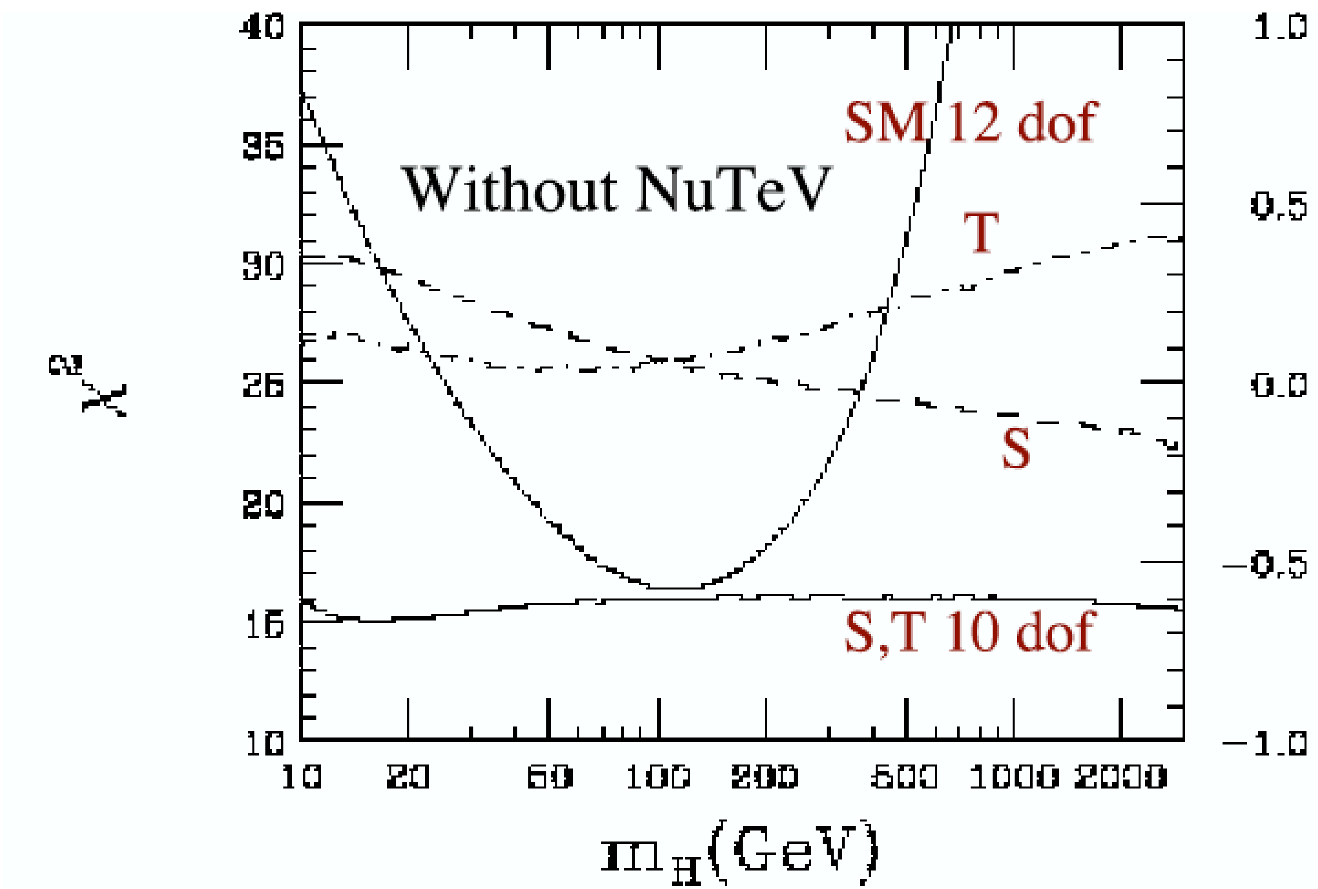
  ... in a bit, we'll discuss what theories it leads us to

- by no means is the light Higgs a certainty - electroweak precision tests at Z-pole can be satisfied with new physics contributions to S and T, of quite a natural order of magnitude...

... while not the generally repeated party line, it is worth dwelling upon the no-light-Higgs option before going back to discuss light Higgs scenarios

J. Bagger, A. Falk, M. Swartz, hep-ph/9908327
M. Chanowitz, hep-ph/0412203

a.) the no-light-higgs scenario...



RHS scale:
required values of S and T to accommodate precision tests with Higgs of a given mass

(Chanowitz, '04)

these are not crazy values:

- correspond to coefficients in electroweak chiral lagrangian of some strongly-coupled theory
  (or even weak: Barbieri, Hall, Rychkov, '06 weak coupling with heavy higgs, low cutoff)

- require no accidental cancellations between UV and IR contributions to S and T

a.) the no-light-higgs scenario...

- write largangian in terms of observed fields only
"higgsless EFT:"

observed fields - Goldstones = longitudinal W,Z: $\Sigma = e^{i\frac{2w^a\sigma^a}{v}}$

$$D_\mu \Sigma = \partial_\mu \Sigma + i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma - i g_1 \Sigma \frac{\sigma^3}{2} B_\mu$$

two derivative terms at Λ_{UV} ~ 3 TeV "gauged electroweak chiral lagrangian:"

$$\mathcal{L}^{(2)} = \frac{v^2}{4} \operatorname{tr} D_\mu \Sigma^\dagger D^\mu \Sigma - \frac{\alpha T_0}{8} v^2 \left(\operatorname{tr} \sigma^3 \Sigma^\dagger D_\mu \Sigma\right)^2 - \frac{\alpha S_0}{4sc} B_{\mu\nu} \operatorname{tr} \Sigma^\dagger W_{\mu\nu} \Sigma \sigma^3$$

bare values of S and T to accommodate precision tests ~ $(S_0, T_0) = (-0.27, 0.46)$

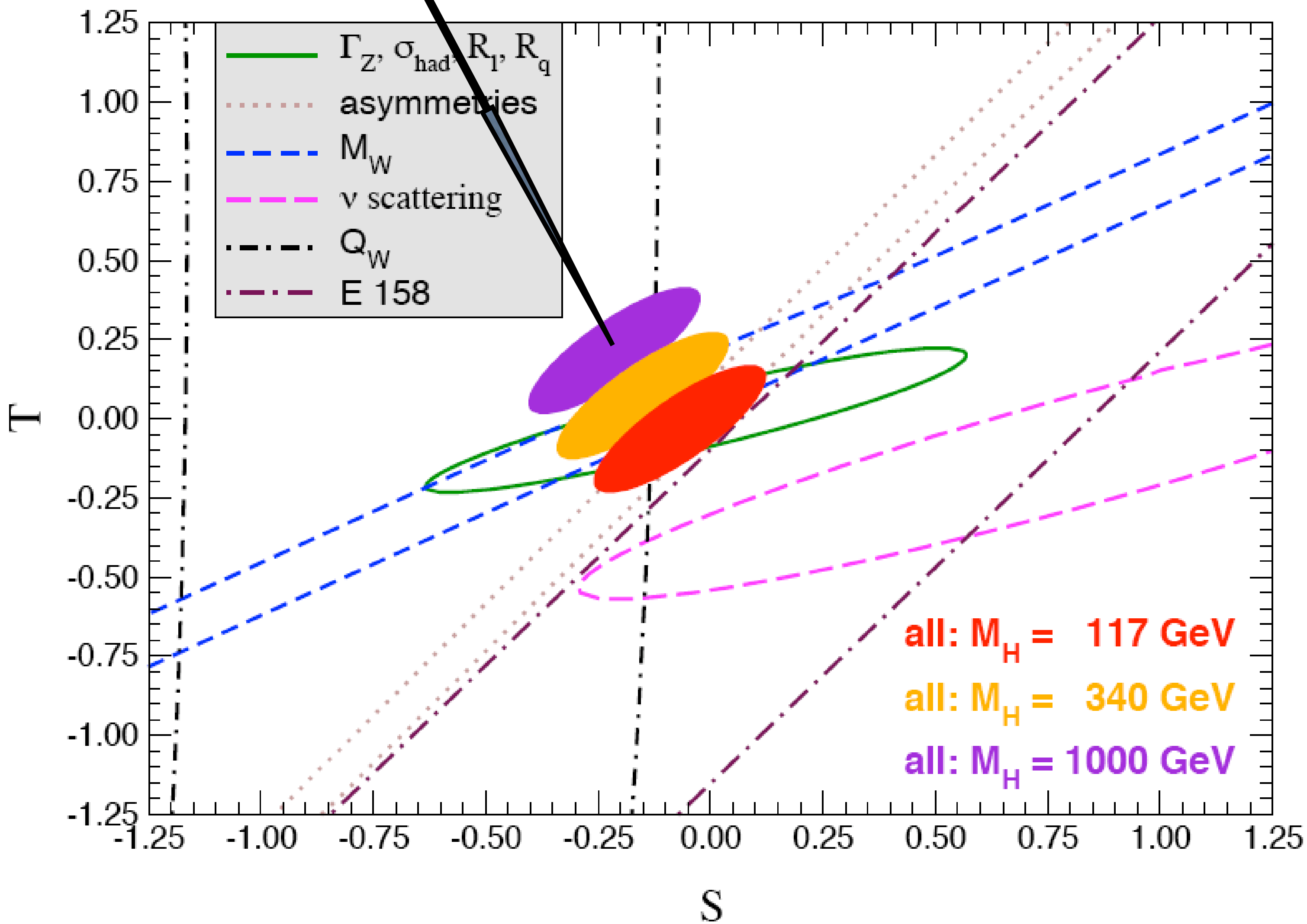
(from 2000; somewhat shifted since -
PDG 2005 heavy-Higgs plot on next page)

produced, in this scenario, by whatever strong dynamics describes physics above Λ_{UV} < 3TeV

a.) the no-light-higgs scenario...

weak-scale values of S and T accommodating precision tests with 1000 GeV Higgs

PDG, updated 9/2005



a.) the no-light-higgs scenario...

all good questions: do we know of such scenarios?
do we understand the strong dynamics involved?
can we calculate and make robust predictions?

with not-so-good answers:

not really

- we do not understand strong gauge dynamics (chiral, in particular) well
- only in "rescaled-QCD" scenarios, like old technicolor, can we make some claims - in particular, that simplest versions are excluded by Z-pole electroweak precision tests (Holdom, Terning, 1990,....)
- but "rescaled-QCD" is a small subspace of "theory space"...
- **does nature care about what theorists can calculate?**

- what are possible LHC-scale signatures ?

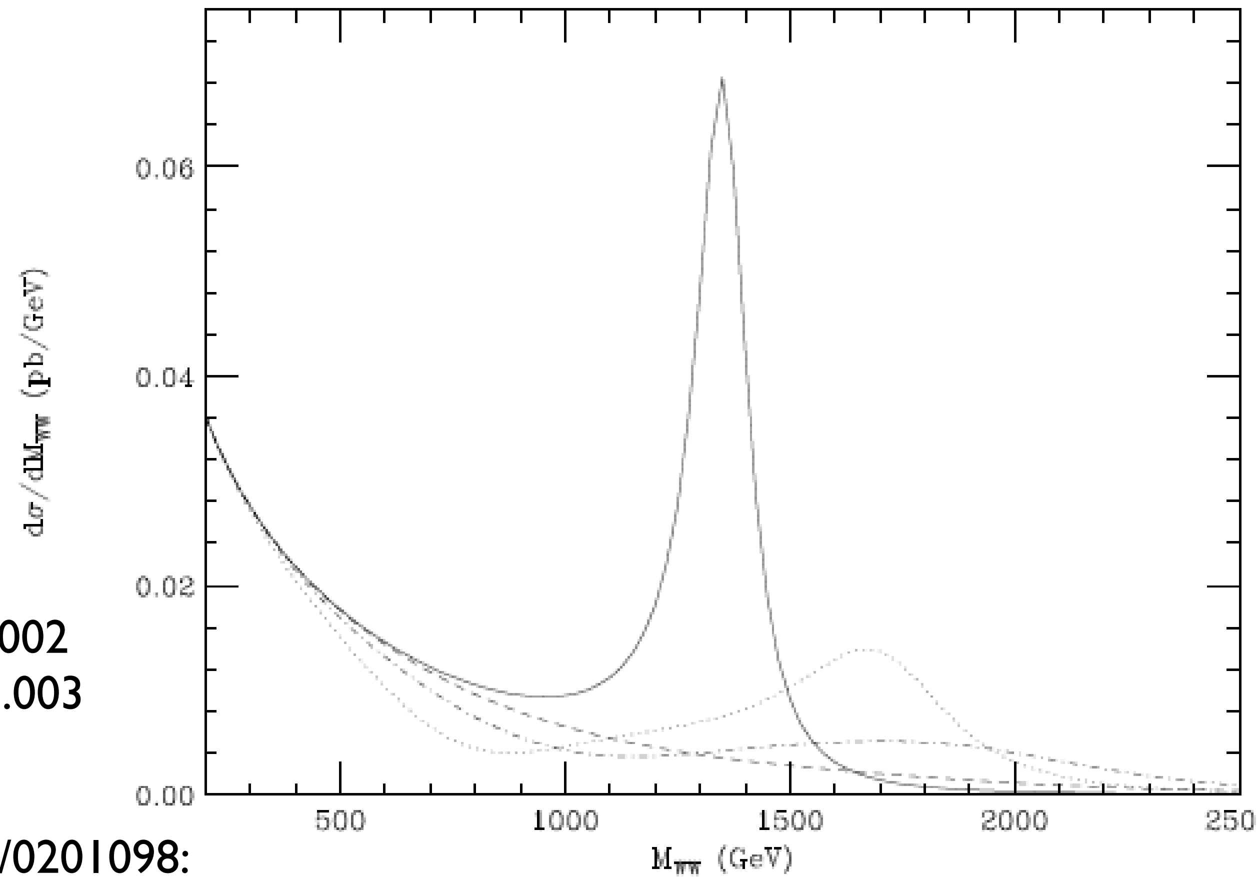
a.) the no-light-higgs scenario...

- possible LHC-scale signatures have been suggested:

- strong WW-scattering, with possible broad resonances...

after all WW scattering should be unitary by some means - unitarize amplitude in chiral lagrangian - "Pade," "N/D," "K-matrix"...

$a_4 = .002$
$a_5 = -.003$



Butterworth, Cox, Forshaw, hep-ph/0201098:

about the underlying event is also studied. We conclude that the channel $WW \to jj + l\nu$ may contain scalar and/or vector resonances which could be measurable after 100 fb^{-1} of LHC data.

a.) the no-light-higgs scenario...

- various LHC-scale signatures have been suggested:

- strong WW-scattering, with possible broad resonances...

  e.g., Butterworth, Cox, Forshaw, '02; Chanowitz, '04...

- a heavy fourth family, directly involved in electroweak symmetry breaking

  Holdom, hep-ph/0702037 - see B. Beare's talk this afternoon

- topcolor and related models - top-pions, top-higgs, Z',...

  e.g., Jenkins, Hill, '03

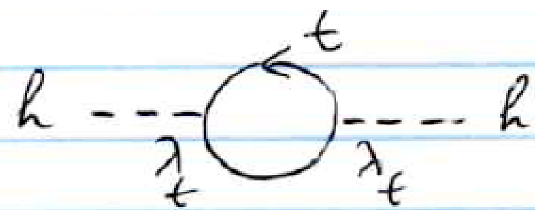
... what if we interpret the data as implying that the higgs is light, indeed?

on to the: b.) the light-higgs scenario...

b.) the light-higgs scenario...

why is it light?

top loop:



$$\delta m_h^2 \approx -\frac{3\lambda_t^2}{4\pi^2}\Lambda_{UV}^2$$

$$m_h^2 = m_0^2 - \left(\frac{\Lambda_{UV}}{3}\right)^2$$

$$|\delta m_h^2| \lesssim m_h^2 \implies \Lambda_{UV} \lesssim \underline{O}(600)\left(\frac{m_h}{200\ \text{GeV}}\right)\text{GeV}$$

if no unexpected cancellations: need new physics at ~600 GeV to cancel

b.) the light-higgs scenario...

however, new physics at ~600 GeV, will produce higher-dimensional operators, suppressed by 1/(600 GeV)^2

are such operators allowed?

Barbieri, Strumia, hep-ph/0007265

Dimensions six operators			$m_h = 115$ GeV $c_i = -1$	$c_i = +1$
$\mathcal{O}_{WB}$	=	$(H^\dagger \tau^a H) W^a_{\mu\nu} B_{\mu\nu}$	9.7	10
$\mathcal{O}_H$	=	$\lvert H^\dagger D_\mu H \rvert^2$	4.6	5.6
$\mathcal{O}_{LL}$	=	$\frac{1}{2}(\bar{L}\gamma_\mu \tau^a L)^2$	7.9	6.1
$\mathcal{O}'_{HL}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{L}\gamma_\mu \tau^a L)$	8.4	8.8
$\mathcal{O}'_{HQ}$	=	$i(H^\dagger D_\mu \tau^a H)(\bar{Q}\gamma_\mu \tau^a Q)$	6.6	6.8
$\mathcal{O}_{HL}$	=	$i(H^\dagger D_\mu H)(\bar{L}\gamma_\mu L)$	7.3	9.2
$\mathcal{O}_{HQ}$	=	$i(H^\dagger D_\mu H)(\bar{Q}\gamma_\mu Q)$	5.8	3.4
$\mathcal{O}_{HE}$	=	$i(H^\dagger D_\mu H)(\bar{E}\gamma_\mu E)$	8.2	7.7
$\mathcal{O}_{HU}$	=	$i(H^\dagger D_\mu H)(\bar{U}\gamma_\mu U)$	2.4	3.3
$\mathcal{O}_{HD}$	=	$i(H^\dagger D_\mu H)(\bar{D}\gamma_\mu D)$	2.1	2.5

- must be suppressed at least by inverse powers of 2-10 TeV, not 600 GeV!

- **“The Matrix”** of Han&Skiba, ‘04: even more operators: 21(!) flavor-singlet ones - similar conclusions

b.) the light-higgs scenario...

but with 10 TeV cutoff (= the scale of new physics, inferred from precision tests)

taking 200 GeV - LEP upper limit - higgs mass:

$$m_h^2 = m_0^2 - \left(\frac{\Lambda_{UV}}{3}\right)^2$$

40,000 = 1,150,000 - 1,110,000

matching (UV) contribution of physics beyond cutoff

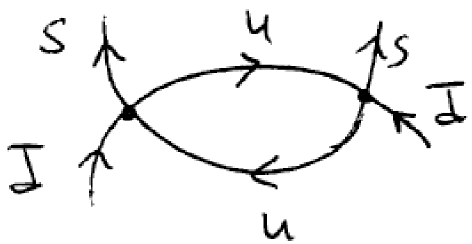
low-scale (IR) contribution of physics below cutoff

UV and IR contributions must cancel rather precisely
- to a few percent -

- how come?

- should we care ...???

once upon a time (1960s), there was a quadratic divergence...



$$\sim (\bar{d}s)(\bar{d}s)\,\frac{G_F^2\,\Lambda_{UV}^2}{16\pi^2}$$

with $\Lambda_{UV} \sim \frac{1}{\sqrt{G_F}}$ it gave $\Delta m_{K\bar{K}} \sim 10^{-2}\,eV \gg 10^{-6}\,eV$!

could have “solved” discrepancy with 0.1% fine tuning -

but nobody seems to have suggested it, back then

...theorists were in disarray... [what’s new?]

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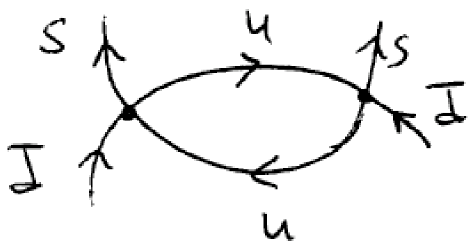

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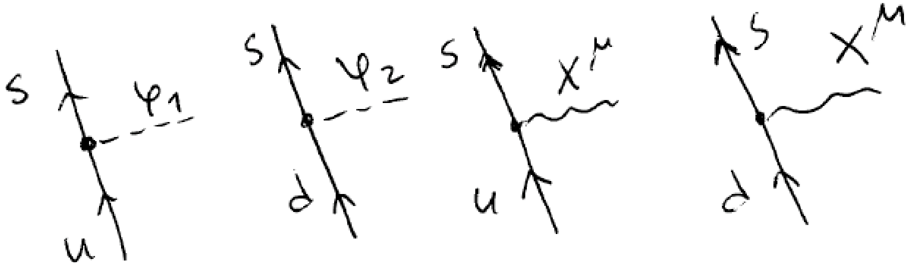
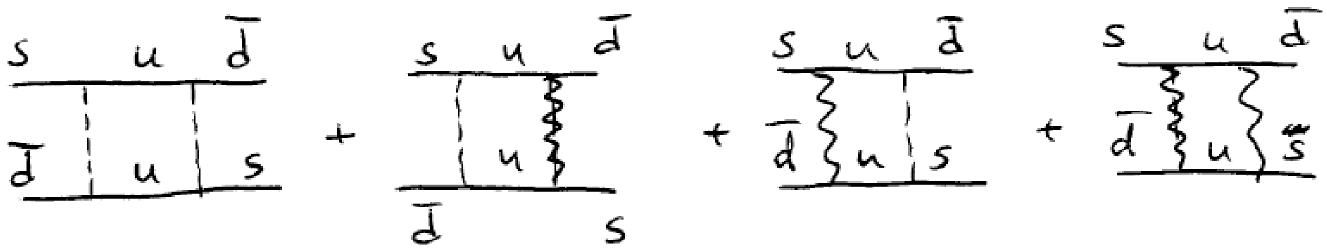
...theorists were in disarray... [what’s new?]

1) some said, maybe Λ_{UV} is a few GeV [Bouchiat, Iliopoulos; Gatto, Tonin...1968]

2) others thought, maybe scalar and vector exchange conspire and cancel Δ S=2 divergence?

[Gell-Mann,Goldberger,Kroll,Low, 1969:
"Amelioration of divergence difficulties in the theory of weak interactions"]



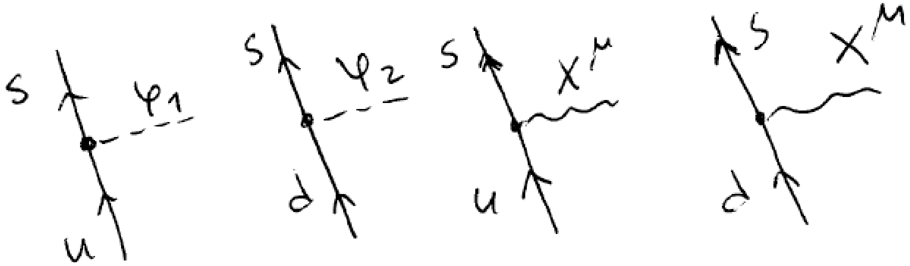


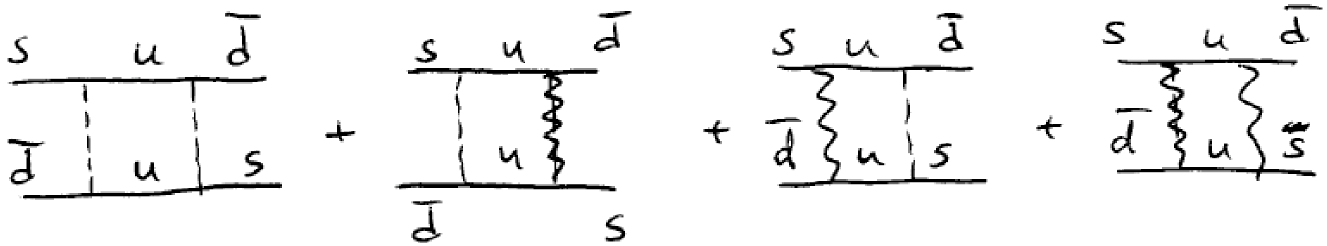
= finite

Δ S=2 piece

2) others thought, maybe scalar and vector exchange conspire and cancel $\Delta S=2$ divergence?

[Gell-Mann, Goldberger, Kroll, Low, 1969: *"Amelioration of divergence difficulties in the theory of weak interactions"*]



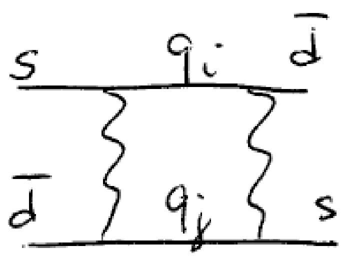


= finite

$\Delta S=2$ piece

3) a third group believed in symmetry [Glashow, Iliopoulos, Maiani, 1970]

$$\sum_{i,j=u,c}$$



$$\sim \bar{d} s \, \bar{d} s \; \frac{G_F^2 m_c^2 \sin^2\theta_c \cos^2\theta_c}{8\pi^2}$$

and inferred $m_c \sim 1.5 \text{ GeV}$

...who was right?

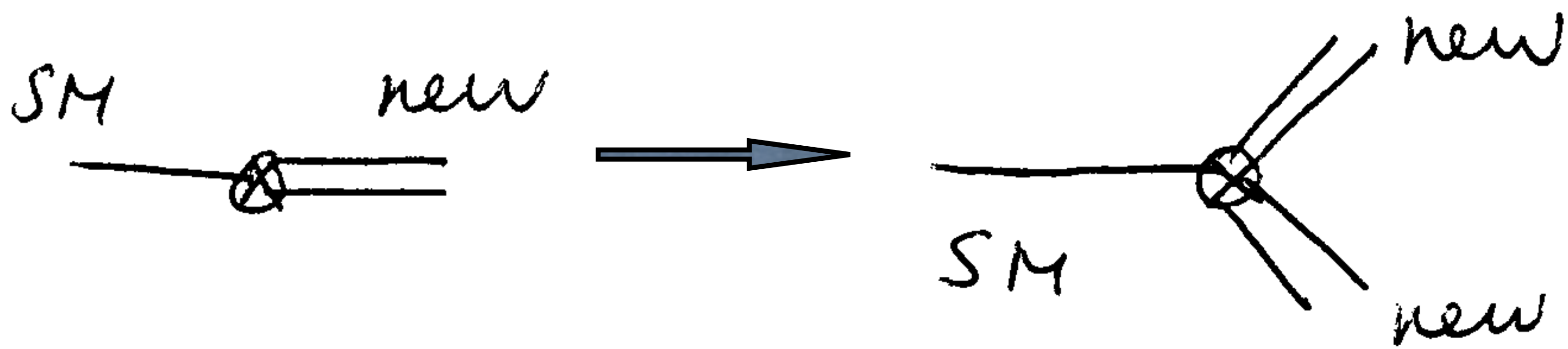
b.) the light-higgs scenario...

so, if we believe, as LEPII may have us to, in light Higgs **and** in naturalness, we have ourselves a **"little hierarchy problem,"** LHP, **"LEP paradox"**

- 2000+: a flurry of model-building addressing the LHP
- all accomplish pretty much the same
- have (coarsely speaking) similar LHC signatures

tension between low scale of new physics needed to cancel quadratic divergence to higgs mass and electroweak measurements resolved by introducing new discrete symmetry:

... R-parity, T-parity, KK-parity...

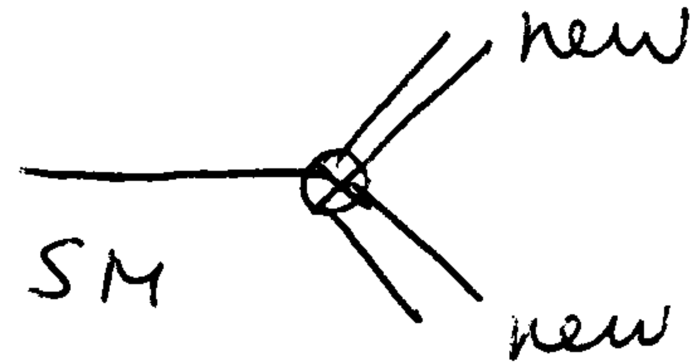


large contributions to Z-pole observables

loop-suppressed contributions to Z-pole observables: loop factor = $1/(4\,\mathrm{pi})^2 \sim (600\mathrm{GeV}/10\mathrm{TeV})^2$ works just right!

b.) the light-higgs scenario...

R-parity, T-parity, KK-parity...



- new physics only pair produced - missing energy!
- lightest R-, T-, or KK-odd particle stable - WIMP dark matter!
- distinguished by spin and details of couplings, but maybe not so easy to tell apart at the LHC
- distinguished also by what happens beyond Λ_{UV} (and by ambition)

all models with weak coupling at TeV introduce new physics at ~600 GeV (or less) to cancel top-loop quadratic divergence:

how do they do it?

by recalling:

"**3)** a third group believed in symmetry" b.) the light-higgs scenario... - supersymmetry

two types of symmetry are known to forbid/protect scalar masses

supersymmetry: imposes chiral symmetry (protecting fermion mass) on scalars

↓

higgs, and all other particles are parts of supermultiplets

↓

supersymmetry must be explicitly broken
(in low energy theory)

↑

we haven't seen the superpartners

b.) the light-higgs scenario... - supersymmetry

...oldest... most developed...the most of the mostest...perhaps valid all the way to Planck scale...
...introduces >100 new parameters...but hopes determined by high-scale dynamics...

- quadratic divergences of higgs mass cancelled by stop loops
- R-parity--dark matter, (string) unification - grand ambitious picture!
- flavor, SUSY-flavor, and SUSY-CP problems - pushed to higher scales
  there are proposed solutions

however:

“where is SUSY?”

SUSY is experiencing some “post-LEPII blues”

main issue:

Higgs > 114 GeV from LEPII, while SUSY @ tree level: Higgs < Z

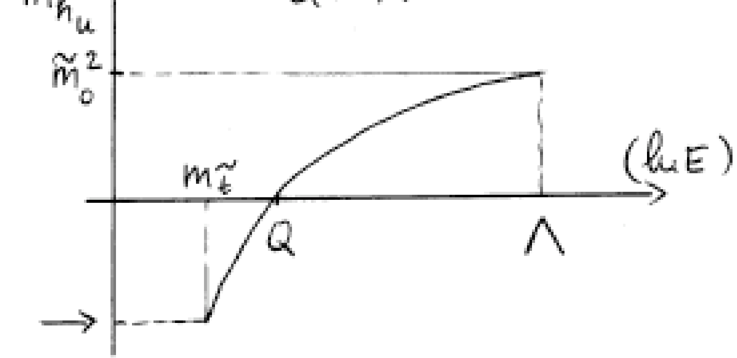
b.) the light-higgs scenario... - supersymmetry

$$m_h^2 \lessapprox m_Z^2 + m_t^2 \frac{3\lambda_t^2}{2\pi^2} \log \frac{m_{\tilde t}}{m_t}$$

simplest in large tan-beta limit (=)

$m_h > 114$ GeV $\Rightarrow$ $m_{\tilde t} \gtrsim \mathcal{O}(600\ \text{GeV})$

$$Q \approx \Lambda e^{-2\pi^2/(3\lambda_t^2)}$$



simple:
heavy higgs - heavy stop - but stop contributes to Z mass:

$$\frac{m_Z^2}{2} \approx m_{\tilde t}^2 \frac{3\lambda_t^2}{2\pi^2} \ln \frac{Q}{m_{\tilde t}} = \tilde m_0^2 - \frac{3\lambda_t^2}{2\pi^2} m_{\tilde t}^2 \ln \frac{\Lambda}{m_{\tilde t}}$$

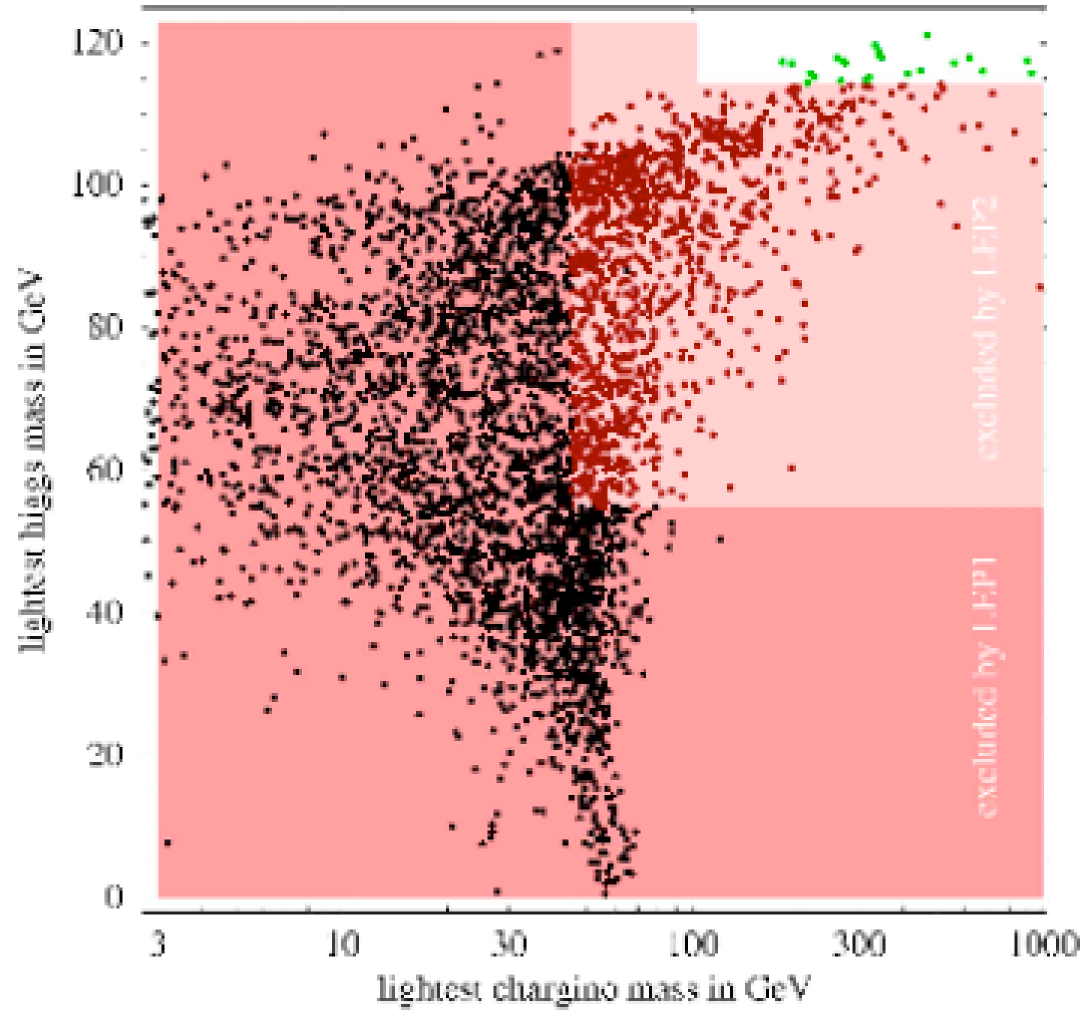
4,050 = 54,750 * 0.073 = 1,924,050 - 1,920,000 (for Planck scale cutoff)

thus, we have a few percent fine tuning in SUSY:

- two unrelated scales - Q, stop mass - very close to each other...
  or,
- IR and UV contributions to Z mass cancel to a few percent

b.) the light-higgs scenario...
- supersymmetry

[from Giusti, Romanino, Strumia,'99]



empirical measure of fine tuning

density ~ "naturalness probability" =
uniform scan of SUSY soft parameters
around central value

remedies?

- large A-terms, 2-3% tuning "improved" to 5-7%
- NMSSM: higgs < 114GeV has new decay modes to light SM singlet, to avoid LEPII
- R-parity violation: new higgs-6j decays

Kitano, Nomura; Dermisek, Gunion;
Carpenter, Kaplan, Rhee...

don't forget other tunings in susy: to get dark matter density right, for one...?

...and doesn't one really shuffle fine-tuning to other places: Schuster, Toro...

b.) the light-higgs scenario...

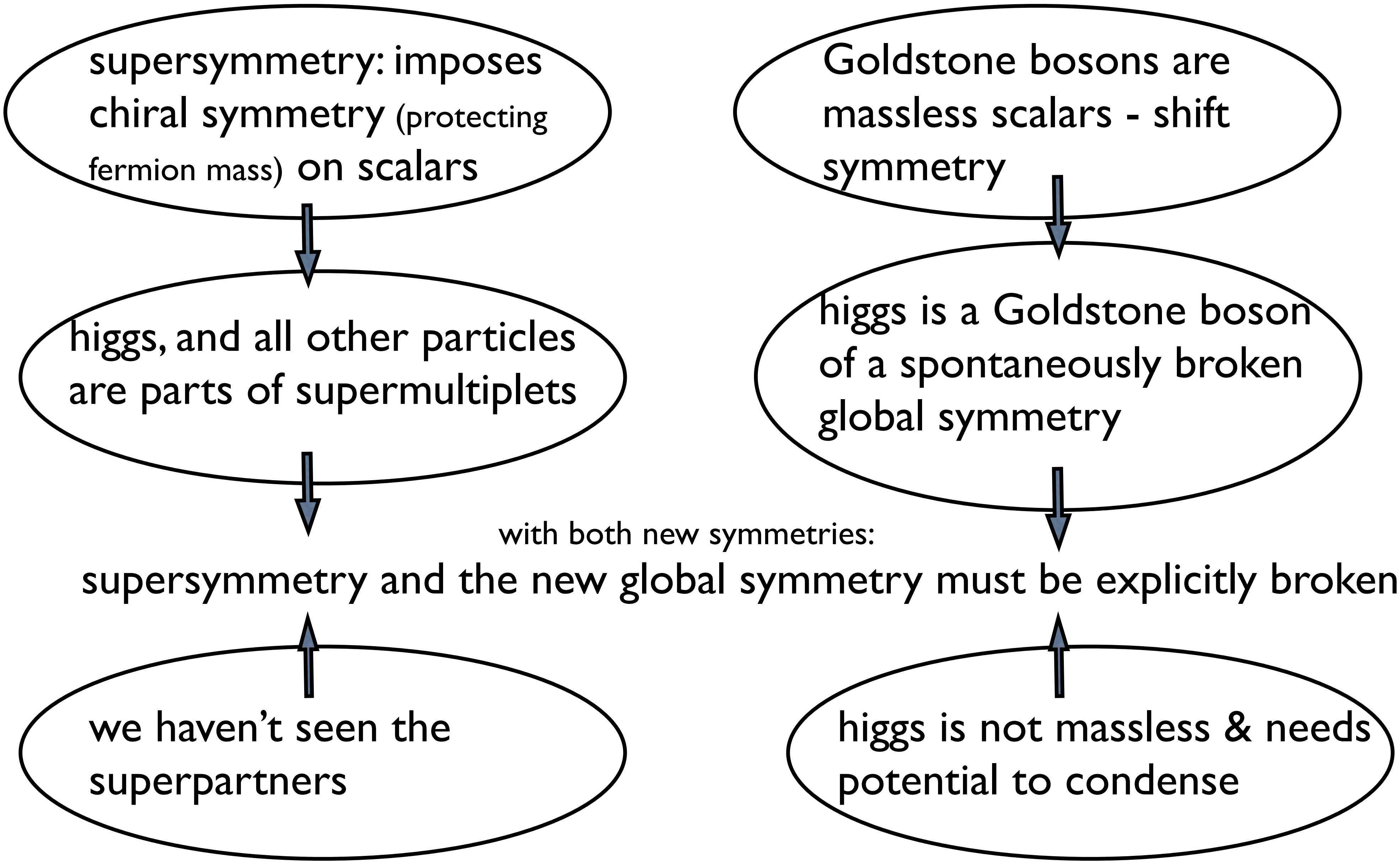
- supersymmetry - summary:

- the grand old dame of the standard “big” hierarchy-big “grand” unification-big picture ...still not dead, so treat with respect!
- some tension post LEPII level of fine-tuning can be reduced by reducing ambition
- it is most important to keep an open mind...

how about the other symmetry forbidding scalar mass?

b.) the light-higgs scenario...

two types of symmetry are known to forbid/protect scalar masses



b.) the light-higgs scenario...

two types of symmetry are known to forbid/protect scalar masses

Goldstone bosons are massless scalars - shift symmetry

$\downarrow$

higgs is a Goldstone boson of a spontaneously broken global symmetry

$\downarrow$

new global symmetry must be explicitly broken

$\uparrow$

higgs is not massless & needs potential to condense b.) the light-higgs scenario... pseudo-Nambu-Goldstone Higgs (PNGB)

- little Higgs, twin Higgs, Higgs as extra-dimensional gauge field -
  - all variations of PNGB Higgs mechanism
- Randall-Sundrum "warped space" models must utilize PNGB or SUSY to solve "little hierarchy" problem

idea is simple - **SM Higgs doublet is** (part of) **a PNGB multiplet:**

- very much like pions: massive because of small explicit breaking of chiral symmetry by "current" quark mass; small pion mass kept in check by smallness of light quark masses wrt Λ_{QCD}
- but not exactly like pions - need not only mass but also quartic to break electroweak symmetry; creates some tension
- one-loop quadratic divergence cancelled by new partners, bosonic - or fermions - with couplings determined by symmetries of model and mass as required by naturalness, in the 500 GeV(-ish) range

b.) the light-higgs scenario... pseudo-Nambu-Goldstone Higgs (PNGB)

- significantly less ambitious than SUSY: most models pretend to only describe physics to 10 TeV, silent about what comes beyond

  ...some have dubbed them **"little physics"**

- some fine tuning ~10% (as in the best of SUSY!) in all cases:
  EW breaking scale or precision tests

- with KK-parity and T-parity:

  get dark matter and avoid precision test problems

- partners produced in pairs, lightest KK-/T-odd particle is stable and gives missing energy signals

- sometimes partners are colored and copiously produced, other times- only weak couplings, and, sometimes *not even charged under SM!*
  - makes versions of "twin higgs" hard to impossible see at LHC

- too much variety and no easy-to-present "canonical" MSSM-like model .
  - although attempts exist **"little M(oose) theory"** of Cheng, Thaler, Wang, '06 -

  - but generic features are as listed

What is my message?

...theorists are in disarray...

We only know for sure that

if there is a natural solution to the hierarchy problem, the LHC data are likely to be spectacular!

We have come up with many scenarios.
The best we can do is study their LHC signatures.

It is not clear if any of these scenarios are true:
Weakly-coupled ones suffer from (mild) fine-tuning problems,
Strong-coupling ideas are plagued by our inability to calculate.

Given the ubiquity of possibilities, one should keep on open mind.

In five years or so...

... at the very least, I hope that the results from the LHC will help cut the scope of theoretical speculation.

... more optimistically, we may (be) learn(ing) about the true origin of electroweak symmetry breaking.