Physics Beyond the Standard Model (Theory)

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ICHEP 2002

What is the most exciting new development in BSM theory ?

Survey among 40 participants at "Beyond the Standard Model" workshop in Aspen, July 2002

» Little Higgs «

80% "very interesting"

50% "I'm working on it"

25% "I fully understand it"

(here: talks by K. Lane, J. Wacker)

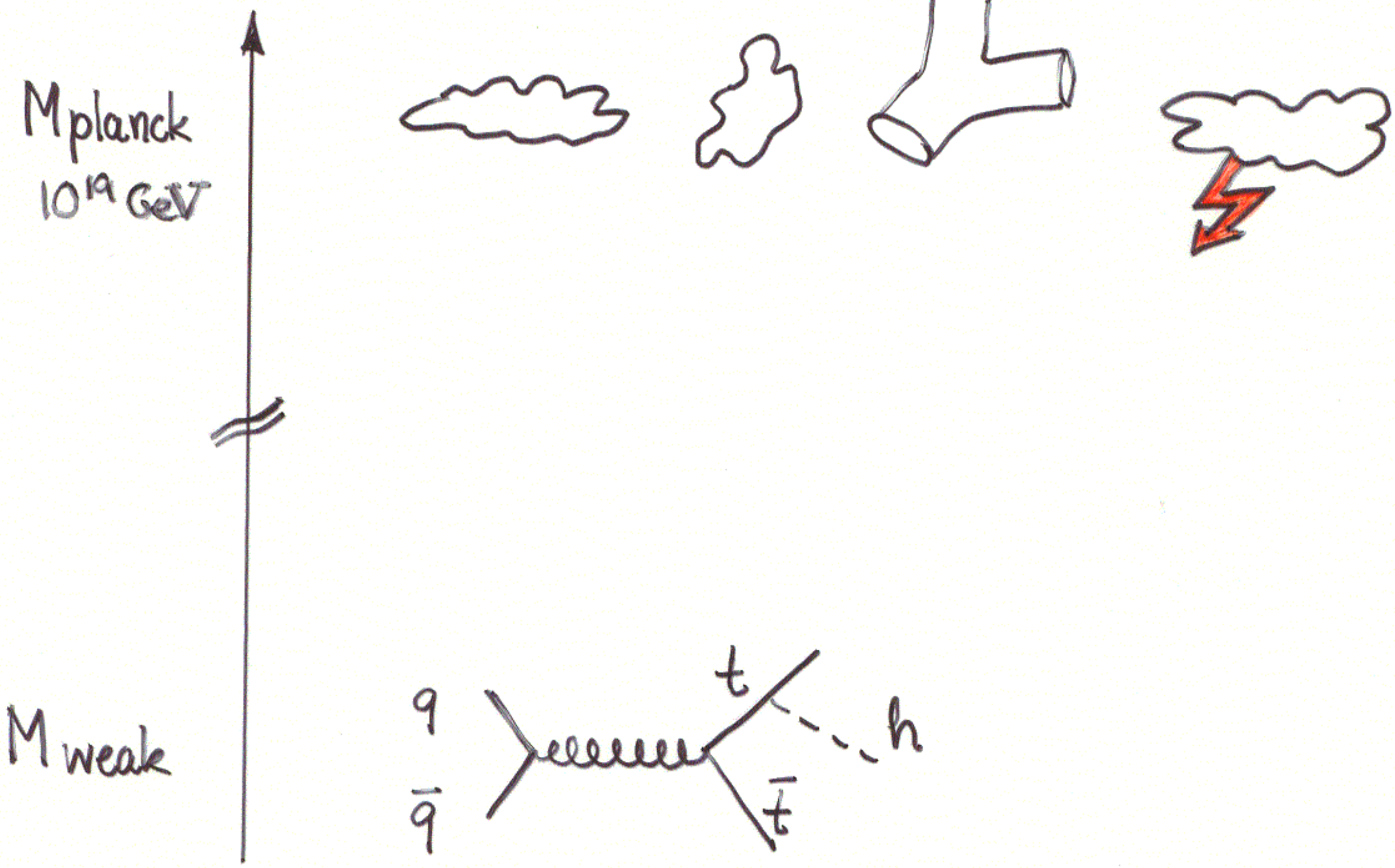
» Little Higgs «

= A new solution to the hierarchy problem

What is the hierarchy problem?

often stated as

"Why is $M_W \ll M_{planck}$?"

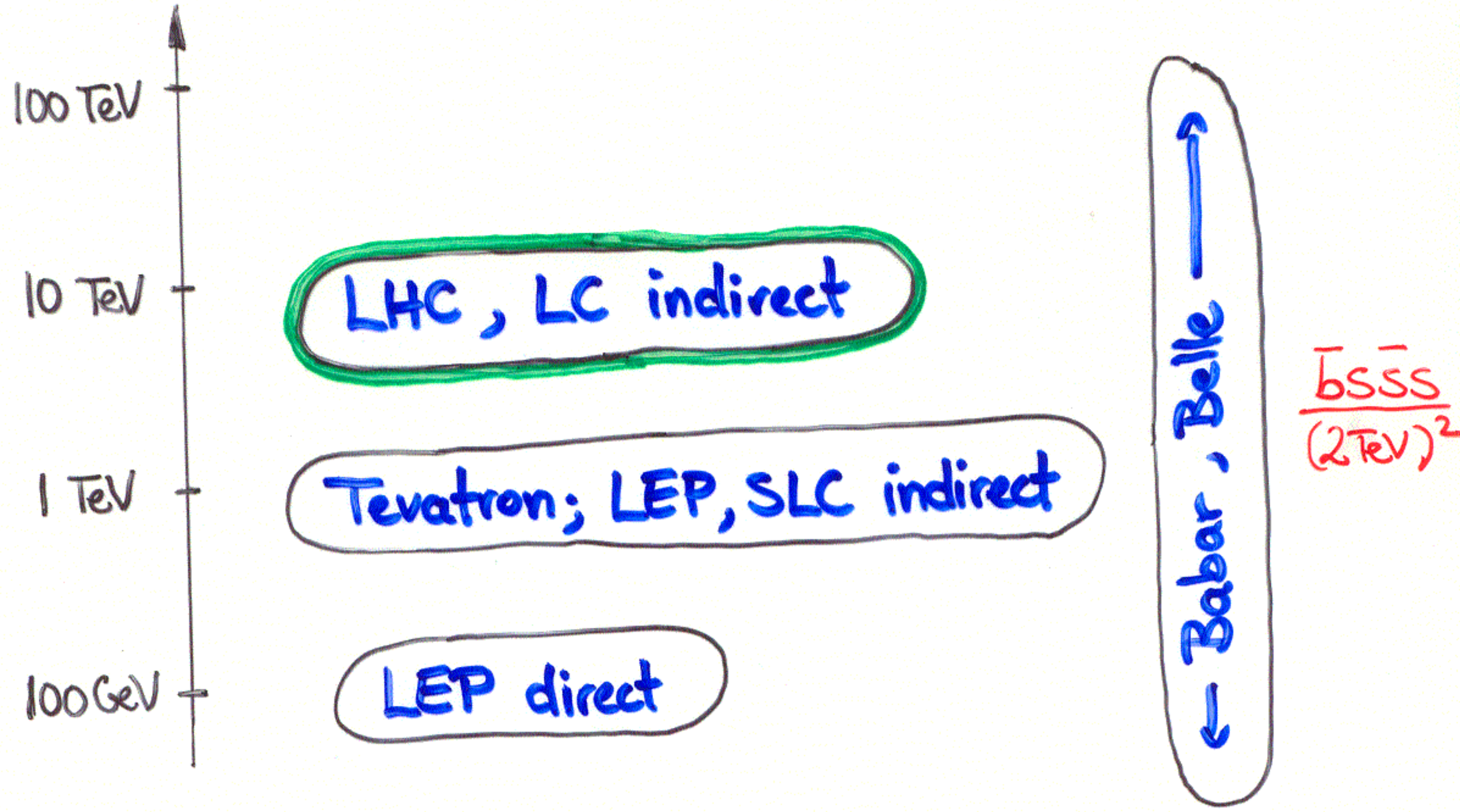


What does Mplanck have to do with collider physics? ...probably very little...

the incredible success of the Standard Model

new particle searches (PDG 2002)

lepton	$\gtrsim$	100 GeV
quark	$\gtrsim$	200 GeV
W', Z'	$\gtrsim$	1 TeV
leptoquark	$\gtrsim$	300 GeV



the Standard Model fits all (?) current data up to TeV energies,
why do we talk so much about new physics at the LHC, Run II ?

Q: can't the SM just be valid up to 10 TeV ?

(i.e. no new physics at the LHC except Higgs)

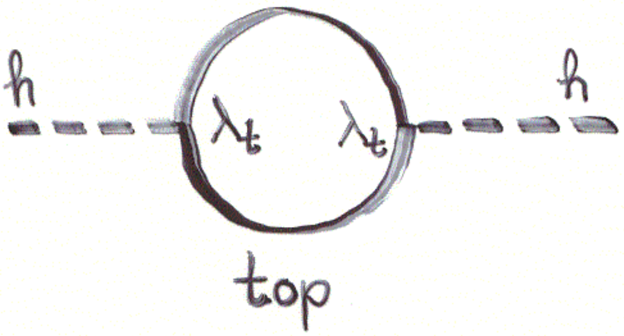
A: Yes, in principle ...

... but we don't believe it because of the

Hierarchy Problem

What is the hierarchy problem?

Assume, the SM with a Higgs ($m_H \approx$ 200 GeV ± 100)
is valid up to $\Lambda \gtrsim 10$ TeV



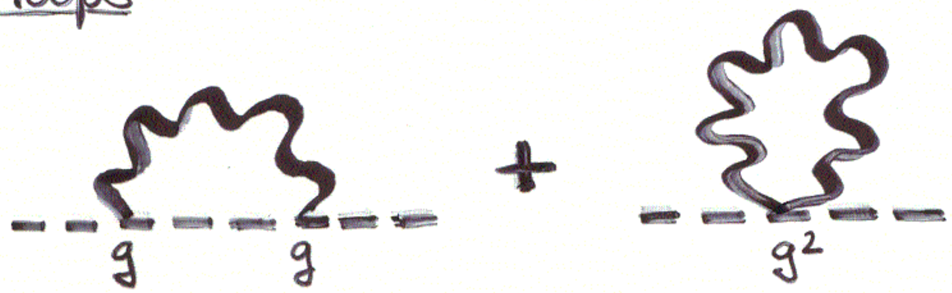
quadratically divergent!

$$\delta m_H^2 \approx -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2 \approx -(2\,\text{TeV})^2$$

100 times too big!

quadratic divergence cont'd

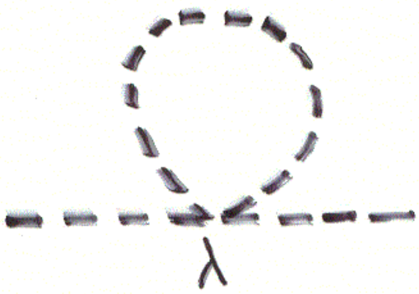
gauge loops



$$\delta m_H^2 \approx (700\ \text{GeV})^2$$

10 x too big

Higgs loop



$$\delta m_H^2 \approx (500\ \text{GeV})^2$$

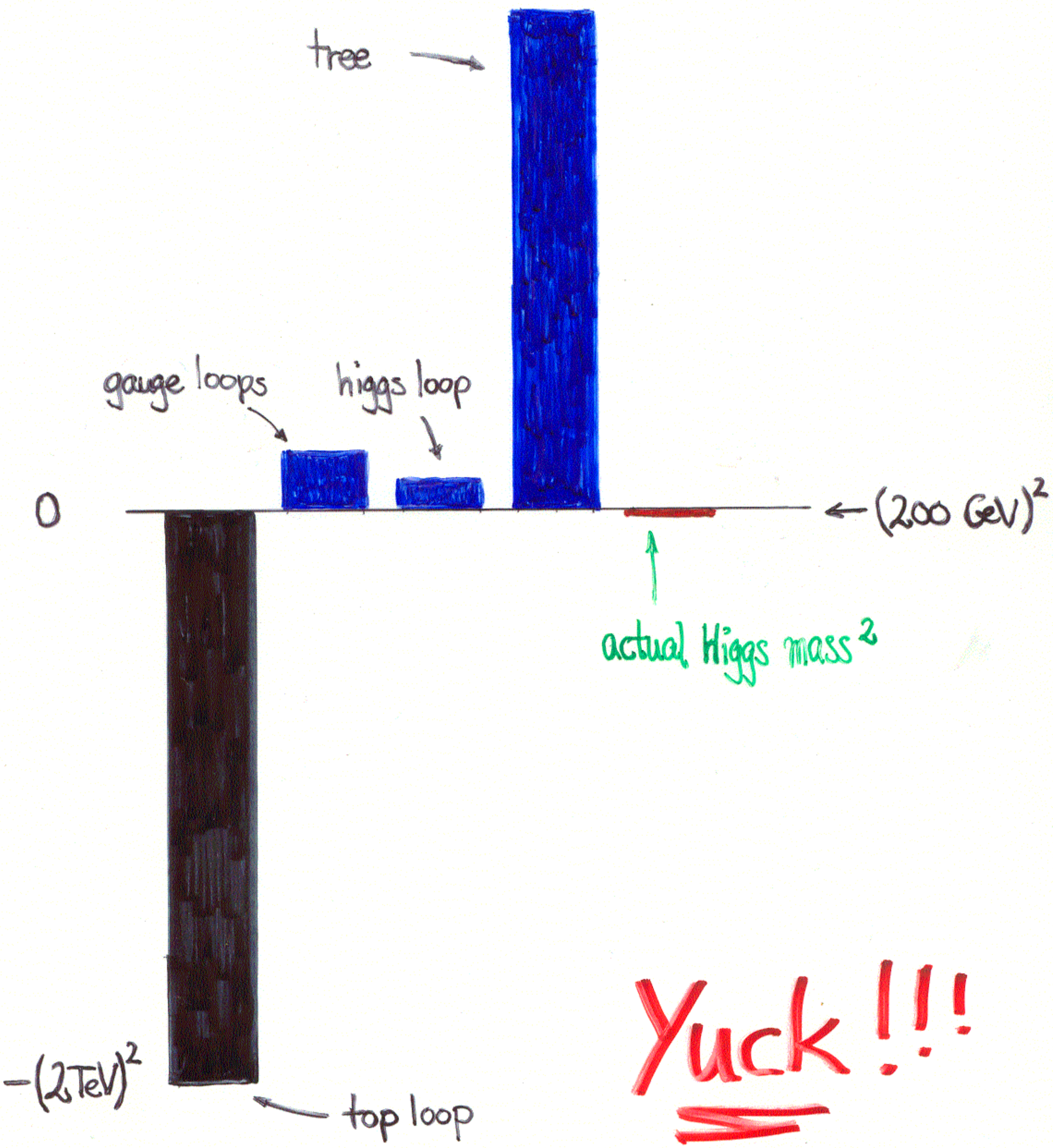
5x too big

want: $m_H^2 \approx (200\ \text{GeV})^2$

$$= m_{H_{tree}}^2 + \delta m_{H_{top}}^2 + \delta m_{H_{gauge}}^2 + \delta m_{H_{higgs}}^2$$

fine tuned!

Fine tuning the Higgs
$\Lambda = 10$ TeV



What if we lower the cutoff Λ to 1 TeV

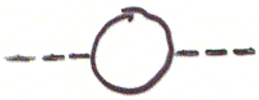
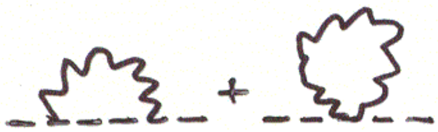
 $= \frac{-3}{8\pi^2} \lambda_t^2 \Lambda^2 \approx -(200\ \mathrm{GeV})^2$ no tuning

⇒ SM with no new physics until 1 TeV is not fine tuned

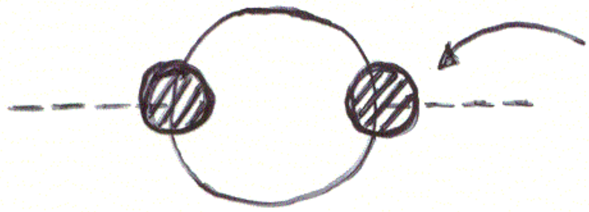
⇒ no big surprise that we have not seen it yet

How can we extend the SM with $m_H \sim 200$ GeV into a theory with a $\Lambda = 10$ TeV and no tuning?

need new physics at ~TeV which cancels the divergences

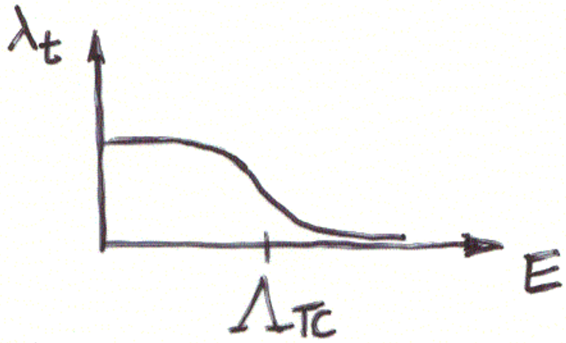
divergence		new physics scale
 top		$\lesssim 2$ TeV
 gauge	allowing for $O(10\%)$ tuning	$\lesssim 5$ TeV
 Higgs		$\lesssim 10$ TeV

Strong dynamics
(topcolor, technicolor)



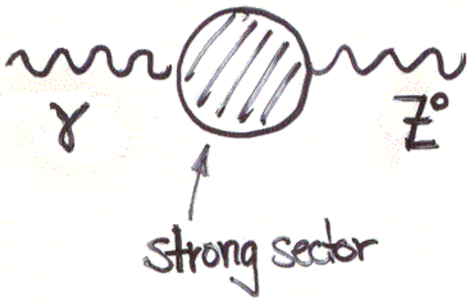
$$\lambda_{top} = \lambda^0_{top}\, e^{-(E/\Lambda_{TC})^2}$$

"form factor"



natural $m_H^2 \approx \frac{-3}{8\pi^2}\Lambda_{TC}^2 \approx -(200\text{ GeV})^2$ for $\Lambda_{TC} \approx 1$ TeV

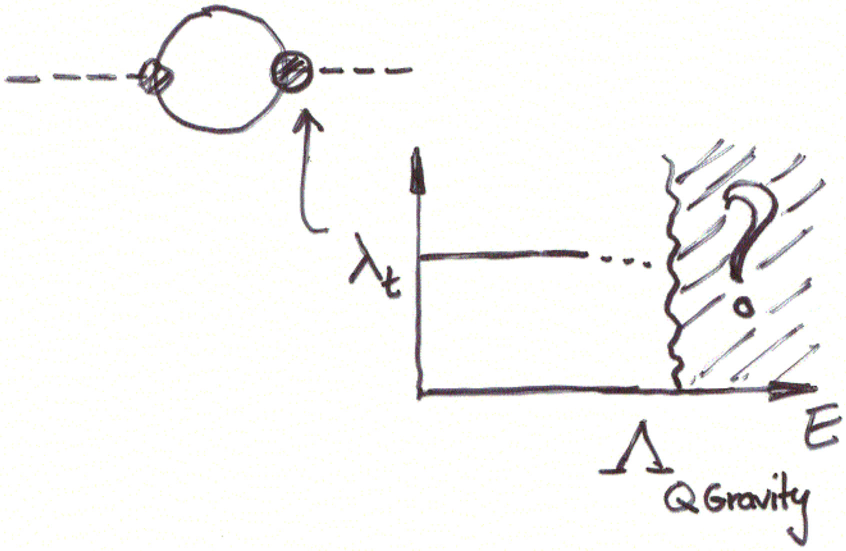
... but precision EW data make this unlikely



(S, T off by 3σ in naive model)

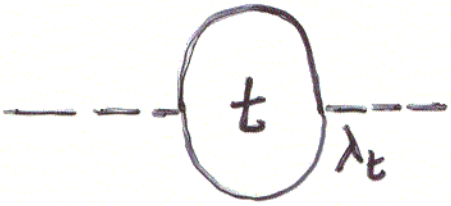
Large Extra Dimensions, TeV scale quantum gravity

gravity gets strong at TeV scale



shares problems of strong dynamics

Supersymmetry



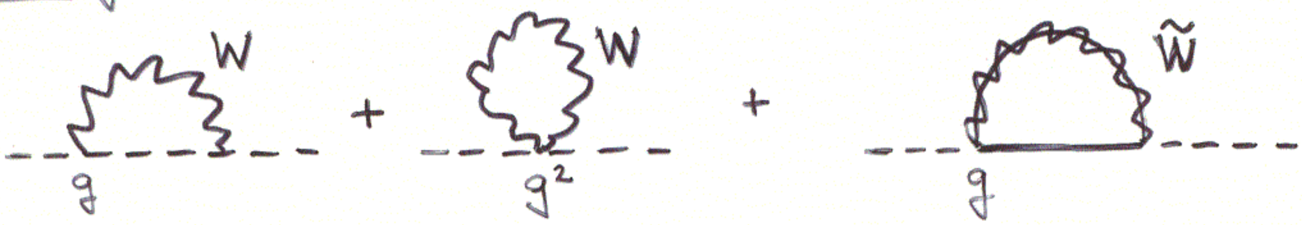
$$\delta m_h^2 = - \frac{3\lambda_t^2}{8\pi^2}\Lambda^2 \qquad + \frac{3\lambda_{\tilde{t}}^2}{8\pi^2}\Lambda^2$$

fermion loop

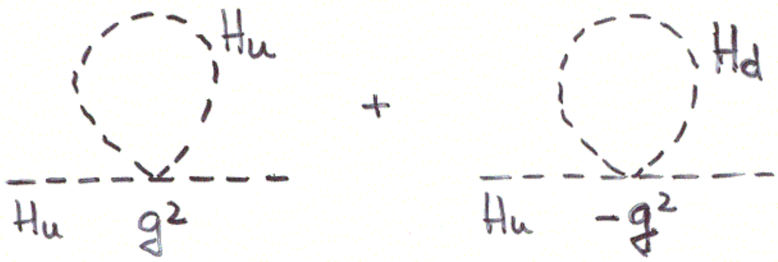
Supersymmetry relates $\lambda_{\tilde{t}} = \lambda_t$

$\Rightarrow$ Λ^2-divergence cancels

similarly



and



What have we learned from this ?

- cancelling the Λ^2 divergences requires new particles related to

top	$\lesssim$ 2 TeV
$SU(2)\times U(1)$	$\lesssim$ 5 TeV
Higgs	$\lesssim$ 10 TeV

"prediction of the hierarchy problem!"

- SUSY is nice because cancellations happen perturbatively, preferred by precision EW (corrections to S,T,U are loop suppressed)

... if we had some other perturbative theory which cancels Λ^2 divergence it would also be preferred by precision EW ...

... but ...

Supersymmetry cont'd

Folk theorem: Perturbative cancellation of quadratic divergences can only work naturally in SUSY

Folk proof:

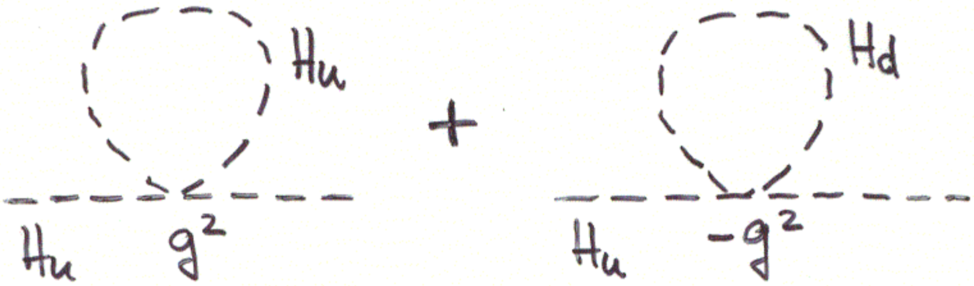
- boson loops have $+\Lambda^2$ divergence
- fermion loops " $-\Lambda^2$ "
- only boson - fermion cancellations possible
- need supersymmetry to relate couplings ($\lambda = \tilde{\lambda}$)

q.e.d.

the Folk Theorem is

Wrong!

counter example to "proof" exists even in MSSM:



divergence cancels between bosons!

Little Higgs theories

	Arkani-Hamed Cohen Georgi	hep-ph-0105239
	A-H Cohen Gregoire Wacker	0202089
	Lane	0203016
	Chivukula Evans Simmons	0204193
$[SU(2)\times U(1)]^2$ Moose →	A-H Cohen Katz Nelson	0206020
$SU(5)/SO(5)$ →	A-H Cohen Katz Nelson	0206021
	Gregoire Wacker	0206023
	Low Skiba Smith	0207243

Earlier work:

Georgi Pais '74

Dimopoulos Georgi Kaplan '84

Minimal Little Higgs Spectrum

? UV completion ?

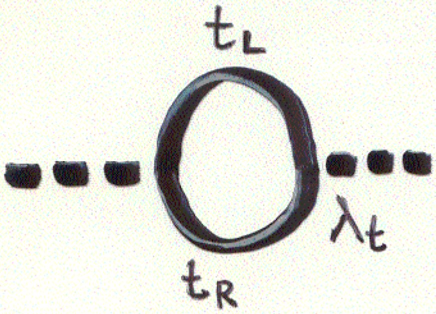
$\Lambda = 10$ TeV — cut off

1 TeV:

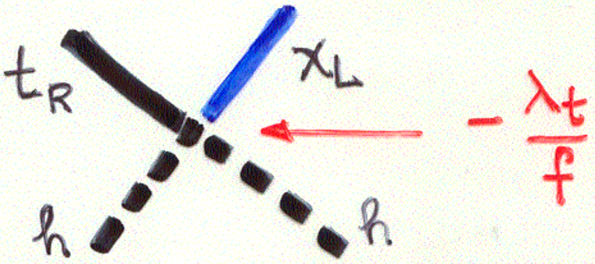
1. colored fermion X ← cancel top loop
2. W′, Z′, γ′ bosons ← cancel gauge loop
3. new scalars ← cancel Higgs loop

200 GeV — 1 or 2 Higgs doublets

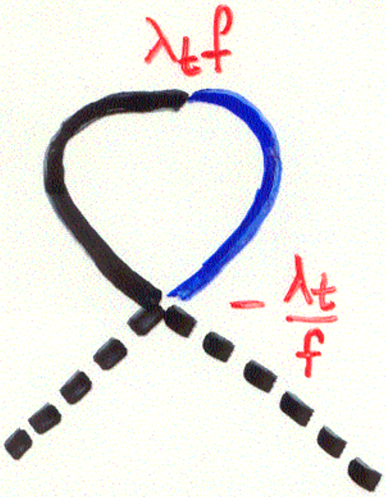
Little Higgs, top loop



$$\approx -\frac{\lambda_t^2}{16\pi^2}\Lambda^2$$



χ_R , χ_L new colored fermion of mass $\approx f \approx 1\,\text{TeV}$



$$\approx +\frac{\lambda_t}{\cancel{f}}\,\frac{\lambda_t \cancel{f}}{16\pi^2}\Lambda^2$$

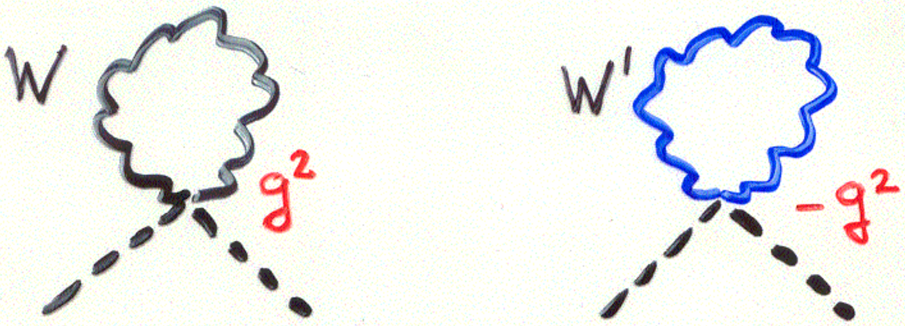
fermion cancels fermion

Little Higgs

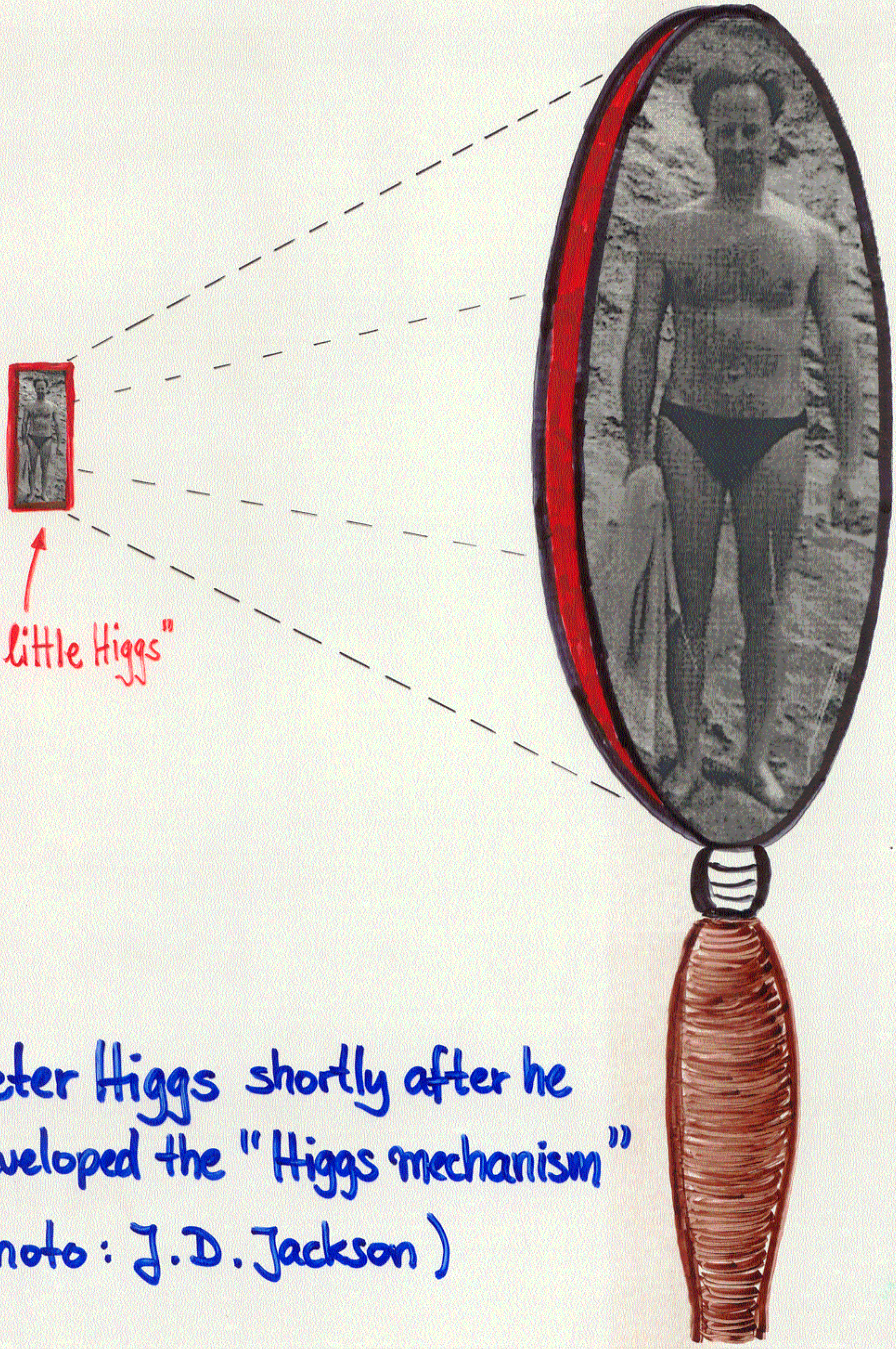
Gauge ▯ & Higgs loops

- new scalar ϕ, mass $\approx f \sim 1$ TeV

- new gauge bosons W', Z', γ', mass $\approx f \sim 1$ TeV



bosons cancel bosons



Peter Higgs shortly after he developed the "Higgs mechanism" (Photo: J.D. Jackson)

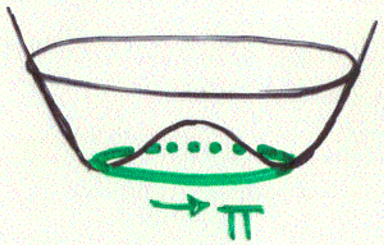
What is the symmetry ?

Higgs as a (pseudo-) Goldstone boson

Recall: Global symmetry, spontaneously broken

$\Rightarrow$ Goldstone boson

(e.g. pions in QCD)



e.g. **SU(3) $\rightarrow$ SU(2)** (not QCD!)

$$\langle\phi\rangle = \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} \Rightarrow \phi = e^{\frac{i\pi}{f}} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$$

Goldstone field $\rightarrow \pi = \begin{pmatrix} & h \\ h^\dagger & \end{pmatrix}$

the "broken" SU(3) symmetry is non-linearly realized

$$\pi \rightarrow \pi + \theta$$

forbids all non-derivative couplings of π

$\Rightarrow$ no mass ← ☺

$\Rightarrow$ no Yukawa, quartic, gauge couplings ← ☹

Exam▯ple: top loop

- enlarge $SU(2)_{\text{weak}}$ to global $SU(3)$

  quark doublet $\longrightarrow$ quark triplet $\begin{pmatrix} t_L \\ b_L \\ \chi_L \end{pmatrix}$

- break spontaneously $\quad \phi = e^{i \begin{pmatrix} & h \\ h^+ & \end{pmatrix} / f} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix}$

- yukawa coupling:

explicit SU(3) breaking

$$\lambda \,(t_L^+ \, b_L^+ \, \chi_L^+)\, e^{i \frac{\begin{pmatrix} & h \\ h^+ & \end{pmatrix}}{f}} \begin{pmatrix} 0 \\ 0 \\ f \end{pmatrix} t_R \quad + \quad M \,\chi_L^+ \chi_R$$

$$\longrightarrow \quad \lambda f \;\chi_L^+ t_R \qquad i\lambda\,(t_L^+ b_L^+)\, h \, t_R \qquad -\frac{\lambda}{2f}\, \chi_L^+ t_R \, h^+ h$$

+ same trick for gauge couplings and Higgs quartic

Little Higgs, Signatures 

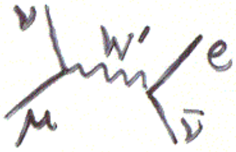
at ~ TeV have new...

... colored fermion χ

- charge $2/3$ (up-type)
- pair produced
- decays $\chi \to ht$, Wb, Zt

... gauge bosons W', Z', "exotic"

- singly produced
- weakly coupled
- couple to light fermions → precision EW



... scalars

- 2^{nd} Higgs
- model dependent, couple to $SU(2)\times U(1)$, Higgs, top
- possible WIMP dark matter

Conclusions

★ The SM works! It is not fine-tuned with cutoff 1 TeV

★ SM with cutoff $\Lambda = 10$ TeV is very fine-tuned
⇒ need new physics

concretely, need

- colored field $\lesssim 2$ TeV
- gauge field partners $\lesssim 5$ TeV
- scalars partners $\lesssim 10$ TeV

★ Little Higgs, new perturbative solution to the "little hierarchy" problem, $\Lambda \approx 10$ TeV

Little Higgs

- Higgs as pseudo-Goldstone
- many less fields than MSSM

- open questions:

  UV completion?

  Flavor origin?

  Precision EW fit

  an even simpler model?

... in progress ...