Uncharted Energy Range at the Large Hadron Collider

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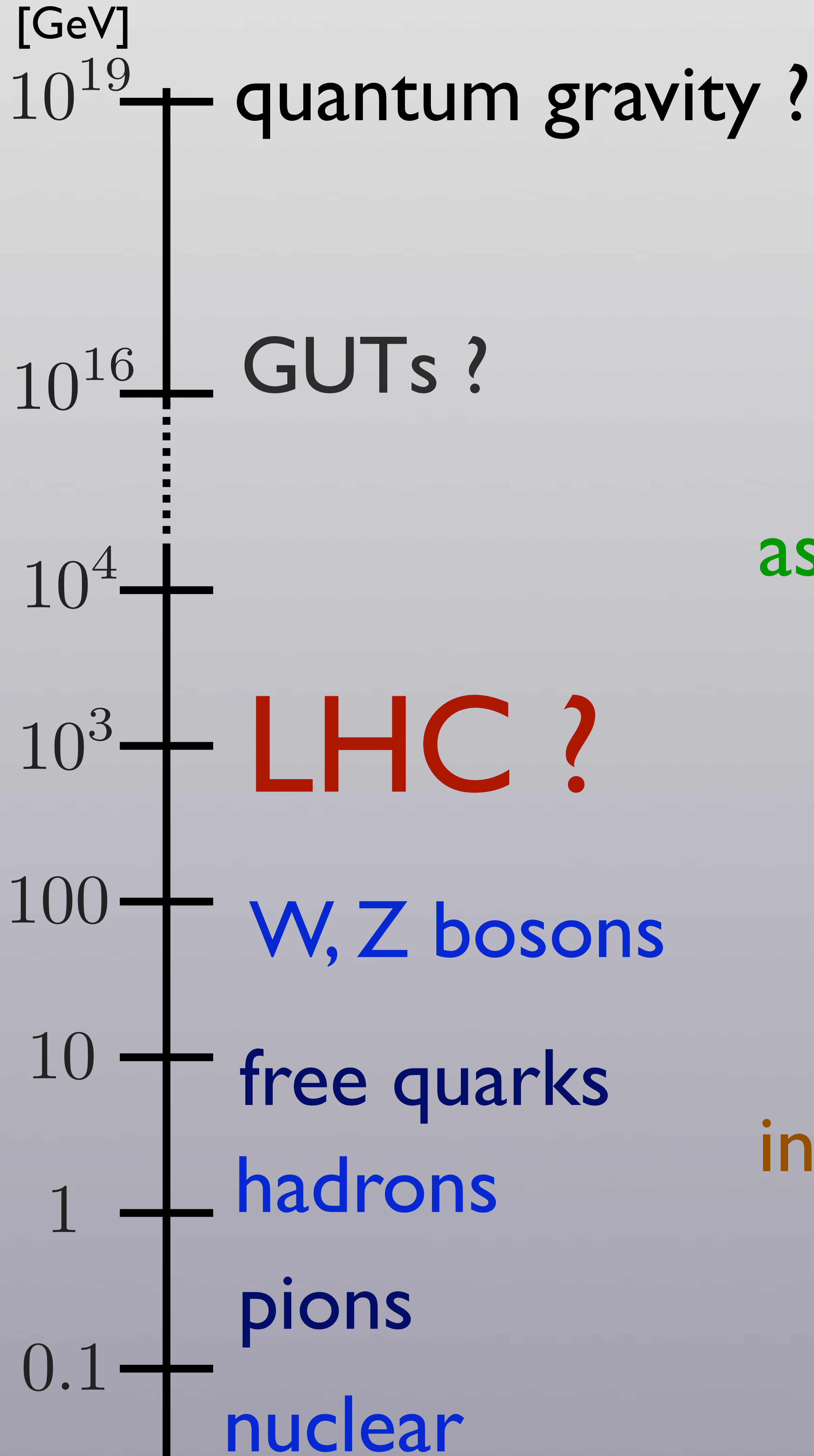
Outline

- The Large Hadron Collider at CERN
- The case for new physics around 1 TeV
- Little Higgs mechanism
- Conclusions

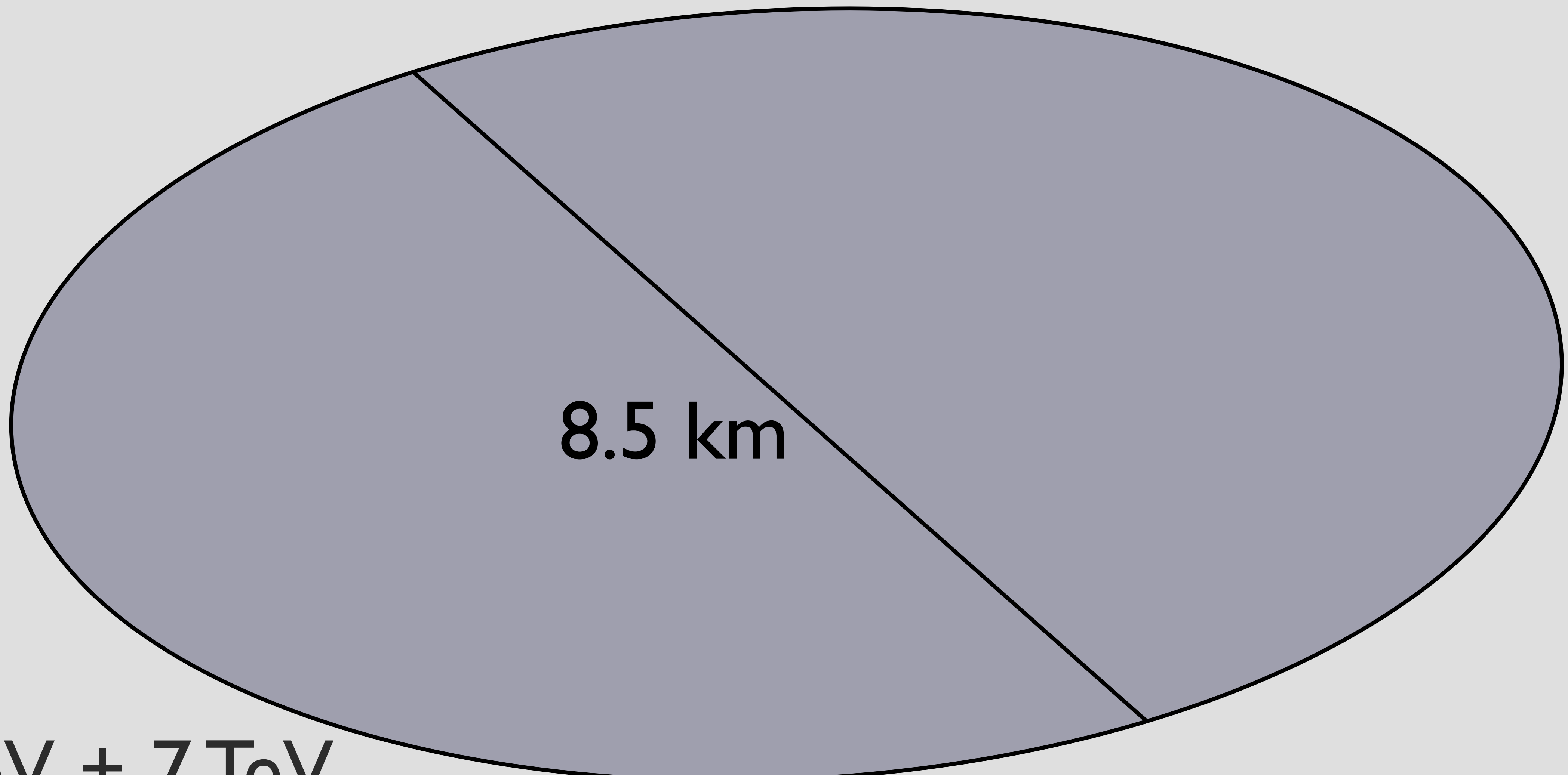


Different relevant degrees
of freedom and dynamics
associated with each energy scale

Limited information about
higher energies contained
in feeble effects at lower energies

$$R \propto \frac{p}{B}$$

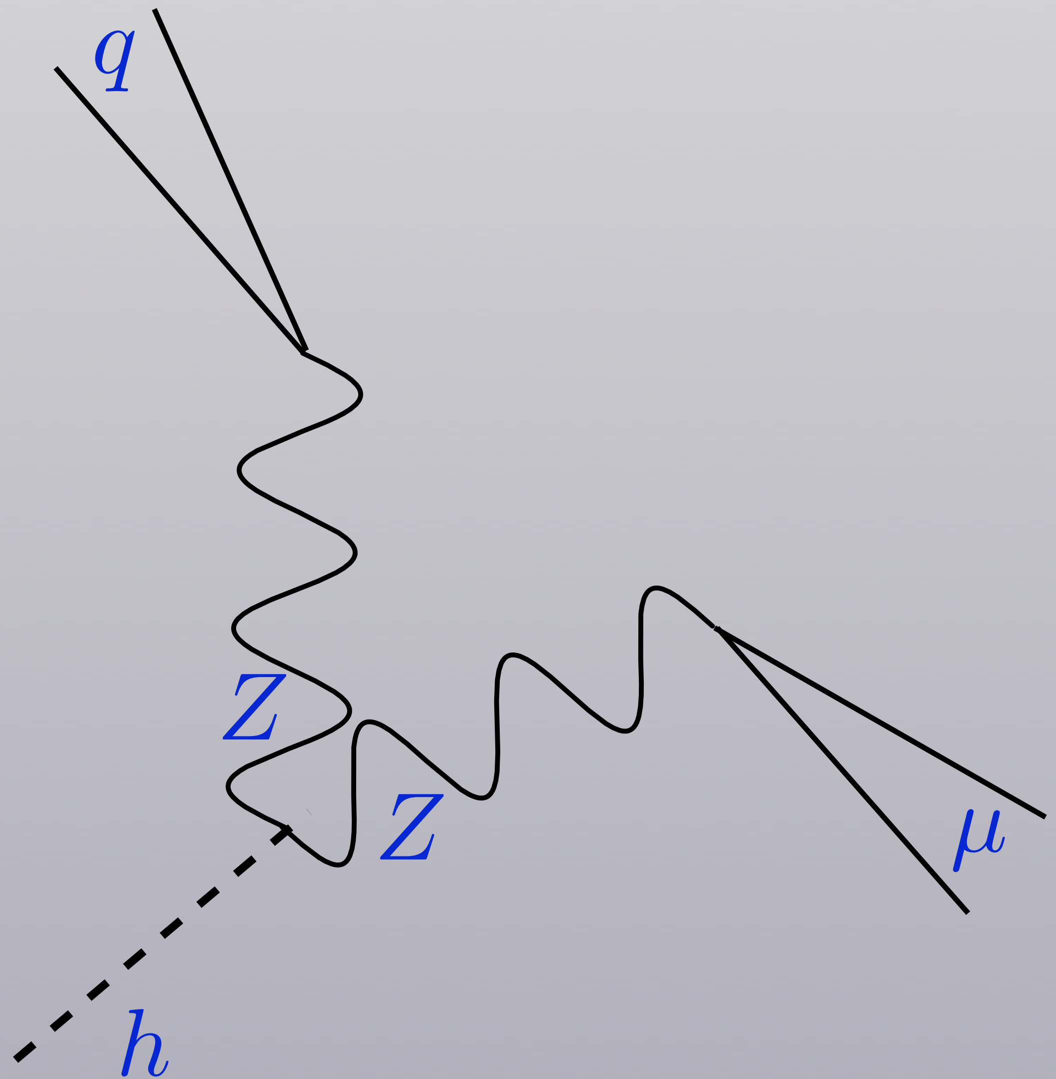
$$\text{synchrotron radiation} \propto \frac{E^4}{R^2 m^4}$$



7 TeV + 7 TeV
protons

Energy use
400 GWh/year

A typical Higgs event



Event rates:

10^9 Hz
$\mathrm{p} + \mathrm{p} \to \mathrm{anything}$

10^{-5} Hz
Higgs events

CMS Collaboration

Maximally Large Hadron Collider

$$\frac{R_{\mathrm{MLHC}}}{R_{\mathrm{LHC}}}\ 7\ \mathrm{TeV} \approx 10,000\ \mathrm{TeV}$$

Ultra-high energy cosmic rays have been observed up to energies of 100,000,000 TeV

The Standard Model of elementary particles

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

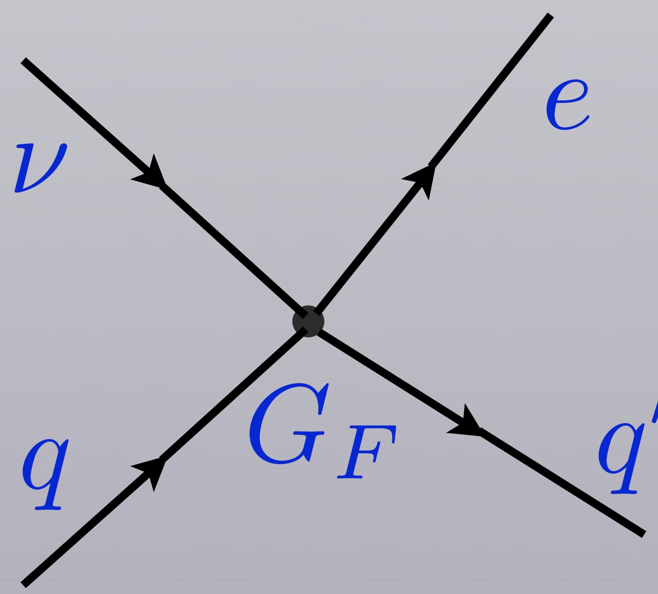
Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Missing piece:

- Higgs boson
- charge=0
- spin=0
- mass>114 GeV

Unitarity argument for the Higgs

Heavy gauge bosons, W and Z, were expected long before their discovery based on scattering cross sections

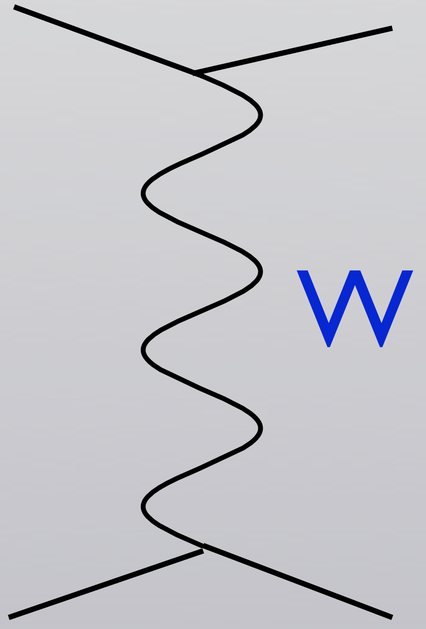


$$G_F \propto \frac{1}{M^2} \Longrightarrow \sigma \propto \frac{E^2}{M^4}$$

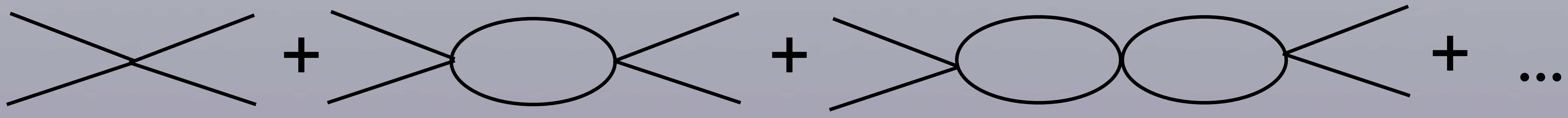
Cross section ceases to be unitary for E > M

a) heavy vector bosons, W and Z,
- the electroweak theory

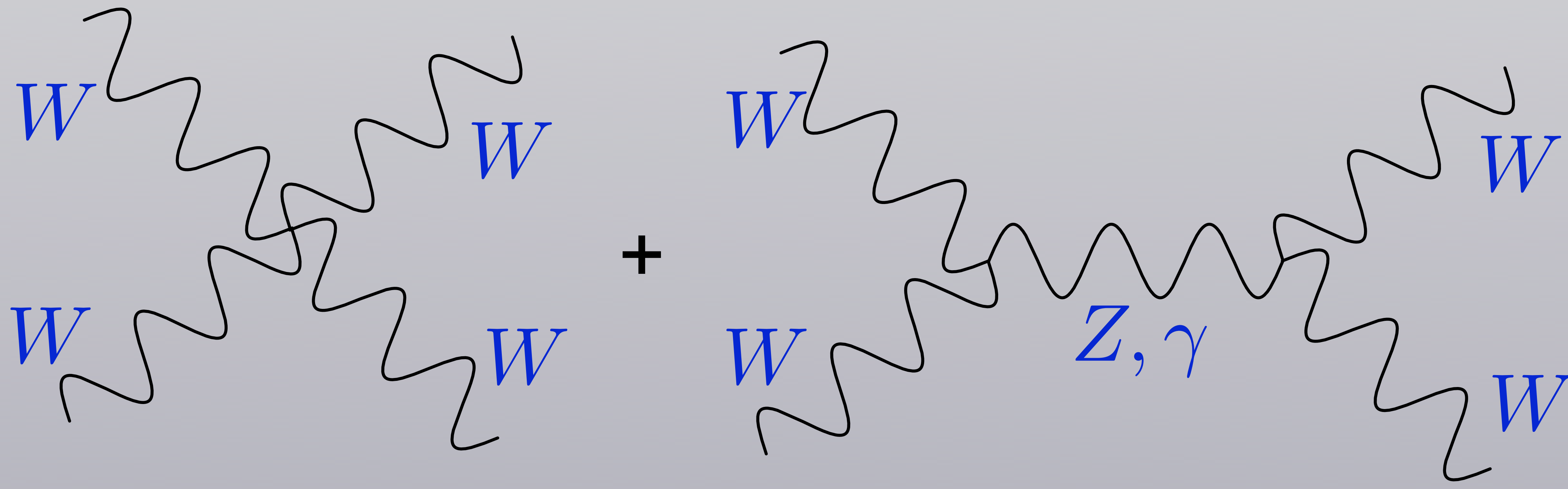
$$\sigma \propto \frac{E^2}{(E^2 - M^2)^2} \approx \frac{1}{E^2}$$



b) strong interactions

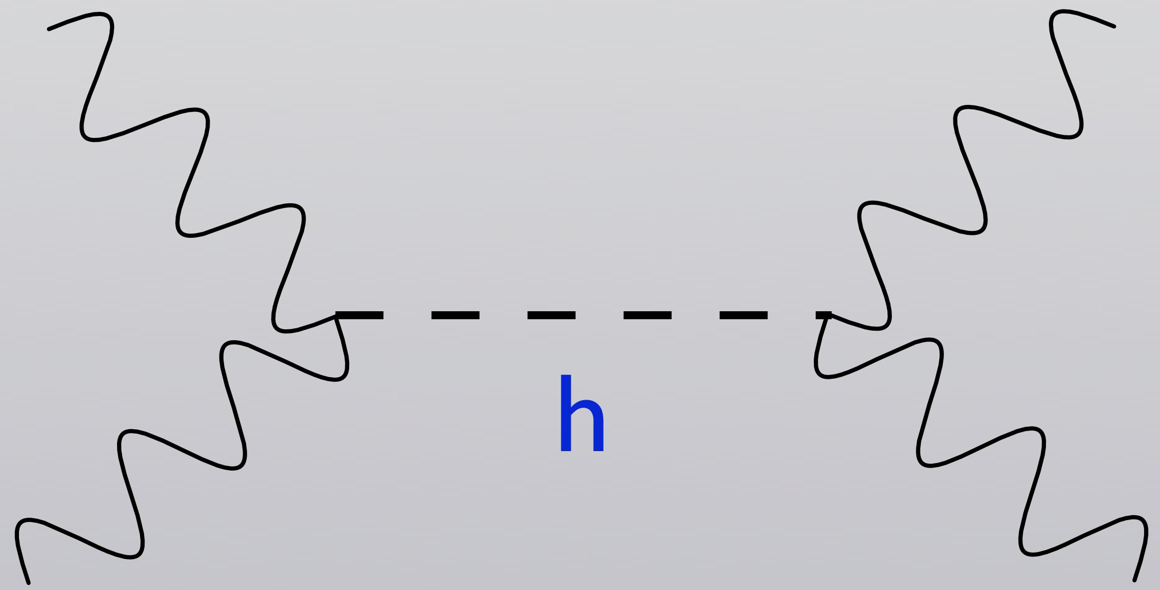


Standard Model with only the particles discovered so far, that is without the Higgs, violates unitarity at about 1 TeV



$$\sigma \propto \frac{E^2}{M_W^4}$$

a) Higgs boson, h, in the range accessible by LHC



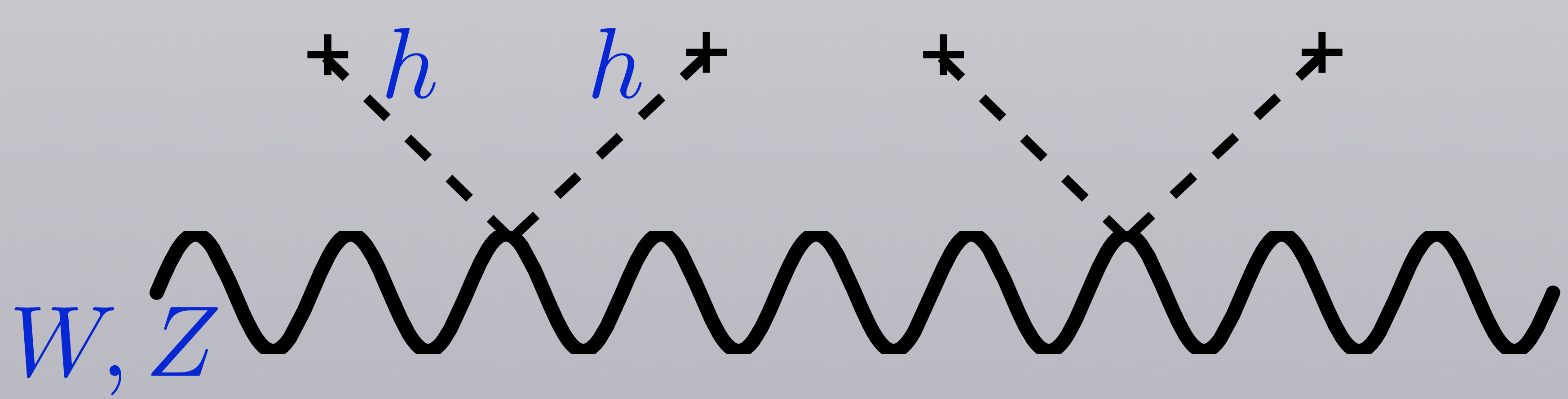
b) strong interactions (technicolor, Higgsless models)

The "no-lose" theorem for the LHC:
either the Higgs
or strong interactions with associated resonances
will be discovered

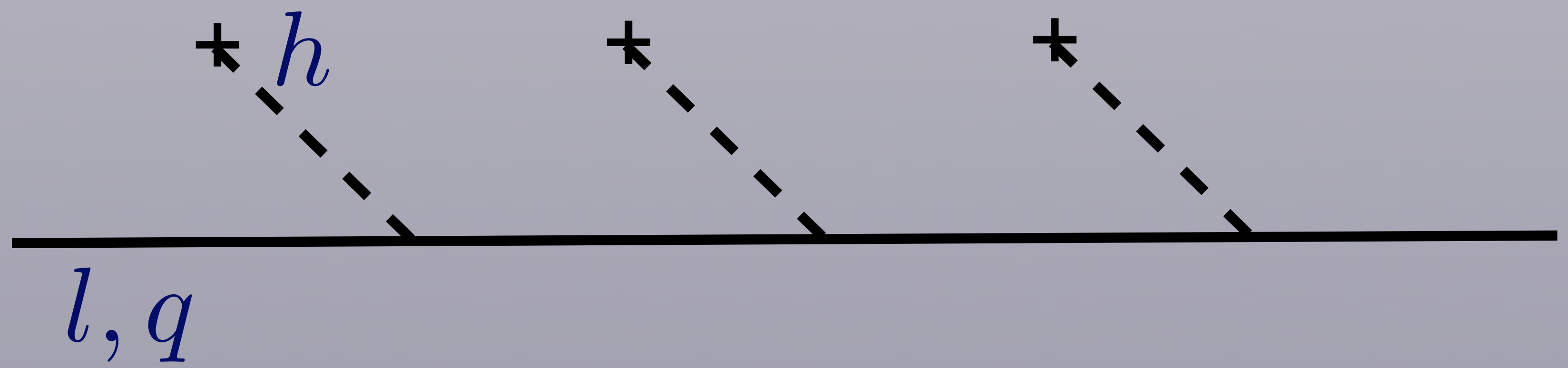
Higgs boson in the Standard Model

a) Restores unitarity in $WW \to WW$ scattering

b) Provides masses for gauge bosons

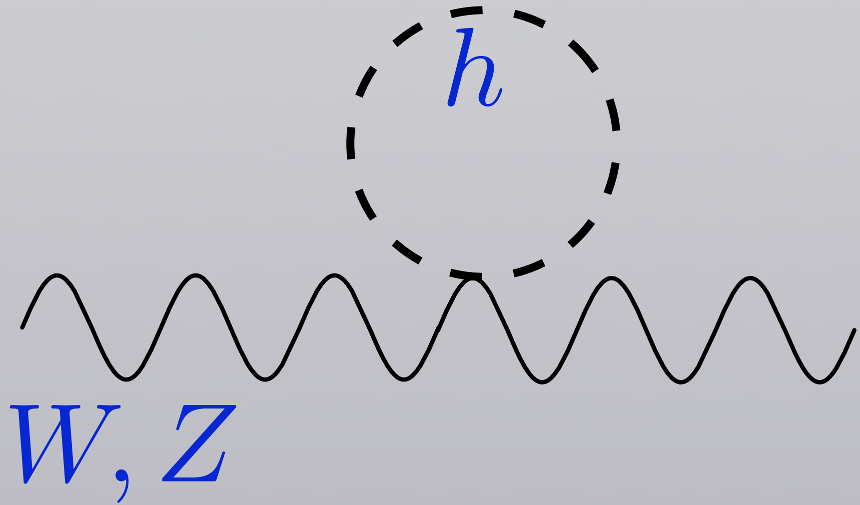


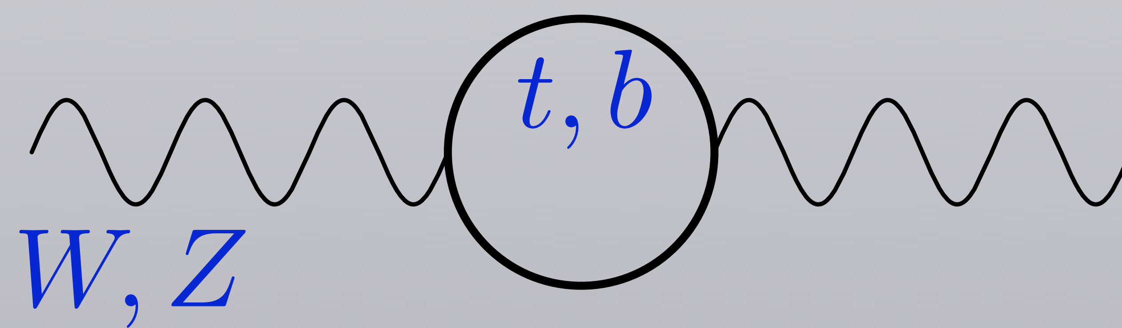
c) Provides masses for matter: leptons and quarks



Precision measurements test Higgs couplings

$$\rho \equiv \frac{M_W^2}{M_Z^2 \cos\theta} \quad (= 1 \text{ without loop corrections })$$



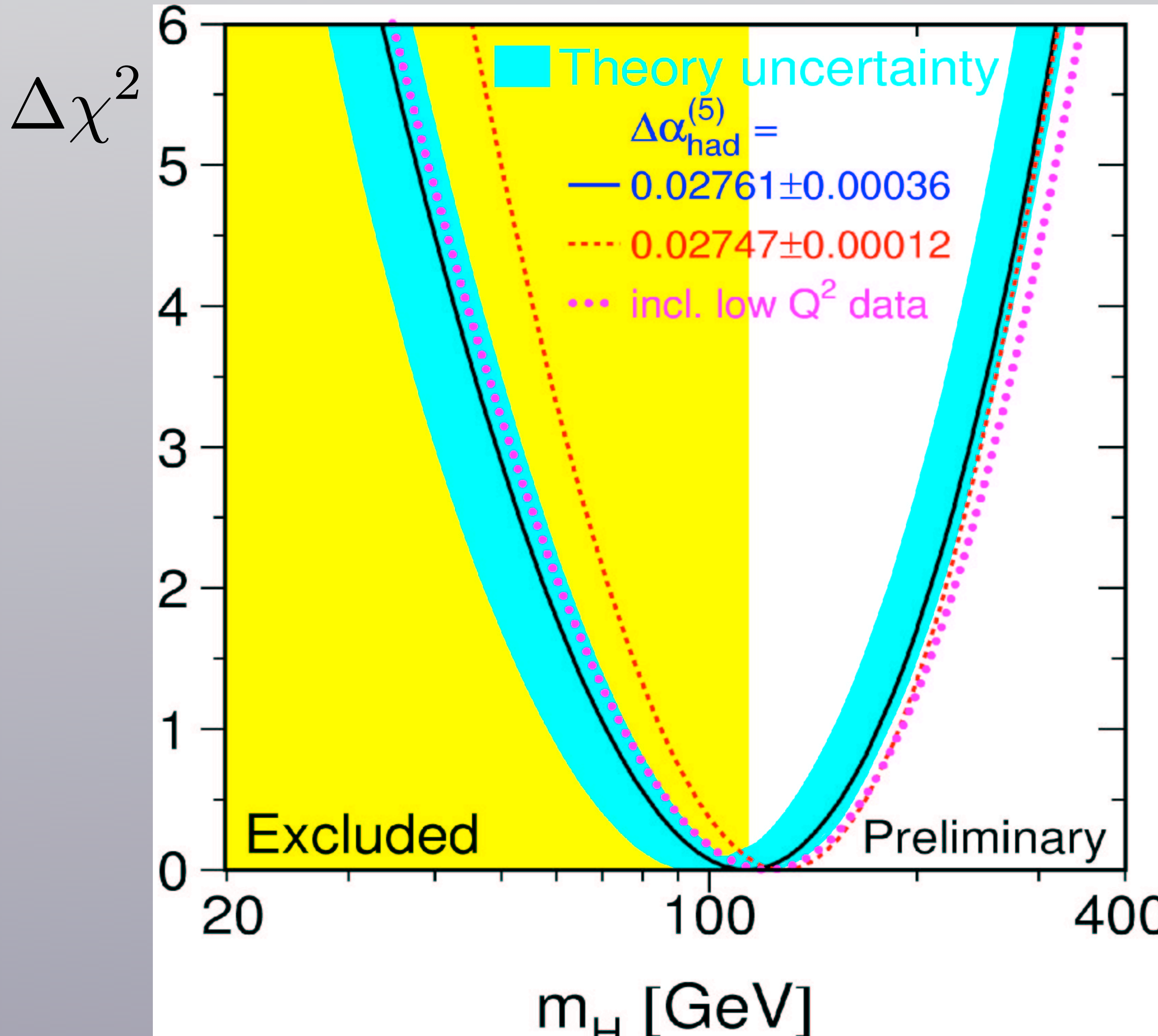


Including loop corrections:

$$\rho = 1.012 \pm 0.001$$

Indirect evidence for light Higgs boson

$$M_H < 269 \text{ GeV} (95\%)$$

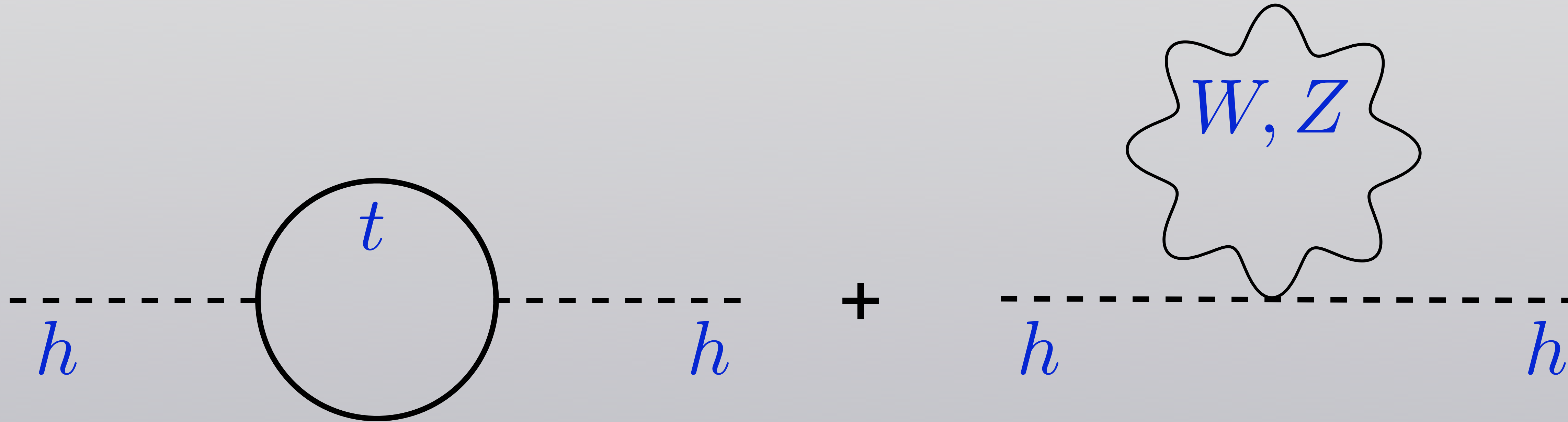


LEP electroweak working group

"only" Higgs at the LHC ?

- unlikely!

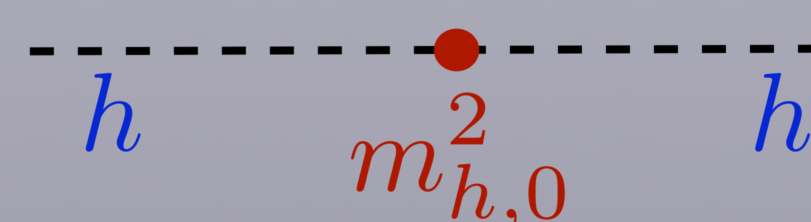
Loop contributions to the Higgs mass



Let's assume that the Standard Model is correct up to energy scale Λ

$$\delta m_h^2 \approx -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2 + \frac{g^2}{16\pi^2}\Lambda^2 + \dots$$

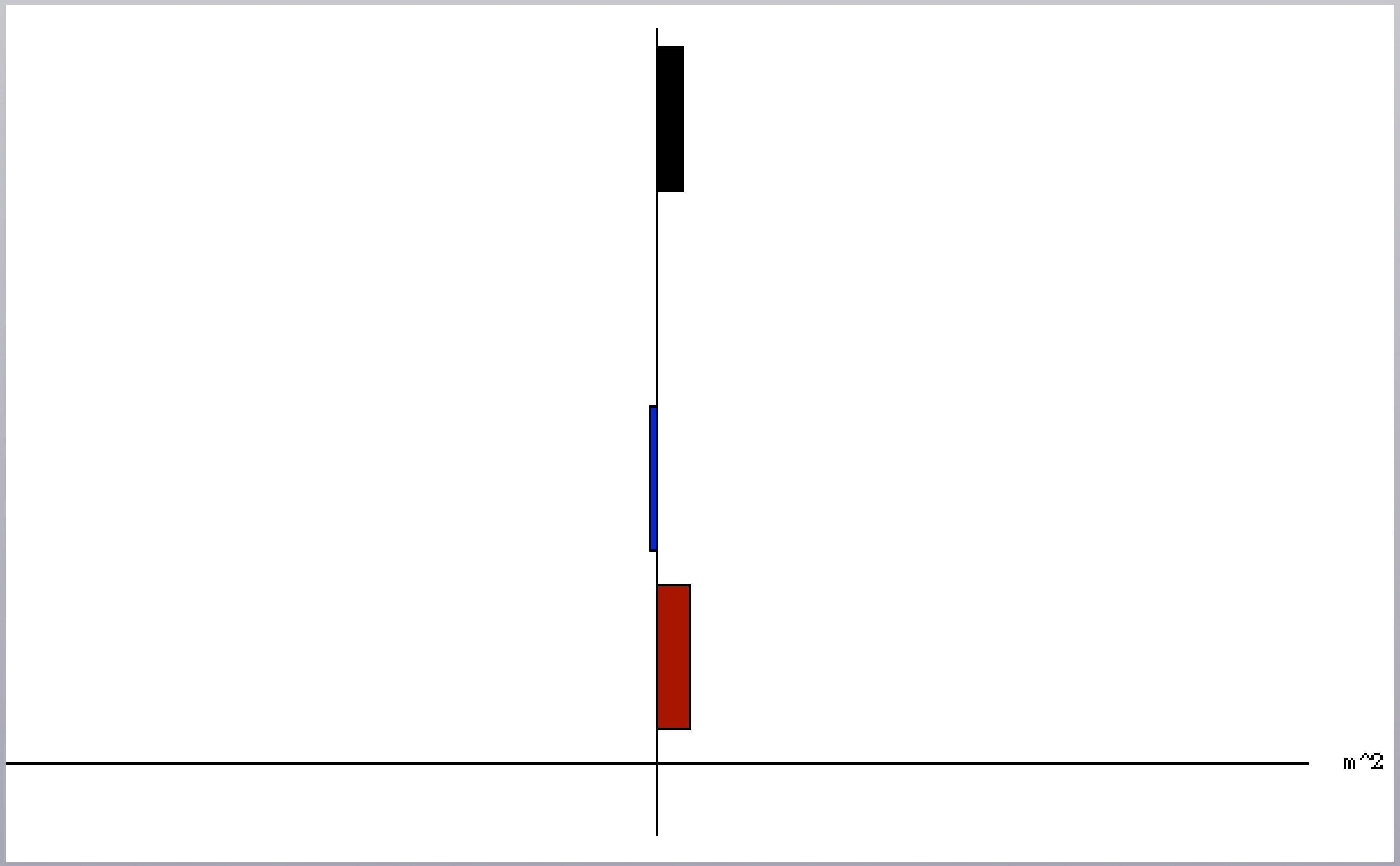
$$m_{h,\text{physical}}^2 = \delta m_h^2 + m_{h,0}^2$$



Higgs naturalness (fine tuning) problem:

$$m^2_{h,\mathrm{physical}} = \delta m^2_h + m^2_{h,0}$$

$(114\text{-}300\ \mathrm{GeV})^2$ increase $\propto \Lambda^2$



$m^2_{h,\mathrm{physical}}$

$\delta_{\mathrm{gauge}}\, m^2_h$

$\delta_{\mathrm{top}}\, m^2_h$

$m^2_{h,0}$

Fine tuning in the Standard Model with a Higgs boson corresponds to

$$\frac{\mathrm{H}}{\mathrm{D}} = 10^{32}$$

All solutions to the naturalness problem : very short pencils with

$$\mathrm{H} \approx \mathrm{D}$$

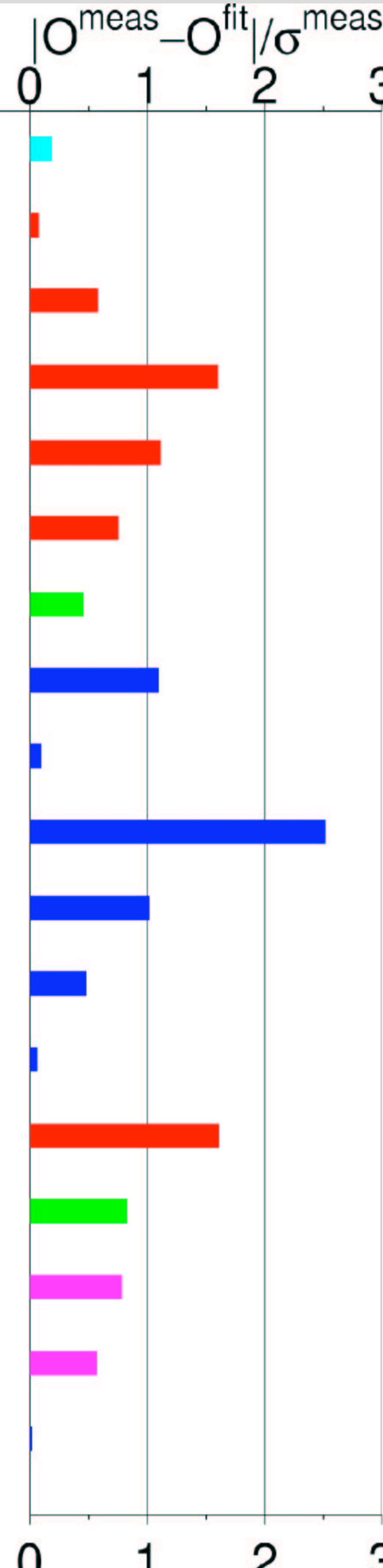
Avoiding fine tuning:

a) Extra dimensions (”large” or “warped”)
- gravity at low scales, no large hierarchy

b) Technicolor, Higgsless models
- there is no elementary Higgs, so there is no problem

c) Supersymmetry, little Higgs
- loop contributions from SM particles
are canceled by new heavier states

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1873
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21638 ± 0.00066	0.21566
R_c	0.1720 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0997 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0706 ± 0.0035	0.0742
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.398
Γ_W [GeV]	2.133 ± 0.069	2.094
m_t [GeV]	178.0 ± 4.3	178.1



LEP electroweak working group

Standard Model agrees very well with the available data

These measurements also constrain new states

New particles need to be heavier than 1-5 TeV depending on their couplings (Lighter if only in loops)

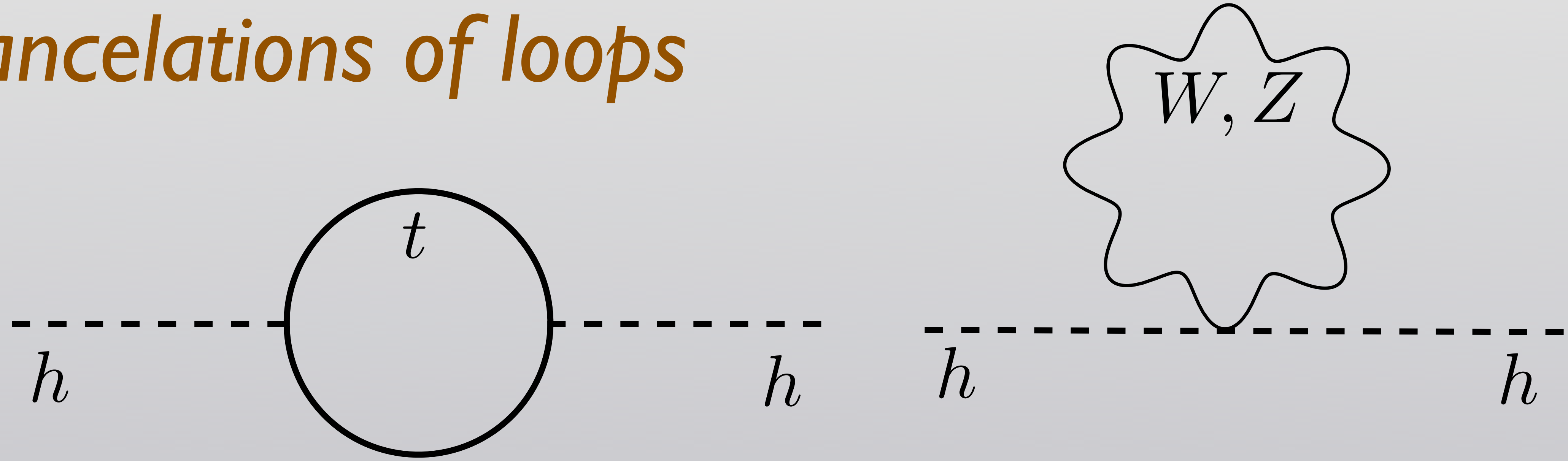
Z. Han, W. Skiba, hep-ph/0412166

Higgs naturalness or lack of fine tuning:

- There must be heavy particles that give additional contributions to the Higgs mass
- Symmetry reason for a cancelation of loop contributions arising from different states
- To minimize fine tuning cancelation of top loops at the lowest scale, followed by cancelation of gauge boson loops

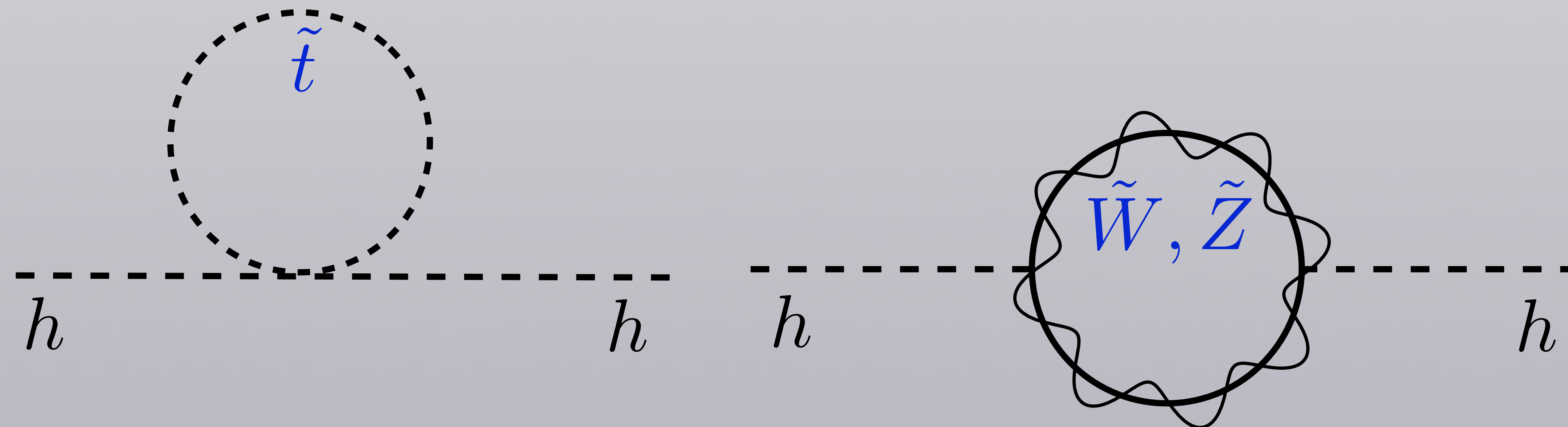
Cancelations of loops

Standard Model



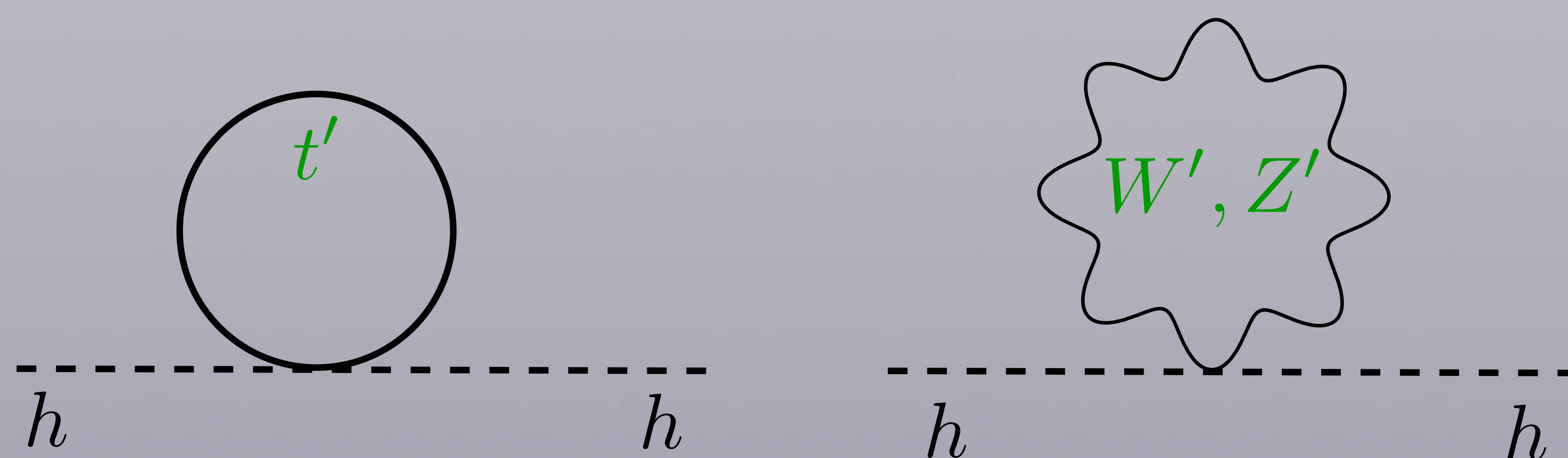
SUSY

boson-fermion

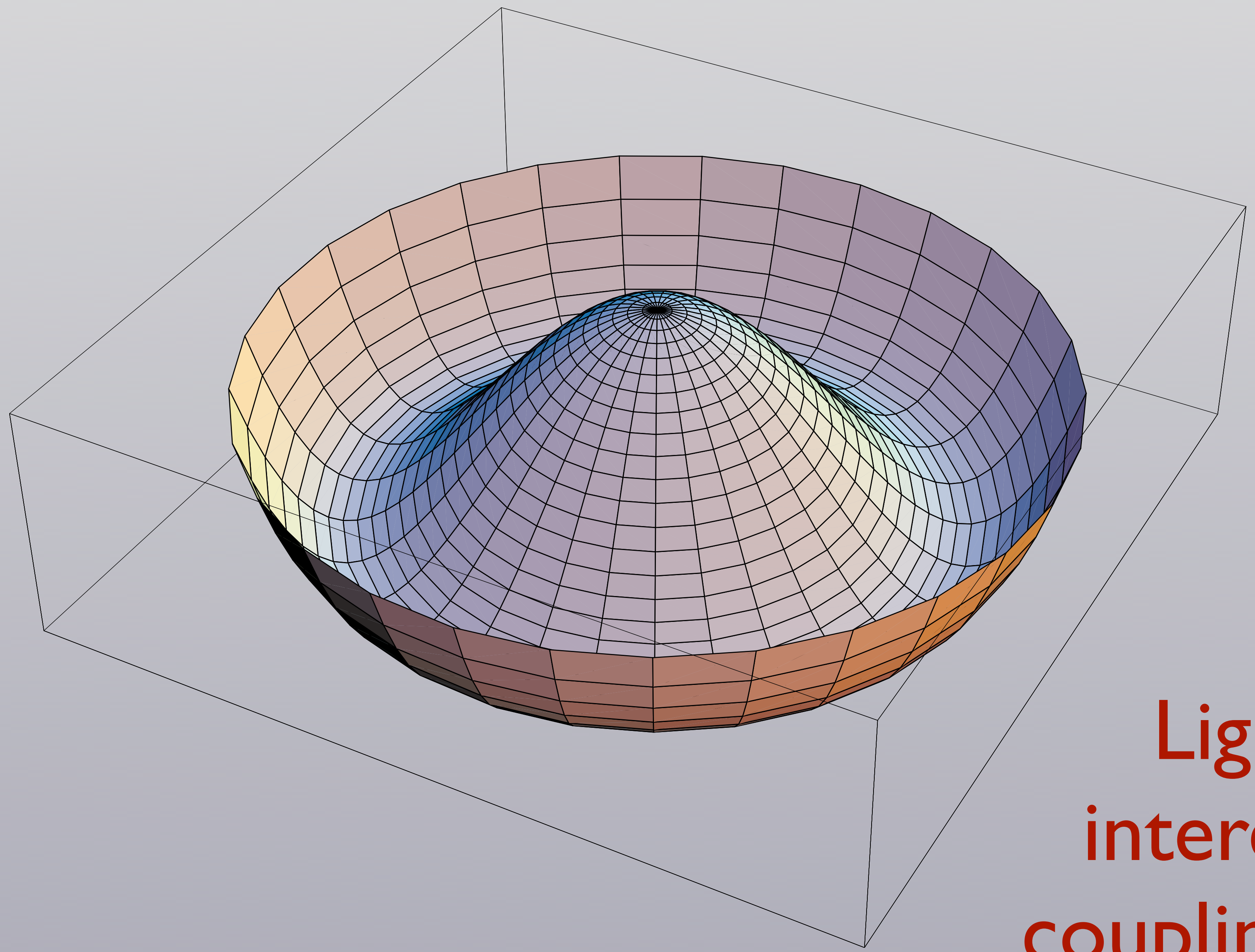


Little Higgs

approximate global shift symmetry



Massless scalar field

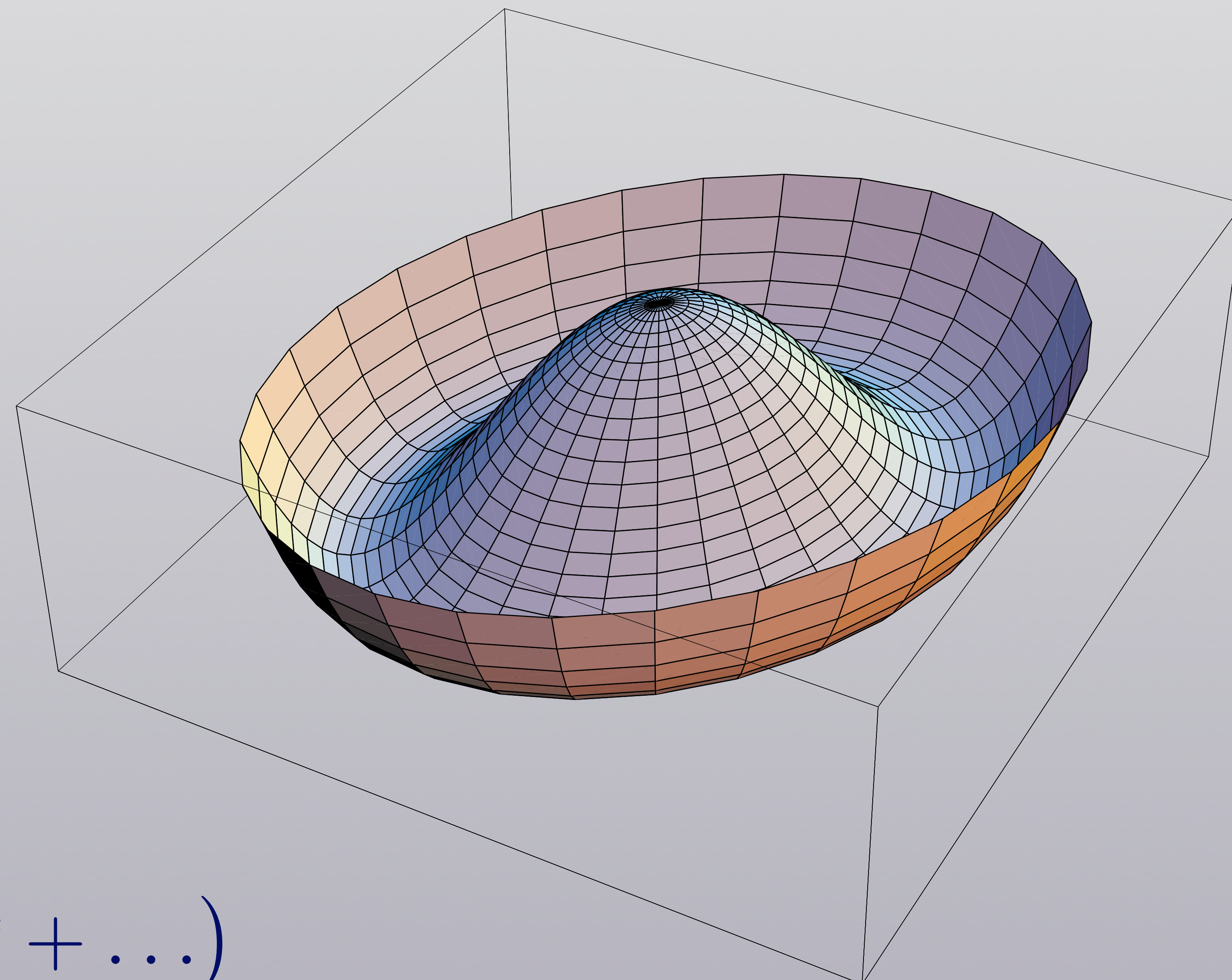


no potential for the angle $\varphi(x)$, symmetry:

$$\varphi(x) \to \varphi(x) + \alpha$$

Light, but not very interesting scalar field: couplings to fermions and gauge bosons are forbidden by the shift symmetry

Broken symmetry



Better, but not good enough!

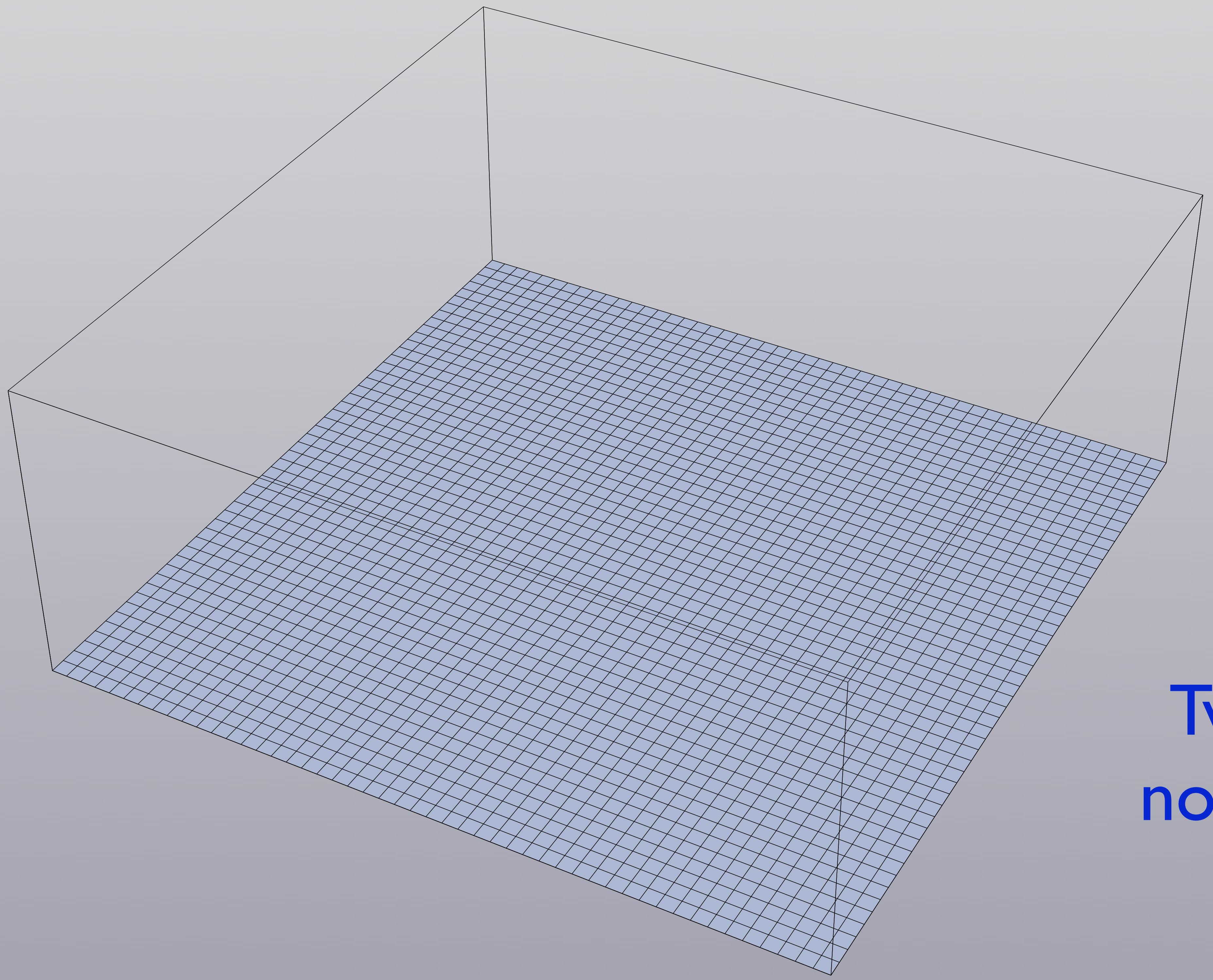
$$V(\varphi) = \epsilon \left(a_2\,\varphi^2 + a_4\,\varphi^4 + \ldots \right)$$

All terms are proportional to ϵ

Higgs boson requires $a_2 \ll \Lambda^2$ and $a_4 \approx 1$

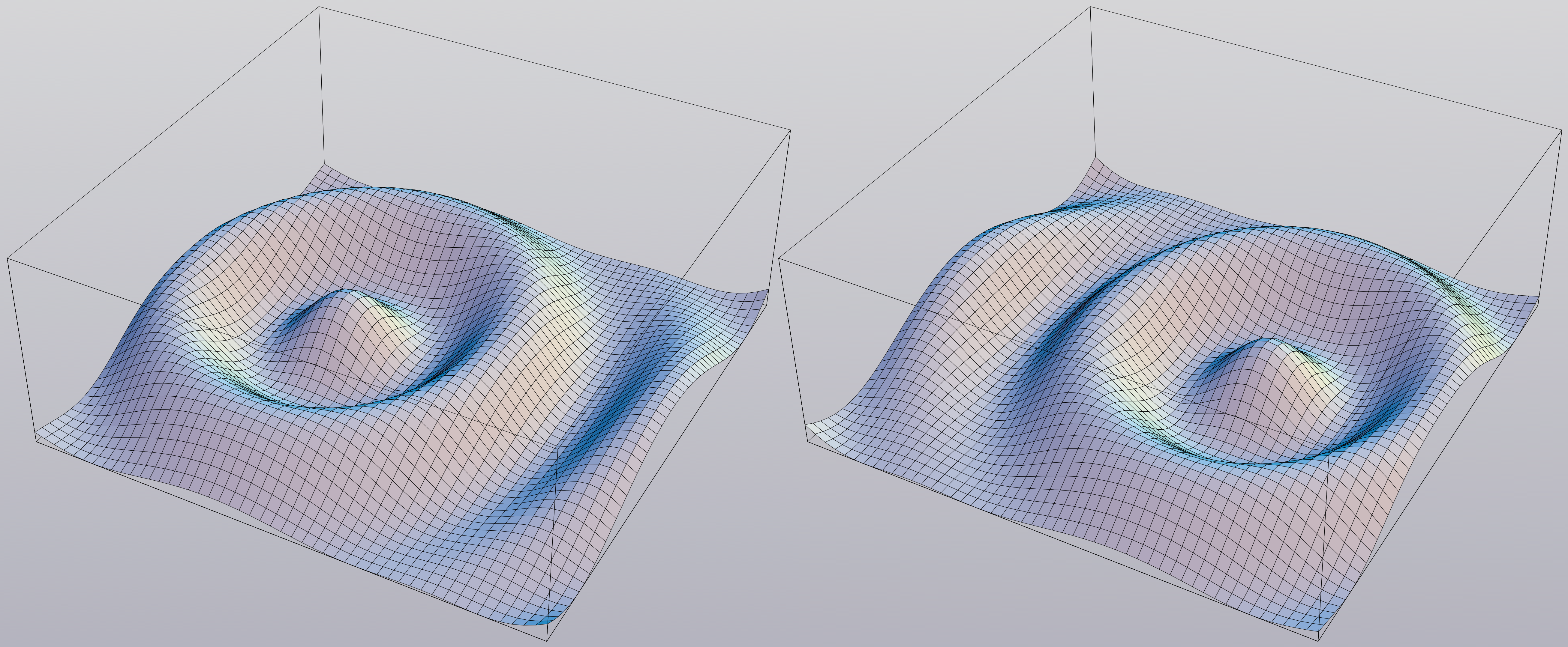
Collective symmetry breaking

Arrange two different sources of symmetry breaking



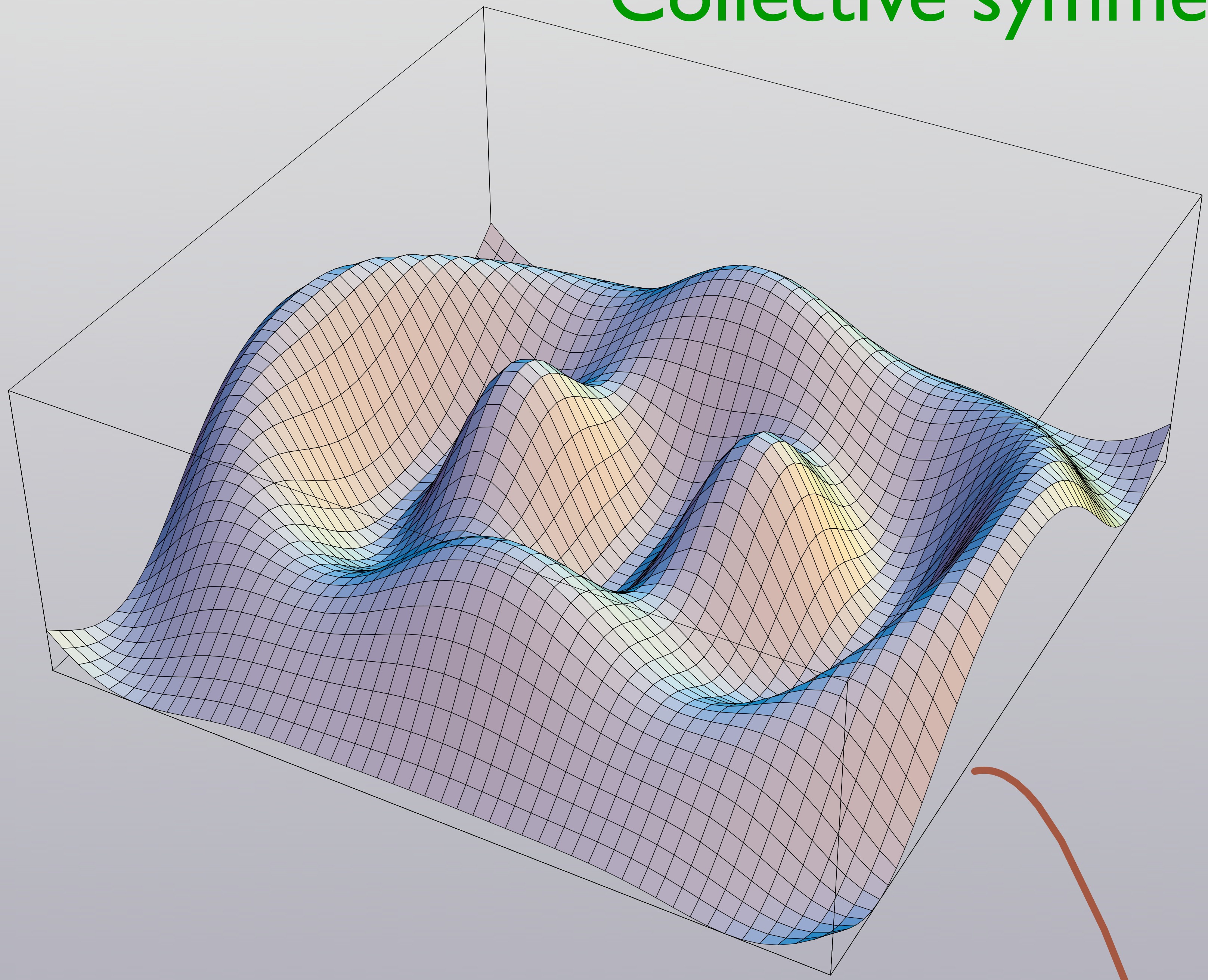
Two fields
no potential

Collective symmetry breaking

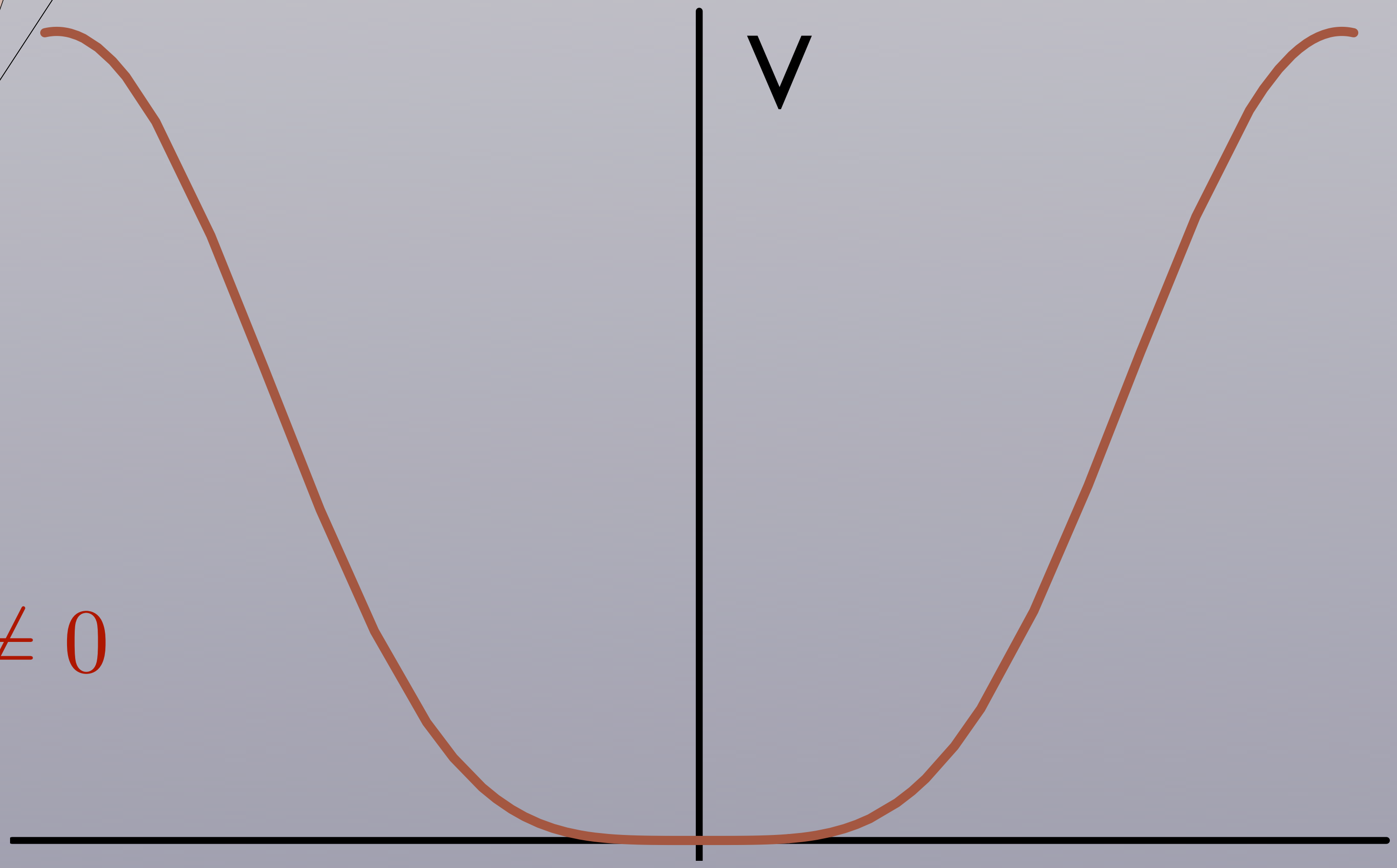


Massless field at the bottom of each potential well

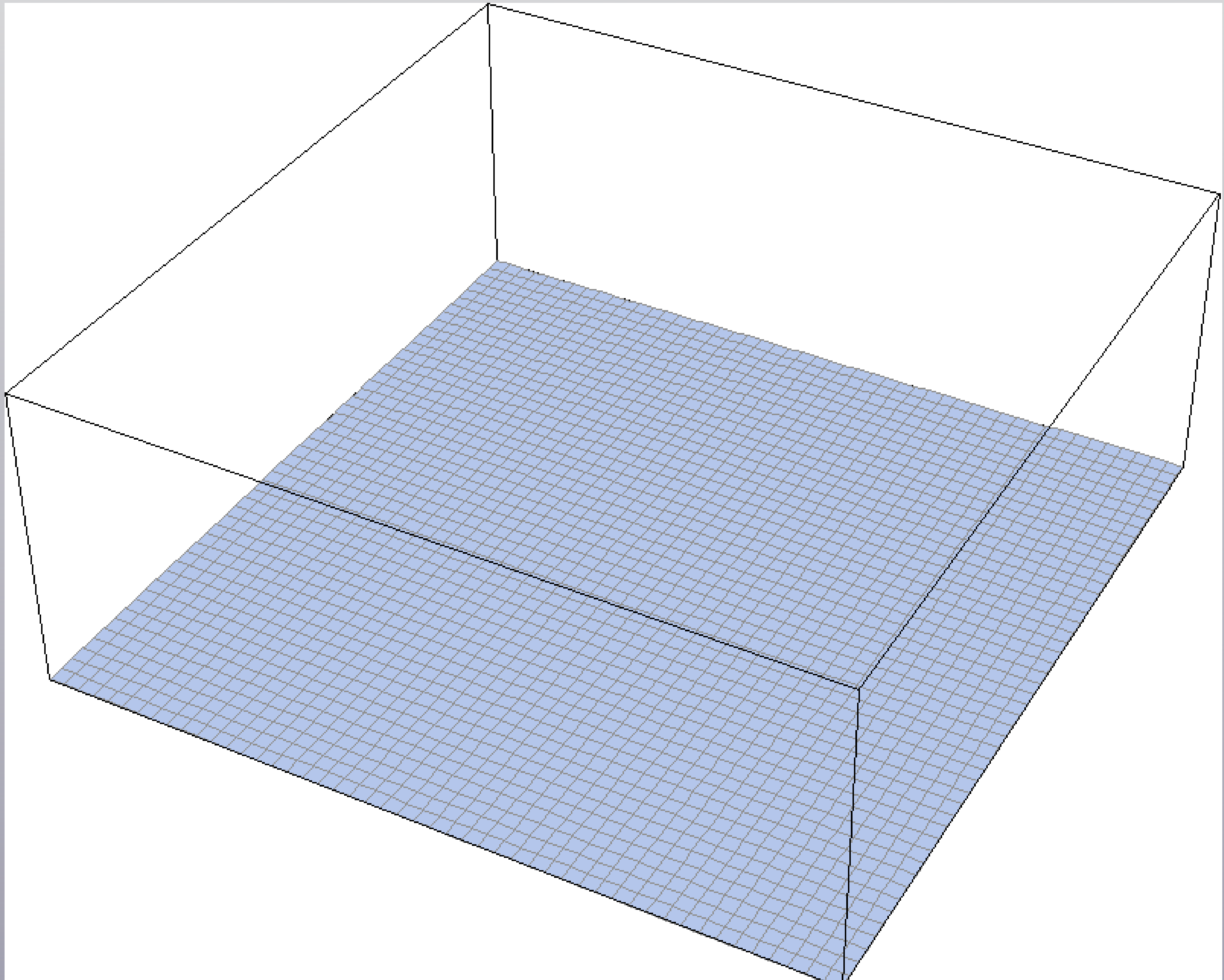
Collective symmetry breaking



$a_2 = 0$ and $a_4 \neq 0$



Collective symmetry breaking



Models

N. Arkani-Hamed, A. Cohen, H. Georgi, ph/0105239 $\left[\frac{SU(3)\times SU(3)}{SU(3)}\right]^N$

N. Arkani-Hamed, A. Cohen, E. Katz, A. Nelson, ph/0206021 $\frac{SU(5)}{SO(5)}$

I. Low, W. Skiba, D. Smith, ph/0207243 $\frac{SU(6)}{Sp(6)}$

D.E. Kaplan, M. Schmaltz, ph/0302049 $\left[\frac{SU(4)}{SU(3)}\right]^4$

W. Skiba, J. Terning, ph/0305302 $\frac{SU(9)}{SU(8)}$

S. Chang, ph/0306034 $\frac{SO(9)}{SO(5)\times SO(4)}$

H. C. Cheng, I. Low, ph/0308199 $\left[\frac{SO(5)\times SO(5)}{SO(5)}\right]^5$

I. Low, ph/0409025 $\frac{SU(5)\times SO(5)}{SO(5)}$

......

Past and ongoing work

Implications of precision electroweak data

Detailed collider phenomenology

Underlying theory for little Higgs

Challenges

Telling apart little Higgs from other scenarios

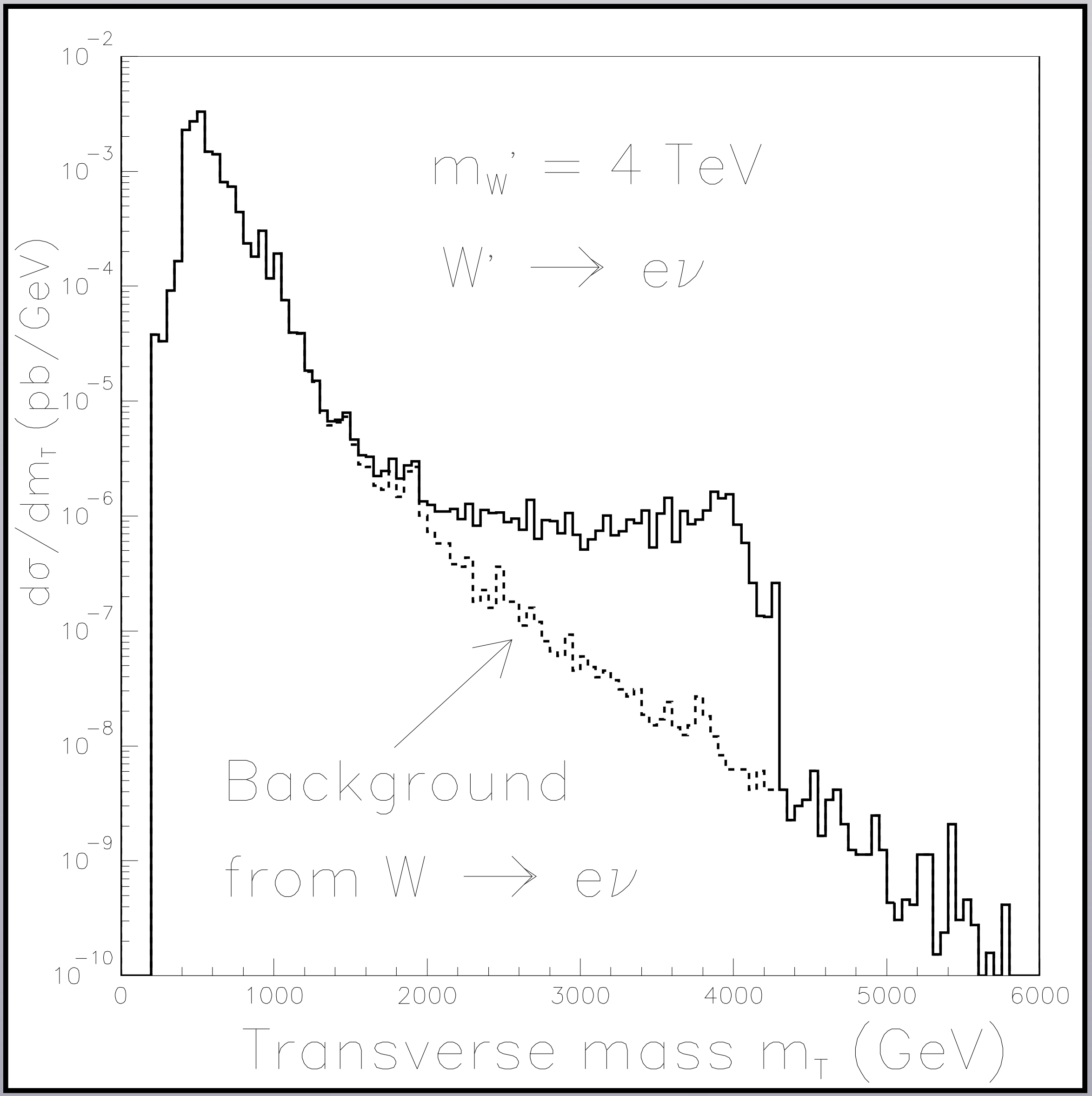
Showing little Higgs cancelation works

Back to the LHC: little Higgs predictions

1. Higgs boson or Higgs bosons
2. New, heavy quarks
3. Z' and W' gauge bosons
4. Heavy scalars

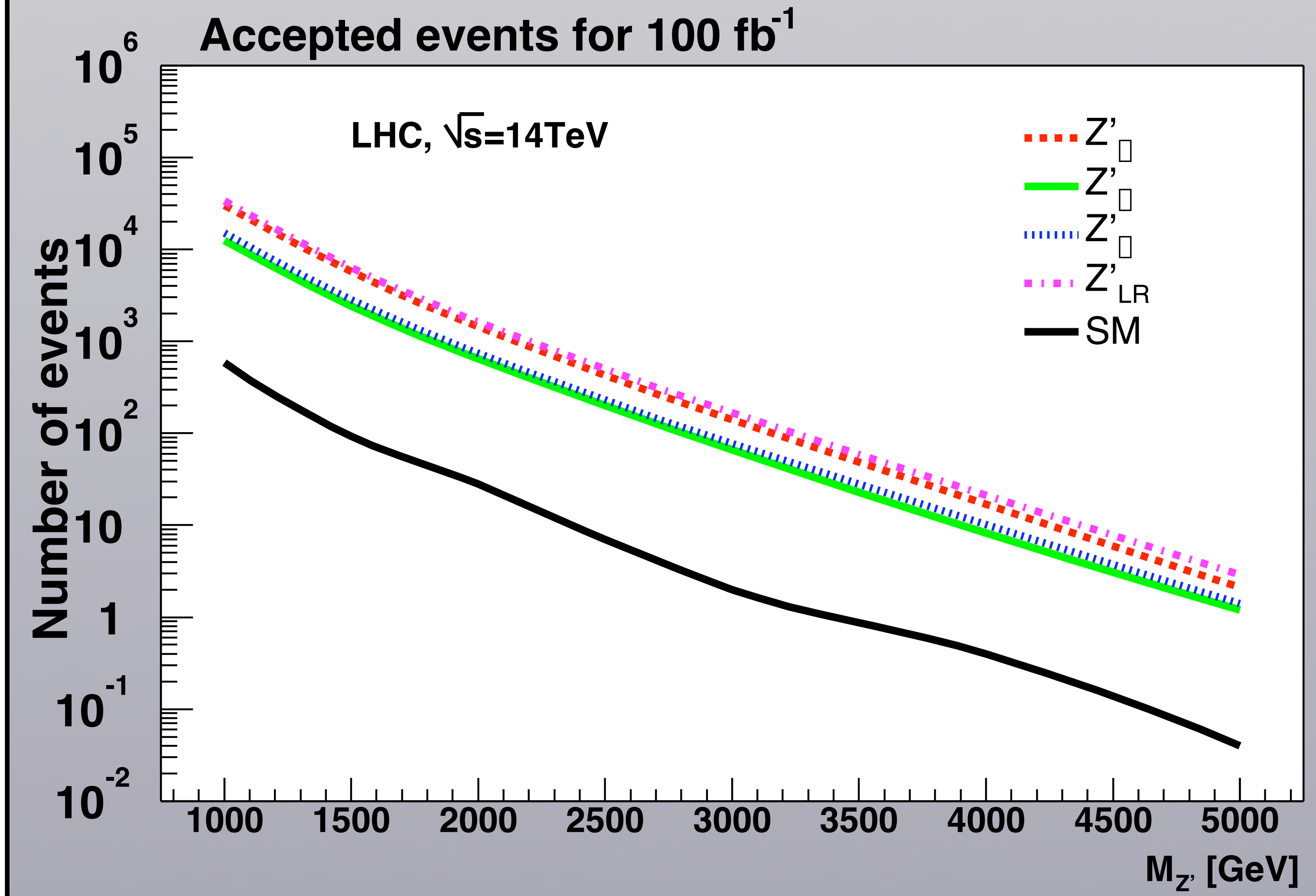
LHC discovery reach for W' and Z'

W'



ATLAS technical proposal

Z'



Dittmar, Nicollerat, Djouadi, ph/0307020

Conclusions

- The outcome of the LHC experiments will certainly not be boring (no-lose)
- A light Higgs boson is preferred by the data, however other options are still viable
- Higgs boson is likely to be accompanied by several other particles that will be within the reach of the LHC

Conclusions

- Little Higgs: a new weakly coupled solution to the Higgs naturalness problem
- Minimal model with a natural Higgs must involve a partner for the top quark and partners for the W and Z bosons
- There are several classes of candidate theories describing the TeV-scale physics, but we may be up for a surprise

the end ▪