The origin of mass and the Brout-Englert-Higgs boson

François Englert

Université Libre de Bruxelles

I. Short and long range fundamental interactions

II. Spontaneous symmetry breaking

III. The BEH mechanism

IV. The Standard Model and the electroweak theory

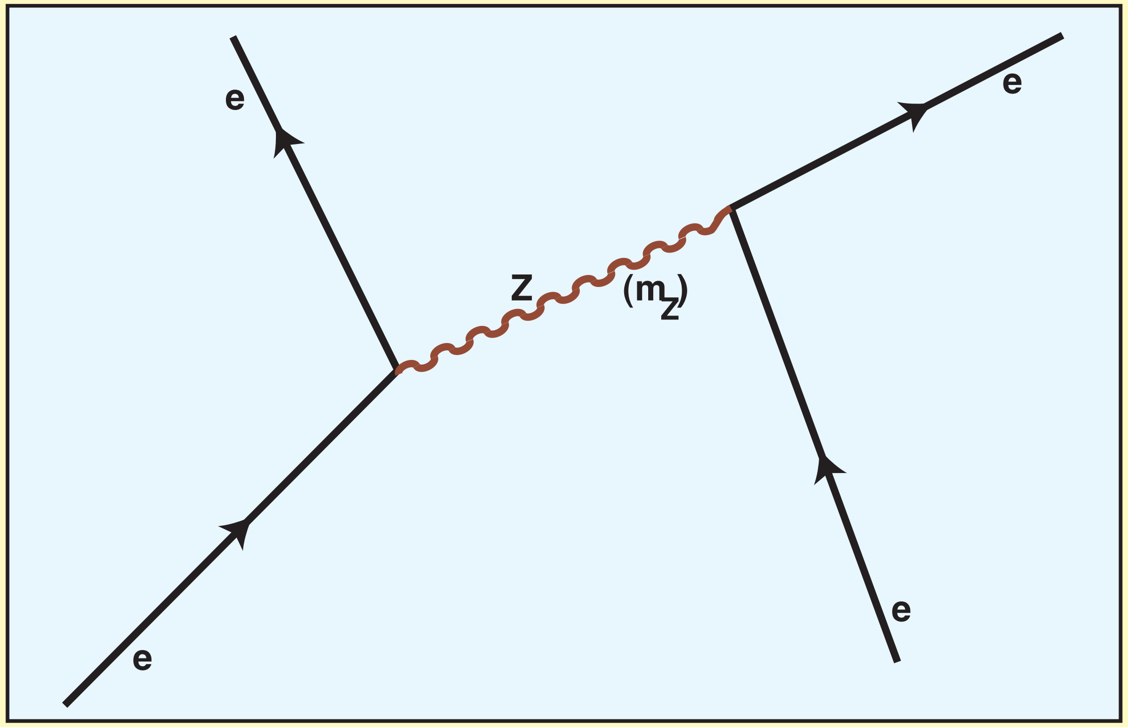
V. The discovery and the two “infinities”

Bourbaphy

29 novembre 2014

I. Short and long range fundamental interactions

The basic assumption

long range interactions	short range interactions
general relativity	
electromagnetism (quantum electrodynamics)	
zero mass vector bosons	
transverse polarization	
local symmetry	how to get vector boson masses ?
↓	↓
Yang-Mills gauge fields	**Spontaneous Symmetry Breaking ?**

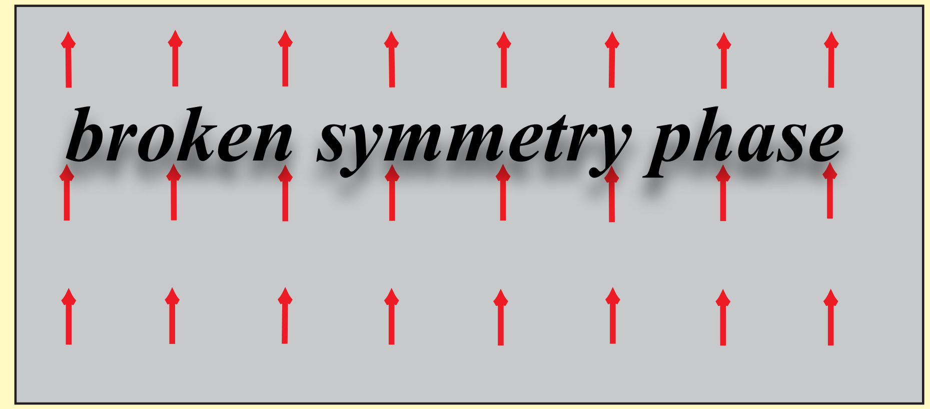
II. Spontaneous symmetry breaking

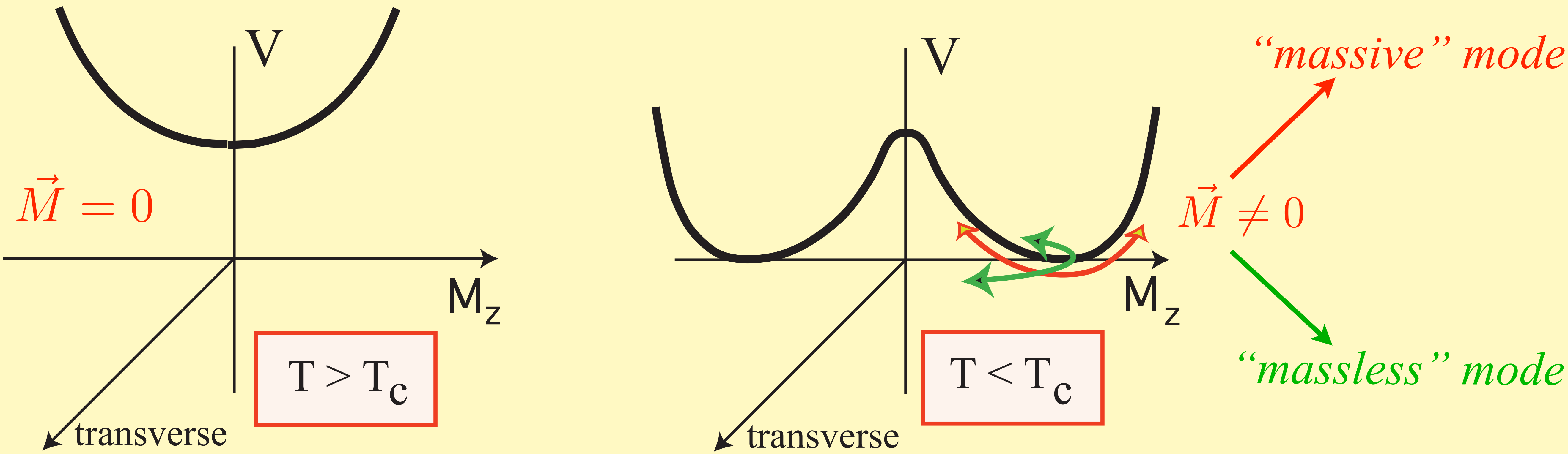
1. Spontaneous symmetry breaking in phase transitions

L.D. Landau, Phys. Z. Sowjet. **11** (1937) 26 [JETP **7** (1937) 19].

Ferromagnetism

$$H = -2 \sum_{i \neq j} v_{ij} \vec{S}_i . \vec{S}_j$$





Superconductivity

P.W. Anderson, Phys. Rev. **112** (1958) 1900; Y. Nambu, Phys.Rev. **117** (1960) 648; P.W. Anderson, Phys. Rev. **130** (1963) 439.

2. Spontaneous symmetry breaking in field theory

[1960] Y. Nambu (Nobel Prize 2008)

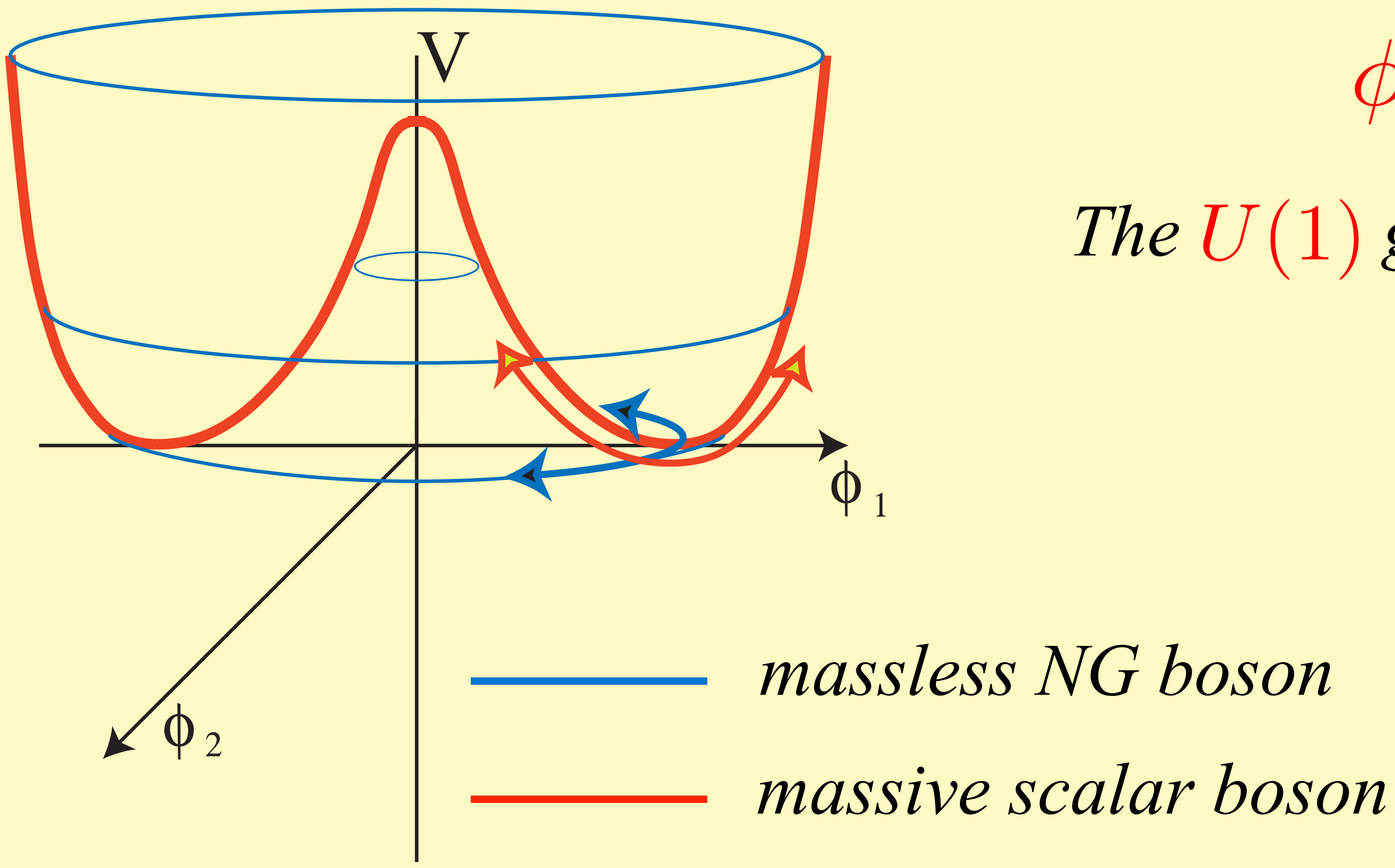
Y. Nambu, Phys. Rev. Lett. **4** (1960) 380; Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122** (1961) 345, Phys. Rev. **124** (1961) 246;
J. Goldstone, Il Nuovo Cimento **19** (1961) 154; J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127** (1962) 965.

Chiral $U(1)$ symmetry breaking

N-G pseudoscalar massless boson (pion) + massive scalar boson

The simple Goldstone $U(1)$ model

$$\mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - V(\phi^*\phi) \qquad V(\phi^*\phi) = -\mu^2 \phi^*\phi + \lambda(\phi^*\phi)^2$$



$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$$

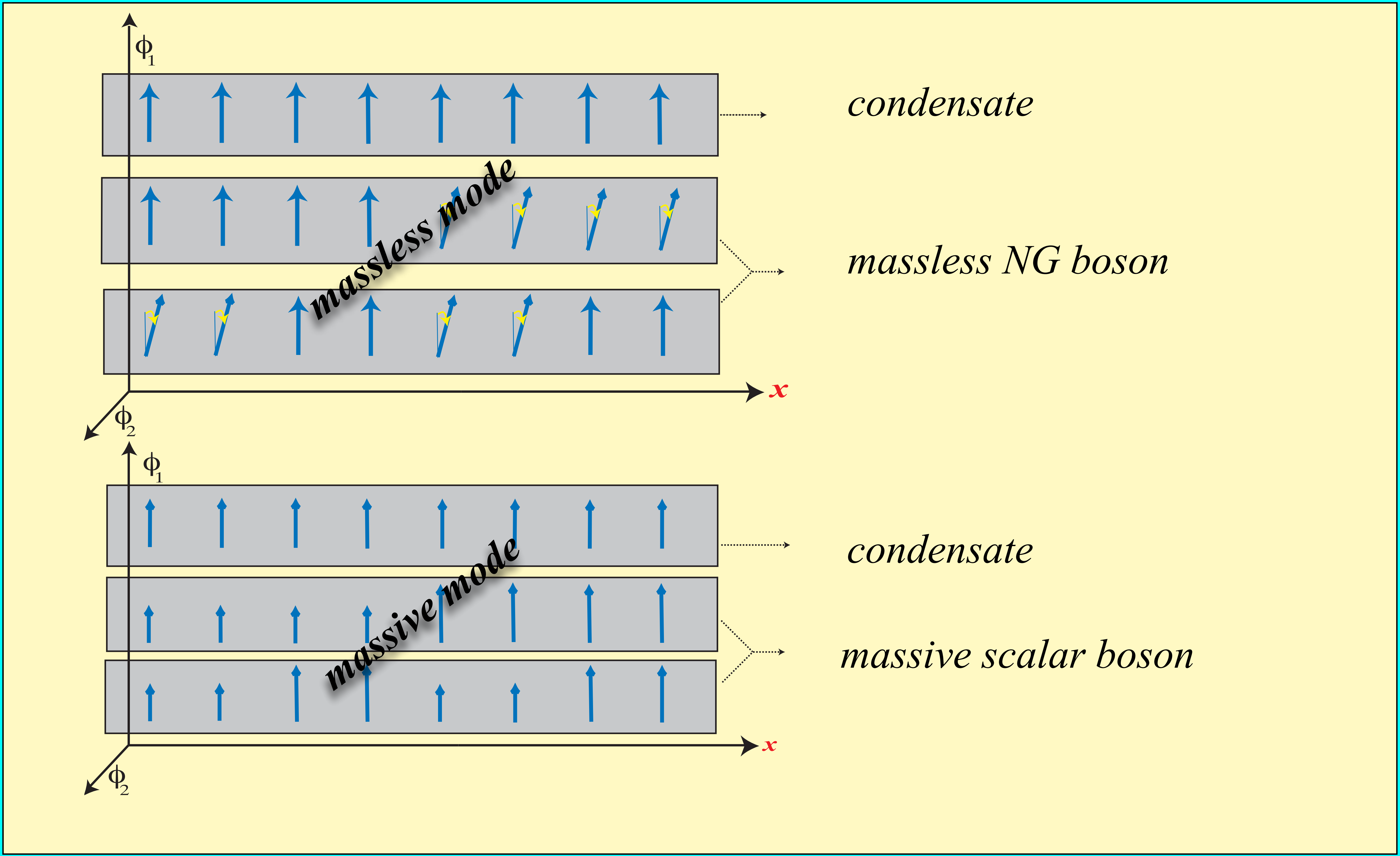
The $U(1)$ global symmetry is broken by $\langle\phi\rangle$

$$\boxed{\langle\phi_1\rangle \neq 0}$$

$$\phi = \langle\phi\rangle + \varphi$$

$$\phi_2 = \varphi_2$$

$$\phi_1 = \langle\phi_1\rangle + \varphi_1$$



ϕ_1
condensate
massless mode
massless NG boson
x
ϕ_2
ϕ_1
condensate
massive mode
massive scalar boson
x
ϕ_2

III. The BEH mechanism

F. Englert and R. Brout, Phys. Rev. Lett. **13** (1964) 321, P.W. Higgs, Phys. Rev. Lett. **13** (1964) 508.

1. From global to local symmetry

Global abelian symmetry

$$\phi \longrightarrow e^{i\alpha}\phi \qquad \mathcal{L} = \partial^\mu \phi^* \partial_\mu \phi - V(\phi^*\phi)$$

Local abelian symmetry

$$\phi \longrightarrow \phi e^{i\alpha(x)} \qquad A_\mu \longrightarrow A_\mu + \frac{1}{e}\partial_\mu \alpha$$

$$D_\mu \phi = \partial_\mu \phi - ieA_\mu \phi \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

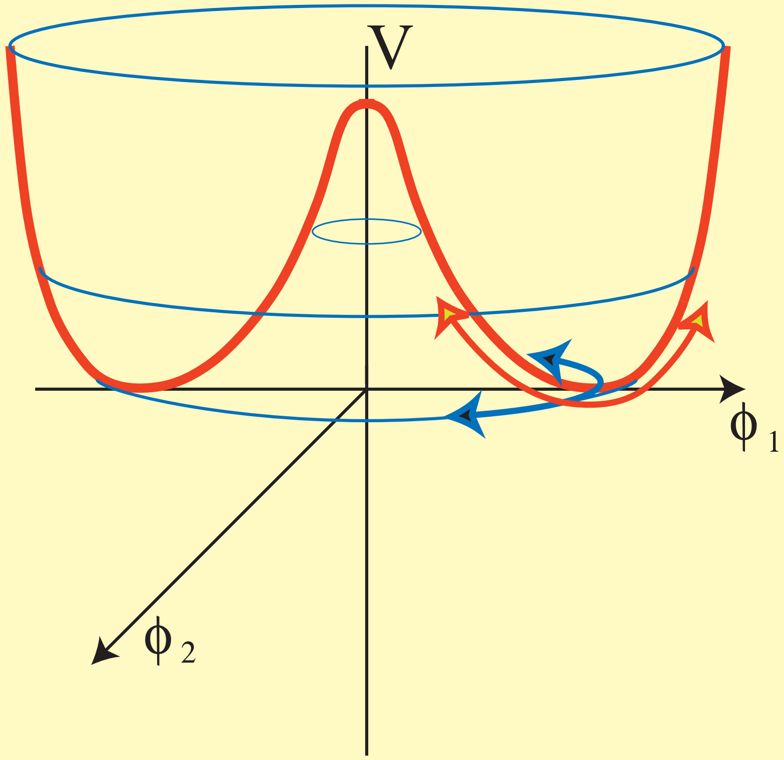
$$\mathcal{L} = D^\mu \phi^* D_\mu \phi - V(\phi^*\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

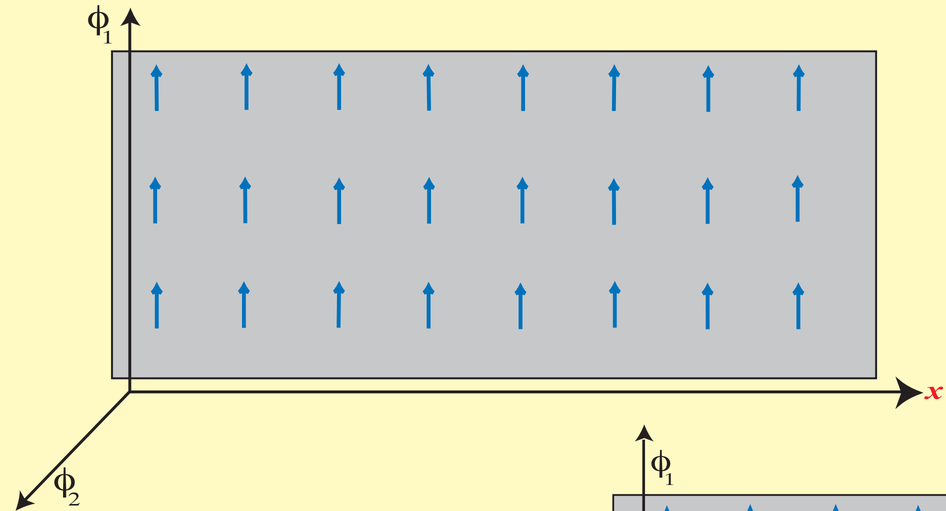
Local non-abelian symmetry

$$\begin{aligned} (D_\mu \phi)^A &= \partial_\mu \phi^A - eA_\mu^a T^{a\,AB} \phi^B \\ F_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + ef^{abc} A_\mu^b A_\nu^c \end{aligned}$$

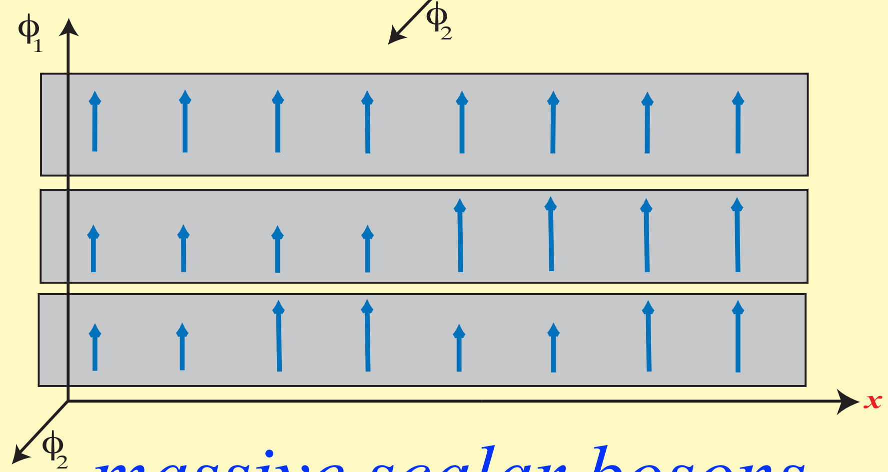
2. The fate of the Nambu-Goldstone boson

The abelian case

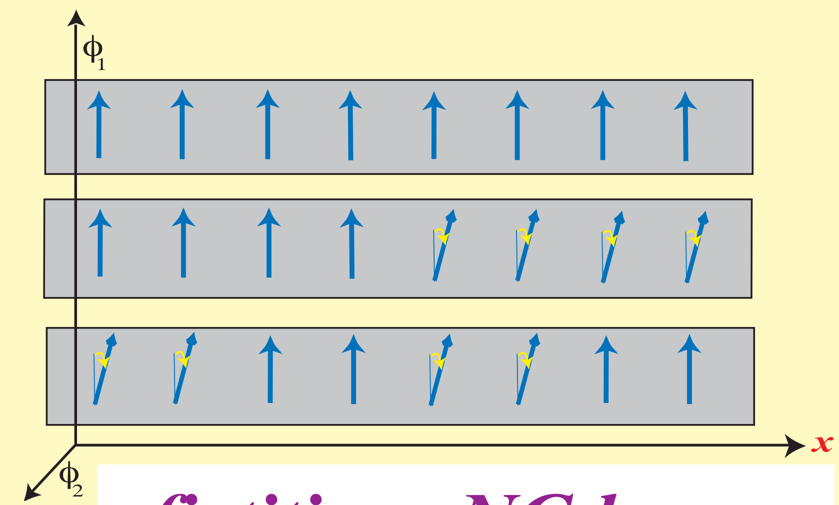




condensate



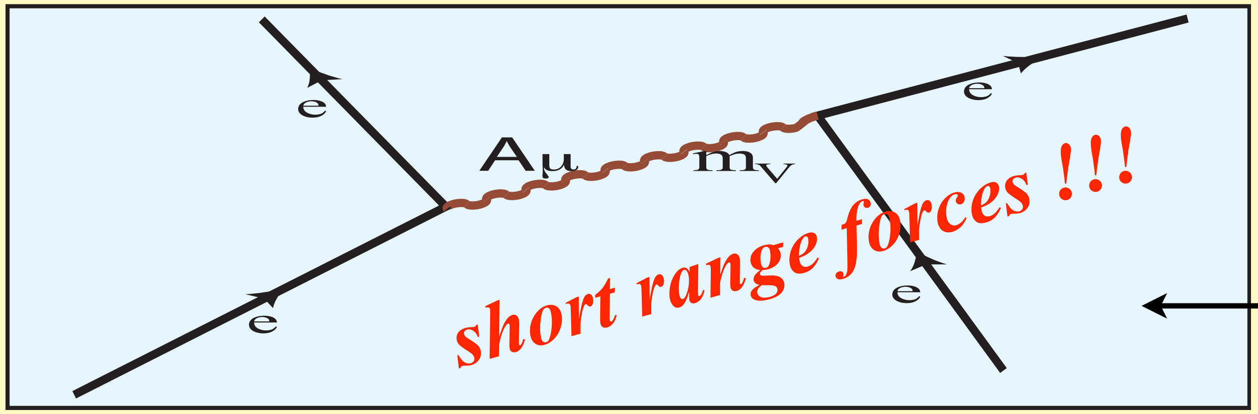
massive scalar bosons



fictitious NG boson

cf. P.W. Higgs, Phys. Letters **12** (1964) 132;
G.S. Guralnik, C.R. Hagen and T.W.B. Kibble, Phys. Rev. Lett. **13** (1964) 585.

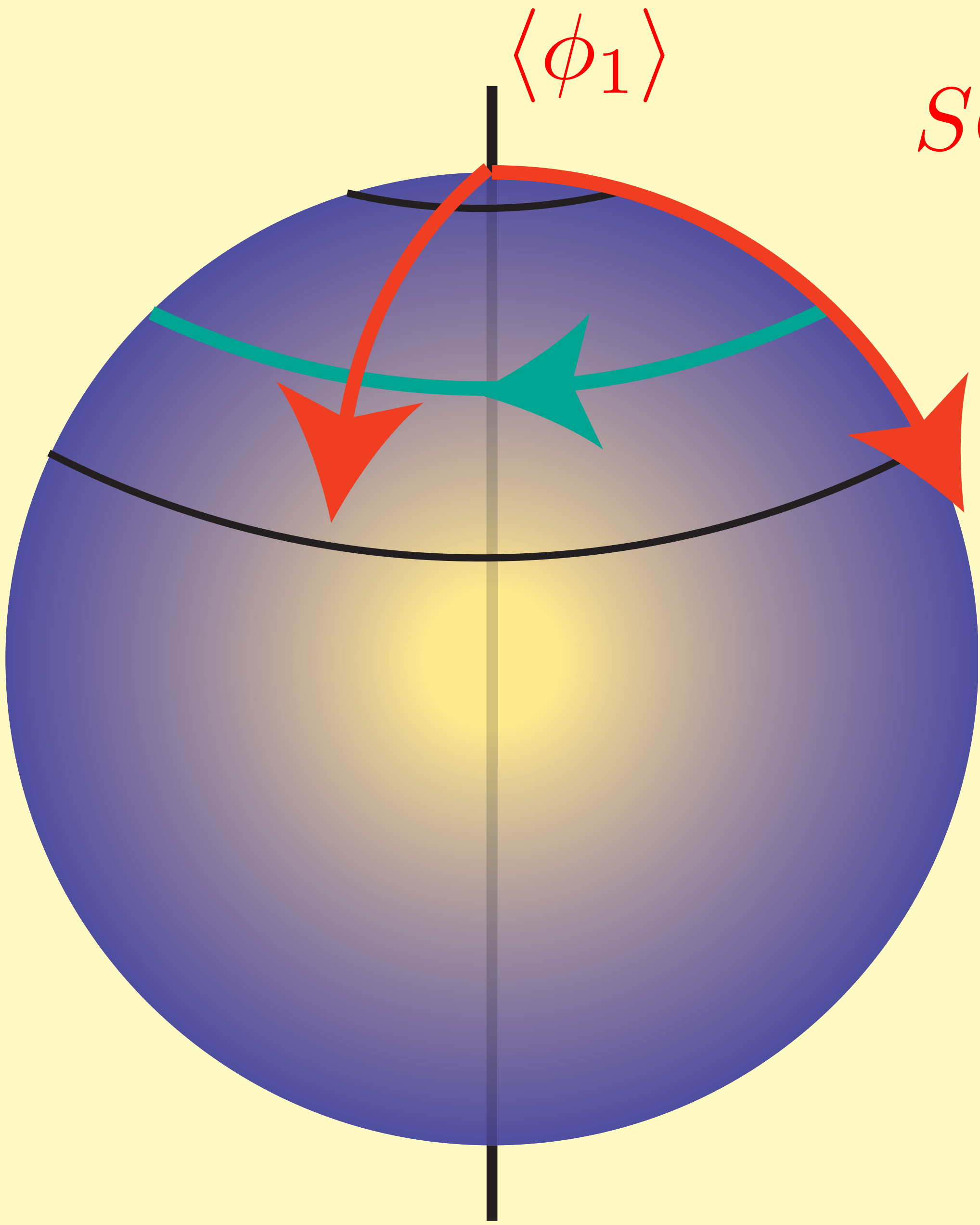
S. Elitzur, Phys. Rev. **D12** (1975) 3978.



absorbed by the gauge field

NG provides the 3rd polarisation

The non-abelian generalisation



Example

$$SO(3) \longrightarrow U(1)$$

3 gauge fields

2 fictitious NG bosons

$\downarrow$

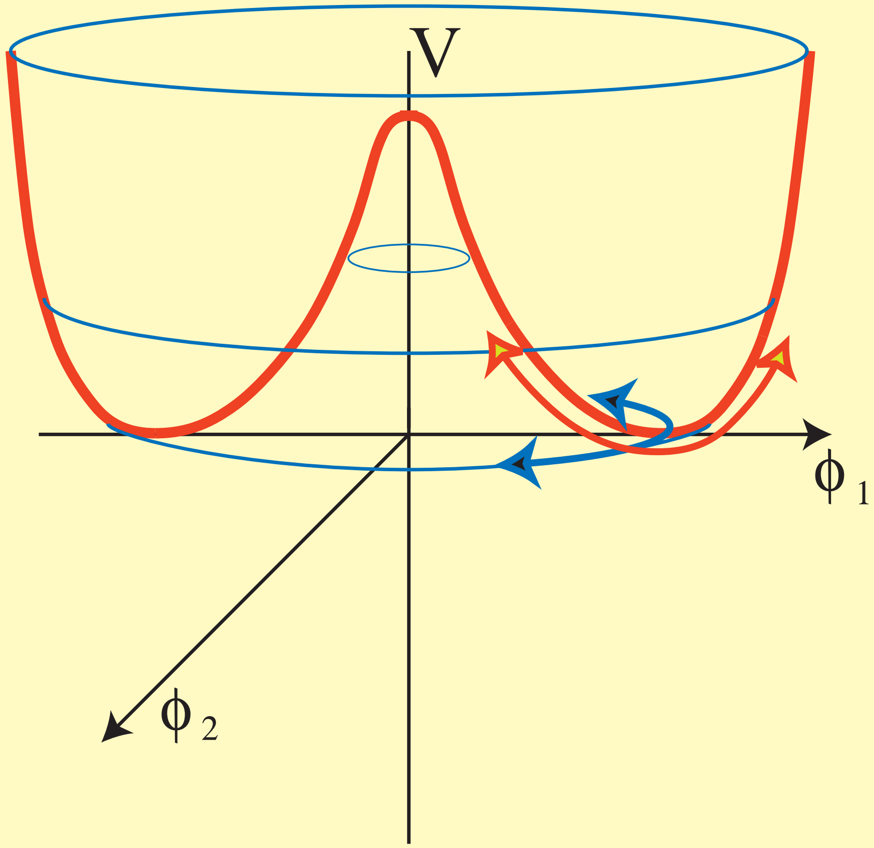
2 massive and 1 massless gauge boson

Each fictitious NG boson yields a massive gauge field

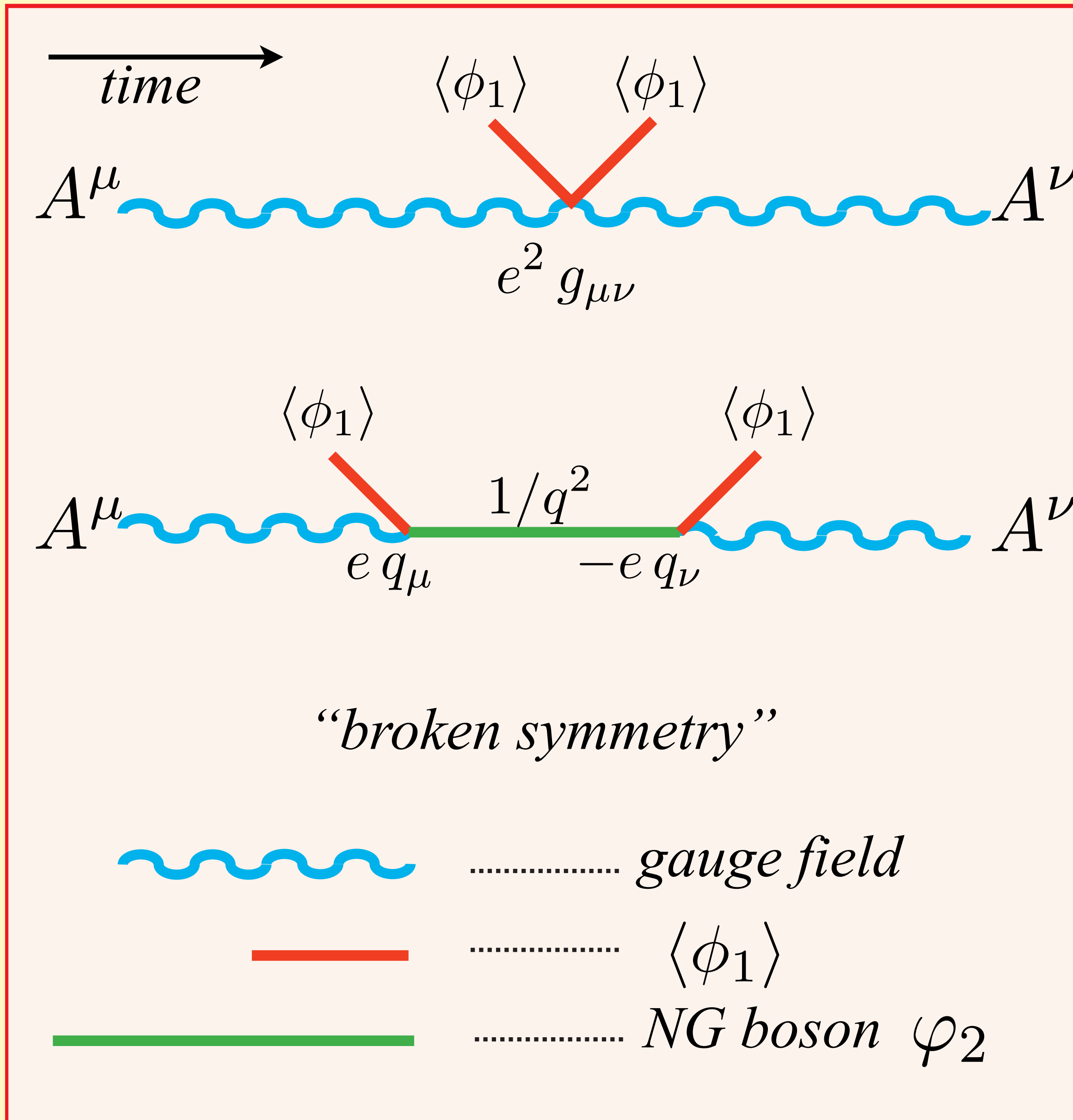
The BEH mechanism unifies short and long range forces

Quantitatively

$$\mathcal{L}_{int} = -ie\left(\partial_\mu\phi^*\phi - \phi^*\partial_\mu\phi\right)A^\mu + e^2 A_\mu A^\mu \phi^*\phi$$



$$\langle\phi_1\rangle \neq 0$$



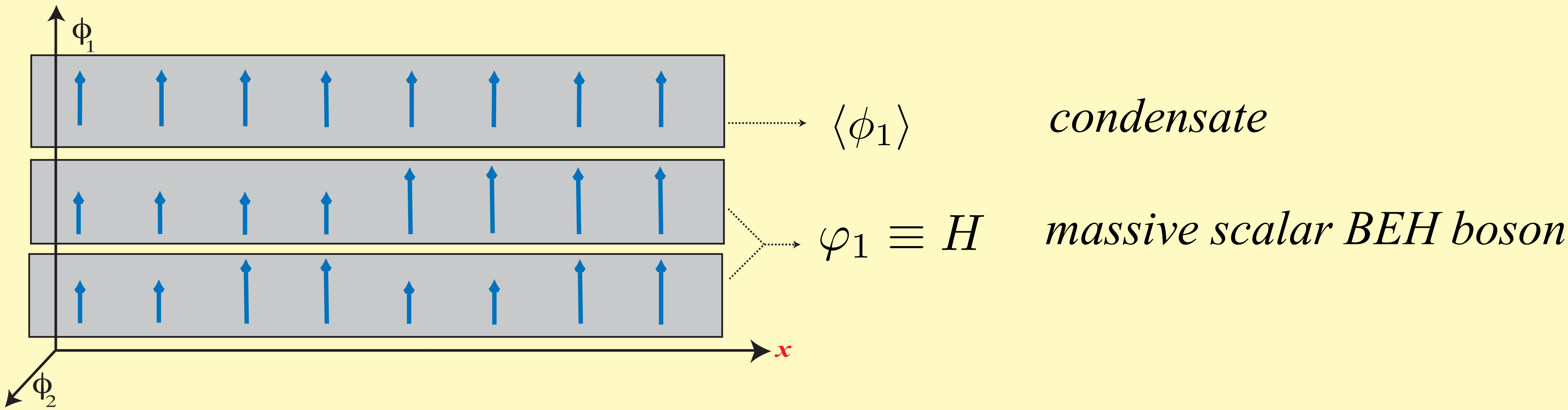
$$\Pi_{\mu\nu} = \left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right) e^2\langle\phi_1\rangle^2$$

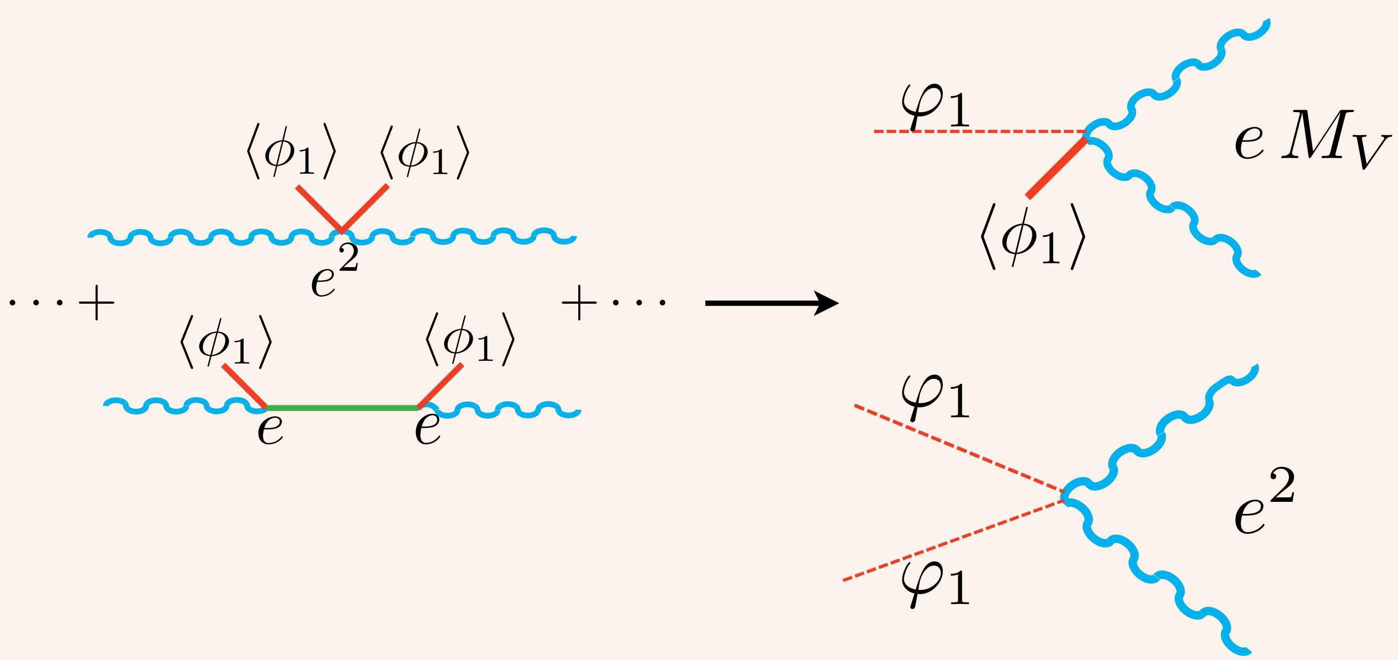
$$D_{\mu\nu} = \frac{g_{\mu\nu} - q_\mu q_\nu/q^2}{q^2 - e^2\langle\phi_1\rangle^2}$$

$$M_V^2 = e^2\langle\phi_1\rangle^2$$

$$(M_V^2)^{ab} = -e^2\langle\phi_B\rangle T^{aBA}T^{bAC}\langle\phi_C\rangle$$

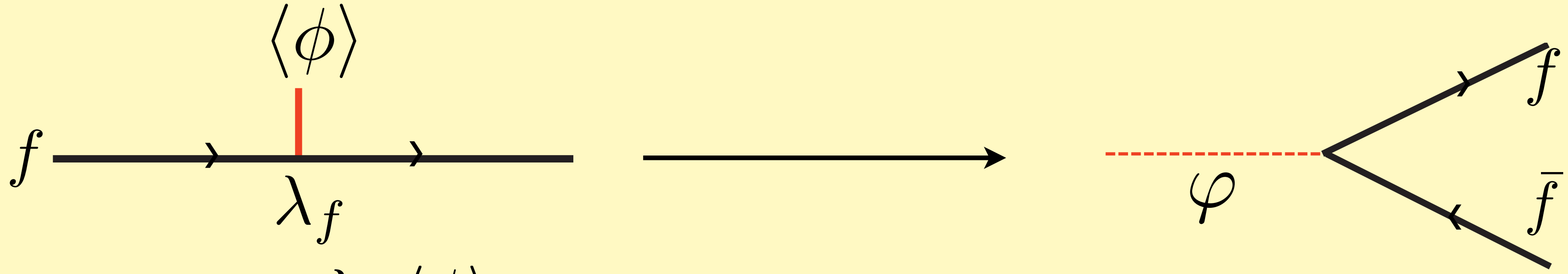
3. The fate of the massive scalar boson





The scalar boson couples to the massive gauge bosons

4. Fermion masses in chiral theories



$$e\,\frac{m_f}{M_V}$$

$$m_f = \lambda_f \langle\phi\rangle$$

but massless NG bosons !!!

These masses could follow from global SSB but consistency requires local SSB

↓

The BEH mechanism can generate masses for fermions interacting with both short and long range forces

Dynamical symmetry breaking

Composite condensate: SSB $\longrightarrow$ *NG boson* ***Local symmetry: BEH mechanism***

fermion and gauge vector masses may have different origin

5. Why is the mechanism needed ?

$$D_{\mu\nu} \equiv \frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - M_V^2}$$

← *renormalizable ?*

F. Englert, Proceedings of the 1967 Solvay Conference, p.18.

$$A_\mu - \frac{1}{e\langle\phi_1\rangle}\partial_\mu \phi_2 = B_\mu$$

← *massive vector field*

P.W. Higgs, Phys. Rev. Lett. **13** (1964) 508.

$$\frac{g_{\mu\nu} - q_\mu q_\nu / q^2}{q^2 - M_V^2} - \frac{1}{M_V^2}\frac{q_\mu q_\nu}{q^2} = \frac{g_{\mu\nu} - q_\mu q_\nu / M_V^2}{q^2 - M_V^2}$$

↑ Brout - Englert: *renormalizable gauge*

↑ Higgs: *unitary gauge*

Precision measurements

Consistent quantum theory → ***Precision measurements***

[1971] G. 't Hooft, M. Veltman (Nobel Prize 1999)

IV. The Standard Model and the electroweak theory

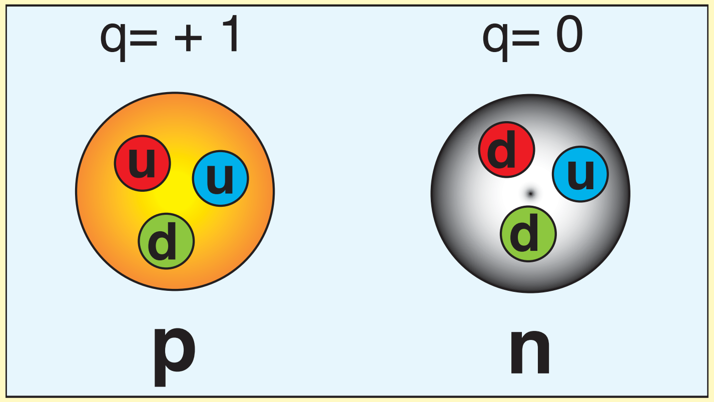
1. The Standard Model

The "interaction" particles : bosons (field constituents)

interaction	range	elementary particles [bosons]
gravitation (1687) - (1915)	∞	graviton (?)
electromagnetism (1864 —)	∞	photon
weak interactions (1967) -(1971)	$\sim 10^{-16}$ cm	$W^+ \; W^- \; Z$
strong interactions ($\sim$ 1970)	$\sim 10^{-13}$ cm	8 gluons

The "source" particles : fermions

particles (charge)	
$e\ (-1)$ $\quad \nu_e\ (0)$	$u\,u\,u\ (\frac{2}{3})$ $\quad d\,d\,d\ (-\frac{1}{3})$
$\mu\ (-1)$ $\quad \nu_\mu\ (0)$	S.L. Glashow, J. Iliopoulos and L. Maiani, Phys.Rev. **D2** (1970) 1285. $c\,c\,c\ (\frac{2}{3})$ $\quad s\,s\,s\ (-\frac{1}{3})$
$\tau\ (-1)$ $\quad \nu_\tau\ (0)$	M. Kobayashi and T. Maskawa, Prog.Theor.Phys. **49** (1973) 652. *(Nobel Prize 2008)* $t\,t\,t\ (\frac{2}{3})$ $\quad b\,b\,b\ (-\frac{1}{3})$



$+$ antiparticles

2. *The electroweak theory*

[1967] S. L. Glashow, A. Salam, S. Weinberg (Prix Nobel 1979)

The mechanism uses 4 gauge fields $SU(2)_L \times U(1) \rightarrow U'(1)$

+ four scalar fields

+ massless elementary fermions

Three scalar fields become fictitious NG bosons

One massive scalar boson remains from condensate fluctuations

↓

Three gauge bosons become massive: $W^+ \quad W^- \quad Z$

One gauge boson remains massless (the photon): A

The elementary fermions get masses

Discovery of the massive gauge bosons *[1983] C. Rubbia, S. van der Meer (Nobel Prize 1984)*

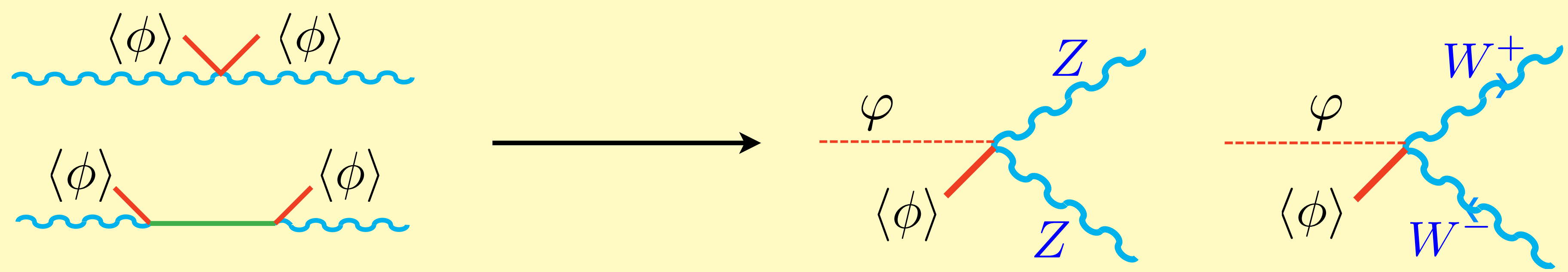
The mechanism is (indirectly) verified

V. The discovery and the two "infinities"

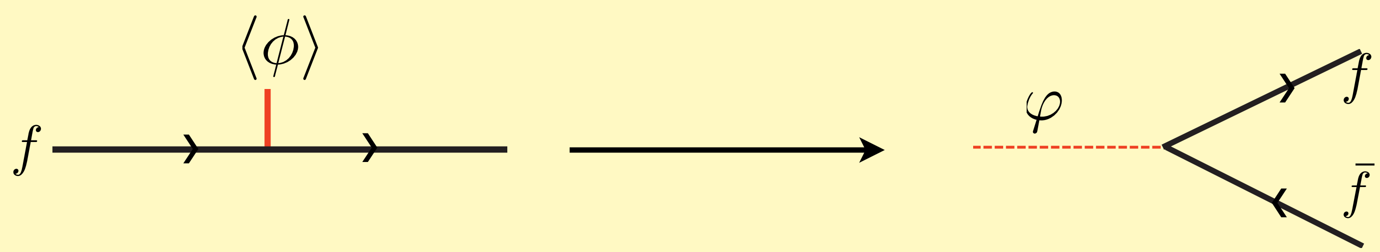
1. The discovery

Decays of the BEH scalar boson

massive gauge bosons

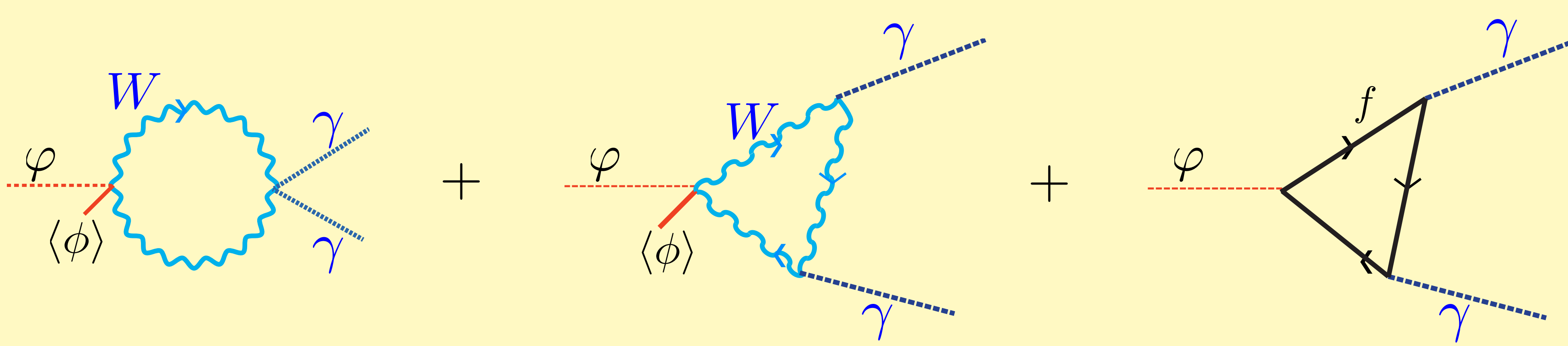


fermion masses

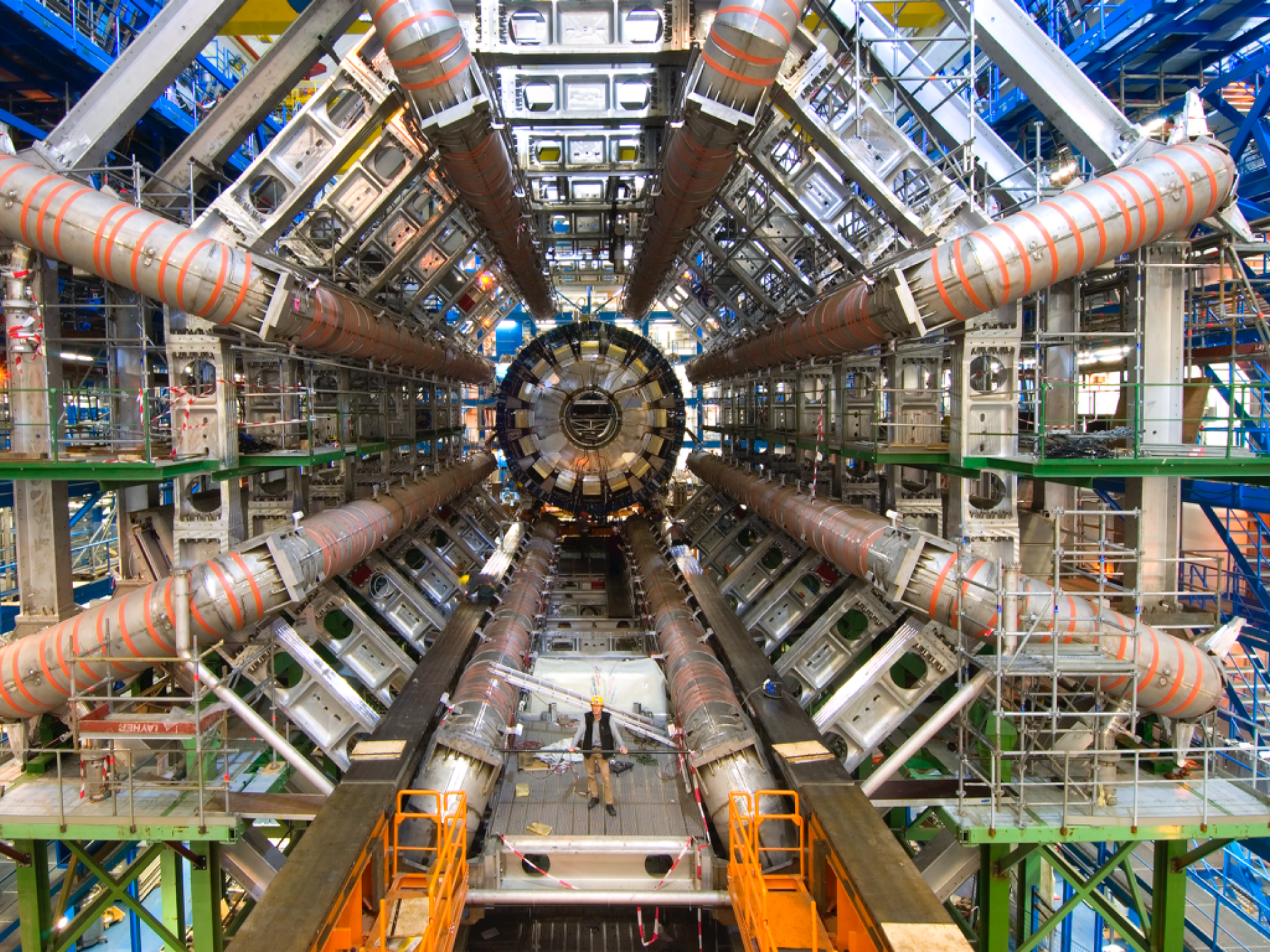


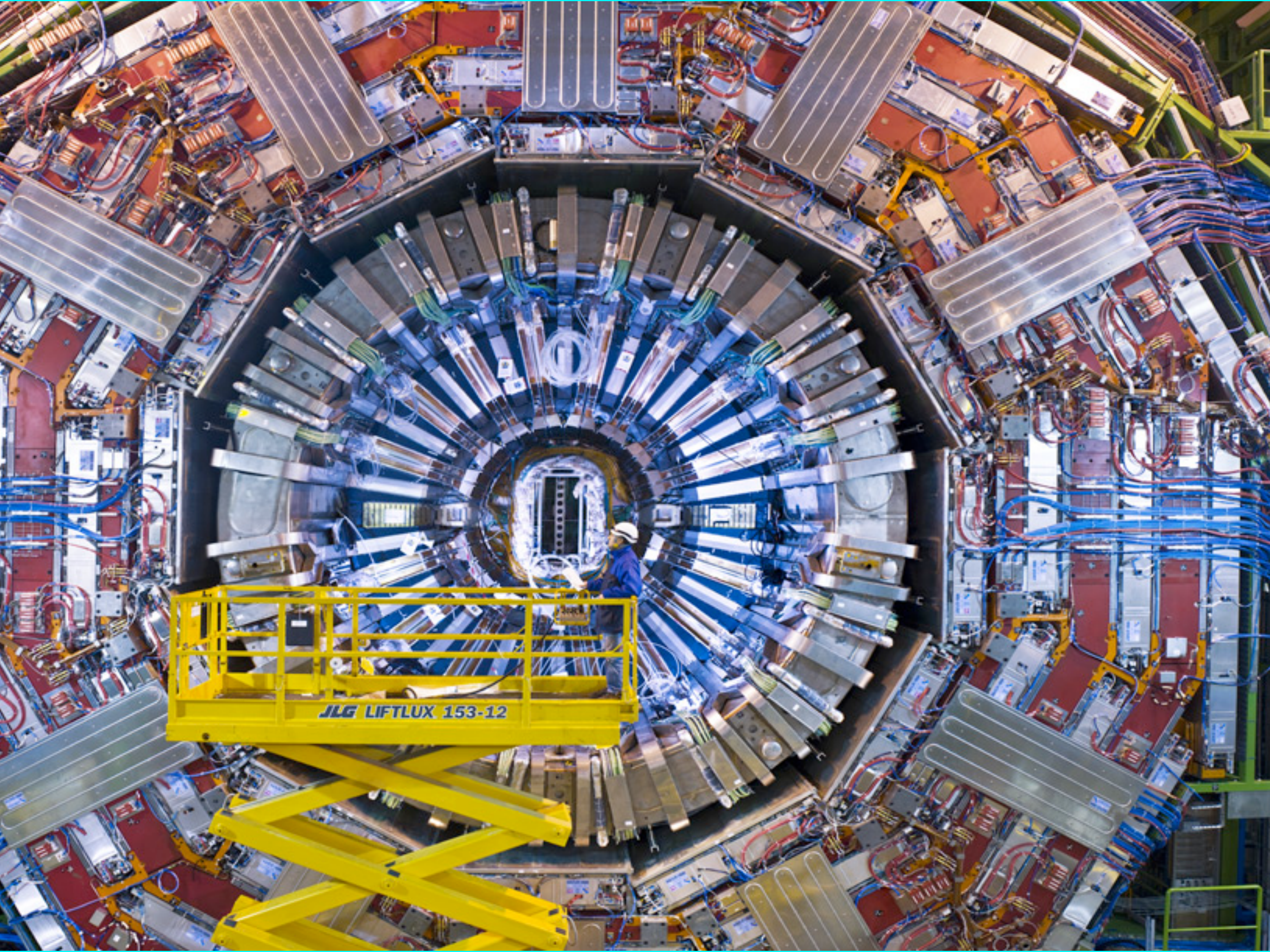
$$\propto \frac{m_f}{M_W}$$

$\varphi \to \gamma\gamma$

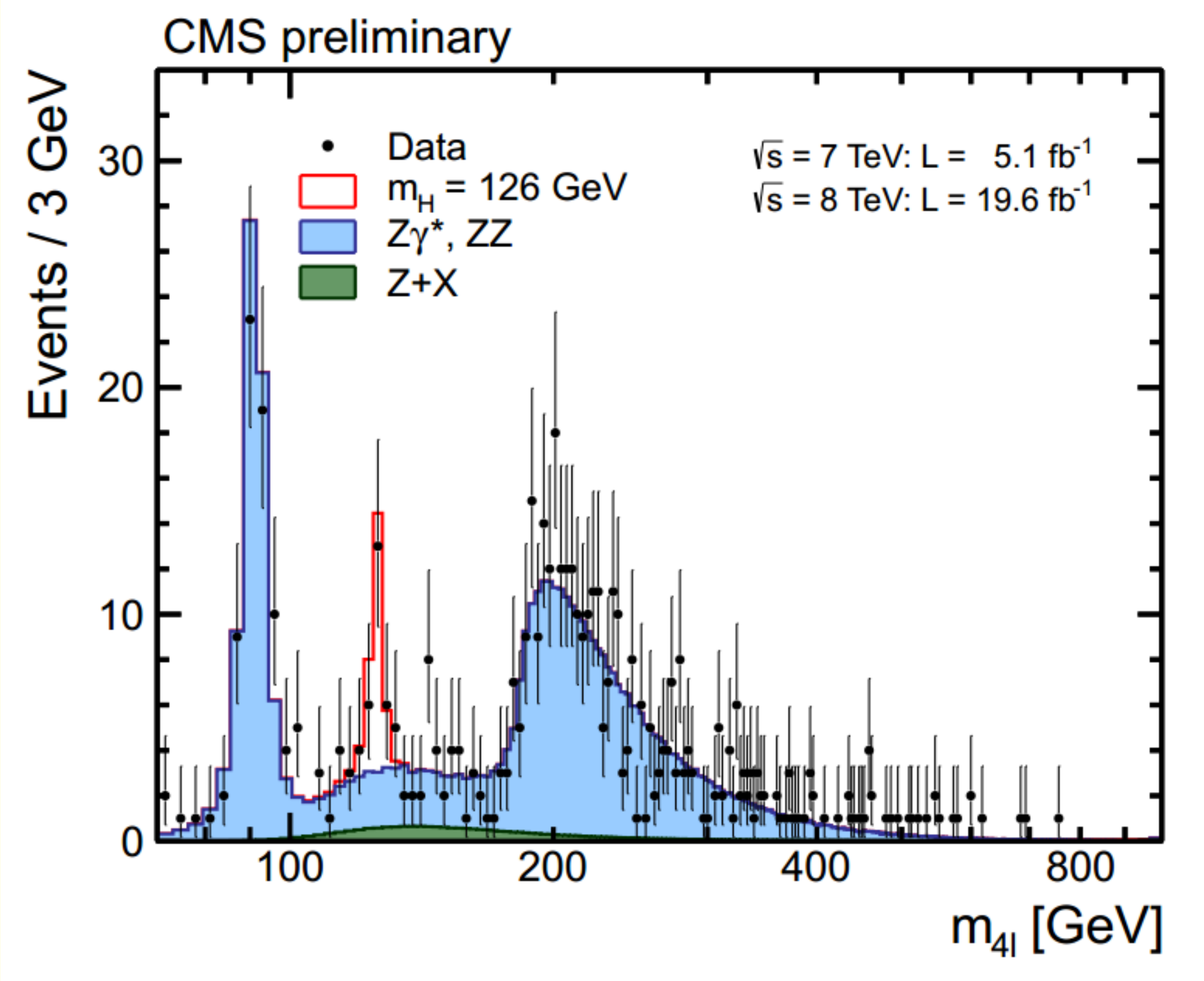


The process may be sensitive to BSM physics




JLG LIFTLUX 153-12

Example: decay of the scalar boson into ZZ^*



$H \to ZZ$

$H \to \gamma\gamma$

$H \to W^+W^-$

$H \to \tau\bar{\tau}$

$H \to b\bar{b}$

$\sigma/\sigma_{SM} = 0.88 \pm 0.21$

The scalar boson appears to be an elementary particle !!!

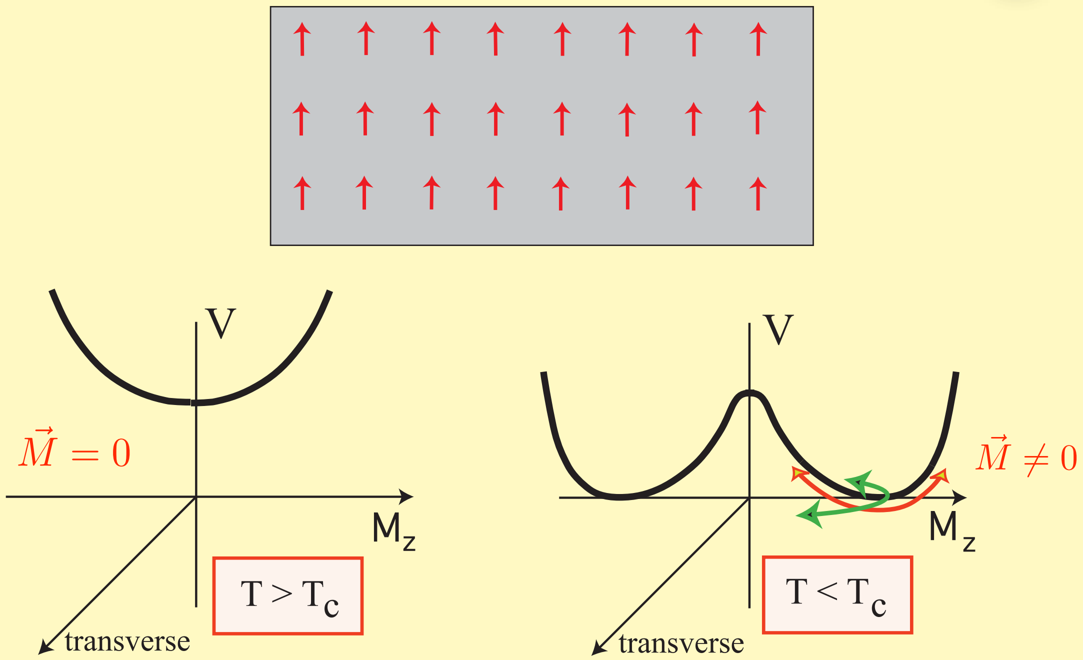
2. The unknown

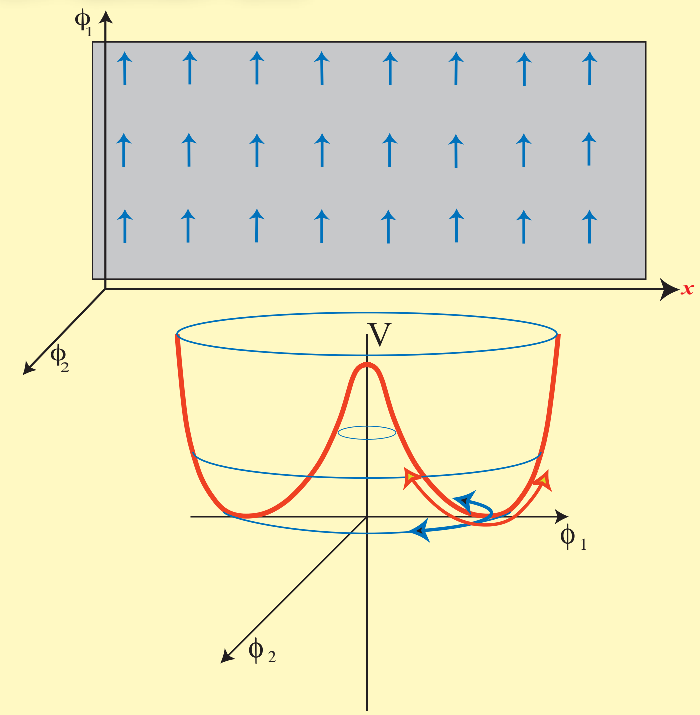
Low energies

Dynamical models are strongly disfavoured: unexplored energies may be emptier

Supersymmetry ? *Dark matter?*

High temperatures





$$M_H = 125\,\text{Gev}$$

$$T \simeq 10^{16}\,\text{K}$$

$$t = 10^{-11}\,\text{sec}$$

Quantum gravity

Dark energy

Birth of the Universe and inflation → *structures*

↑

Quantum fluctuation → *structures*

R. Brout, F. Englert, E. Gunzig, Ann. of Physics **115** (1978) 78, Gen. Rel. and Grav. **10** (1979) 1; R. Brout, F. Englert, Ph. Spindel, Phys. Rev. Lett. 4**3** (1979) 417.