

The BEH mechanism, its scalars, and the elusive quest

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I. Spontaneous symmetry breaking by a condensate

II. The BEH mechanism

III. From the discovery to the elusive quest

Rencontres du Vietnam 2014

Quy Nhon, 16 August 2014

I. Spontaneous symmetry breaking by a condensate

[1960] Y. Nambu (Nobel Prize 2008)

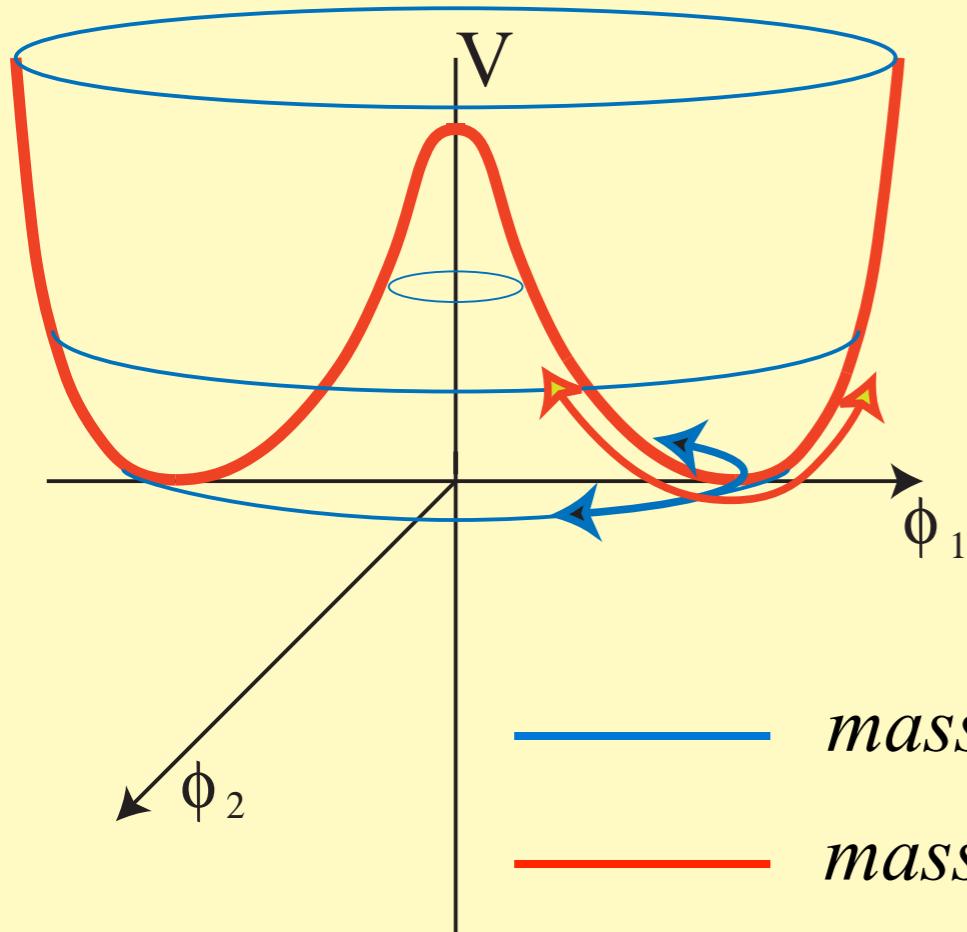
Y. Nambu, Phys. Rev. Lett. **4** (1960) 380; Y. Nambu and G. Jona-Lasinio, Phys. Rev. **122** (1961) 345, Phys. Rev. **124** (1961) 246;
J. Goldstone, Il Nuovo Cimento **19** (1961) 154; J. Goldstone, A. Salam and S. Weinberg, Phys. Rev. **127** (1962) 965.

Chiral $U(1)$ symmetry breaking

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

The simple Goldstone $U(1)$ model: scalar field condensation

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



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

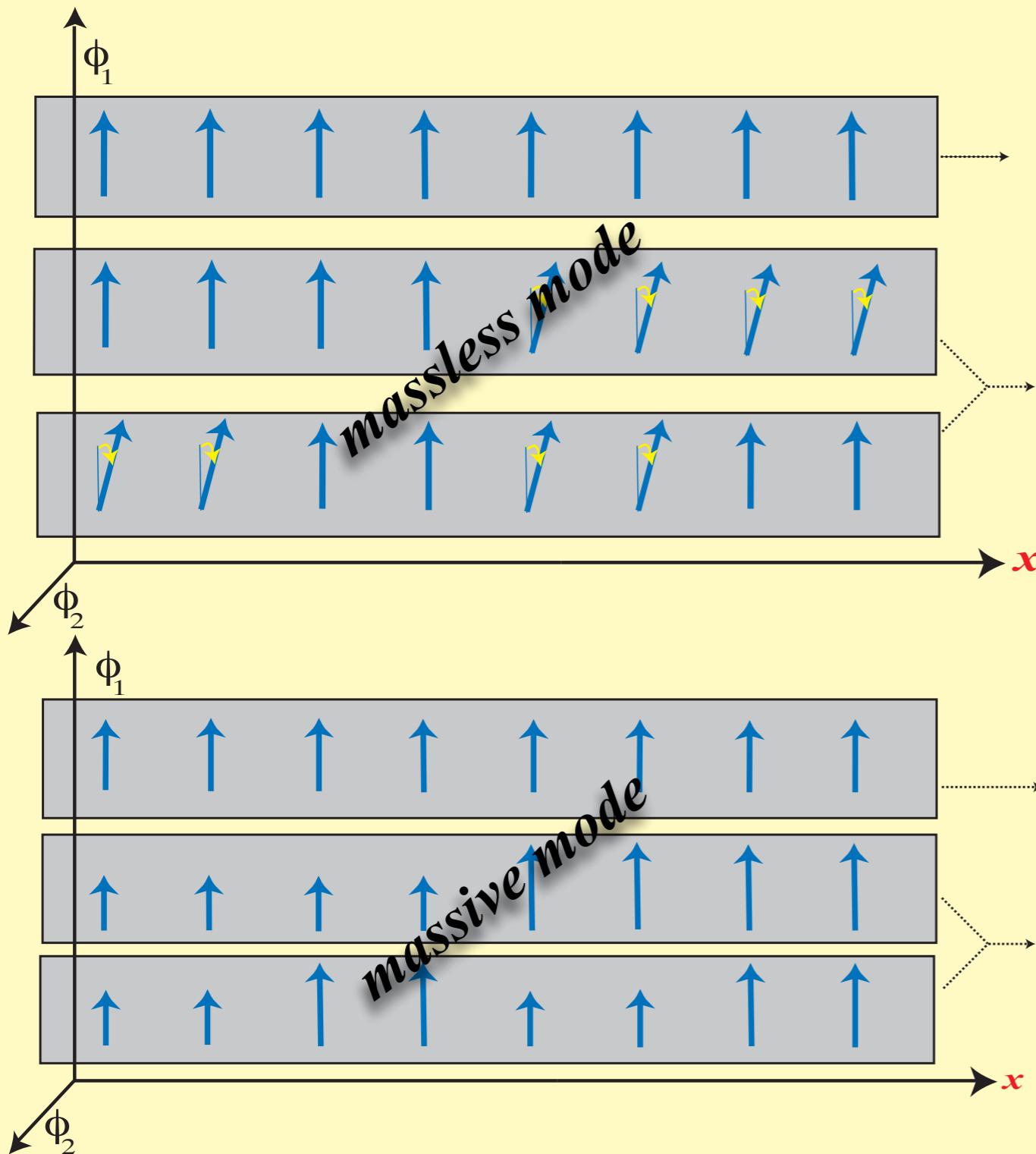
The $U(1)$ global symmetry is broken by $\langle \phi \rangle$

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

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

$$\phi_2 = \varphi_2$$

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



II. 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

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

Local abelian symmetry

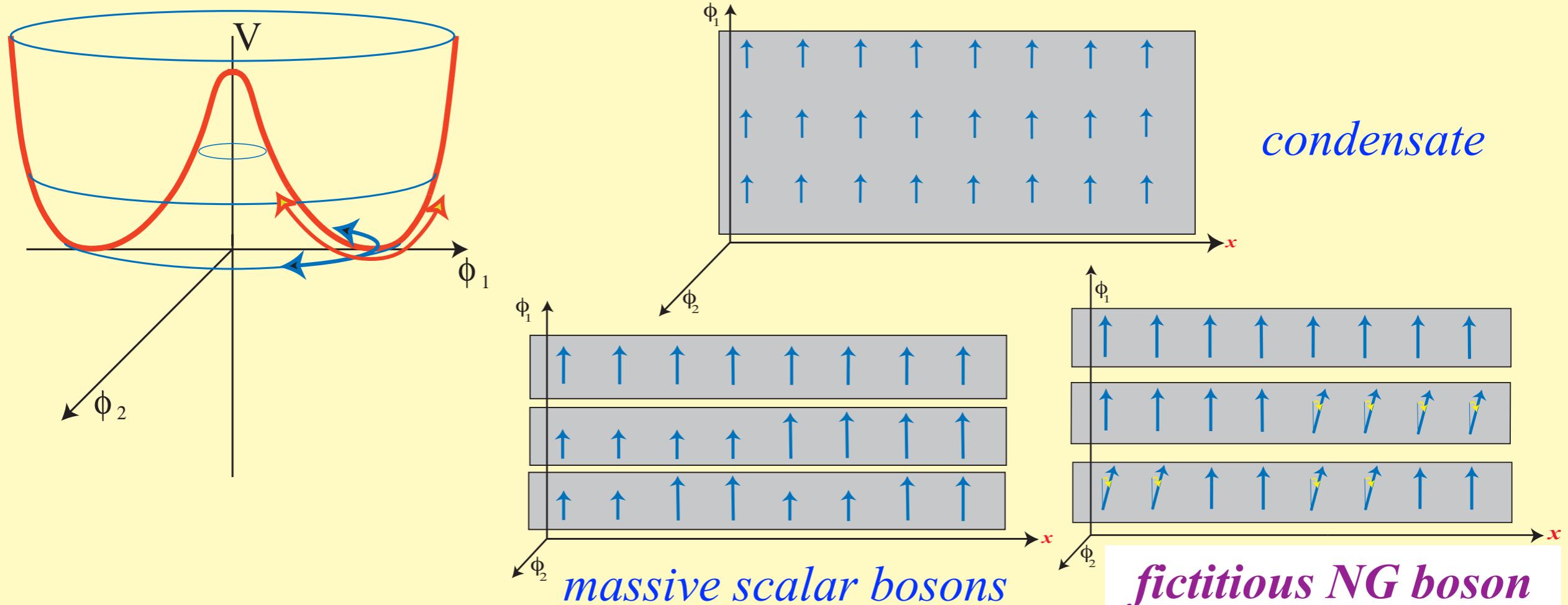
$$\begin{aligned} \phi &\rightarrow \phi e^{i\alpha(x)} & A_\mu &\rightarrow A_\mu + \frac{1}{e} \partial_\mu \alpha \\ D_\mu \phi &= \partial_\mu \phi - ieA_\mu \phi & F_{\mu\nu} &= \partial_\mu A_\nu - \partial_\nu A_\mu \\ \mathcal{L} &= D^\mu \phi^* D_\mu \phi - V(\phi^* \phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \end{aligned}$$

Local non-abelian symmetry

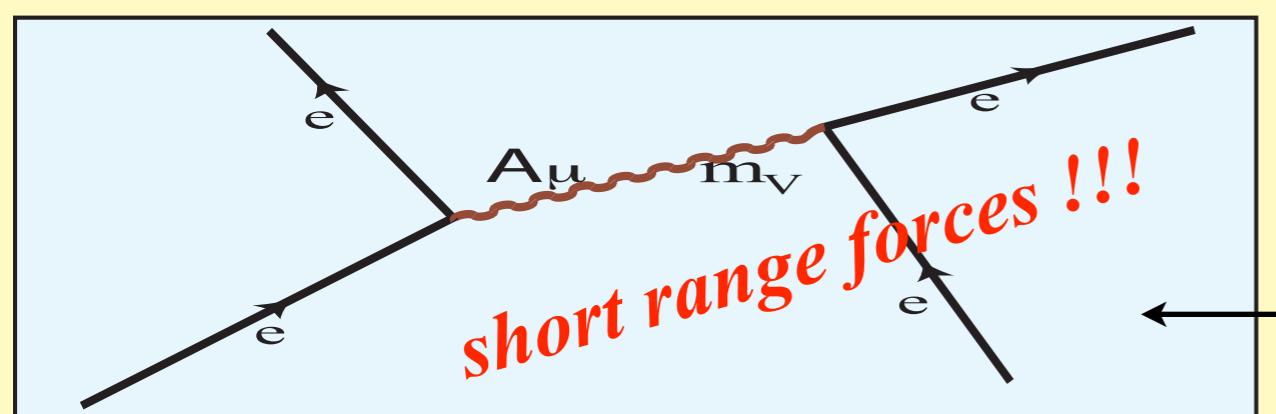
$$\begin{aligned} (D_\mu \phi)^A &= \partial_\mu \phi^A - e A_\mu^a T^{aAB} \phi^B \\ F_{\mu\nu}^a &= \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + e f^{abc} A_\mu^b A_\nu^c \end{aligned}$$

2. The fate of the Nambu-Goldstone boson

The abelian case



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.

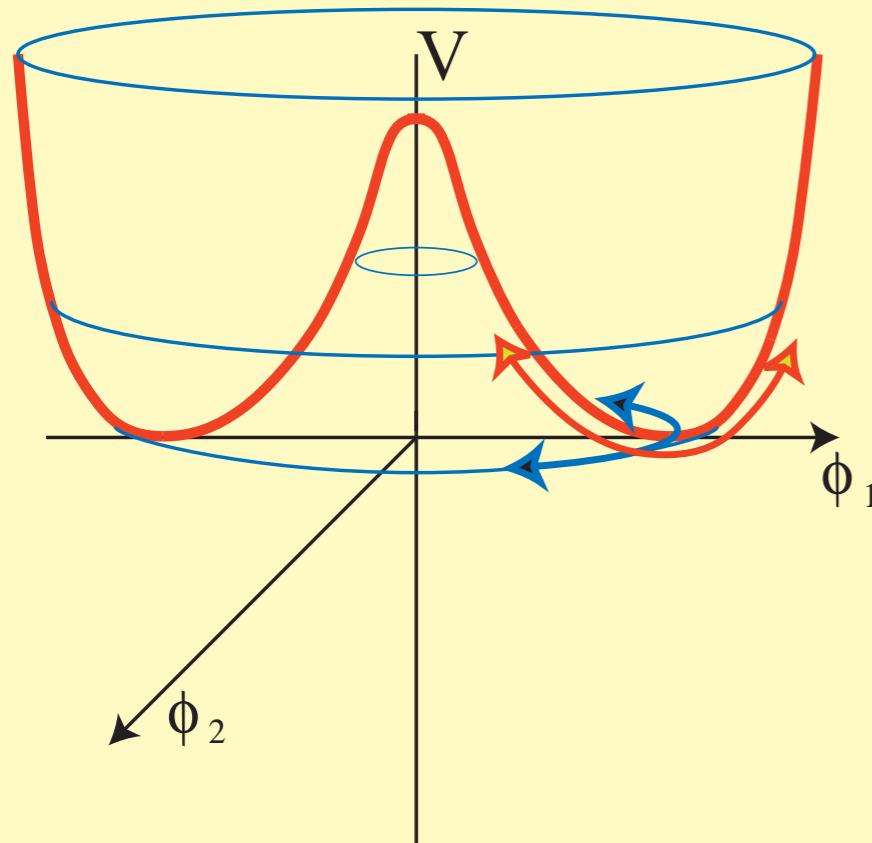


absorbed by the gauge field

NG provides the 3rd polarisation

Quantitatively

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

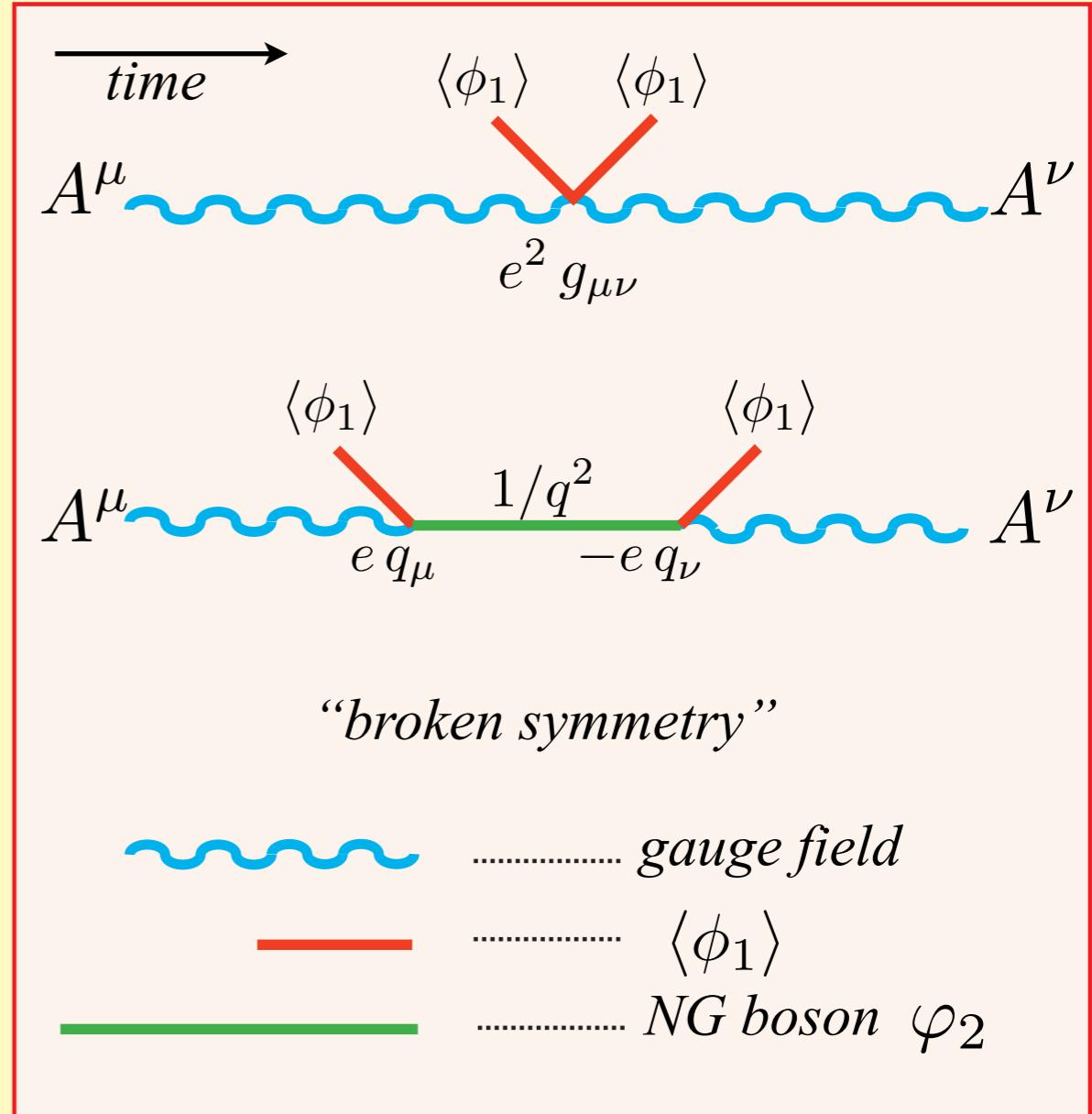


$$\Pi_{\mu\nu} = (g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}) e^2 \langle \phi_1 \rangle^2$$

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

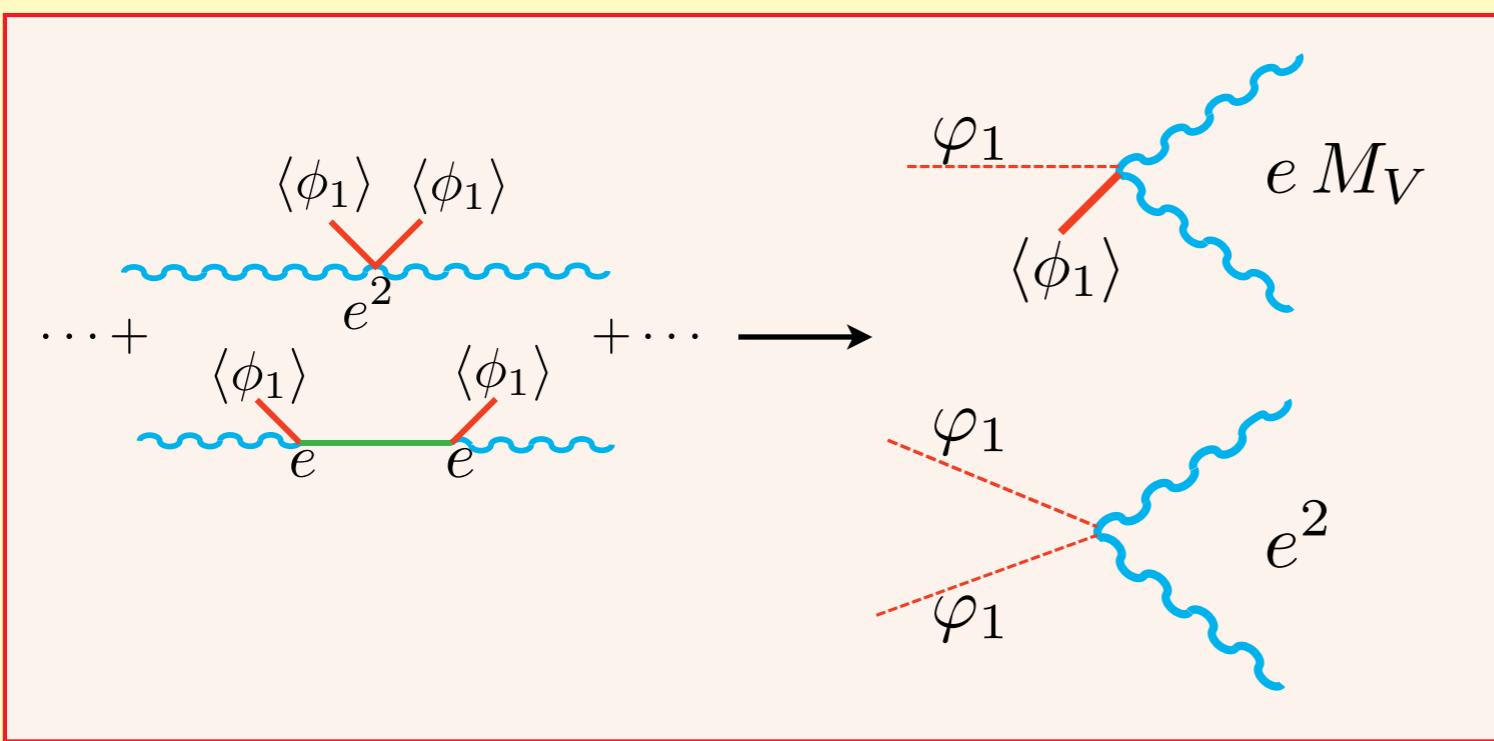
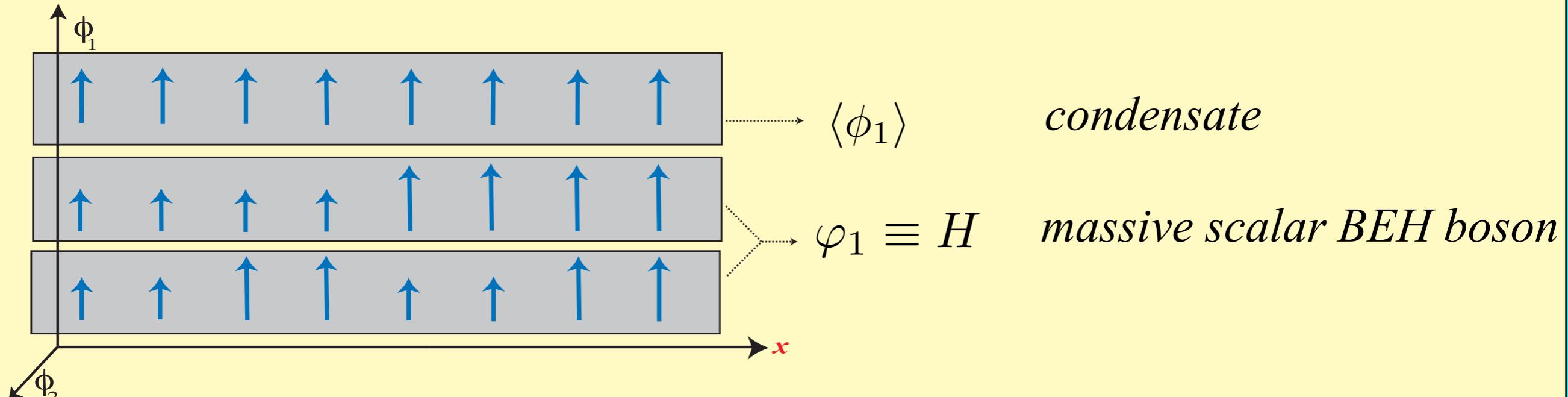
$$M_V^2 = e^2 \langle \phi_1 \rangle^2$$

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



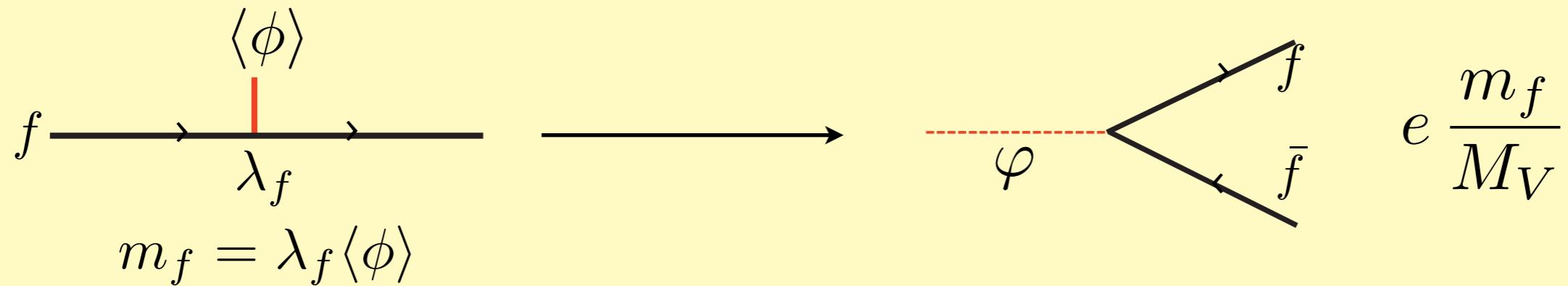
$$(M_V^2)^{ab} = -e^2 \langle \phi_B \rangle T^{aBA} T^{bAC} \langle \phi_C \rangle$$

3. The fate of the massive scalar boson



The scalar boson couples to the massive gauge bosons

4. Fermion masses in chiral theories



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: $SSB \longrightarrow NG \text{ boson}$ *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

↑ Higgs

renormalizable gauge

unitary gauge

↓

Consistent quantum theory

Precision measurements

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

6. The electroweak theory and the Standard Model

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

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

fermions in $SU(2)_L \times U(1) \rightarrow U'(1)$

4 massless vector bosons and 4 scalar bosons (3NG)

$\gamma \quad W^+ W^- Z$

[1983] C. Rubbia, S. van der Meer (Nobel Prize 1984)

8 gluons $SU(3)_C$

confinement

$\langle \phi \rangle \neq 0 \quad \varphi \equiv H$

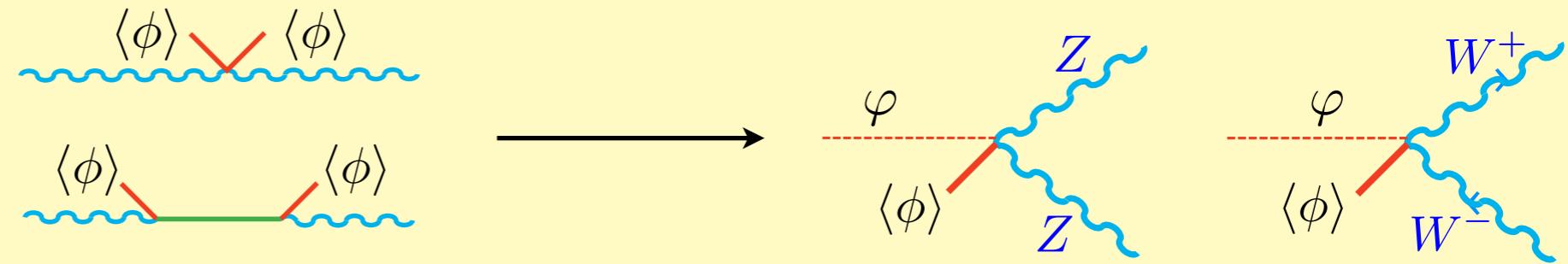
The mechanism is (indirectly) verified !

III. From the discovery to the elusive quest

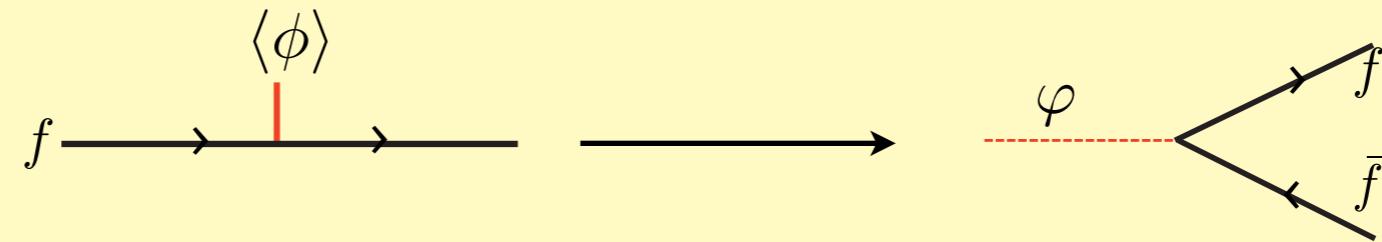
1. The discovery

Decays of the BEH scalar boson

massive gauge bosons

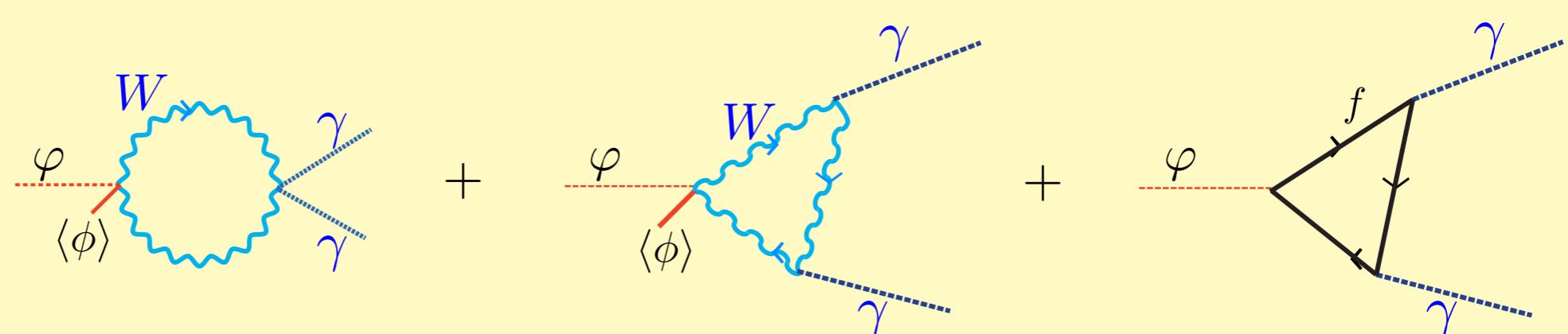


fermion masses



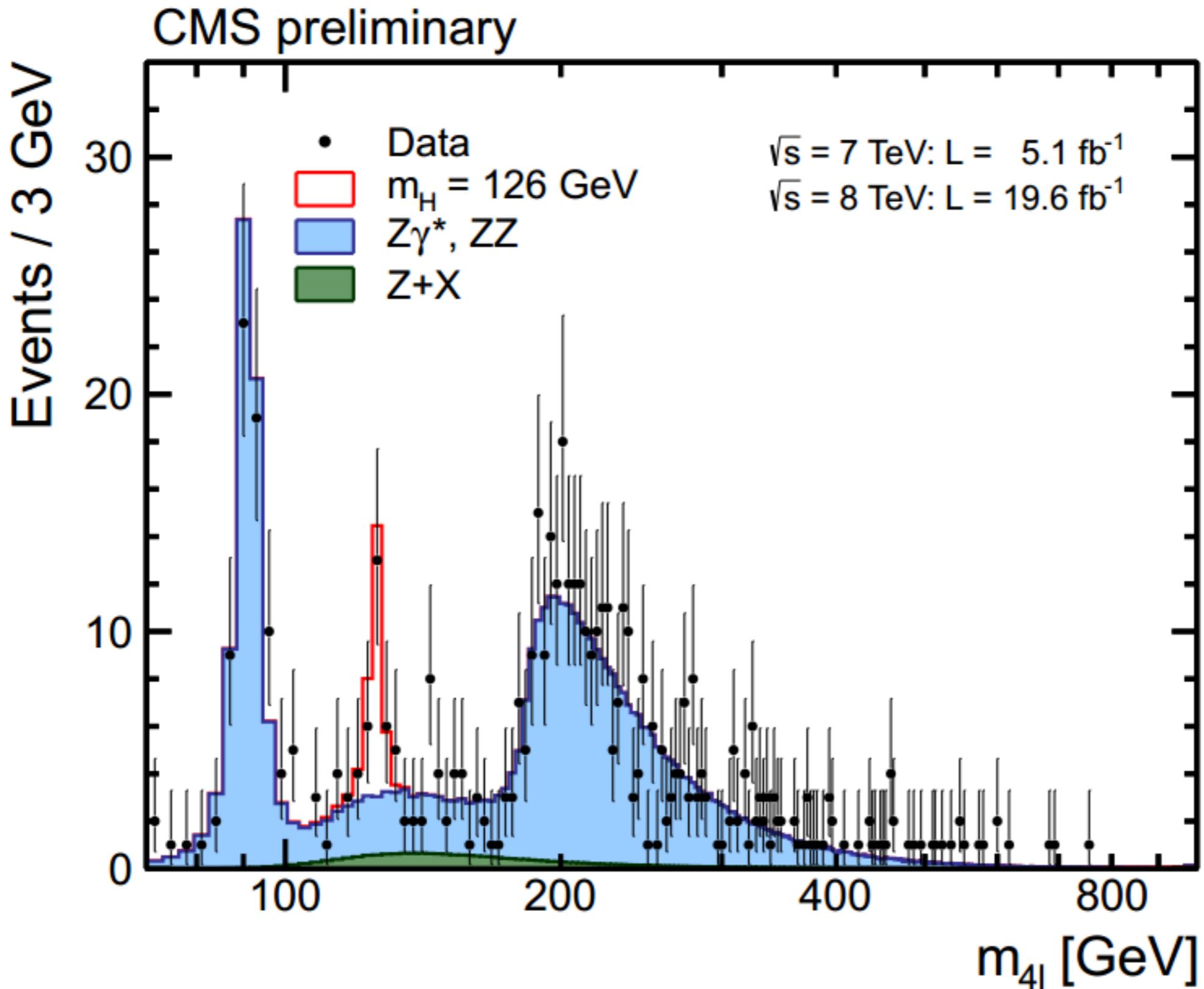
$$\propto \frac{m_f}{M_W}$$

$\varphi \rightarrow \gamma\gamma$



The process may be sensitive to BSM physics

Example: decay of the scalar boson into ZZ^*



$H \rightarrow ZZ$

$H \rightarrow \gamma\gamma$

$H \rightarrow W^+W^-$

$H \rightarrow \tau\bar{\tau}$

$H \rightarrow b\bar{b}$

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

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

2. The elusive quest

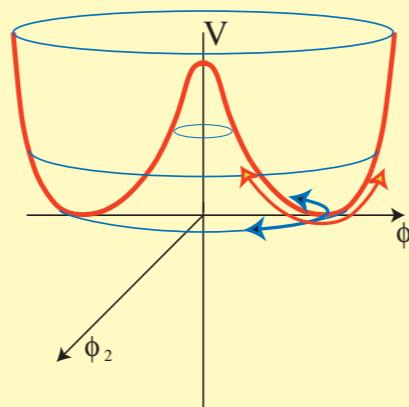
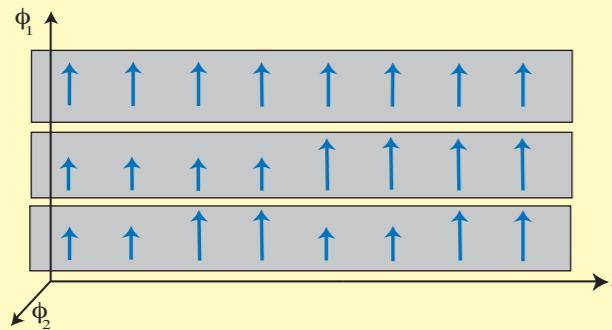
Low energies

Dynamical models are strongly disfavoured: unexplored energies may be emptier

Supersymmetry ?

Dark matter?

High temperatures



$$M_H = 125 \text{ GeV} \quad T \simeq 10^{16} \text{ K}$$

$$t = 10^{-11} \text{ sec} \ll 10^{-43} \text{ sec}$$

Quantum gravity

- *Birth of the universe from a quantum fluctuation*
Inflation ←

$$\boxed{\begin{array}{cc} D_{\text{grav}} + D_{\text{matter}} = 0 \\ < 0 & > 0 \end{array}}$$

R. Brout, F. Englert, E. Gunzig, Ann. of Phys. **115** (1978) 78; Gen. Rel. and Grav. **10** (1979) 1;
R. Brout, F. Englert, Ph. Spindel, Phys. Rev. Lett. **43** (1979) 417.

- *Structures stem from quantum fluctuations !!!*

- *QG might affect all scales !!!* ← → *Dark energy*

How should gravity be reconciled with quantum theory ???