# LECTURES ON ELECTROWEAK SYMMETRY BREAKING

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# Outline

- LECTURE 1 - Evidence for EWSB
- LECTURE 2 - The role of the Higgs boson
- LECTURE 3 - Higgs couplings: present status and future strategies

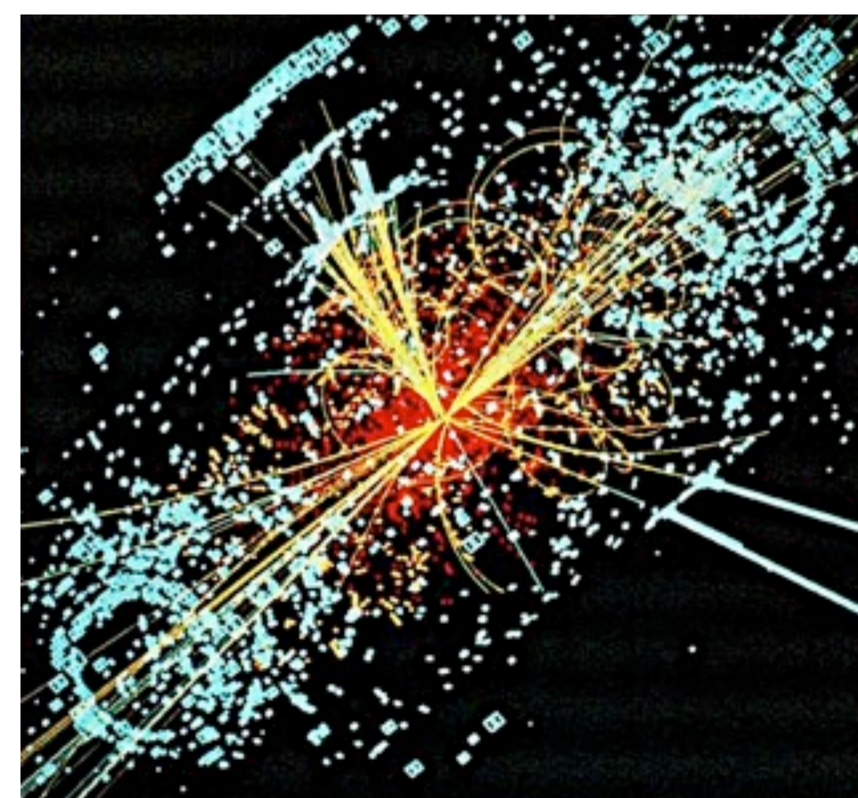
# Lecture 1

Evidence for EWSB

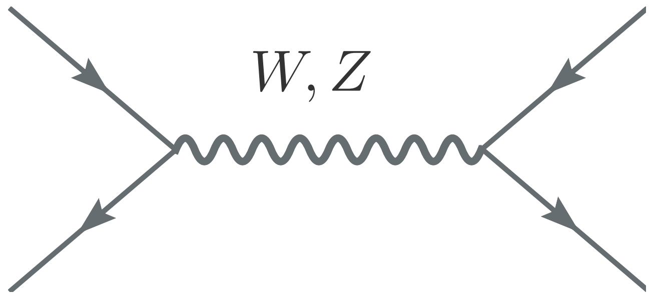
We have discovered a zoo of particles, yet simple rules govern their phenomenology:

- Interactions and decays obey selection rules: electromagnetic charge Q is always conserved
- Spectrum degeneracy: particles organized in multiples with same electromagnetic charge
- We feel a long-range force: electromagnetism

$U(1)_Q$ is a gauge (= local) symmetry and the photon is its carrier



In the spectrum of fundamental particles there are also massive spin-1 fields: $W^{\pm}$, $Z^0$

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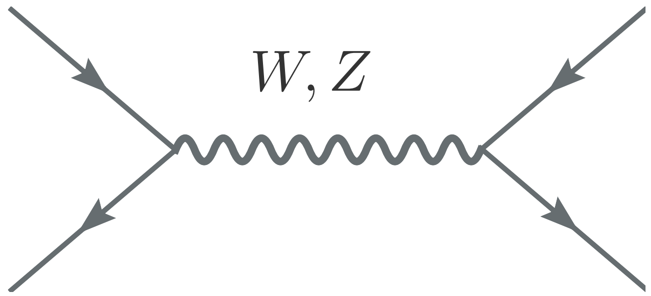


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It is natural to conjecture that:

W and Z are the gauge fields of a larger local $SU(2)_L x U(1)_Y$ invariance

Problem: W and Z are *massive*, and the EW force is *not* long-range

what is the origin of the W,Z mass ?

It is known that a global symmetry G can be realized in two ways in a quantum theory:

[1] A la Wigner [ Linear Realization ]

- vacuum is invariant under G transformations

$$\Phi_0 \rightarrow g \cdot \Phi_0 = \Phi_0 \qquad\qquad g = e^{i\alpha} \in G$$

- physical states are classified in multiplets of G

- fields transform linearly under G

$$\psi \rightarrow g \cdot \psi$$

- at the classical level there exist conserved currents

$$\partial_\mu J^\mu = 0$$

Example: $U(1)_Q$ is linearly realized

[2] A la Nambu-Goldstone [ Non-Linear Realization ]

- vacuum is NOT invariant under G transformations: there is a whole set of degenerate, inequivalent vacua:

$$\Phi(g) = g \cdot \Phi_0$$

- physical states are NOT classified in multiplets of G

- fields transform non-linearly under G

$$\psi \to \psi\, F(g, \psi) \qquad\qquad F(g = 1, \psi) = 1$$

- at the classical level there still exist conserved currents

- there exist massless scalar fields (Nambu-Goldstone bosons)

the symmetry G is said to be spontaneously broken (or hidden)

## Existence of massless scalar modes first noticed by Yoichiro Nambu

- First original observation made in the context of the BCS theory of superconductivity (1959):

  [ Y. Nambu Phys. Rev. 117 (1959) 648 ]

  *Gauge invariance (hence the conservation of the electromagnetic current) is maintained thanks to the existence of collective (long wave-length) excitations*

- Nambu later applied the argument by analogy to the case of the axial current in QCD (1960):

  [ Y. Nambu Phys. Rev. Lett. 4 (1960) 380 ]

  *The conservation of the axial current* $J_A^\mu = \bar{\psi}\gamma^\mu\gamma^5\psi$ *in QCD is compatible with the nucleon mass if massless scalars exist. These are identified with the pions.*

- Conservation of axial current previously proposed in analogy with the conserved vector current hypothesis (CVC)

$$\mathcal{L}_{EW}^{\Delta S=0} = -\frac{G\cos\theta_C}{\sqrt{2}}\left(J_V^{\mu\,+} - J_A^{\mu\,+}\right)\sum_l \bar{l}\gamma^\mu\nu_l + h.c. \qquad J_{V,A}^{\mu\,\pm} = J_{V,A}^{\mu\,1} \pm i\, J_{V,A}^{\mu\,2}$$

In modern notation:

$$J_V^{\mu,a}(x) = \bar{q}(x)\gamma^\mu\frac{\sigma^a}{2}q(x)$$

$$J_A^{\mu,a}(x) = \bar{q}(x)\gamma^\mu\gamma^5\frac{\sigma^a}{2}q(x)$$

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Universality and CVC tested in allowed β transitions ($0^+ \to 0^+$) at zero-momentum transfer (only the vector current contributes):

$$^{14}\mathrm{O} \to {}^{14}\mathrm{N} \qquad \langle p|J_V^{\mu\,+}|n\rangle = \bar{u}_p\gamma^\mu g_V(0)u_n$$

$$^{26}\mathrm{Al} \to {}^{26}\mathrm{Mg} \qquad \frac{G_F}{G} = g_V(0) = 1.006$$

$$\pi^+ \to \pi^0 e^+ \nu_e$$

$G_F$ measured in μ-decay

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Lorentz invariance and CP conservation imply:

$$\langle p|J_A^{\mu\,+}|n\rangle = \bar{u}_p\left[\gamma^\mu\gamma^5 g_A(q^2) + q_\mu\gamma^5 h_A(q^2) + i\gamma^5\frac{\sigma^{\mu\nu}q_\nu}{2m_N}f_A(q^2)\right]u_n$$

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Current conservation implies:

$$q_\mu\langle p|J_A^{\mu\,+}|n\rangle = 0 \qquad -2m_N\, g_A(q^2) + q^2\, h_A(q^2) = 0$$

For $q^2 \longrightarrow 0$ this requires:

$$h_A(q^2) \longrightarrow \frac{2m_N g_A(0)}{q^2}$$

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pole naturally provided by the exchange of massless scalars

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The pole in axial matrix element comes from the one-pion exchange:

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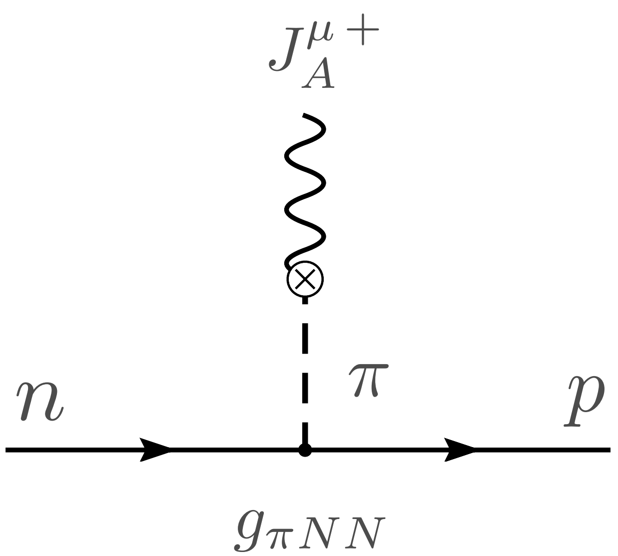


$$\langle 0|J_A^{\mu\,a}|\pi^b(q)\rangle = iq^\mu \delta^{ab} f_\pi e^{-iq\cdot x}$$

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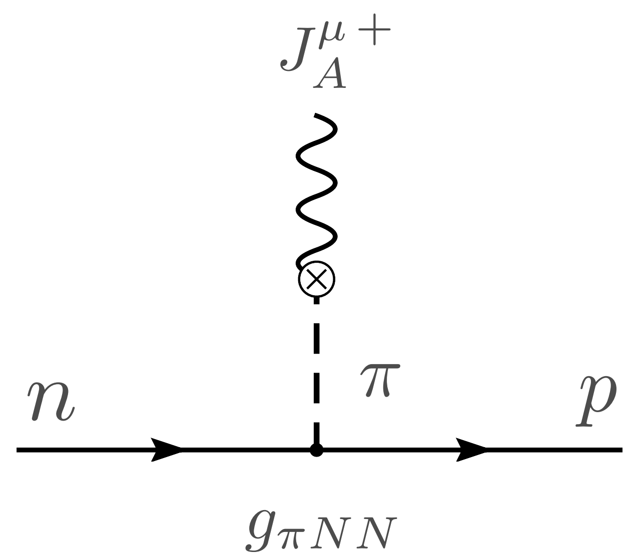


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Comparing with the current conservation result

$$h_A(q^2) \to \frac{2m_N g_A(0)}{q^2}$$

implies the Goldberger-Treiman relation:

$$g_{\pi NN} = \frac{2m_N g_A(0)}{f_\pi} \simeq 12.7$$

( $g_{\pi NN} = 13.5$ from direct measurement)

- In a subsequent calculation with Jona-Lasinio he showed that the value $g_A(0) = 1.22$ can be computed in terms of the pion mass, as they both come from the breaking of the axial symmetry and are thus related

[ Y. Nambu, G. Jona-Lasinio Phys. Rev. 122 (1961) 345; 124 (1961) 246 ]

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Evidence for hidden $SU(2)_L x SU(2)_R \rightarrow SU(2)_V$ symmetry:

[1] current conservation ⟶ Goldberger-Treiman relation

[2] existence of almost massless scalars: $m_\pi \ll m_\rho$

In general: let G be the global symmetry group and H its largest linearly-realized subgroup, so that:

- vacuum is invariant under H
- physical states fill multiplets of H

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## GOLDSTONE'S THEOREM

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J. Goldstone, A. Salam, S. Weinberg Phys. Rev. 127 (1962) 965 ]

*For each broken generator there is a massless scalar particle (Nambu-Goldstone boson) which is excited out of the vacuum by the corresponding Noether current*

$$\forall\, T^{\hat{a}} \in \mathrm{Alg}(G/H) \qquad \exists\, \pi^{\hat{a}} \;/\quad \langle 0|J_0^{\hat{a}}|\pi^{\hat{a}}\rangle \neq 0$$

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Is the local $SU(2)_L \mathrm{x} U(1)_Y$ spontaneously broken ?

but:
- what is the origin on the W,Z mass ?
- where are the massless NG bosons ?

## Spontaneously broken *local* symmetries: the Englert-Brout-Higgs mechanism

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*“ it is precisely these singularities [of the NG bosons] which maintain the gauge invariance of the theory, despite the fact that the vector meson acquires a mass ”*

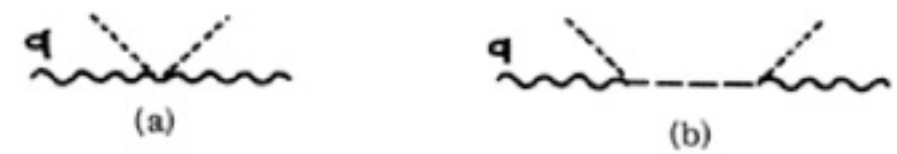


**FIG. 1. Broken-symmetry diagram leading to a mass for the gauge field. Short-dashed line, $\langle\varphi_1\rangle$; long-dashed line, $\varphi_2$ propagator; wavy line, $A_\mu$ propagator. (a) $\rightarrow (2\pi)^4 ie^2 g_{\mu\nu}\langle\varphi_1\rangle^2$, (b) $\rightarrow -(2\pi)^4 ie^2(q_\mu q_\nu/q^2) \times\langle\varphi_1\rangle^2$.**

# Spontaneously broken *local* symmetries: the Englert-Brout-Higgs mechanism

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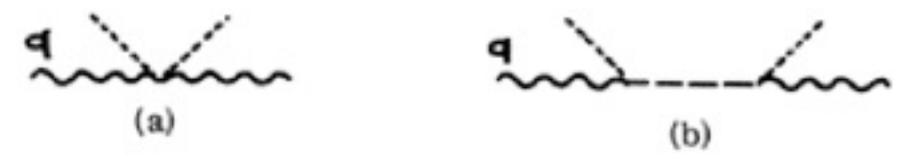


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- Higgs, Phys. Lett. 12 (1964) 132, “Broken symmetries, massless particles and gauge fields”

*choice of Coulomb gauge to quantize a gauge theory implies the existence of a time-like vector and thus invalidates Goldstone’s theorem based on manifest Lorentz covariance*

the group as coefficients. Now the structure of the Fourier transform of $i\langle[A_\mu'(x), \varphi_1(y)]\rangle$ must be given by eq. (3). Applying eq. (5) to this commutator gives us as the Fourier transform of $i\langle[f_\mu(x), \varphi_1(y)]\rangle$ the single term $[k^2 n_\mu - k_\mu(nk)]\rho(k^2, nk)$. We have thus exorcised both Goldstone's zero-mass bosons and the "spurion" state (at $k_\mu = 0$) proposed by Klein and Lee.

In a subsequent note it will be shown, by considering some classical field theories which dis-

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An abelian example (Stueckelberg trick):

$$\phi(x) = e^{i\chi(x)/f} \qquad \phi \to g\cdot\phi \qquad g = e^{i\alpha} \in U(1)$$

$$D_\mu\phi = \partial_\mu\phi + i\,eA_\mu\phi \qquad A_\mu \to A_\mu + i\,\partial_\mu\alpha$$

The U(1) global invariance is broken in the vacuum $\langle\phi^\dagger\phi\rangle = 1$

$\chi(x)$ is the associated (massless) Nambu-Goldstone boson

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$$\mathcal{L} = f^2\, (D_\mu \phi)^\dagger (D^\mu \phi) \xrightarrow{\text{in the unitary gauge } \chi(x)=0} \mathcal{L} = (ef)^2\, A_\mu A^\mu$$

invariant under U(1) local transformations

$$m_A = ef$$

vector mass does *not* break the local symmetry

The non-abelian case: how to rewrite the W,Z mass terms in a manifestly $SU(2)_L x U(1)_Y$ invariant way

Consider the field $$\Sigma(x) = \exp\left(i\sigma^a \chi^a(x)/v\right)$$ ( 2x2 matrix )

$a = 1, 2, 3$

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Under $SU(2)_L \times U(1)_Y$ : $\Sigma \to U_L \, \Sigma \, U_Y^\dagger$ ( $SU(2)_L$ acts on the left, $U(1)_Y$ acts on the right )

$$U_L(x) = \exp(i\,\alpha_L^a(x)\sigma^a/2)$$

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The vacuum $\langle\Sigma\rangle = 1$ spontaneously breaks $SU(2)_L x U(1)_Y \to U(1)_Q$ ( $Q = T_{3L} + Y$ )

The $\chi^a(x)$ are the (three) associated Nambu-Goldstone bosons.

The $\chi^a(x)$ transform:

- non-linearly under SU(2)LxU(1)Y

ex: under SU(2)L

$$\hat{\chi}'^{\,a} = \hat{\chi}^a \left(1 + \frac{1}{2}\,\vec{\alpha}\cdot\hat{\chi}\,\cot\!\left(\frac{\chi}{v}\right)\right) + \frac{\alpha^a}{2}\cot\!\left(\frac{\chi}{v}\right) + O(\alpha^2)$$

$$\sin\left(\frac{\chi'}{v}\right) = \sin\left(\frac{\chi}{v}\right)\left[1 + \frac{1}{2}\,\vec{\alpha}\cdot\hat{\chi}\,\cot\!\left(\frac{\chi}{v}\right)\right] + O(\alpha^2)$$

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- linearly under the unbroken U(1)$_Q$ subgroup:

$$U_L = U_Y = \exp(i\alpha\,\sigma^3/2) \equiv U_Q$$

$$\Sigma' = U_Q\, e^{i\chi\cdot\sigma/v}\, U_Q^{-1} = e^{i\,U_Q(\chi\cdot\sigma)U_Q^{-1}/v}$$

$$(\vec{\chi}'\cdot\vec{\sigma}) = U_Q\,(\vec{\chi}\cdot\vec{\sigma})\,U_Q^{-1}$$

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$$(\vec{\chi}'\cdot\vec{\sigma}) = U_Q\,(\vec{\chi}\cdot\vec{\sigma})\,U_Q^{-1}$$

Notice: the field $\Sigma$ transforms linearly, but it is subject to the non-linear constraint $\Sigma^\dagger\Sigma = 1$

It is natural then to define the covariant derivative:

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

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There are *two* kinetic terms invariant under $SU(2)_L x U(1)_Y$ local transformations:

$$\mathcal{L}_{mass} = \frac{v^2}{4} \mathrm{Tr}\left[ (D_\mu \Sigma)^\dagger (D^\mu \Sigma) \right] + \frac{a_T}{8} v^2 \, \mathrm{Tr}\left[ \Sigma^\dagger D_\mu \Sigma \, \sigma^3 \right]^2$$

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$$= m_W^2 \, W_\mu^+ W^{\mu\,-} + \frac{1}{2} m_Z^2 \, Z_\mu Z^\mu$$

in the unitary gauge $\chi(x) = 0$

$$M_W^2 = \frac{v^2}{4} g_2^2$$

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It is natural then to define the covariant derivative:

$$D_\mu \Sigma = \partial_\mu \Sigma - i g_2 \frac{\sigma^a}{2} W_\mu^a \Sigma + i g_1 \Sigma \frac{\sigma_3}{2} B_\mu$$

There are *two* kinetic terms invariant under $SU(2)_L \times U(1)_Y$ local transformations:

$$\mathcal{L}_{mass} = \frac{v^2}{4} \mathrm{Tr}\left[ (D_\mu \Sigma)^\dagger (D^\mu \Sigma) \right] + \frac{a_T}{8} v^2 \, \mathrm{Tr}\left[ \Sigma^\dagger D_\mu \Sigma \, \sigma^3 \right]^2$$

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MUST BE SMALL

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- The pattern of global non-linearly realized symmetry is $SU(2)_L$x$SU(2)_R \rightarrow SU(2)_V$

→ complete analogy with chiral symmetry in QCD !

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- The pattern of global non-linearly realized symmetry is $SU(2)_L$x$SU(2)_R$→$SU(2)_V$

  ⟶ complete analogy with chiral symmetry in QCD !

- the vacuum preserves a global $SU(2)_V$ 'custodial' symmetry

  ⟶ physical states come in multiplets of $SU(2)_V$

  ⟶ the NG bosons $\chi^a$ form a triplet of $SU(2)_V$ ⟺ $M_W = M_Z$ for $g_1 = 0$

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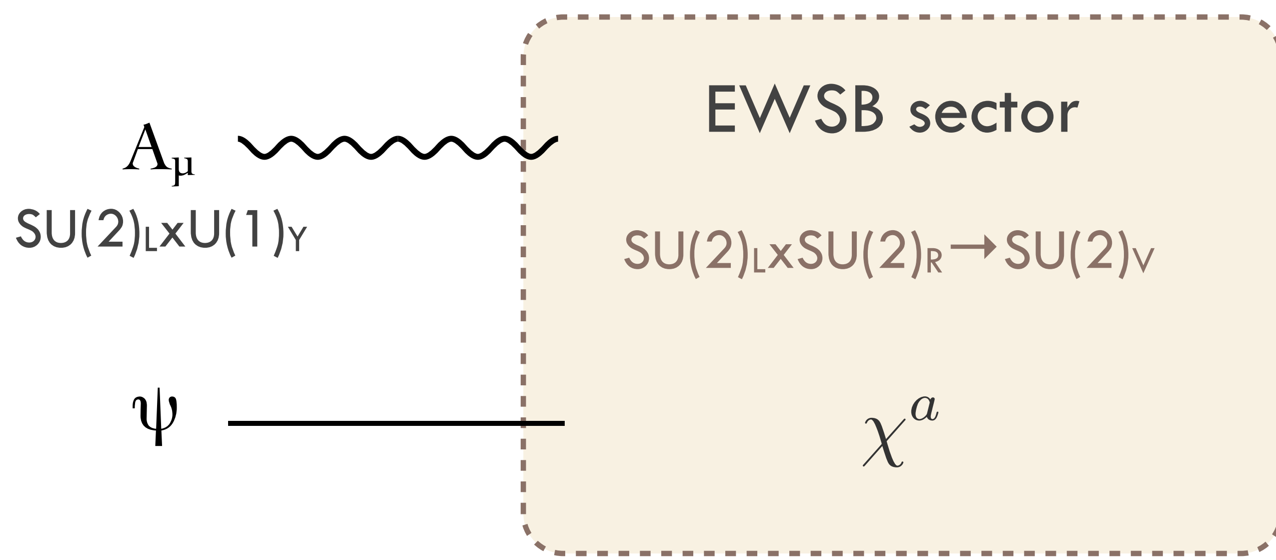

The EW effective Lagrangian:

$$\mathcal{L}_0 = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}G_{\mu\nu}G^{\mu\nu} + \sum_{j=1}^{3}\left(\bar{\Psi}^{(j)}_L i\not{D}\Psi^{(j)}_L + \bar{\Psi}^{(j)}_R i\not{D}\Psi^{(j)}_R\right)$$

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Q: *... but if 'breaking of gauge invariance' is not the issue, why the above Lagrangian is not a complete description of Nature ?*

A: *the Lagrangian $\mathcal{L}_{mass}$ gives an effective description (it is not renormalizable) valid below some cutoff scale:*

$$\frac{v^2}{4}(\partial_\mu \Sigma)^\dagger(\partial_\mu \Sigma) = \frac{1}{2}\left(\partial_\mu \chi^a\right)^2 + \frac{1}{6v^2}\left[\left(\chi^a \partial_\mu \chi^a\right)^2 - \left(\chi^a \partial_\mu \chi^b\right)^2\right] + O(\chi^6)$$

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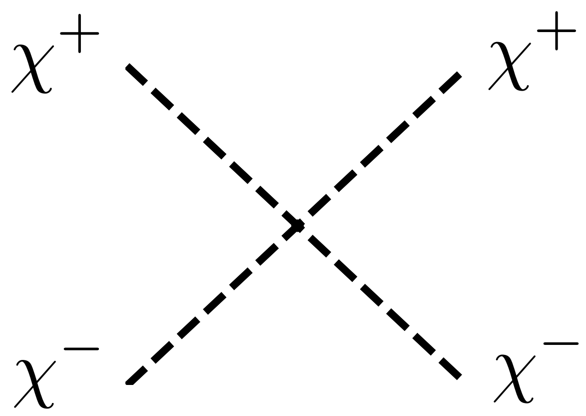


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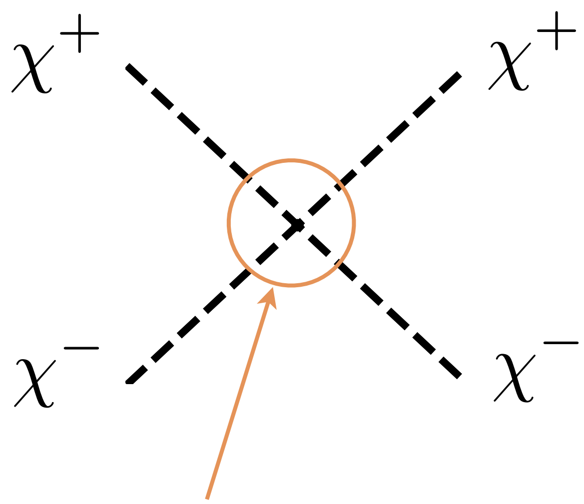


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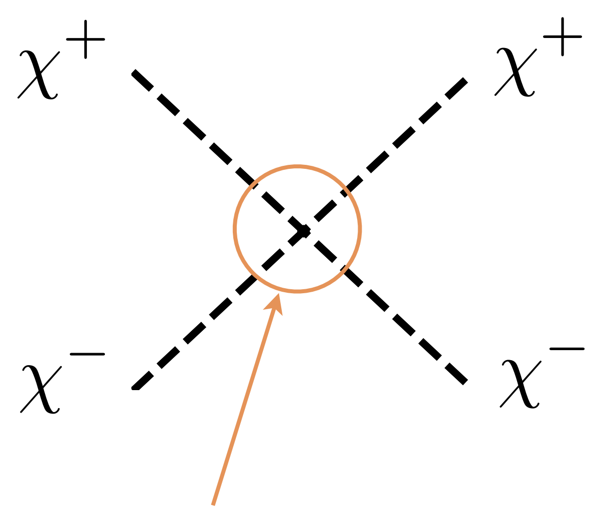


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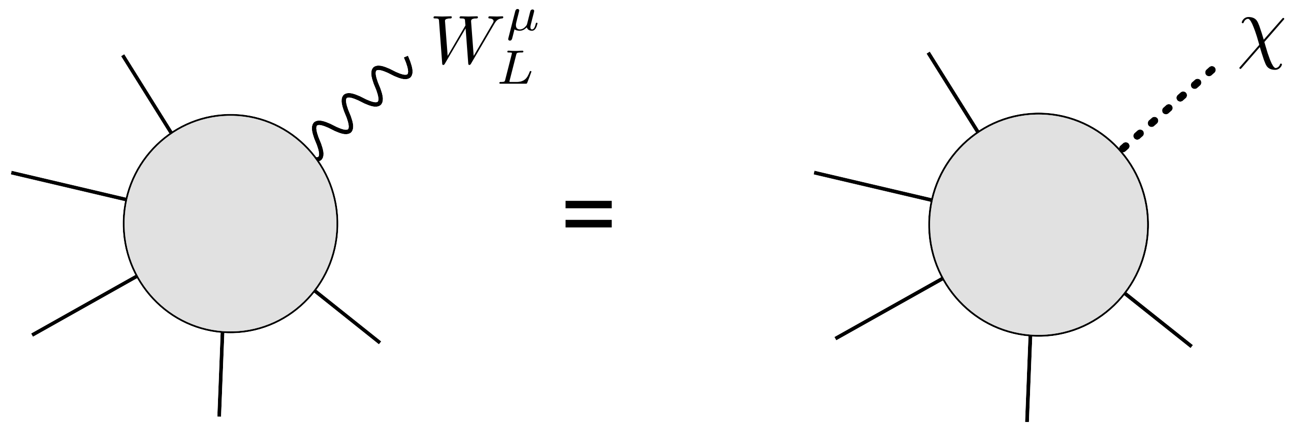
If no new physics comes in before then, the scattering of NG bosons becomes non-perturbative at energy scales $E \sim \Lambda_s = 4\pi v$

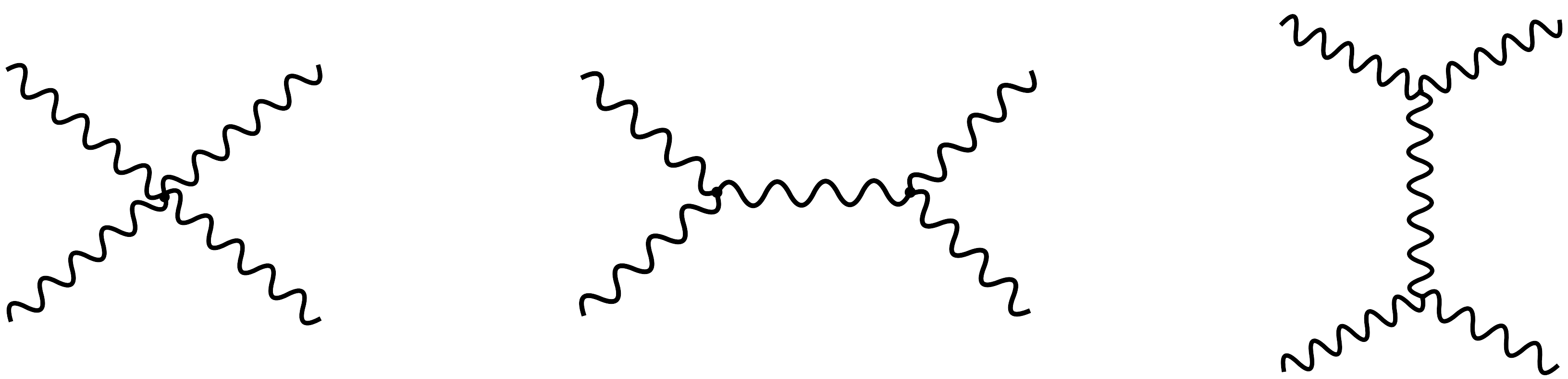
## The Equivalence Theorem




$$\left(1 + O\left(\frac{M_W^2}{E^2}\right)\right)$$

relates the scattering of NG bosons to that of longitudinal vector bosons

$V_L V_L \to V_L V_L$ ( $V = W, Z$ ) at high energies $E \gg m_W$



$$\mathcal{A}(W_L^+ W_L^- \to W_L^+ W_L^-) = \mathcal{A}(\chi^+ \chi^- \to \chi^+ \chi^-) \left(1 + O\left(\frac{M_W^2}{E^2}\right)\right) = \frac{g_2^2}{4 m_W^2}(s+t) + \ldots$$

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[3] the *transverse* $W^T_\mu, Z^T_\mu$ are elementary up to energies $E \gg 4\pi\, m_V/g$

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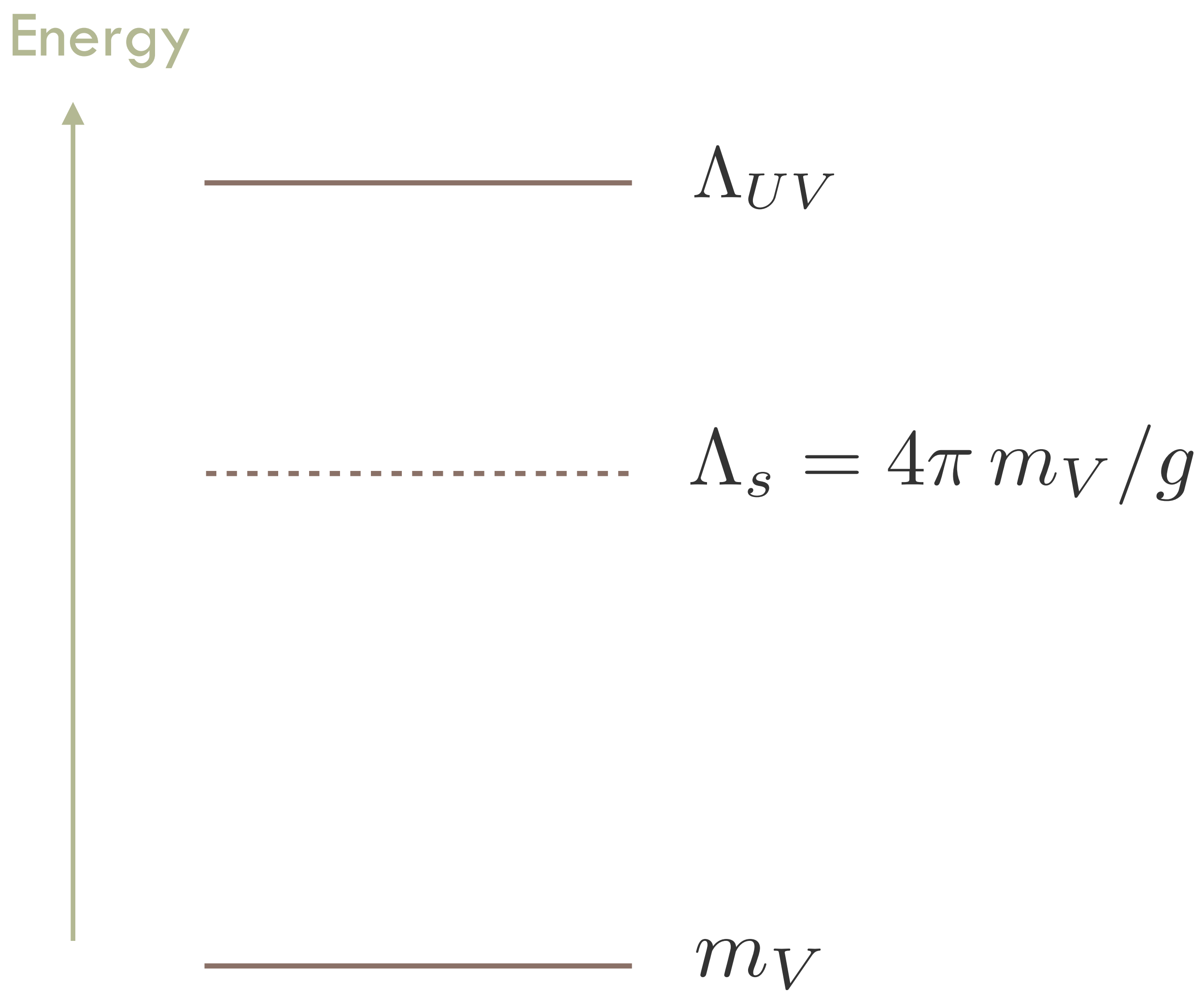

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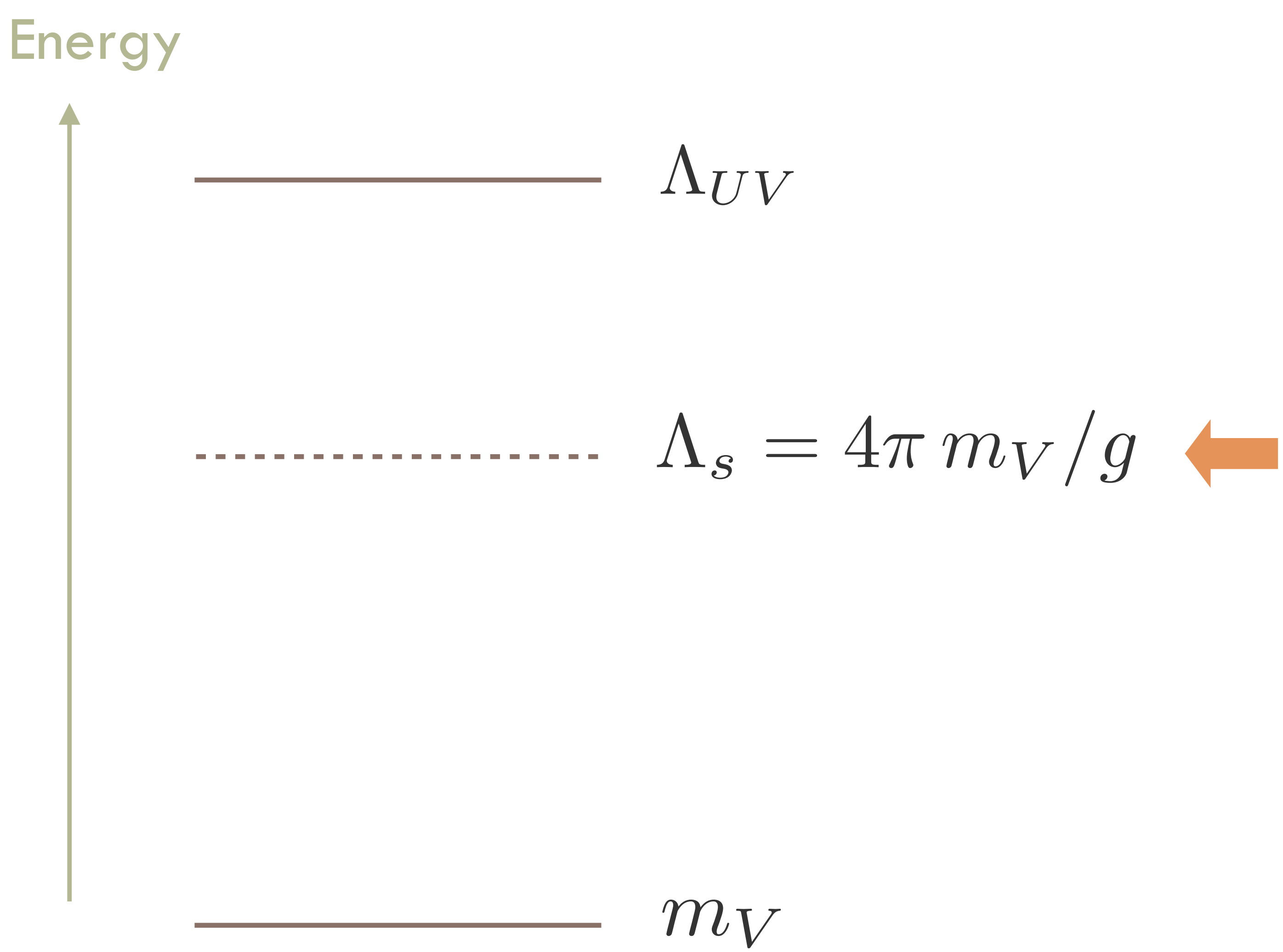


scale at which $V_L \sim \chi$ eventually become strongly interacting

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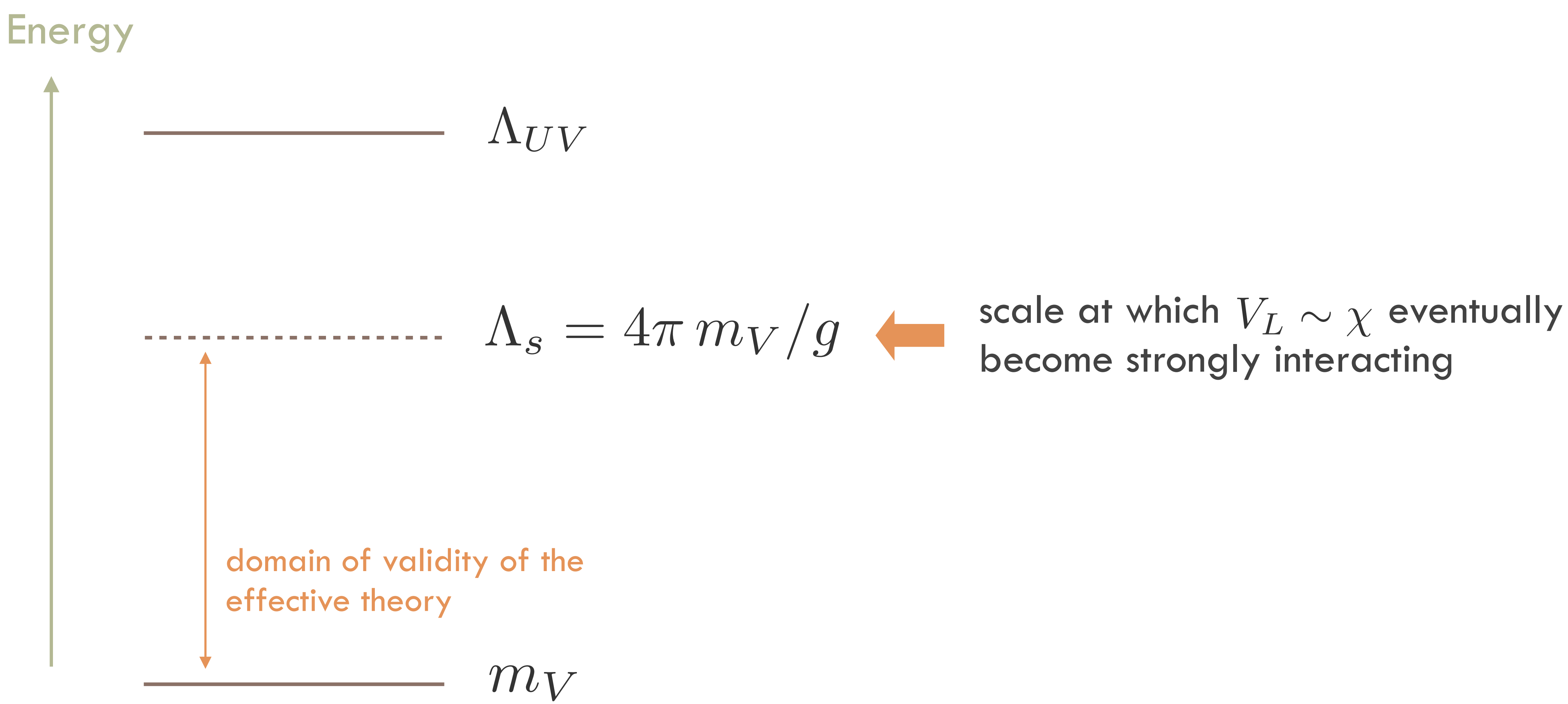

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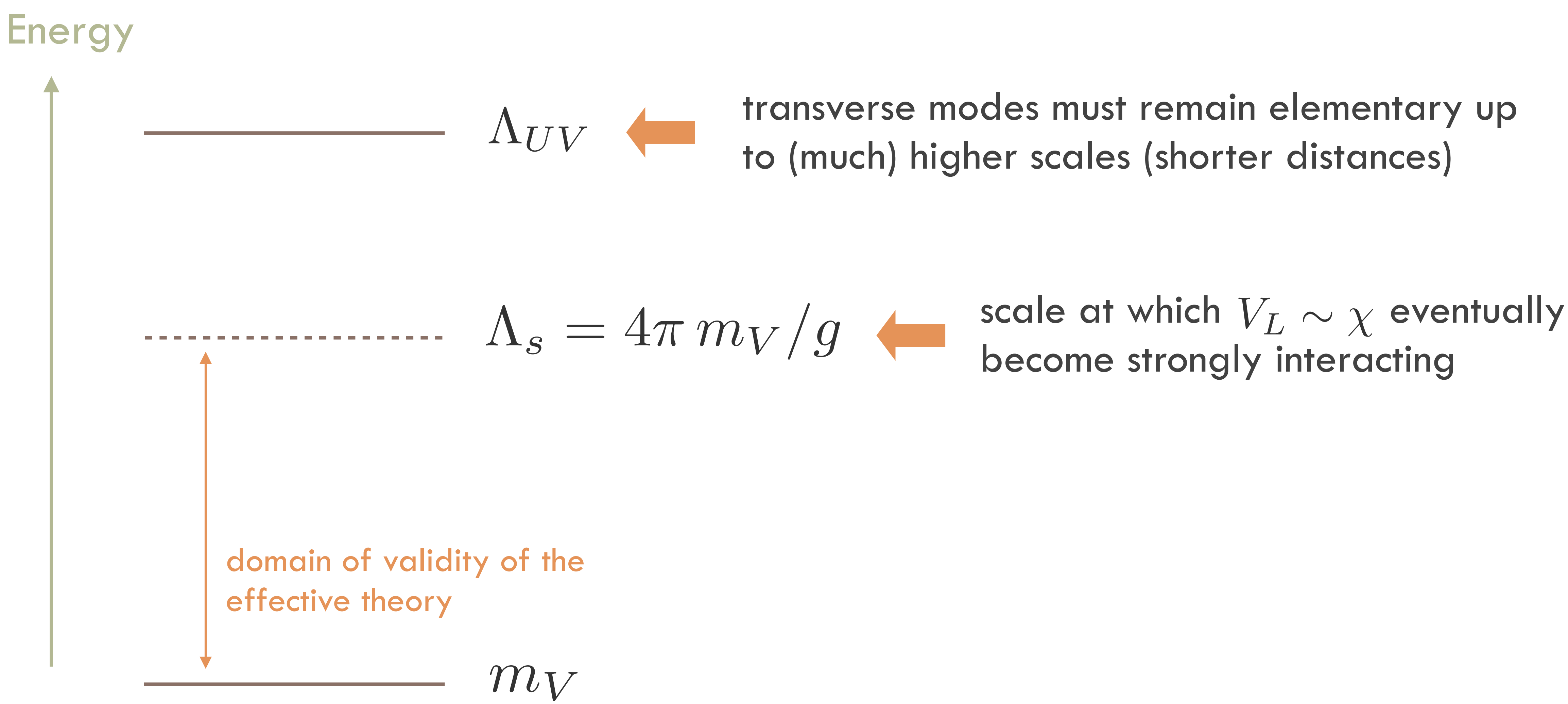

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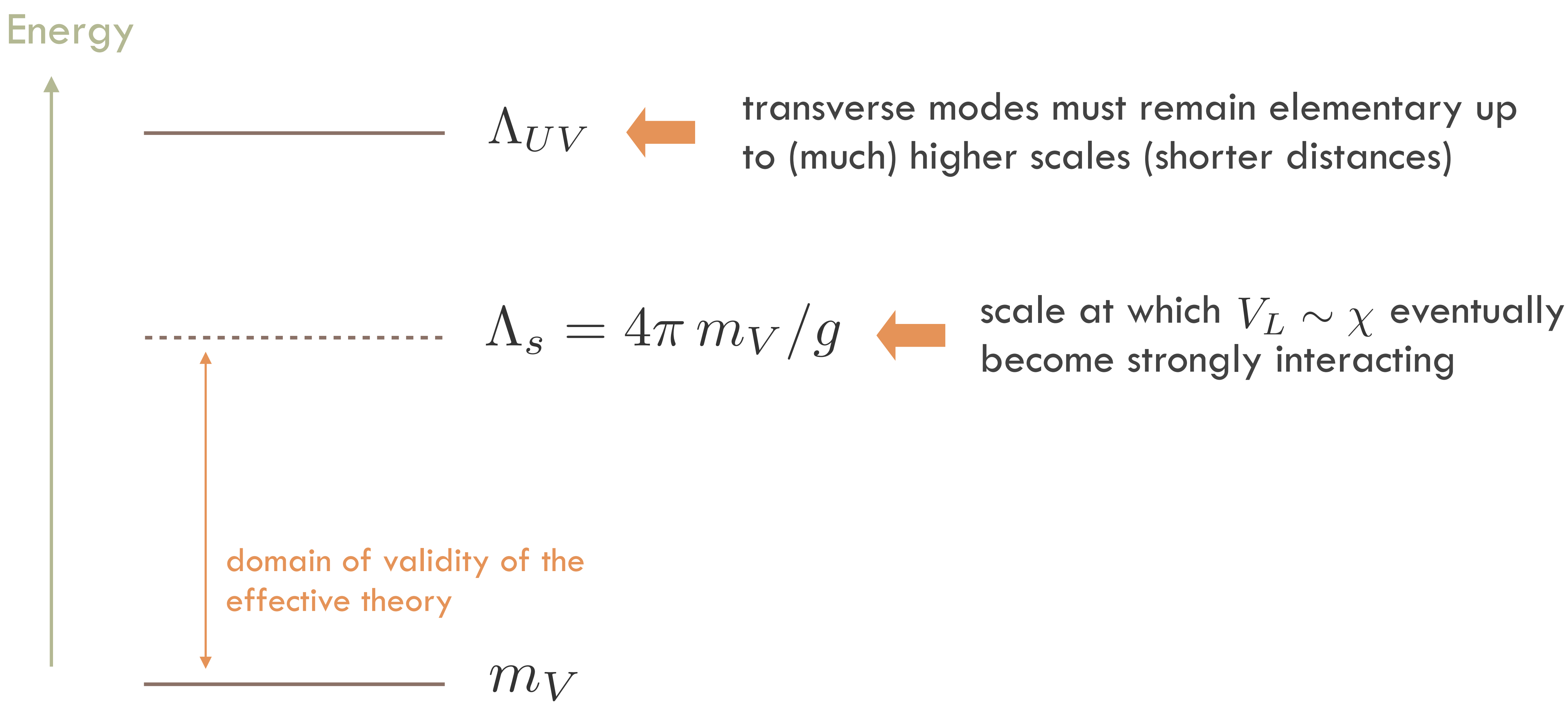


NOTICE:

the longitudinal polarizations need *not* be elementary

(i.e. they can be composites of some new dynamics)

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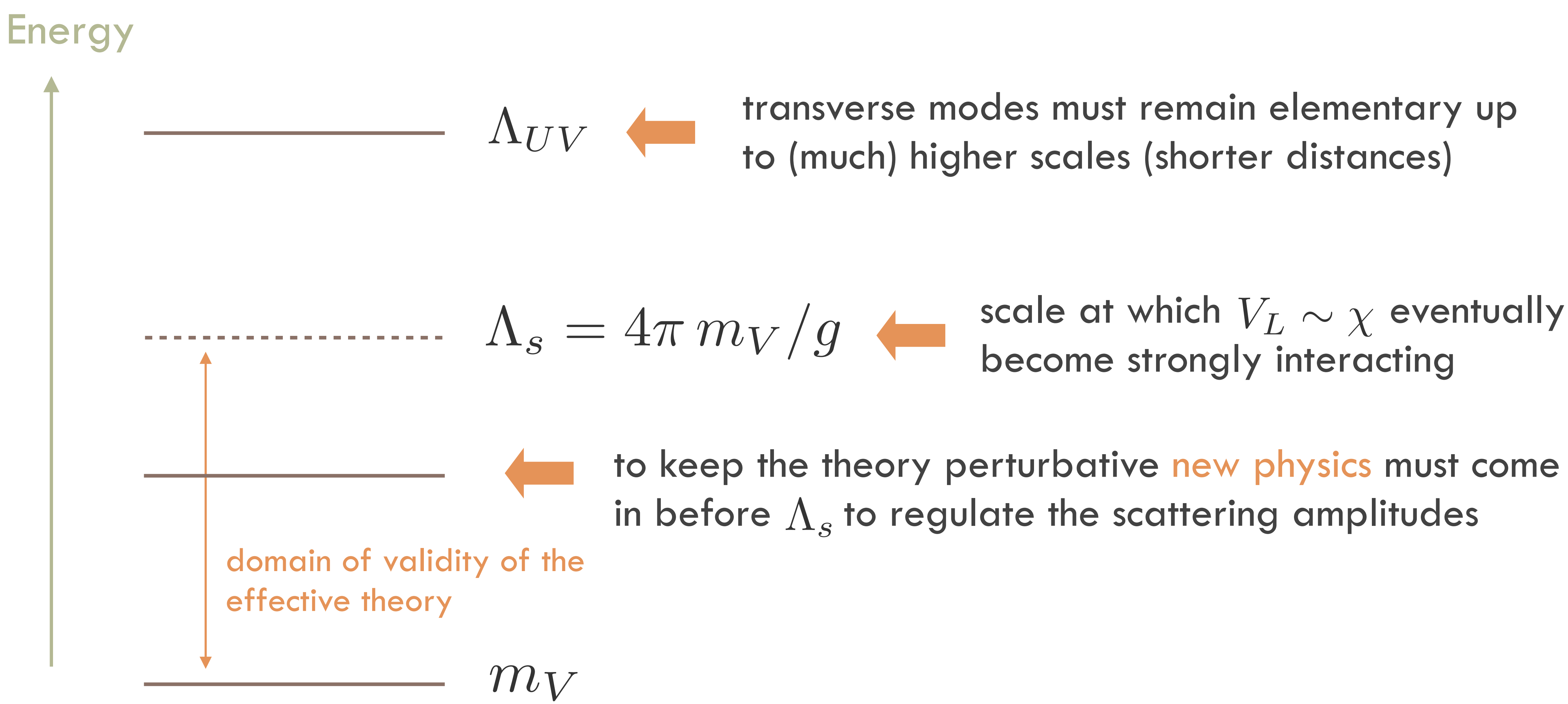


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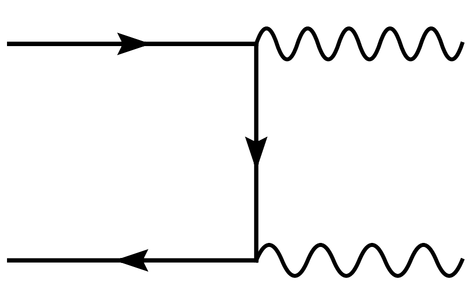
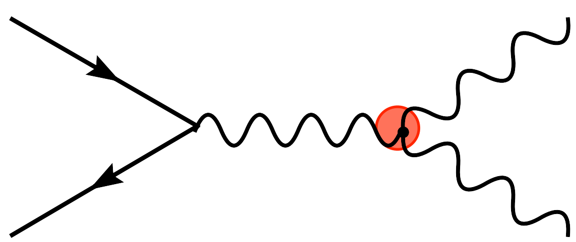
# Evidence for EWSB

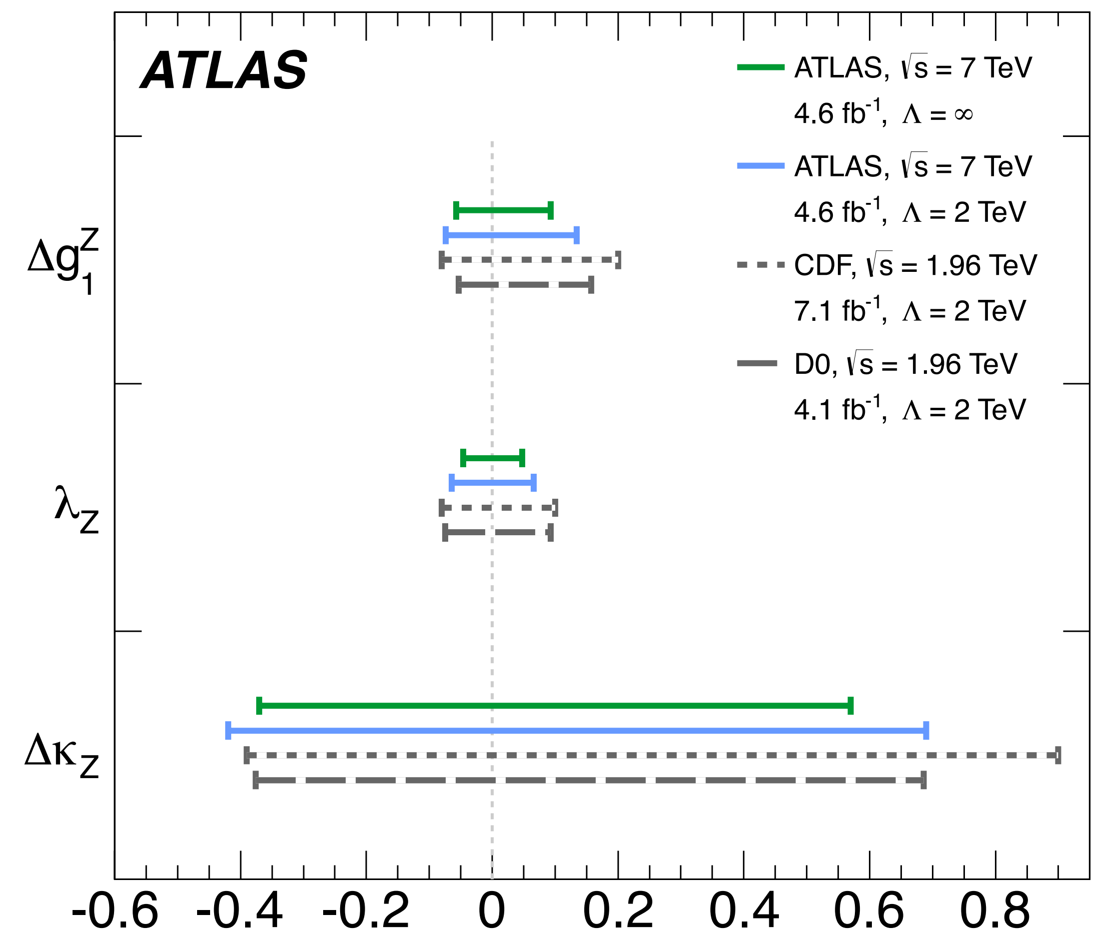
Elementary nature of W,Z tested at LEP, Tevatron and LHC through Triple Gauge Couplings (TGC)





$$i\mathcal{L} = e\cot\theta_W\left[g_1^Z\, Z^\mu(W^-_{\mu\nu}W^{+\,\nu} - W^+_{\mu\nu}W^{-\,\nu}) + \kappa_Z\, W^+_\mu W^-_\nu Z^{\mu\nu} + \frac{\lambda_Z}{m_W^2} W^{+\,\rho}_\nu W^-_{\rho\mu} Z^{\mu\nu}\right] + e\left[\kappa_\gamma\, W^+_\mu W^-_\nu \gamma^{\mu\nu} + \frac{\lambda_\gamma}{m_W^2} W^{+\,\rho}_\nu W^-_{\rho\mu}\gamma^{\mu\nu}\right]$$

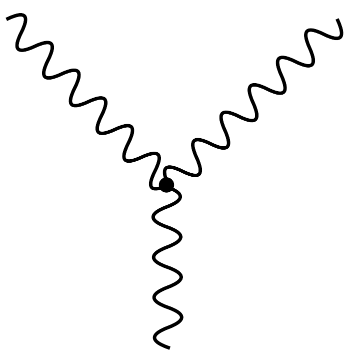
95% CL limits from WZ production




| 95% CL limits | | ATLAS | LEP |
|---|---|---|---|
| [from WW] | $\lambda_\gamma = \lambda_Z$ | [-0.079, 0.077] | [-0.059, 0.026] |
| [from WZ] | $\lambda_Z$ | [-0.046, 0.047] | — |
| [from Wγ] | $\lambda_\gamma$ | [-0.060, 0.0460] | — |

# Evidence for EWSB

No evidence so far of compositeness or \`structure\` for the transverse modes



$$O_1 = \frac{e\lambda_\gamma}{m_W^2}\, \gamma_{\mu\nu} W^+_{\nu\rho} W^-_{\rho\mu}$$

$$O_2 = \frac{e\lambda_Z}{m_W^2}\, Z_{\mu\nu} W^+_{\nu\rho} W^-_{\rho\mu}$$

$$\Longleftrightarrow$$

$$\frac{g_2 c_{W3}}{m_W^2}\, \epsilon^{abc}\, W^a_{\mu\nu} W^b_{\nu\rho} W^c_{\rho\mu}$$

$$\frac{g_1 c_{WWB}}{m_W^2}\, \mathrm{Tr}\left[W_{\mu\nu} W_{\nu\rho}\, \Sigma\, \sigma^3 B_{\rho\mu}\, \Sigma^\dagger\right]$$

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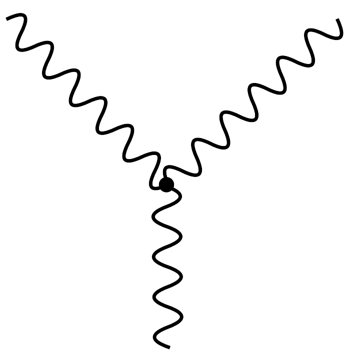

$$\sim g\left(1 + c_{W3}\,\frac{E^2}{m_W^2}\right)$$

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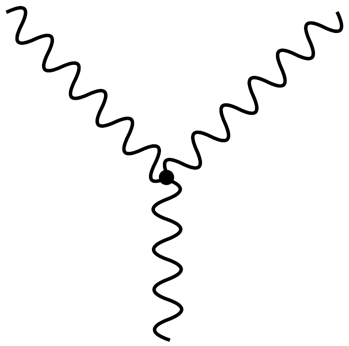

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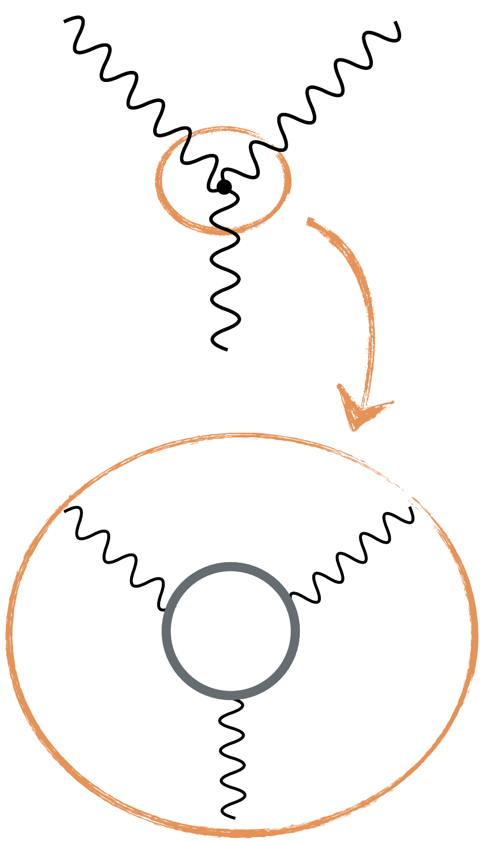

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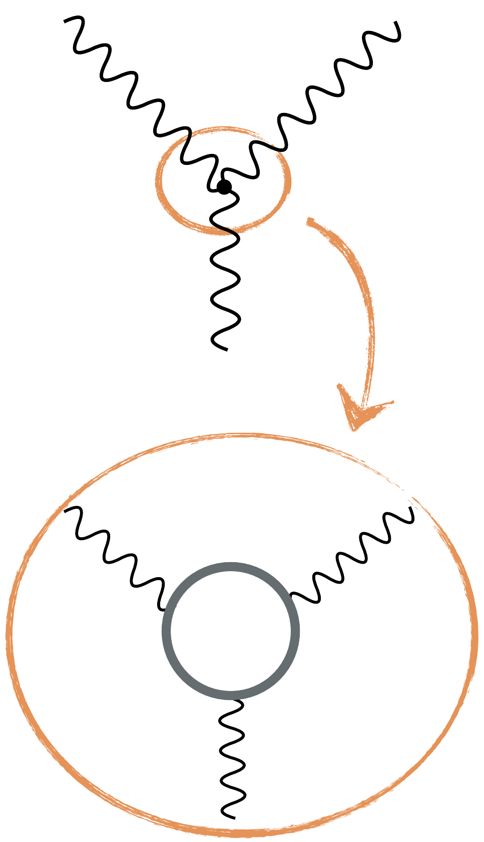

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$$m_* \approx \frac{m_W}{\sqrt{c_{W3}}} \times \frac{4\pi}{g}$$

if new physics arises
at the 1-loop level

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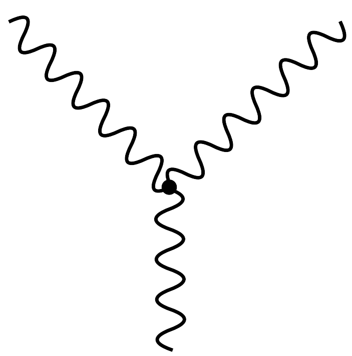

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if no `structure` appears at $m_*$ , interaction becomes strong at

$$E \sim m_W\sqrt{\frac{4\pi}{c_{W3}\,g}} \equiv \Lambda_S$$

(transverse modes are *composite*)

$\Lambda_S$

$E$ $\uparrow$

$\dfrac{m_W}{\sqrt{c_{W3}}}$

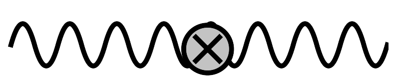
LEP + Tevatron + LHC

$$\Lambda_S \gtrsim 4\,\mathrm{TeV}$$

# Evidence for EWSB

Stronger bounds on `structure` scale $m_*$ come from modifications to the vector propagator

Ex: S-parameter $a_S \, \mathrm{Tr}\left[W_{\mu\nu}\, \Sigma\, \sigma^3 B_{\mu\nu}\, \Sigma^\dagger\right] \supset \gamma_{\mu\nu} Z_{\mu\nu}$ ( Z-photon mixing )



$$\sim \left(g_1 g_2\, v^2 + a_S\, E^2\right)$$

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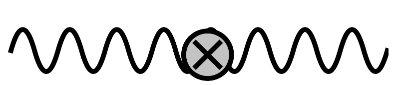

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# Evidence for EWSB

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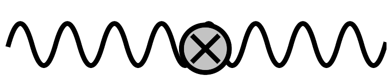 $\sim \left(g_1 g_2\, v^2 + a_S\, E^2\right)$

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LEP

$$\frac{g_2}{g_1}\, a_S(m_Z) = \frac{m_W^2}{m_*^2} \lesssim 2 \times 10^{-3}$$

$$m_* \gtrsim 1.8\,\mathrm{TeV}$$

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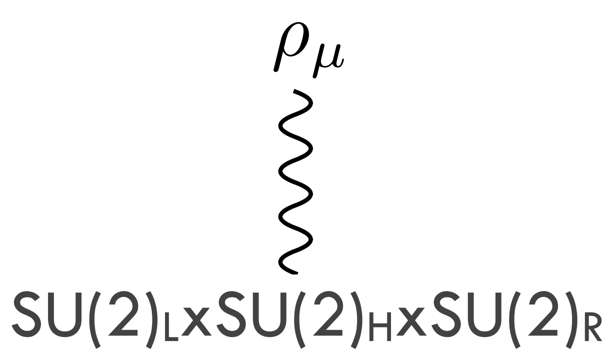


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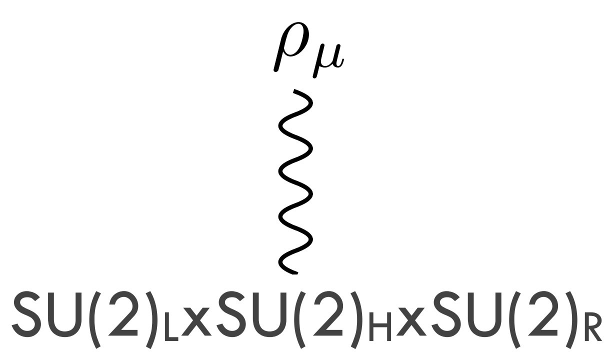


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The gauged $SU(2)_H$ group was dubbed the *Hidden Local Symmetry*

Sakurai, *Currents and Mesons*, 1969
Schwinger, PRL 24B (1967) 473
Wess, Zumino, Phys. Rev. 163, (1967) 1727
Weinberg, Phys. Rev. 166 (1968) 1568
Bando, et al., PRL 54 (1985) 1215

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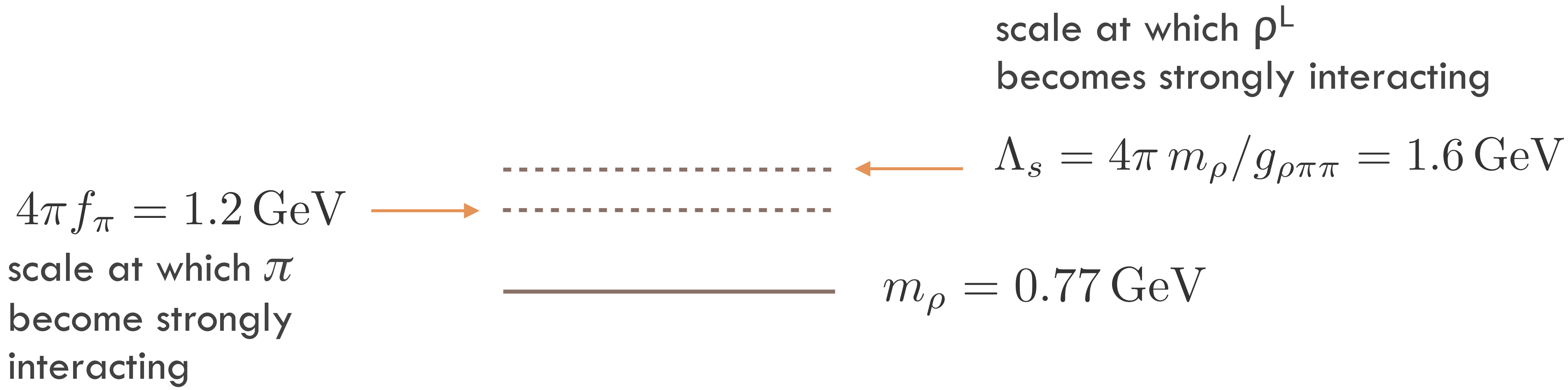

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Now we know that:

*both* longitudinal and transverse polarizations of ρ (as well as the pions) are composites of the QCD dynamics

$$\Lambda_{QCD} \sim 4\pi f_\pi \sim 4\pi\, m_\rho / g_{\rho\pi\pi} \approx 1\,\mathrm{GeV}$$

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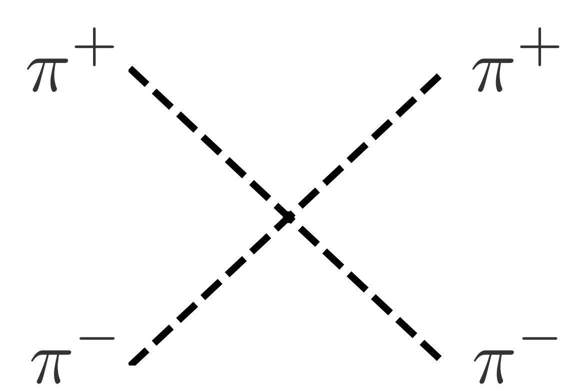
In fact:

$\pi\pi$ scattering grows strong up to the cutoff scale $4\pi f_\pi$ and no *light* new physics comes in before to regulate the energy behavior of the scattering amplitude



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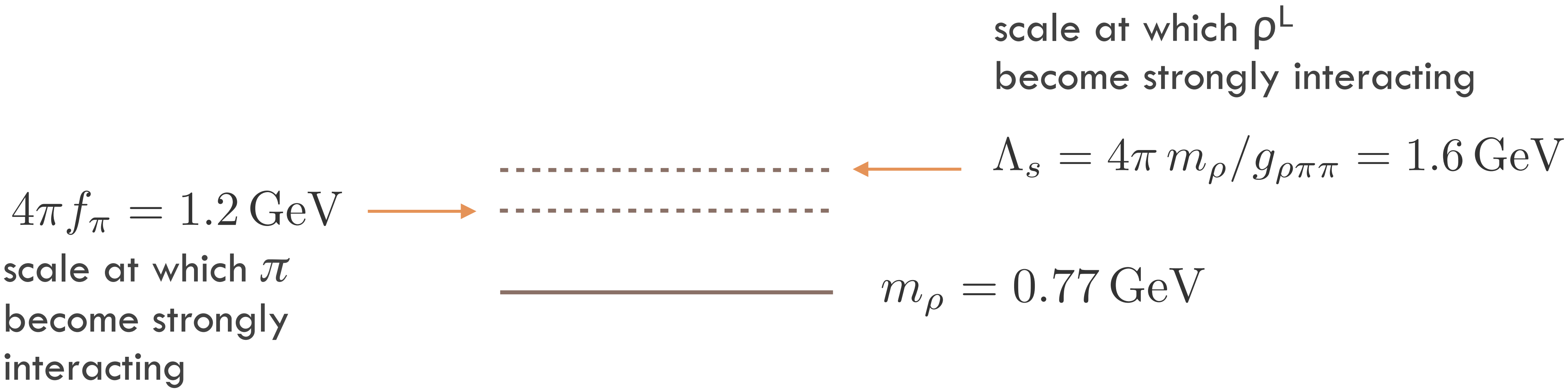


Hence:

> there is *no* energy region in which the theory has a (non-linearly realized) $SU(2)_L \times SU(2)_H \times SU(2)_R \to SU(2)_V$ symmetry and the ρ can be considered a gauge field

# Weak or Strong EWSB ?

To summarize:

- There is convincing evidence (from LEP, Tevatron and LHC) that the transverse W and Z polarizations are elementary up to energies much higher than the EW scale, hence of a non-linear realization $SU(2)_L x U(1)_Y \rightarrow U(1)_Q$ of the electroweak symmetry

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The question to address is now the following:

- *Is the EWSB strong (as for the chiral symmetry in QCD) or weak ?*