The Standard Model of Electroweak Physics

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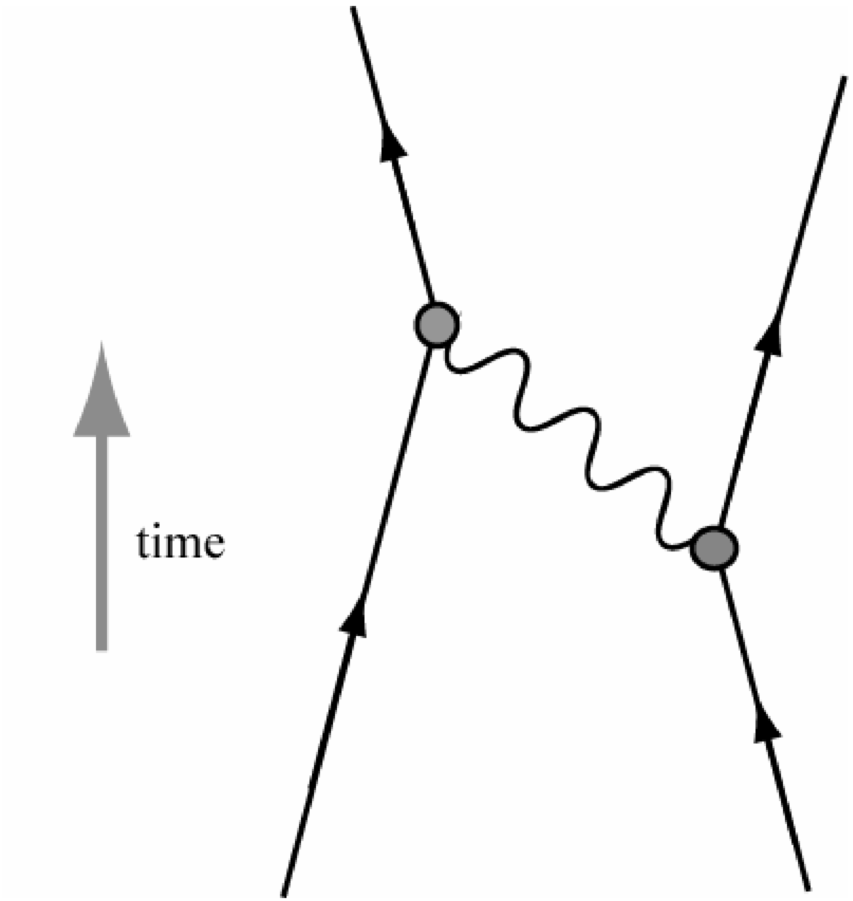
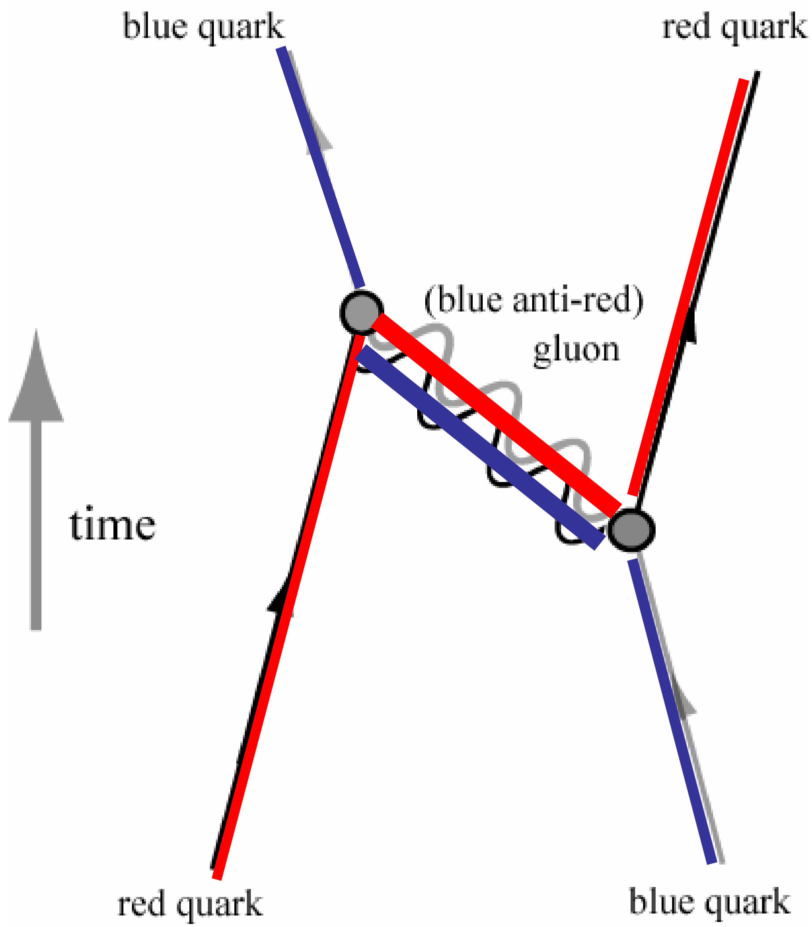
Lecture II: Structure of the Electroweak Theory

Electromagnetic force

Quark color force

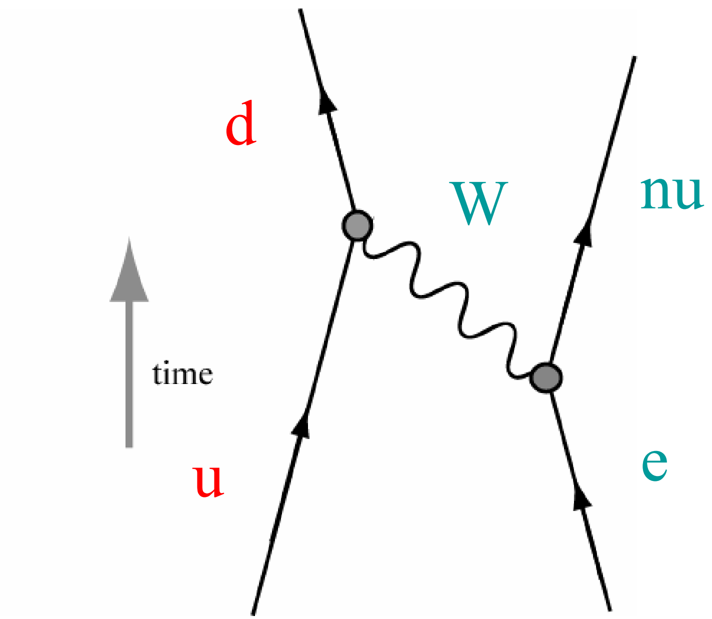




Standard Electroweak Model

Weak Force:

SU(2) x U(1)



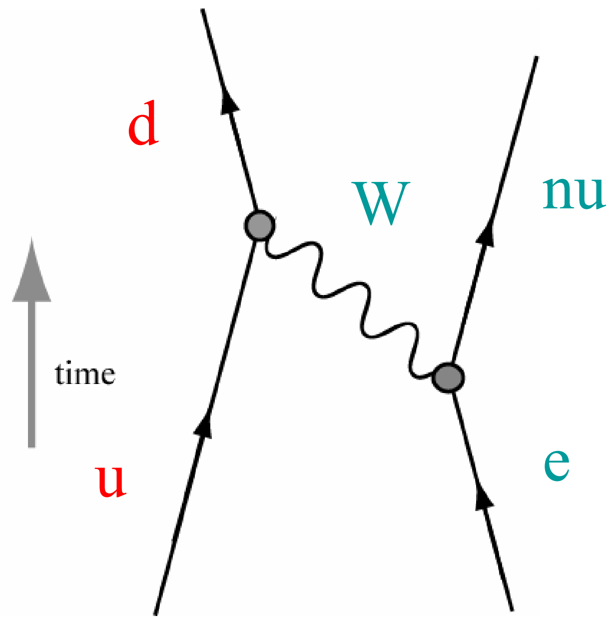
What gives rise to masses of W and Z boson?

SU(2)xU(1) is "Spontaneously broken Symmetry"

Higgs Field?

Standard Electroweak Model

Weak Force:



SU(2) x U(1)

Based upon a nonabelian gauge symmetry: Yang-Mills Field Theory

SU(2)xU(1) is "Spontaneously broken Symmetry"

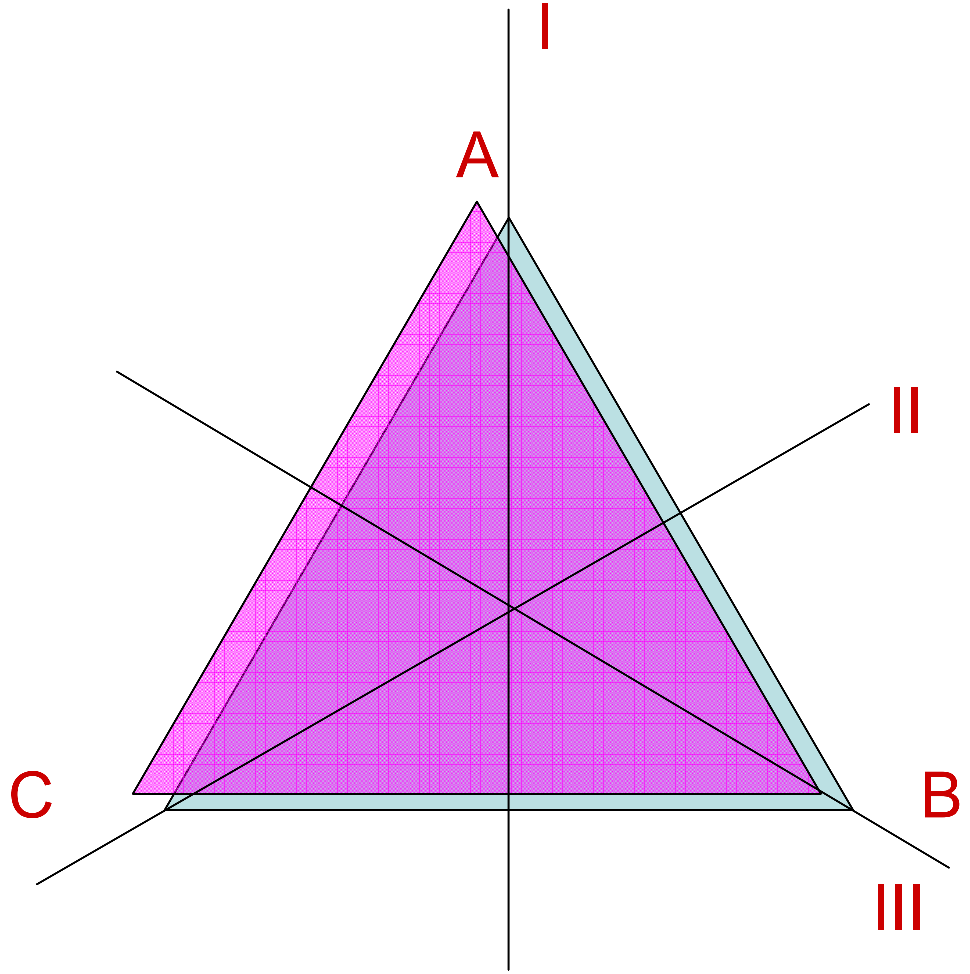
Higgs Field?

Symmetry is:

Invariance of a system or object under a transformation or collection of transformations.

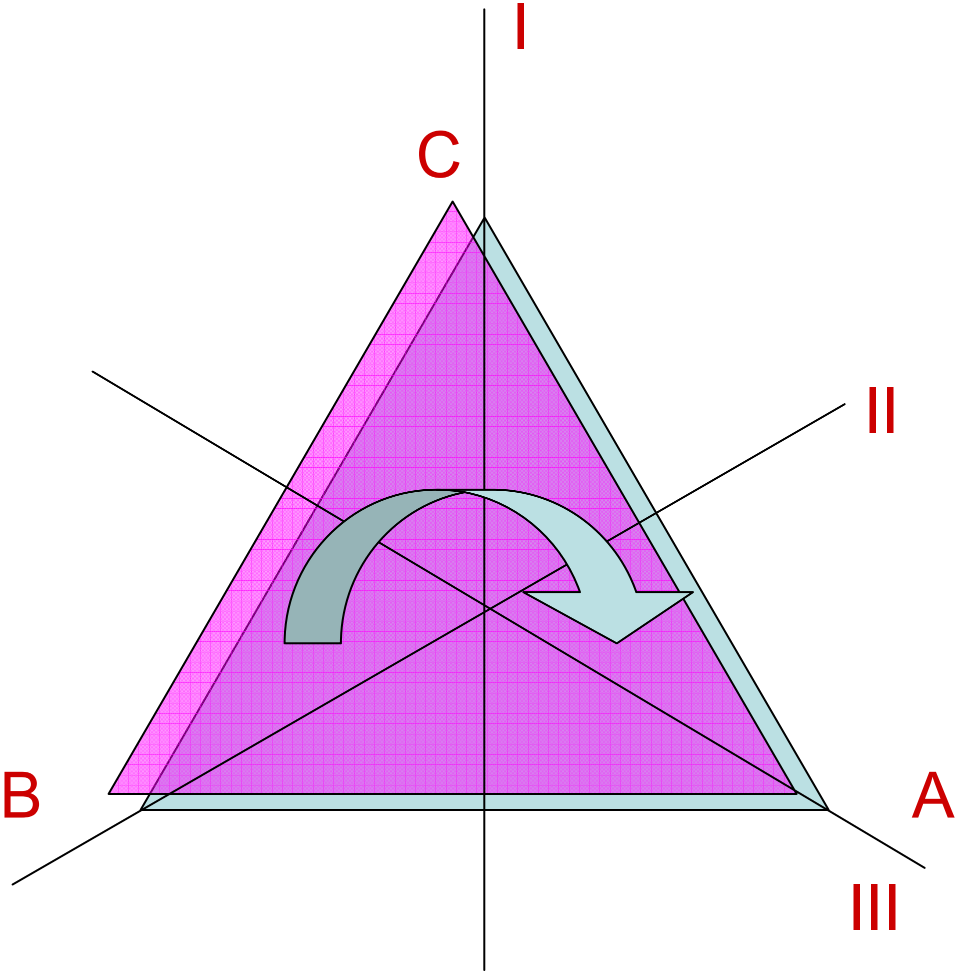
Symmetry Groups

Symmetry of the Equilateral Triangle



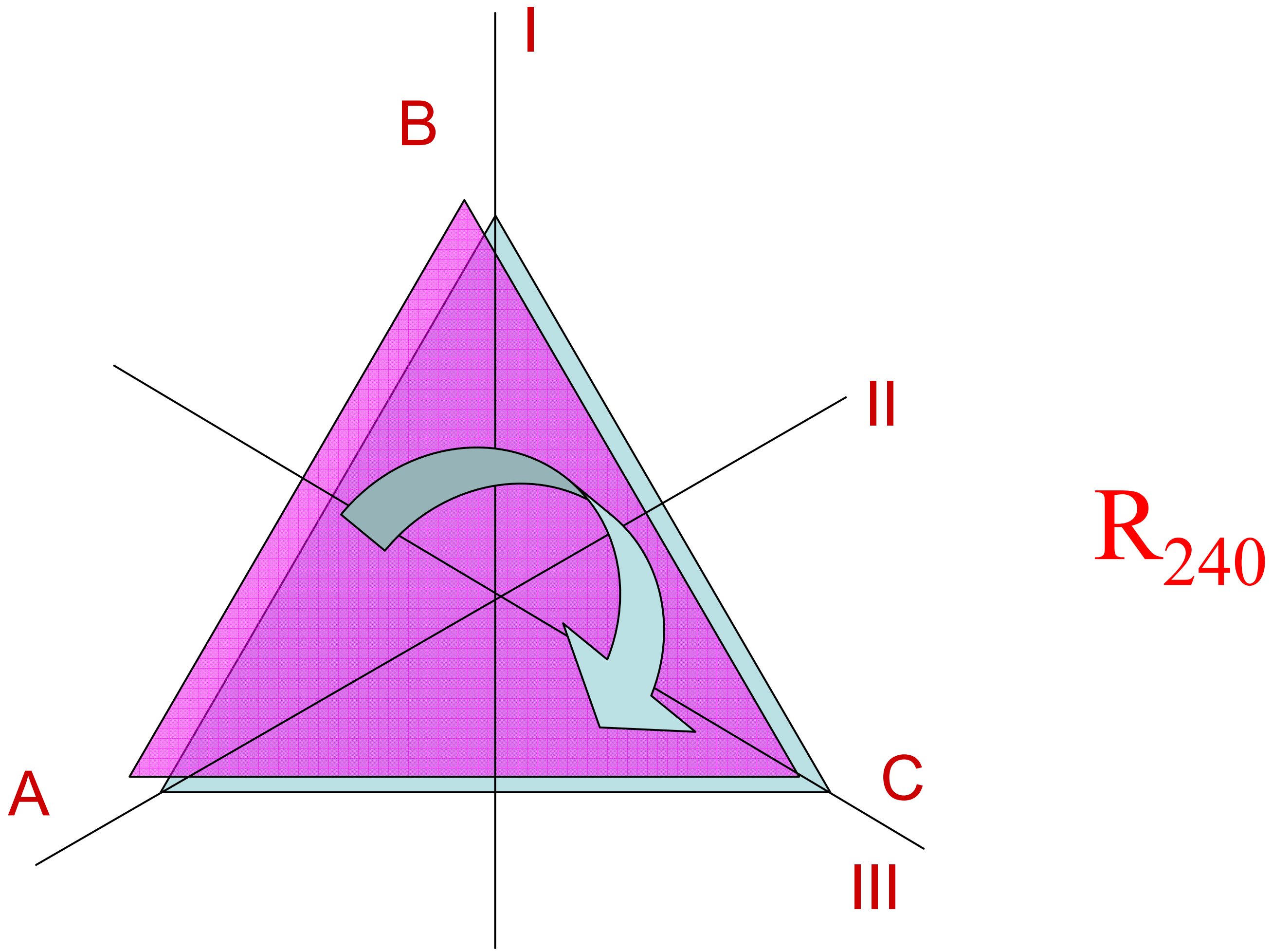
1

identity

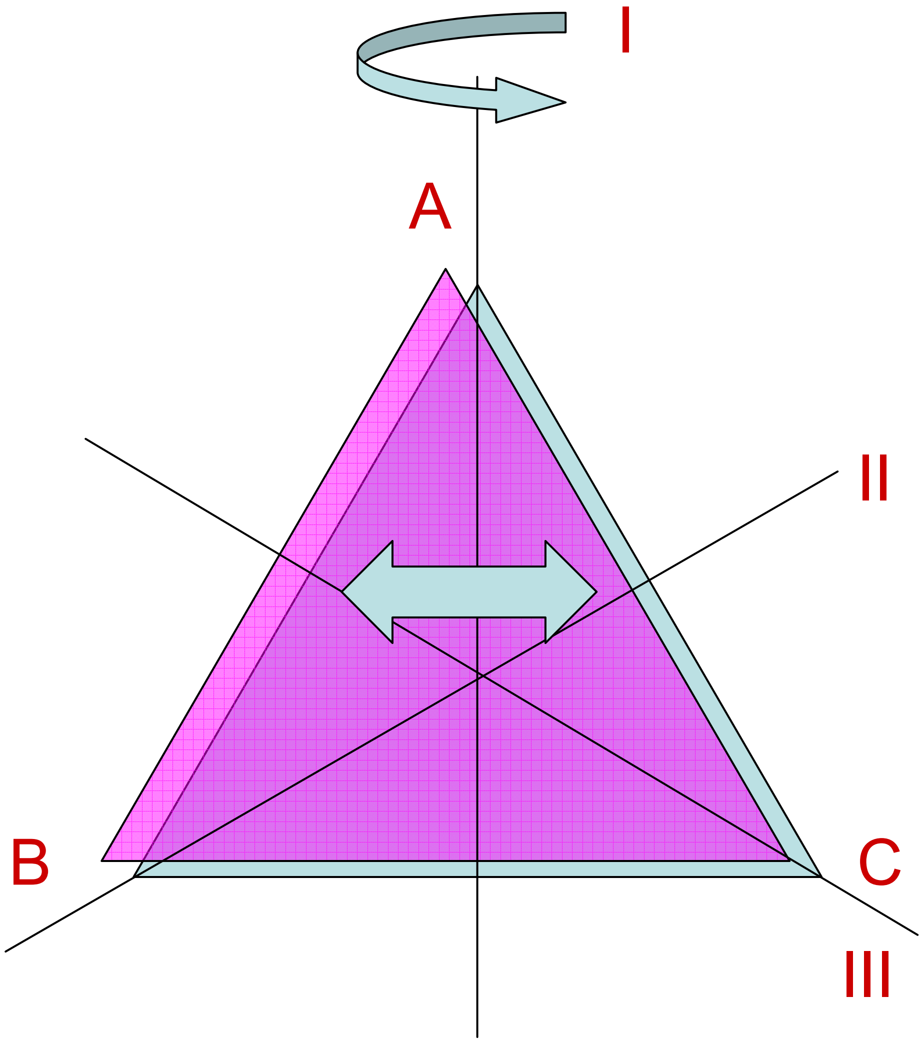


R_{120}

Rotation about center through 120 degrees

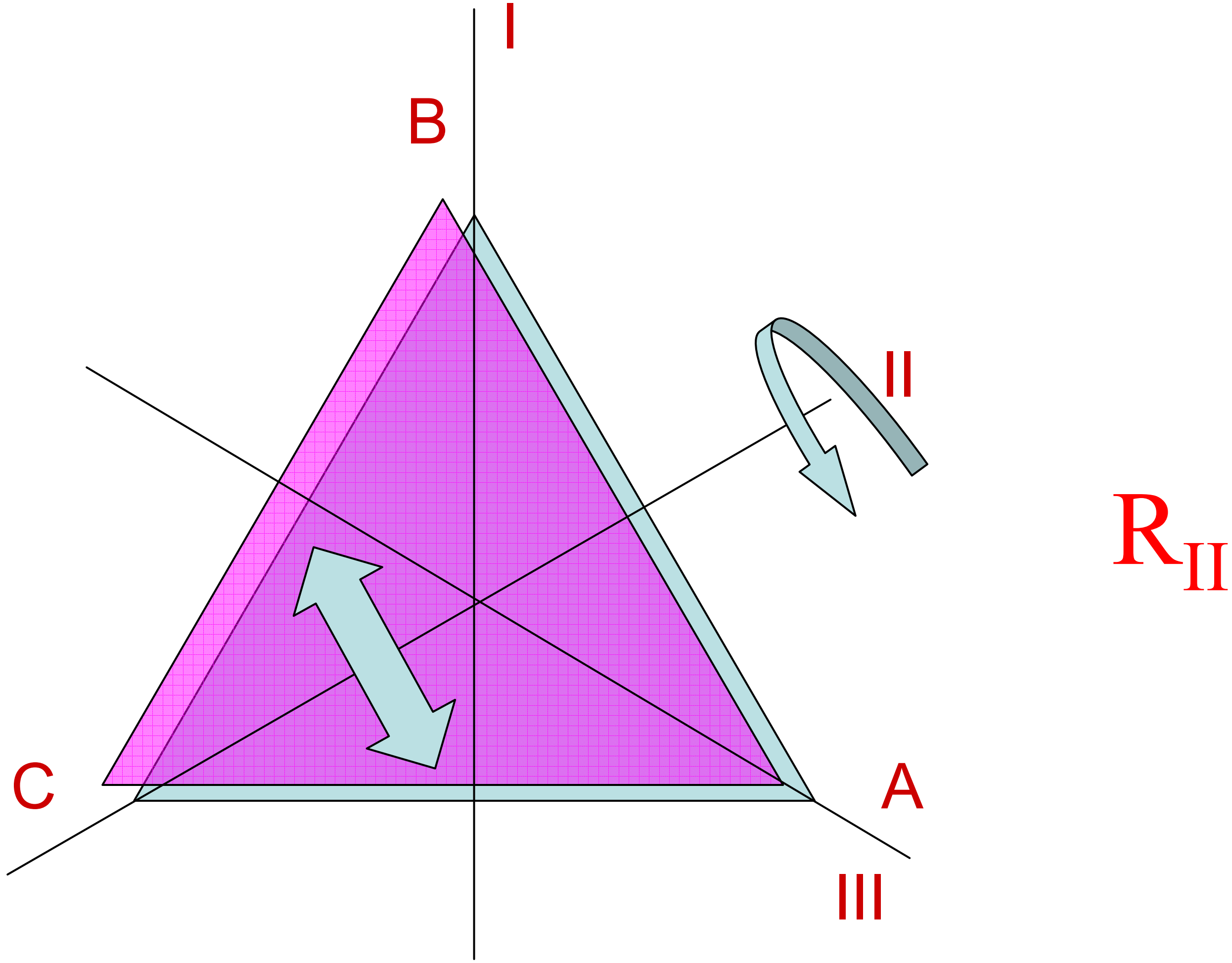


Rotation about center through 240 degrees

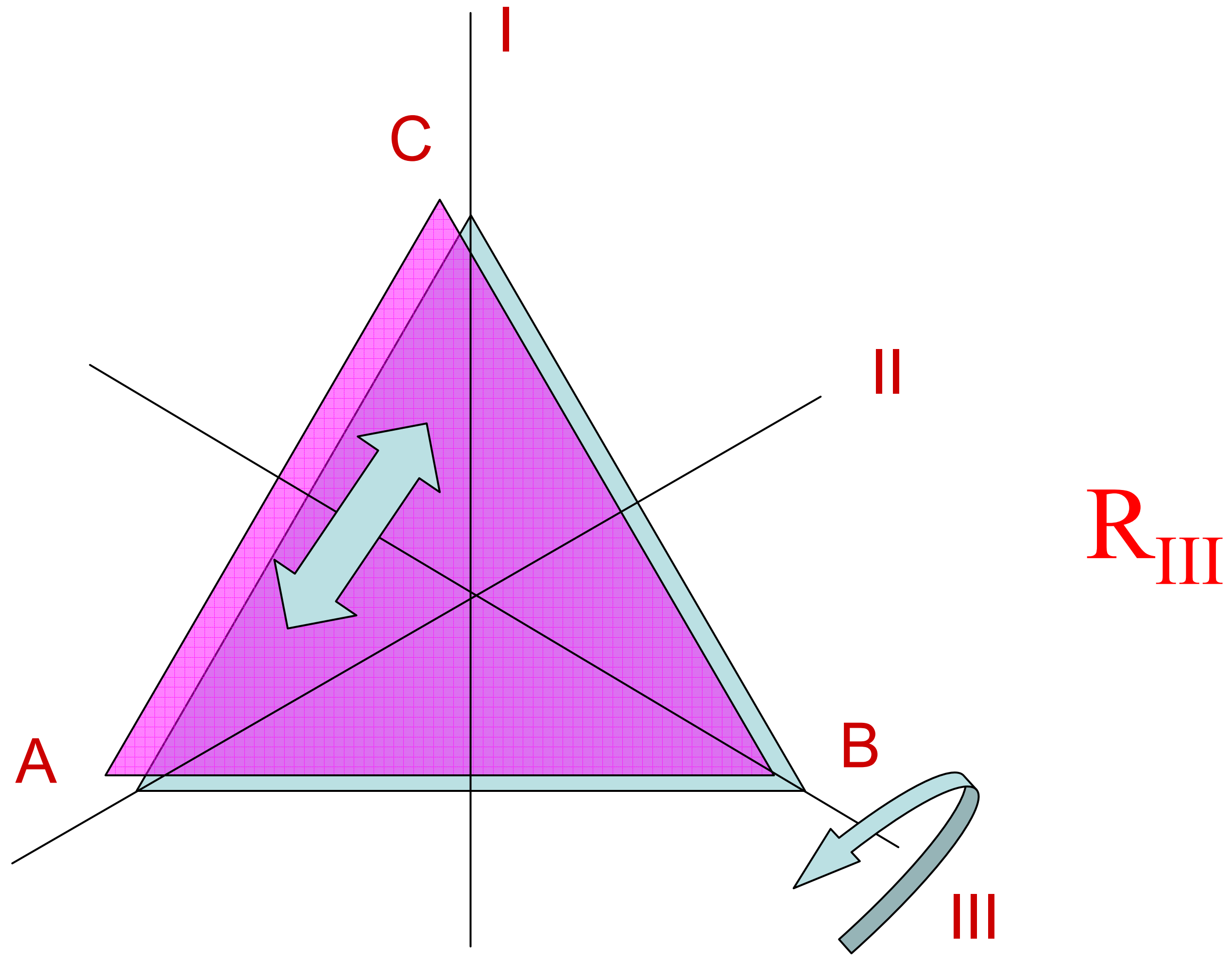


R_I

Reflection about axis I



Reflection about axis II



Reflection about axis III

The Symmetry Operations of the Equilateral Triangle

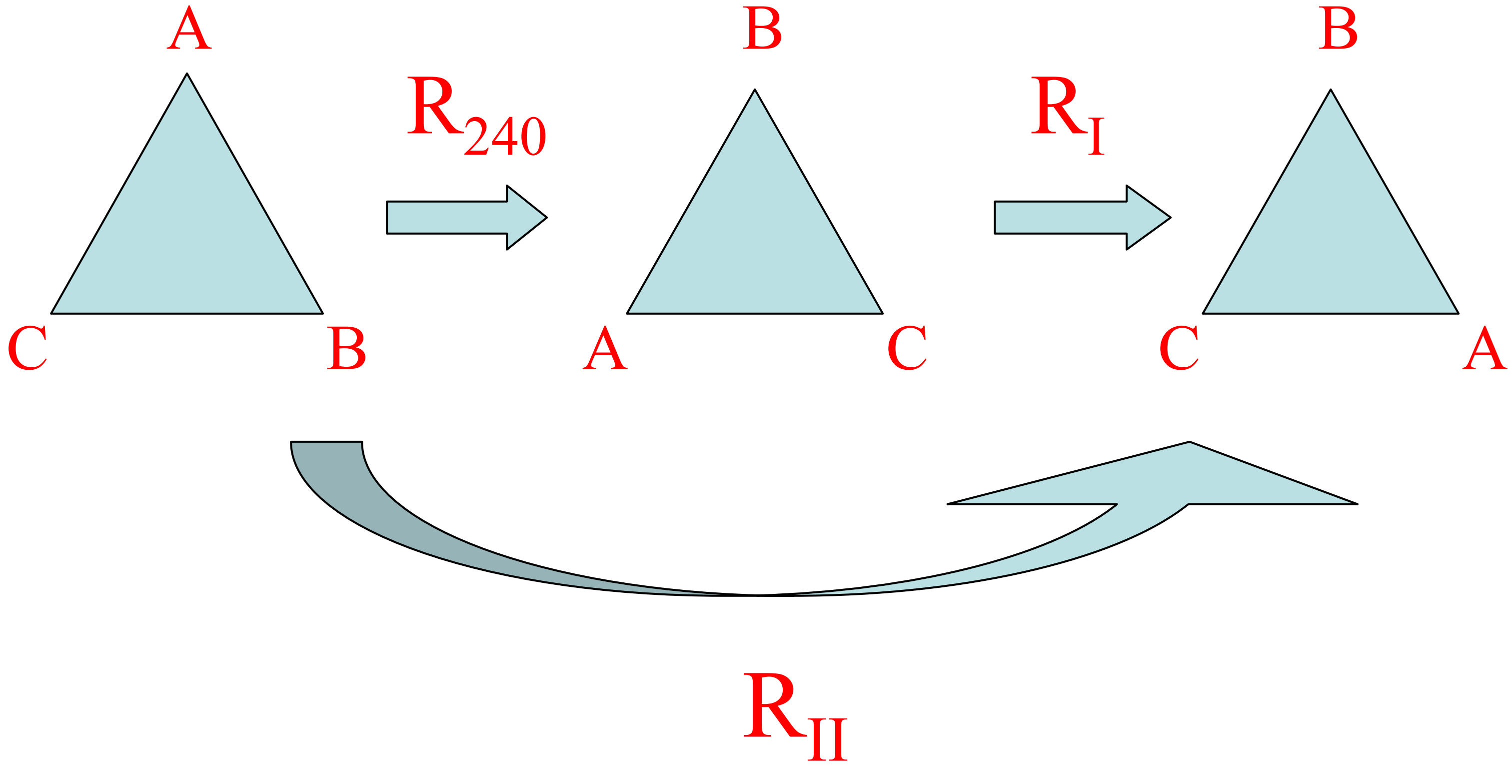
1	do nothing	ABC
R_{120}	rotate through 120 degrees	CAB
R_{240}	rotate through 240 degrees	BCA
R_{I}	reflect about axis I	ACB
R_{II}	reflect about axis II	BAC
R_{III}	reflect about axis III	CBA

How do we know we have them all?
What principle is at work here?

Evariste Galois

“Combine symmetry operations”

$$R_{240} \text{ x } R_I = ?$$



$$R_{240} \times R_I = R_{II}$$

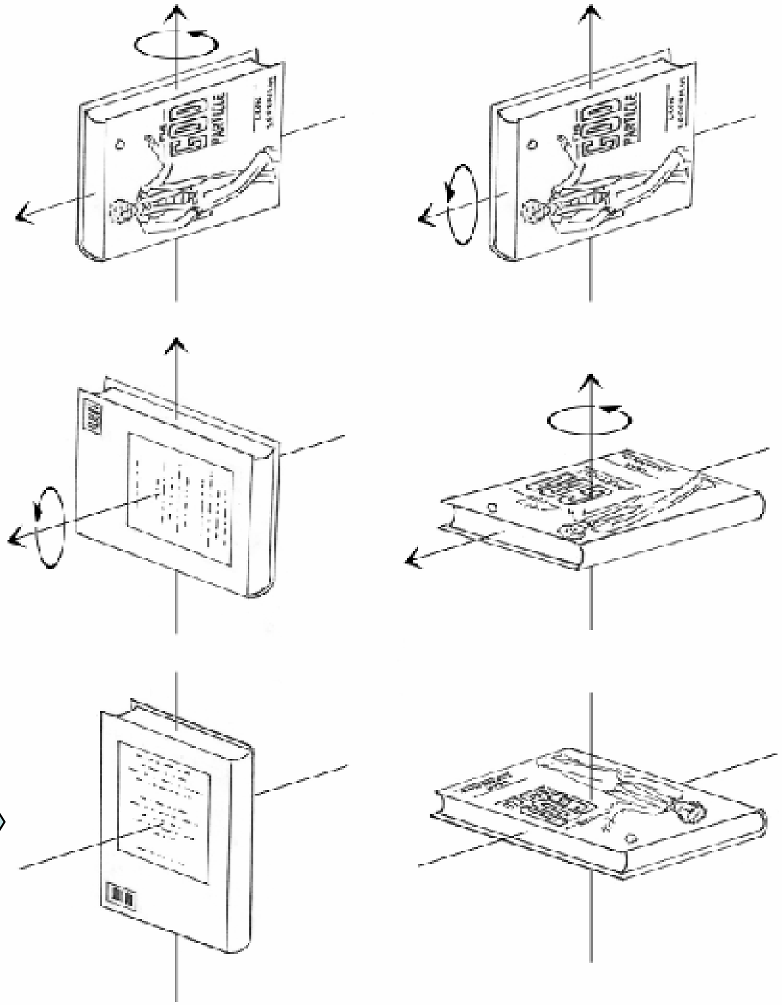
Symmetry Group of the Equilateral Triangle: S_3

	1	$R_{(120)}$	$R_{(240)}$	R_{I}	R_{II}	R_{III}
1	1	$R_{(120)}$	$R_{(240)}$	R_{I}	R_{II}	R_{III}
$R_{(120)}$	$R_{(120)}$	$R_{(240)}$	1	R_{III}	R_{I}	R_{II}
$R_{(240)}$	$R_{(240)}$	1	$R_{(120)}$	R_{II}	R_{III}	R_{I}
R_{I}	R_{I}	R_{II}	R_{III}	1	$R_{(120)}$	$R_{(240)}$
R_{II}	R_{II}	R_{III}	R_{I}	$R_{(240)}$	1	$R_{(120)}$
R_{III}	R_{III}	R_{I}	R_{II}	$R_{(120)}$	$R_{(240)}$	1

$$A \times B = C$$

Commutation generally doesn't hold in nature:

$A \times B \neq B \times A$

A |  | B

B | | A

A x B → | | ← B x A

Symmetry Groups

- A group G is a collection of elements $\{ r_j \}$
- G has a "multiplication" operation: $r_j \times r_k = r_k$ where r_k is in G
- There is a unique identity in G, 1, such that $1 \times r_k = r_k \times 1 = r_k$
- Each element r_k has a unique inverse r_k^{-1} such that $r_k^{-1} \times r_k = r_k \times r_k^{-1} = 1$
- Group multiplication is associative

Continuous Symmetry Groups
Cartan Classification

- Spheres in N dimensions: O(2), O(3), ..., SO(N)
- Complex Spheres in N dimensions: U(1), SU(2), ..., SU(N)
- N dimensional phase space Sp(2N)
- Exceptional Groups: G_2, F_4, E_6, E_7, E_8

Continuous rotations are exponentiated angles x generators. Generators form a Lie Algebra, e.g. SU(N) has N^2-1 generators.

Generators are in 1:1 correspondence with the gauge fields in a Yang-Mills threory.

Electroweak Theory:
SU(2) X U(1) Yang-Mills Gauge Theory

two gauge coupling constants, g_2 and g_1

$$iD_\mu = i\partial_\mu - g_2 W_\mu^a Q^a - g_1 B_\mu \frac{Y}{2}$$

$$= i\partial_\mu - g_2 W_\mu^+ Q^- - g_2 W_\mu^- Q^+ - g_2 W_\mu^3 Q^3 - g_1 B_\mu \frac{Y}{2}$$

$$Q^\pm = (Q^1 \pm i Q^2)/\sqrt{2} \qquad W_\mu^\pm = (W_\mu^1 \pm i W_\mu^2)/\sqrt{2}$$

Q^a are the $SU(2)$ weak charges

Y is the $U(1)$ hypercharge

$$[Q^a, Q^b] = i\epsilon^{abc} Q^c.$$

⟺ SU(2) Lie Algebra

particular *representations* for the charges,

left-handed fermions, and Higgs boson, $Q^a = \tau^a/2$

right-handed fermions are singlets, annihilated by the Q^a.

abstract operator Y ⟷ eigenvalue, Y_r

$$Q_{EM} = Q^3 + \frac{Y}{2}$$

$$\begin{pmatrix} u^{2/3} \\ d^{-1/3} \end{pmatrix}_L, Y_r = \frac{1}{3}; \qquad \begin{pmatrix} \nu^0 \\ e^{-1} \end{pmatrix}_L, Y_r = -1; \qquad H = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix} \qquad Y_r = -1$$

$$u_R^{2/3}, \ \ Y_r = \frac{4}{3}; \qquad d_R^{-1/3}, \ \ Y_r = -\frac{2}{3}; \qquad e_R^{-1}, \ \ Y_r = -2; \qquad \nu_R^0, \ \ Y_r = 0.$$

A right–handed neutrino is sterile

$$
\begin{aligned}
W_\mu^3 &= Z_\mu^0 \cos\theta + A_\mu \sin\theta \\
B_\mu &= -Z_\mu^0 \sin\theta + A_\mu \cos\theta
\end{aligned}
$$

$$
\Rightarrow \quad = \quad i\partial_\mu - g_2 W_\mu^+ Q^- - g_2 W_\mu^- Q^+ - g_2 W_\mu^3 Q^3 - g_1 B_\mu \frac{Y}{2}
$$

$$
Q_{EM} = Q^3 + \frac{Y}{2}
$$

$$
\Rightarrow \quad g_2 \sin\theta = e; \qquad g_1 \cos\theta = e; \qquad \tan\theta = \frac{g_1}{g_2}
$$

The photon thus couples to eQ_{EM} with strength e where:

$$
\frac{1}{e^2} = \frac{1}{g_2^2} + \frac{1}{g_1^2}
$$

The gauge covariant field strengths are defined by commutators of the covariant derivative:

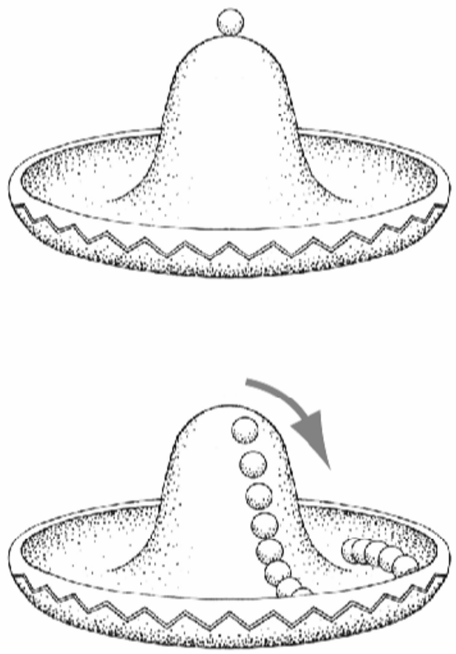
$$
\begin{aligned}
F^a_{\mu\nu} &= -\frac{i}{g_2^2}\,\mathrm{Tr}\left(\tau^a[D_\mu, D_\nu]\right) = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + \epsilon^{abc} A^b_\mu A^c_\nu \\
F_{\mu\nu} &= -\frac{i}{g_1^2} Y_r^{-1}\,\mathrm{Tr}\left([D_\mu, D_\nu]\right) = \partial_\mu B_\nu - \partial_\nu B_\mu
\end{aligned}
$$

Then the gauge field kinetic terms are:

$$
\mathcal{L}_{G.B.\ kinetic} = -\frac{1}{4} F^a_{\mu\nu} F^a_{\mu\nu} - \frac{1}{4} F_{\mu\nu} F_{\mu\nu}
$$

Spontaneous Symmetry Breaking

Consider the complex doublet scalar Higgs-boson with $Y_r = -1$:



$$H = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$$

$$\mathcal{L}_H = \quad (D_\mu H)^\dagger (D^\mu H) - V(H)$$

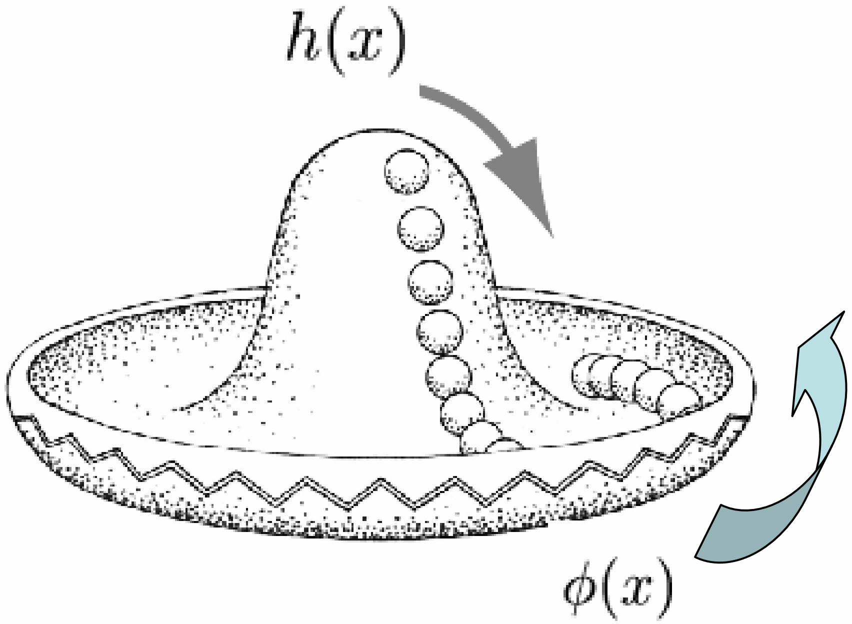
$$V(H) = \frac{\lambda}{2}(H^\dagger H - v_{weak}^2)^2$$

Standard Model Symmetry Breaking

$$\langle H \rangle = \begin{pmatrix} v_{weak} \\ 0 \end{pmatrix} \qquad H = \exp\left(i \frac{\pi^a \tau^a}{\sqrt{2} v_{weak}} \right) \begin{pmatrix} v_{weak} + \frac{h}{\sqrt{2}} \\ 0 \end{pmatrix}$$

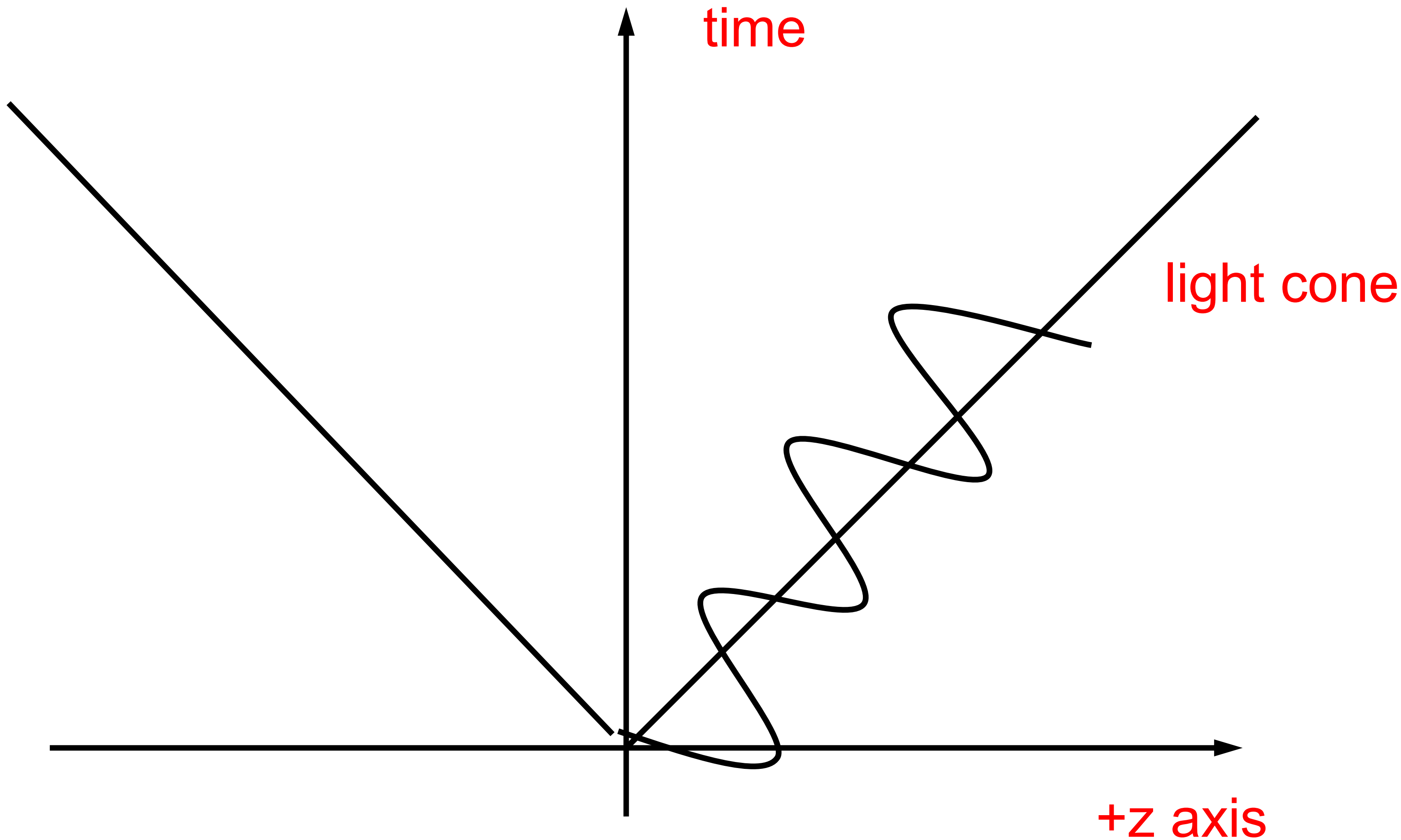
$$v_{weak} = 175 \ \text{GeV}$$

“Higgs” Boson is physical

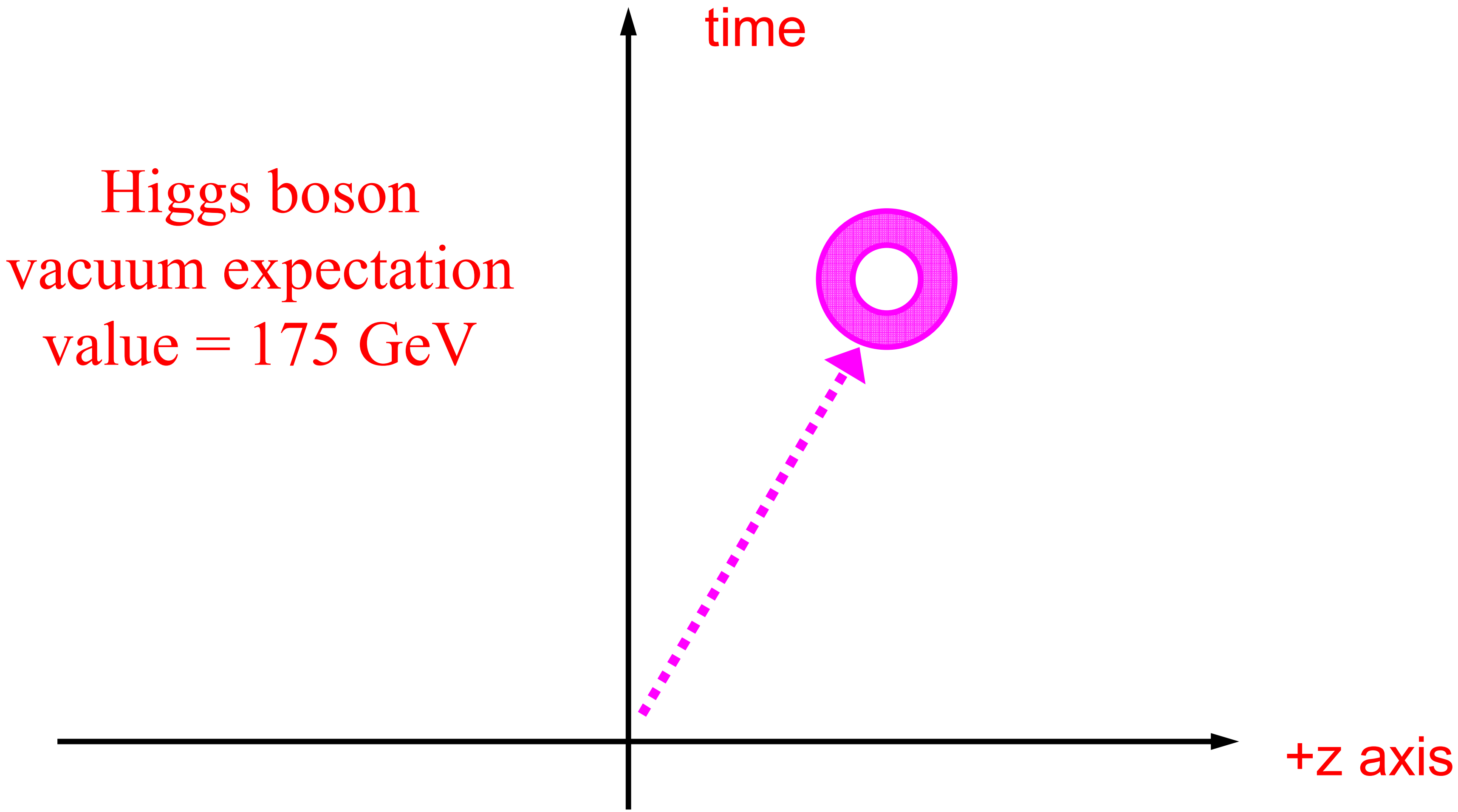


Nambu-Goldstone Bosons
are eaten

Massless W, Z

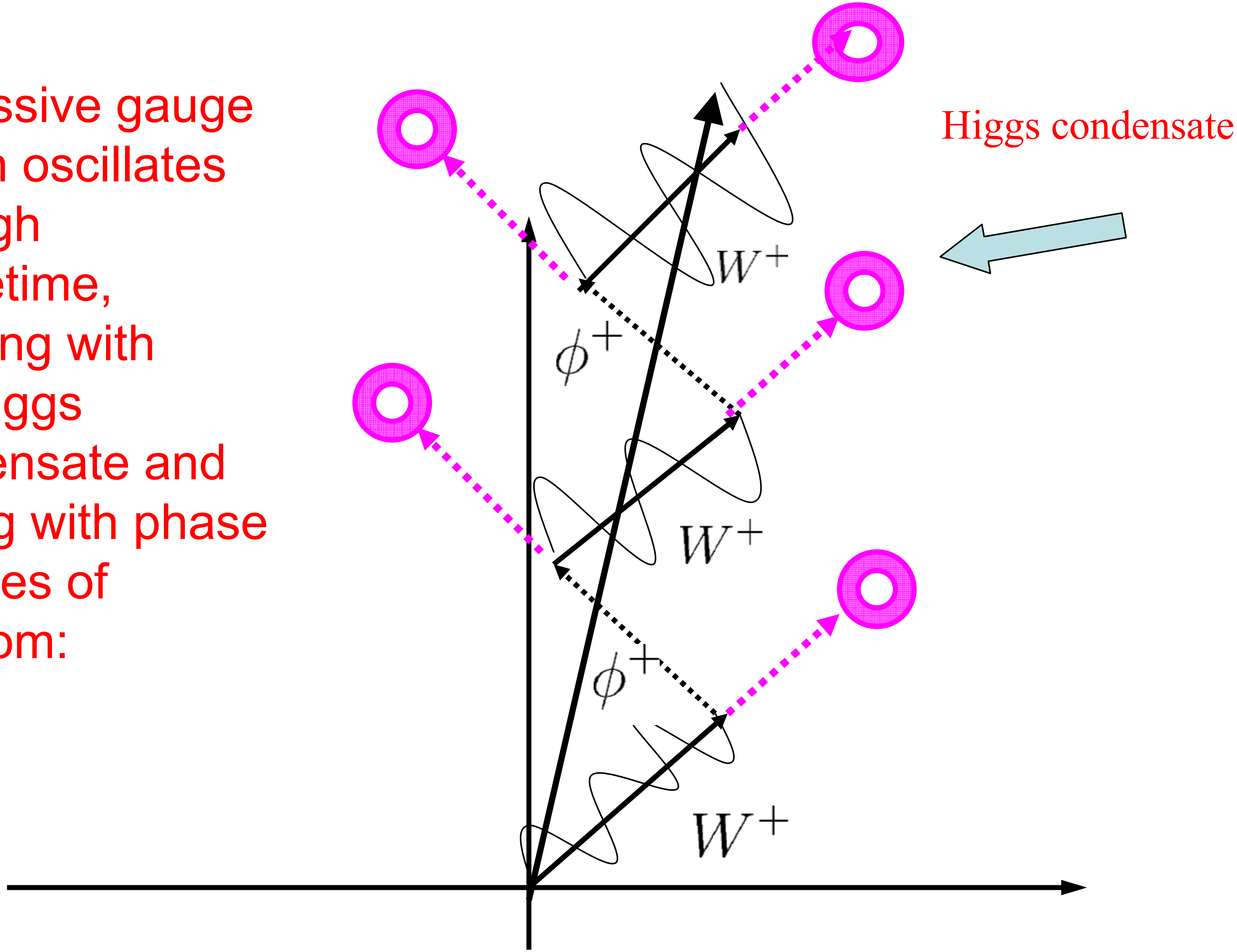


Higgs Boson Condenses in vacuum

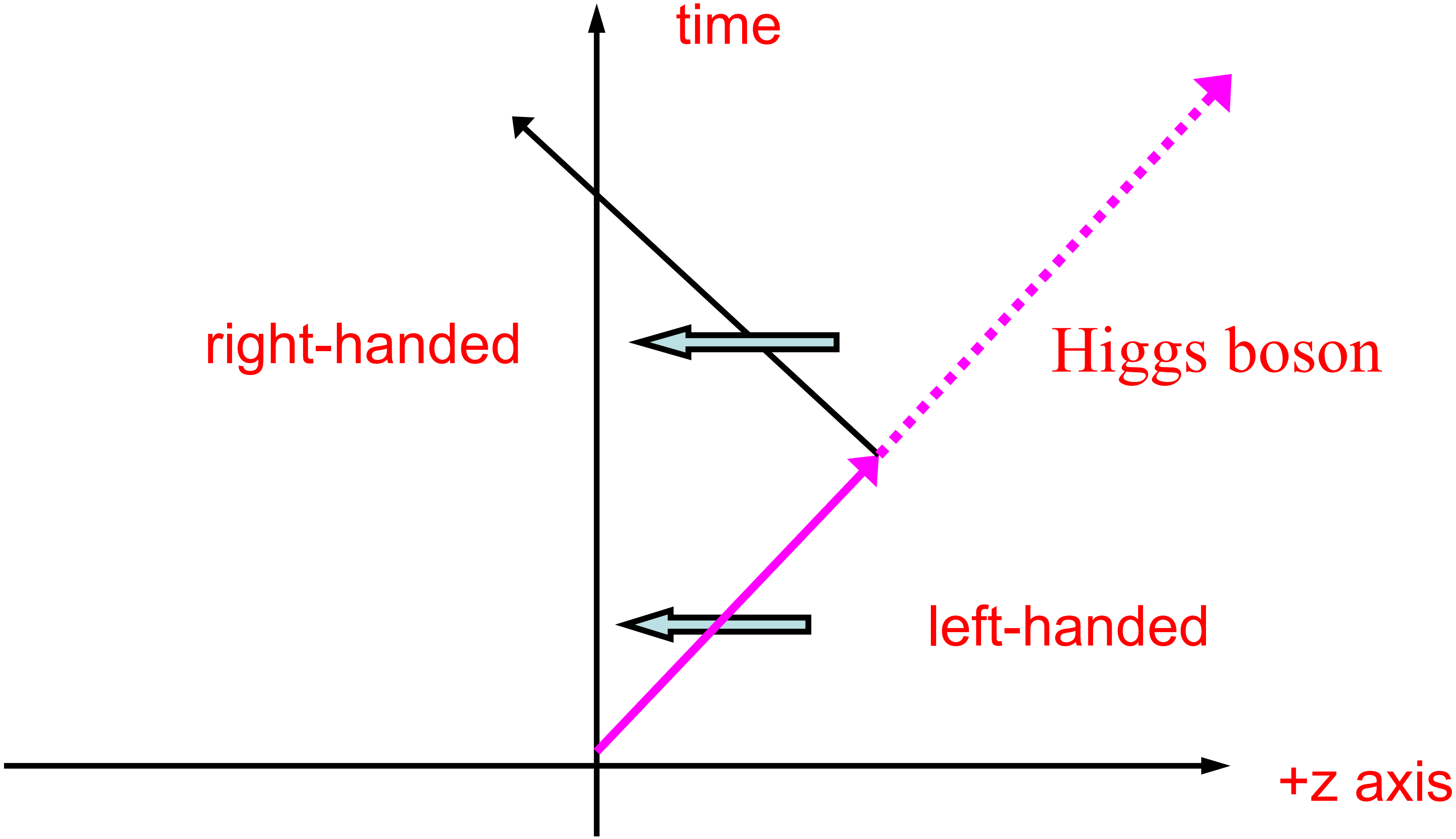


Weak charge is hidden in vacuum !!

A massive gauge boson oscillates through spacetime, colliding with the Higgs condensate and mixing with phase degrees of freedom:

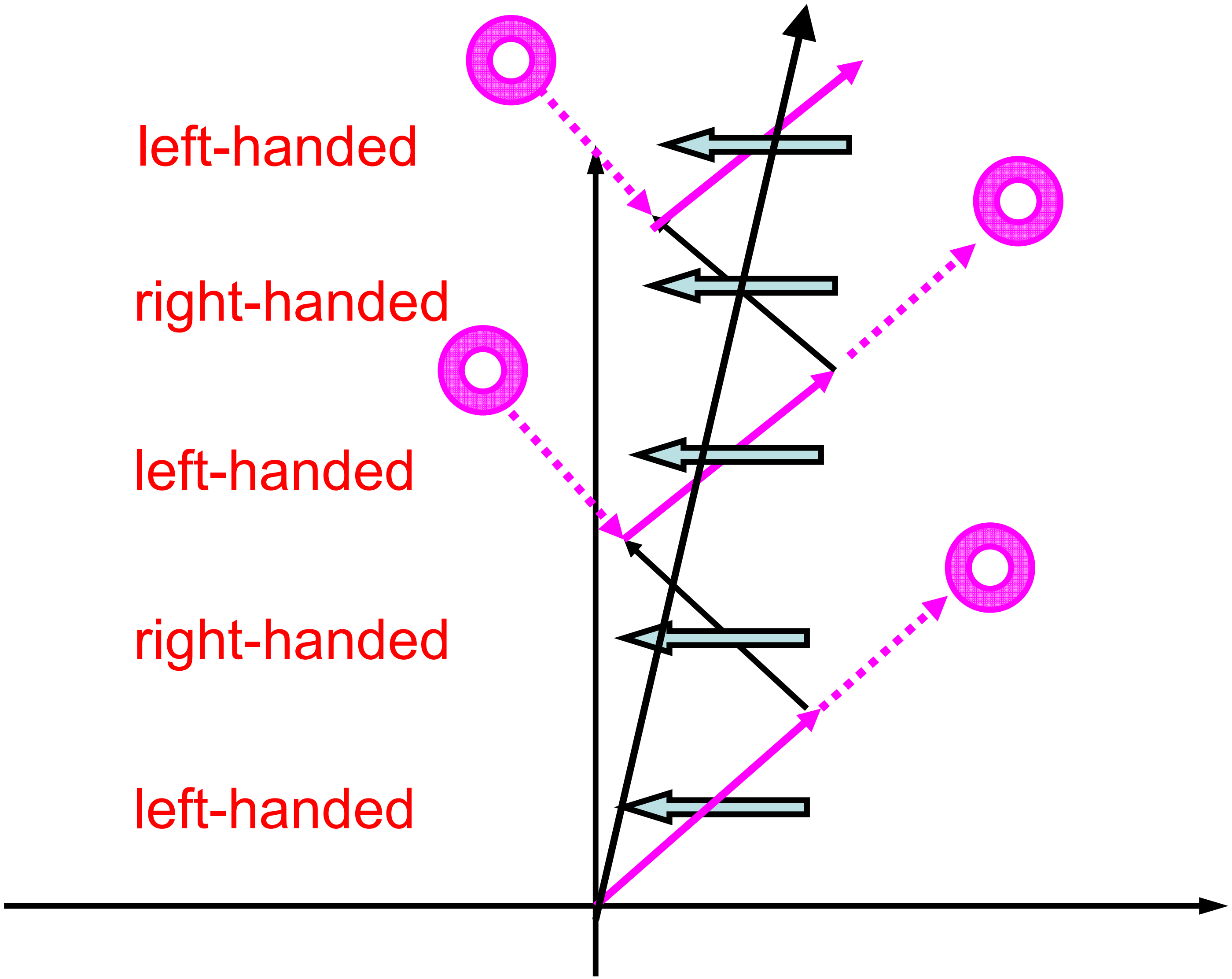


Couple fermions to the Higgs



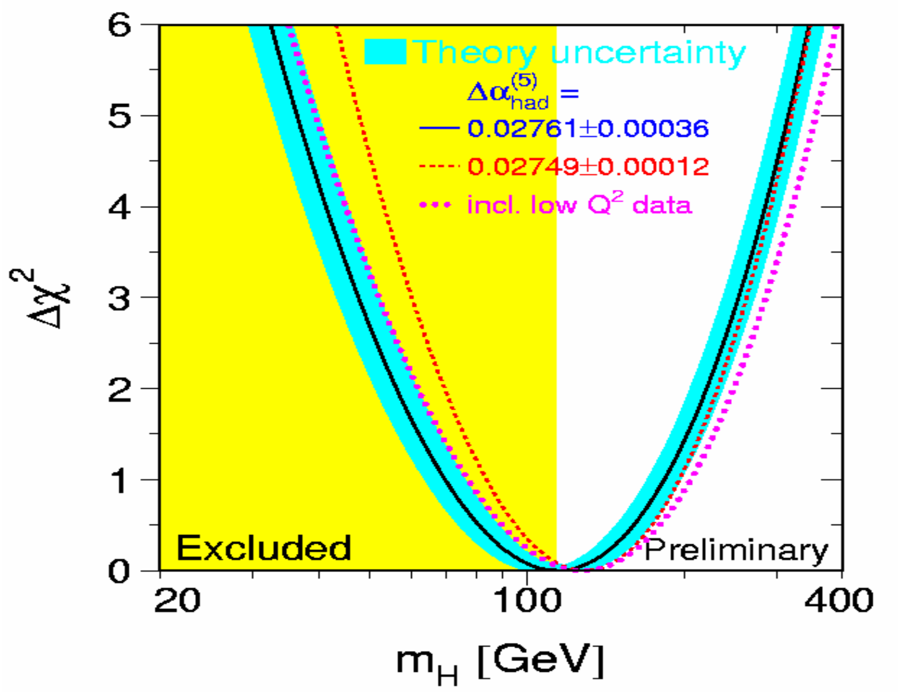
Weak charge is conserved

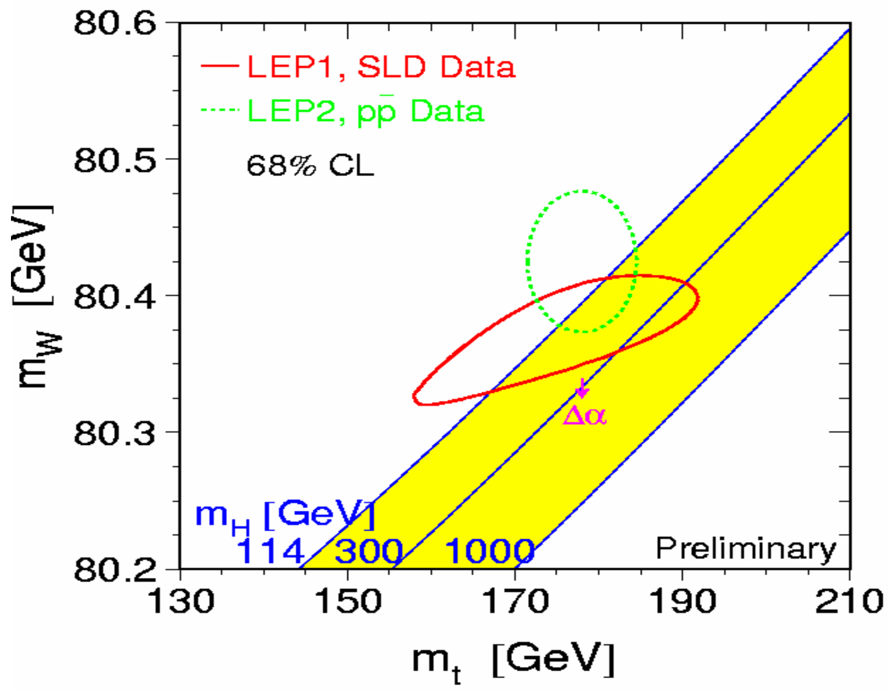
Fermion Masses in Electroweak Theory



Fermion Mass requires Higgs to maintain Electroweak Gauge Symmetry!!!

Searching for the Higgs
(Vacuum Electroweak Superconductivity)





114 GeV < m_H < 260 GeV

Mass Eigenstates

$$
\begin{aligned}
A_\mu &= \sin\theta\, W_\mu^3 + \cos\theta\ B_\mu \\
Z_\mu &= \cos\theta\, W_\mu^3 - \sin\theta\ B_\mu = \frac{(g_2 W_\mu^3 - g_1 B_\mu)}{\sqrt{g_1^2 + g_2^2}}
\end{aligned}
$$

$$
iD_\mu = i\partial_\mu - g_2 W_\mu^+ Q^- - g_2 W_\mu^- Q^+ - eA_\mu \left(Q^3 + \frac{Y}{2} \right) - Z_\mu \tilde{Q}
$$

$$
\begin{aligned}
\tilde{Q} &= \sqrt{g_1^2 + g_2^2} \left(\cos^2\theta\, \frac{\tau^3}{2} - \sin^2\theta\, \frac{Y}{2} \right) \\
&= e \left(\cot\theta\, \frac{\tau^3}{2} - \tan\theta\, \frac{Y}{2} \right)
\end{aligned}
$$

Mass Eigenstates

$$\mathcal{L}_H = \tfrac{1}{2}(\partial h)^2 + \tfrac{1}{2}M_W^2 W_\mu^+ W^{\mu-} + \tfrac{1}{2}M_Z^2 Z_\mu Z^\mu - \tfrac{1}{2}M_H^2 h^2 - \frac{\sqrt{\lambda}}{2} M_H h^3 - \frac{1}{8}\lambda h^4$$
$$+\tfrac{1}{2}\left(h^2 + \frac{M_H}{\lambda} h\right)\left(g_2^2 W_\mu^+ W^{\mu-} + (g_1^2 + g_2^2) Z_\mu Z^\mu\right)$$

$$M_W^2 = \tfrac{1}{2} g_2^2 v_{weak}^2; \qquad M_Z^2 = \frac{1}{2} v_{weak}^2 (g_1^2 + g_2^2).$$

$$\frac{M_W^2}{M_Z^2} = \cos^2\theta_W \qquad v_{weak}^2 = \frac{1}{2\sqrt{2}G_F}$$

Fermions

e.g., Top and Bottom $\Psi_L = (t,\ b)_L$ $L = \frac{1}{2}(1-\gamma^5)$

$$\bar{\Psi}_L i \not{D} \Psi_L = \bar{\Psi}_L i \not{\partial} \Psi_L - \frac{1}{\sqrt{2}} \bar{t}\gamma_\mu L b W^{\mu\,+} - \frac{1}{\sqrt{2}} \bar{b}\gamma_\mu L t W^{\mu\,-} - \frac{2e}{3} \bar{t}\gamma_\mu L t A_\mu + \frac{e}{3} \bar{b} L b A_\mu - \bar{\Psi}_L \widetilde{Q} \gamma_\mu \Psi_L Z_\mu$$

Dirac mass terms would be of the form $\bar{\Psi}_L \psi_R$ isospin$-\frac{1}{2}$

$$g_t \bar{\Psi}_L \cdot H t_R + g_b \bar{\Psi}_L \cdot H^c b_R$$

$$m_t = g_t v_{weak}$$

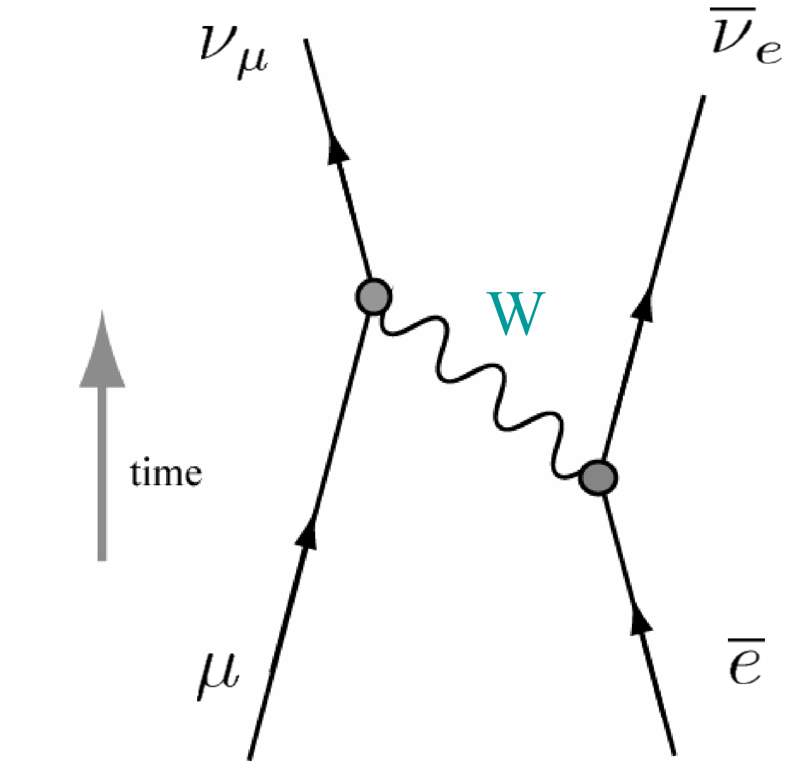
$$m_b = g_b v_{weak}$$

apply to muon decay

$$\frac{ig_2^2}{(1/2)g_2^2 v_{weak}^2}\overline{\nu}_\mu \gamma^\mu \mu_L \; \overline{e}\gamma^\mu \nu_{eL}$$

$$= (G_F/\sqrt{2})\overline{\nu}_\mu \gamma^\mu \mu_L \; \overline{e}\gamma^\mu \nu_{eL}$$

$$v_{weak}^2 = \frac{G_F}{2\sqrt{2}} = (175 \;\; \text{GeV})^2$$



leptonic doublet $\Psi_L = (\nu, \ell)_L$

$$\frac{g_\nu}{M}(\bar{\Psi}_L H)(H^C \Psi_L^C)$$

Majorana mass for ν_L $\qquad g_\nu v_{weak}^2/M$

The interplay between *gauge symmetries*, and *chiral symmetries*, both of which are broken spontaneously, is fundamental to the Standard Model. The left-handed fermions carry the electroweak $SU(2)$ quantum numbers, while the right-handed do not. All of the mathematical features of the symmetric Lagrangian remain intact, but the spectrum of the theory does not retain the original obvious symmetry properties. When a massive gauge boson was discovered, such as the $W^\pm$ or Z of the Standard Model, we also discovered an extra piece of physics: the longitudinal component, i.e., the NGB which comes from the symmetry breaking sector.

I apologize for not giving a review
of CKM physics, rare electroweak
processes, CP-violation and all that.

One Lecture on the Standard Model or
Five Lectures is sufficient;
Two is not.

Lightning Review of
Radiative Corrections to Standard Model

generalize slightly our definition of v_{weak}

$$M_W^2 = \tfrac{1}{2} v_W^2 g_2^2; \qquad M_Z^2 = \frac{1}{2} v_Z^2 (g_1^2 + g_2^2)$$

v_W (v_Z) is the Higgs VEV "as seen by" the W-boson (Z=boson)

tree level $\qquad v_W^2 = v_Z^2 = v_{weak}^2$

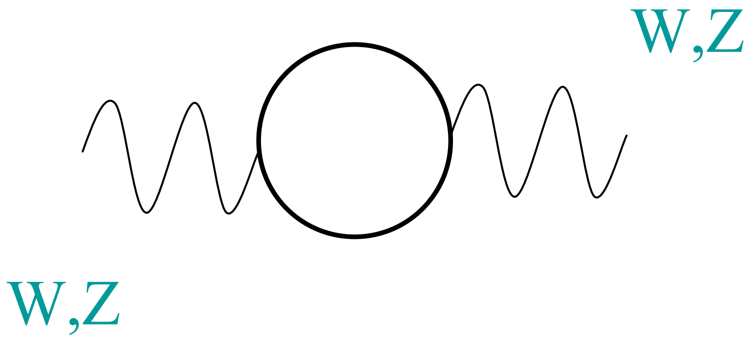
radiative corrections $\qquad g_1^2(q^2),\ g_2^2(q^2) \qquad v_W^2(q^2)$ and $v_Z^2(q^2)$

to a good approximation, we really only need to know $\alpha(M_Z) \approx \alpha(M_W)$

T stands for "transverse"

$$F.T. < 0|T\tilde{A}^A_\mu(0)\tilde{A}^B_\mu(x)|0 >= g_{\mu\nu}\Pi_{AB} - q_\mu q_\nu \Pi^T_{AB}$$

$$\begin{aligned}
\tfrac{1}{2}v_Z^2 &= \tfrac{1}{2}v_{weak}^2 - \Pi_{3B} \\
&= \tfrac{1}{2}v_{weak}^2 - \Pi_{3Q} + \Pi_{33} \\
\tfrac{1}{2}v_W^2 &= \tfrac{1}{2}v_{weak}^2 + \Pi_{WW} - \Pi_{3Q}
\end{aligned}$$



$$\begin{aligned}
\frac{1}{g_2^2} &= \frac{1}{g_{2un}^2} - \Pi^T_{33} - \Pi^T_{3B} \\
&= \frac{1}{g_{2un}^2} - \Pi^T_{3Q} \\
\frac{1}{g_1^2} &= \frac{1}{g_{1un}^2} - \Pi^T_{BB} - \Pi^T_{3B} \\
&= \frac{1}{g_{1un}^2} + \Pi^T_{3Q} - \Pi^T_{QQ}
\end{aligned}$$

$$v_W^2 - v_Z^2 = \frac{N_c}{32\pi^2}\left[(m_t^2 + m_b^2) - \frac{2m_t^2 m_b^2}{(m_t^2 - m_b^2)}\log(m_t^2/m_b^2) + \frac{M_W^2 m_H^2}{m_H^2 - M_W^2}\ln(m_H^2/M_W^2) - \frac{M_Z^2 m_H^2}{m_H^2 - M_Z^2}\ln(m_H^2/M_Z^2)\right]$$

The ρ parameter of Veltman is:

$$\begin{aligned}\rho &= \frac{v_W^2}{v_Z^2} \\ &= 1 + \frac{N_c}{32 v_0^2 \pi^2}\left[(m_t^2 + m_b^2) - \frac{2m_t^2 m_b^2}{(m_t^2 - m_b^2)}\log(m_t^2/m_b^2)\right. \\ &\quad \left. + \frac{M_W^2 m_H^2}{m_H^2 - M_W^2}\ln(m_H^2/M_W^2) - \frac{M_Z^2 m_H^2}{m_H^2 - M_Z^2}\ln(m_H^2/M_Z^2)\right]\end{aligned}$$

A simple set of parameters

$$v_W^2(q^2) = v_{weak}^2 + \sigma q^2 + \tau v_r^2 + \omega q^2$$

$$v_Z^2(q^2) = v_{weak}^2 + \sigma q^2 - \tau v_r^2 - \omega q^2$$

Peskin and Takeuchi define:

$$S = 16\pi \left[\frac{\partial}{\partial q^2} \Pi_{33}|_{q^2=0} - \frac{\partial}{\partial q^2} \Pi_{3Q}|_{q^2=0} \right]$$

$$T = \frac{4\pi}{\sin^2\theta \cos^2\theta M_Z^2} \left[\Pi_{WW}|_{q^2=0} - \Pi_{33}|_{q^2=0} \right]$$

$$U = 16\pi \left[\frac{\partial}{\partial q^2} \Pi_{WW}|_{q^2=0} - \frac{\partial}{\partial q^2} \Pi_{33}|_{q^2=0} \right]$$

we see that:

$$\sigma = \frac{2S+U}{16\pi}; \qquad \omega = \frac{U}{16\pi}; \qquad \tau = \frac{\sin^2\theta \cos^2\theta M_Z^2 T}{4\pi v_r^2} = \frac{\alpha}{2} T;$$

input parameters:

$$G_F = 1.16639\ (1)\ \times 10^{-5}\ \text{GeV}^{-2}$$

$$m_Z^2 = 8315.18(38)\ \text{GeV}^{-2}$$

$$\alpha^{-1}(m_Z) =\ :$$

$$\alpha^{-1}(m_Z) = \alpha^{-1}(0)\left[1 - \Delta\alpha_\ell - \Delta\alpha_h - \Delta\alpha_{t,W}\right]$$

0.03150 ? < 0.0001

$$\Delta\alpha_h = 0.02761\ (36) \quad \text{Burkhardt–Pietrzyk}\ \ (01)$$

$$= 0.02757\ (36) \quad \text{Jegerlehner}\ \ (03)$$

$$= 0.02737\ (20) \quad \text{Jegerlehner (Euclidean)}\ \ (03)$$

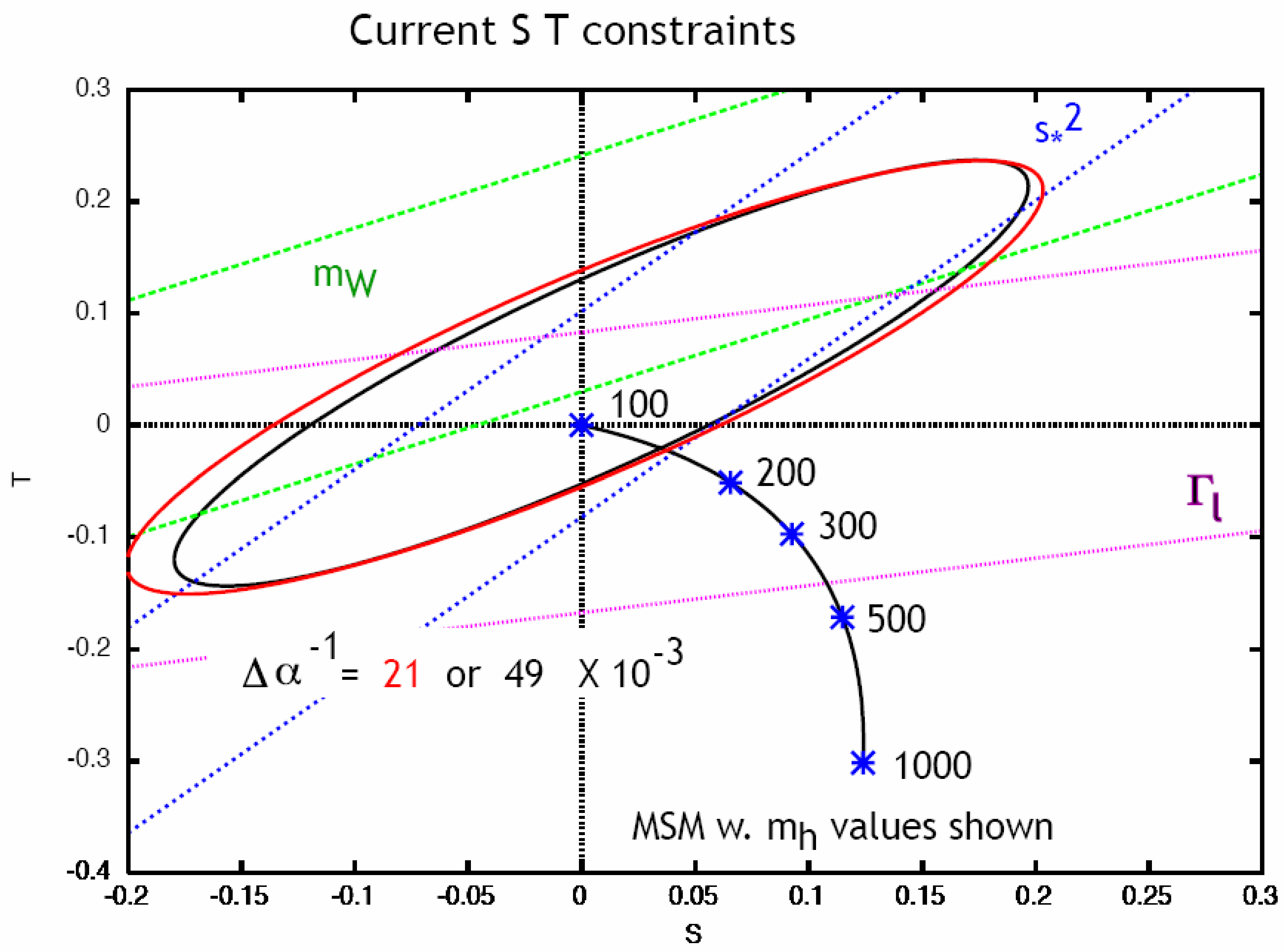
$$= 0.02763\ (16) \quad \text{Davier–Höcker}\ \ (\tau,\ \text{QCD})\ \ (98)$$

$$G_F = 1/2\sqrt{2}v_{weak}(0)^2$$

$$M_Z^2 = \frac{1}{2}(g_1^2(M_Z^2) + g_2^2(M_Z^2))v_{weak}^2(M_Z^2)$$

$$4\pi\alpha(0) = \left.\frac{g_1^2 g_2^2}{g_1^2 + g_2^2}\right|_{\mu^2=0}$$

$$\left\{\begin{aligned}
\sin^2\theta_{Z-pole} &= g_1(M_Z^2)/(g_1(M_Z^2) + g_2(M_Z^2)) \\
M_W^2 &= \frac{1}{2}g_2^2(M_W^2)v_{weak}^2(M_W^2) \\
T &= \frac{N_c}{4\pi\sin^2\theta\cos^2\theta M_Z^2}\left[(m_t^2 + m_b^2) - \frac{2m_t^2 m_b^2}{(m_t^2 - m_b^2)}\log(m_t^2/m_b^2)\right. \\
&\quad \left. + \frac{M_W^2 m_H^2}{m_H^2 - M_W^2}\ln(m_H^2/M_W^2) - \frac{M_Z^2 m_H^2}{m_H^2 - M_Z^2}\ln(m_H^2/M_Z^2)\right] \\
S &= \frac{N_c}{6\pi}\left[1 - Y\log\left\{m_b^2/m_t^2\right\}\right]
\end{aligned}\right.$$



Current S T constraints
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
S
T
m_W
s_*2
Γ_l
100
200
300
500
1000
$\Delta\alpha^{-1}$ = 21 or 49 X 10^{-3}
MSM w. m_h values shown

Application: Top Seesaw Model

Mass matrix for $t-\chi$ system is,

$$-\left(\overline{t_L}\ \ \overline{\chi_L}\right)\begin{pmatrix} 0 & \mu \approx 600\ GeV \\ m \approx 1\ TeV & M \approx 4\ TeV \end{pmatrix}\begin{pmatrix} t_R \\ \chi_R \end{pmatrix}$$

Diagonalized:

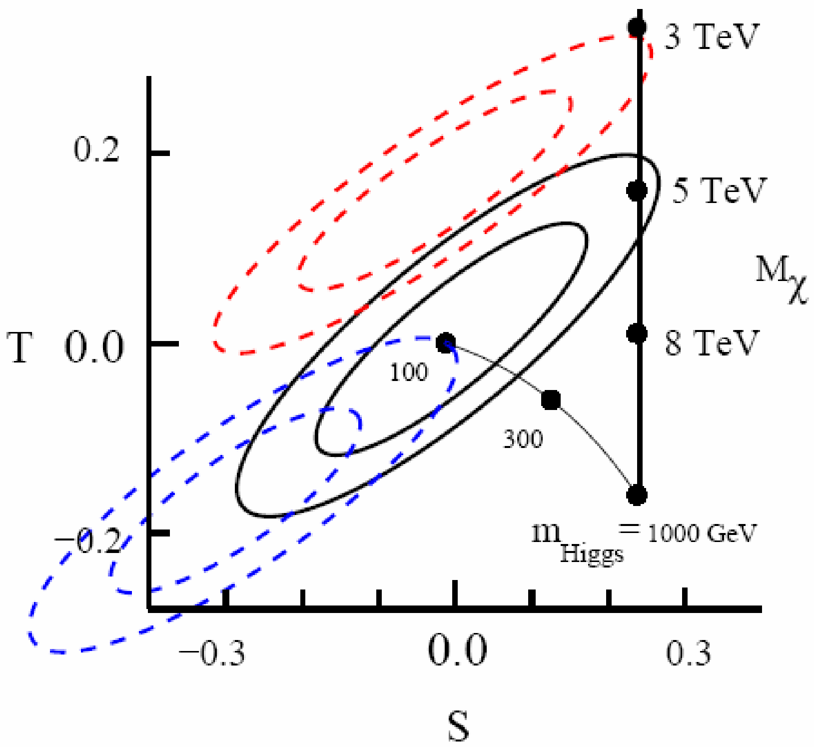
$$m_t \approx \frac{\mu m}{M}$$
$$m_\chi \approx M$$

1998: Top Seesaw DOA (outside of the S-T ellipse $\sim 4\sigma$. (Chivukula, Dobrescu, Georgi, Hill)

1999: S-T error ellipse shifts along major axis towa upper right (predicted by the theory!).

2001: Inconsistencies in data; keep only leptons $\rightarrow$ Top Seesaw consistent and SM ruled out at $\sim 2\sigma$!!!

Theory consistent for natural values of its parameters at the 2σ level (He, CTH, Tait)



What is the Higgs Boson?

The mysterious role of Scale Symmetry

- We live in 1+3 dimensions
- The big cosmological constant conundrum
- The Higgs Boson mass scale
- QCD solves its own problem of hierarchy
- New Strong Dynamics?

Origin of Mass in QCD

Gell-Mann and Low:

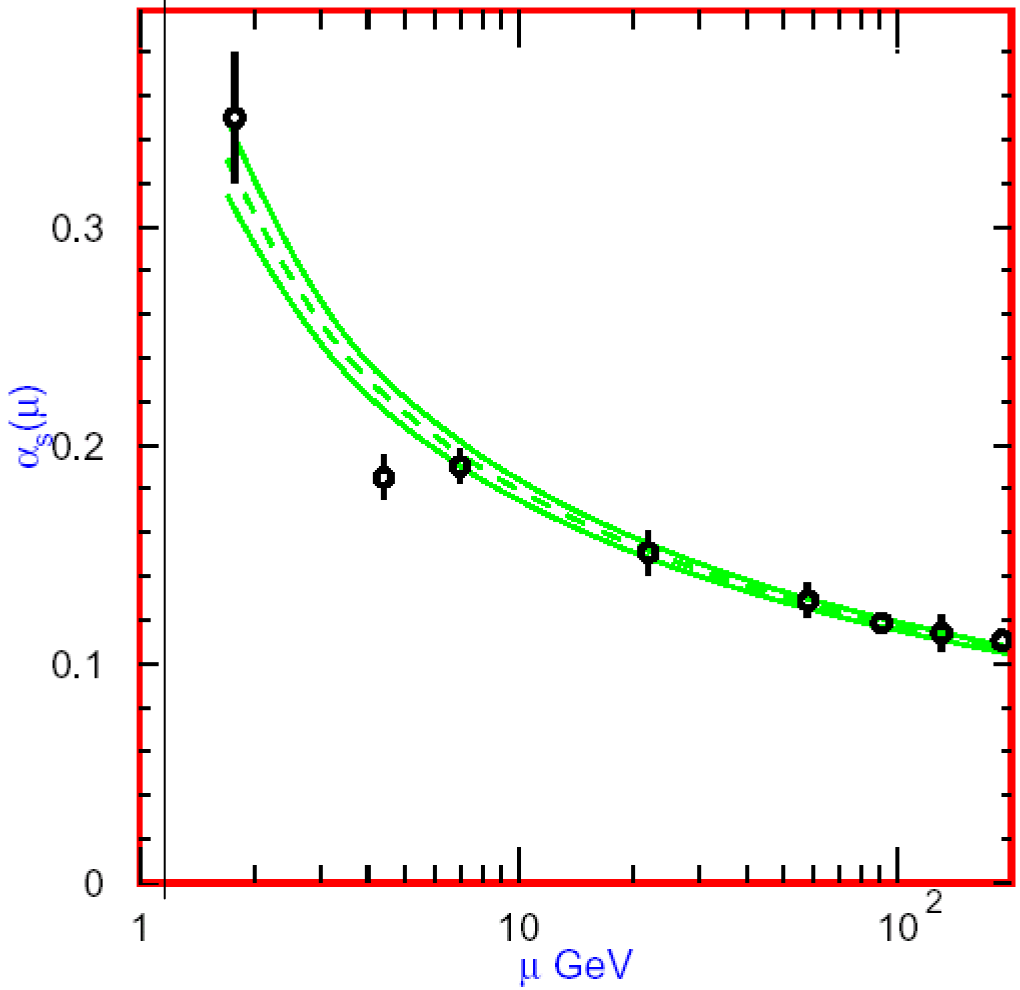
$$\frac{dg}{d\ln\mu} = \beta(g)$$

Gross, Politzer and Wilczek:

$$\beta(g) = \hbar\beta_0 g^3 \qquad \text{where} \qquad \beta_0 = -\frac{1}{16\pi^2}\left(\frac{11}{3}N_c - \frac{2}{3}n_f\right)$$

$$\frac{\Lambda_{QCD}}{M_0} = \exp\left(\frac{1}{2\hbar\beta_0 g_0^2}\right)$$

$$\Lambda_{MS} = 217^{+25}_{-23}\ \text{MeV}$$



$$\beta(g) = \mu \frac{\partial g}{\partial \mu}.$$

$$\alpha_s(k^2) \equiv \frac{g_s^2(k^2)}{4\pi} \approx \frac{1}{\beta_0 \ln(k^2/\Lambda^2)}$$

A Puzzle: Murray Gell-Mann lecture ca 1975

$$S_\mu = x^\nu T_{\mu\nu}$$

$$\partial_\mu S^\mu = T^\mu_\mu$$

$$T_{\mu\nu} = \mathrm{Tr}(G_{\mu\rho} G^\rho_\nu) - \frac{1}{4} g_{\mu\nu} \, \mathrm{Tr}(G_{\rho\sigma} G^{\rho\sigma})$$

$$\partial_\mu S^\mu = T^\mu_\mu = \mathrm{Tr}(G_{\mu\nu} G^{\mu\nu}) - \frac{4}{4} \mathrm{Tr}(G_{\mu\nu} G^{\mu\nu}) = 0 \qquad !???$$

QCD is scale invariant!!!???

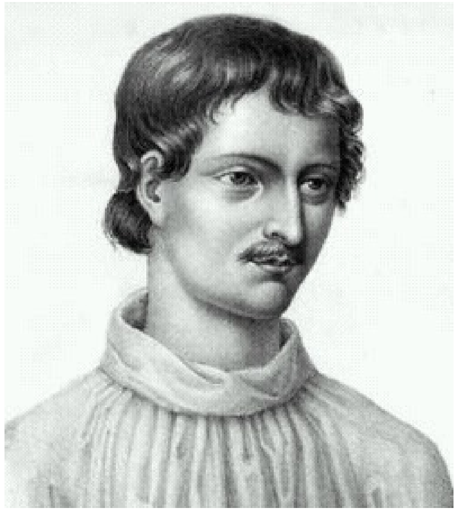
Resolution: The Scale Anomaly

$$\partial_\mu S^\mu = \frac{\beta(g)}{g} \operatorname{Tr} G_{\mu\nu} G^{\mu\nu} = \mathcal{O}(\hbar)$$

Origin of Mass in QCD = Quantum Mechanics

A heretical Conjecture:

All mass scales in physics are intrinsically quantum mechanical and associated with scale anomalies. The $\hbar \to 0$ limit of nature is exactly scale invariant.

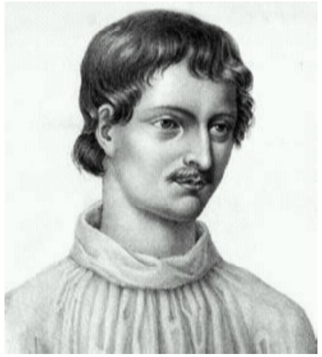


"Predictions" of the Conjecture:

We live in D=4!

$$T^{\mu}_{\mu} = \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu} - \frac{D}{4} \mathrm{Tr}\, G_{\mu\nu} G^{\mu\nu}$$

Cosmological constant is zero in classical limit



QCD scale is generated in this way; Hierarchy is naturally generated

Testable in the Weak Interactions?

Weyl Gravity in D=4 is QCD-like:

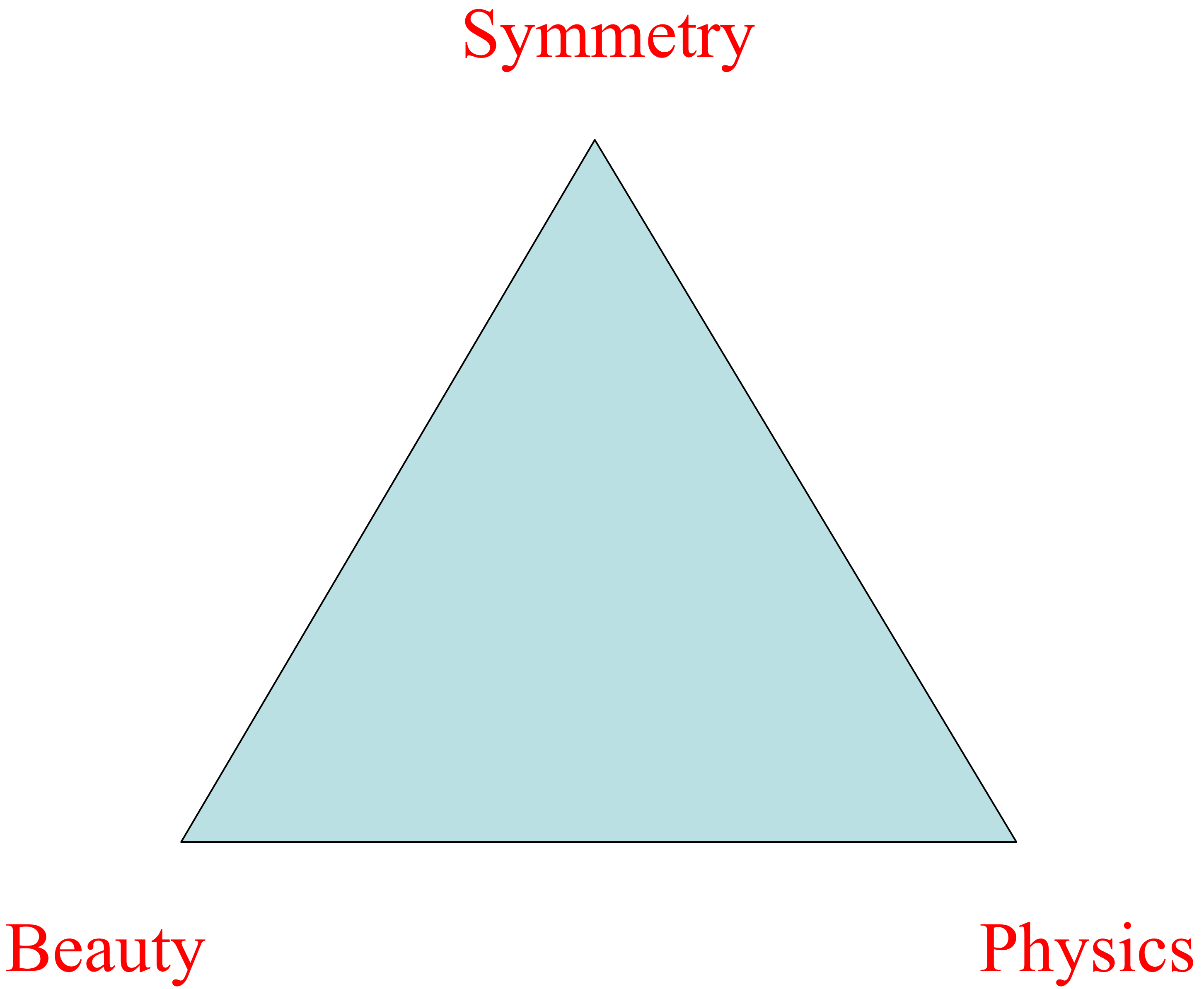
$$\frac{1}{h^2}\sqrt{-g}(R_{\mu\nu}R^{\mu\nu} - \frac{1}{3}R^2)$$

Is the Higgs technically natural?

On naturalness in the standard model.
William A. Bardeen (Fermilab) . FERMILAB-CONF-95-391-T, Aug 1995. 5pp.

Conjecture on the physical implications of the scale anomaly.
Christopher T. Hill (Fermilab) . **hep-th/0510177**

Symmetry Principles Define Modern Physics


Symmetry
Beauty
Physics