Monopoles and Electroweak Symmetry Breaking

John Terning
with Csaba Csaki, Yuri Shirman
hep-ph/1003.1718

Outline

* Motivation
* A Brief History of Monopoles
* Anomalies
* Models
* LHC
* Conclusions

Hierarchy Problem Now

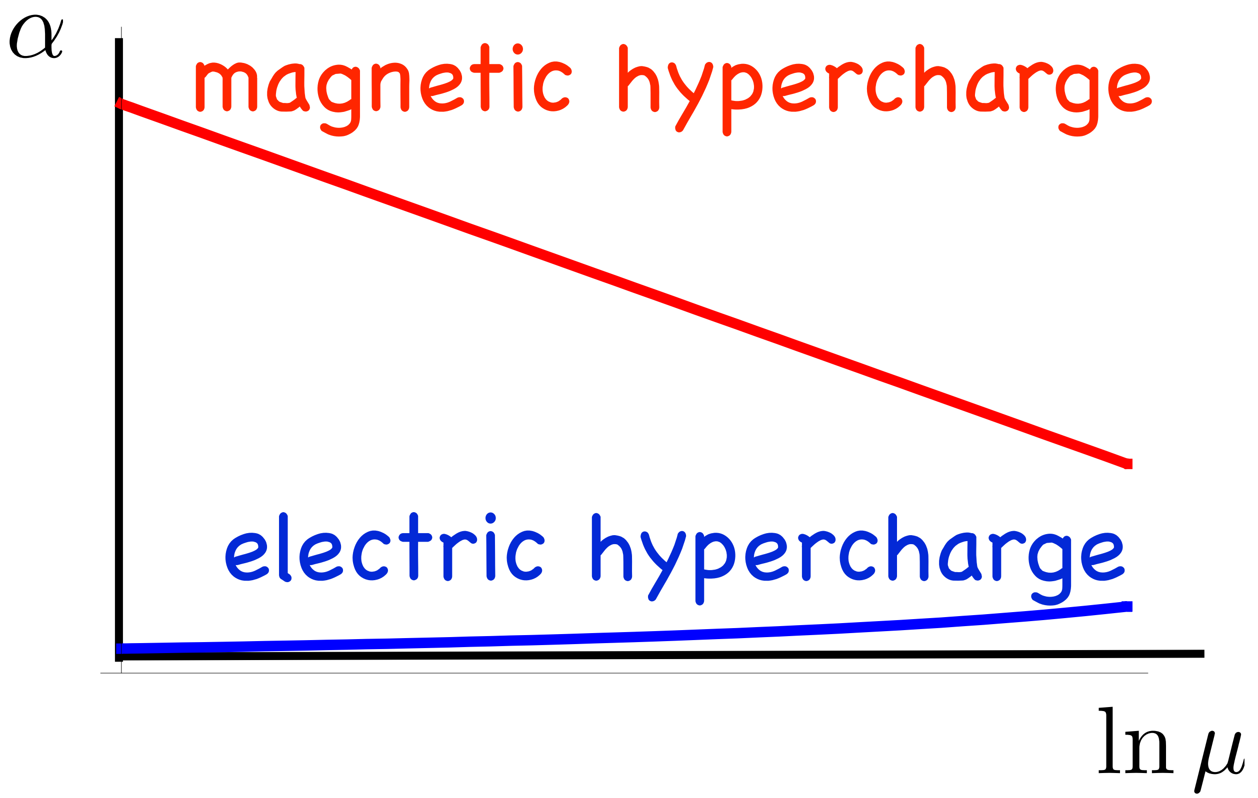
SUSY

conspicuous in it's absence so far

Technicolor

ETC doesn't work

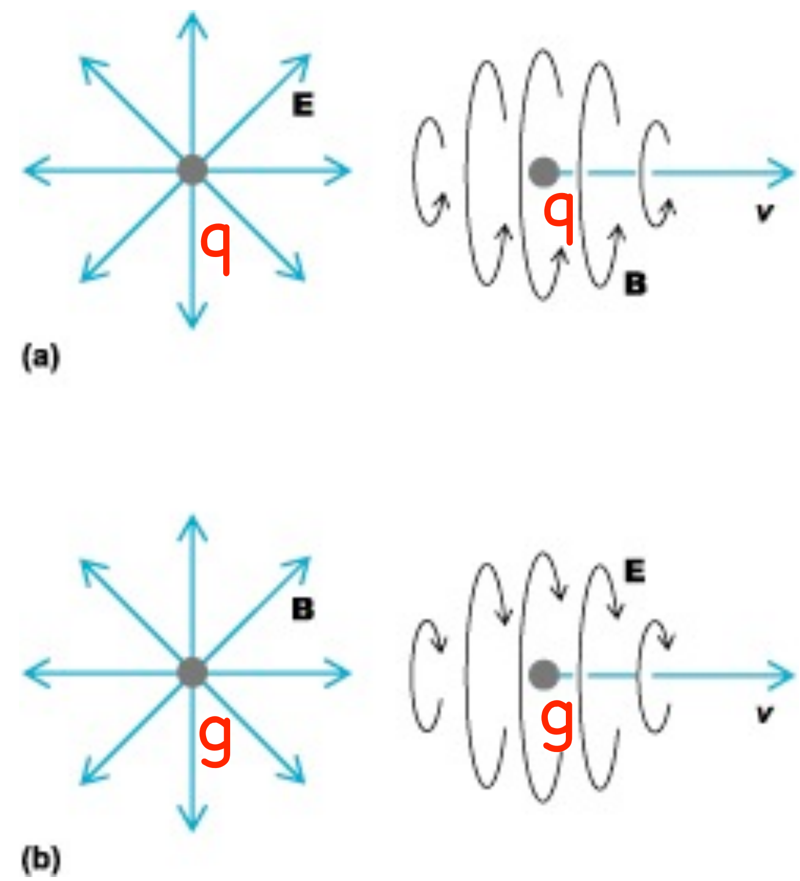
The Vision Thing



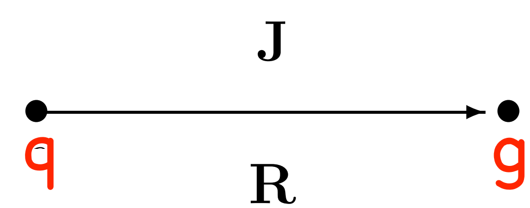
consistent theory of massless dyons?

chiral symmetry breaking -> EWSB?

J.J. Thomson

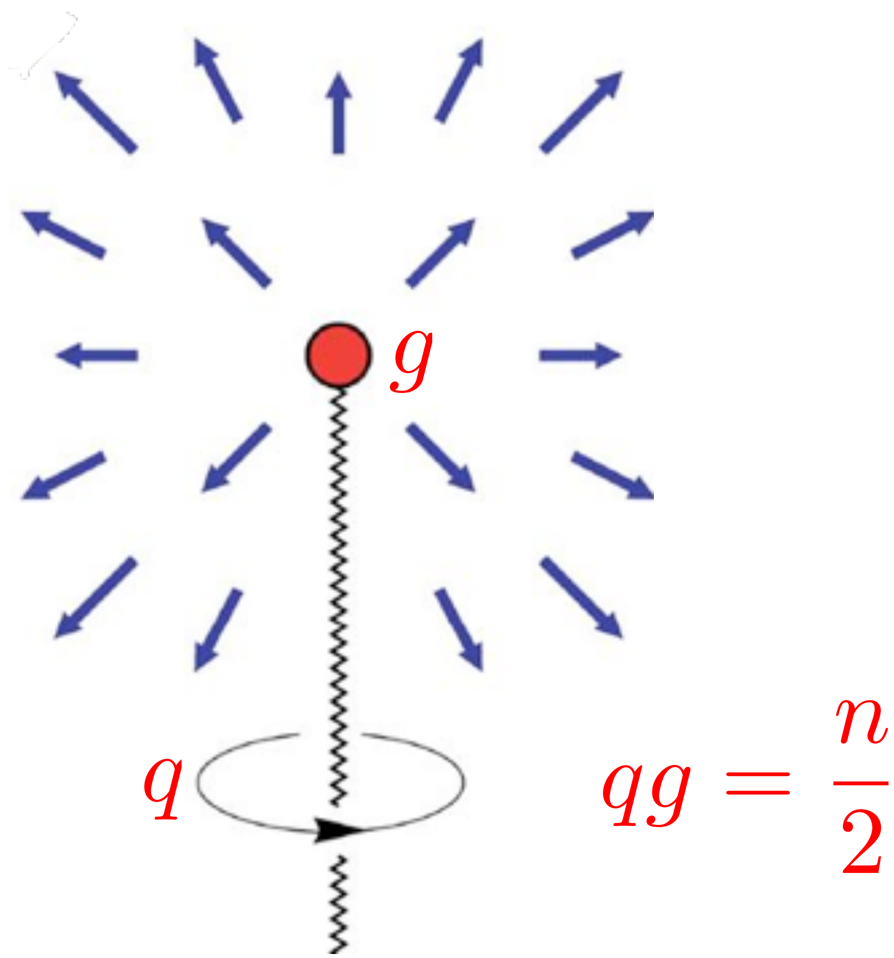


$$J = q\,g$$



Philos. Mag. 8 (1904) 331

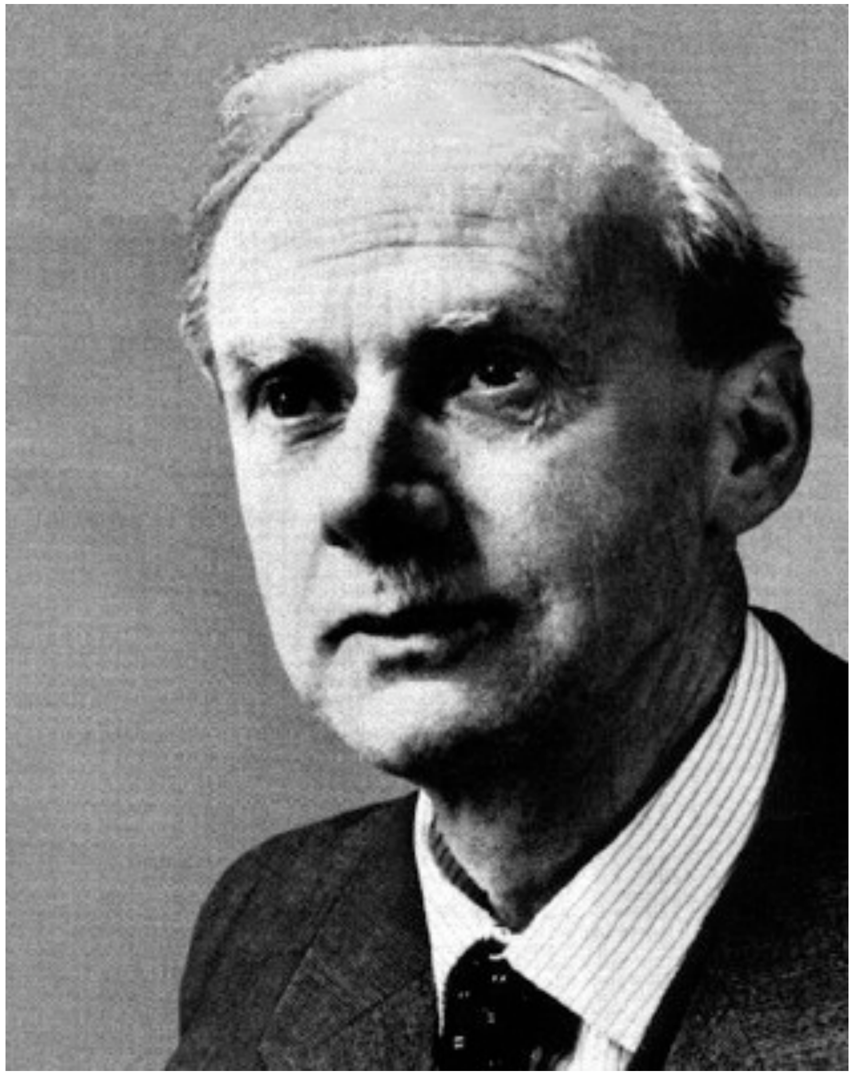
Dirac



charge quantization

Proc. Roy. Soc. Lond. A133 (1931) 60

Dirac



non-local action?

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + {}^*G_{\mu\nu}$$

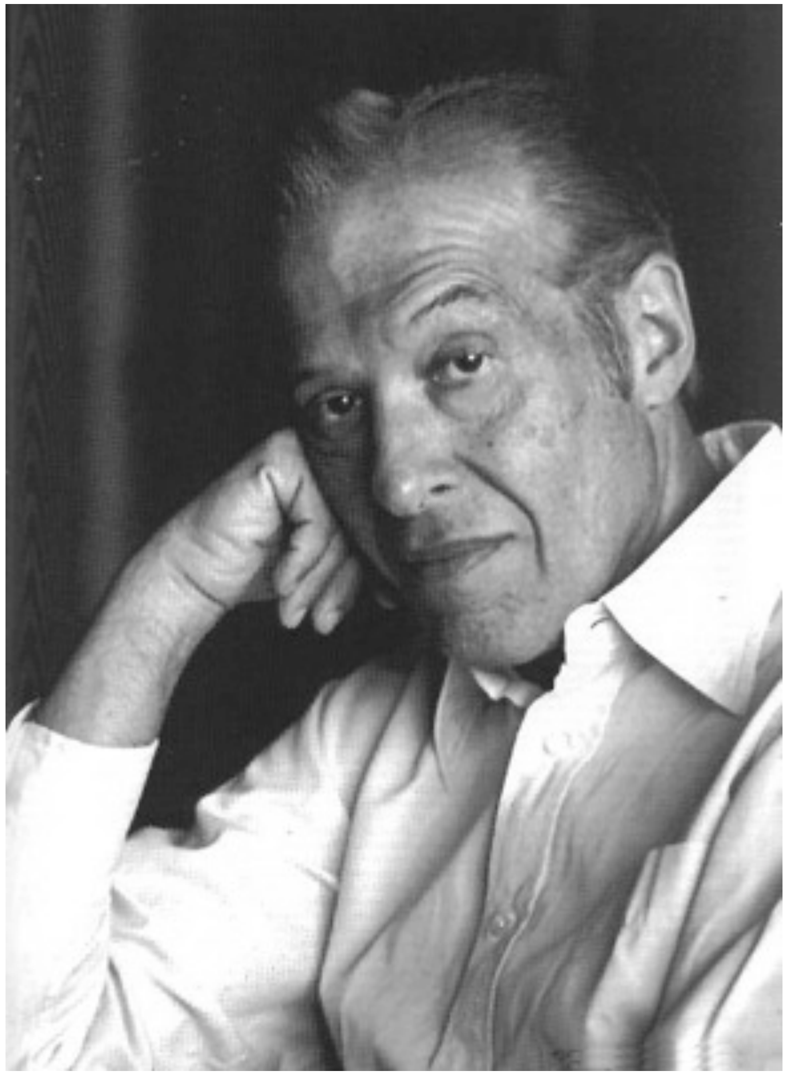
$$\begin{aligned} G_{\mu\nu}(x) &= 4\pi (n \cdot \partial)^{-1} \left[n_\mu K_\nu(x) - n_\nu K_\mu(x) \right] \\ &= \int d^4y \left[f_\mu(x-y) K_\nu(y) - f_\nu(x-y) K_\mu(y) \right] \end{aligned}$$

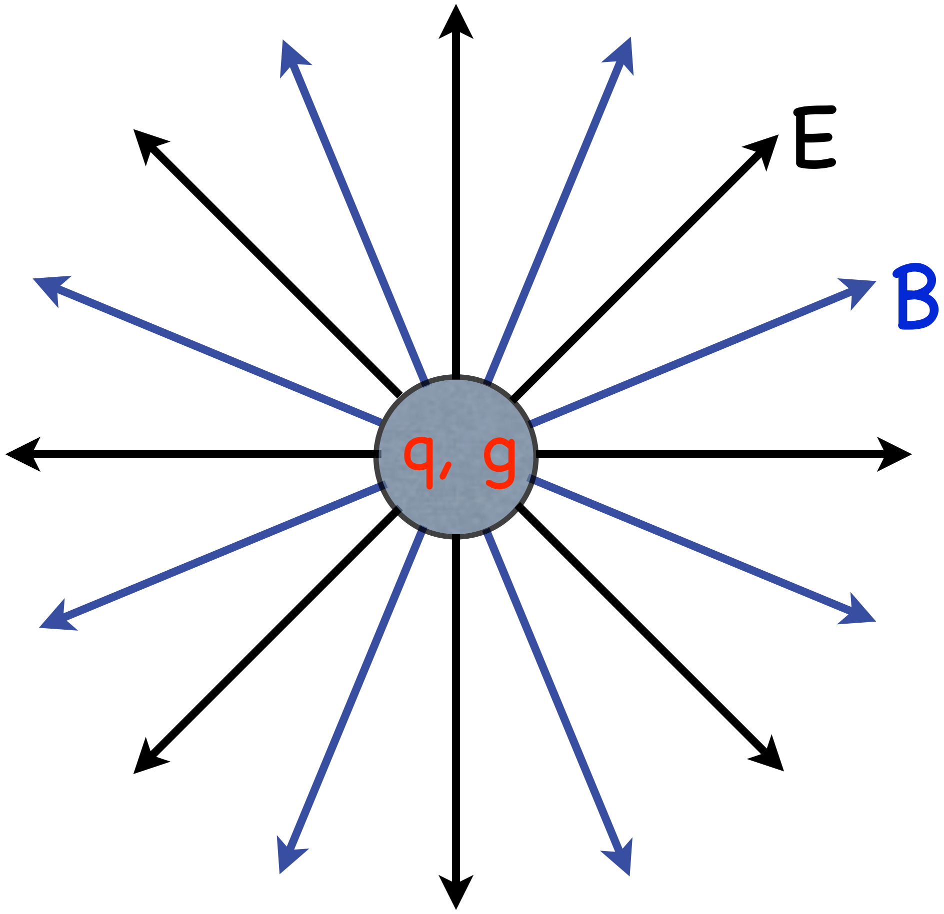
$$\partial_\mu f^\mu(x) = 4\pi \delta(x)$$

$$f^\mu(x) = 4\pi n^\mu \, (n \cdot \partial)^{-1} \, \delta(x)$$

Phys. Rev. 74 (1948) 817

Schwinger



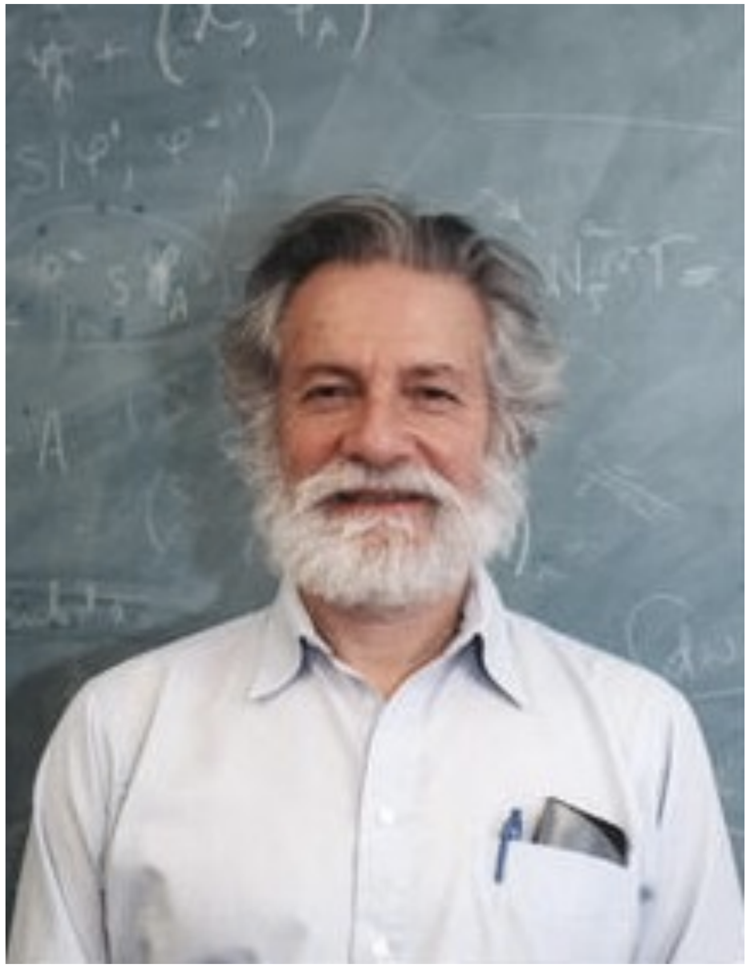


dyons

$$q_1 g_2 - q_2 g_1 = \frac{n}{2}$$

Science 165 (1969) 757

Zwanziger



non-Lorentz invariant, local action?

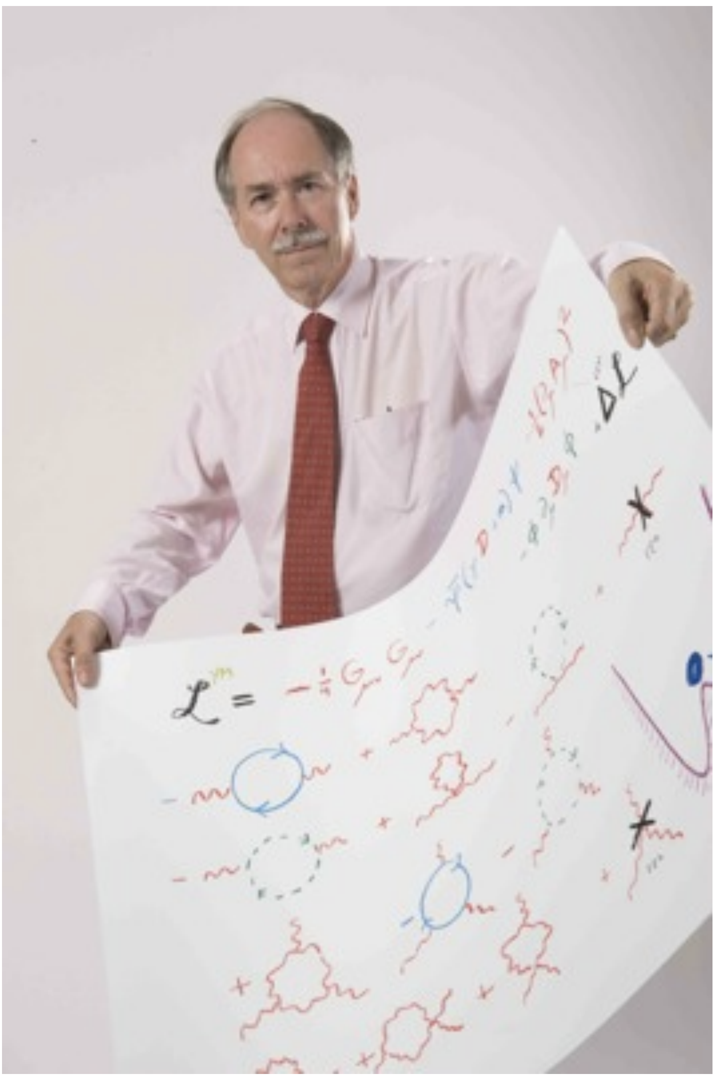
$$\mathcal{L} = -\frac{1}{2n^2e^2}\{[n\cdot(\partial\wedge A)]\cdot[n\cdot^*(\partial\wedge B)] - [n\cdot(\partial\wedge B)]\cdot[n\cdot^*(\partial\wedge A)] + [n\cdot(\partial\wedge A)]^2 + [n\cdot(\partial\wedge B)]^2\} - J\cdot A - \frac{4\pi}{e^2}K\cdot B.$$

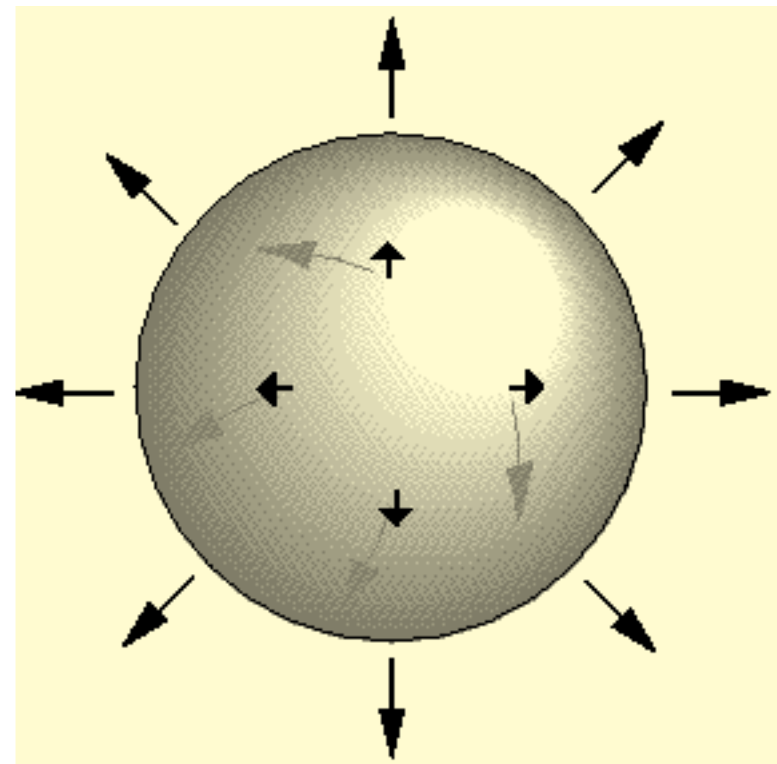
electric   magnetic

$$F = \frac{1}{n^2}(\{n\wedge[n\cdot(\partial\wedge A)]\} - {}^*\{n\wedge[n\cdot(\partial\wedge B)]\})$$

Phys. Rev. D3 (1971) 880

‘t Hooft-Polyakov

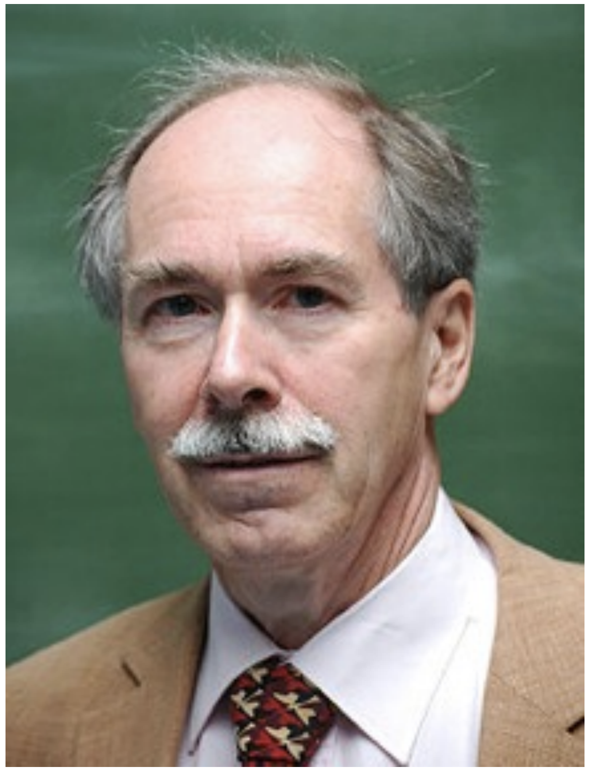




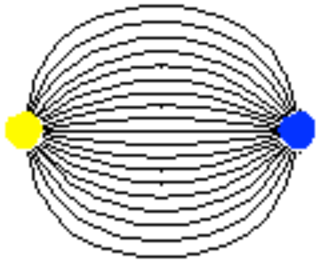
topological monopoles

Nucl. Phys., B79 1974, 276
JETP Lett., 20 1974, 194

't Hooft-Mandelstam

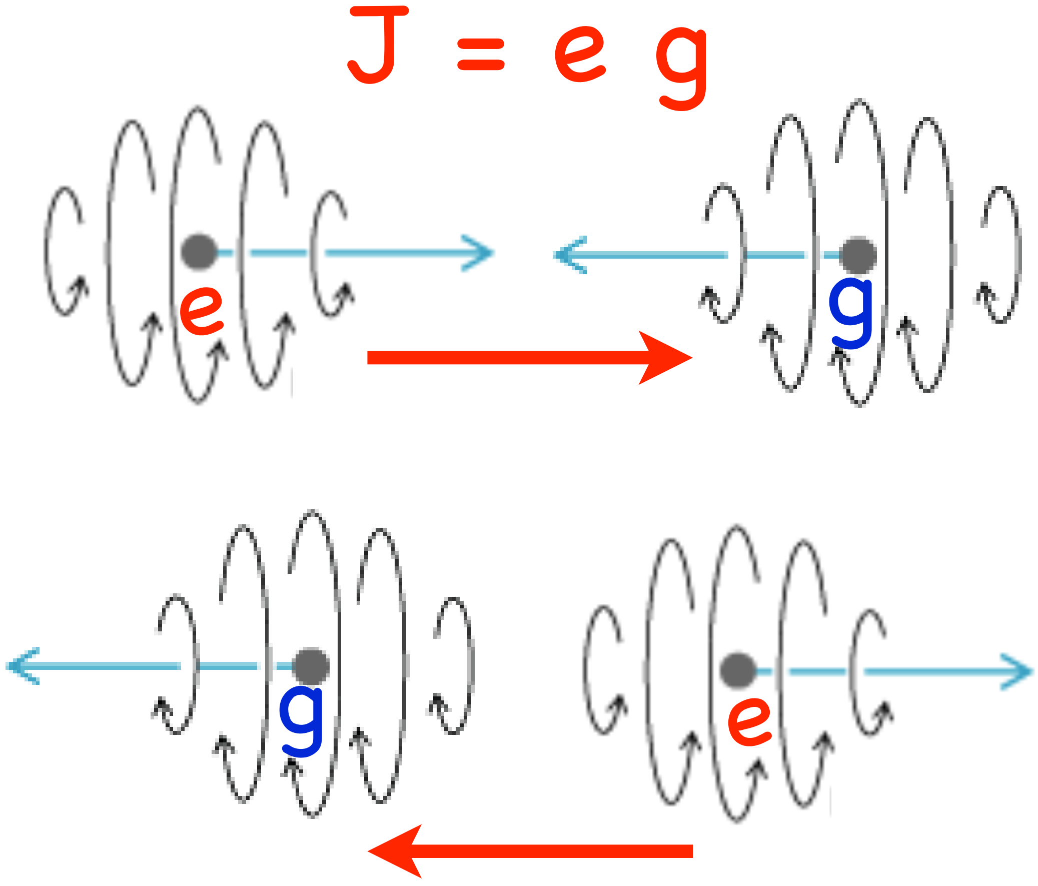


magnetic condensate
confines electric charge



High Energy Physics Ed. Zichichi, (1976) 1225
Phys. Rept. 23 (1976) 245

Rubakov-Callan



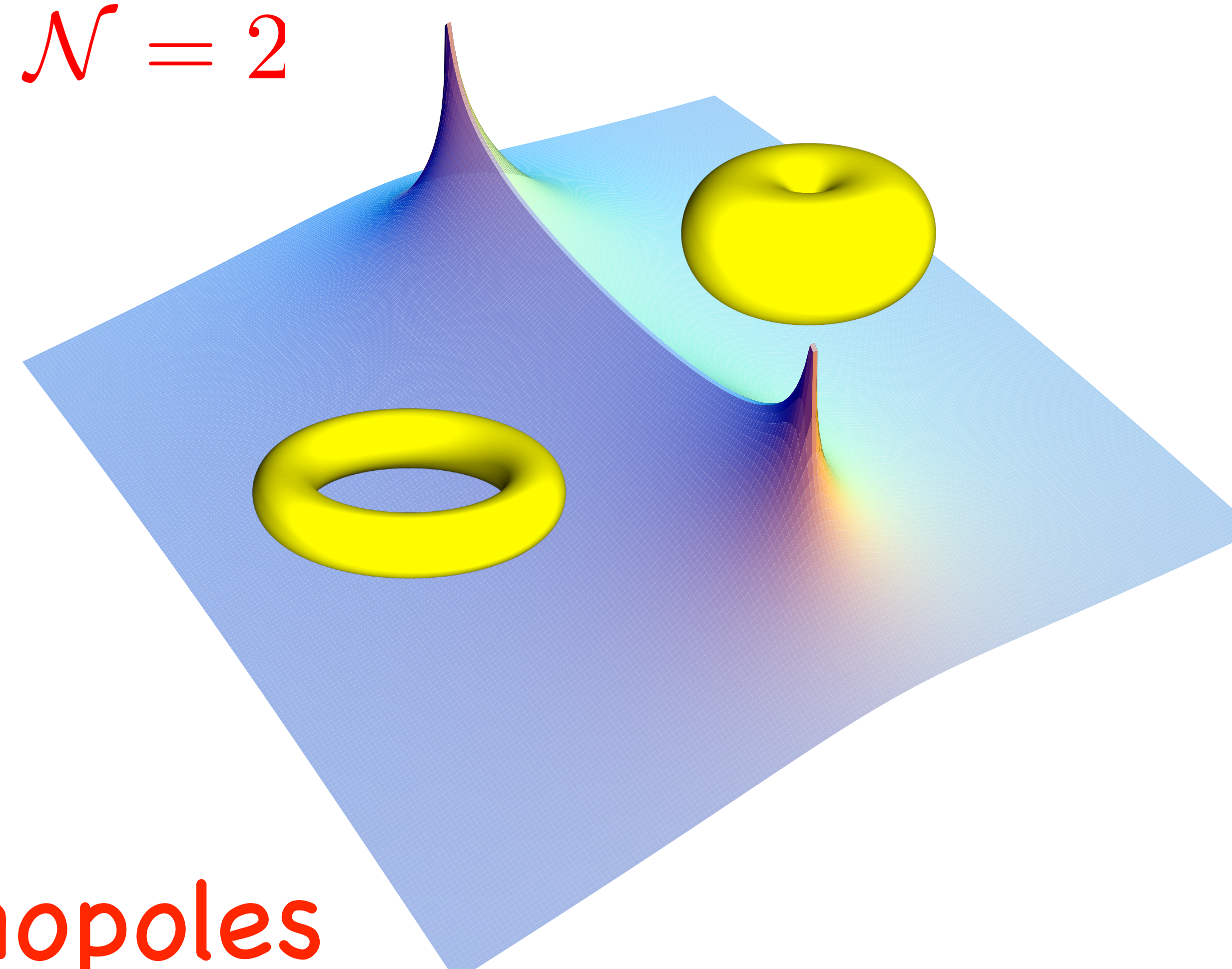
new unsuppressed contact interactions!

JETP Lett. 33 (1981) 644

Phys. Rev. D25 (1982) 2141

Seiberg-Witten

$\mathcal{N} = 2$

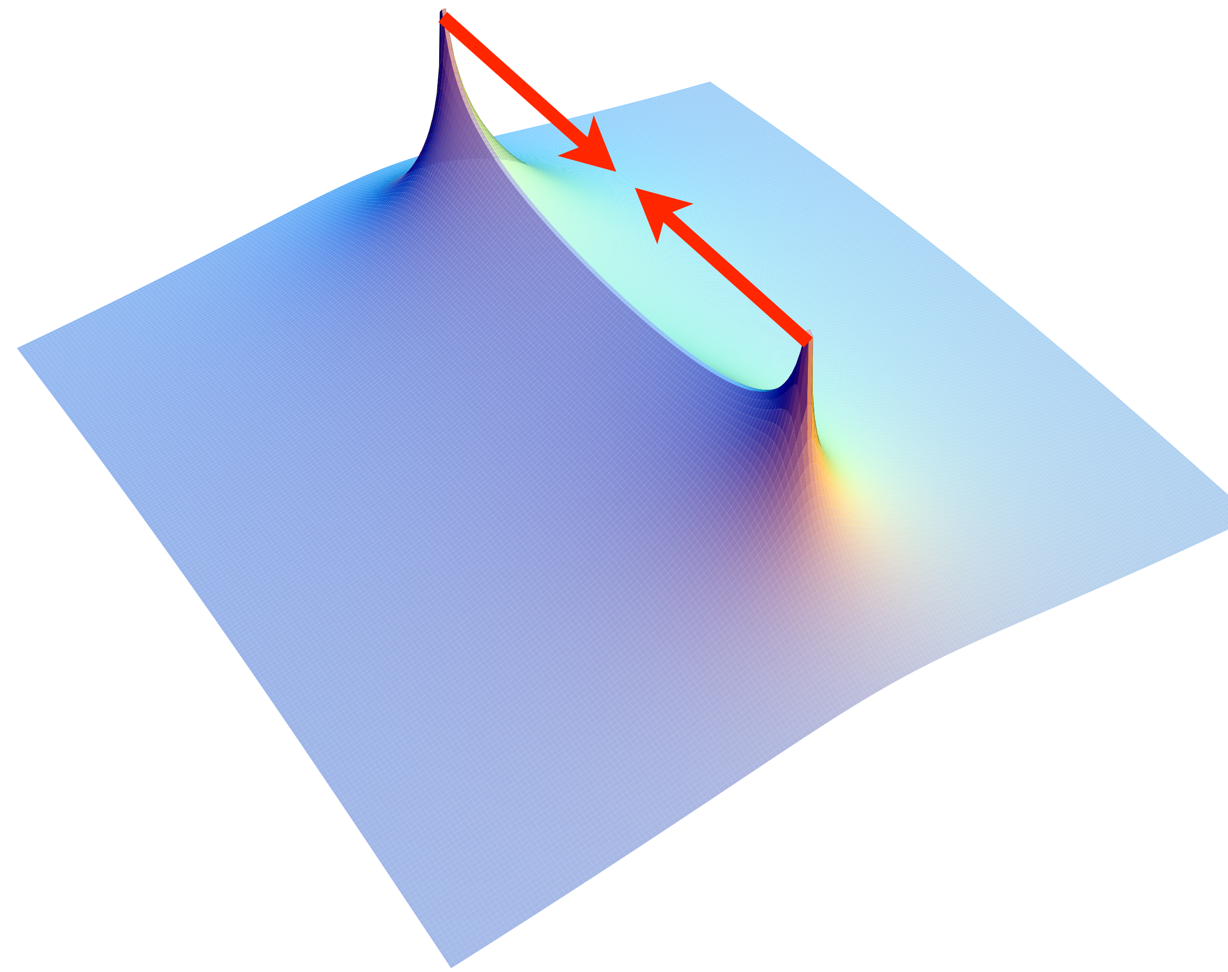


massless fermionic monopoles

hep-th/9407087

Argyres-Douglas





CFT with massless electric and magnetic charges

hep-th/9505062

Toy Model

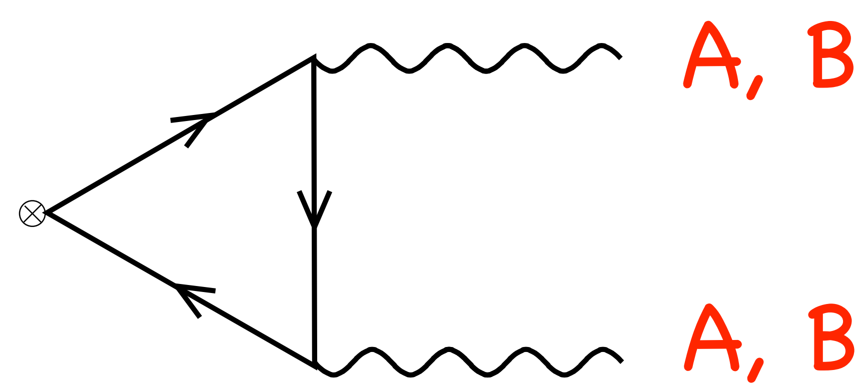
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y : q$	$U(1)_Y : g$
Q	$\square$	$\square$	$\frac{1}{6}$	3
L	1	$\square$	$-\frac{1}{2}$	-9
$\bar{U}$	$\bar{\square}$	1	$-\frac{2}{3}$	-3
$\bar{D}$	$\bar{\square}$	1	$\frac{1}{3}$	-3
$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

$$q_i g_j - q_j g_i = \frac{n}{2}$$

is this anomaly free?

Anomalies

$$\mathcal{L} = -\frac{1}{2n^2e^2}\{[n\cdot(\partial\wedge A)]\cdot[n\cdot^*(\partial\wedge B)]-[n\cdot(\partial\wedge B)]\cdot[n\cdot^*(\partial\wedge A)] + [n\cdot(\partial\wedge A)]^2+[n\cdot(\partial\wedge B)]^2\} - J\cdot A - \frac{4\pi}{e^2}K\cdot B.$$



Csaki, Shirman, JT hep-th/1003.0448

Toy Model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y : q$	$U(1)_Y : g$
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$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

$$\sum_j q_j^3 = 0\ , \quad \sum_j g_j^3 = 0\ , \quad \sum_j g_j^2 q_j = 0\ , \quad \sum_j q_j^2 g_j = 0\ , \quad \sum_j q_j = 0\ , \quad \sum_j g_j = 0\ ,$$

$$\sum_j \mathrm{Tr}\, T^a_{r_j} T^b_{r_j} q_j = 0\ , \quad \sum_j \mathrm{Tr}\, \tau^a_{r_j} \tau^b_{r_j} q_j = 0\ , \quad \sum_j \mathrm{Tr}\, T^a_{r_j} T^b_{r_j} g_j = 0\ , \quad \sum_j \mathrm{Tr}\, \tau^a_{r_j} \tau^b_{r_j} g_j = 0$$

Dynamics

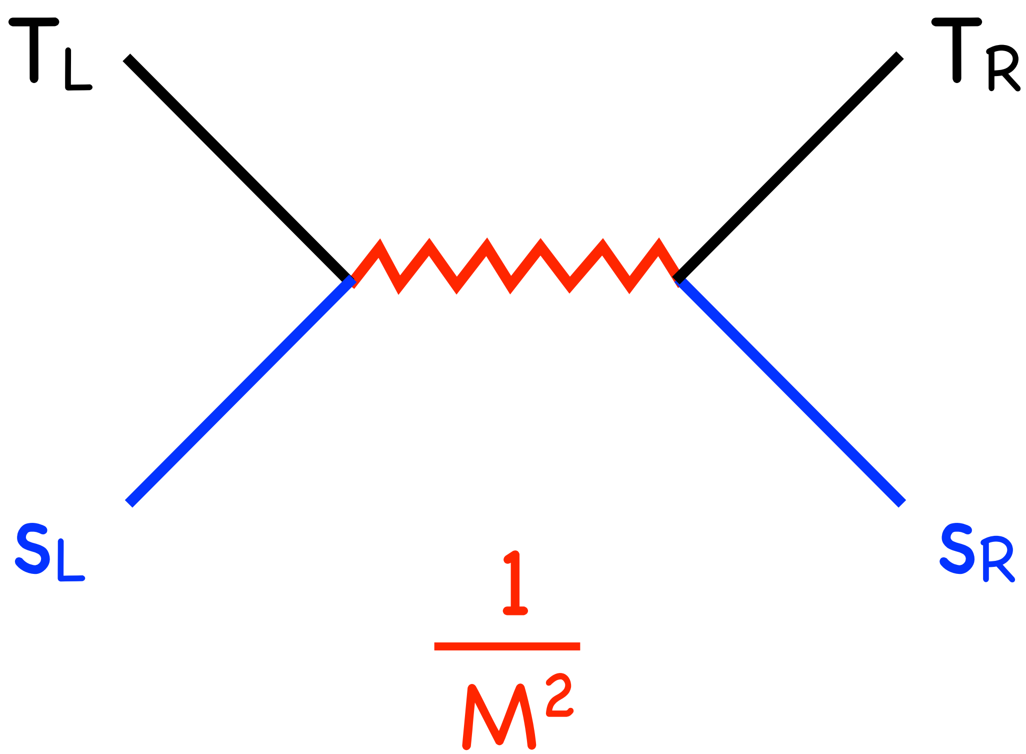
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y : q$	$U(1)_Y : g$
Q	$\square$	$\square$	$\frac{1}{6}$	3
L	1	$\square$	$-\frac{1}{2}$	-9
$\bar{U}$	$\bar{\square}$	1	$-\frac{2}{3}$	-3
$\bar{D}$	$\bar{\square}$	1	$\frac{1}{3}$	-3
$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

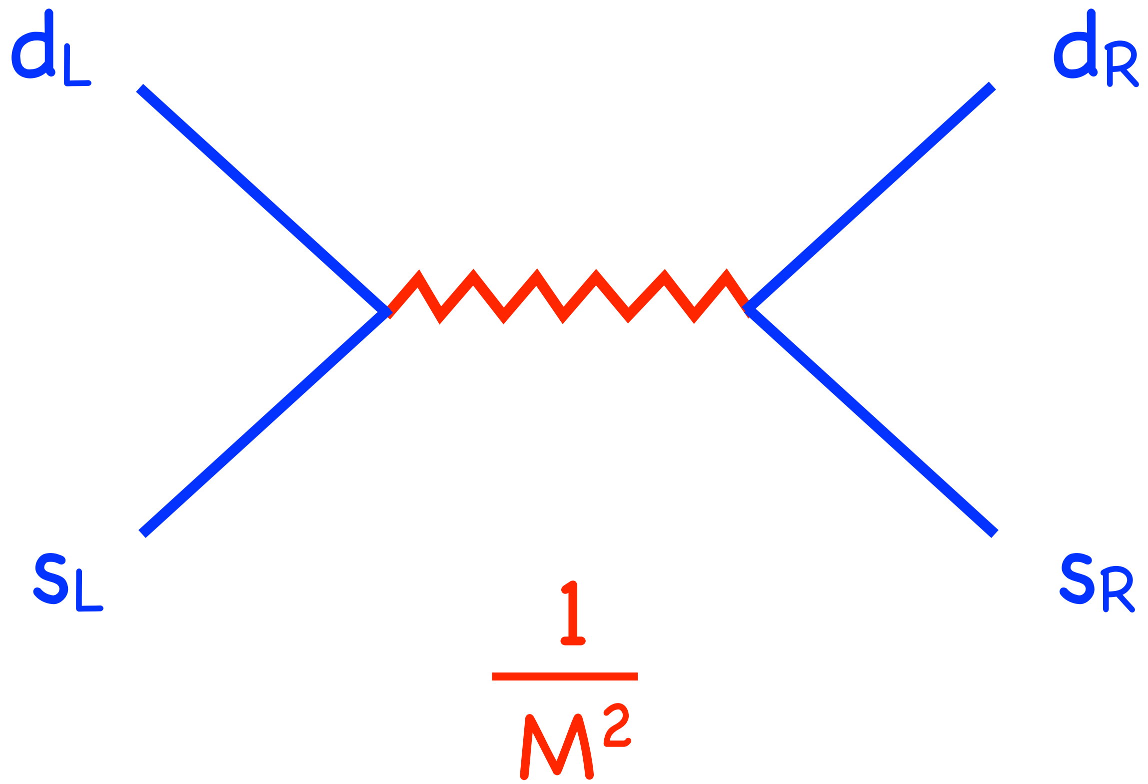
$$\left(\frac{1}{6}\right)^2 \alpha_Y 3^2 \alpha_m = \frac{1}{4}$$

$$\alpha_m \sim 98$$

Quark Masses

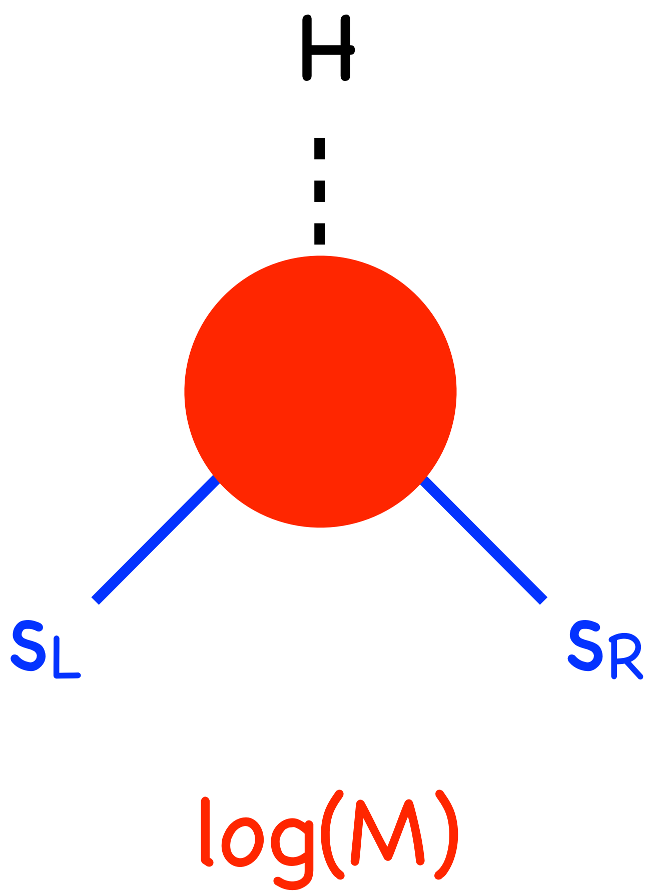
technicolor: fail

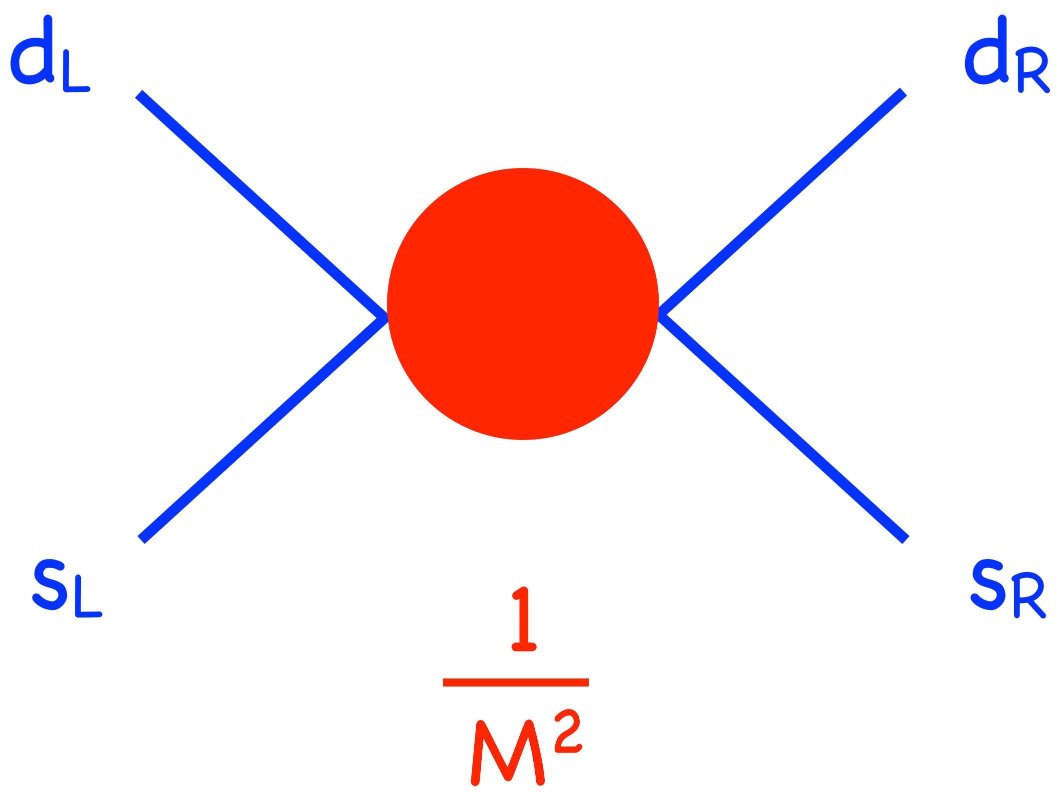




Quark Masses

Standard Model

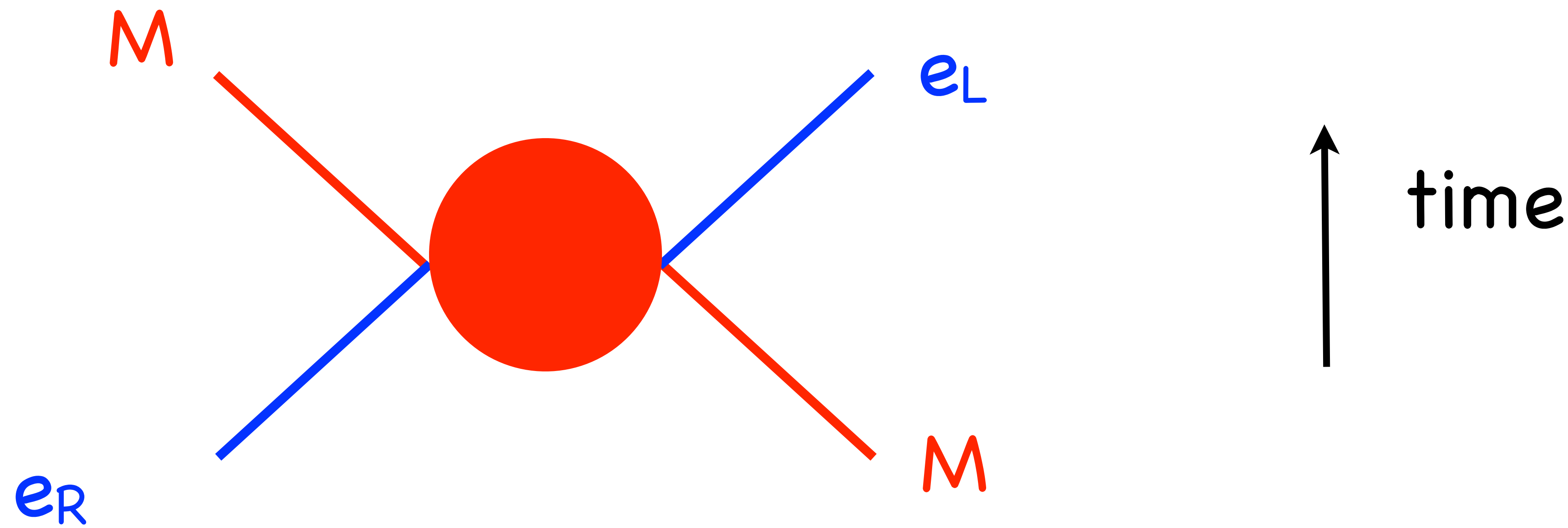




Rubakov-Callan

$J_f = -q\,g = 1/2$

$S_f = -1/2$



$J_i = q\,g = -1/2$

$S_i = 1/2$

New dimension 4, four particle operator

Angular Momentum

Classical:

$$\vec{L} = \vec{r} \times \vec{p} - q\, g\, \hat{r}$$

$$L^2 = |\vec{r} \times \vec{p}|^2 + q^2\, g^2$$

Quantum:

$$[L_i, L_j] = i\, \epsilon_{ijk} L_k$$

$$L^2 = \ell(\ell + 1), \qquad \ell \geq q\, g$$

Wu, Yang Nucl. Phys. B107, (1976) 365

Angular Momentum

$$\left[(\partial_\mu - iqA_\mu)^2 - \frac{q}{2}\sigma^{\mu\nu}F_{\mu\nu} - m^2\right]\Psi = 0$$

$$\left[-\frac{1}{r^2}\frac{\partial}{\partial r}(r^2\frac{\partial}{\partial r}) + \frac{1}{r^2}(\vec{L}^2 - q^2g^2) - q\,\vec{\sigma}\cdot\vec{B} - (E^2 - m^2)\right]\Psi = 0$$

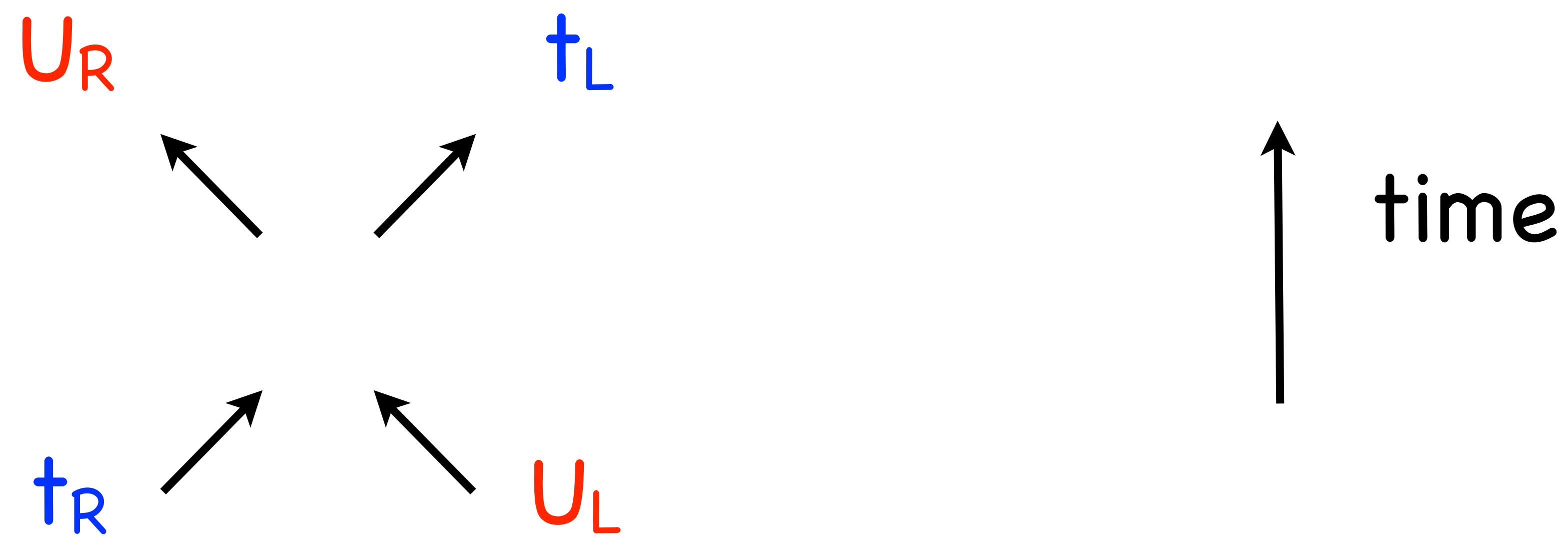
$$\frac{1}{r^2}(\ell(\ell+1) - q^2g^2) - q\,g\frac{\vec{\sigma}\cdot\hat{r}}{r^2}$$

for $\ell = q\,g$ one helicity can reach the origin

Four Fermion Ops

$J_f = -q\ g = -1/2$

$S_f = -1$



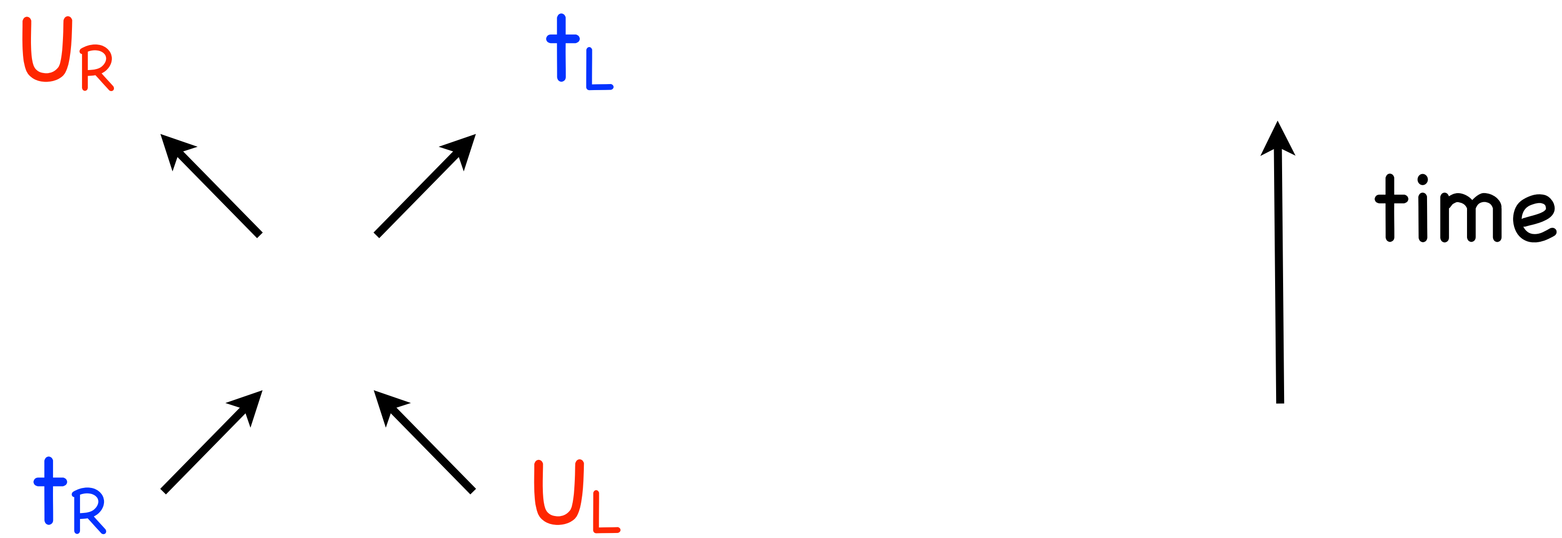
$J_i = q\ g = 2$

$S_i = 1$

Four Fermion Ops

$J_f = -q\ g = -1/2$

$S_f = -1$



$J_i = q\ g = 2$

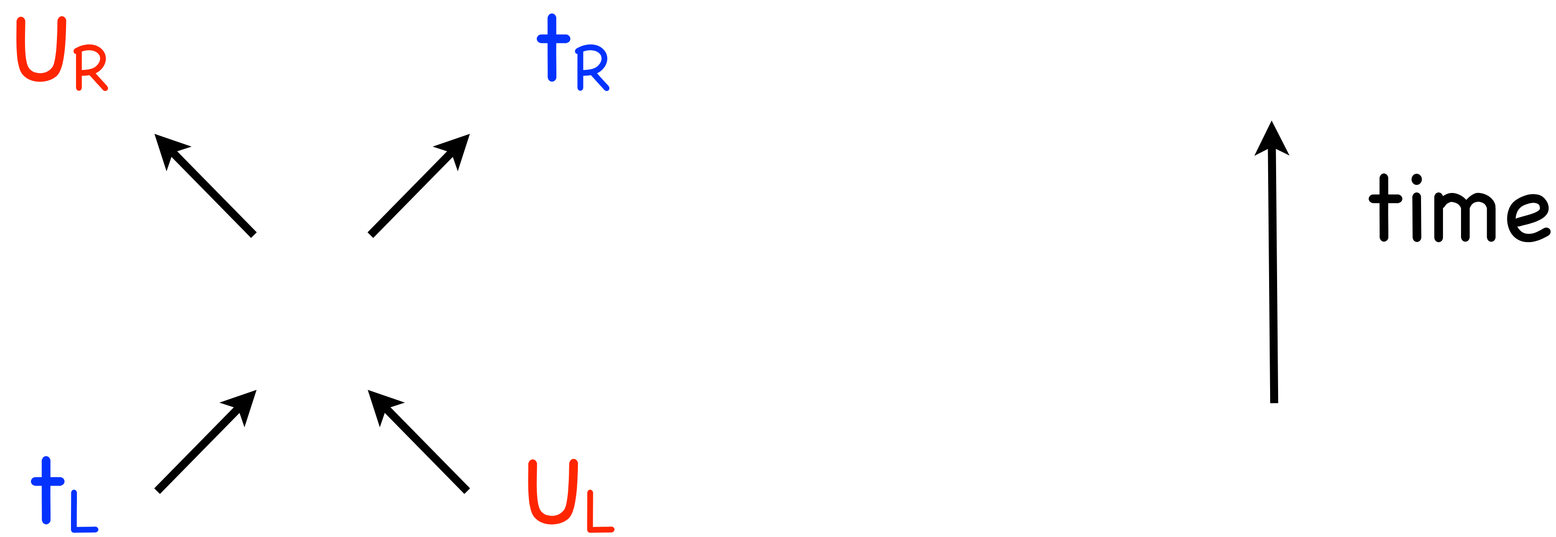
$S_i = 1$

fail!

Four Fermion Ops

$J_f = -q\ g = -2$

$S_f = 0$



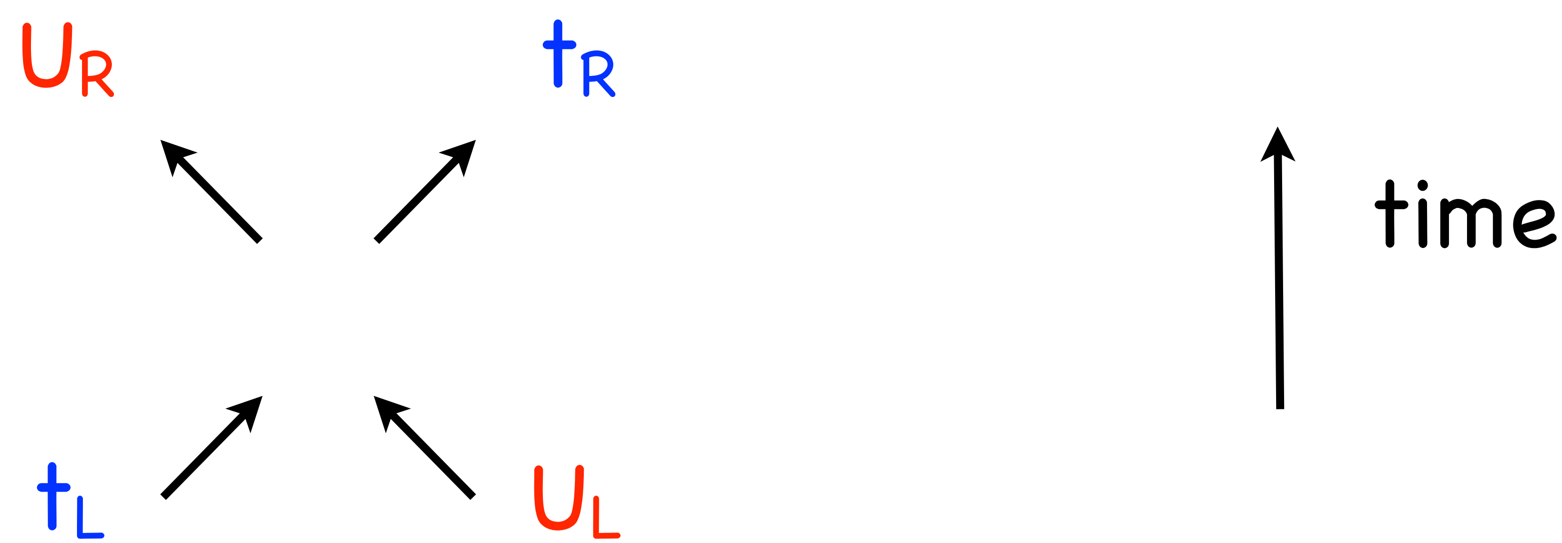
$J_i = q\ g = 1/2$

$S_i = 0$

Four Fermion Ops

$J_f = -q\ g = -2$

$S_f = 0$



$J_i = q\ g = 1/2$

$S_i = 0$

fail!

non-Abelian magnetic charge

$$Q = T^3 + Y$$

$$Q_m = T^3_m + Y_m$$

explicit examples known in GUT models

EWSB is forced to align with the monopole charge

non-Abelian magnetic charge

$$\vec{B}^a_Y = \frac{g}{g_Y}\frac{\hat{r}}{r^2}$$

$$\vec{B}^a_L = \delta^{a3}_L \frac{g\,\beta_L}{g_L}\frac{\hat{r}}{r^2}$$

$$\vec{B}^a_c = \delta^{a8}_c \frac{g\,\beta_c}{g_c}\frac{\hat{r}}{r^2}$$

$$4\pi\left(T^8_c\, g\,\beta_c + T^3_L\, g\,\beta_L + Y g\right) = 2\pi n$$

non-Abelian magnetic charge

$$4\pi \left(T_c^8\, g\, \beta_c + T_L^3\, g\, \beta_L + Y g\right) = 2\pi n$$

$$eA^\mu = g_L A_L^{3\mu} + g_Y A_Y^\mu$$

$$\beta_L = 1$$

$$T_c^8\, g\, \beta_c + q\, g = \frac{n}{2}$$

The Model

$$(SU(3)_c \times SU(2)_L \times U(1)_Y)/Z_6$$

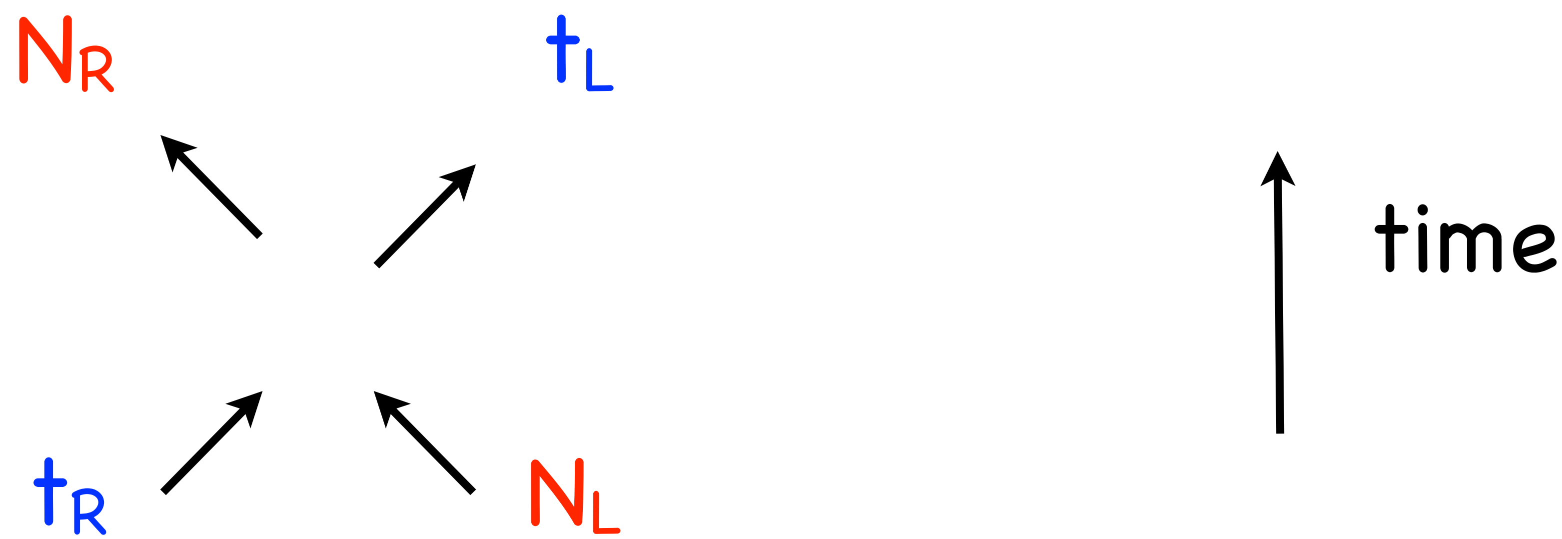
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q_L	$\square^m$	$\square^m$	$\frac{1}{6}$	$\frac{1}{2}$
L_L	1	$\square^m$	$-\frac{1}{2}$	$-\frac{3}{2}$
U_R	$\square^m$	1^m	$\frac{2}{3}$	$\frac{1}{2}$
D_R	$\square^m$	1^m	$-\frac{1}{3}$	$\frac{1}{2}$
N_R	1	1^m	0	$-\frac{3}{2}$
E_R	1	1^m	-1	$-\frac{3}{2}$

$$\alpha_m = \frac{1}{4\alpha} \approx 32$$

Four Fermion Ops

$$J_f = -q\,g = -\frac{2}{3}\left(-\frac{3}{2}\right)$$

$$S_f = -1$$



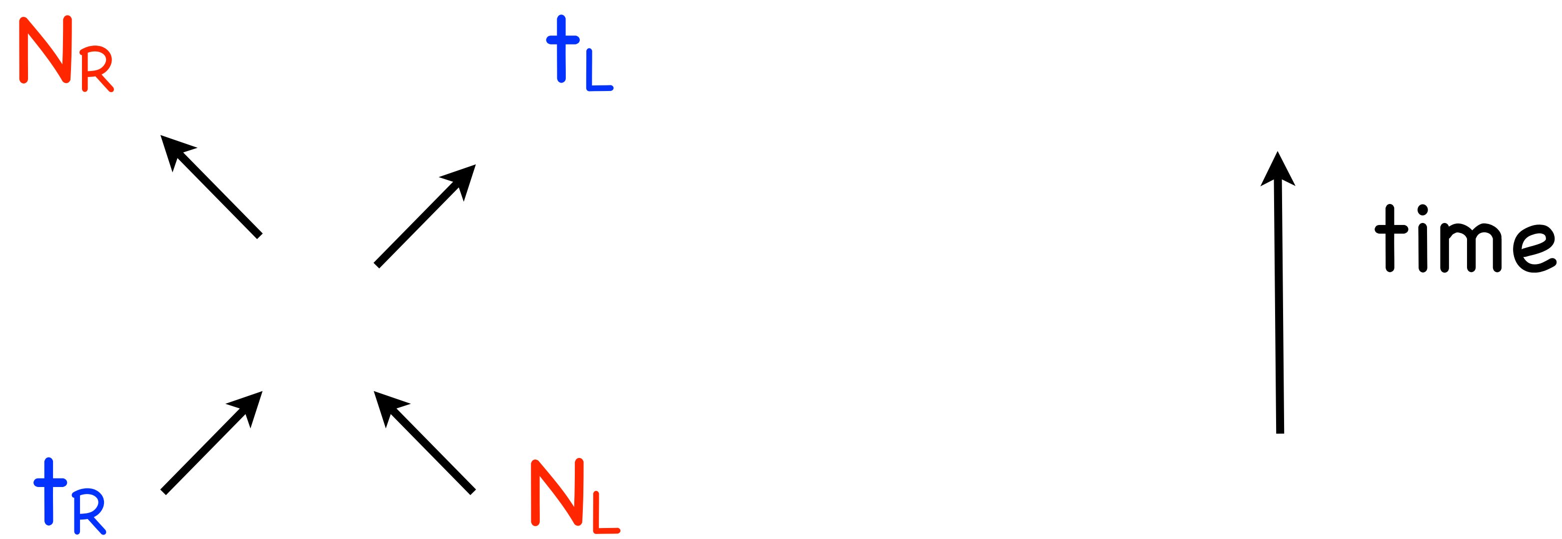
$$J_i = q\,g = \frac{2}{3}\left(-\frac{3}{2}\right)$$

$$S_i = +1$$

Four Fermion Ops

$$J_f = -q\,g = -\frac{2}{3}\left(-\frac{3}{2}\right)$$

$$S_f = -1$$



$$J_i = q\,g = \frac{2}{3}\left(-\frac{3}{2}\right)$$

$$S_i = +1$$

hooray!

Four Fermion Ops

$$\lambda_{ij}^{(u)} N_R(p_2)\bar{\sigma}^\mu u_L^j(p_1)\, a_{\mu,-}(p_1,p_2,n)\, \left[u_R^i(p_3)\bar{\sigma}^\nu N_L(p_4)\, a_{\nu,+}(p_4,p_3,n)\right]^\dagger$$

$$E_R(p_2)\bar{\sigma}^\mu D_L(p_1)\, a_{\mu,+}(p_1,p_2,n)\, [D_R(p_3)\bar{\sigma}^\nu E_L(p_4)\, a_{\nu,-}(p_4,p_3,n)]^\dagger$$

$$N_R(p_2)\bar{\sigma}^\mu U_L(p_1)\, a_{\mu,-}(p_1,p_2,n)\, [U_R(p_3)\bar{\sigma}^\nu N_L(p_4)\, a_{\nu,+}(p_4,p_3,n)]^\dagger$$

$$a_\pm^\mu(p_1,p_2,n) \equiv (\Lambda_{p_1p_2})^\mu{}_\nu \epsilon_\pm^\nu = \epsilon_2^\mu \pm i\epsilon_1^\mu = -\frac{\epsilon^\mu(p_1,p_2,n)}{|\epsilon^\mu(p_1,p_2,n)|} - \pm i \frac{\epsilon^\mu(p_1,p_2,\epsilon(p_1,p_2,n))}{|\epsilon^\mu(p_1,p_2,n)|\sqrt{(p_1\cdot p_2)^2 - p_1^2p_2^2}}$$

$$\epsilon^\mu(p_1,p_2,n) = \epsilon^{\mu\nu\alpha\beta} p_{1\nu} p_{2\alpha} n_\beta$$

Effective Theory

$$SU(6)_{qL} \times SU(6)_{qR} \times SU(2)_{\ell L} \times SU(2)_{\ell R} \times U(1)_q \times U(1)_\ell$$

$$\downarrow$$

$$SU(6)_q \times SU(2)_\ell \times U(1)_q \times U(1)_\ell$$

3 Nambu-Goldstone Bosons

38 PNGBS

$$(1,3) + (8,1) + (8,3)$$

Effective Theory

$$\Sigma_\ell = e^{2i\pi_\ell^a T^a} \quad , \qquad \Sigma_q = e^{2i\pi_q^a T^a}$$

$$\mathcal{L} \;=\; \frac{f_{\ell,0}^2}{4}\,\mathrm{Tr}\,D^\mu\Sigma_\ell^\dagger D_\mu\Sigma_\ell + \frac{f_{q,0}^2}{4}\,\mathrm{Tr}\,D^\mu\Sigma_q^\dagger D_\mu\Sigma_q + \left(f_{\ell,0}\,\mathrm{Tr}\,\Sigma_\ell\lambda^{(u)} q_L u_R + h.c.\right) + \left(a\, f_{\ell,0}^2 f_{q,0}^2\,\mathrm{Tr}\,\left(\Sigma_\ell\,\Sigma_q^\dagger\right) + h.c.\right)$$

$$\Gamma(P^0 \to \gamma\gamma) \sim \frac{1}{192\pi^3}\frac{m_P^3}{f_P^2}$$

Conclusions

Monopoles are still fascinating
after all these years

monopoles can break EWS and give the
top quark a large mass

monopole phenomenolgy has open questions