Monopoles, Anomalies, 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

Technicolor

Hierarchy Problem Now

SUSY

Extra Dimensions

Technicolor

Hierarchy Problem Now

SUSY

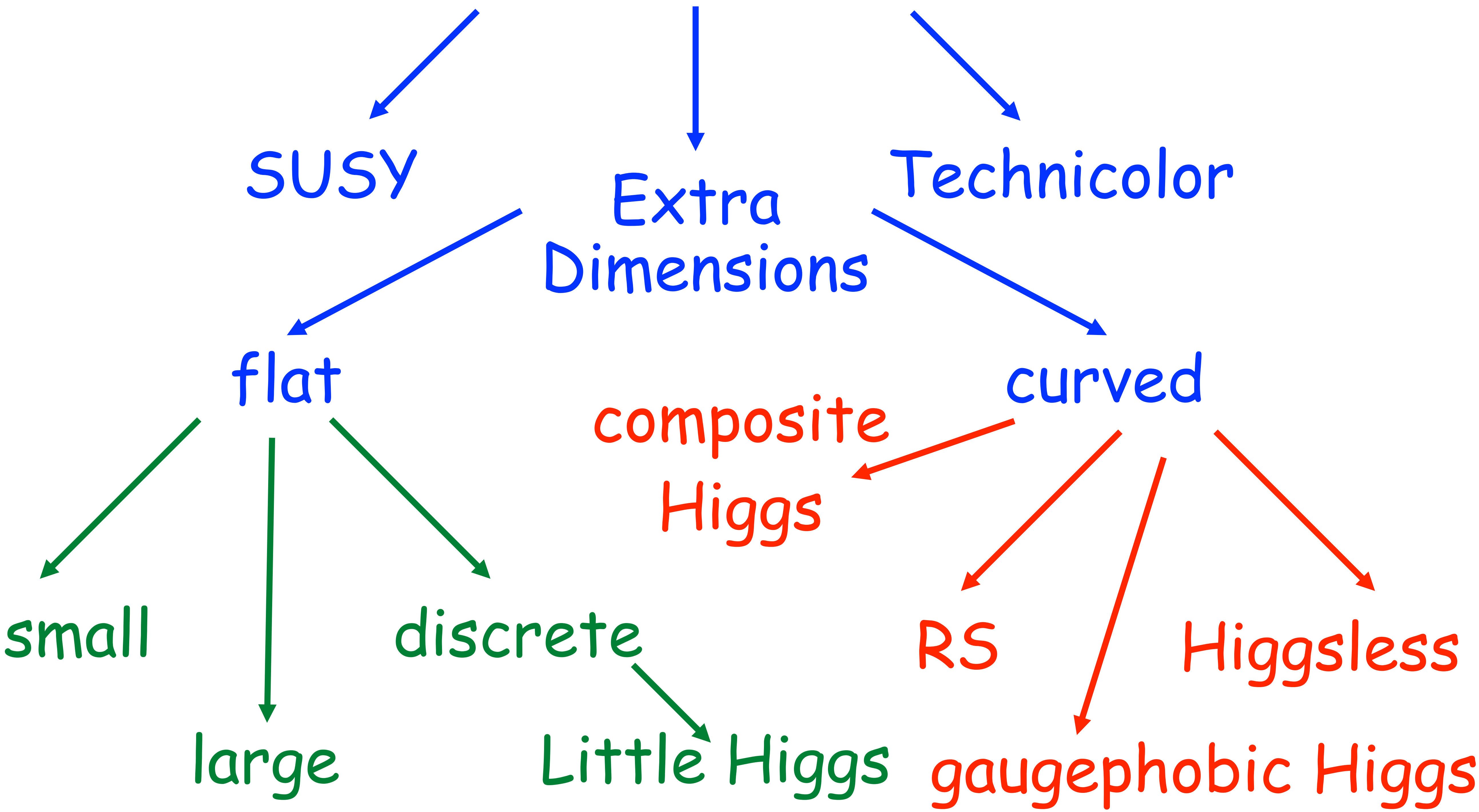
Extra Dimensions

Technicolor

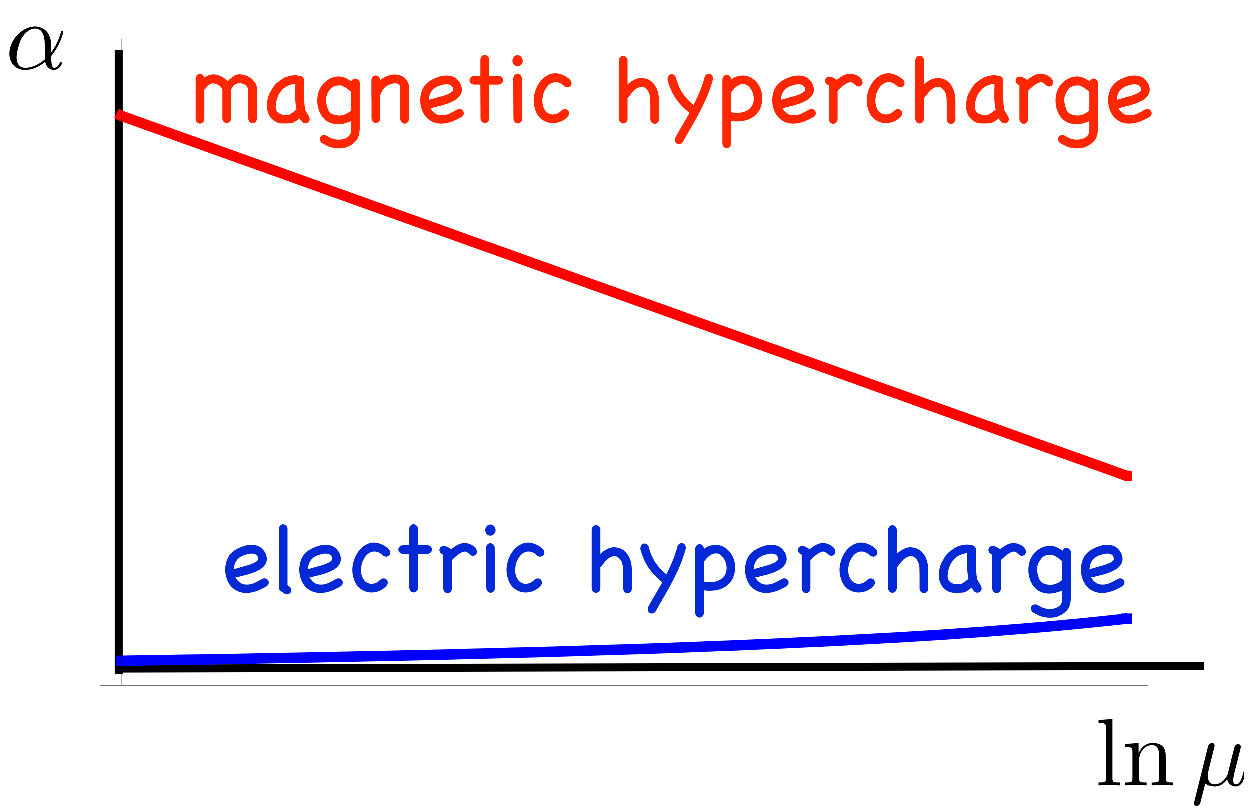
flat

curved

Hierarchy Problem Now



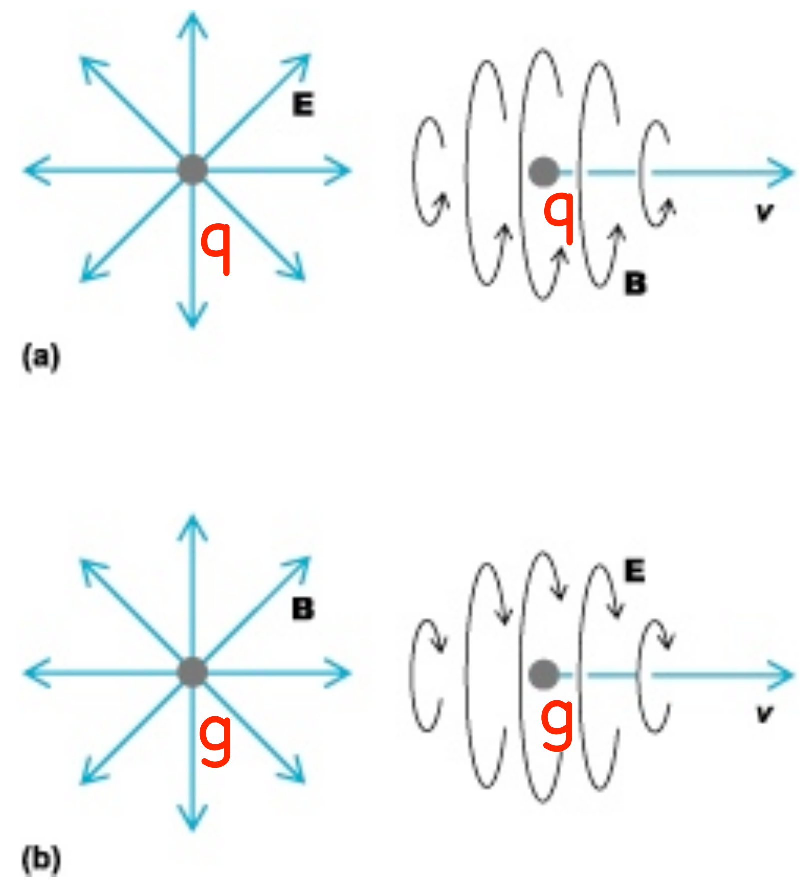
The Vision Thing



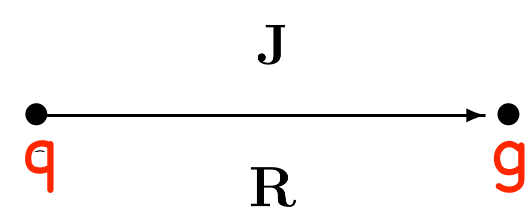
consistent theory of massless dyons?

chiral symmetry breaking -> EWSB?

J.J. Thomson

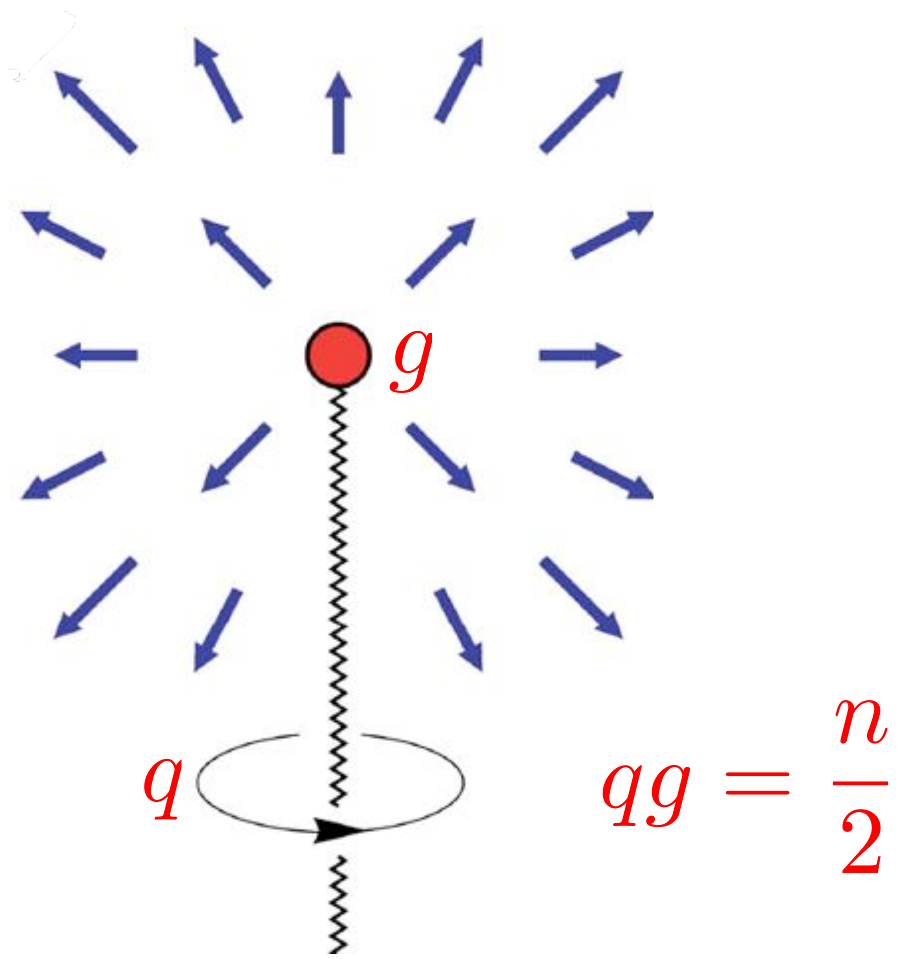


$$J = q\,g$$



Philos. Mag. 8 (1904) 331

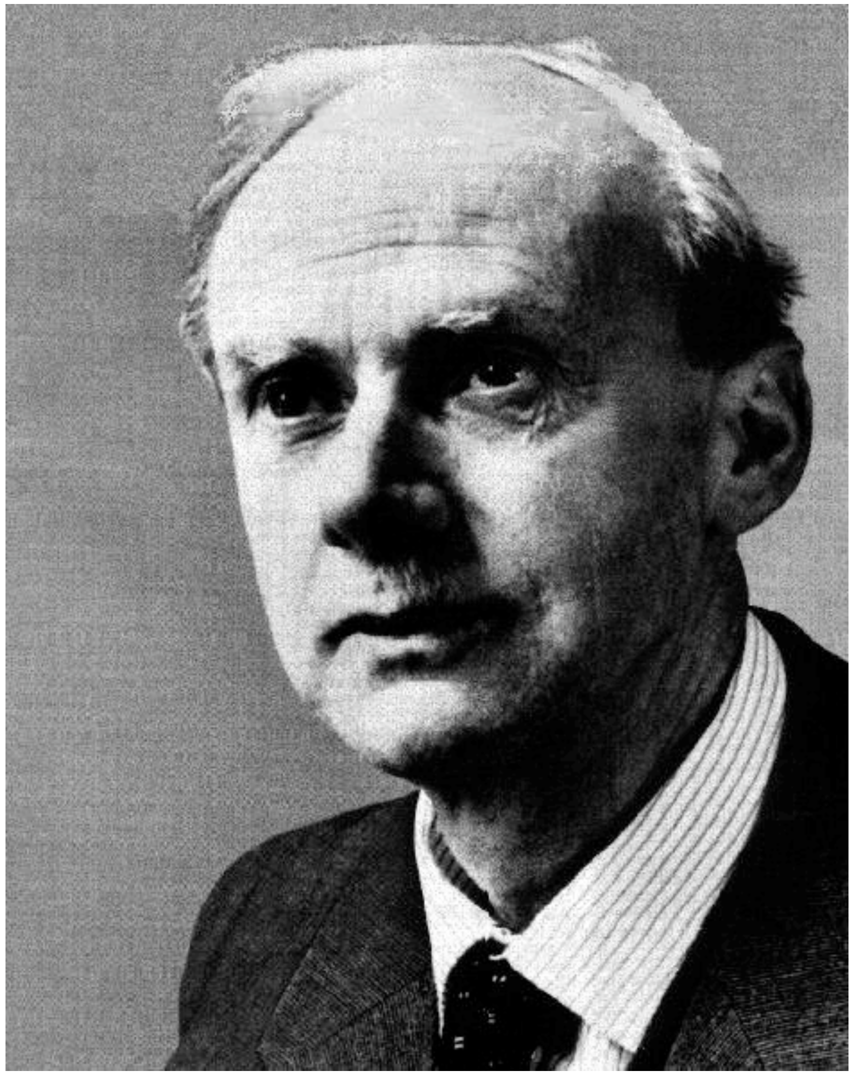
Dirac



charge quantization

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

Dirac



non-local action?

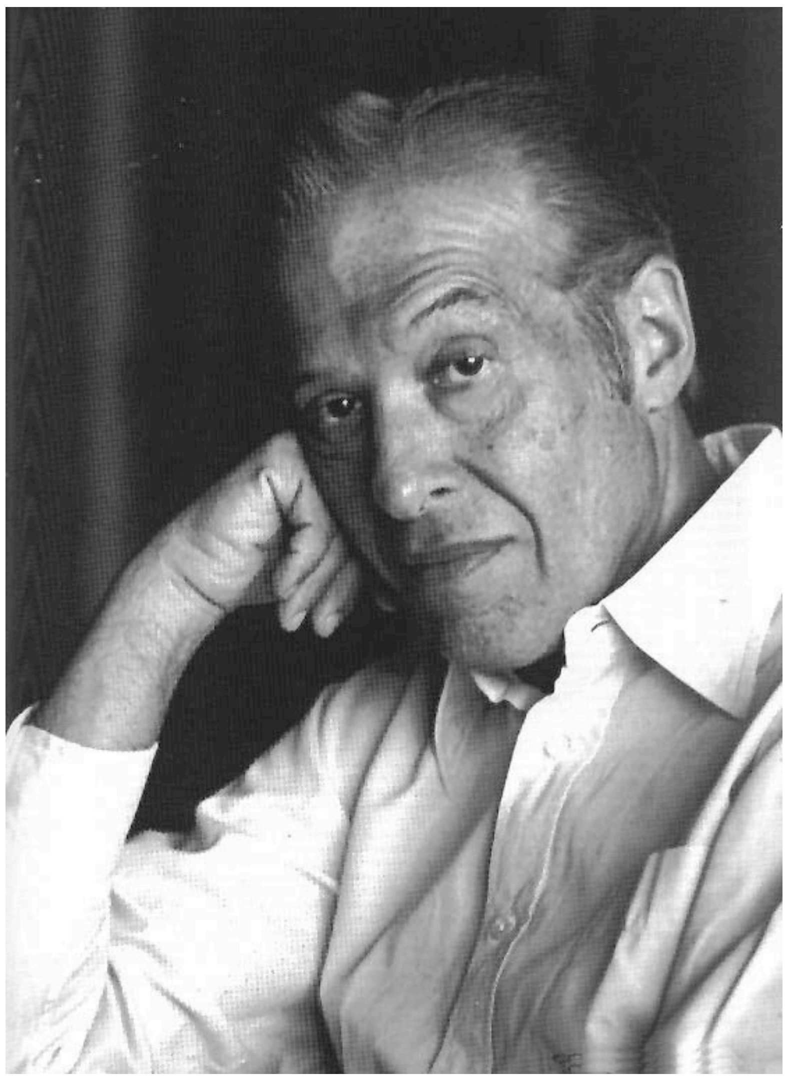
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + {}^*G_{\mu\nu}$$

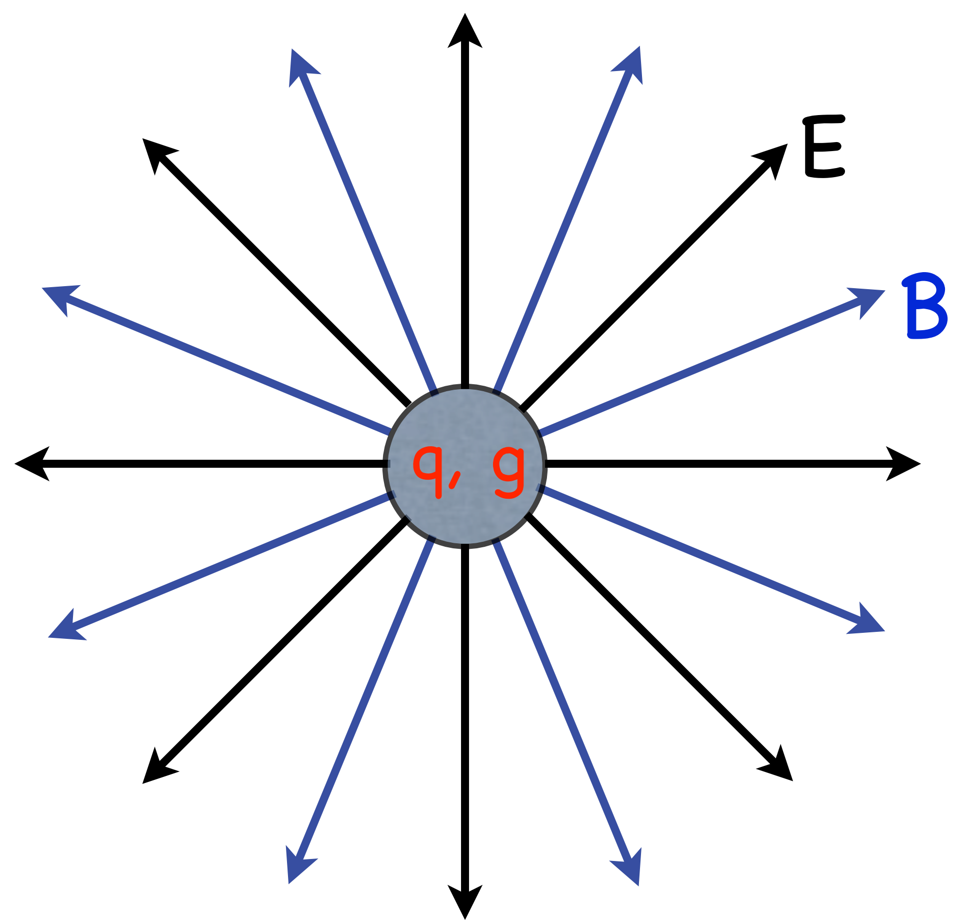
$$G_{\mu\nu}(x) = 4\pi\,(n\cdot\partial)^{-1}\left[n_\mu\,{}^*j_\nu(x) - n_\nu\,{}^*j_\mu(x)\right]$$
$$= \int (\mathrm{d}y)\left[f_\mu(x-y)\,{}^*j_\nu(y) - f_\nu(x-y)\,{}^*j_\mu(y)\right]$$

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

Phys. Rev. 74 (1948) 817

Schwinger



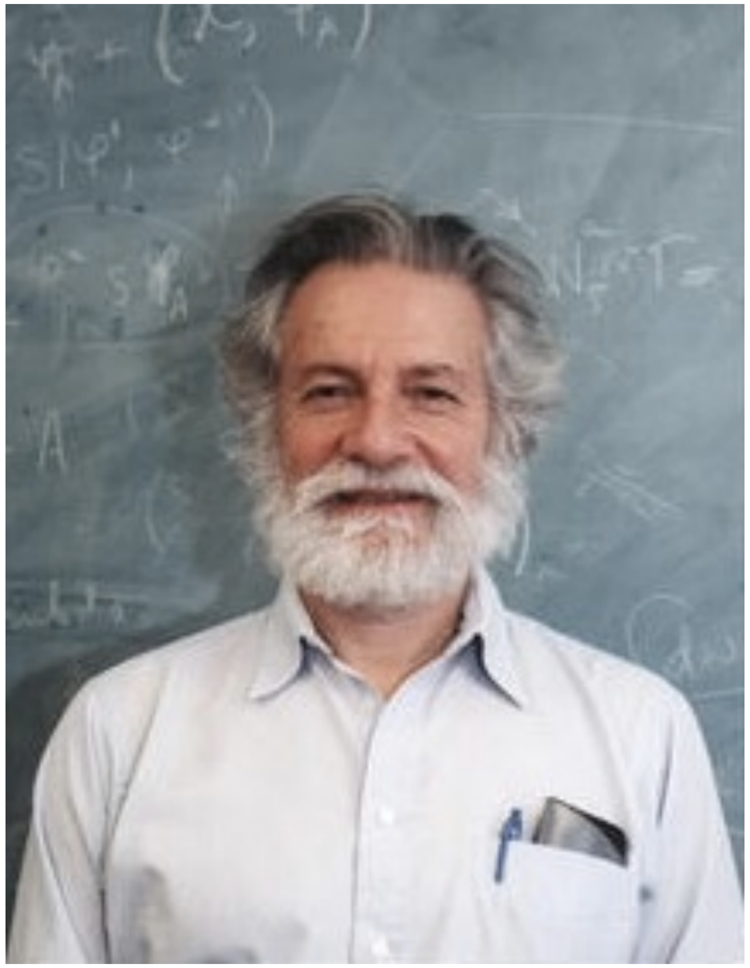


dyons

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

Science 165 (1969) 757

Zwanziger



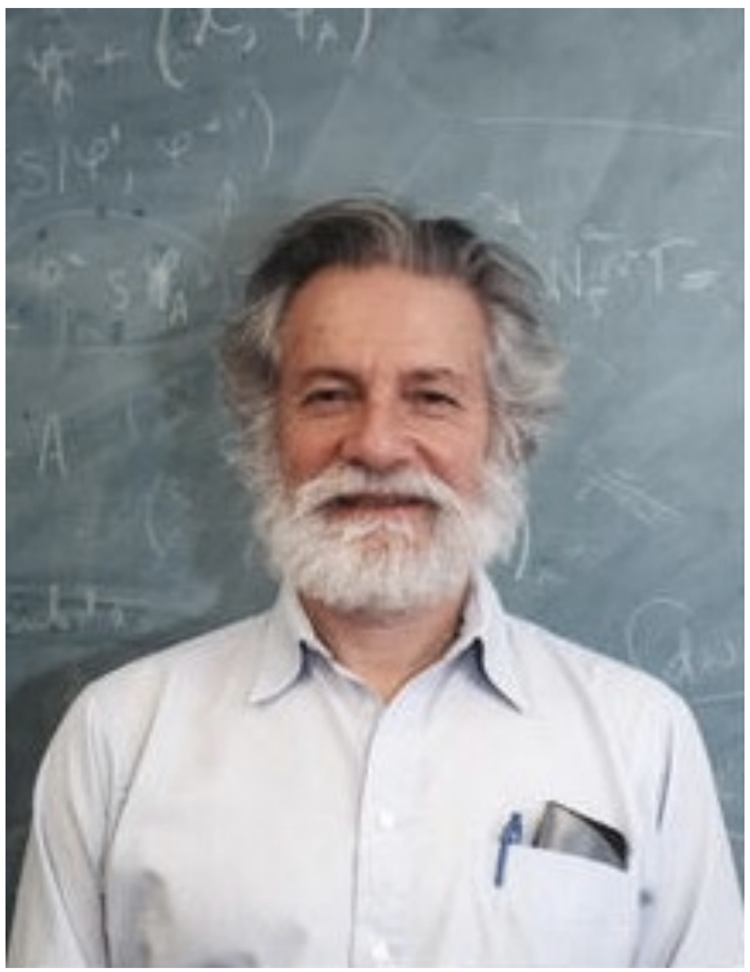
non-Lorentz invariant, local action?

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

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

Phys. Rev. D3 (1971) 880

Zwanziger



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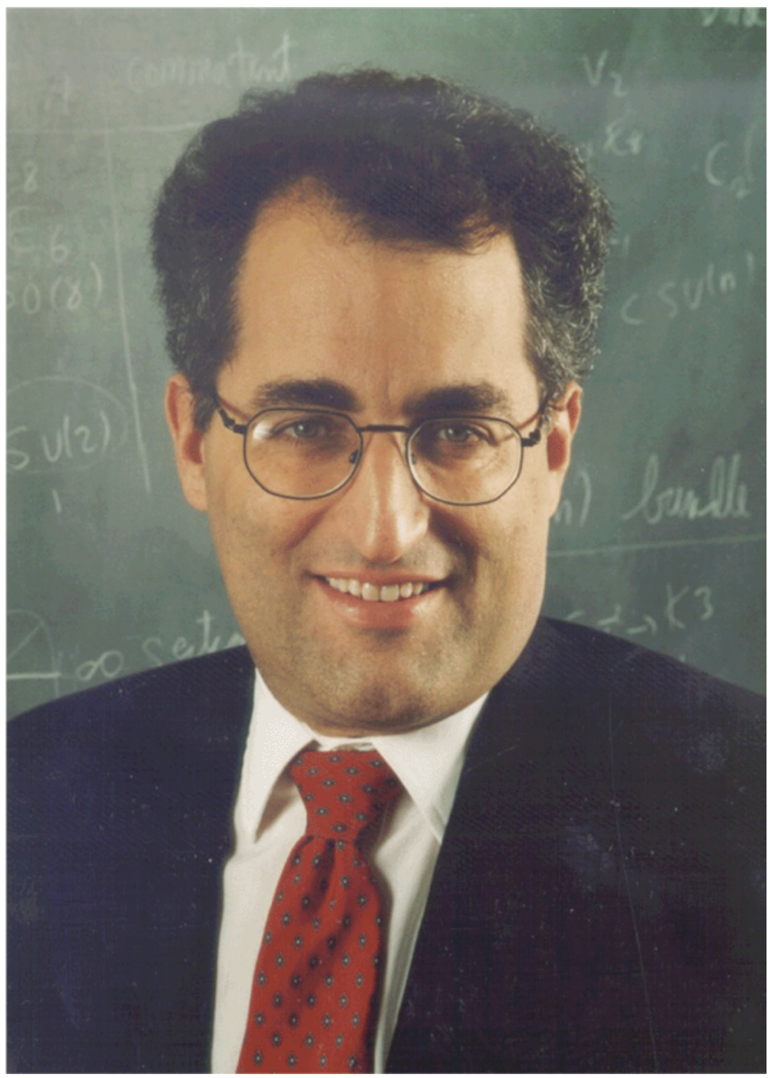
$$\mathcal{L} = -\frac{1}{2n^2e^2}\{[n\cdot(\partial\wedge A)]\cdot[n\cdot^*(\partial\wedge B)]-[n\cdot(\partial\wedge B)]\cdot[n\cdot^*(\partial\wedge A)] + [n\cdot(\partial\wedge A)]^2+[n\cdot(\partial\wedge B)]^2\} - J\cdot A - \frac{4\pi}{e^2}K\cdot B.$$

electric magnetic

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

Phys. Rev. D3 (1971) 880

Witten



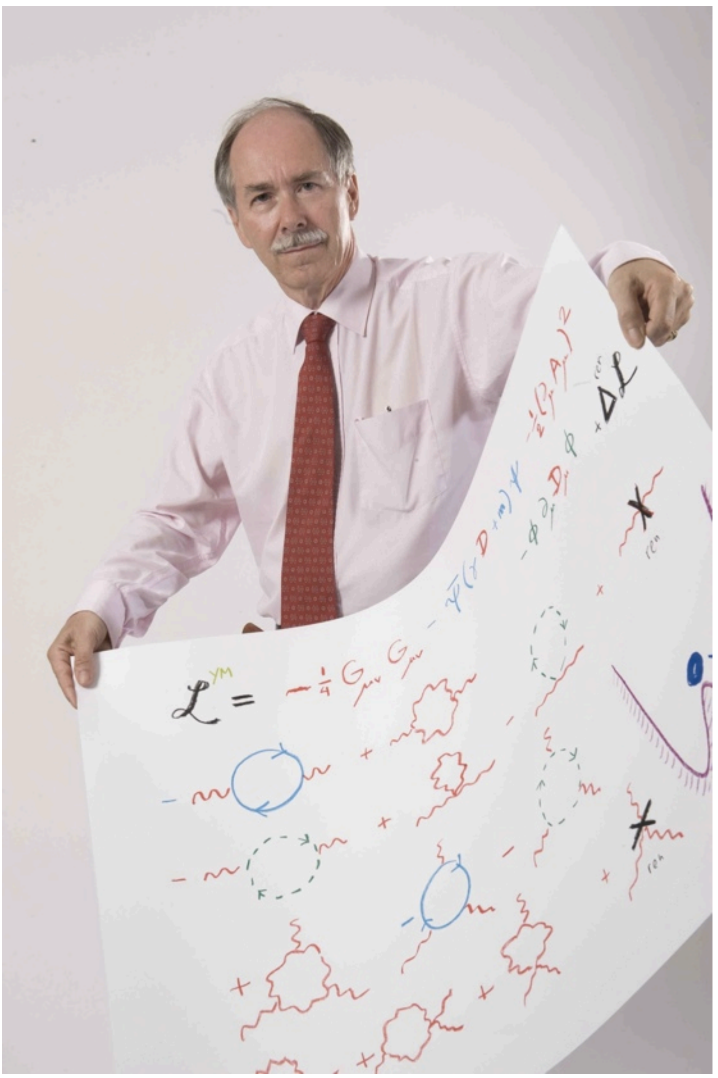
effective charge shifted

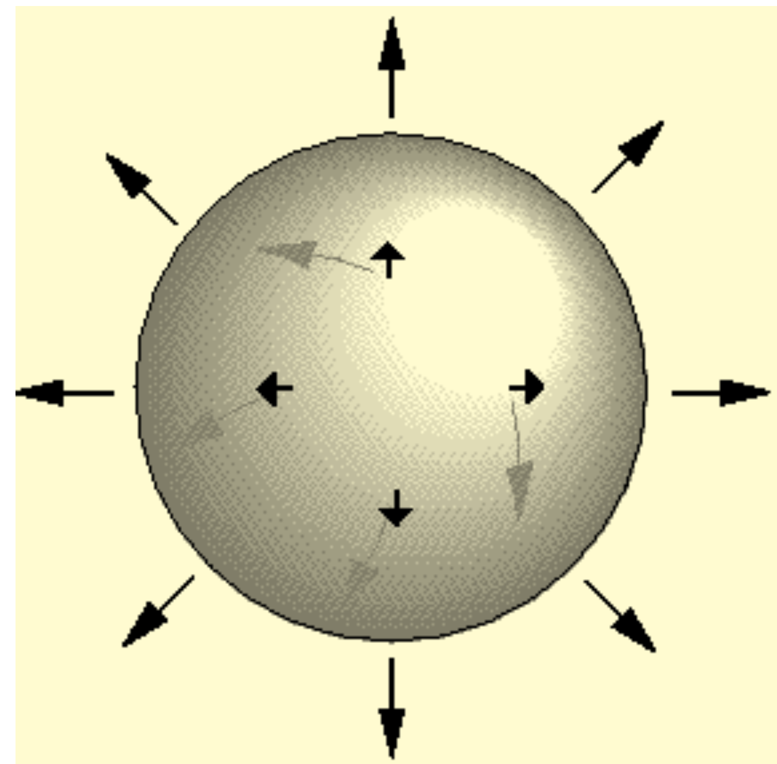
$$\mathcal{L}_{\rm free} = -\frac{1}{4e^2} F^{\mu\nu} F_{\mu\nu} - \frac{\theta}{32\pi^2} F^{\mu\nu} \, {}^*F_{\mu\nu}$$

$$q_{\mathrm{eff},j} = q_j + g_j \frac{\theta}{2\pi}$$

Phys. Lett. B86 (1979) 283

‘t Hooft-Polyakov

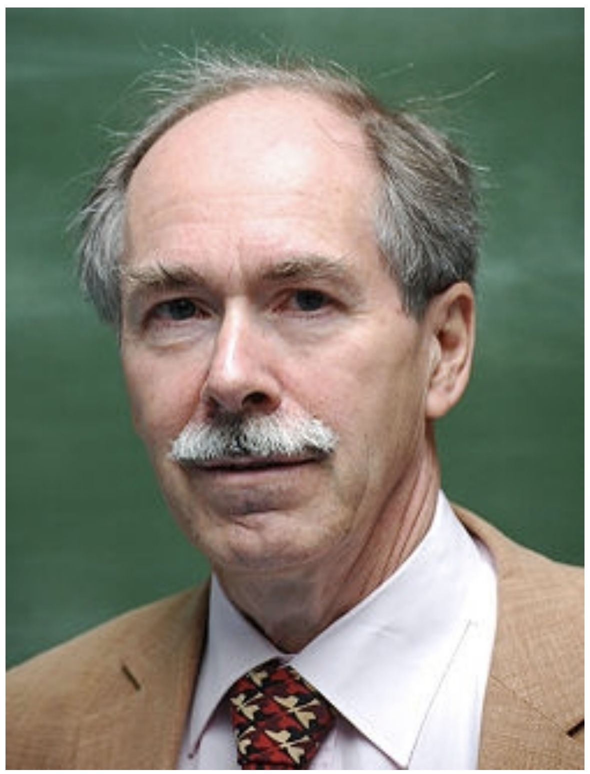




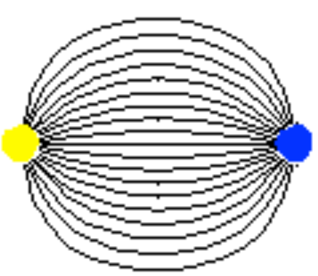
topological monopoles

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

‘t Hooft-Mandelstam

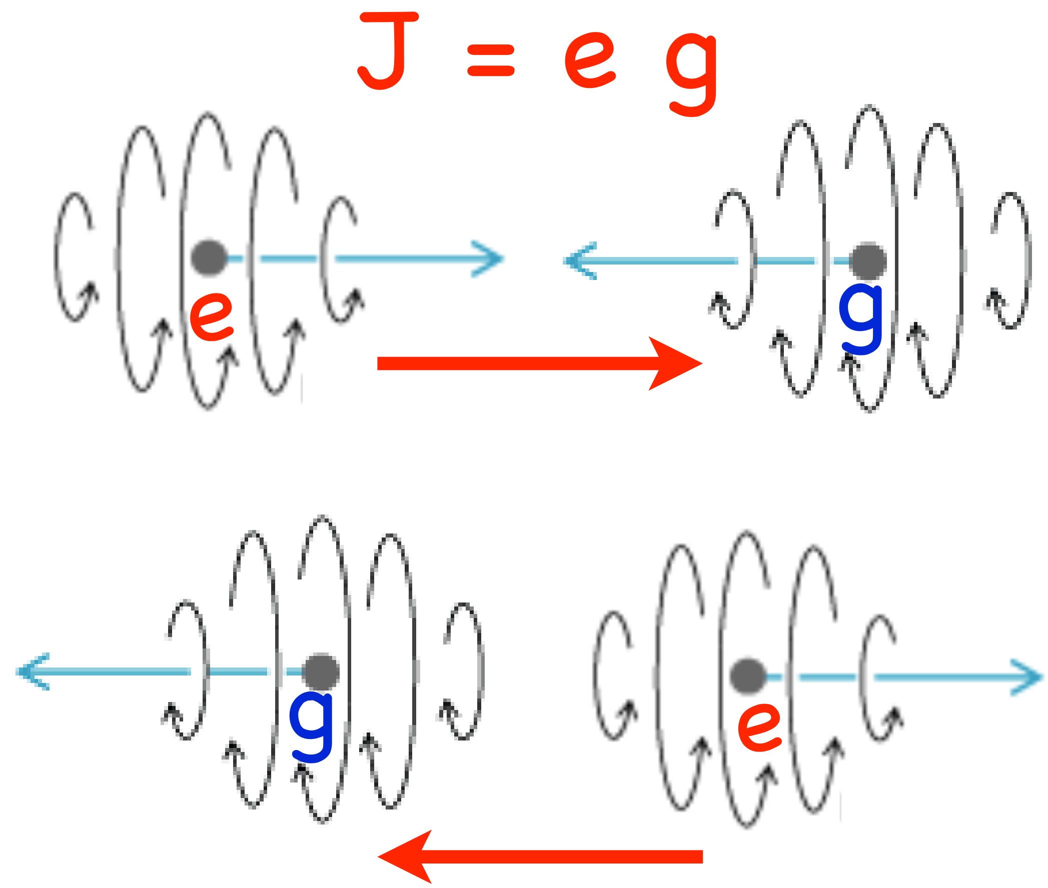


magnetic condensate
confines electric charge



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

Rubakov-Callan



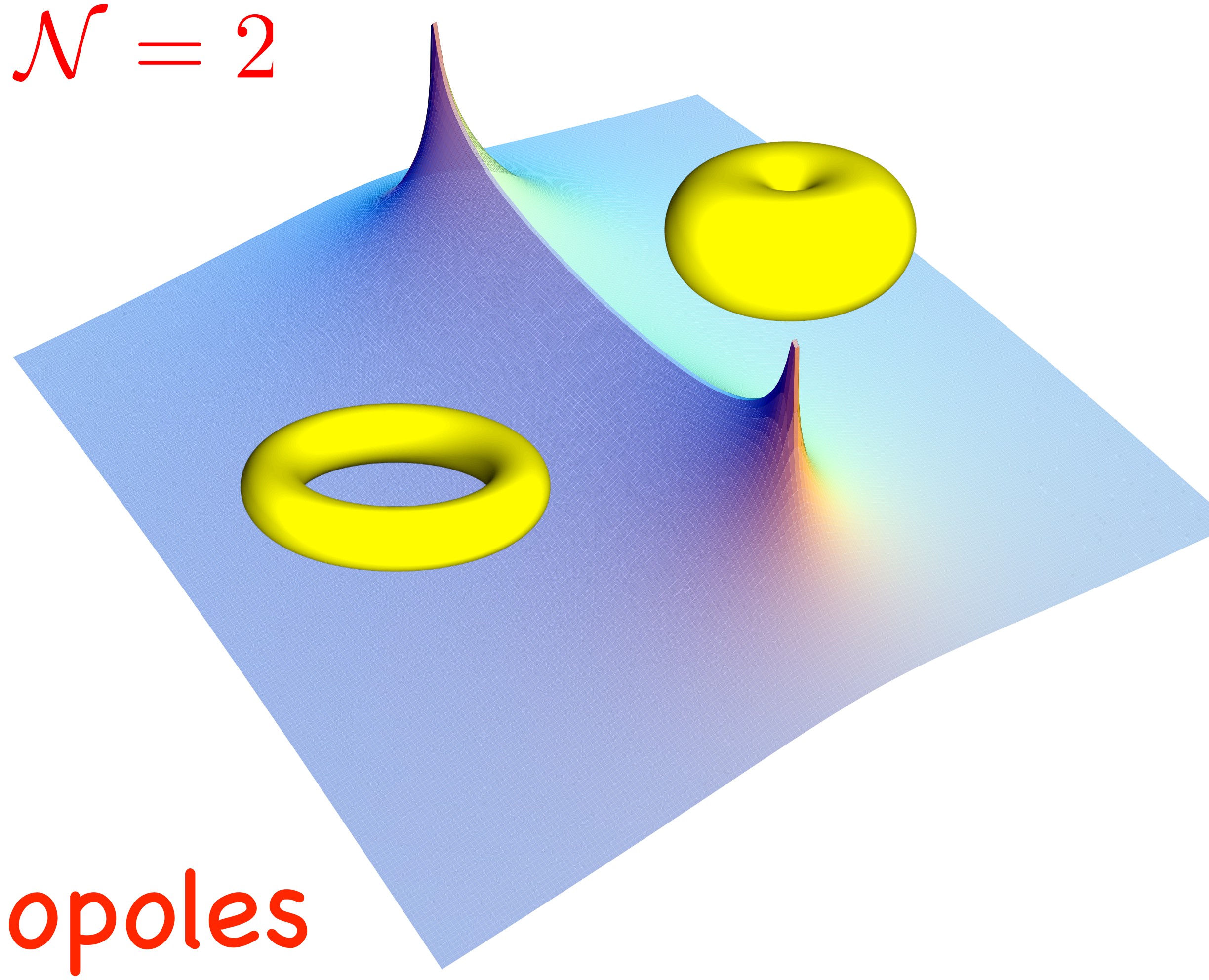
new unsuppressed contact interactions!

JETP Lett. 33 (1981) 644

Phys. Rev. D25 (1982) 2141

Seiberg-Witten

$\mathcal{N} = 2$

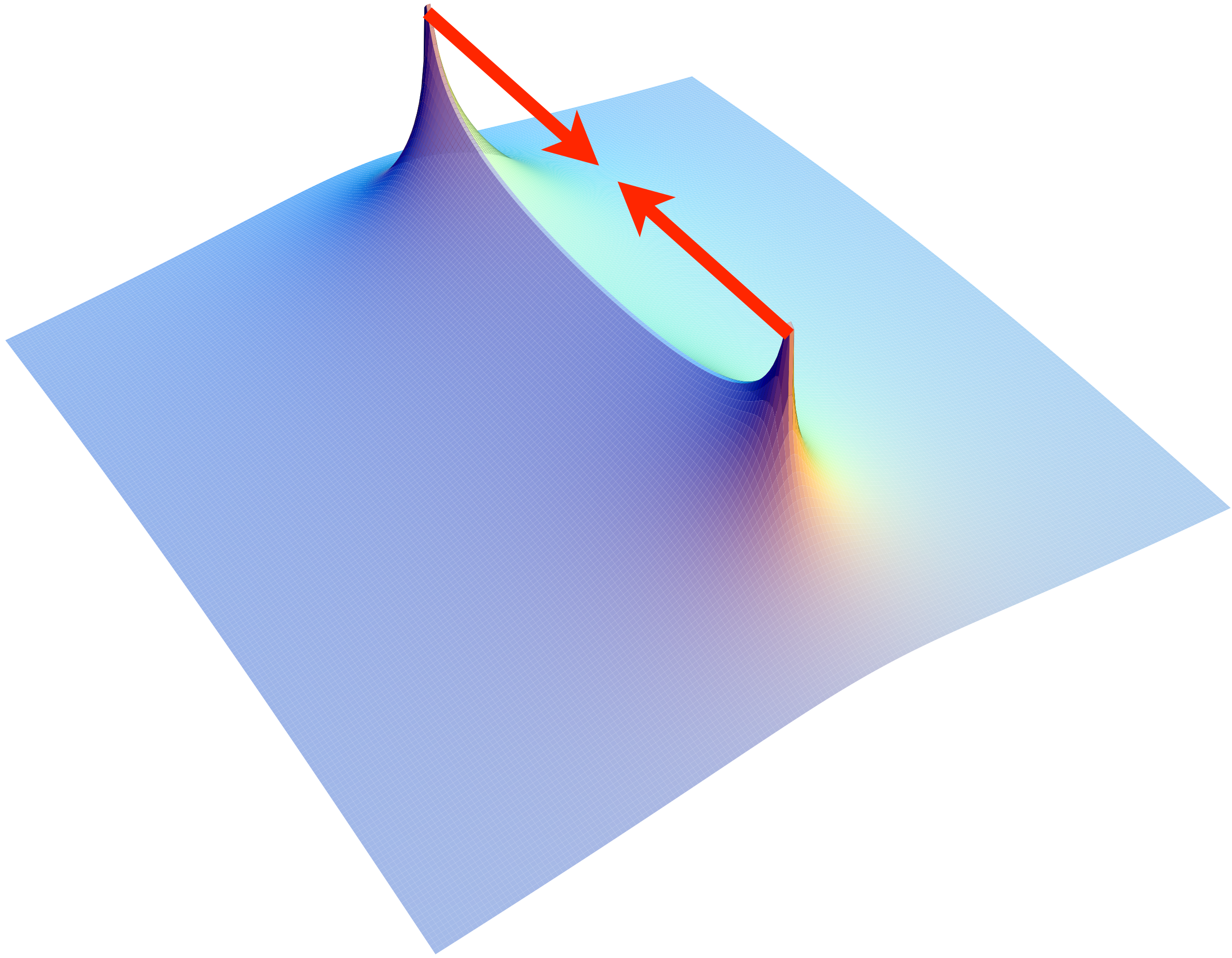


massless fermionic monopoles

hep-th/9407087

Argyres-Douglas





CFT with massless electric and magnetic charges

hep-th/9505062

Toy Model

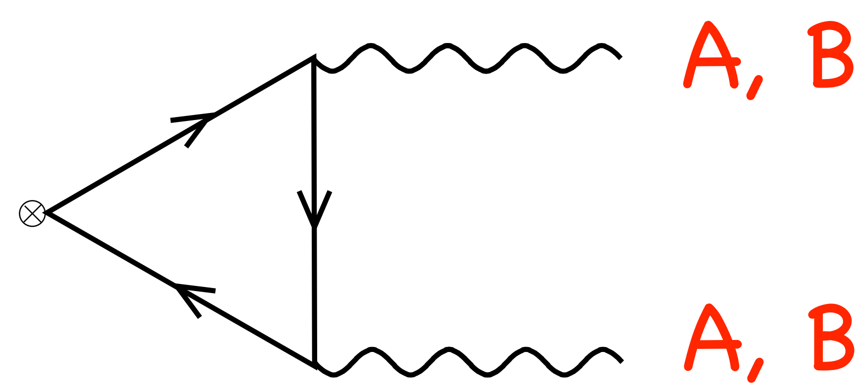
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y : q$	$U(1)_Y : g$
Q	$\Box$	$\Box$	$\frac{1}{6}$	3
L	1	$\Box$	$-\frac{1}{2}$	-9
$\bar{U}$	$\bar{\Box}$	1	$-\frac{2}{3}$	-3
$\bar{D}$	$\bar{\Box}$	1	$\frac{1}{3}$	-3
$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

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

is this anomaly free?

Anomalies

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



Toy Model

	$SU(3)_c$	$SU(2)_L$	$U(1)_Y : q$	$U(1)_Y : g$
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$\bar{D}$	$\bar{\square}$	1	$\frac{1}{3}$	-3
$\bar{N}$	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

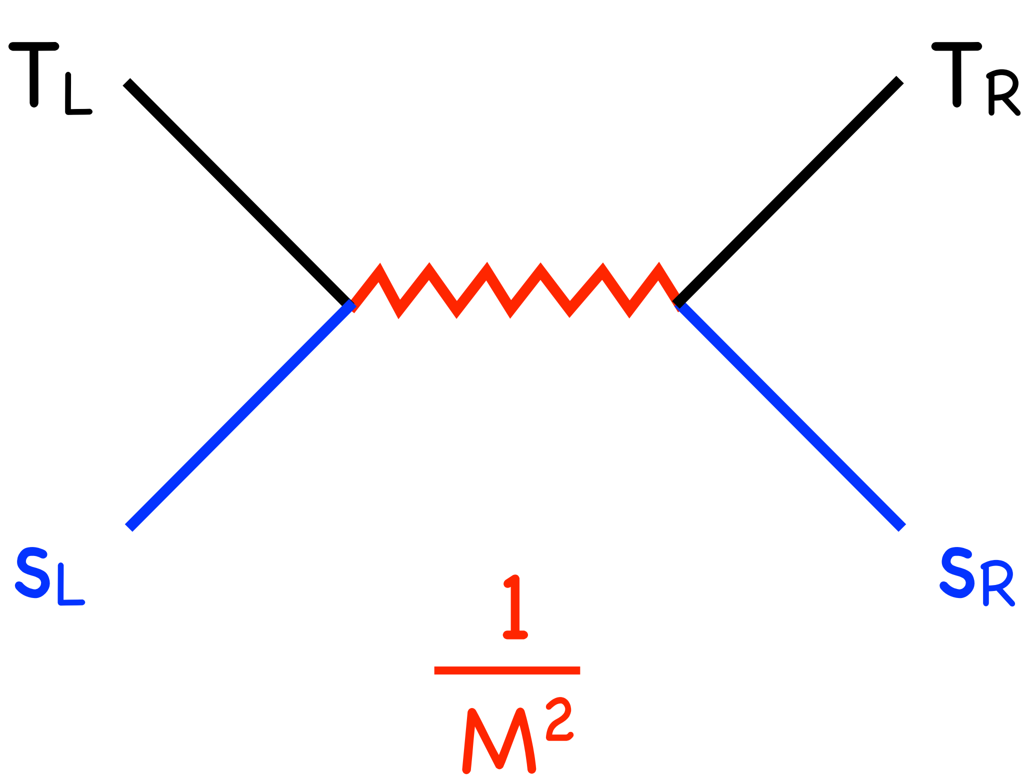
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y : q$	$U(1)_Y : g$
Q	$\square$	$\square$	$\frac{1}{6}$	3
L	1	$\square$	$-\frac{1}{2}$	-9
$\bar{U}$	$\bar{\square}$	1	$-\frac{2}{3}$	-3
$\bar{D}$	$\bar{\square}$	1	$\frac{1}{3}$	-3
$\bar{N}$	1	1	0	9
$\bar{E}$	1	1	1	9

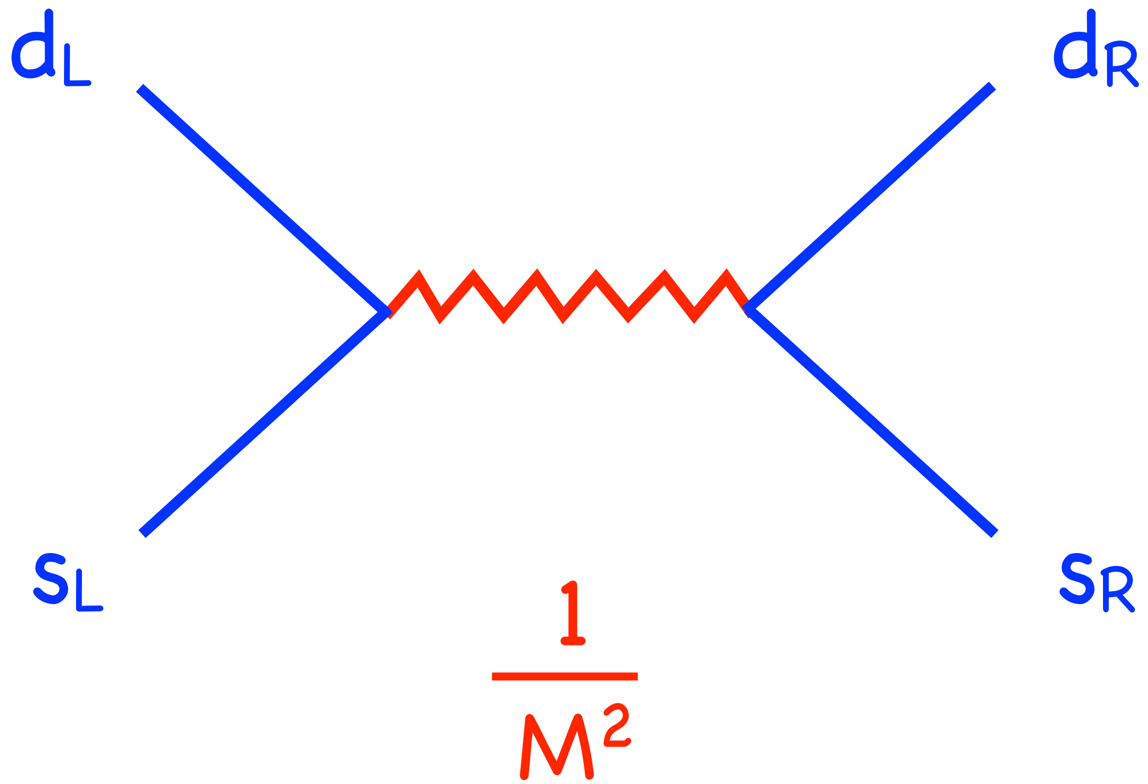
$$\left(\frac{1}{6}\right)^2 \alpha_Y 3^2 \alpha_m = \frac{1}{4}$$

$$\alpha_m \sim 98$$

Quark Masses

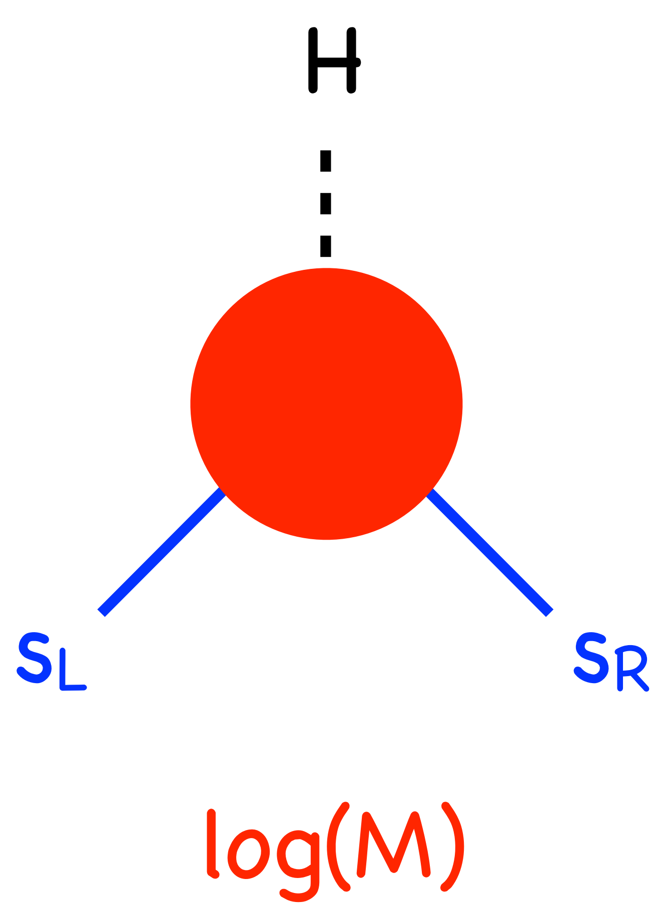
technicolor: fail

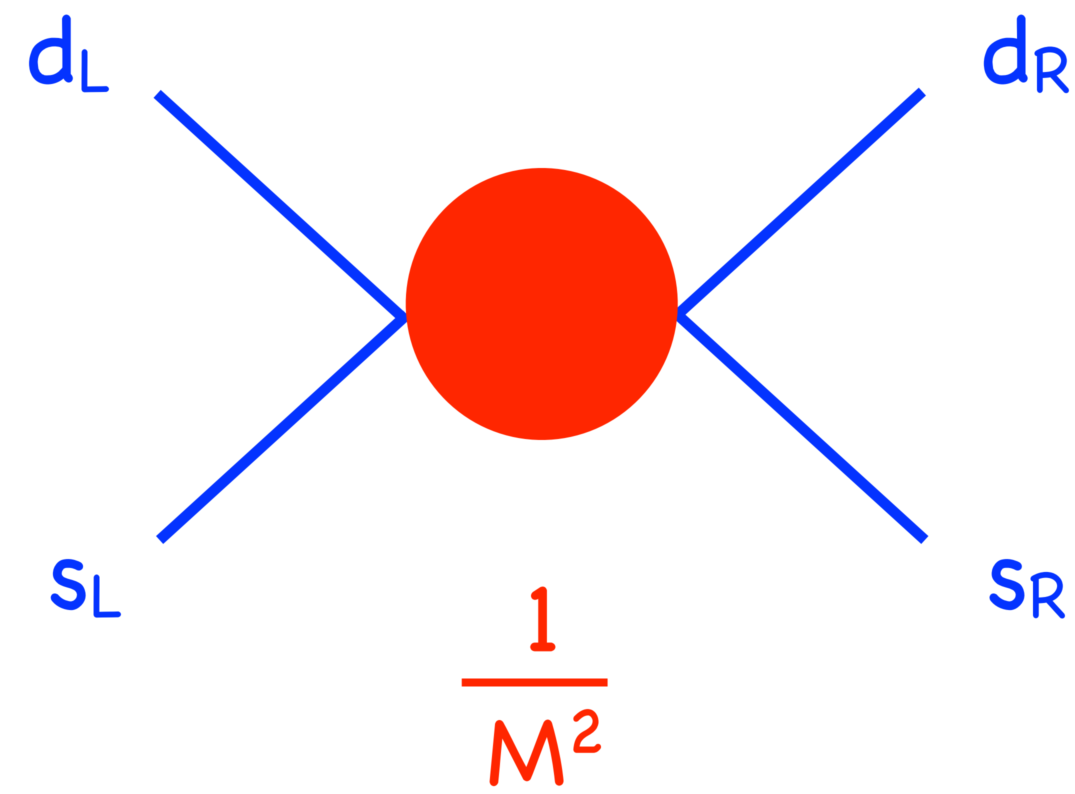




Quark Masses

Standard Model

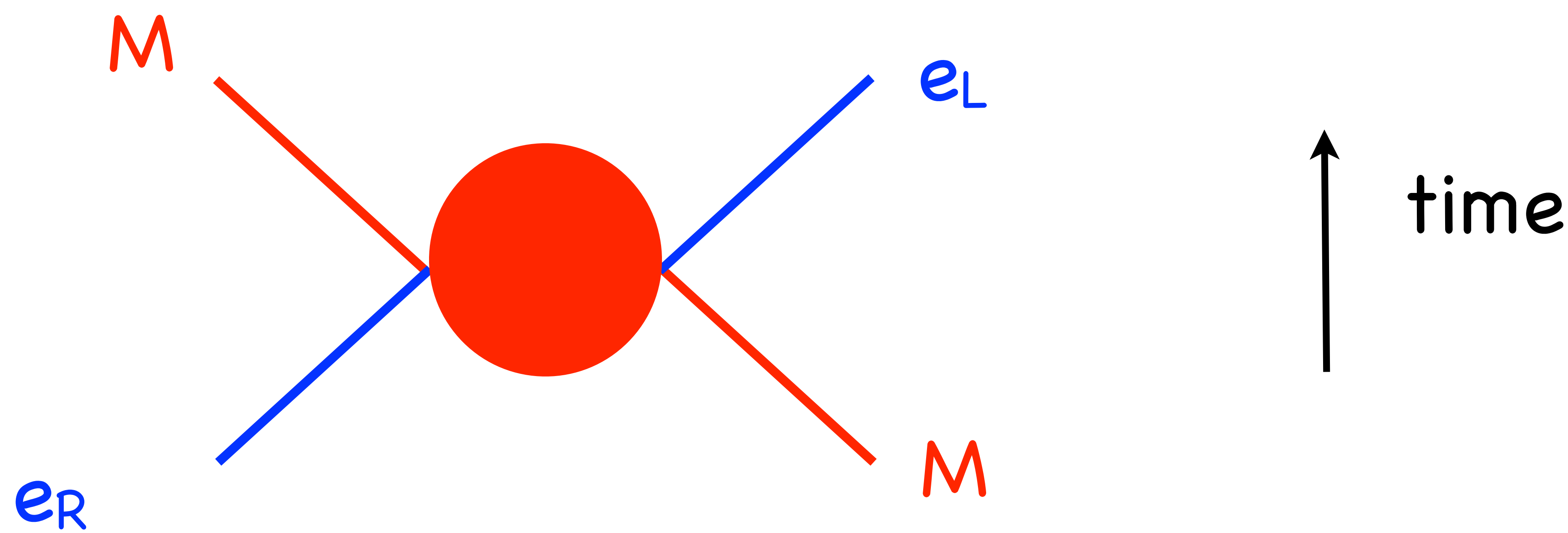




Callan-Rubakov

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

$S_f = -1/2$



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

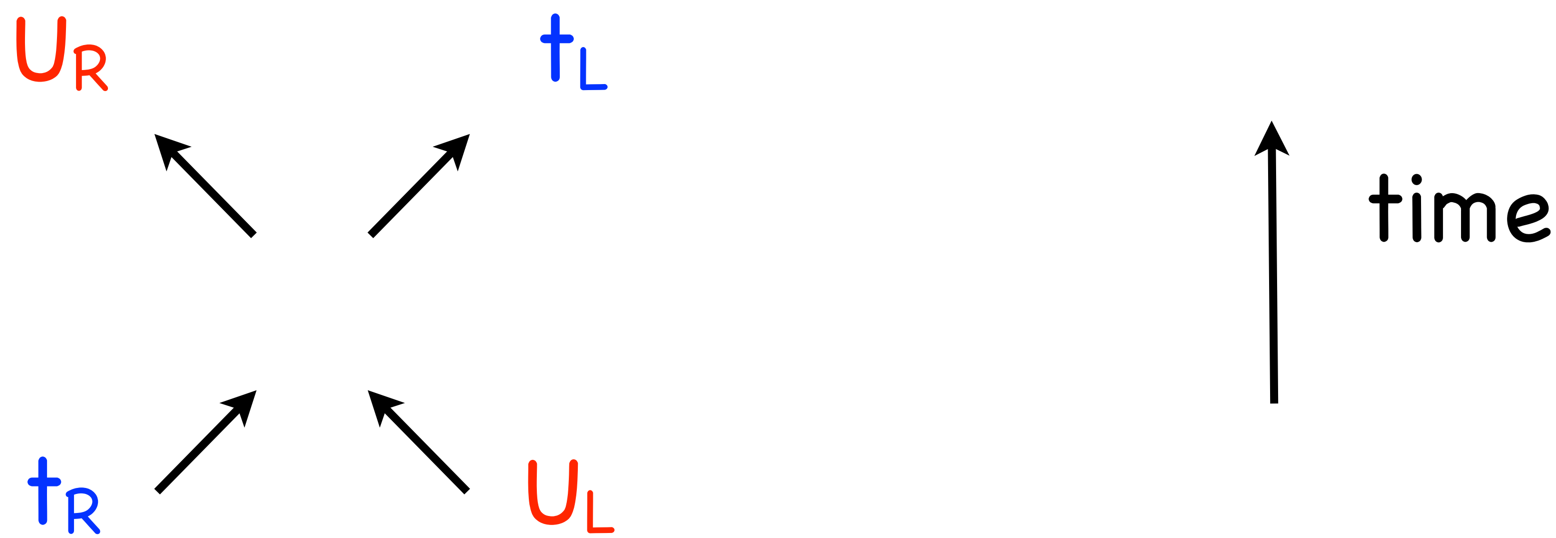
$S_i = 1/2$

New dimension 4, four particle operator

Four Fermion Ops

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

$S_f = -1$



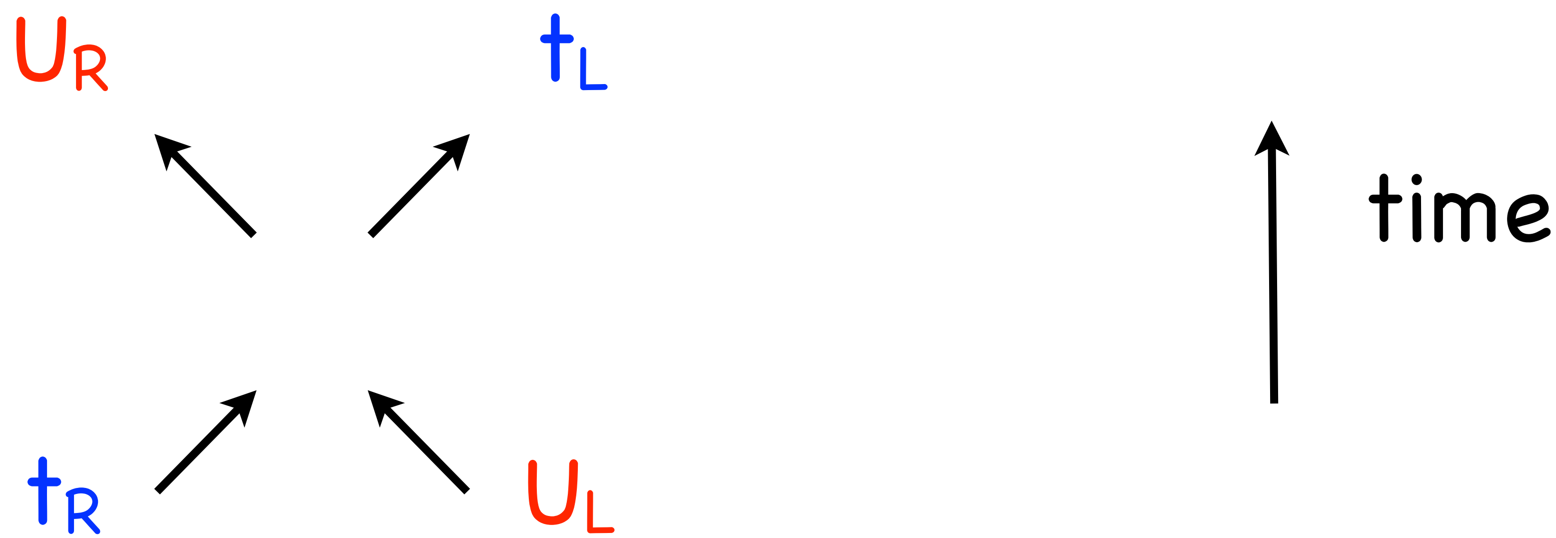
$J_i = q\ g = 2$

$S_i = 1$

Four Fermion Ops

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

$S_f = -1$



$J_i = q\ g = 2$

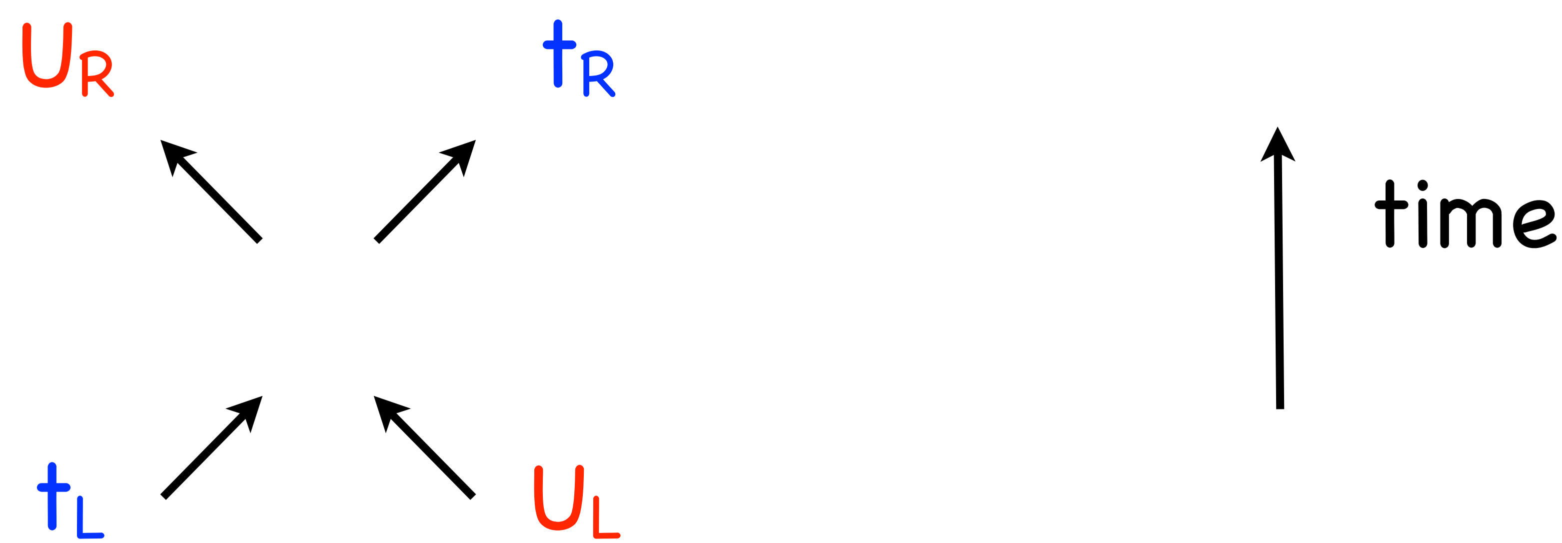
$S_i = 1$

fail!

Four Fermion Ops

$J_f = -q\ g = -2$

$S_f = 0$



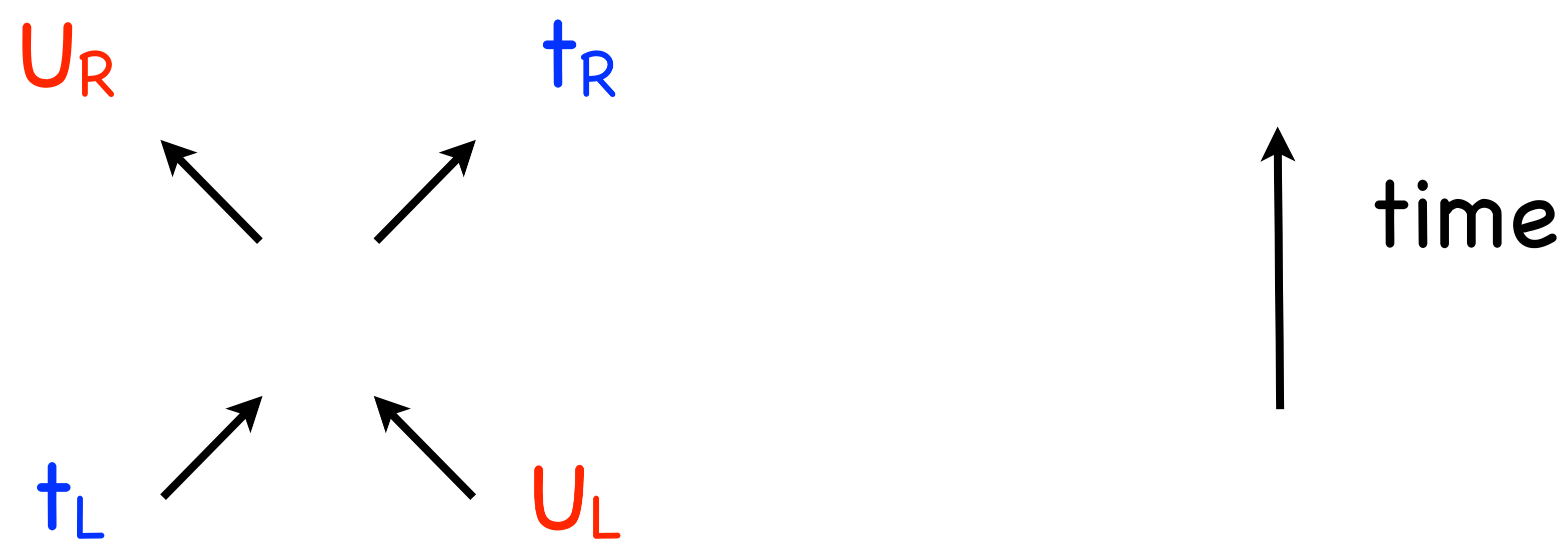
$J_i = q\ g = 1/2$

$S_i = 0$

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

$$
\begin{aligned}
\vec{B}^a_Y &= \frac{g}{g_Y}\,\frac{\hat{r}}{r^2} \\
\vec{B}^a_L &= \delta^{a3}_L\,\frac{g\,\beta_L}{g_L}\,\frac{\hat{r}}{r^2} \\
\vec{B}^a_c &= \delta^{a8}_c\,\frac{g\,\beta_c}{g_c}\,\frac{\hat{r}}{r^2}
\end{aligned}
$$

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

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

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

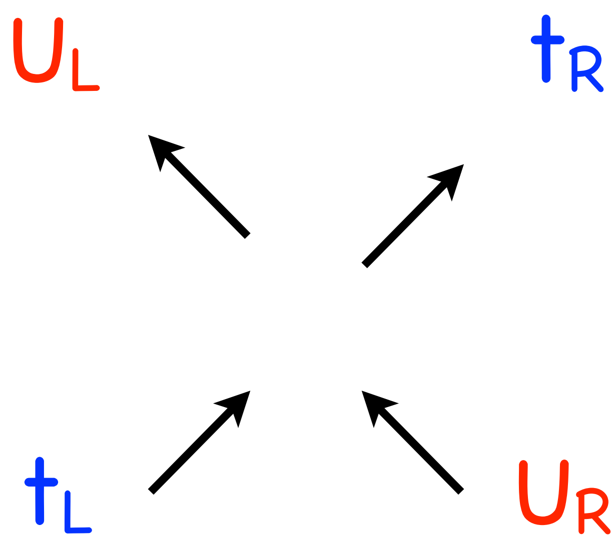
	$SU(3)_c$	$SU(2)_L$	$U(1)_Y^{el}$	$U(1)_Y^{mag}$
Q_L	$\square^m$	$\square^m$	$\frac{1}{6}$	$\frac{1}{2}$
L_L	1	$\square^m$	$-\frac{1}{2}$	$-\frac{3}{2}$
U_R	$\square^m$	1^m	$\frac{2}{3}$	$\frac{1}{2}$
D_R	$\square^m$	1^m	$-\frac{1}{3}$	$\frac{1}{2}$
N_R	1	1^m	0	$-\frac{3}{2}$
E_R	1	1^m	-1	$-\frac{3}{2}$

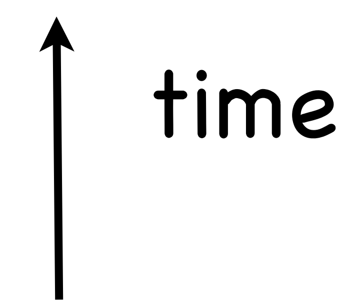
$$\alpha_m = \frac{1}{4\alpha} \approx 32$$

Four Fermion Ops

$$J_f = -\left(\frac{1}{3}\cdot 1 + \frac{2}{3}\cdot 1\right)$$

$$S_f = +1$$





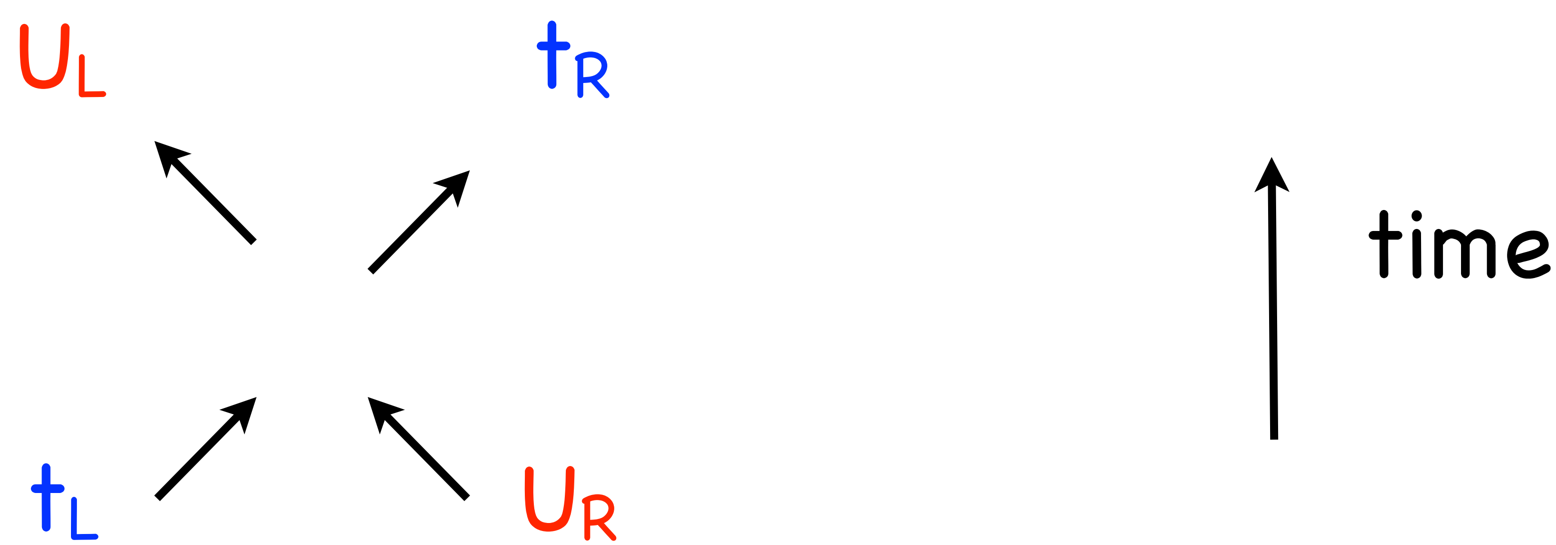
$$J_i = \frac{1}{3} + \left(\frac{1}{2} + \frac{1}{6}\right)\cdot 1$$

$$S_i = -1$$

Four Fermion Ops

$$J_f = -\left(\frac{1}{3}\cdot 1 + \frac{2}{3}\cdot 1\right)$$

$$S_f = +1$$

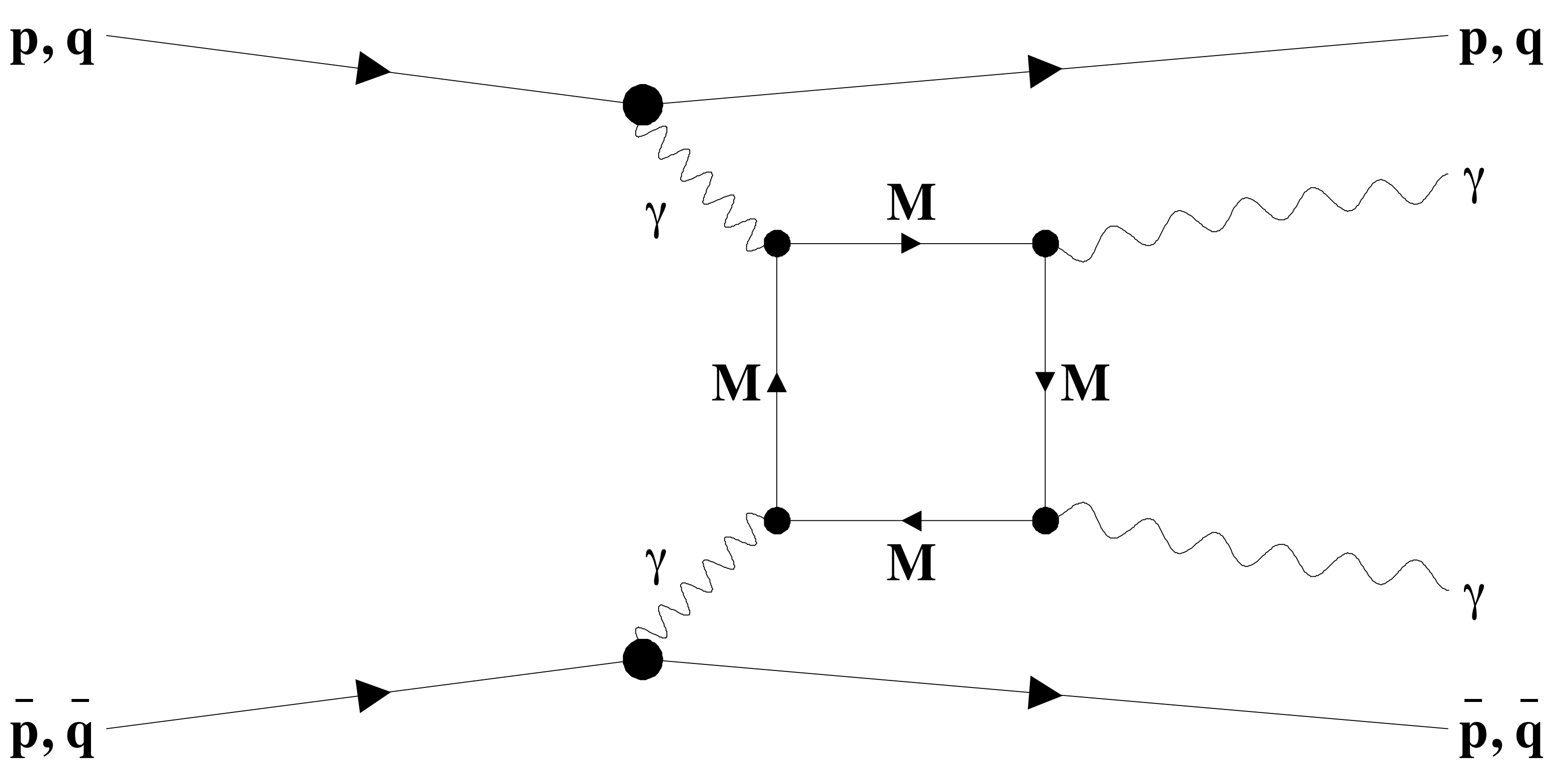


$$J_i = \frac{1}{3} + \left(\frac{1}{2} + \frac{1}{6}\right)\cdot 1$$

$$S_i = -1$$

hooray!

Phenomenology

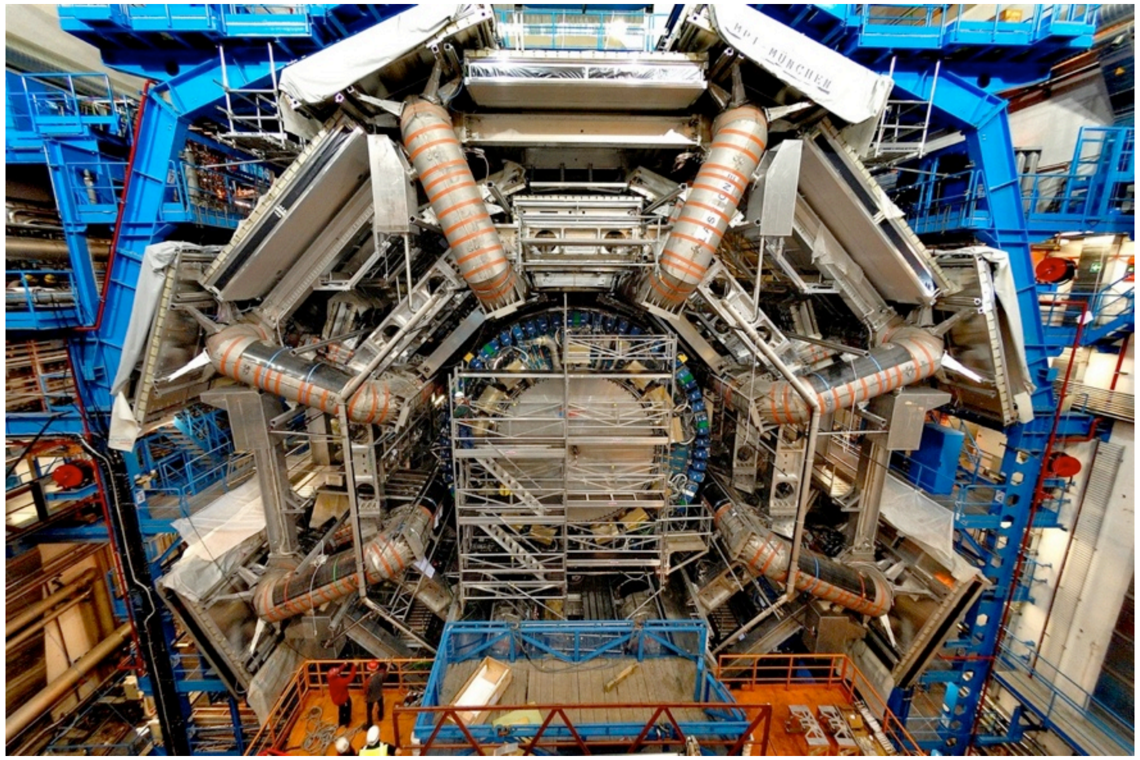


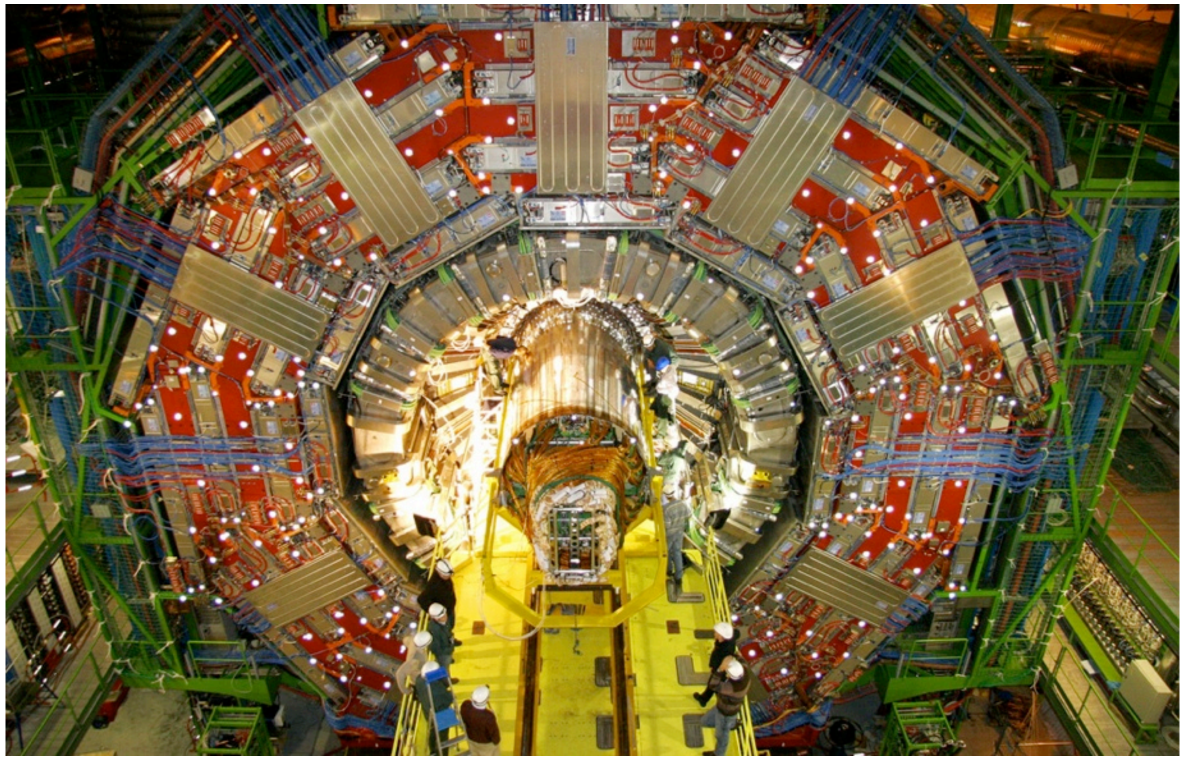
uncontrolled perturbation theory

Ginzburg, Schiller hep-th/9802310

LHC

naively expect pair production,
unconfined, highly ionizing



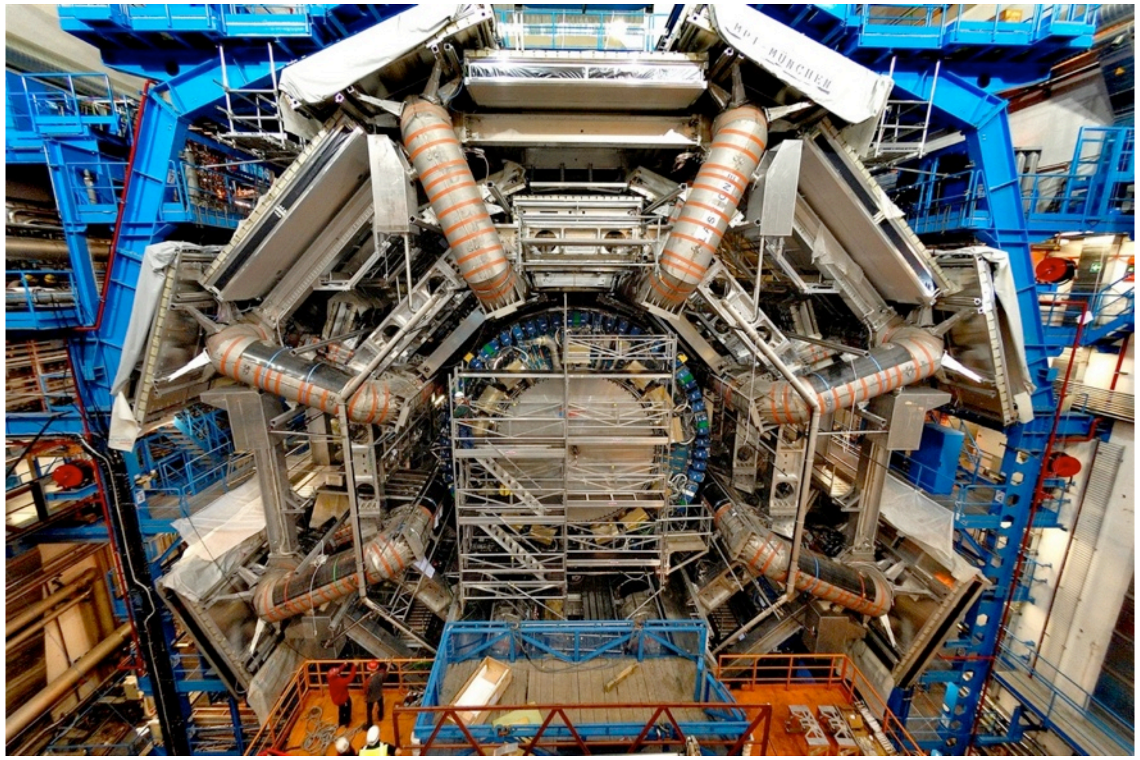


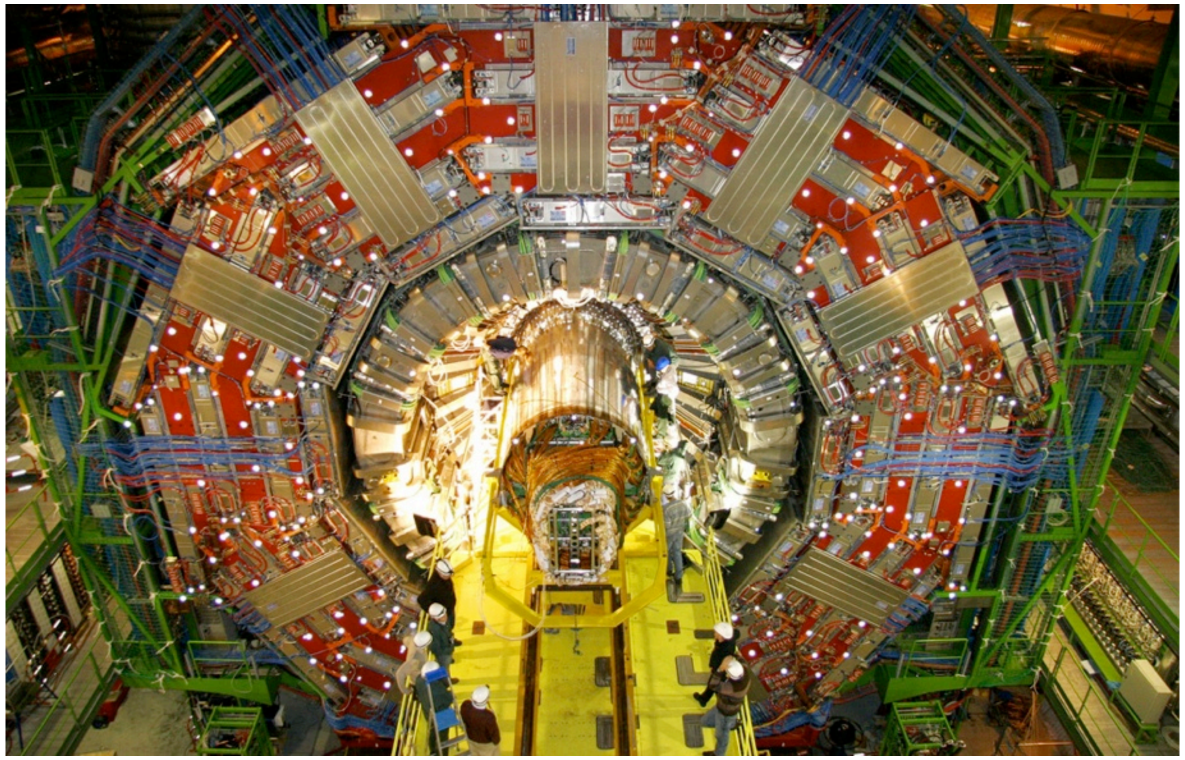
ATLAS has a trigger for monopoles

CMS does not

LHC

naively expect pair production,
unconfined, highly ionizing



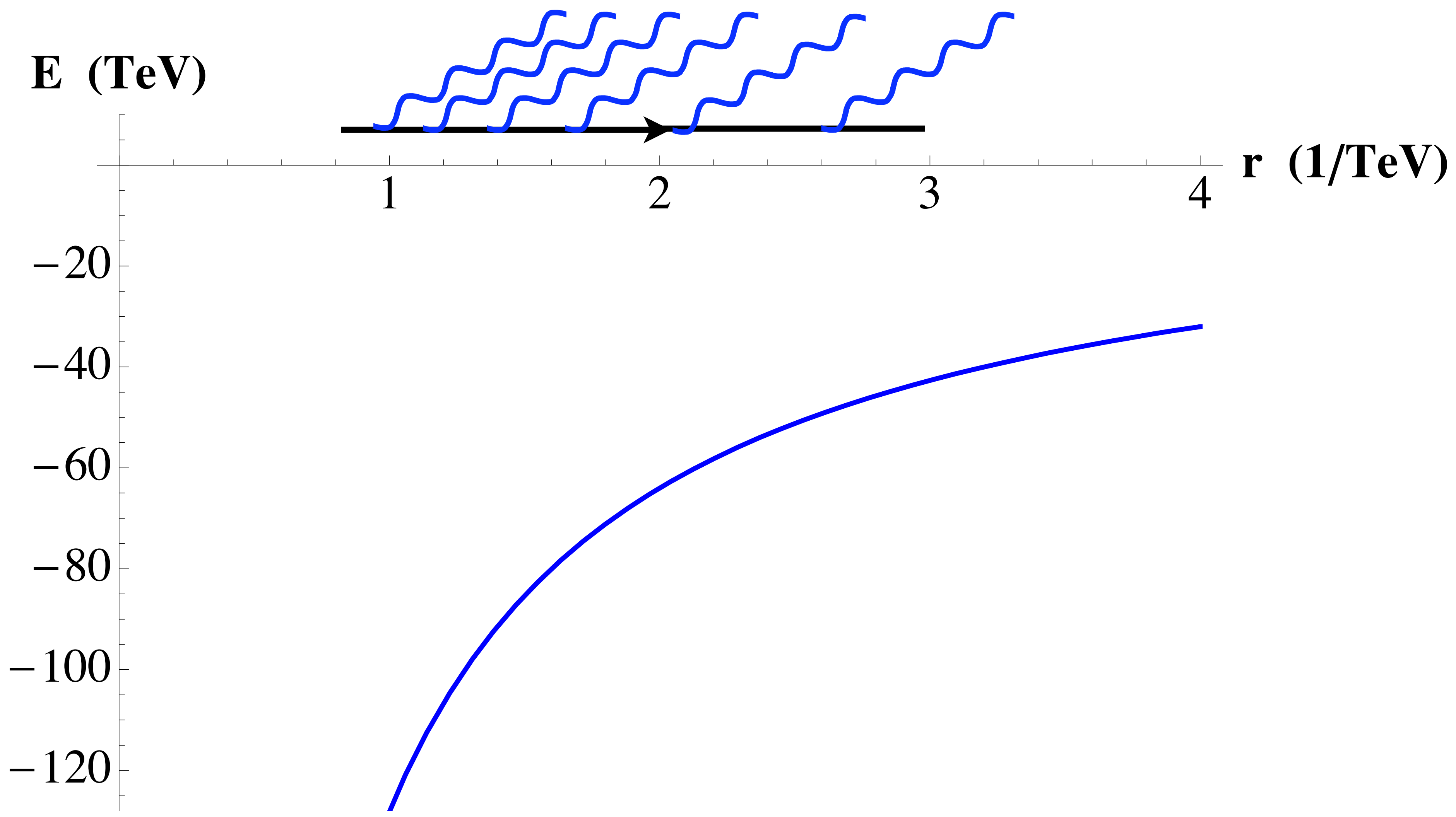


ATLAS has a trigger for monopoles

CMS does not

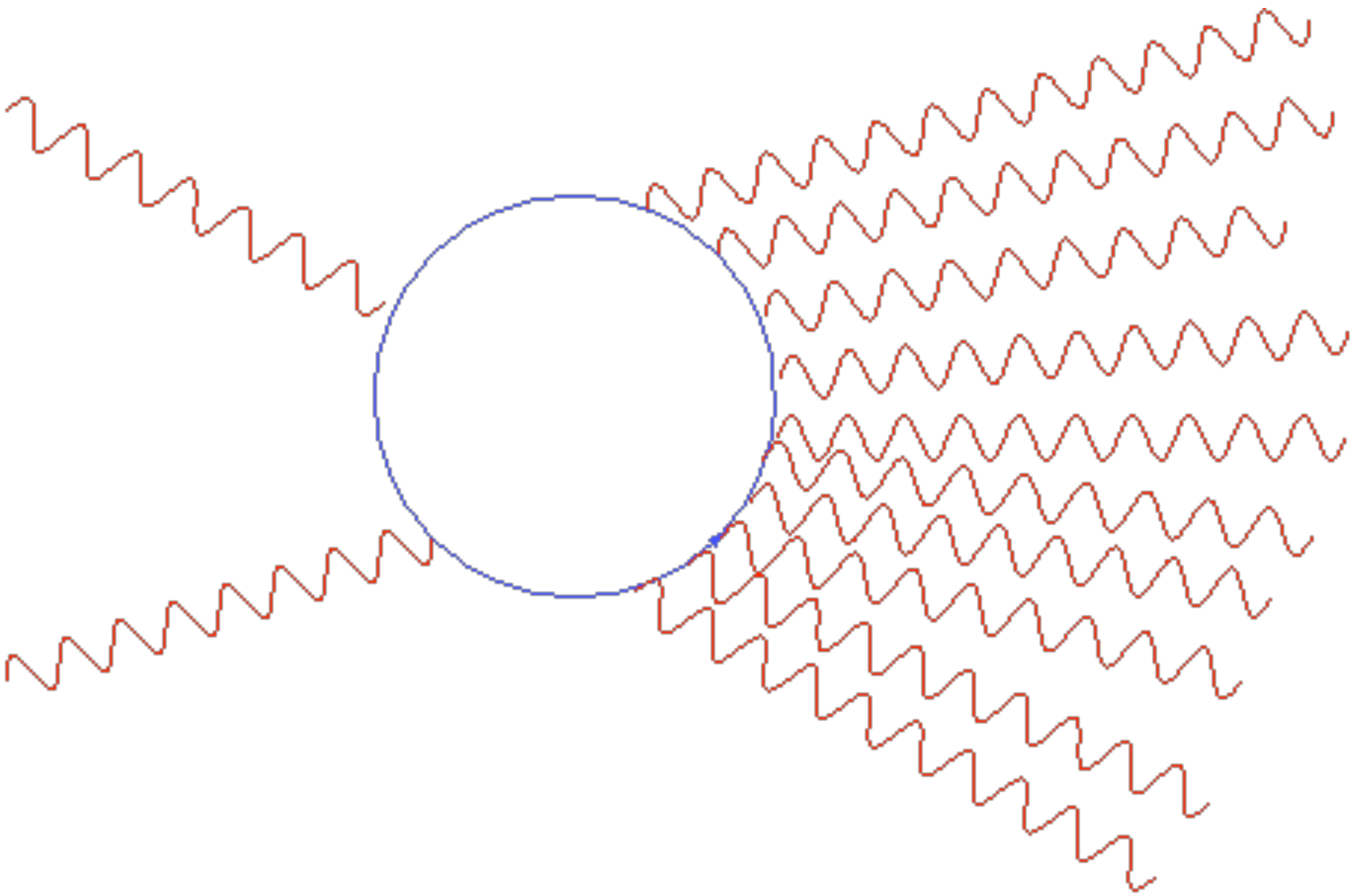
but it won't work

Bremstrahlung



Andersen, Grojean, Weiler, JT

Annihilation



Heisenberg and Euler,

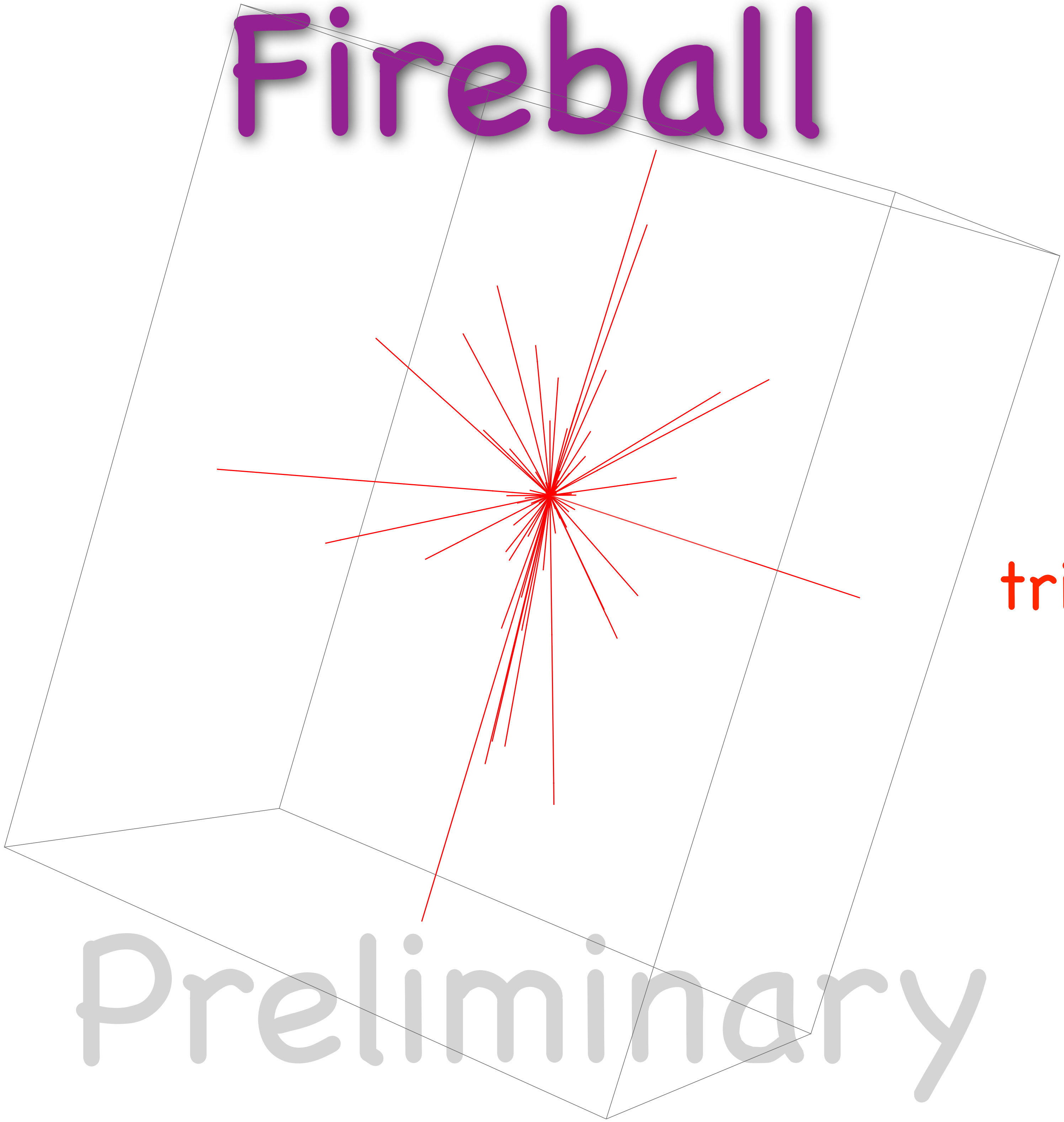
Z. Phys. **98**, 714 (1936) arXiv:physics/0605038

Fireball

Preliminary

Andersen, Grojean, Weiler, JT

Fireball



CMS has a trigger for this

Preliminary

Andersen, Grojean, Weiler, JT

Conclusions

Monopoles are still fascinating
after all these years

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

monopole phenomenolgy is pushing
at the boundaries of MC4BSM

CP

$$e_\alpha \rightarrow \sigma^2_{\alpha\dot{\alpha}} e^{\dagger\dot{\alpha}}$$

$$\begin{aligned} (q, g) &\rightarrow (-q, g) \\ (q, -g) &\rightarrow (-q, -g) \end{aligned}$$

$$\mathcal{L}_{\rm int} = -\chi^\dagger\,(q\,A_\mu + \tilde{g}\,B_\mu)\,\bar{\sigma}^\mu \chi - \psi^\dagger\,(q\,A_\mu - \tilde{g}\,B_\mu)\,\bar{\sigma}^\mu \psi$$

non-Abelian magnetic charge

$$(SU(2)_L \times U(1)_Y)/Z_2$$

$$Q = T^3 + Y$$

$$Y \text{ integer}$$

$$\begin{aligned} e^{2\pi i Q} &= e^{2\pi i T^3} e^{2\pi i Y} \\ &= \mathrm{diag}(e^{i\frac{1}{2}2\pi}, e^{-i\frac{1}{2}2\pi}) \\ &= Z \end{aligned}$$

Z element of center of $SU(2)$