The Standard Model and the LHC

John Terning

Outline

- E&M, Relativity, Quantum Mechanics
- Gauge Interactions
- Strong Interactions
- Weak Interactions
- The Standard Model and the LHC

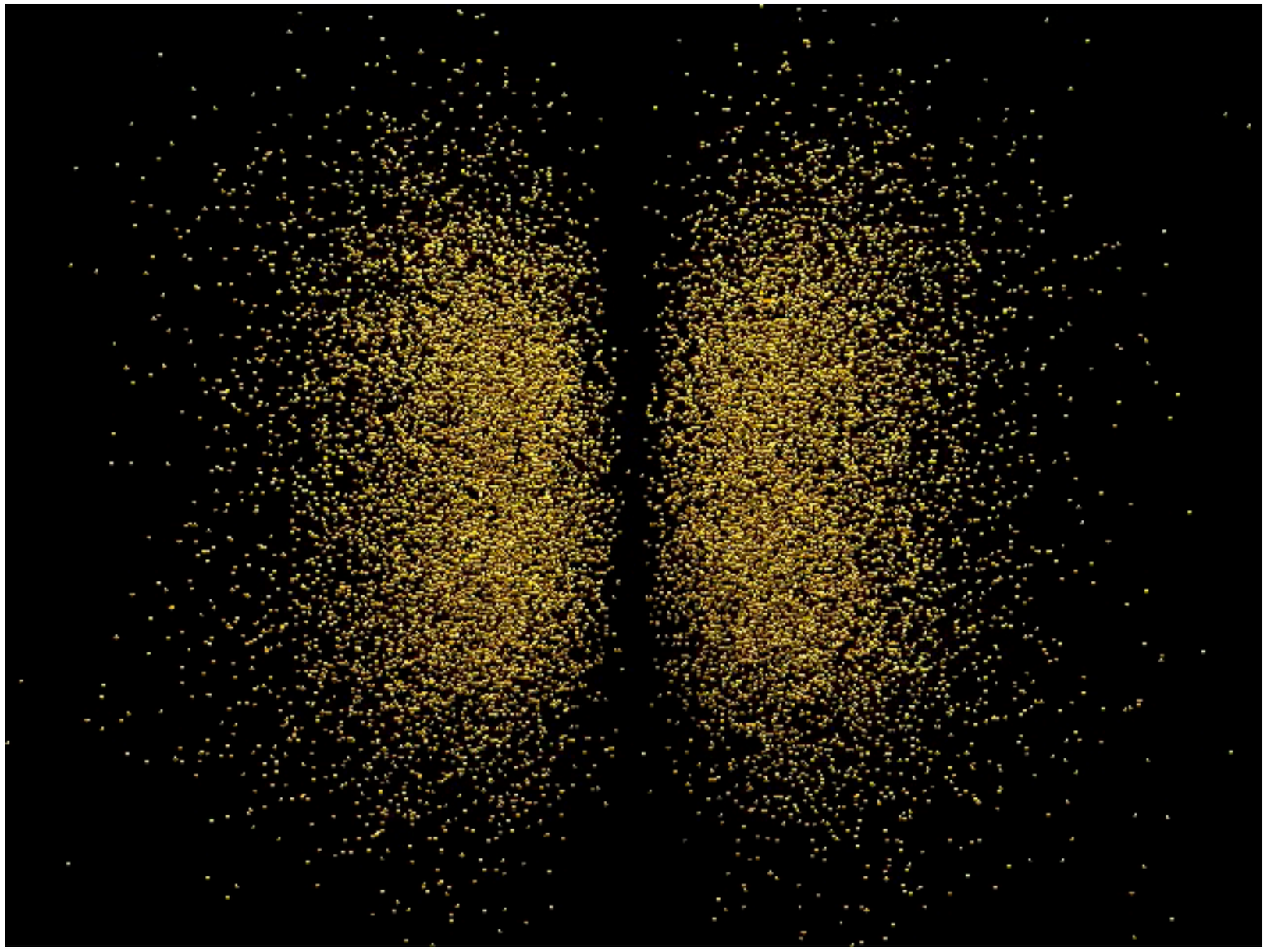
Motivation

Is there a new layer of reality at smaller scales?

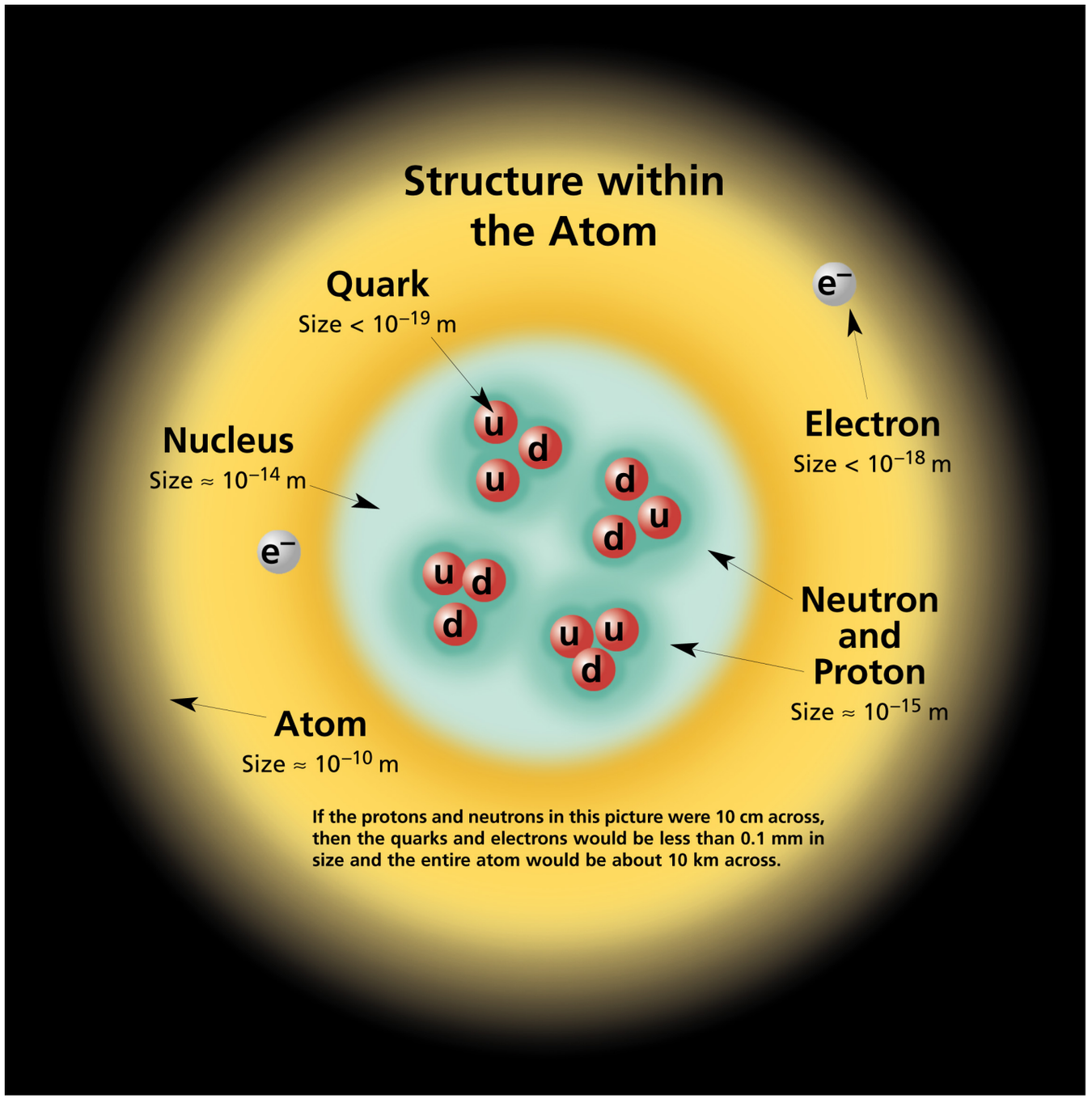
Why do some particles have a mass?

If there is something there how do we look for it?

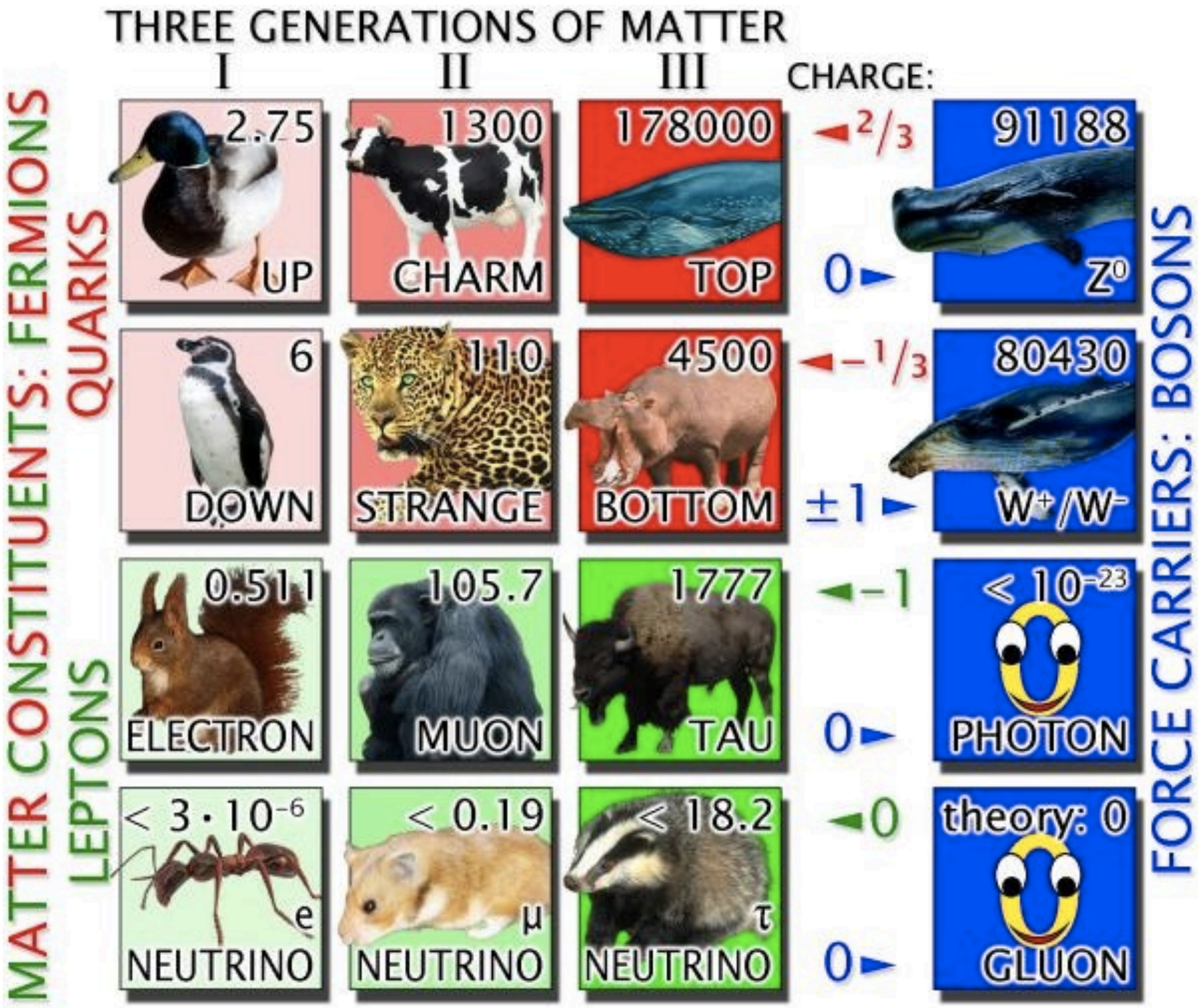
Atoms



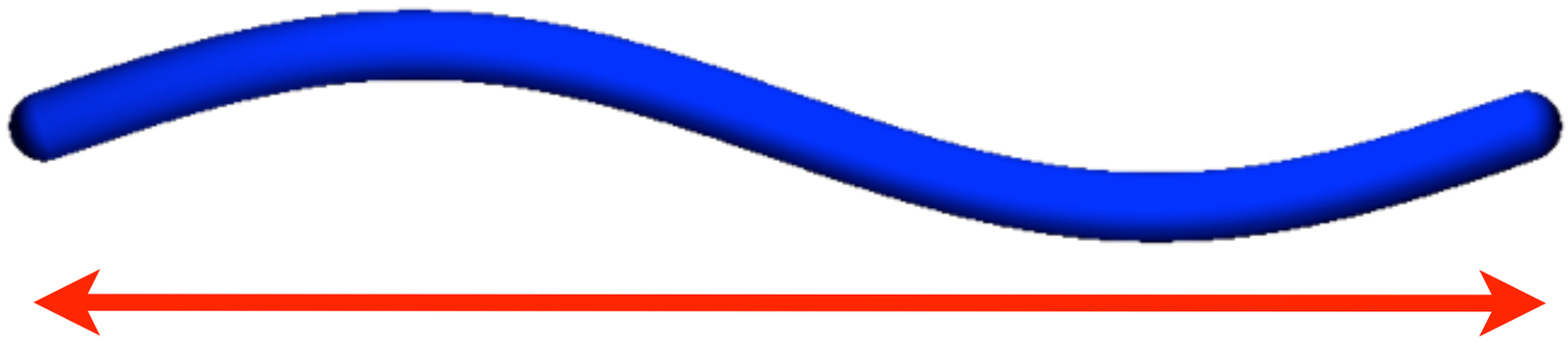
Inside Atoms



Standard Model

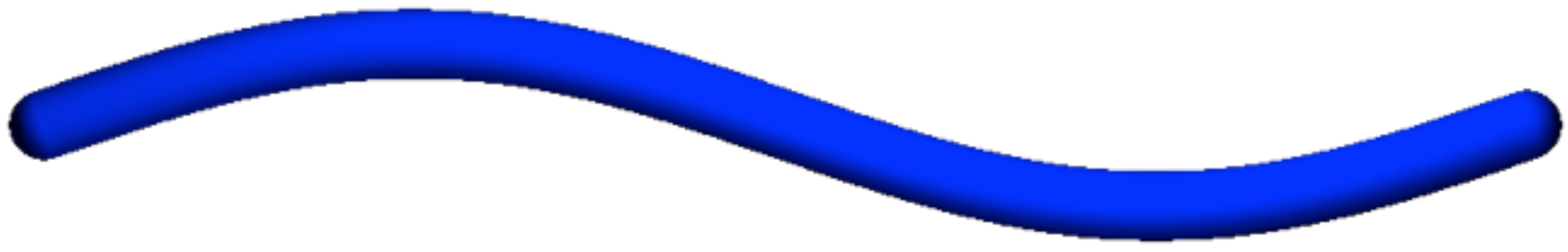


Waves



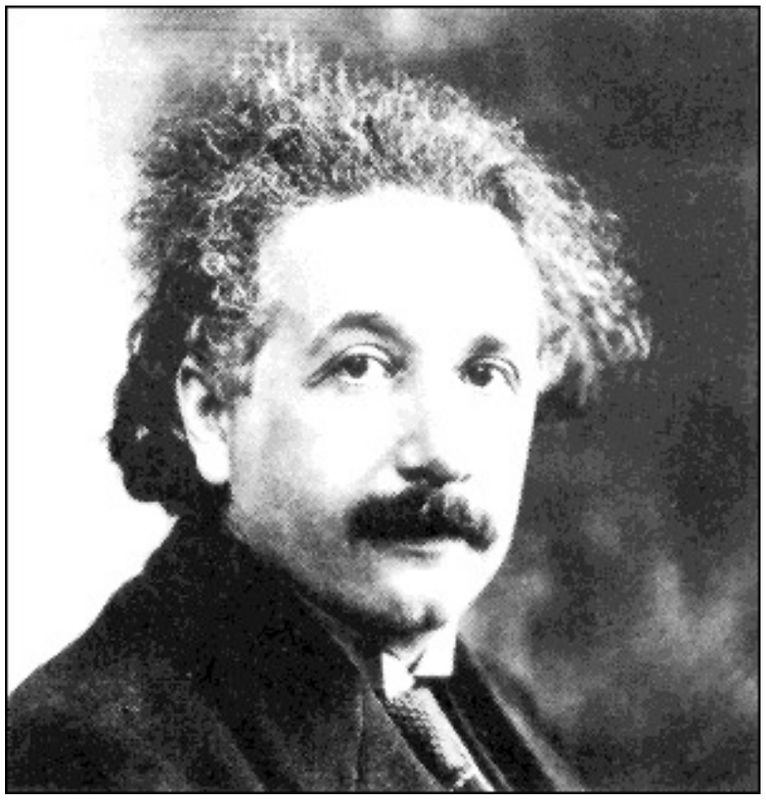
wavelength

Waves



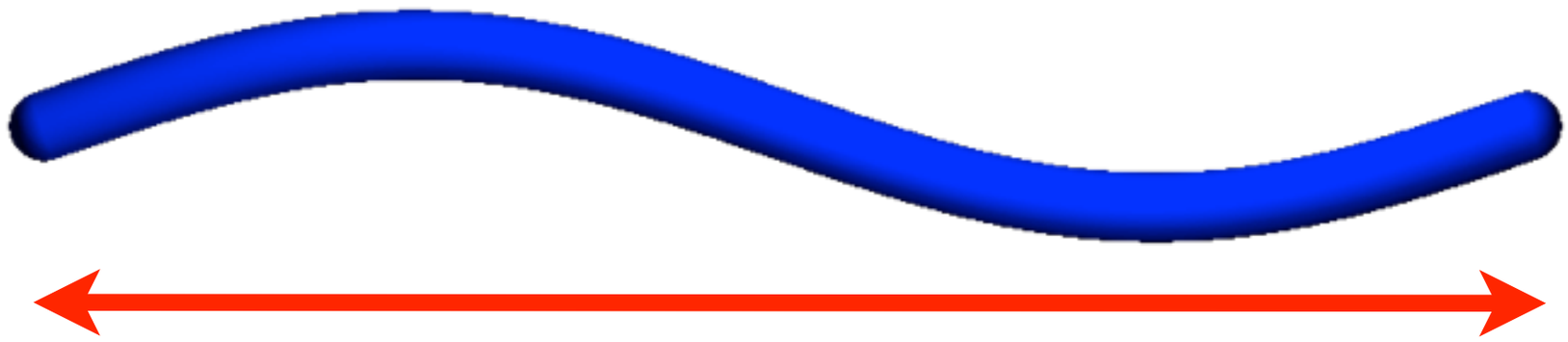
$$\text{frequency} = \frac{\text{speed}}{\text{wavelength}}$$

Light Waves



$$\text{Energy} \sim \text{frequency} \sim \frac{1}{\text{wavelength}}$$

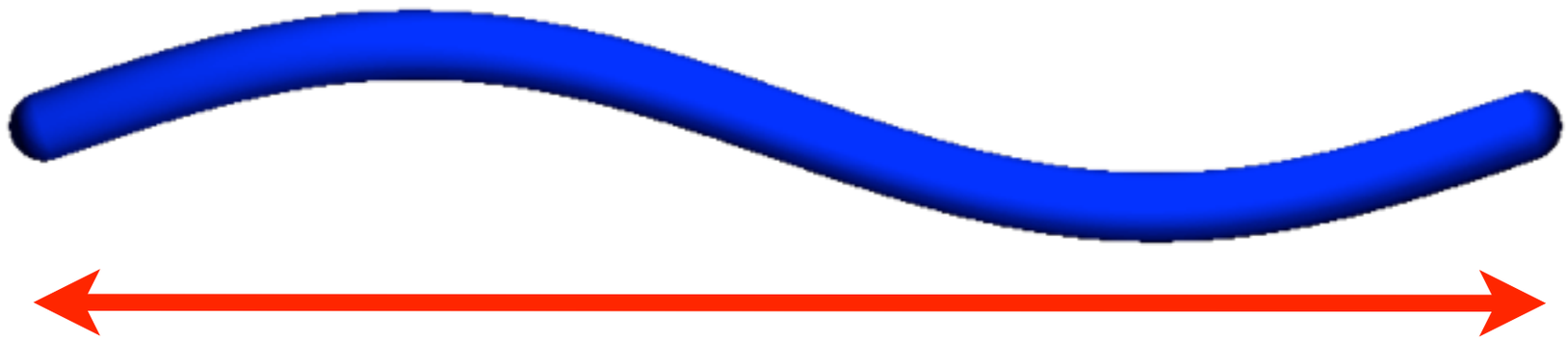
WiFi



wavelength = 5 in

$$\text{Energy} = \frac{1 \text{ eV}}{100{,}000}$$

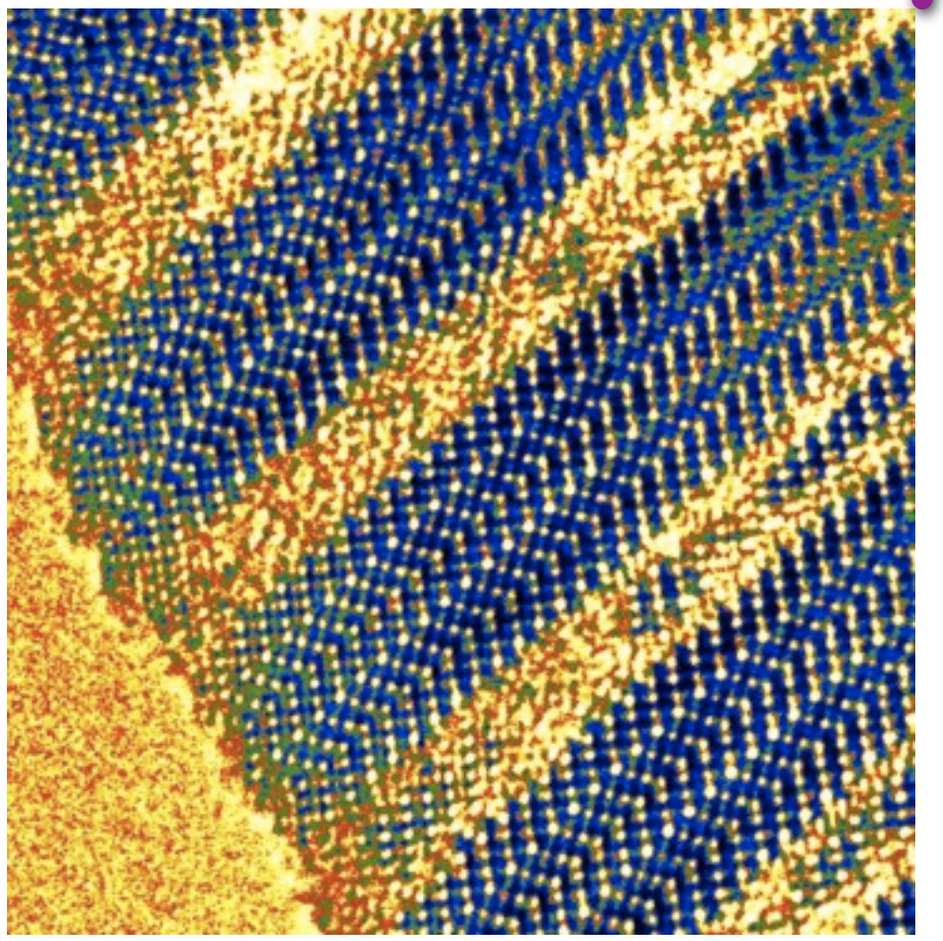
UV



wavelength = $\frac{1 \text{ in}}{100{,}000}$

Energy = 5 eV

Electron Microscope



$$\text{wavelength} = \frac{1 \text{ in}}{100{,}000{,}000}$$

$$\text{Energy} = 5000 \text{ eV}$$

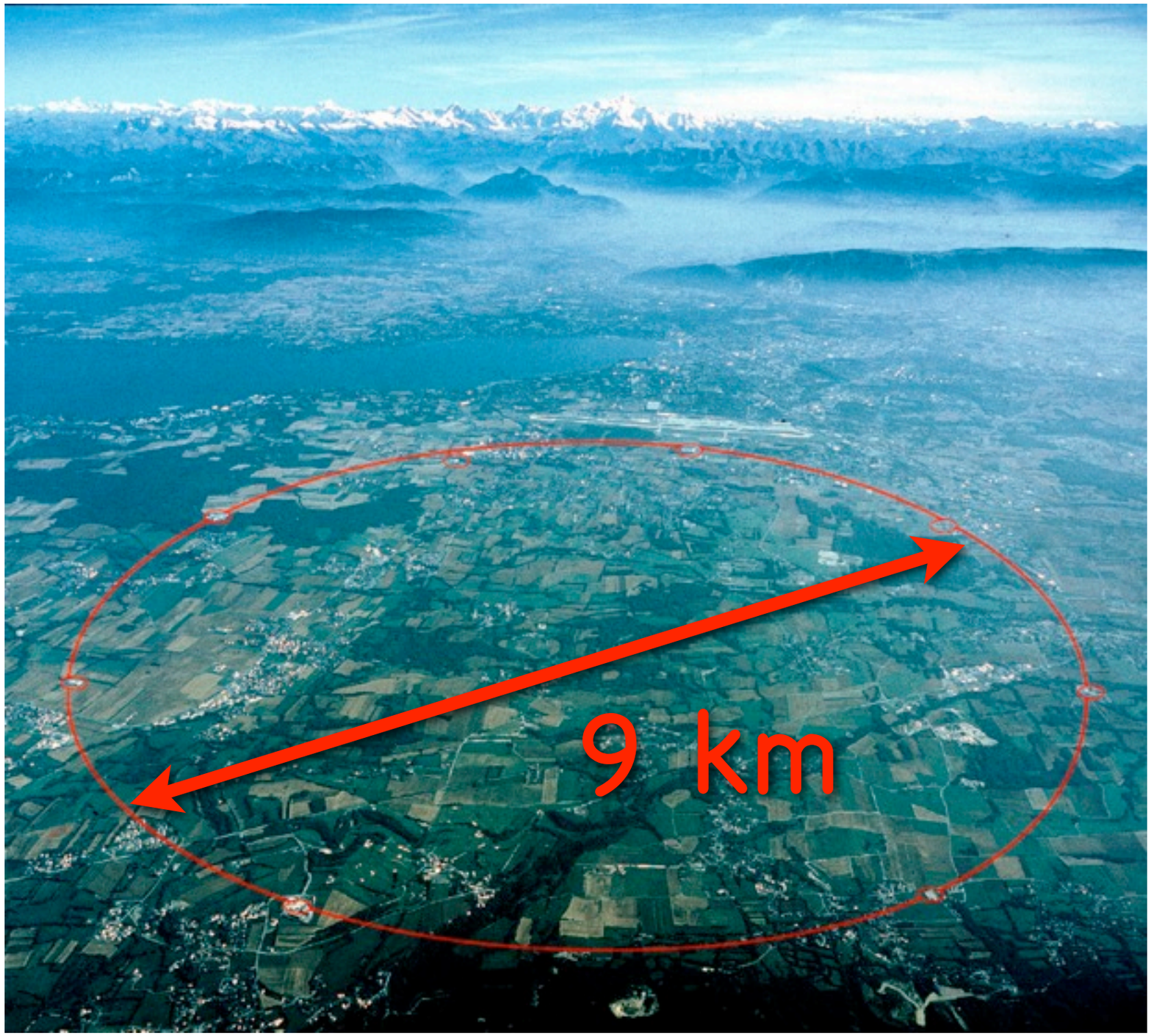
We Need

$$\text{wavelength} = \frac{5 \text{ in}}{1{,}000{,}000{,}000{,}000{,}000{,}000}$$

$$\text{Energy} = 10{,}000{,}000{,}000{,}000 \text{ eV}$$

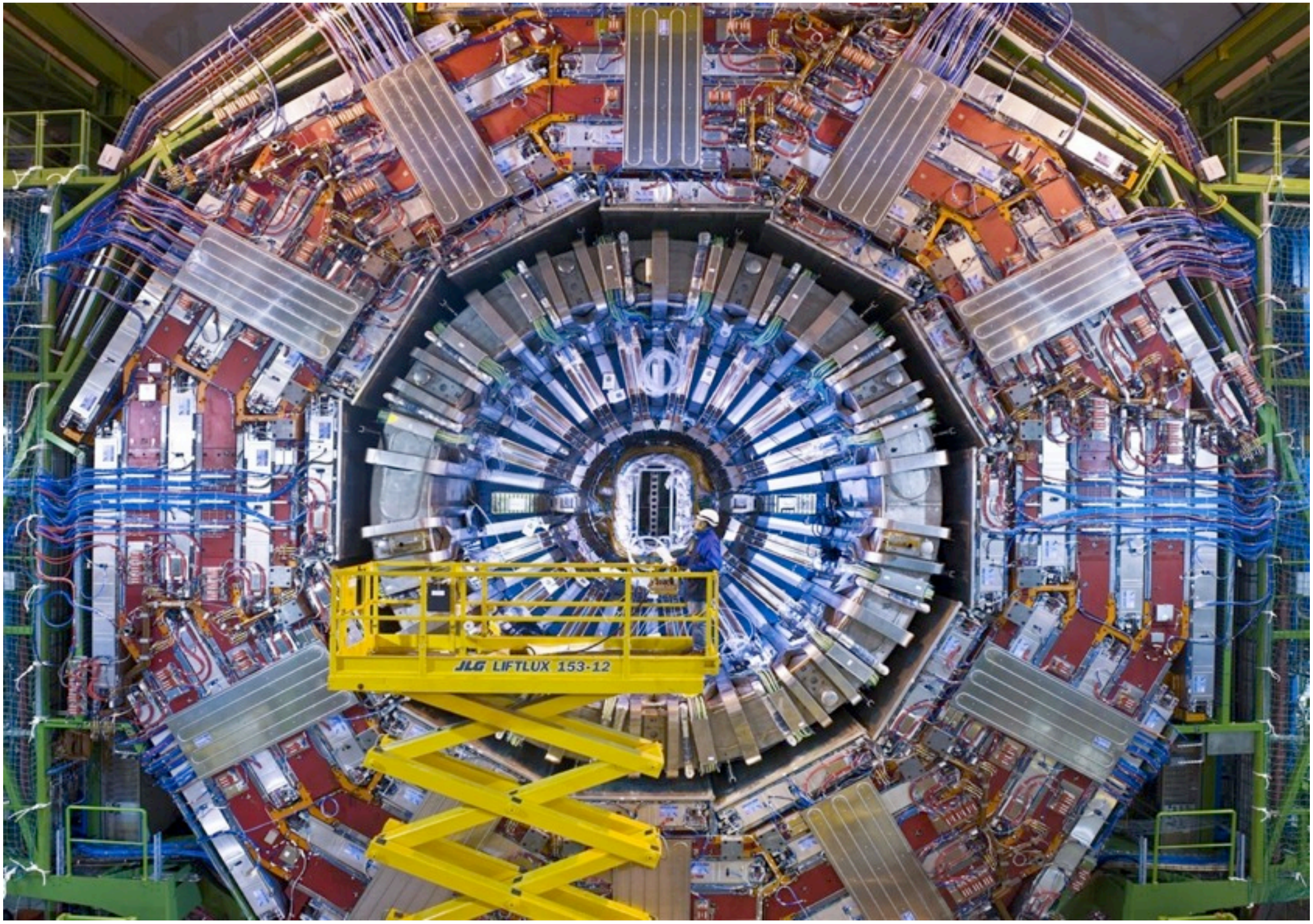
Large Hadron Collider

Large Hadron Collider

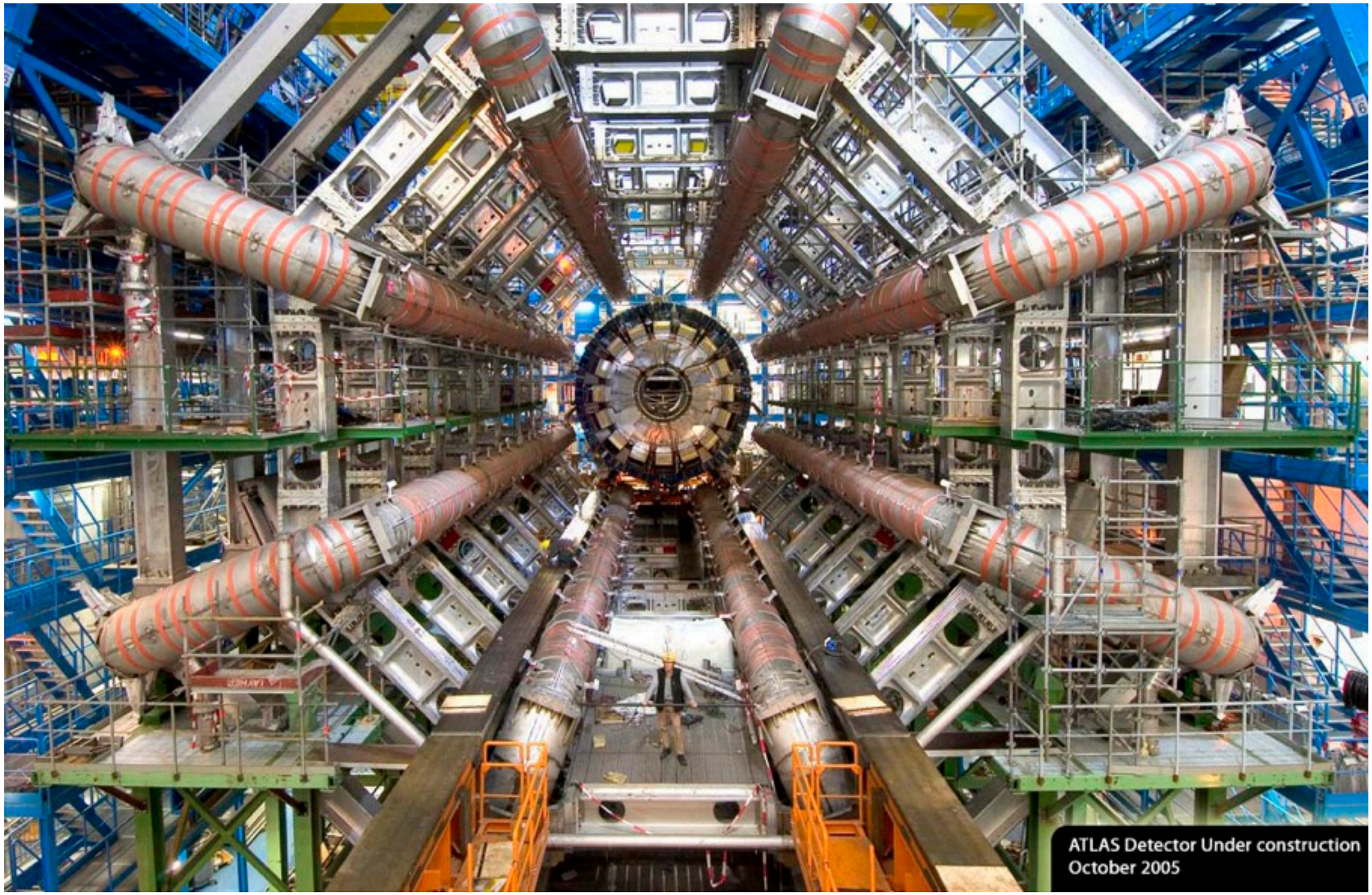


CMS

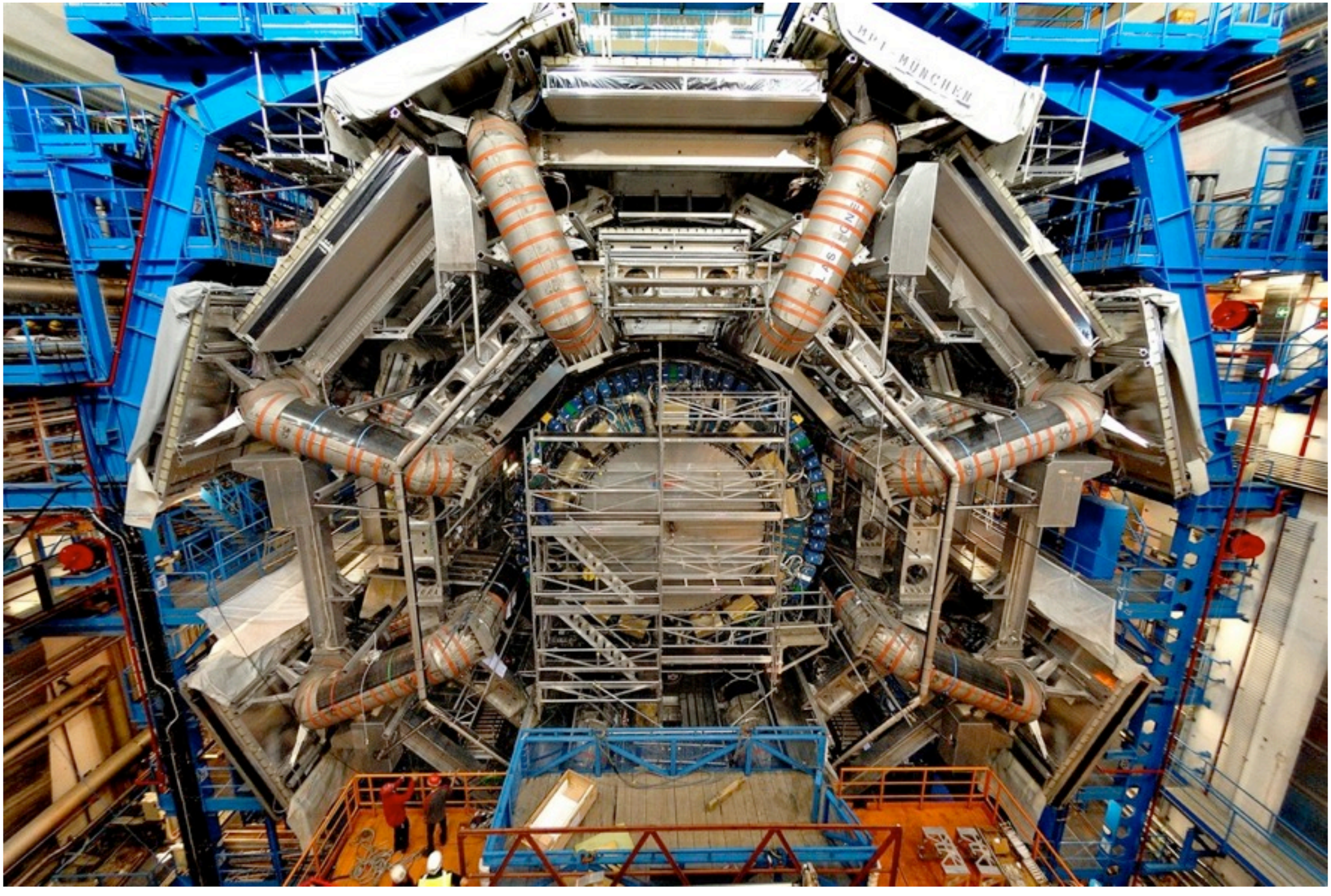
CMS



ATLAS



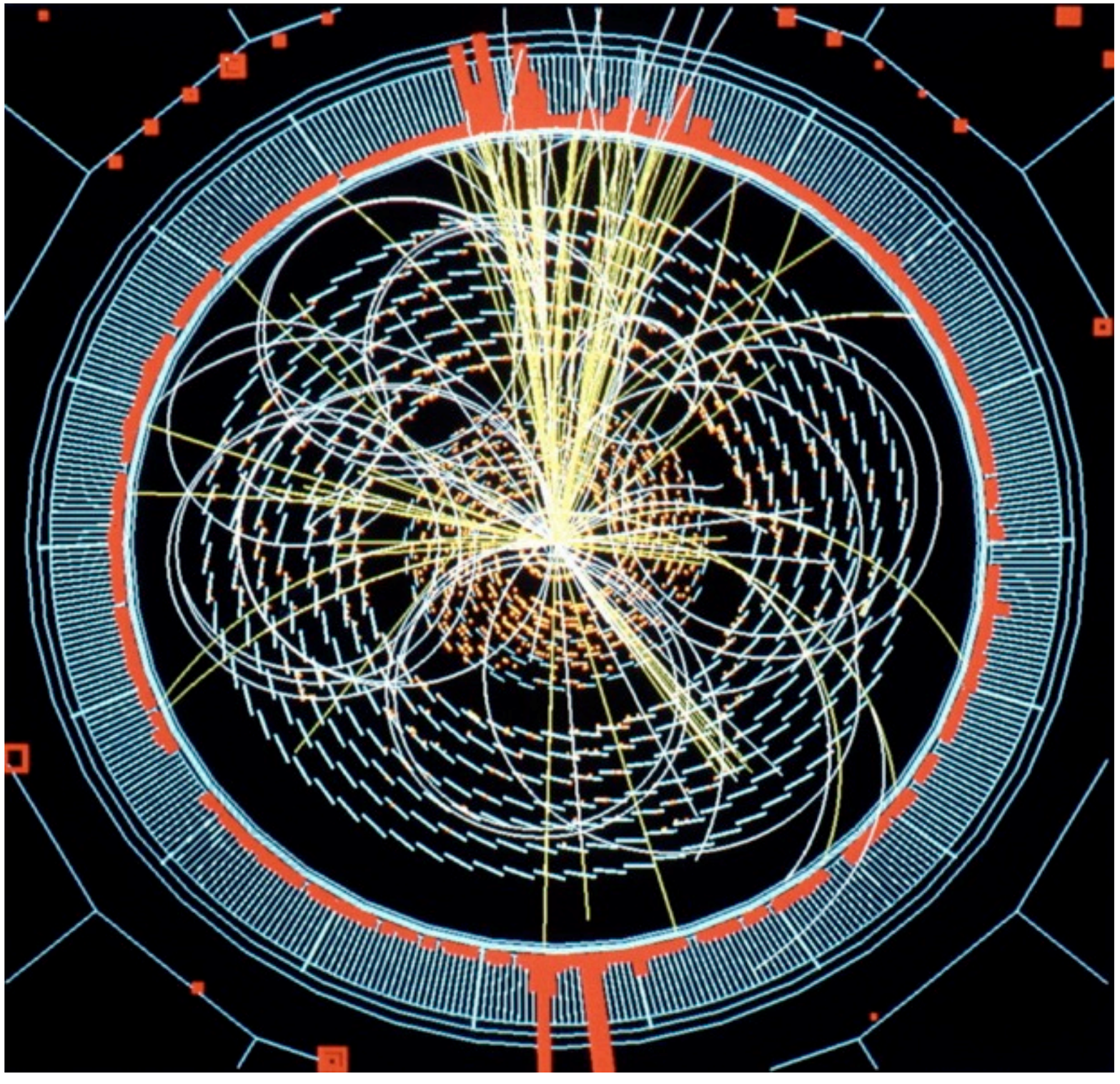
ATLAS



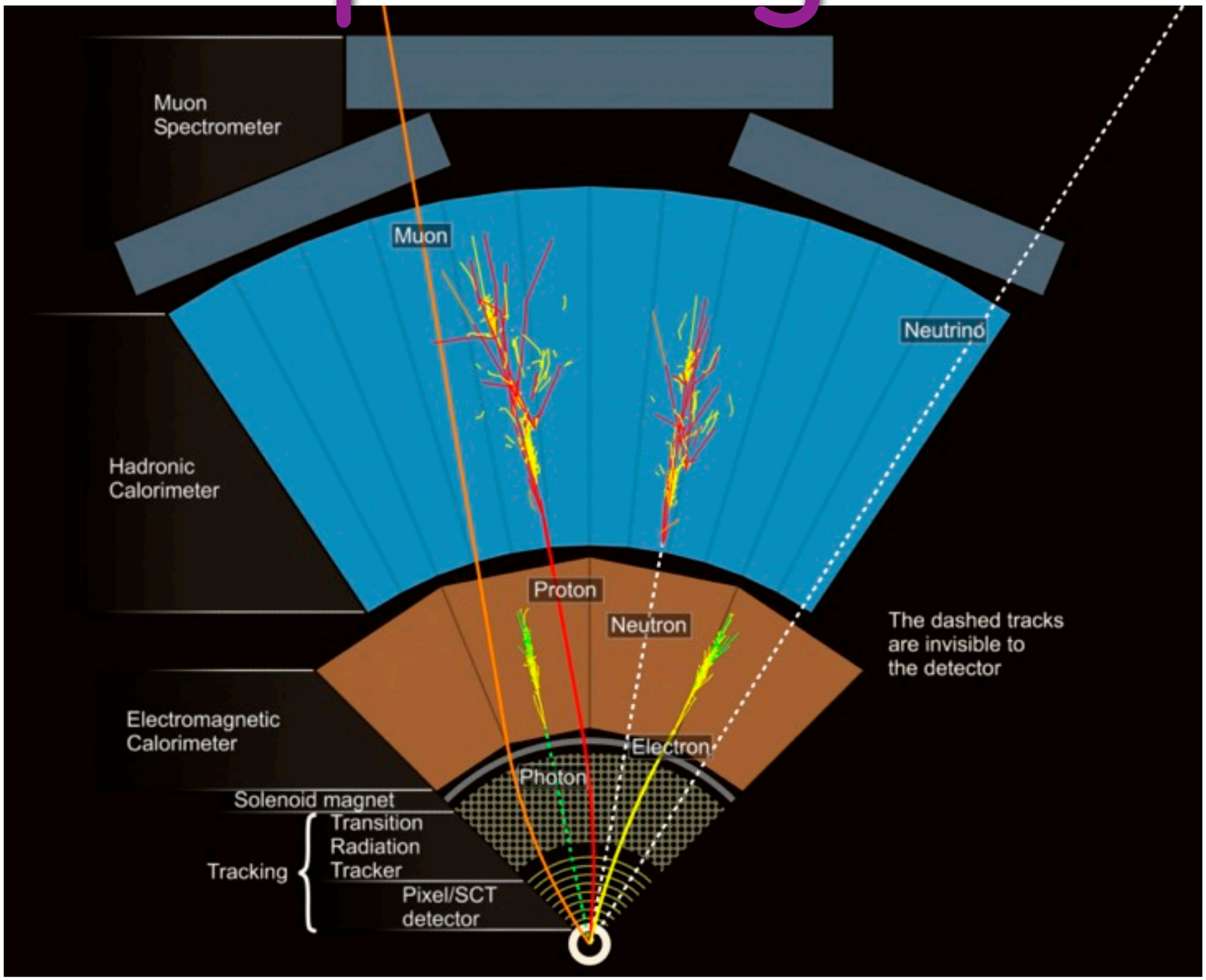
Particles in Collision

Particles in Collision

Data



Interpreting Data



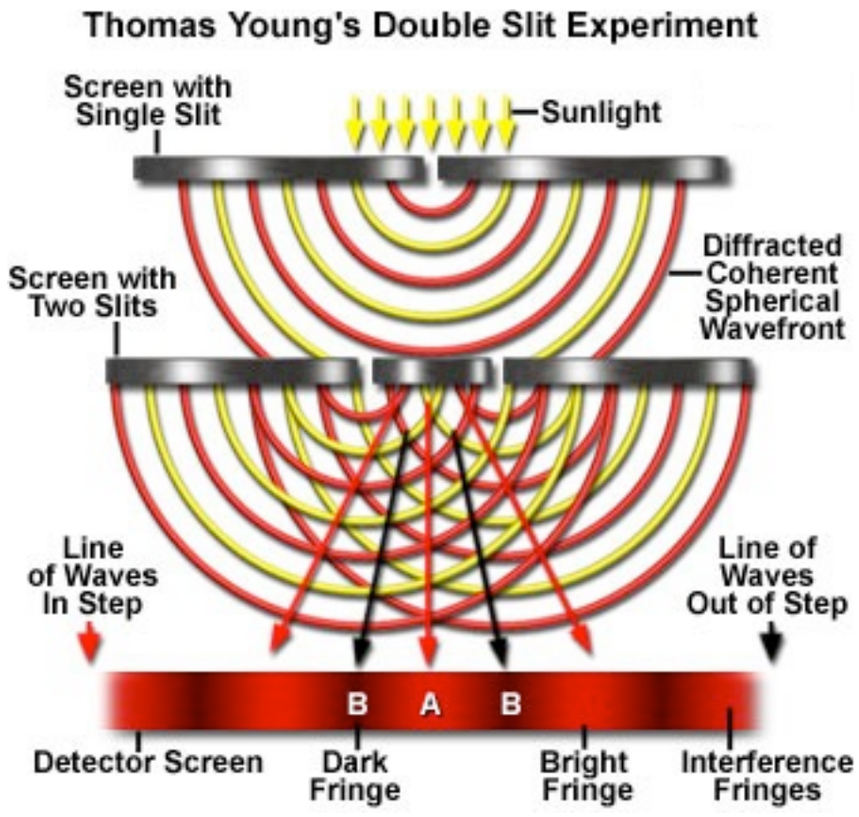
Quantum Field Theory

the standard model is a type of
quantum field theory

it incorporates
quantum mechanics and relativity

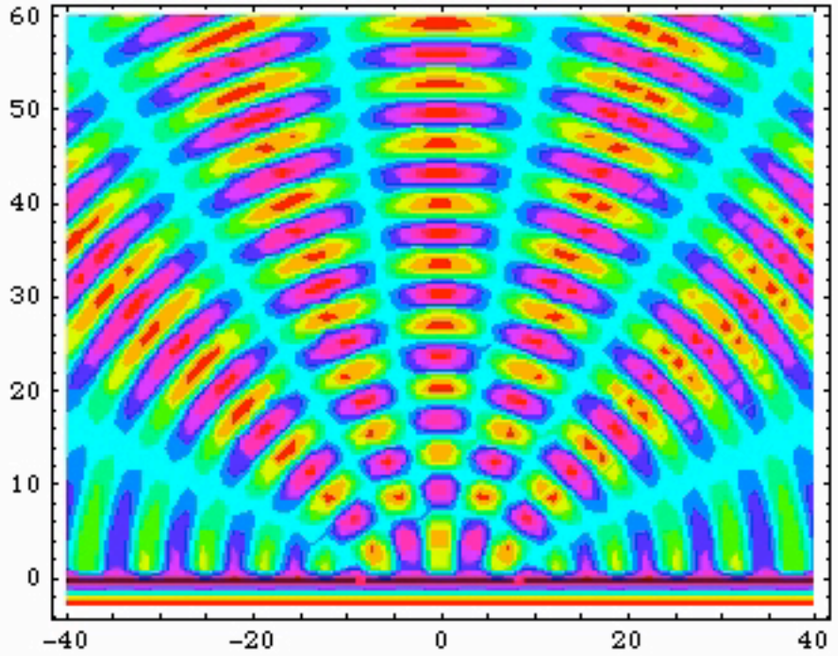
specifies a list of fields (particles)
and their interactions

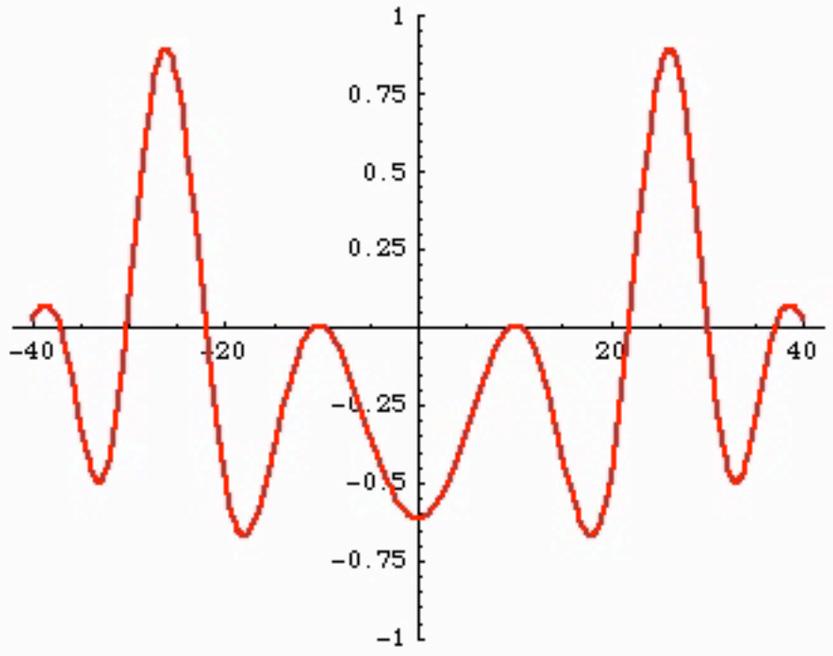
Light is a Wave



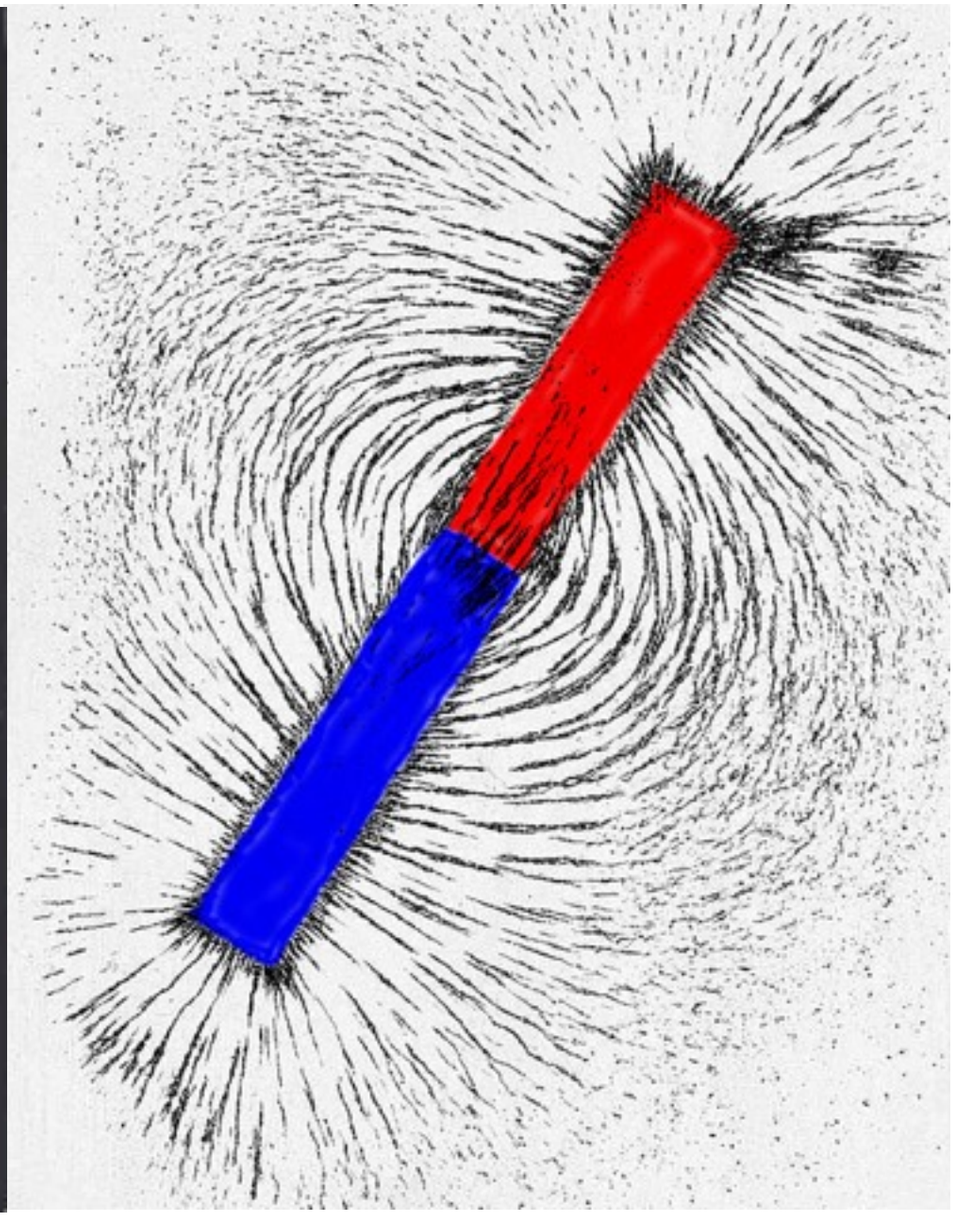
Thomas Young 1801

Double Slit





Field Theory



Electromagnetism

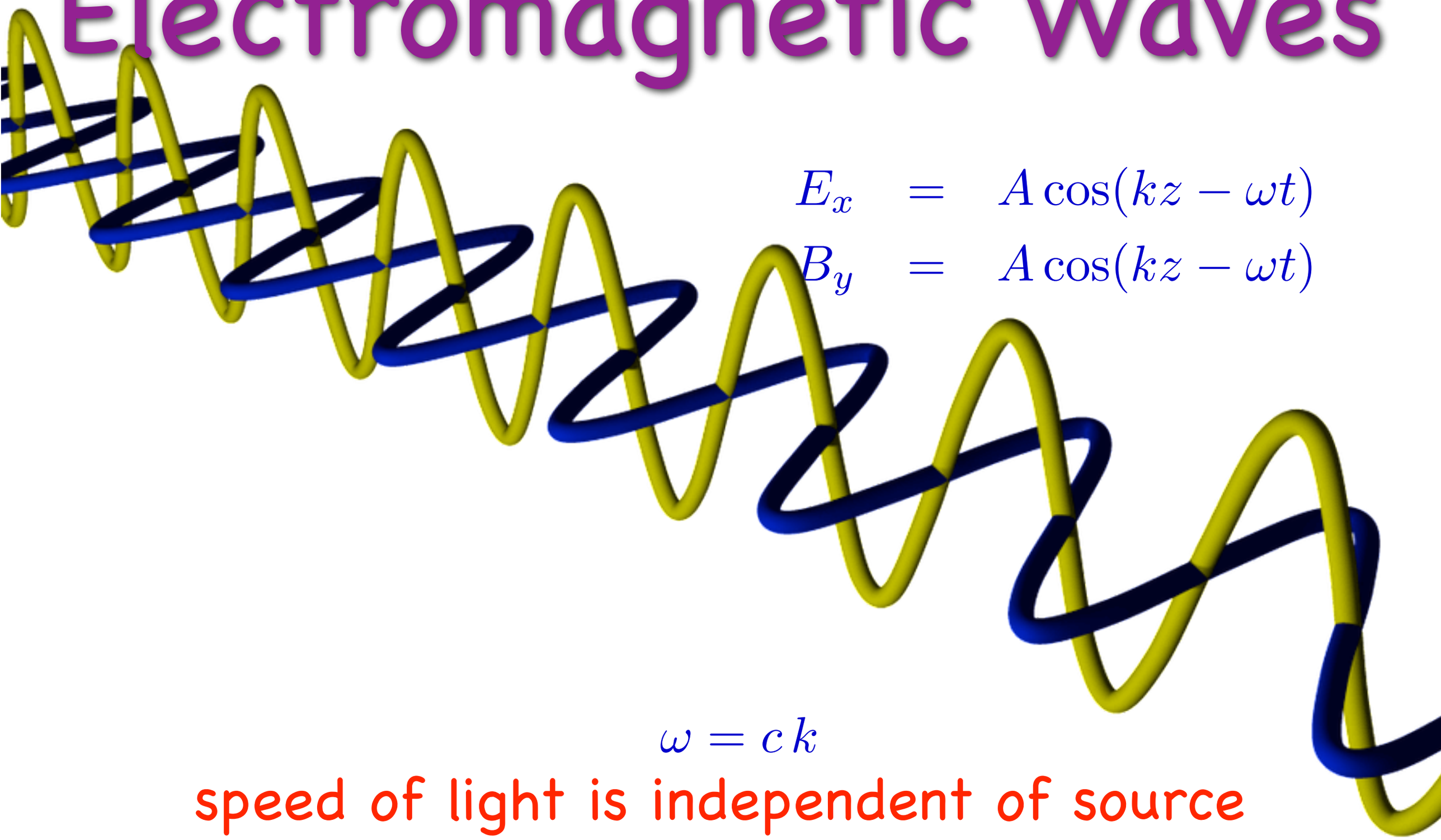
$$\vec{\nabla} \cdot \vec{E} = \rho$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c}\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \times \vec{B} = \frac{1}{c}\vec{J} + \frac{1}{c}\frac{\partial \vec{E}}{\partial t}$$

Electromagnetic Waves



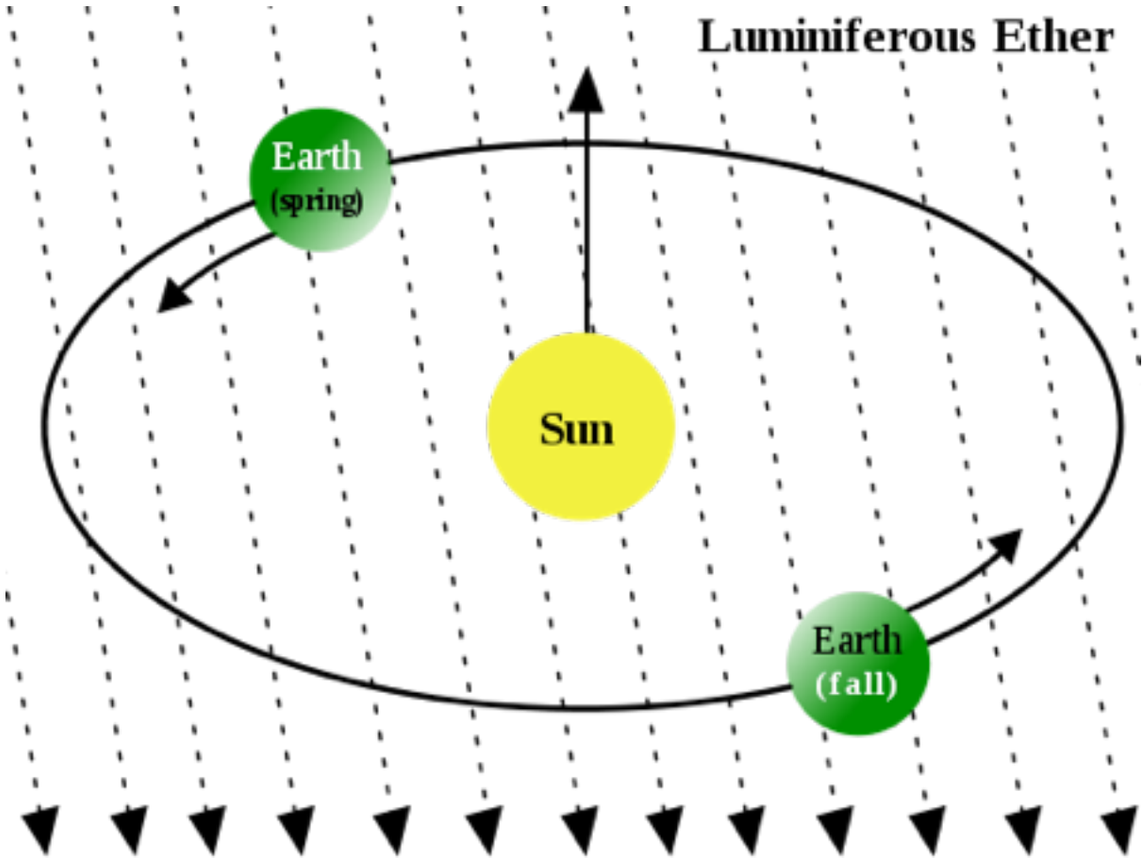
$$E_x = A\cos(kz - \omega t)$$

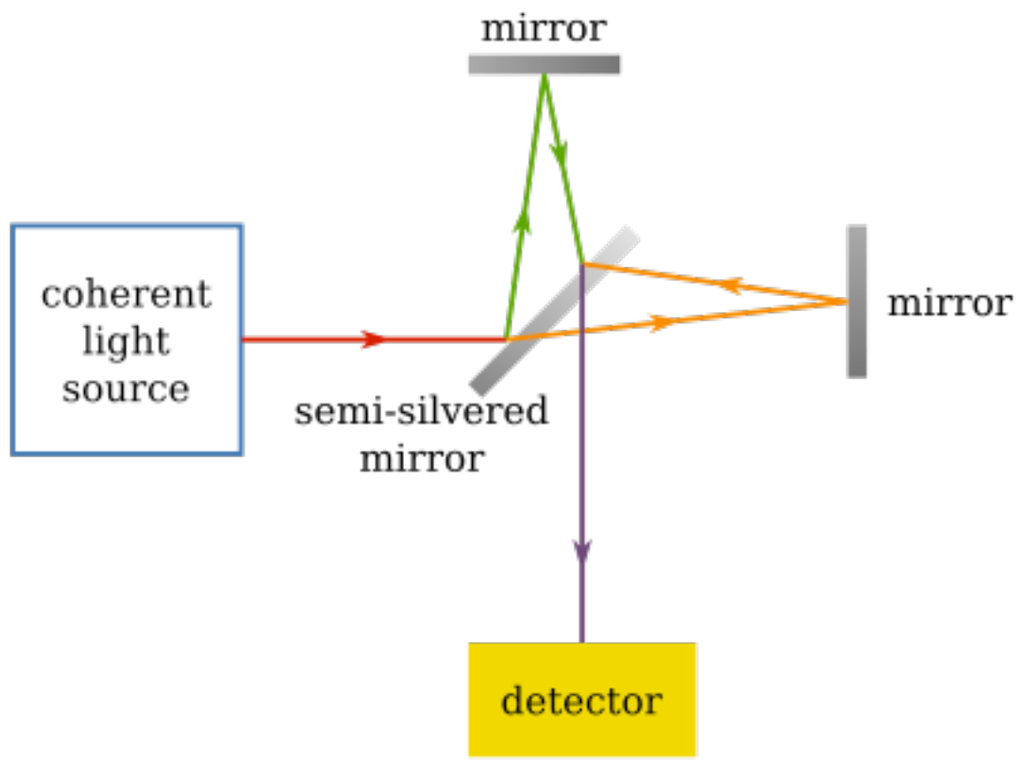
$$B_y = A\cos(kz - \omega t)$$

$$\omega = c\,k$$

speed of light is independent of source

Michelson-Morley





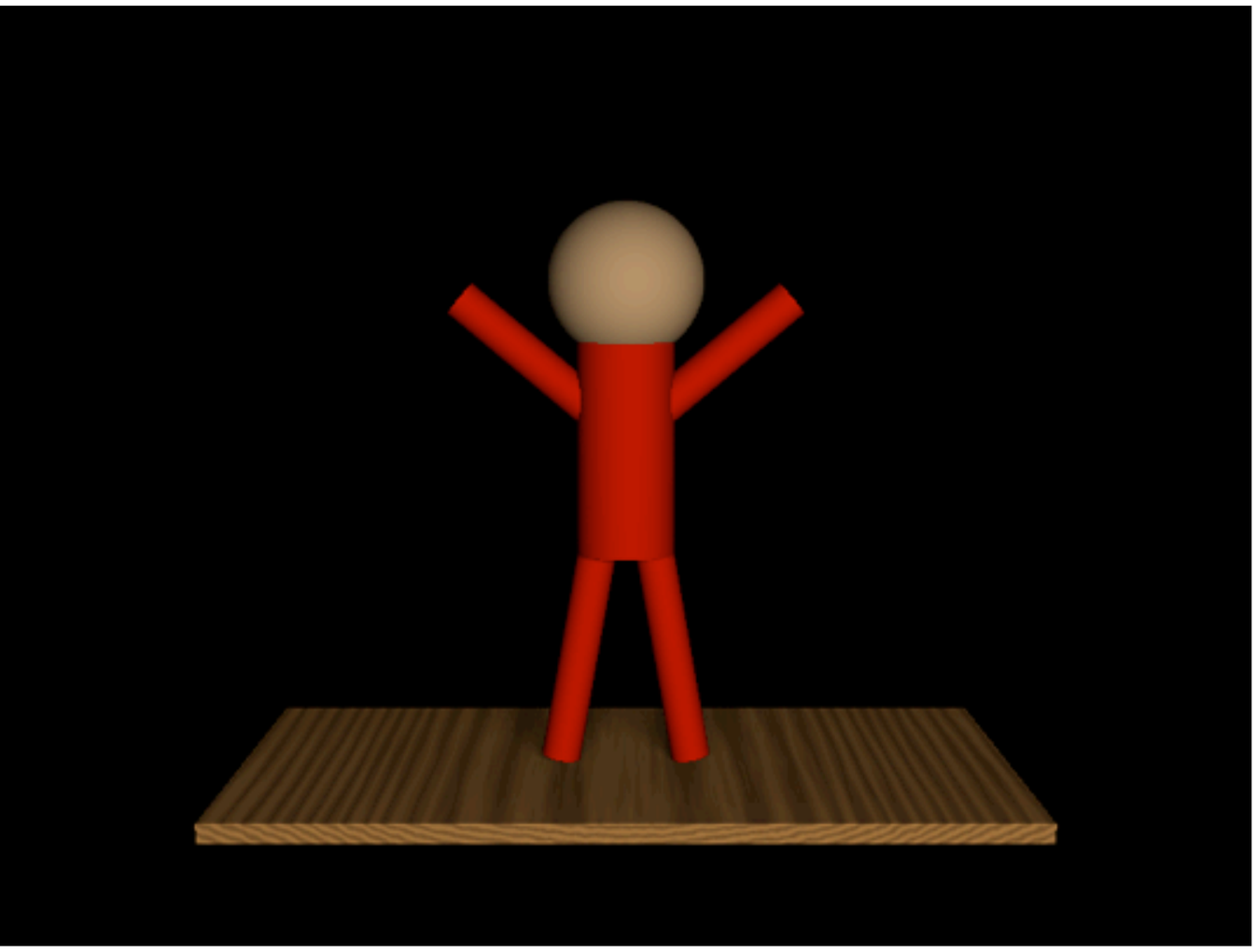
speed of light is independent of velocity through the "ether"

Einstein

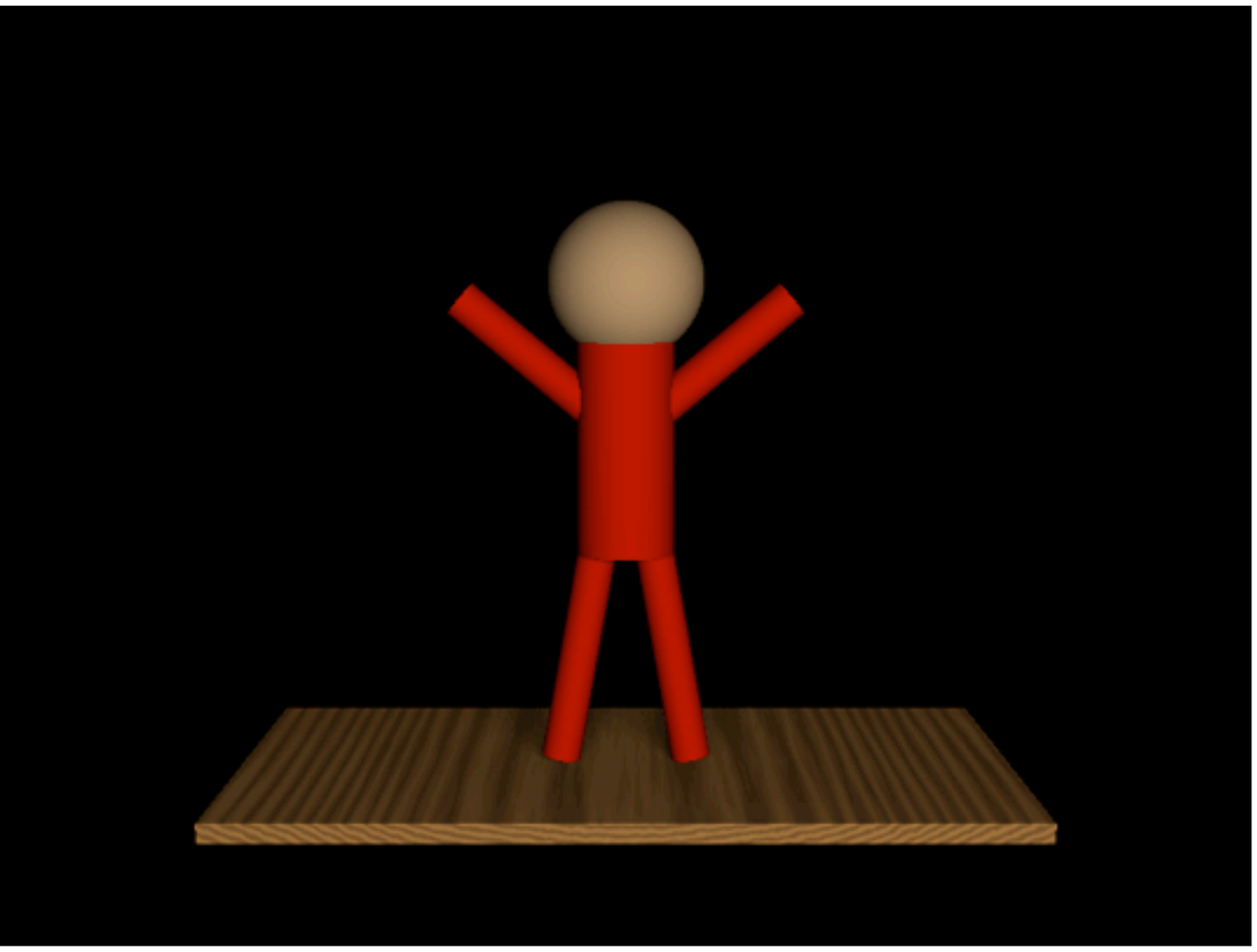
if the speed of light is constant then space and time have to vary

Relativity of Simultaneity

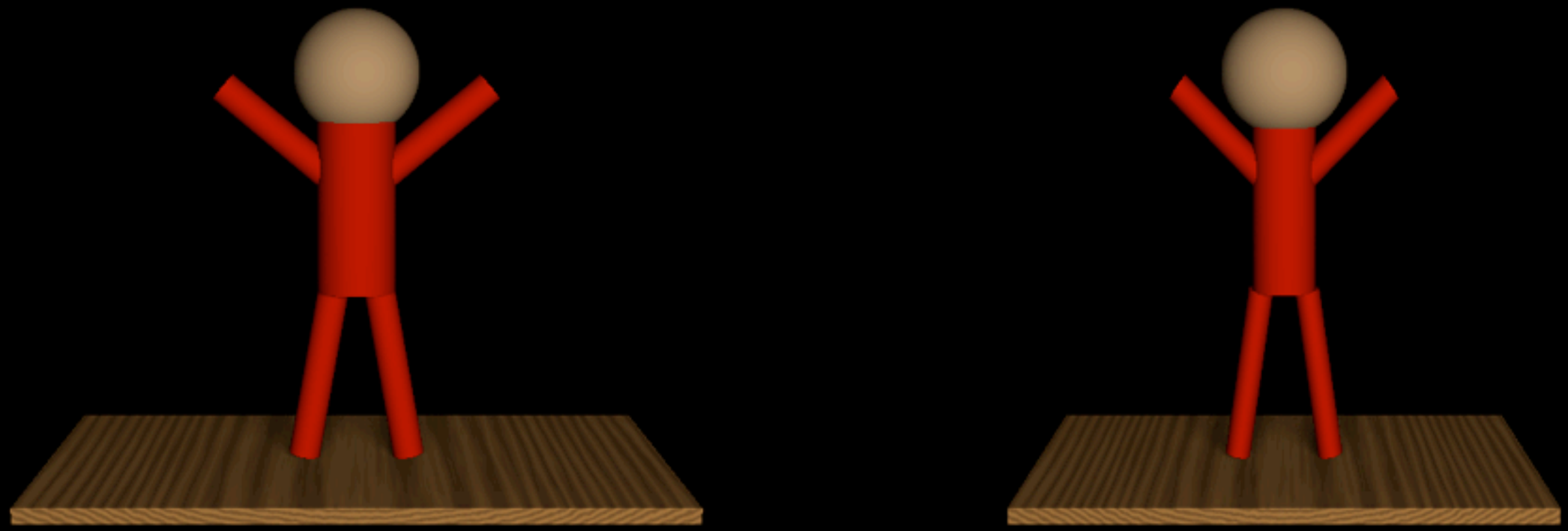
Relativity of Simultaneity



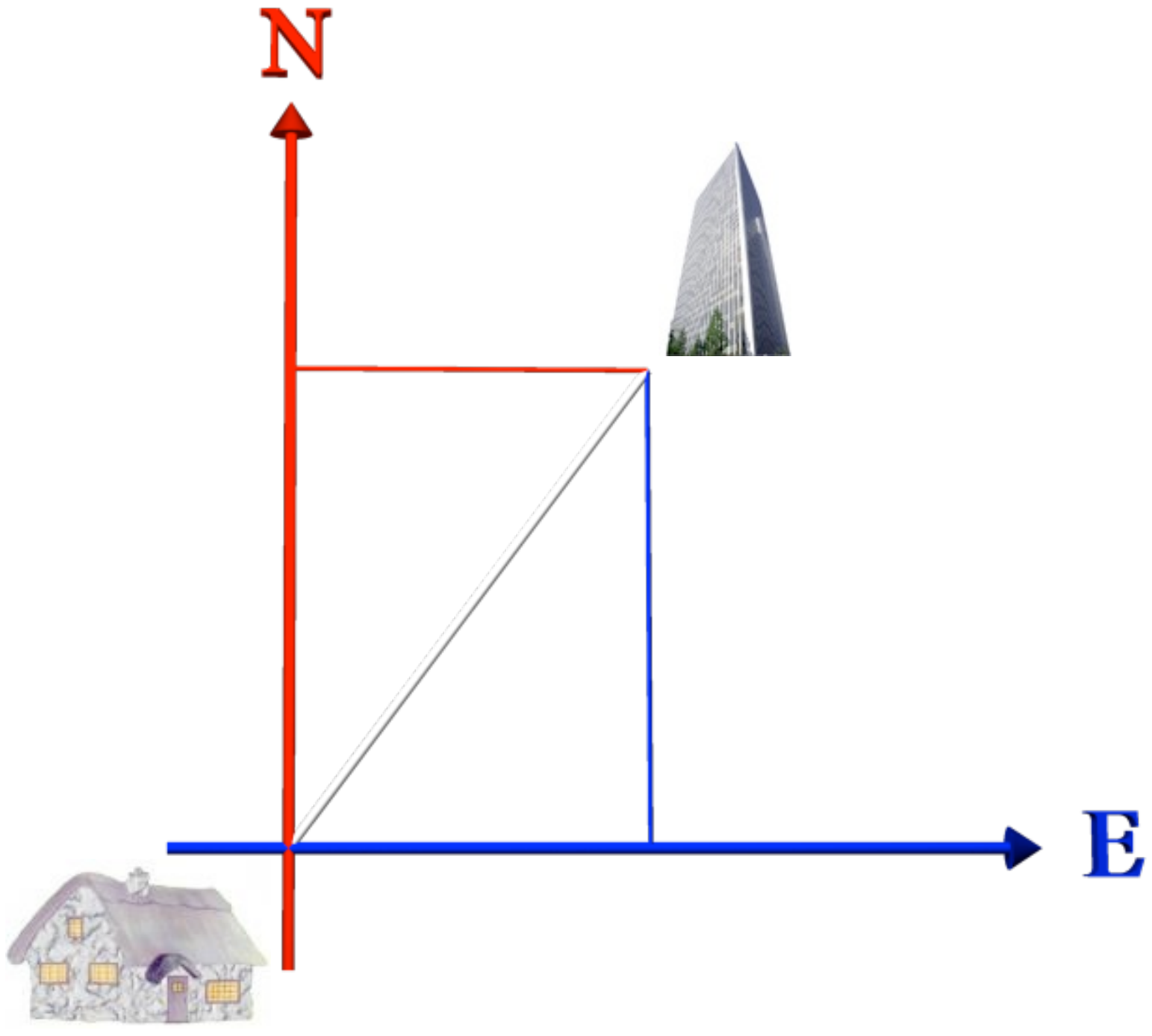
Relativity of Simultaneity



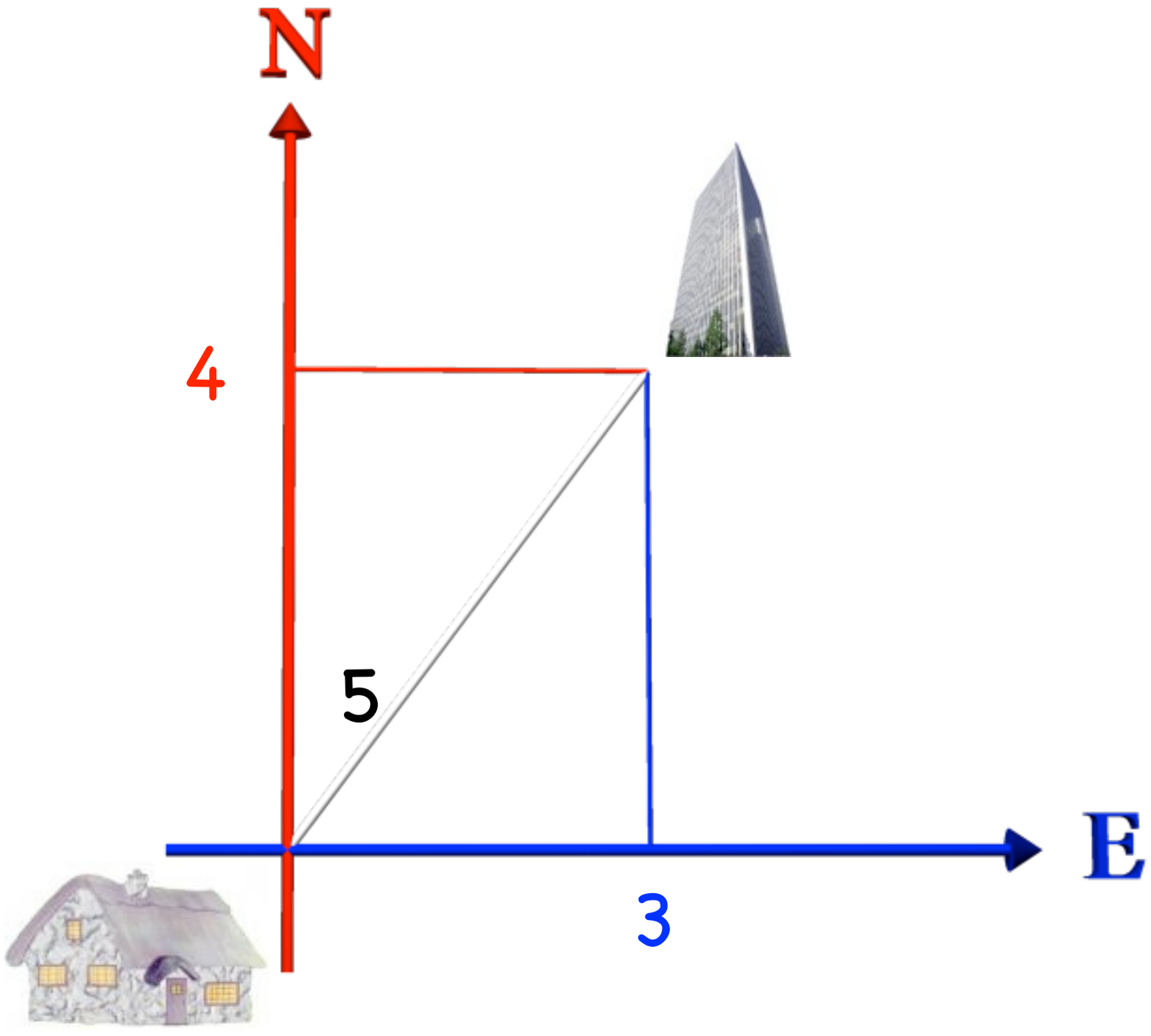
Relativity of Simultaneity



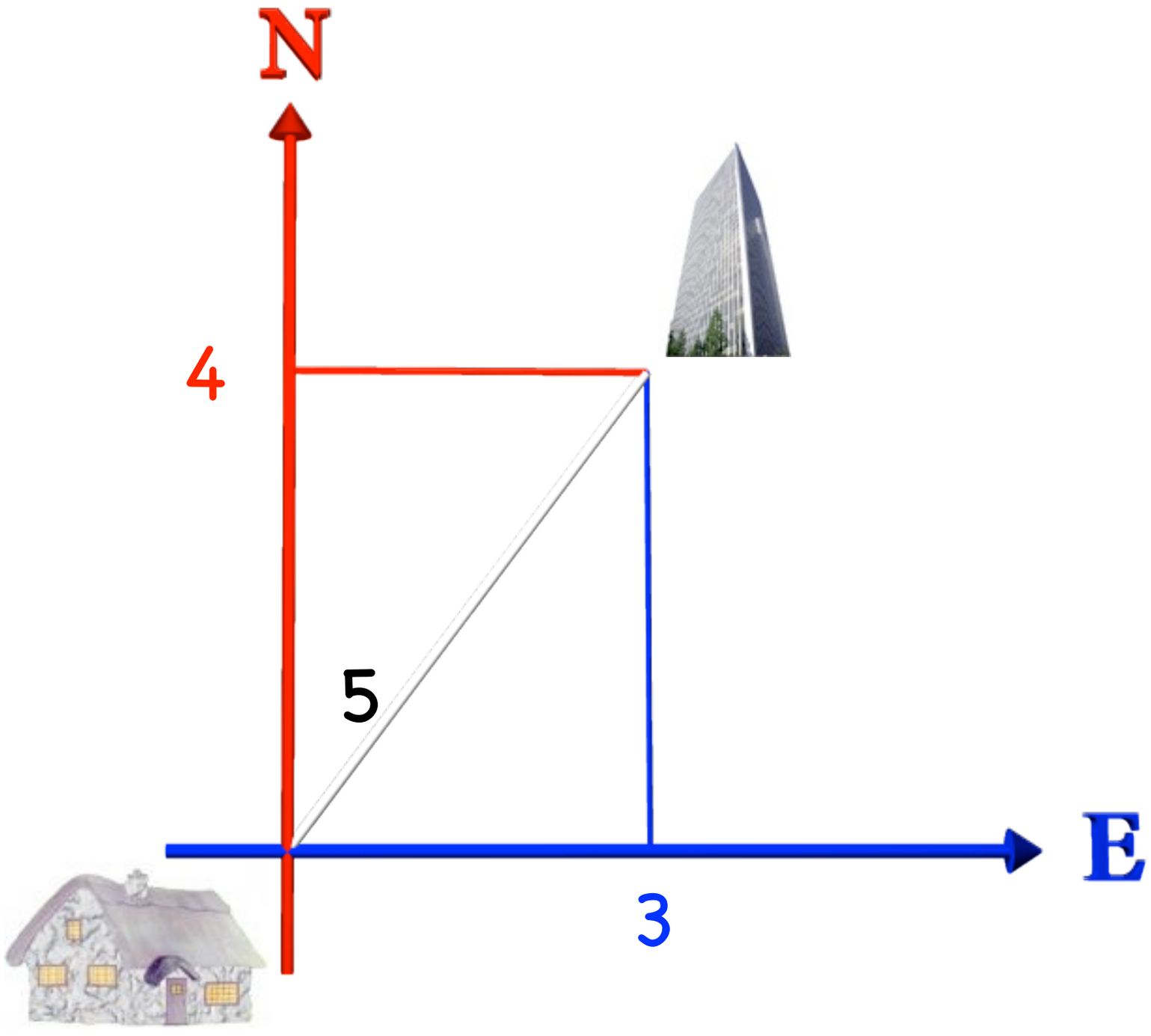
Rotational Invariance



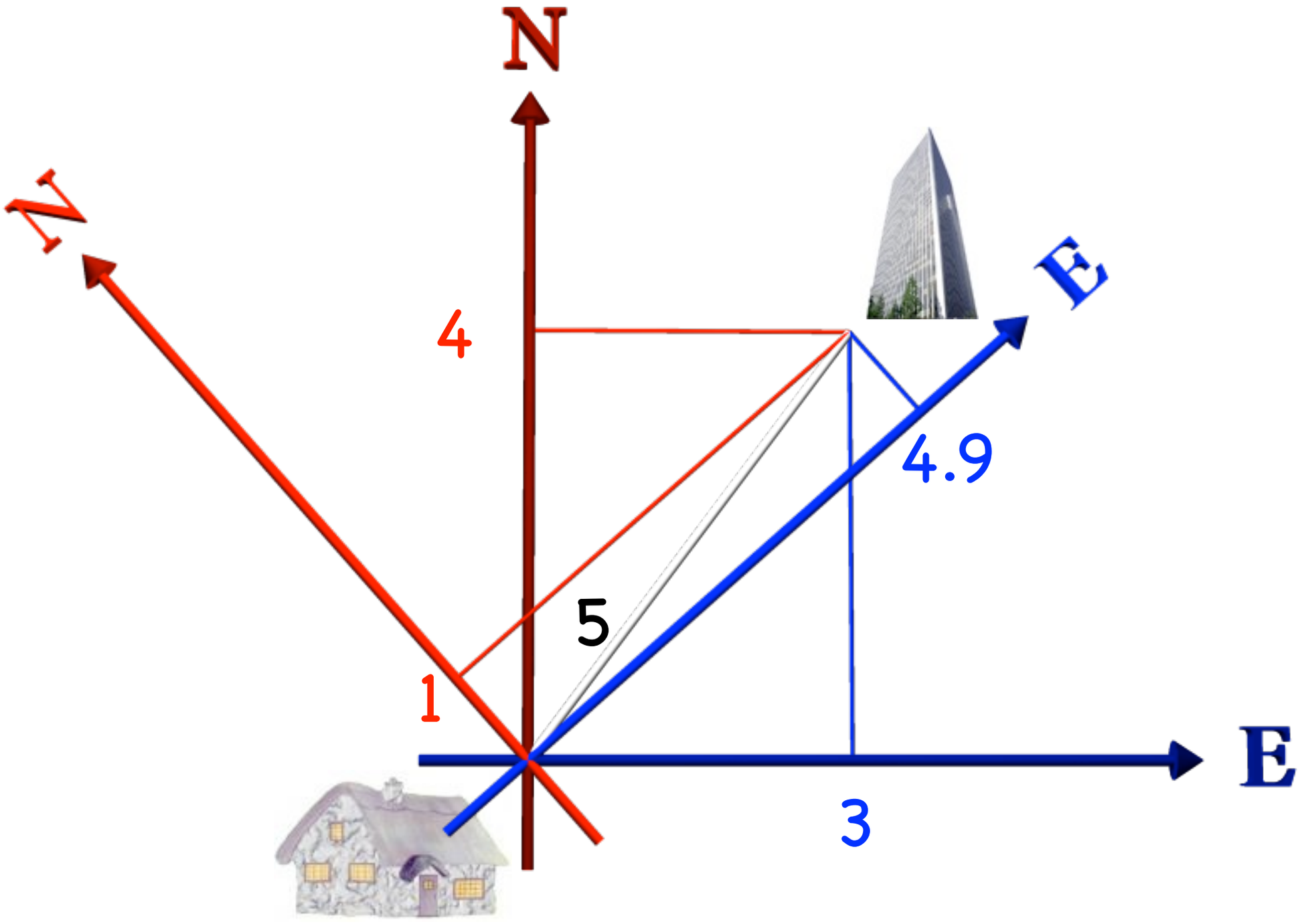
Rotational Invariance



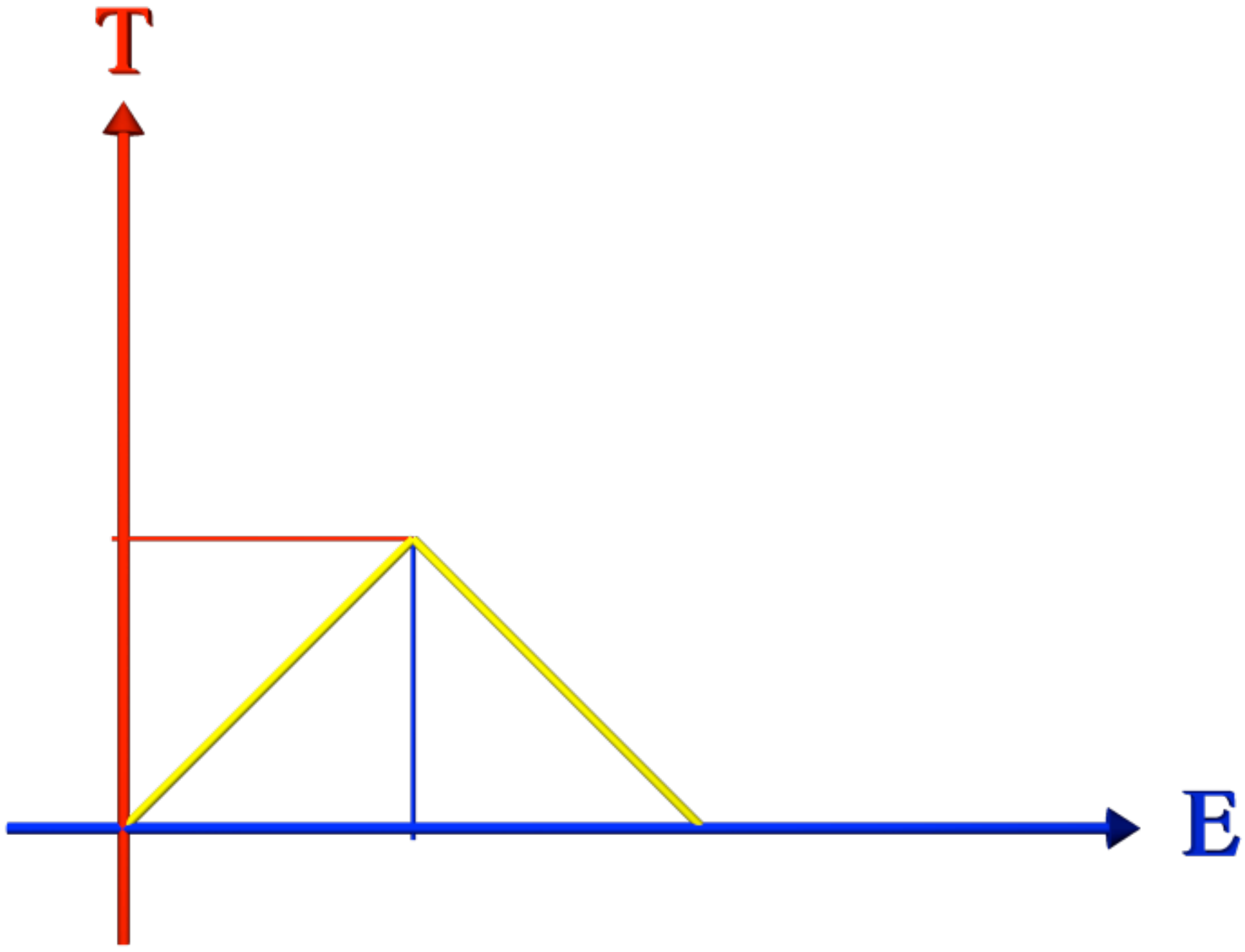
Rotational Invariance



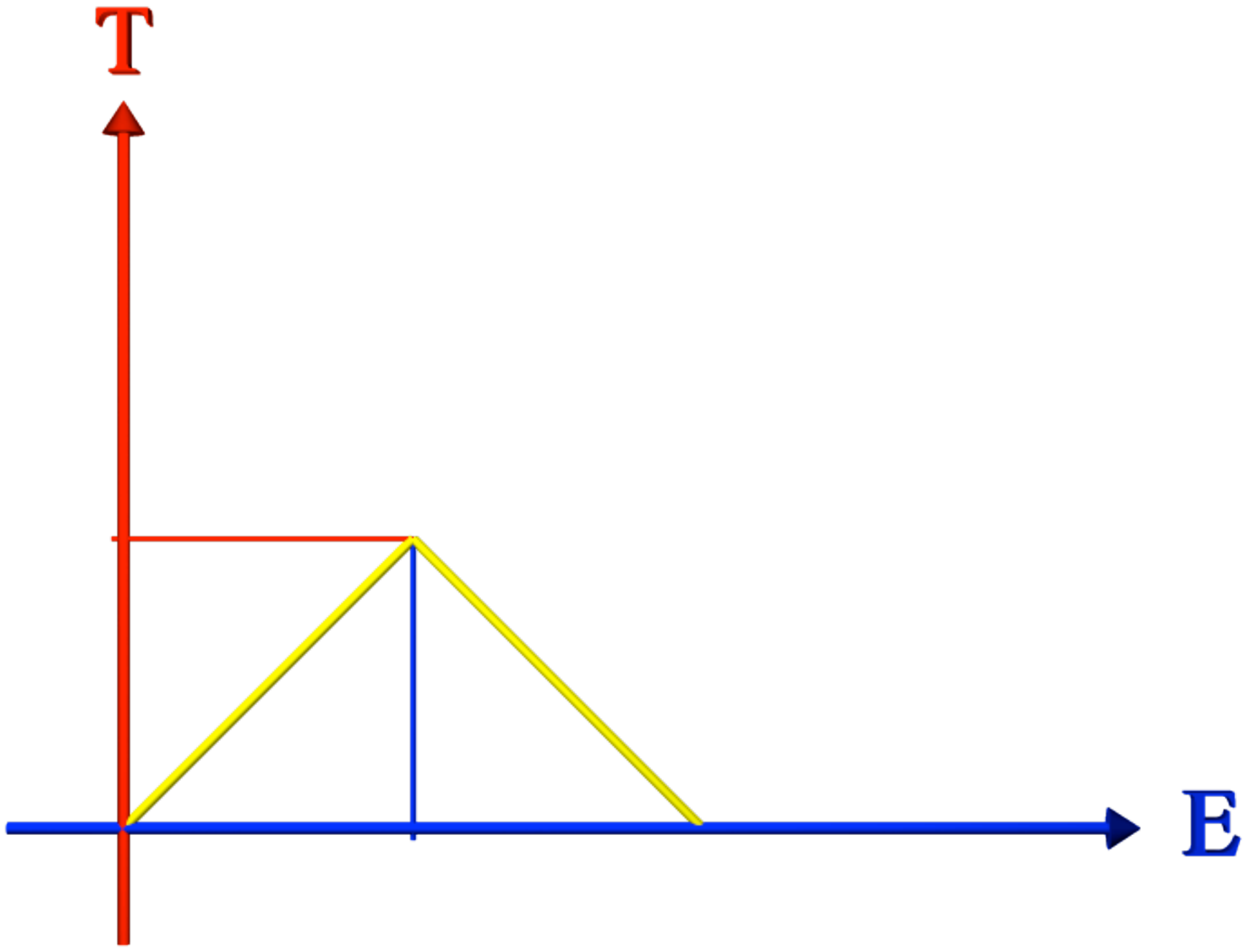
Rotational Invariance



Time: the Fourth Dimension



Time: the Fourth Dimension



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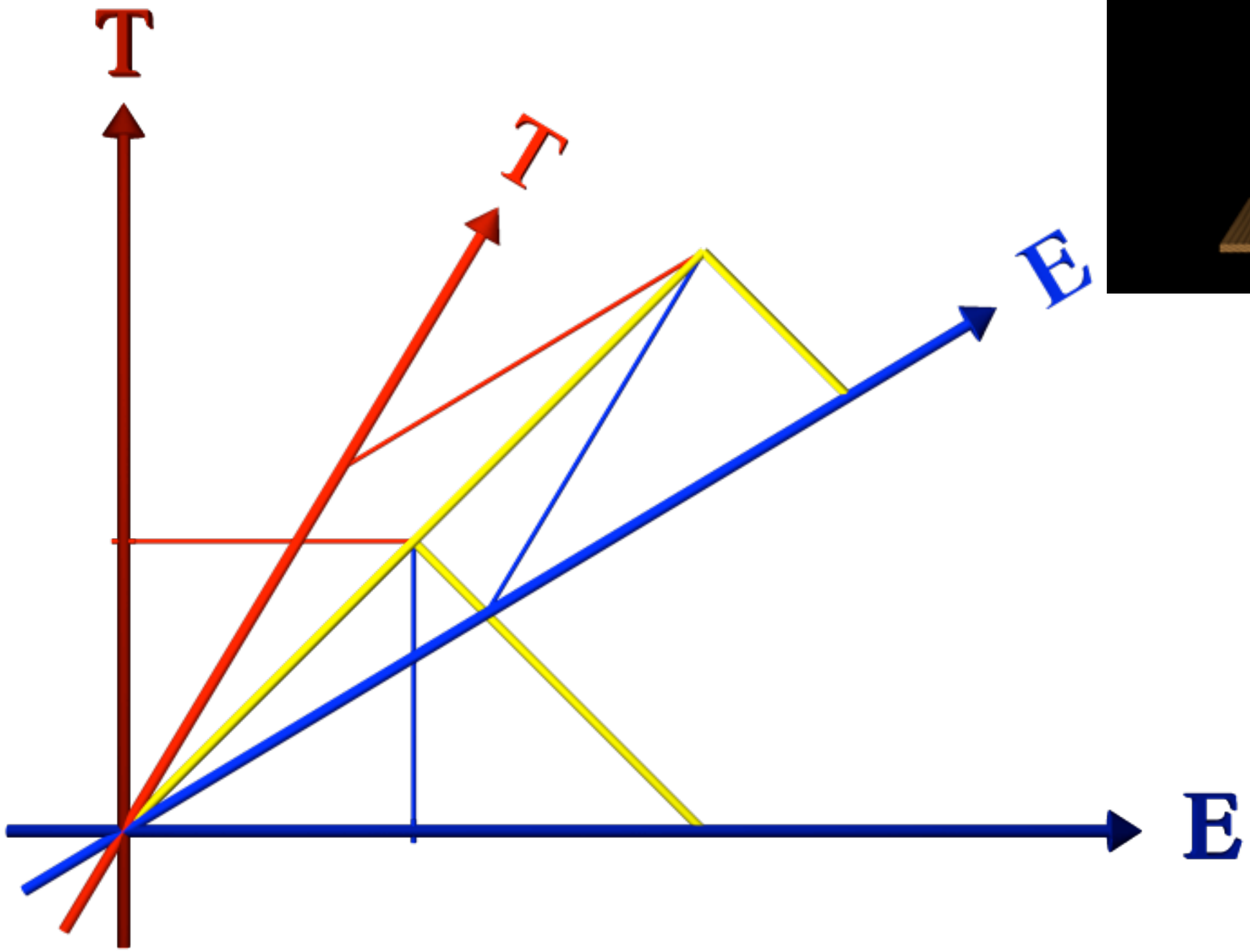
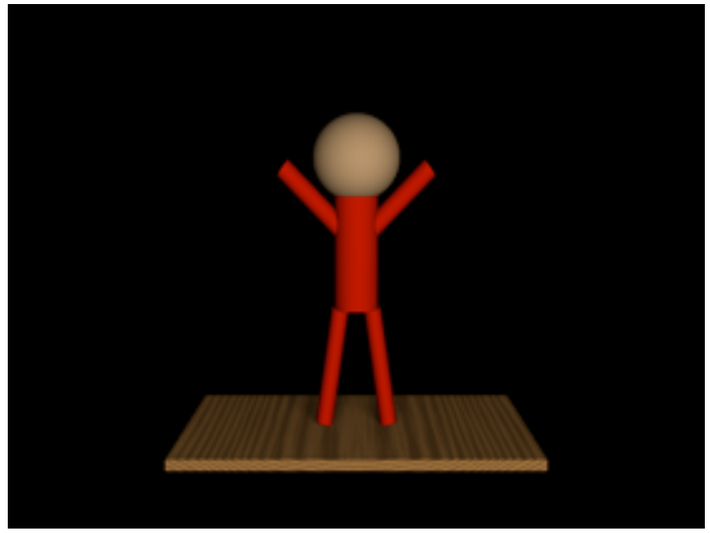
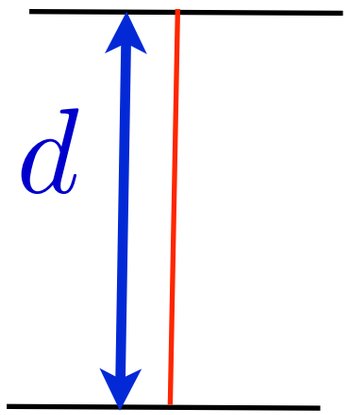
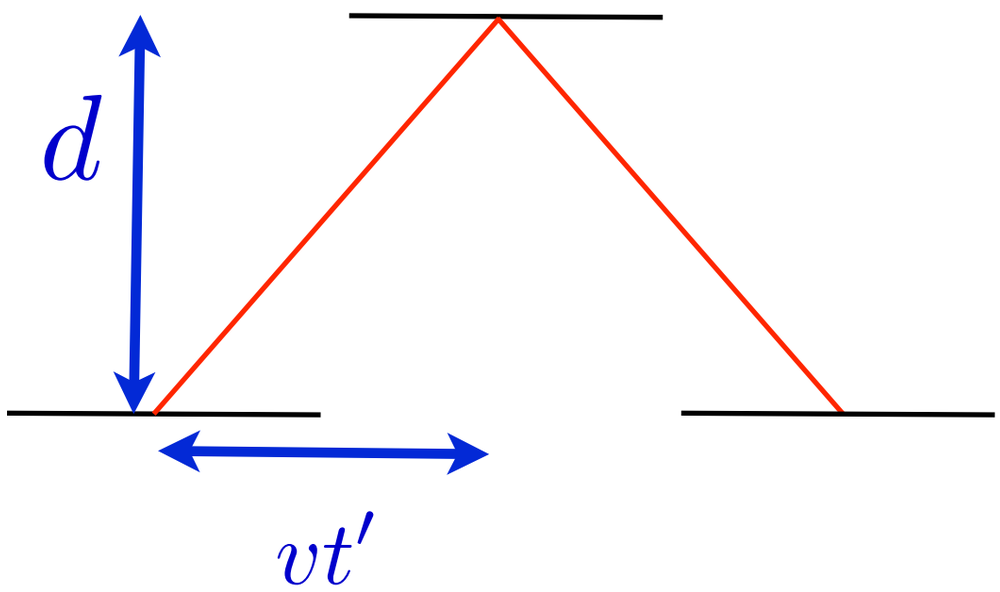




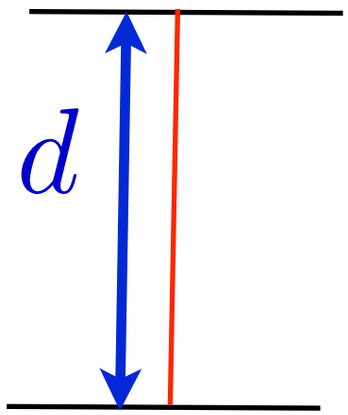
Time Dilation



$$t = d/c$$



Time Dilation



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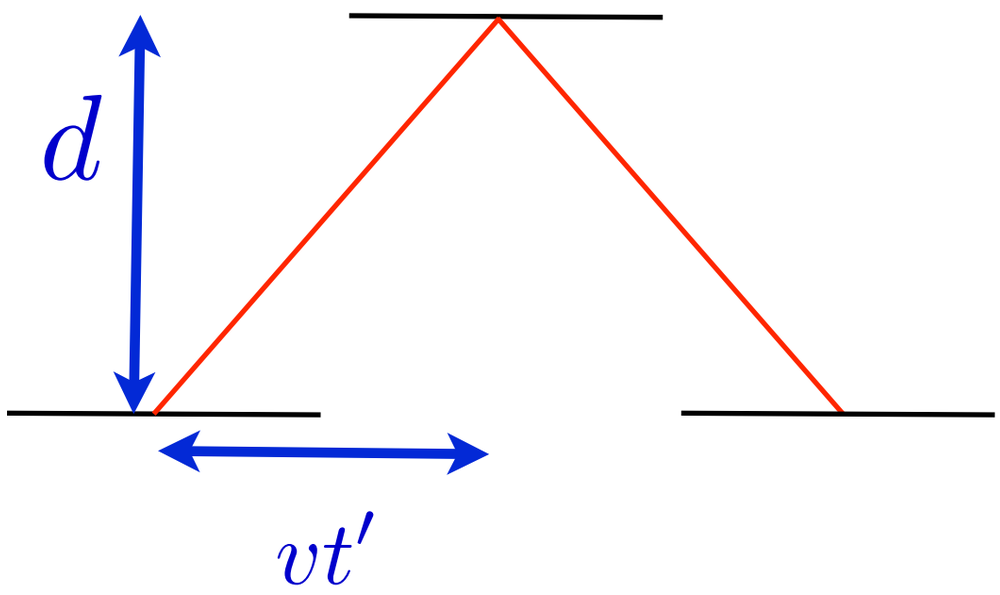
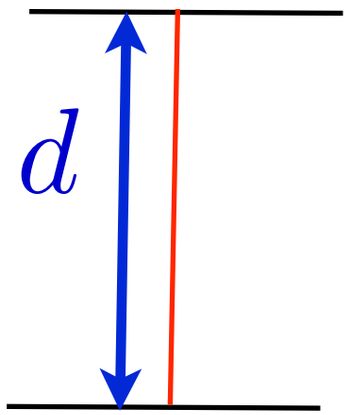


$$t' = \sqrt{d^2 + v^2 t'^2}/c$$

Time Dilation



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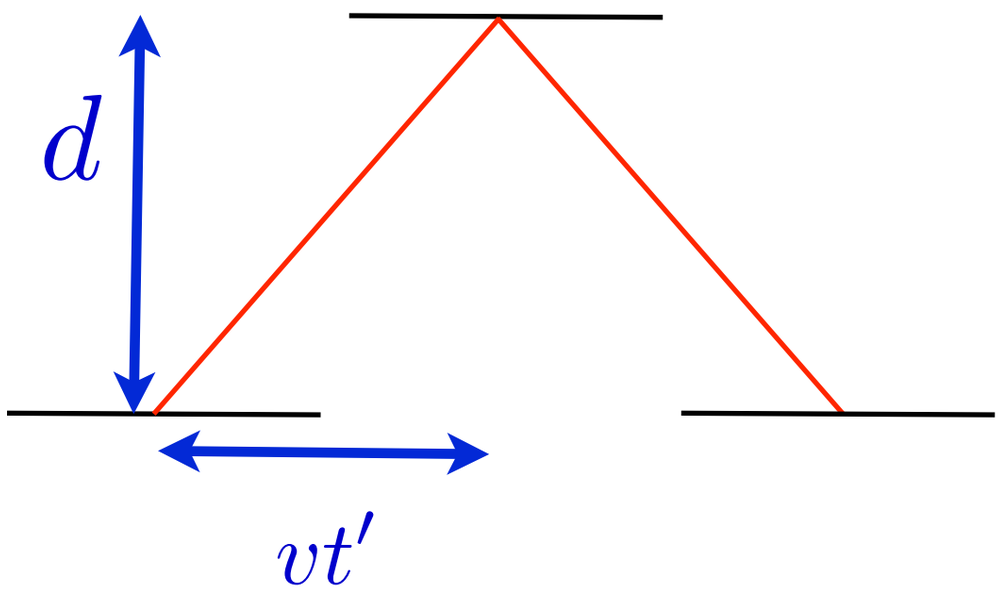
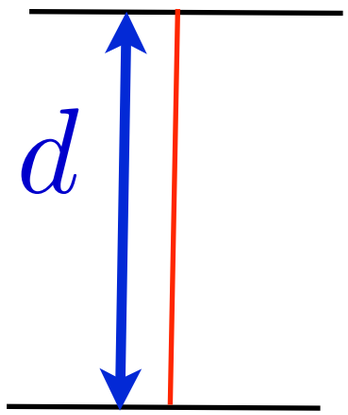


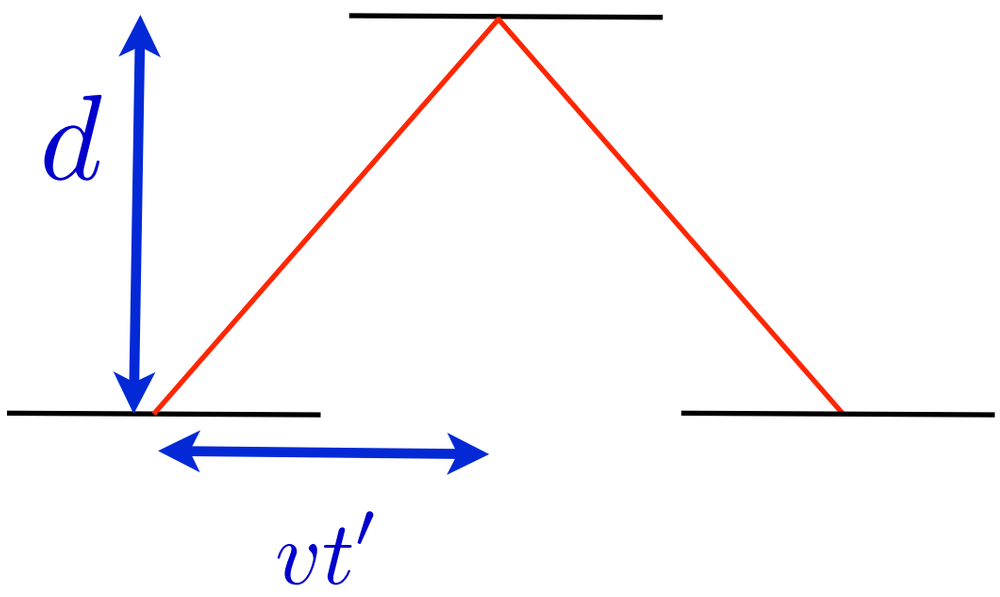
$$t' = \sqrt{d^2 + v^2 t'^2}/c$$

$$t'^2 c^2 = d^2 + v^2 t'^2$$

Time Dilation



$$t = d/c$$

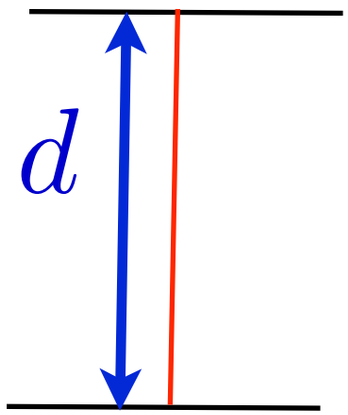


$$t' = \sqrt{d^2 + v^2 t'^2}/c$$

$$t'^2 c^2 = d^2 + v^2 t'^2$$

$$t' c \sqrt{1 - v^2/c^2} = d = ct$$

Time Dilation



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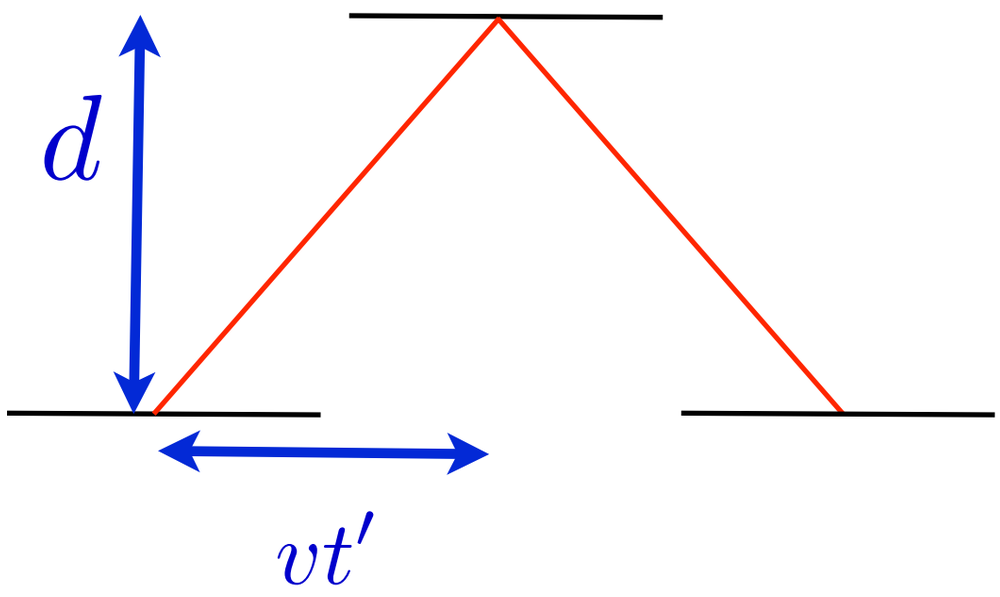


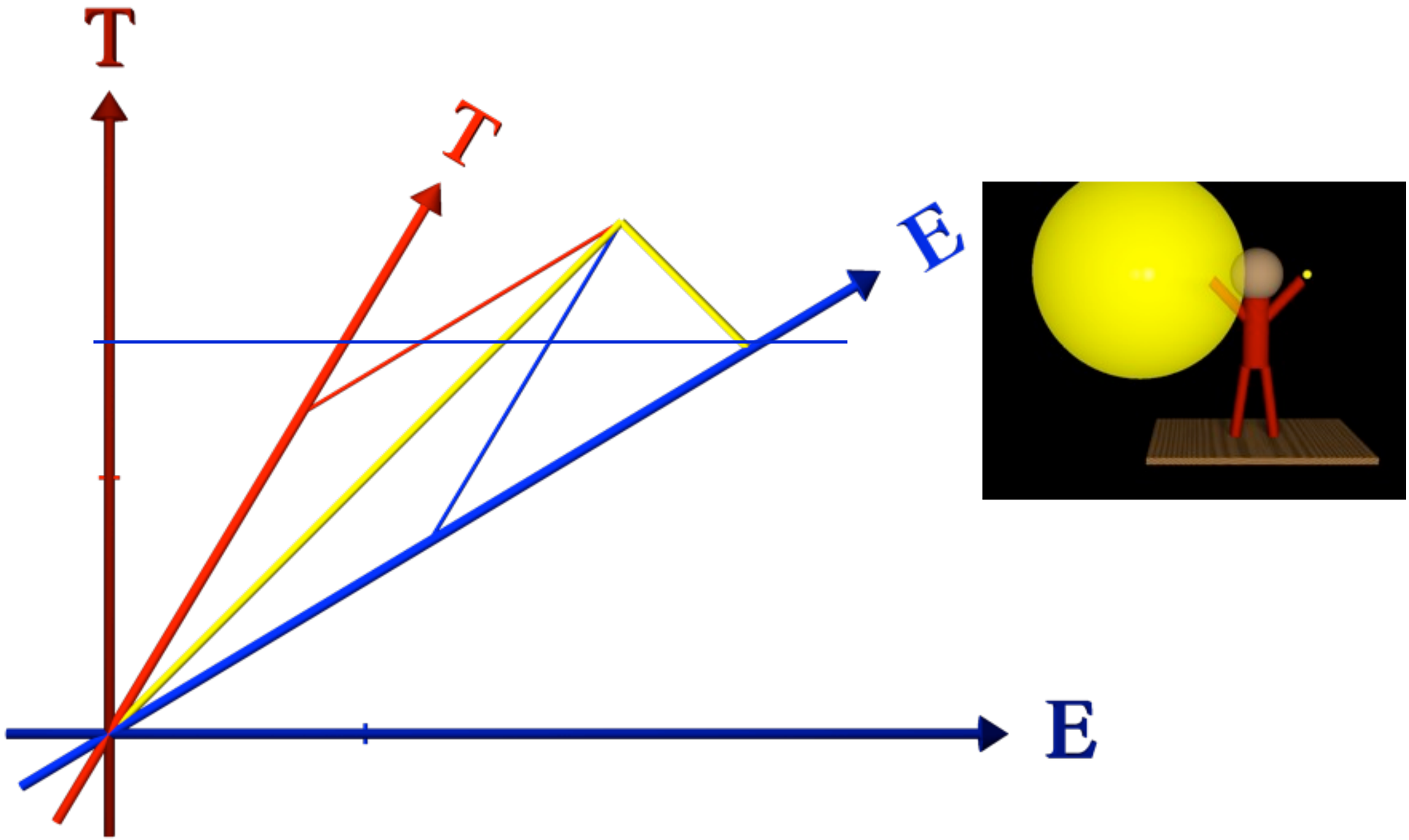
$$t' = \sqrt{d^2 + v^2 t'^2}/c$$

$$t'^2 c^2 = d^2 + v^2 t'^2$$

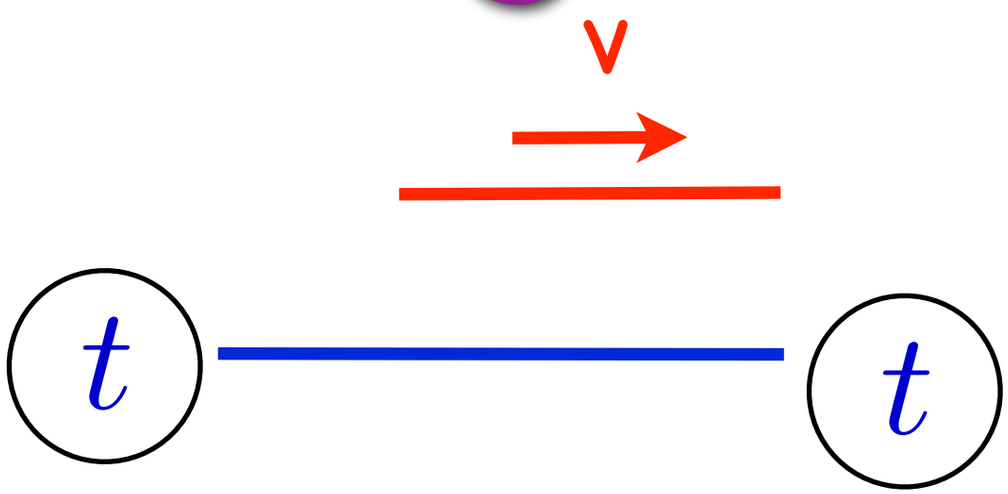
$$t' c \sqrt{1 - v^2/c^2} = d = ct$$

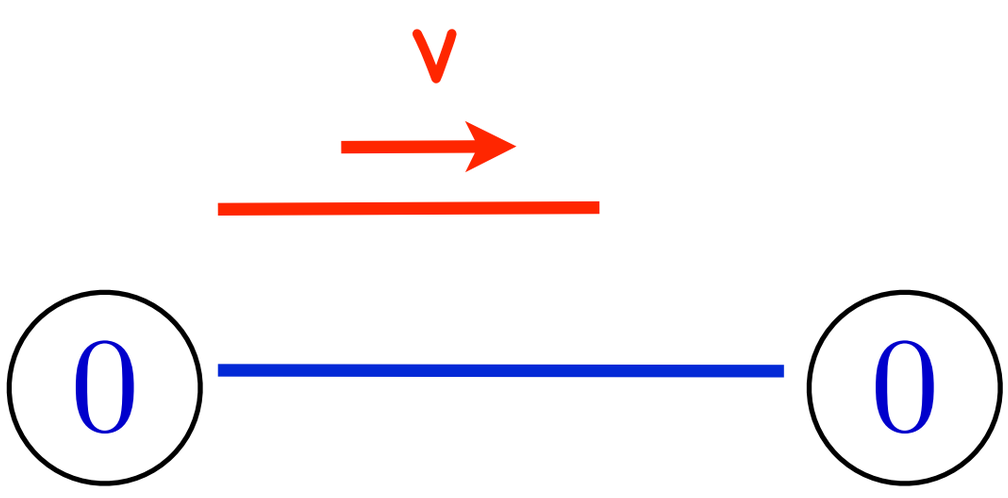
$$t' = \frac{t}{\sqrt{1 - v^2/c^2}}$$

Leading Clock is Behind

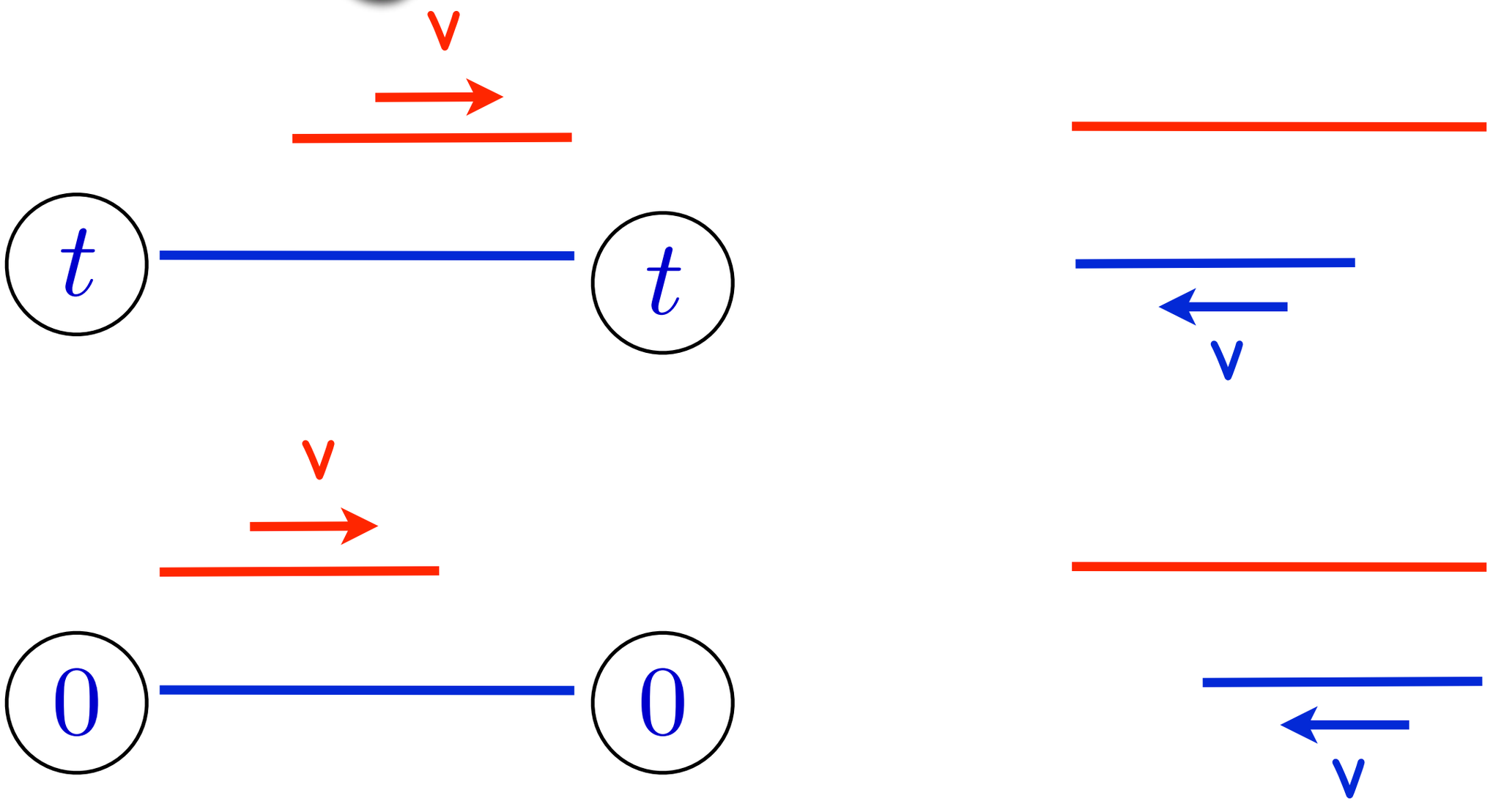


Length Contraction

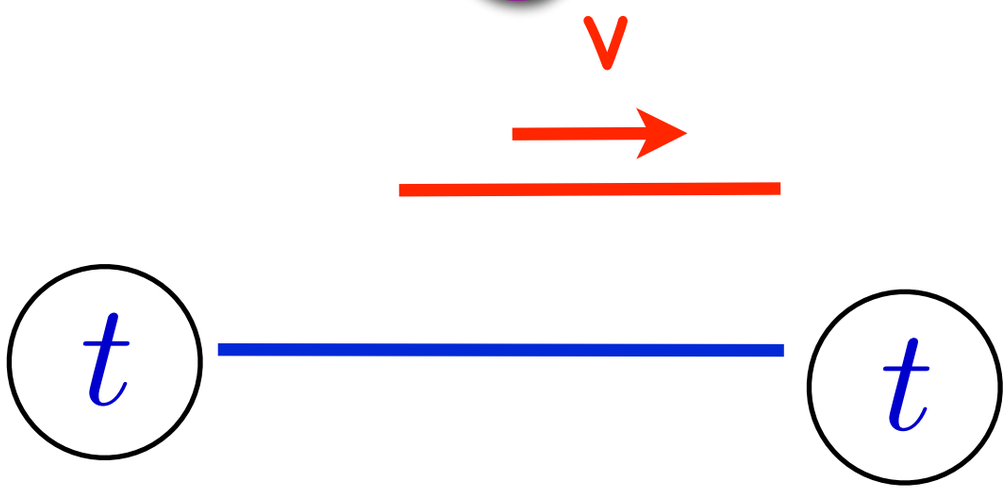


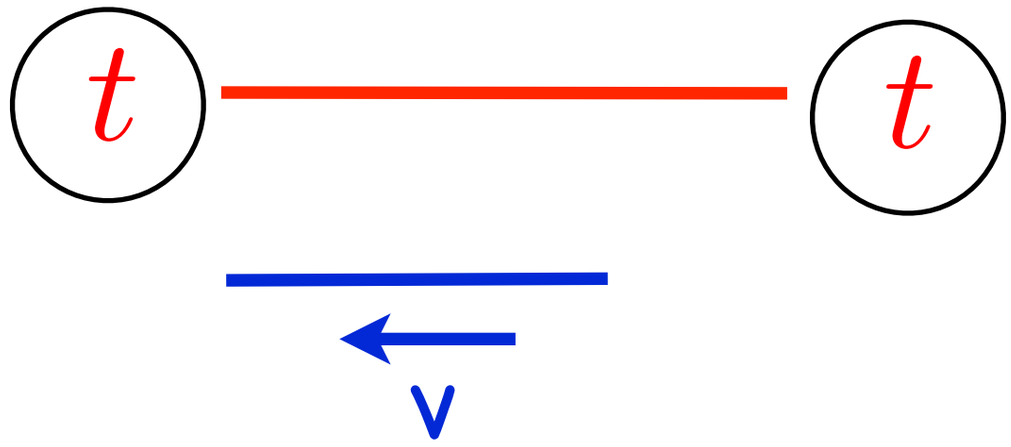


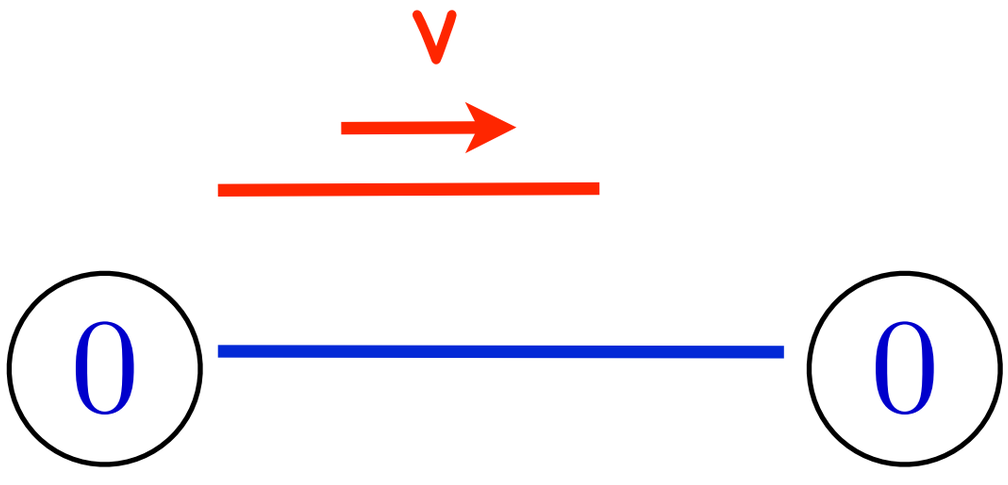
Length Contraction

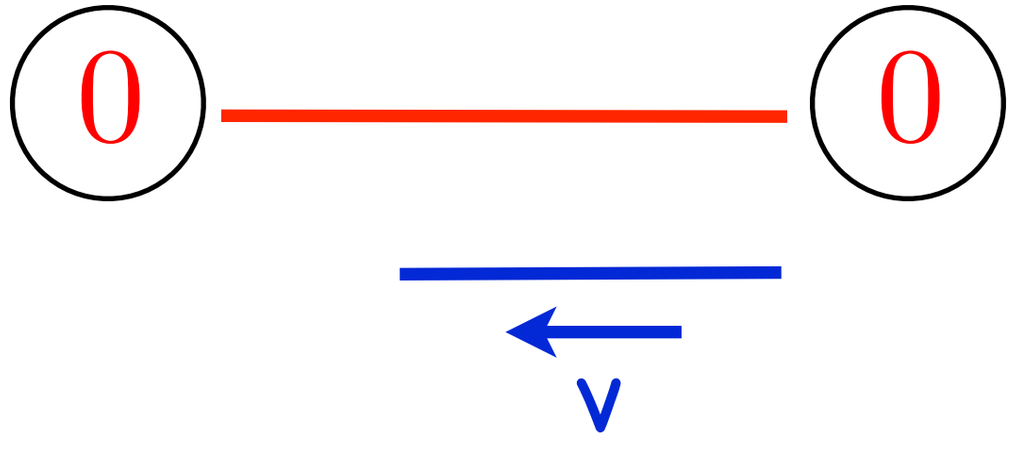


Length Contraction









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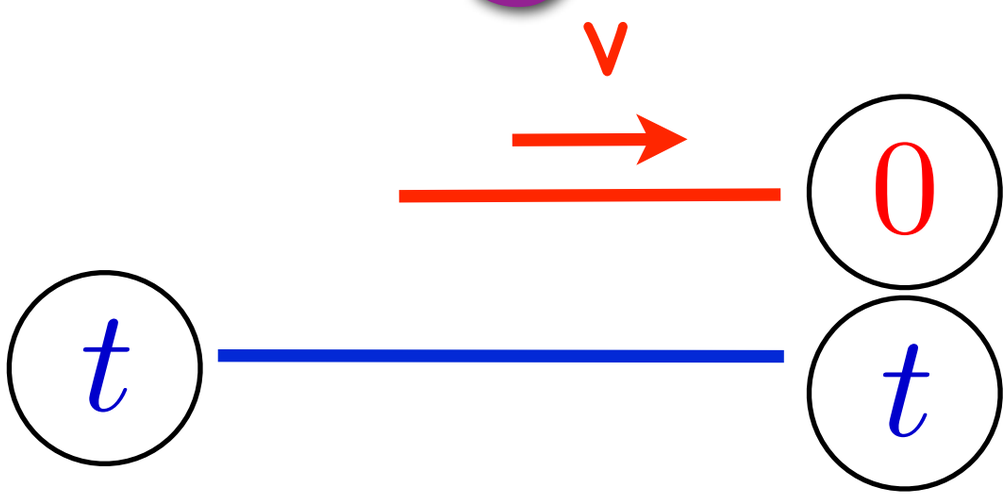
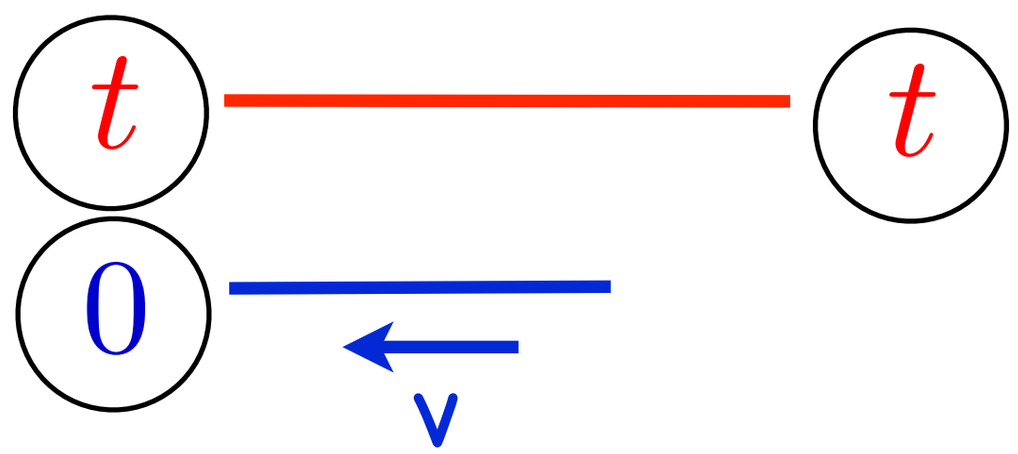
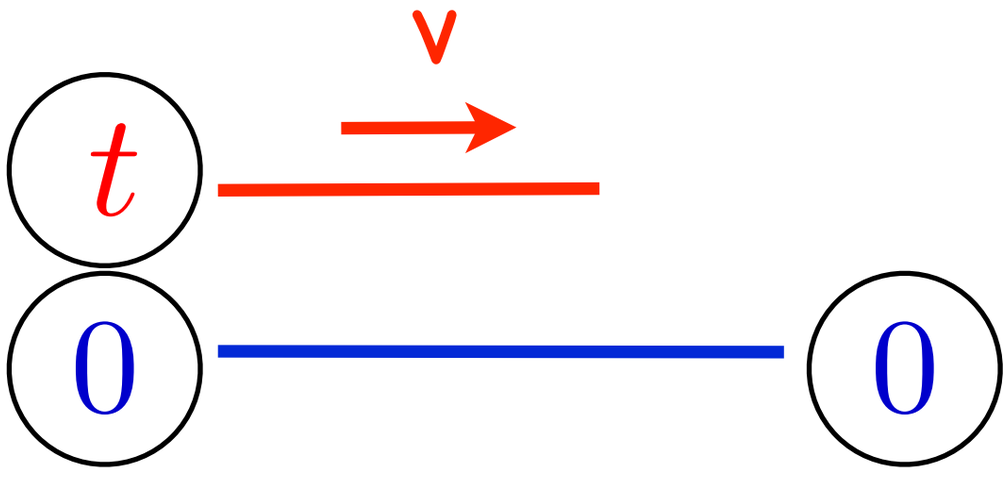
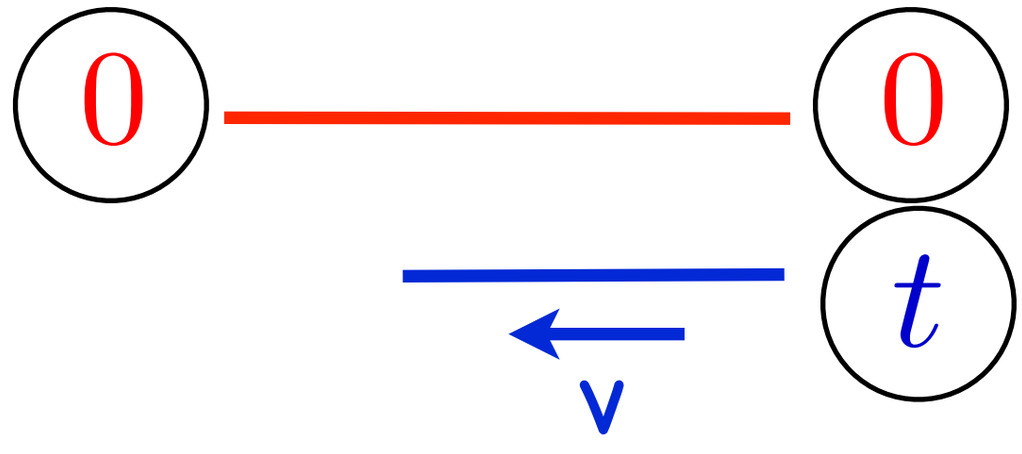
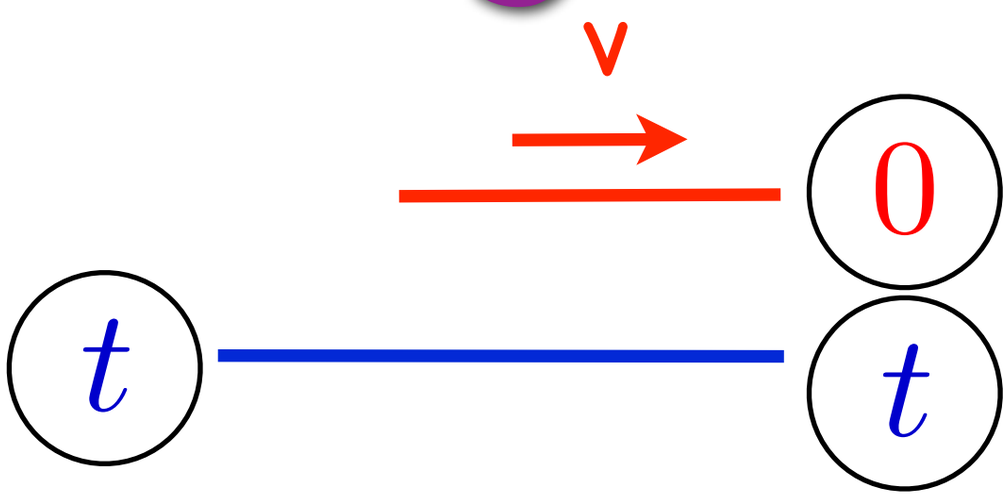


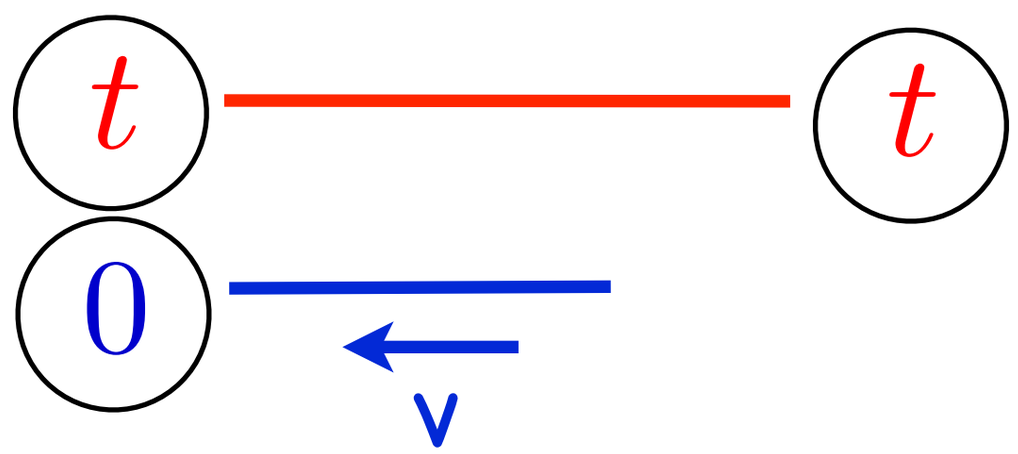


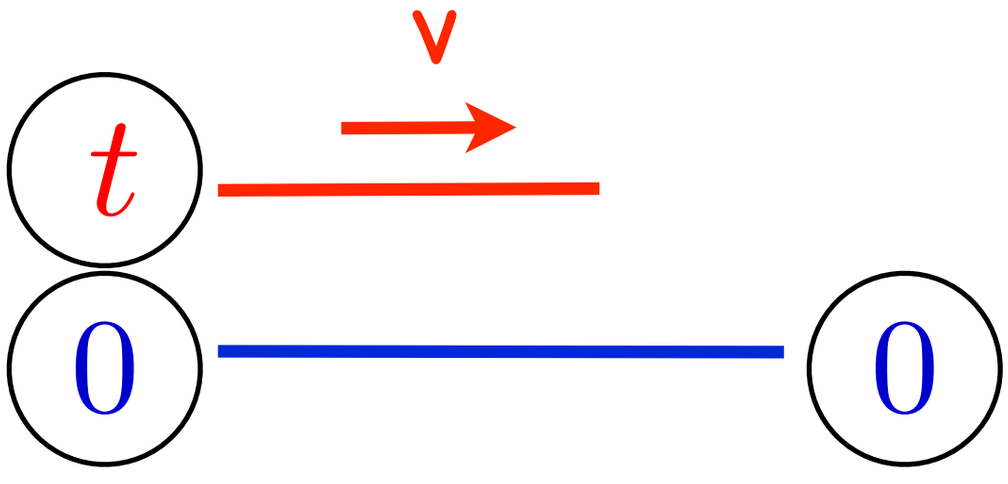


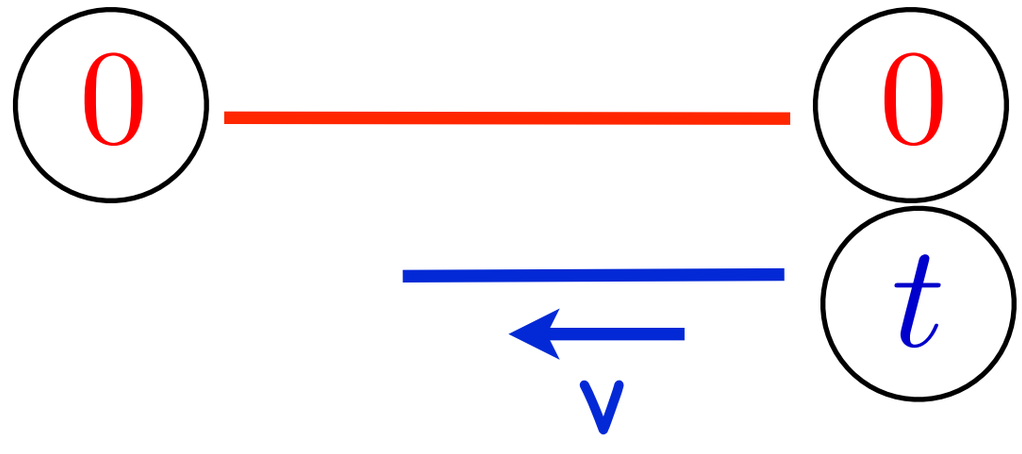


Length Contraction

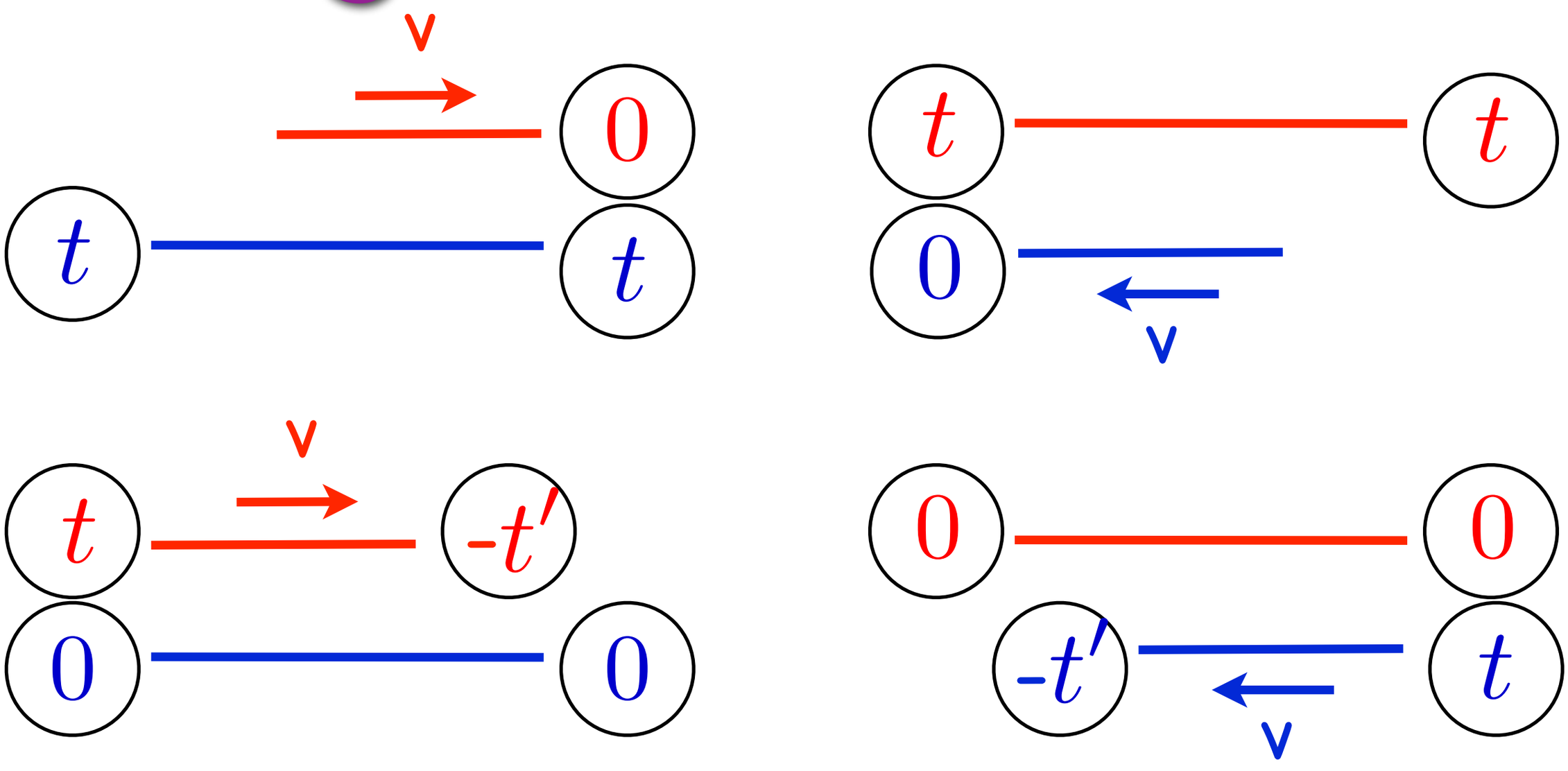




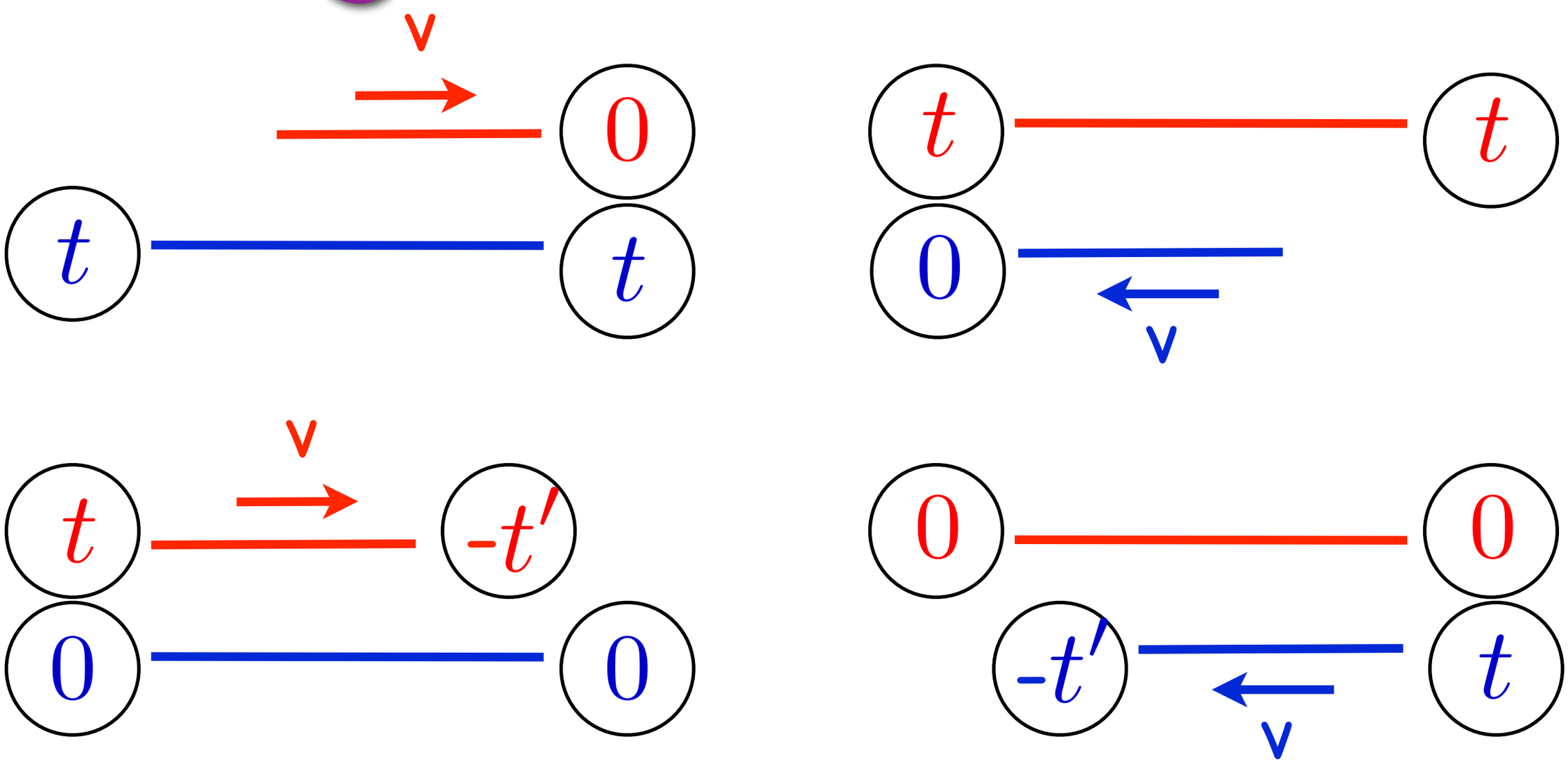




Length Contraction

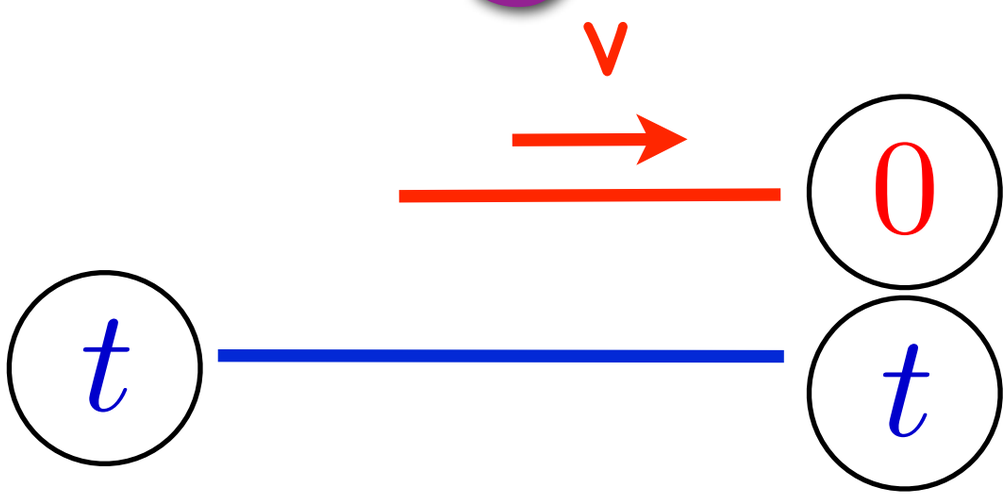


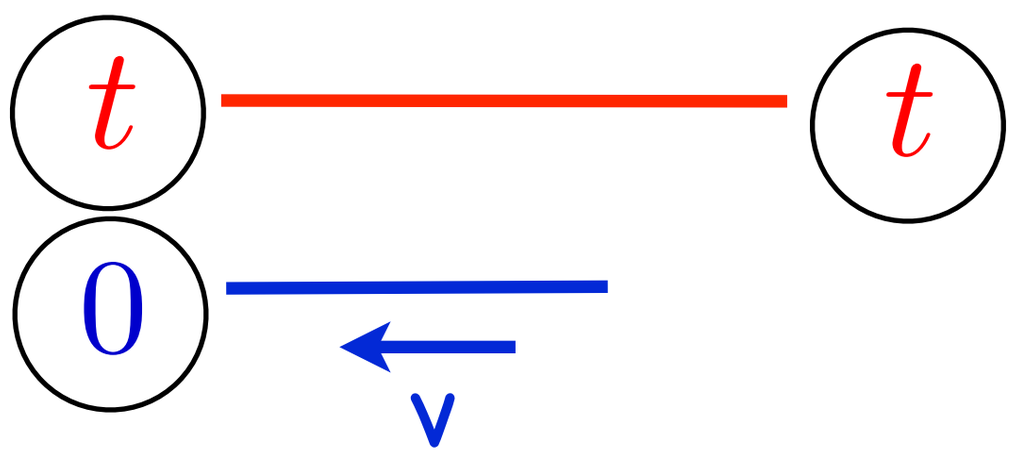
Length Contraction

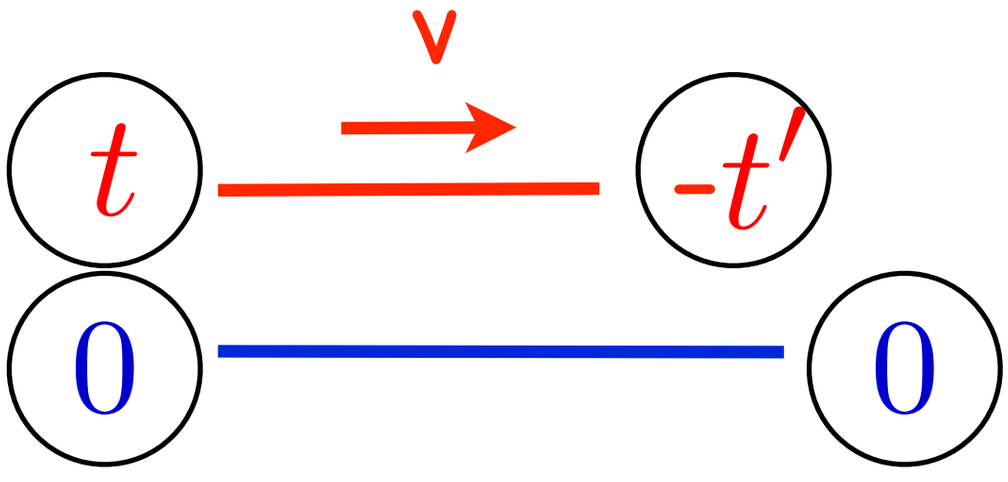


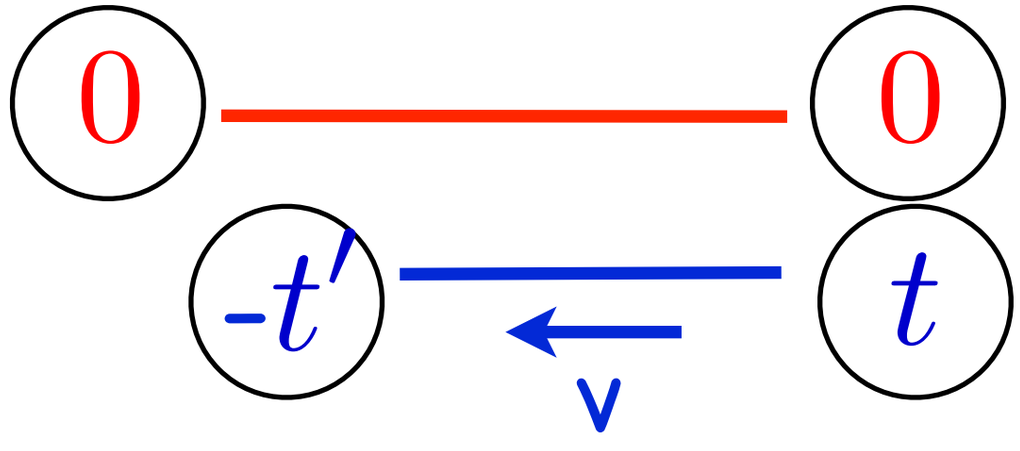
red shorter than blue

Length Contraction









red shorter than blue

blue shorter than red

Lorentz Transform

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$\begin{aligned} x^\mu &= (t, x, y, z) \\ x'^\mu &= (\gamma(t - \frac{\mathrm{v}}{c^2}\, x), \gamma(x - \mathrm{v}t)\ , y, z) \end{aligned}$$

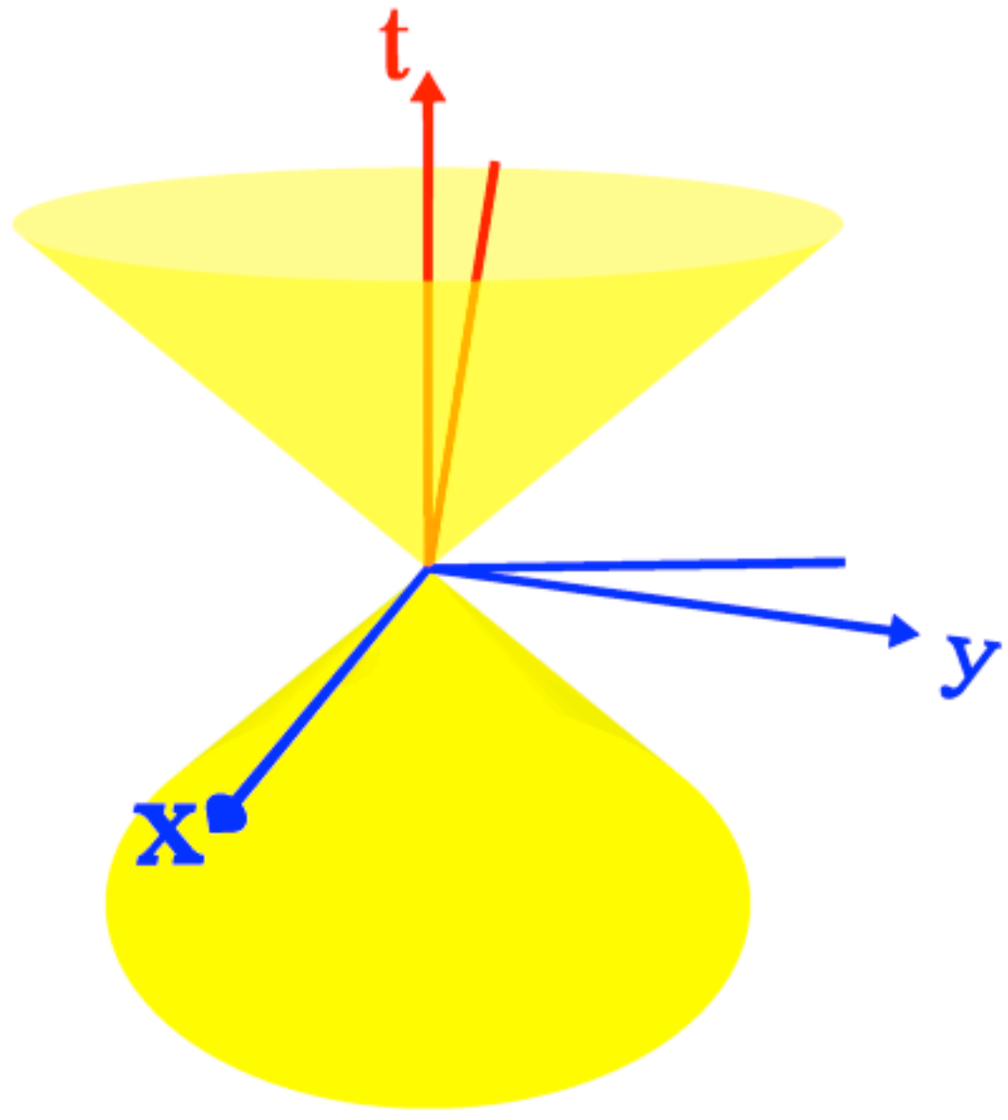
Lorentz Transform

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}}$$

$$\begin{aligned} x^\mu &= (t, x, y, z) \\ x'^\mu &= (\gamma(t - \frac{\mathrm{v}}{c^2}\, x), \gamma(x - \mathrm{v}t)\ , y, z) \end{aligned}$$

time and space coordinates
make up a four vector

Lorentz Transform



Four Vectors

$$\vec{p} = \gamma\, m\, \vec{v}$$

$$\begin{aligned} p^\mu &= (E/c, p_x, p_y, p_z) \\ p^2 &= p^\mu p_\mu = \frac{E^2}{c^2} - p_x^2 - p_y^2 - p_z^2 = m^2 c^2 \\ E^2 &= \vec{p}^{\,2} c^2 + m^2 c^4 \\ E &= \sqrt{\vec{p}^{\,2} c^2 + m^2 c^4} \end{aligned}$$

$$\vec{p} = 0 \quad \rightarrow \quad E = m\, c^2$$

Energy

$$
\begin{aligned}
E &= \sqrt{\vec{p}^{\,2}c^2 + m^2c^4} \\
&= \sqrt{\gamma^2 m^2 \vec{v}^{\,2} c^2 + m^2 c^4} \\
&= m\,c\sqrt{\frac{v^2}{1 - v^2/c^2} + c^2} \\
&= m\,c\sqrt{\frac{v^2 + c^2 - v^2}{1 - v^2/c^2}} \\
&= \gamma\, m\, c^2
\end{aligned}
$$

Application

a proton with $E = 3.5\,\mathrm{TeV}$

$$m_p = 938\,\mathrm{MeV}/c^2$$

$$\gamma = 3731$$

$$\frac{v}{c} = 0.999999964$$

Application

muon lifetime is $t = 2.2 \times 10^{-6}\,\mathrm{s}$

$$d_{max} = c\,t = 3 \times 10^{8}\,\mathrm{m/s} \times 2.2 \times 10^{-6}\,\mathrm{s} = 660\,\mathrm{m}$$

muons created by cosmic rays in upper atmosphere travel 15-20 km

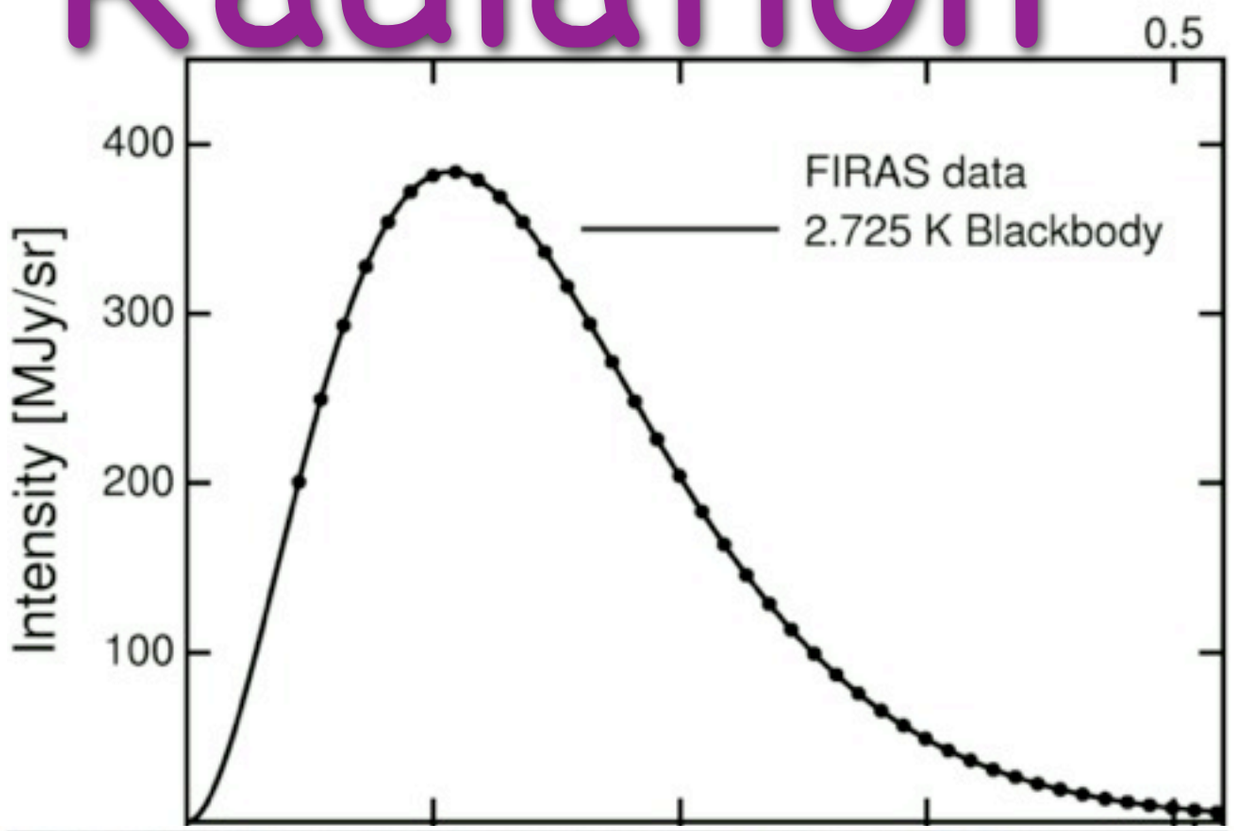
consider a high energy muon: $E = \gamma\, mc^2 = 100\,\mathrm{GeV}$

$$\gamma \approx 950$$

$$d_{max} = c\,\gamma\,t = 627\,\mathrm{km}$$

Quantum Mechanics

Blackbody Radiation

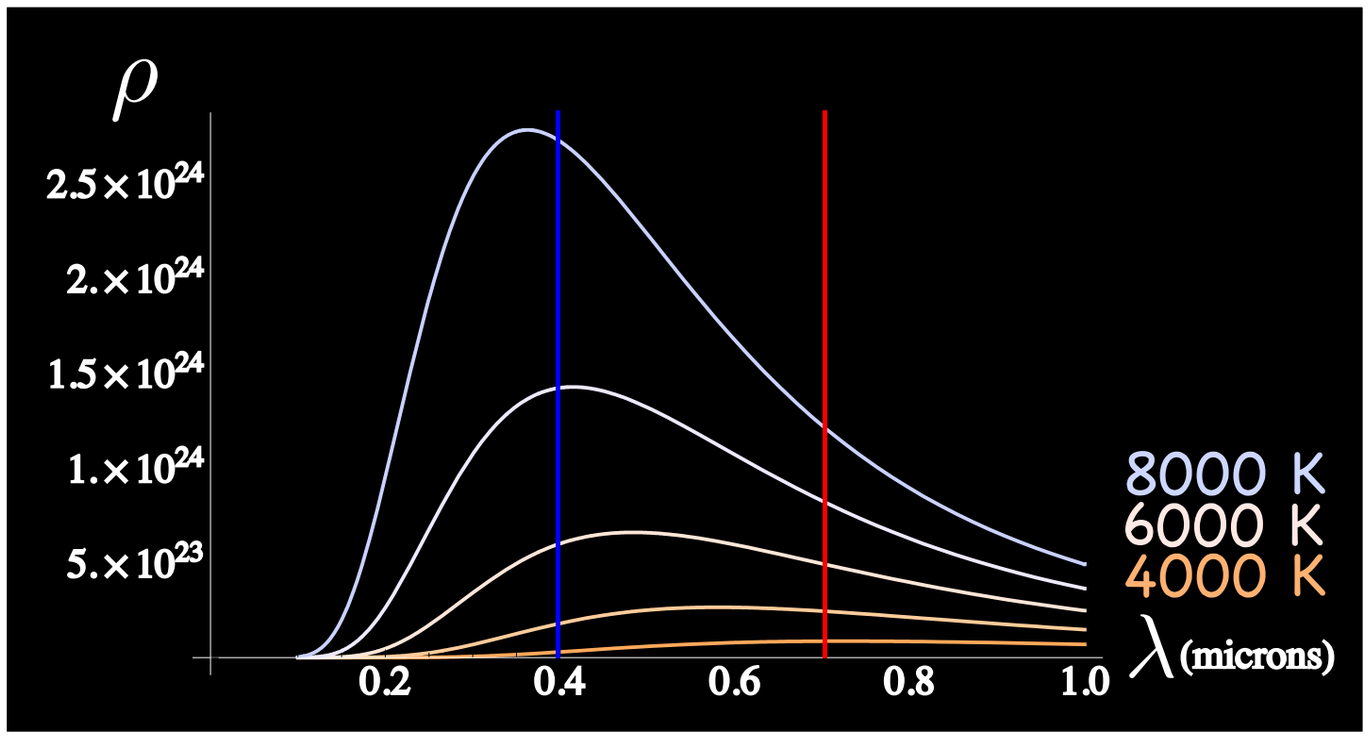


Blackbody Radiation

classical energy density: $\rho_c(\lambda) = \dfrac{k_B T}{\lambda^4}$

infinite energy density a zero wavelength

Blackbody Radiation

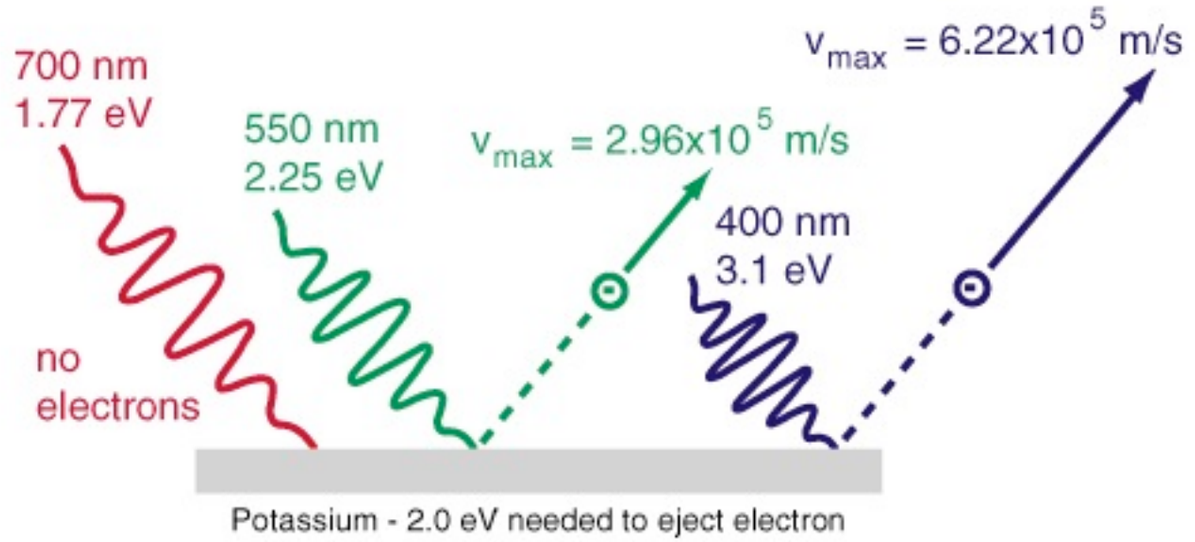


$$\rho(\lambda) = \frac{2\,c\,h}{\lambda^5(e^{hc/(\lambda k_B T)} - 1)}$$

Hilfsgröβe

$$h = 6.63 \times 10^{-34}\text{Joules} \cdot \text{seconds}$$
$$= 4.14 \times 10^{-15}\text{eV} \cdot \text{seconds}$$

Photoelectric Effect



$$E = h\,f = \hbar\,2\pi\,f = \hbar\omega$$

Photoelectric Effect

$$E = h\,f = \hbar\,2\pi f = \hbar\omega$$

light is made of packets of energy
called photons

Natural Units

$$\hbar = c = 1$$

$$1\,\mathrm{kg} = 5.61 \times 10^{26}\,\mathrm{GeV} \qquad \frac{\mathrm{GeV}}{c^2}$$

$$1\,\mathrm{m} = 5.07 \times 10^{15}\,\mathrm{GeV}^{-1} \qquad \frac{\hbar\, c}{\mathrm{GeV}}$$

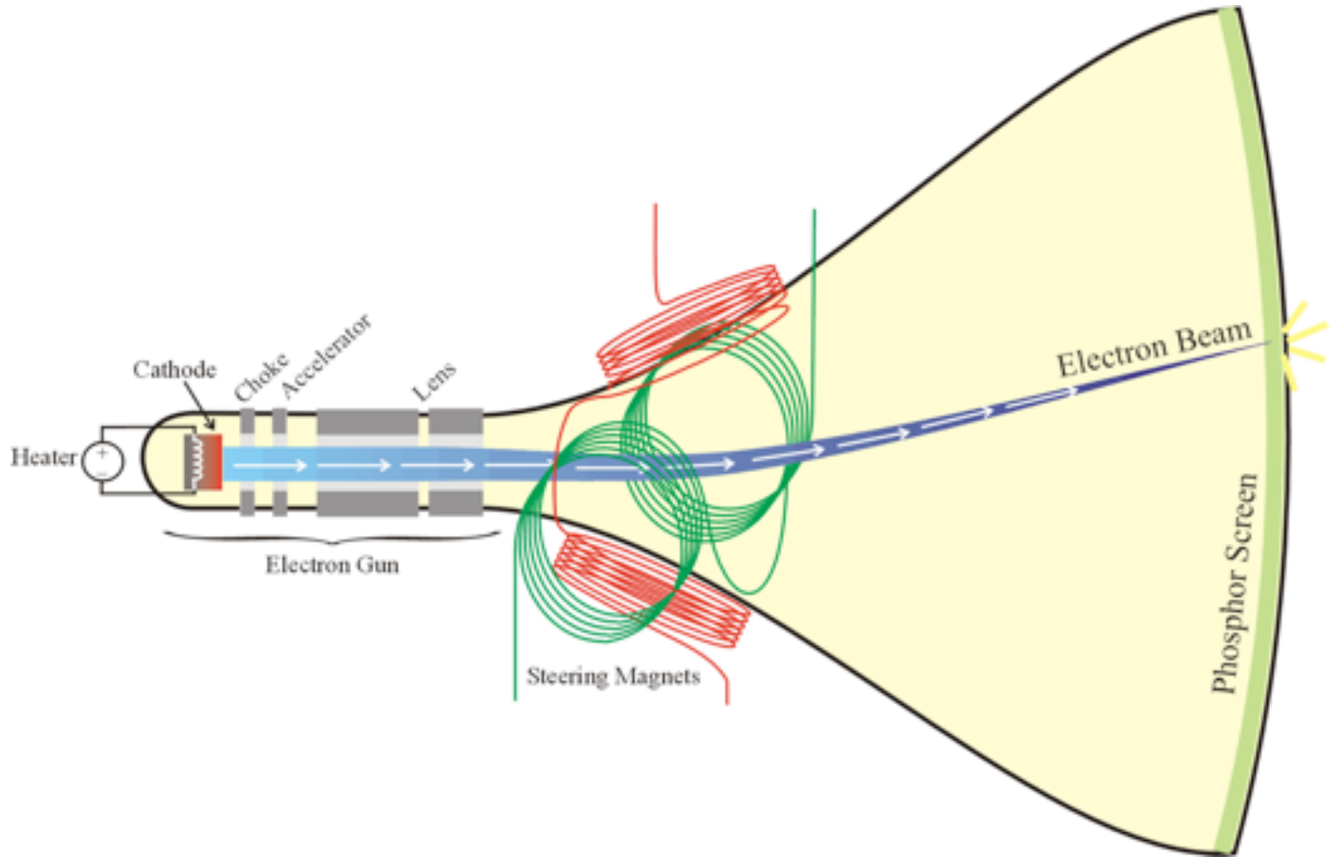
$$1\,\mathrm{s} = 1.52 \times 10^{24}\,\mathrm{GeV}^{-1} \qquad \frac{\hbar}{\mathrm{GeV}}$$

$$e = 0.303 \qquad (\hbar\, c)^{1/2}$$

$$1\,\mathrm{TeV} = 10^3\,\mathrm{GeV} = 10^{12}\,\mathrm{eV}$$

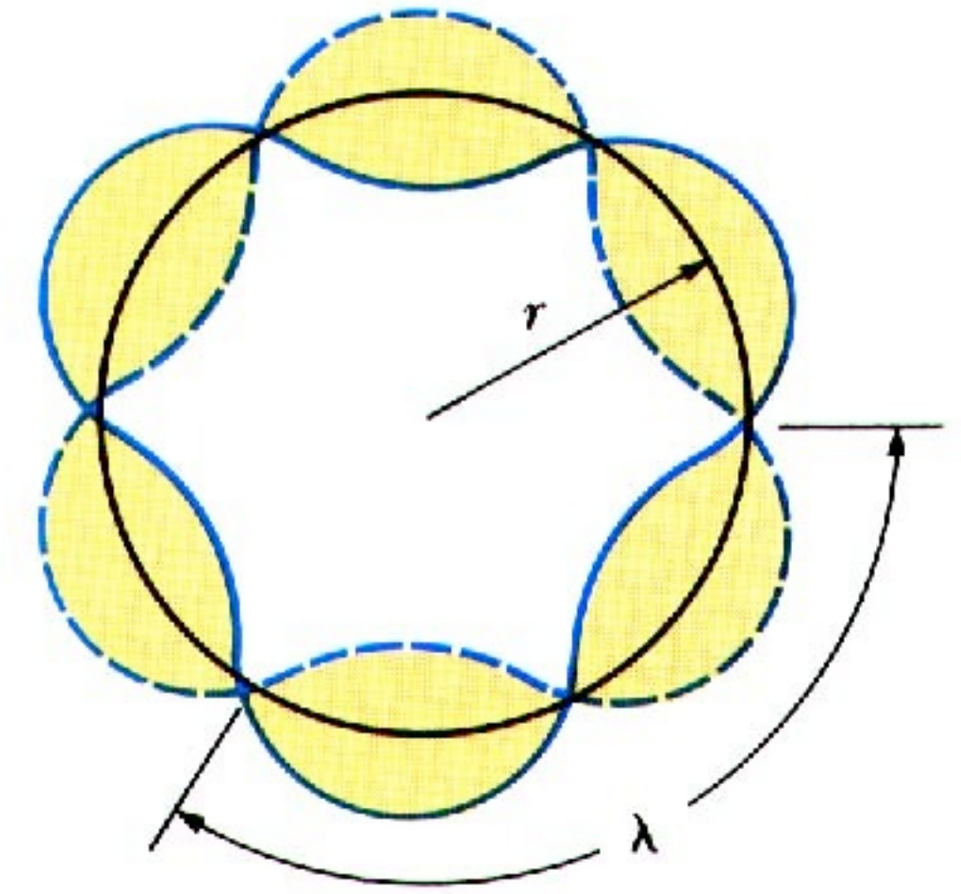
$$1\,\mathrm{fm} = 10^{-15}\,m = 5.07\,\mathrm{GeV}^{-1}$$

J.J. Thomson



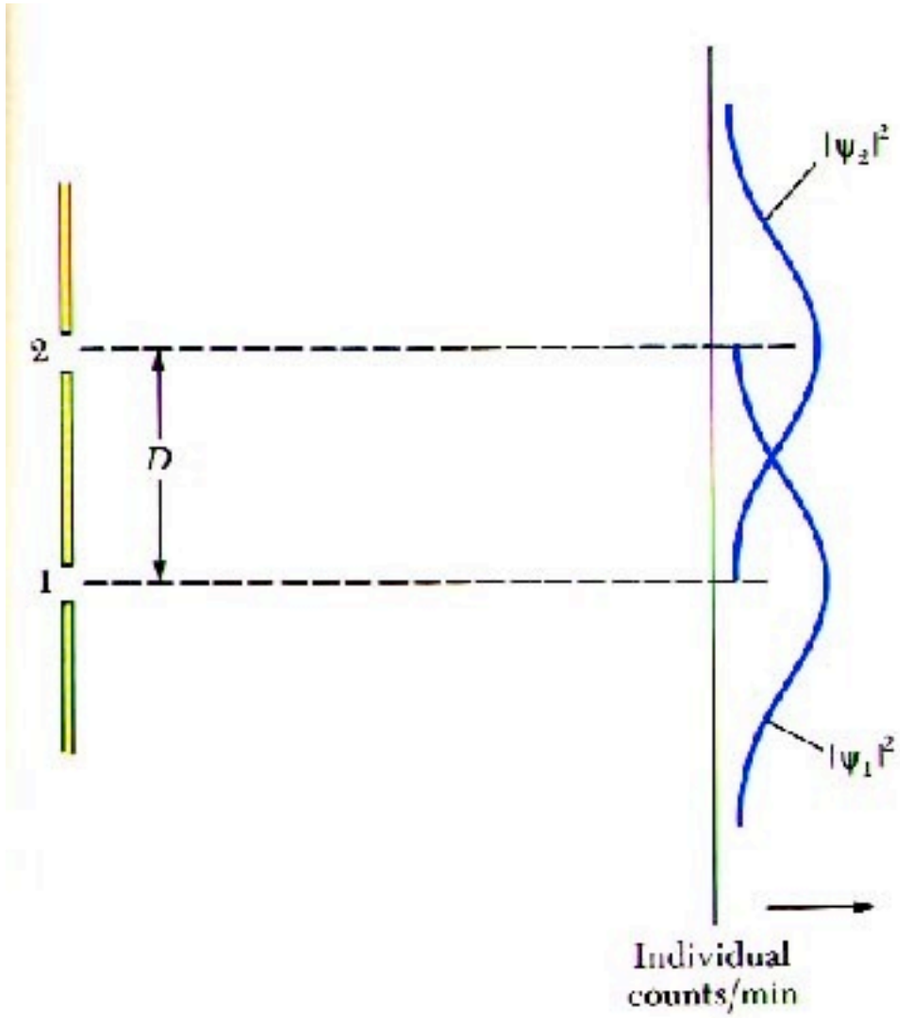
discovered electron in 1897

Bohr and de Broglie

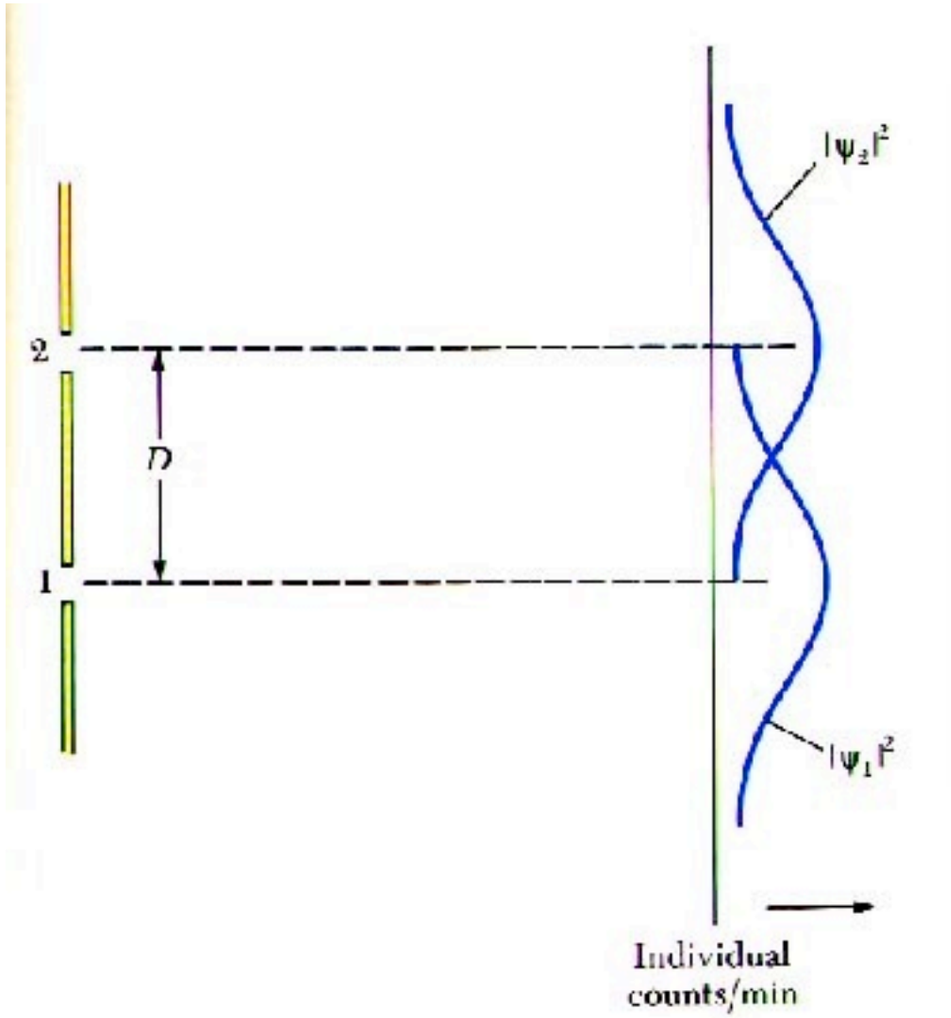


electron should also have wave behavior

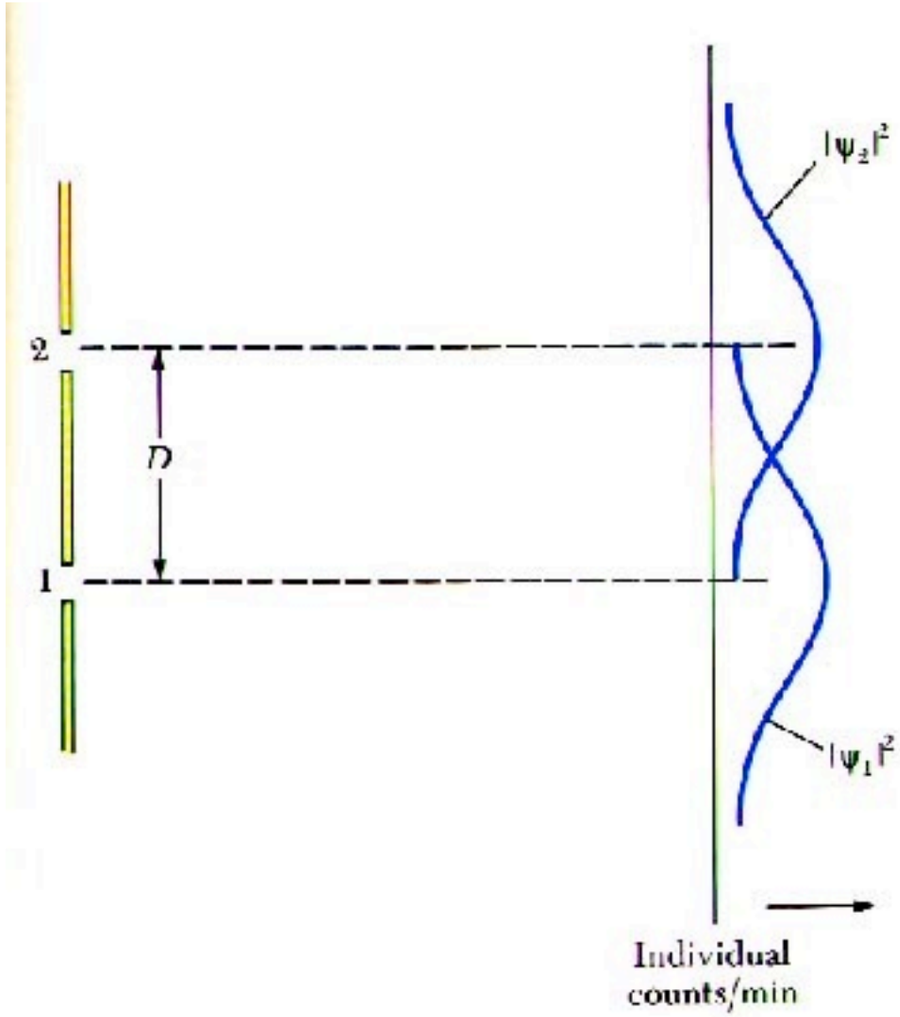
Double Slit Revisited

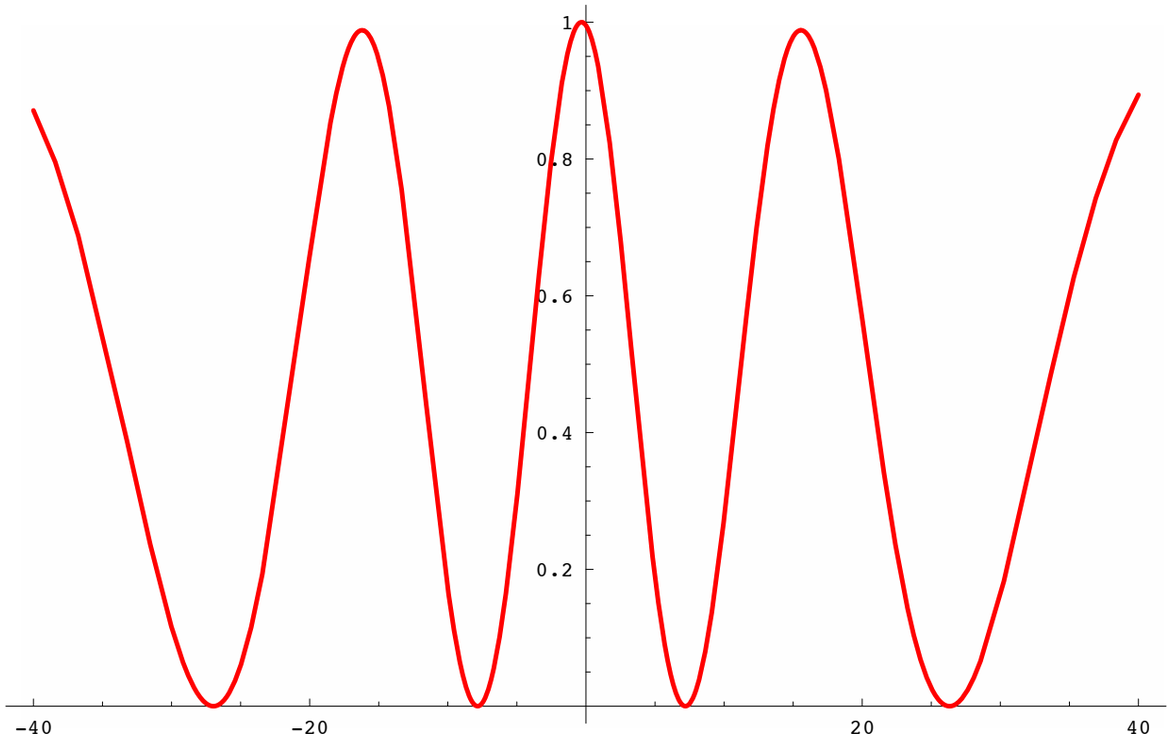


Double Slit Revisited

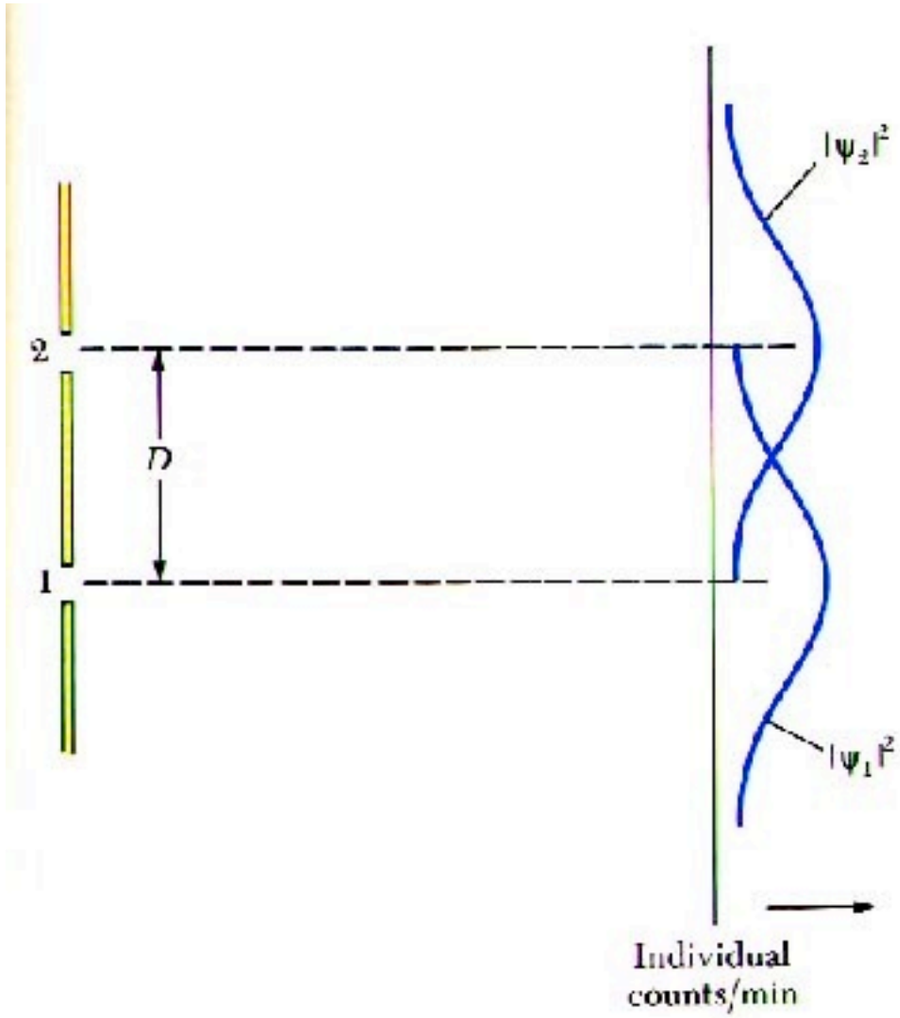


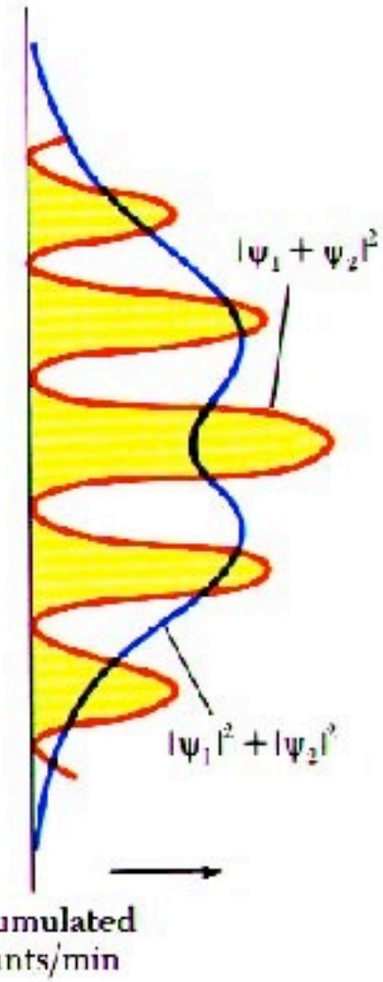
Double Slit Revisited





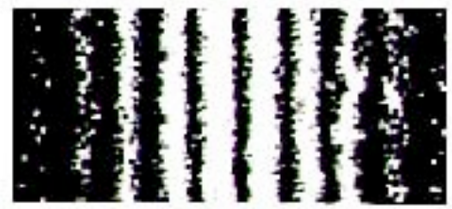
Double Slit Revisited






(a) After 28 electrons


(b) After 1000 electrons

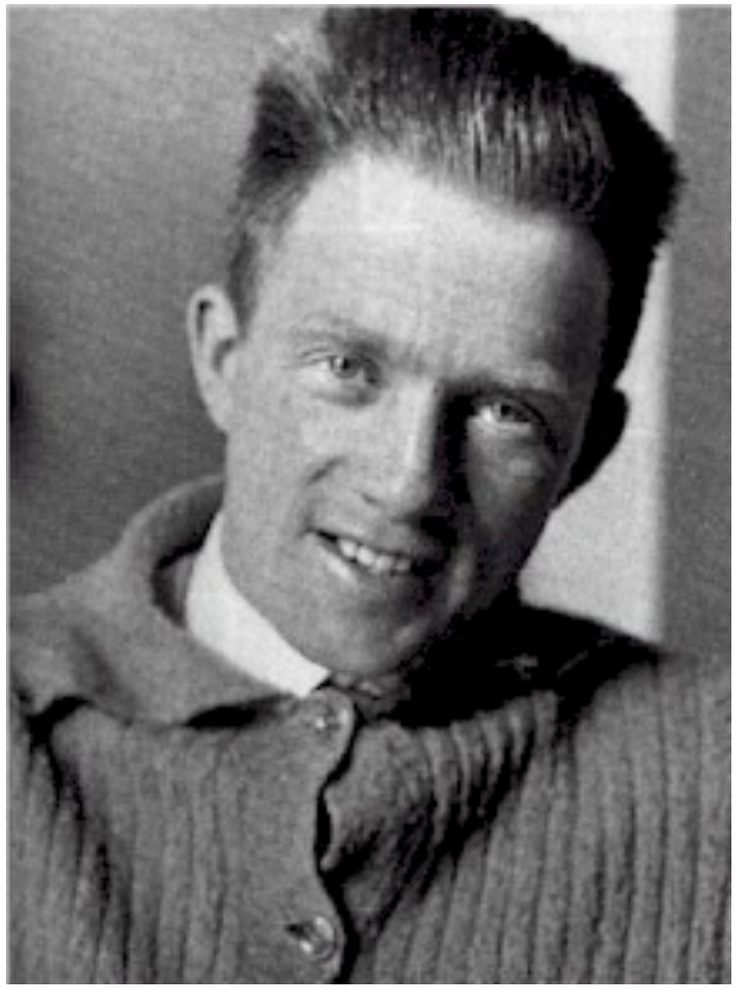

(c) After 10,000 electrons


(d) Two slit electron pattern

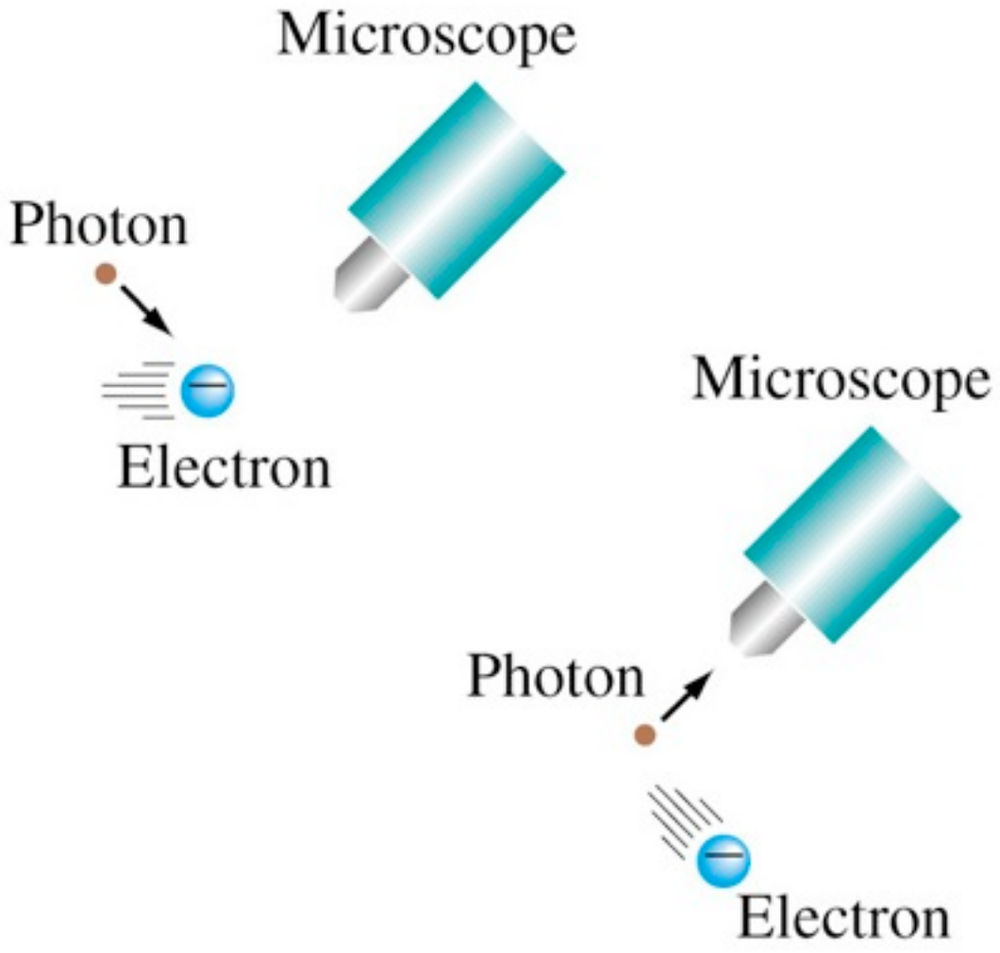
probability = | probability amplitude |^2

probability amplitude acts like a wave

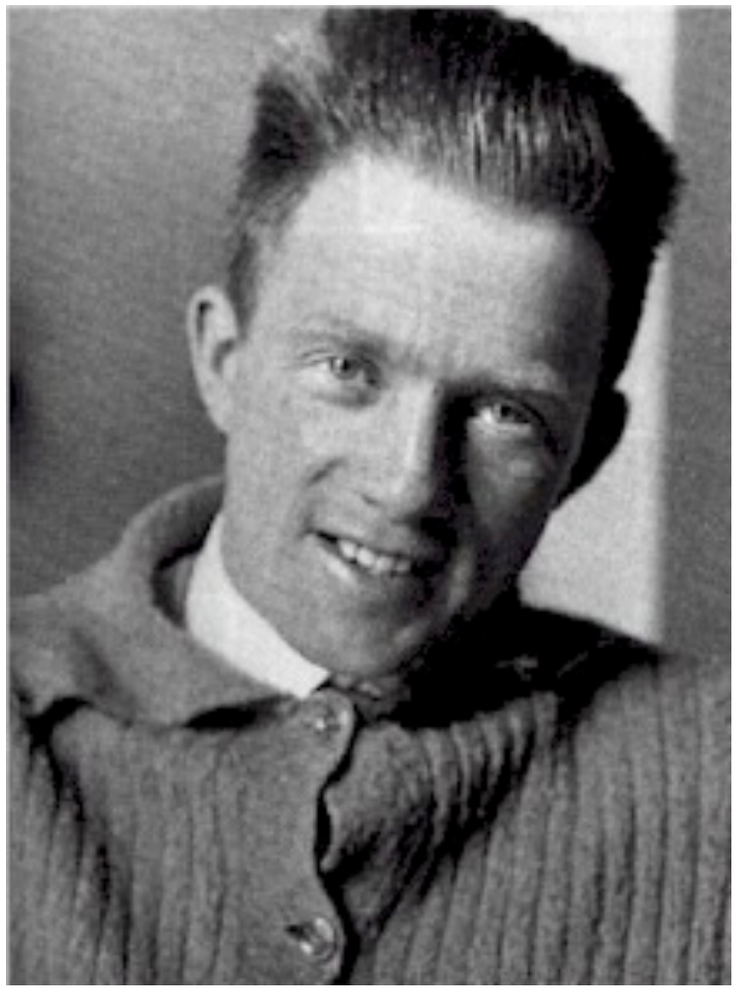
Uncertainty Principle



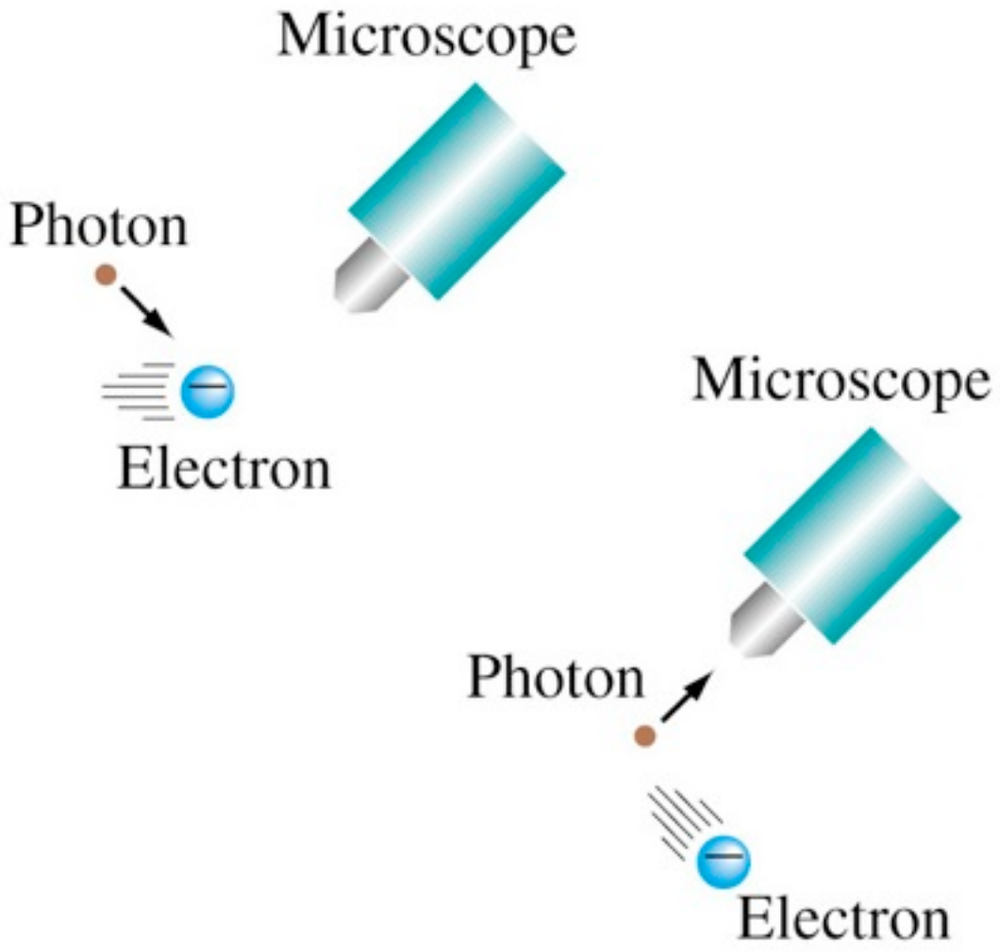
Heisenberg



Uncertainty Principle



Heisenberg



$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

Uncertainty Principle

$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

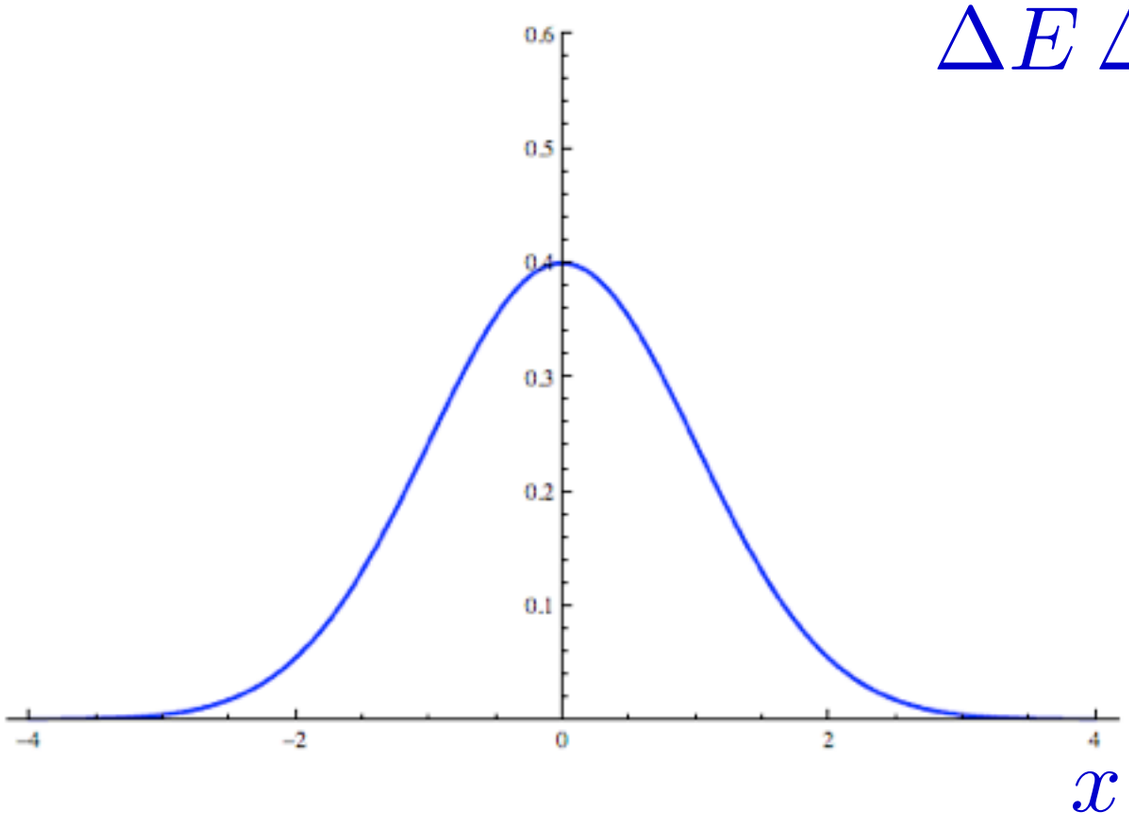
$$\Delta E \, \Delta t \geq \frac{\hbar}{2}$$

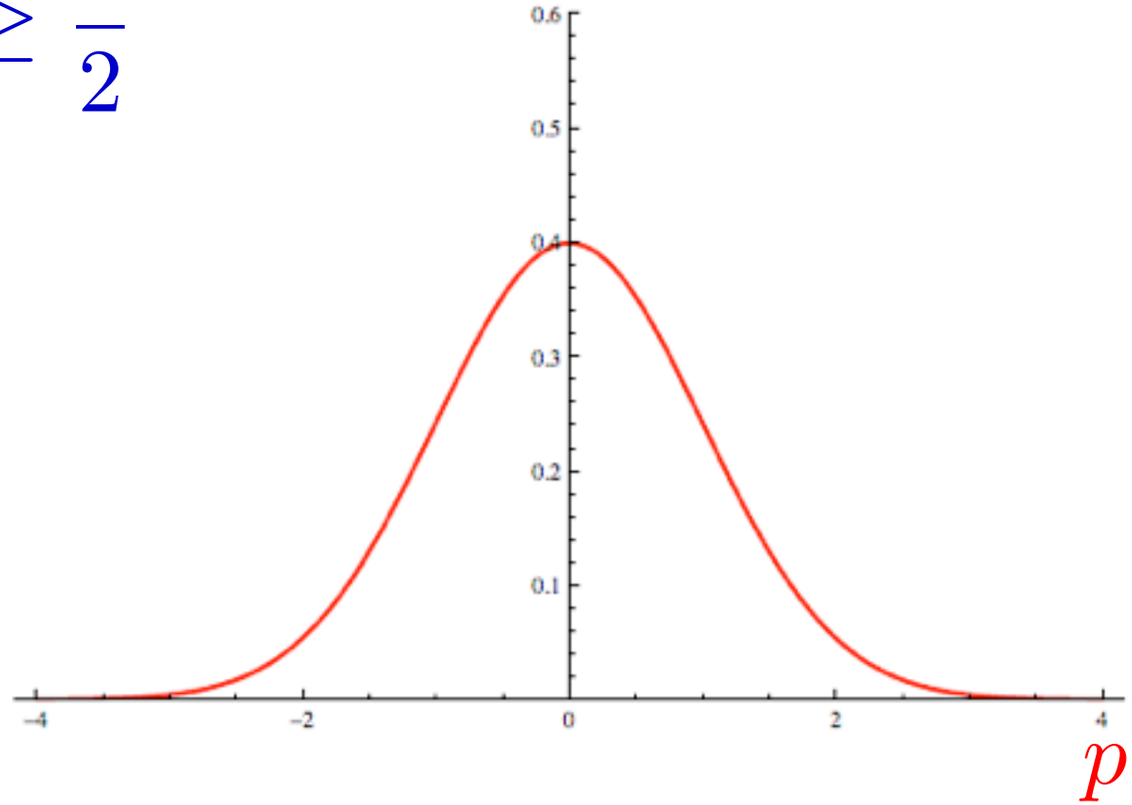
x p

Uncertainty Principle

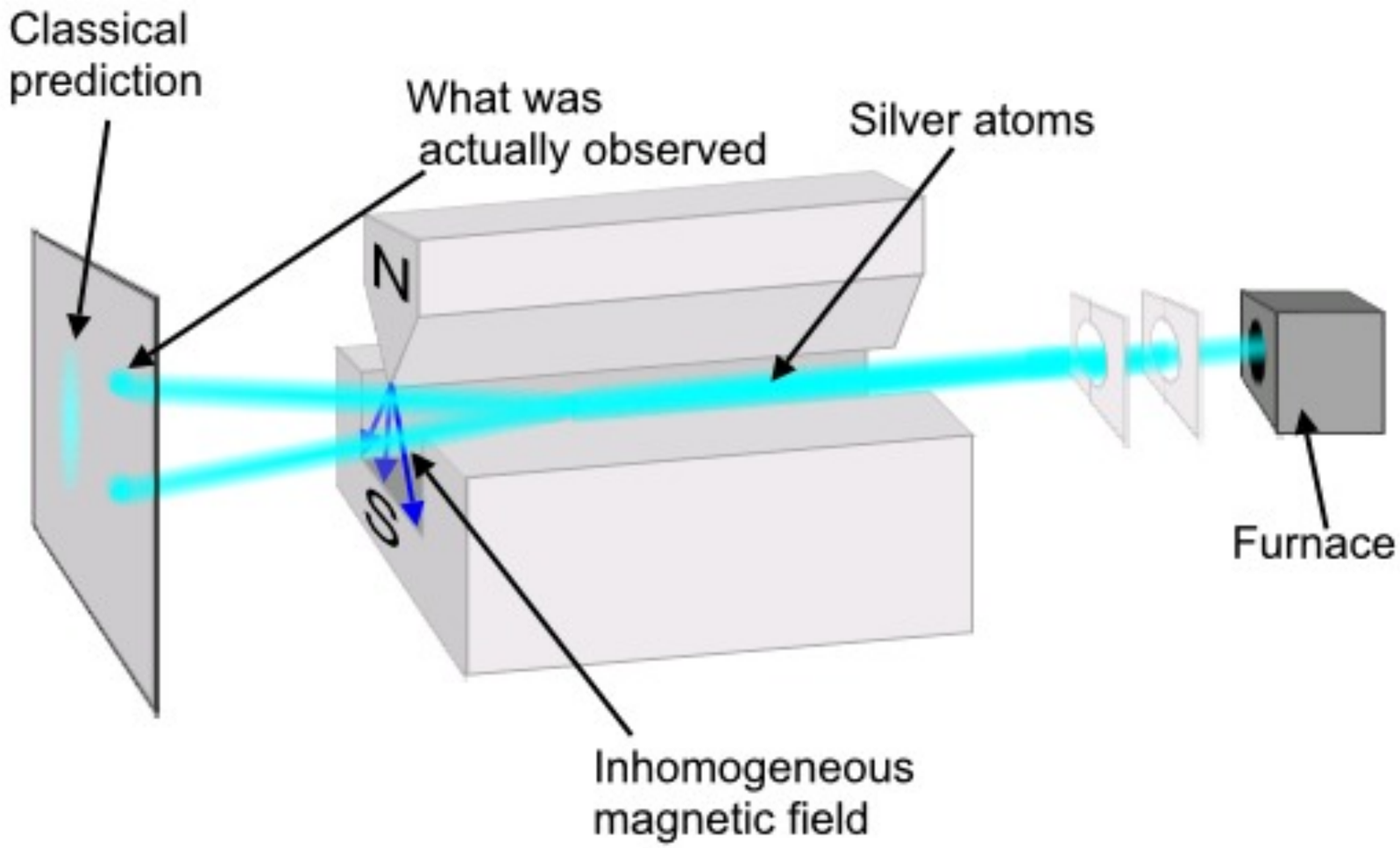
$$\Delta x \, \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \, \Delta t \geq \frac{\hbar}{2}$$





Stern-Gerlach



Stern-Gerlach

suppose electron has intrinsic angular momentum

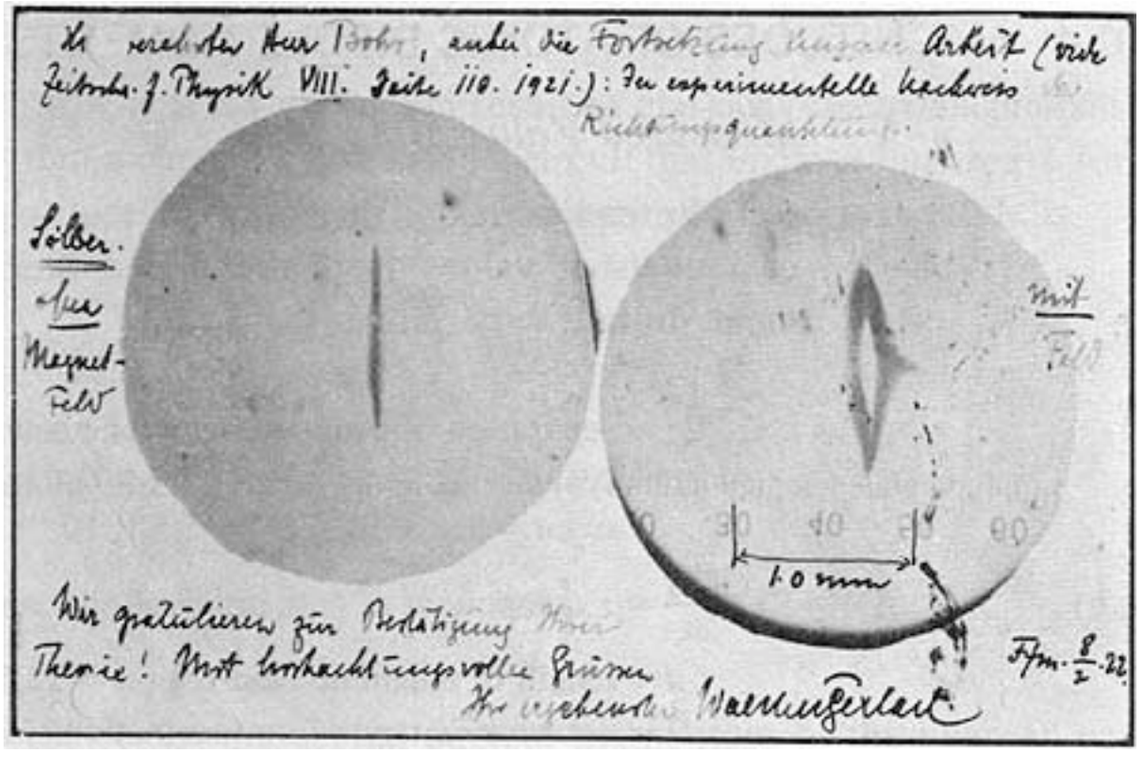
$$\rightarrow$$

$$\vec{\mu} = \gamma S$$

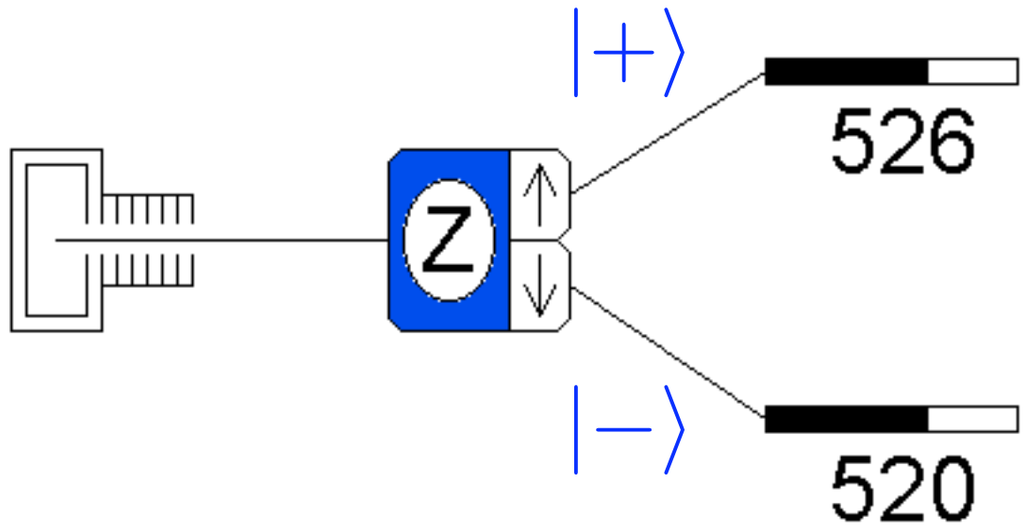
$$F_z = \gamma S_z \frac{\partial B_z}{\partial z}$$

$$S_z = \pm \frac{\hbar}{2}$$

Stern-Gerlach

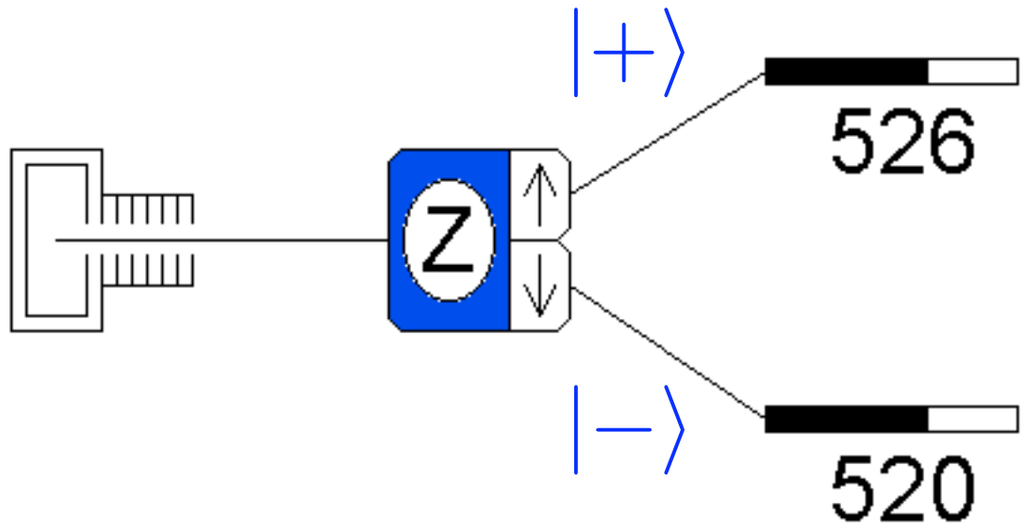


Stern-Gerlach



simulation software: http://bit.ly/spinsoft

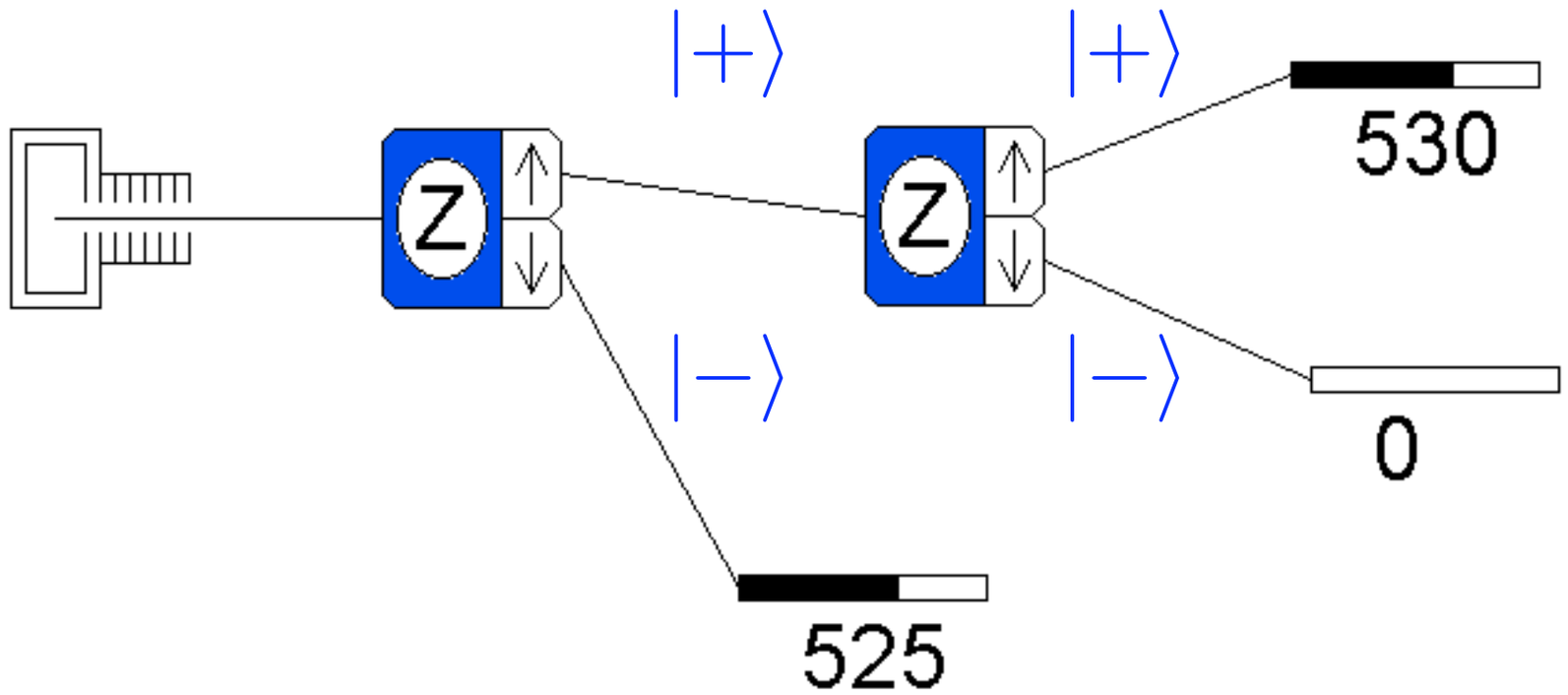
Stern-Gerlach



observables are Hermitian operators, they act on states

$$S_z \qquad |+\rangle \qquad |-\rangle$$

Stern-Gerlach

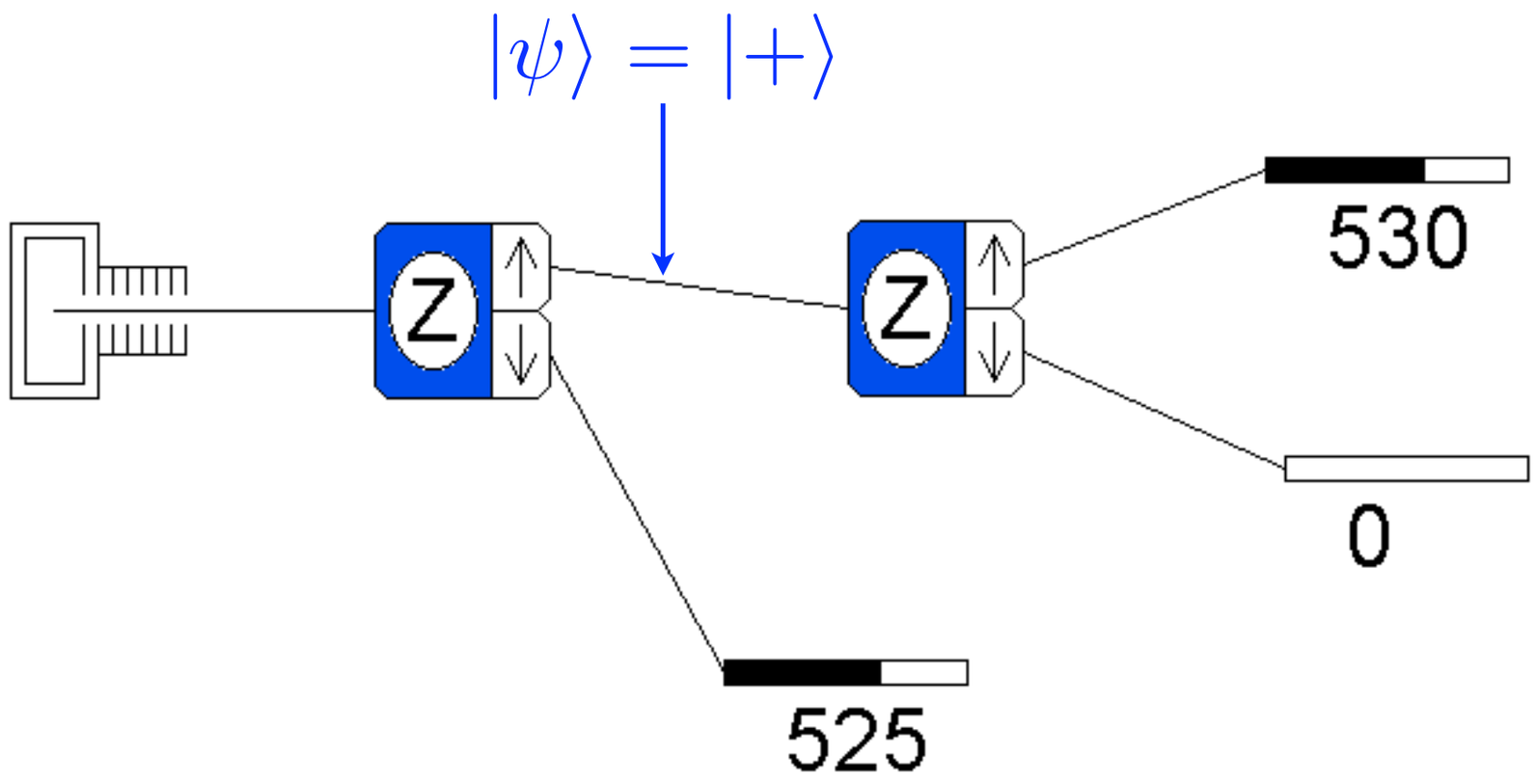


the only possible result of a measurement is an eigenvalue of the operator

$$S_z|+\rangle = +\frac{\hbar}{2}|+\rangle$$

$$S_z|-\rangle = -\frac{\hbar}{2}|-\rangle$$

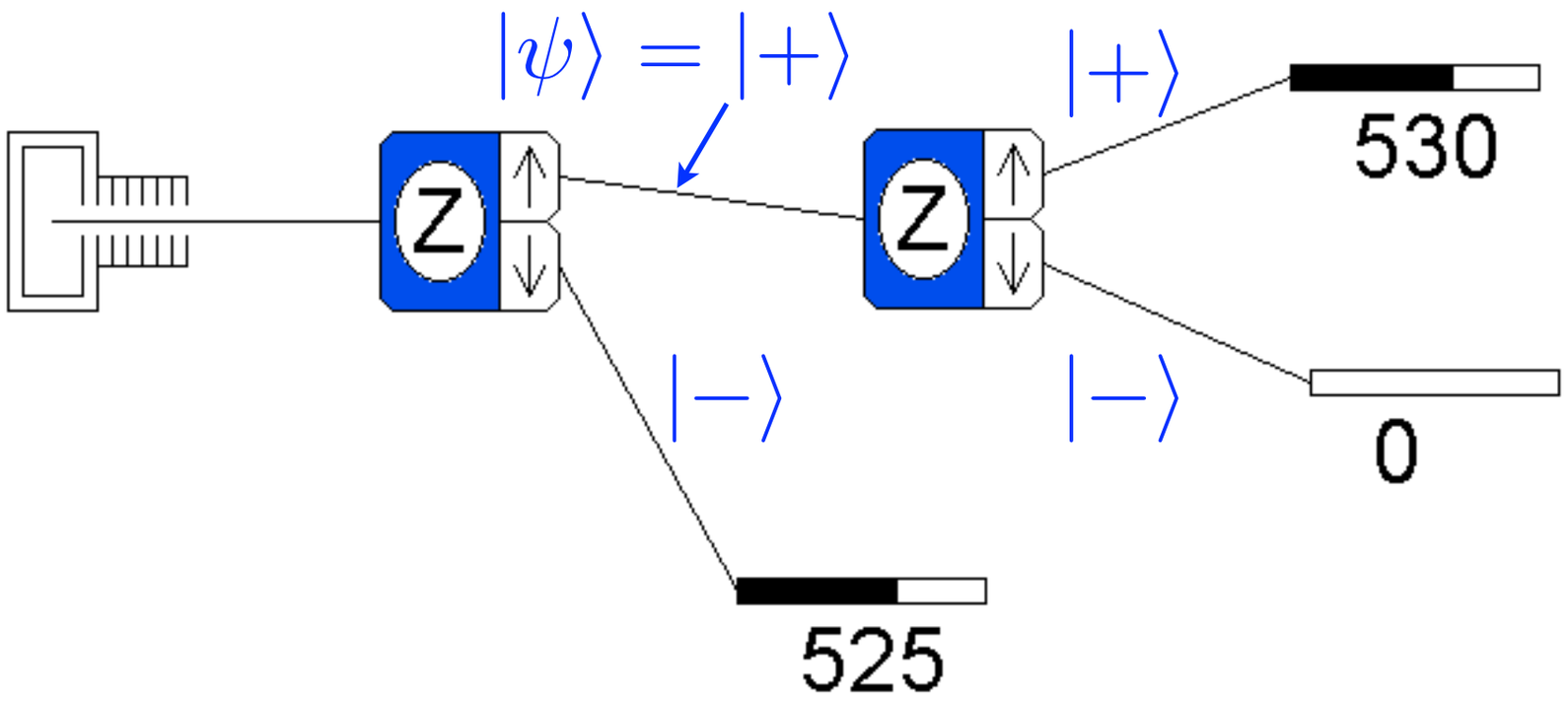
Stern-Gerlach



the probability of measuring + or - is

$$|\langle +|\psi\rangle|^2$$
$$|\langle -|\psi\rangle|^2$$

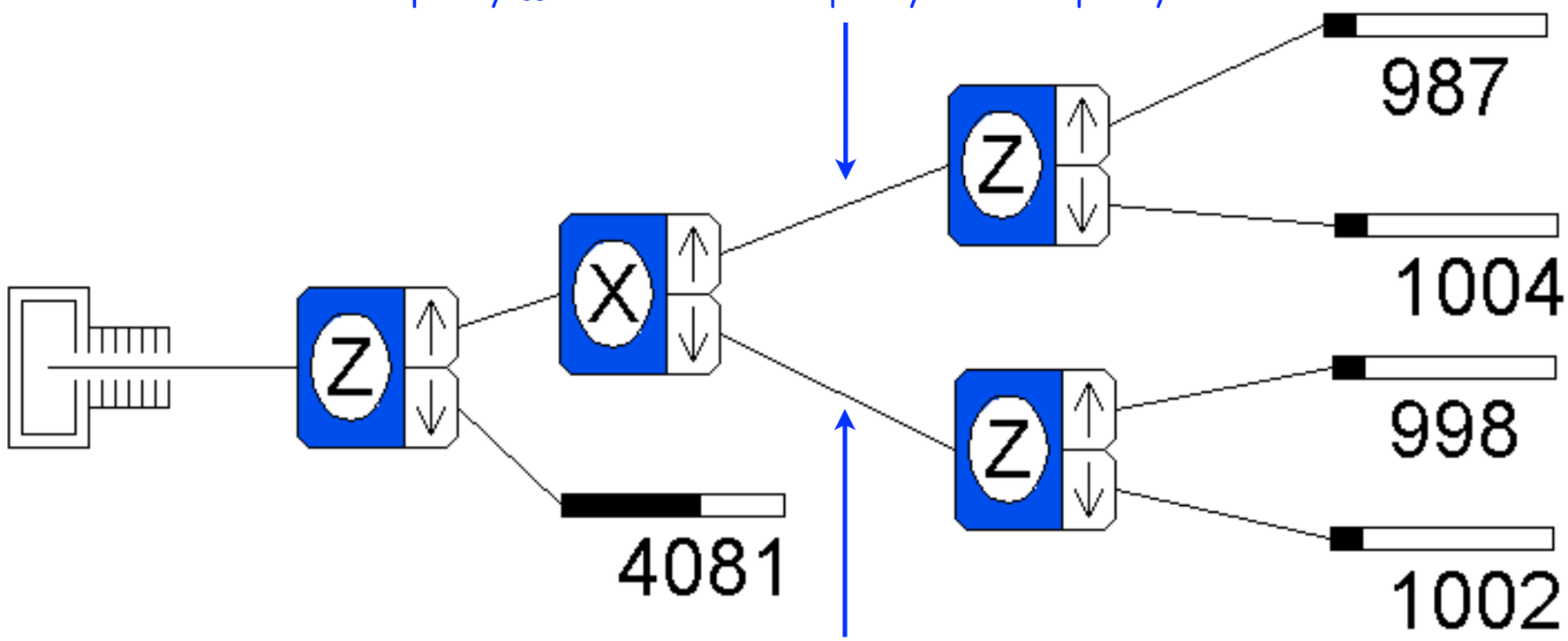
Stern-Gerlach



after a measurement yielding + the new state
is a + eigenstate

Stern-Gerlach

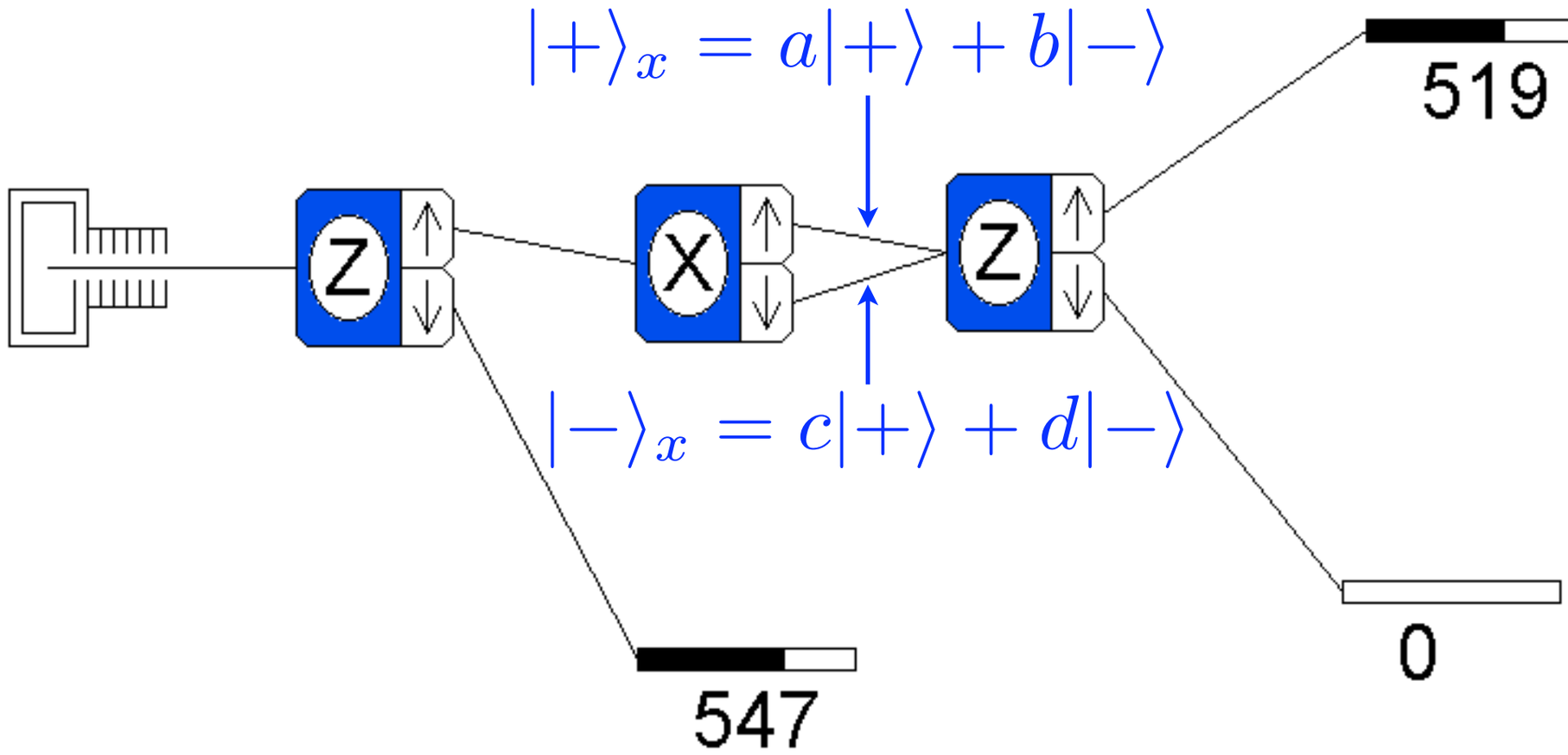
$$|+\rangle_x \quad = \quad a|+\rangle + b|-\rangle$$



$$|-\rangle_x = c|+\rangle + d|-\rangle$$

$$|a| = |b| = |c| = |d| = \frac{1}{\sqrt{2}}$$

Stern-Gerlach



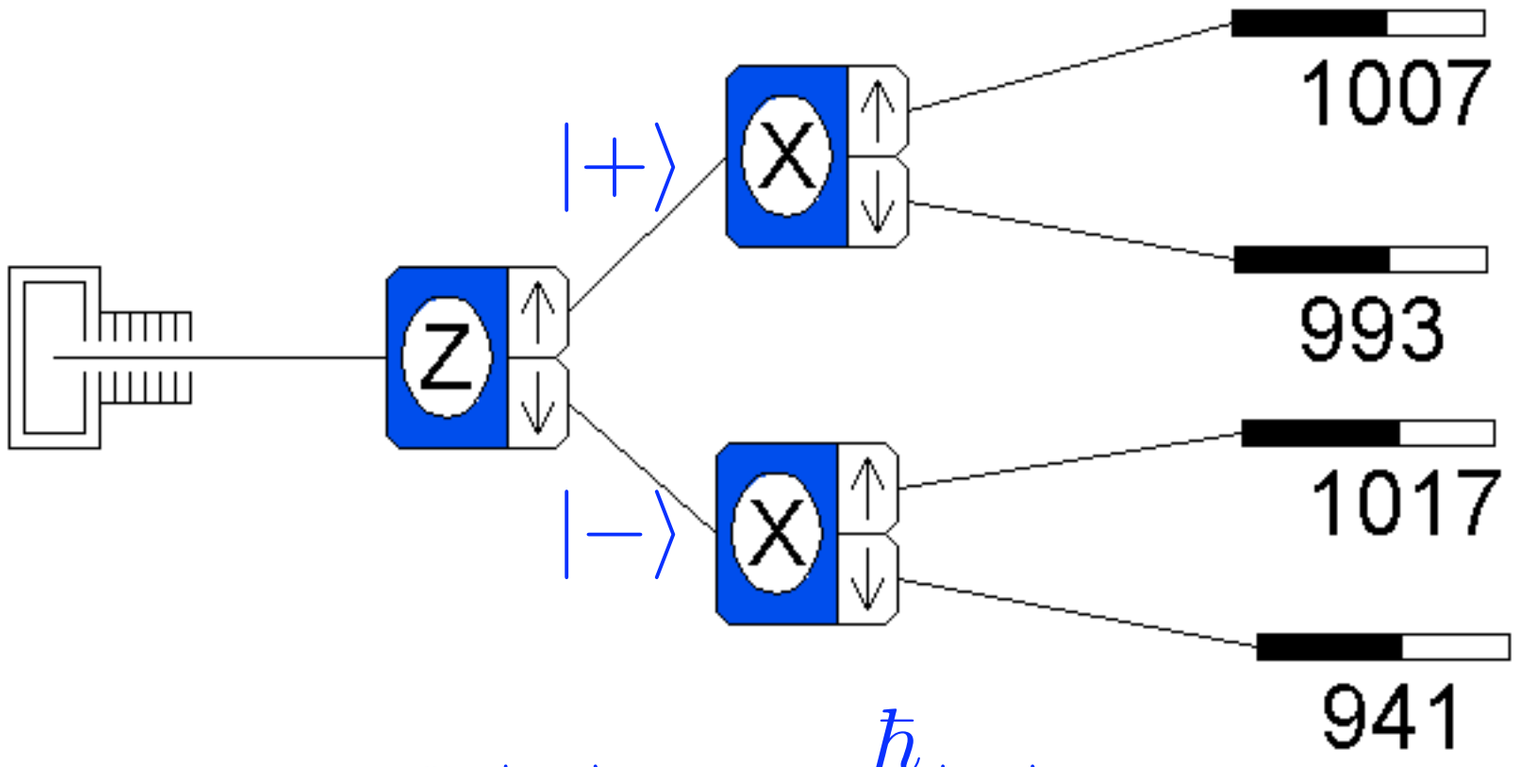
$$b = -d$$

destructive interference

Superposition

$$|+\rangle_x = \frac{1}{\sqrt{2}}\left(|+\rangle + |-\rangle\right)$$

not the same as a mixture



$$S_x|+\rangle_x = +\frac{\hbar}{2}|+\rangle_x$$

Matrix Notation

$$|+\rangle \rightarrow \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$|-\rangle \rightarrow \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$|\psi\rangle = a|+\rangle + b|-\rangle \rightarrow \begin{pmatrix} a \\ b \end{pmatrix}$$

Matrix Notation

$$|\psi\rangle = a|+\rangle + b|-\rangle \rightarrow \begin{pmatrix} a \\ b \end{pmatrix}$$

$$\langle\psi|\psi\rangle \rightarrow (a^* \;\; b^*) \begin{pmatrix} a \\ b \end{pmatrix} = |a|^2 + |b|^2$$

$$S_z \rightarrow \begin{pmatrix} \hbar/2 & 0 \\ 0 & -\hbar/2 \end{pmatrix}$$

$$\langle\psi|S_z|\psi\rangle \rightarrow \quad (a^* \;\; b^*) \begin{pmatrix} \hbar/2 & 0 \\ 0 & -\hbar/2 \end{pmatrix} \begin{pmatrix} a \\ b \end{pmatrix}$$

$$= |a|^2 (\hbar/2) + |b|^2 (-\hbar/2)$$

Pauli Matrix Notation

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$S_x = \frac{\hbar}{2}\sigma^1, S_y = \frac{\hbar}{2}\sigma^2, S_z = \frac{\hbar}{2}\sigma^3,$$

$$\begin{aligned} S_x|+\rangle_x &= \frac{\hbar}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \frac{1}{2} \\ \frac{1}{2} \end{pmatrix} = \frac{\hbar}{2}|+\rangle_x \\ S_x|-\rangle_x &= \frac{\hbar}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix} = -\frac{\hbar}{2}|-\rangle_x \end{aligned}$$

Pauli Matrix Notation

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$\sigma^+ = \frac{1}{2}\left(\sigma^1 + i\,\sigma^2\right) = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}$$

$$\sigma^- = \frac{1}{2}\left(\sigma^1 - i\,\sigma^2\right) = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$\sigma^+|-\rangle = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\begin{pmatrix} 0 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} = |+\rangle$$

$$\sigma^-|+\rangle = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 \\ 0 \end{pmatrix} = \begin{pmatrix} 0 \\ 1 \end{pmatrix} = |-\rangle$$

Pauli Matrix Notation

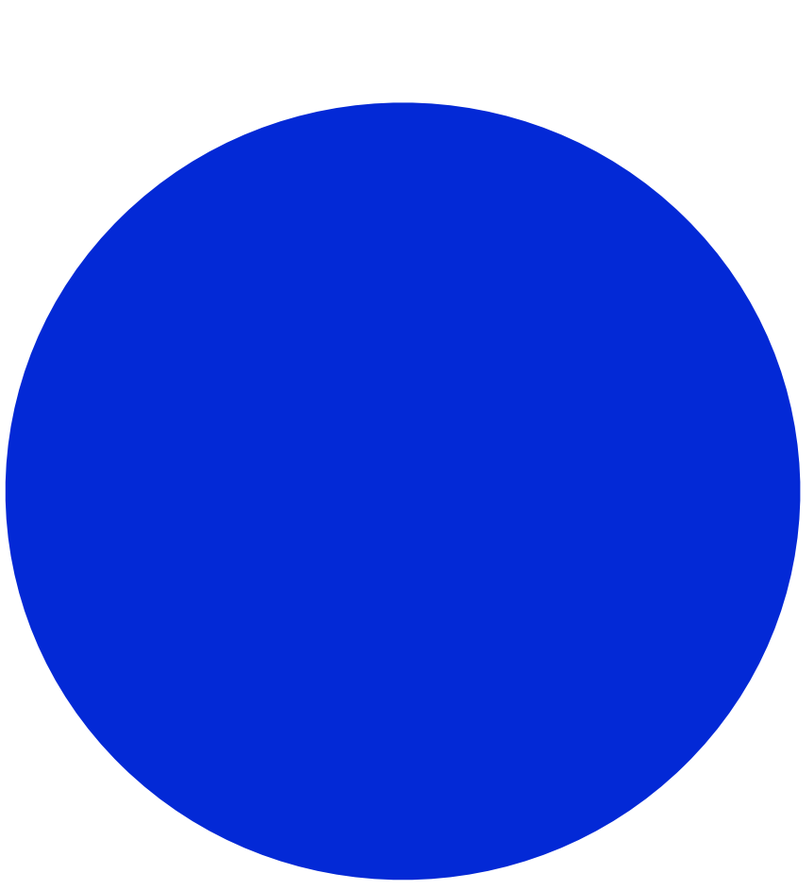
$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

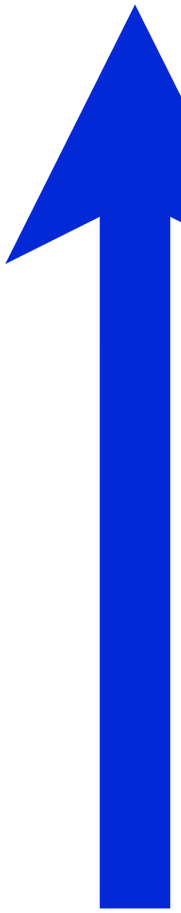
$$\sigma^1\sigma^3 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} = -i\,\sigma^2$$

$$\sigma^1\sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} = i\,\sigma^2$$

only know $\vec{S}^2, S^z$ at the same time

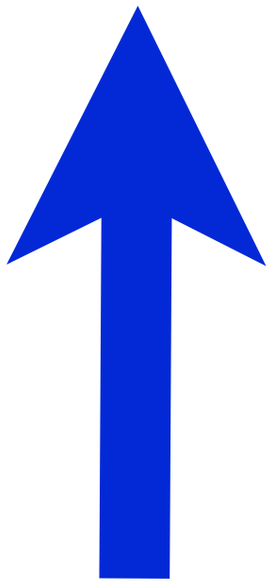
Spin





spin	0	1	2
unchanged if we rotate by:	anything	360^0	180^0

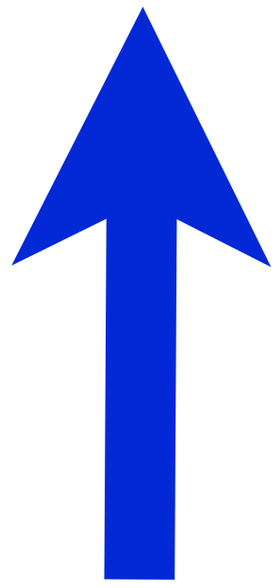
Fermion Spin



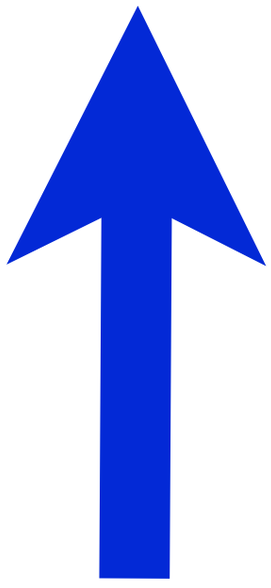
Fermion Spin

Rotate once

−1



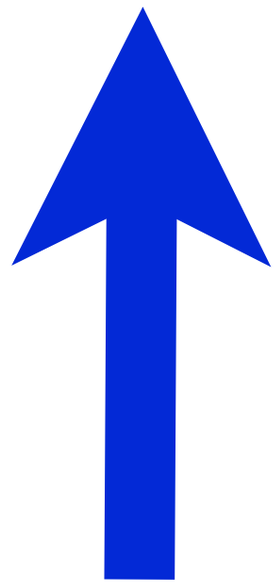
Fermion Spin



Fermion Spin

Rotate twice

$-1 \times -1 = +1$



Bosons and Fermions

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

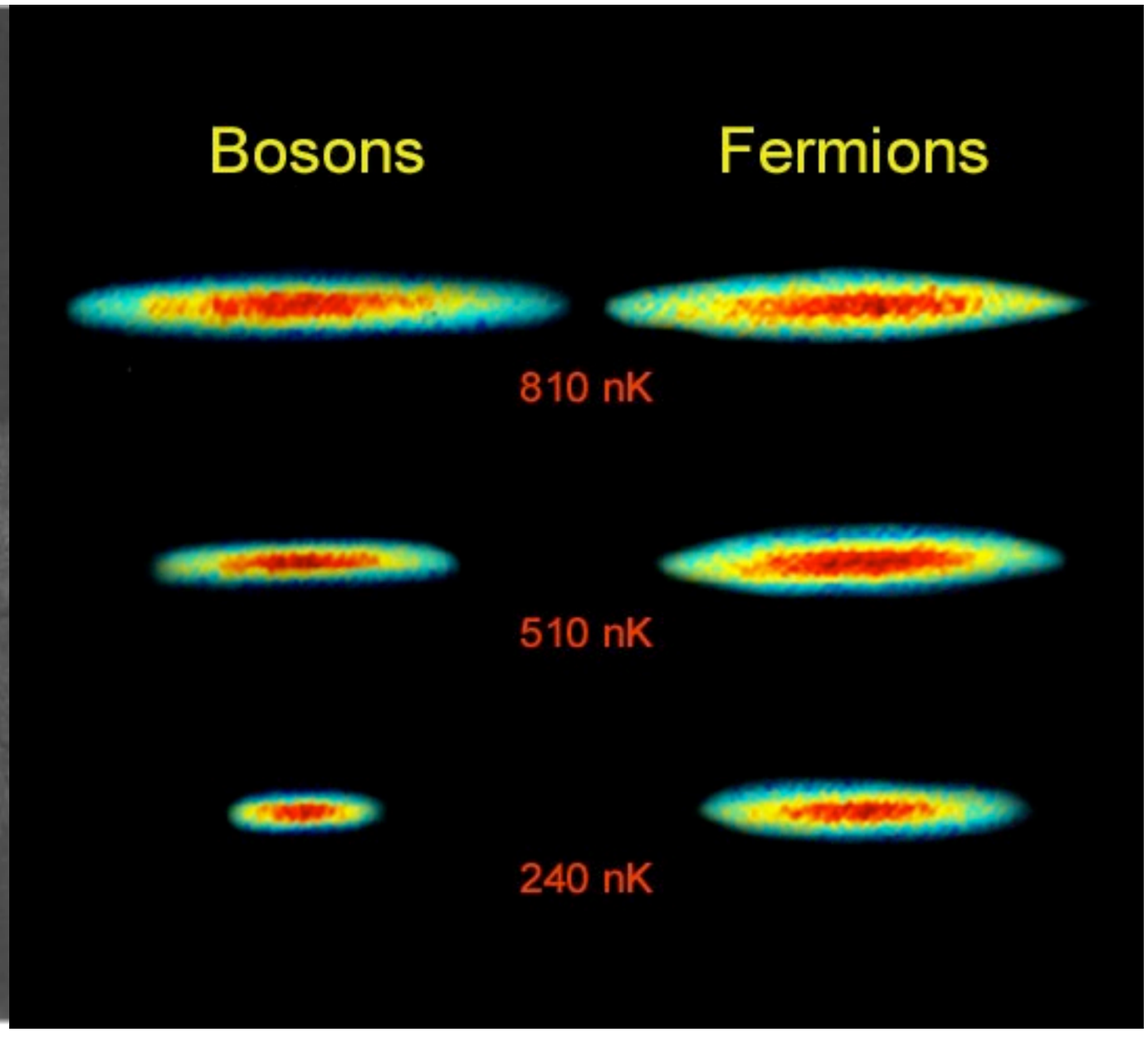
FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Pauli Exclusion



Massive Particles & Spin

$$2\,s+1 \text{ states}$$

$s = \frac{1}{2}$ massive fermions have spin up and down

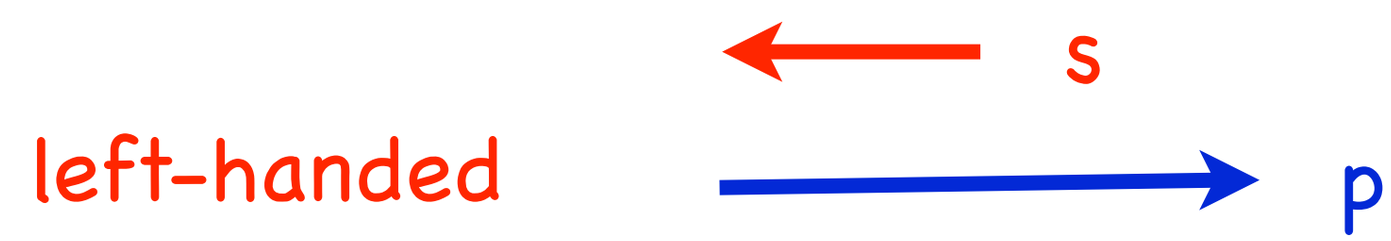
$$\begin{pmatrix} \frac{1}{2} \\ -\frac{1}{2} \end{pmatrix}$$

$s = 1$ massive spin 1 bosons have 3 polarizations

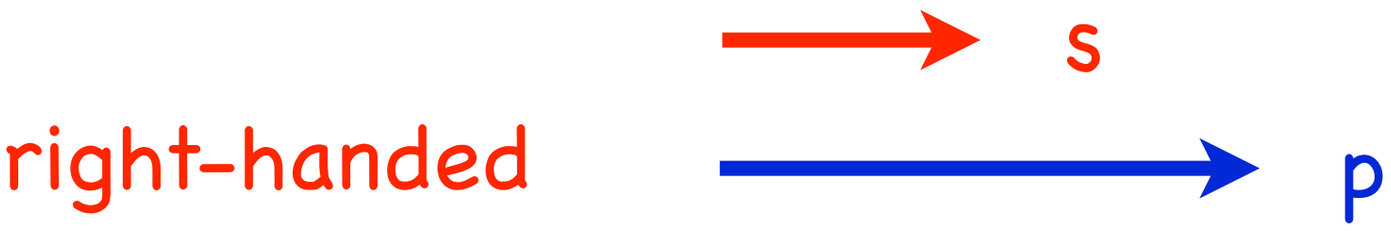
$$\begin{pmatrix} 1 \\ 0 \\ -1 \end{pmatrix}$$

Massive Fermion

measure spin along momentum direction: chirality



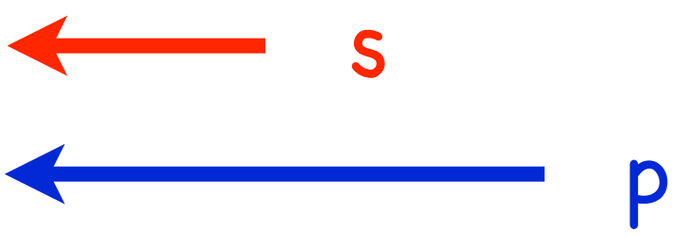
left-handed

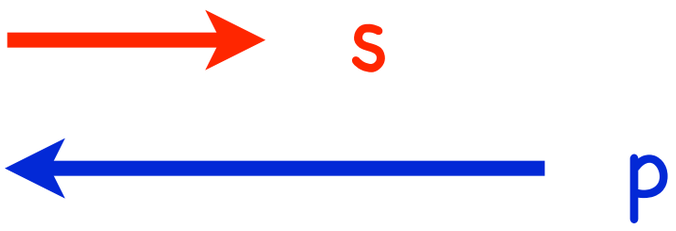


right-handed

Massive Fermion

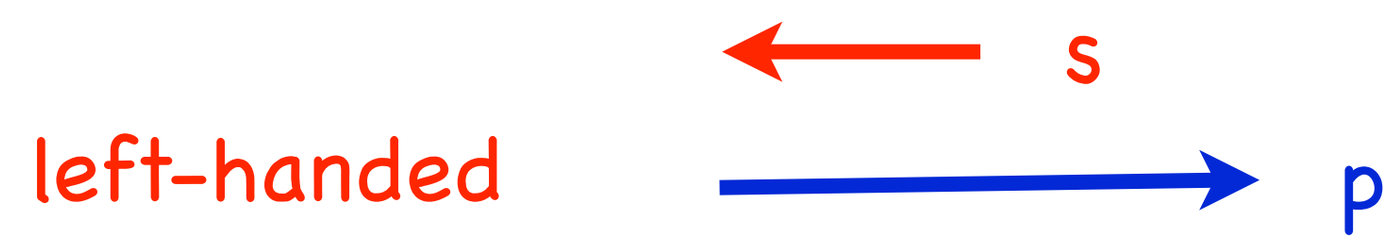
moving faster than the fermion flips p
also flips handedness

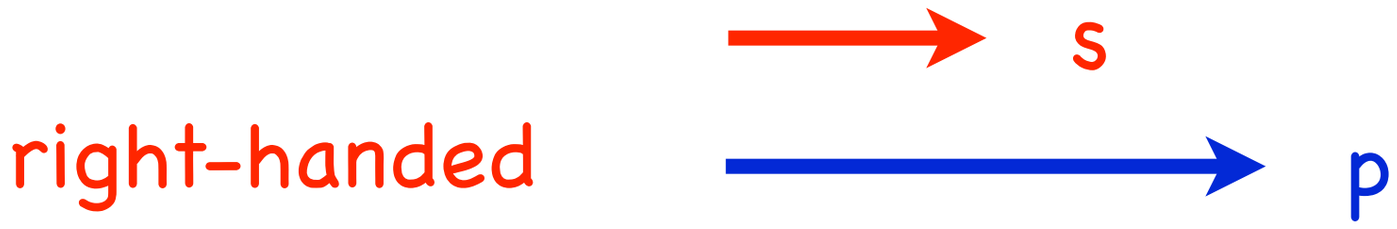




Massless Fermion

can't move faster than the fermion:
chirality is invariant



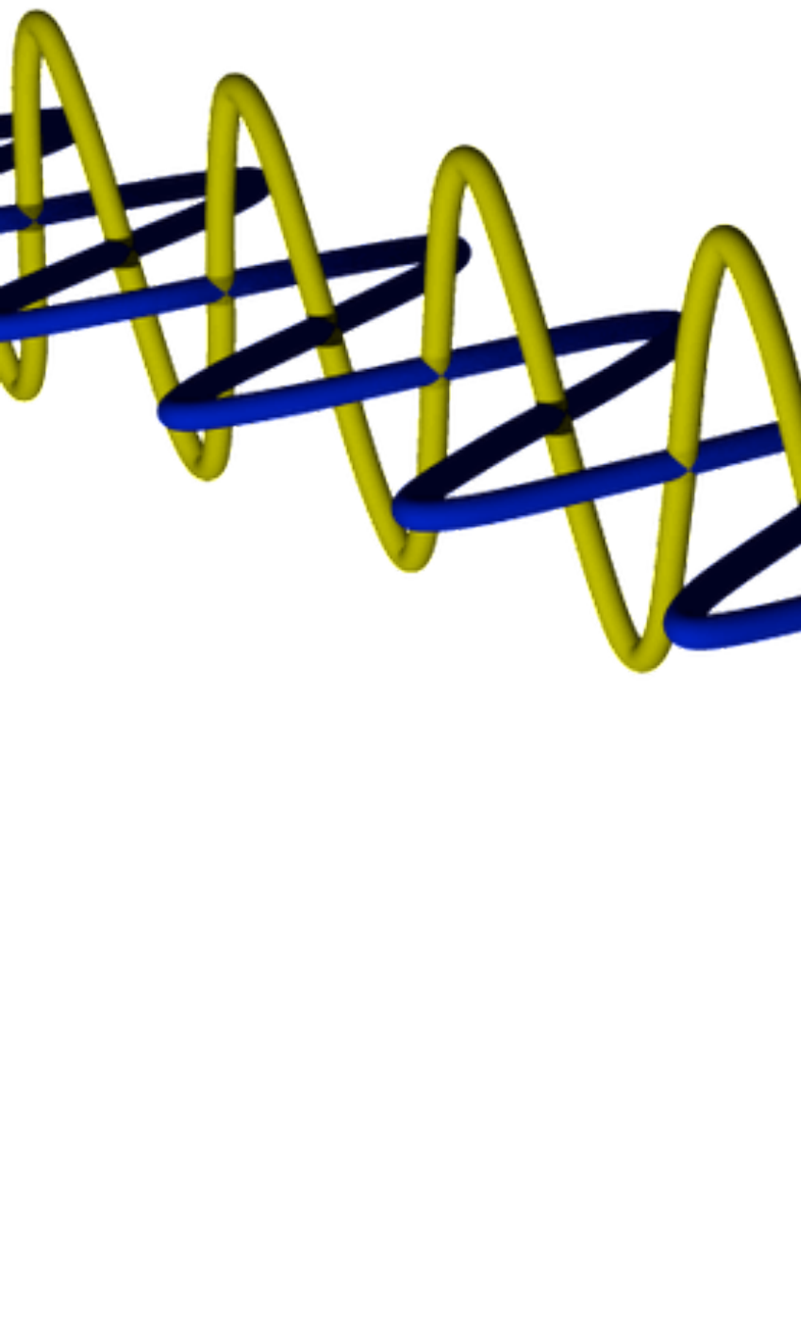


Massless Particles & Spin

$s = \frac{1}{2}$ left-handed and right-handed
fermions are decoupled

$s = 1$ massless gauge bosons have 2 polarizations
longitudinal polarization is unphysical

Electromagnetic Waves



$$E_x = A\cos(kz - \omega t)$$

$$B_y = A\cos(kz - \omega t)$$

$$\omega = ck$$

"Massive EM" Waves

$$
\begin{aligned}
E_x &= A\cos(kz-\omega t) \\
B_y &= \frac{k}{\omega} A\cos(kz-\omega t) \\
E_z &= \frac{m^2}{\omega^2} A\cos(kz-\omega t)
\end{aligned}
$$

$$\omega = \sqrt{k^2+m^2}$$

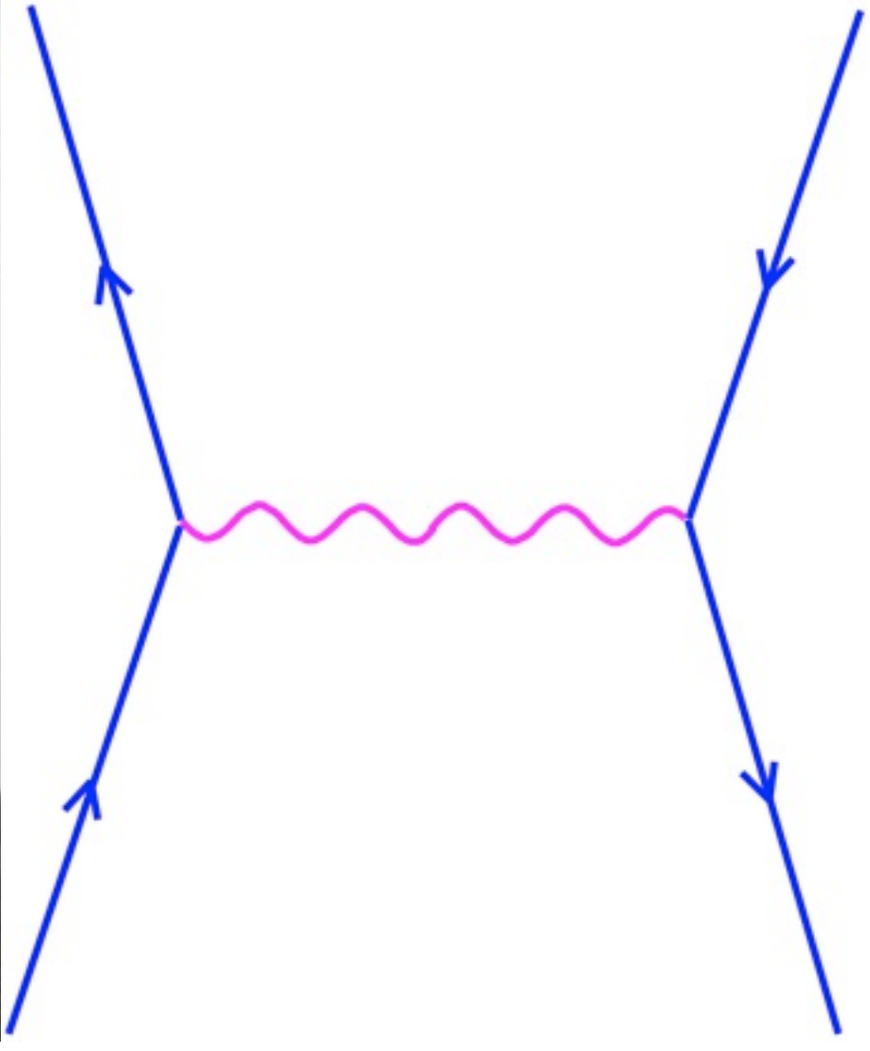
taking m to zero removes longitudinal polarization

Quantum Electrodynamics

charged fermions and photons

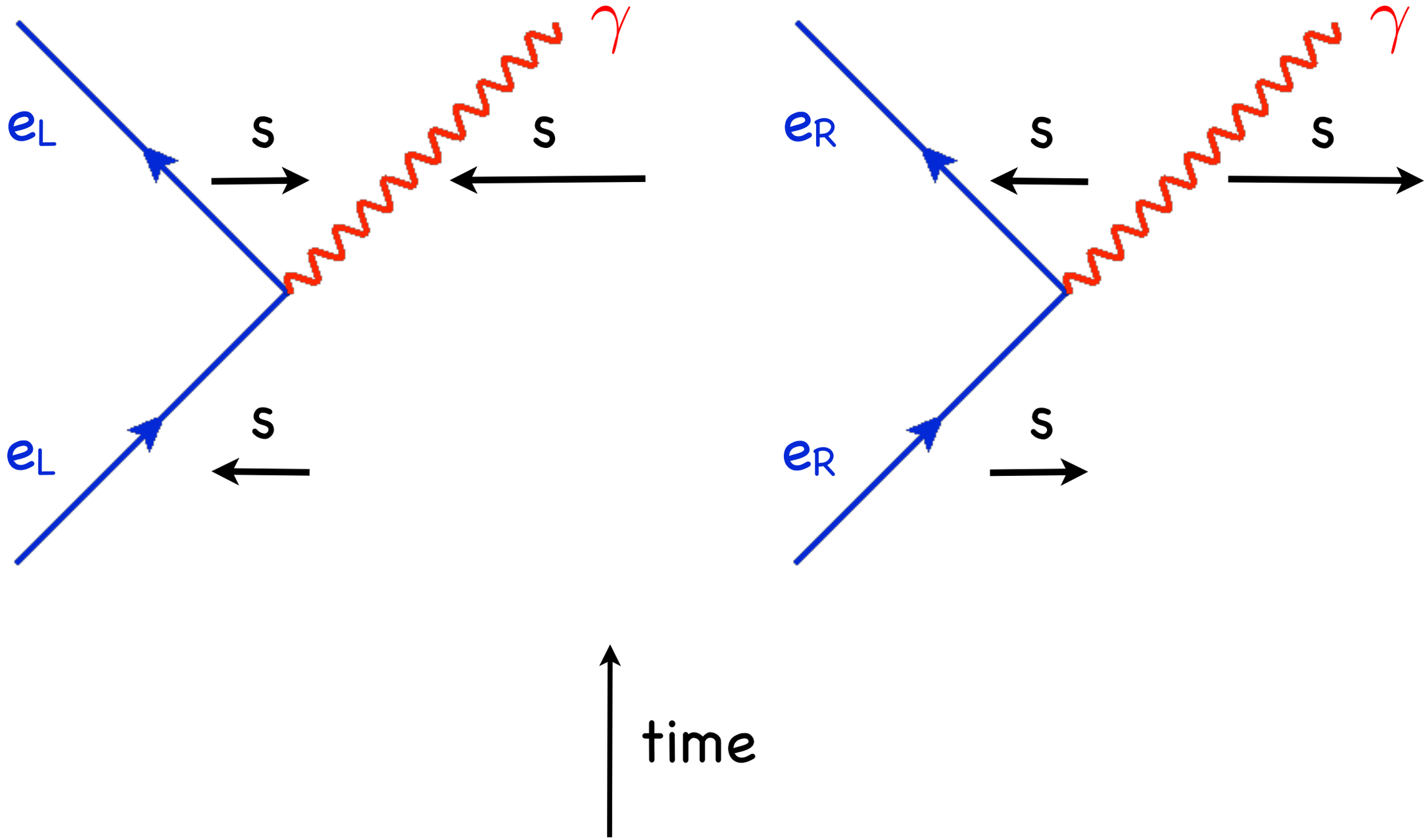
a fermion can emit or absorb photons
with a probability amplitude
proportional to its charge

Feynman Diagrams

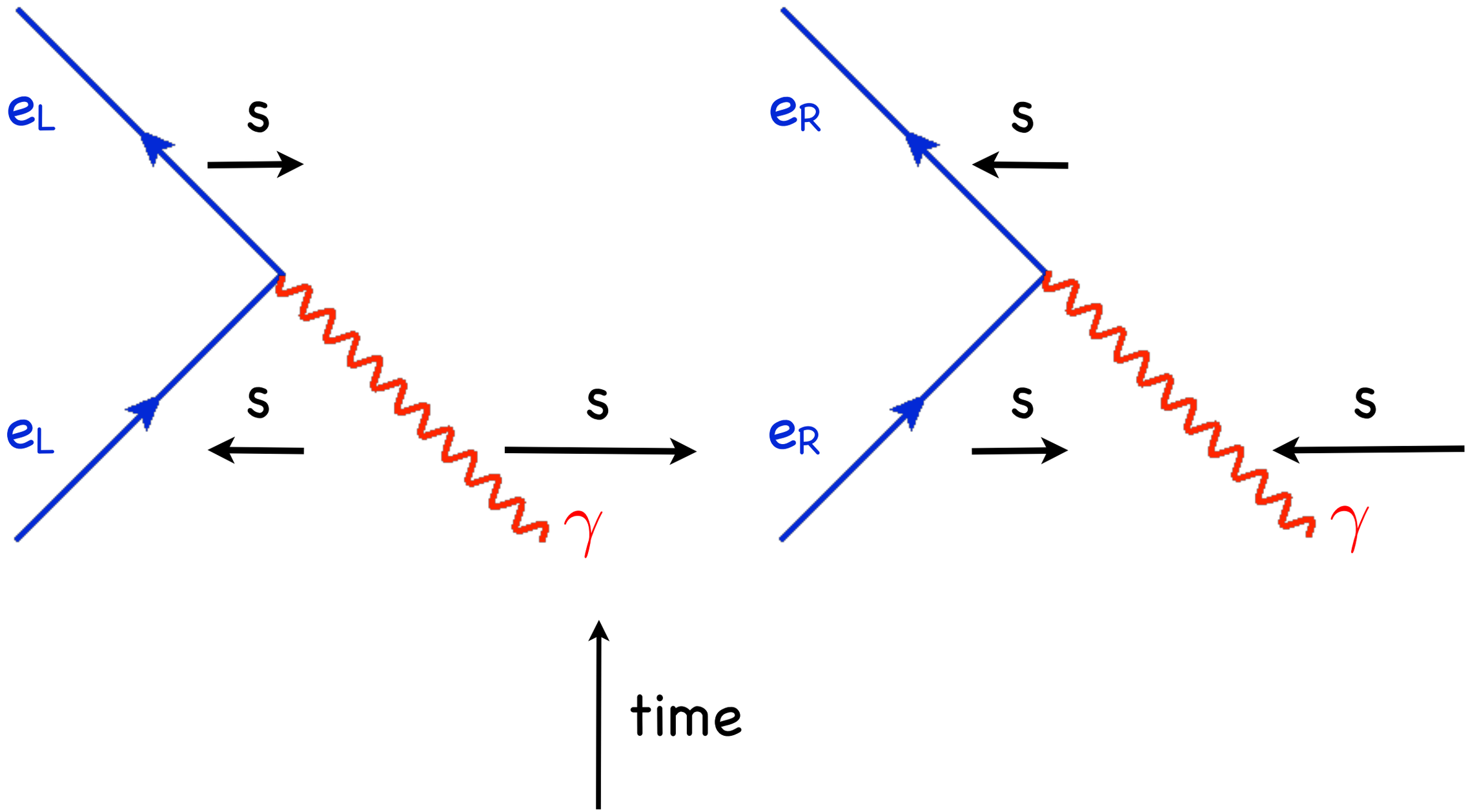


each diagram represents a probability amplitude

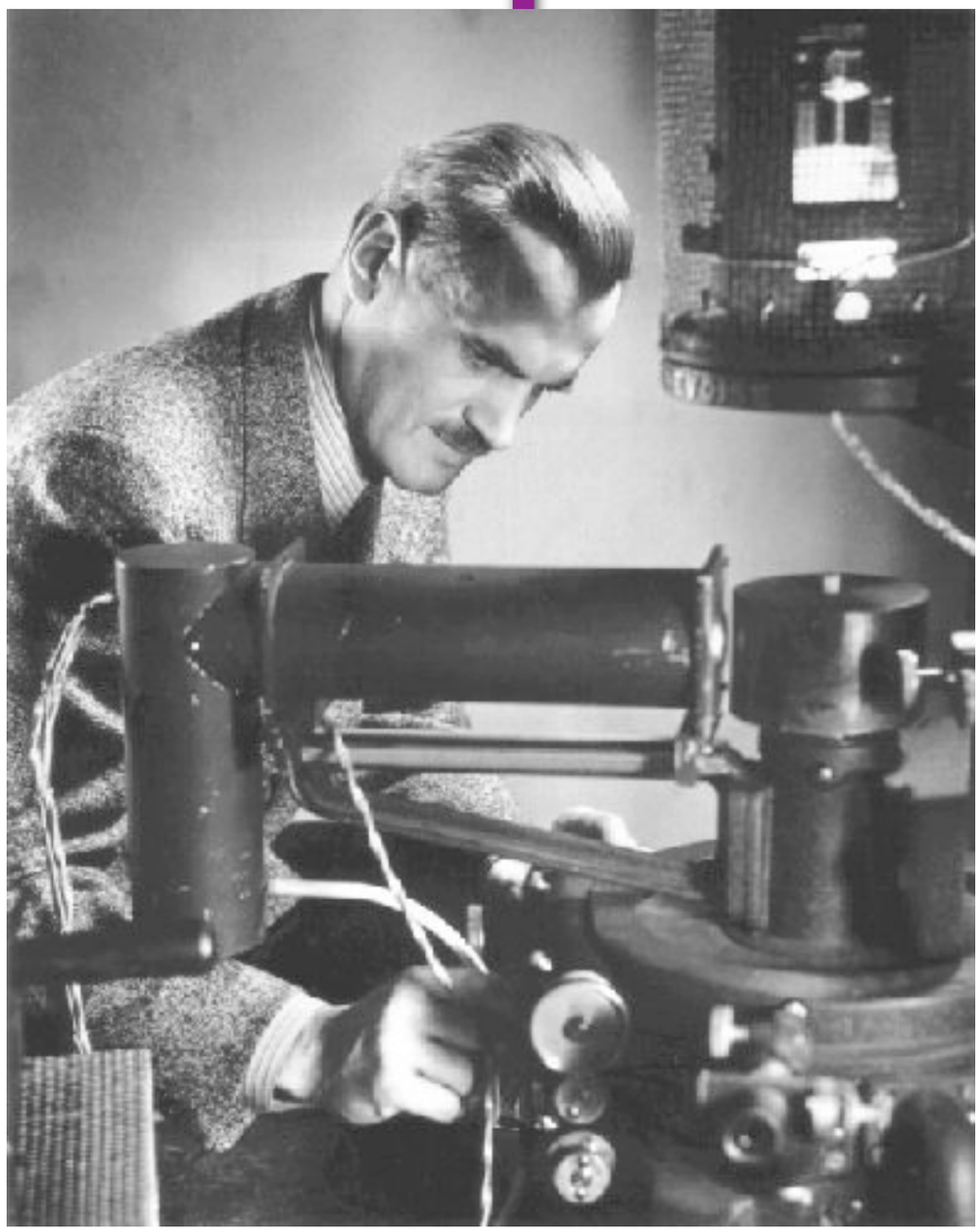
Emission

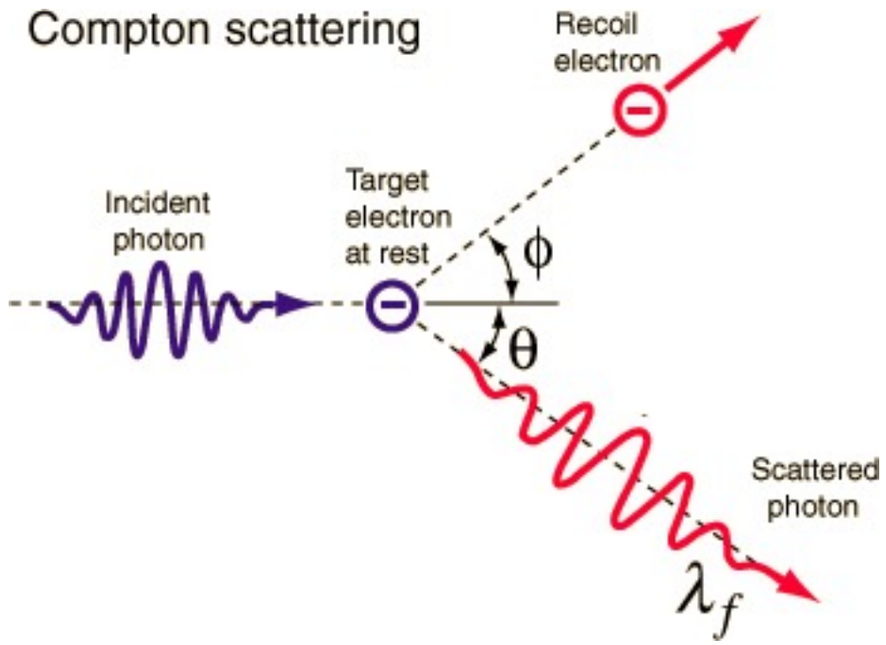


Absorbtion

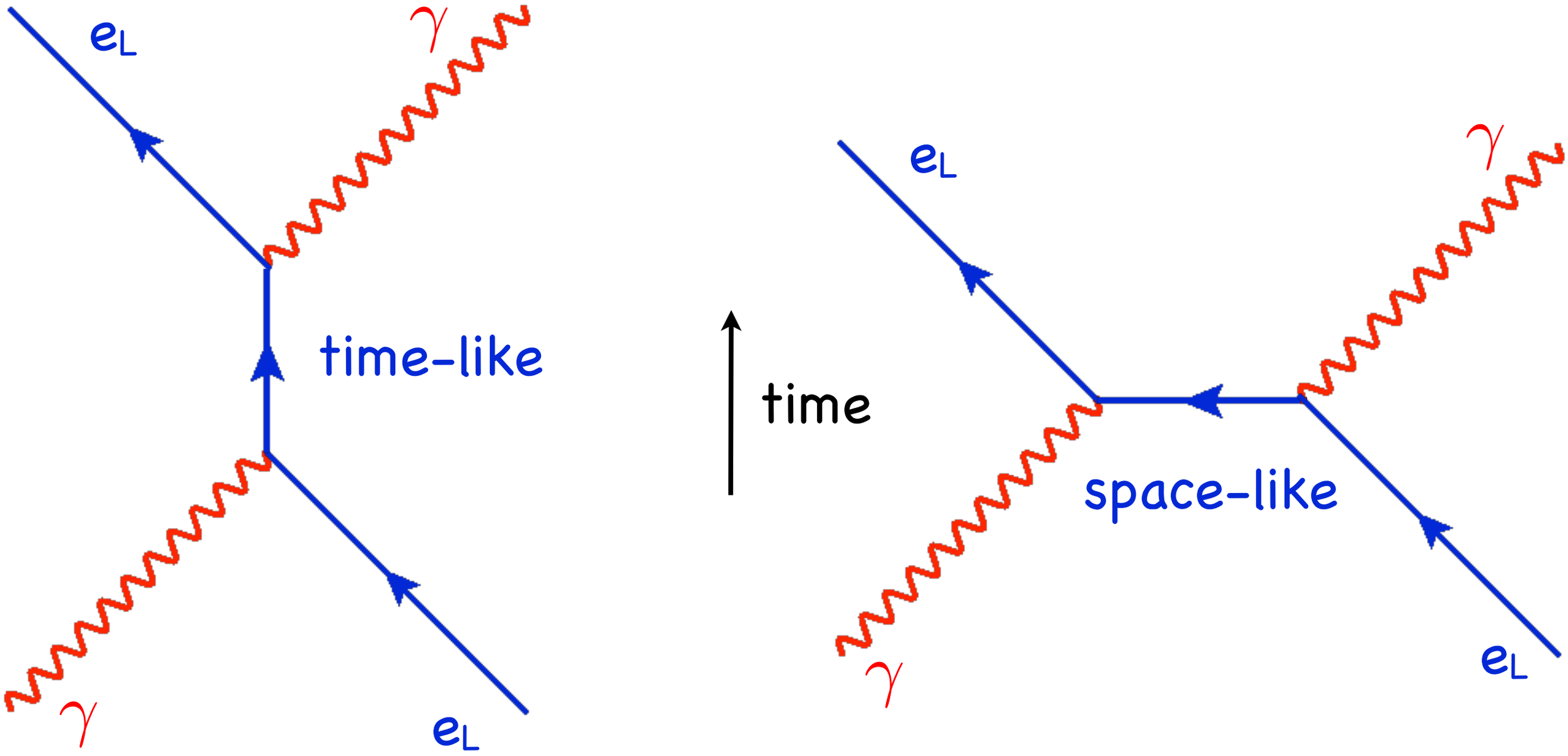


Compton Scattering



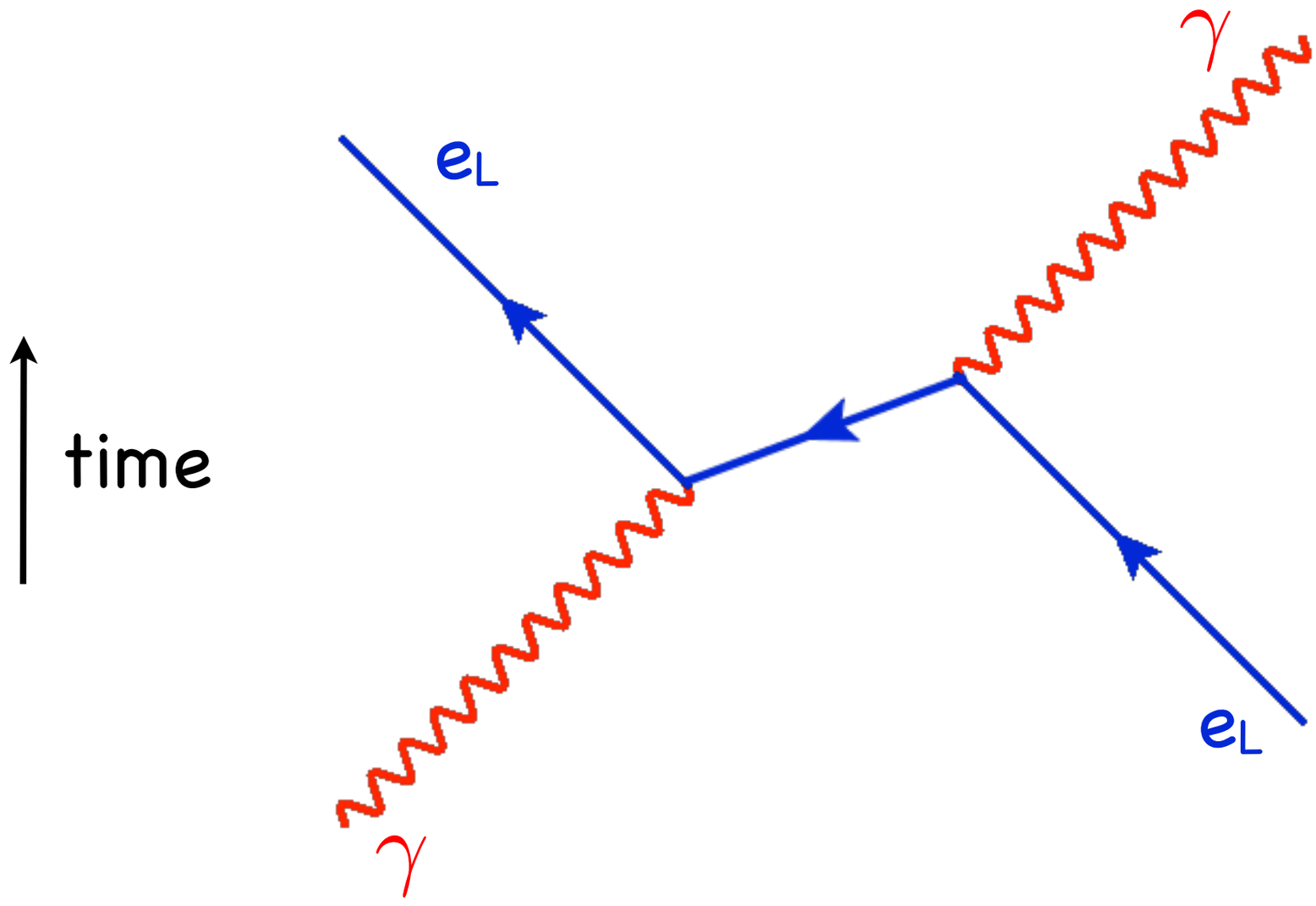


Scattering

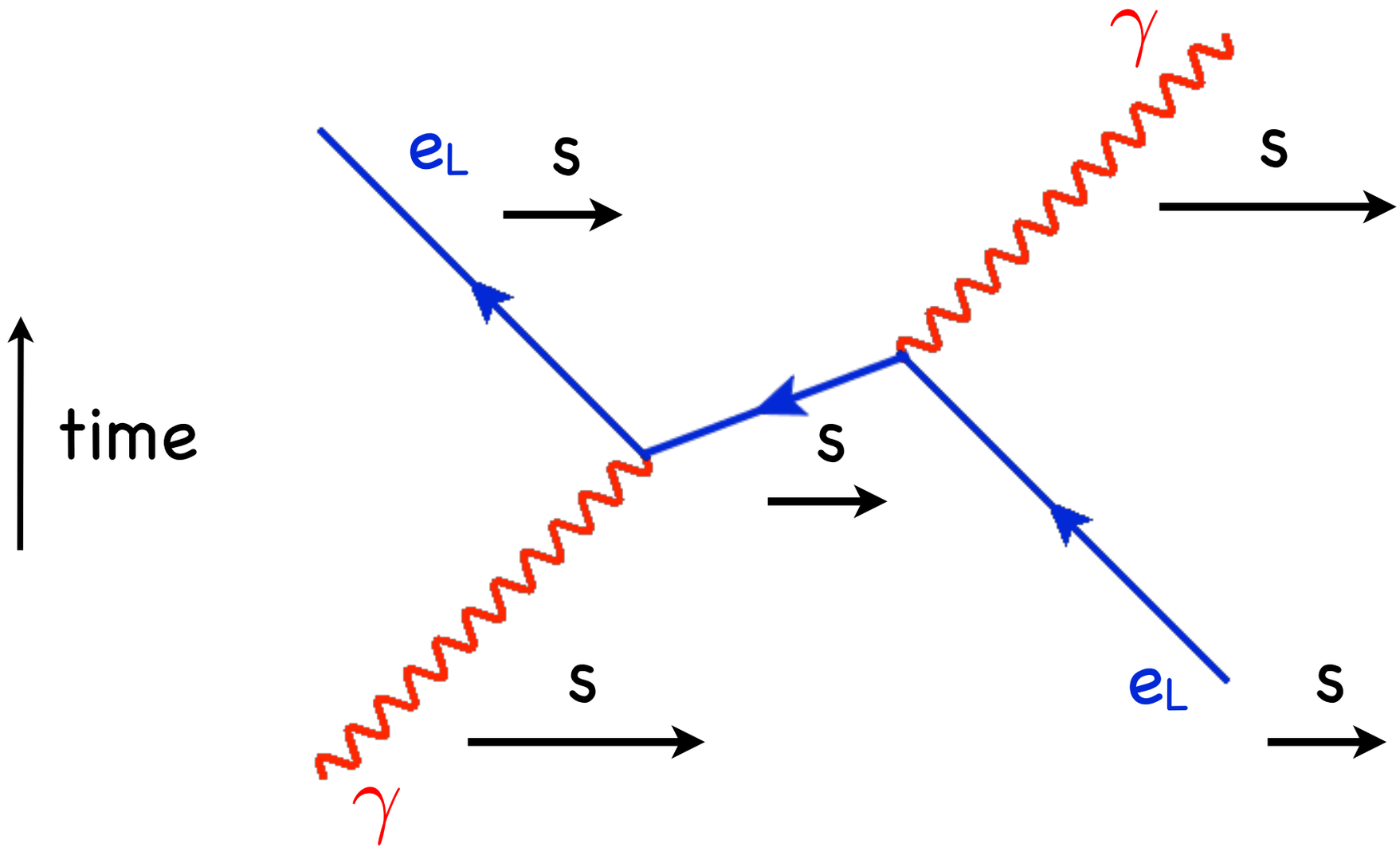


boost changes space or time ordering

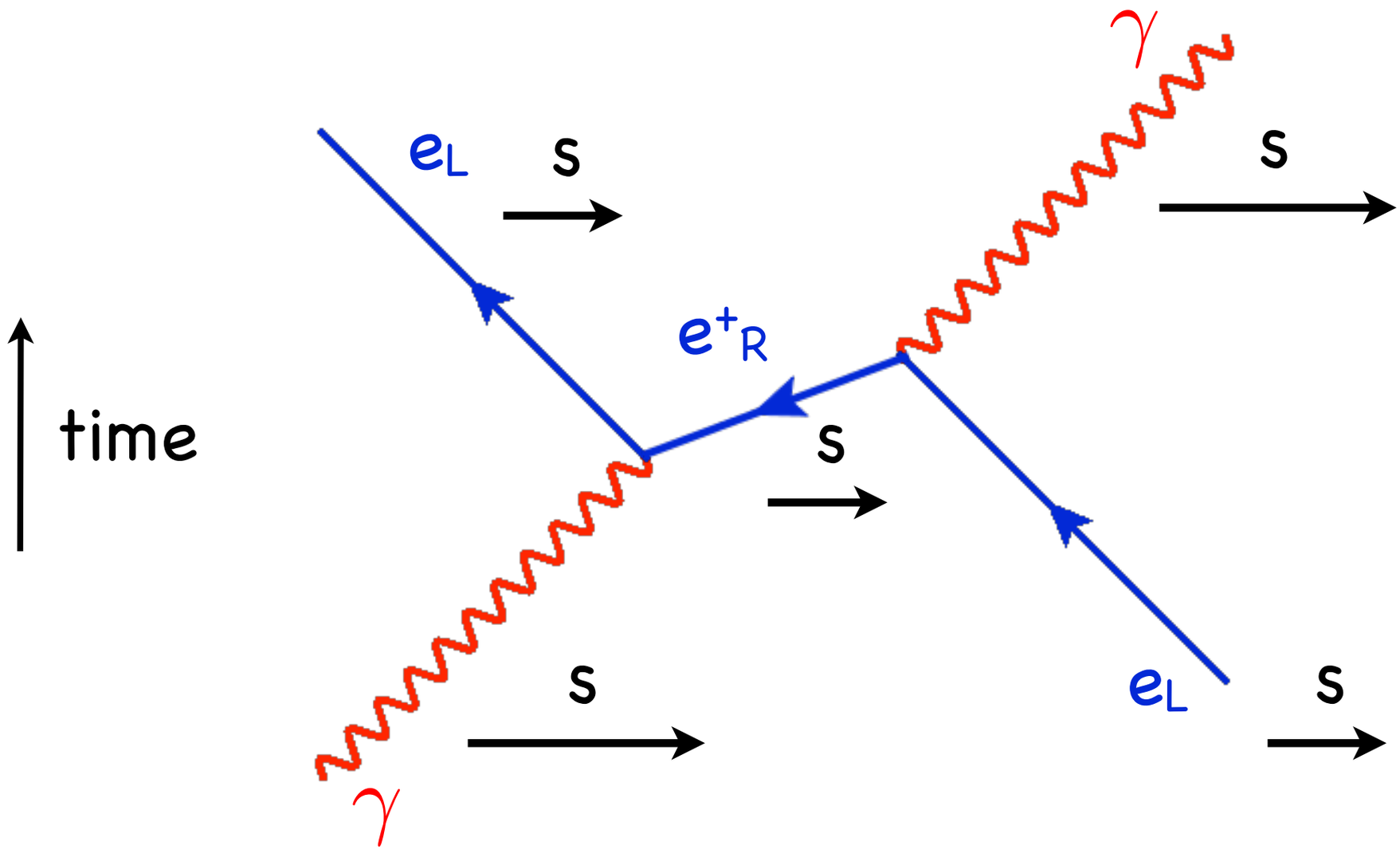
Scattering



Scattering

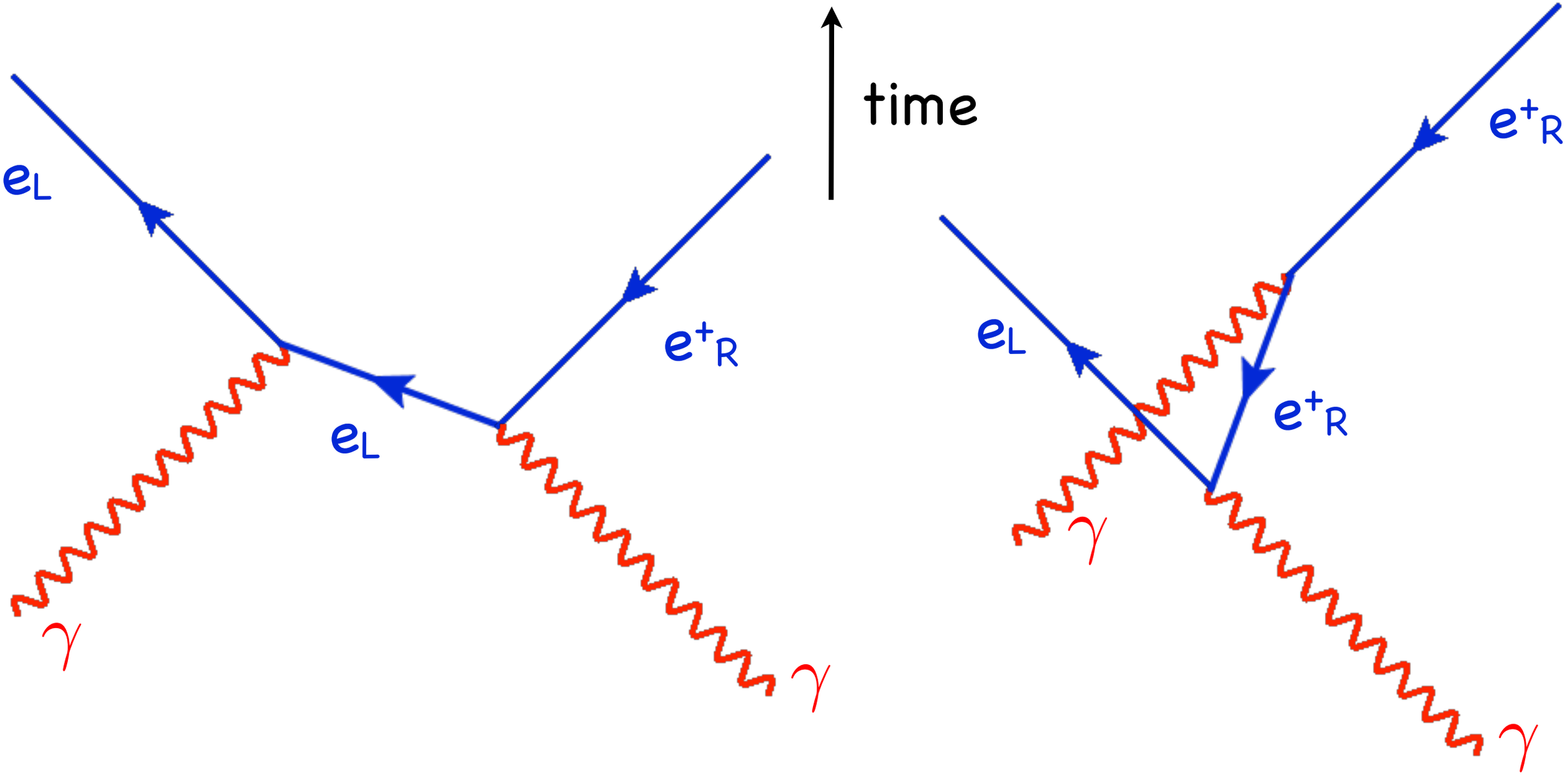


Scattering

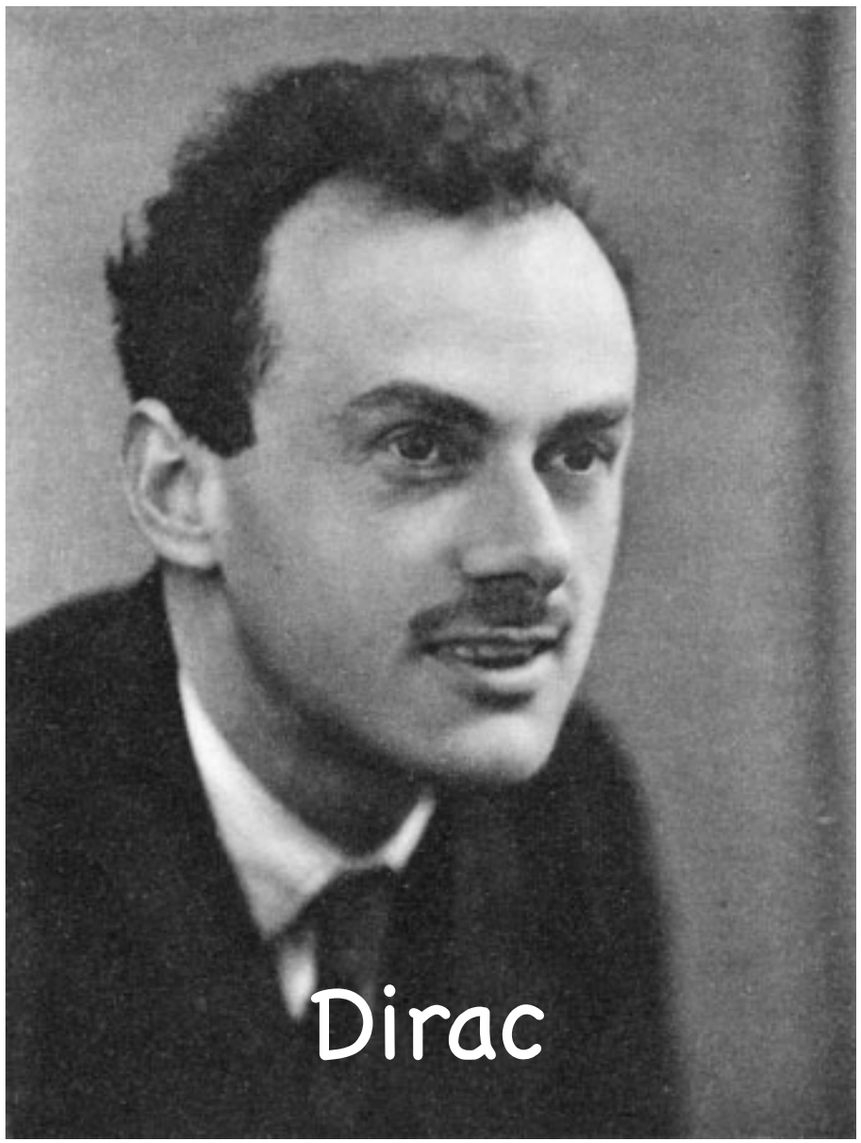


antimatter!

Pair Creation



Antimatter

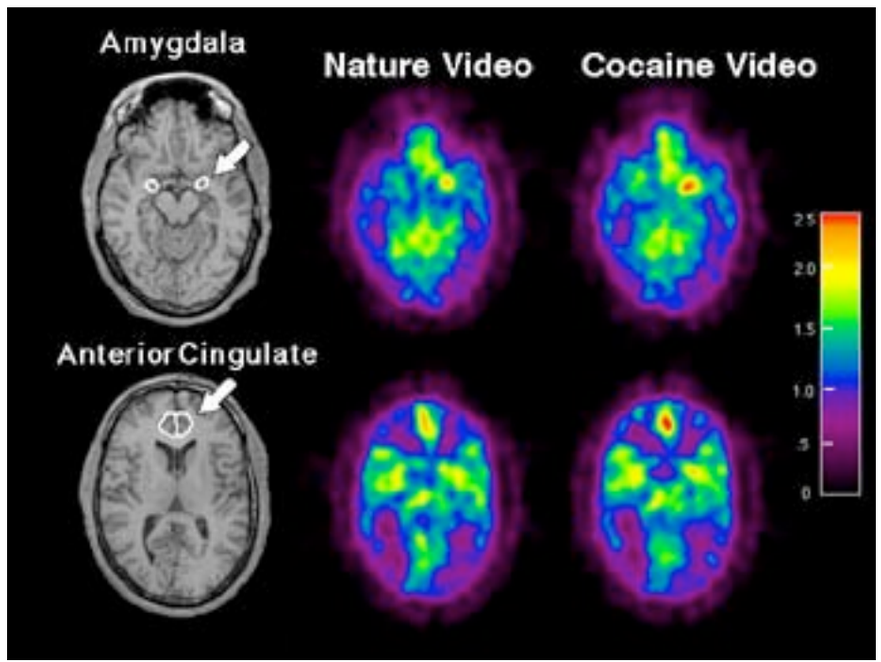


relativity

+

quantum physics

antimatter

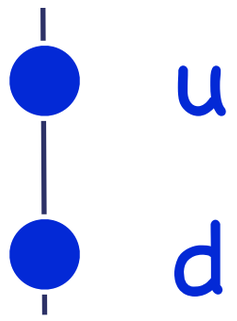
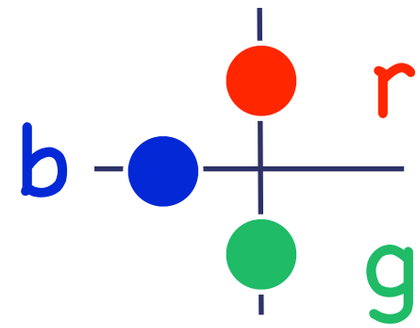
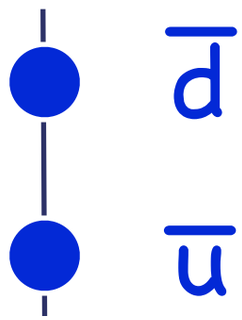
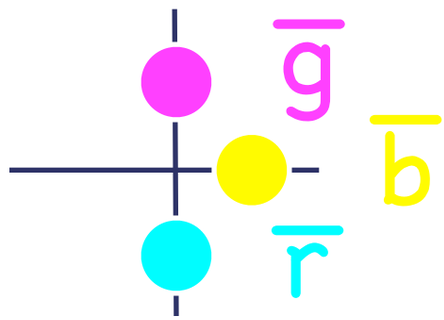


Gauge Interactions

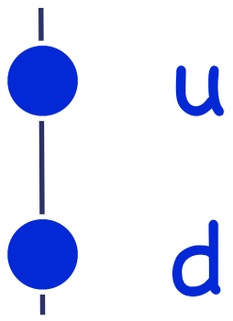
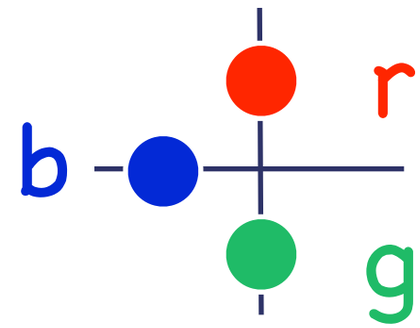
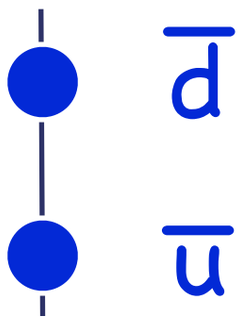
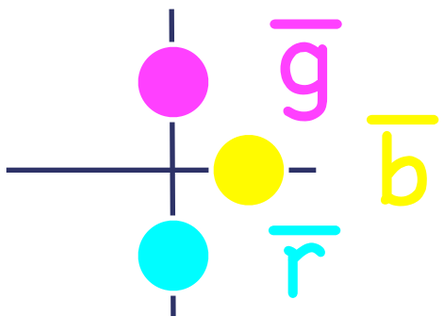
The Standard Model has 3 types of gauge interactions:

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

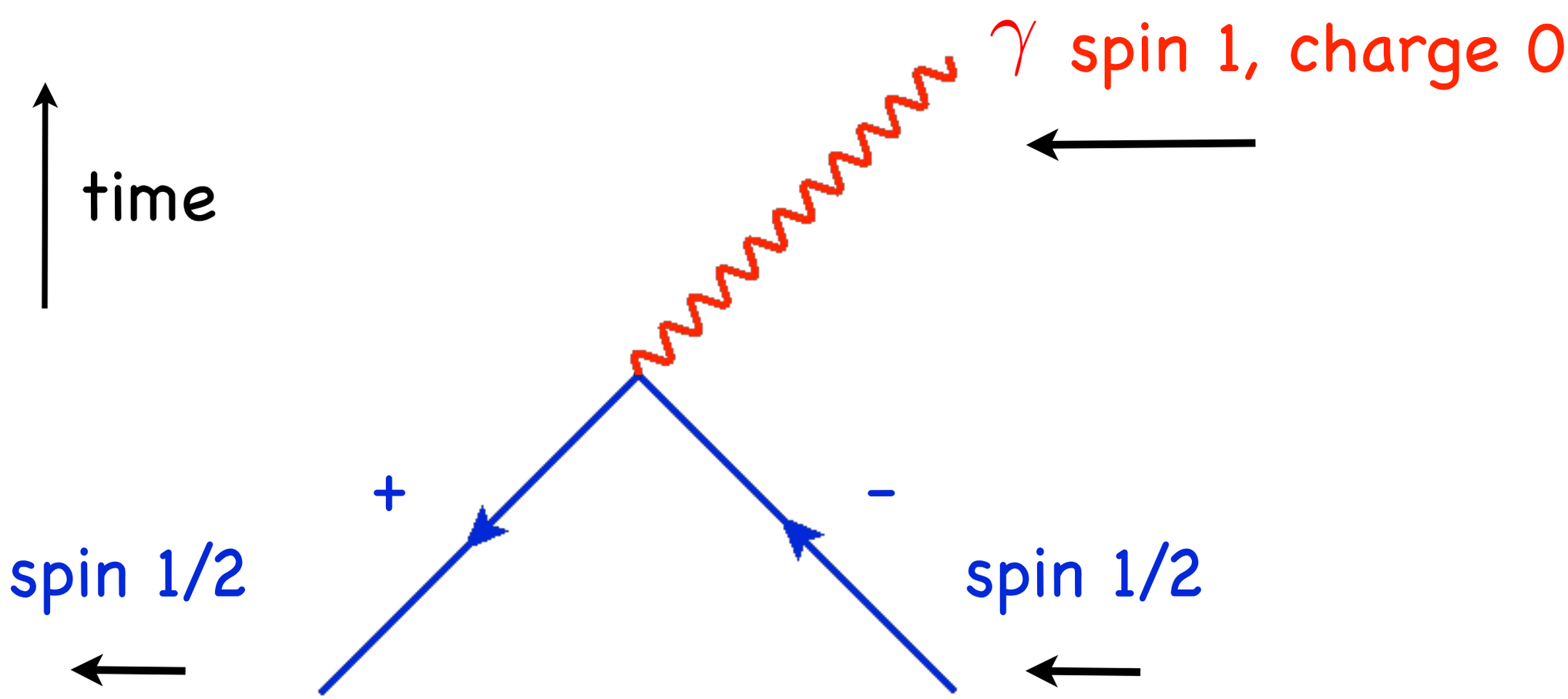
Gauge Interactions

	U(1)	SU(2)	SU(3)
charge	+		
anticharge	−		

Gauge Interactions

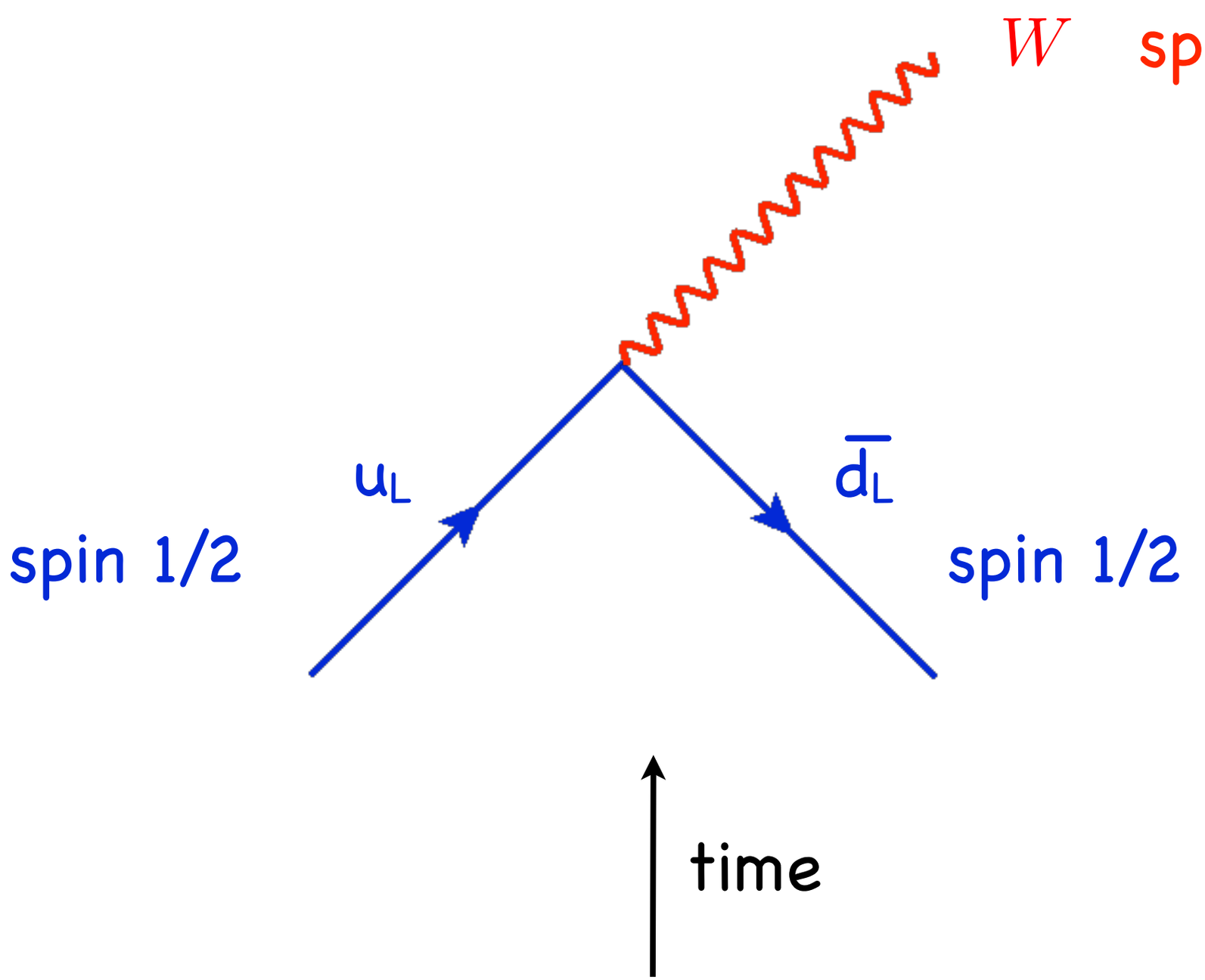
	U(1)	SU(2)	SU(3)
charge	+		
anticharge	−		
	one complex number	three 2x2 matrices	eight 3x3 matrices

U(1)



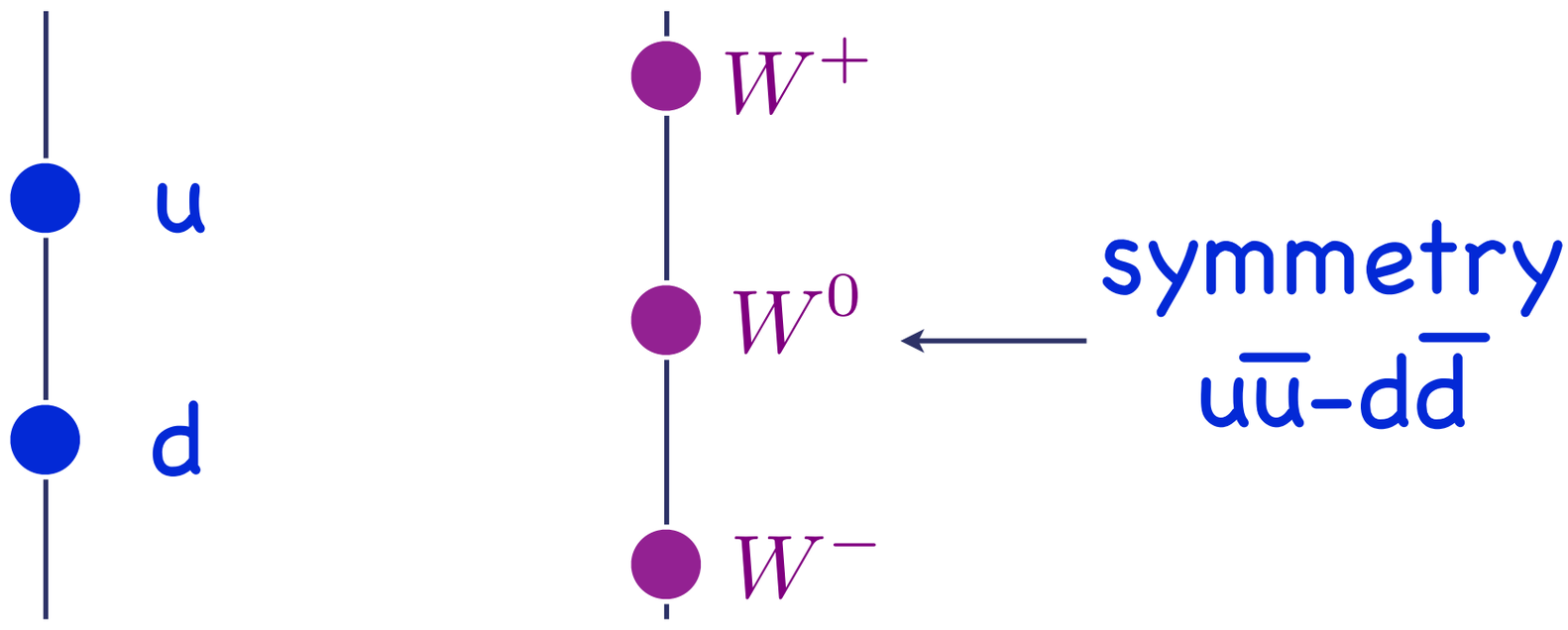
spin and charge must add up

$SU(2)_L$



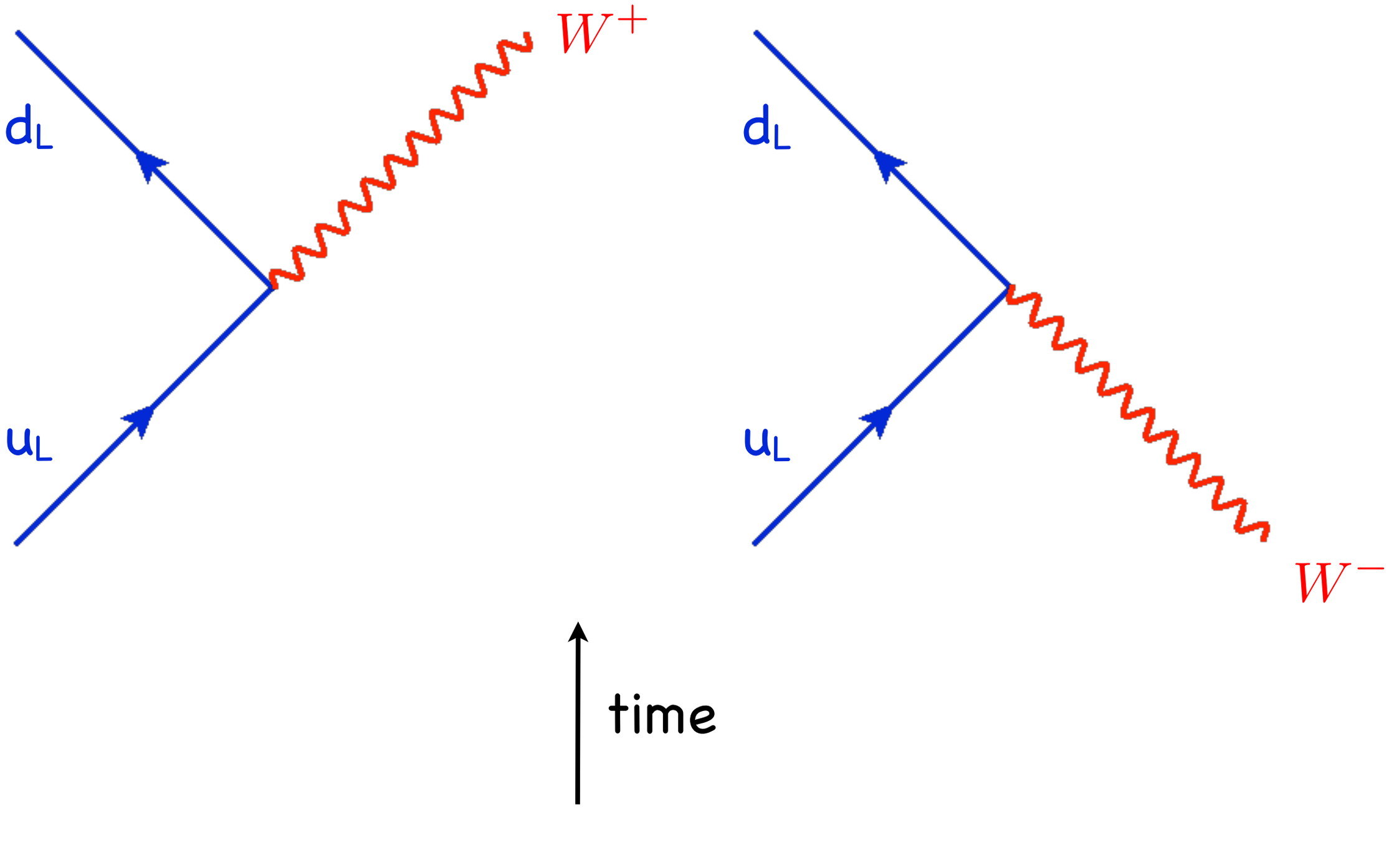
SU(2) Gauge Bosons

adding SU(2) charges
works just like spin: $\pm\frac{1}{2} \pm \frac{1}{2} = -1, 0, 1$

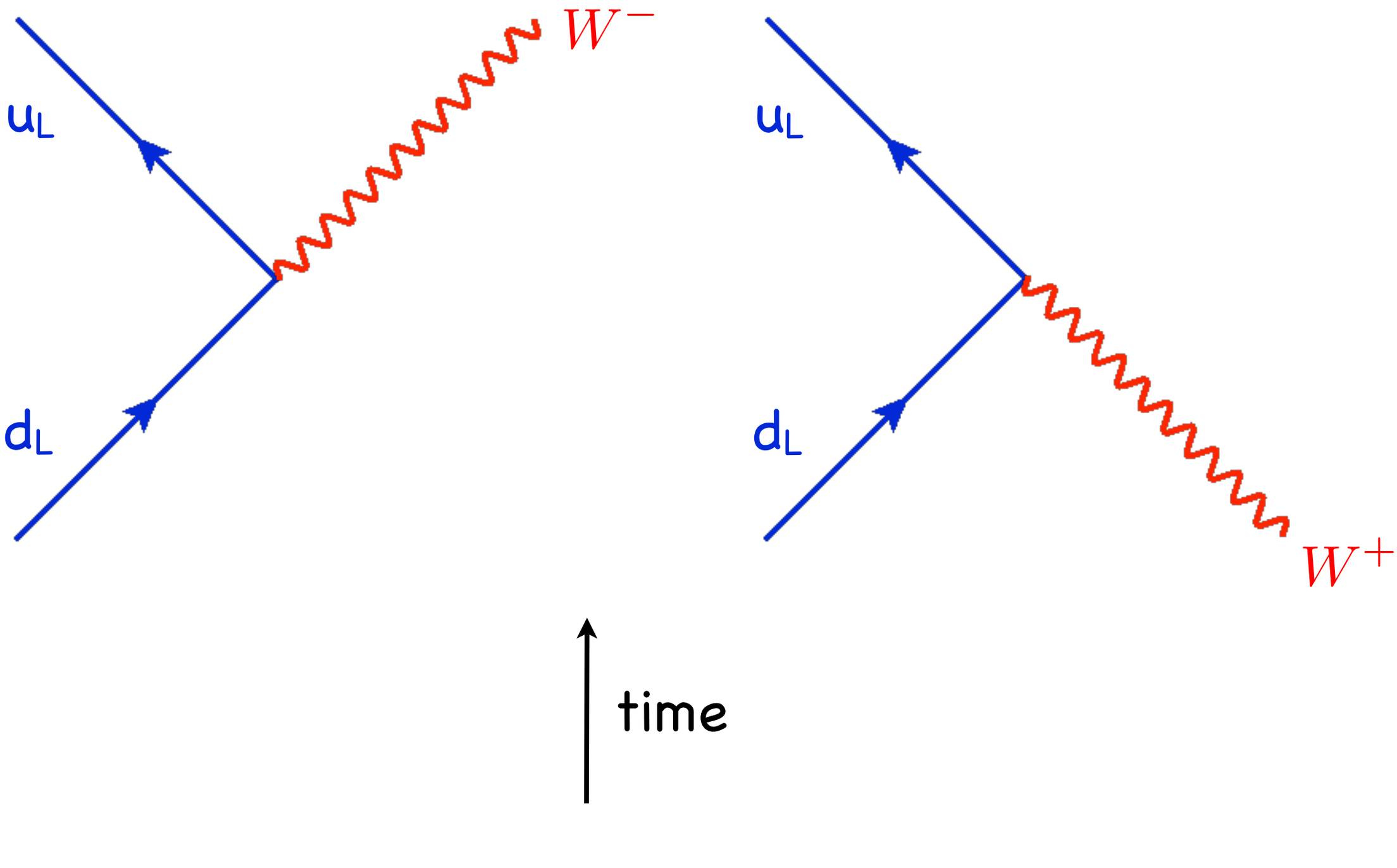


three weak gauge bosons

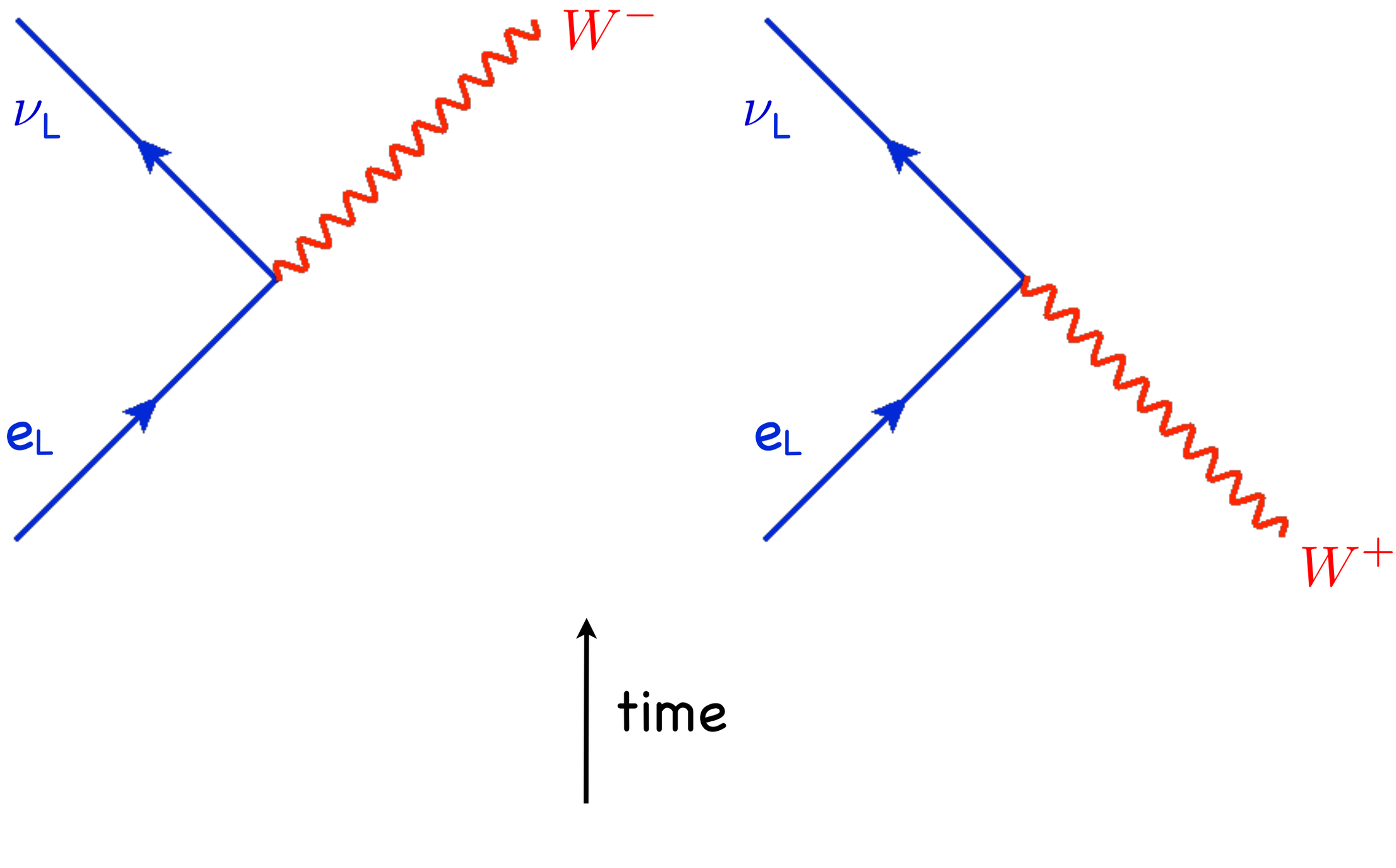
$SU(2)_L$ Weak Interactions



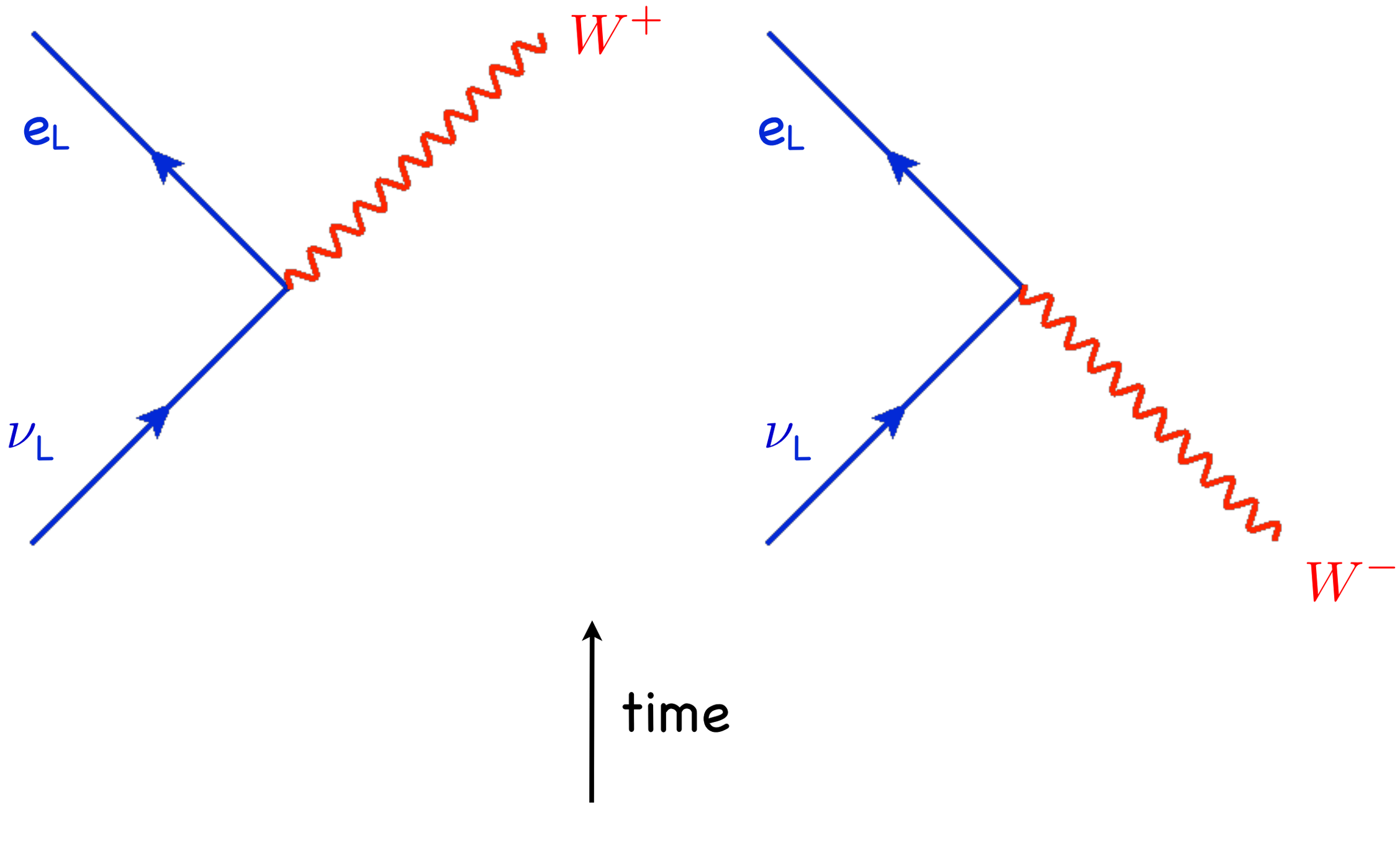
$SU(2)_L$ Weak Interactions



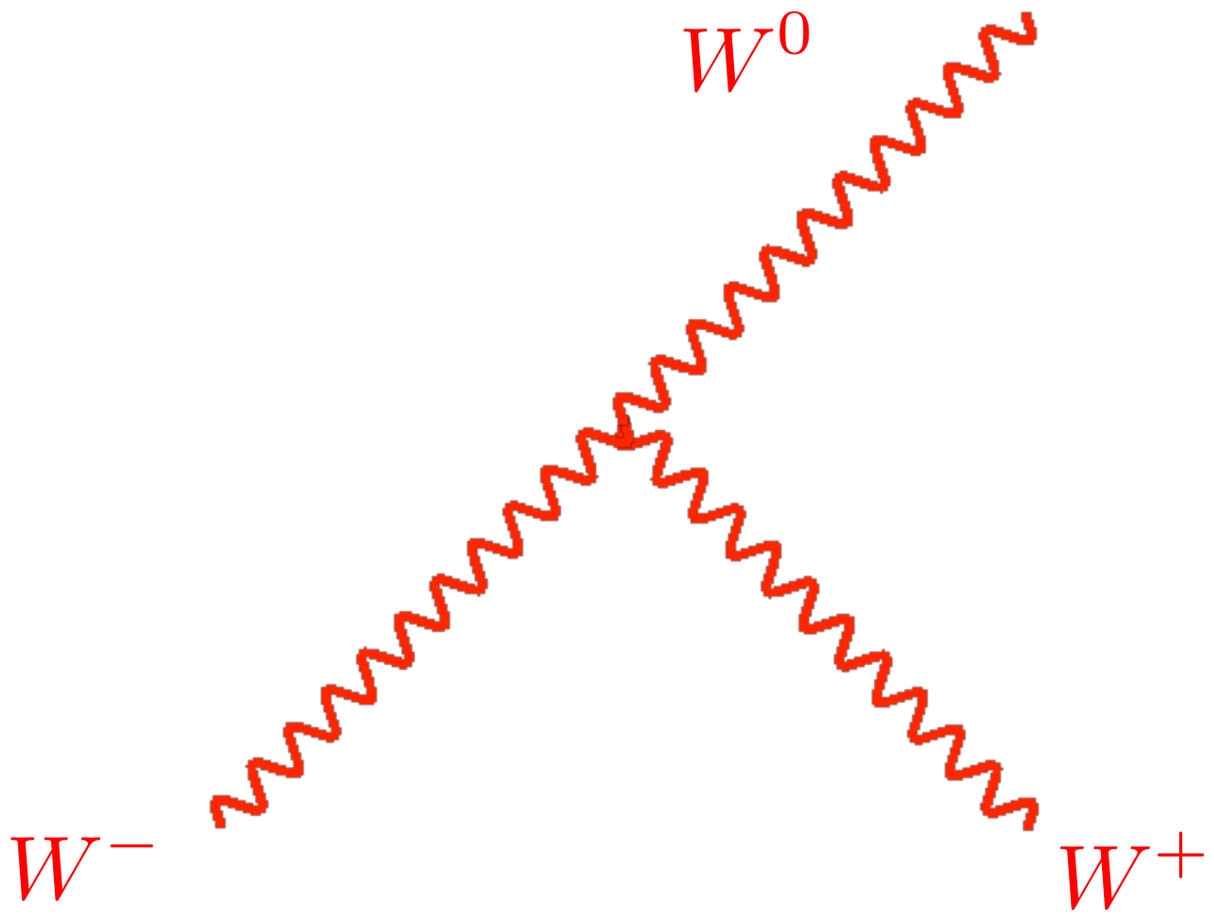
$SU(2)_L$ Weak Interactions



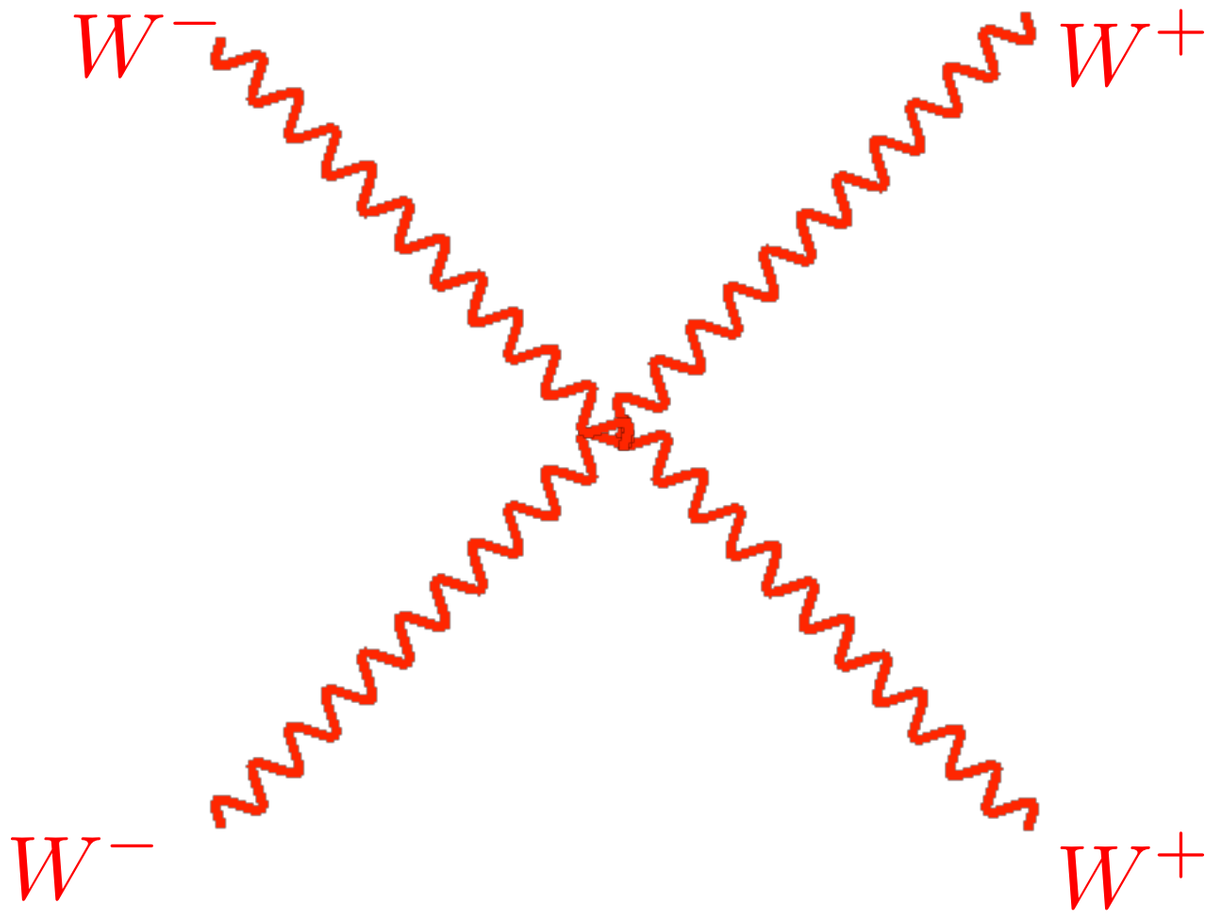
$SU(2)_L$ Weak Interactions



$SU(2)_L$ Weak Interactions



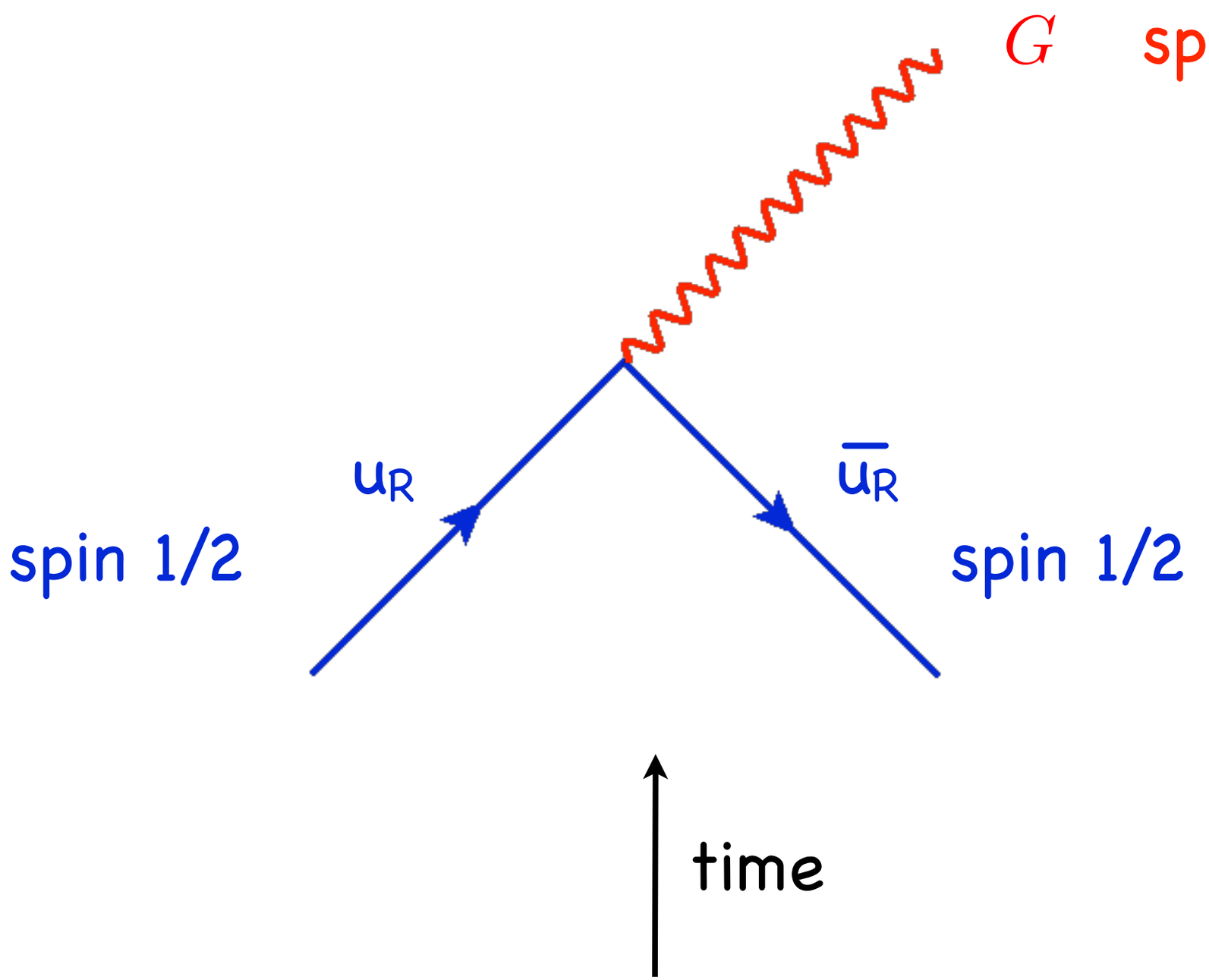
$\sim g$



$\sim g^2$

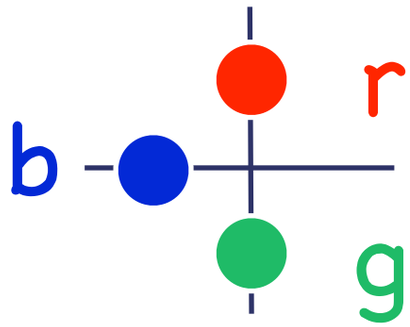
QCD

$SU(3)_c$

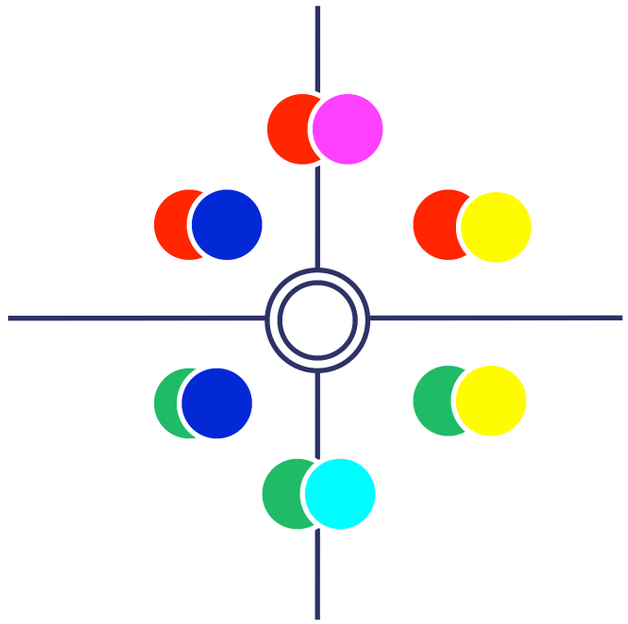


$SU(3)_c$ Gauge Bosons

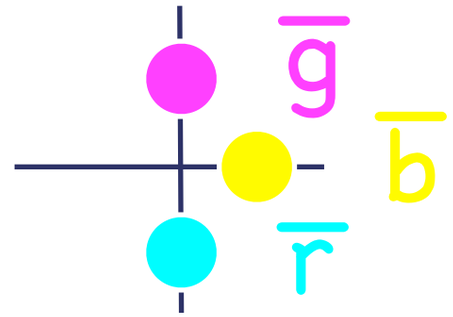
adding SU(3) charges:



three quarks

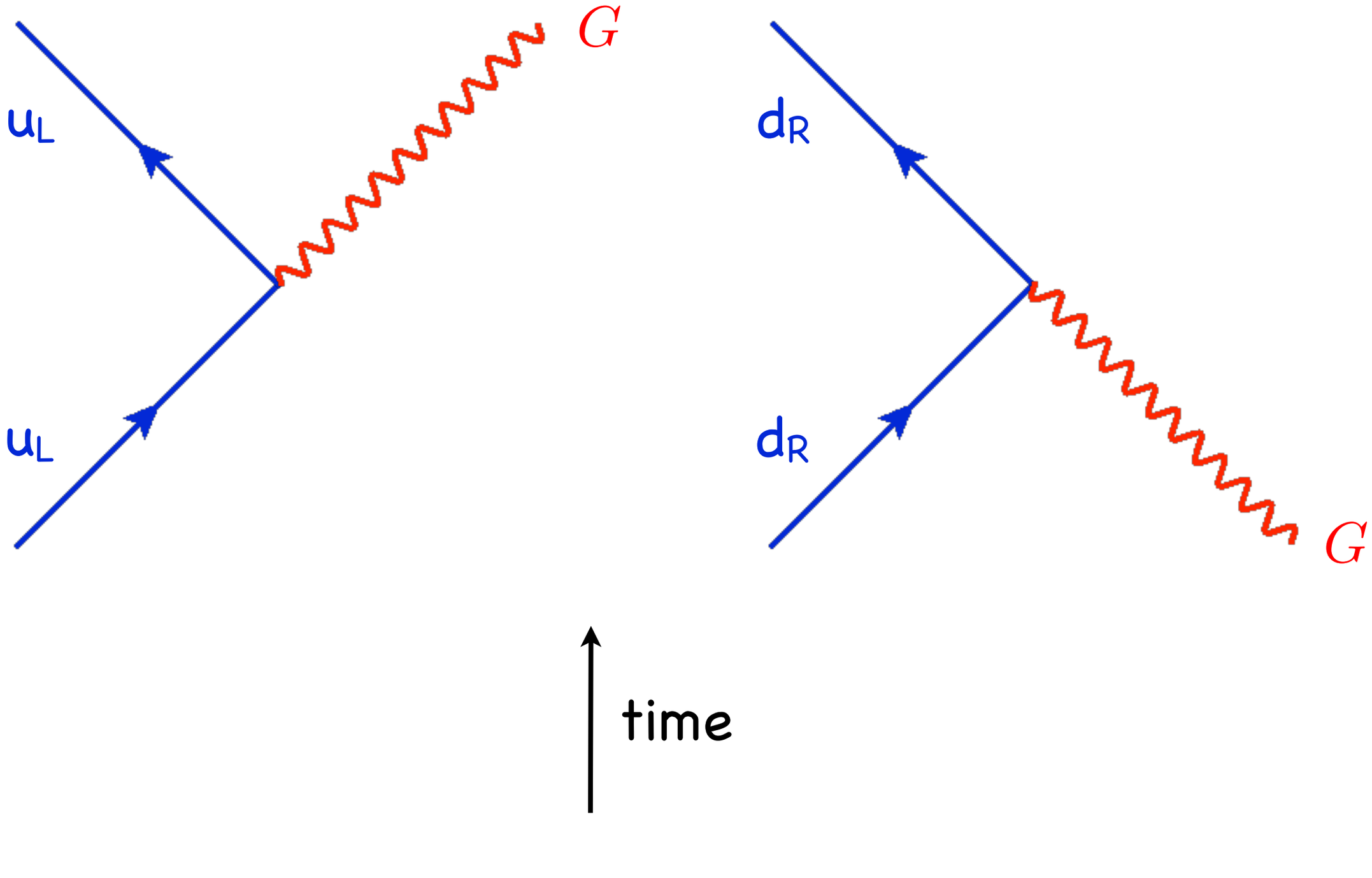


eight gluons

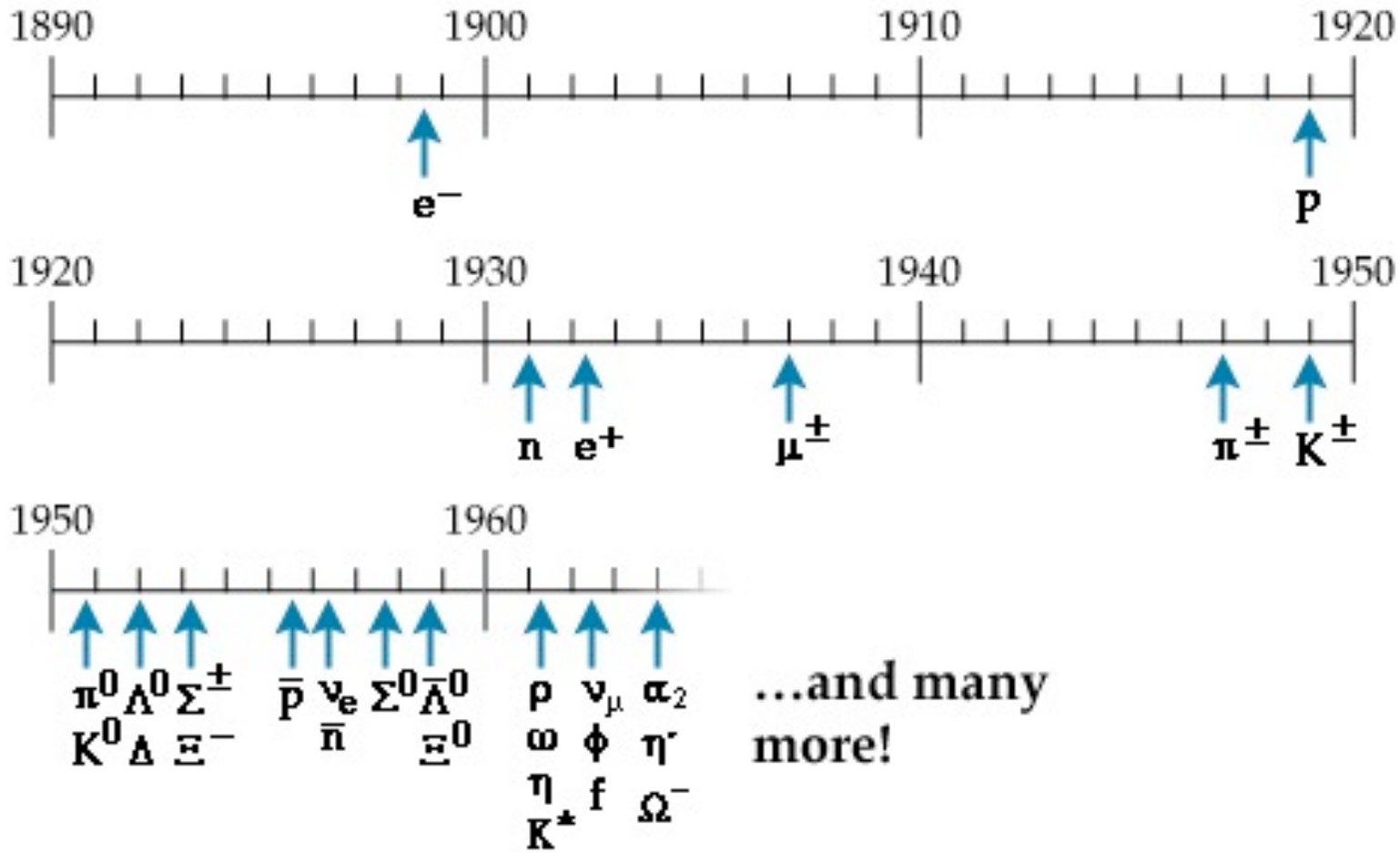


three antiquarks

SU(3) Color Interactions



The Particle Zoo



Quarks

"Three quarks for Muster Mark!"

Quark Bound States

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

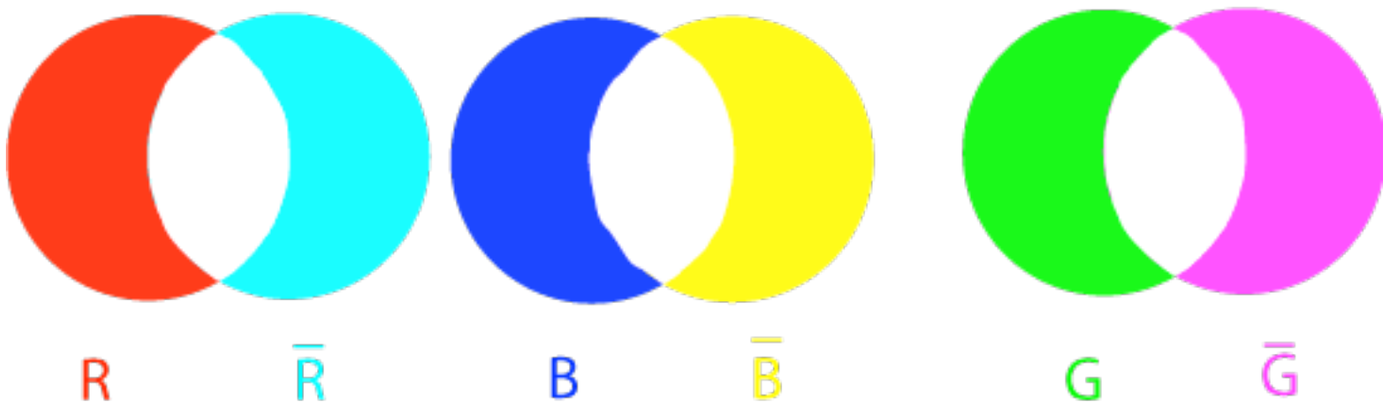
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

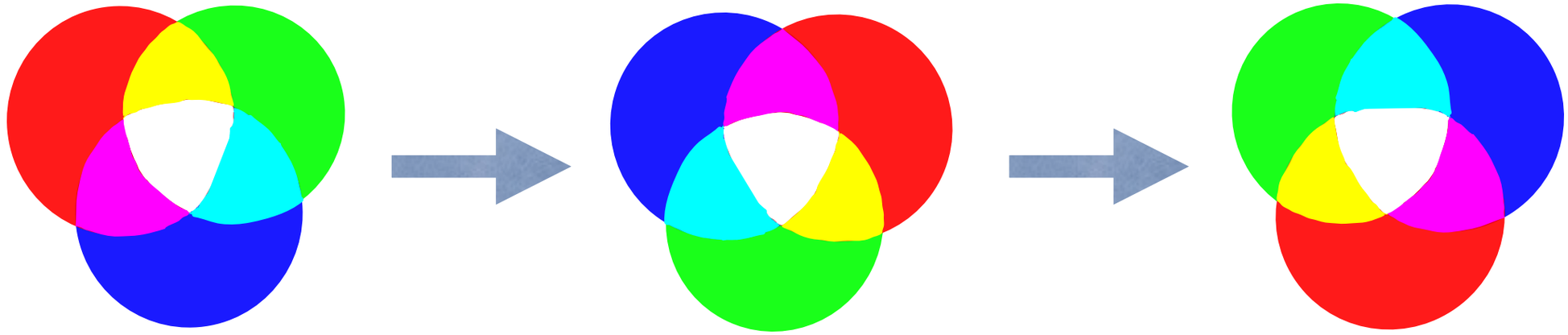
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

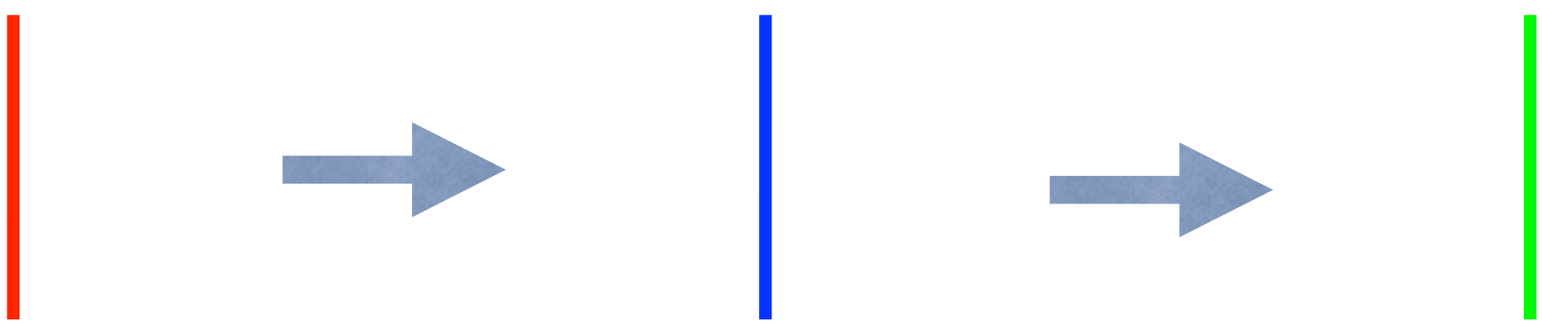
let's look at the three
light flavors first: u, d, s

Colors

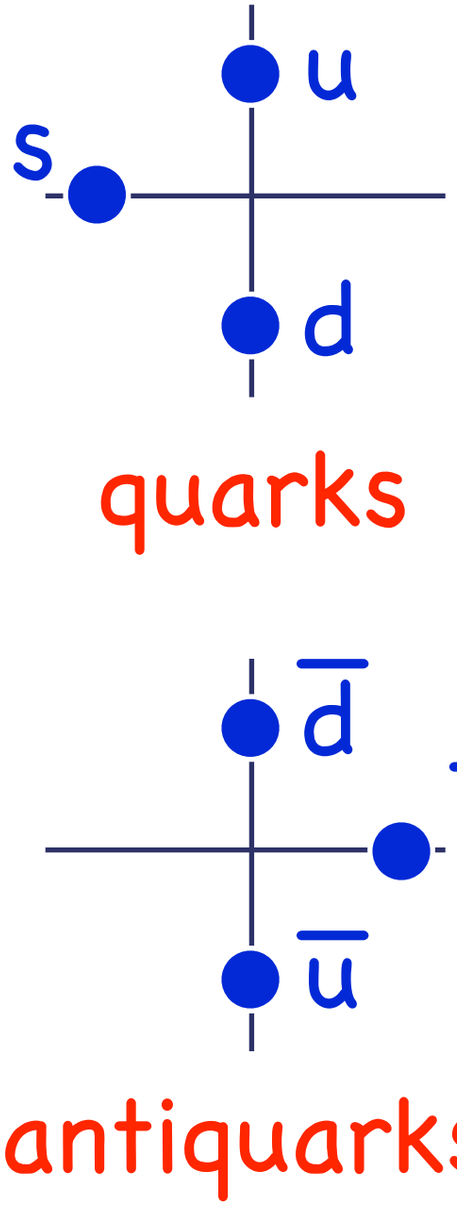


Color Gauge Symmetry





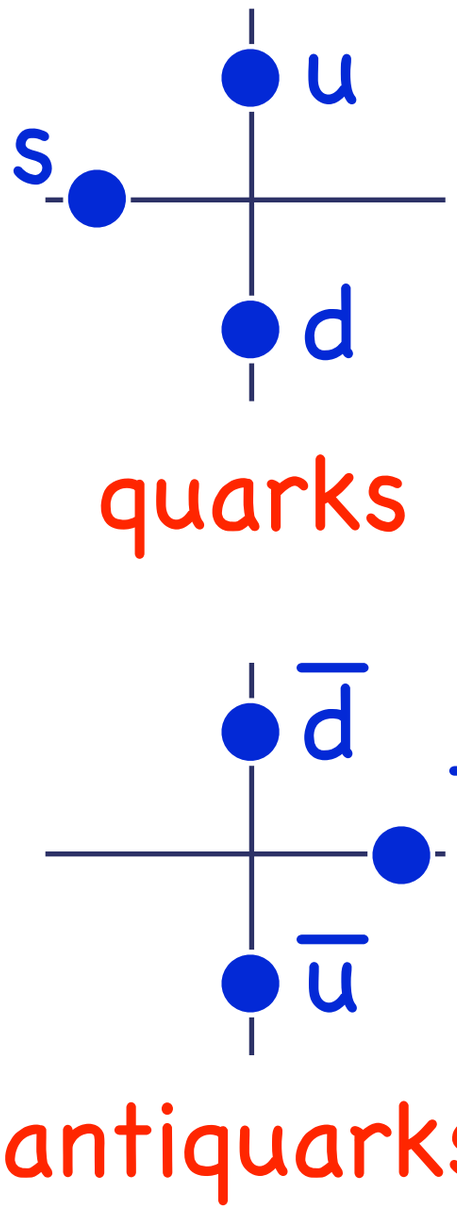
SU(3) Flavor



quarks

antiquarks

SU(3) Flavor


u
s
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quarks
$\bar{d}$
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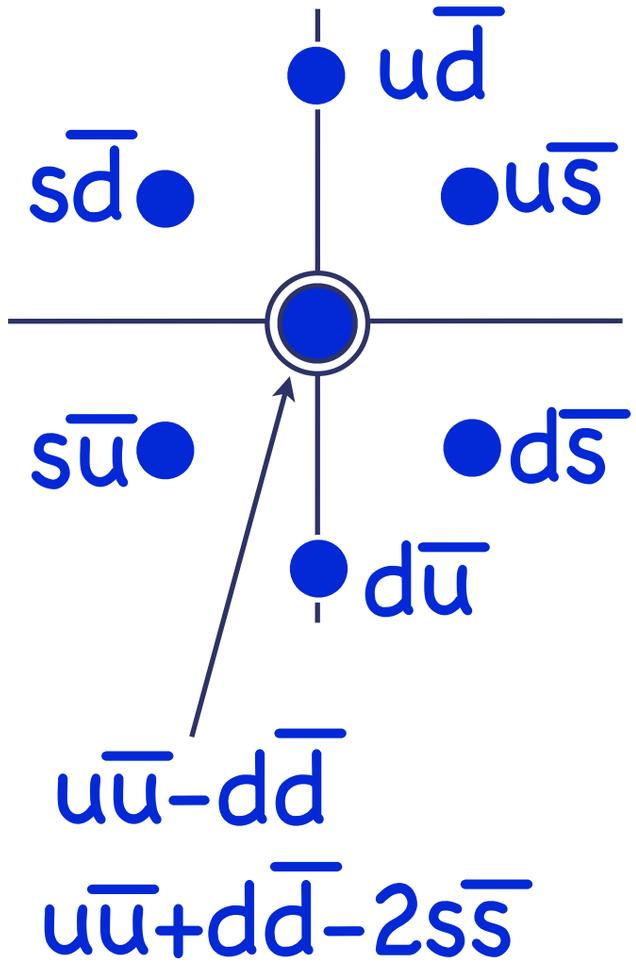
antiquarks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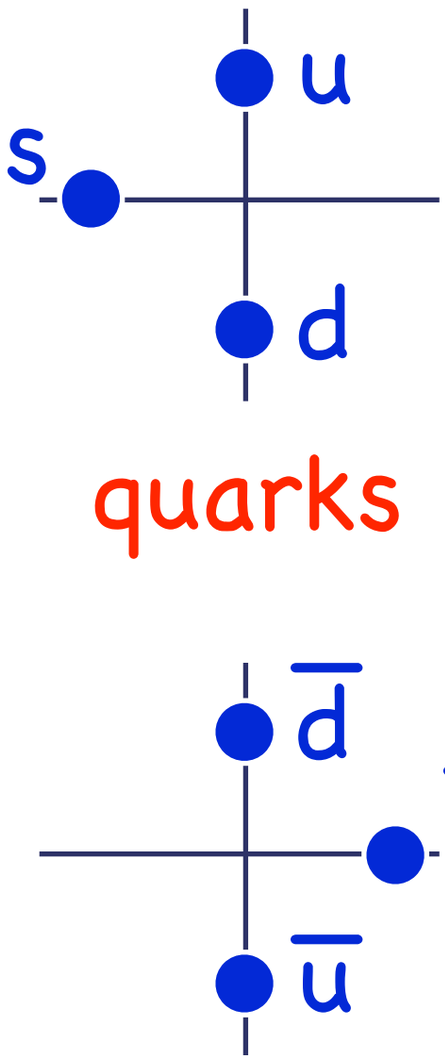
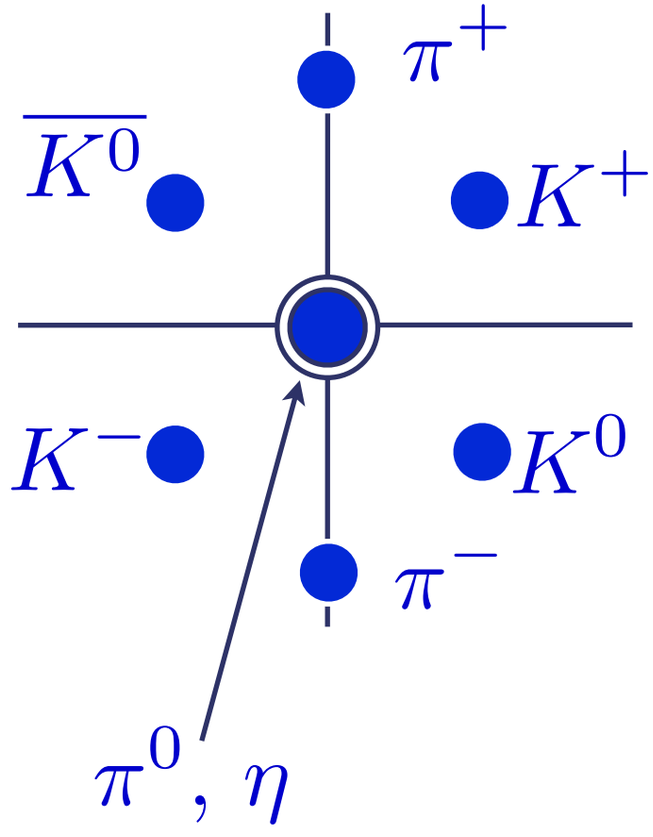
$u\bar{s}$
$s\bar{u}$
$d\bar{s}$
$d\bar{u}$
$u\bar{u}-d\bar{d}$
$u\bar{u}+d\bar{d}-2s\bar{s}$

SU(3) Flavor



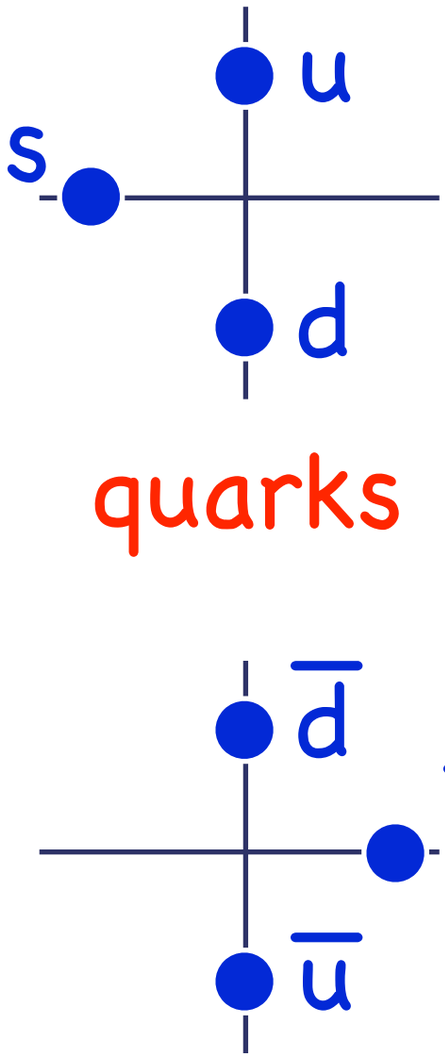
quarks

antiquarks



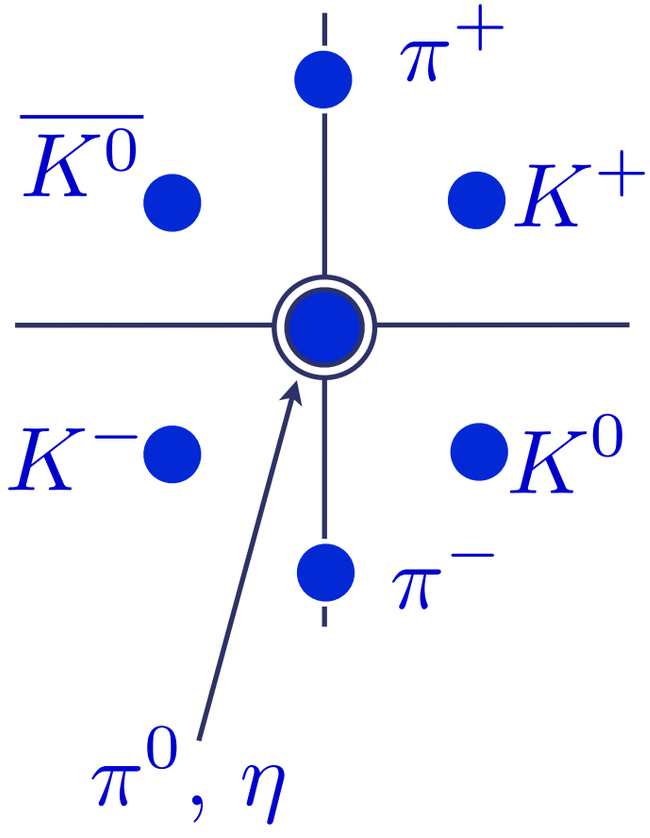
mesons

SU(3) Flavor

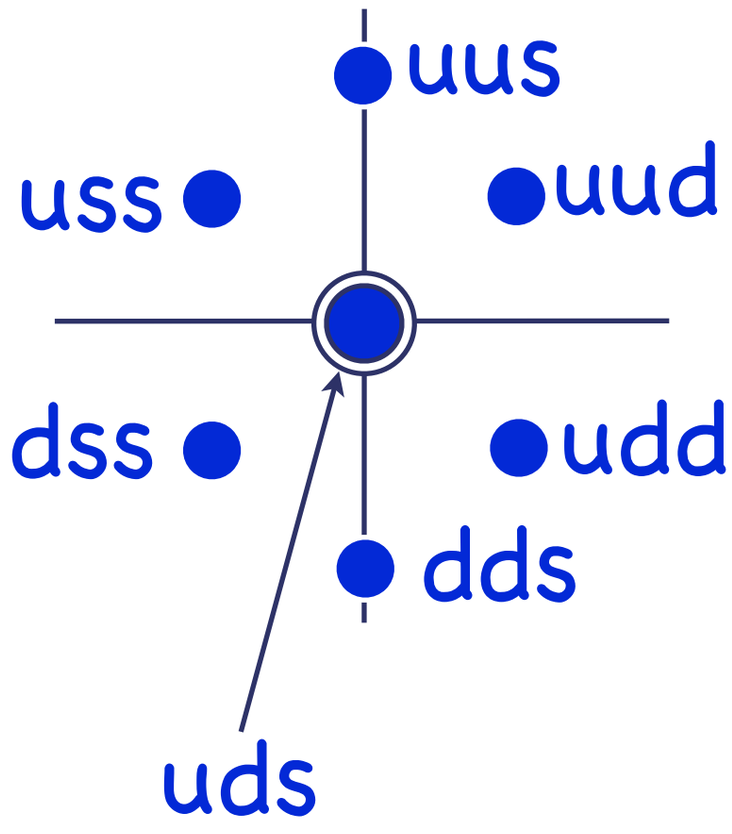


quarks

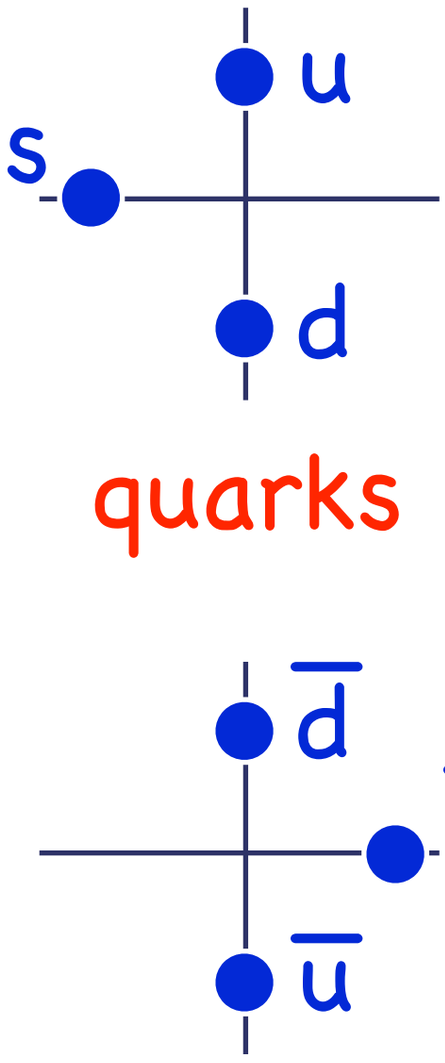
antiquarks



mesons

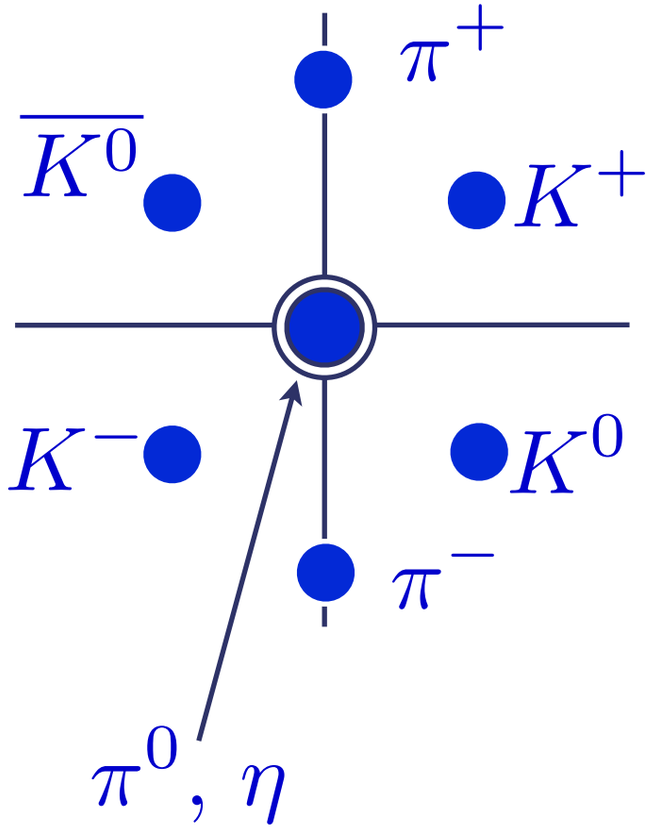


SU(3) Flavor

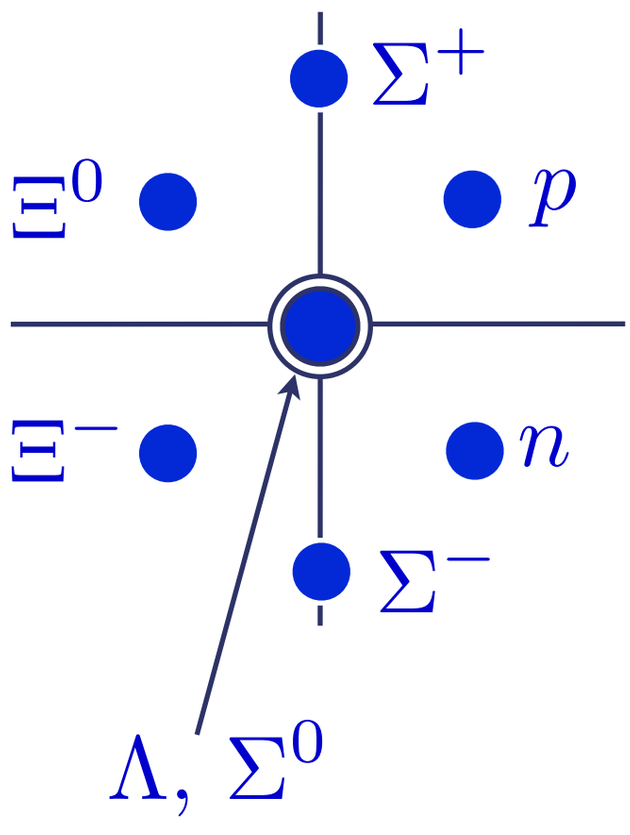


quarks

antiquarks

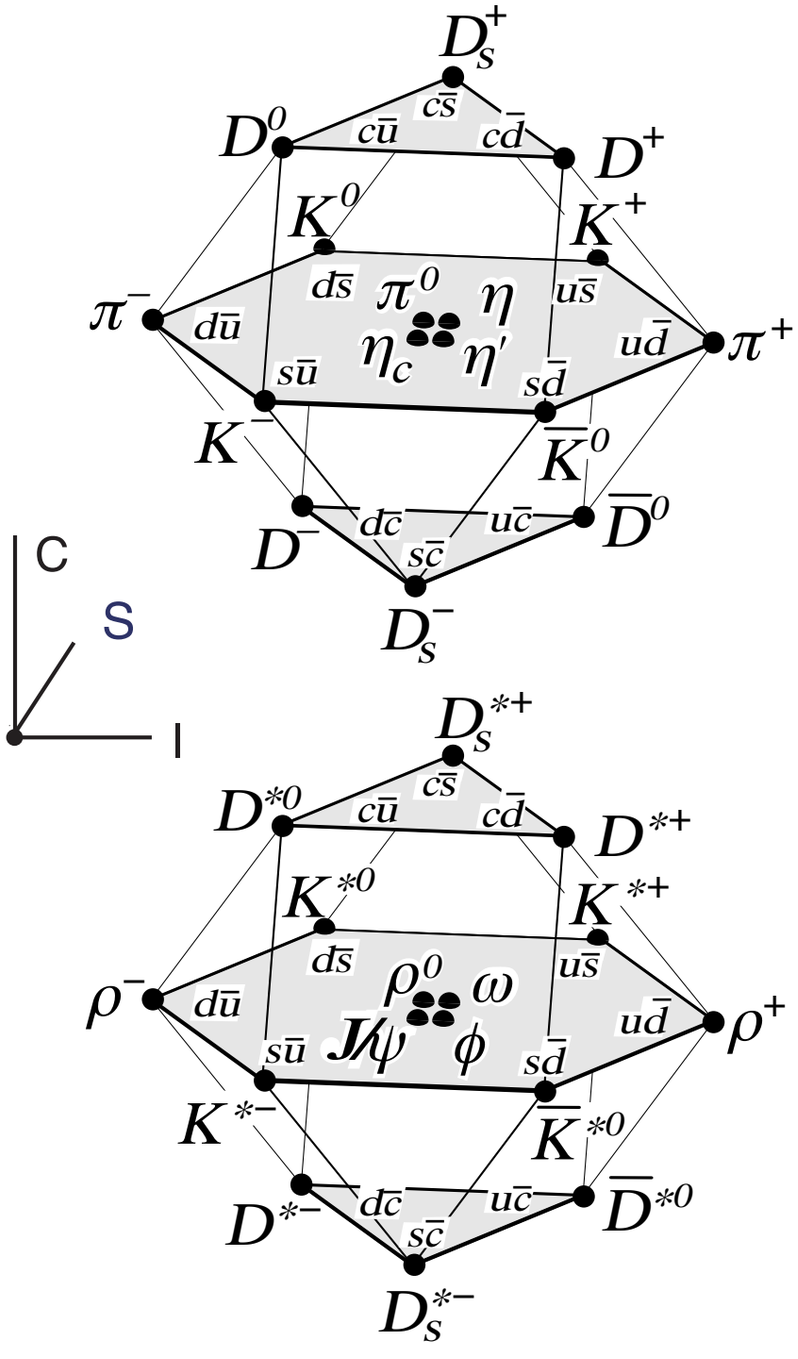


mesons

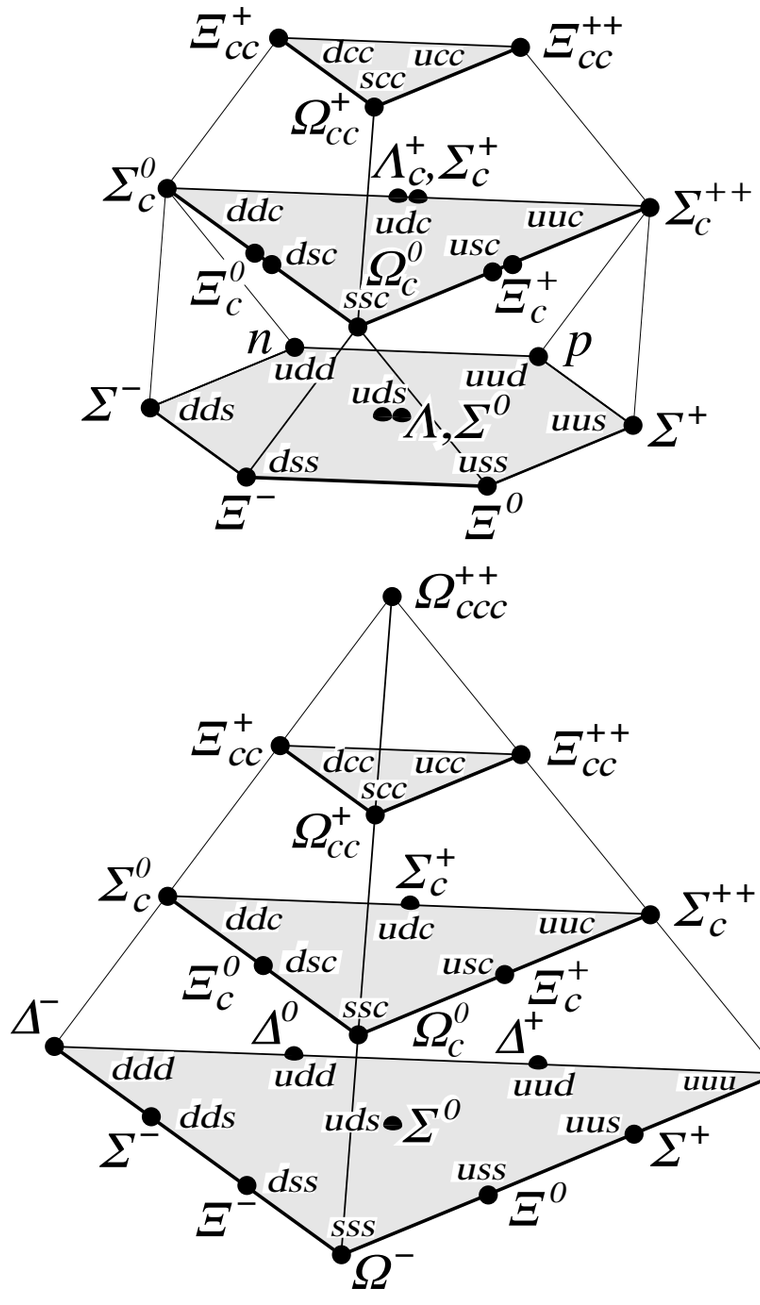


baryons

4 Flavors



mesons



baryons

QED Potential

1/r potential:

Fourier Transform

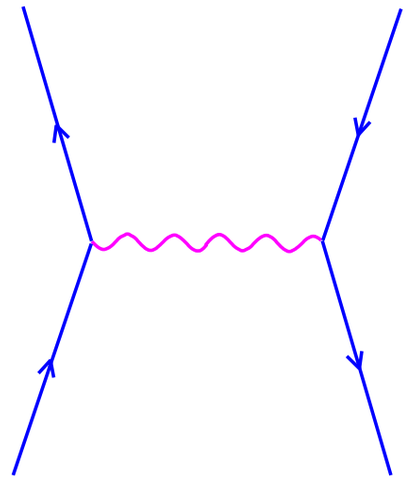
$$J^\mu(x)\frac{e^2}{|x-y|}J_\mu(y) \quad \longleftrightarrow \quad J^\mu\frac{e^2}{q^2}J_\mu$$

QED Potential

1/r potential:

Fourier Transform

$$J^\mu(x)\frac{e^2}{|x-y|}J_\mu(y) \quad \longleftrightarrow \quad J^\mu\frac{e^2}{q^2}J_\mu$$



elastic scattering amplitude

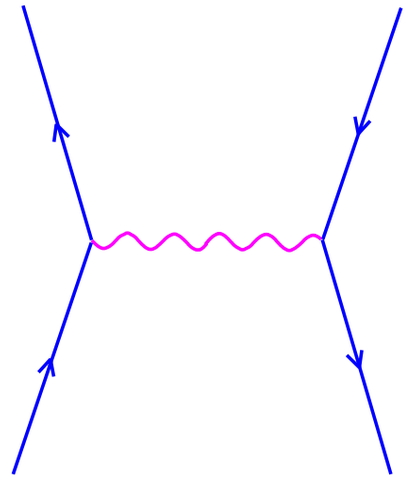
QED Potential

1/r potential:

Fourier Transform

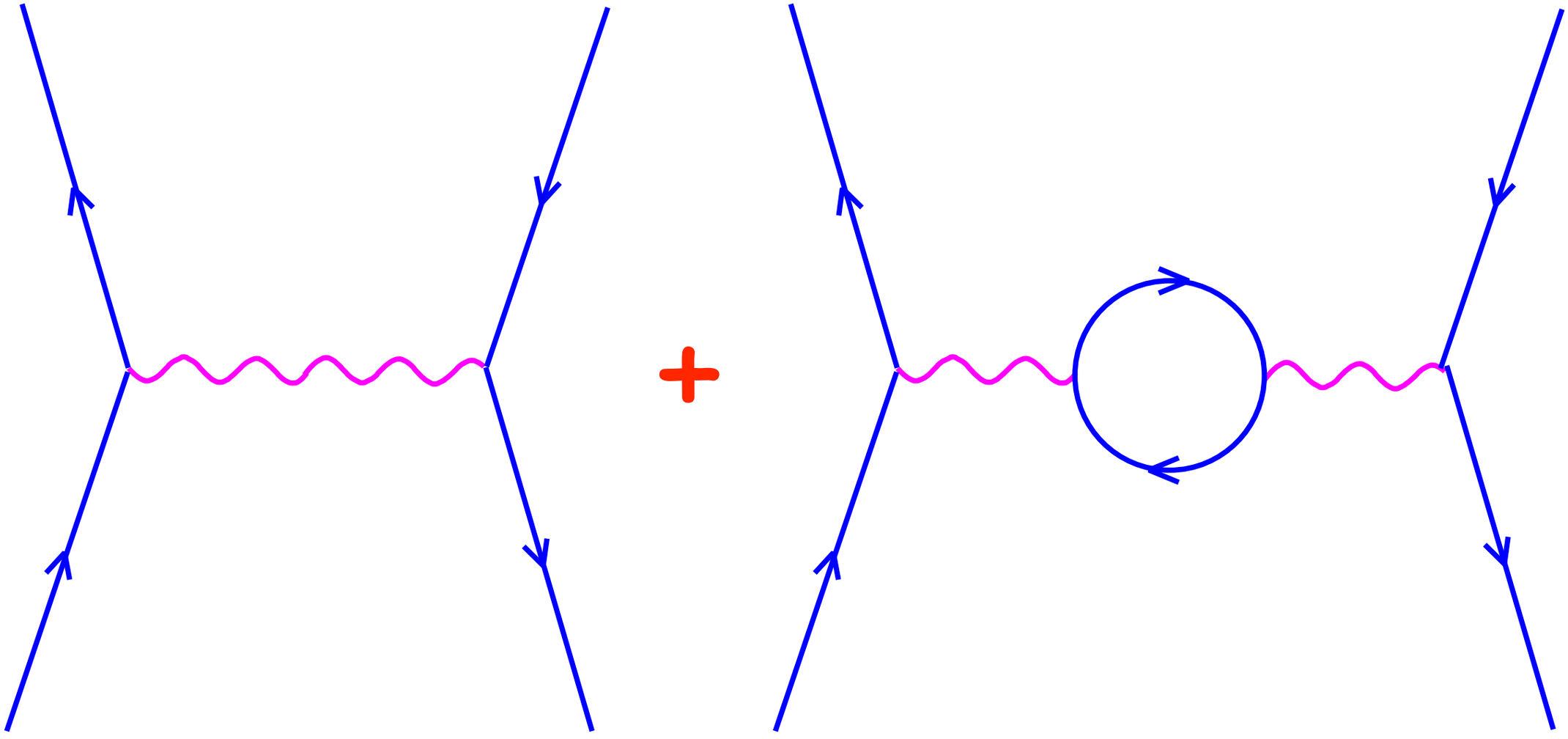
$$J^\mu(x)\frac{e^2}{|x-y|}J_\mu(y) \quad \longleftrightarrow \quad J^\mu\frac{e^2}{q^2}J_\mu$$

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$



elastic scattering amplitude

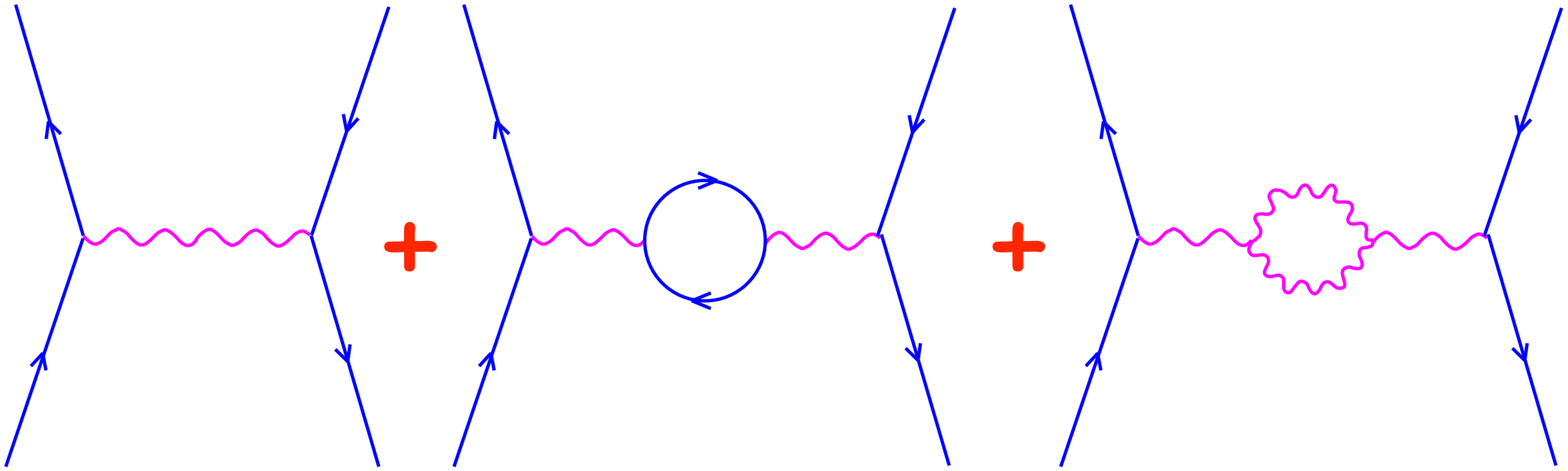
Quantum Corrections



coupling is distance dependent

$$\alpha(10^{-10}\ \mathrm{m}) \approx \frac{1}{137} \qquad \alpha(10^{-17}\ \mathrm{m}) \approx \frac{1}{128}$$

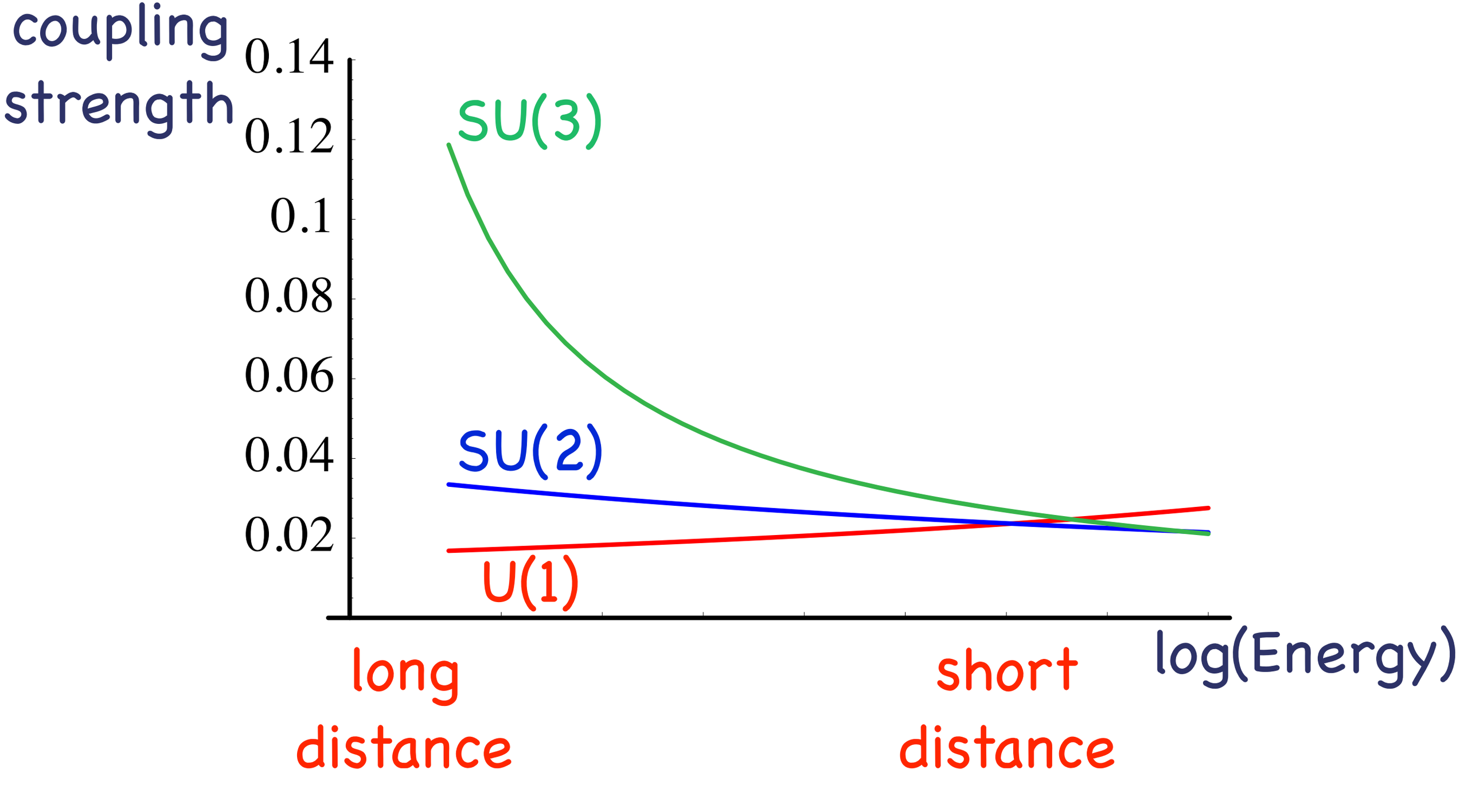
Quantum Corrections



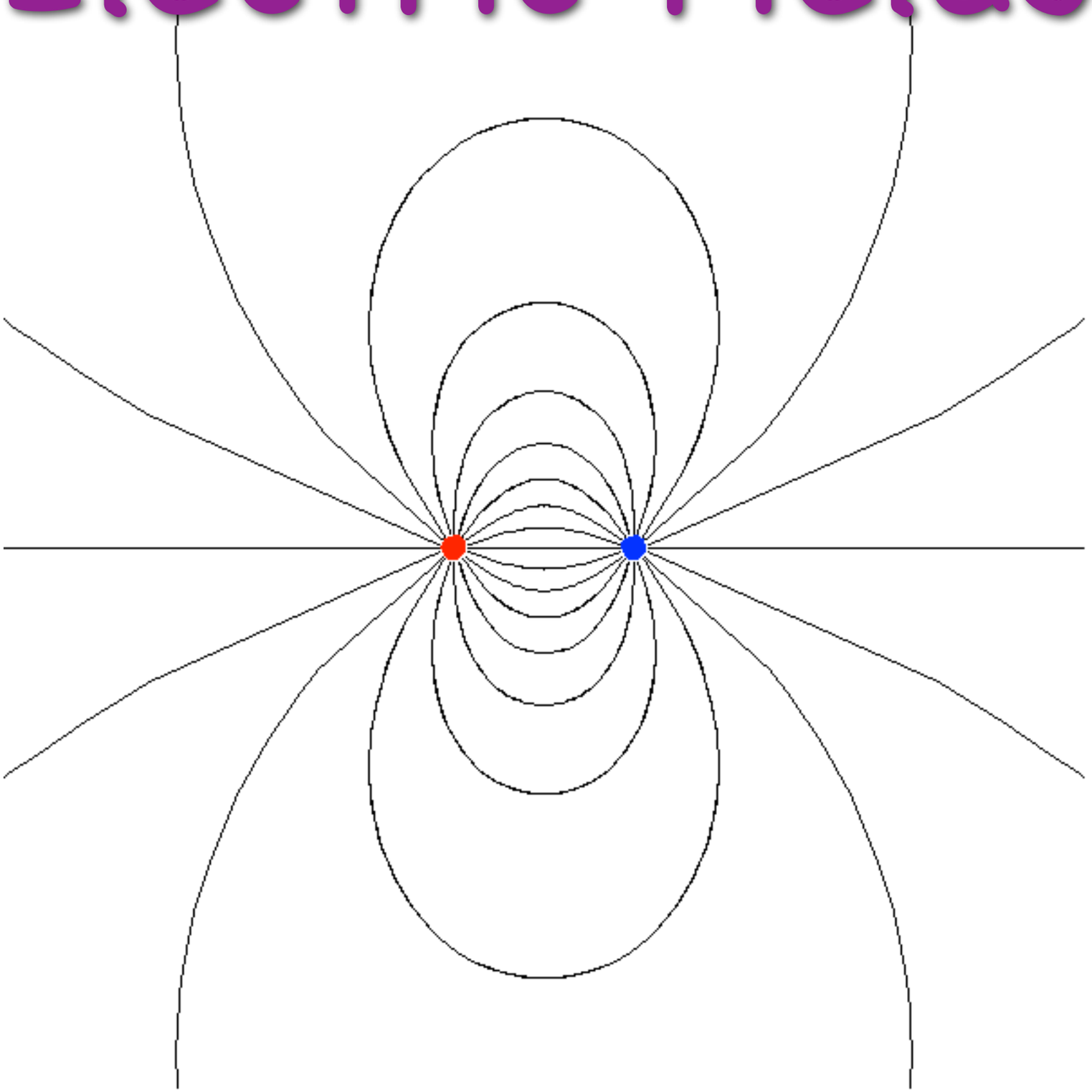
gluons contribute
with opposite sign

QCD coupling gets stronger at larger distances

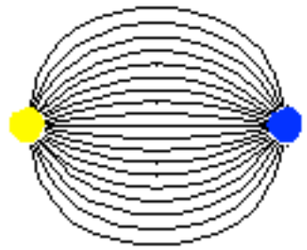
Running Coupling



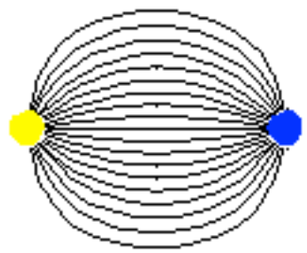
Electric Fields

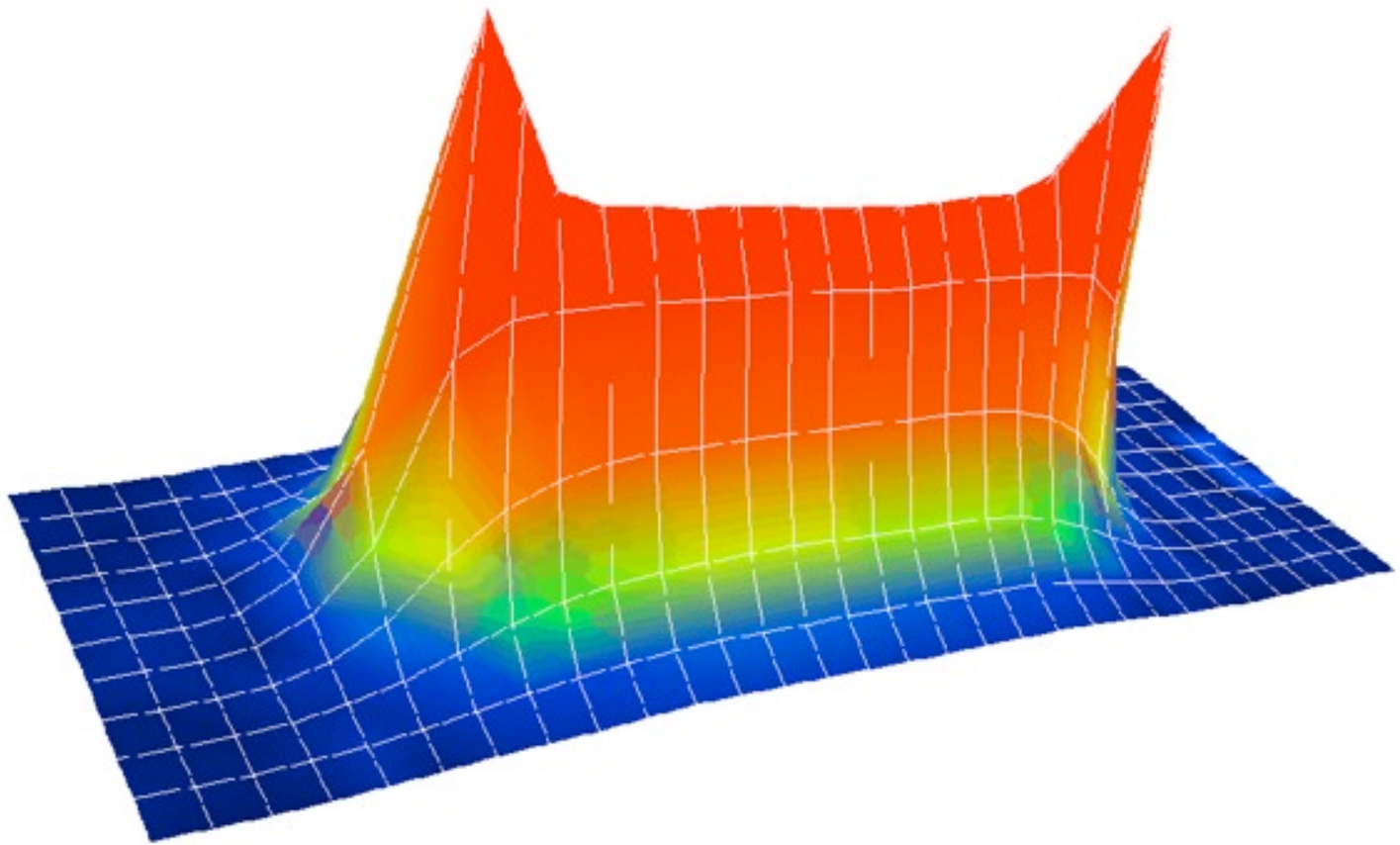


"Color" Fields

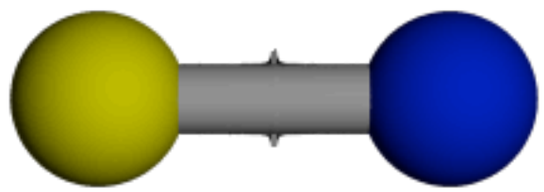


"Color" Fields

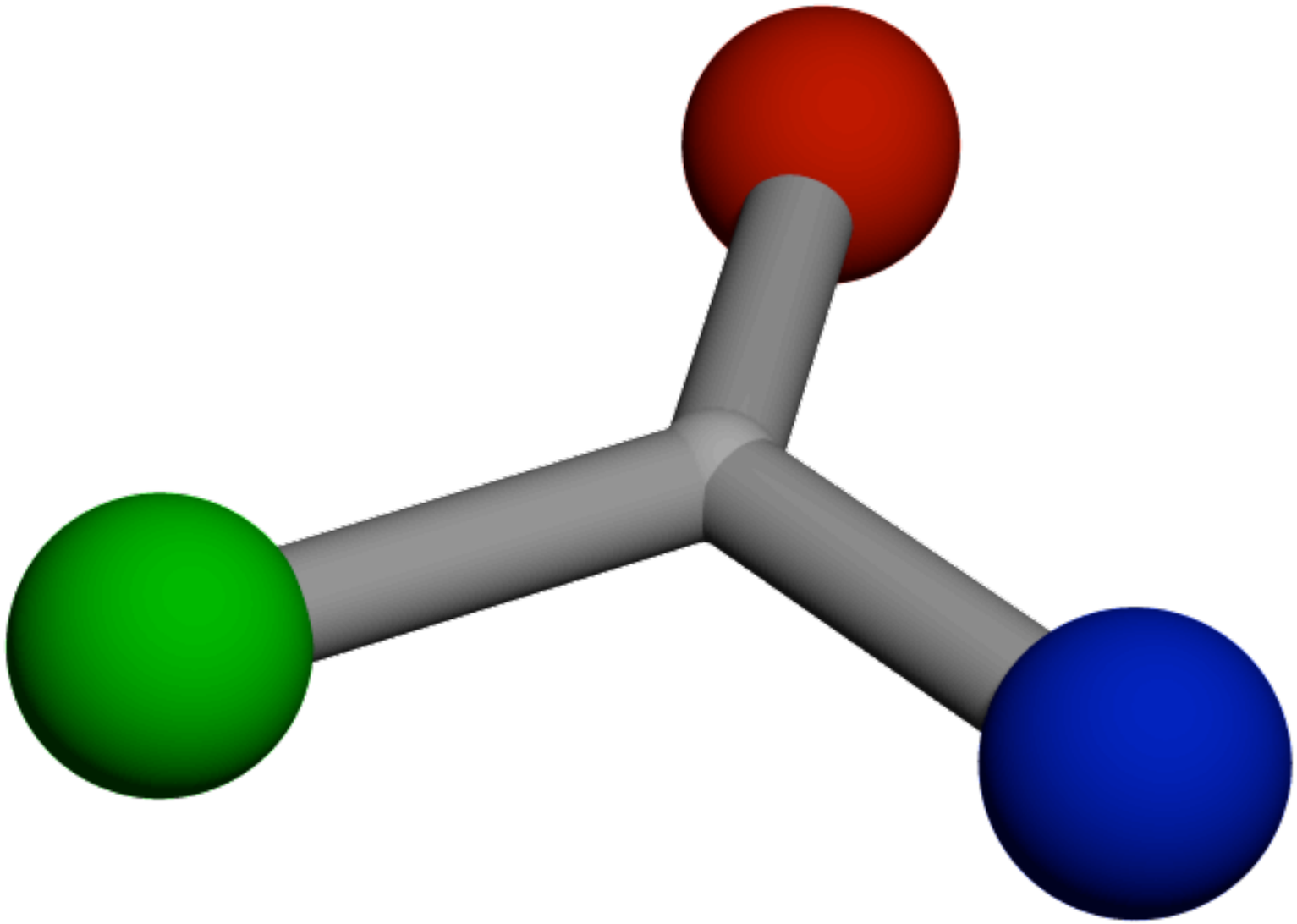




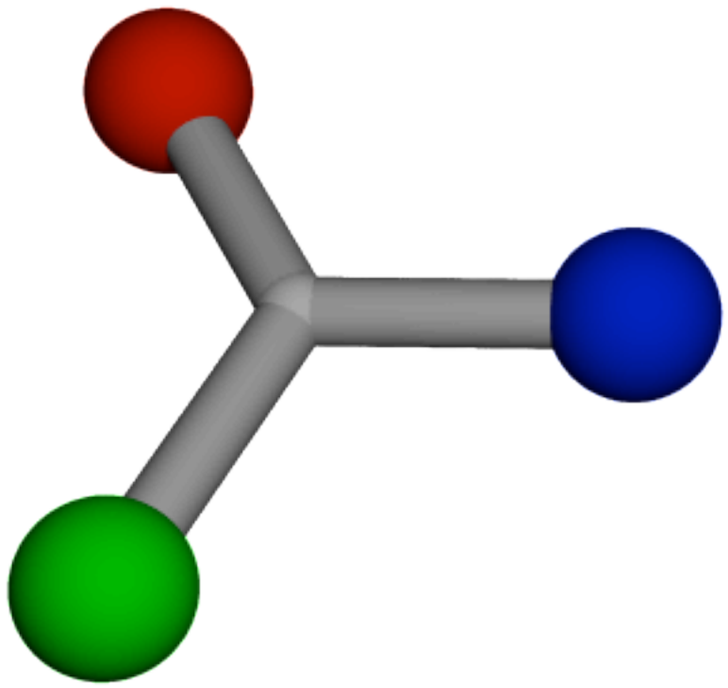
Flux Tube -> Meson



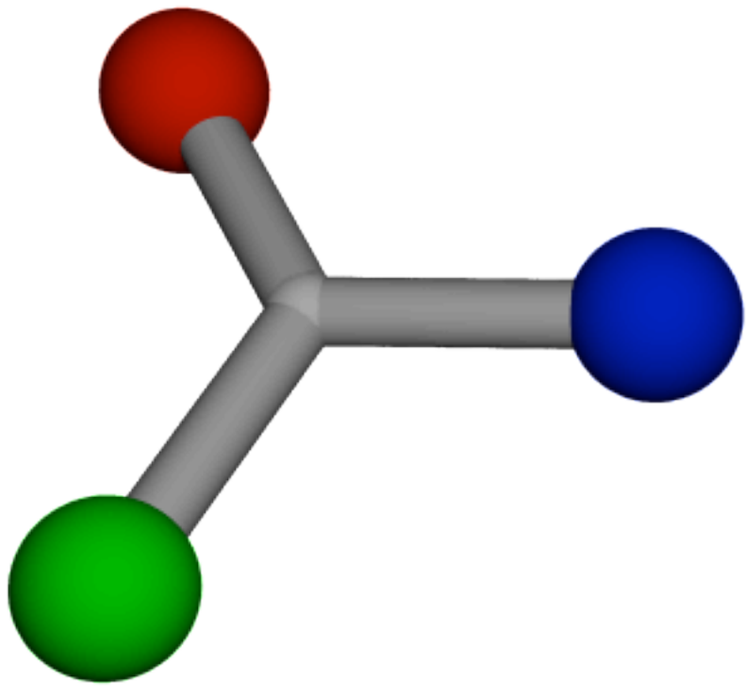
Proton



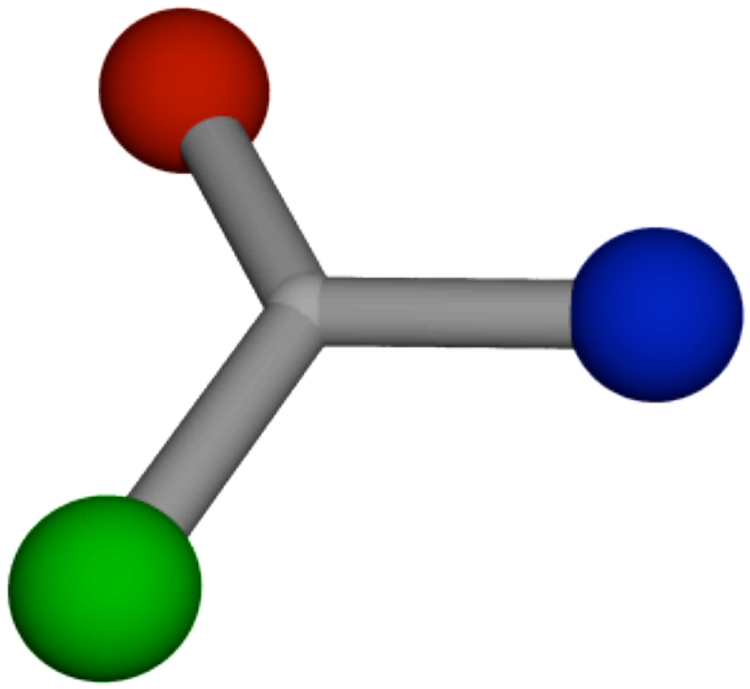
Pulling out a quark



Pulling out a quark

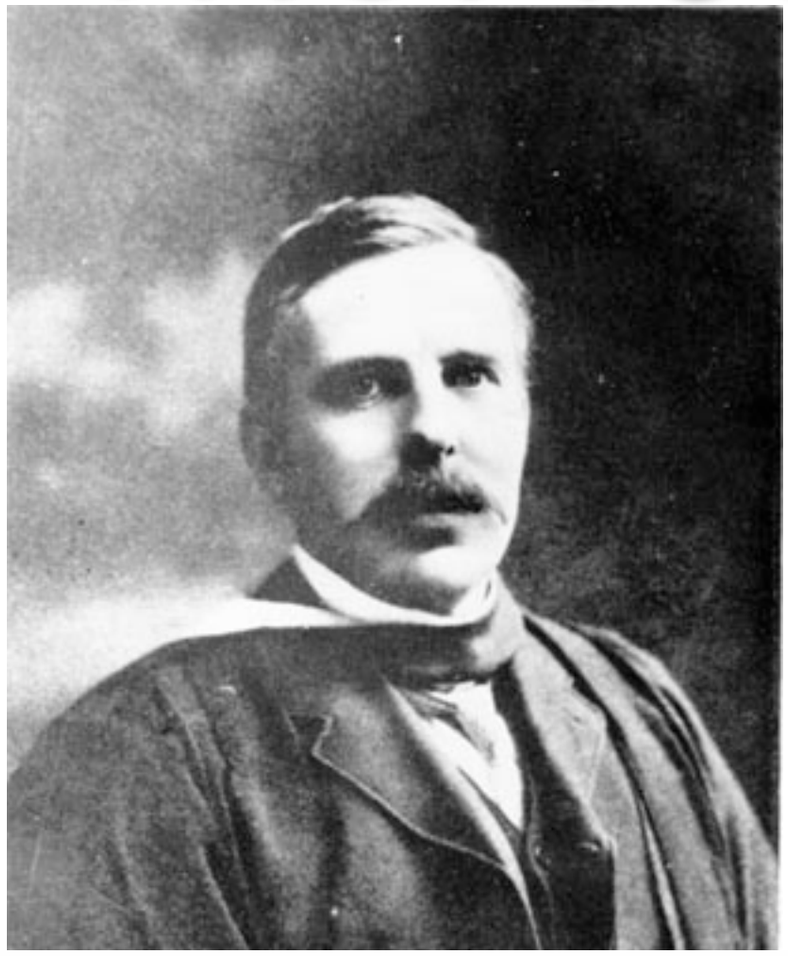


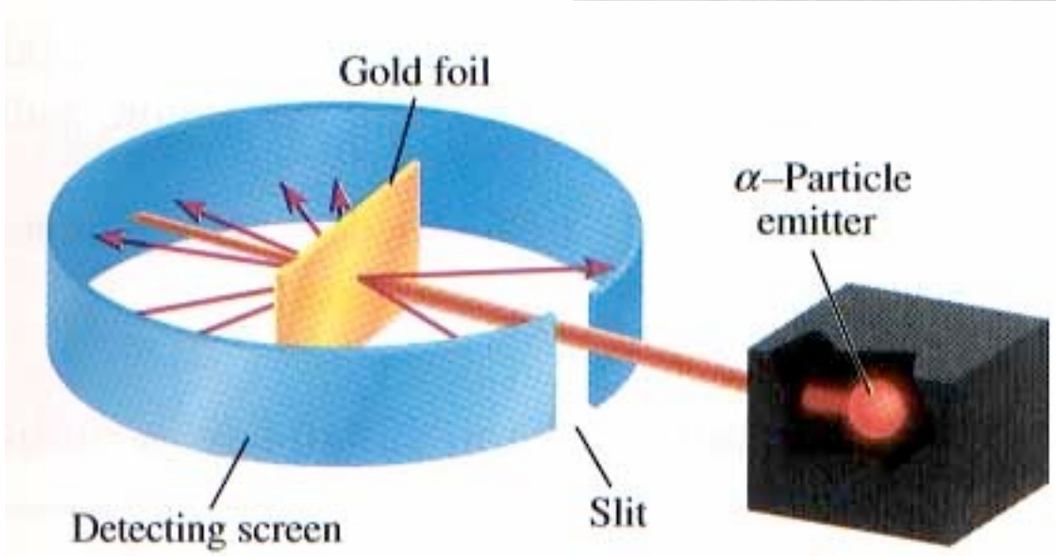
Pulling out a quark

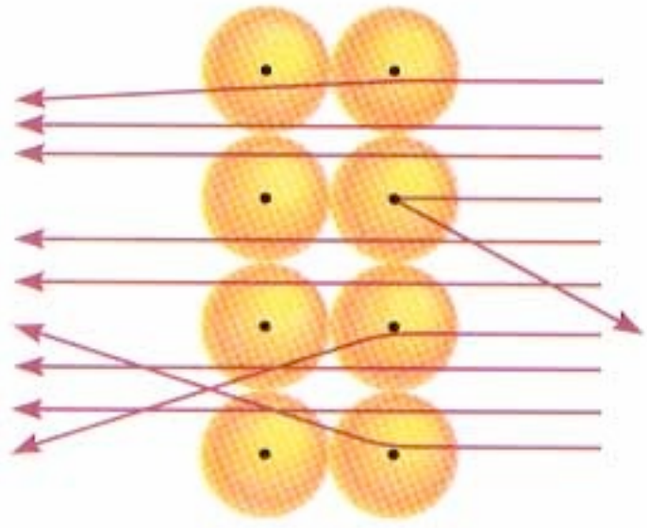


If quarks and gluons are confined,
how do we know they exist?

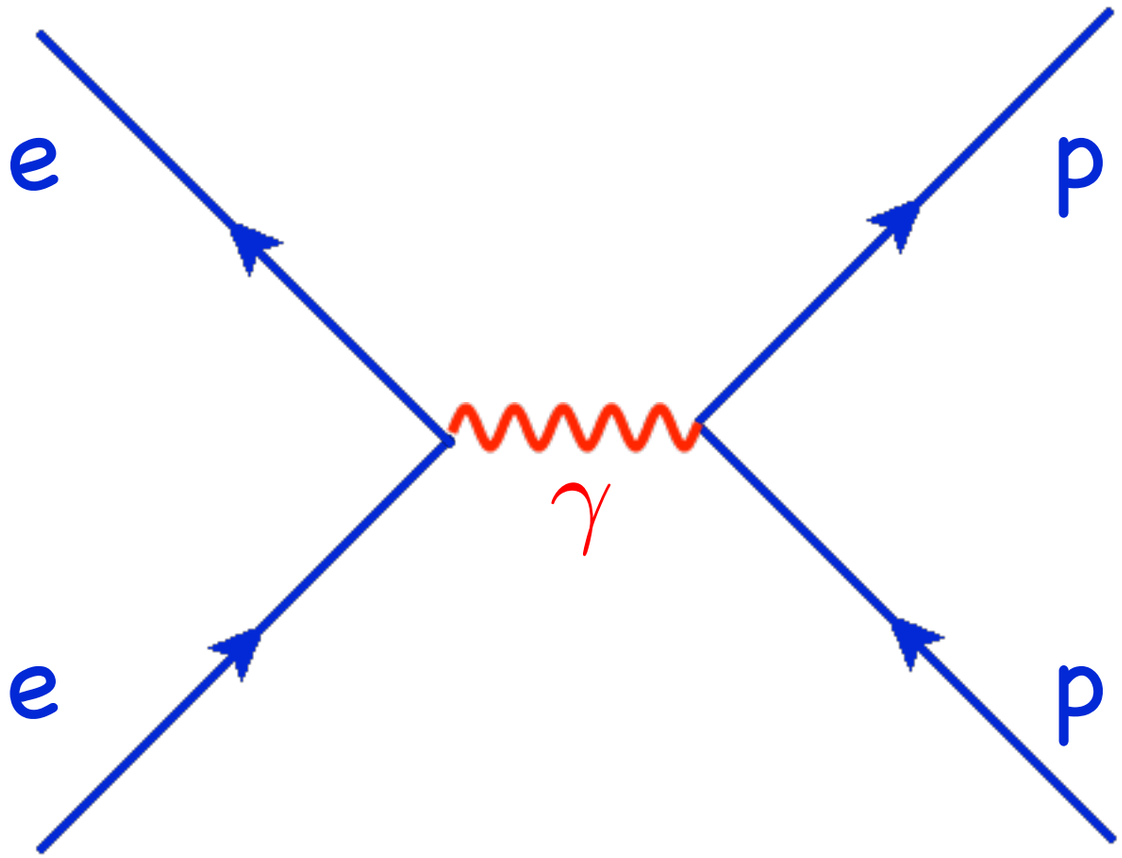
Rutherford





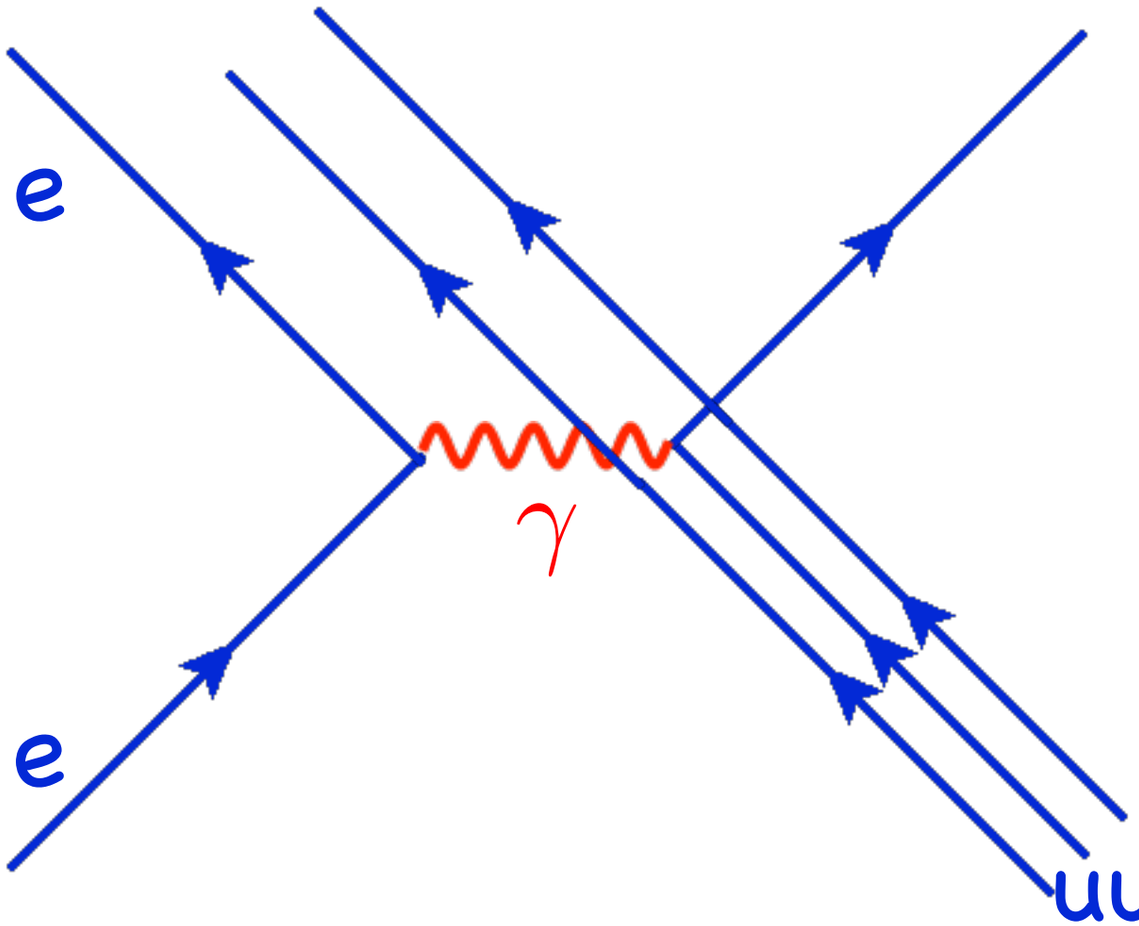


Low Energy



low energy photon cannot
resolve proton structure

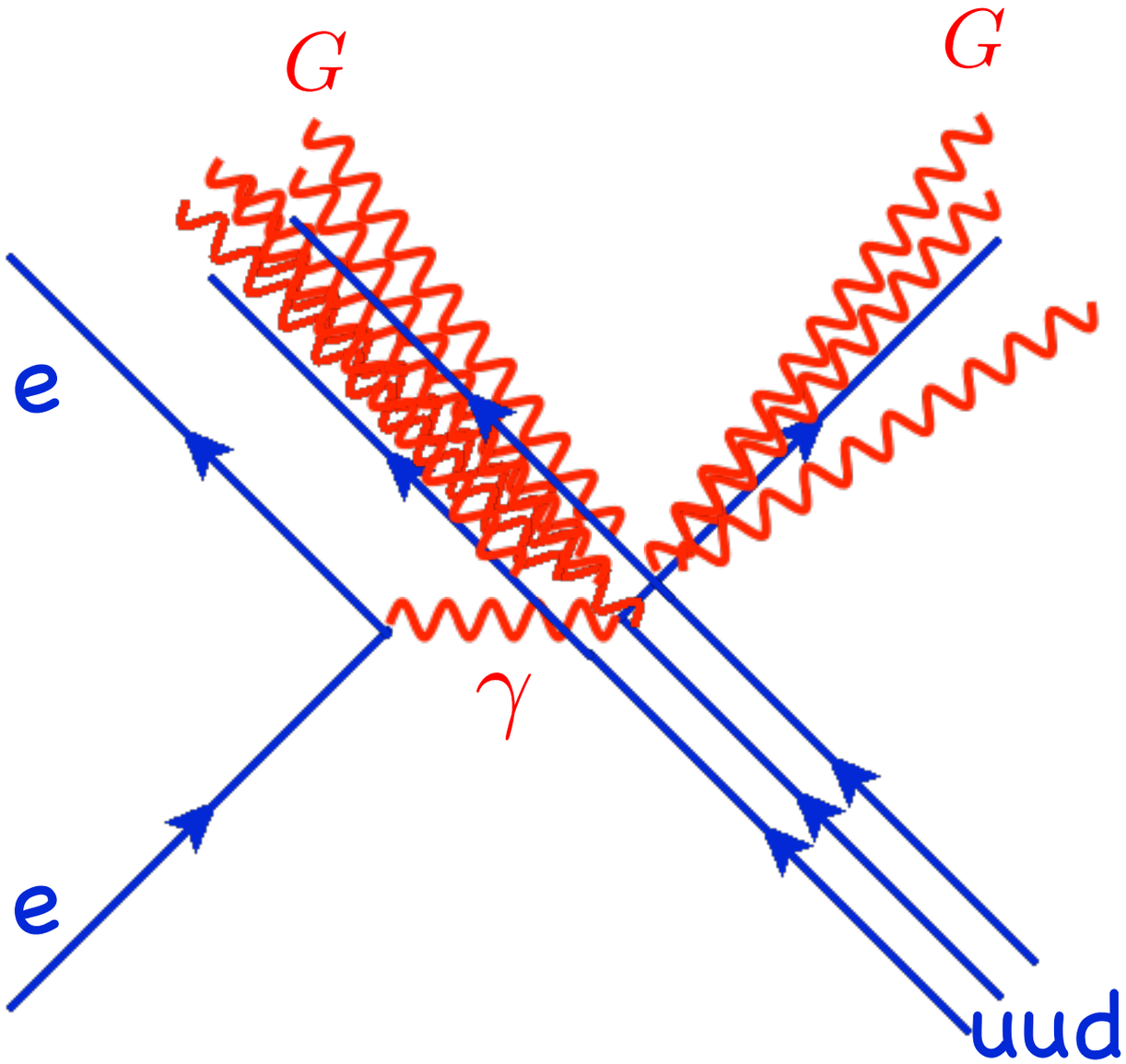
SLAC–MIT Experiment



1968

high energy photon resolves quarks

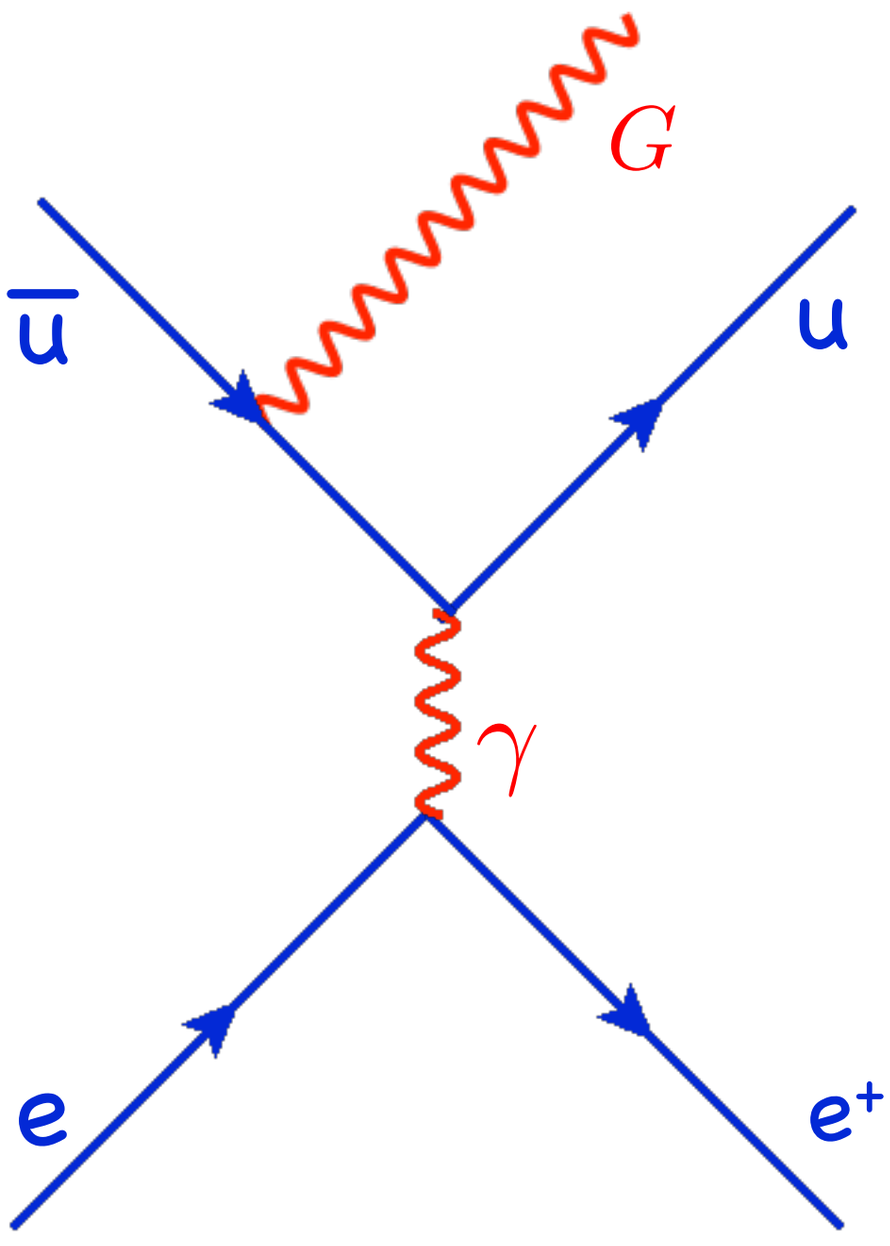
SLAC-MIT Experiment



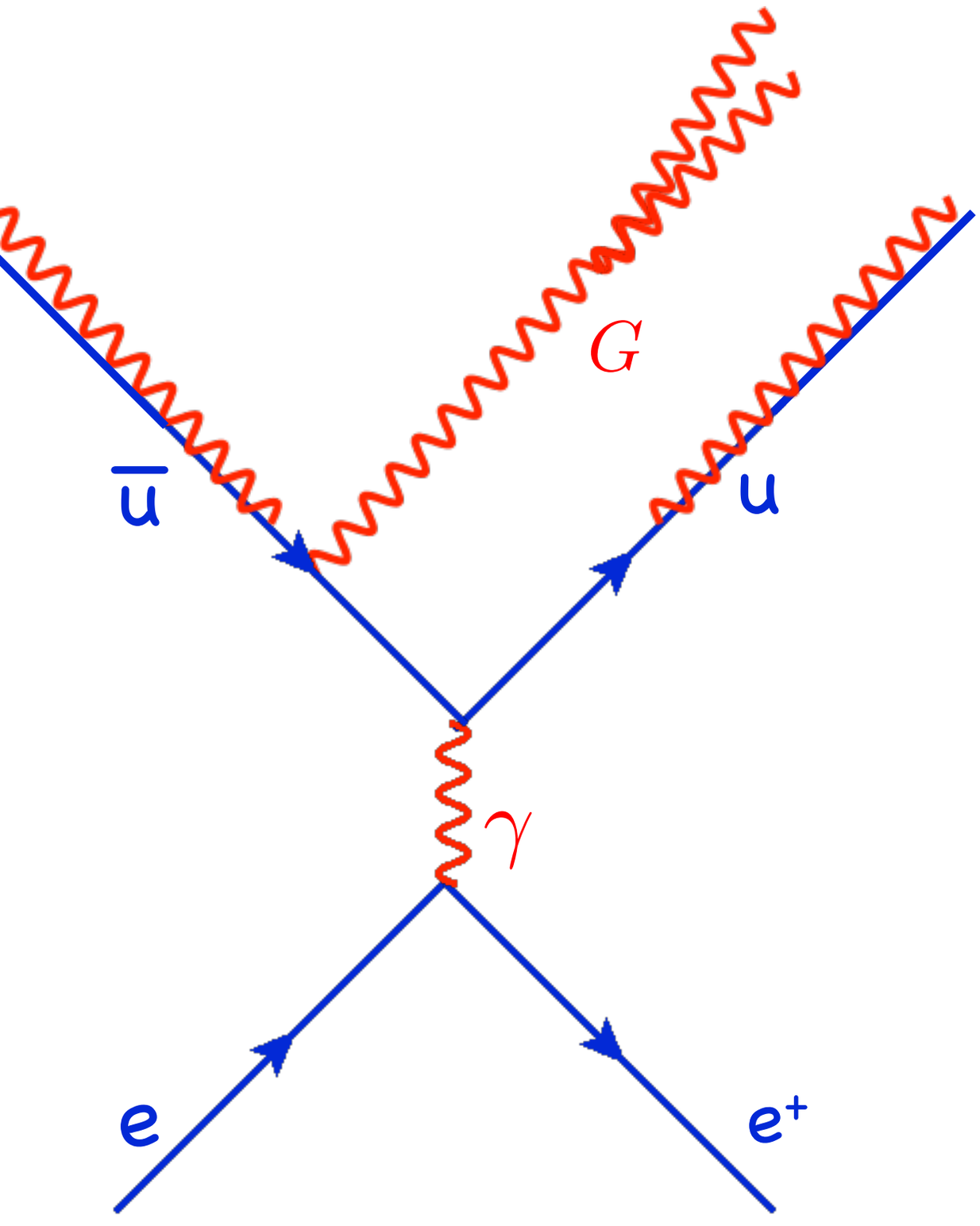
1968

high energy photon resolves quarks

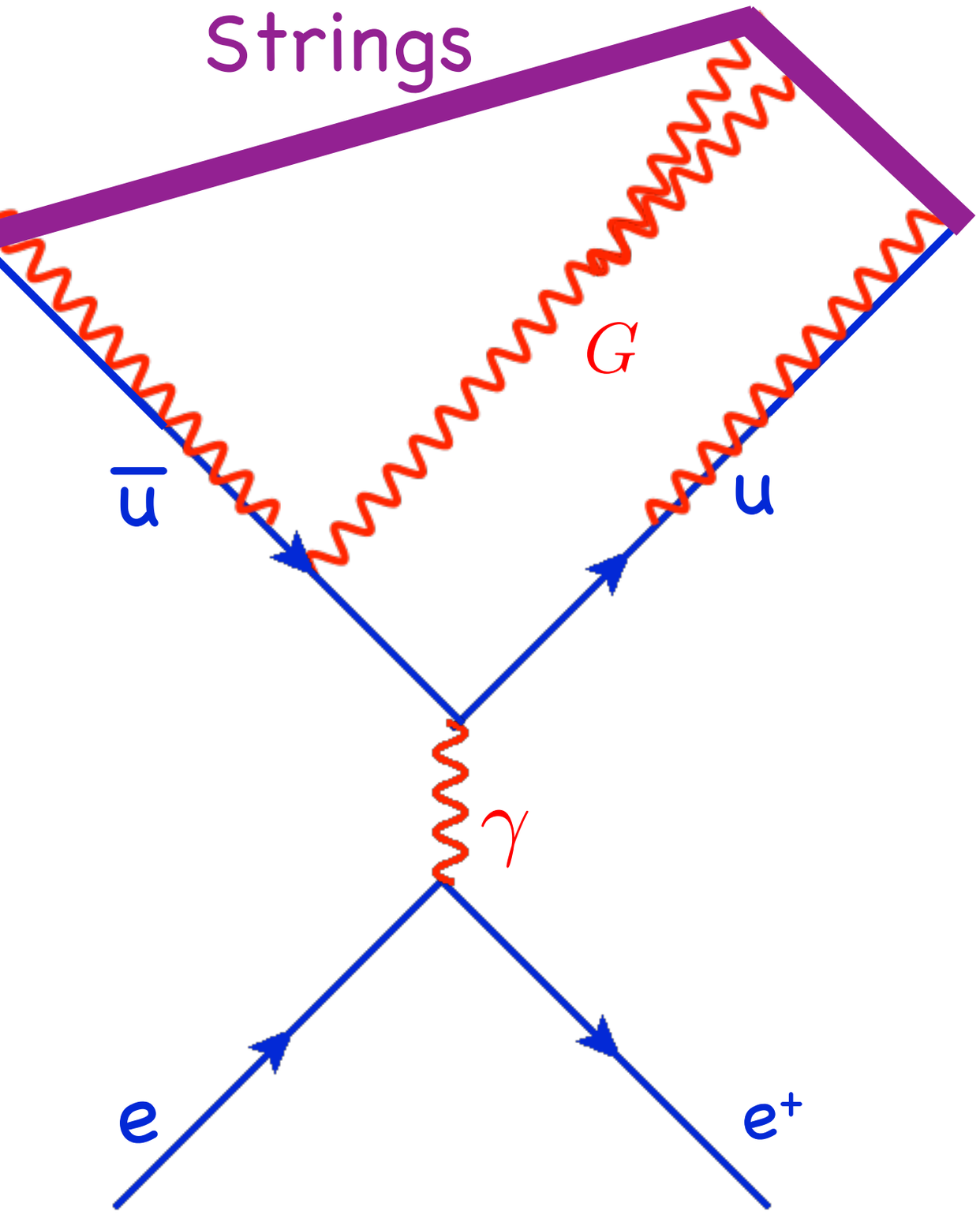
Jets



Jets

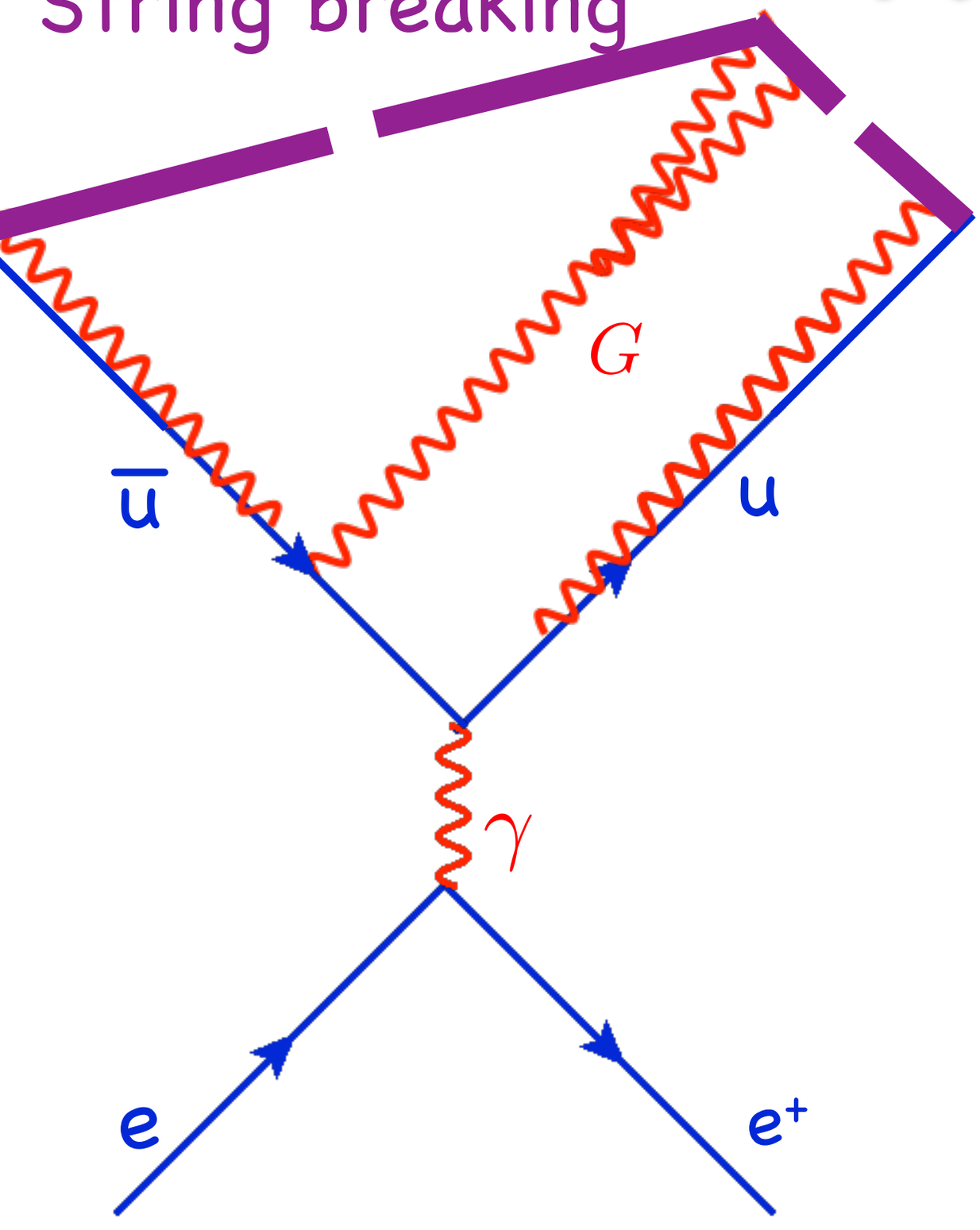


Jets

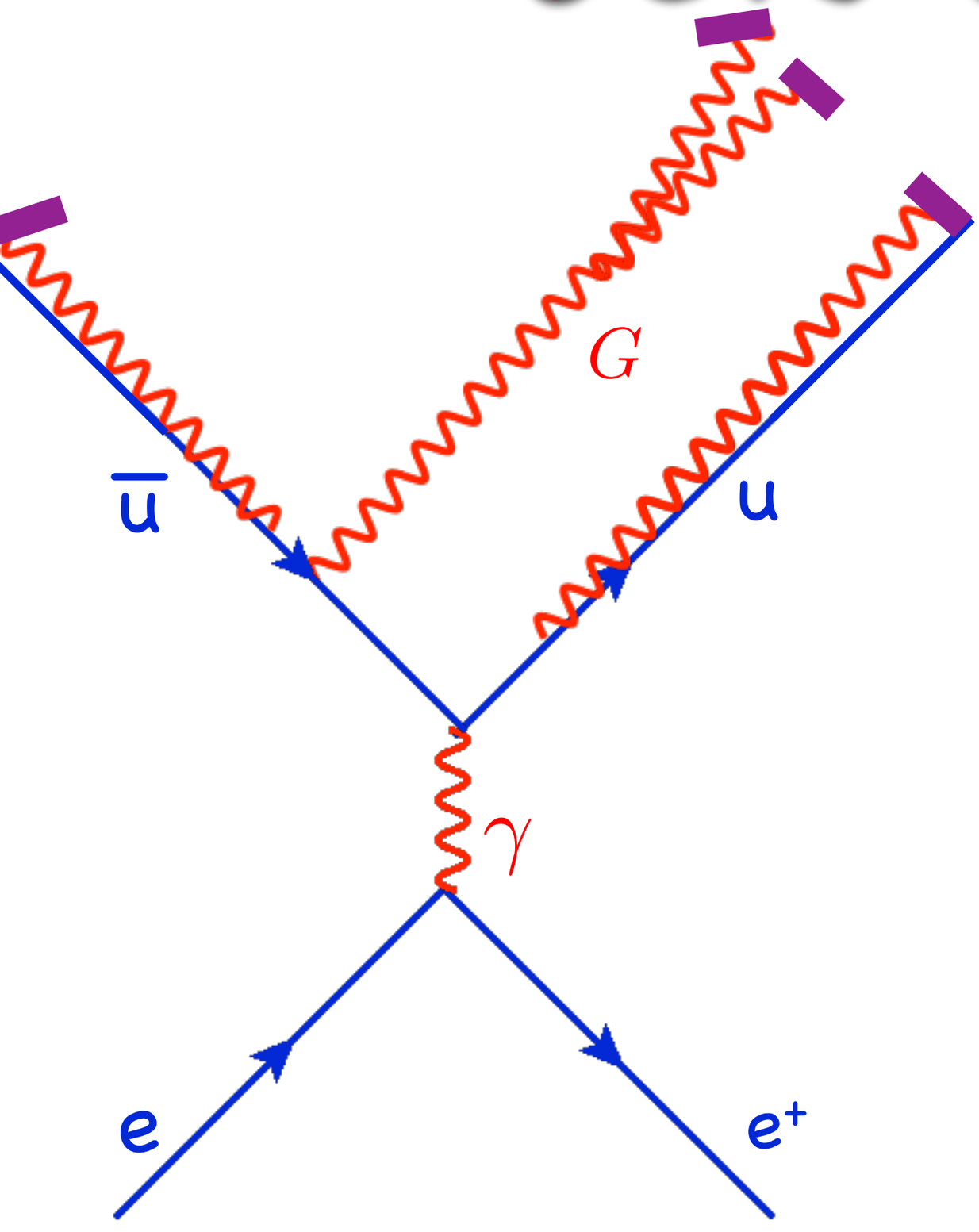


Hadrons

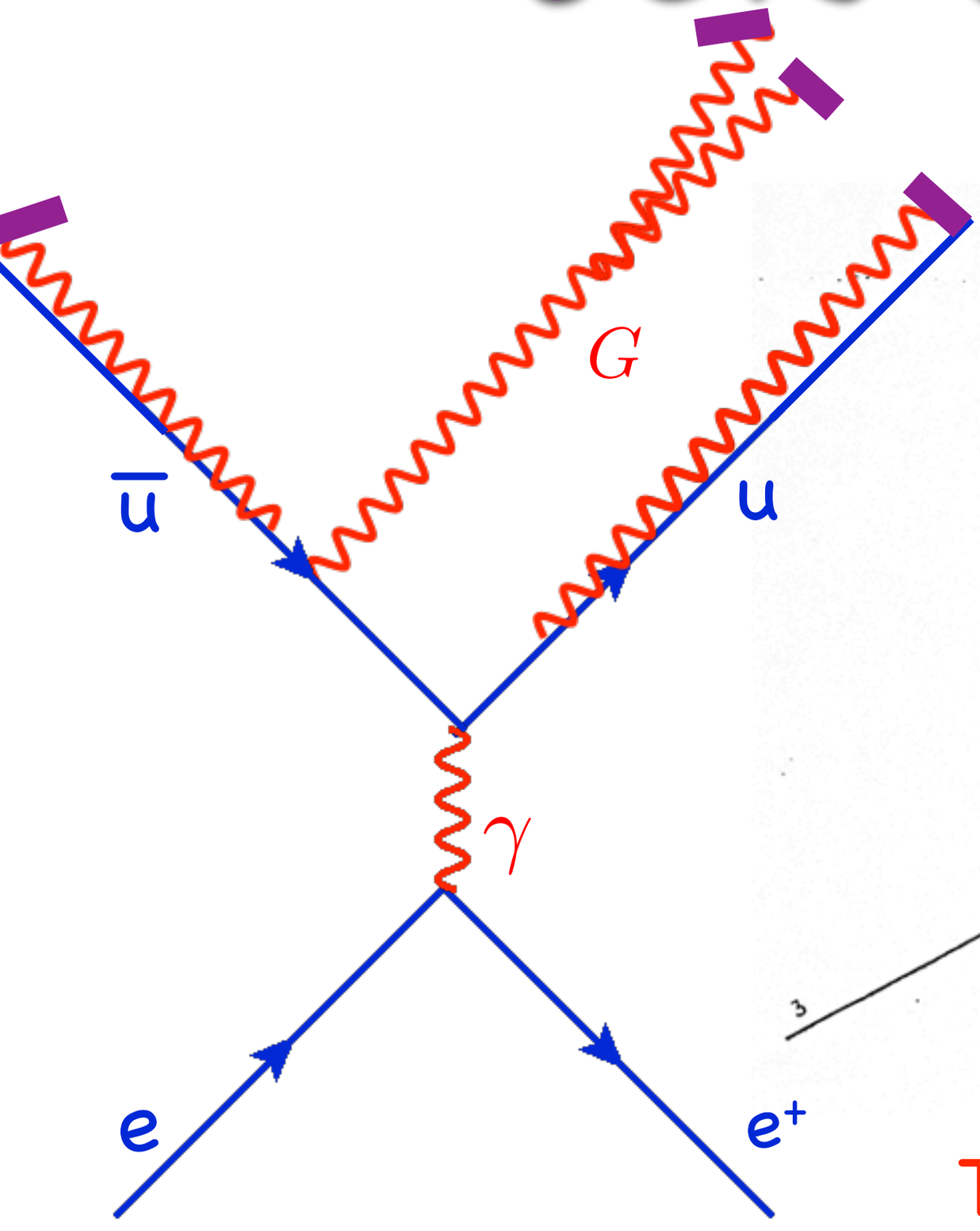
String breaking

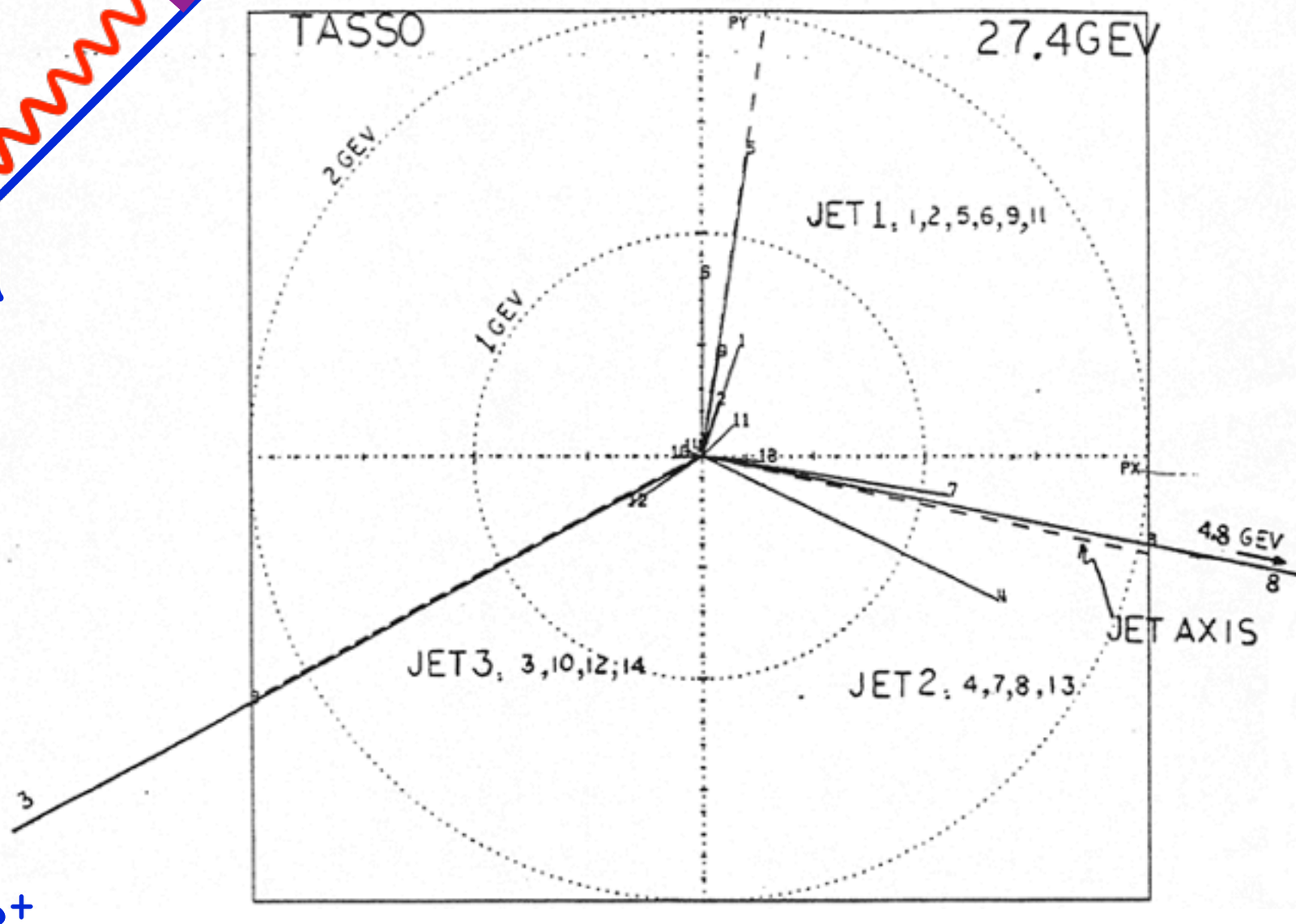


Jets of Hadrons



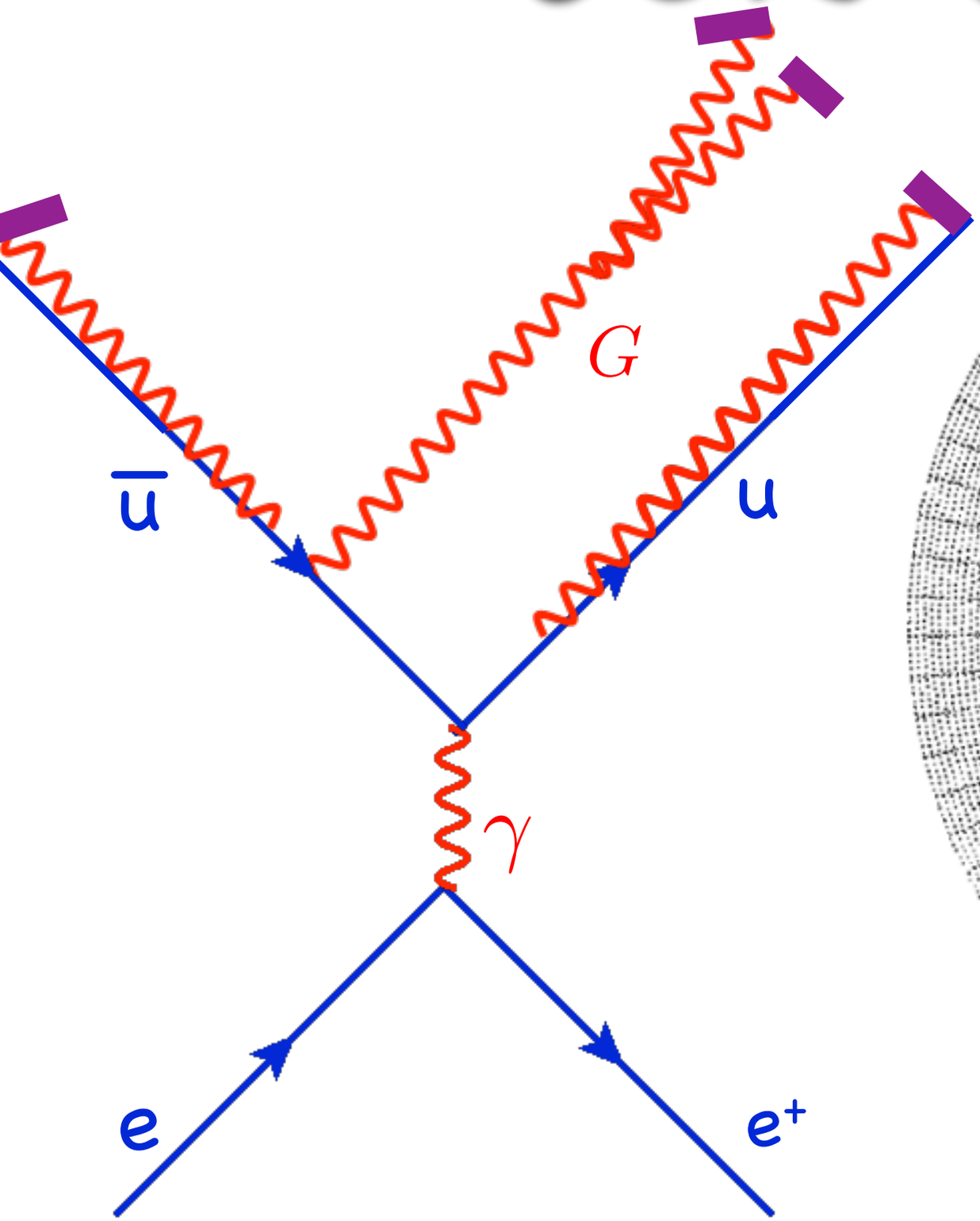
Jets of Hadrons

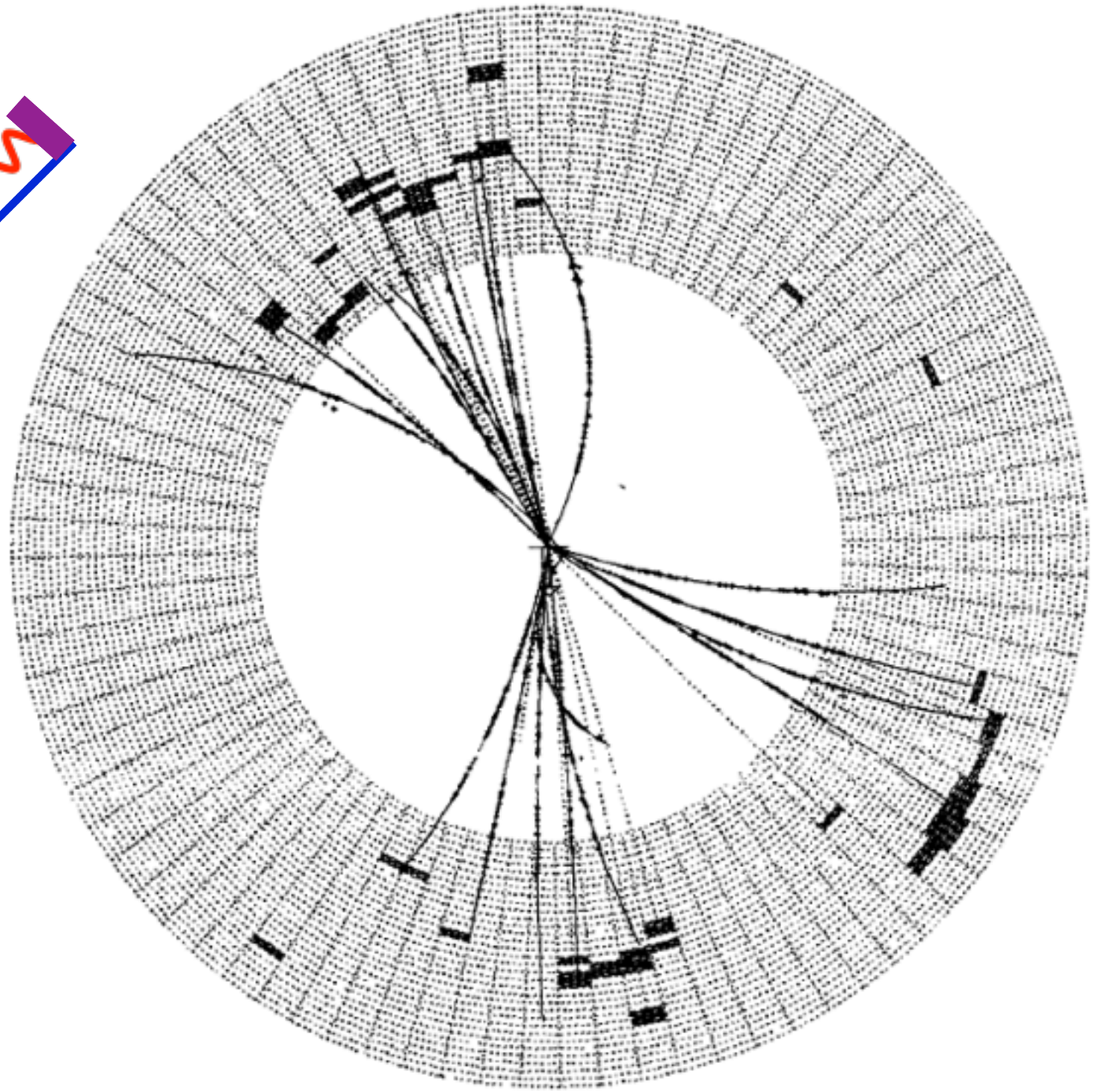




TASSO detector at PETRA

Jets of Hadrons

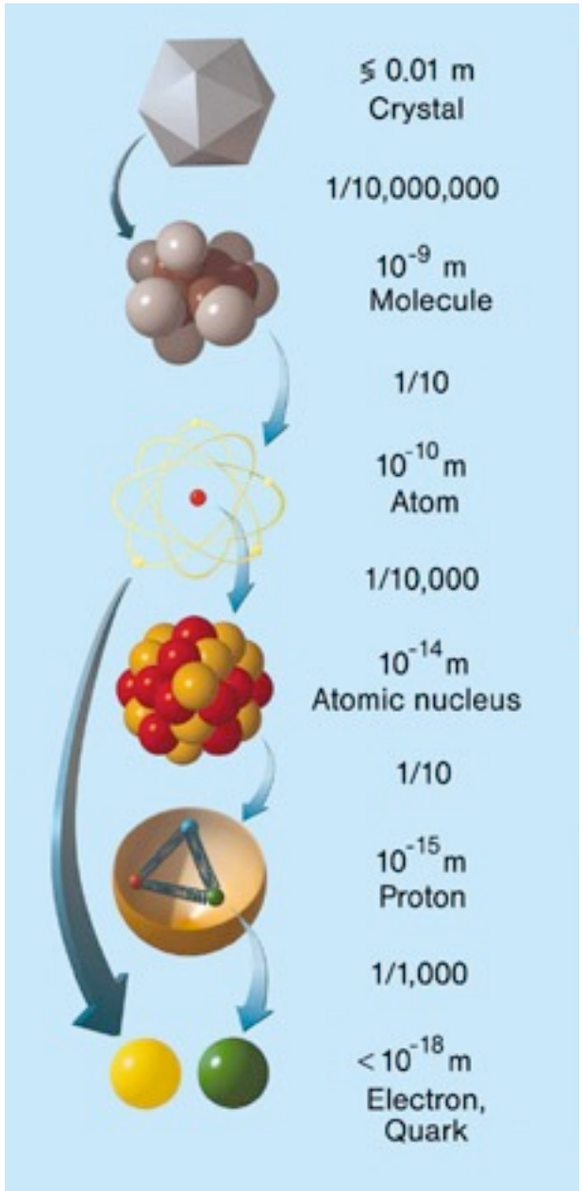




JADE detector at PETRA

Weak Interactions

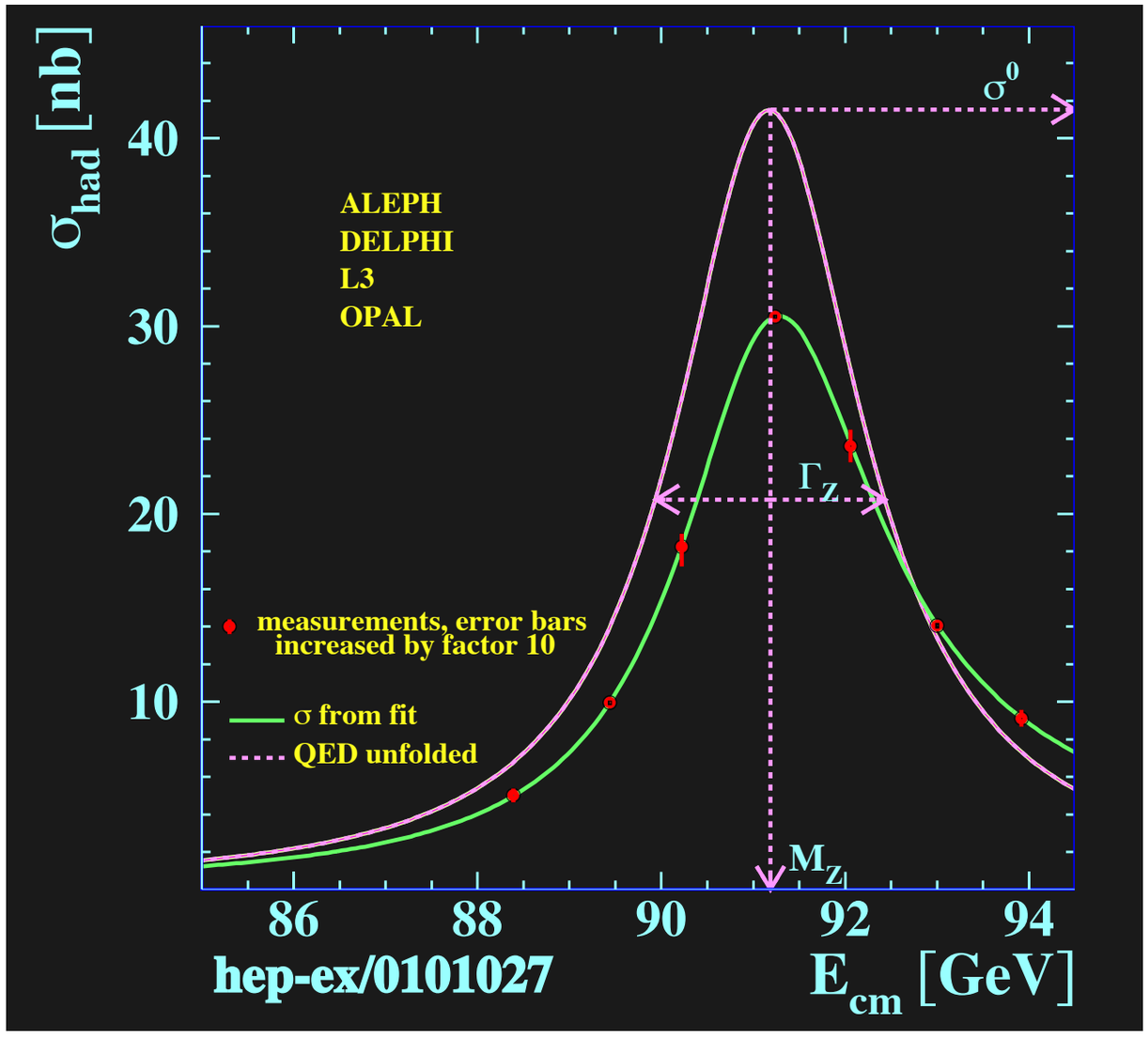
Weak Scale



$$\frac{1}{100000000}\,A$$

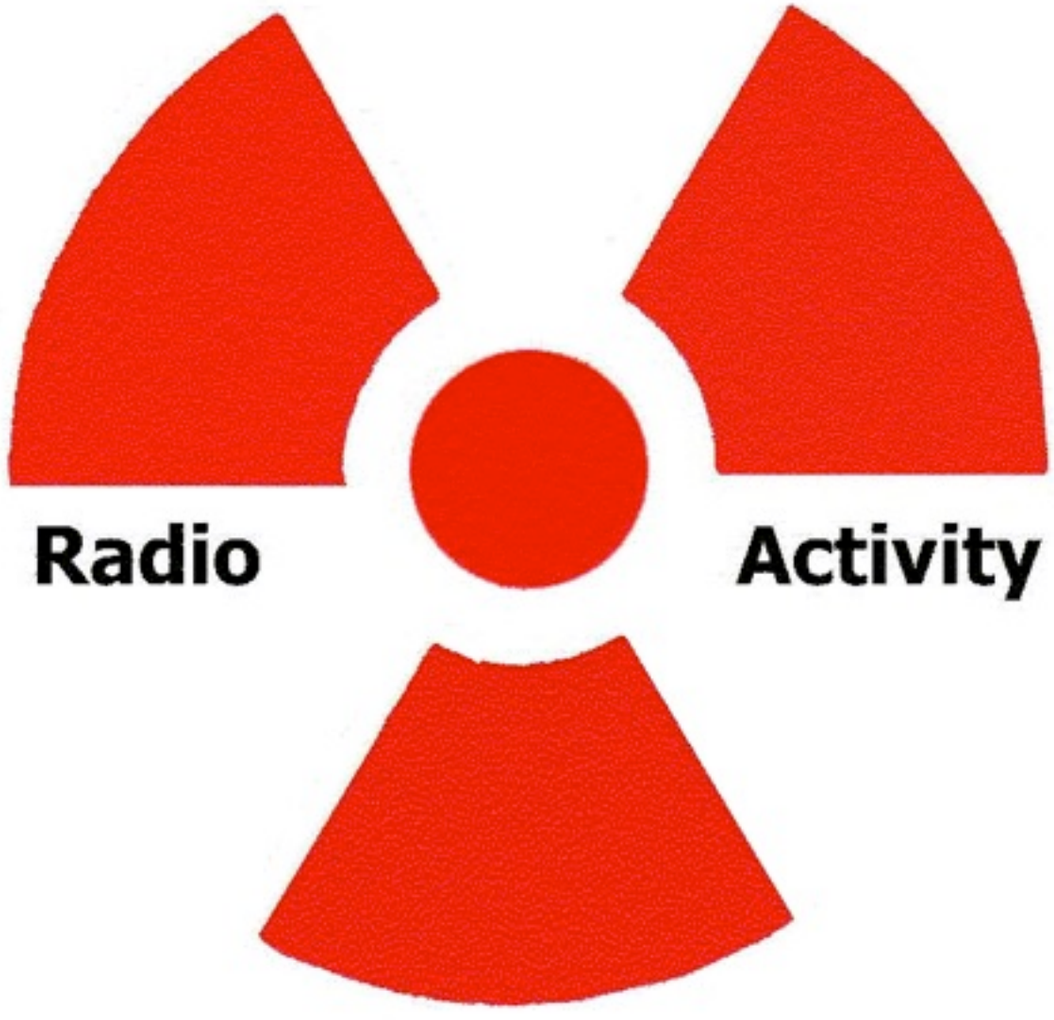
250 GeV

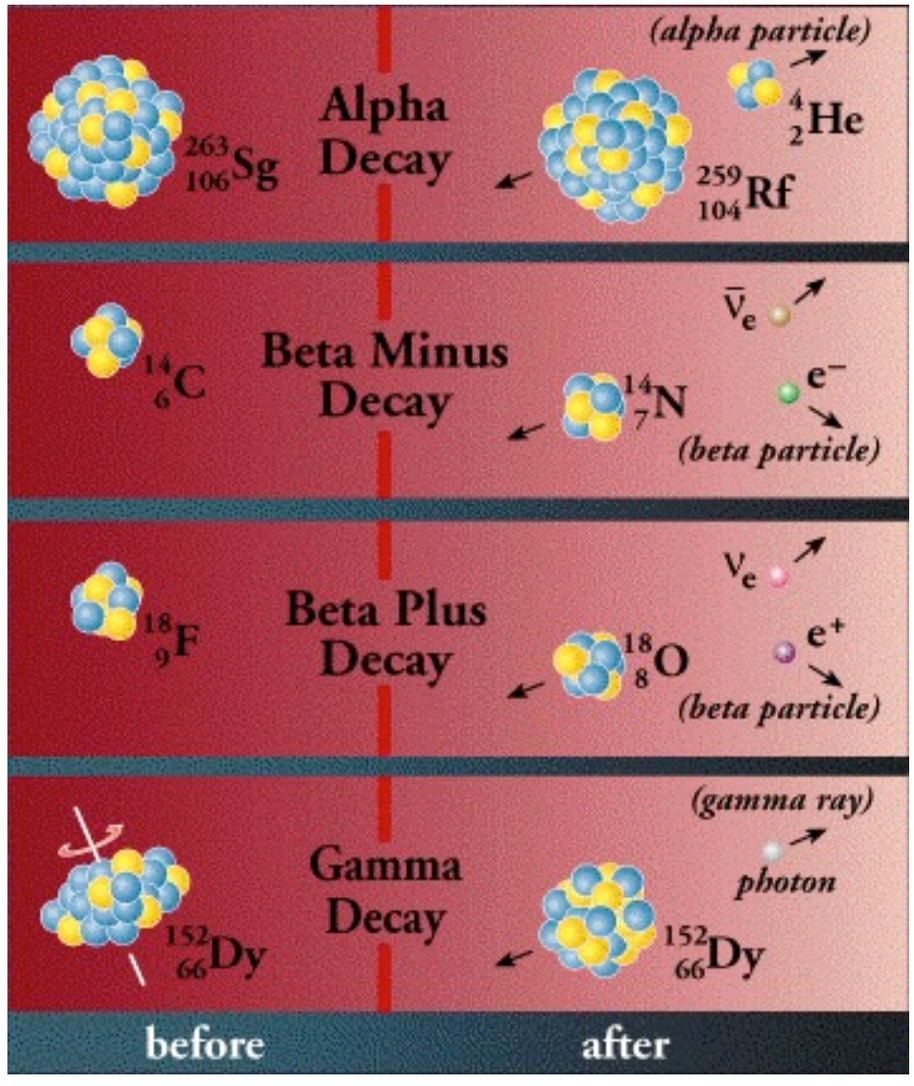
SM Weak Interactions



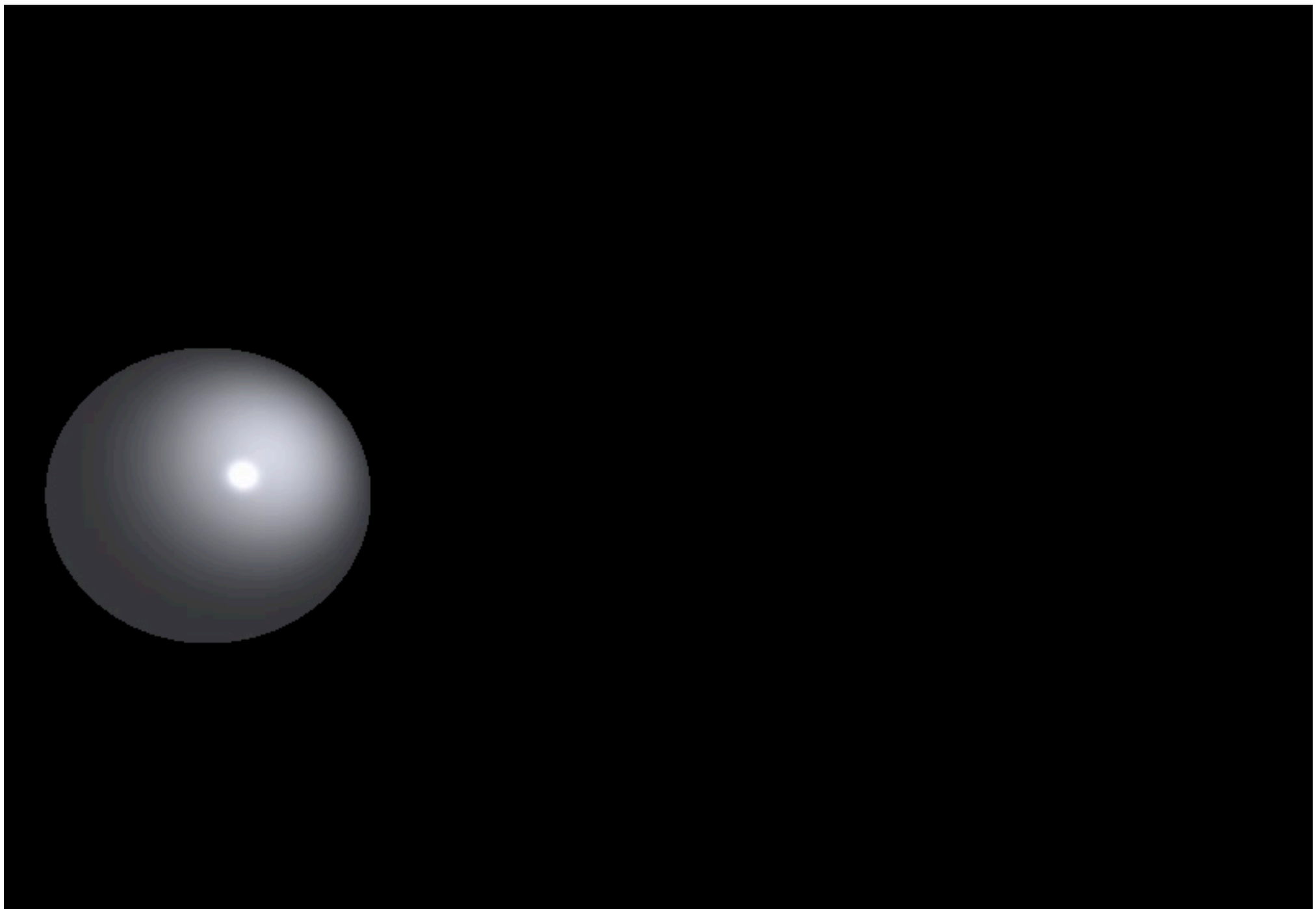
- ☑ consistent with all precision data
- fine-tuned to 1 part in 10^{30}
- must be incomplete

Radioactivity

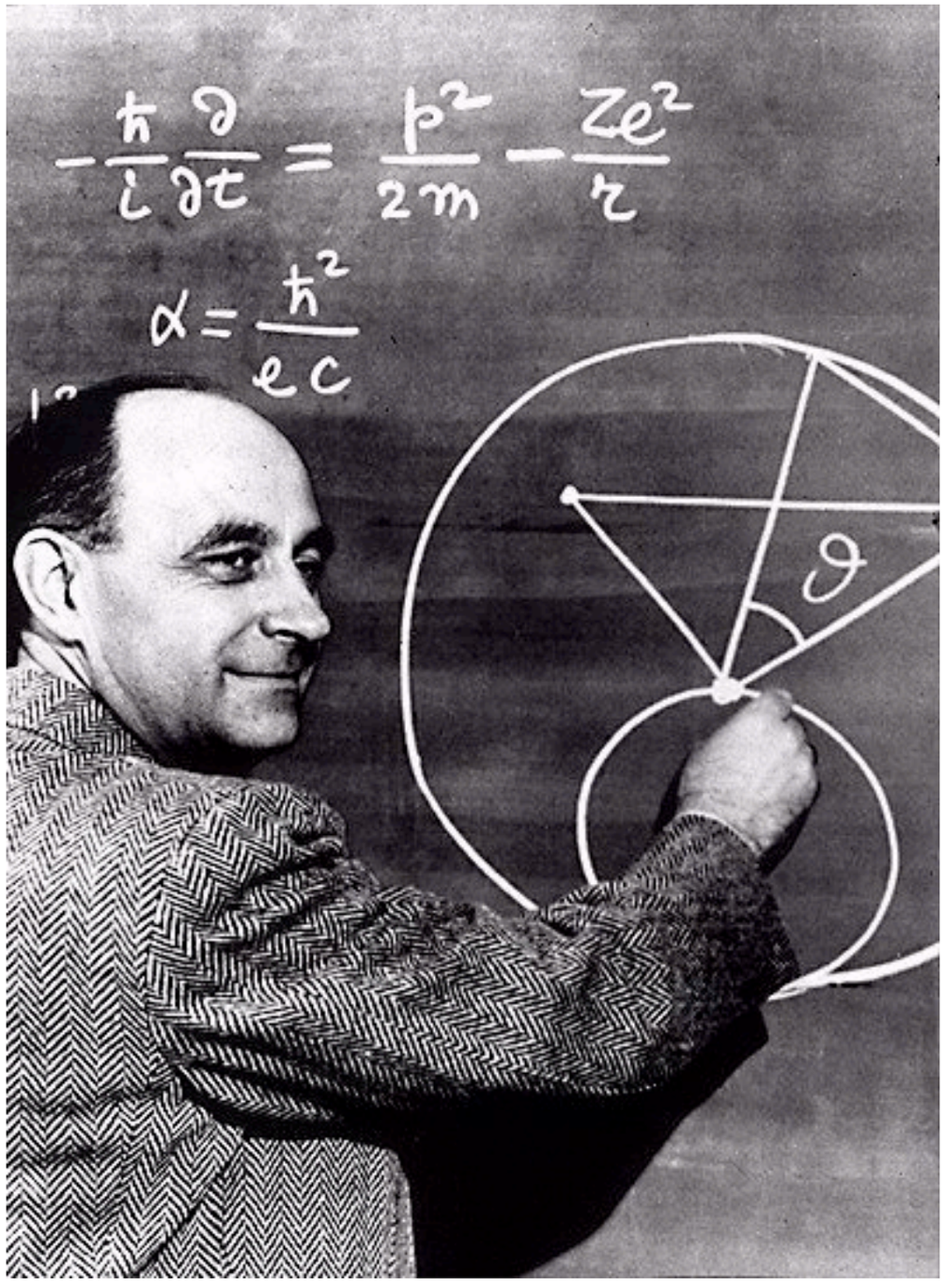




Weak Decays



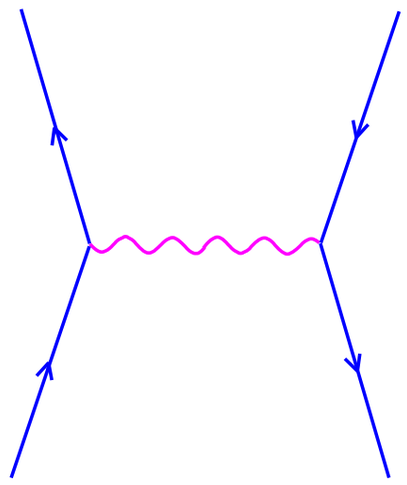
Fermi's Theory



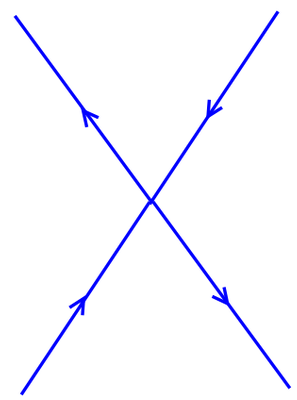
Fermi's Theory

Fourier Transform

QED: $J^\mu(x)\frac{e^2}{|x-y|}J_\mu(y) \longleftrightarrow J^\mu\frac{e^2}{q^2}J_\mu$



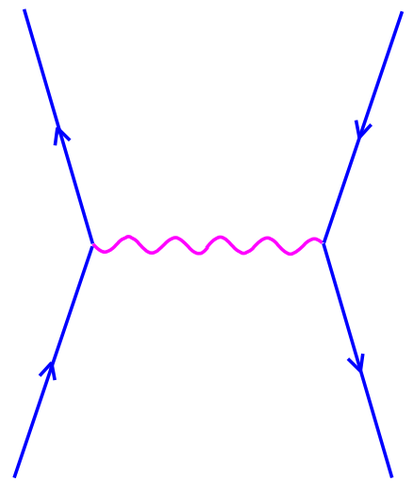
Weak: $K^\mu(x)G_F\delta(x-y)K_\mu(y) \longleftrightarrow K^\mu G_F K_\mu$



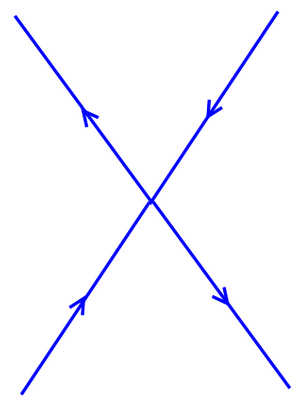
Fermi's Theory

Fourier Transform

QED: $J^\mu(x)\frac{e^2}{|x-y|}J_\mu(y) \longleftrightarrow J^\mu\frac{e^2}{q^2}J_\mu$



Weak: $K^\mu(x)G_F\delta(x-y)K_\mu(y) \longleftrightarrow K^\mu G_F K_\mu$

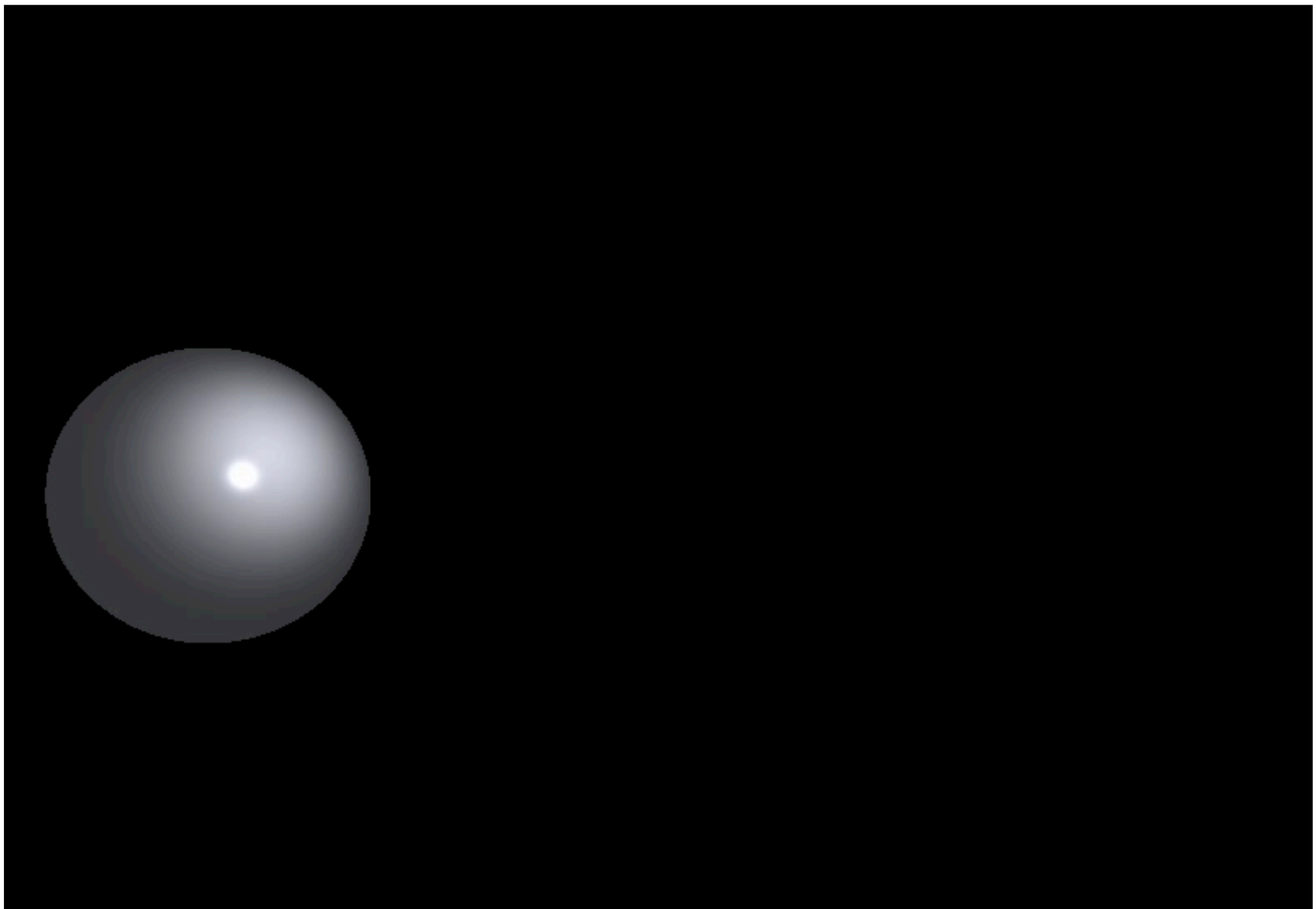


$$K^\mu(x)\frac{g^2 e^{-M_W|x-y|}}{|x-y|}K_\mu(y) \longleftrightarrow K^\mu\frac{g^2}{q^2-M_W^2}K_\mu$$

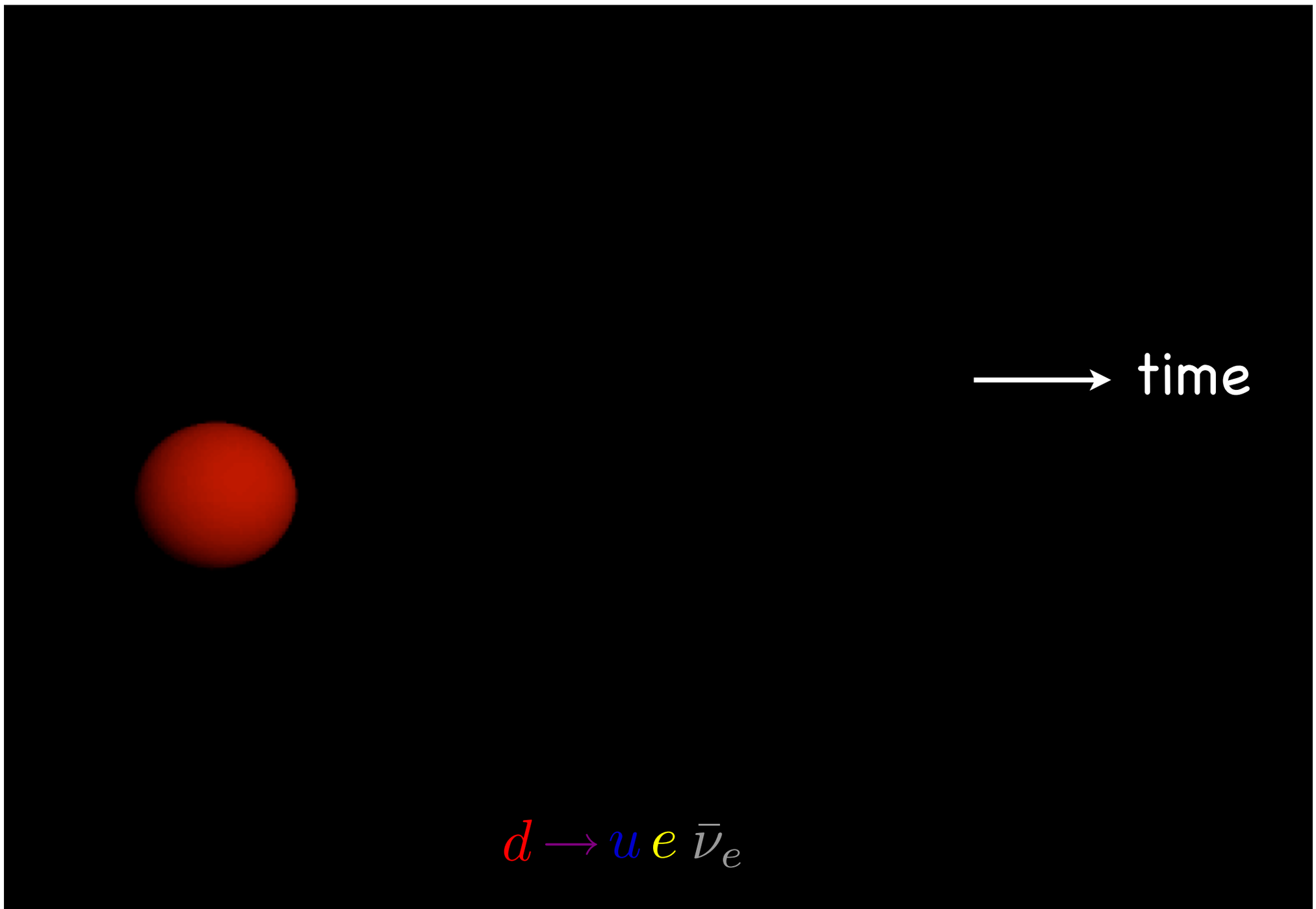
Superconducting Vacuum

Charged Bose Condensate	$\longleftrightarrow$	$\langle H \rangle \neq 0$
Meissner Effect	$\longleftrightarrow$	Massive Gauge Bosons
Inverse Penetration Depth	$\longleftrightarrow$	M_W, M_Z

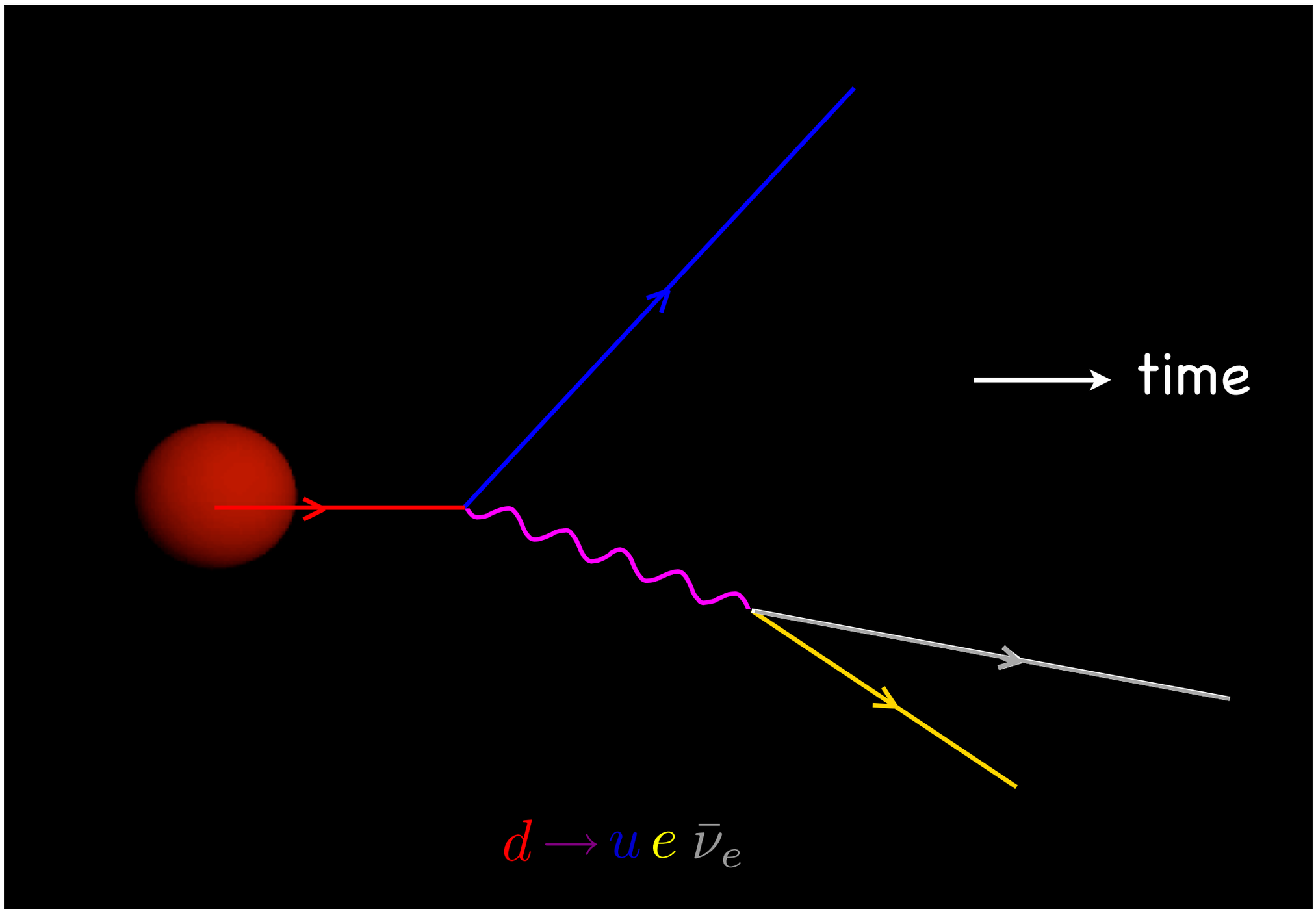
Weak Decays



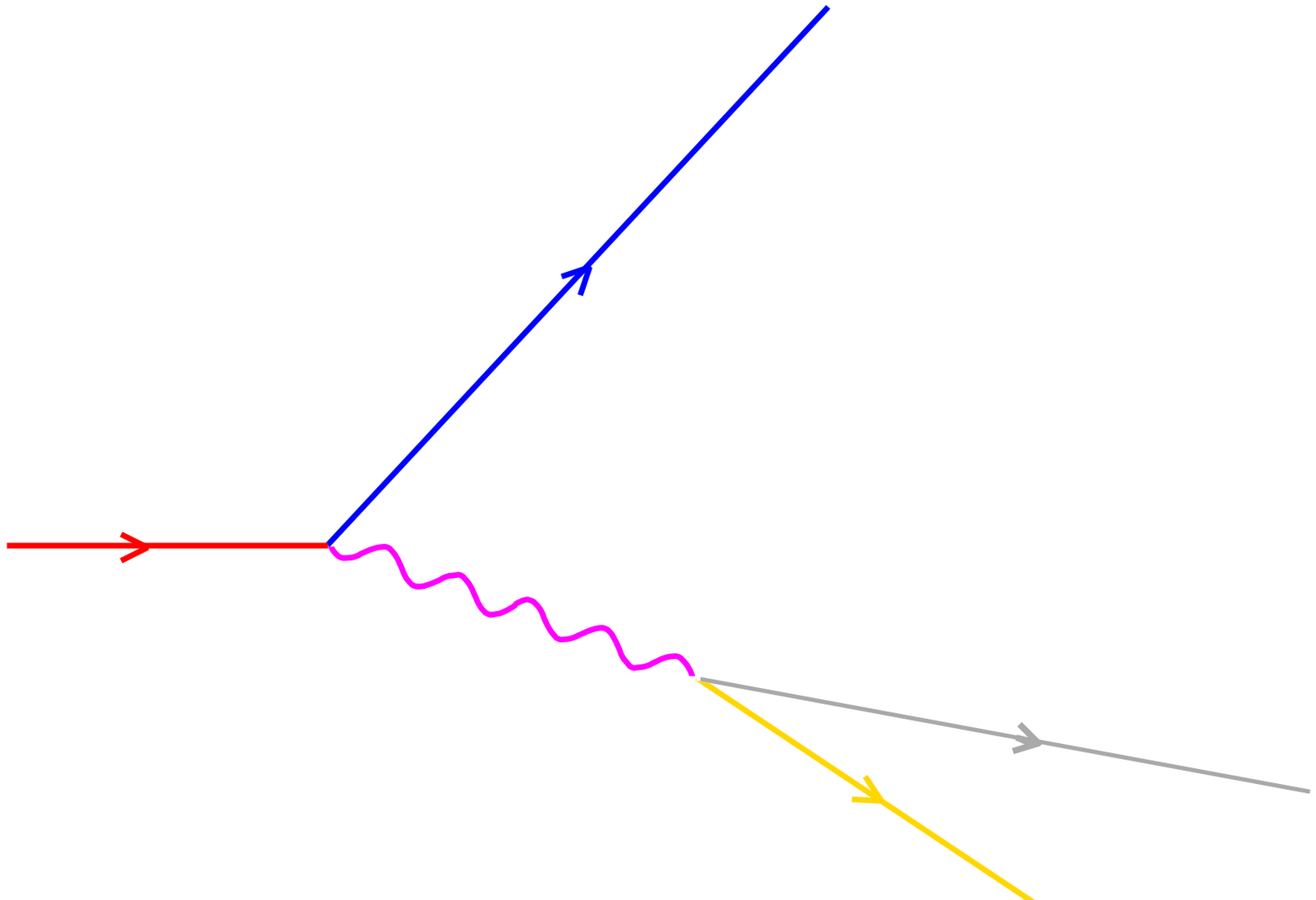
Weak Decays



Weak Decays

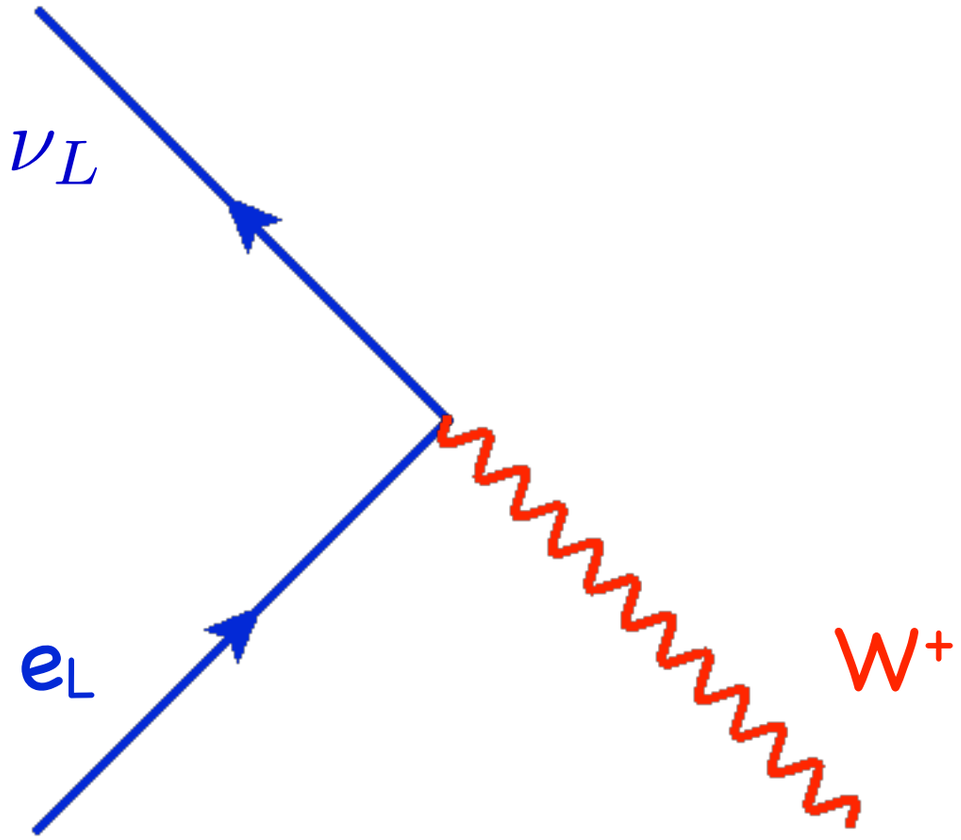


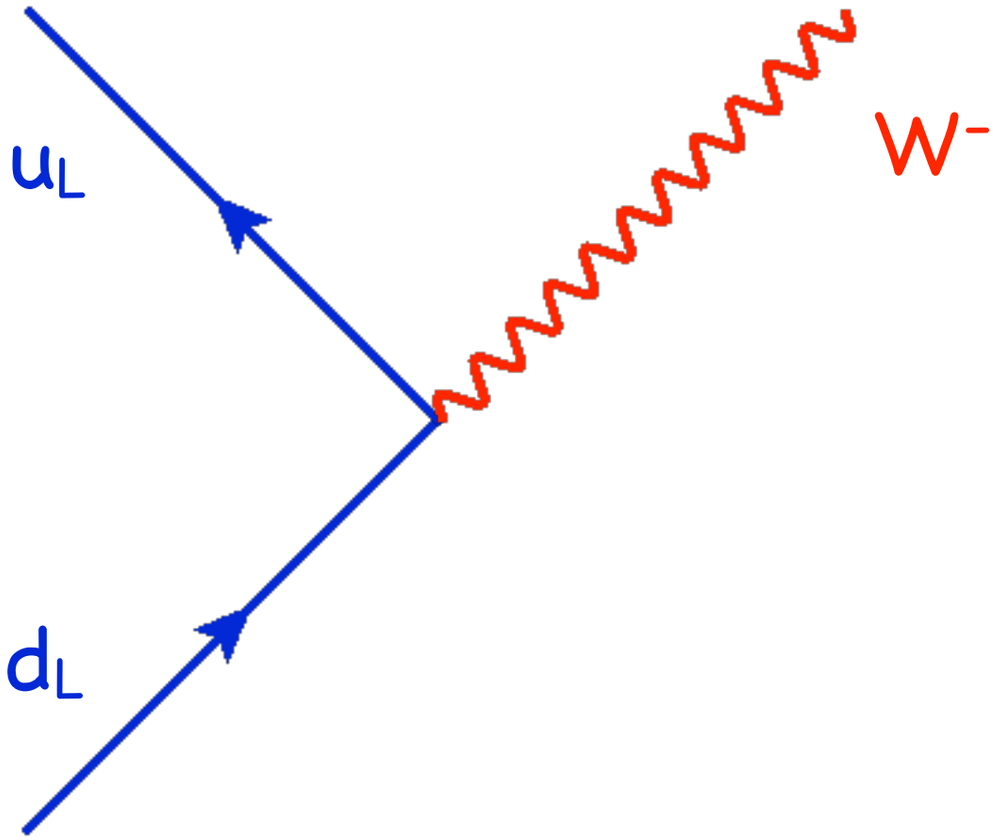
Weak Decays



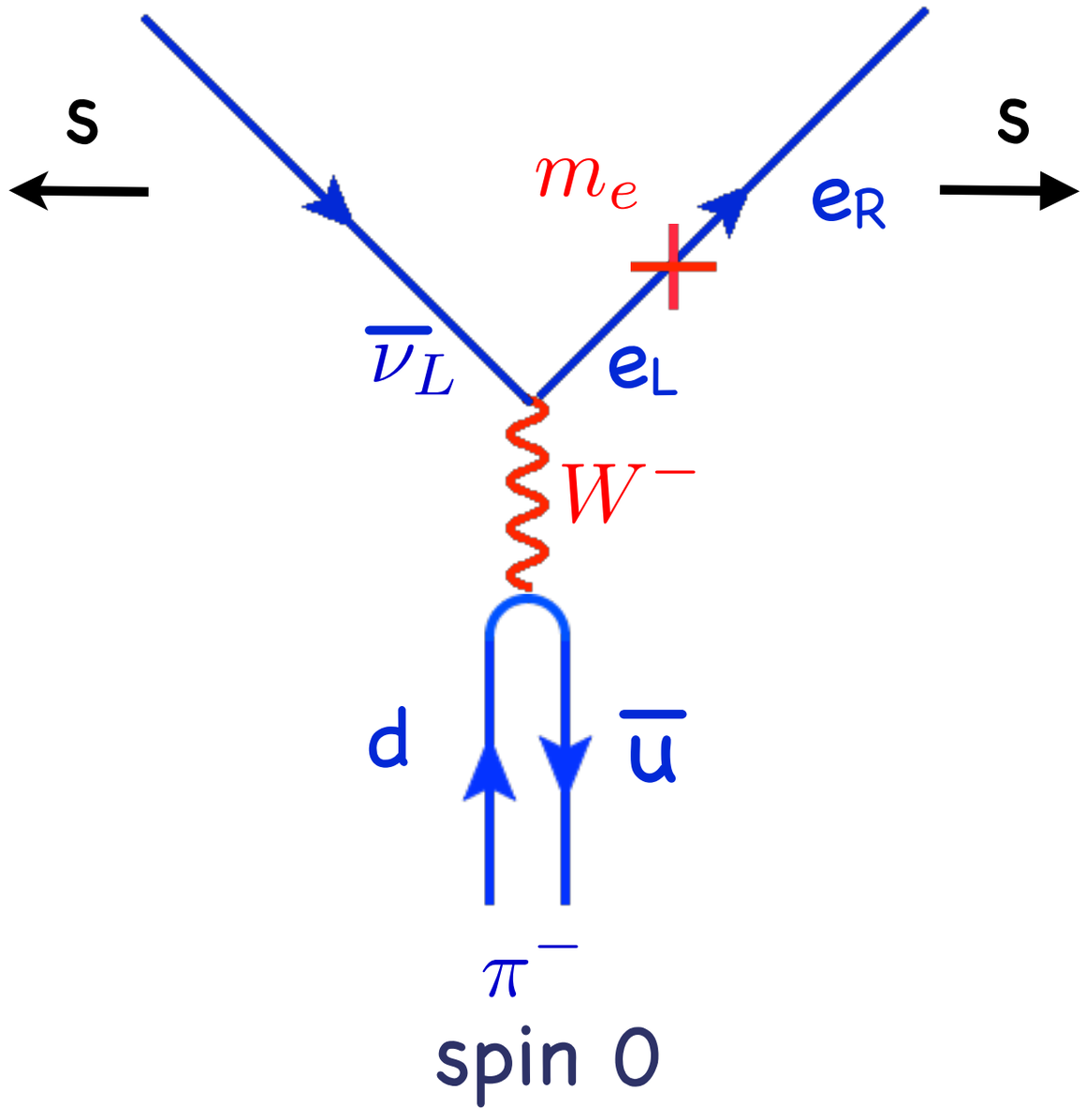
$$d \rightarrow u\, e\, \bar{\nu}_e$$

Weak Charged Interactions



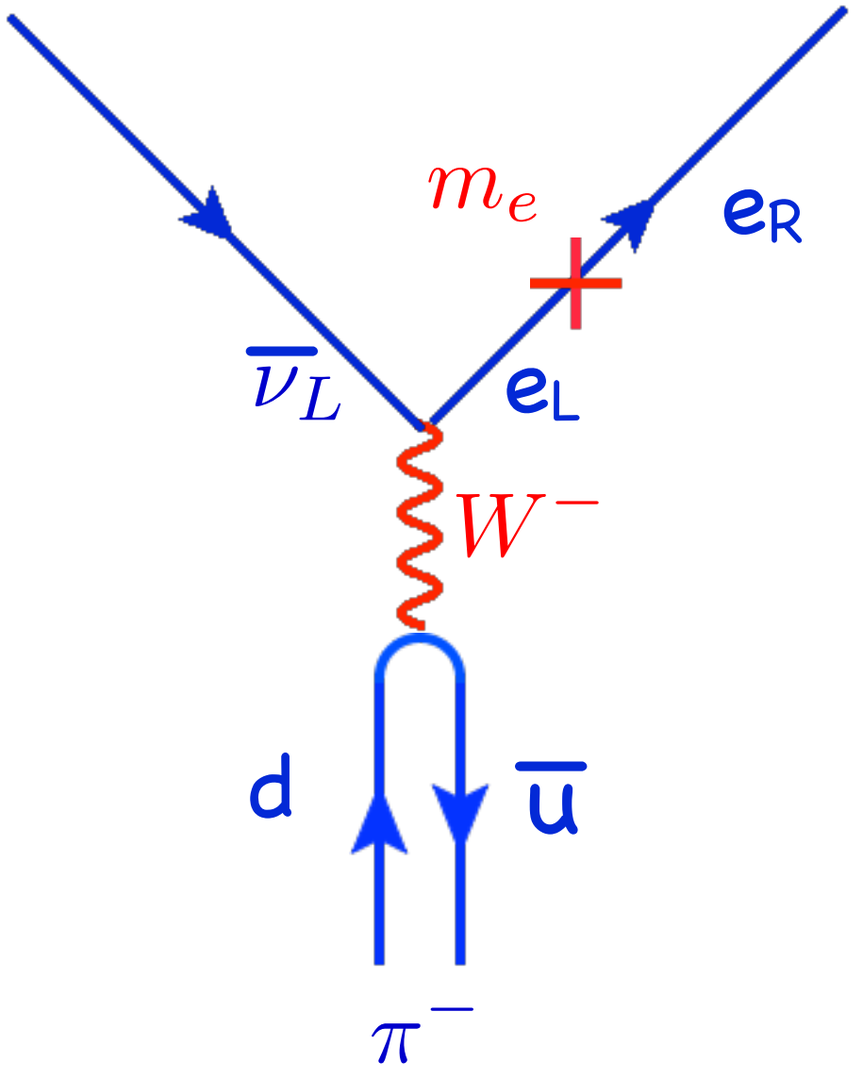


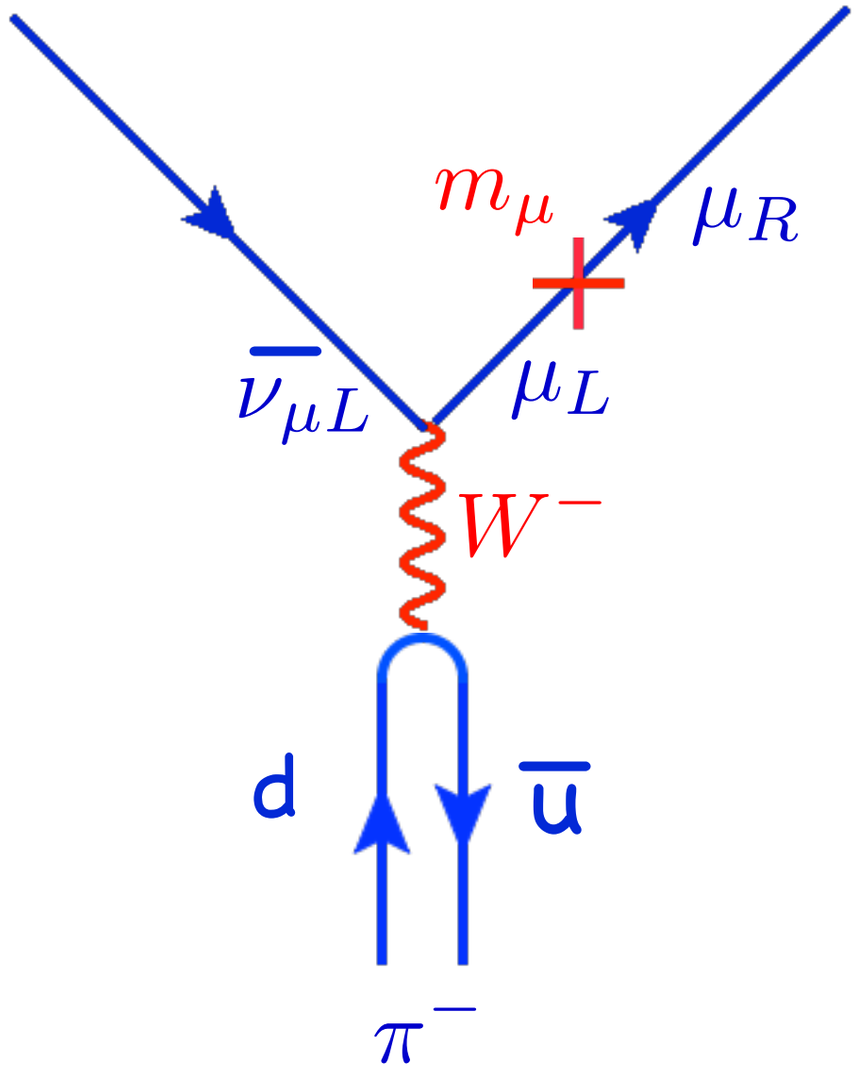
Charged Pion Decay



Prob. amplitude proportional to electron mass

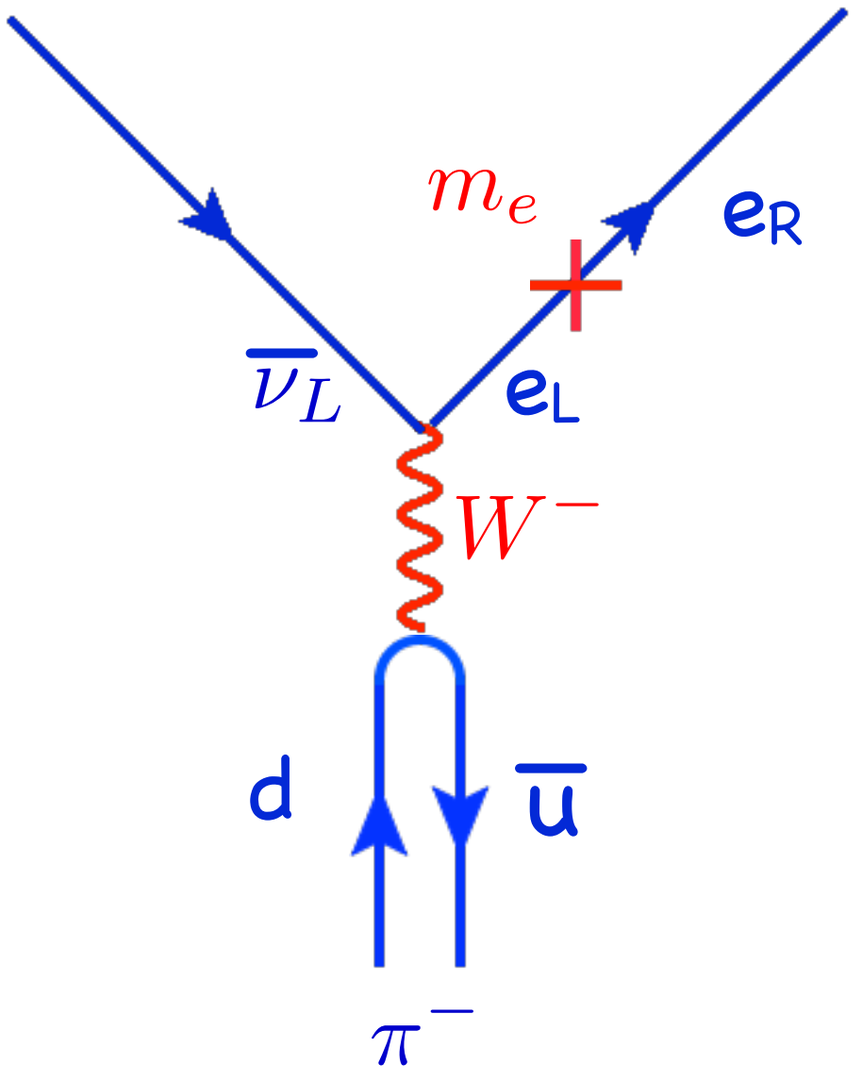
Charged Pion Decay

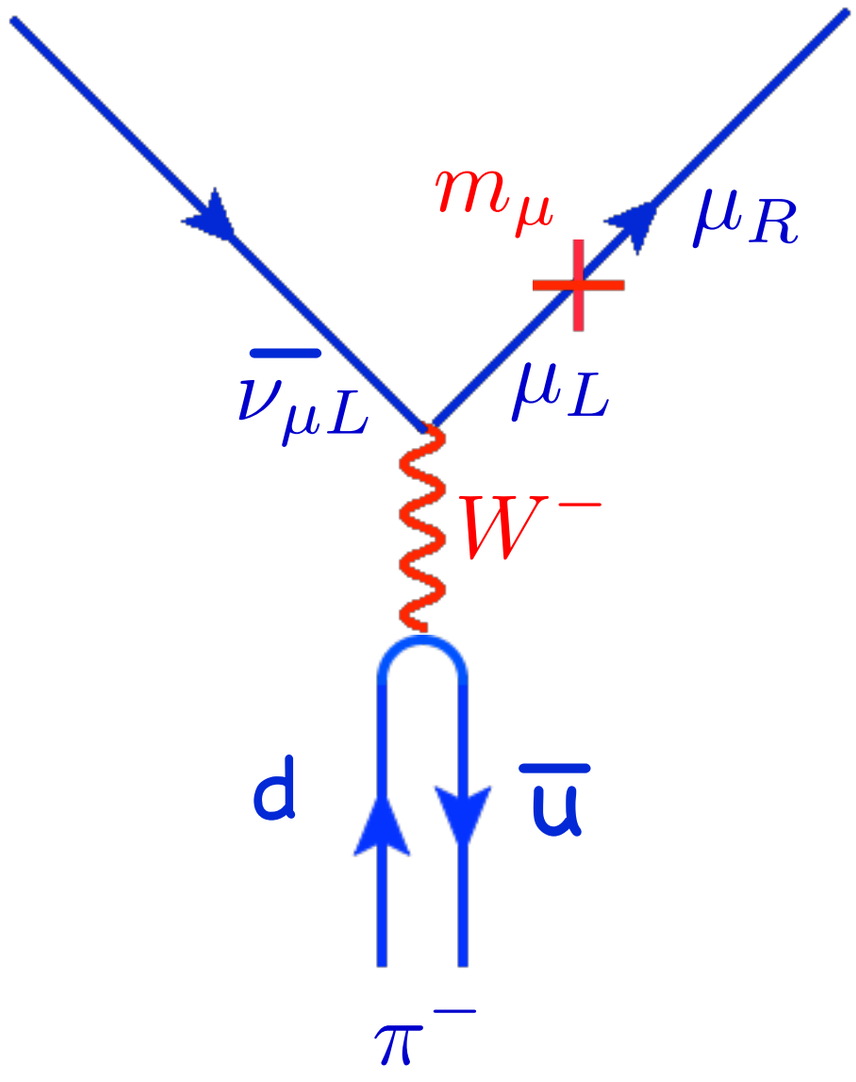




Probability: $\propto m_e^2$ $\propto m_\mu^2$

Charged Pion Decay





Probability: $\propto m_e^2$ $\propto m_\mu^2$

Experimentally ratio is 10^{-4}

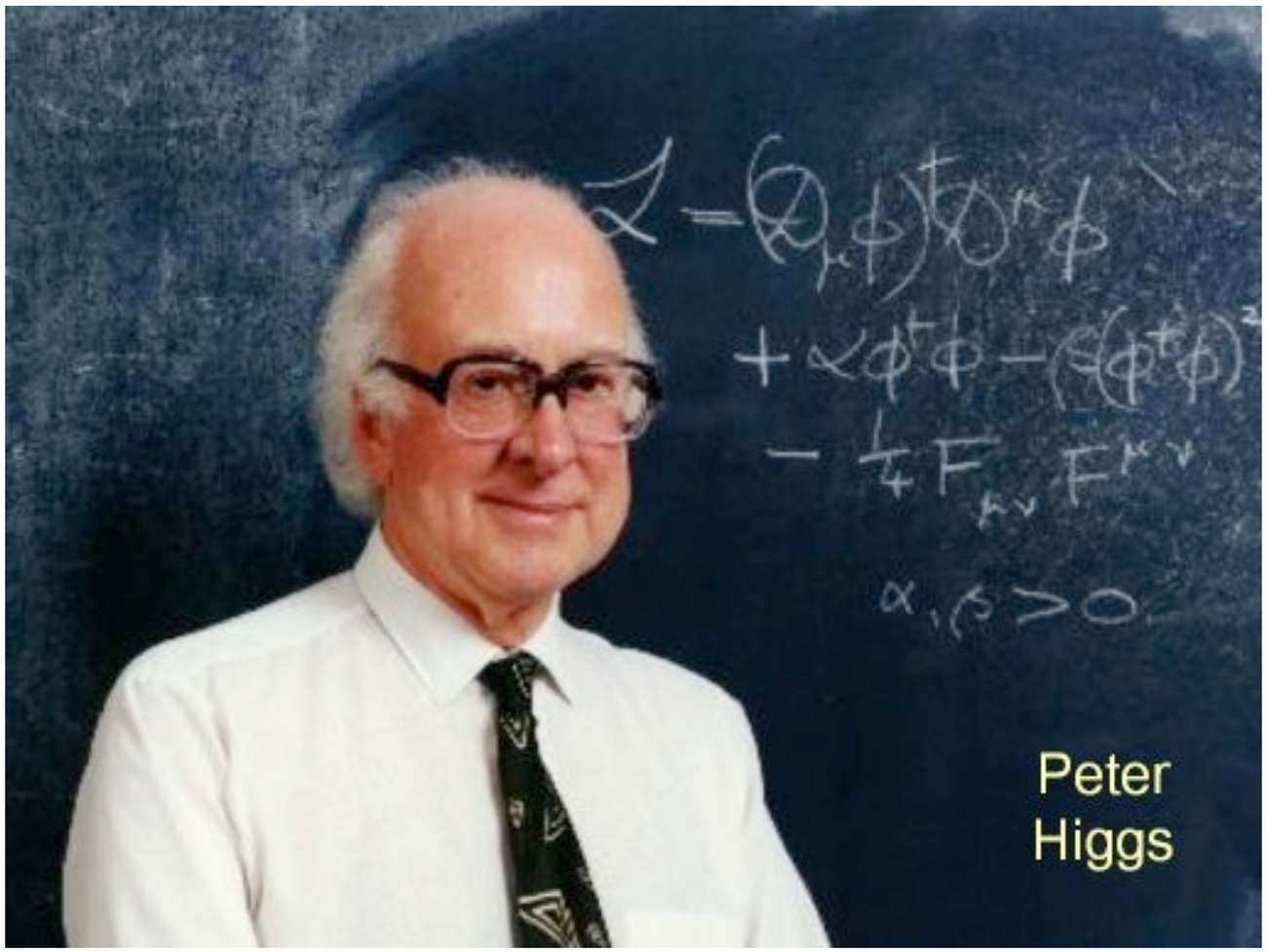
The Origin of Mass

After the Big Bang
all the known particles were massless.

They are not massless now.

Their masses violate $SU(2)_L$ charge conservation!

Higgs



HIGGS BOSON

H

The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe get its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.99% the speed of light.

Wool felt with gravel fill for maximum mass.

LIGHT ●●●●●●●●●●●● HEAVY

$9.75 PLUS SHIPPING

GLUON PHOTON NEUTRINO TACHYON ELECTRON UP QUARK DOWN QUARK TAU NEUTRINO MUON UP QUARK
NEUTRON DOWN QUARK TAU GLUON **HIGGS BOSON** NEUTRINO TACHYON ELECTRON UP QUARK DOWN
NEUTRINO MUON UP QUARK PROTON NEUTRON DOWN QUARK TAU GLUON PHOTON NEUTRINO TACHY

The PARTICLE ZOO

the missing piece

Higgs Mechanism

mass is proportional how much you stick to empty space

Origin of Mass

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Mass comes from Higgs field
that pervades all space.

Origin of Mass

FERMIONS

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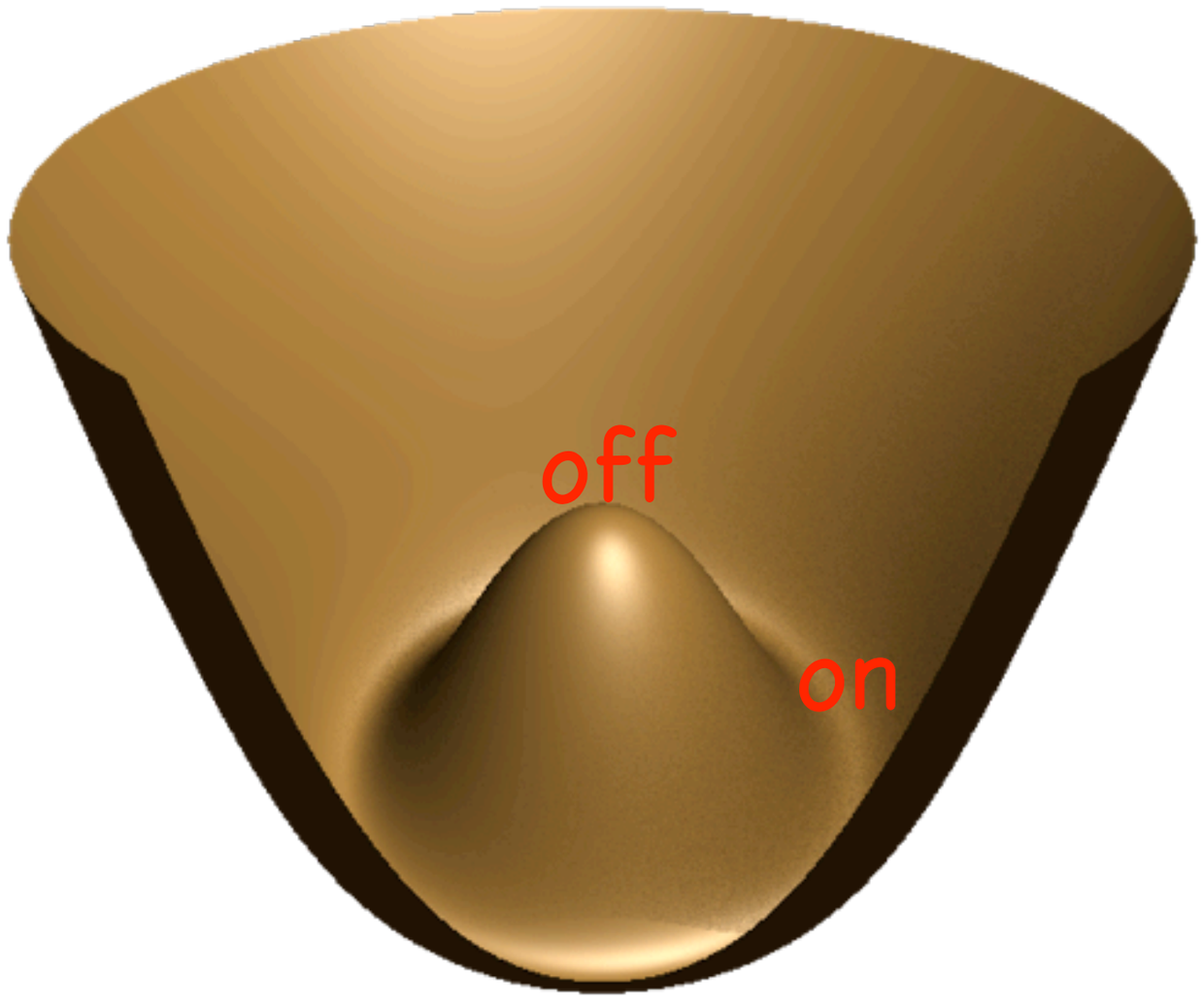
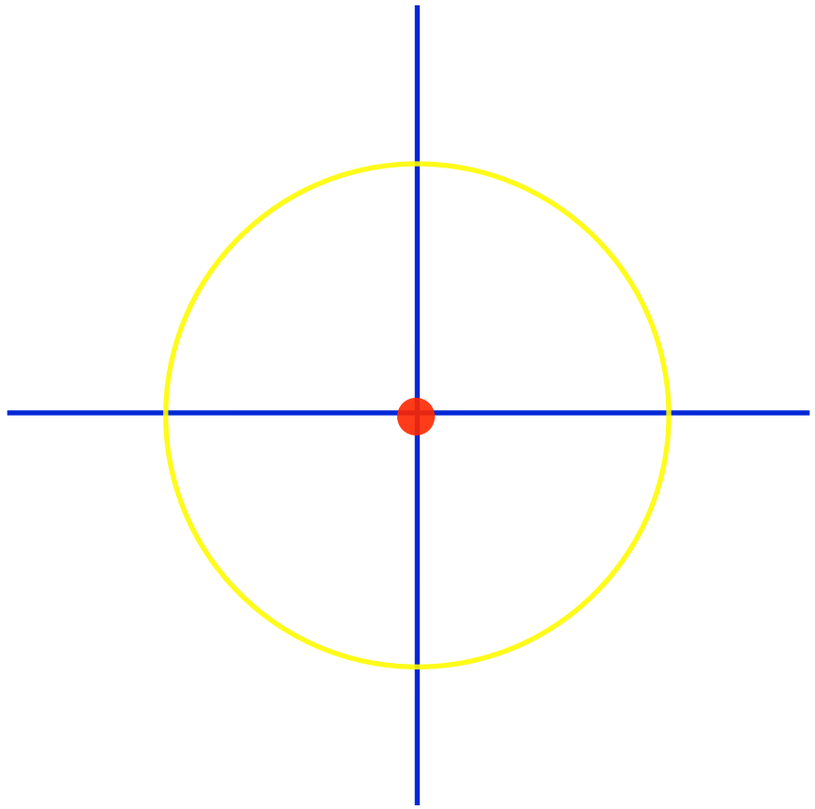
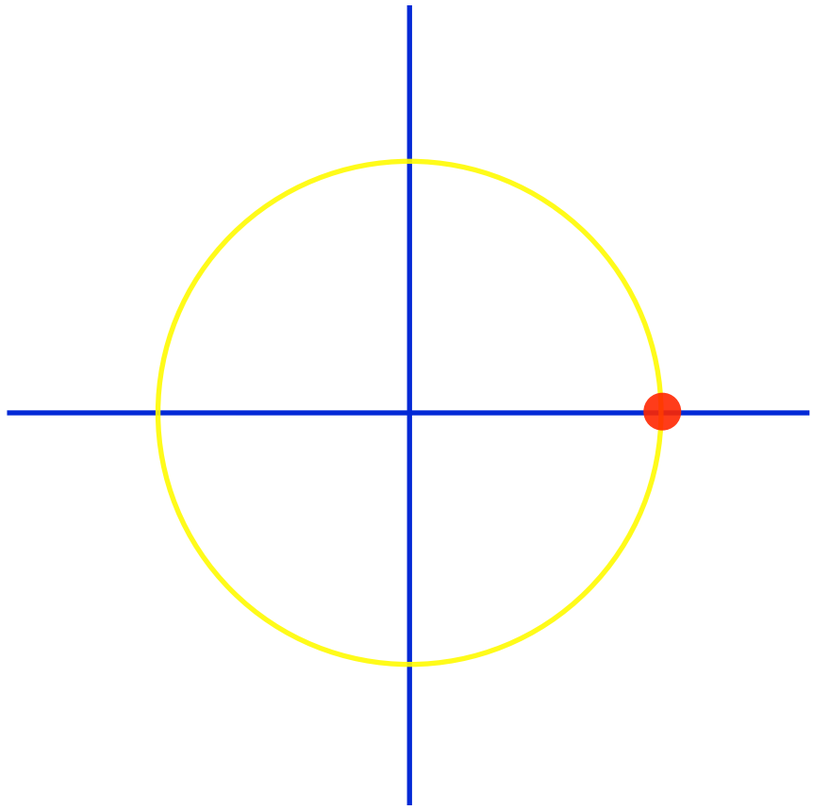
Mass comes from Higgs field
that pervades all space.
Just like the ether...

Higgs Energy Cost

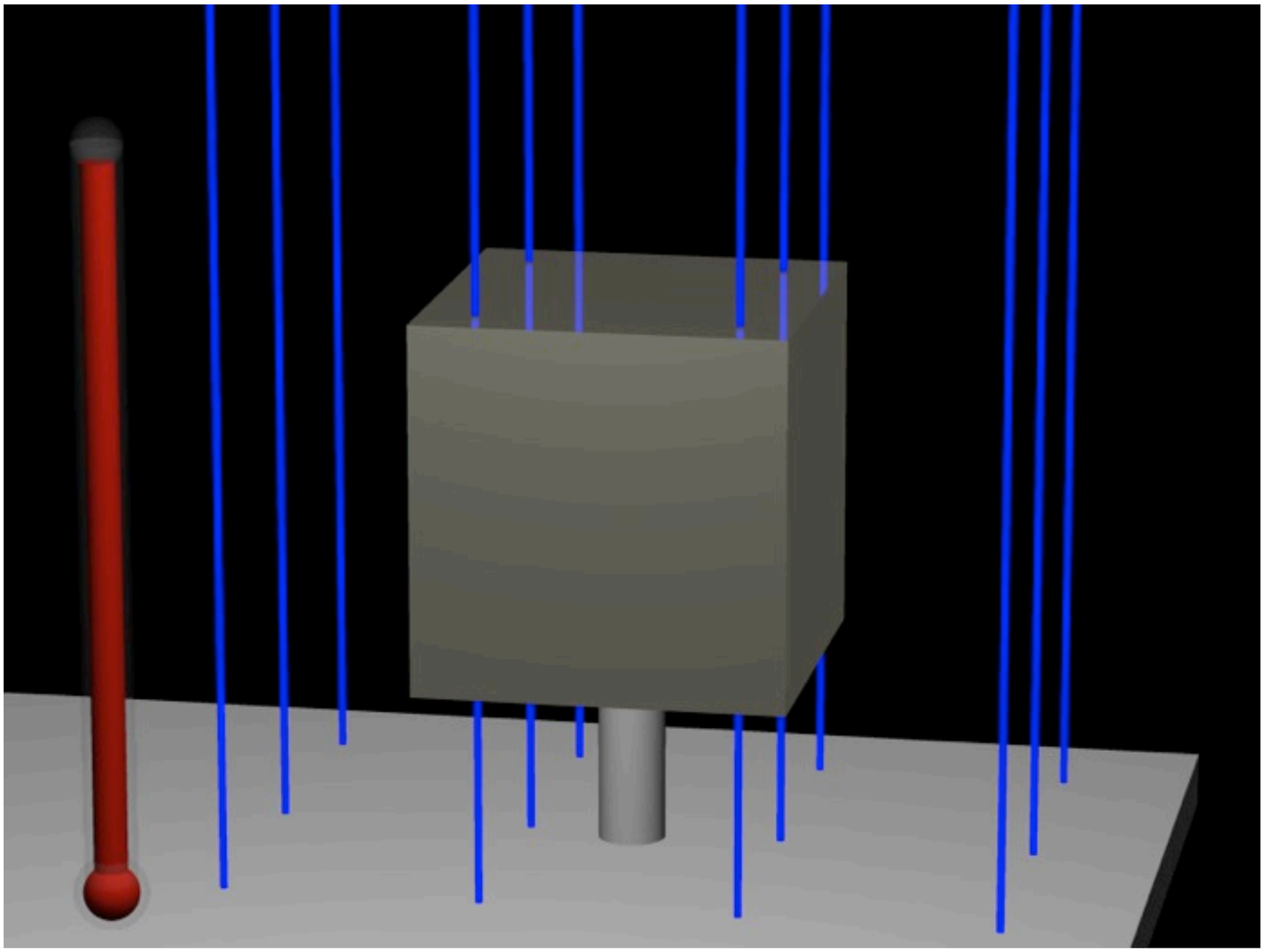


Broken Symmetry

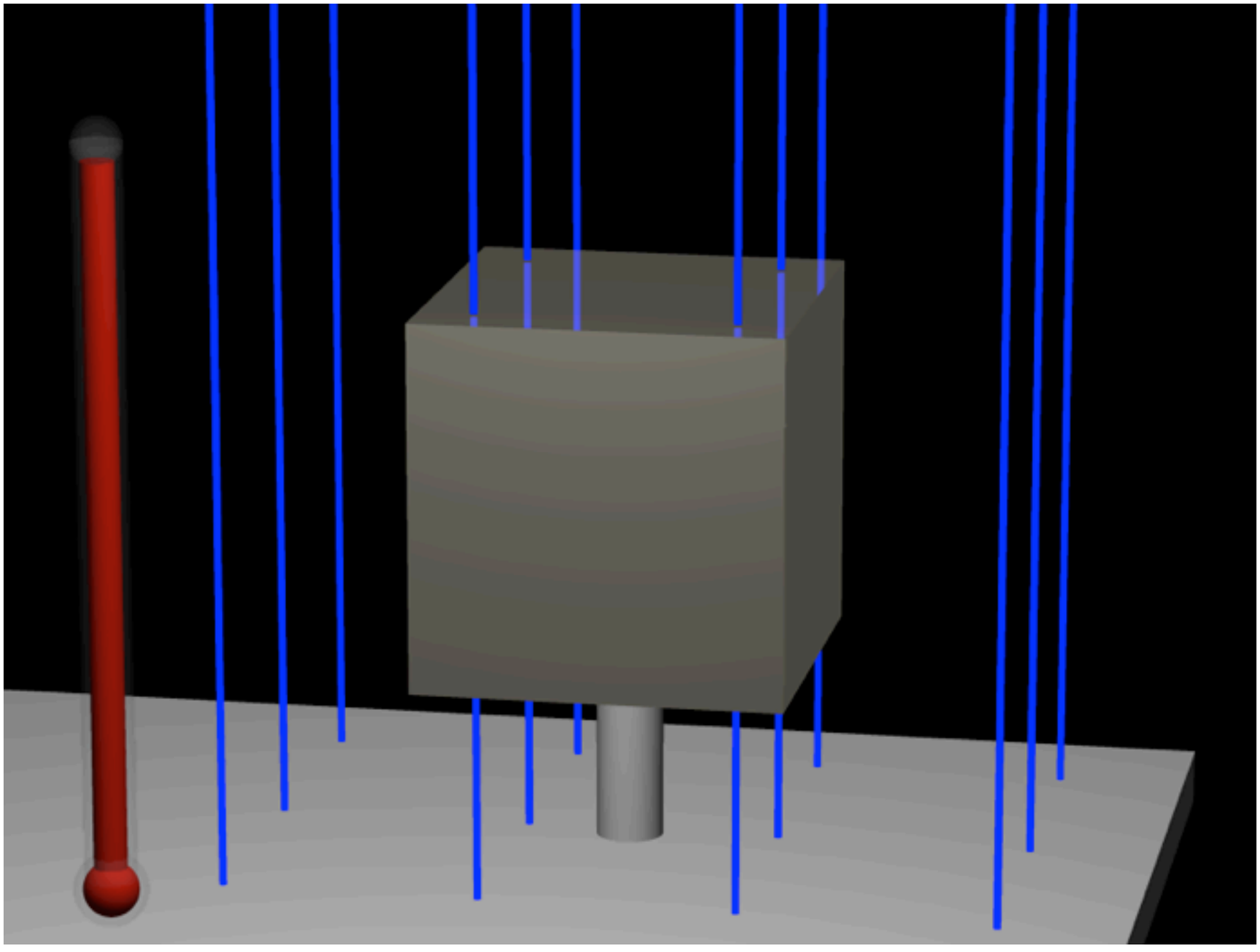




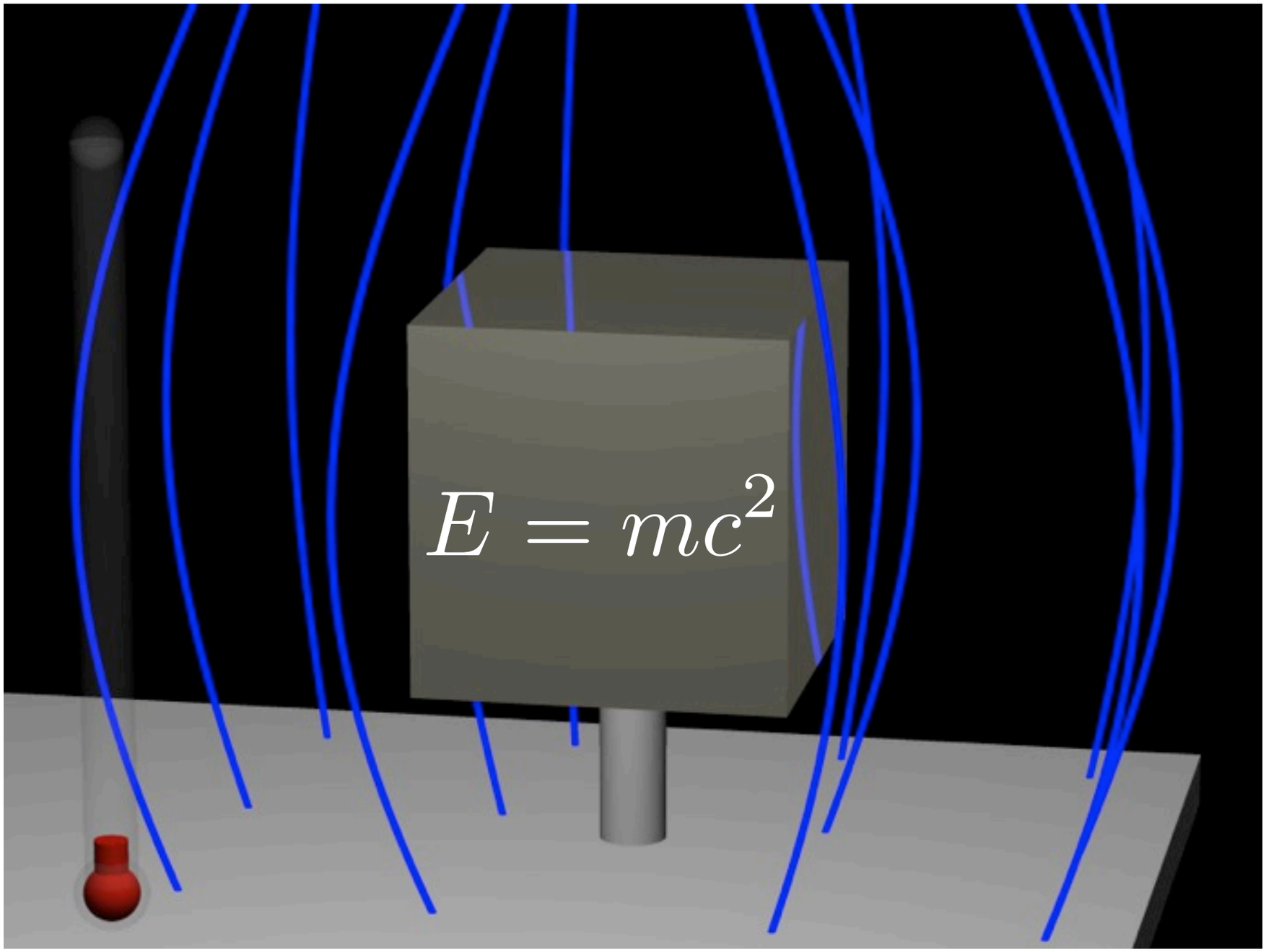
Phase Transition



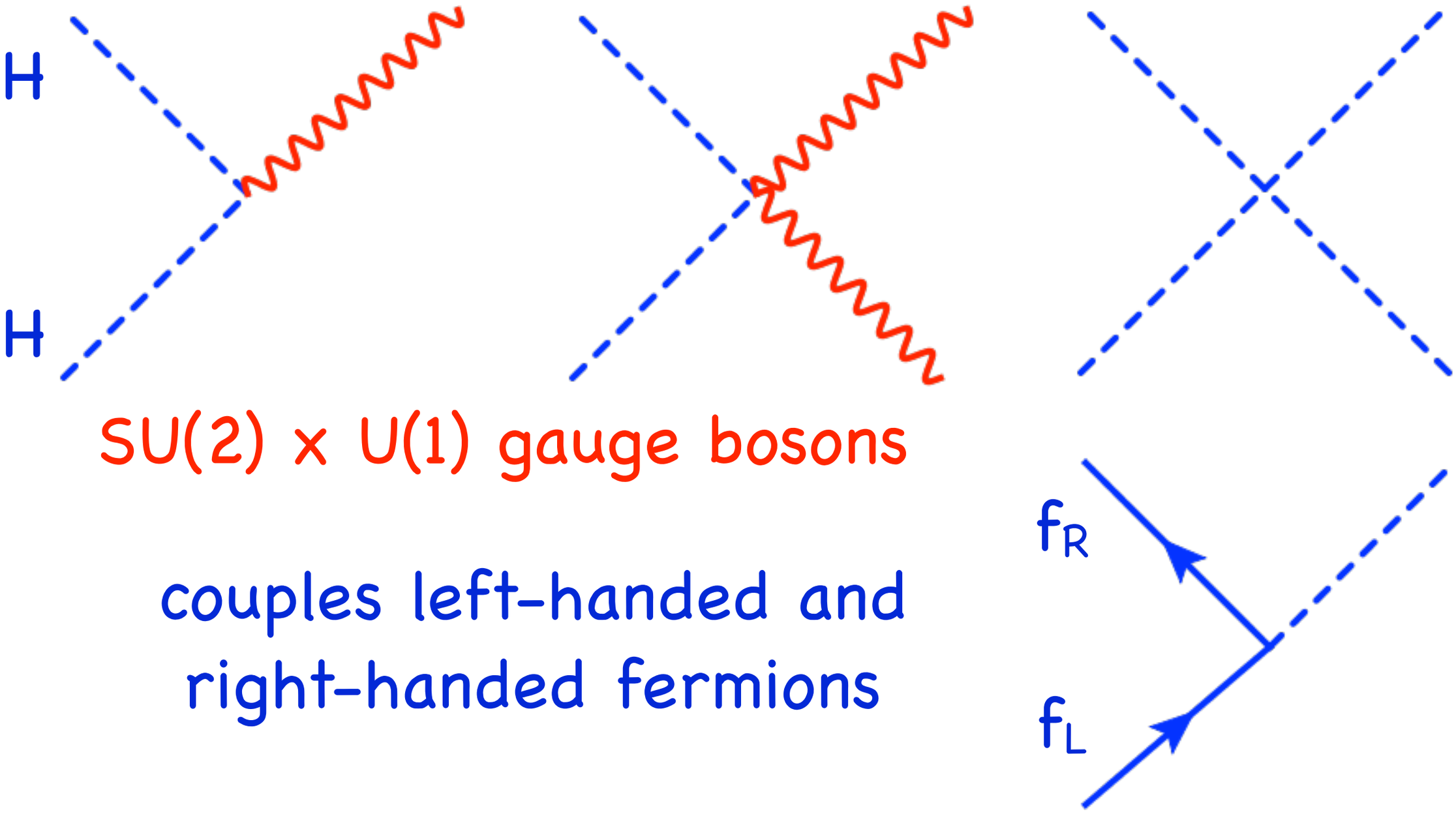
Phase Transition



Phase Transition



Higgs Boson



SU(2) x U(1) gauge bosons

couples left-handed and right-handed fermions

Higgs Field and Mass

$$2\,s+1 \text{ states}$$

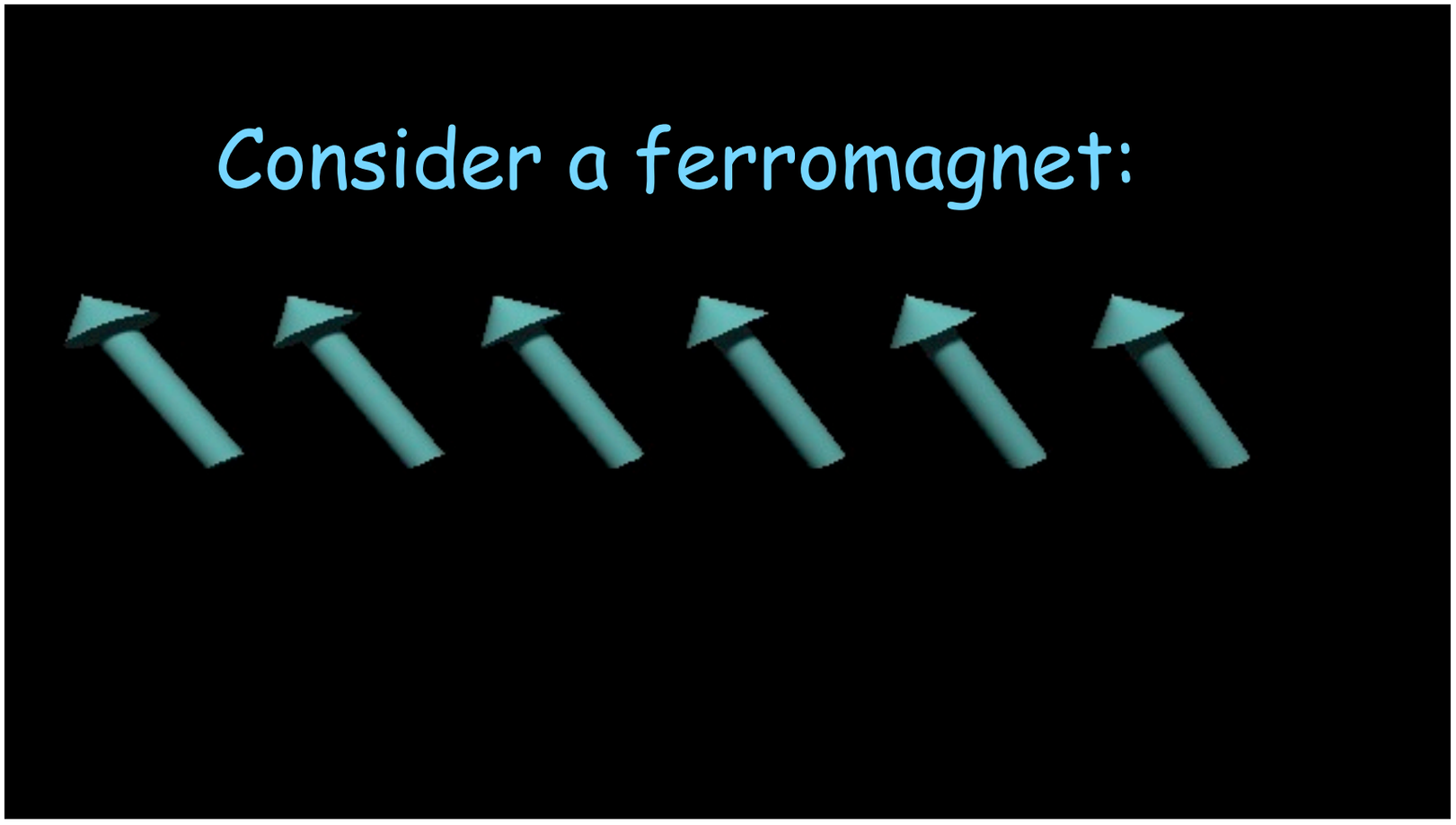
$s = \frac{1}{2}$ mass connects left-handed and right-handed electrons

$s = 1$ massless gauge bosons have 2 polarizations but massive gauge bosons have 3 polarizations

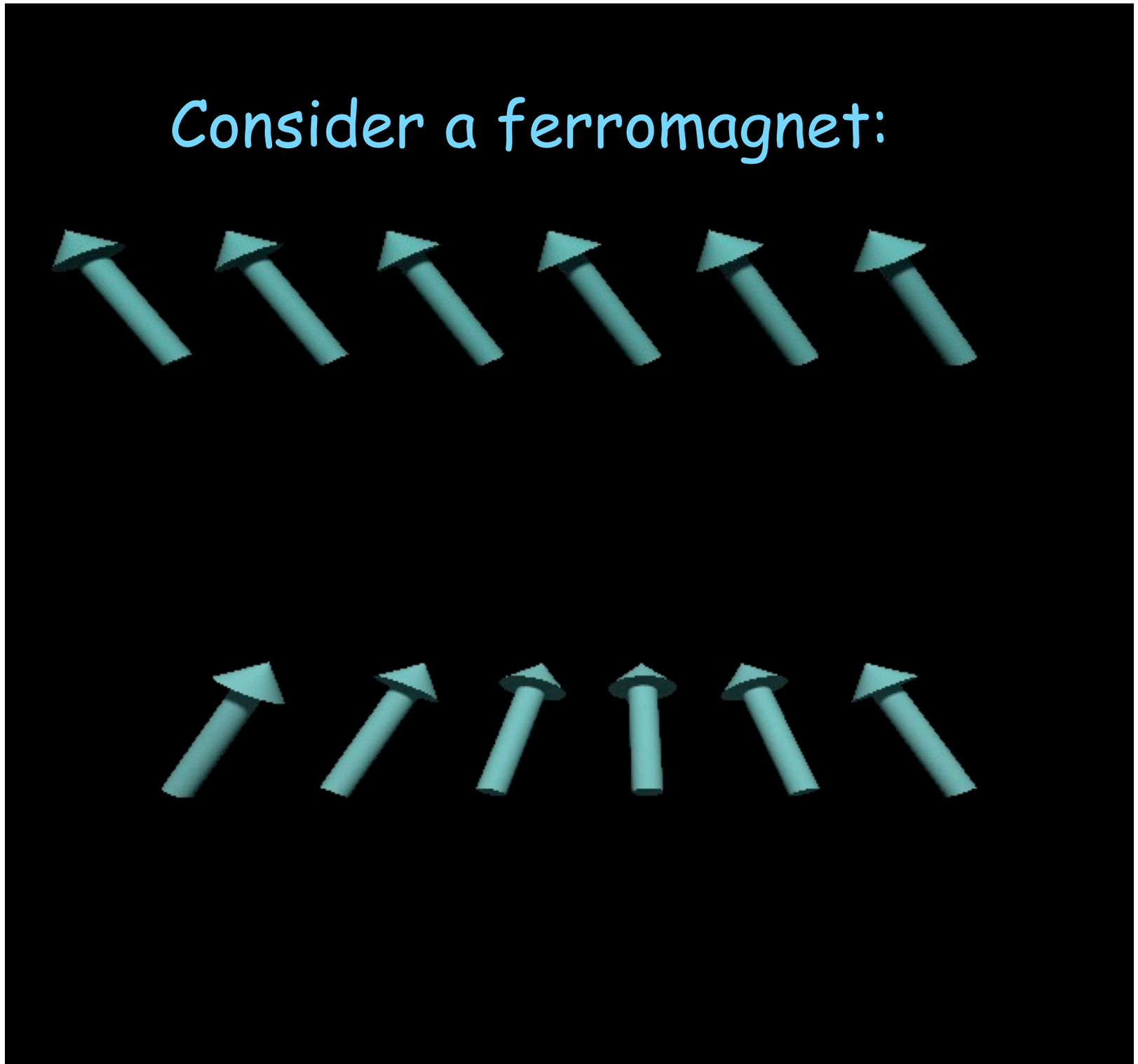
Goldstone's Theorem

There is a massless mode whenever the ground state transforms under a continuous symmetry of the Hamiltonian

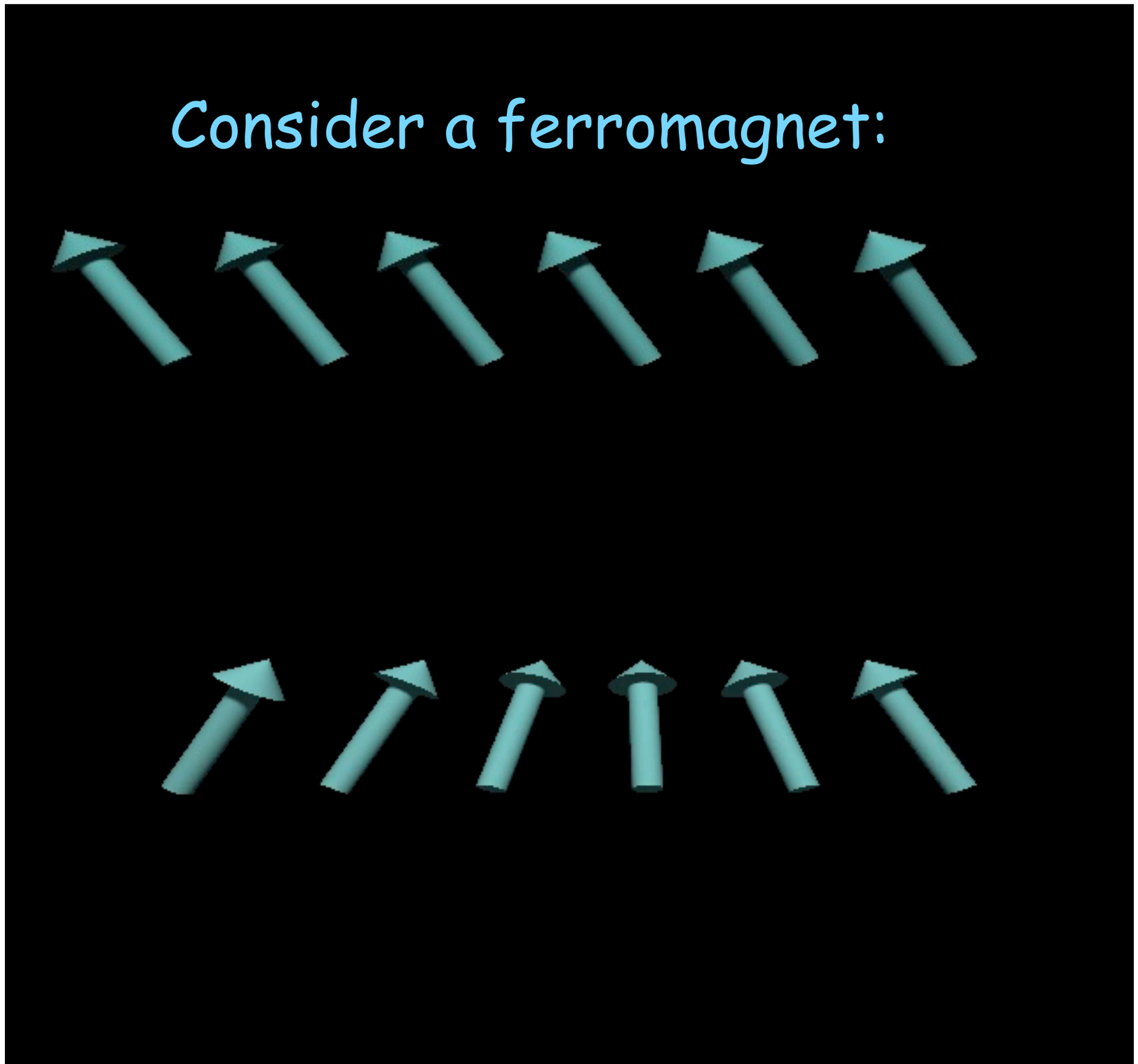
Goldstone's Theorem



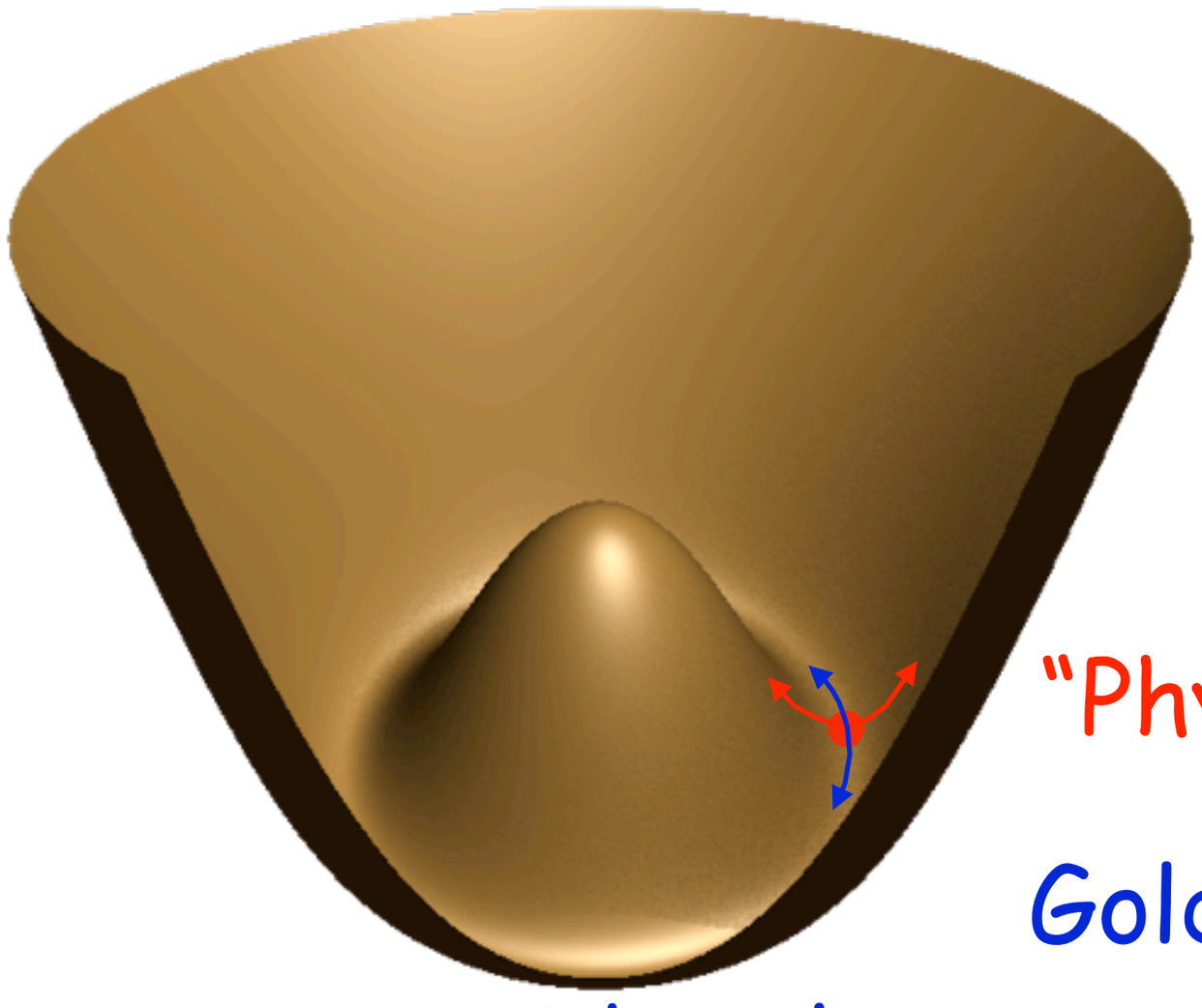
Goldstone's Theorem



Goldstone's Theorem



Higgs Potential

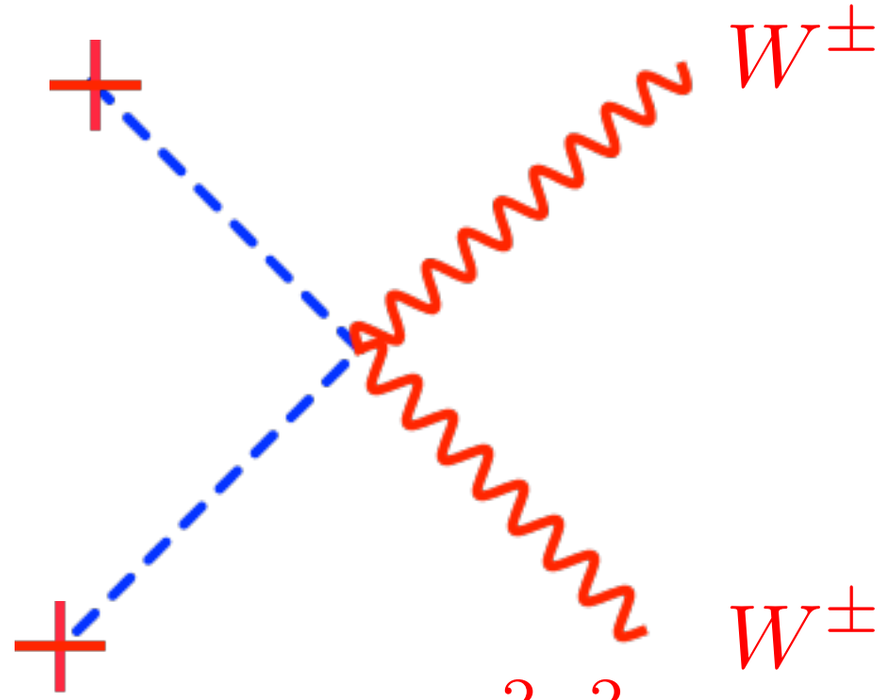


"Physical" Higgs

Goldstone Boson
provides the extra polarization

Gauge Boson Masses

$$\langle H \rangle = \frac{v}{\sqrt{2}}$$

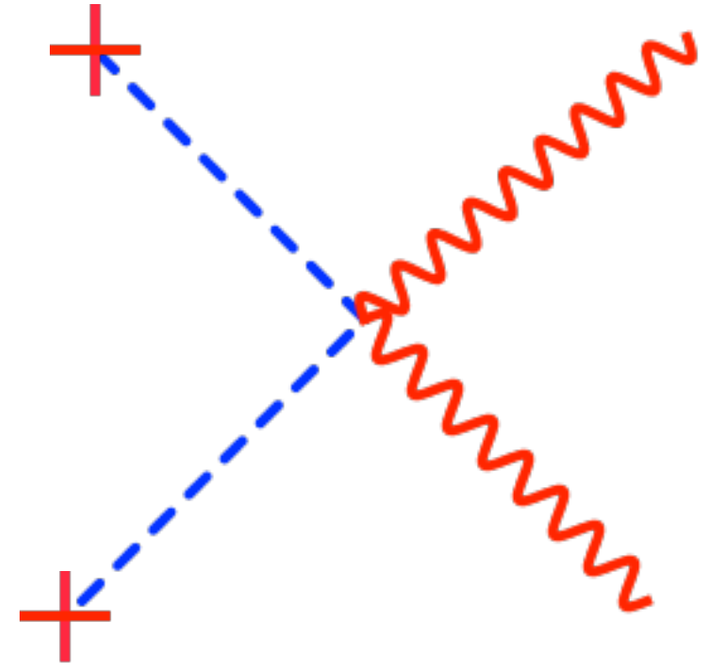


$$M_W^2 = \frac{g^2 v^2}{4}$$

$$M_W = 80.4\,\mathrm{GeV}$$

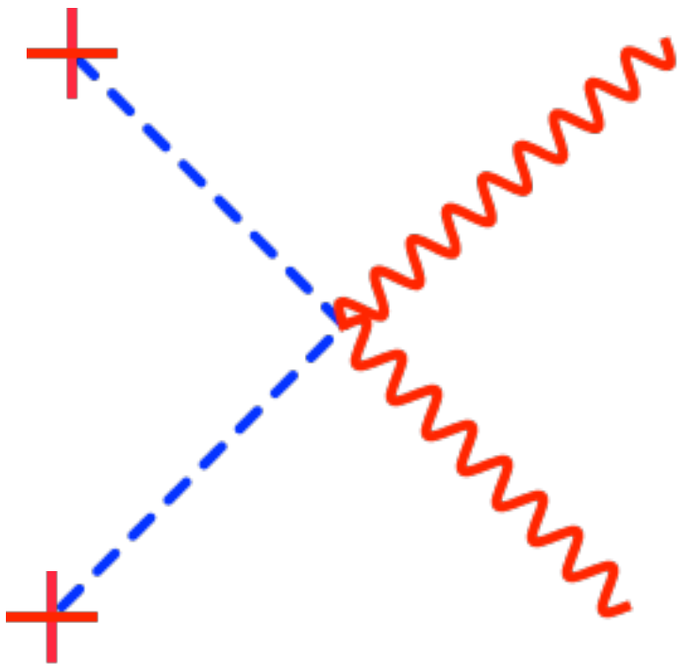
Gauge Boson Masses

$$\langle H \rangle = \frac{v}{\sqrt{2}}$$



$$(W^0,\, B)\, \frac{v^2}{4} \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^0 \\ B \end{pmatrix}$$

Gauge Boson Masses



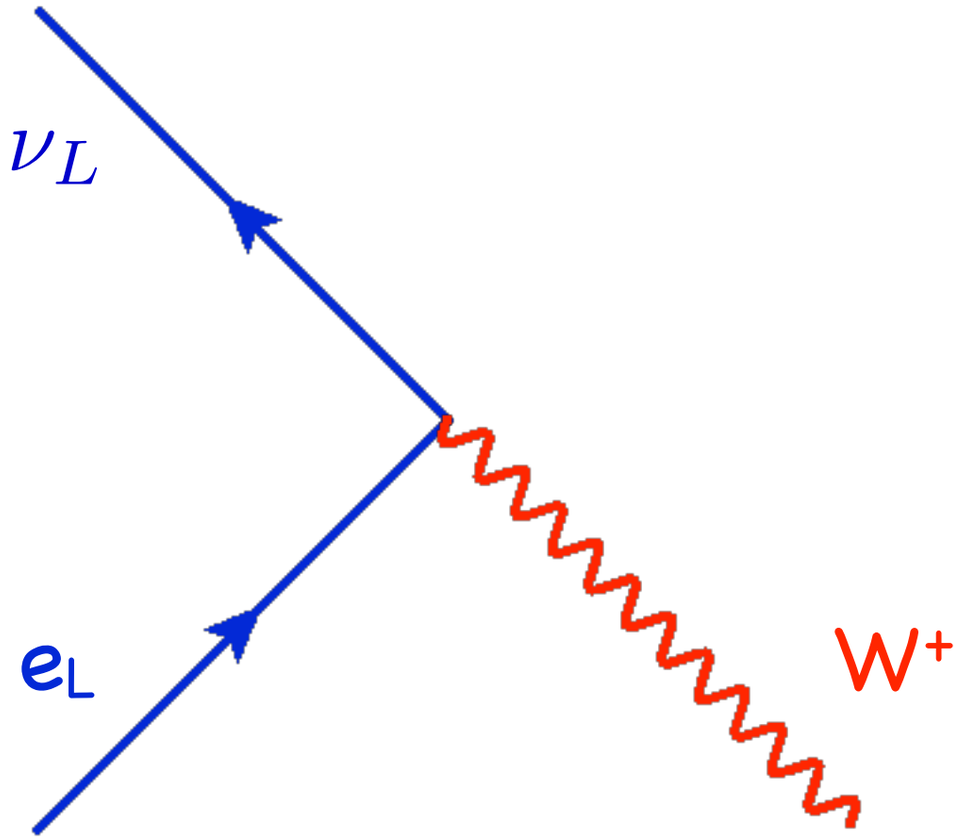
$$(W^0,\, B)\, \frac{v^2}{4} \begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} W^0 \\ B \end{pmatrix}$$

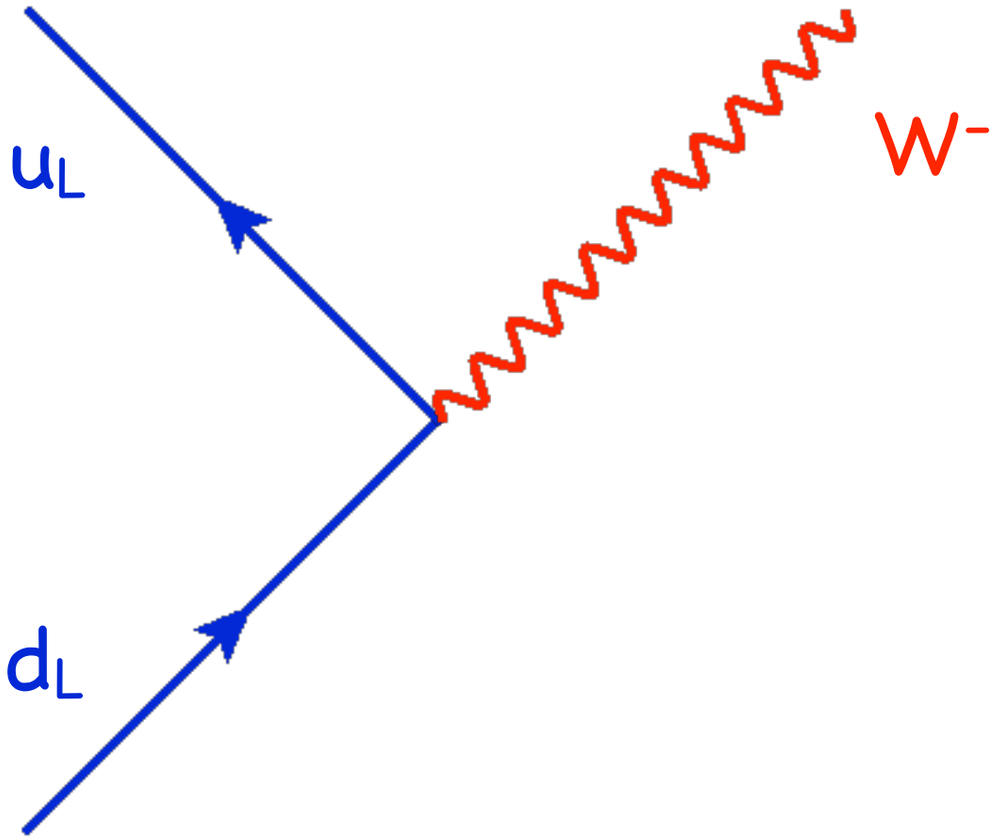
$$\begin{pmatrix} g^2 & -gg' \\ -gg' & g'^2 \end{pmatrix} \begin{pmatrix} g' \\ g \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$$

$$\begin{aligned} W^0 &\propto g\, Z^0 + g'\, A \\ B &\propto -g'\, Z^0 + g\, A \end{aligned}$$

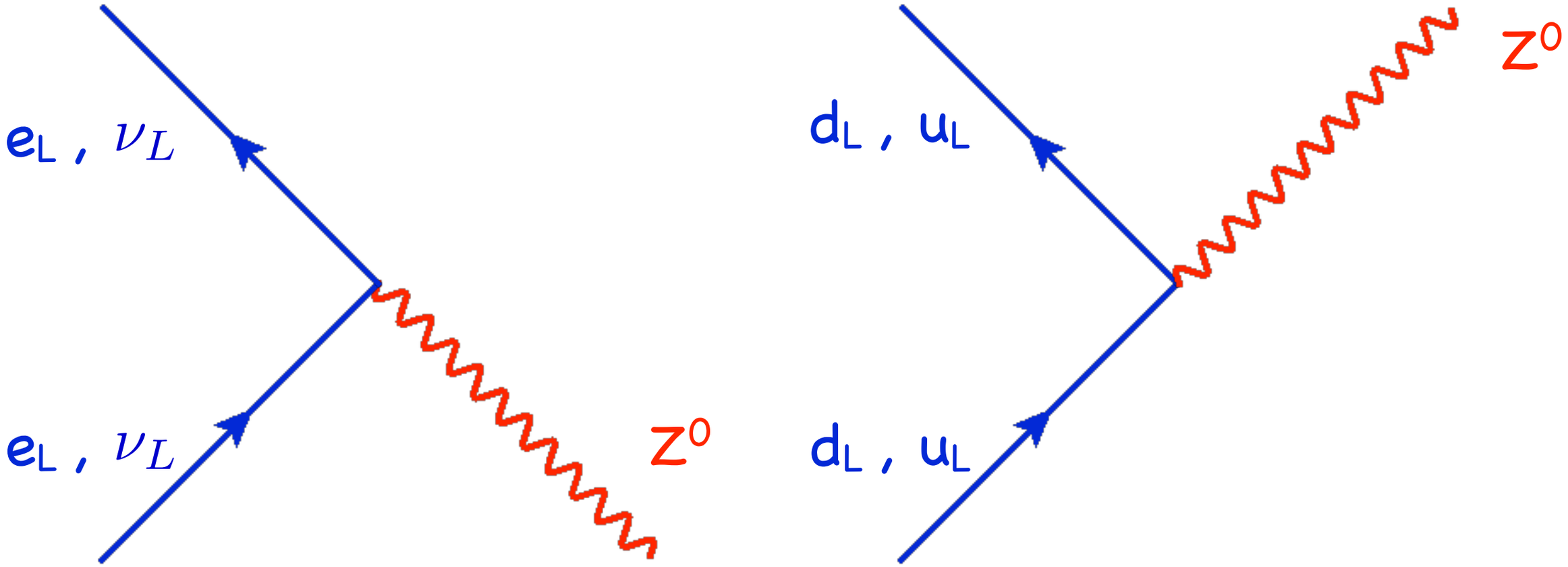
$$M_A = 0, \quad M_Z = \frac{\left(g^2 + g'^2\right) v^2}{4} = 91.19\,\mathrm{GeV}$$

Weak Charged Interactions

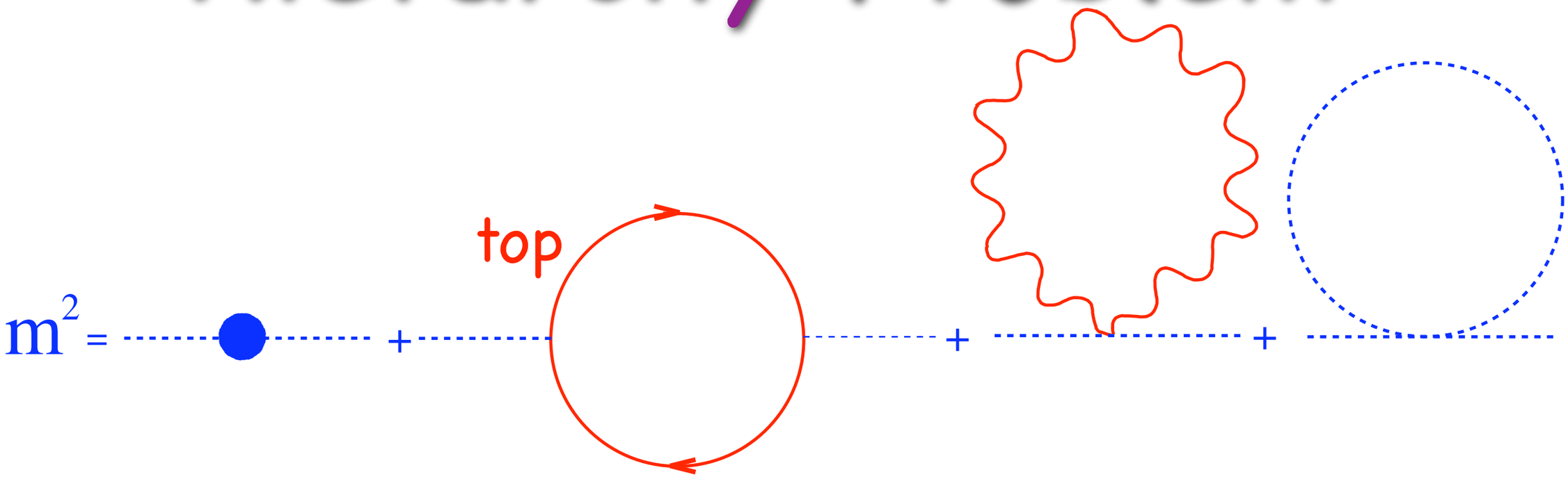




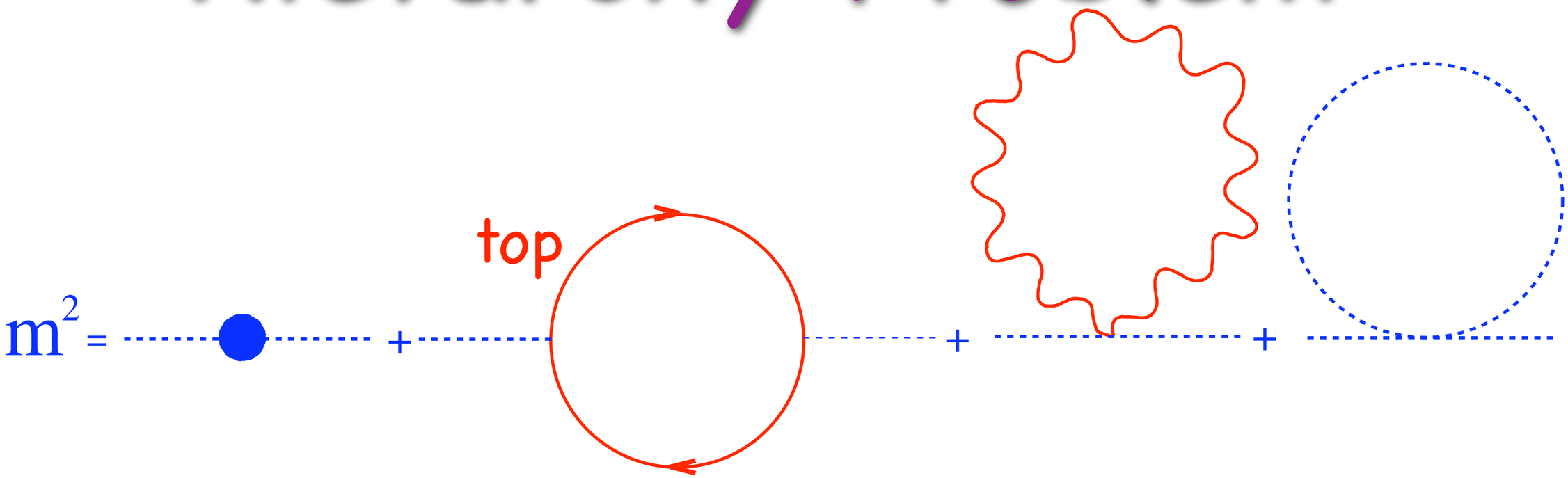
Weak Neutral Interactions



Hierarchy Problem



Hierarchy Problem



$$
\begin{aligned}
100^2 \quad = \quad & 16419971512763993607881093447038089115 \\
& -19402031160008016677277886179991476752 \\
& +24412810990665995494381822573963714 2 \\
& +54077854817746311445297450721375 1495
\end{aligned}
$$

Fine Tuning

Fine Tuning Solutions

supersymmetry

new strong interactions

extra dimensions

magnetic monopoles

.

.

.

LHC will look for these too!

Phenomenology

proton-proton collisions produce
mainly lots of hadrons

Garden Variety Hadrons

particle	mass	main decay	lifetime
π^0	$135\,\mathrm{MeV}$	$\to \gamma\,\gamma$	$8 \times 10^{-17}\,\mathrm{s}$
$\pi^\pm$	$140\,\mathrm{MeV}$	$\to \mu\,\nu_\mu$	$3 \times 10^{-8}\,\mathrm{s}$
$K^\pm$	$494\,\mathrm{MeV}$	$\to \mu\,\nu_\mu$	$10^{-8}\,\mathrm{s}$
η	$548\,\mathrm{MeV}$	$\to \gamma\,\gamma$	$5 \times 10^{-19}\,\mathrm{s}$
ρ^0	$775\,\mathrm{MeV}$	$\to \pi\,\pi$	$4 \times 10^{-24}\,\mathrm{s}$
p	$938\,\mathrm{MeV}$	$-$	$> 10^{38}\,\mathrm{s}$
n	$940\,\mathrm{MeV}$	$\to p\,e^-\,\bar{\nu}_e$	$886\,\mathrm{s}$
B^0	$5,280\,\mathrm{MeV}$	$\to K^\pm + \text{ hadrons}$	$2 \times 10^{-12}\,\mathrm{s}$

Cross Sections

events/s = cross section x luminosity

$$\frac{\Delta N}{\Delta t} = \sigma L$$

σ traditionally measured in barns

$$1\,b = 10^{-28}\,\mathrm{m}^2 = 100\,\mathrm{fm}^2$$

typical nuclear cross section

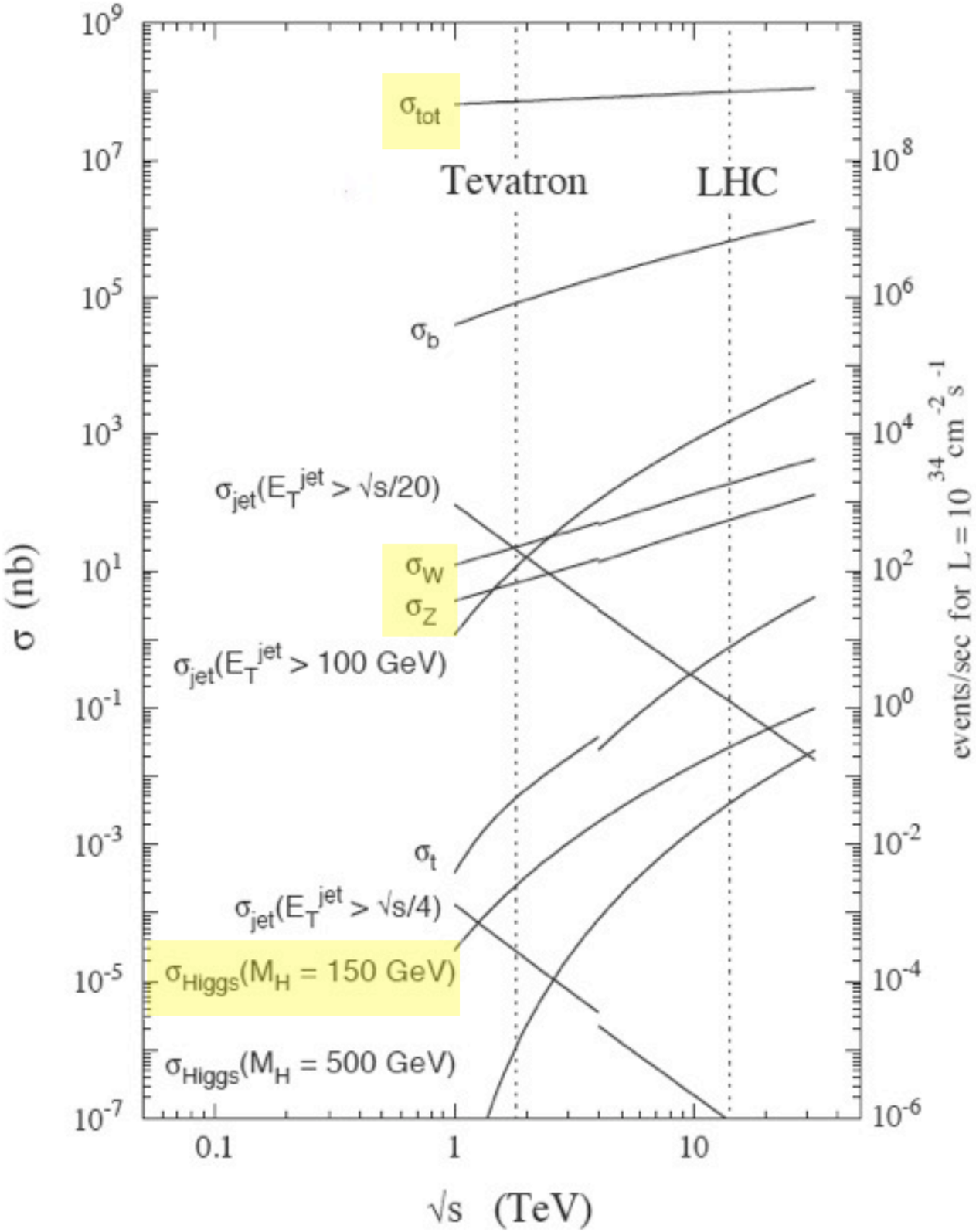
Cross Sections

$$\sigma_{QCD} \sim (1\,\mathrm{fm})^2 = 10^7\,\mathrm{nb}$$

$$\sigma_{weak} \sim \frac{1}{M_W^2} = \frac{1}{(80\,\mathrm{GeV})^2} = 60\,\mathrm{nb}$$

$$\sigma_{higgs} \sim \frac{1}{(16\pi^2 m_{top})^2} = 10^{-3}\,\mathrm{nb}$$

Cross Sections



Travel Distances

$$E = \gamma\, m = 10\,\mathrm{GeV}$$

particle	mass	distance
ρ^0	$775\,\mathrm{MeV}$	$2 \times 10^{-14}\,\mathrm{m}$
η	$548\,\mathrm{MeV}$	$3 \times 10^{-9}\,\mathrm{m}$
π^0	$135\,\mathrm{MeV}$	$2 \times 10^{-6}\mathrm{m}$
B^0	$5,280\,\mathrm{MeV}$	$10^{-3}\,\mathrm{m}$
$K^\pm$	$494\,\mathrm{MeV}$	$60\,\mathrm{m}$
$\pi^\pm$	$140\,\mathrm{MeV}$	$640\,\mathrm{m}$
n	$940\,\mathrm{MeV}$	$3 \times 10^{12}\,\mathrm{m}$
p	$938\,\mathrm{MeV}$	$> 10^{47}\,\mathrm{m}$

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π^0	$135\,\mathrm{MeV}$	$2 \times 10^{-6}\mathrm{m}$	
B^0	$5,280\,\mathrm{MeV}$	$10^{-3}\,\mathrm{m}$	
$K^\pm$	$494\,\mathrm{MeV}$	$60\,\mathrm{m}$	detector stable
$\pi^\pm$	$140\,\mathrm{MeV}$	$640\,\mathrm{m}$	
n	$940\,\mathrm{MeV}$	$3 \times 10^{12}\,\mathrm{m}$	
p	$938\,\mathrm{MeV}$	$> 10^{47}\,\mathrm{m}$	

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particle	mass	distance	
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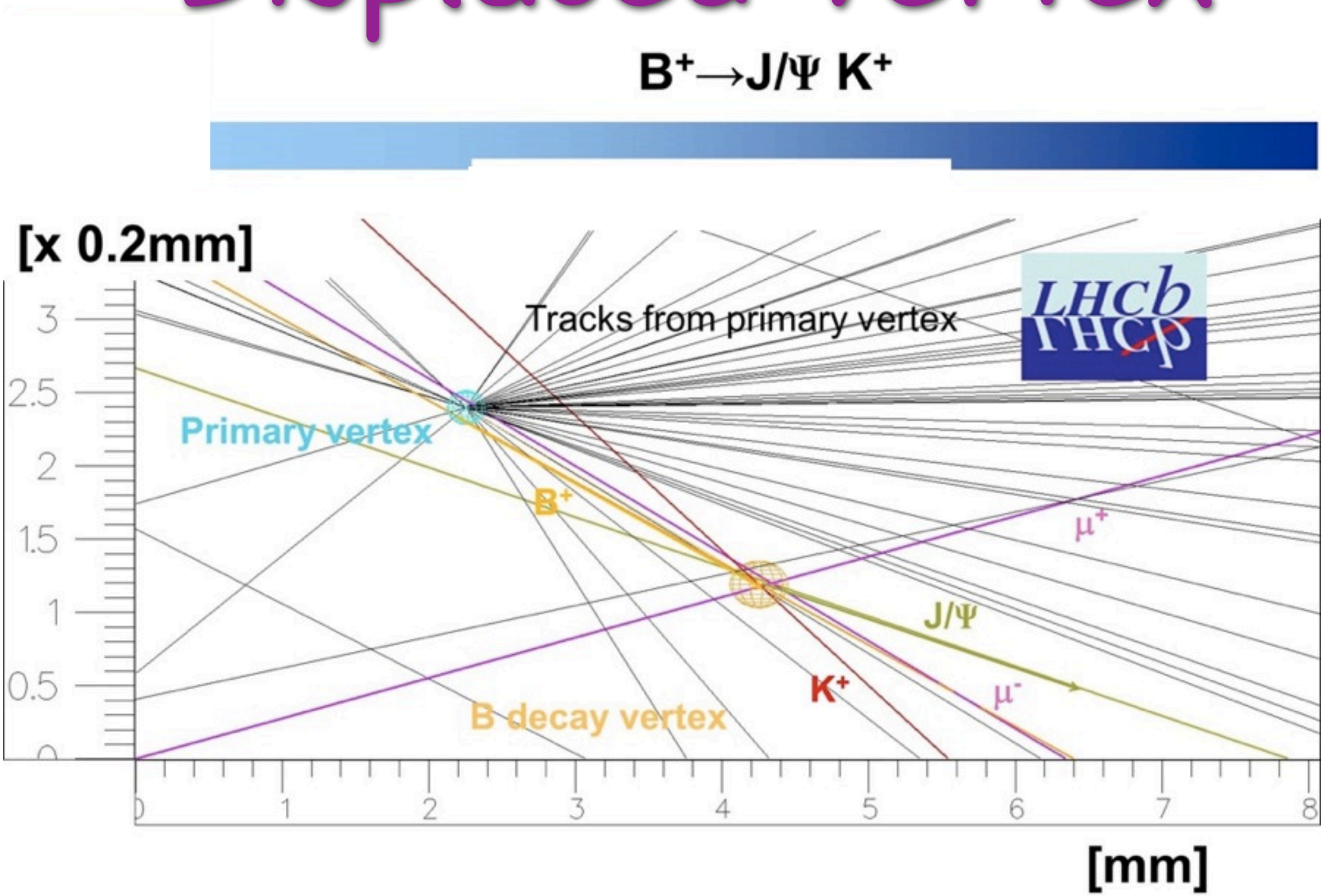
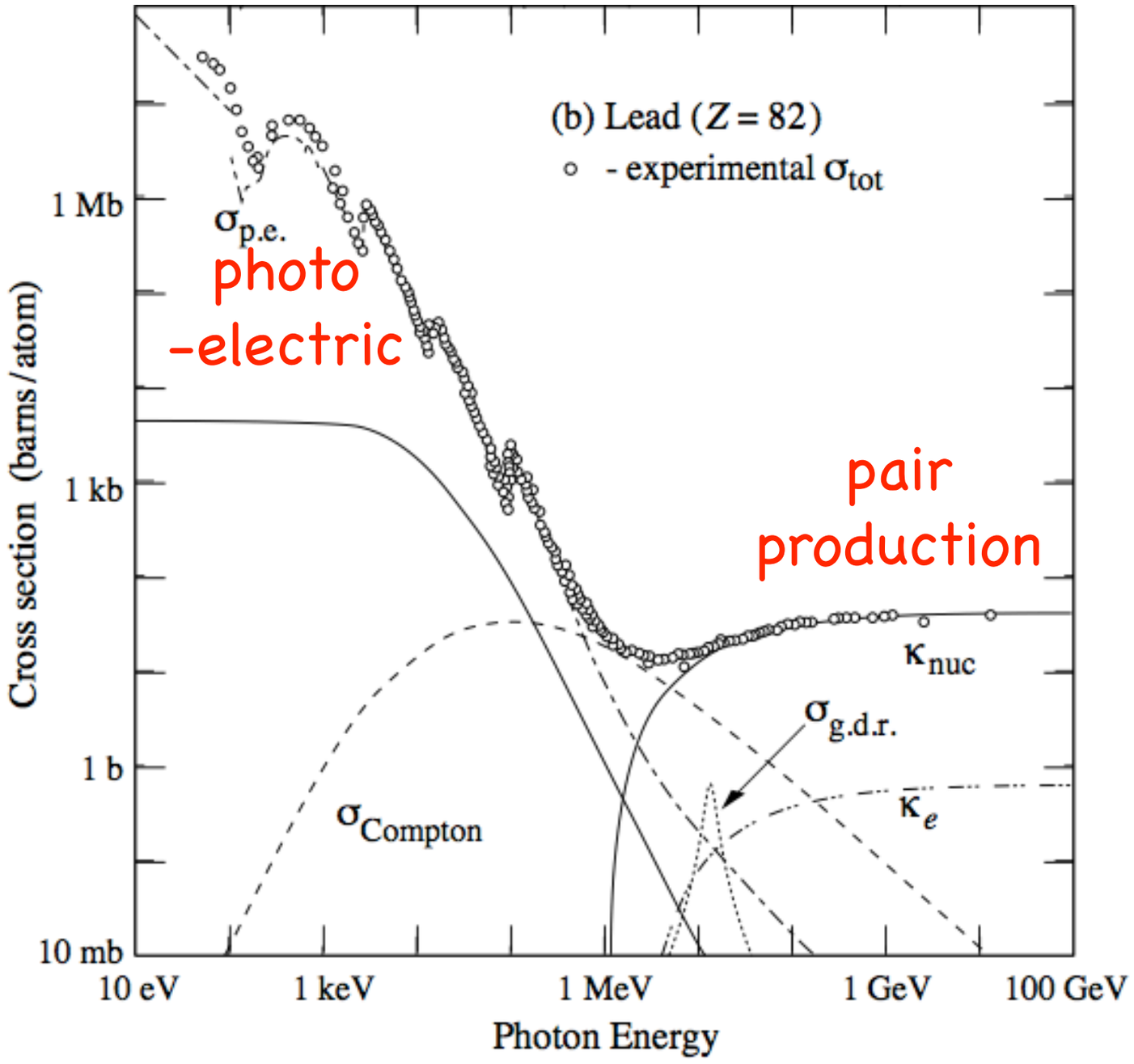
π^0	$135\,\mathrm{MeV}$	$2 \times 10^{-6}\mathrm{m}$	
B^0	$5,280\,\mathrm{MeV}$	$10^{-3}\,\mathrm{m}$	displaced vertex
$K^\pm$	$494\,\mathrm{MeV}$	$60\,\mathrm{m}$	detector stable
$\pi^\pm$	$140\,\mathrm{MeV}$	$640\,\mathrm{m}$	
n	$940\,\mathrm{MeV}$	$3 \times 10^{12}\,\mathrm{m}$	
p	$938\,\mathrm{MeV}$	$> 10^{47}\,\mathrm{m}$	

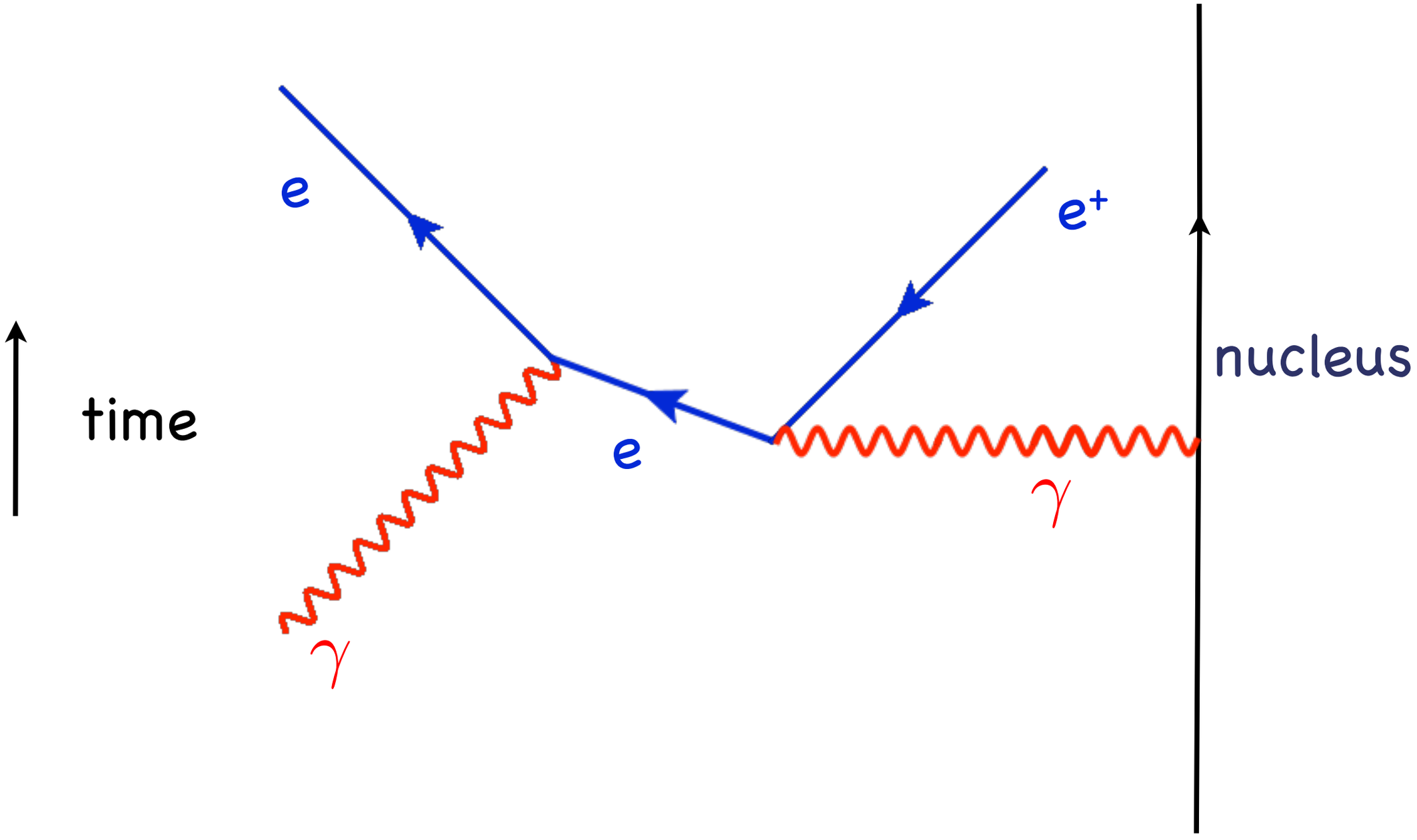
Displaced Vertex



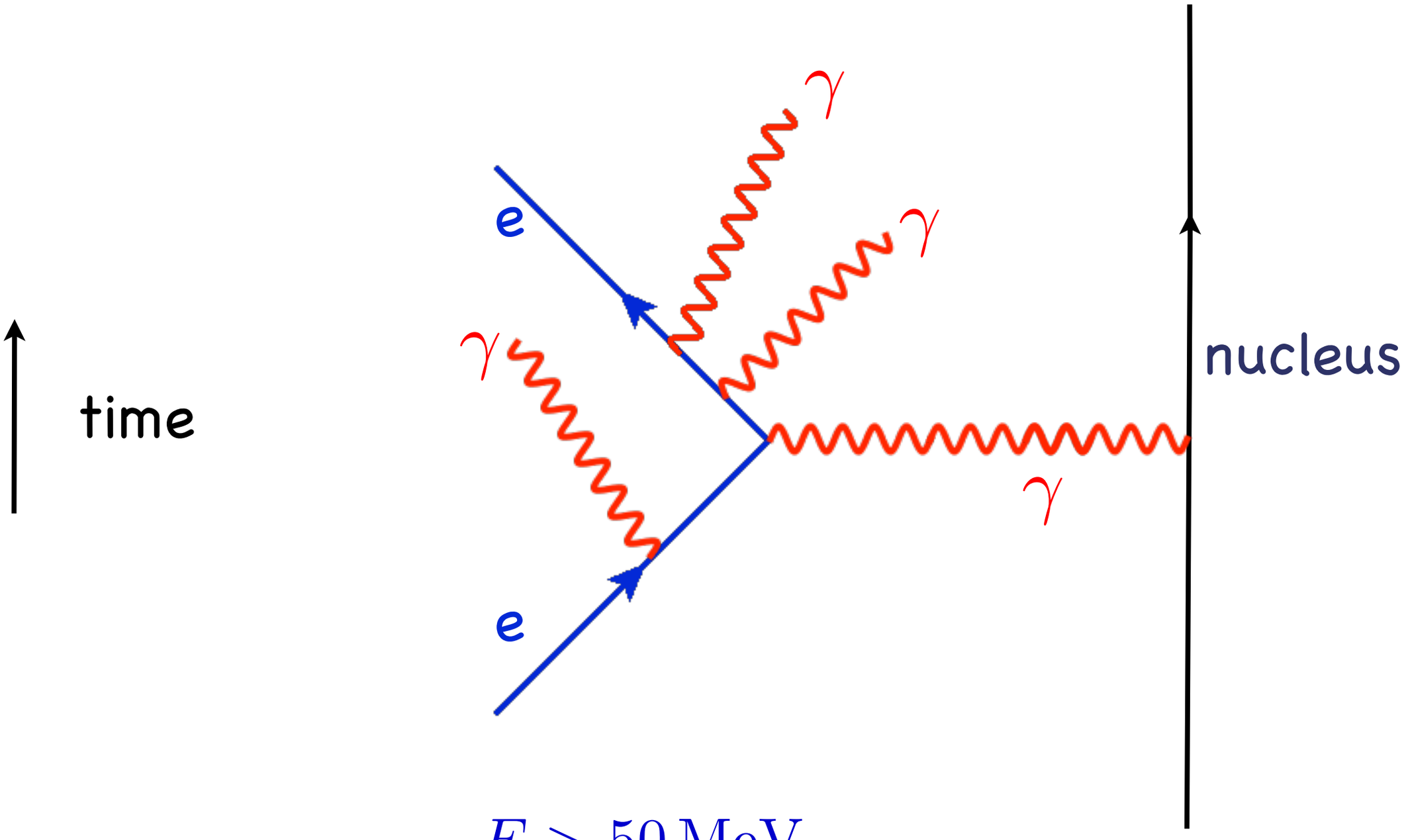
Photon Energy Loss



Pair Production



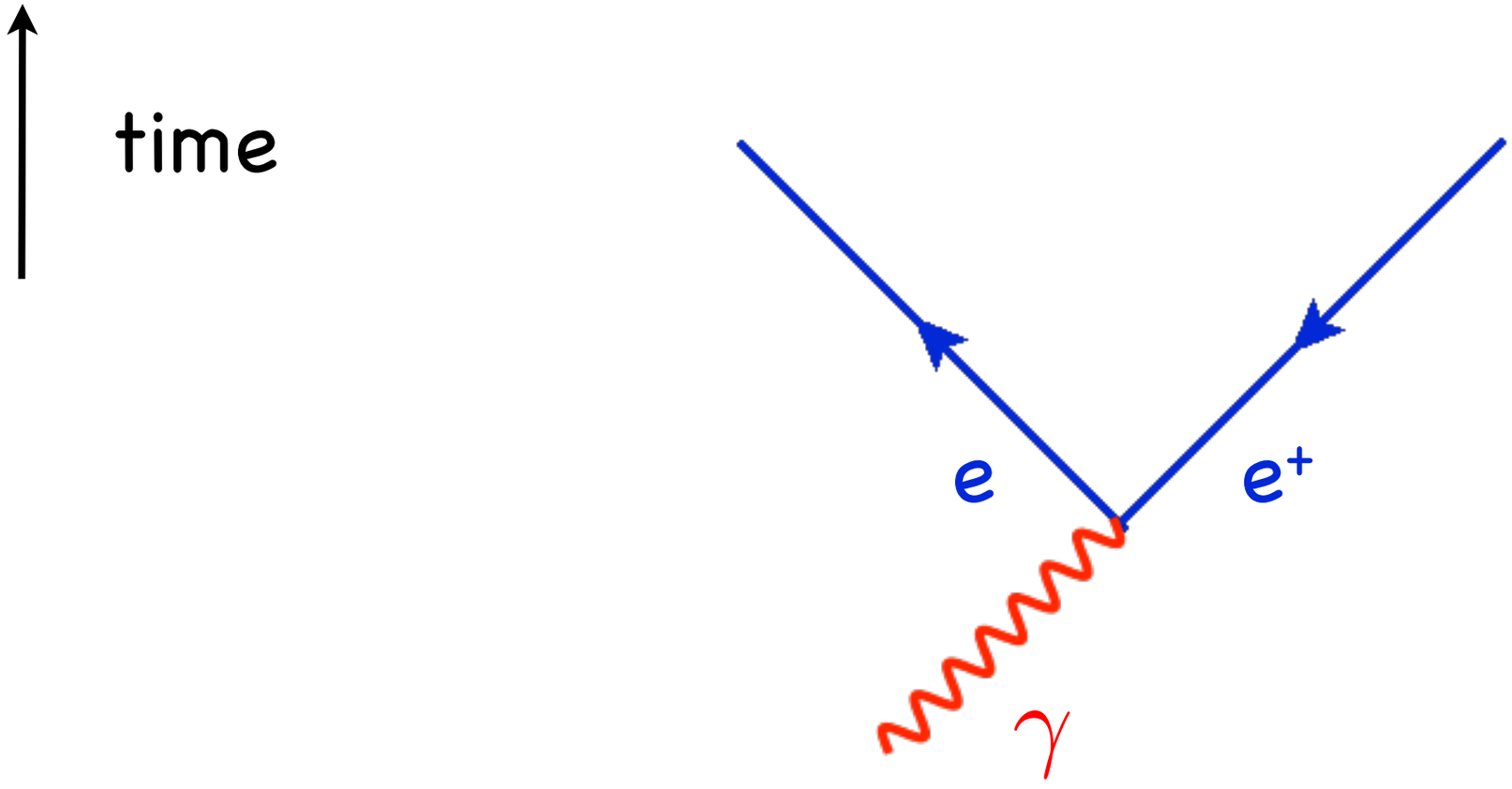
Electron Bremsstrahlung



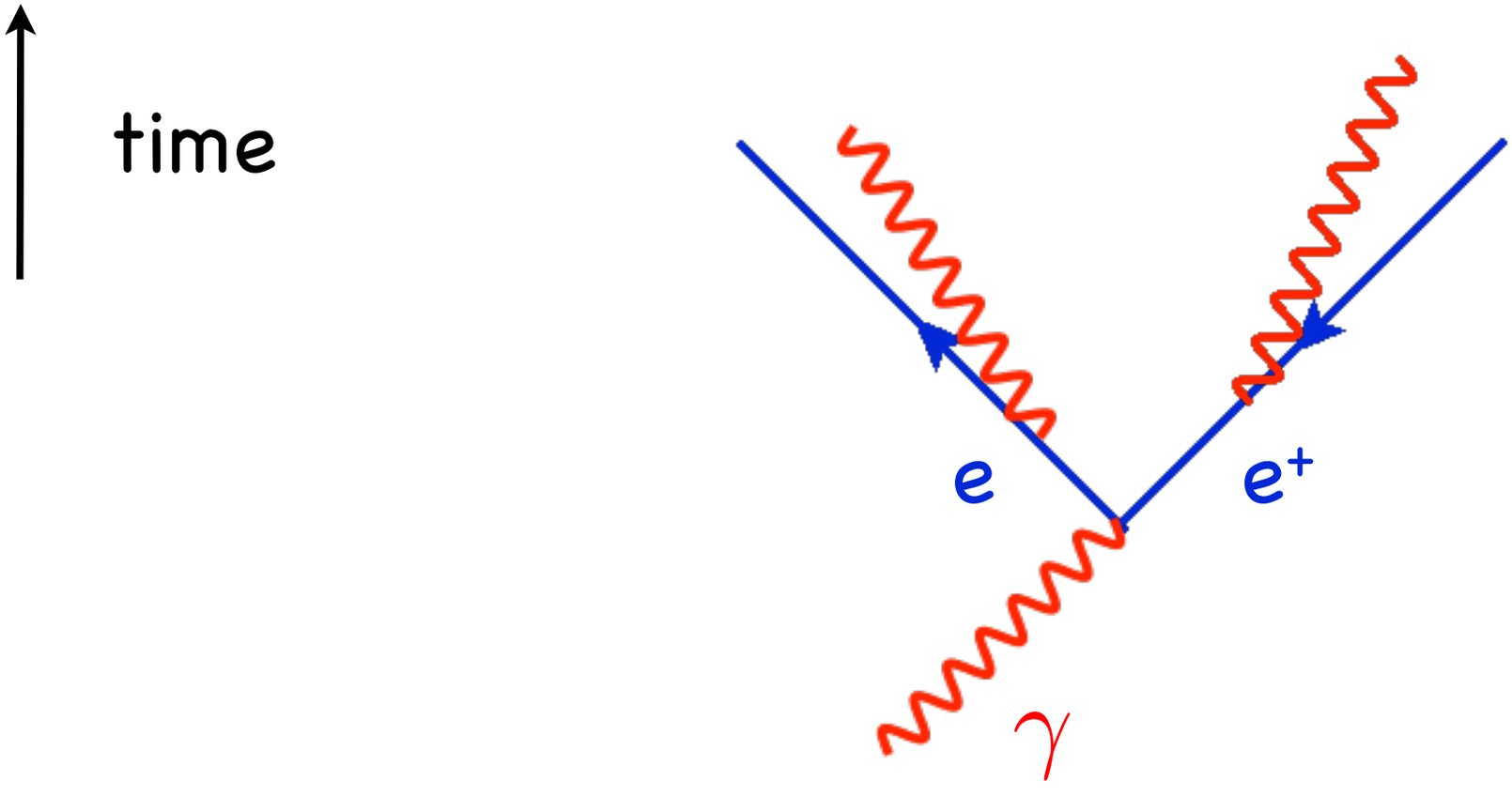
$$E > 50\,\mathrm{MeV}$$

$$\gamma > 100$$

EM Shower

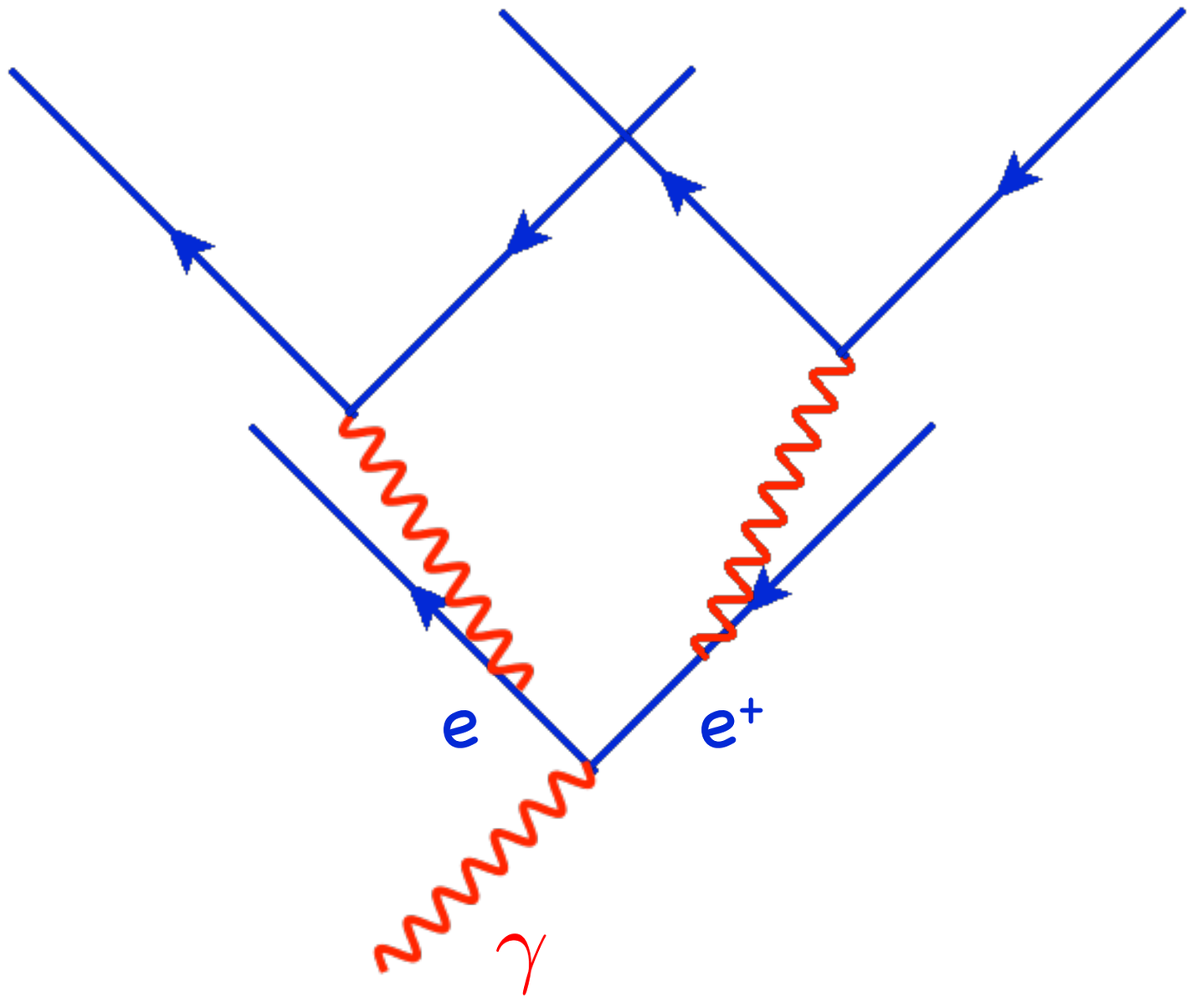


EM Shower

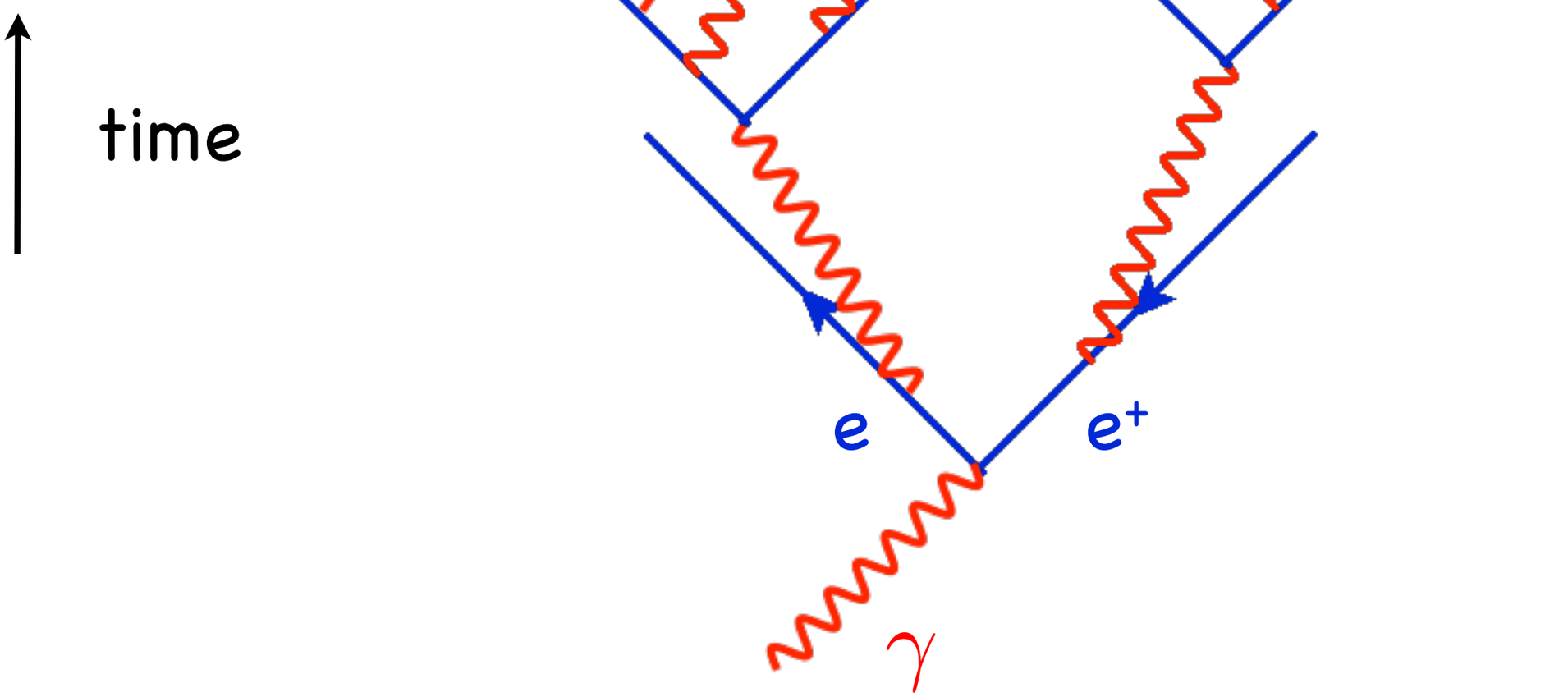


EM Shower

time

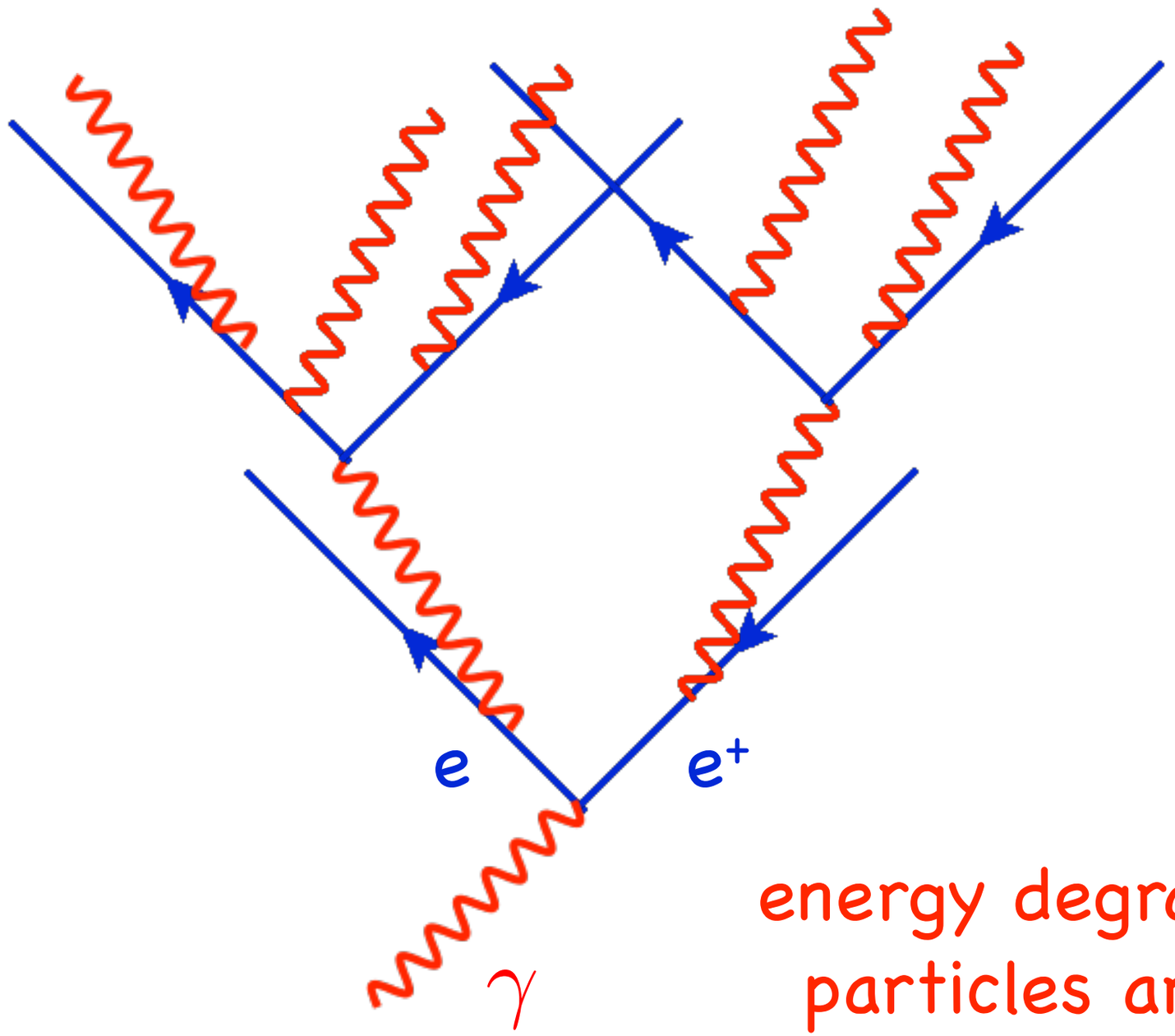


EM Shower



EM Shower

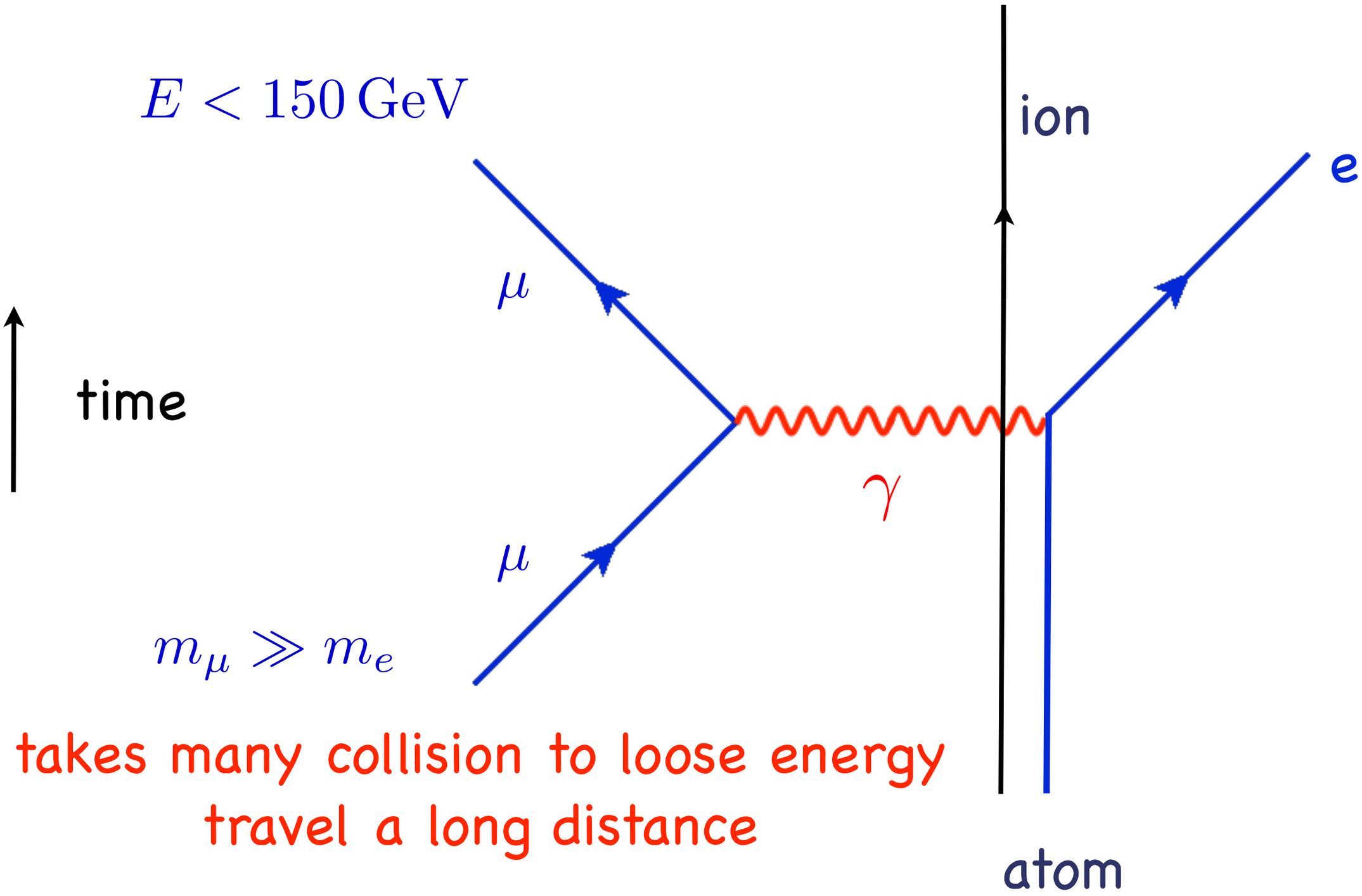
time



energy degrades as more particles are produced

Muons Ionize

$E < 150\,\mathrm{GeV}$

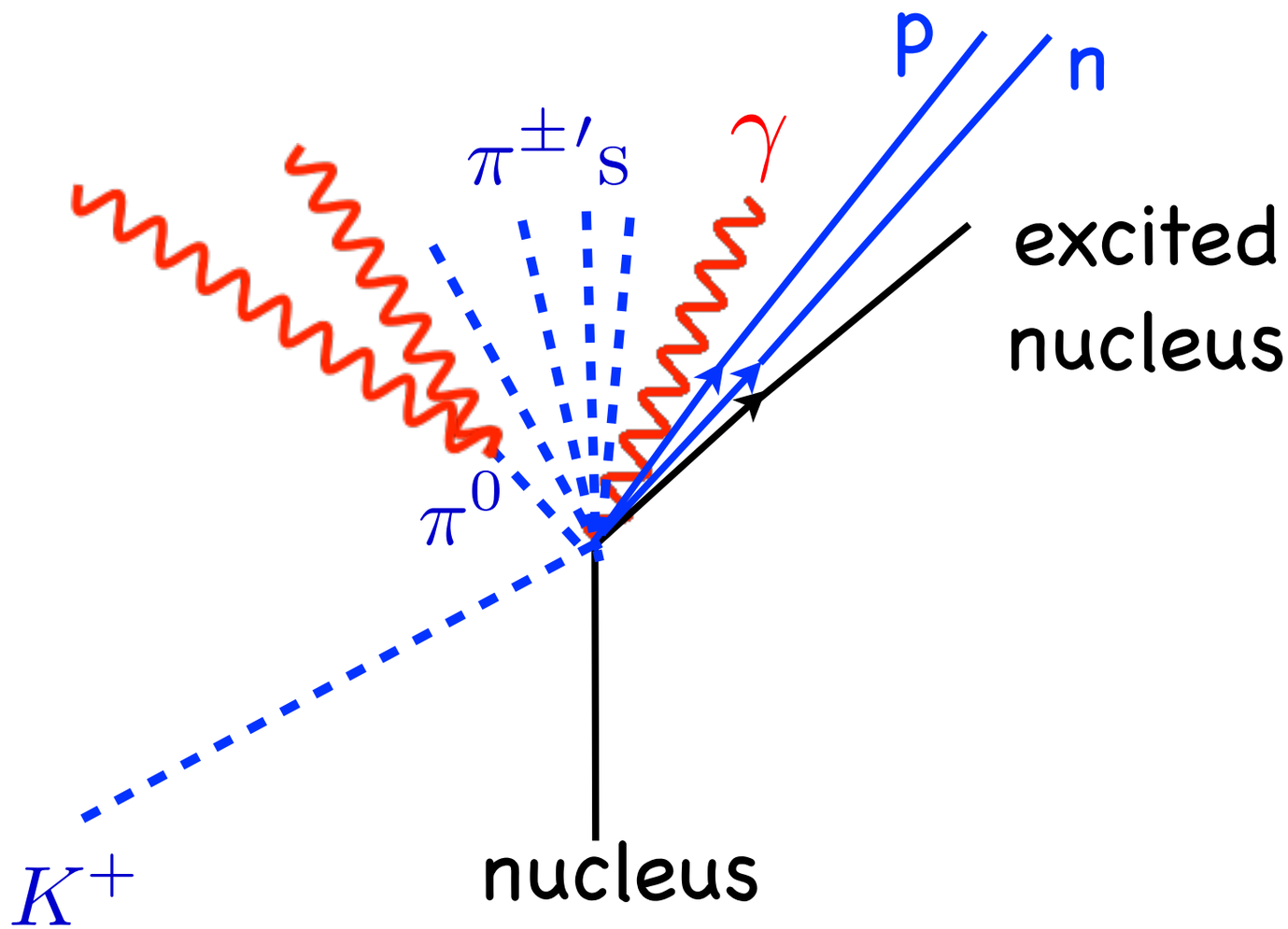


$m_\mu \gg m_e$

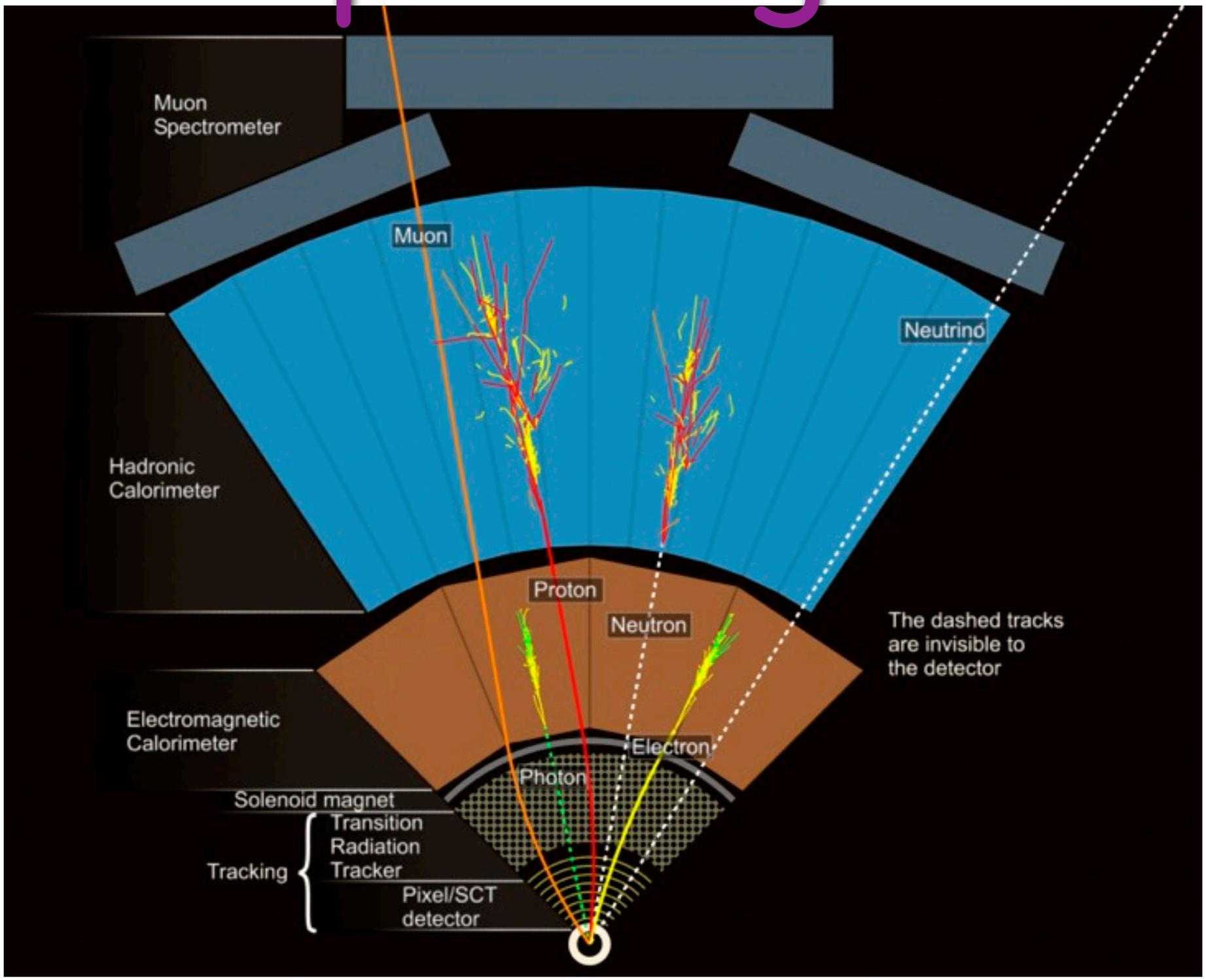
takes many collision to loose energy
travel a long distance

Hadronic Showers

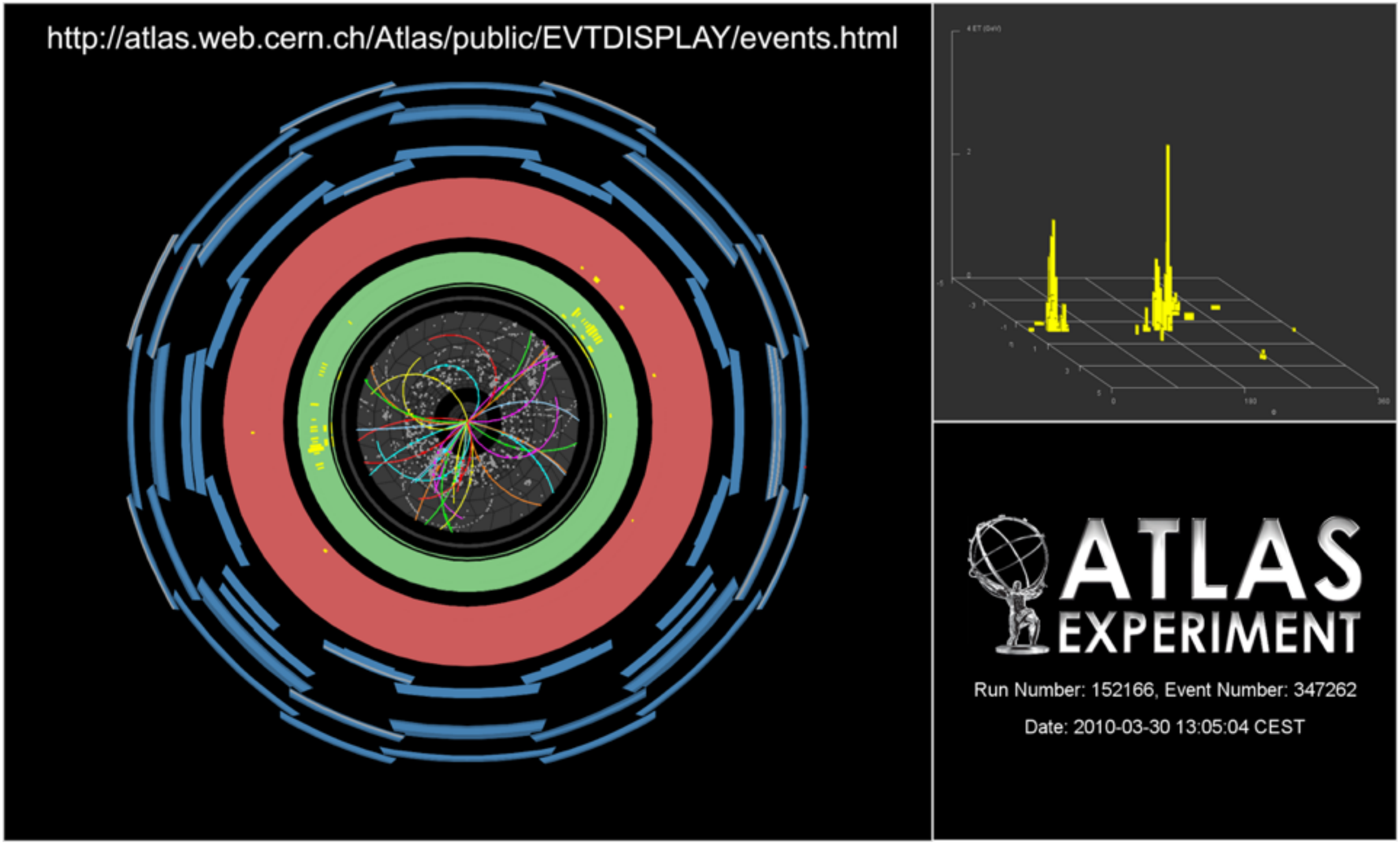
hadrons are heavier than muons
but have strong nuclear interactions
more complicated showers



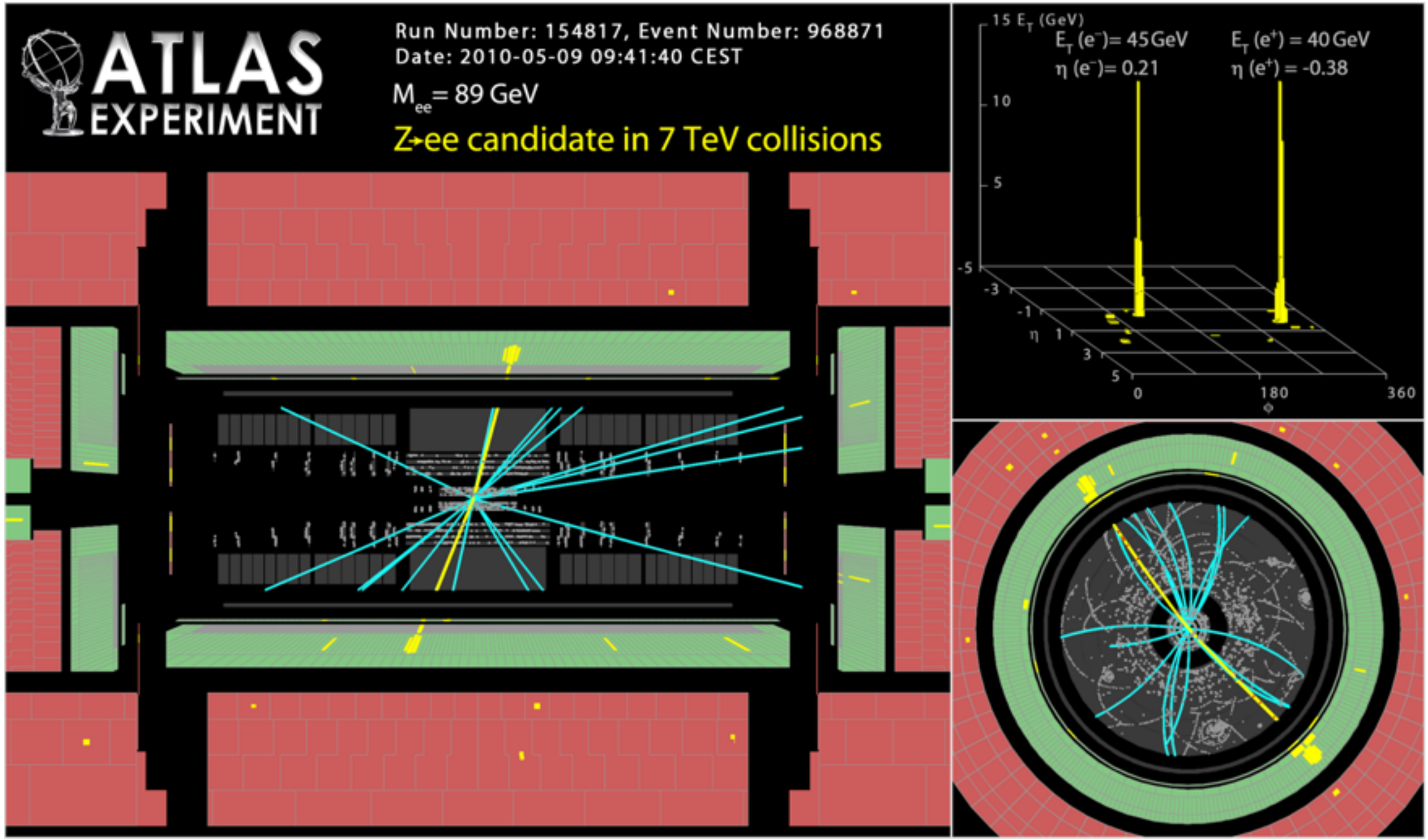
Interpreting Data



Actual Data


http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html
ATLAS
EXPERIMENT
Run Number: 152166, Event Number: 347262
Date: 2010-03-30 13:05:04 CEST

Actual Data


ATLAS
EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e^-)= 45GeV
E_T (e^+) = 40GeV
η (e^-)= 0.21
η (e^+) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ

Conclusions

The LHC is running.

First we have to understand how to identify all the Standard Model processes, then we can find something new.

If we're lucky it will be something no one has thought of.