Chiedere alla polvere

Introduzione al Modello Standard della Fisica delle particelle elementari

International Masterclasses hands on Particle Physics
Laboratori Nazionali di Frascati

F. Dettori
(Università degli Studi di Cagliari e INFN Cagliari)

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Legge delle proporzioni definite: *Quando due o più elementi reagiscono a formare una data sostanza, si combinano sempre secondo proporzioni in massa definite e costanti.*

Legge delle proporzioni multiple o di Dalton *Se due elementi formano più di un composto, i rapporti tra le masse del secondo elemento, combinati con una massa fissa del primo, stanno tra loro in rapporti pari a frazioni tra numeri interi piccoli.*

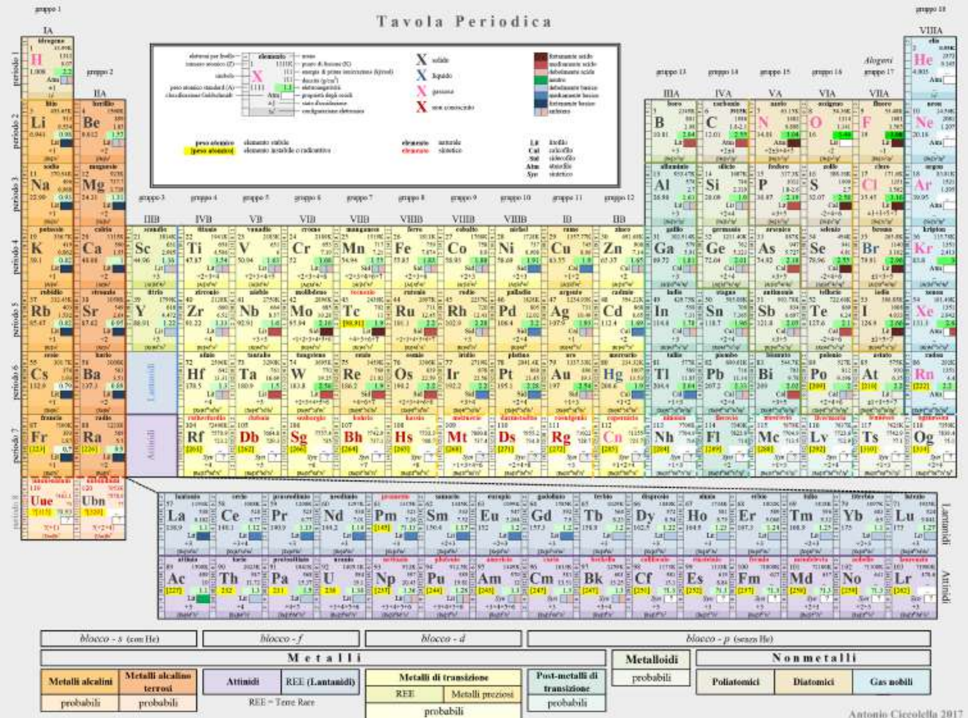


Tavola Periodica
IA
IIA
gruppo 2
IIIA
IVA
VA
VIA
VIIA
VIIIA
gruppo 13
gruppo 14
gruppo 15
gruppo 16
gruppo 17
Alogeni
gruppo 3
gruppo 4
gruppo 5
gruppo 6
gruppo 7
gruppo 8
gruppo 9
gruppo 10
gruppo 11
gruppo 12
IIIB
IVB
VB
VIB
VIIB
VIIIB
VIIIB
VIIIB
IB
IIB
periodo 1
periodo 2
periodo 3
periodo 4
periodo 5
periodo 6
periodo 7
H He
Li Be B C N O F Ne
Na Mg Al Si P S Cl Ar
K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr
Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe
Cs Ba Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn
Fr Ra Rf Db Sg Bh Hs Mt Ds Rg Cn Nh Fl Mc Lv Ts Og
Uue Ubn
Lantanidi
Attinidi
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
Ac Th Pa U Np Pu Am Cm Bk Cf Es Fm Md No Lr
X solido
X liquido
X gassoso
X non conosciuto
blocco - s (con He)
blocco - f
blocco - d
blocco - p (senza He)
Metalli
Metalloidi
probabili
Nonmetalli
Metalli alcalini
Metalli alcalino terrosi
probabili
probabili
Attinidi
REE (Lantanidi)
REE = Terre Rare
Metalli di transizione
REE
Metalli preziosi
probabili
Post-metalli di transizione
probabili
Poliatomici
Diatomici
Gas nobili
Antonio Ciccolella 2017

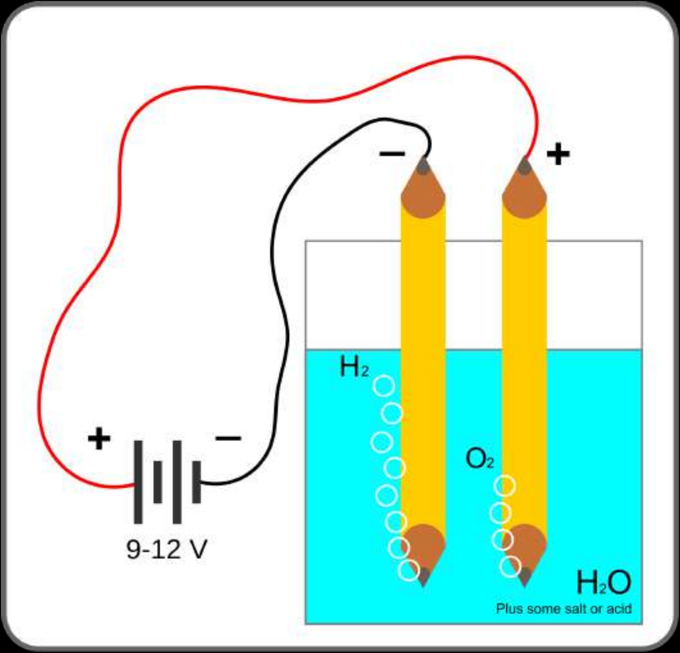


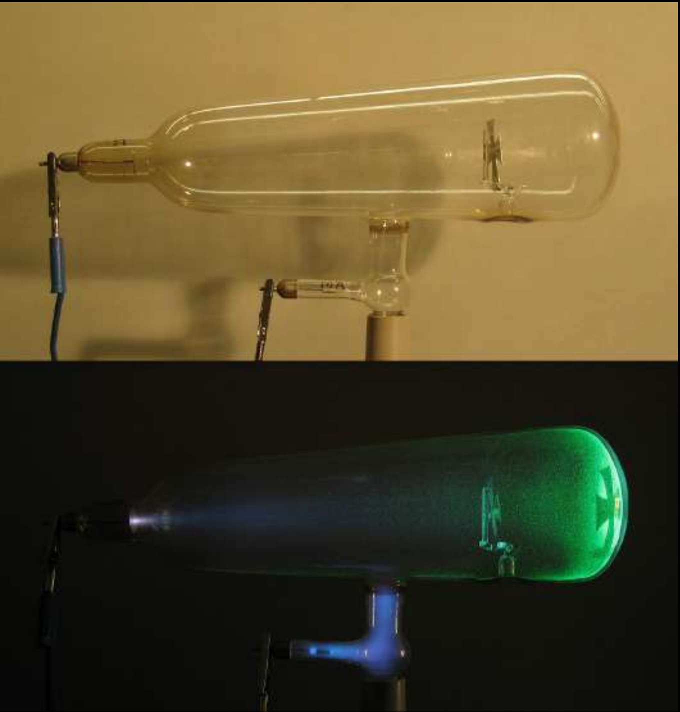
Image Credits: Wikipedia

$$M = \frac{AQ}{Fz} \qquad M = Nm$$

$$m = \frac{A}{N_A} \qquad e = F/N_A$$

$$Q = Nze$$

Image Credits: Mivar



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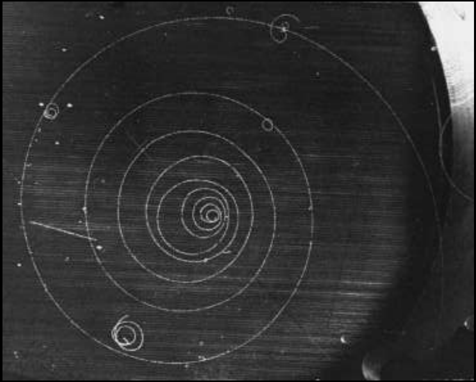
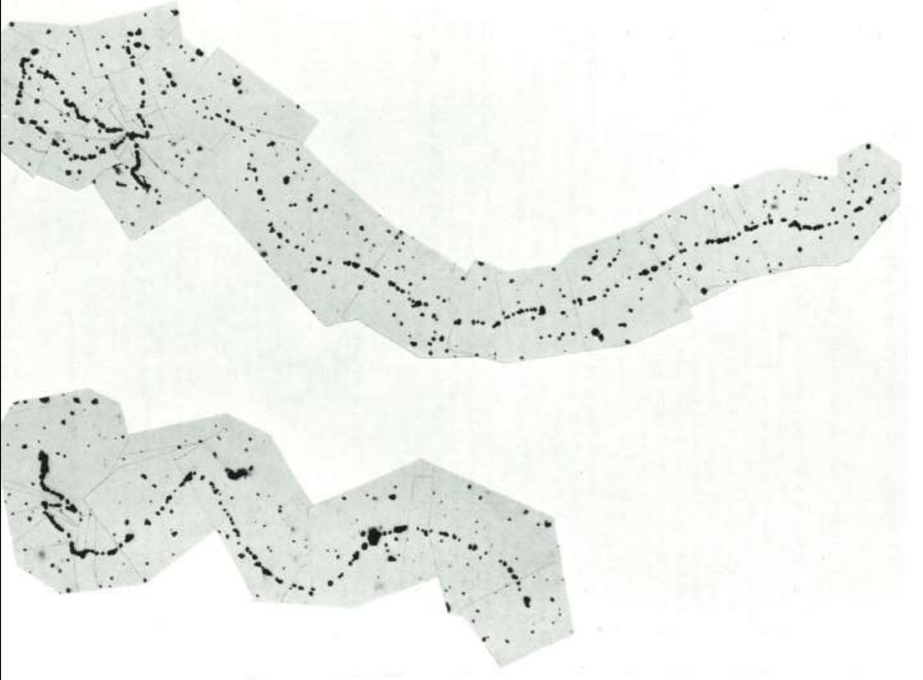
$$F = ma = m\frac{v^2}{R} \qquad F = e(E + vB)$$

$$R = \frac{mv}{eB}$$





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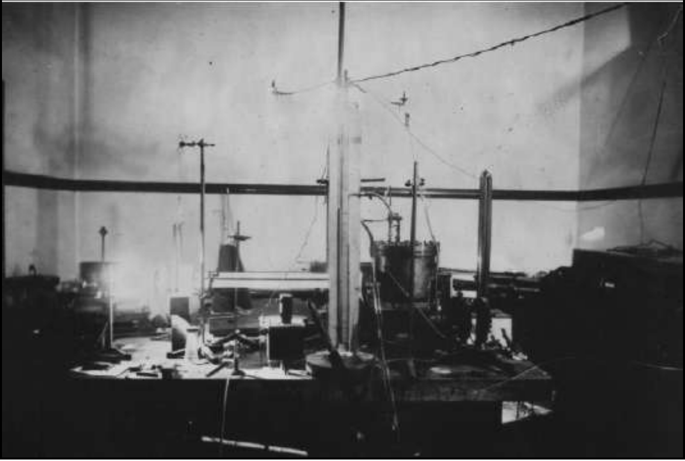
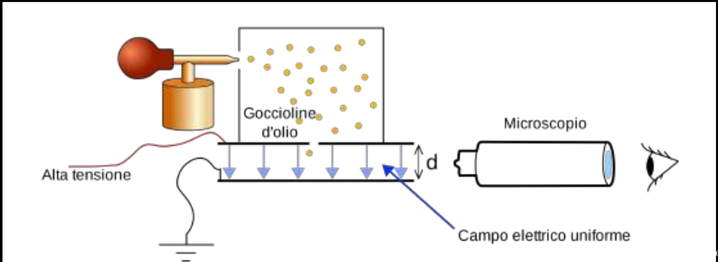


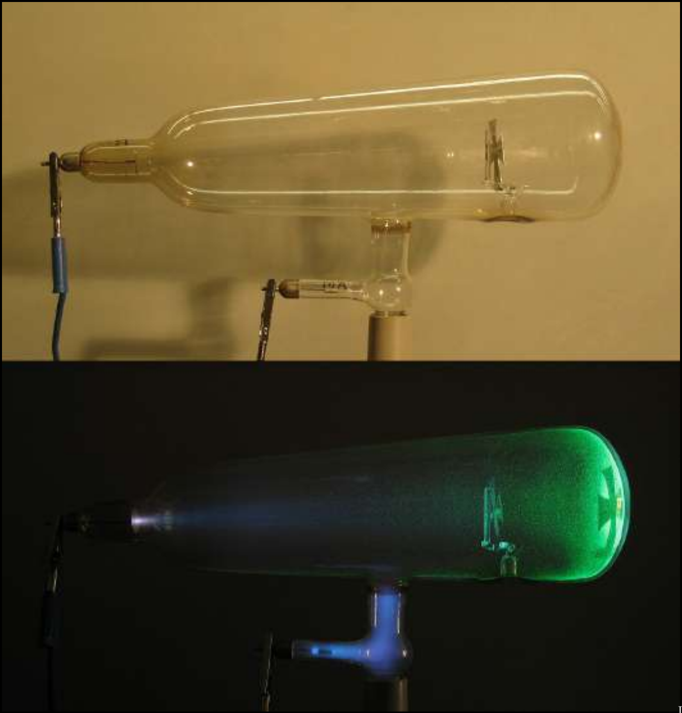


e Credits: Wikipedia

$$F = ma = mg \qquad F = eE$$

$$F_A \propto r$$

$$m = \rho V = \frac{4}{3}\pi r^3 \rho$$



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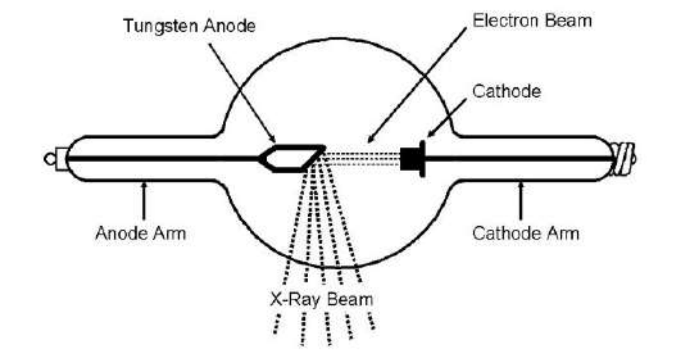
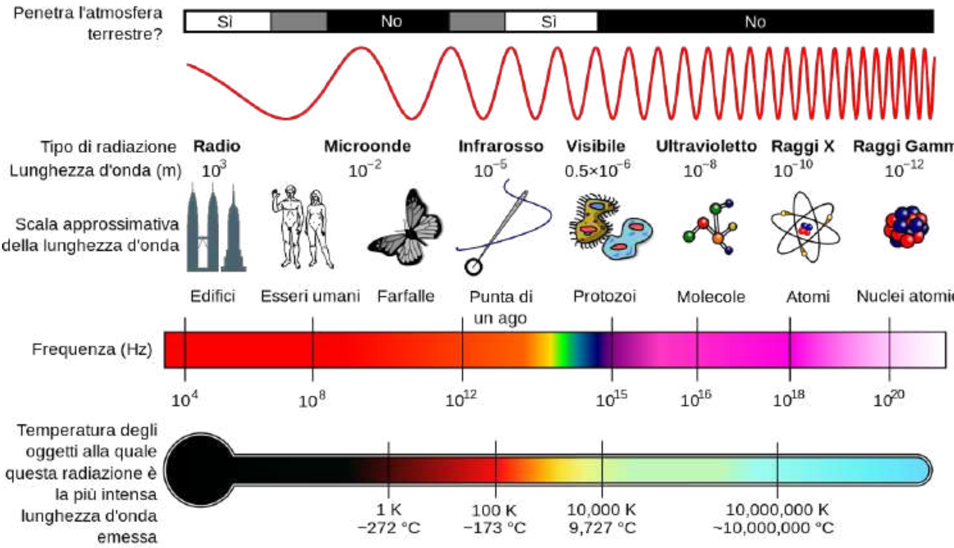

Tungsten Anode
Electron Beam
Cathode
Anode Arm
Cathode Arm
X-Ray Beam

Image Credits: Radiopaedia



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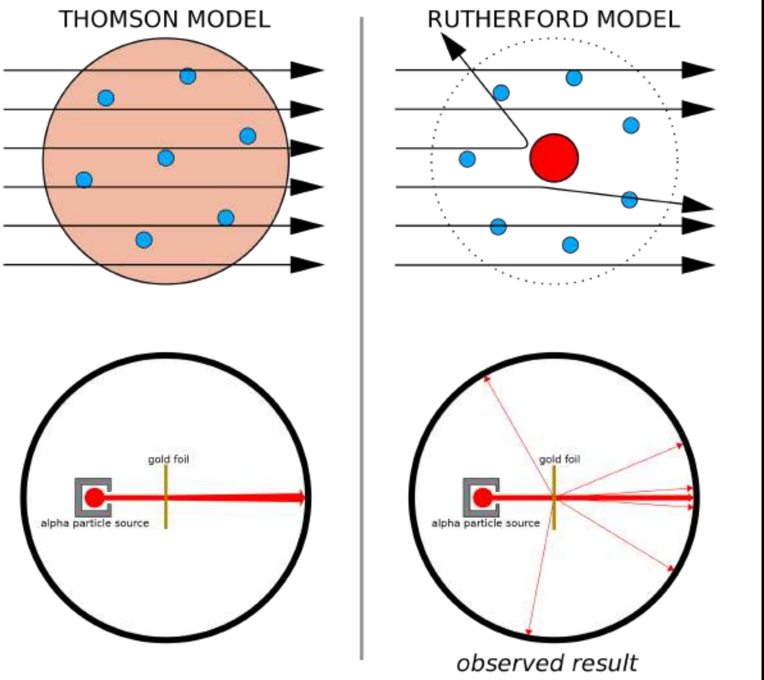
$\alpha \qquad \beta \qquad \gamma$

$$N = N_0 e^{-t/\tau}$$

Image Credits: Wikipedia

Image Credits: Wikipedia



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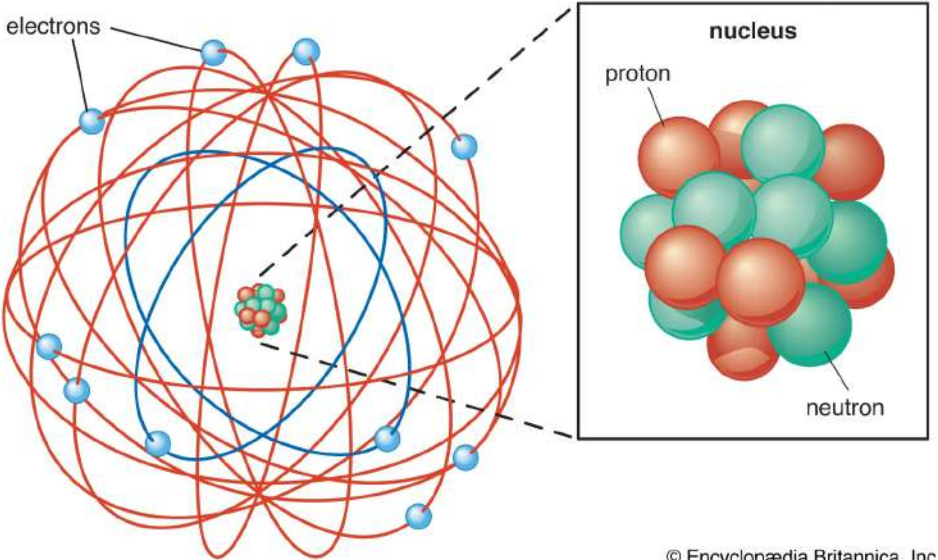
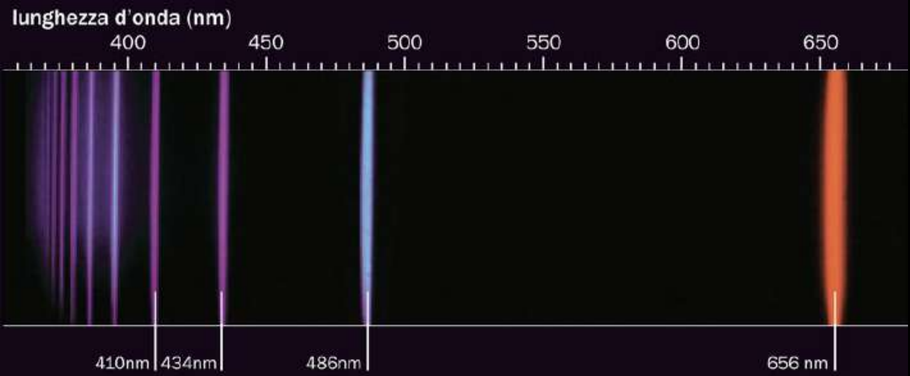
$$E = \frac{1}{2}mv^2 \qquad E = k\frac{qQ}{r}$$

$$r = 2k\frac{qQ}{mv^2}$$


electrons
nucleus
proton
neutron

$$E = h\nu$$



$$\frac{1}{\lambda_{n,m}} = Ry\left(\frac{1}{n^2}-\frac{1}{m^2}\right)$$

$$E = \sqrt{m^2c^4 + p^2c^2}$$

$$m = 0 \Rightarrow E = pc$$

$$v = 0 \Rightarrow E = mc^2$$

$$E = h\nu = pc$$

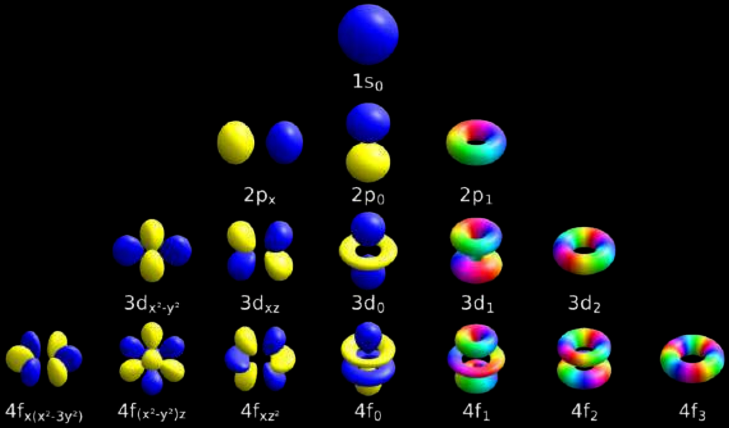
$$p = \frac{h\nu}{c} = \frac{h}{\lambda} \qquad \Rightarrow \lambda = \frac{h}{p}$$

$$\psi = \psi(A)\psi(B)$$

$$\psi_S = \psi_{Caio}(A)\psi_{Tizio}(B) + \psi_{Caio}(B)\psi_{Tizio}(A) \qquad \text{Simmetrico}$$

$$\psi_A = \psi_{Caio}(A)\psi_{Tizio}(B) - \psi_{Caio}(B)\psi_{Tizio}(A) \qquad \text{Antisimmetrico}$$

Principio di esclusione di Pauli *Due fermioni non possono occupare simultaneamente lo stesso stato quantico.*



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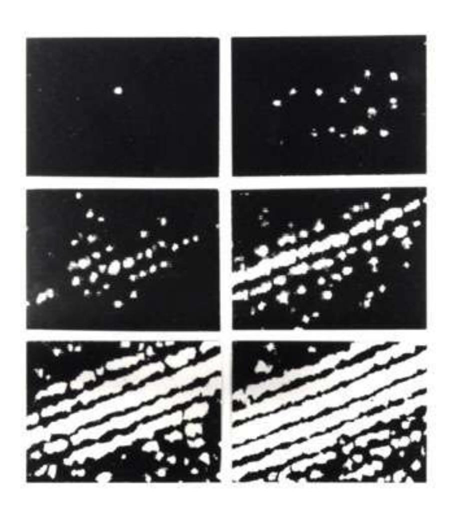

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$$^{14}_{7}\mathrm{N} + \alpha \rightarrow {}^{17}_{8}\mathrm{O} + \mathrm{H}$$

Neutronografia di una caffettiera
https://www.youtube.com/watch?v=VESMU7JfVHU

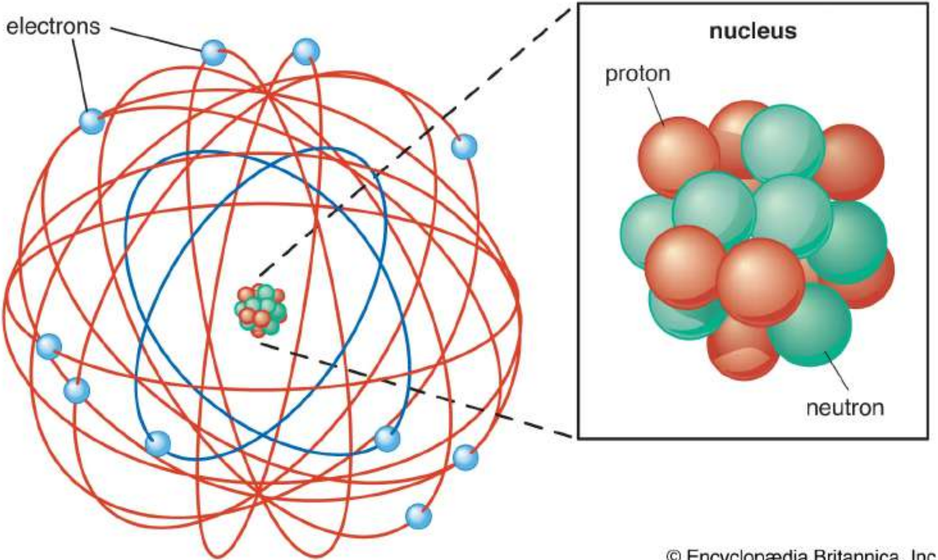
Il Modello Standard a inizio ’900?				
	e^-	n	p	γ
Carica	-1	0	$+1$	0
Spin	$1/2$	$1/2$	$1/2$	1
Massa (MeV)	0.511	939	938	0

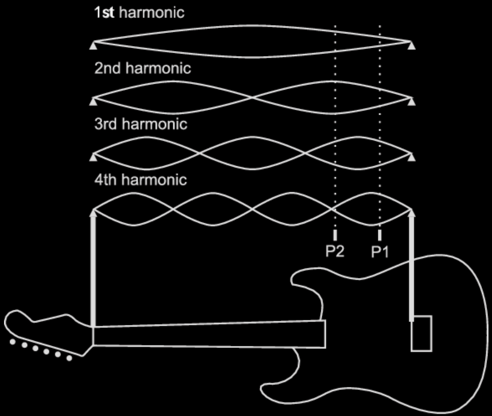
Il Modello Standard a inizio '900?

	Fermioni			Bosoni
	e^-	n	p	γ
Carica	-1	0	$+1$	0
Spin	$1/2$	$1/2$	$1/2$	1
Massa (MeV)	0.511	939	938	0
	Materia			Interazione

$$E = h\nu$$

$$E = \sqrt{m^2c^4 + p^2c^2}$$


electrons
nucleus
proton
neutron



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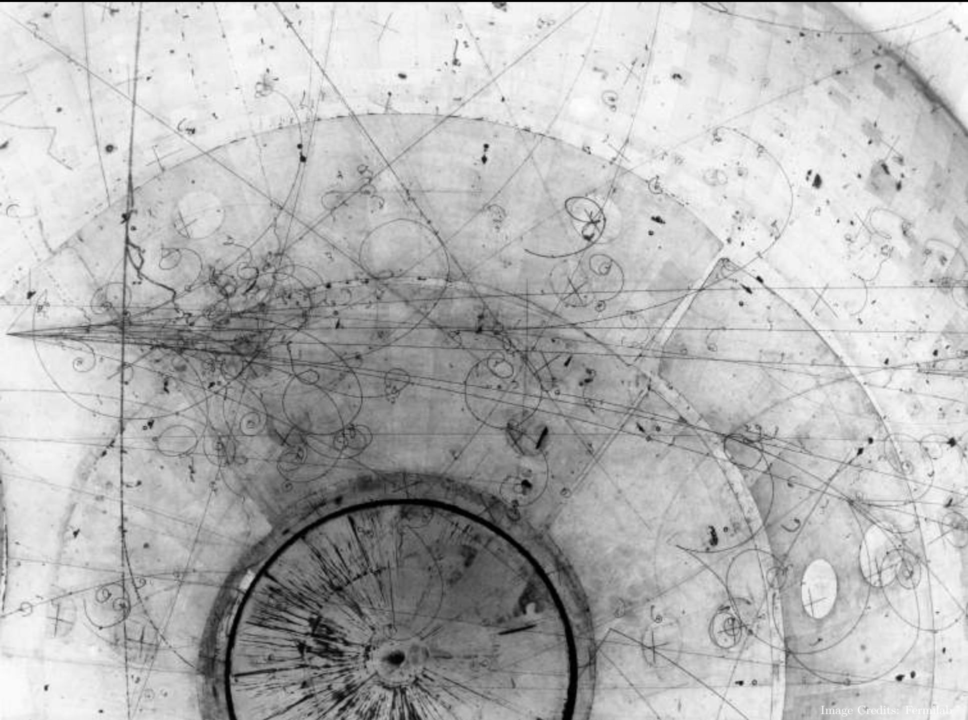
Camera a Nebbia

https://www.youtube.com/watch?v=i15ef618DP0



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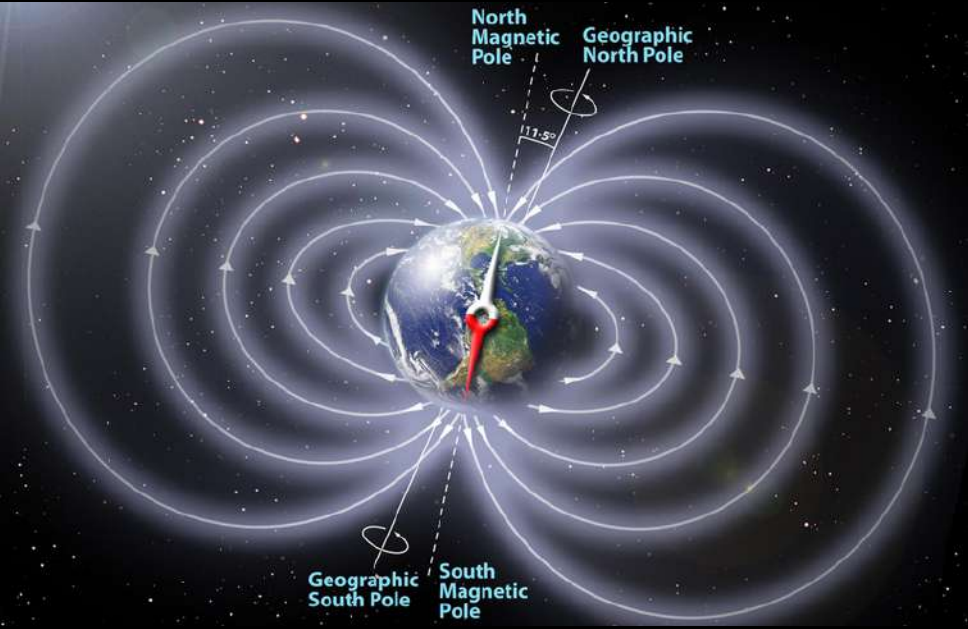

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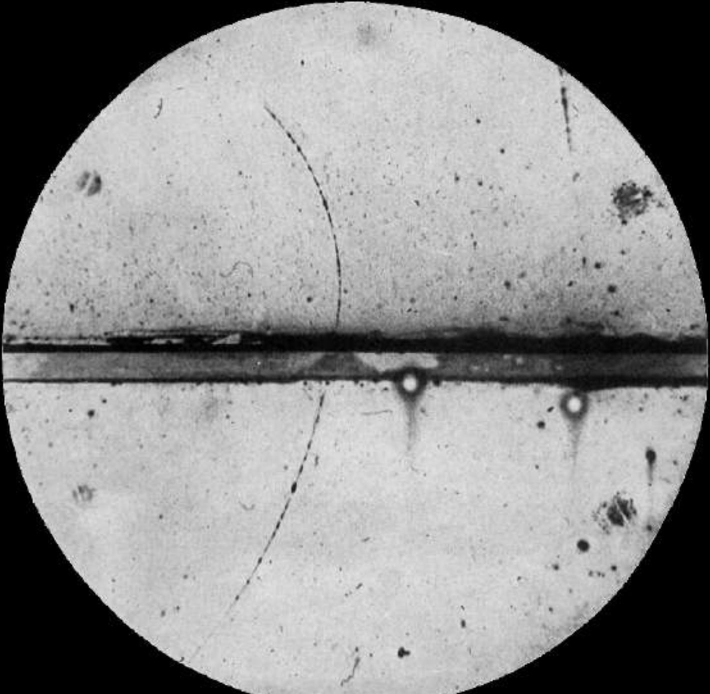
$$i\hbar\gamma^{\mu}\partial_{\mu}\psi(x) - m\psi(x) = 0$$



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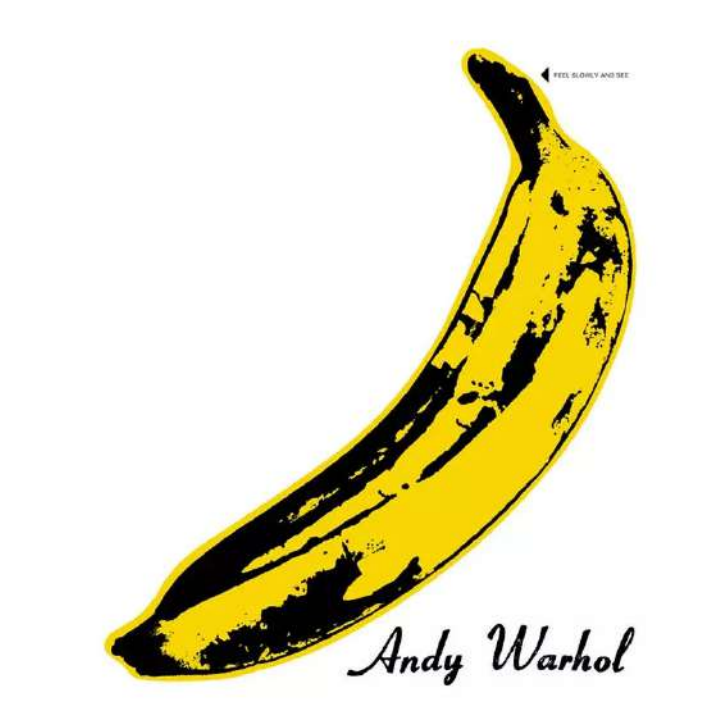
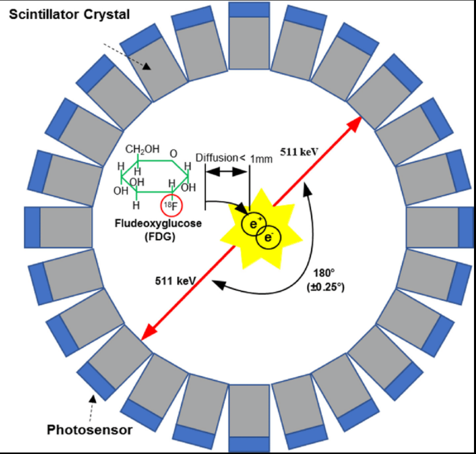


Velvet Underground



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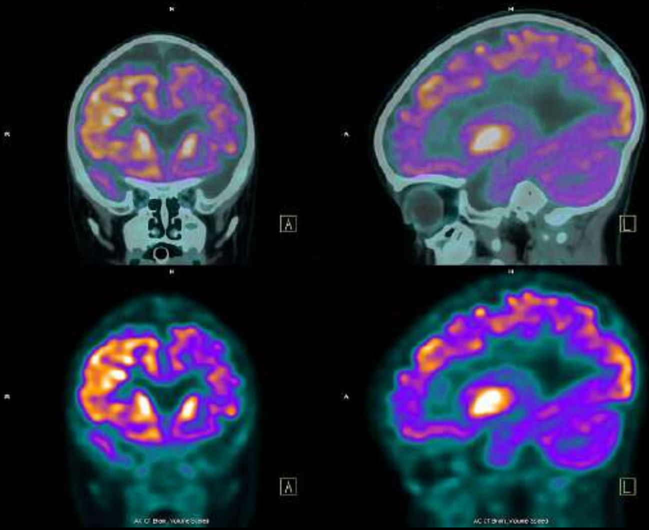


Image Credits: radiologyinfo.org

$$N = N_0 e^{-t/\tau}$$

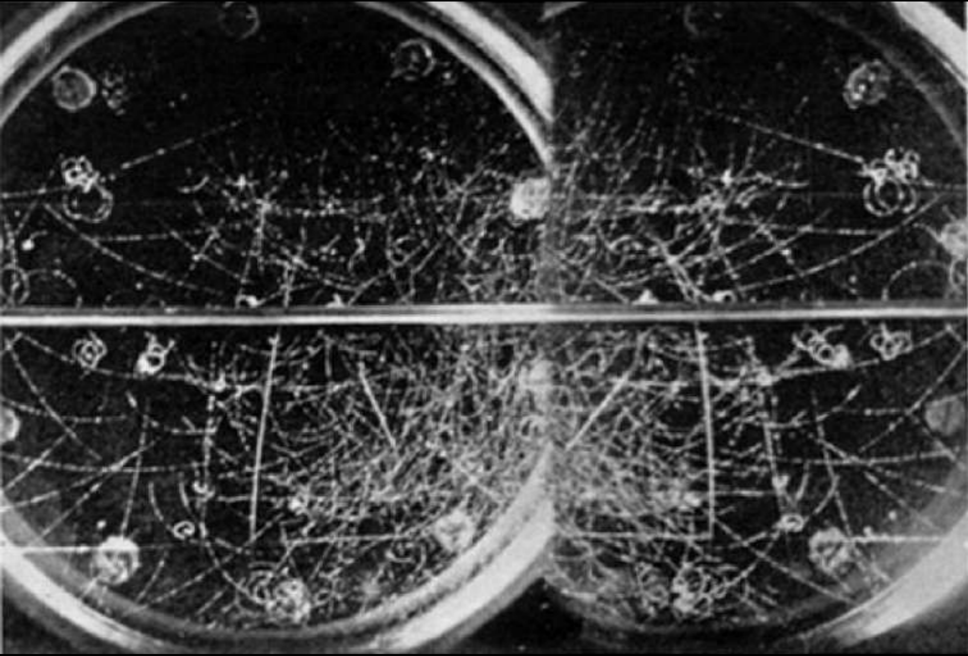
$$\tau = 2.2\mu s$$

$$v = 99.5\% c$$

$$d = \tau \cdot v \simeq 2.2 \cdot 10^{-6}\mathrm{s} \cdot 0.995 \cdot 3 \cdot 10^{8}\mathrm{m/s} = 660\mathrm{m}$$

$$d' = \frac{d}{\sqrt{1 - \frac{v^2}{c^2}}} \simeq 10 \cdot d = 6600\mathrm{m}$$

$$\tau' = \tau\sqrt{1 - \frac{v^2}{c^2}} \simeq 10 \cdot \tau = 22\mu s$$



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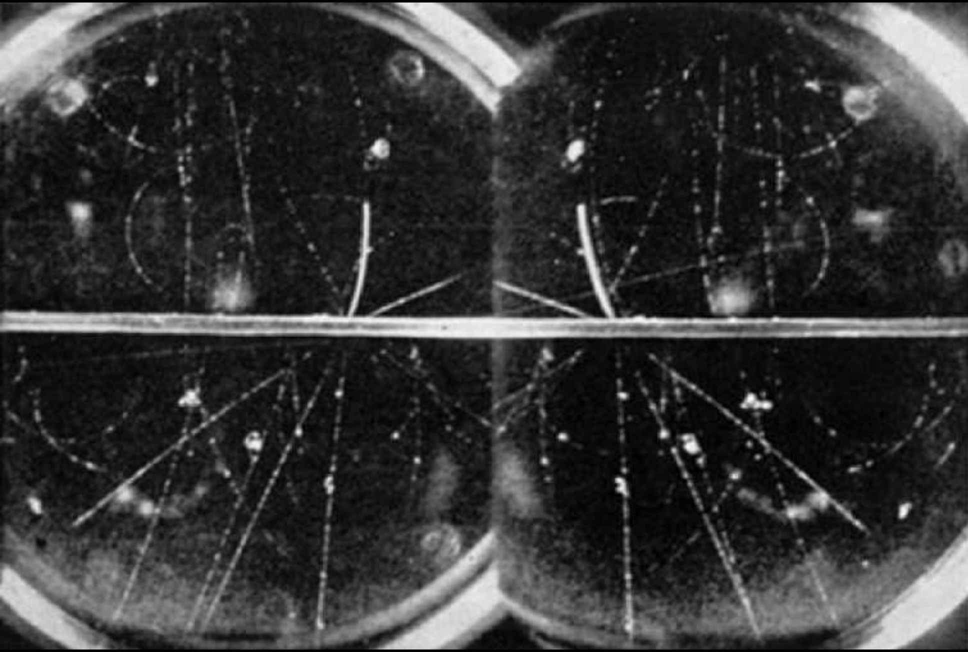

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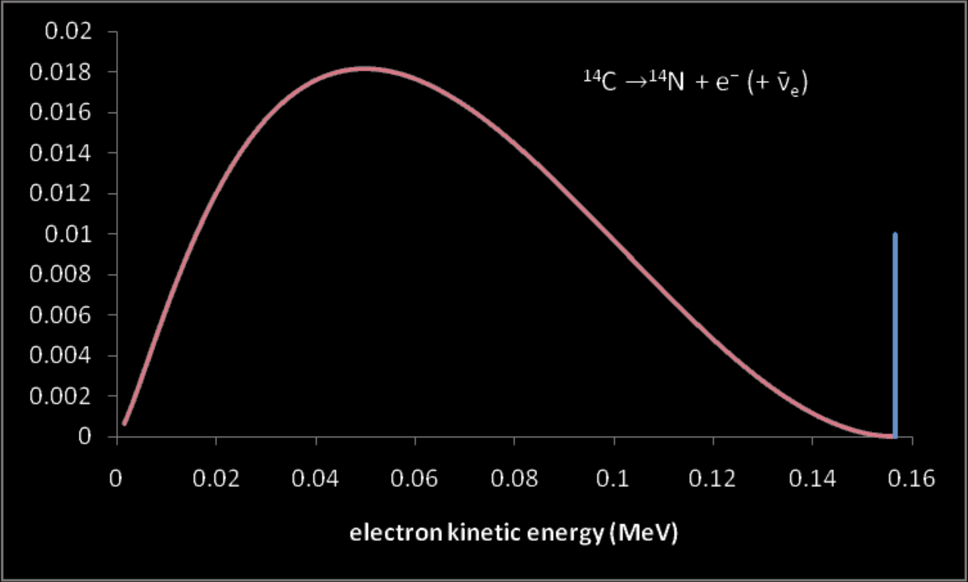
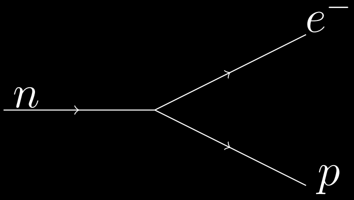
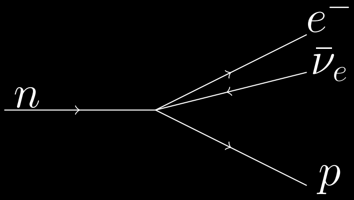


0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
$^{14}C \rightarrow {}^{14}N + e^- \ (+ \bar{\nu}_e)$
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
electron kinetic energy (MeV)

$$ {}^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + \mathrm{e}^{-} (+\bar{\nu}_{\mathrm{e}}) $$

$$ n \rightarrow p + e^{-} (+\bar{\nu}_{e}) $$





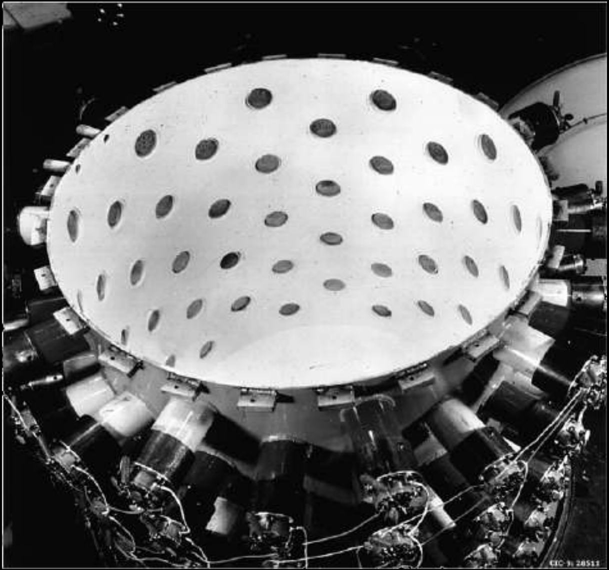


Image Credits: Washington University

Detection of the Free Neutrino*

F. REINES AND C. L. COWAN, JR.
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

(Received July 9, 1953; revised manuscript received September 14, 1953)

AN experiment[1] has been performed to detect the free neutrino. It appears probable that this aim has been accomplished although further confirmatory work is in progress. The cross section for the reaction employed,

$$\nu_- + p \rightarrow n + \beta^+, \tag{1}$$

Image Credits: Physical Review

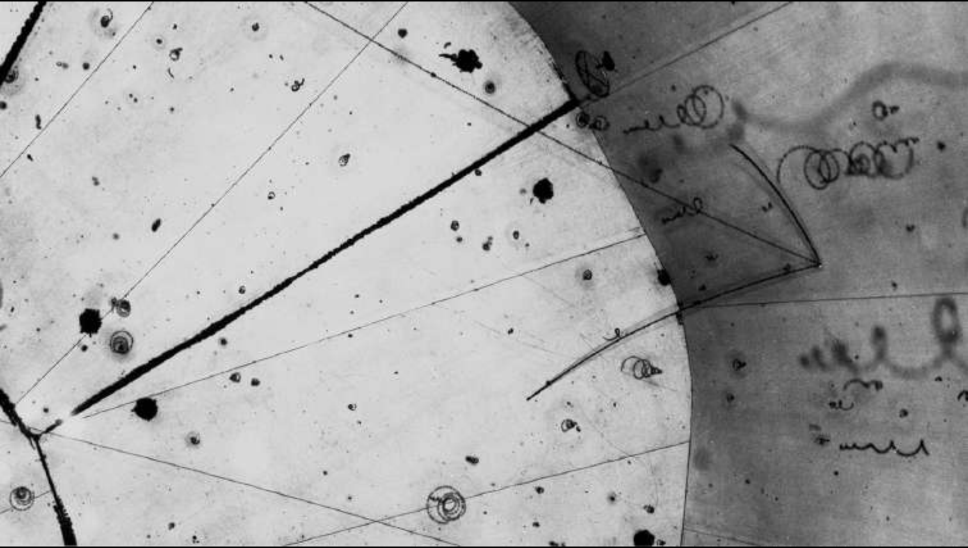
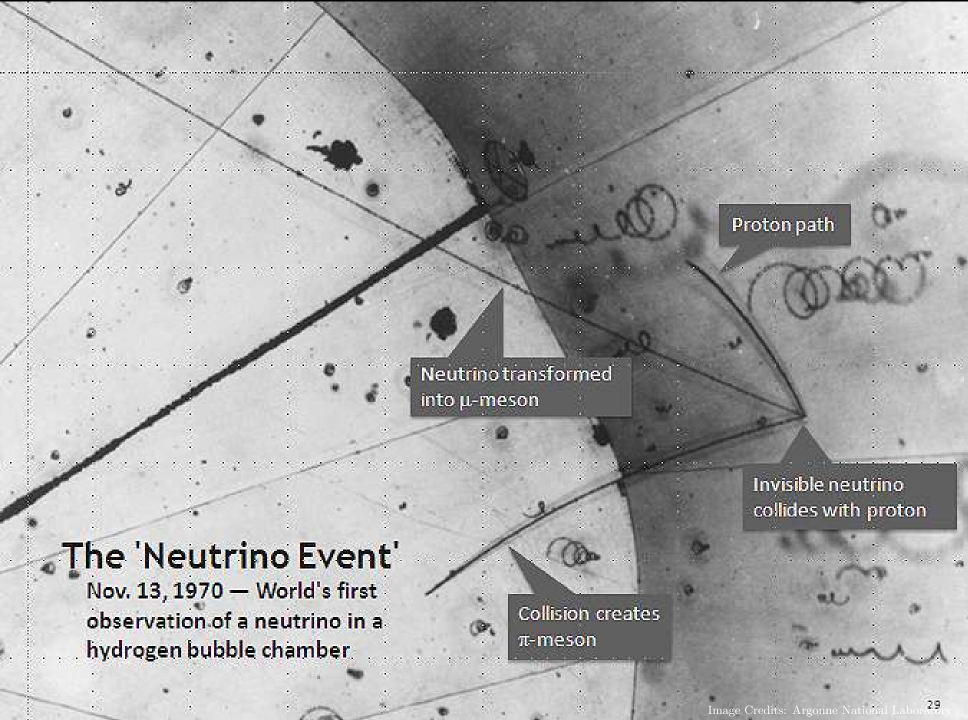
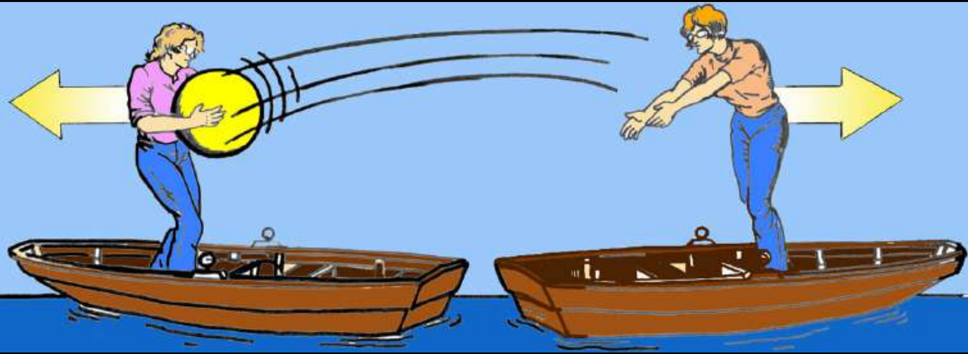


Image Credits: Argonne National Laboratory


The 'Neutrino Event'
Nov. 13, 1970 — World's first observation of a neutrino in a hydrogen bubble chamber
Proton path
Neutrino transformed into μ-meson
Invisible neutrino collides with proton
Collision creates π-meson
Image Credits: Argonne National Laboratory

$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



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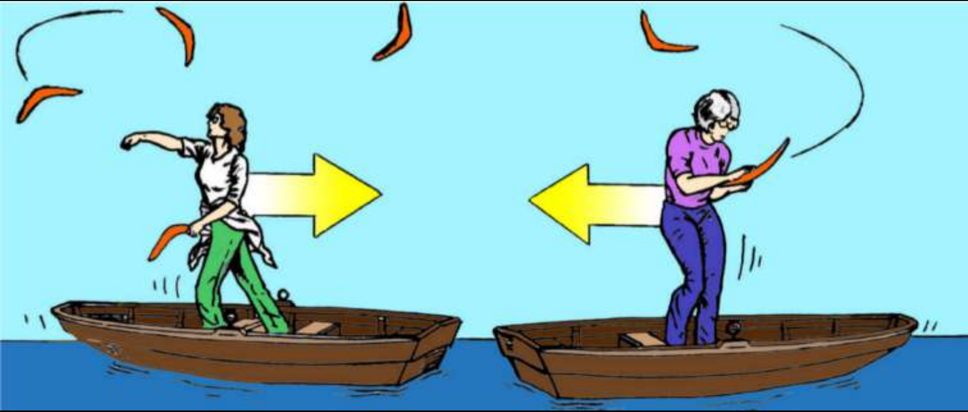
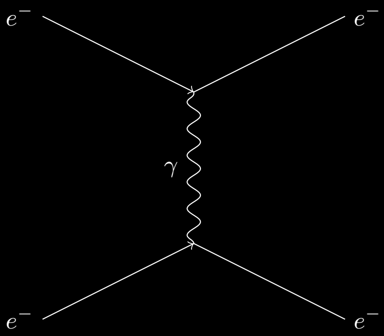
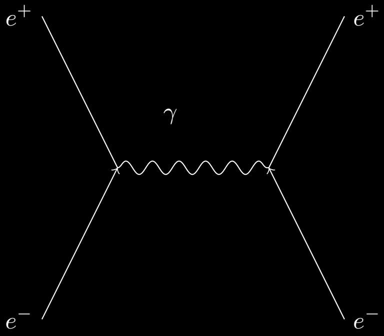


Image Credits: Fermilab


e^-
e^-
γ
e^-
e^-


e^+
e^+
γ
e^-
e^-

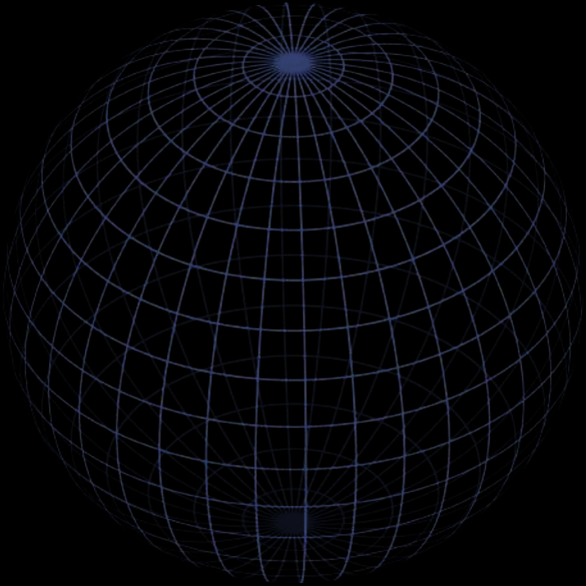


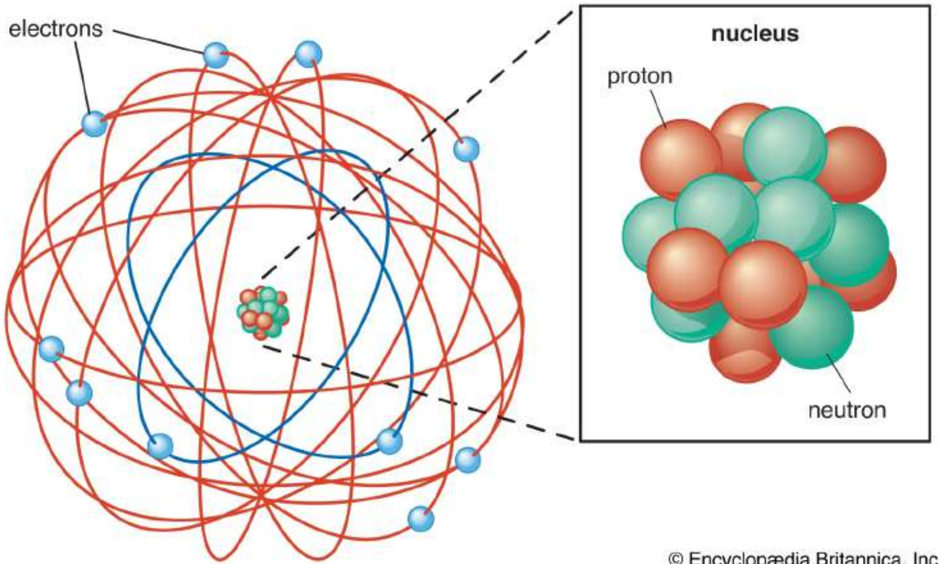
Image Credits: Wikipedia

$$S = 4\pi r^2$$

$$n = \frac{N}{4\pi r^2}$$

$$F \propto \frac{1}{r^2}$$

$$F = \frac{GmM}{r^2} \qquad F = k\frac{qQ}{r^2}$$

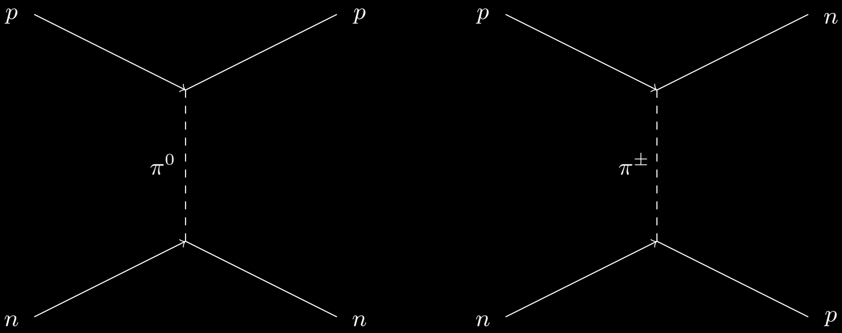

electrons
nucleus
proton
neutron

Principio di indeterminazione *Di uno stato quantistico non possiamo misurare con precisione arbitraria tutte le grandezze simultaneamente.*

Se conosciamo con alta precisione l'impulso allora non conosciamo la posizione e come abbiamo detto prima la particella è delocalizzata. Viceversa se si può conoscere la posizione non se ne conosce l'impulso, quindi la velocità.

$$\Delta x \Delta p > \hbar$$

$$\Delta E \Delta t > \hbar$$



$$F \propto \frac{e^{-\lambda r}}{r^2}$$

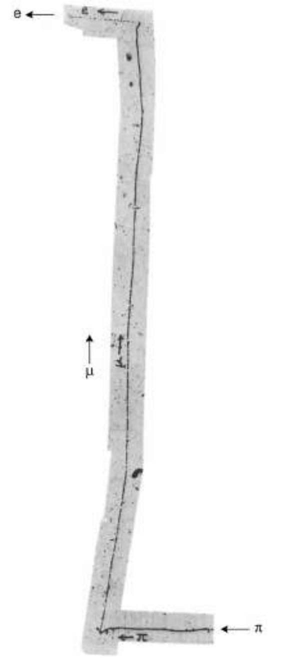


Image Credits: C. Powell

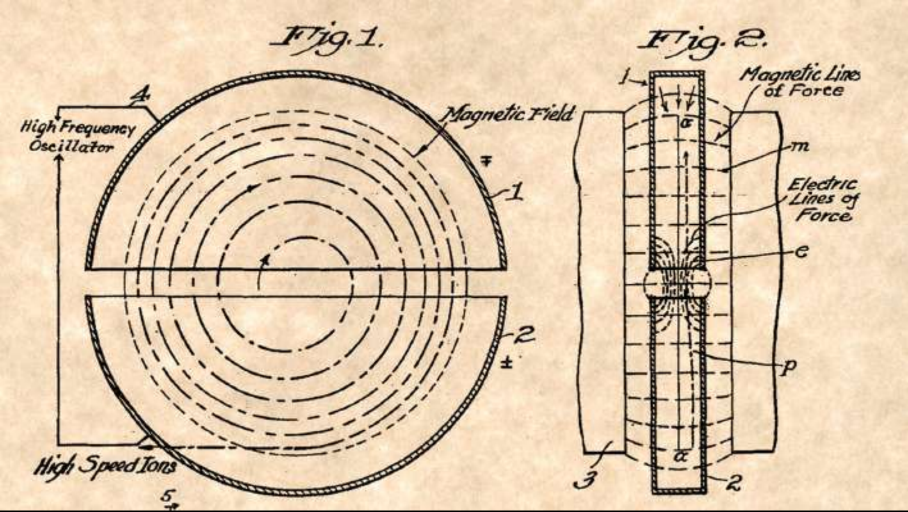


Image Credits: E. Lawrence

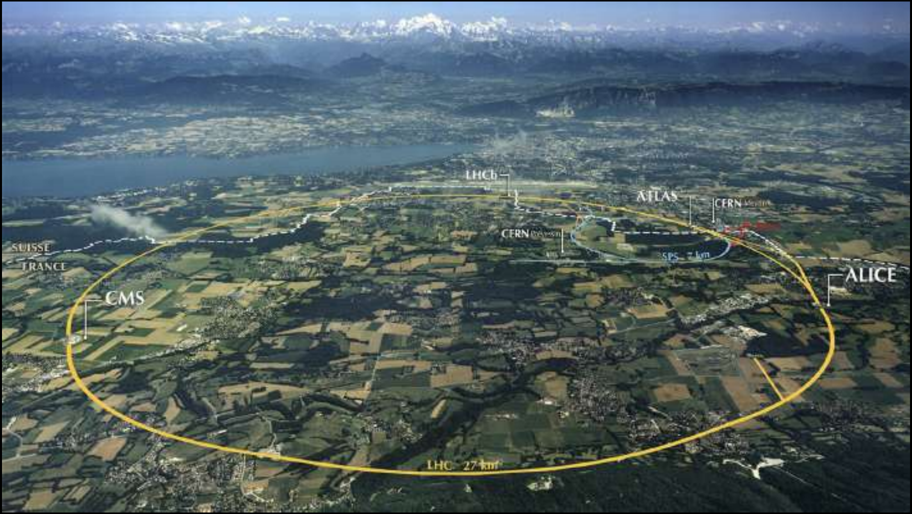
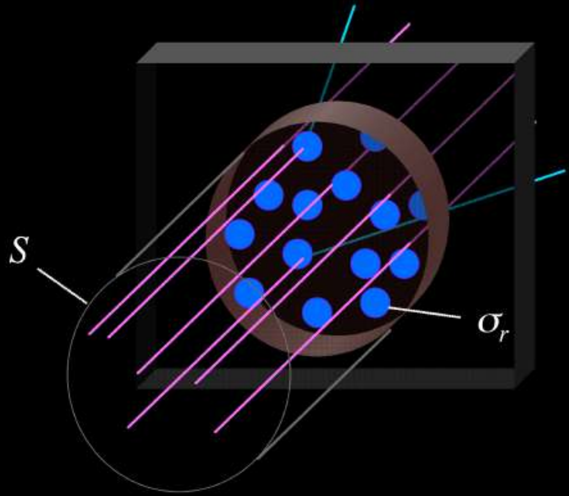


Image Credits: CERN

$$e^-, \nu, \mu^-$$
$$n, p,$$
$$\pi^+, \pi^0,$$
$$\Delta^+, \Delta^+, \Delta^0,$$
$$\Sigma^0, \Sigma^+, \Lambda^0,$$
$$K^+, K^0$$
$$\Xi^+, \Xi^0, \ldots$$


S
σr

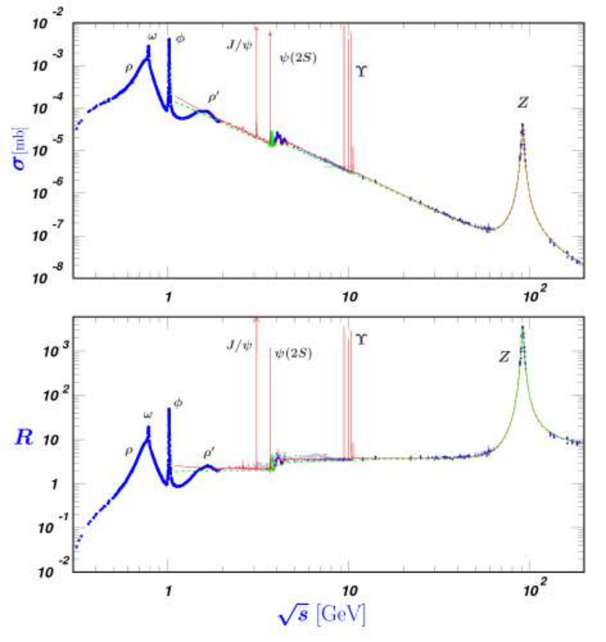


Image Credits: CERN

$$p + p \to n + p + \pi^+$$

$$p + p \to n + \Delta^{++} \to n + p + \pi^+$$

$$\begin{aligned} E &= E_1 + E_2 \\ p &= p_1 + p_2 \\ E &= \sqrt{m^2c^4 + p^2c^2} \\ m &= \sqrt{E^2 - p^2c^2}/c^2 \end{aligned}$$

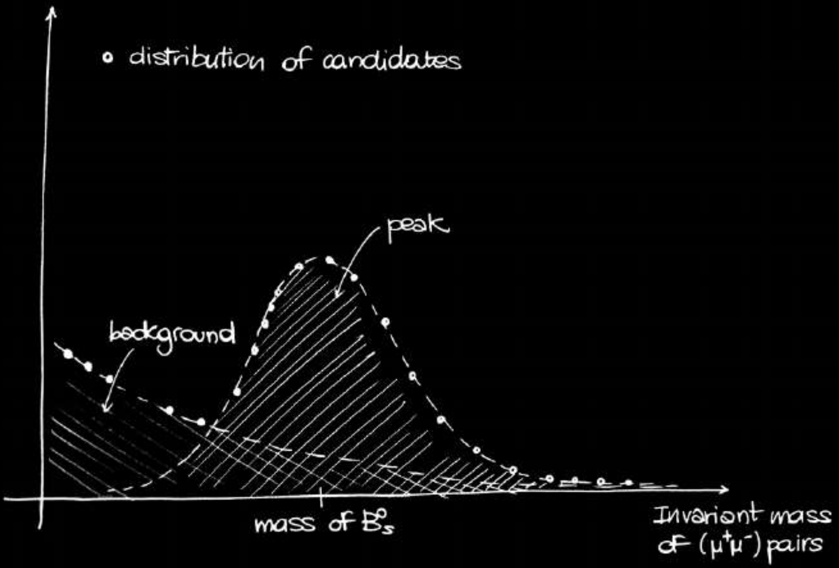
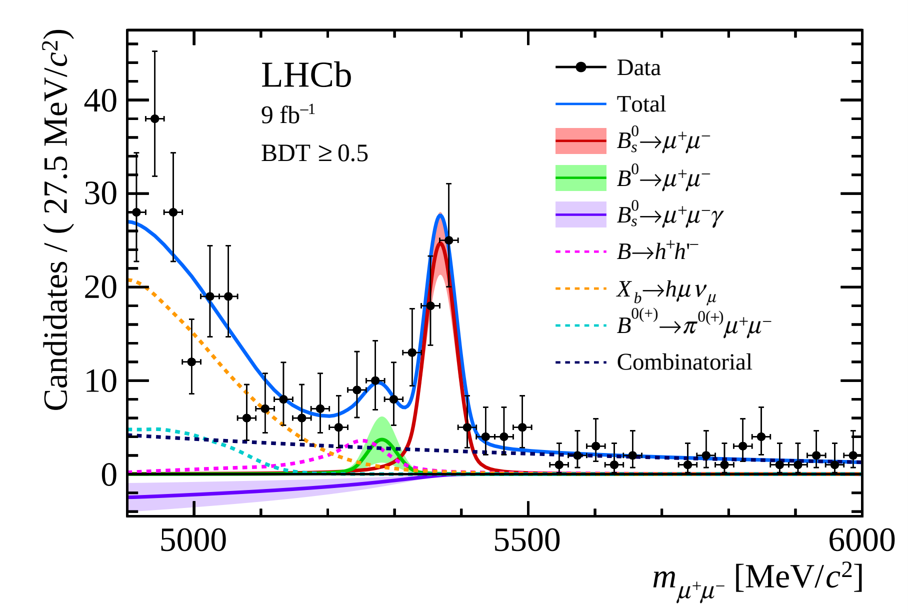


Image Credits: S. Oggero



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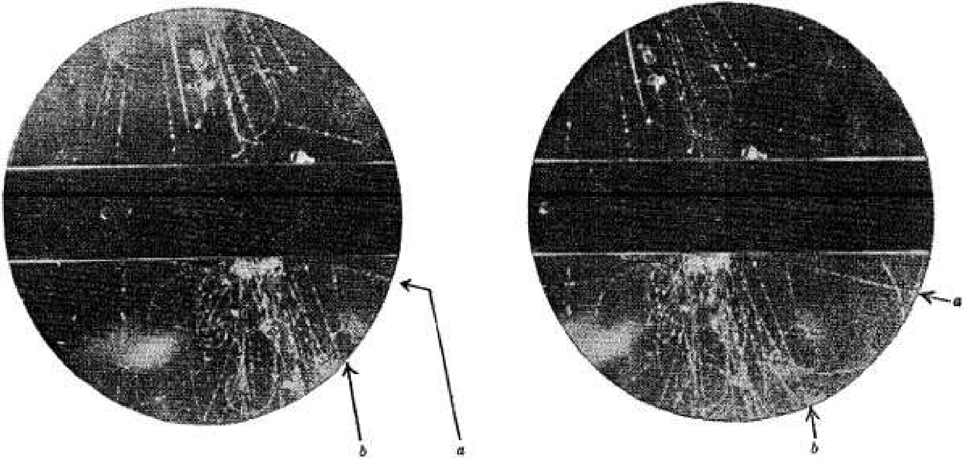
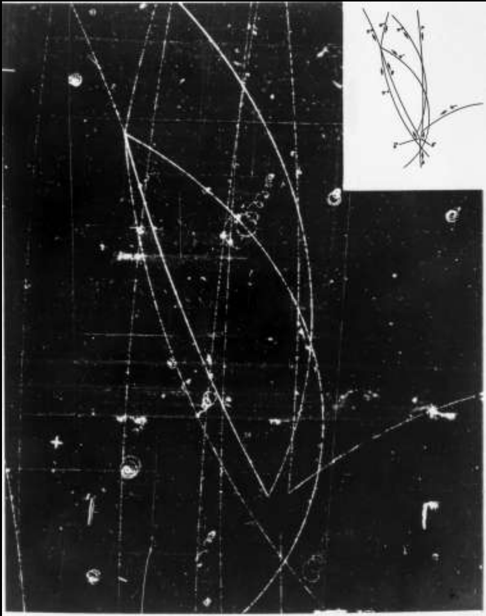


Image Credits: D. Rochester, C. C. Butler, Nature 160 (1947) 855-857



Production and decay of neutral lambda and anti–lambda hyperons

Image Credits: Lawrence Berkeley National Laboratory

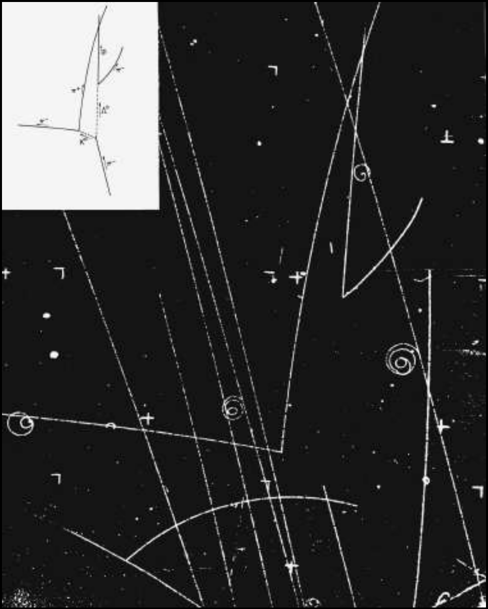
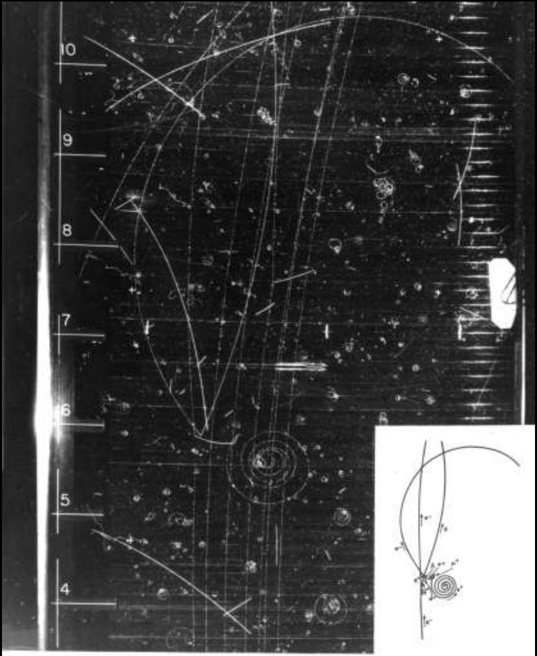


Image Credits: Lawrence Berkeley National Laboratory



Production and decay of a xi zero

Image Credits: Lawrence Berkeley National Laboratory

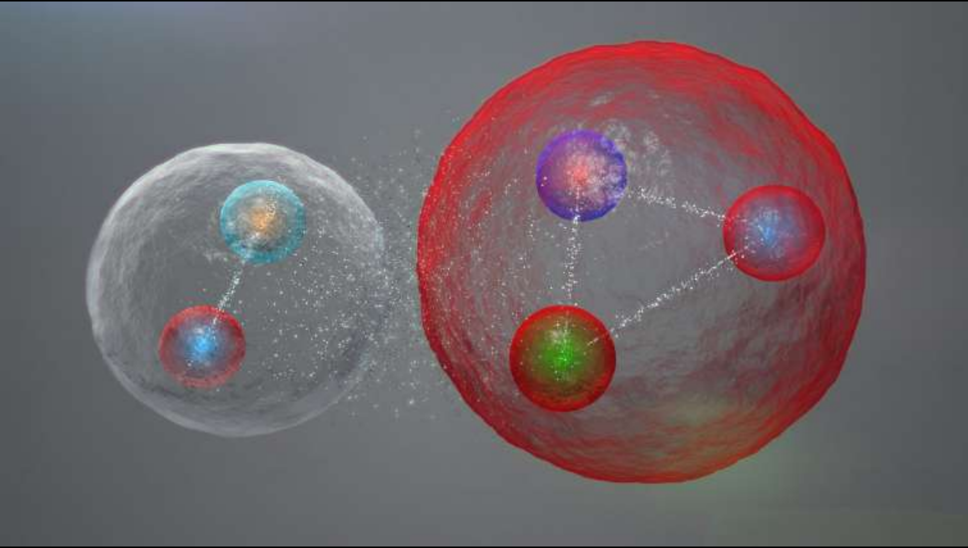
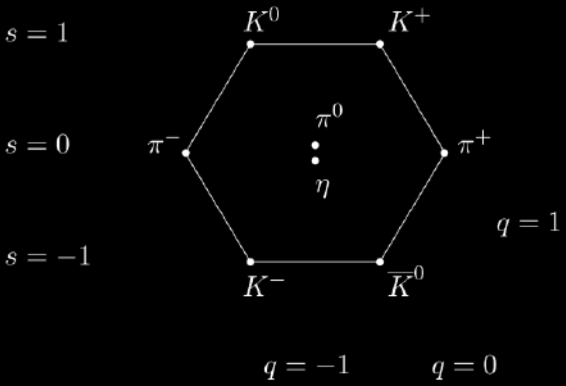
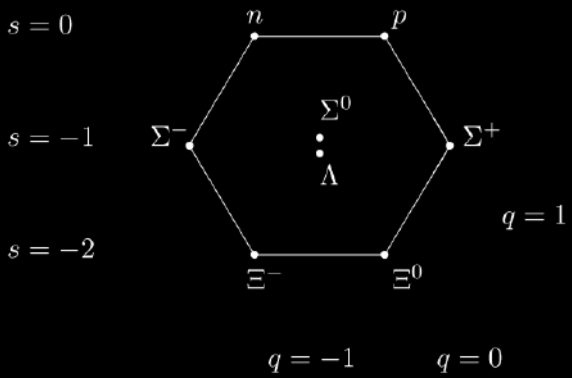
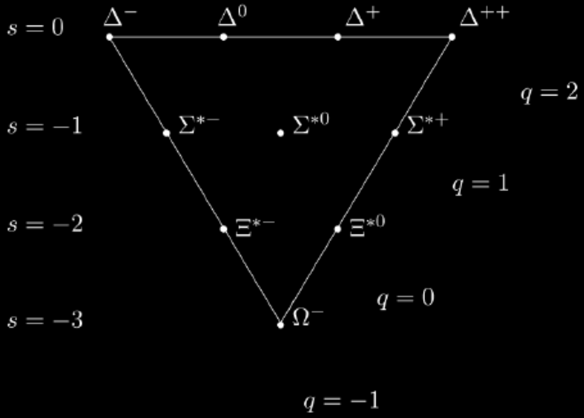


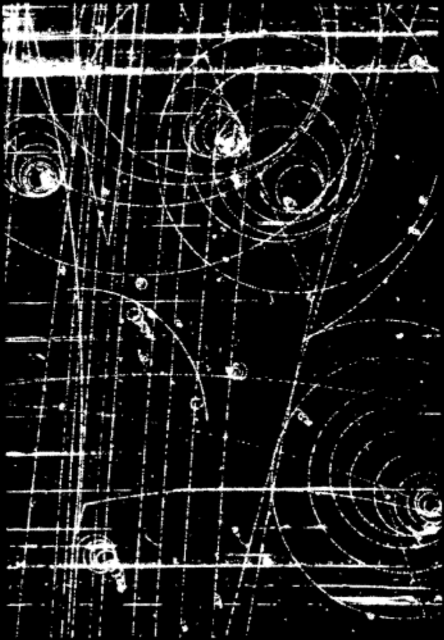
Image Credits: CERN

	Fermioni		Bosoni
	Spin 1/2 …		Spin 0, 1 …
	Leptoni	Adroni	
		Barioni	Mesoni
	e, μ, ν	p, n,	π, π^0
Strani		Λ, Σ, …	K, K^0


$s = 1$
$s = 0$
$s = -1$
K^0
K^+
π^-
π^0
η
π^+
K^-
$\overline{K}^0$
$q = 1$
$q = -1$
$q = 0$


$s = 0$
$s = -1$
$s = -2$
n
p
Σ^-
Σ^0
Λ
Σ^+
Ξ^-
Ξ^0
$q = 1$
$q = -1$
$q = 0$


$s = 0$
Δ^-
Δ^0
Δ^+
Δ^{++}
$q = 2$
$s = -1$
Σ^{*-}
Σ^{*0}
Σ^{*+}
$q = 1$
$s = -2$
Ξ^{*-}
Ξ^{*0}
$q = 0$
$s = -3$
Ω^-
$q = -1$



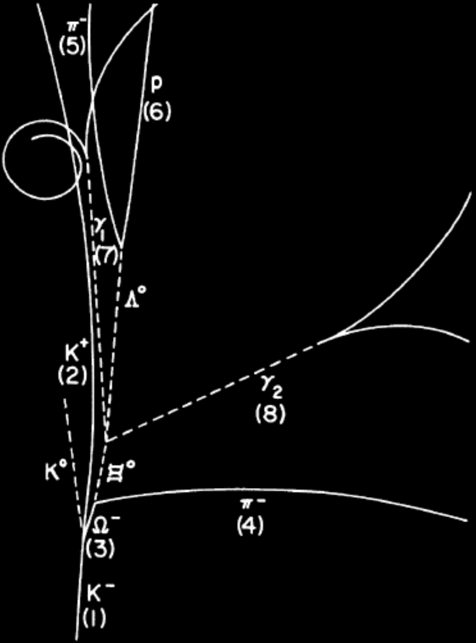


Image Credits: V. E. Barnes et al. Phys. Rev. Lett. 12, 204

Image Credits: A. Orru

$$\lambda = \frac{h}{p}$$

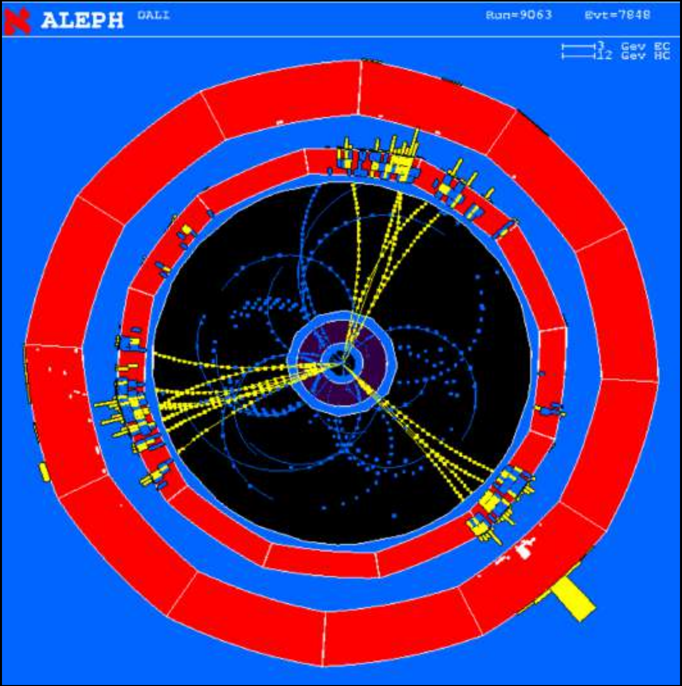


Image Credits: CERN

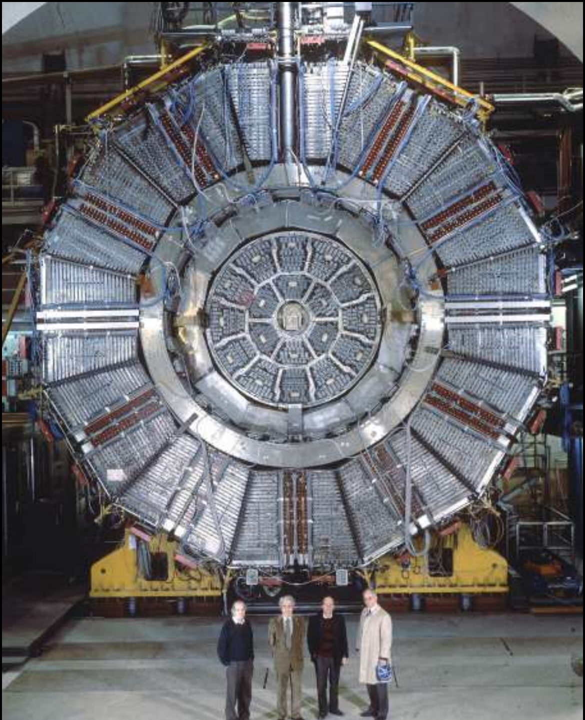
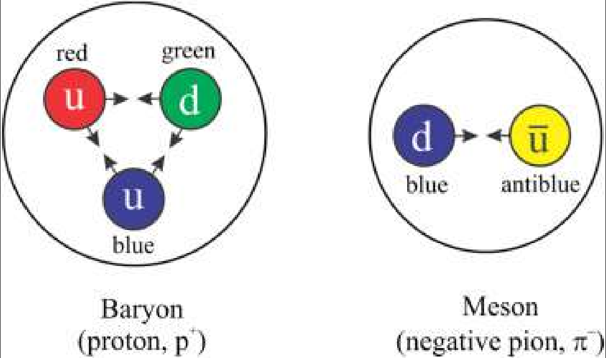


Image Credits: CERN

Quark	Carica	Spin
u	+2/3	1/2
d	-1/3	1/2
s	-1/3	1/2
$\bar{u}$	-2/3	1/2
$\bar{d}$	+1/3	1/2
$\bar{s}$	+1/3	1/2

Particella	Carica	Spin	Quark
p	$+1$	$1/2$	uud
$\bar{p}$	-1	$1/2$	$\bar{u}\bar{u}\bar{d}$
n	0	$1/2$	udd
n	0	$1/2$	$\bar{u}\bar{d}\bar{d}$
π^+	$+1$	0	$u\bar{d}$
π^-	$+1$	0	$u\bar{d}$
π^0	0	0	$u\bar{u} + d\bar{d}$
ρ^+	$+1$	$+1$	$u\bar{d}$
Δ^{++}	$+2$	$3/2$	uuu
Δ^+	$+1$	$3/2$	uud
Δ^0	0	$3/2$	udd

Particella	Carica	Spin	Quark
Λ^0	0	1/2	uds
Σ^0	0	1/2	uds
Σ^+	1	1/2	uus
Σ^-	-1	1/2	dds
K^+	+1	0	$u\bar{s}$
K^0	0	0	$d\bar{s}$
$\bar{K}^0$	0	0	$s\bar{d}$
Ξ^-	-1	1/2	ssd
Ξ^0	0	1/2	uss
Ω^-	-1	1/2	sss


red
green
u
d
u
blue
Baryon
(proton, p⁺)
d
ū
blue
antiblue
Meson
(negative pion, π⁻)

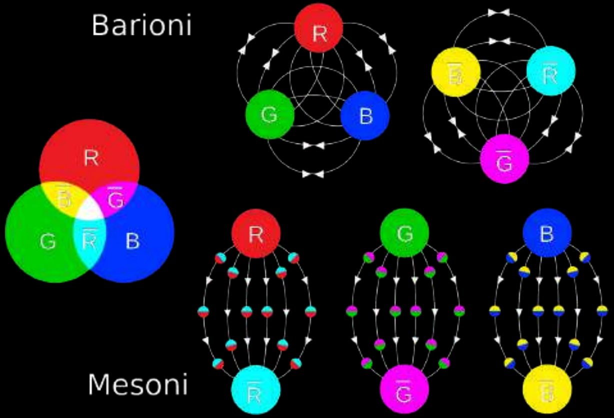
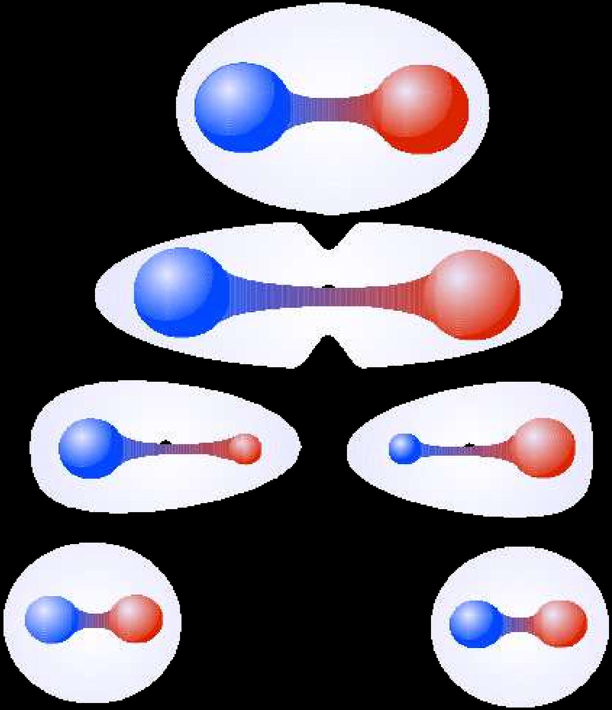
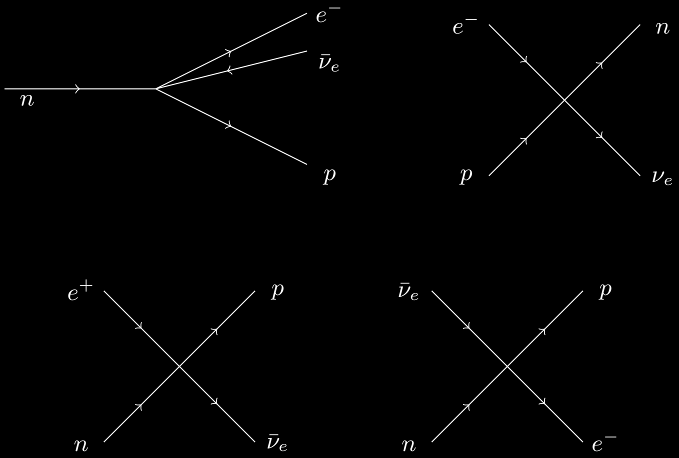


Image Credits: Wikipedia



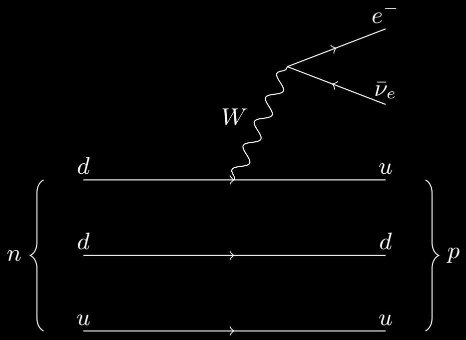

n
e^-
$\bar{\nu}_e$
p
e^-
n
p
ν_e
e^+
p
n
$\bar{\nu}_e$
$\bar{\nu}_e$
p
n
e^-

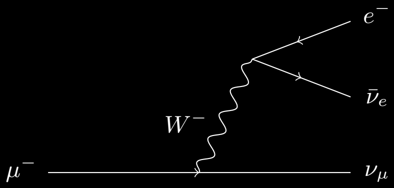
$$F = \mathbf{G}\frac{mM}{r^2}$$

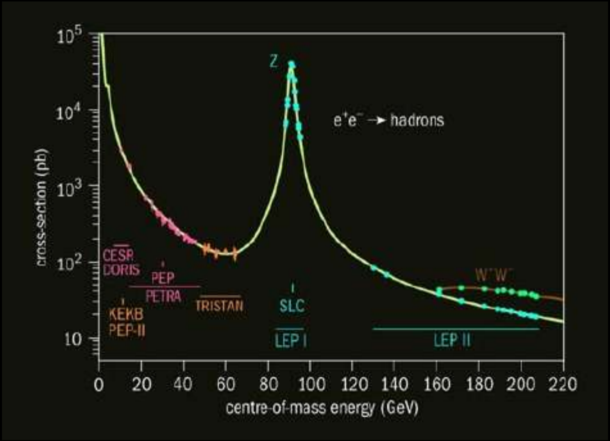
$$F = \mathbf{k}\frac{qQ}{r^2}$$

$$F \propto \mathbf{g}\frac{e^{-\lambda r}}{r^2}$$

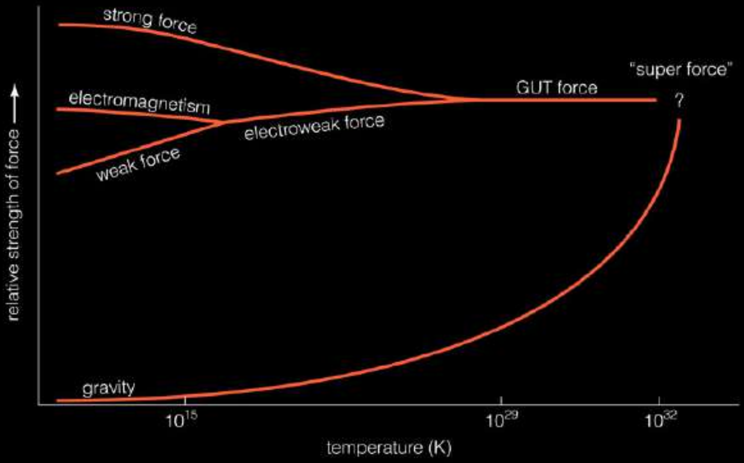
$$F \propto \mathbf{G_F} \qquad ? \qquad F \propto \mathbf{k}e^{-\omega r}$$


e^-
$\bar{\nu}_e$
W
d
u
n
d
d
p
u
u

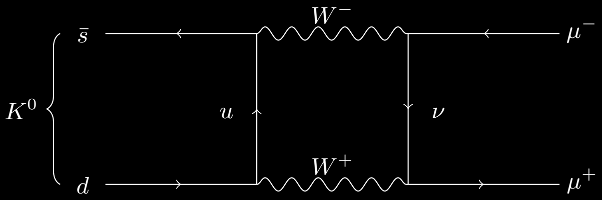

e^-
$\bar{\nu}_e$
W^-
μ^-
ν_μ



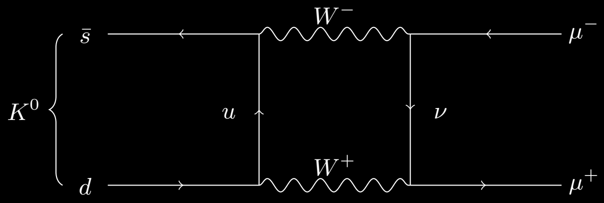
10^5
10^4
10^3
10^2
10
cross-section (pb)
Z
$e^+e^- \rightarrow$ hadrons
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II
W^+W^-
0 20 40 60 80 100 120 140 160 180 200 220
centre-of-mass energy (GeV)


strong force
electromagnetism
weak force
electroweak force
GUT force
"super force"
?
gravity
relative strength of force
10^{15}
10^{29}
10^{32}
temperature (K)

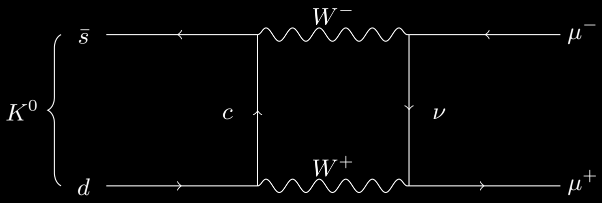
$$K^0 \to \mu^+\mu^-$$

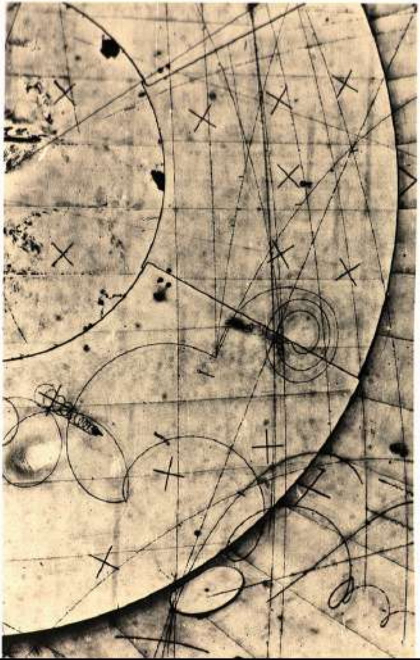


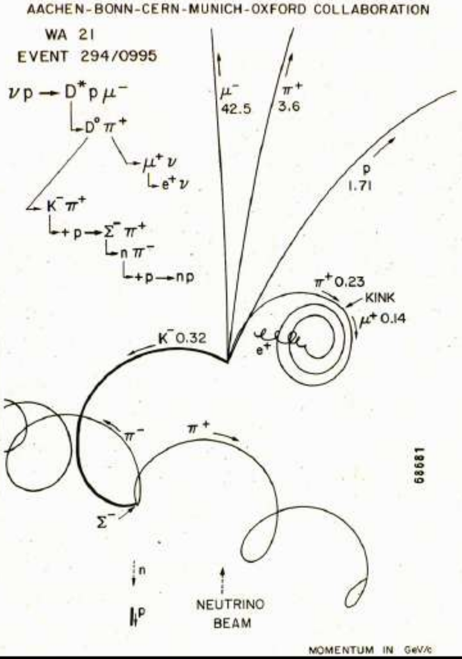
$$K^0 \to \mu^+\mu^-$$



$$-$$







AACHEN-BONN-CERN-MUNICH-OXFORD COLLABORATION
WA 21
EVENT 294/0995
$\nu p \rightarrow D^{*} p \mu^{-}$
$\rightarrow D^{0} \pi^{+}$
$\rightarrow \mu^{+} \nu$
$\rightarrow e^{+} \nu$
$\rightarrow K^{-} \pi^{+}$
$\rightarrow + p \rightarrow \Sigma^{-} \pi^{+}$
$\rightarrow n \pi^{-}$
$\rightarrow + p \rightarrow np$
μ^{-} 42.5
π^{+} 3.6
p 1.71
π^{+} 0.23
KINK
μ^{+} 0.14
e^{+}
K^{-} 0.32
π^{-}
π^{+}
Σ^{-}
n
p
NEUTRINO BEAM
68681
MOMENTUM IN GeV/c

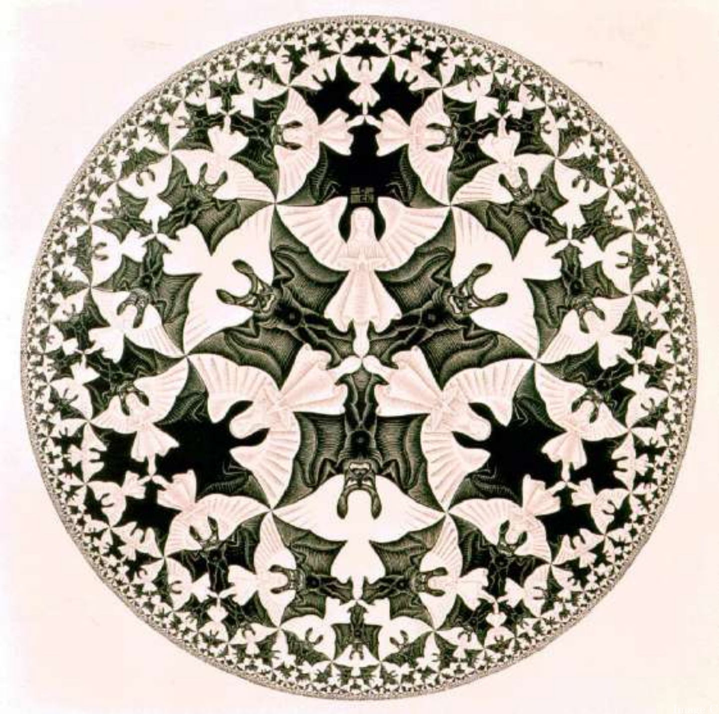


Image Credits: M. C. Escher

Image Credits: M. C. Escher

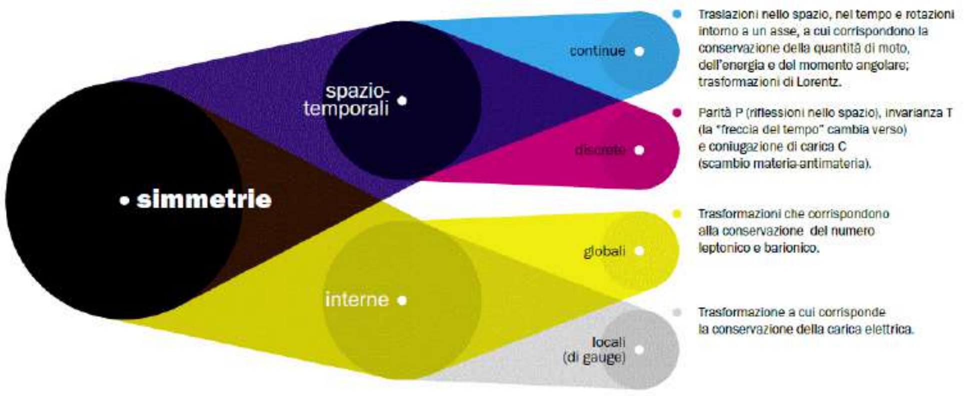
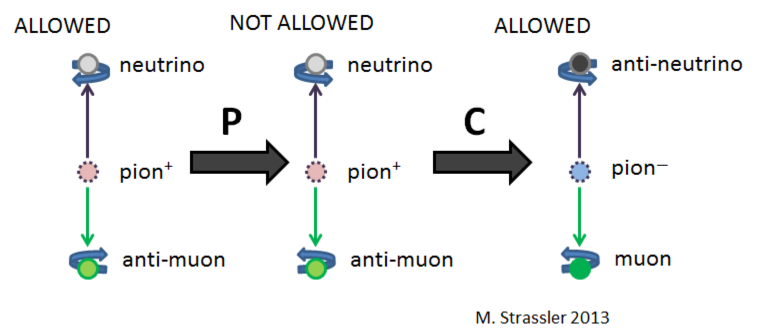


Image Credits: Simmetrie

Simmetria	Proprietà	Quantità conservata
Traslazione nello spazio	Omogeneità dello spazio	Quantità di moto
Rotazione nello spazio	Isotropia dello spazio	Momento angolare
Traslazione nel tempo	Omogeneità del tempo	Energia

CPT
(Inversione di)
Carica Parità Tempo


ALLOWED
NOT ALLOWED
ALLOWED
neutrino
neutrino
anti-neutrino
P
C
pion+
pion+
pion–
anti-muon
anti-muon
muon
M. Strassler 2013

$$^{60}_{27}\mathrm{Co} \rightarrow^{60}_{28} \mathrm{Ni} \rightarrow \mathrm{e}^{-}\nu_{\mathrm{e}}$$

Image Credits: Columbia University

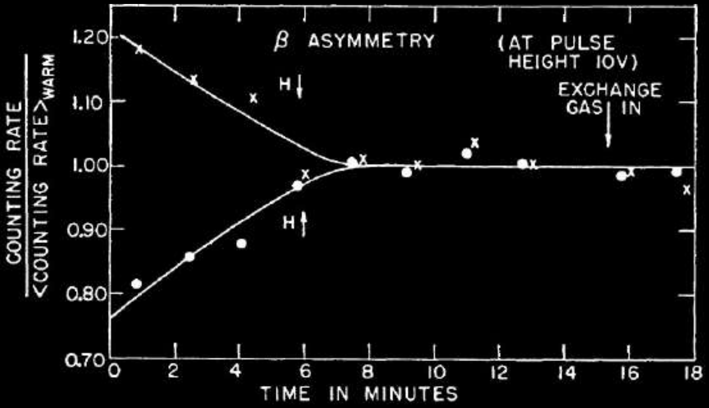
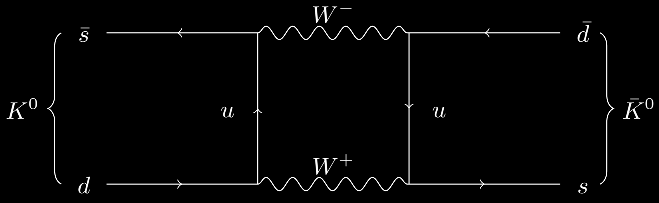


Image Credits: C. S. Wu, et al. - Phys. Rev. 105, 1413



W^-
$\bar{s}$
$\bar{d}$
K^0
u
u
$\bar{K}^0$
W^+
d
s

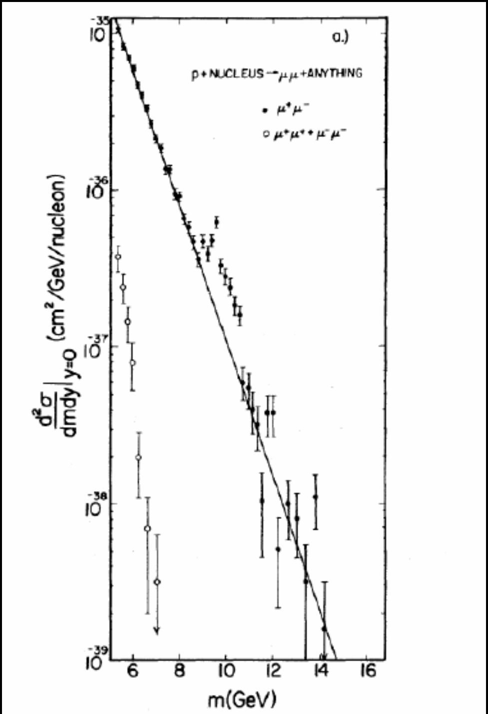


Image Credits: Fermilab

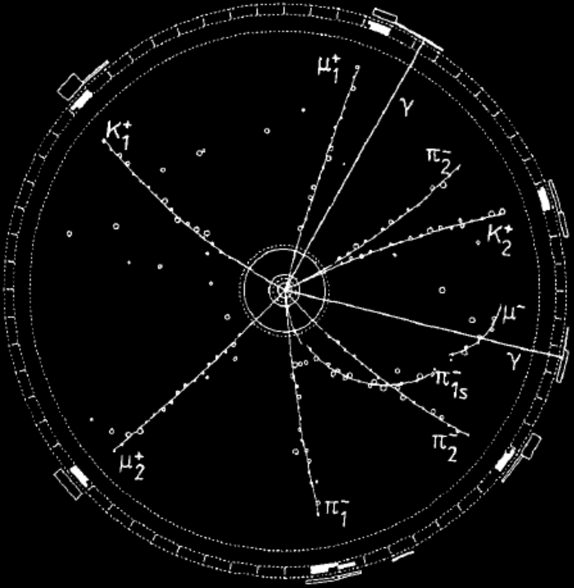


Image Credits: SLAC

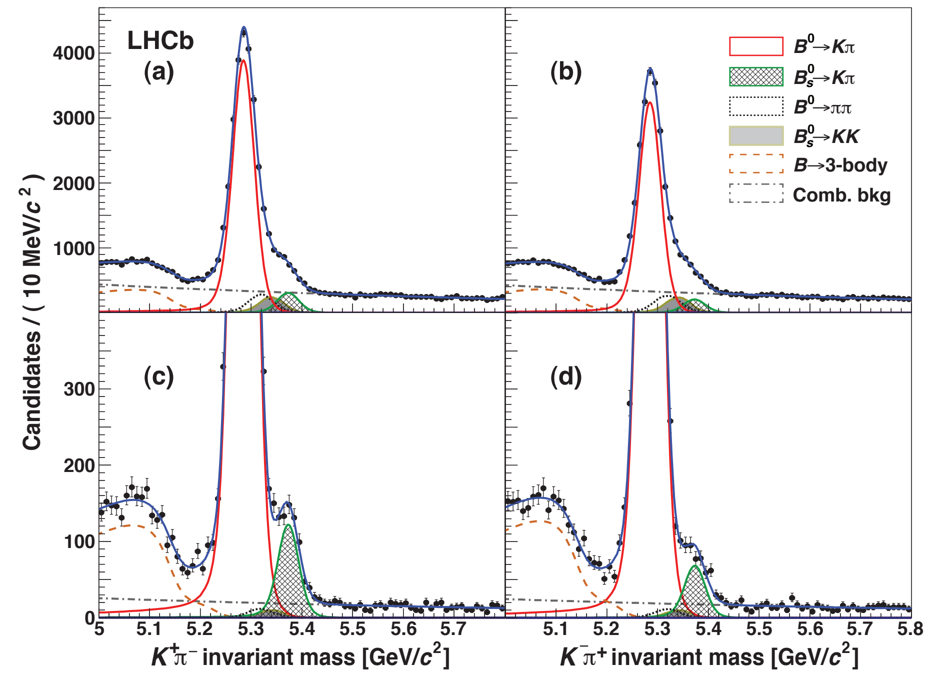


Image Credits: CERN

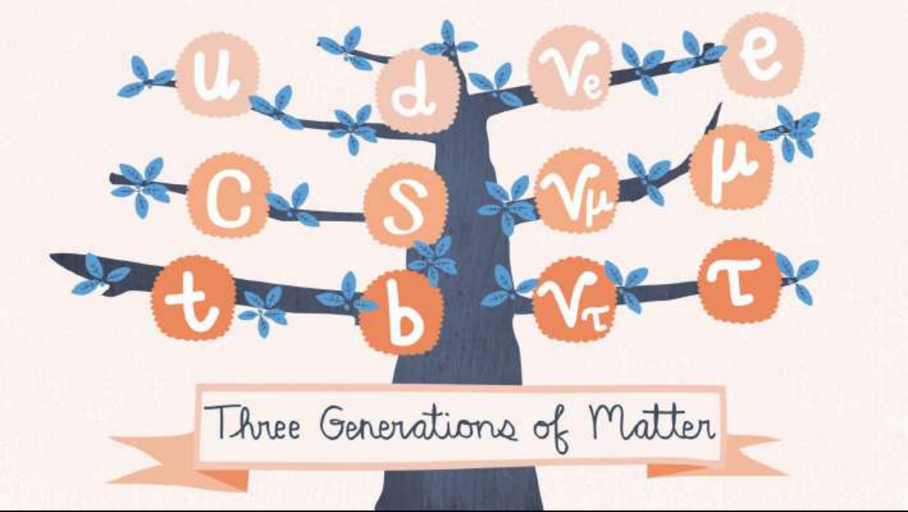
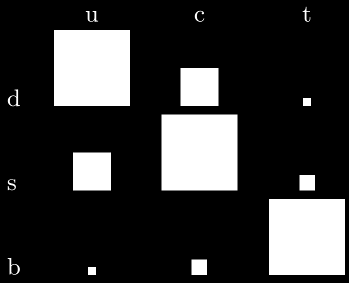
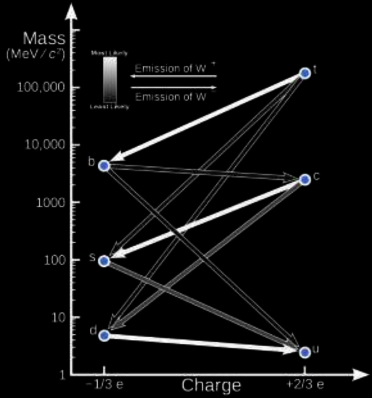


Image Credits: Symmetry Magazine


u
c
t
d
s
b


Mass
(MeV / c²)
100,000
10,000
1000
100
10
1
Emission of W+
Emission of W−
t
b
c
s
d
u
−1/3 e
Charge
+2/3 e

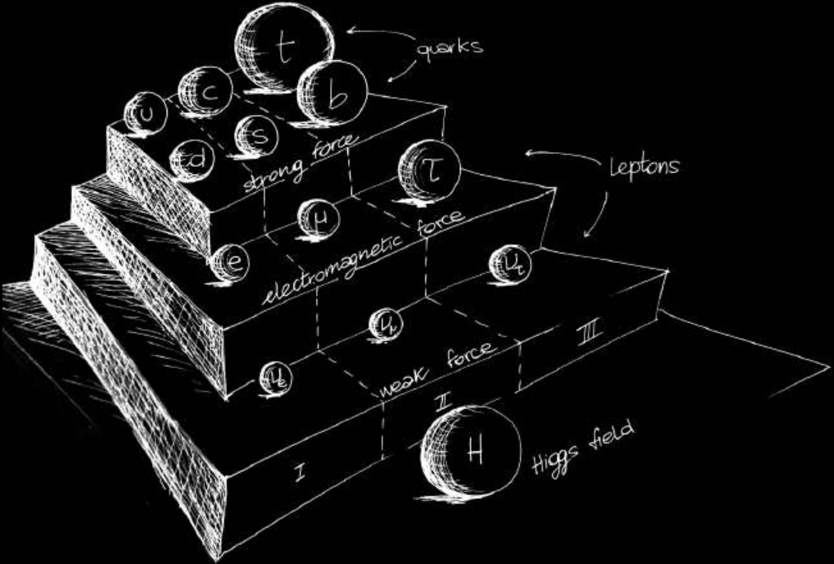
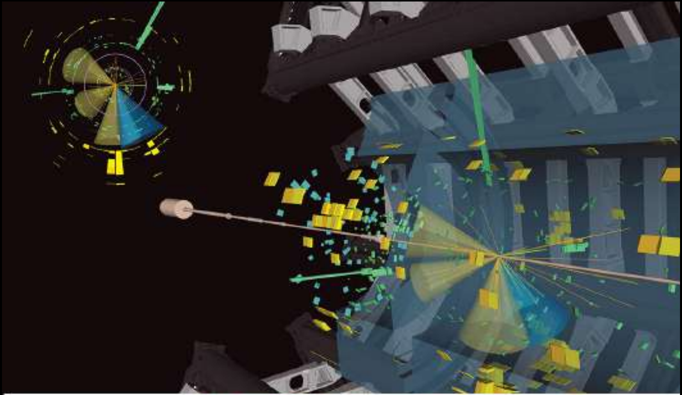


Image Credits: S. Oggero



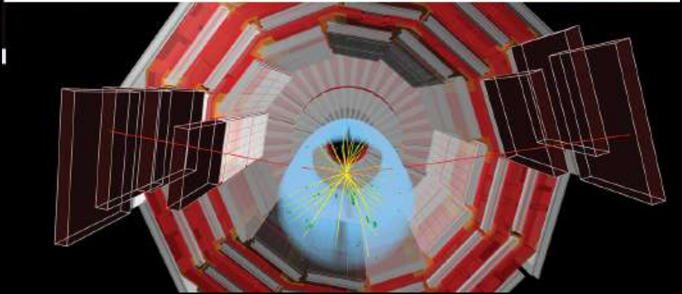


Image Credits: CERN

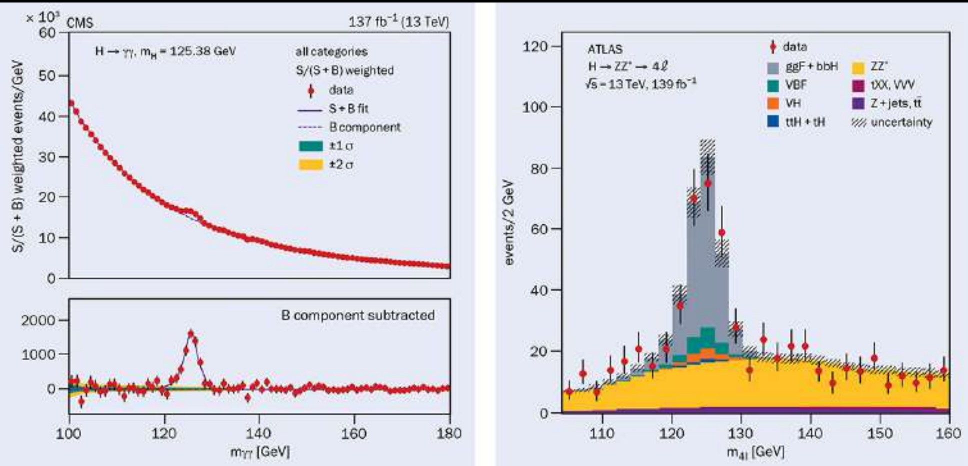


Image Credits: CERN

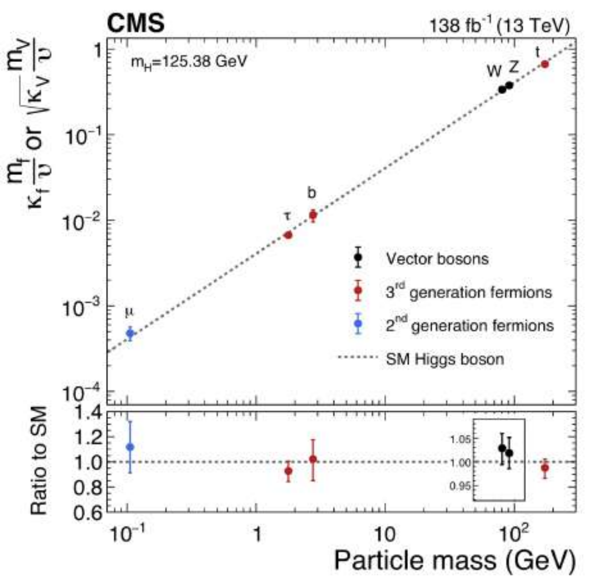


Image Credits: CERN

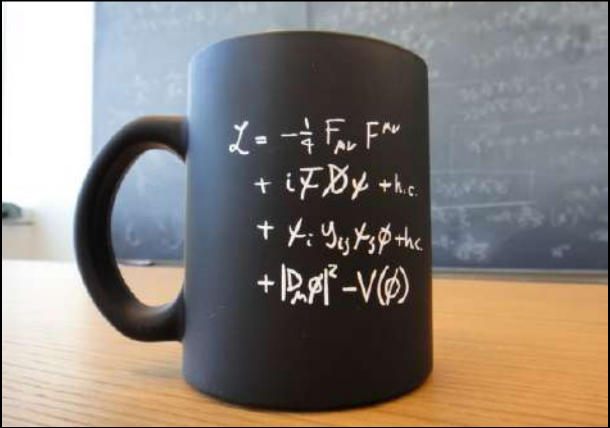


Image Credits: CERN

1

$$
\begin{aligned}
&-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
&\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -
\end{aligned}
$$

2

$$
\begin{aligned}
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
&\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
&\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - \\
&W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - \\
&W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
&\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
&g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
&\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
&W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
&\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
&igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
&igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
&\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j -
\end{aligned}
$$

3

$$
\begin{aligned}
&\bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
&\tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - \\
&1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
&(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1 + \\
&\gamma^5)u^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] -
\end{aligned}
$$

4

$$
\begin{aligned}
&\tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
&m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \\
&\gamma^5)u^\kappa_j] - \tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
&\tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 -
\end{aligned}
$$

5

$$
\begin{aligned}
&\tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \\
&\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
&\partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
&\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
&\tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
&igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{aligned}
$$

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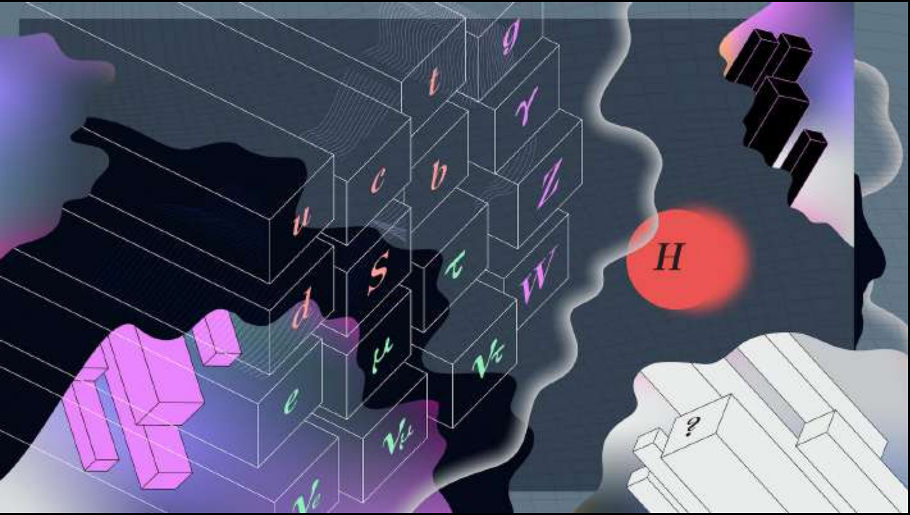

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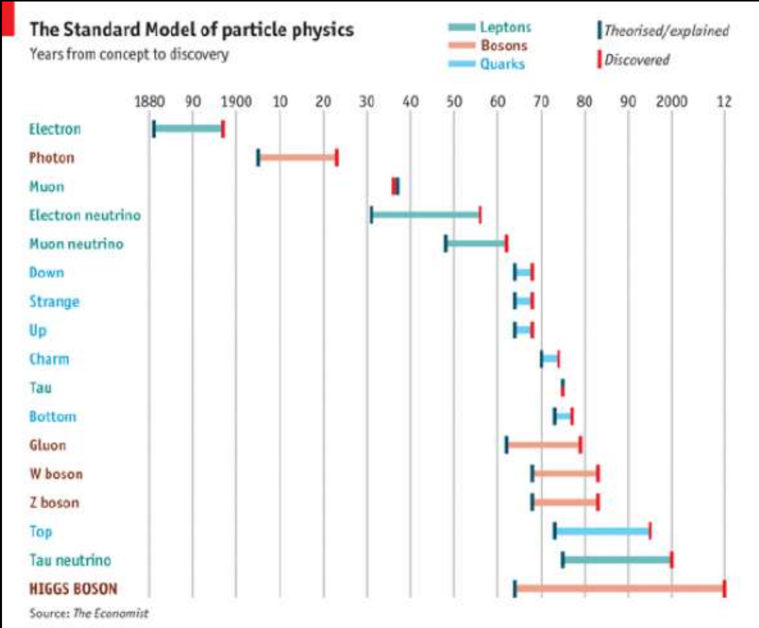
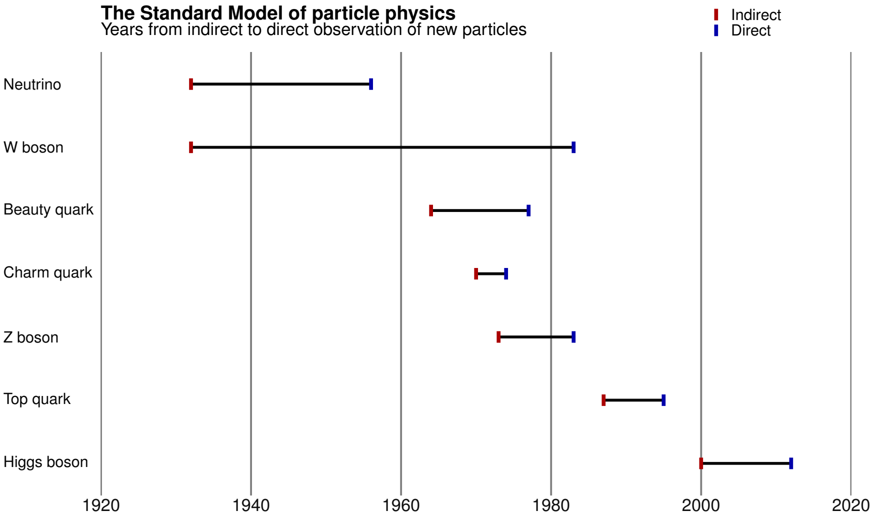


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON
Source: The Economist



The Standard Model of particle physics
Years from indirect to direct observation of new particles
Indirect
Direct
Neutrino
W boson
Beauty quark
Charm quark
Z boson
Top quark
Higgs boson
1920
1940
1960
1980
2000
2020

The end?