

It's a (Particle) zoo out there!

(A quick tour of the Standard Model of Particle Physics)

Alex Wright

Institute of Particle Physics and Queen's University

"Astronomy on Tap"

24 September 2020

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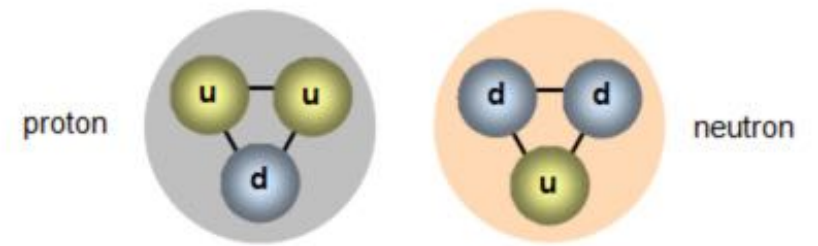
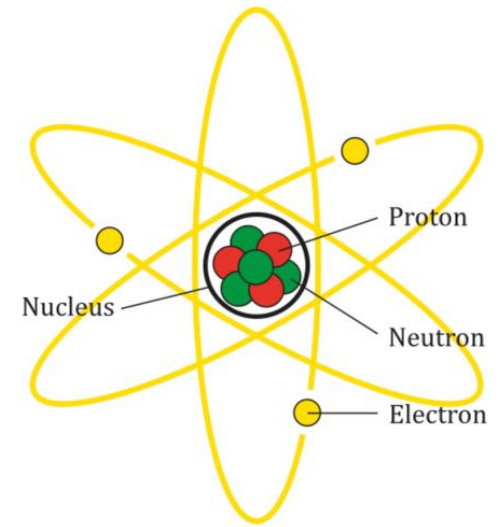
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The “Elementary” Particles

The periodic table is color-coded by groups: Group 1 (Li, Na, K, Rb, Cs, Fr) is yellow; Group 2 (Be, Mg, Ca, Sr, Ba, Ra) is light green; Groups 3-10 (Sc to Zn, Y to Cd, Hf to Hg) are orange; Groups 11-12 (Cu, Ag, Au, Hg, Pt, Pd, Ni, Co, Fe, Mn, Cr, V, Ti, Sc) are light blue; Groups 13-16 (B, C, N, O, Al, Si, P, S, Ga, Ge, As, Se, In, Sn, Sb, Te, Tl, Pb, Bi, Po, Nh, Fl, Mc, Lv, Ts, Og) are green; Group 17 (F, Cl, Br, I, At) is pink; Group 18 (He, Ne, Ar, Kr, Xe, Rn) is light blue. The lanthanide series (La to Lu) and actinide series (Ac to Lr) are shown below the main table.



The “Elementary” Particles

1	2																	3	4													
H	He																	B	C	N	O	F	Ne									
3	4																	5	6	7	8	9	10									
Li	Be																	B	C	N	O	F	Ne									
11	12																	13	14	15	16	17	18									
Na	Mg																	Al	Si	P	S	Cl	Ar									
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36															
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr															
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54															
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe															
55	56																	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Cs	Ba																	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
87	88																	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103
Fr	Ra																	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



The Elementary Particles

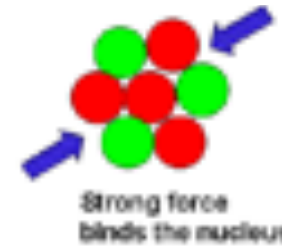
		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
mass		=2.2 MeV/c ²	=1.28 GeV/c ²	=173.1 GeV/c ²	0	=124.97 GeV/c ²
charge		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
	QUARKS					
		=4.7 MeV/c ²	=96 MeV/c ²	=4.18 GeV/c ²	0	
		$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		d down	s strange	b bottom	γ photon	
						SCALAR BOSONS
		=0.511 MeV/c ²	=105.66 MeV/c ²	=1.7768 GeV/c ²	=91.19 GeV/c ²	
		-1	-1	-1	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		e electron	μ muon	τ tau	Z Z boson	
	LEPTONS					GAUGE BOSONS
		<1.0 eV/c ²	<0.17 MeV/c ²	<18.2 MeV/c ²	=80.39 GeV/c ²	
		0	0	0	±1	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
						VECTOR BOSONS

The Forces and Force Carriers

Electromagnetic Force



Strong Nuclear Force



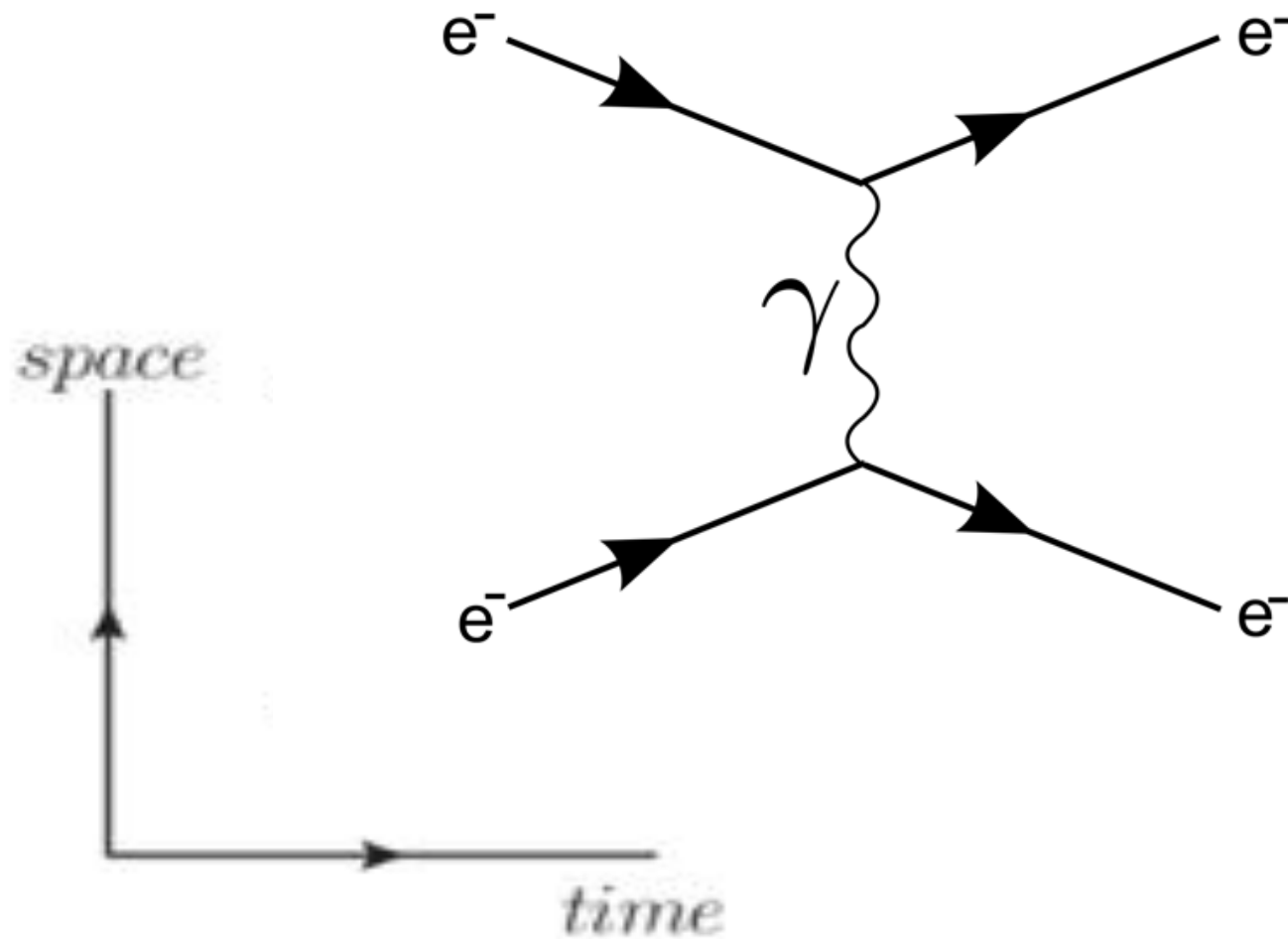
Weak Nuclear Force



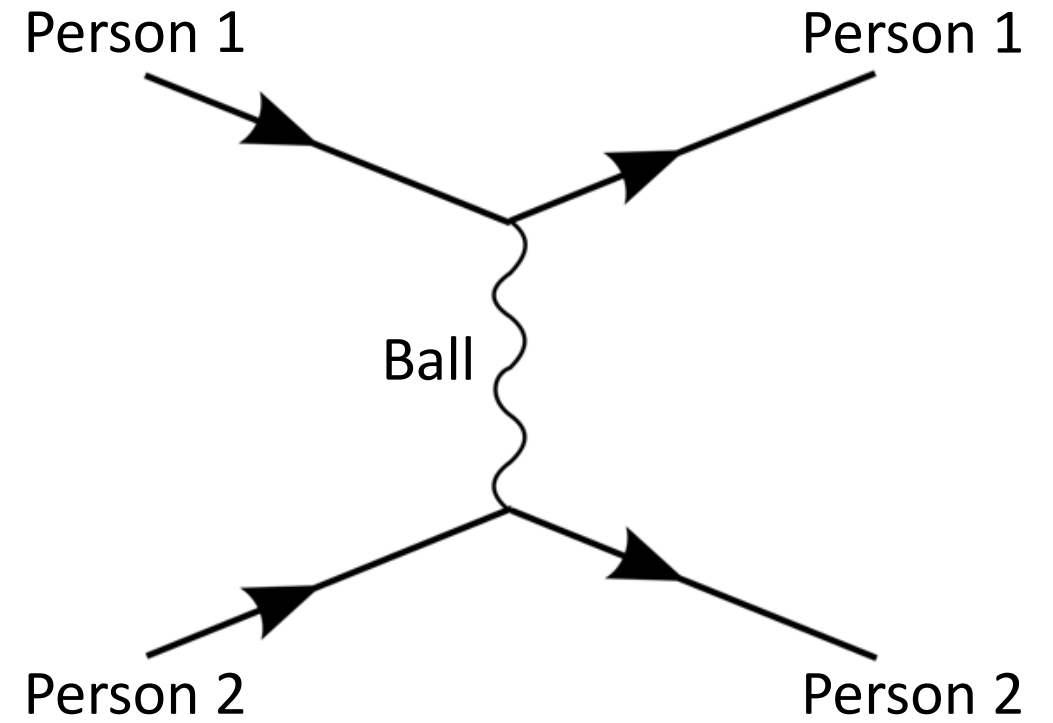
The Forces and Force Carriers

		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
mass		=2.2 MeV/c ²	=1.28 GeV/c ²	=173.1 GeV/c ²	0	=124.97 GeV/c ²
charge		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
	QUARKS	d down	s strange	b bottom	γ photon	
		e electron	μ muon	τ tau	Z Z boson	
	LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
					GAUGE BOSONS VECTOR BOSONS	SCALAR BOSONS

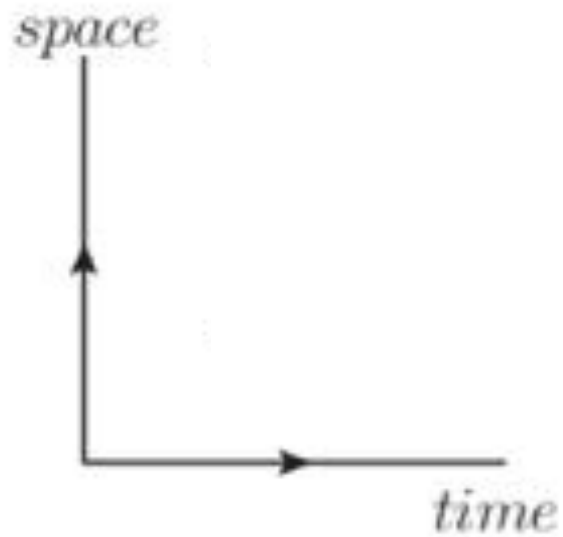
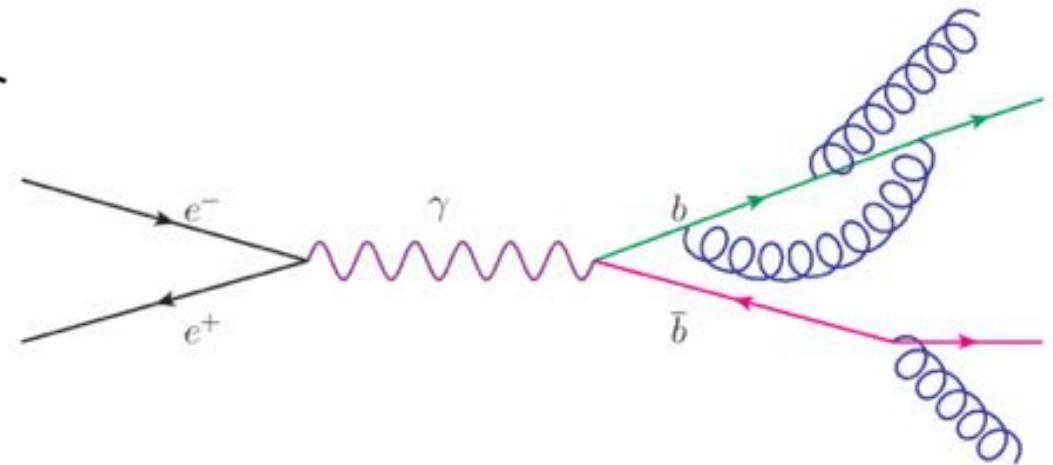
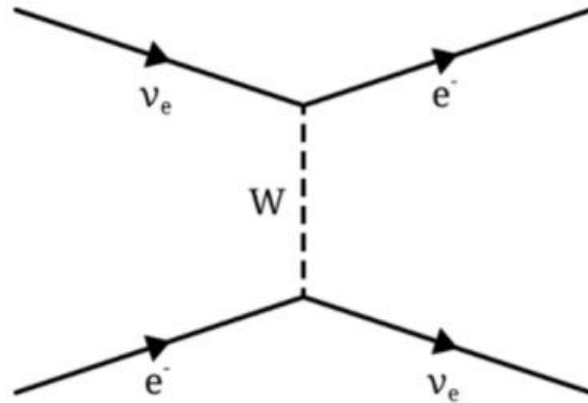
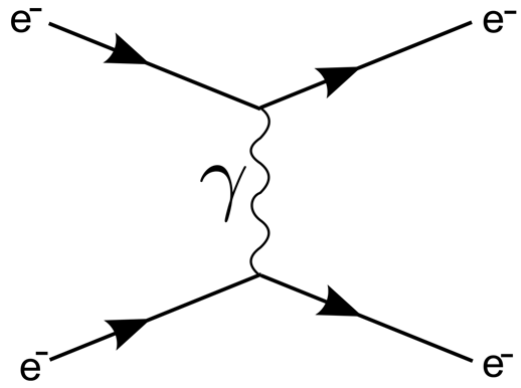
Forces from Particles



Forces from Particles



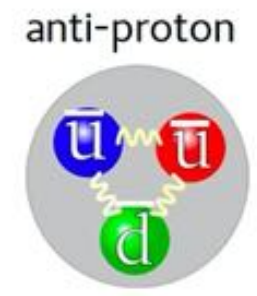
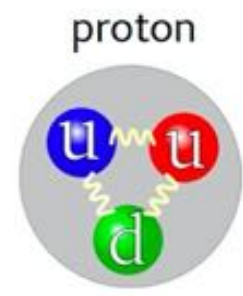
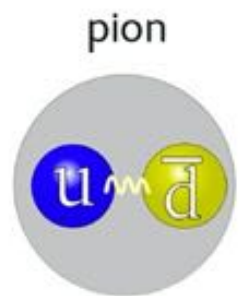
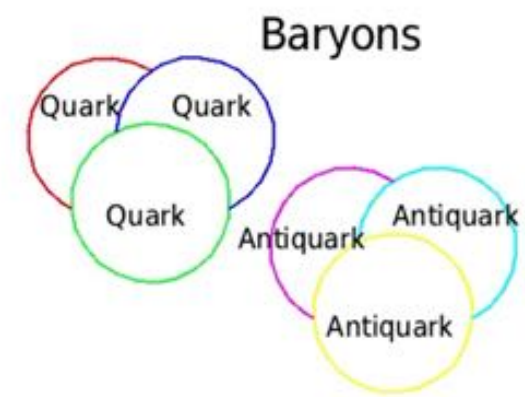
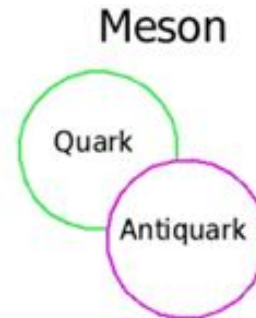
Forces from Particles



Quarks: The Gregarious Particles

three generations of matter (fermions)			
	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	u up	c charm	t top
	d down	s strange	b bottom

QUARKS



The Elementary Particles

		three generations of matter (fermions)			interactions / force carriers (bosons)	
		I	II	III		
mass		=2.2 MeV/c ²	=1.28 GeV/c ²	=173.1 GeV/c ²	0	=124.97 GeV/c ²
charge		$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	g gluon	H higgs
	QUARKS	d down	s strange	b bottom	γ photon	
		=0.511 MeV/c ²	=105.66 MeV/c ²	=1.7768 GeV/c ²	=91.19 GeV/c ²	
		-1	-1	-1	0	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
		e electron	μ muon	τ tau	Z Z boson	
	LEPTONS	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	
		<1.0 eV/c ²	<0.17 MeV/c ²	<18.2 MeV/c ²	=80.39 GeV/c ²	
		0	0	0	±1	
		$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	
						GAUGE BOSONS VECTOR BOSONS
						SCALAR BOSONS

Neutrinos and Particle Oscillations

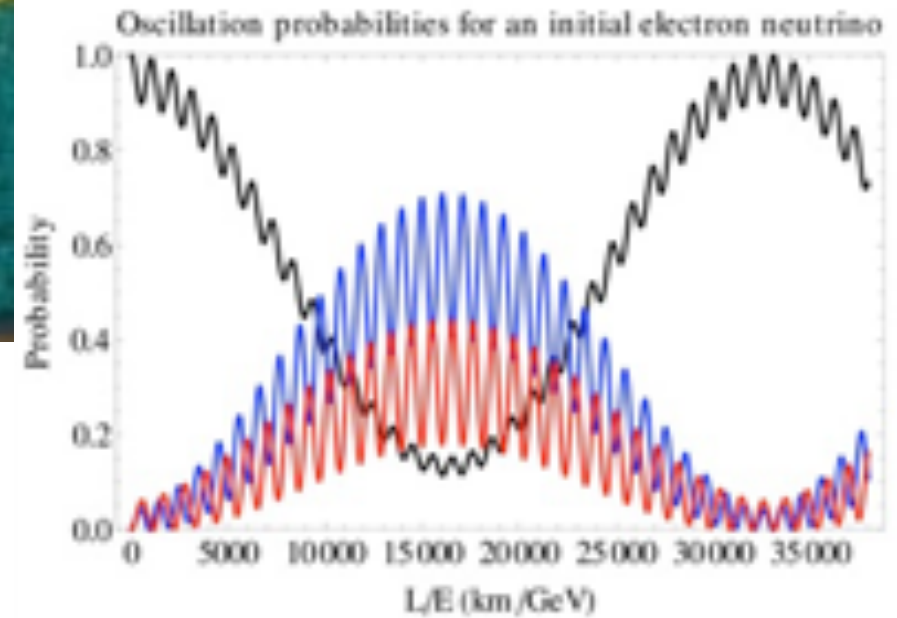
	three generations of matter (fermions)			interactions / force carriers (bosons)	
	I	II	III		
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.97 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
	u up	c charm	t top	g gluon	H higgs
	d down	s strange	b bottom	γ photon	
	e electron	μ muon	τ tau	Z Z boson	
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson	

QUARKS (left side of table)

LEPTONS (left side of table)

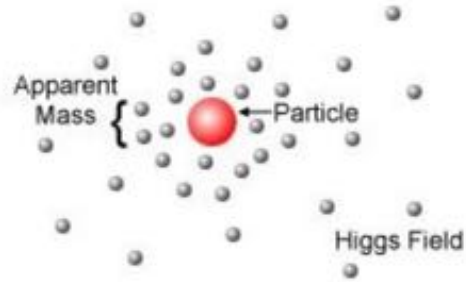
GAUGE BOSONS VECTOR BOSONS (bottom center)

SCALAR BOSONS (right side of table)

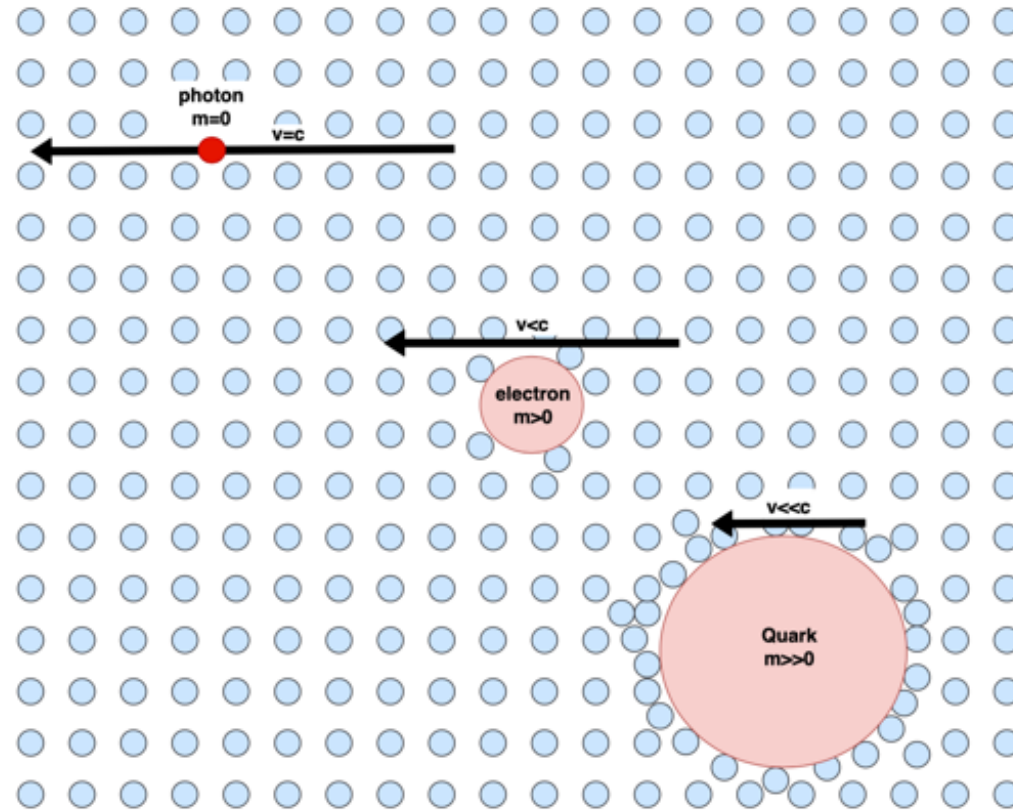
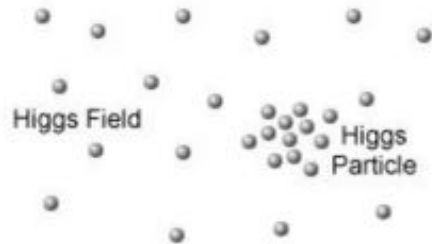


Particle Masses and the Higgs Field

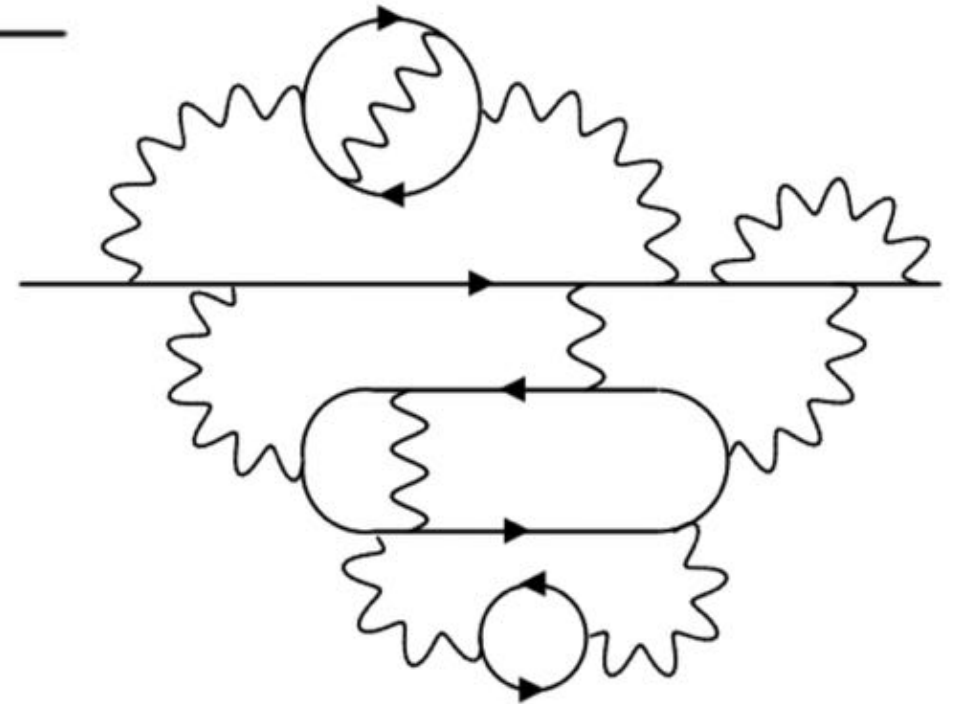
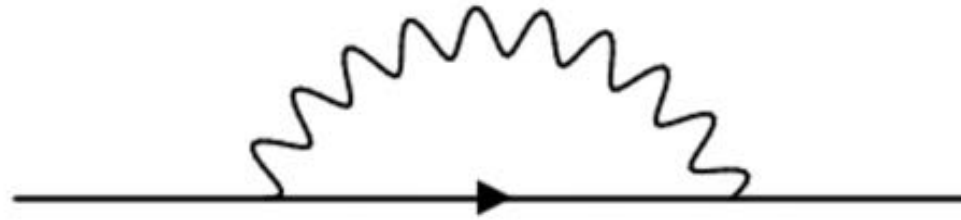
Higgs Mechanism



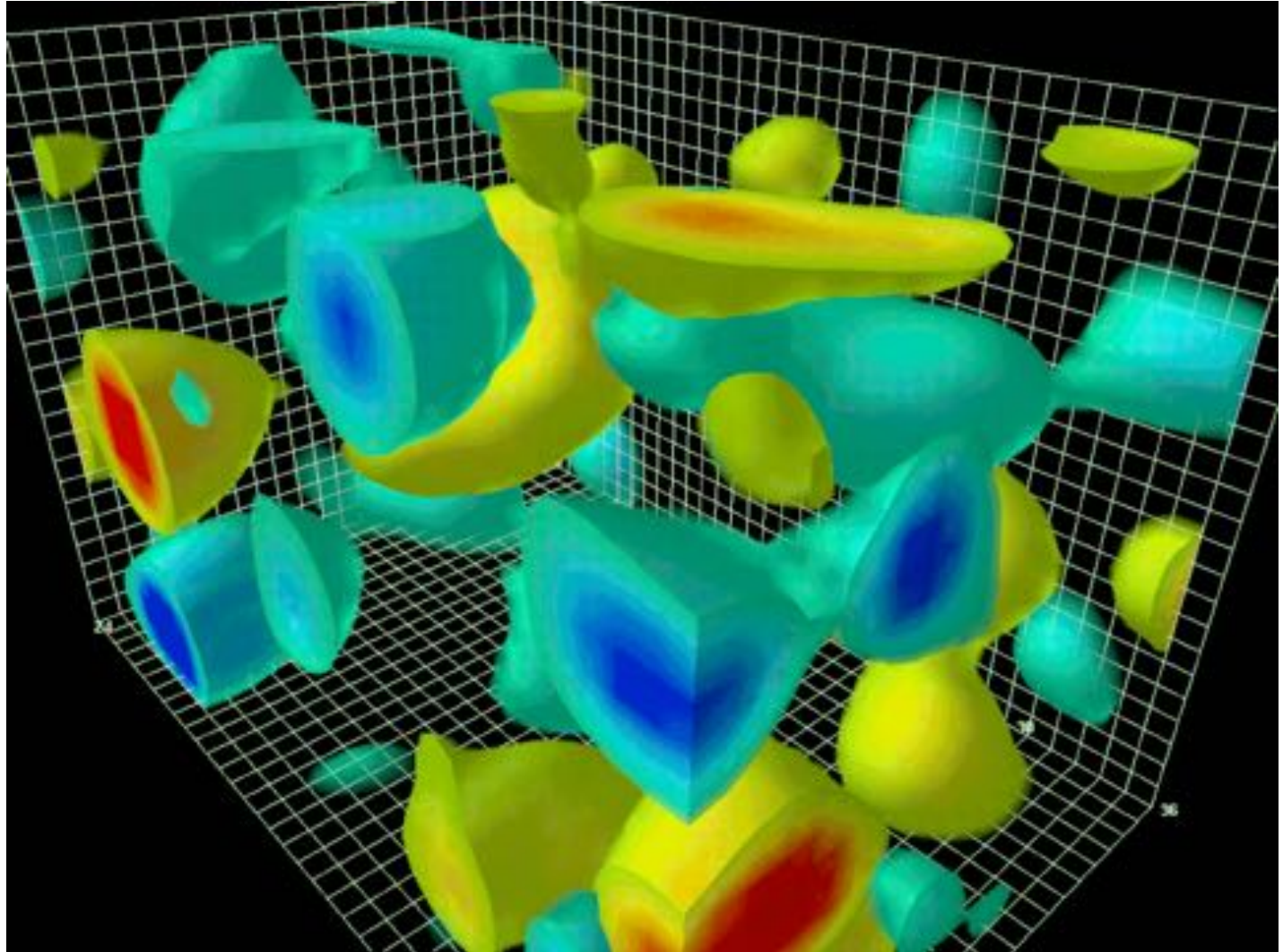
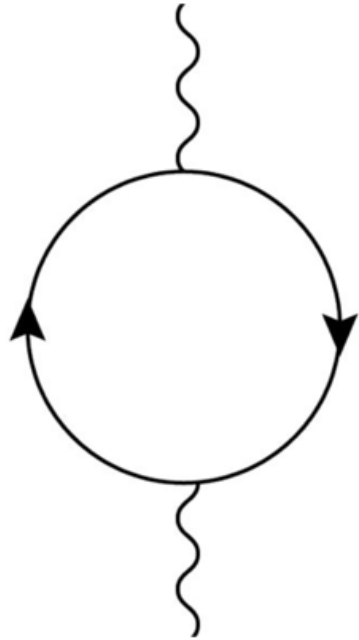
Higgs Particles



'Virtual' Particles



The “Empty” Vacuum



The Elementary Particles

		three generations of matter (elementary fermions)			three generations of antimatter (elementary antifermions)			interactions / force carriers (elementary bosons)	
		I	II	III	I	II	III		
QUARKS	mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 124.37 \text{ GeV}/c^2$
	charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	$-\frac{2}{3}$	0	0
	spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0
		u up	c charm	t top	\bar{u} antiup	\bar{c} anticharm	\bar{t} antitop	g gluon	H higgs
		d down	s strange	b bottom	\bar{d} antidown	\bar{s} antistrange	\bar{b} antibottom	γ photon	
		e electron	μ muon	τ tau	e^+ positron	$\bar{\mu}$ antimuon	$\bar{\tau}$ antitau	Z Z ⁰ boson	
		ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	$\bar{\nu}_e$ electron antineutrino	$\bar{\nu}_\mu$ muon antineutrino	$\bar{\nu}_\tau$ tau antineutrino	W⁺ W ⁺ boson	W⁻ W ⁻ boson

GAUGE BOSONS
 VECTOR BOSONS
 SCALAR BOSONS