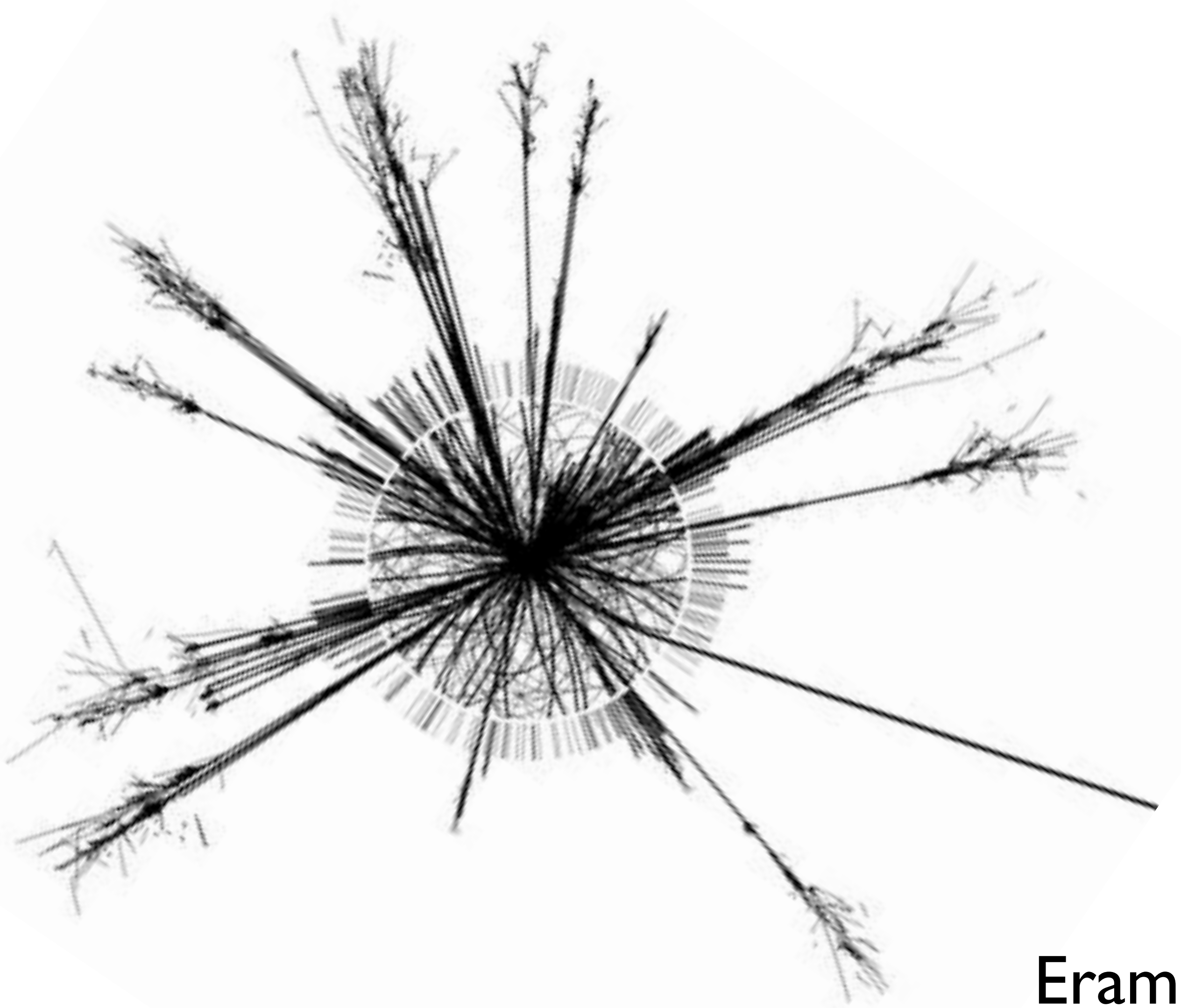
The Standard Model of Particle Physics - II

Lecture 4

- Gauge Theory and Symmetries
- Quantum Chromodynamics
- Neutrinos



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Outline

A Century of Particle Scattering 1911 - 2011
- scales and units
- overview of periodic table → atomic theory
- Rutherford scattering → birth of particle physics
- quantum mechanics - a quick overview
- particle physics and the Big Bang

A Particle Physicist's World - The Exchange Model
- quantum particles
- particle detectors
- the exchange model
- Feynman diagrams

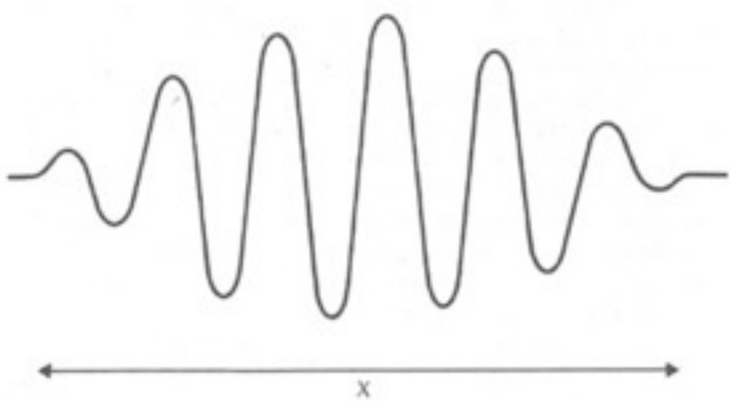
The Standard Model of Particle Physics - I
- quantum numbers
- spin statistics
- symmetries and conservation principles
- the weak interaction
- particle accelerators

The Standard Model of Particle Physics - II
- perturbation theory & gauge theory
- QCD and QED successes of the SM
- neutrino sector of the SM

Beyond the Standard Model
- where the SM fails
- the Higgs boson
- the hierarchy problem
- supersymmetry

The Energy Frontier
- large extra dimensions
- selected new results
- future experiments

Recap



a wave packet corresponding to a particle located somewhere in the region X

$$\psi = Ae^{i(kx-\omega t)}$$

- A quantum mechanical particle is associated with a wave function ψ
- The wave function encapsulates all information about the particle
- The wave function squared is proportional to probability of finding the particle at a particular place, time, energy, momentum etc..

kinetic energy + potential energy = total energy

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

Schrödinger equation describes the particle ψ behaves under influence of an energy field *V(x,y,z)*
x,y,z,t are co-ordinates in space and time
V(x,y,z) could be e.g. another particle's electric field

$$\frac{\partial}{\partial t}$$

The equation involves "derivative" operators:
⇒ mathematical operators acting on wave function
They calculate slopes - or how the wave function changes per meter, or per second

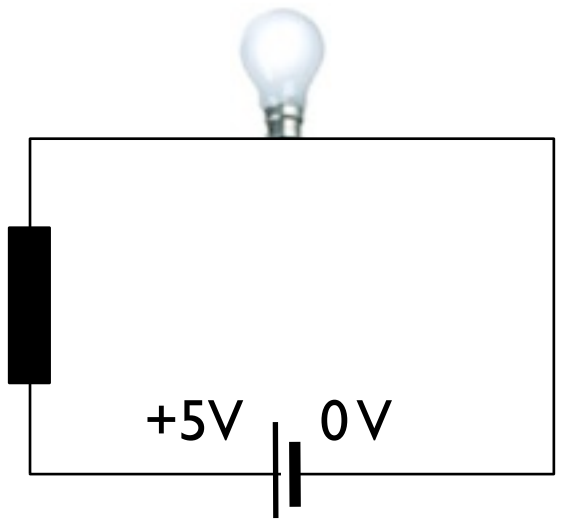
$$\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$$

operators act on something, just like + or ÷ or √
In this case they act on the wave function ψ

Symmetry:
A transformation which leaves an experiment unchanged
Each quantum symmetry is related to a conservation law

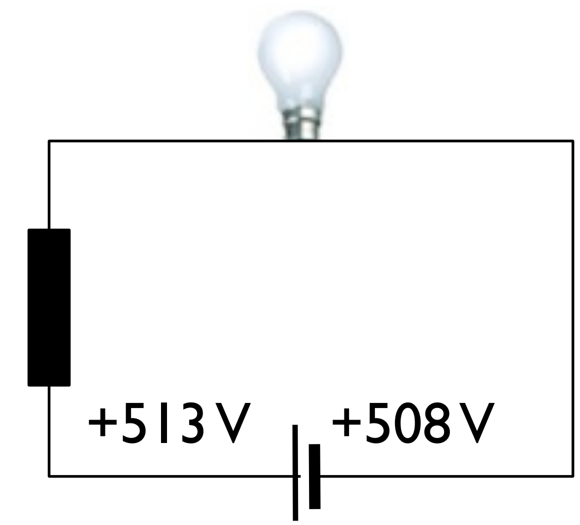
Translation in time	Energy conservation
Translation in space	Momentum conservation
Rotations	Angular Momentum conservation
Gauge Transformation	Charge conservation

Gauge Theory



A gauge transformation is one in which a symmetry transformation leaves the physics unchanged

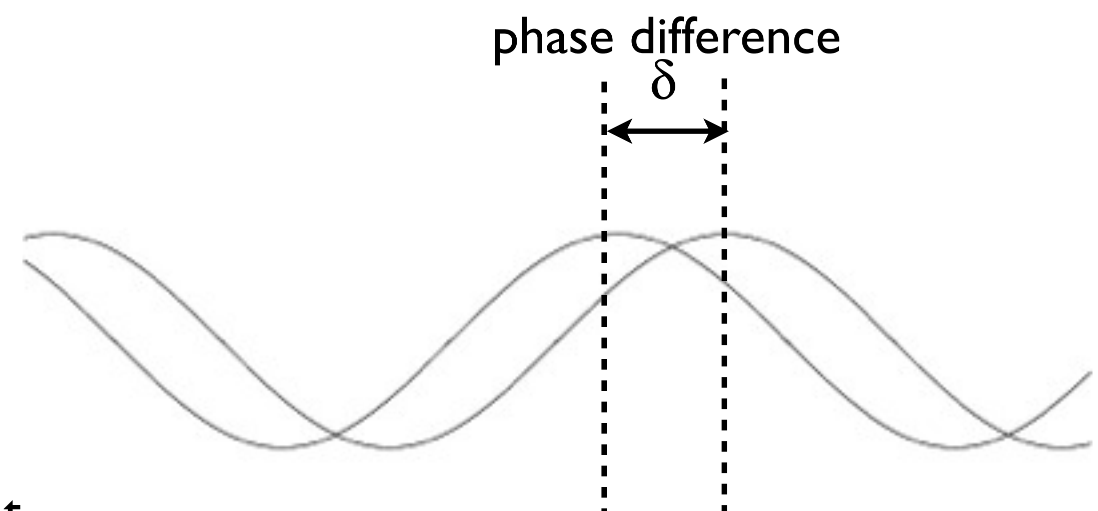
Both circuits behave identically
Circuit is only sensitive to potential differences
Change the ground potential of the earth and see no difference!
Leads to concept of charge conservation



In electromagnetism we are insensitive to phase δ of EM radiation
All experiments can only measure phase <u>differences</u>
Could globally change the phase at all points in universe
Yields no observable change

$\Rightarrow$ global gauge transformation

(In electromagnetism this is the gauge symmetry expressed by the U(1) group)



What happens if we demand <u>local</u> phase transformations? $\delta \rightarrow \delta(x,t)$
i.e. δ is no longer a single number, it depends on position x and time t

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

Wave functions of all particles get an extra piece from the change in δ
This spoils the Schrödinger equation
(actually, relativistic versions are the Klein-Gordon and Dirac equations)

$\delta(x,t)$ spoils the spatial & time derivatives

(see lecture 2)

$$\psi = Ae^{-i(kx-\omega t)} \rightarrow \psi = Ae^{-i\delta(x,t)}e^{-i(kx-\omega t)}$$

... and since energy (E) and momentum (p) measurements are represented by operators in quantum mechanics

$$i\hbar\frac{\partial}{\partial t}\psi = E\psi \qquad \frac{\hbar}{i}\frac{\partial}{\partial x}\psi = p_x\psi$$

The derivatives cause nuisance terms to appear in equations arising from $\delta(x,t)$

But we still want physics to work the way it did before the gauge transformation!
We want the Schrödinger equation to still work!

So - add an additional term to the equation to cancel out those nuisance terms
After adding these to the equation we ask ourselves: what do the new equation pieces look like?

The alterations required to accommodate these changes introduce a new quantum field
This field has a 'spin' = 1
This field interacts with charged particles
This field no charge itself
The field particle has zero mass
- it is the photon!

Our consideration of local symmetry leads us to predict the photon

Gauge Theory

This can be applied to other quantum interactions:

local gauge invariance introduces new fields

oscillations in the fields <u>are</u> the probability wave functions of particles

Interaction	Gauge particle	Gauge group	Symbol	Felt by
Electromagnetism	photon	U(1)		q, $W^{\pm}$, $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$
Strong force	gluons	SU(3)		q , gluons
Weak force	$W^{\pm}$ and Z^0	$SU(2)_L$		q, $W^{\pm}$, Z^0 , $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$, all ν

These are not simply abstract mathematical manipulations - the particles exist!

Weak bosons (spin 1 particles) discovered in 1983 at CERN's UA1 experiment

Energy of electrons from the decay of the W^- particle: $W \rightarrow e\nu_e$

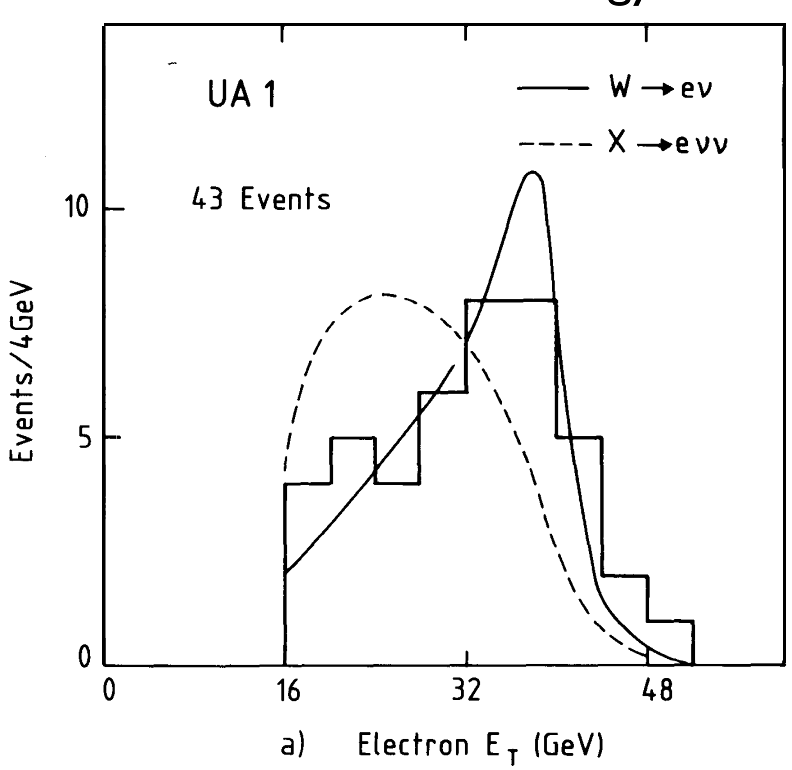
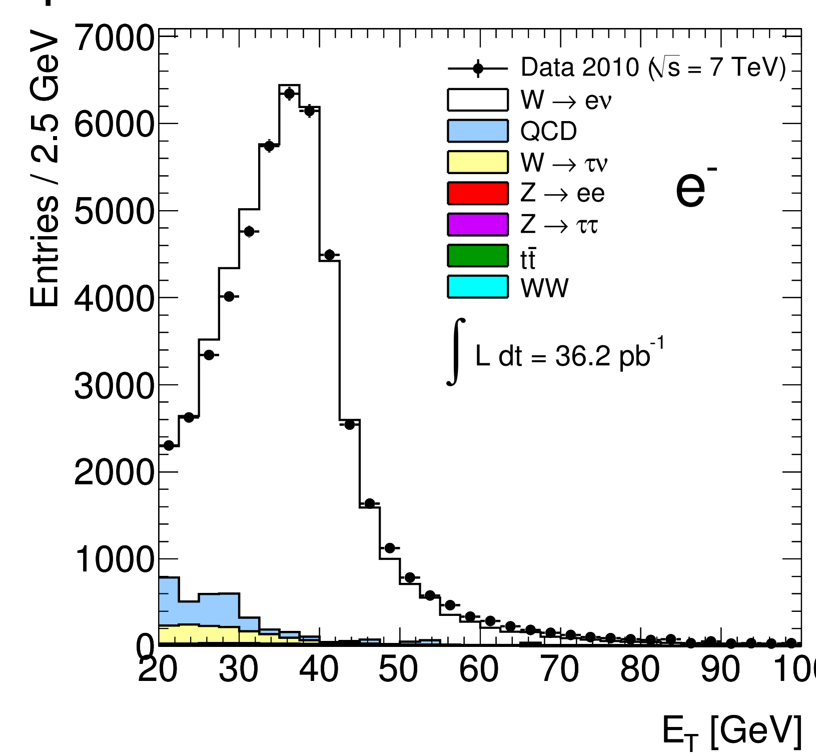


Fig. 19a. The electron transverse energy distribution. The two curves show the results of a lit of the enhanced transverse mass distribution to the hypotheses W→e+ν and X→e+ν+ν. The first hypothesis is clearly preferred.

1983 to 2010



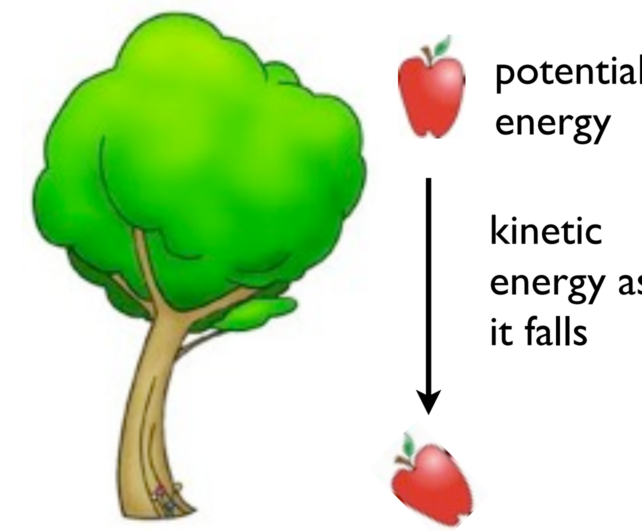
(In 2011 LHC has 40x more data than in 2010)

Perturbation Theory

So far theory predicted new particle's existence
How do we calculate particle reaction rates?
e.g. reaction rate of electron - positron scattering??

$$\frac{-\hbar^2}{2m}\nabla^2\psi + V(x,y,z)\psi = i\hbar\frac{\partial}{\partial t}\psi$$

In Schrödinger equation a particle interacts with a potential energy field V
Potential energy is energy an object has by virtue of position
Apple in a tree → it has potential energy in Earth's gravitational field
Apple falls → it releases potential energy into kinetic energy
Total energy is constant!



In quantum mechanics the potential causes a transition from initial state to final state wave functions $\psi_i \rightarrow \psi_f$

Potential = V + V'

V gives rise to stable, time independent quantum states ψ_f and ψ_i

V' is a weak additional perturbation leading to transitions between states

$$P = |M_{fi}|^2 = |\int \psi_f V' \psi_i \; dv|^2$$

P = probability of transition from initial to final state

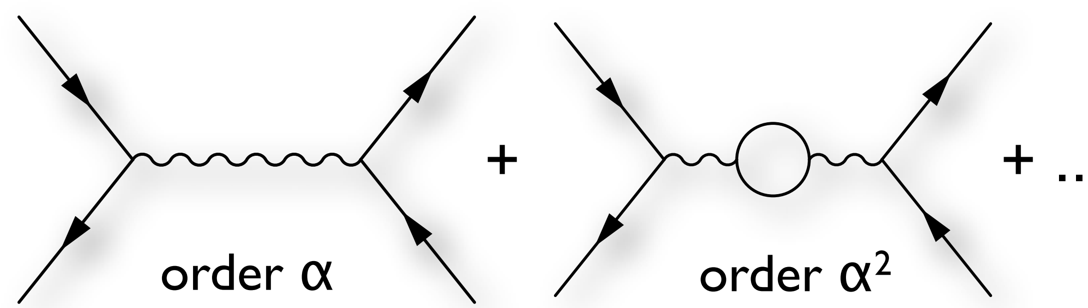
M_{fi} is known as the matrix element for the scattering process

V' contains the standard model Lagrangian - describes the dynamics of all interactions

Feynman Diagrams

Transition due to the exchange of a gauge boson
Exchanges momentum & quantum numbers
Strength of the interaction is parameterised by couplings α
One α for each fundamental force

Draw all possible Feynman diagrams for your experiment:



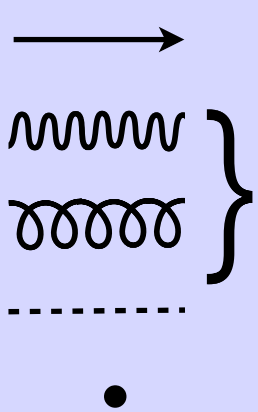
For each diagram calculate the transition amplitude
Add all transition amplitudes
Square the result to get the reaction rate

Simplest interaction is single boson exchange

More complicated loop diagrams also contribute

Potentially infinite series of diagrams for 2 → 2 scattering process

Feynman Rules: start from left side



Write a free particle wave function for each particle
$$\psi = Ae^{i(kx-\omega t)}$$

Multiply by an exchanged boson write $\frac{1}{p^2+m^2}$ for particle of momentum p and mass m

For each vertex multiply by coupling $\sqrt{\alpha}$

Sum over all allowed particle states i.e. all quark flavours / colours / spins

If perturbation is small i.e. α < 1 then contributions from extra loop diagrams is suppressed

Diagrams are ordered in powers of α

Form a power series

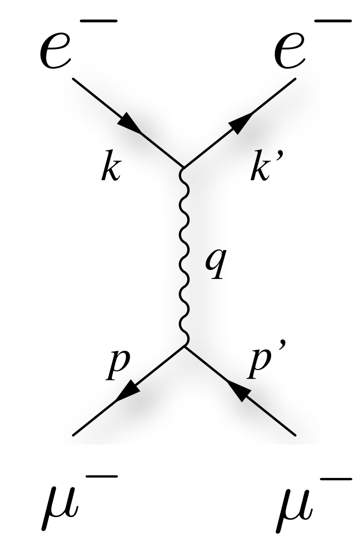
The sum to infinity of a power series can be finite!

$$\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}\ldots=\sum_{n=1}^{\infty}\frac{1}{2^n}=1$$

Feynman Diagrams

in case you don’t believe me...

$$|M_{fi}|^2 = \frac{e^4}{q^4}\frac{1}{4}\sum_{spin}\{[\bar{u}(k')\gamma^{\mu}u(k)]\,[\bar{u}(k')\gamma^{\nu}u(k)]^*\}\{[\bar{u}(p')\gamma_{\mu}u(p)]\,\{[\bar{u}(p')\gamma_{\nu}u(p)]^*\}$$



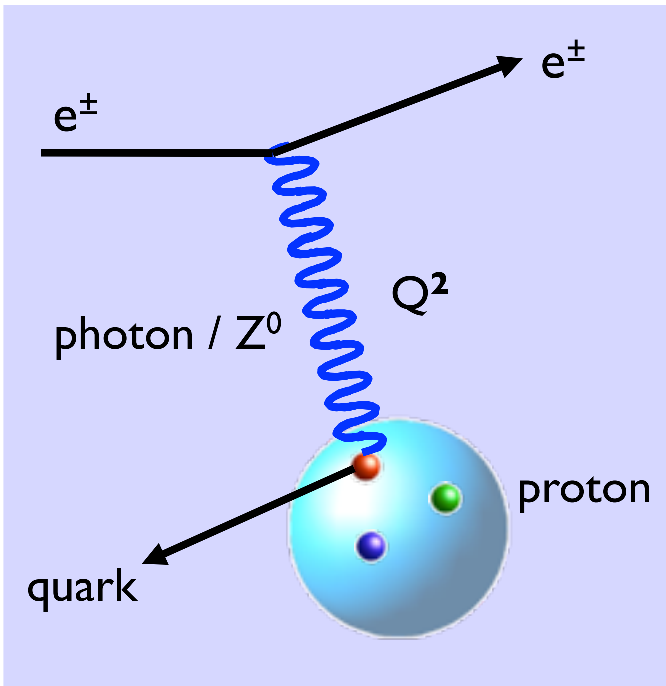
k, k' = incoming , outgoing electron momentum
p, p' = incoming , outgoing muon momentum
q = momentum transfer
e = strength of electromagnetic interaction (electric charge)

electron charge

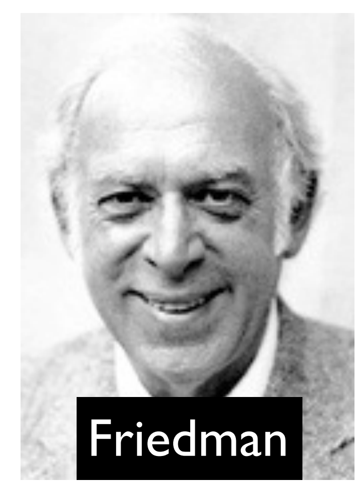
For electromagnetism α_{EM} = 1/137 $\sim e^2$
Small enough for perturbation theory to work

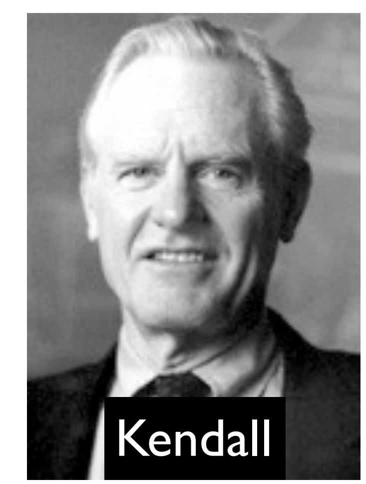
For strong interaction $\alpha_S \sim 0.1$
Perturbation theory works but need to calc more diagrams for precision - difficult!
For QCD it took 10 years to calculate second order diagrams!

Quarks discovered in scattering experiments at
Stanford Linear Accelerator Laboratory - California



$$ep \rightarrow e + X$$



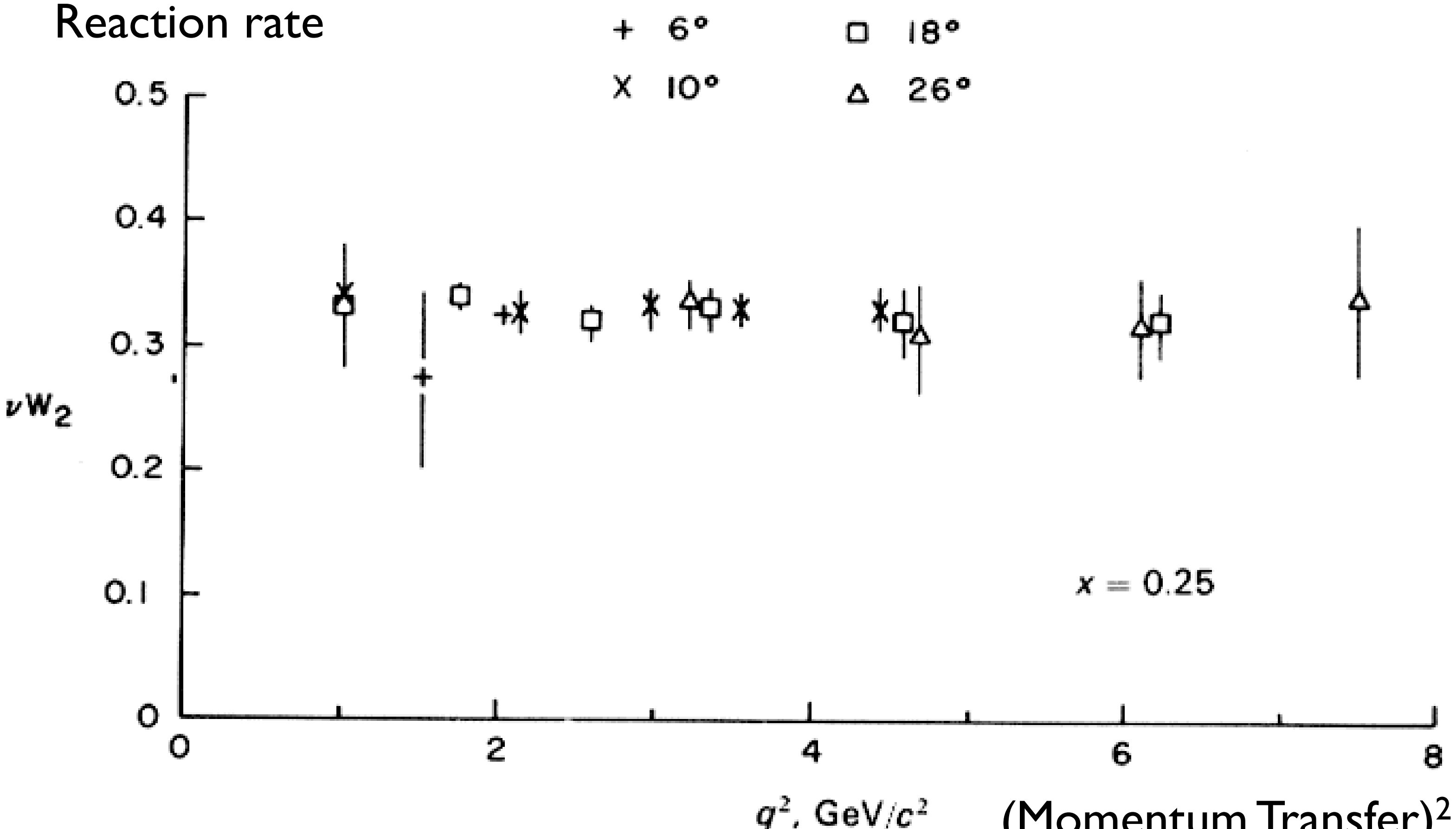


Nobel Laureates 1990

High energy electron beam strikes stationary proton
High energy = small wavelength
Quarks kicked out of proton
Seen as jet / spray of new particles - why?
What keeps quarks bound inside proton?

$ep \to e + X$ in 1968

Reaction rate



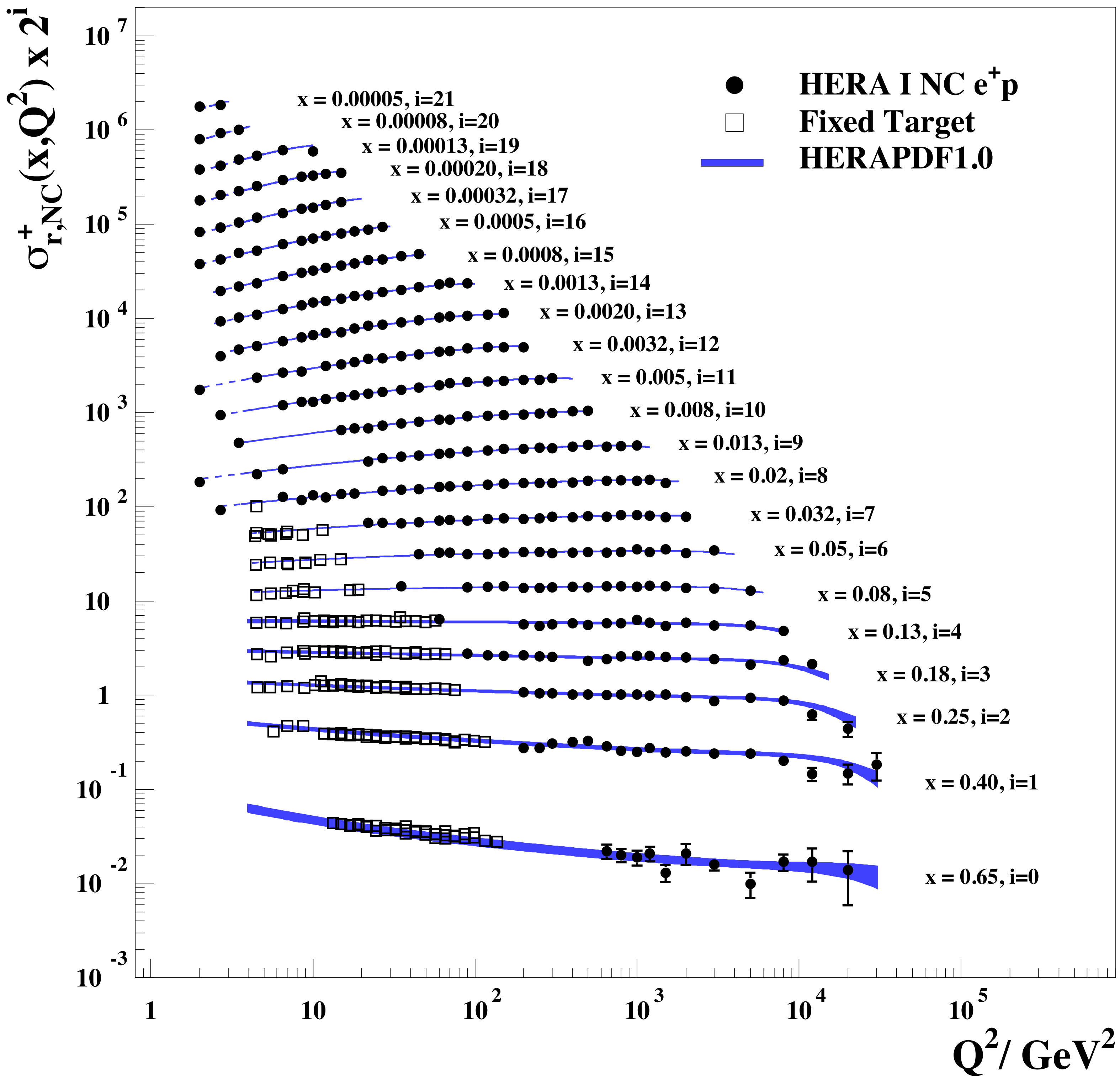
(Momentum Transfer)^2

The data demonstrate proton has:

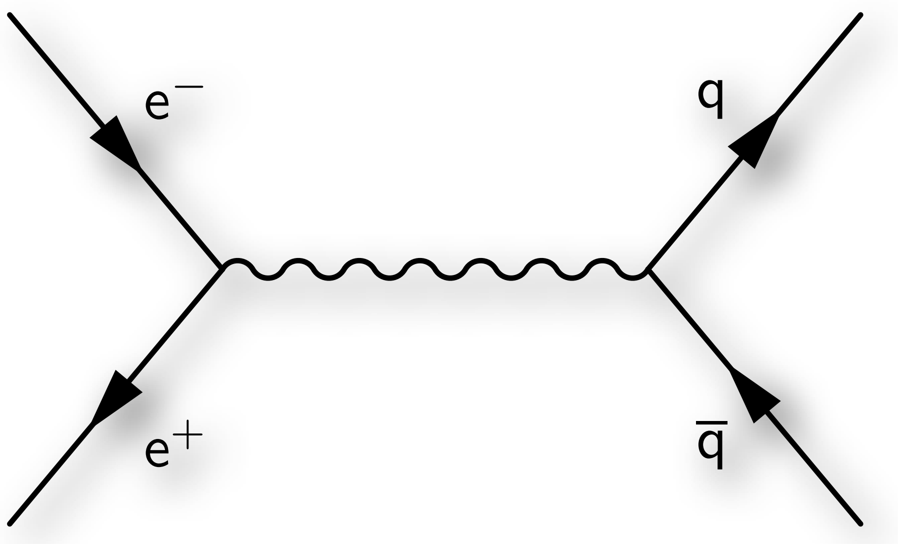
- point-like constituents
- they have fractional electric charge
- they are spin $^1/_2$ fermions
- behave as free "unbound" particles

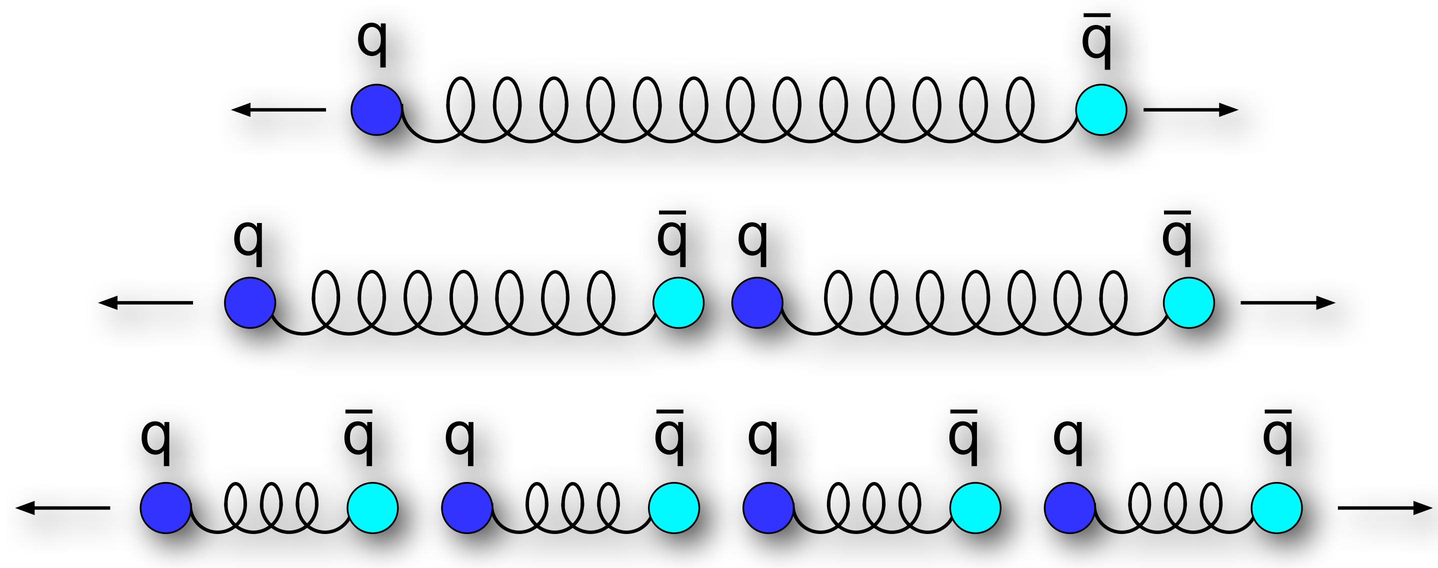
Additional measurements showed only 50% of proton's momentum is carried by quarks!

$ep \to e + X$ in 2011



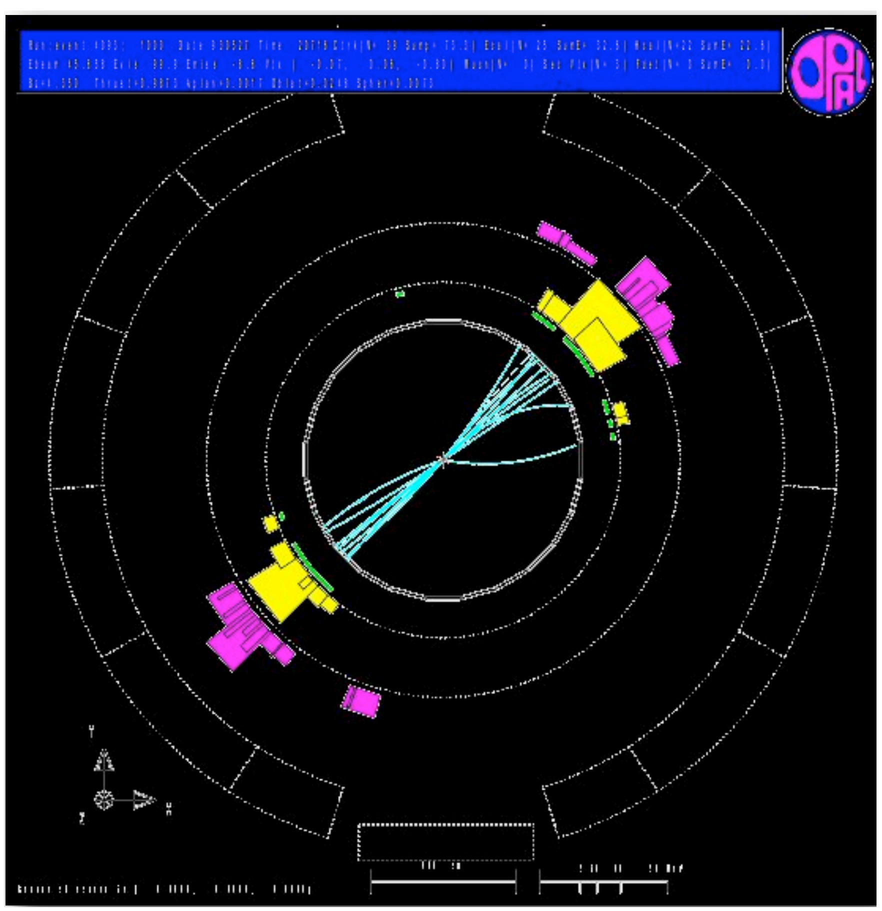
LEP at CERN: 1989 - 2000
Large Electron Positron Collider





Several particles make up two distinct 'jets' as quarks fragment
New particles always consist of:

3 quarks (baryons e.g. proton & neutron)
or
quark and anti-quark (mesons e.g. pion, kaon)



Two quark jets from e^+e^- annihilation at LEP
Seen in the OPAL experiment

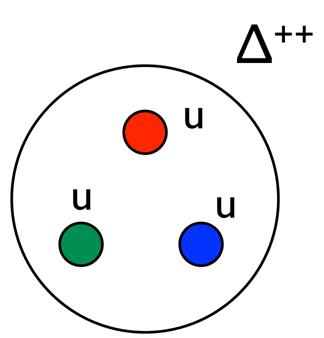
One baryon was seen called Δ^{++}
Known to consist of 3 u quarks - each has charge $+{}^{2}/_{3}$
Spin = $+{}^{3}/_{2}$ i.e. all quark spins aligned in same direction
All three quarks have same quantum state!

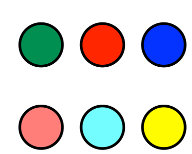
The quarks violate the Pauli Exclusion Principle

This led to development of theory of strong interactions

A new quantum number was invented to circumvent the problem: colour
The new quantum number also explained why quarks are bound in composite particles

The colour quantum number is the "charge" of the strong interaction - takes 3 values: red green blue





anti-quarks take anti-colours: anti-red anti-green anti-blue

Quantum Chromodynamics

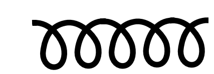
Quark colour is an analogy - not <u>actual</u> colour
Composite particles must remain colourless overall

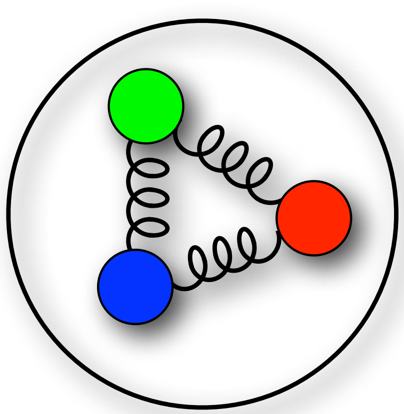
red + green + blue = white
colour + anti-colour = black

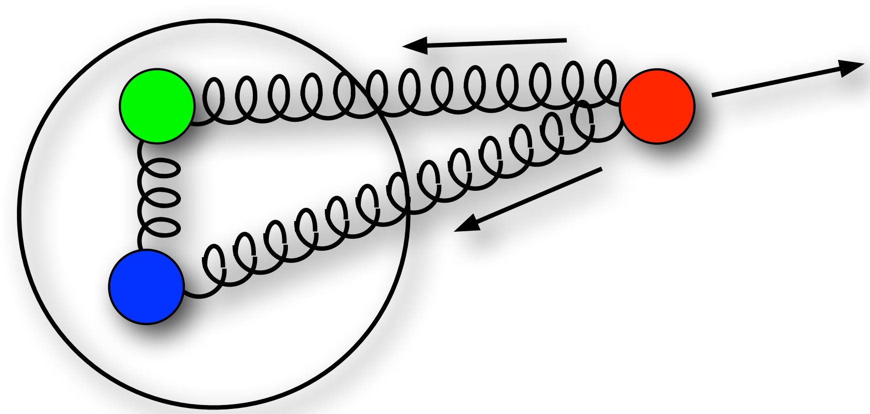
Only white / black particles are observable in nature
Particles with colour feel the strong force

Electron has no colour quantum number ⇒ ignores strong force

Mediated by gluons:





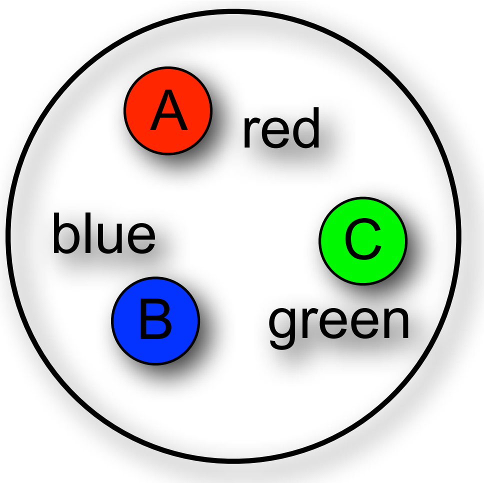


As quarks separate, field strength <u>increases</u>

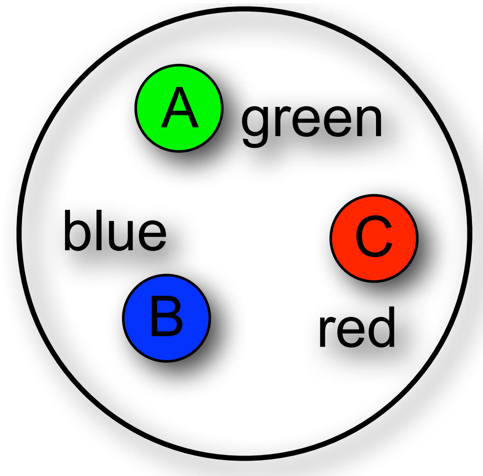
Known as quantum chromodynamics: QCD

Quantum Chromodynamics

Proton is colourless
Contains 3 quarks



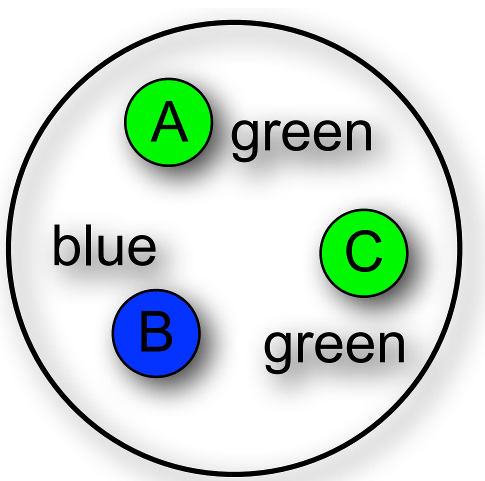
Perform global colour transform r ⇔ g

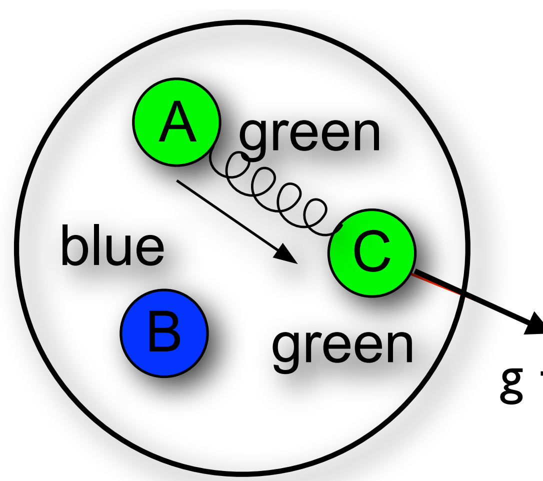


Proton is colourless
No observable difference

Perform <u>local</u> colour transform r ⇔ g at one quark only

A emits $r\bar{g}$ gluon
C absorbs gluon to become r



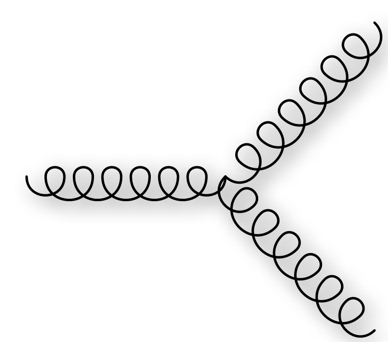


$g + r\bar{g} \rightarrow r$

Local transformations yield gluon exchange

Gluons "carry" the strong force

Since gluons are coloured they self-interact

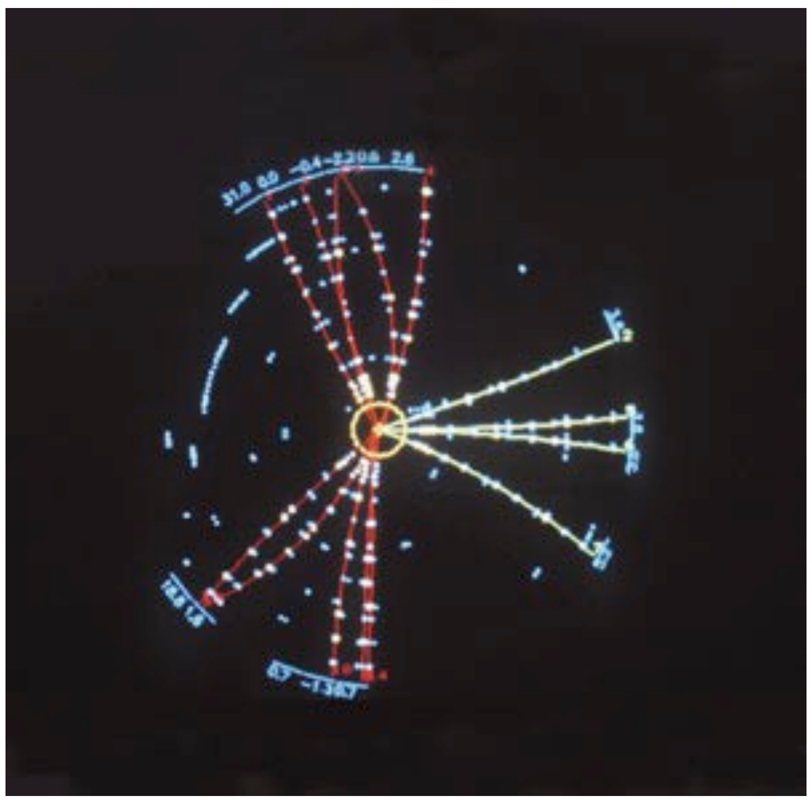


Proton has gained colour
Need to make it colourless again

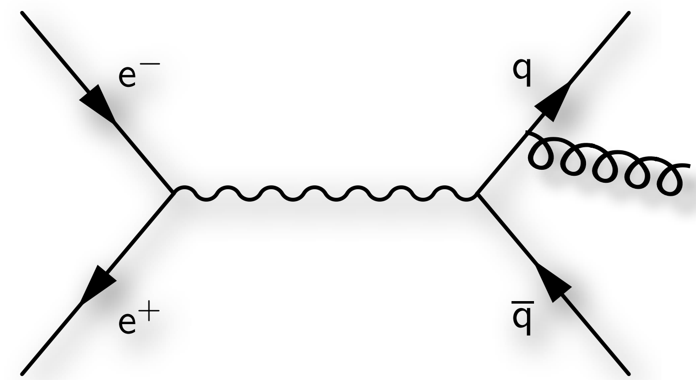
Modify equations to force no colour
Introduce a spin 1 field with colour & anti-colour

TASSO experiment 1979 at DESY

$$e^+e^- \rightarrow q\bar{q}g$$



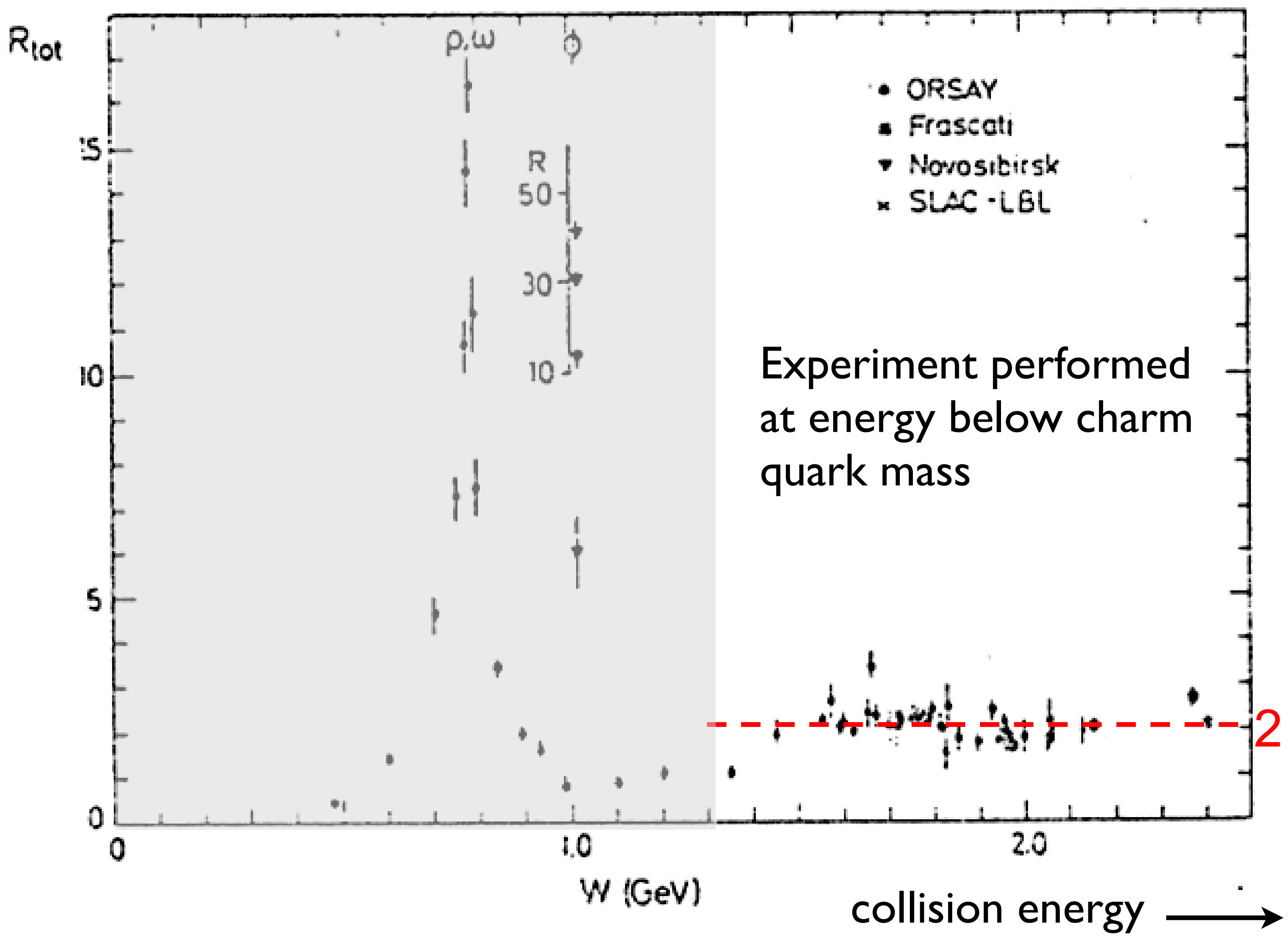
First evidence for the gluon



This 3-jet event demonstrates existence of gluons
As quark is accelerated it radiates a gluon

Measurement of angular distribution of jets confirms gluons are spin 1 particles

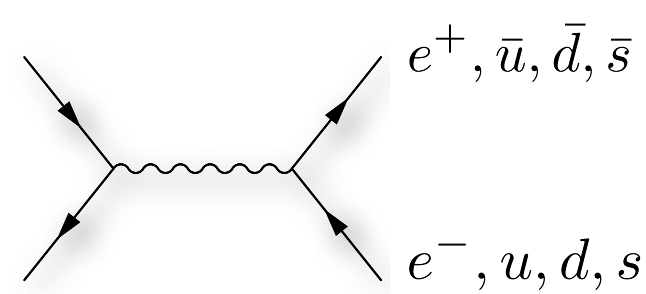
Gluons make up the missing 50% of proton's momentum



Experiments observed fragmenting quarks
but...
how do we know colour exists?

Measure reaction rate ratio:

$$R = \frac{e^+e^- \to q\bar{q}}{e^+e^- \to \mu^+\mu^-}$$

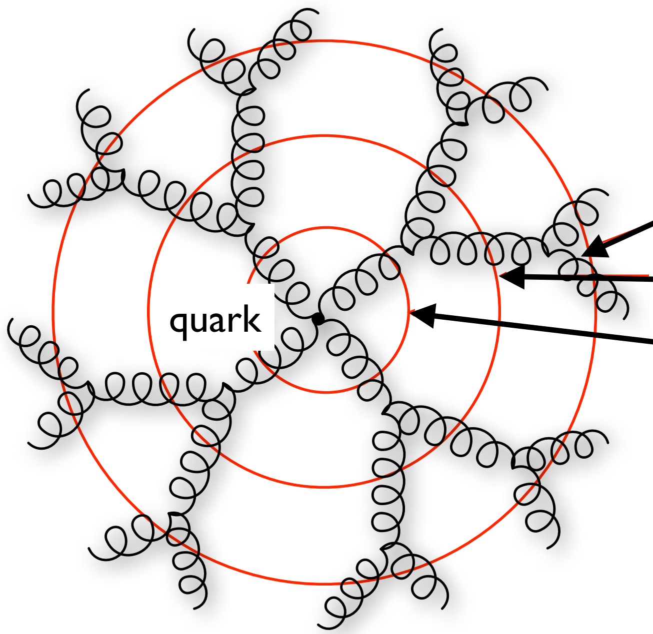


Calculate Feynman diagrams. In the ratio everything cancels except coupling (i.e. charge) and number of quarks

$$R = \frac{(\frac{2}{3})^2 + (\frac{1}{3})^2 + (\frac{1}{3})^2}{1^2} = \frac{2}{3}$$ since u,d,s quarks have charges of $^2/_3$, $^1/_3$ and $^1/_3$

But: quarks come in 3 colours, so we need to multiply by 3 for each red, green and blue quark

Colour predicts R = 2
Well verified by experiment!



16 gluons

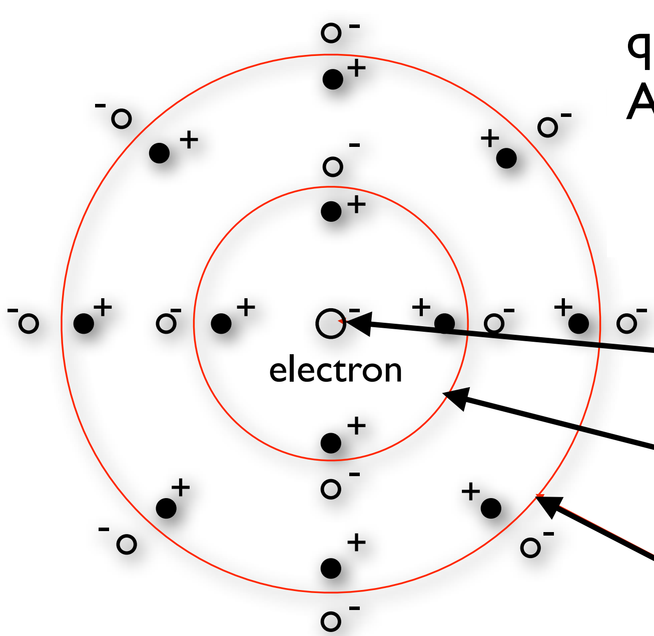
12 gluons

4 gluons

Probing smaller distances
(i.e. higher energies)
we see less gluons!
Strong force get weaker

At low energy the strong force binds quarks into colourless objects - “confinement”
At high energy strong force is feeble and quarks are ‘free’ - “asymptotic freedom”

At low energy an electron’s charge Q is ‘screened’ by quantum fluctuations of the vacuum - many e^+e^- pairs formed
At high energy less screening occurs - EM force is stronger



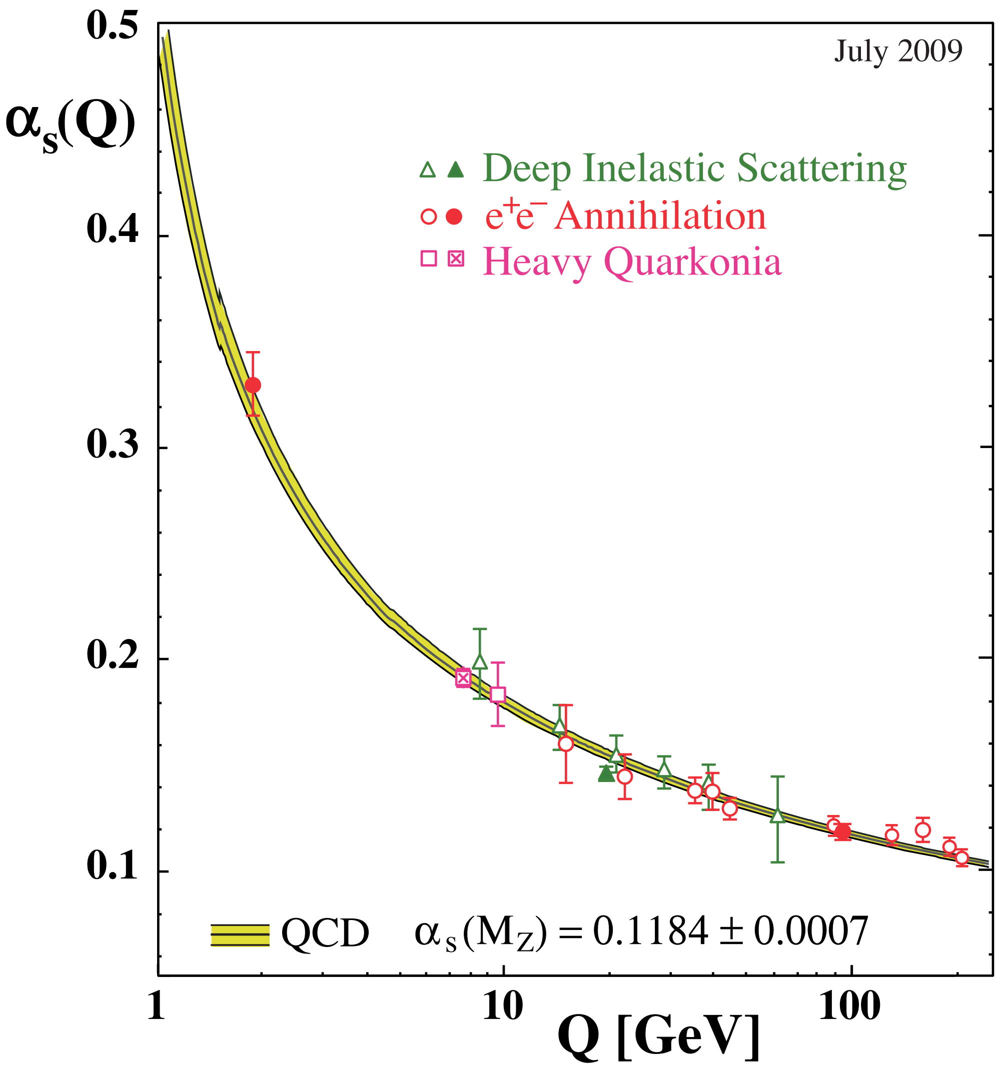
charge = -Q

charge = -Q + $4q^+$

charge = -Q + $8q^+$

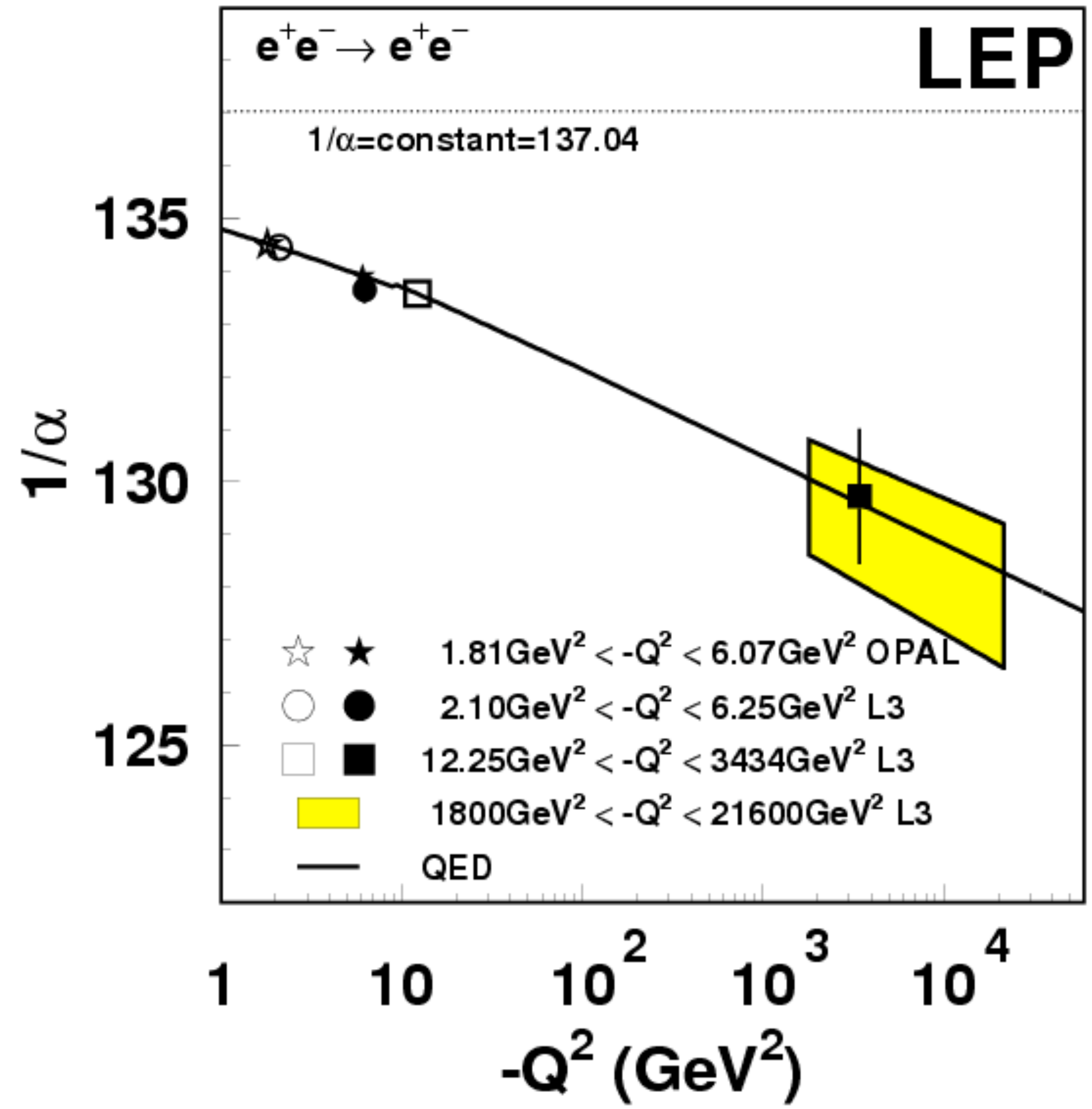
Probing smaller distances
(i.e. higher energies)
we see more electron charge
EM force get weaker

Strong Coupling



Momentum Transfer

Electromagnetic (inverse) Coupling



The strong force coupling decreases with increasing energy

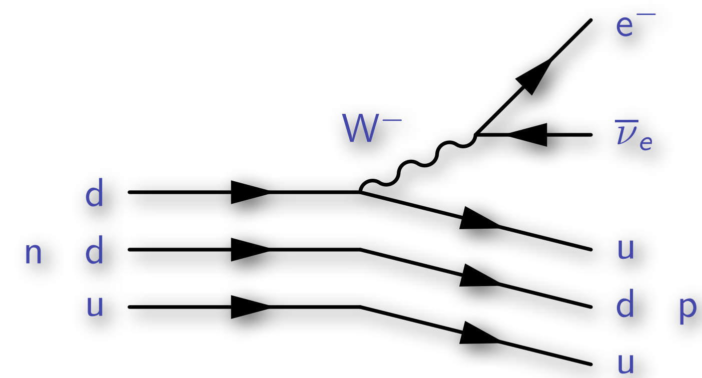
This is why quarks are 'free' at high energy
and bound into composite particles at low energy

The electromagnetic force coupling increases with increasing energy

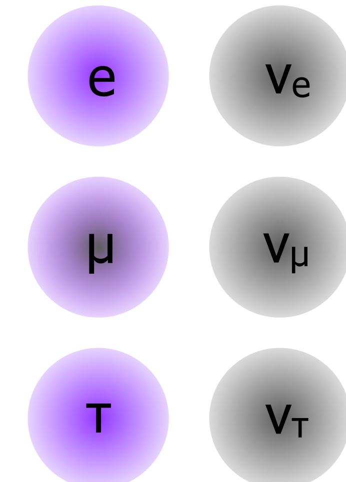
The Weak Force

The weak force is mediated by $W^{\pm}$ and Z^0 bosons
Beta decay is due to weak interactions

All particles experience weak force except gluons



3 flavours of charged lepton
3 flavours of neutrino



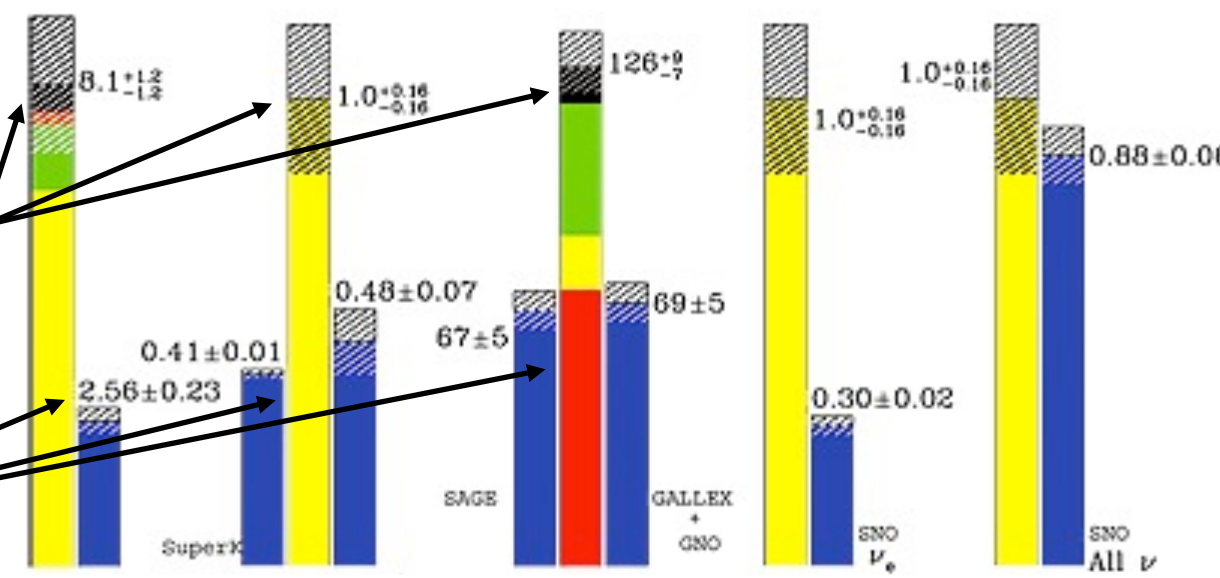
Neutrinos only interact via weak force ⇒ very inert

involved in weak beta decays powering solar fusion
Solar neutrino flux is large ~ 10^6 through your thumbnail every second!

Sun produces calculable rate of ν_e
measure ~30% less than expected

calculated rate

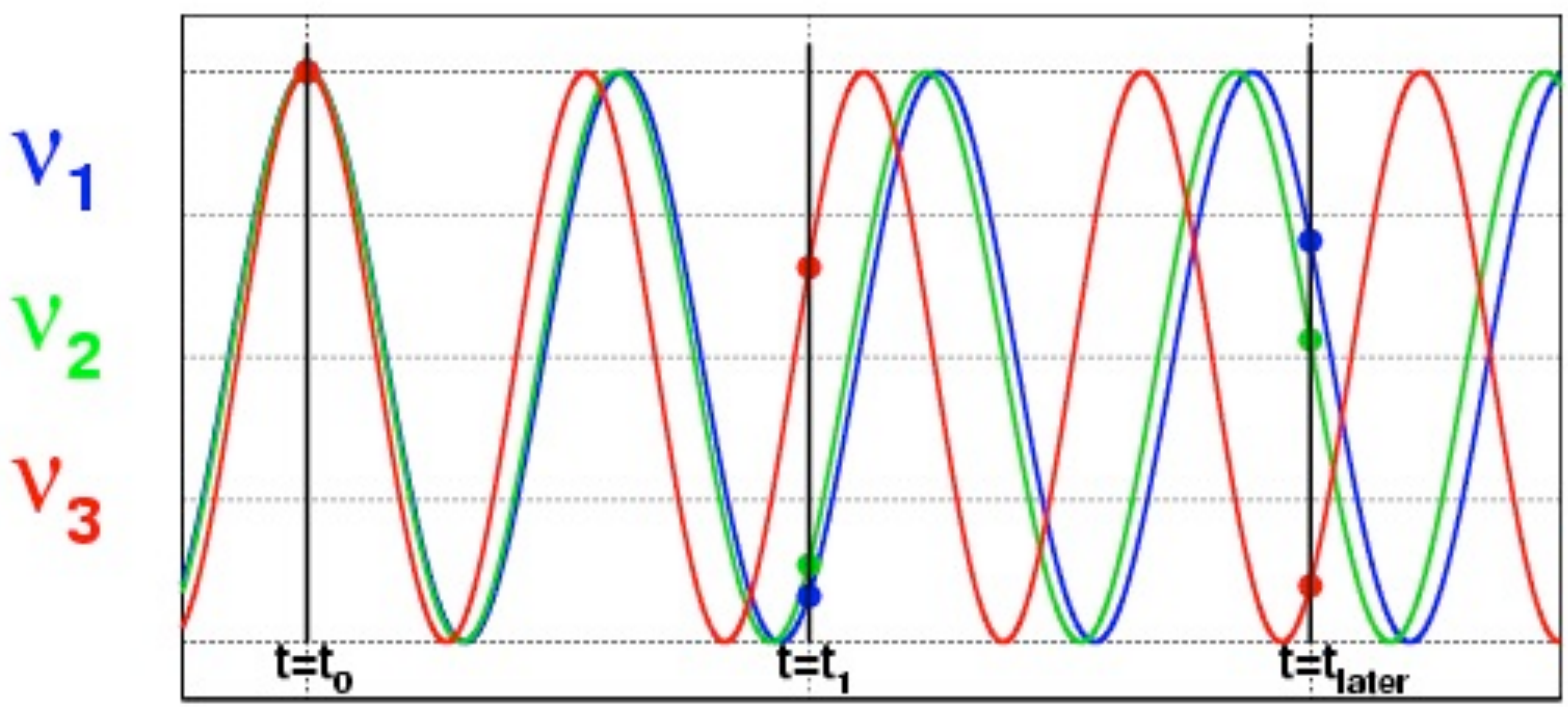
measured rates



Experiments sensitive to different neutrino flavours

sensitive to all flavours!

We assumed neutrinos of fixed flavour have fixed mass
This does not need to be the case
Can describe neutrino wave functions by an alternative <u>but equivalent</u> set of wave functions
Purely quantum mechanical effect
One set has definite flavour but indefinite mass (ν_e ν_μ ν_τ)
One set had definite mass but indefinite flavour (ν_1 ν_2 ν_3)



defined:
•total flow rate
•temperature

defined:
•hot flow rate
•cold flow rate

Solar neutrinos are produced as electron neutrinos: ν_e
These oscillate into different flavours as they propagate to Earth
Only experiments sensitive to all flavours of neutrino see full solar neutrino flux

But both are equivalent

The Standard Model

Fermions

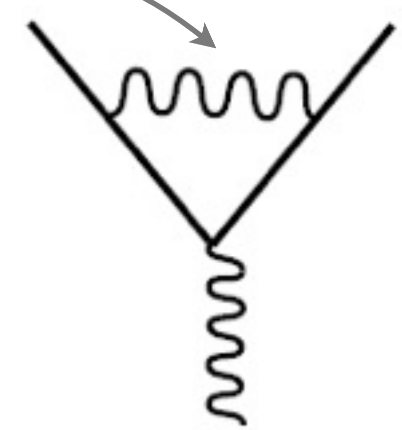
	Quarks						Leptons		
	+2/3			-1/3			-1	0	
	u	u	u	d	d	d	e	ν_e	I
	c	c	c	s	s	s	μ	ν_μ	II
	t	t	t	b	b	b	τ	ν_τ	III

Bosons

g g g g g g g g	8 gluons
W Z γ	3 electroweak bosons
H	1 higgs boson

The Standard Model

Quantum mechanics predicts the gyromagnetic ratio of the electron g=2
(ratio of magnetic dipole moment to it's spin)



Experiment measures g_{exp}=2.0023193043738 ± 0.0000000000082

Discrepancy of g-2 due to radiative corrections

Electron emits and reabsorbs additional photons

Corresponds to higher terms in perturbative series expansion

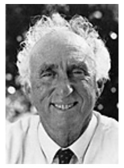
$$\frac{g_{theory} - 2}{2} = 0.0011596521400 \pm 0.0000000000280$$

$$\frac{g_{exp} - 2}{2} = 0.0011596521869 \pm 0.0000000000041$$

Phenomenal agreement between theory and experiment! 4 parts in 10^8
QED (quantum electrodynamics) is humanity's most successful theory
Demonstrates understanding of our universe to unprecedented precision

Equivalent to measuring distance from me to centre of moon
and asking if we should measure from top of head or my waist!

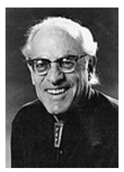
The Standard Model


Perl


Gross


Rubbia

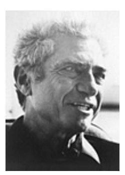

van der Meer


Reines


Lederman


Gell-man

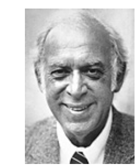

Cronin


Steinberger


Feynman

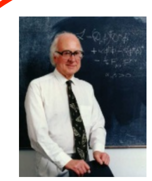

Glashow


Taylor

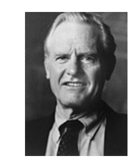

Friedman


Hofstadter


Schwinger


Higgs

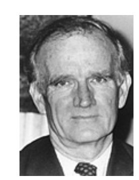

Veltman


Kendall


Politzer


Ting


Alvarez


Fitch


Schwarz


Richter


Weinberg

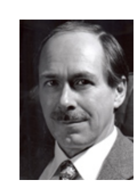

Yang

29 Nobel prizes awarded for the Standard Model


Wilczek


Salam


Lee


t'Hooft

1 more yet to come?

The Standard Model

$$
\begin{gathered}
-\frac{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 - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu\partial_\nu W^-_\mu - \\
M^2W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \\
\frac{1}{2}m_h^2H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{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)] - \frac{1}{2}g^2W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2s_wc_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^-] - \\
\frac{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 - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{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)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_wMA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2s_wA_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2s_wA_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1s_w^2A_\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 - \bar{d}^\lambda_j(\gamma\partial + \\
m_d^\lambda)d^\lambda_j + igs_wA_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \frac{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(\frac{4}{3}s_w^2-1-\gamma^5)u^\lambda_j) + \\
(\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{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)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)] + \\
\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
i\phi^0(\bar{e}^\lambda\gamma^5e^\lambda)] + \frac{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] + \frac{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] - \\
\frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5d^\lambda_j) + \\
\bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2Y + \\
igc_wW^+_\mu(\partial_\mu\bar{X}^0X^- - \partial_\mu\bar{X}^+X^0) + igs_wW^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+Y) + \\
igc_wW^-_\mu(\partial_\mu\bar{X}^-X^0 - \partial_\mu\bar{X}^0X^+) + igs_wW^-_\mu(\partial_\mu\bar{X}^-Y - \partial_\mu\bar{Y}X^+) + \\
igc_wZ^0_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) + igs_wA_\mu(\partial_\mu\bar{X}^+X^+ - \partial_\mu\bar{X}^-X^-) - \\
\frac{1}{2}gM[\bar{X}^+X^+H + \bar{X}^-X^-H + \frac{1}{c_w^2}\bar{X}^0X^0H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+X^0\phi^+ - \\
\bar{X}^-X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-] + igMs_w[\bar{X}^0X^-\phi^+ - \\
\bar{X}^0X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0]
\end{gathered}
$$

This equation is the sum of all ‘small’ perturbations V’ describing all interactions of quarks and leptons and the electroweak and strong gauge fields

Welcome to the Standard Model of particle physics!