Introduction to Particle Physics

(for non physics students)

3. FORCES

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FORCES

Gravity

Electromagnetic. Weak. Strong

 ep in H atom

$$\frac{\text{Gravity P.E.}}{\text{Electromag}} \simeq 10^{-40}$$

c.f. size of proton $\simeq 10^{-15}$ m.

size of univ. $\lesssim 10^{10}$ yr. $\times 10^{16}$ m yr^{-1}

$\lesssim 10^{26}$ m.

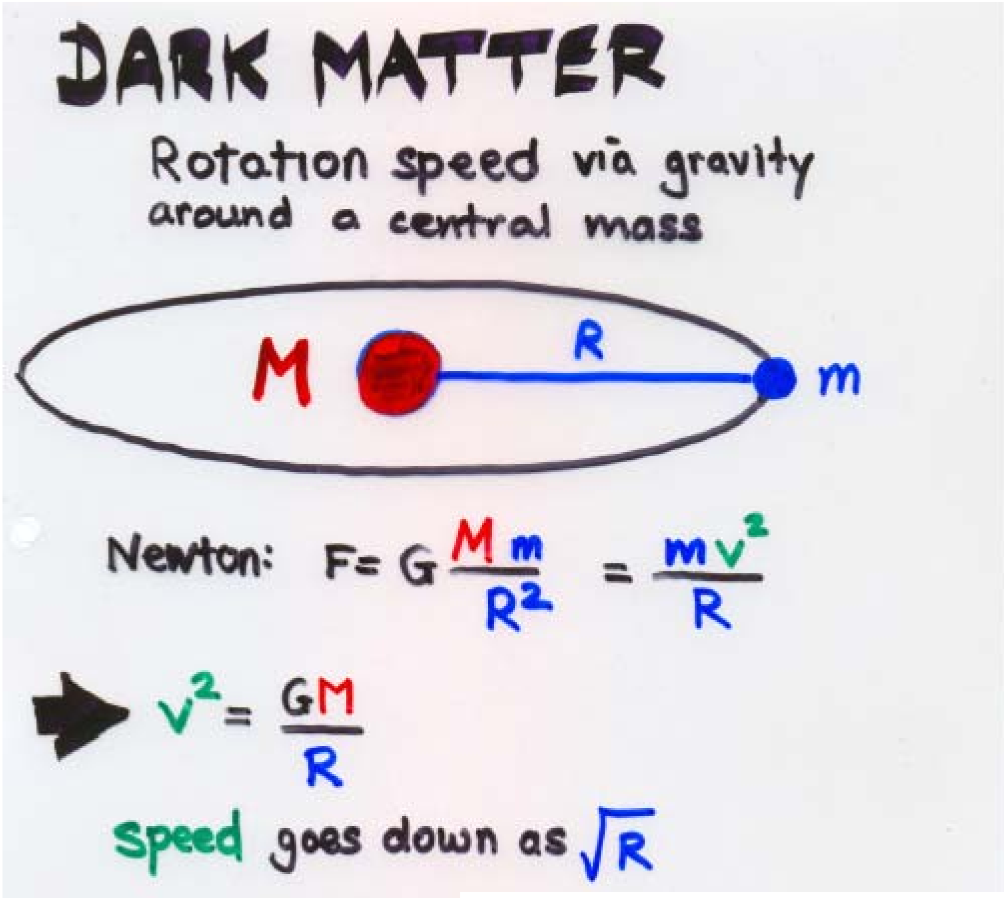
$$10^{-40} \simeq \frac{\text{Radius of proton}}{\text{Radius of Universe}}$$

→ Ignore Gravity for individual particles at present energies

(10^{-35} m length or 10^{19} GeV grav. strong ....)

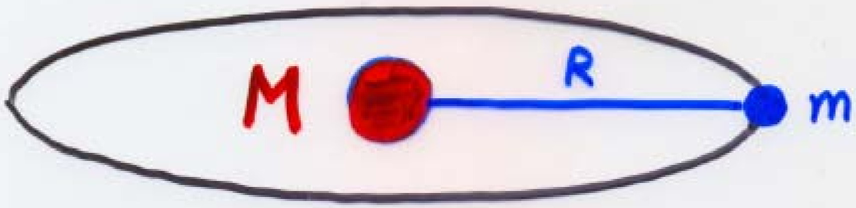
GRAVITY

Gravity wins for large bodies and reveals surprises that may link with particles



DARK MATTER

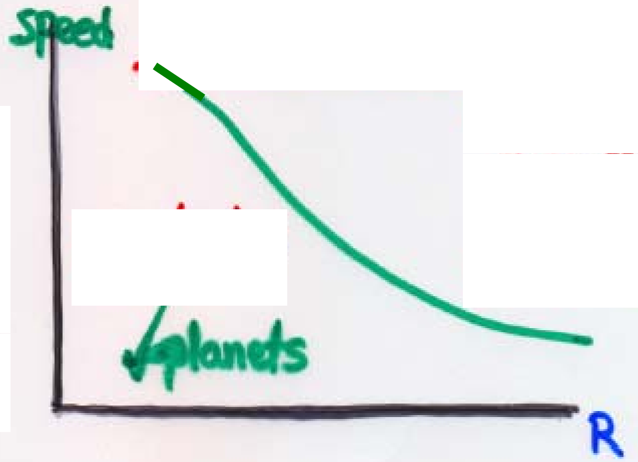
Rotation speed via gravity around a central mass



Newton: $F = G\frac{Mm}{R^2} = \frac{mv^2}{R}$

$\Rightarrow v^2 = \frac{GM}{R}$

speed goes down as $\sqrt{R}$



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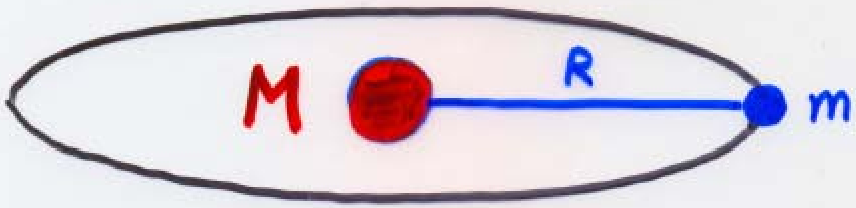

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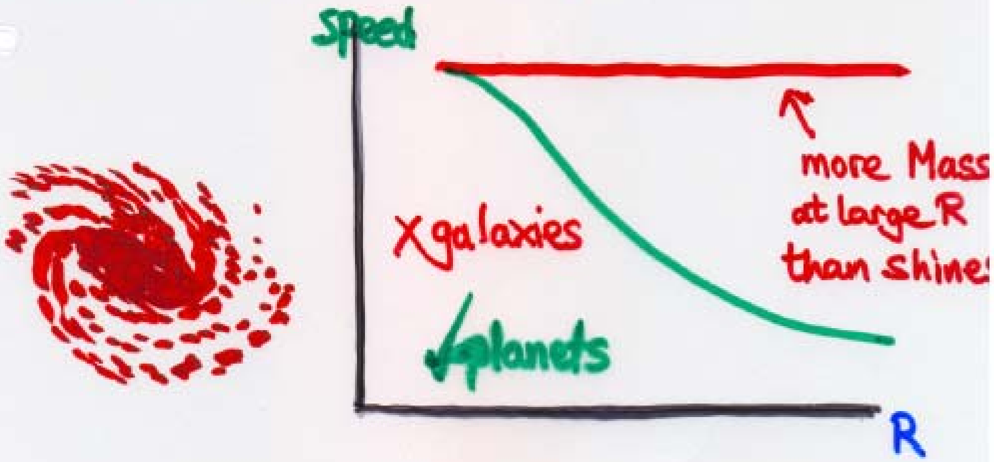
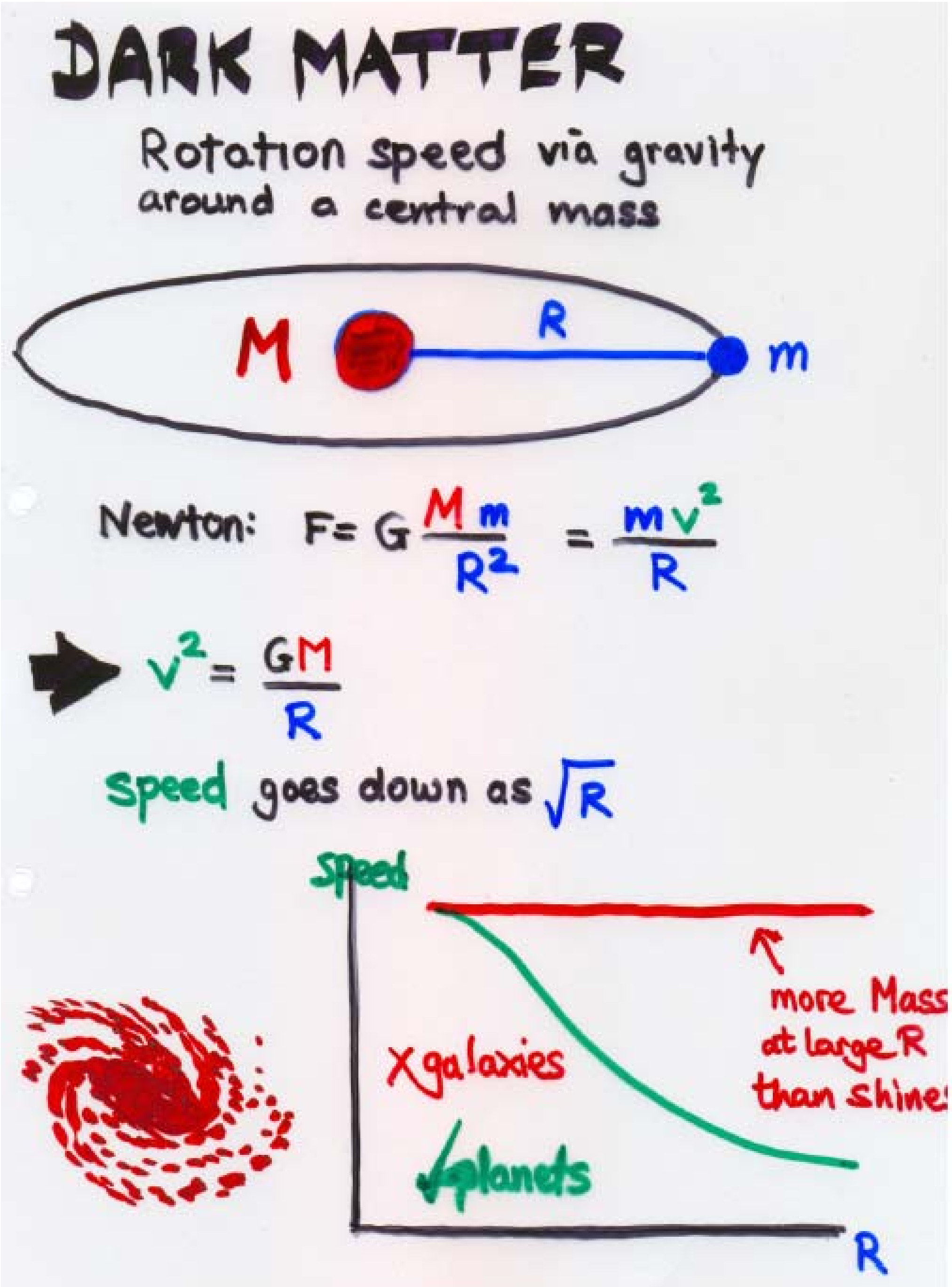




What is dark matter?

Electrically neutral.

Hot DM – lightweight like neutrinos

Cold DM – heavyweight
Maybe SUSY (next lecture)

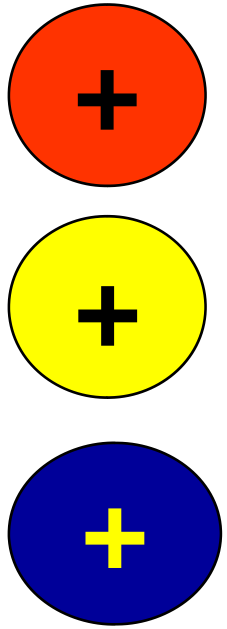
Colour and the Strong Force

How quarks work:

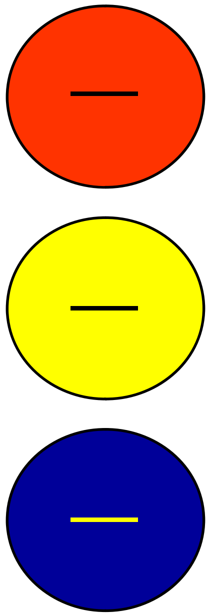
CHROMOSTATICS

(like electrostatics but with three types of + (-) charges)

Three colour charges



Quarks “positive”

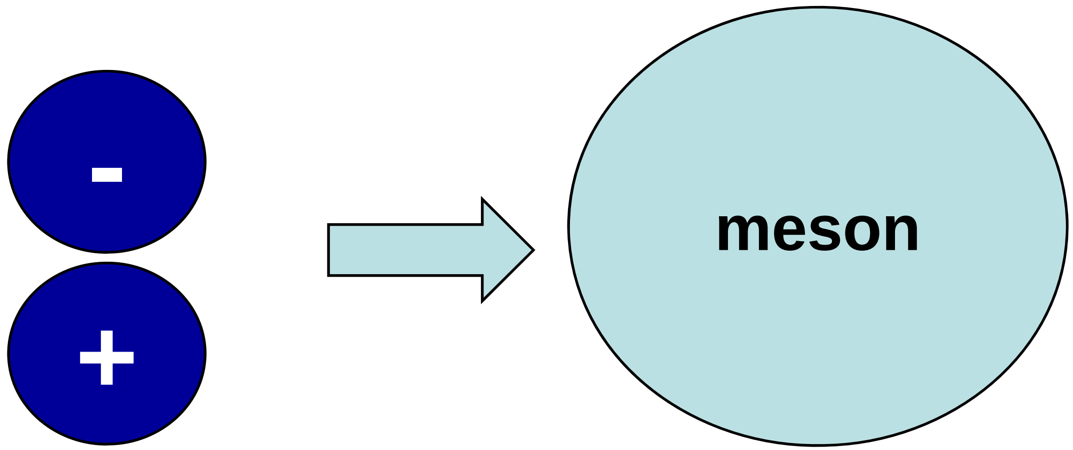


Antiquarks “negative”

Now use familiar rules

“Like charges (colours) repel;
opposite (colours) attract”

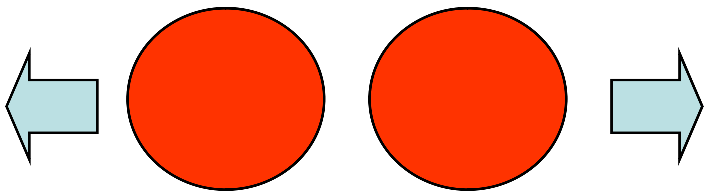
Simplest state: QQ* Meson

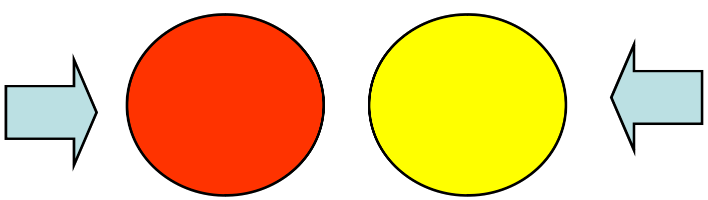


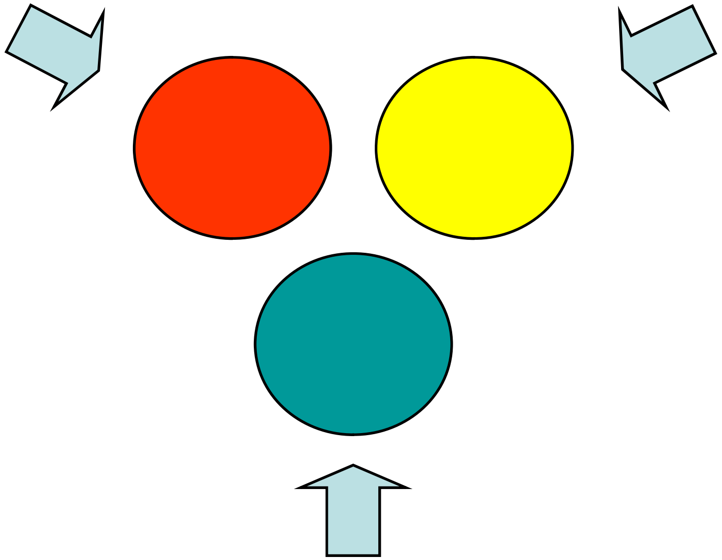
The THREE colours

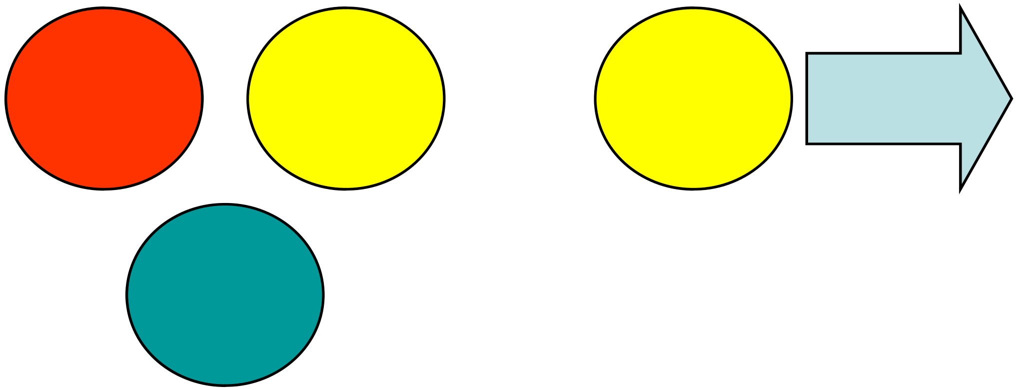
enable quarks to attract one another

making BARYONS (e.g. the proton)

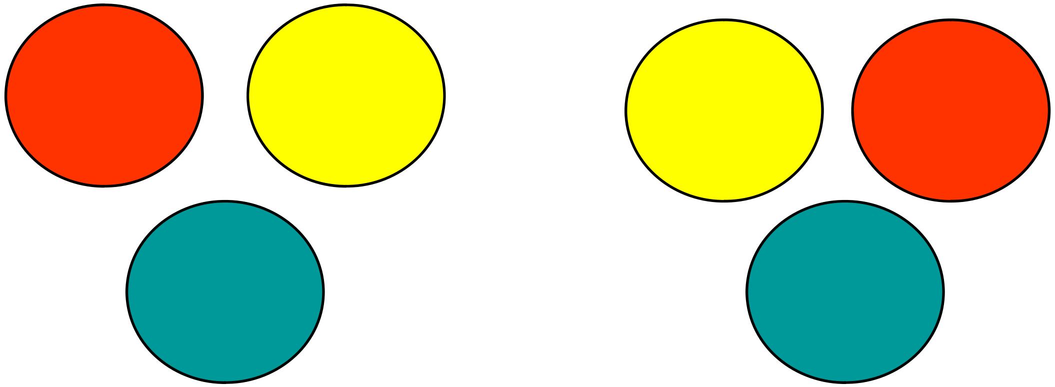








Three colour charges neutralise
Makes baryon (e.g. proton)



Simple nucleus (deuteron)

Electric charge ⇨ Atoms ⇨ Molecules

Colour charge ⇨ Baryons ⇨ Nucleus

Quantum Electrodynamics: QED

Electric charge ➡ Atoms ➡ Molecules

Quantum Chromodynamics: QCD

Colour charge ➡ Baryons ➡ Nucleus

Quantum Electrodynamics: QED

Electric charge ⇨ Atoms ⇨ Molecules

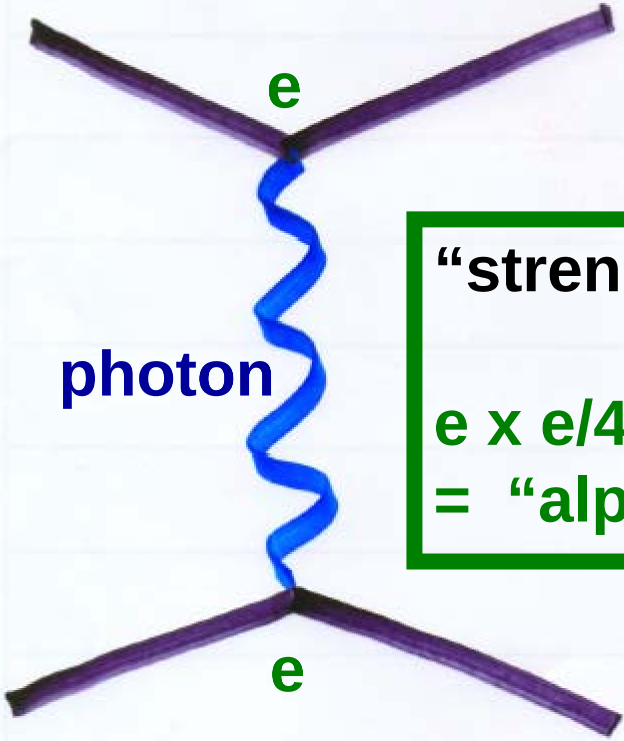
Interaction of electric charges and photons

Quantum Chromodynamics: QCD

Colour charge ⇨ Baryons ⇨ Nucleus

Interaction of colour charges and gluons

Feynman diagrams for electromagnetic interaction

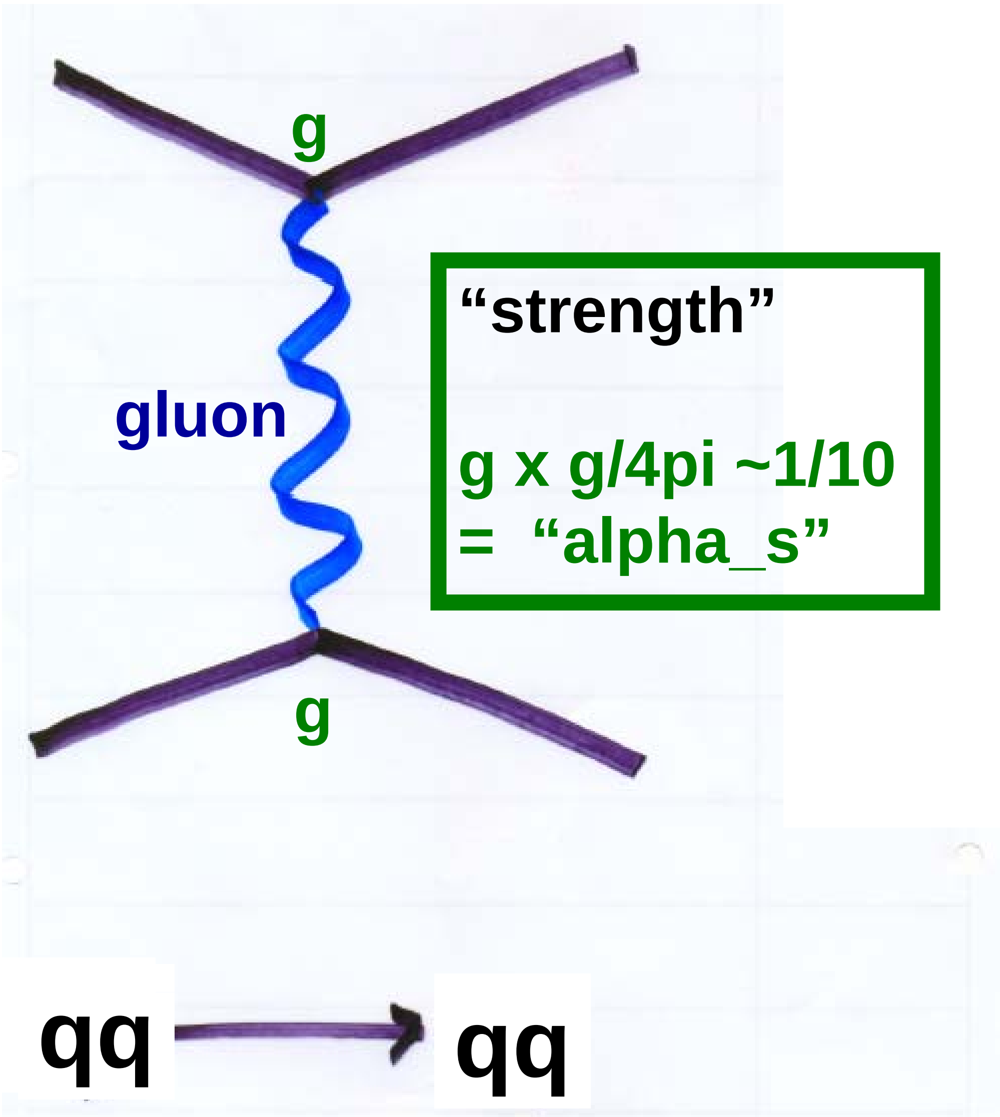


"strength"

e x e/4pi = 1/137
= "alpha"

ee → ee

Feynman diagrams for chromomagnetic interaction



"strength"

g x g/4pi ~1/10
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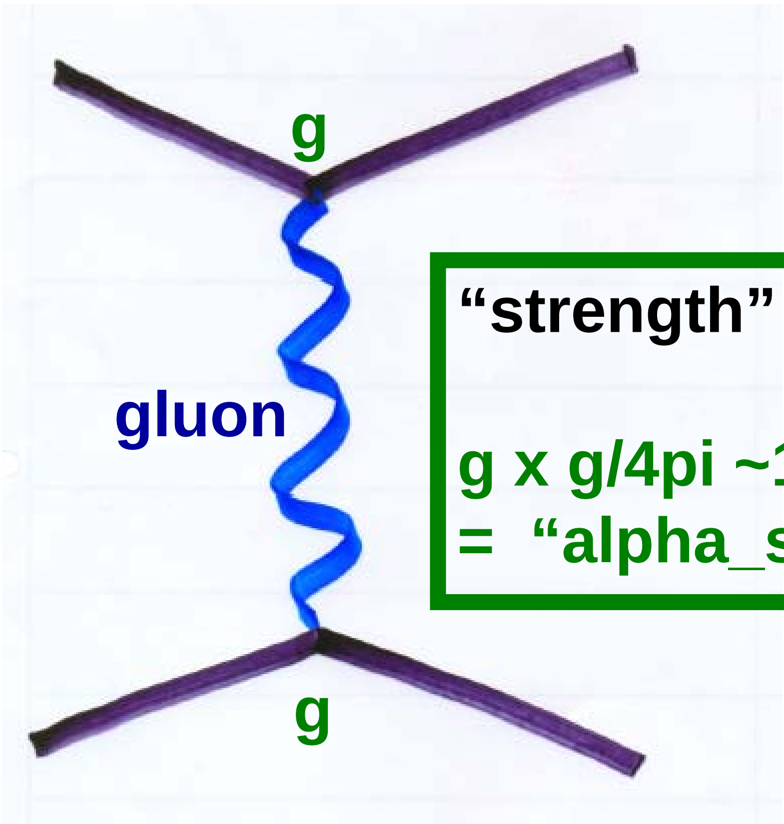

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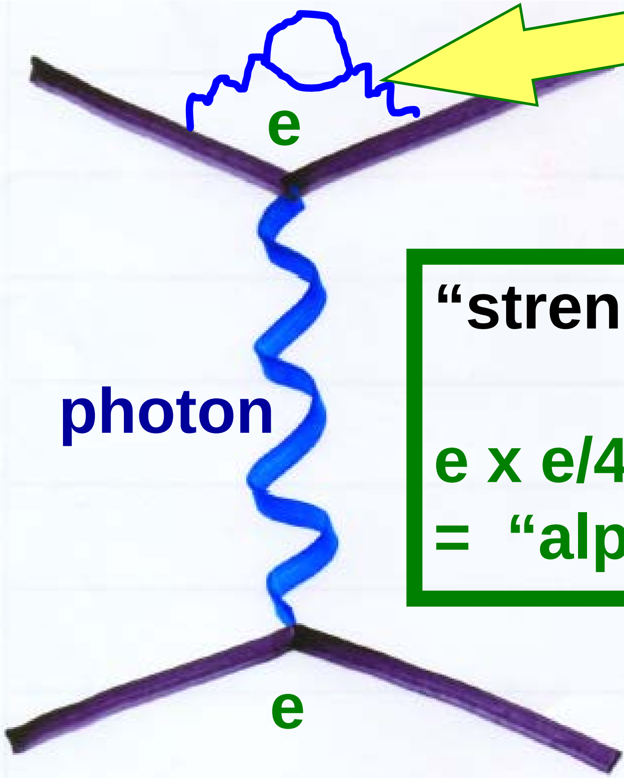
Feynman diagrams for electromagnetic interaction



Quantum effects
Virtual e+e- pairs…
Resolved at high p
“alpha” varies with p

“strength”

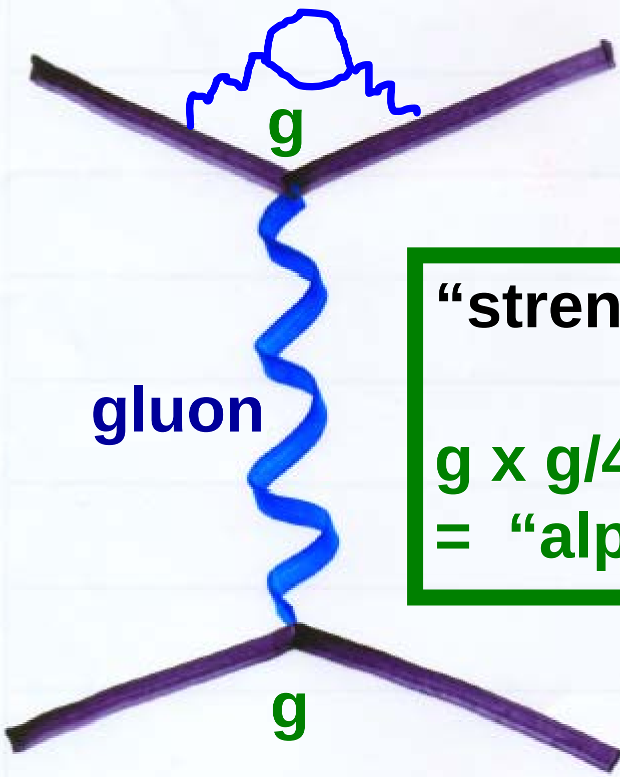
e x e/4pi = 1/137
= “alpha”

(when p --> 0)

“alpha” grows with p
~ 1/128 at p ~ 100Gev

ee → ee

Feynman diagrams for chromomagnetic interaction



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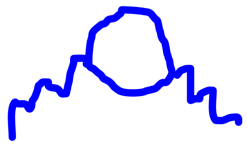
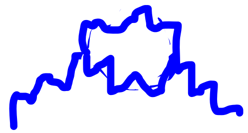
Like QED, QCD has



and also



“alpha_s” **falls** with p
= is **big** at **small p**
“STRONG” force
= **small** at **large p**
“pQCD” in HEPhys

Quantum Electrodynamics: QED

Electric charge → Atoms → Molecules

Interaction of electric charges and photons

“alpha” = 1/137 small; perturbation; 12 places of decimals

Quantum Chromodynamics: QCD

Colour charge → Baryons → Nucleus

Interaction of colour charges and gluons

Quantum Electrodynamics: QED

Electric charge ⇨ Atoms ⇨ Molecules

Interaction of electric charges and photons

“alpha” = 1/137 small; perturbation; 12 places of decimals

Quantum Chromodynamics: QCD

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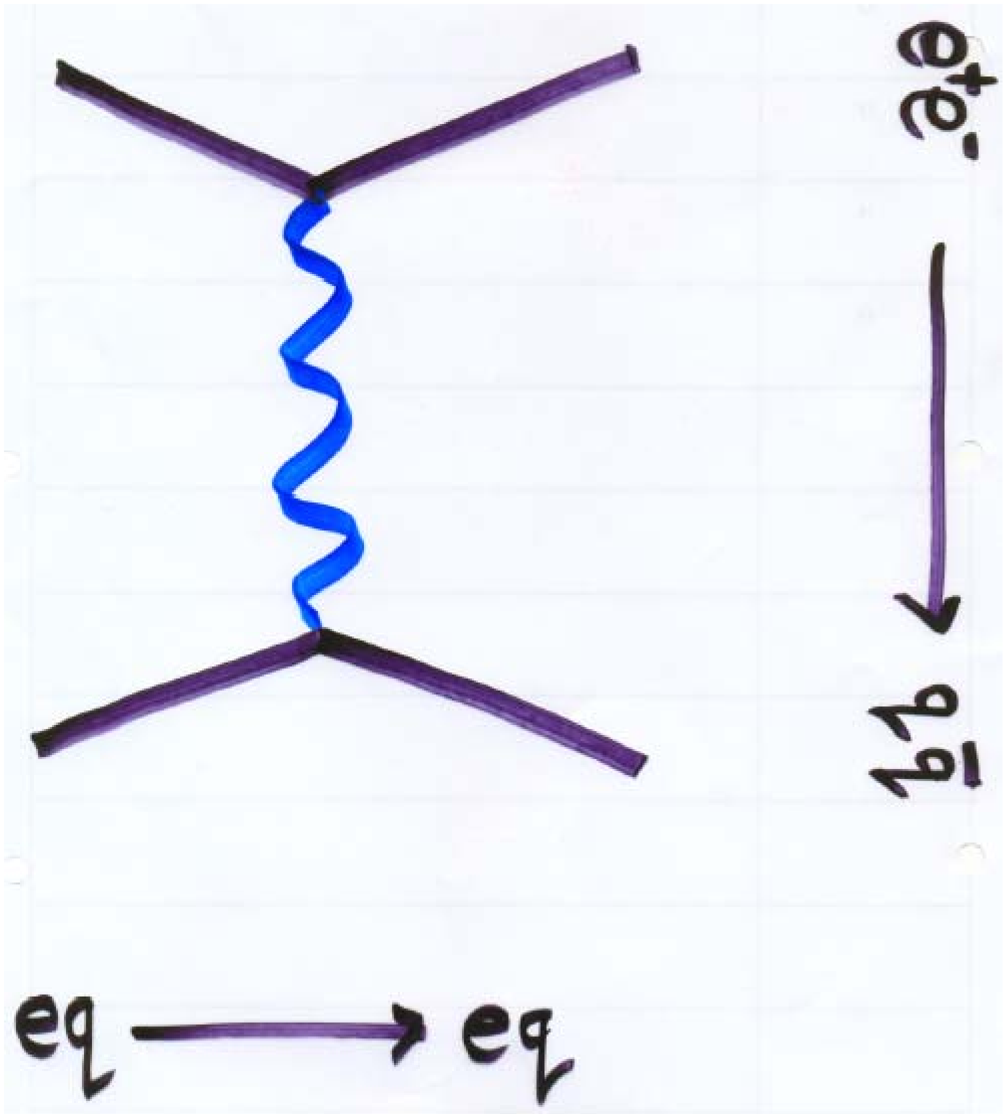
Interaction of colour charges and gluons

short distance: high momentum
“alpha” = 1/10 small; perturbation; “pQCD” v.precise

hadron size: low momentum “alpha” = large. lattice/models

Feynman diagrams for electromagnetic interaction



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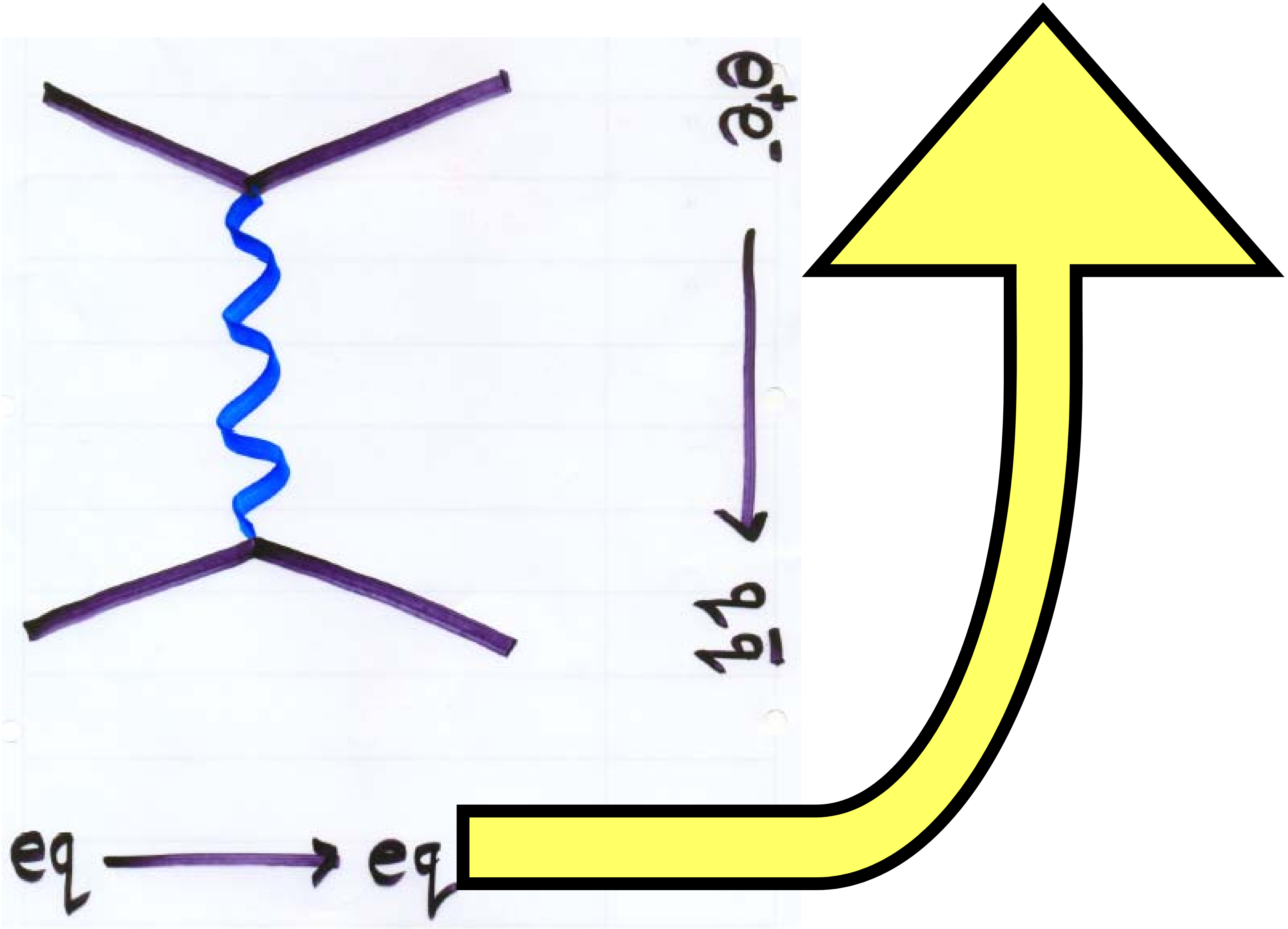

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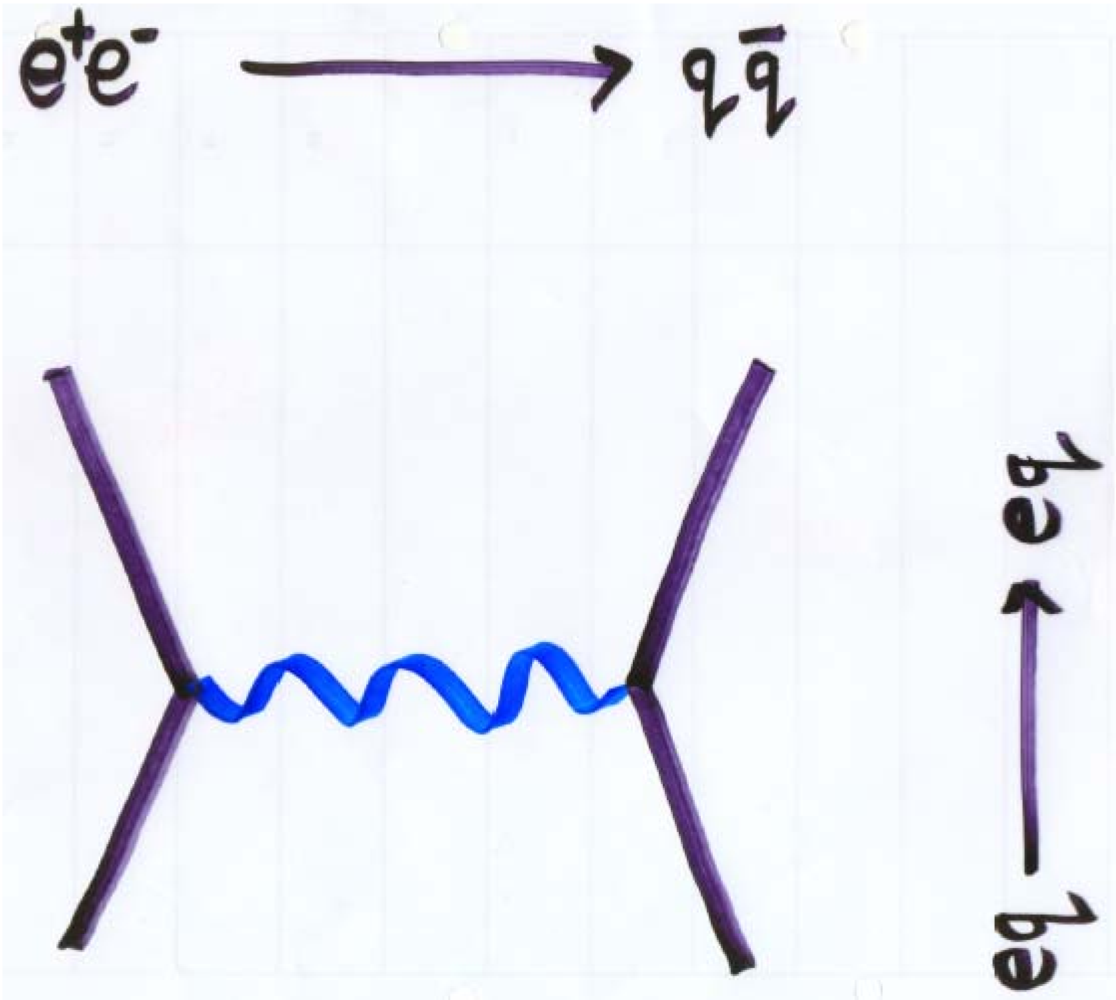


Photon	**Emag**
Gluon	**Strong**

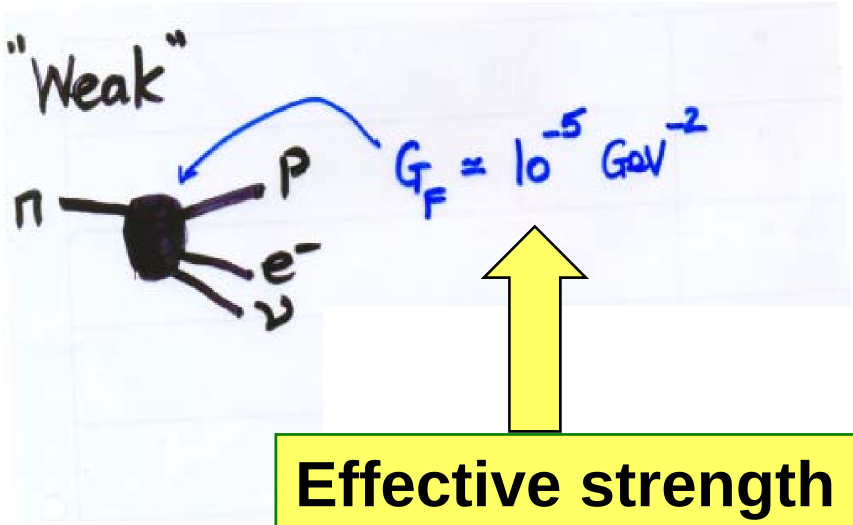
Feynman diagram for QCD analogous

QED: electron; positron; photon
QCD: quark; antiquark; gluon

The Electroweak Story

Part 1: The WEAK Force

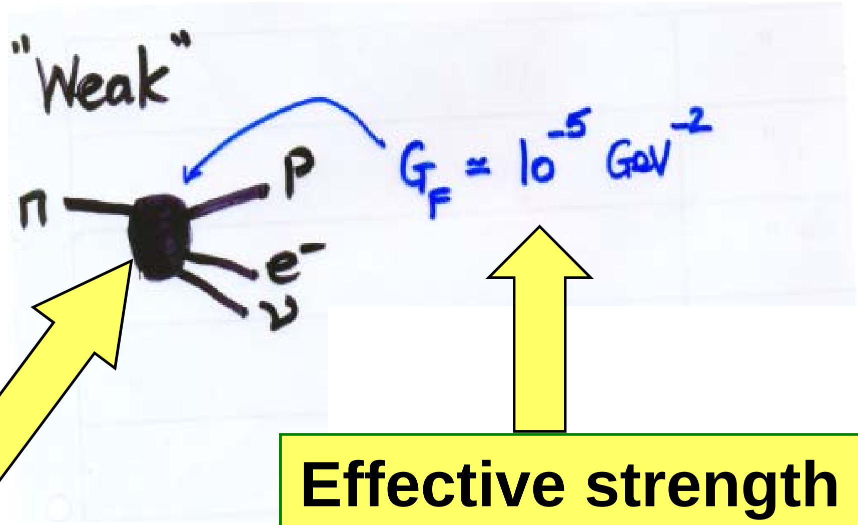
Fermi model (1934) of neutron beta decay



Effective strength "G_F " "Fermi constant" deduced by observed rate of beta decay.

Empirical.
No theory (1934)
Small = feeble = "weak"

Fermi model (1934) of neutron beta decay



Now look into the black box with a modern high resolution microscope and reveals W-boson being exchanged

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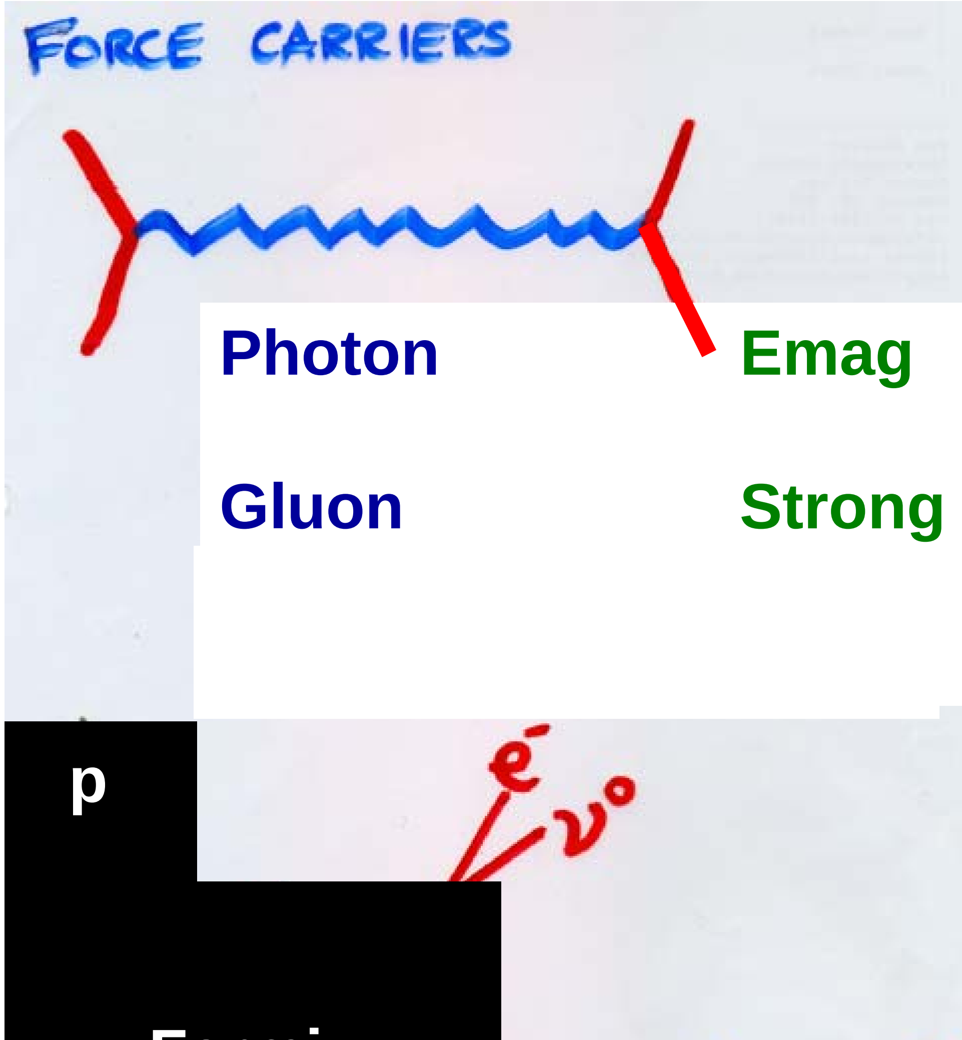


Photon Emag

Gluon Strong

p

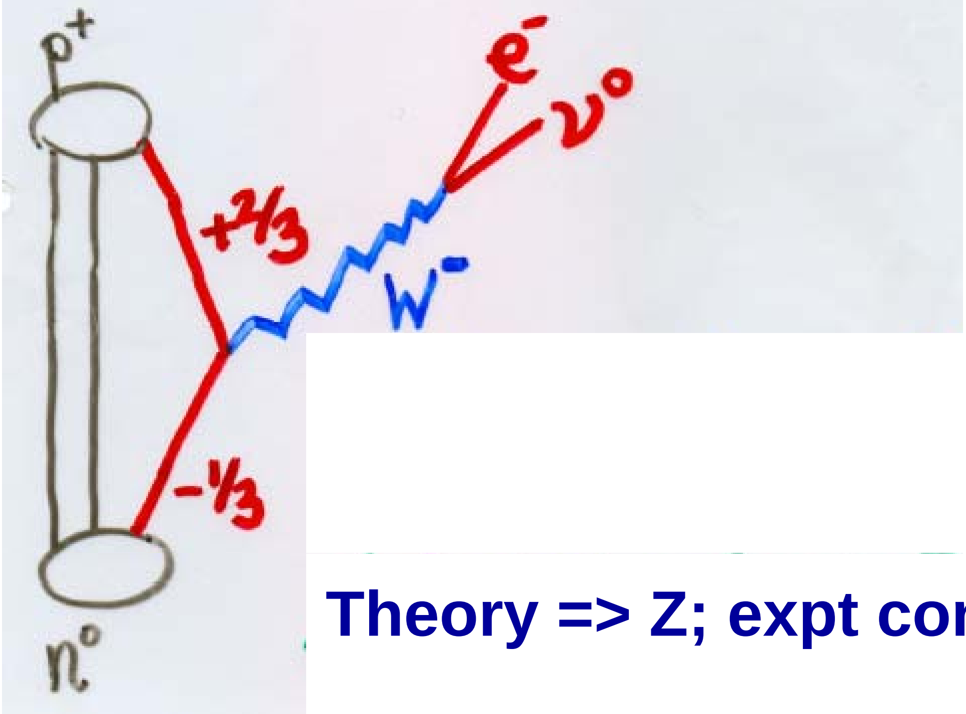
Fermi model

n

Photon Emag

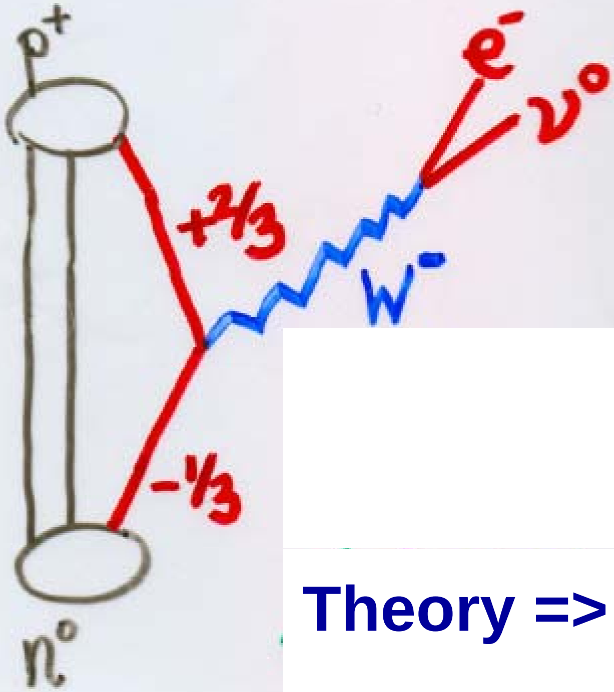
Gluon Strong

W Weak



Theory => Z; expt confirmed

Photon	**Emag**	**m= 0**
Gluon	**Strong**	**m= 0**
W	**Weak**	**m= 80 x proton**



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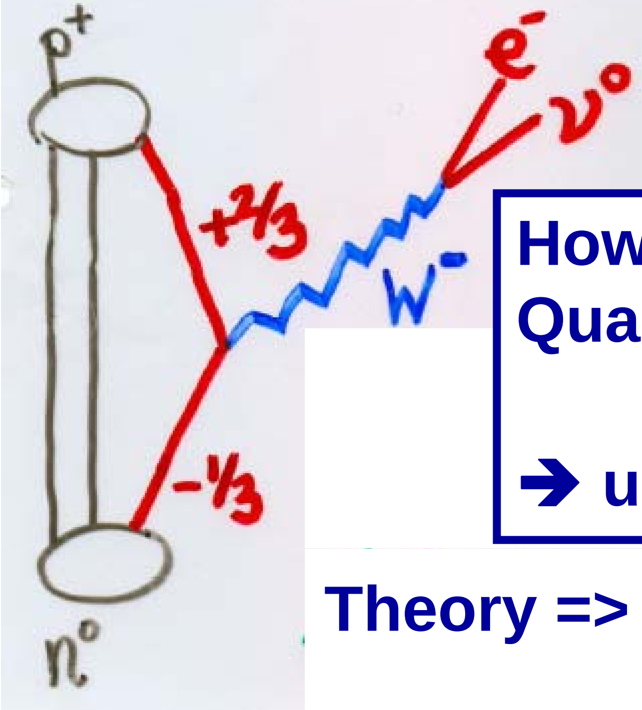


How can 1 eject 80?
Quantum weirdness: Heisenberg uncertainty

➔ unlikely ➔ "weak"

Theory => Z; expt confirmed

The Electroweak Story

Part 2: History and Unity

“Weak force as Electromagnetism in disguise”

The Electroweak Story

1864

Maxwell unifies electricity and magnetism

→ electromagnetism

100 years later

Glashow Salam Weinberg propose unification of Electromagnetic and weak

electro-weak

They use Higgs mechanism

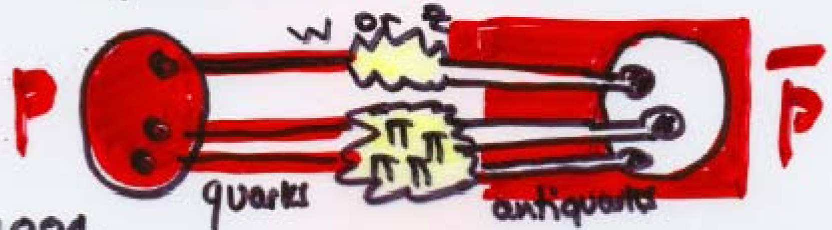
→ predict force carriers

W^+ W^- Z^0

→ masses predicted. ($m_\gamma = 0$)!

1983–84

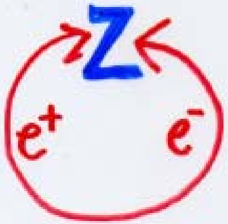
W and Z particles found by CERN experiments UA1 + UA2



1984

Rubbia + van der Meer → Nobel Prize

1989–95



Tune $E_+ + E_- = M_Z c^2 \simeq 91\,\text{GeV}$

LEP 4 experiments
20 million Z^0

Z unstable. Decays "democratically" to

$q\bar{q}$ e^+e^- $\mu^+\mu^-$ $\tau^+\tau^-$

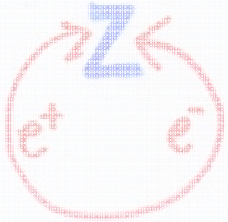
$\nu_e\bar{\nu}_e$ $\nu_\mu\bar{\nu}_\mu$ $\nu_\tau\bar{\nu}_\tau$ .....

$\frac{1}{\text{Life}}$ ~ # of holes

⇒ # of decay paths

Perfect match if $\#\nu = 3$

1989-95



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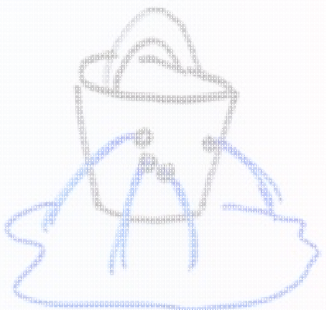

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Perfect match if #ν = 3

Z Lifetime

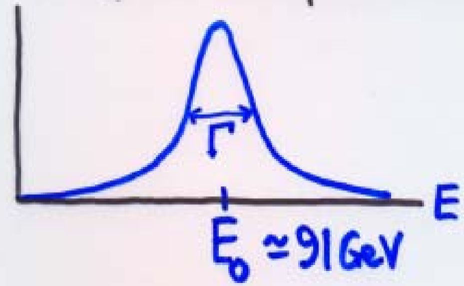
Heisenberg Uncertainty Principle

$$\Delta E \, \Delta t \simeq \hbar \approx 6 \times 10^{-25} \text{ GeV sec}$$

example Δt = lifetime of unstable particle

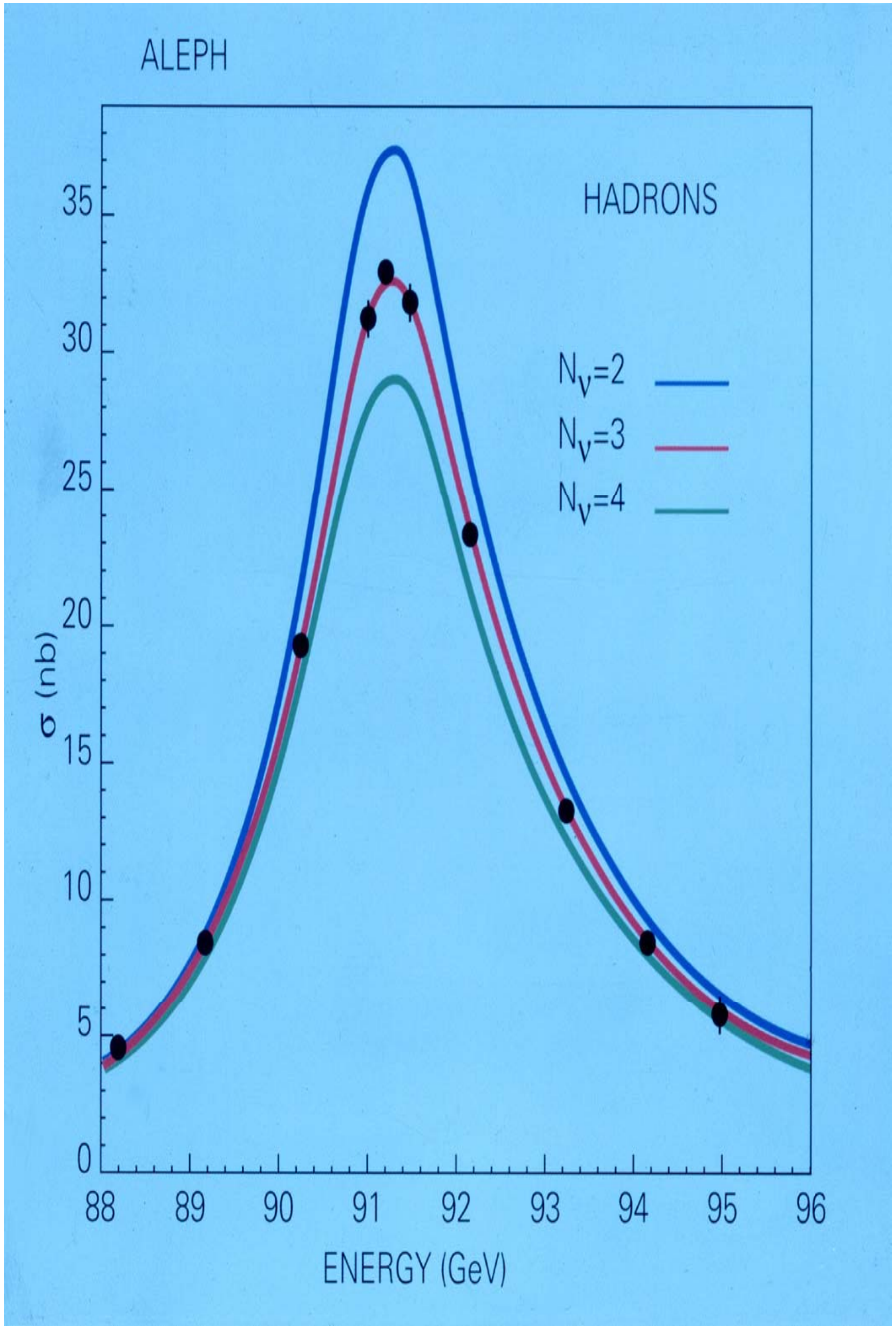
$$\Rightarrow \Delta E = \Delta M c^2 = \frac{6 \times 10^{-25} \text{ GeV}}{\Delta t \text{ (sec)}}$$

$e^+e^- \to Z$ (production probability)



$\Gamma = \Delta E = 2.5$ GeV

$\Rightarrow$ Lifetime $\simeq 10^{-25}$ sec



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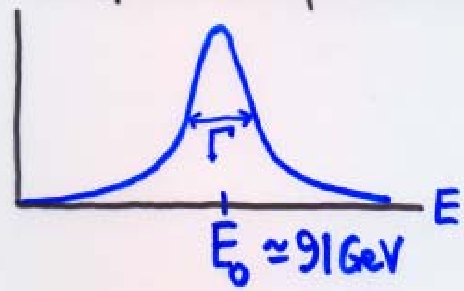

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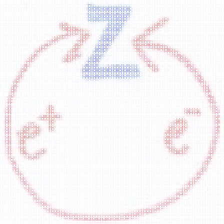

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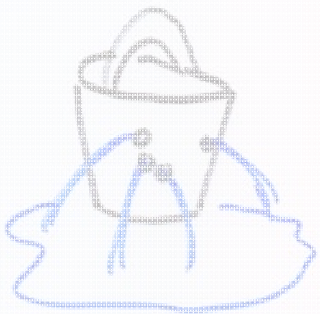

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⇒ # of decay paths

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Z Lifetime

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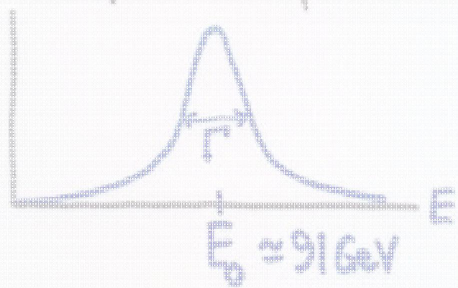


$\Gamma = \Delta E = 2.5$ GeV

⇒ Lifetime = 10^{-25} sec

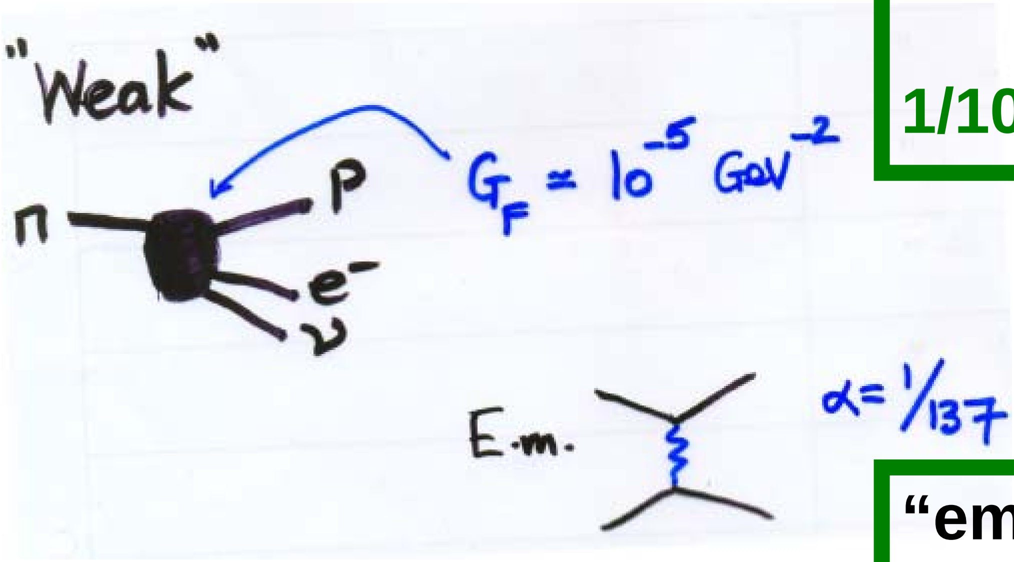
1996-2000 LEP $e^+(100 \text{ GeV}) + e^-(100 \text{ GeV}) \to W^+W^-$
+ look for Higgs ....

The Electroweak Story

Part 3: Unity

“Weak force as Electromagnetism in disguise”

Beta decay (weak interaction):
Feynman diagram for Fermi's original model



"weak strength"

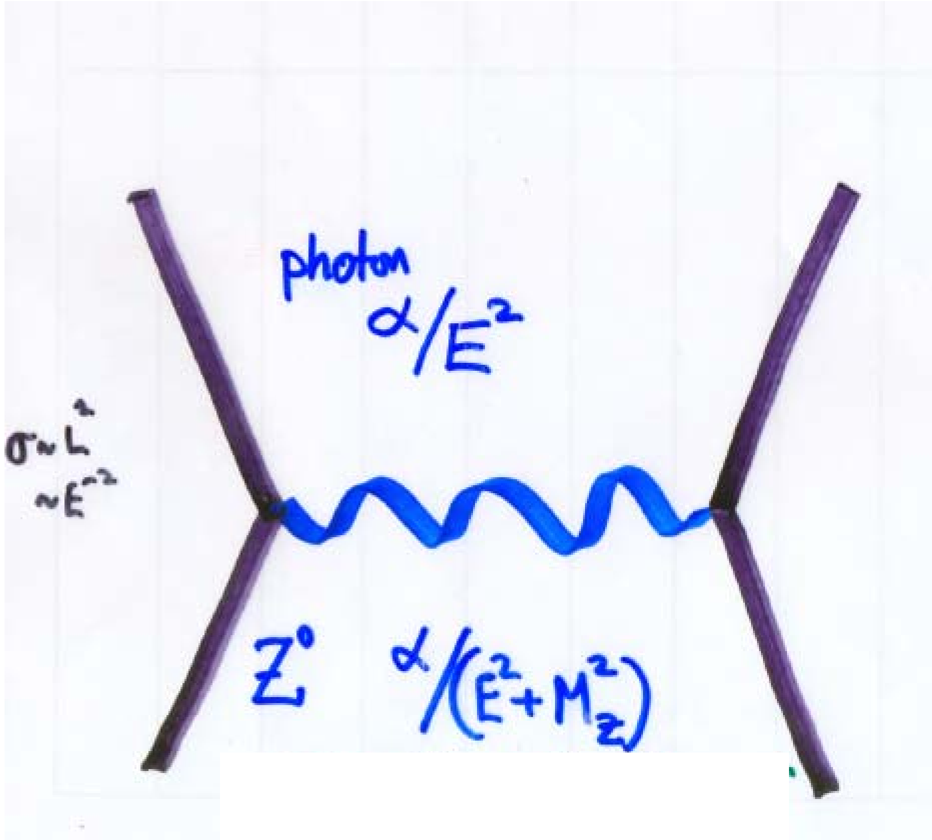
1/100,000 GeV^2

contrast with

"emag strength"

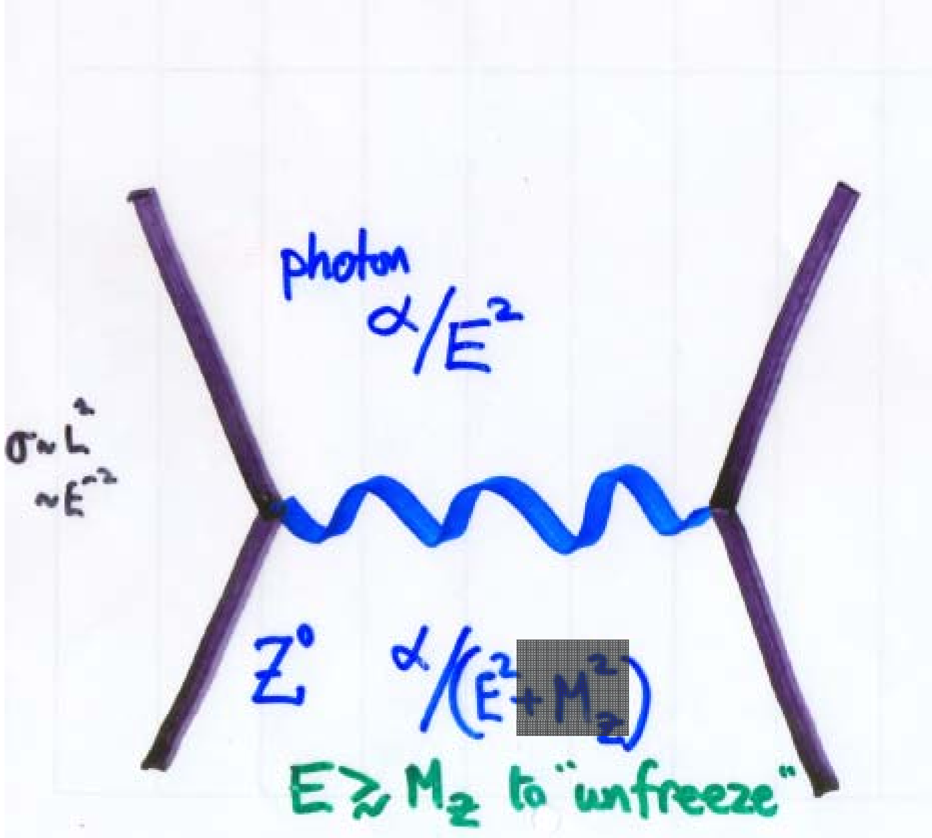
e x e/4pi = 1/137
= "alpha"

Notice a number (e.m.) but
dimensions of 1/GeV^2 (weak)………



Feynman rules:

If energy E flows through the transmitted “virtual” particle (photon; Z) it costs 1/(E^2+M^2)



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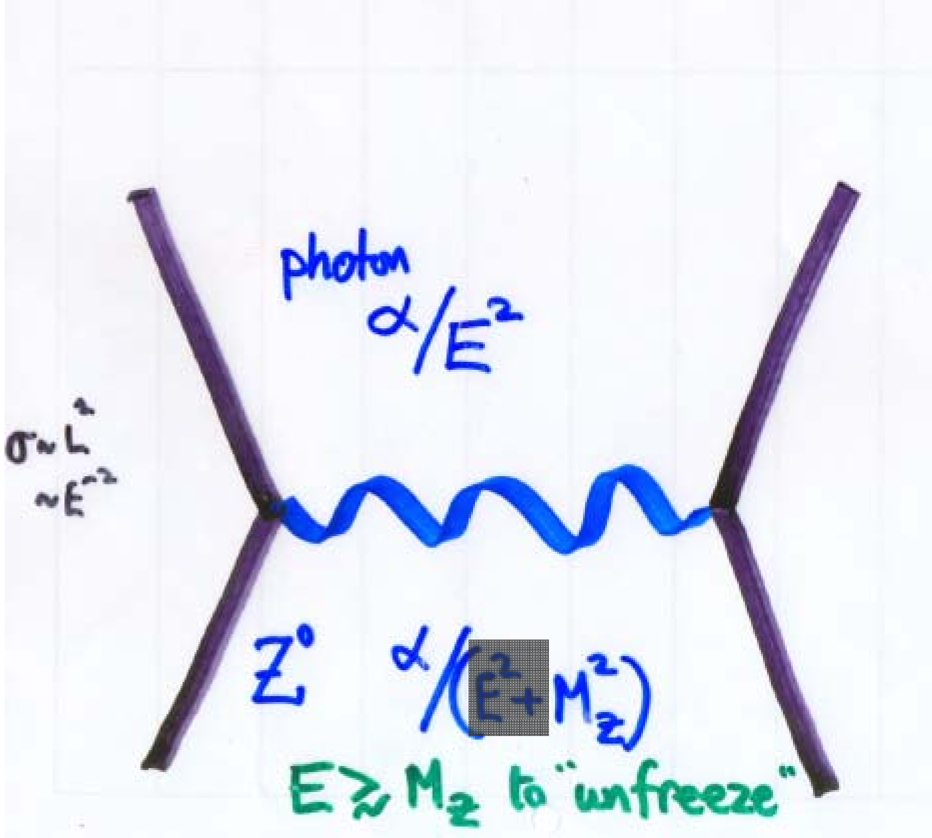
If E >> M the cost is 1/E^2….like the case of the photon



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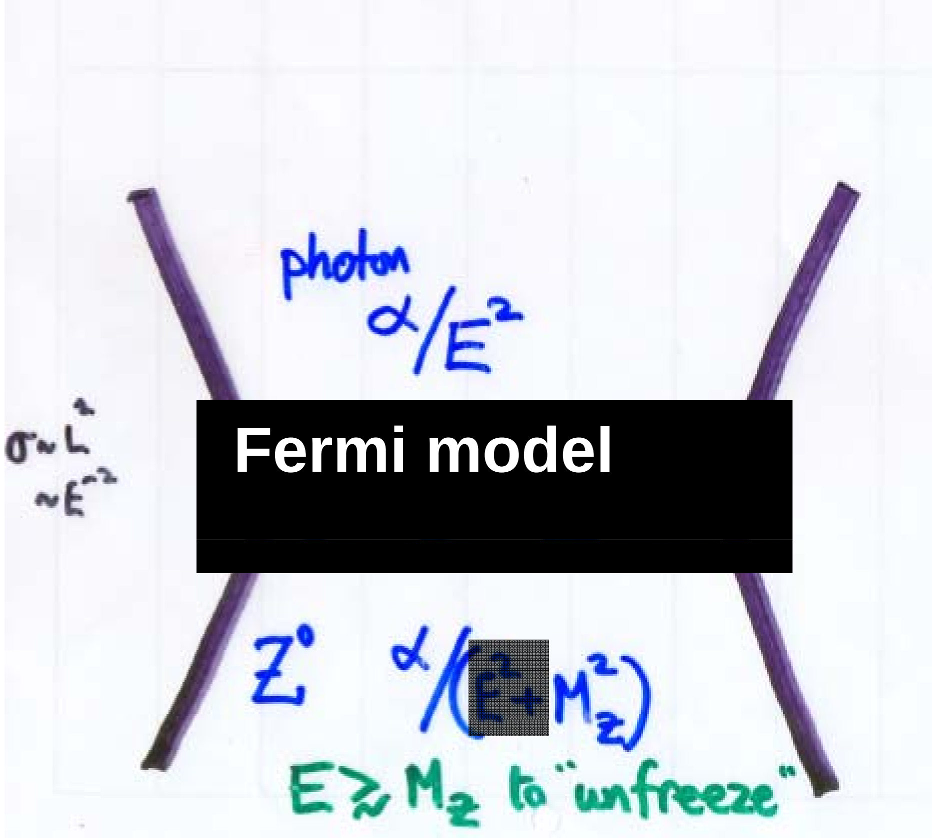
If E << M the cost is 1/M^2



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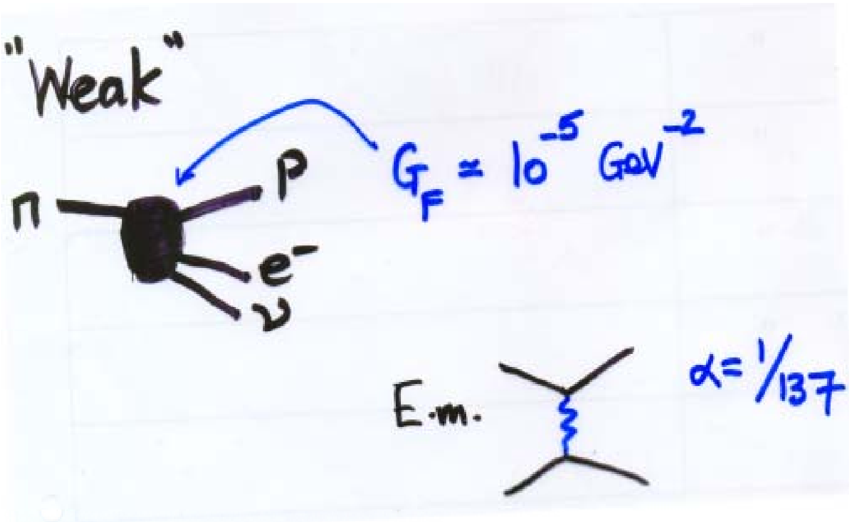
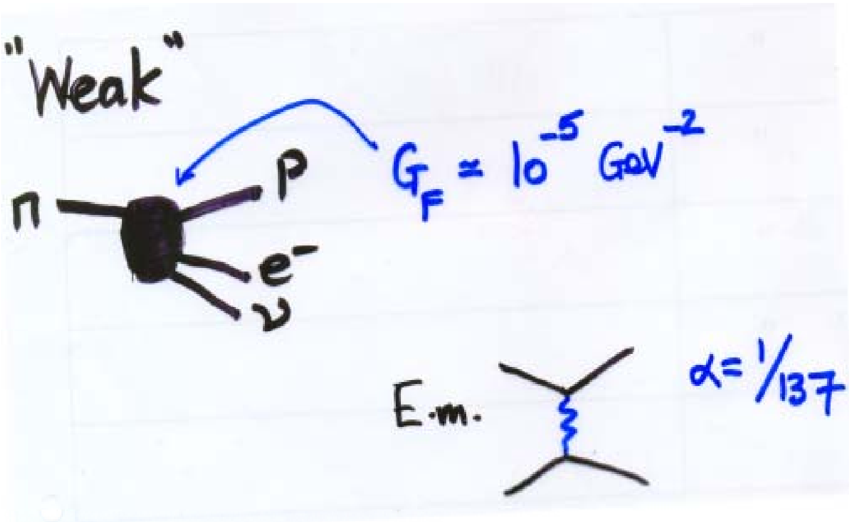


"weak strength"

1/100,000 GeV^2

= **1/137 x 1/(28 GeV)**^2



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1/100,000 GeV^2

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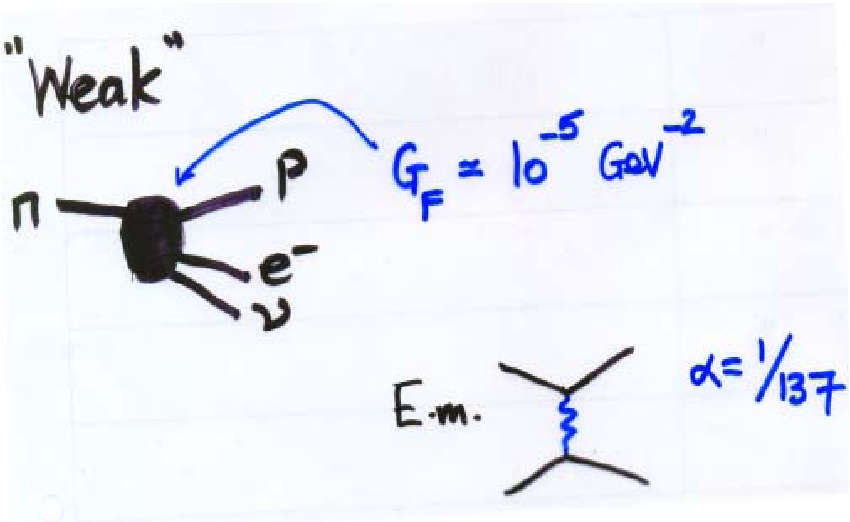
“weak” has fundamentally electromagnetic strength if m ~ 30GeV



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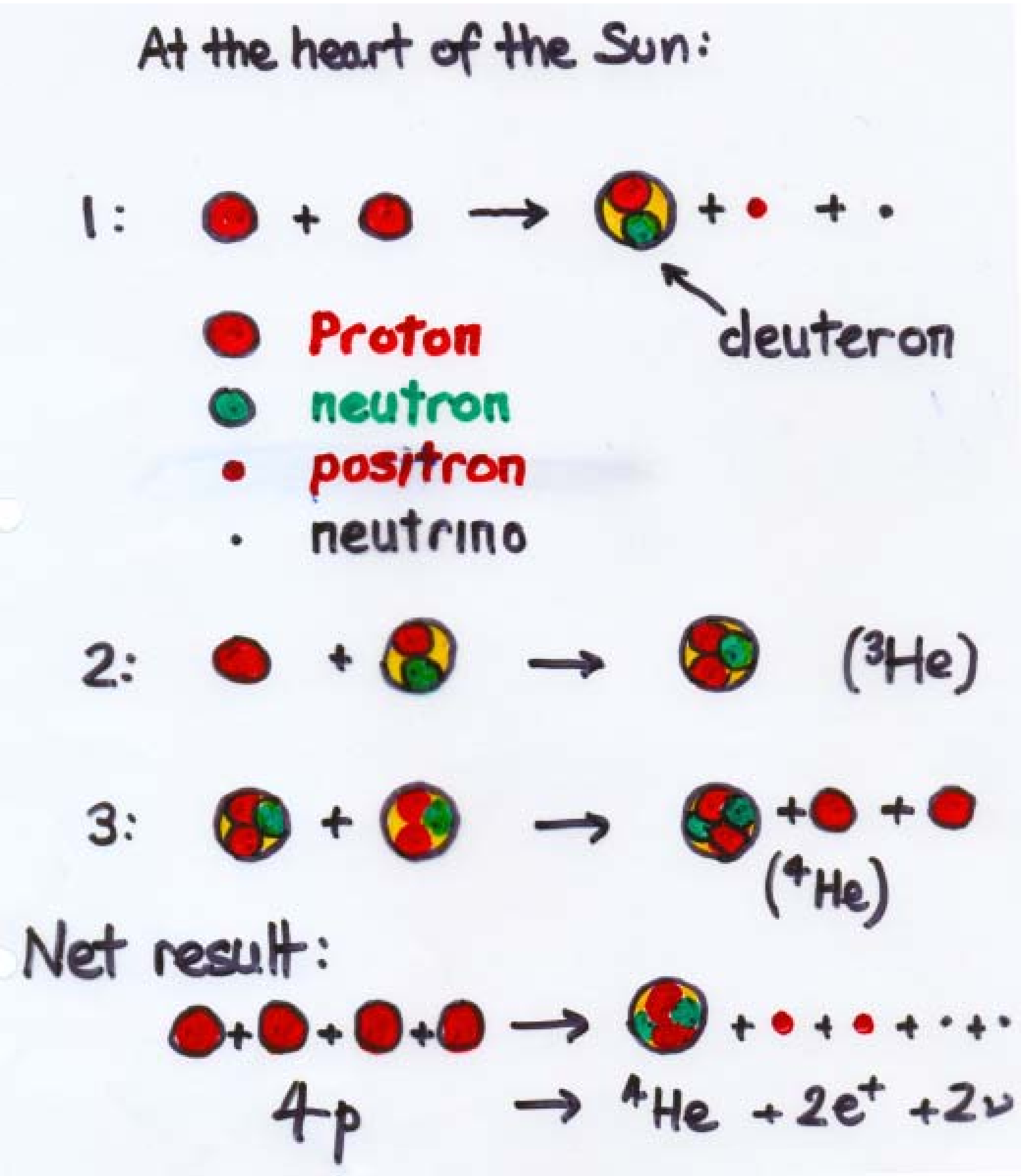
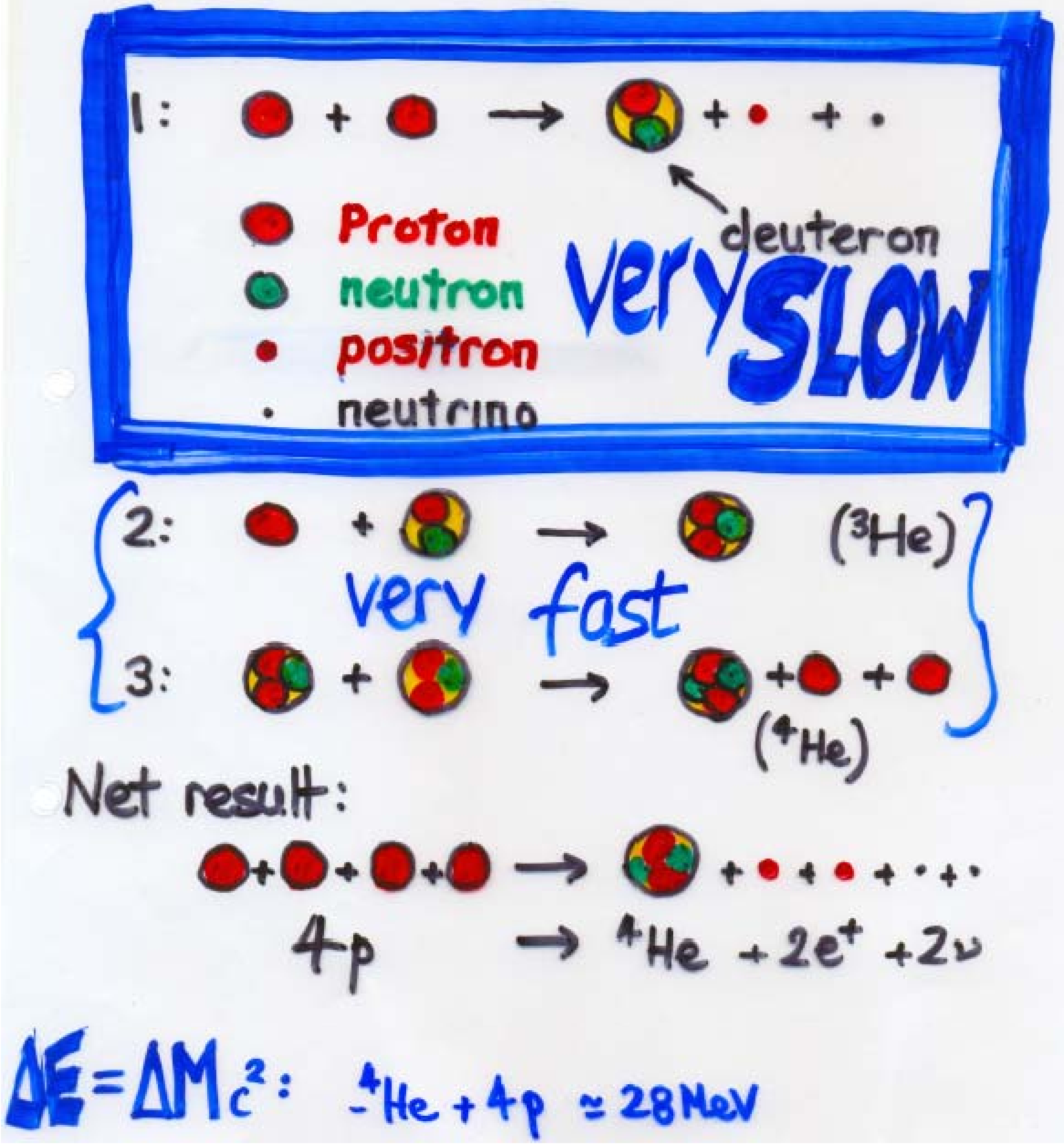
"weak" has fundamentally electromagnetic strength if m ~ 30GeV

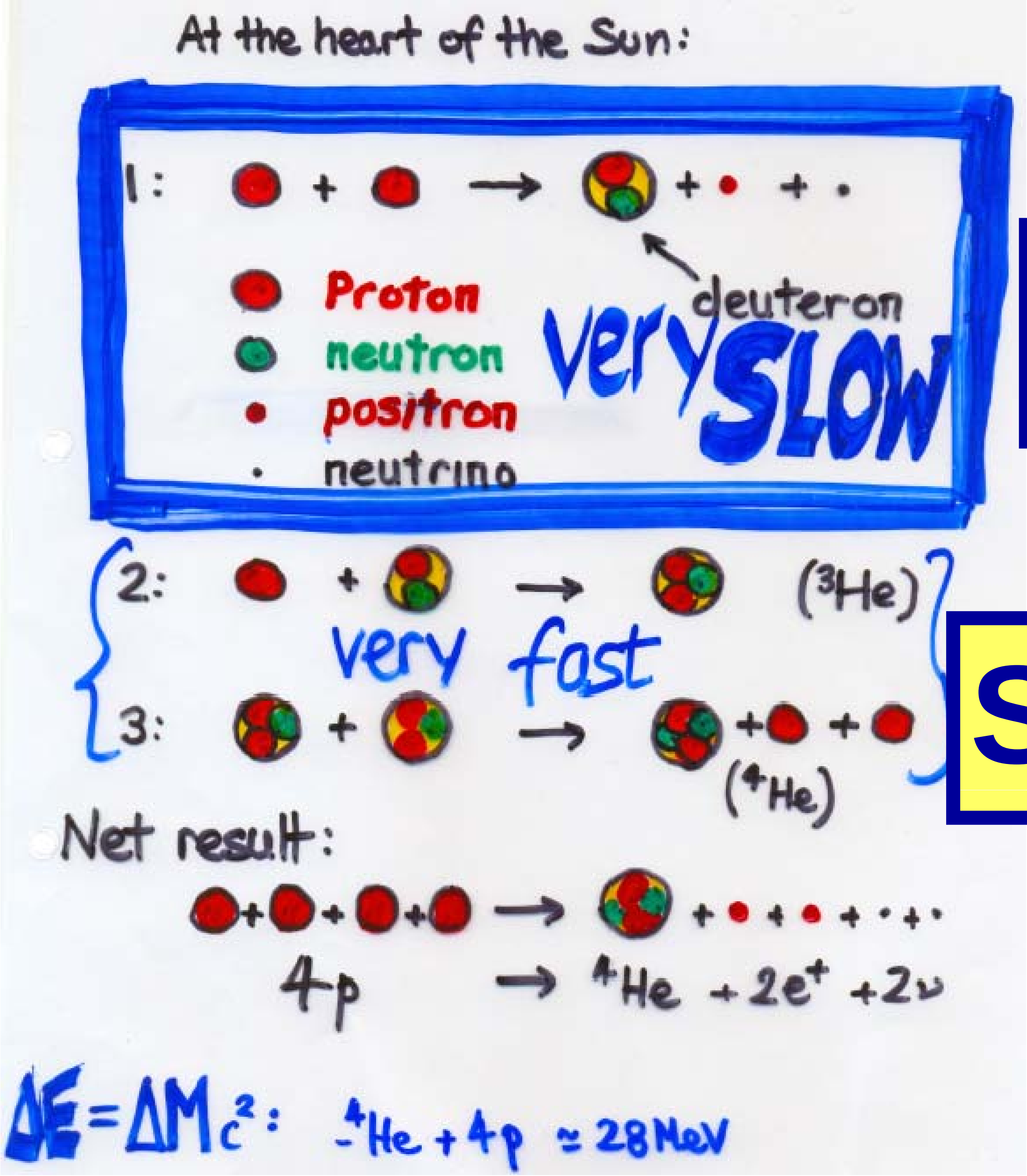
More carefully: root 2; parity violation;
SU2 x U1; Weinberg angle..
requires m(W) ~ 80 GeV; m(Z) ~ 90 GeV

Experimentally verified!!


At the heart of the Sun:
1:
deuteron
Proton
neutron
positron
neutrino
2:
(3He)
3:
(4He)
Net result:
4p → 4He + 2e+ + 2ν

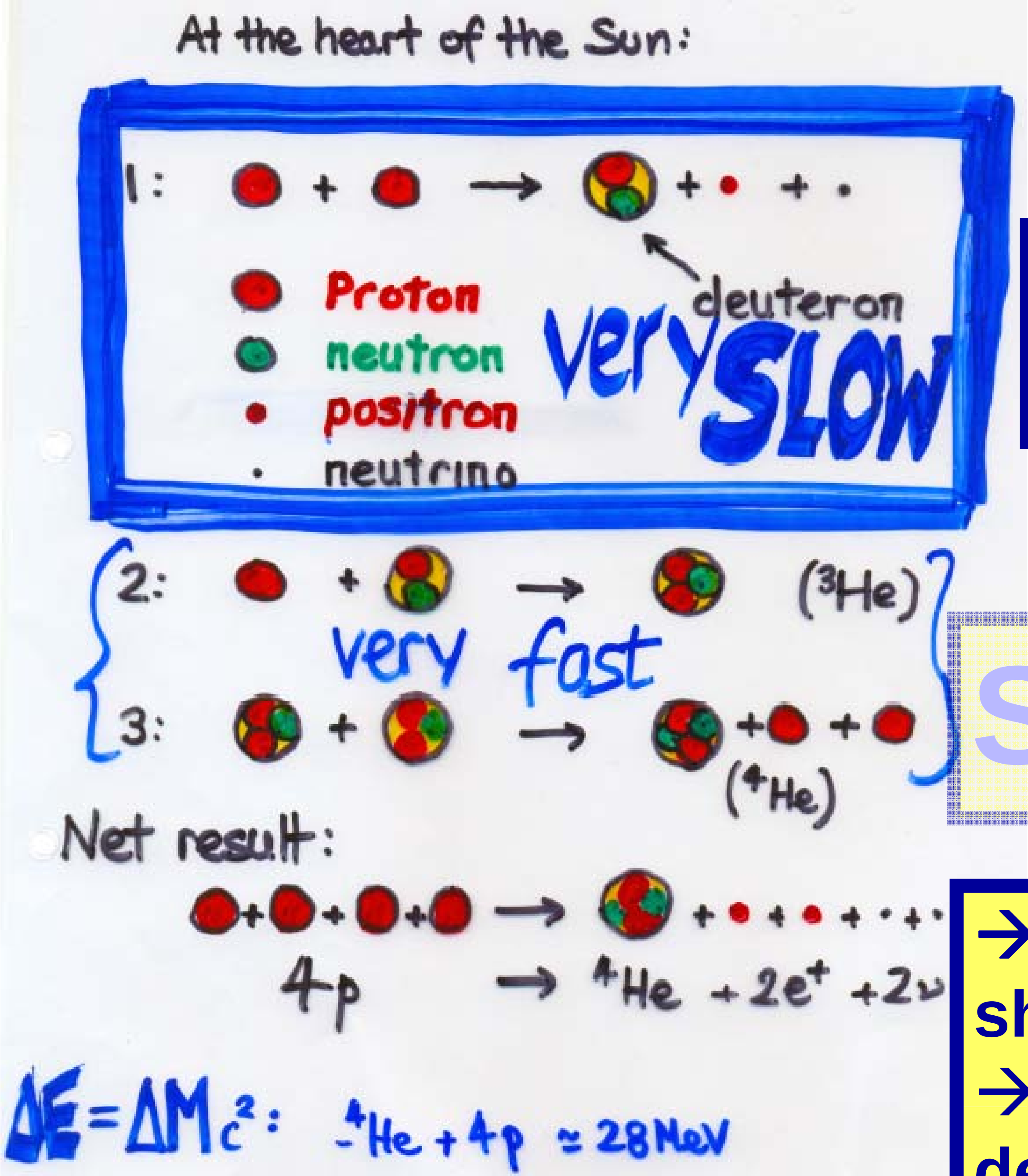
At the heart of the Sun:




At the heart of the Sun:
1:
deuteron
Proton
neutron
positron
neutrino
very SLOW
2:
(³He)
very fast
3:
(⁴He)
Net result:
4p → ⁴He + 2e⁺ + 2ν
ΔE = ΔMc²: -⁴He + 4p ≃ 28MeV

WEAK

STRONG



WEAK

STRONG

→ why sun has shone for 5 Byr…
→Intelligent life developed

The weak force is feeble in the Sun ..

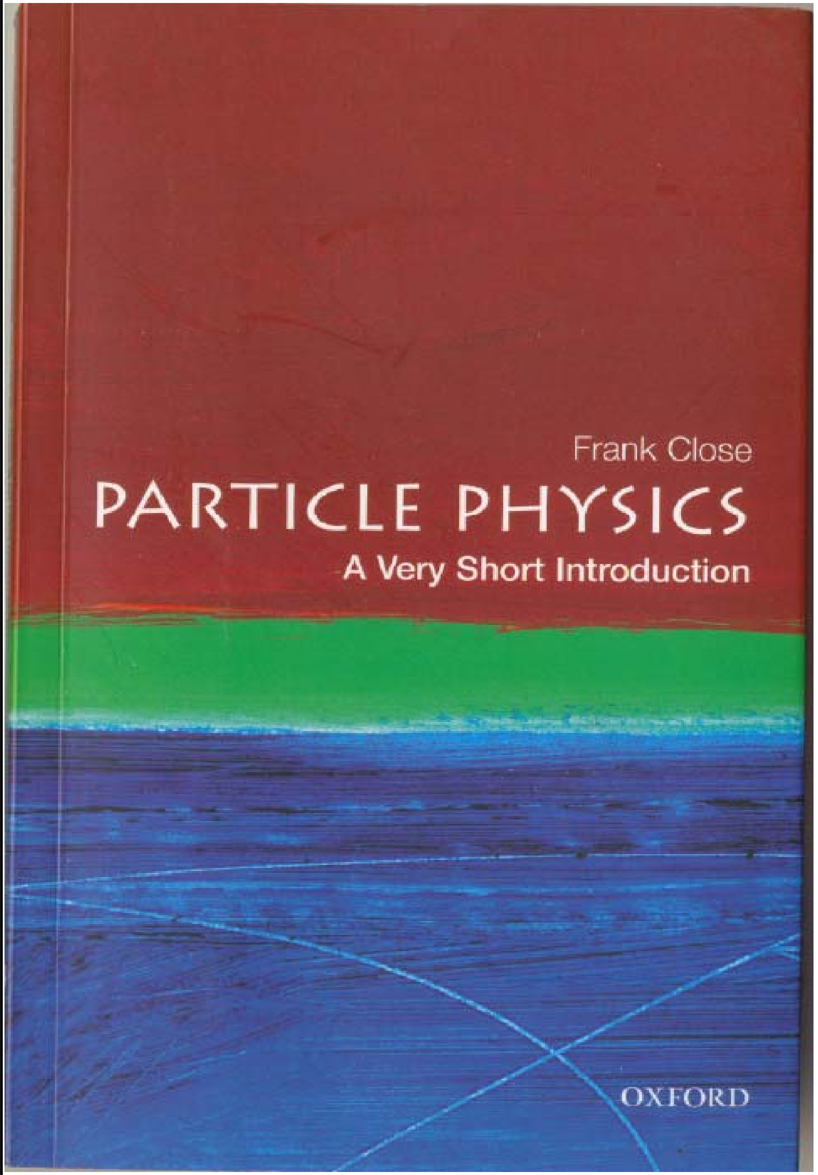
..because 10,000,000K ~ 1 keV << 80 GeV

…this is why the sun has stayed active long enough for us to have evolved and be having this conversation.

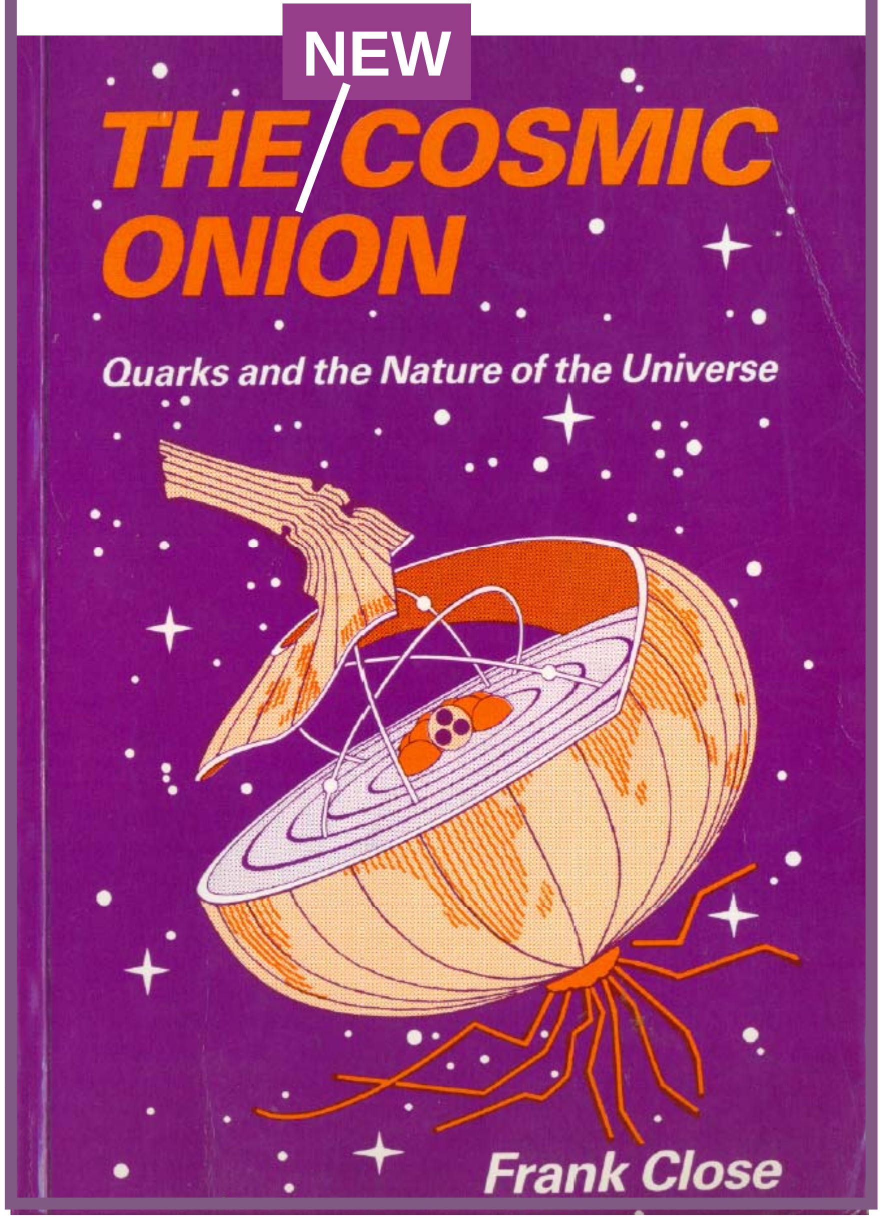
→We exist because m(W) is not zero

→ Mass matters

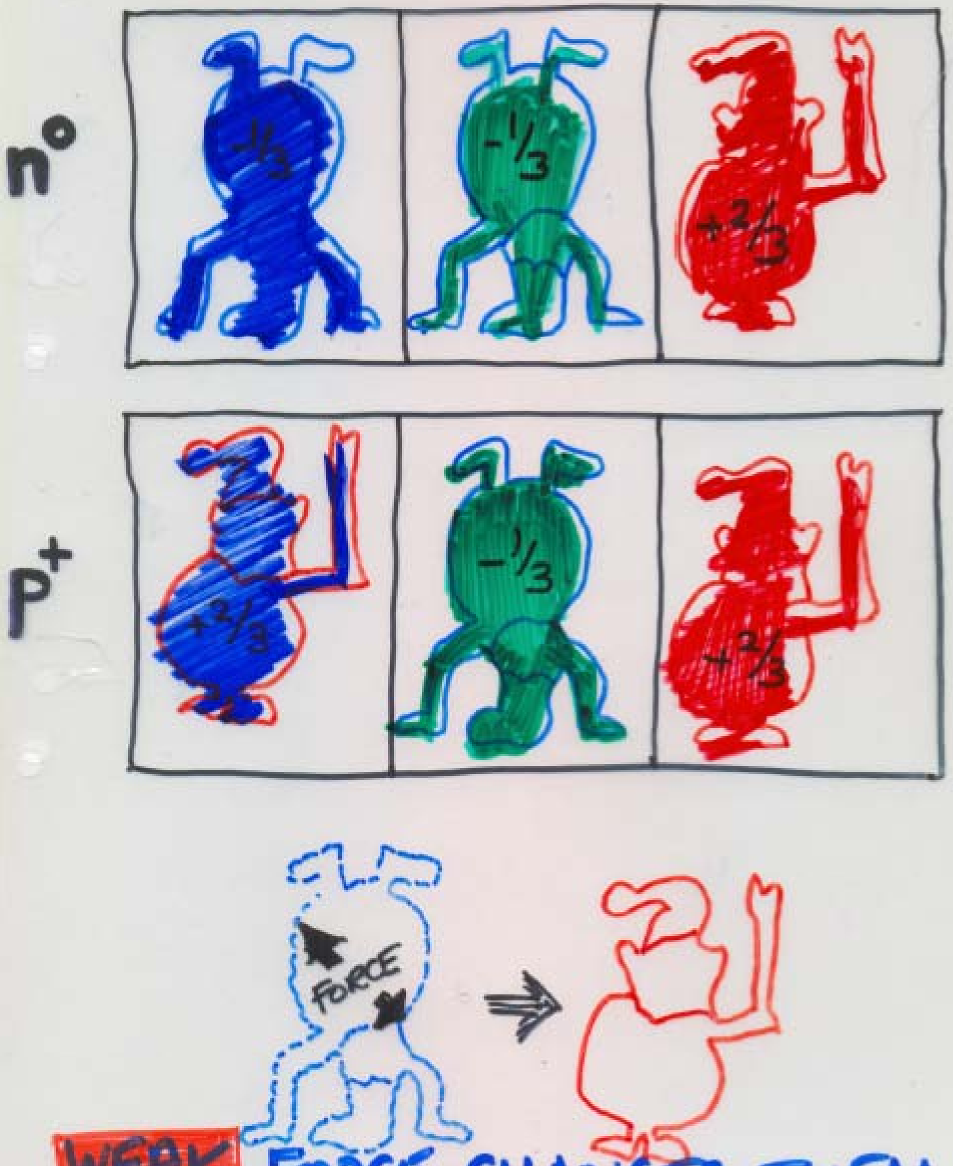
A Very Short Introduction



Coming out in December



1960s QUARKS **STRONG** force glues them



WEAK FORCE CHANGES THEM

QED (electrons and photons)

QCD (quarks and gluons)

LEP
@ CERN

1989-2000