

What's inside the electron?

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$$J = \frac{1}{2}$$

Mass $m = (548.579909065 \pm 0.000000016) \times 10^{-6} \text{ u}$

Mass $m = 0.51099895000 \pm 0.00000000015 \text{ MeV}$

$|m_{e^+} - m_{e^-}|/m < 8 \times 10^{-9}, \text{ CL} = 90\%$

$|q_{e^+} + q_{e^-}|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$$(g-2)/2 = (1159.65218062 \pm 0.00000012) \times 10^{-6}$$

$$(g_{e^+} - g_{e^-}) / g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$$

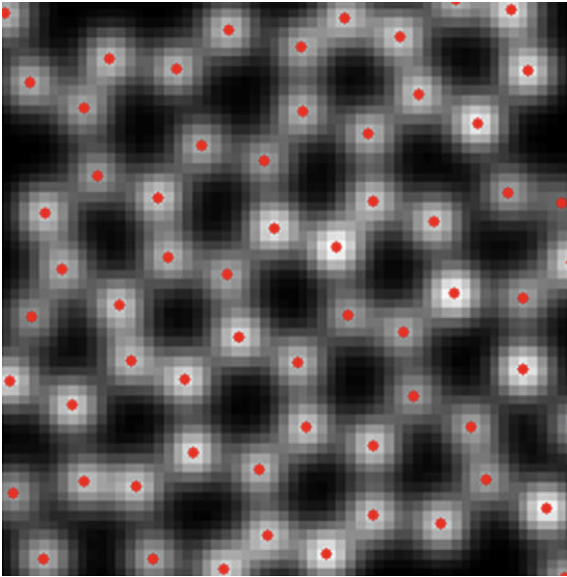
Electric dipole moment $d < 0.041 \times 10^{-28} \text{ e cm}, \text{ CL} = 90\%$

Mean life $\tau > 6.6 \times 10^{28} \text{ yr}, \text{ CL} = 90\% [a]$

Particle Properties:

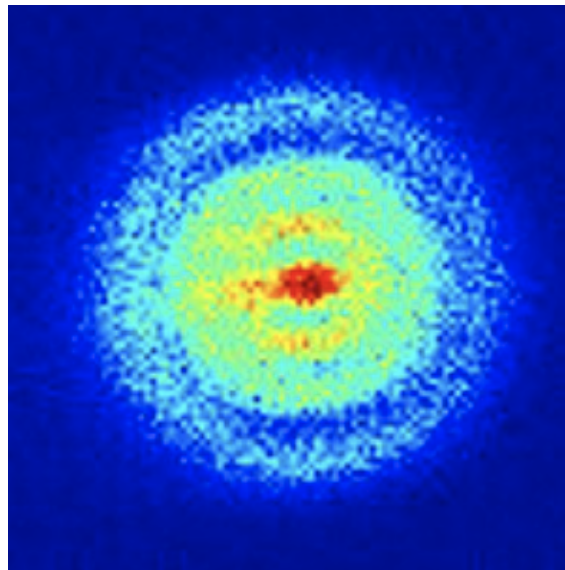


Macroscopic objects are made of atoms:



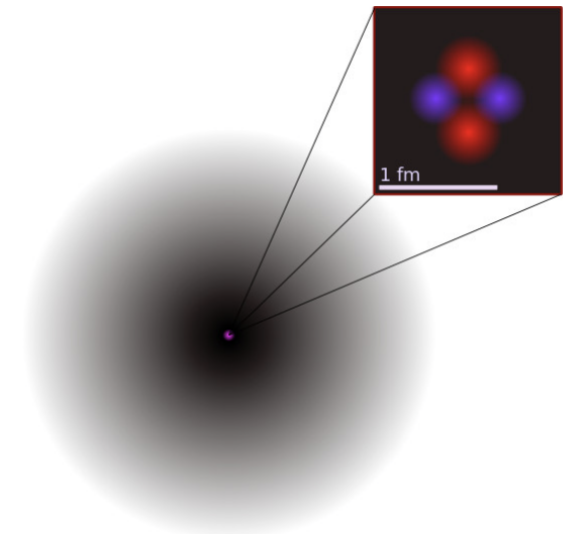
Electron microscopy
PRL 121, 056101 (2018)

Each atom is made of electron(s) moving around a nucleus:



Photoionization microscopy
PRL 110, 213001 (2013)

Nucleus is made of protons and neutrons:



art (x-engineer.org)

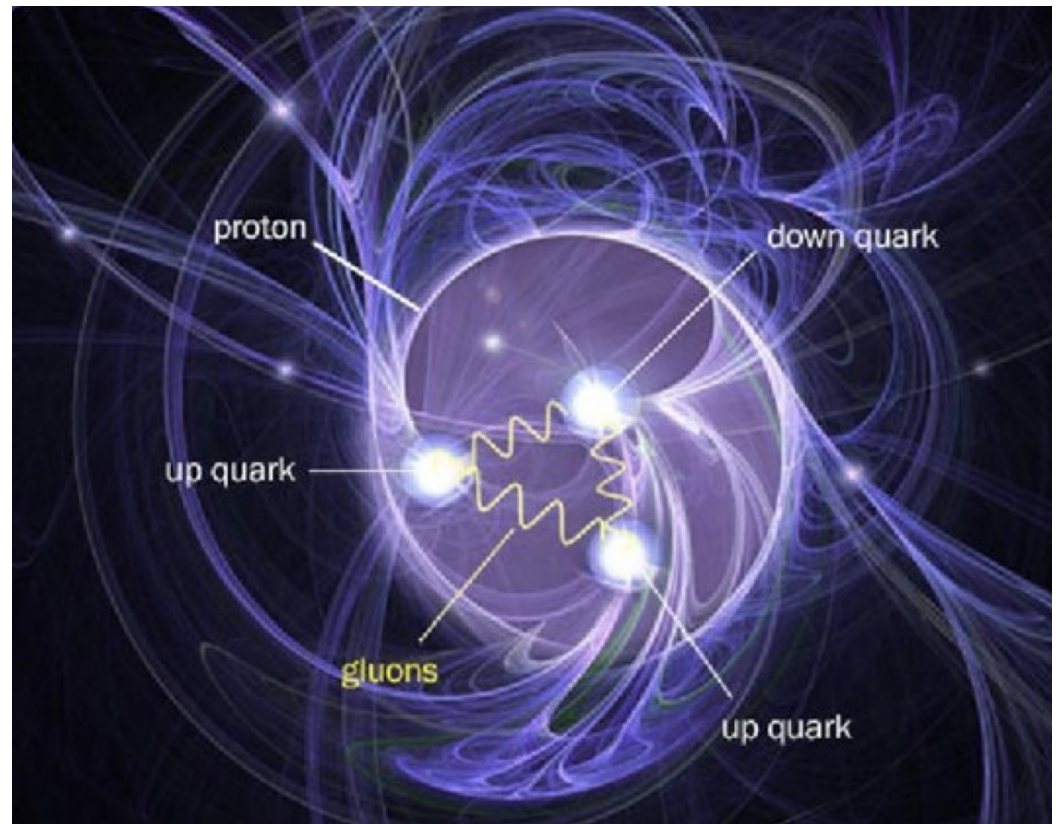
“Everything” around — and in — us is built out of:

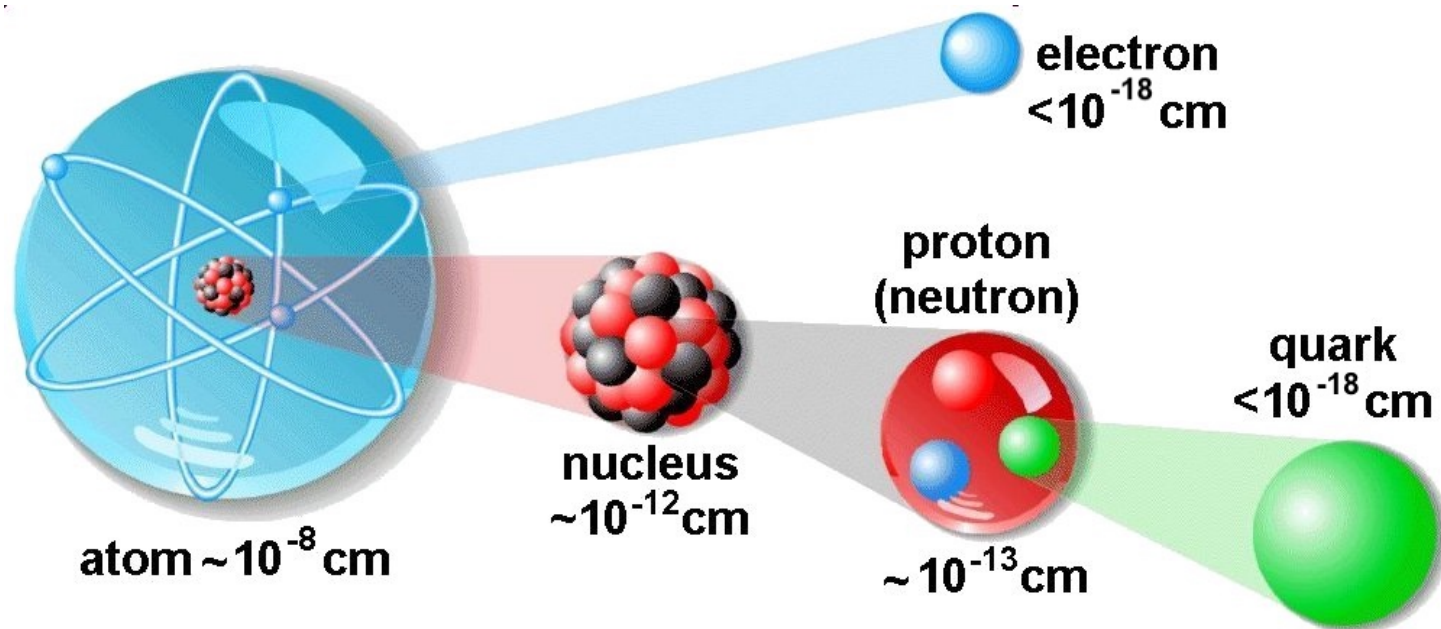
up and down quarks,

and electrons

+ **gluons**
that keep the quarks
inside the nucleons,

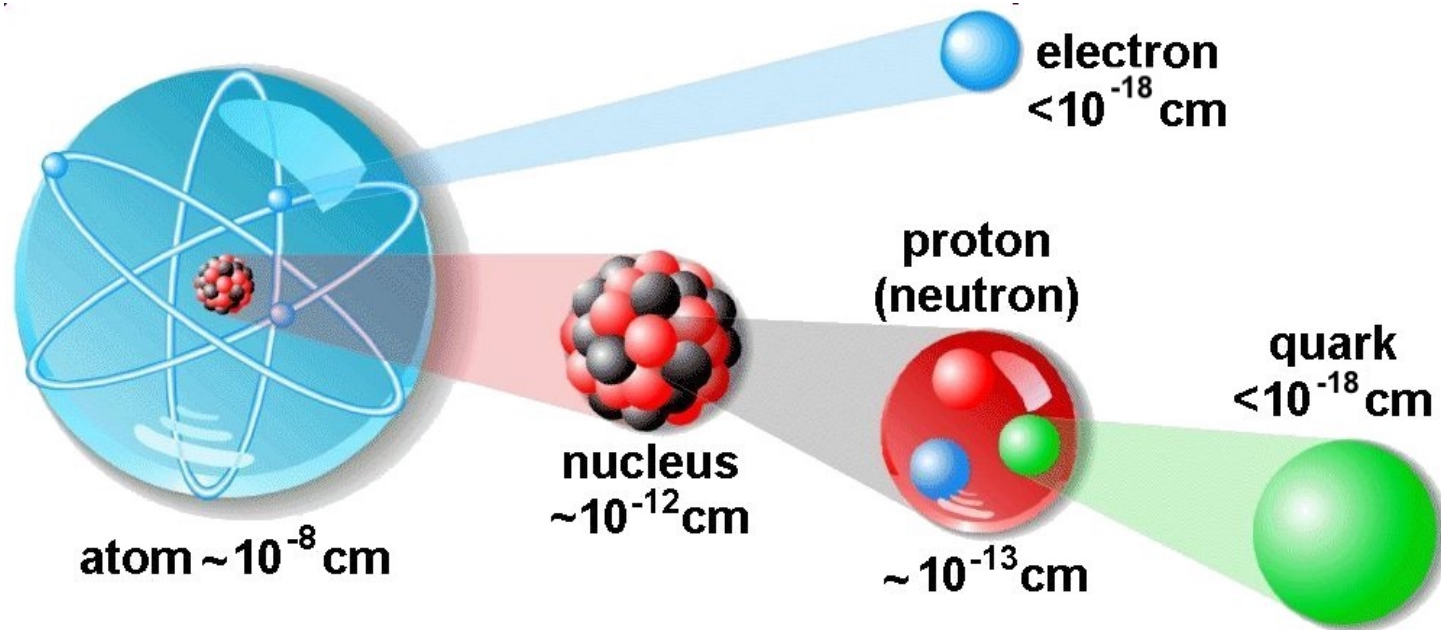
*(there are also
photons, neutrinos,
& unstable particles)*





Does the electron have substructure?

How about the quarks?



Does the electron have substructure?

How about the quarks?



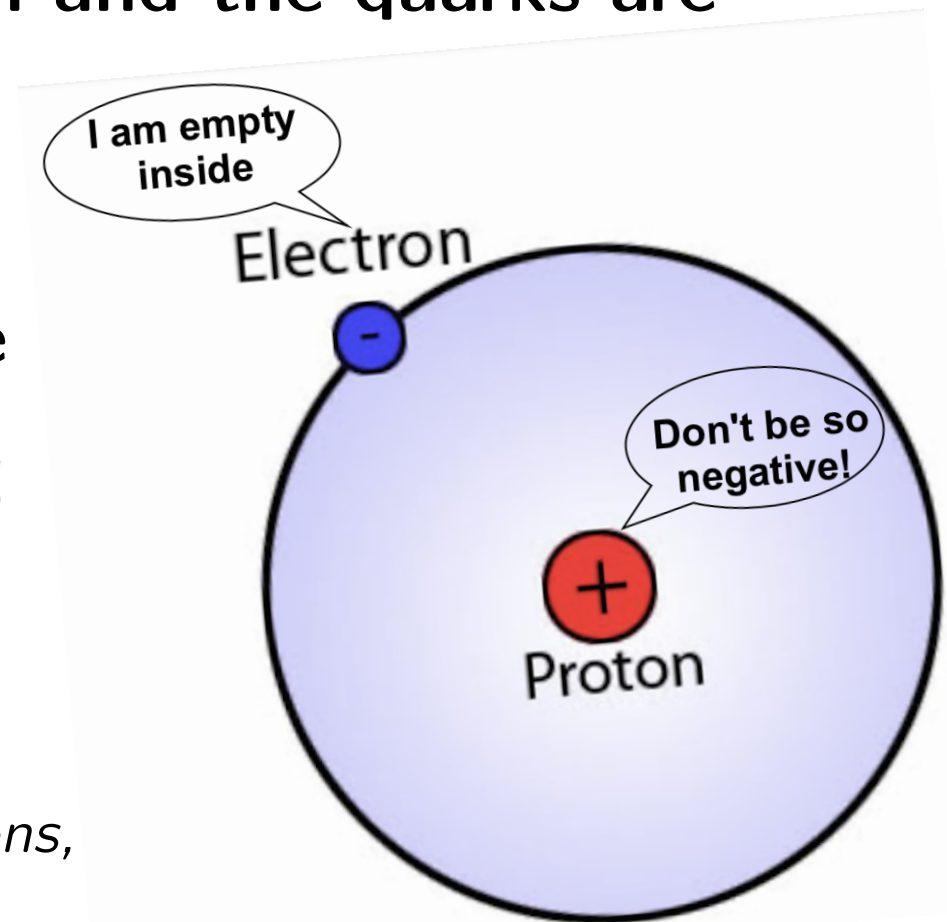
In Quantum Field Theory:

elementary particles are point-like objects.

If QFT describes nature down to arbitrarily small distances, and **if** the electron and the quarks are elementary particles,

then there is nothing inside
the electron or the quarks!

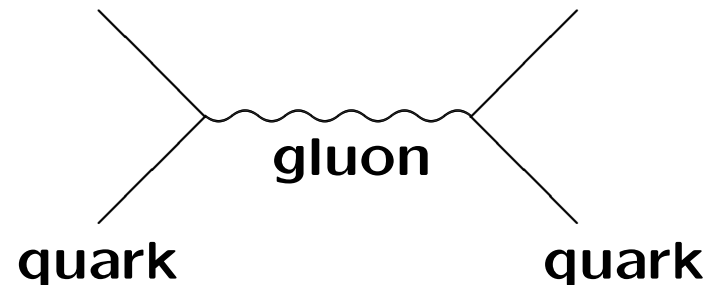
*The electron emits and absorbs photons,
so it is never alone.*



QCD: the strong interaction between quarks

- ★ is due to *gluon* exchange:

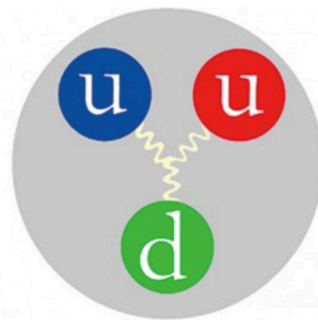
↙
gauge boson of $SU(3)_c$ symmetry



strongly coupled at the QCD scale: $\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$

- ★ it forms $\langle \bar{q}q \rangle$ condensates (*chiral symmetry breaking*).

- ★ it forms the proton (*confinement at Λ_{QCD}*)



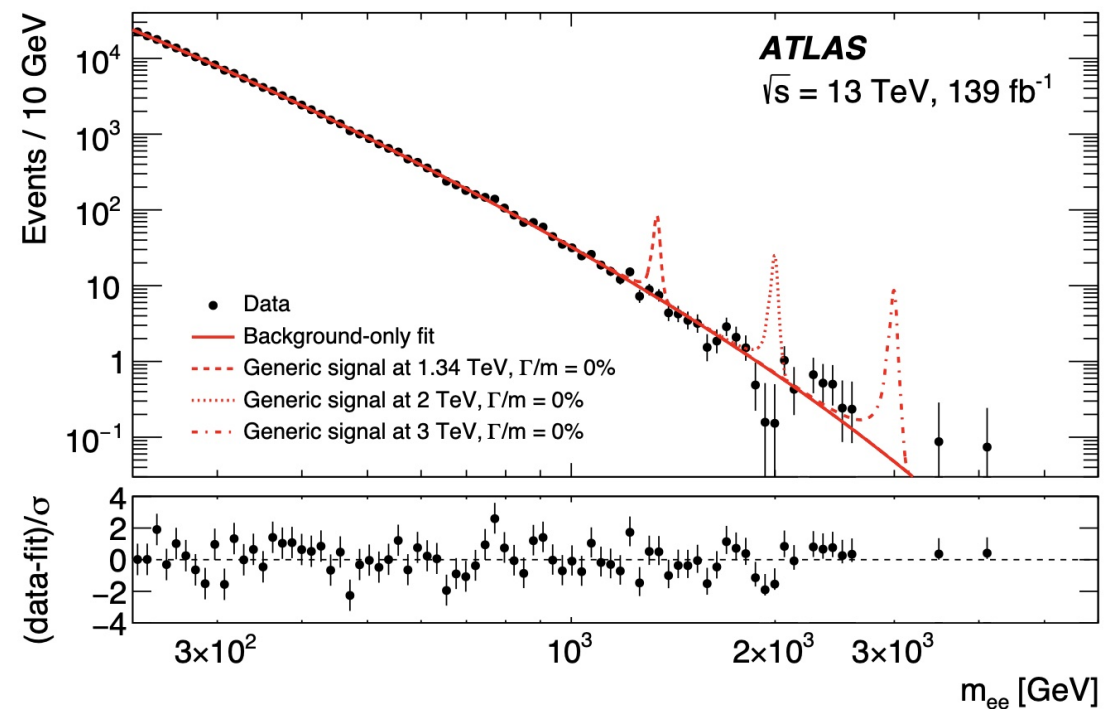
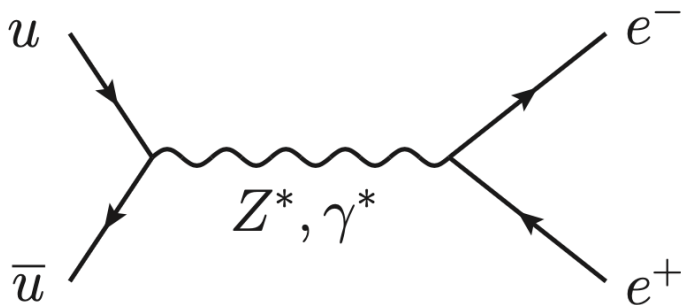
, other baryons, and mesons.

Up and down quark masses: $m_u, m_d \ll \Lambda_{\text{QCD}}$

Proton mass: $m_p = 938 \text{ MeV} > \Lambda_{\text{QCD}}$

If the electron has substructure, it cannot be due to a QCD-like interaction:

scale of electron compositeness is > 5 TeV (inferred from CMS and ATLAS searches at the LHC), so $> 10^7 m_e$.



1903.06248

Chiral fermions

All Standard Model fermions are chiral: Left- and Right-handed components have different $SU(2)_W \times U(1)_Y$ charges.

E.g., electron:

e_L (feels the weak interaction), e_R (no interaction with $W^\pm$)

e_L

ν_L

e_R

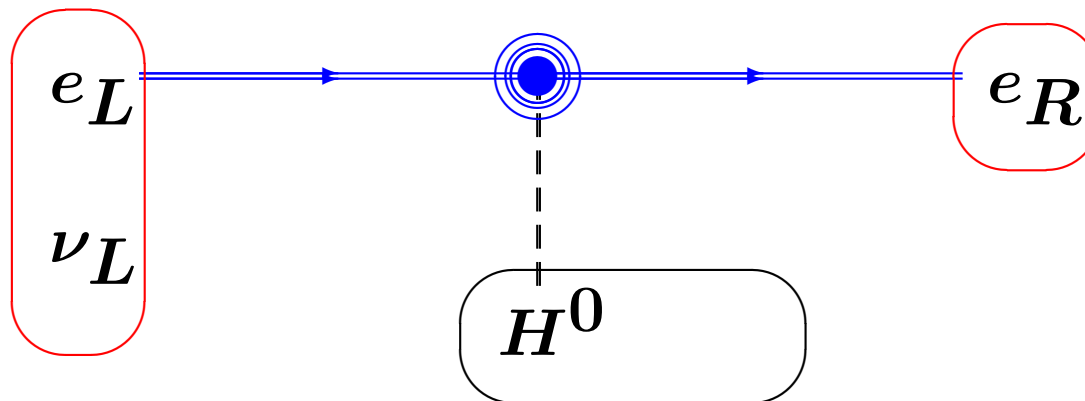
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Electron mass: e_L turns into e_R and vice-versa due to its interaction with the Higgs field:



★ If the electron is a composite particle, then the ν_e neutrino must also be composite!

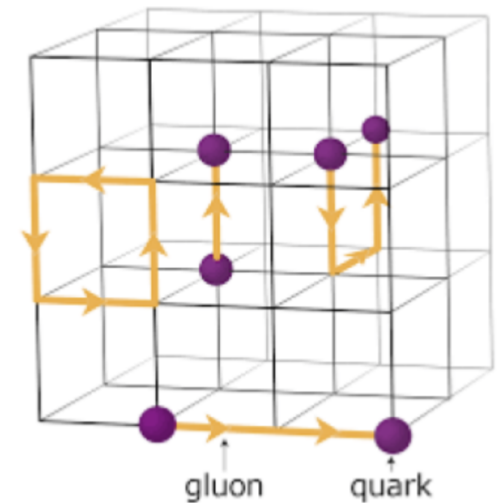
★ Any theory that predicts electron compositeness must be a strongly-coupled chiral theory.

So far, nobody knows how to compute observables in a chiral theory at large coupling.

QCD (not a chiral theory): computations at $\alpha_s \approx 1$ are done (heroic progress over 50 years) using simulations on a space-“time” Lattice.

Same methods don't work (yet) for chiral theories.

There are, however, some methods for guessing the spectrum of light composite particles ...



Standard Model

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
quark doublet: $q_L^i = (u_L^i, d_L^i)$	3	2	1/6
right-handed up-type quark: u_R^i	3	1	2/3
right-handed down-type quark: d_R^i	3	1	-1/3
lepton doublet: $l_L^i = (\nu_L^i, e_L^i)$	1	2	-1/2
right-handed charged lepton: e_R^i	1	1	-1
Higgs doublet: H	1	2	1/2

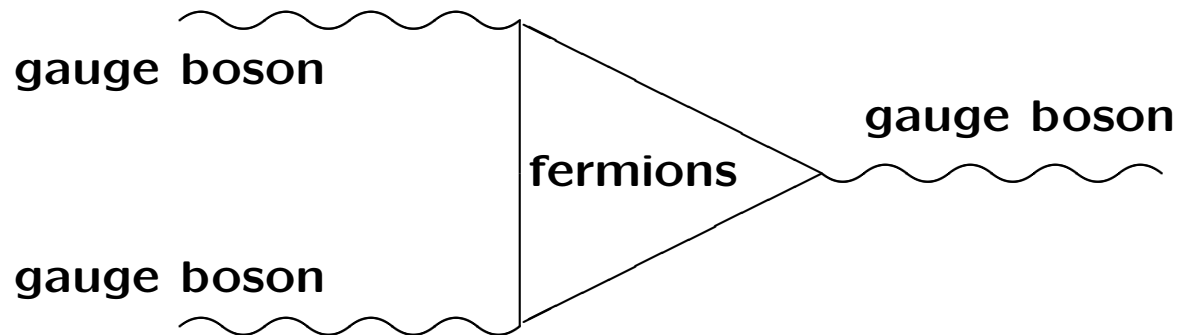
$i = 1, 2, 3$ labels the fermion generations.

There are $2 \times 3 + 3 + 3 + 2 + 1 = 15$ fermions per generation.

Charge conservation $\rightarrow$ gauge anomaly cancellation

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



Standard Model – anomalies cancel within each fermion generation:

$$[SU(3)_c]^2 U(1)_Y: \quad 2(1/6) + (-2/3) + (1/3) = 0$$

$$[U(1)_Y]^3: \quad 3 \left[2(1/6)^3 + (-2/3)^3 + (1/3)^3 \right] + 2(-1/2)^3 + (-1)^3 = 0$$

$$\dots \quad (u_L, d_L) \quad u_R \quad d_R \quad (\nu_L, e_L) \quad e_R$$

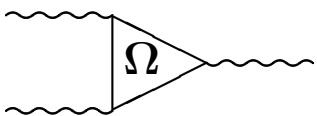
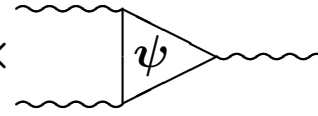
If the electron is a composite particle, then the u and d quarks must also be composite!

Example of strongly-coupled chiral theory

$SU(N)$ gauge symmetry with:

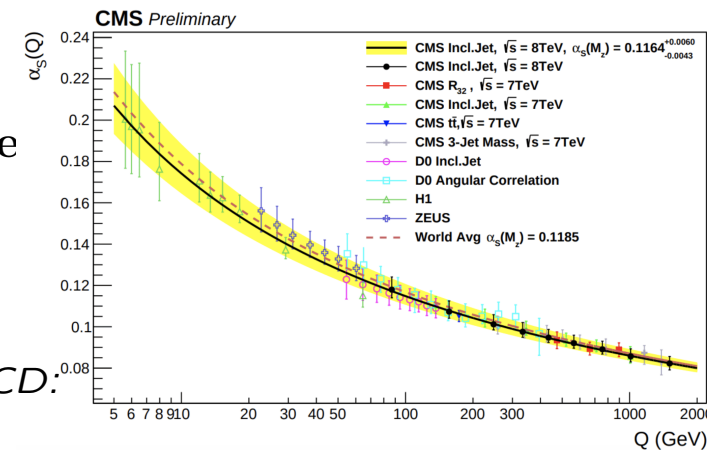
- a chiral fermion (Ω) in the symmetric representation $\square\square$,
- $N+4$ chiral fermions (ψ_k) in the fundamental representation $\square$

(Dimopoulos, Raby, Susskind, 1980; Eichten, Peccei, Preskill, Zeppenfeld, 1986)

Free of gauge anomalies:  + $(N + 4) \times$  = 0

Asymptotic freedom: α_N grows at smaller energy scales, until it becomes strong at Λ_{pre}

similar to QCD:



Most likely forms $\Omega \psi_k \psi_\ell$ bound states: massless chiral “baryons” !

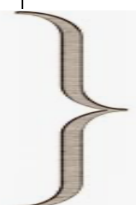


based on consistency checks
(’t Hooft anomaly matching; large N arguments; ...)

A model of quark and lepton compositeness

B. Dobrescu, Phys.Rev.Lett. (2022)

Preons: hypothetical left-handed fermions charged under the confining gauge group $SU(15)_p$

Preons	$SU(15)_p$	$SU(3)_c \times SU(2)_W \times U(1)_Y$	
ψ_Q	$\square$	$(3, 2, +1/6)$	 same charges as one generation of SM fermions
ψ_U	$\square$	$(\bar{3}, 1, -2/3)$	
ψ_D	$\square$	$(\bar{3}, 1, +1/3)$	
ψ_L	$\square$	$(1, 2, -1/2)$	
ψ_E	$\square$	$(1, 1, +1)$	
$\psi_1, \dots, \psi_4$	$\square$	$(1, 1, 0)$	 SM singlets
Ω	$\overline{\square\square}$	$(1, 1, 0)$	

Chiral “pre-baryons” (bound states of 3 preons) have exactly the quantum numbers of the Standard Model fermions:

electron = $\Omega \psi_E \psi_1$ 

down quark = $\Omega \psi_D \psi_1$  , up quark = $\Omega \psi_U \psi_1$ 

...

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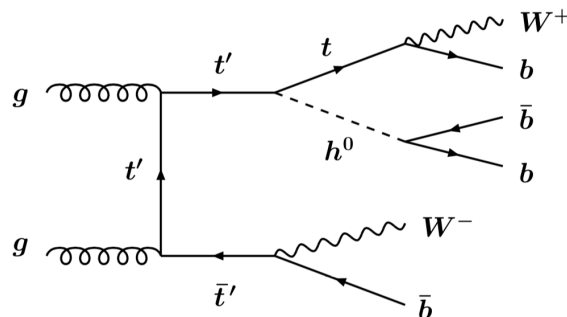
...

Prediction – much heavier new fermions must also exist:

‘vectorlike’ quarks (both Left & Right) $\Omega \psi_U \psi_E \leftrightarrow \Omega \psi_U \psi_D$  

...

ongoing searches at the LHC!



Chiral “pre-baryons” of $SU(15)_p$

Preon flavor index $i = 1, \dots, 4$ implies 3 generations of SM fermions!

pre-baryons	$SU(3)_c \times SU(2)_W \times U(1)_Y$	name
$\Omega \psi_Q \psi_i \ (i = 1, 2, 3)$	$(3, 2, +1/6)$	$(u_L, d_L)_i$
$\Omega \psi_U \psi_i$	$(\bar{3}, 1, -2/3)$	u_i^c
$\Omega \psi_D \psi_i$	$(\bar{3}, 1, +1/3)$	d_i^c
$\Omega \psi_L \psi_i$	$(1, 2, -1/2)$	$(\nu_L, e_L)_i$
$\Omega \psi_E \psi_i$	$(1, 1, +1)$	e_i^c
$\Omega \psi_i \psi_j \ (i \neq j)$	$(1, 1, 0)$	N_{ij}
$\Omega \psi_D \psi_4 \leftrightarrow \Omega \psi_U \psi_D$	$(3, 2, +1/6)$	$\mathcal{D}$
$\Omega \psi_L \psi_4 \leftrightarrow \Omega \psi_L \psi_E$	$(1, 2, -1/2)$	$\mathcal{L}$
$\Omega \psi_E \psi_4 \leftrightarrow \Omega \psi_L \psi_L$	$(1, 1, +1)$	$\mathcal{E}$

■ ■ ■

■ ■ ■



*3 generations
of SM quarks
and leptons*

6 “right-handed”
neutrinos

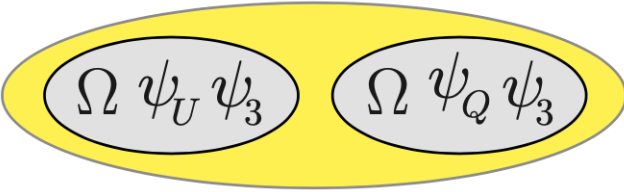


*vectorlike
fermions
(Dirac masses)*

Composite Higgs field

Deuteron: proton-neutron bound state due to nuclear forces
(a remnant of QCD)

Similarly, there must be bound states of two pre-baryons:



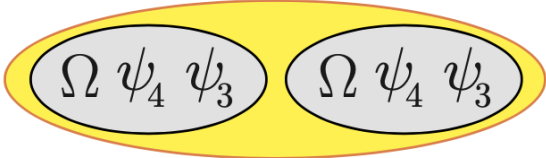
The diagram shows a large yellow oval containing two smaller grey ovals. The left grey oval contains the text $\Omega \psi_U \psi_3$ and the right grey oval contains $\Omega \psi_Q \psi_3$. To the right of the yellow oval is an equals sign followed by the letter H .

$$\Omega \psi_U \psi_3 \quad \Omega \psi_Q \psi_3 = H$$

same quantum numbers as the Higgs doublet in the Standard Model

If the $SU(15)_p$ remnant interaction (preonic- “nuclear” force) is strong enough, then H breaks the electroweak symmetry.

There are also composite pseudoscalar particles:
(potentially light gauge-singlets)

$$A^0 =$$


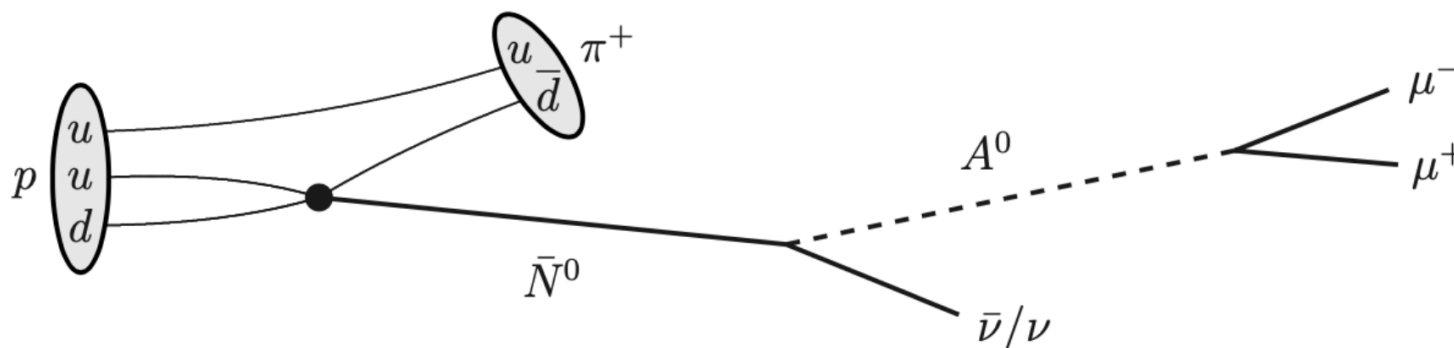
The diagram shows a large yellow oval containing two smaller grey ovals. The left grey oval contains the text $\Omega \psi_4 \psi_3$ and the right grey oval contains $\Omega \psi_4 \psi_3$.

Another indirect test of electron & quark substructure:

Ben Assi, B.D., JHEP (2022)

Compositeness scale constrained by proton lifetime: $\Lambda_{\text{pre}} \gtrsim 10^3 \text{ TeV}$

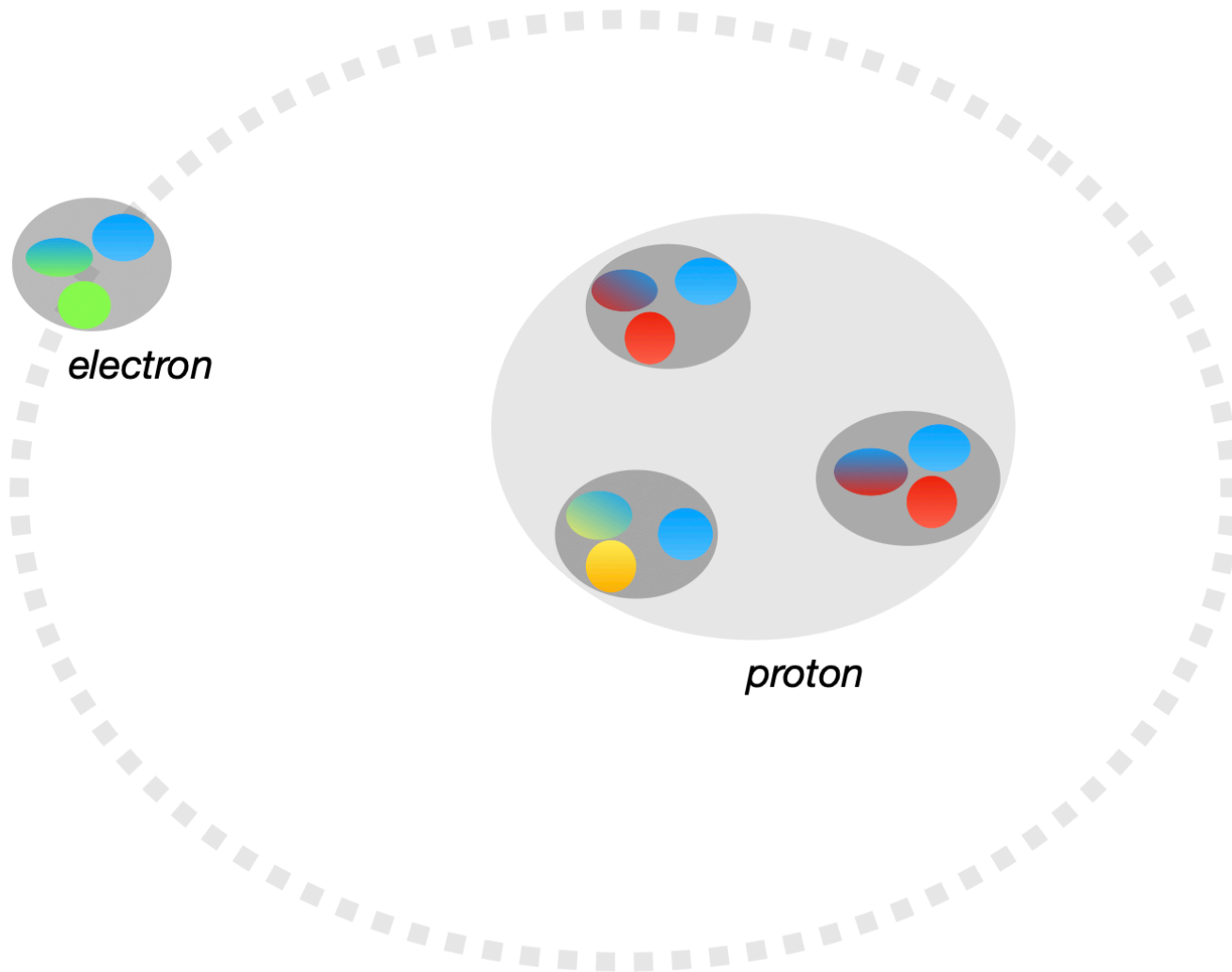
Exotic proton decay $p \rightarrow \bar{N}^0 \pi^+$ followed by a displaced decay of “right-handed neutrino” via a axion-like particle A^0 (if $M_A < m_N$):



Signal can be probed at future proton decay experiments:

HyperKamiokande and especially DUNE (*liquid Argon detector allows reconstruction of the resonances*)

In this (unproven yet!) theory of electron and quark compositeness, the hydrogen atom is made up of 12 preons:

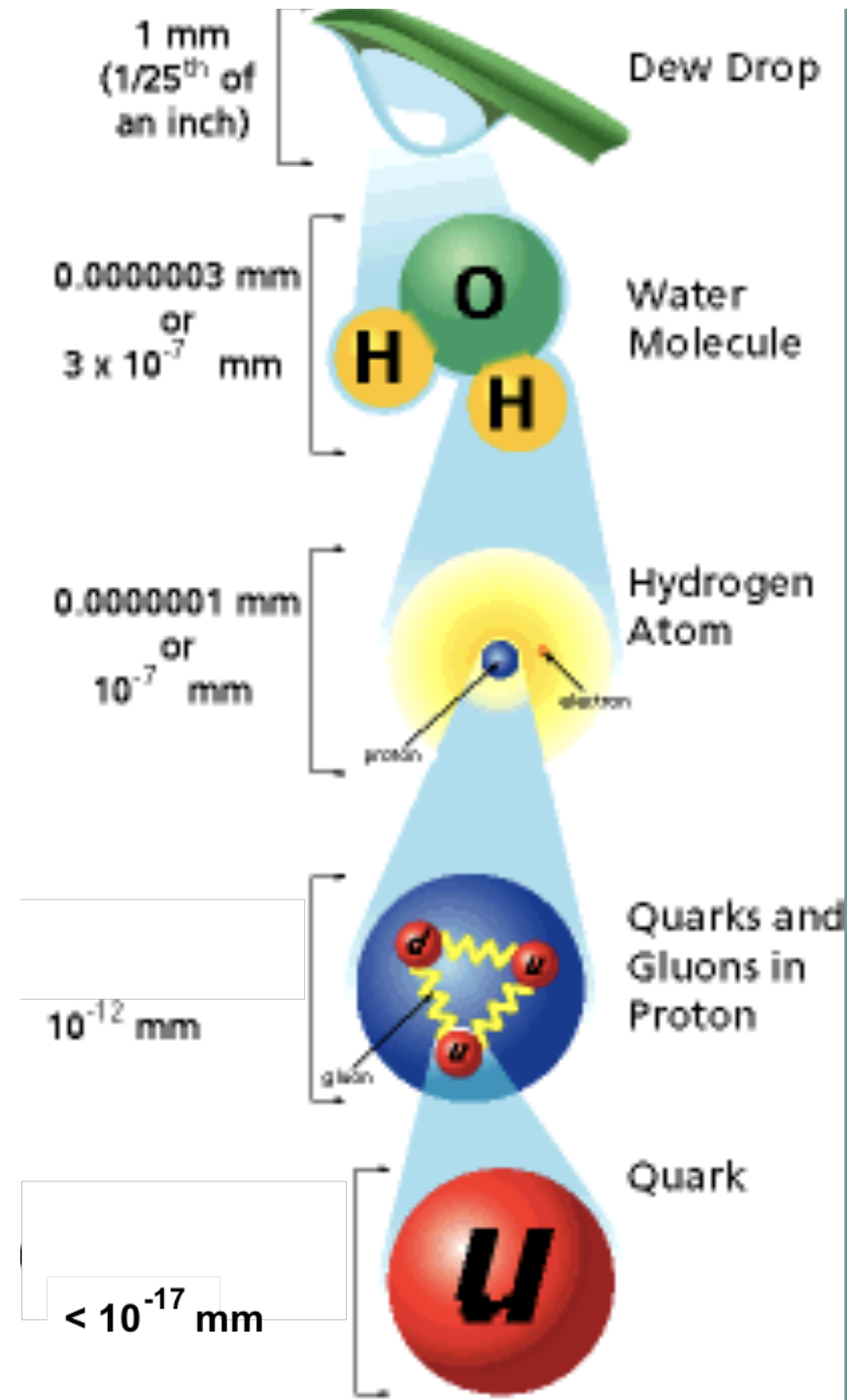


Conclusions

- Not known if the electron, ν 's, quarks are elementary particles (point-like) or composite particles.
- In a theoretical model where the all Standard Model fermions are made of preons:
 - vectorlike quarks and leptons also form and will be probed at the LHC
 - rich sterile neutrino sector and axion-like particles to be probed at DUNE

Homework: find out what's
inside the electron.

Due date: 2040 or so.



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