Nucleons structure and modern atom’s model

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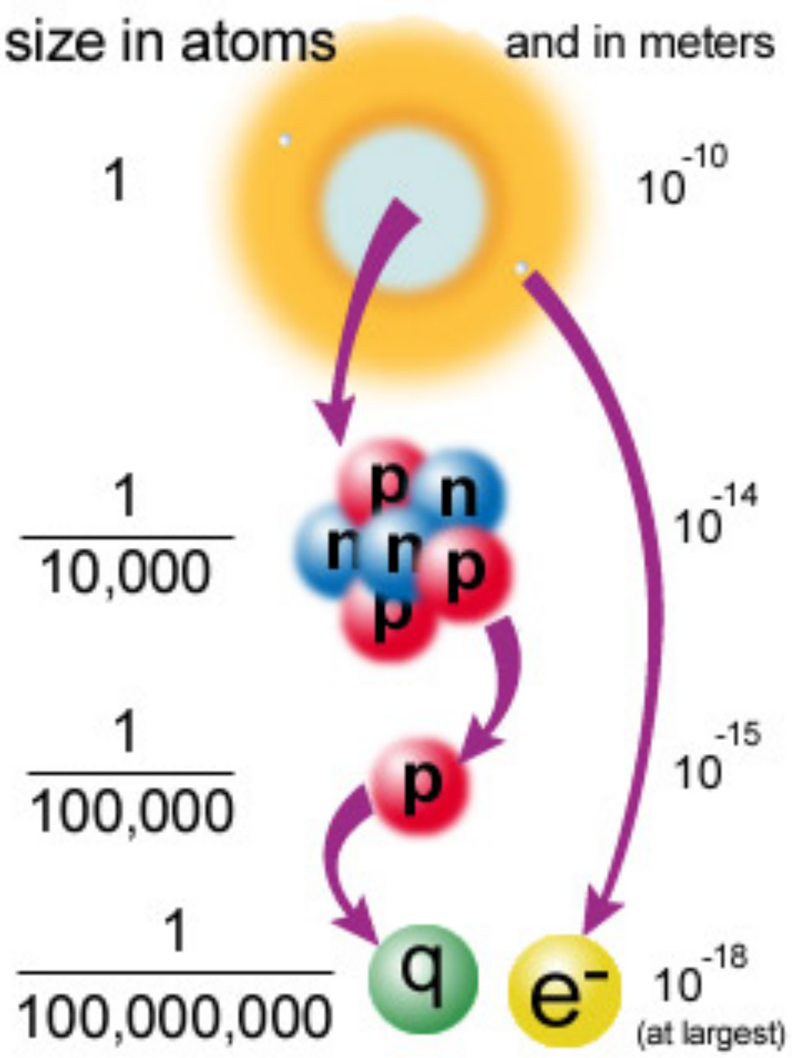
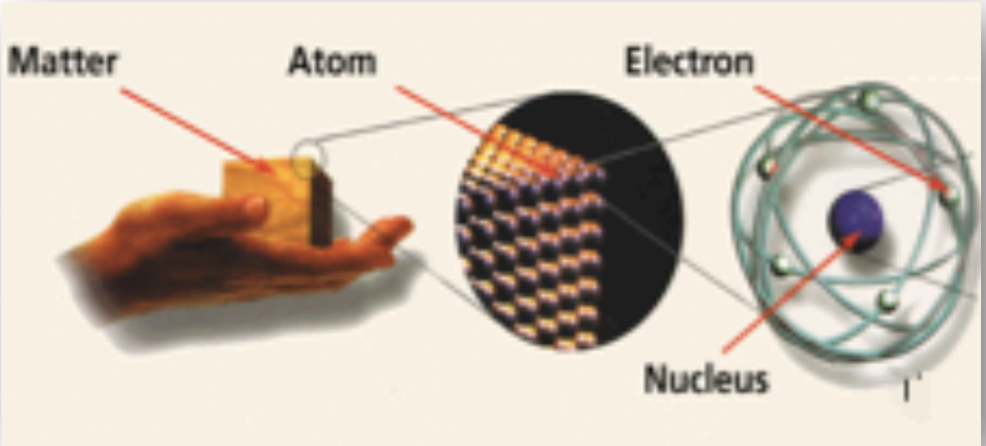
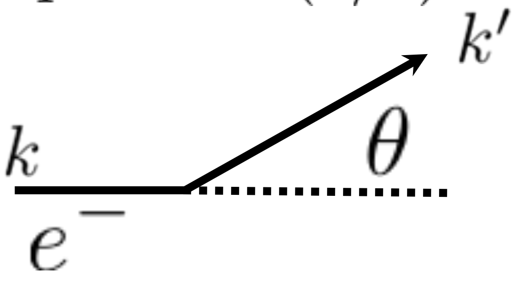
Scale of the atom



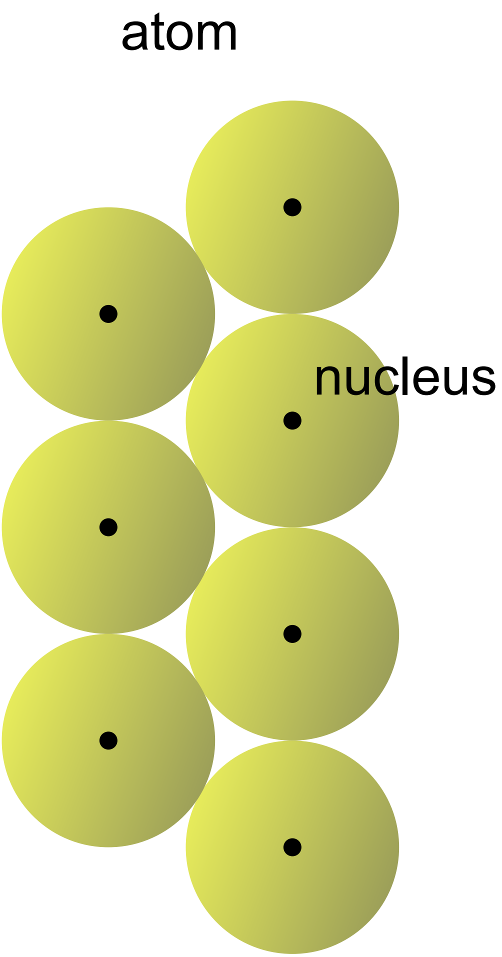


$$q^2 \propto \sin^2(\theta/2)$$



$$q = k - k'$$

$$\frac{d\sigma}{dq^2} = 4\pi\alpha^2 \frac{Z^2}{q^4}$$



What is particle physics or HEP?

- **Particle physics** is a branch of physics that studies the elementary constituents of matter, and the interactions between them.

- It is also called "**high energy physics**", because many elementary particles do not occur under normal circumstances in nature, but can be created and detected during energetic collisions of other particles, as is done in particle accelerators.

What is particle physics or HEP?

- Everything in the universe, from stars and planets, to us is made from the **same basic building blocks - particles** of matter.

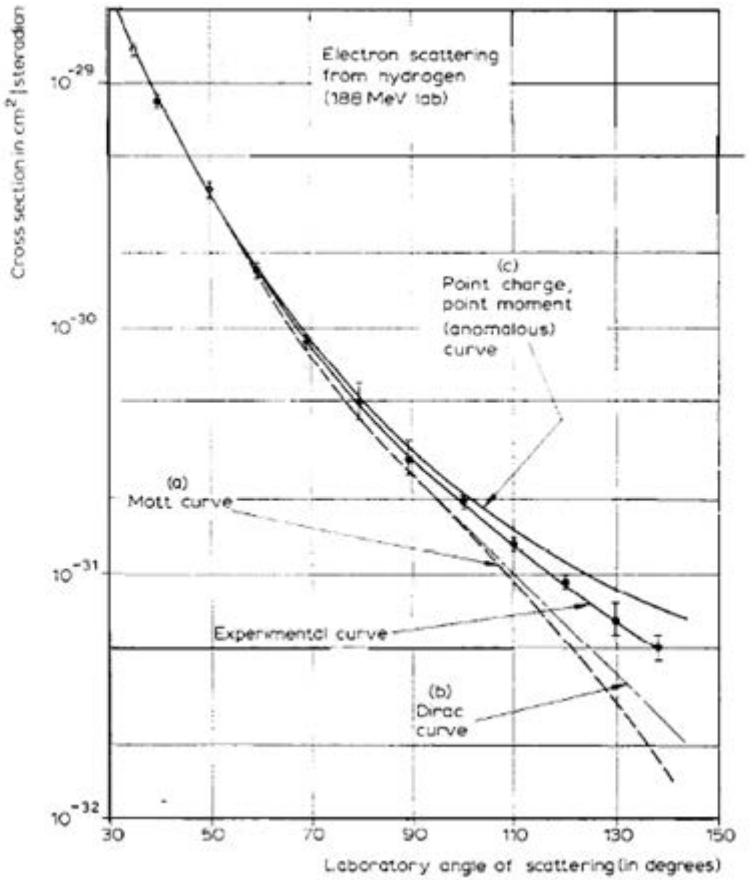
- Particle physics studies these very small building block particles and works out how they **interact** to make the universe look and behave the way it does.

What is the universe made of?

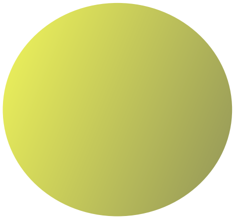
Experiment has taught us:

- Complex structures in the universe are made by combining simple objects in different ways
  - Periodic Table
- Almost everything is made of small objects that like to stick together
  - Particles and Forces
- Everyday intuition is not necessarily a good guide
  - We live in a quantum world, even if it’s not obvious to us

$$\frac{d\sigma}{dQ^2} = 4\pi\alpha^2 \frac{Z^2}{q^4} F(q^2)$$



$$q^2 \propto \sin^2(\theta/2)$$



$$R \approx 1\,\mathrm{fm} = 10^{-15}\mathrm{m}$$

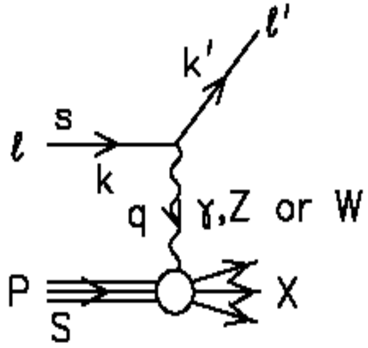
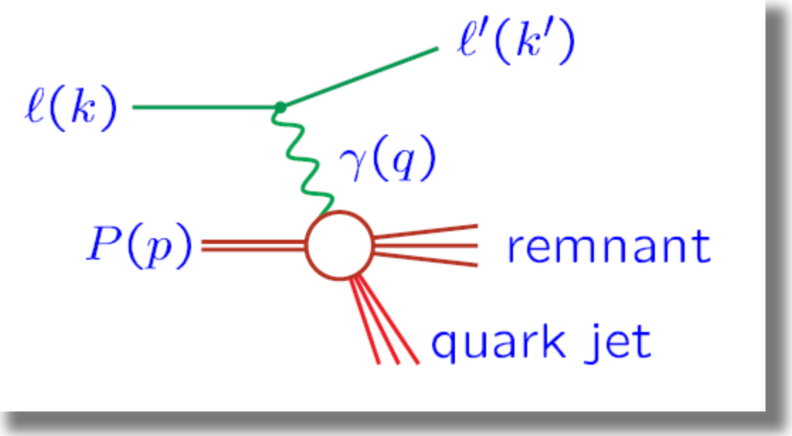


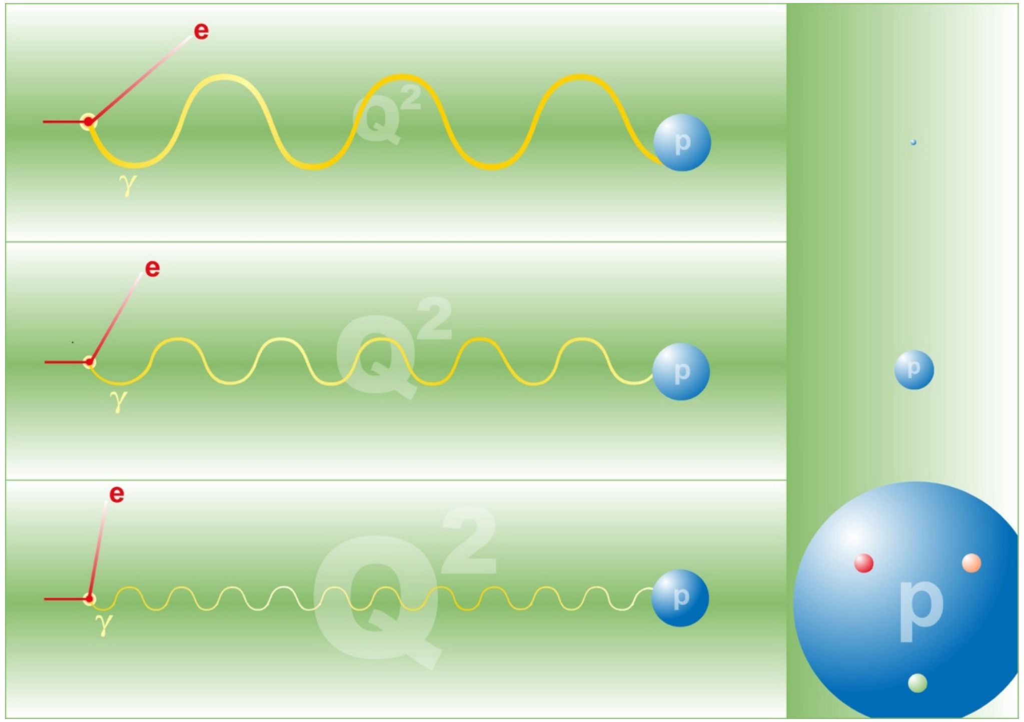
Figure 1: The basic polarized deep inelastic scattering process

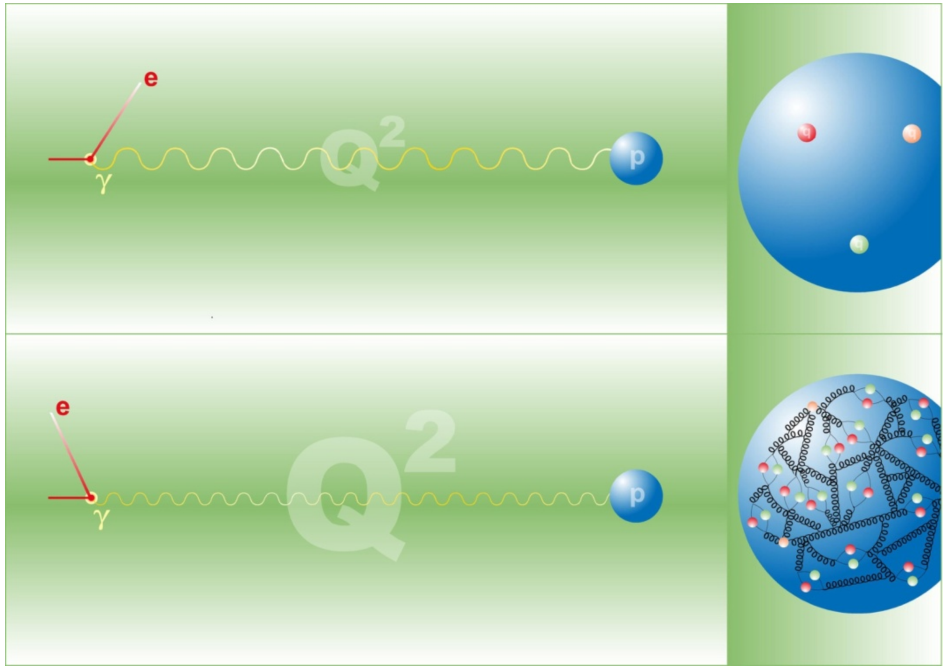
History of the particle physics: Deep Inelastic Scattering (DIS)



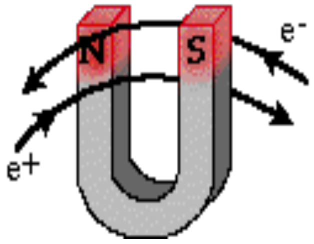
s	$= (k+p)^2$	ℓP centre of mass energy squared
Q^2	$= -q^2$	Negative 4-momentum transfer squared
x	$= Q^2/(2p\cdot q)$	Parton momentum fraction in Breit frame
y	$= (p\cdot q)/(p\cdot k)$	E_γ/E_ℓ in proton rest frame (inelasticity)
W^2	$= (p+q)^2$	γP centre of mass energy squared

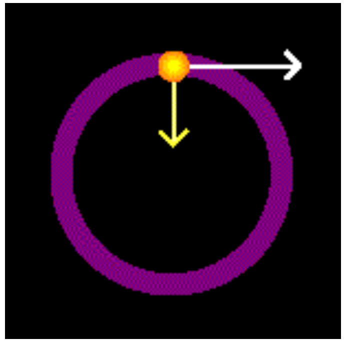
History of the particle physics: Deep Inelastic Scattering (DIS)

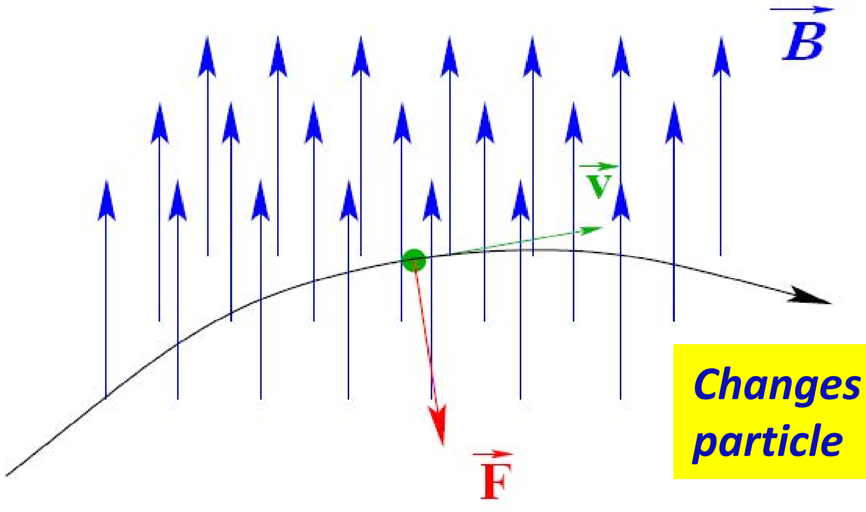



e
γ
Q^2
p
e
γ
Q^2
p

Forces on the Protons





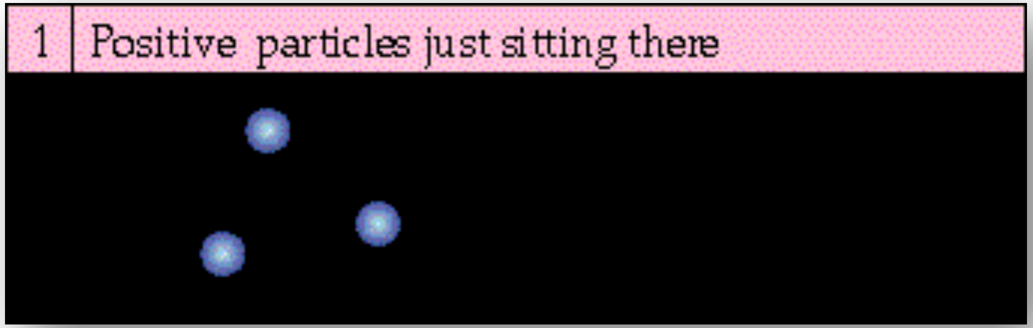


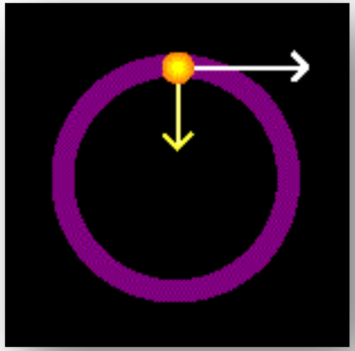
$$\frac{d\vec{p}}{dt} = Q * (\vec{E} + \vec{v} \times \vec{B})$$

Changes the direction of the particle

Acceleration of the particles, field in the same direction as the velocity

- Linear
- Circular

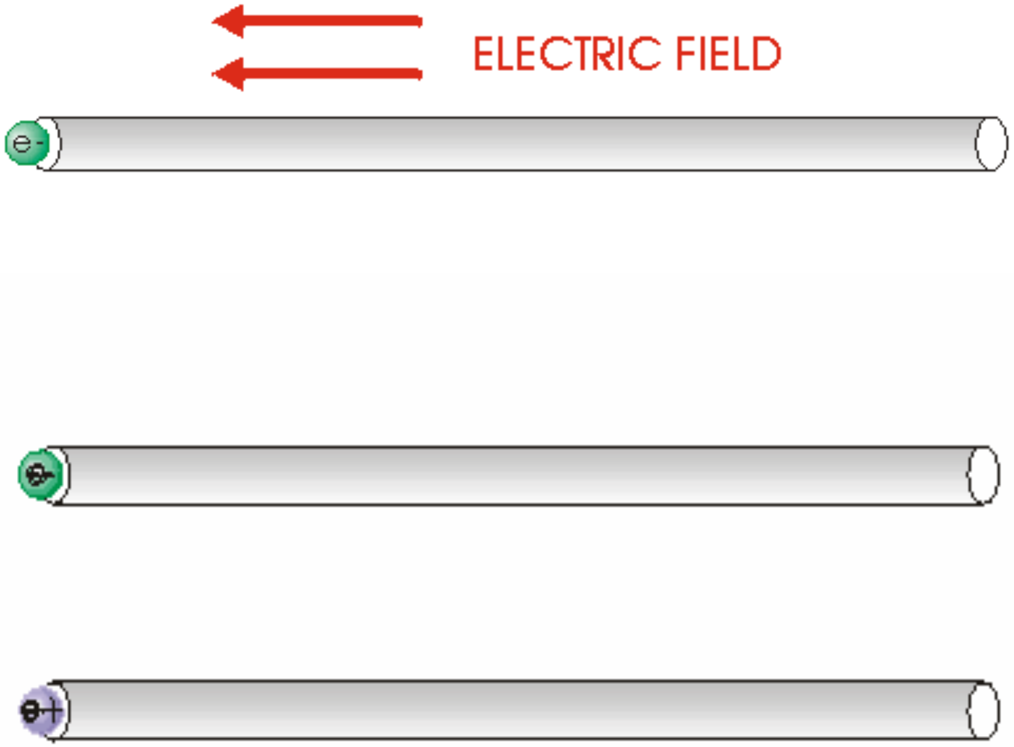




- Linear
- Circular

Linear Accelerator

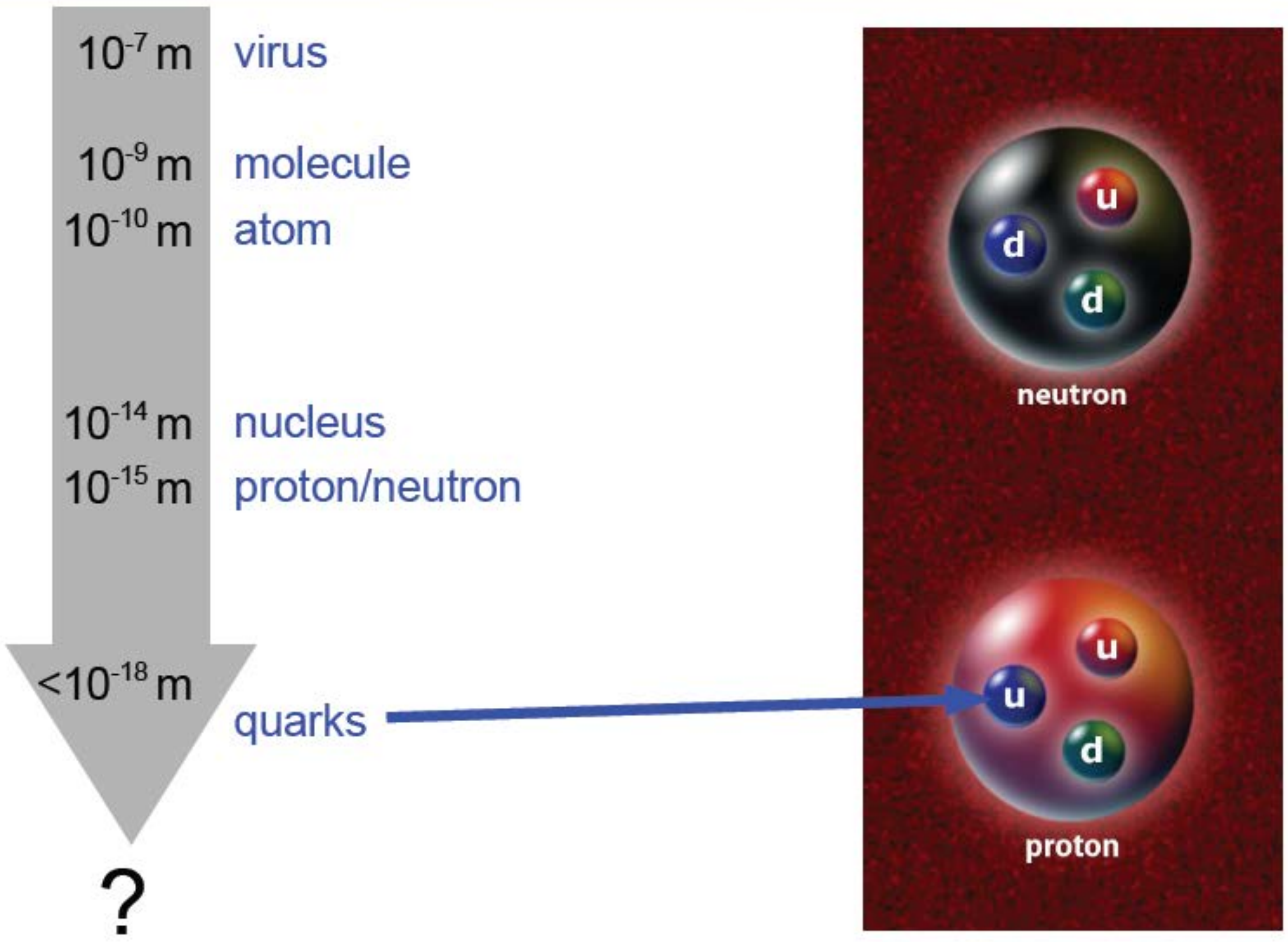
Linear Accelerator



Circular Accelerator

Circular Accelerator

How small is small?

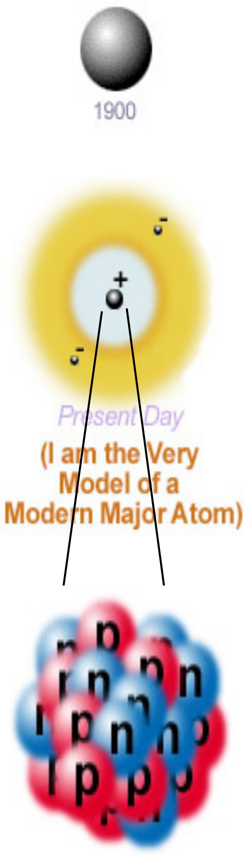


Modern particle physics

Modern particle physics began in the early 20th century as an exploration into the structure of the atom.

The discovery of the atomic nucleus in the gold foil experiment of Geiger, Marsden, and Rutherford was the foundation of the field.

The components of the nucleus were subsequently discovered in 1919 (the proton) and 1932 (the neutron).

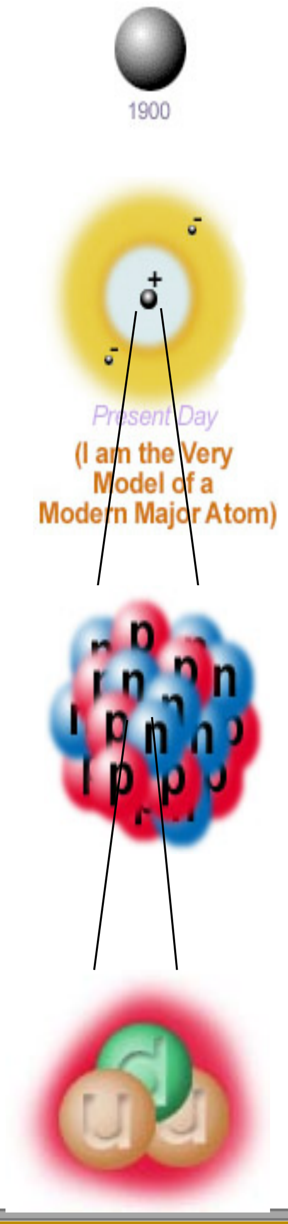


Modern particle physics

Baryons and Mesons are made of other particles.
These particles were named Quarks.

- As far as we know, quarks are like points in geometry. They're not made up of anything else.

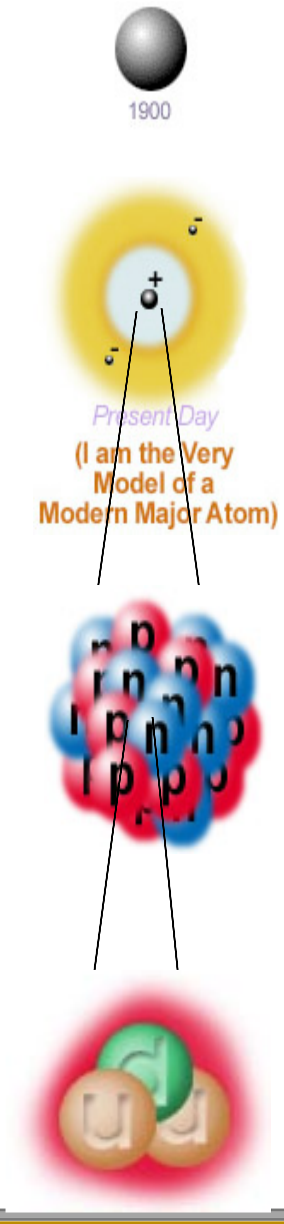
- After extensively testing this theory, scientists now suspect that quarks and the electron (and a few other things we'll see in a minute) are fundamental.



Modern particle physics

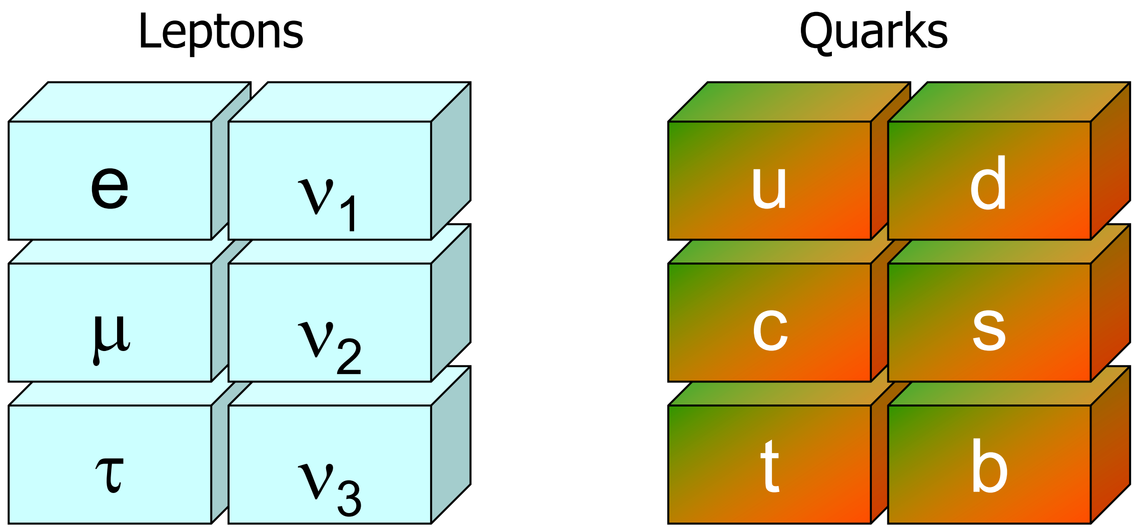
- An elementary particle or fundamental particle is a particle not known to have substructure; that is, it is not known to be made up of smaller particles.

- If an elementary particle truly has no substructure, then it is one of the basic particles of the universe from which all larger particles are made.



Fundamental blocks

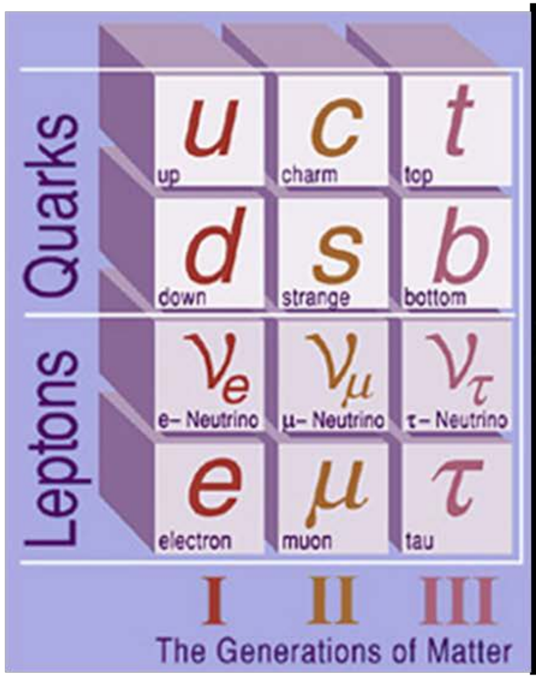
Two types of point like constituents

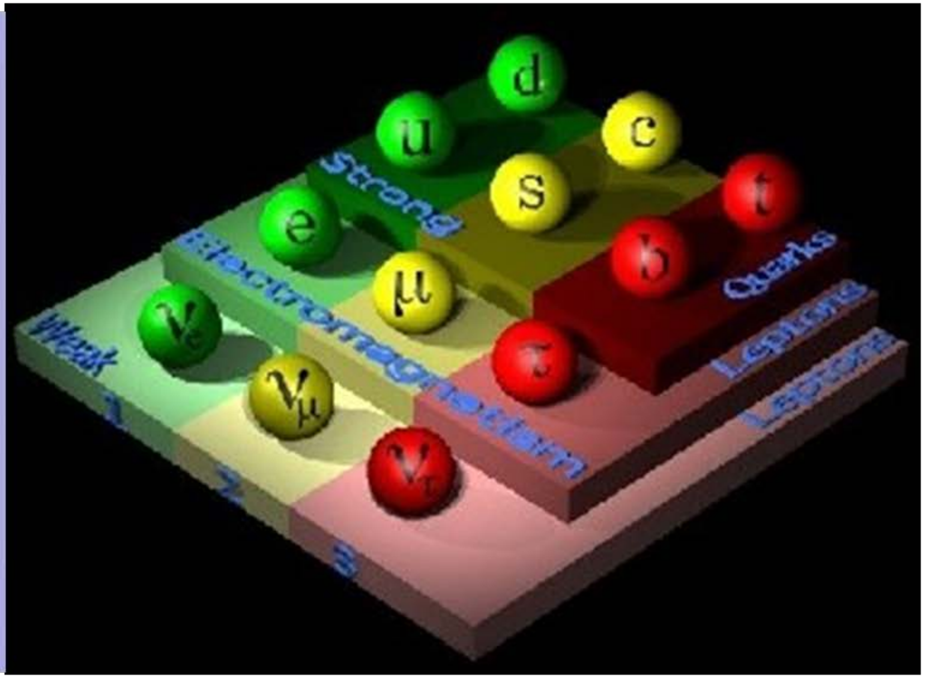


- **Plus force carriers** (will come to them later)
- For every type of matter particle we've found, there also exists a corresponding **antimatter** particle, or **antiparticle**.
- Antiparticles look and behave just like their corresponding matter particles, except they have opposite charges.

Generations of quarks and leptons

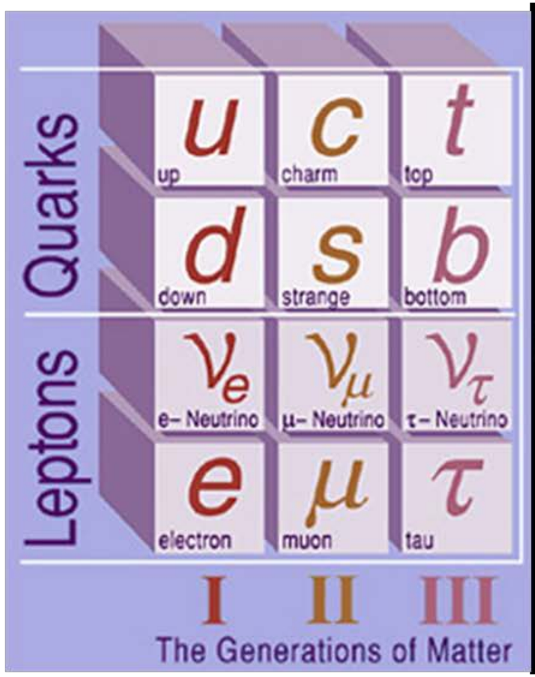
- Note that both quarks and leptons exist in **three** distinct sets. Each set of quark and lepton charge types is called a generation of matter (charges +2/3, -1/3, 0, and -1 as you go down each generation). The generations are organized by increasing mass.

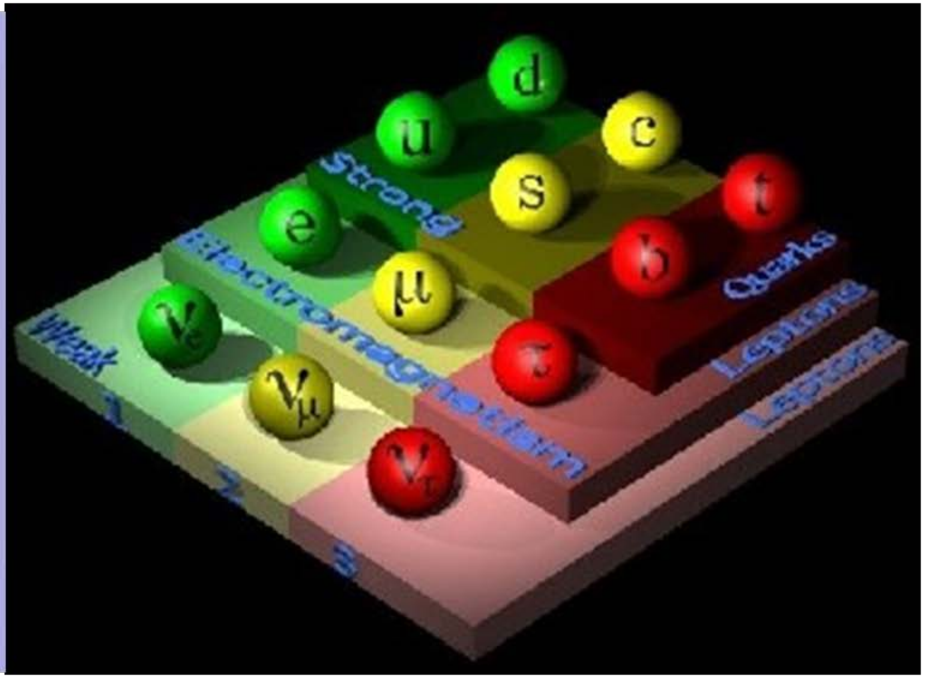




Generations of quarks and leptons

- **All visible matter in the universe** is made from the first generation of matter particles -- up quarks, down quarks, and electrons.
- This is because all second and third generation particles are **unstable** and quickly decay into **stable first generation particles**.





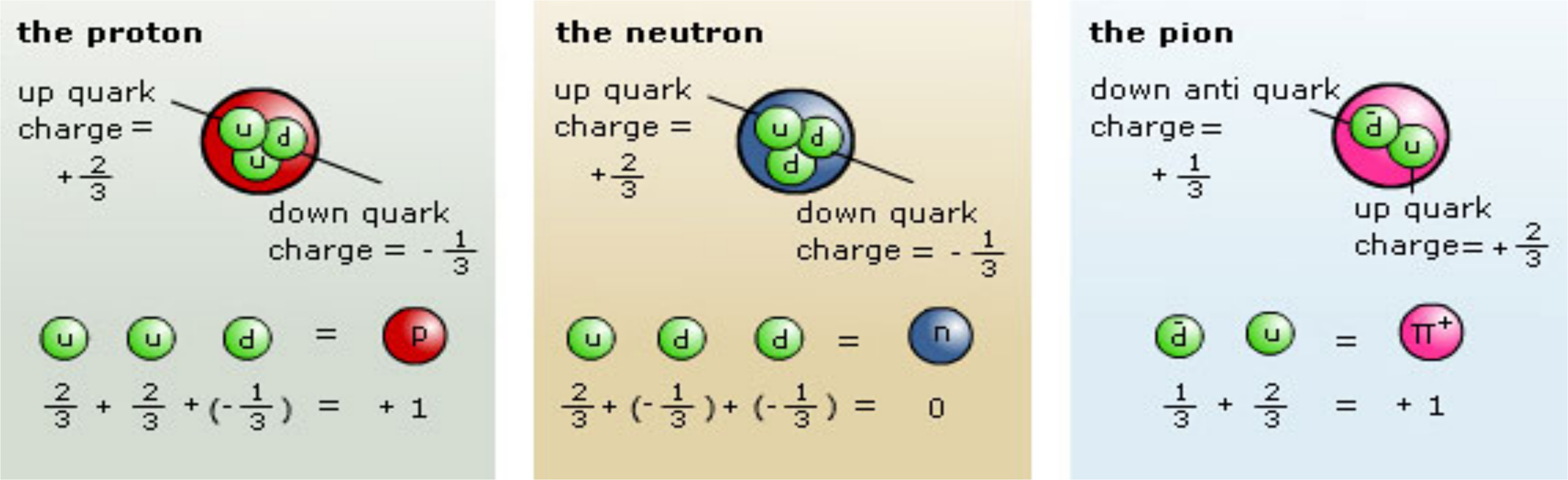
Quarks

- Most of the matter we see around us is made from protons and neutrons, which are composed of up and down quarks.
- There are six quarks, but physicists usually talk about them in terms of three pairs: up/down, charm/strange, and top/bottom. (Also, for each of these quarks, there is a corresponding antiquark.)
- Quarks have the unusual characteristic of having a **fractional electric charge**, unlike the proton and electron, which have integer charges of +1 and -1 respectively. Quarks also carry another type of charge called color charge.

Quantum numbers of quarks

Type of quark	Charge	Spin
u (up)	+2/3	1/2
d (down)	-1/3	1/2
s (strange), S = 1	-1/3	1/2
c (charm), C =1	+2/3	1/2
b (bottom), B = 1	-1/3	1/2
t (top)	+2/3	1/2

Quantum numbers of quarks



Color charge of quarks

They proposed that quarks can have three color charges. This type of charge was called "color" because certain combinations of quark colors would be "neutral" in the sense that three ordinary colors can yield white, a neutral color.

Only particles that are color neutral can exist, which is why only qqq and qq-bar are seen.

Just like the combination of red and blue gives purple, the combination of certain colors give white. One example is the combination of red, green and blue.

Color charge of quarks

- There are 6 quarks and 6 leptons which we believe are fundamental blocks of nature.

- They have antiparticles, i.e. the same quantum numbers except electric charge.

- Quarks have fractional electric charges.

- A new charge for quarks has been introduced: this charge is color.

Forces

Although there are apparently many types of forces in the Universe, they are all based on four fundamental forces:
Gravity, Electromagnetic force, Weak force and Strong force.

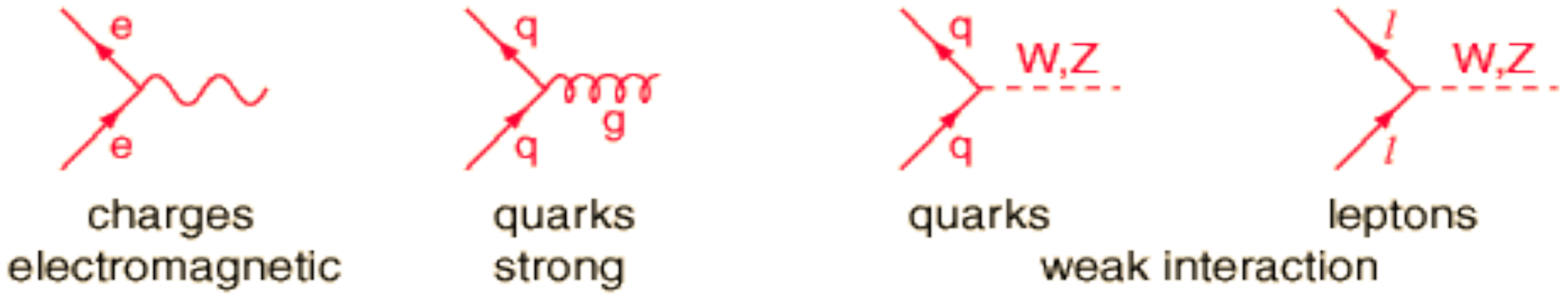
The strong and weak forces only act at very short distances and are responsible for holding nuclei together.

The electromagnetic force acts between electric charges.
The gravitational force acts between masses.

Forces at the fundamental level

The particles (quarks and leptons) interact through different "forces", which we understand as due to the exchange of "field quanta" known as "gauge bosons".

Electromagnetism (QED)	**Photon (γ) exchange**
Strong interactions (QCD)	**Gluon (g) exchange**
Weak interactions	**W and Z bosons exchange**
Gravitational interactions	**Graviton (G) exchange**

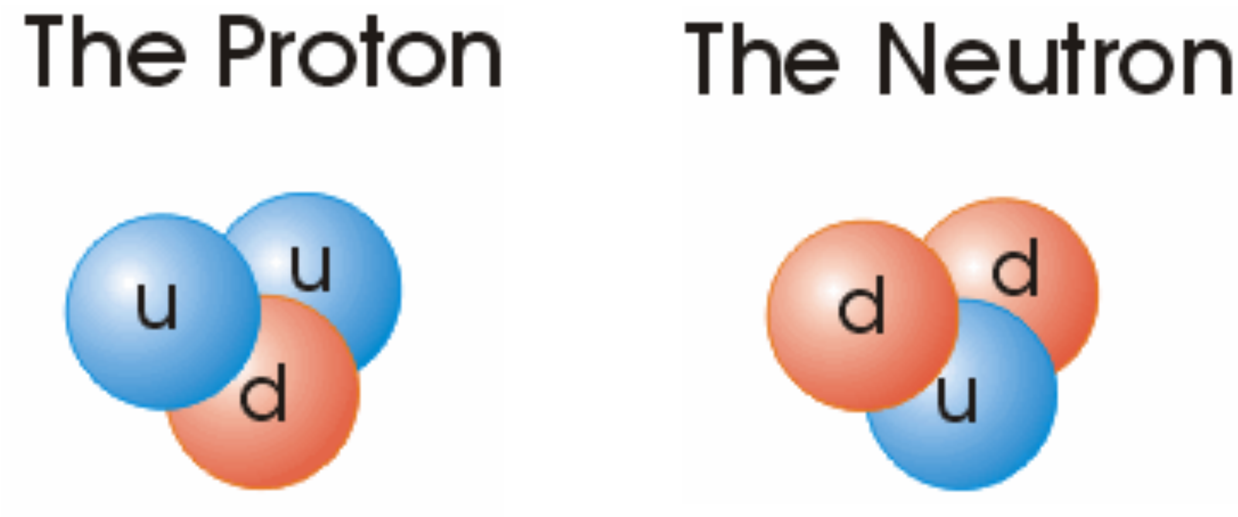


Which forces act on which particles?

- The weak force acts between all quarks and leptons
- The electromagnetic force acts between all charged particles
- The strong force acts between all quarks (i.e. objects that have color charge)
- Gravity does not play any role in particle physics

	Weak	EM	Strong
Quarks	+	+	+
Charged leptons	+	+	–
Neutral leptons	+	–	–

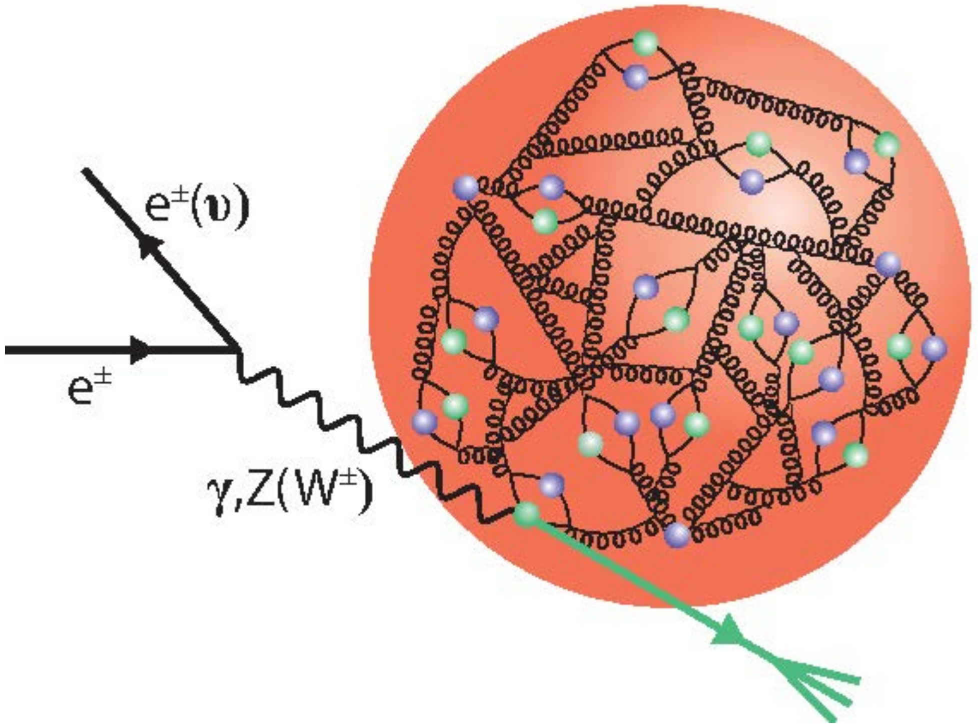
Proton and neutron internal structure



Proton internal structure

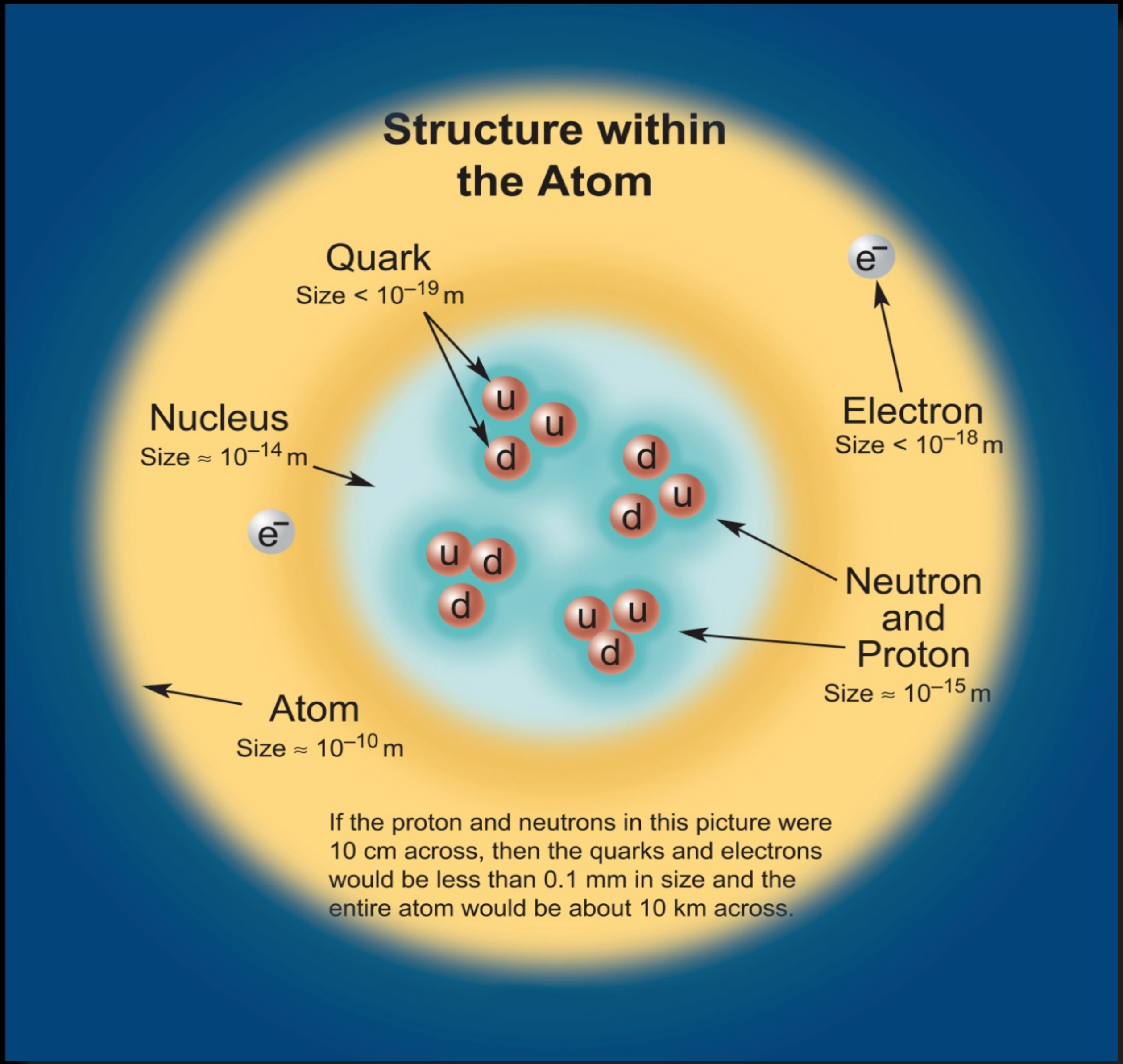
Valence quarks (uud)

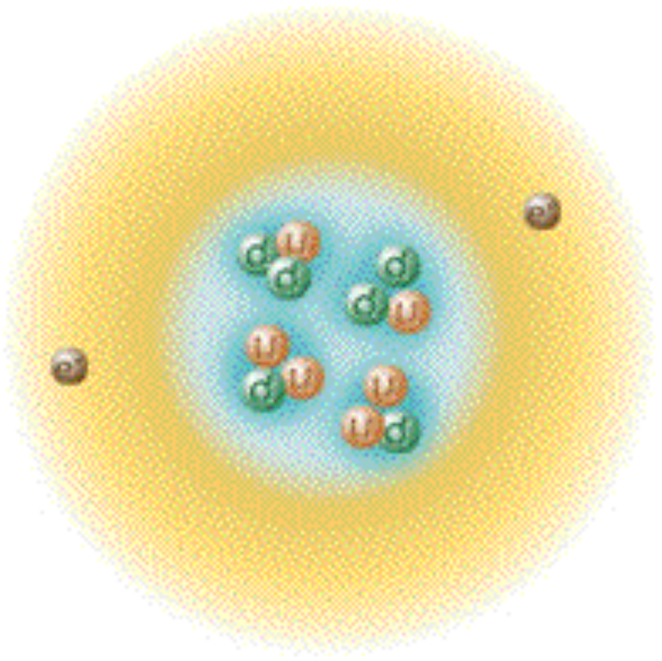
Gluons(g)



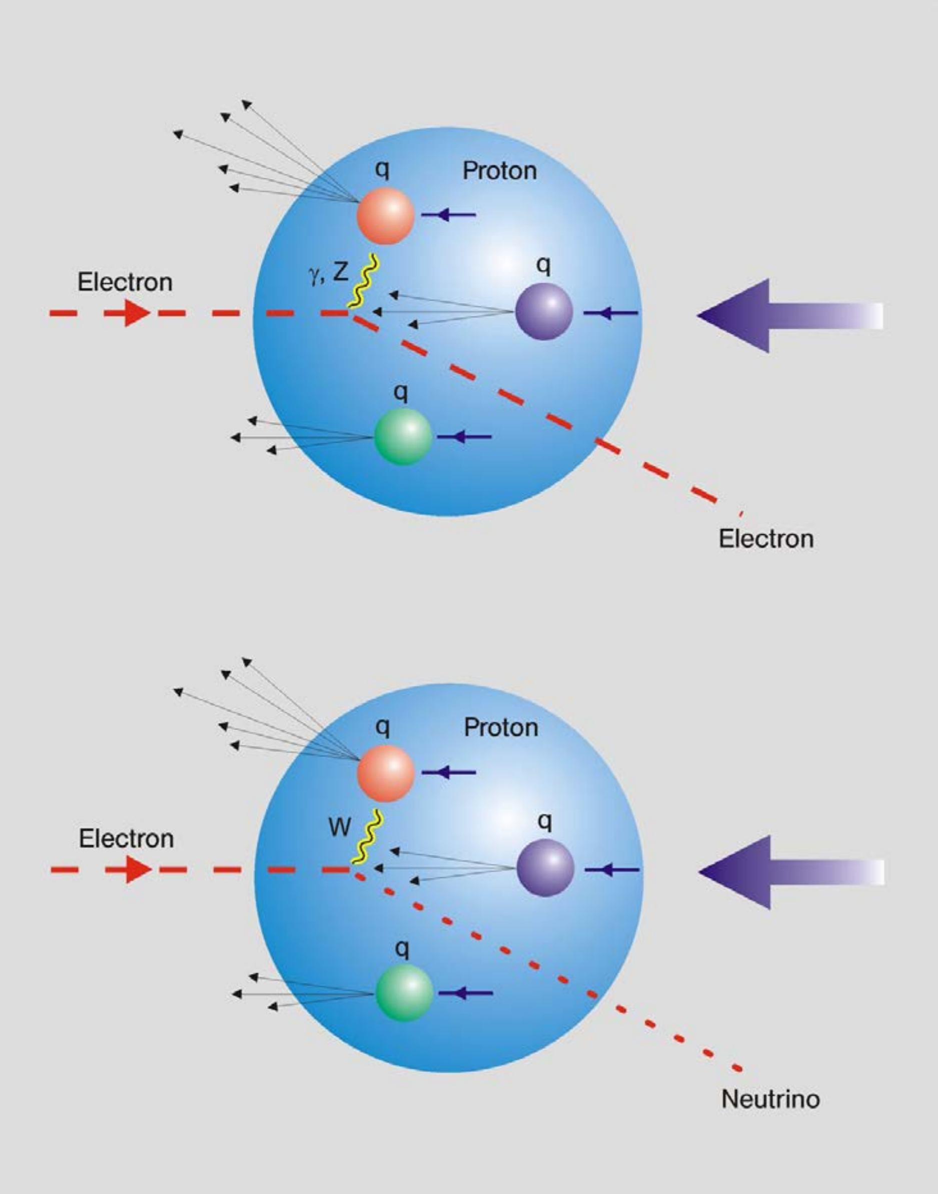
Sea quarks

$\bar{u}u, \bar{d}d, \bar{s}s, \bar{c}c, \bar{b}b$

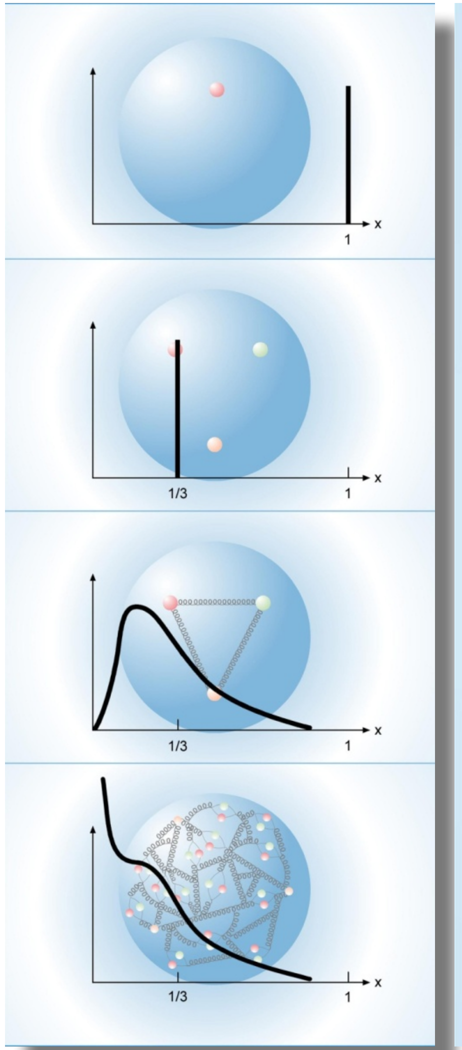

Structure within the Atom
Quark
Size < 10⁻¹⁹ m
e⁻
Electron
Size < 10⁻¹⁸ m
Nucleus
Size ≈ 10⁻¹⁴ m
u
u
d
d
u
d
e⁻
u
d
d
u
u
d
Neutron and Proton
Size ≈ 10⁻¹⁵ m
Atom
Size ≈ 10⁻¹⁰ m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

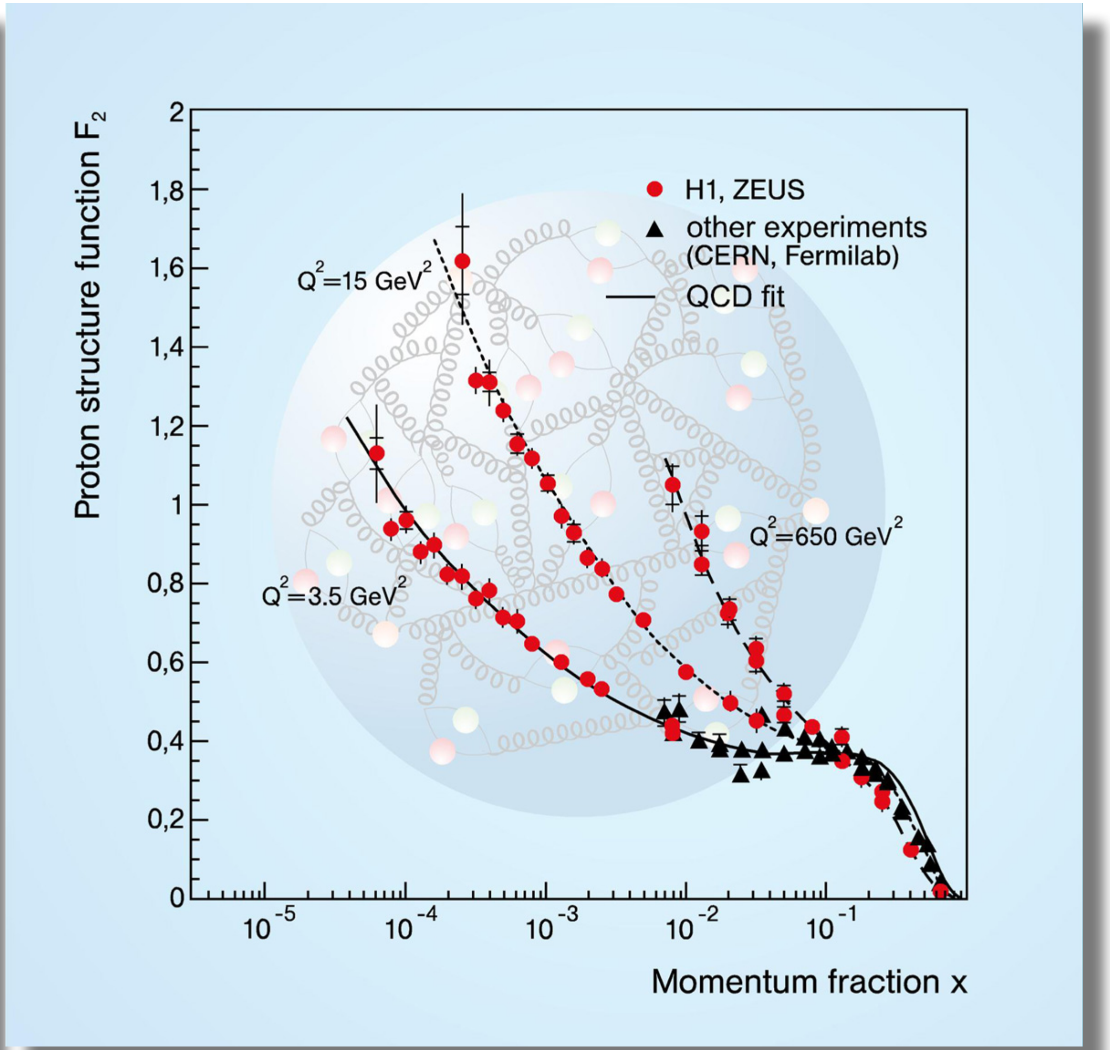


DIS and Proton Structure



DIS and Proton PDFs





The Theory of Deeply Inelastic Scattering: PDFs

Write DIS X-section to zeroth order in α_s ('quark parton model'):

$$\frac{d^2\sigma^{em}}{dx dQ^2} \simeq \frac{4\pi\alpha^2}{xQ^4}\left(\frac{1+(1-y)^2}{2} F_2^{em} + \mathcal{O}(\alpha_s)\right)$$

$\propto F_2^{em}$ [structure function]

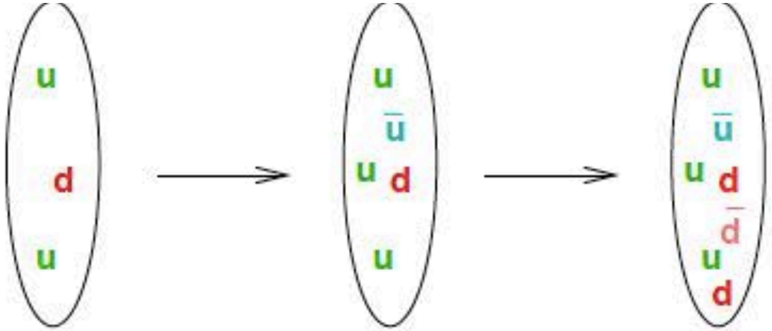
$$F_2 = x(e_u^2 u(x) + e_d^2 d(x)) = x\left(\frac{4}{9}u(x) + \frac{1}{9}d(x)\right)$$

[$u(x)$, $d(x)$: parton distribution functions (PDF)]

<u>NB:</u>

- use perturbative language for interactions of up and down quarks
- but distributions themselves have a *non-perturbative* origin.

Anti quarks in proton: Sea PDFs



How can there be infinite number of quarks in proton?

Proton wavefunction *fluctuates* — extra $u\bar{u}$, $d\bar{d}$ pairs (*sea quarks*) can appear:

Antiquarks also have distributions, $\bar{u}(x)$, $\bar{d}(x)$

$$F_2 = \frac{4}{9}(xu(x) + x\bar{u}(x)) + \frac{1}{9}(xd(x) + x\bar{d}(x))$$

NB: photon interaction $\sim$ square of charge $\rightarrow$ +ve

- Previous transparency: we were actually looking at $\sim u + \bar{u}$, $d + \bar{d}$
- Number of extra quark-antiquark pairs can be *infinite,* so

$$\int dx\,(u(x) + \bar{u}(x)) = \infty$$

as long as they carry little momentum (mostly at low x)

Assumption ($SU(2)$ isospin): neutron is just proton with $u \Leftrightarrow d$:

proton = uud; neutron = ddu

Isospin: $u_n(x) = d_p(x)\,, \qquad d_n(x) = u_p(x)$

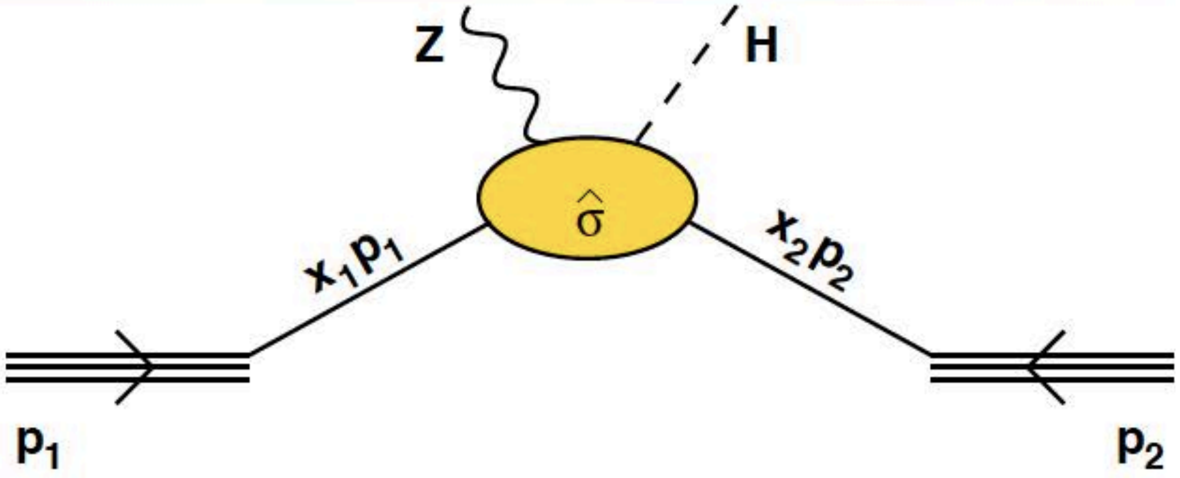
$$F_2^p = \frac{4}{9}u_p(x) + \frac{1}{9}d_p(x)$$
$$F_2^n = \frac{4}{9}u_n(x) + \frac{1}{9}d_n(x) = \frac{4}{9}d_p(x) + \frac{1}{9}u_p(x)$$

Linear combinations of F_2^p and F_2^n give separately $u_p(x)$ and $d_p(x)$.

Experimentally, get F_2^n from deuterons: $F_2^d = \frac{1}{2}(F_2^p + F_2^n)$

Factorization & Parton distribution

Cross section for some hard process in hadron-hadron collisions

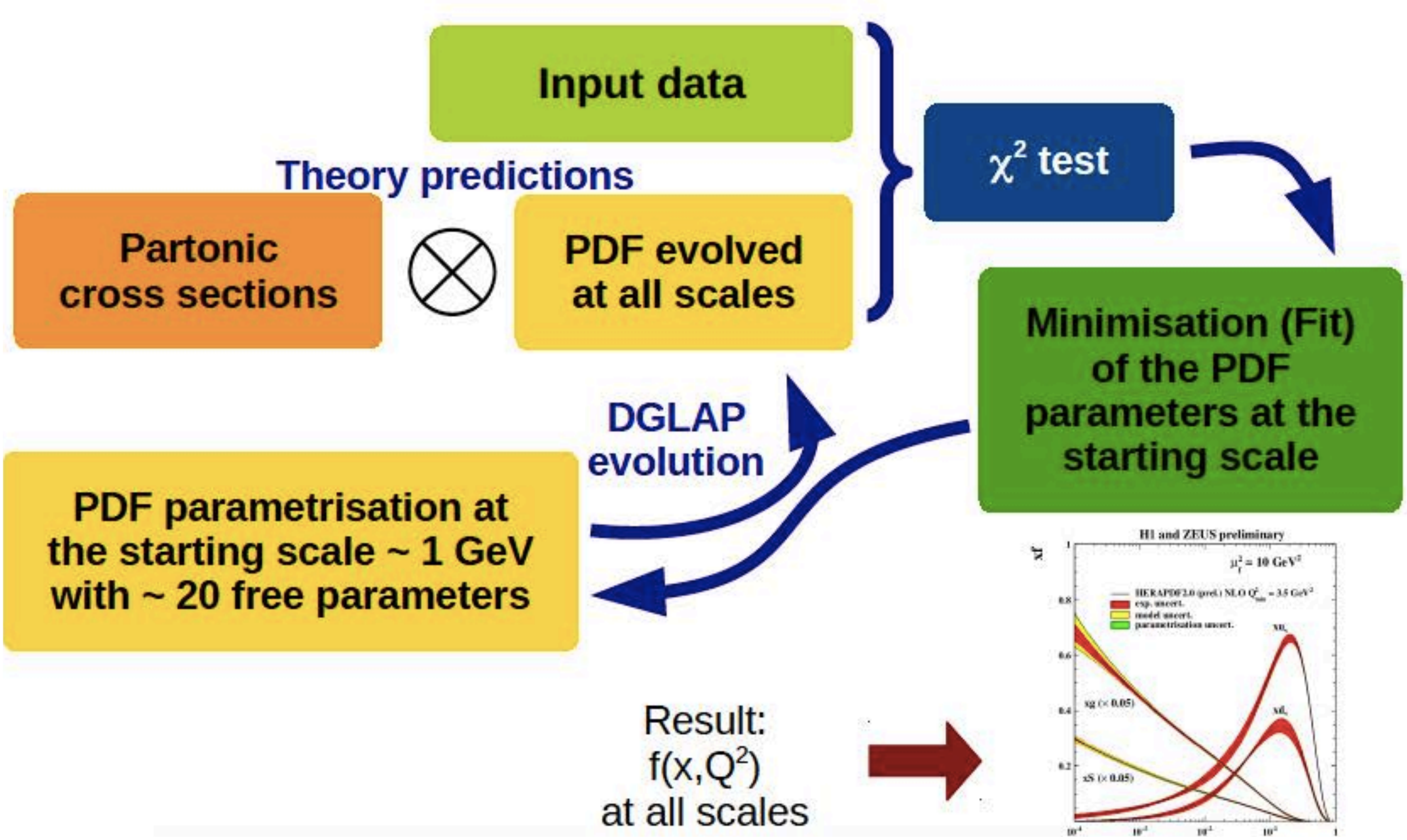


$$\sigma = \int dx_1 f_{q/p}(x_1, \mu^2) \int dx_2 f_{\bar{q}/\bar{p}}(x_2, \mu^2)\, \hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)\,, \quad \hat{s} = x_1 x_2 s$$

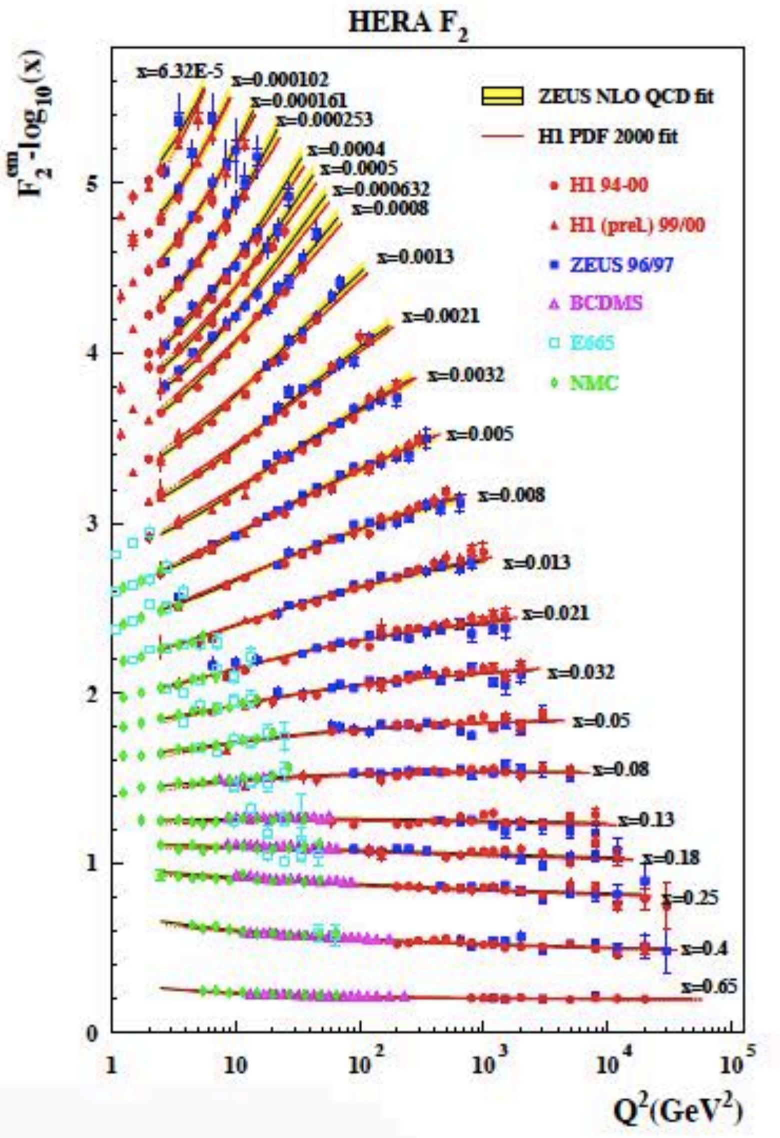
- Total X-section is *factorized* into a 'hard part' $\hat{\sigma}(x_1 p_1, x_2 p_2, \mu^2)$ and 'normalization' from parton distribution functions (PDF).
- Measure total cross section $\leftrightarrow$ *need to know PDFs* to be able to test hard part
  - how can we determine the PDFs?
  - does picture really stand up to QCD corrections?

NB: non-perturbative

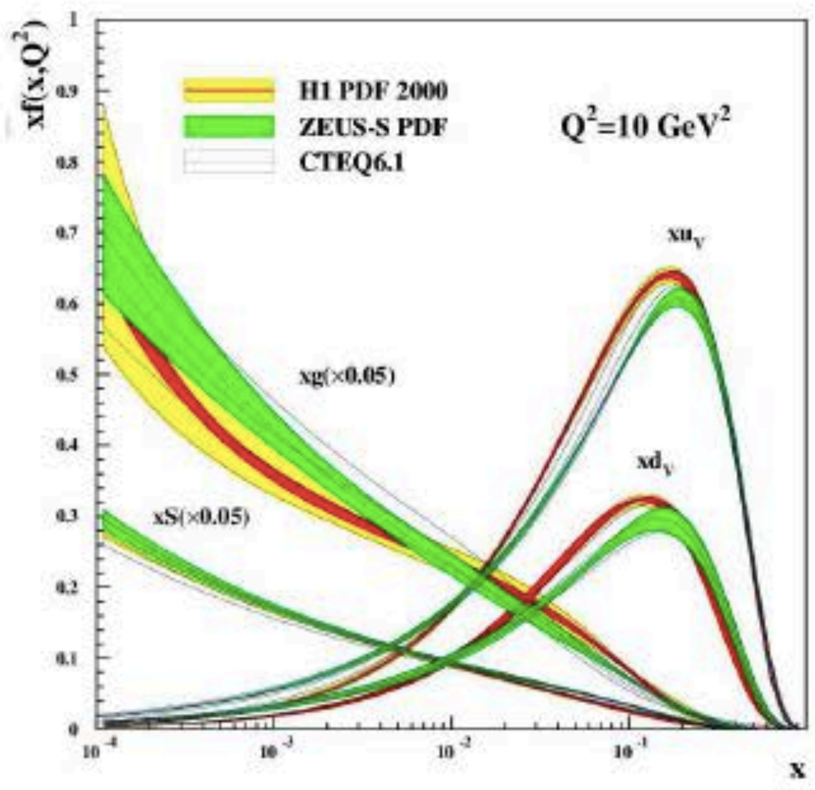
DIS and PDFs


Input data
Theory predictions
Partonic cross sections
PDF evolved at all scales
χ² test
Minimisation (Fit) of the PDF parameters at the starting scale
DGLAP evolution
PDF parametrisation at the starting scale ~ 1 GeV with ~ 20 free parameters
Result: f(x,Q²) at all scales
H1 and ZEUS preliminary

DIS and PDFs


HERA F2
$F_2^{em}-\log_{10}(x)$
x=6.32E-5
x=0.000102
x=0.000161
x=0.000253
x=0.0004
x=0.0005
x=0.000632
x=0.0008
x=0.0013
x=0.0021
x=0.0032
x=0.005
x=0.008
x=0.013
x=0.021
x=0.032
x=0.05
x=0.08
x=0.13
x=0.18
x=0.25
x=0.4
x=0.65
ZEUS NLO QCD fit
H1 PDF 2000 fit
H1 94-00
H1 (prel.) 99/00
ZEUS 96/97
BCDMS
E665
NMC
$Q^2(GeV^2)$

DIS and PDFs



Major activity is translation of experimental errors (and theory uncertainties) into *uncertainty bands on extracted PDFs.*

PDFs with uncertainties allow one to estimate *degree of reliability* of future predictions

1. Ali Khorramian, Elliot Leader, Dimiter B. Stamenov, Amir Shabanpour
Phys. Rev. D 103 (2021) 5, 054003. [arXiv:2009.04808 [hep-ph]].
2. H. Abdolmaleki, A. N. Khorramian
Phys. Rev. D 99, 116019 (2019) [arXiv:1903.02583 [hep-ph]].
3. M. Salimi-Amiri, A. N. Khorramian, H. Abdolmaleki, F. Oldness
Phys. Rev. D 98, no. 5, 056020 (2018) [arXiv: 1805.02613 [hep-ph]]

Thanks for your attention