Experimental results on nucleon structure
Lecture I

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Outline

Course literature

1. D. H. Perkins, “Introduction to high energy physics”, CUP 2000 (4th edition or later).
2. B.R. Martin and G. Shaw, “Particle Physics” Wiley 1997 or later.
3. A. W. Thomas and W. Weise, “The structure of the nucleon”, Wiley-VCH 2001.
4. B. Povh, et al., “Particles and Nuclei”, Springer 2008 (6th edition or later)
5. R. G. Roberts, “The structure of the proton: Deep inelastic scattering”, CUP 1990.
6. and original papers, e.g. for spin see C. A. Aidala et al., arXiv: 1209.2803 v2 (1 April 2013)

Outline

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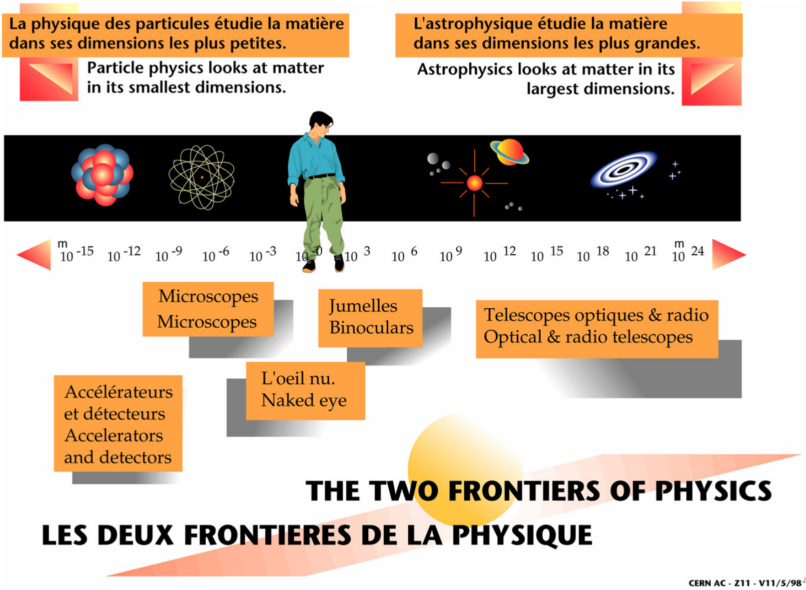
1. Course literature

2. Introduction
   - Scales, elementary particles, interactions
   - Kinematics, experiments and observables

Two limits of research



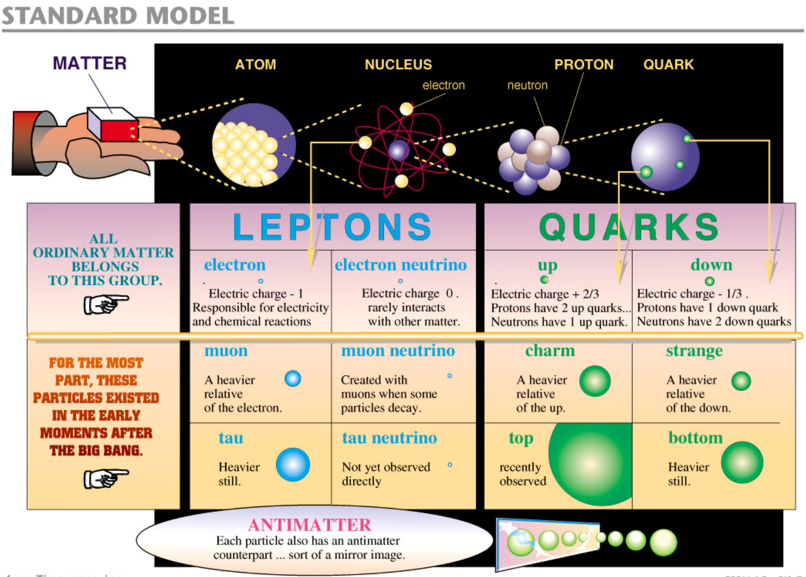
Reminder: scales (distance, energy, mass,...) and constants

- $r \sim$ 1 fm (presently: an object is pointlike if its dimensions $\lesssim$ 0.001 fm = 10^{-18} m)
  $E \sim$ 1 GeV
  $m \sim$ 1 GeV/c^2

- Important constants:
  - Planck constant, $h \approx 6 \cdot 10^{-34}$ J·s (quantum physics must be applied),
  - speed of light, $c \approx 3 \cdot 10^{8}$ m/s (relativistic physics must be applied),
  - fine structure constant, $\alpha = \frac{e^2}{4\pi\epsilon_0\hbar c} \approx \frac{1}{137}$.
  - Heaviside – Lorentz system: $1 = \hbar = c = \epsilon_0 = \mu_0 \implies \alpha = \frac{e^2}{4\pi}$ will be used

- Very useful quantity: $\hbar c = 1 \approx 0.197$ GeV·fm

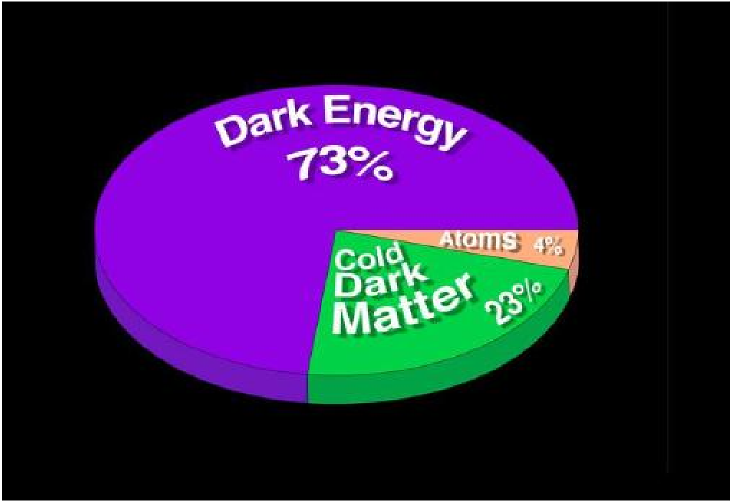
Elementary building blocks of matter



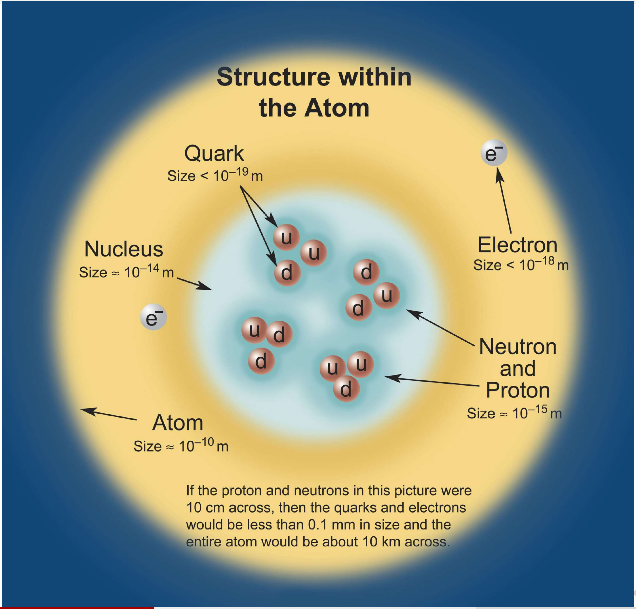
from Time magazine

Photo: BB, 2012

Do we REALLY understand the structure of matter?



Reminder: dimensions of atom and its constituents



Baryons: nucleons & Co.

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons

Mesons $q\bar{q}$ Mesons are bosonic hadrons These are a few of the many types of mesons.					
Symbol	**Name**	**Quark content**	**Electric charge**	**Mass GeV/c^2**	**Spin**
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

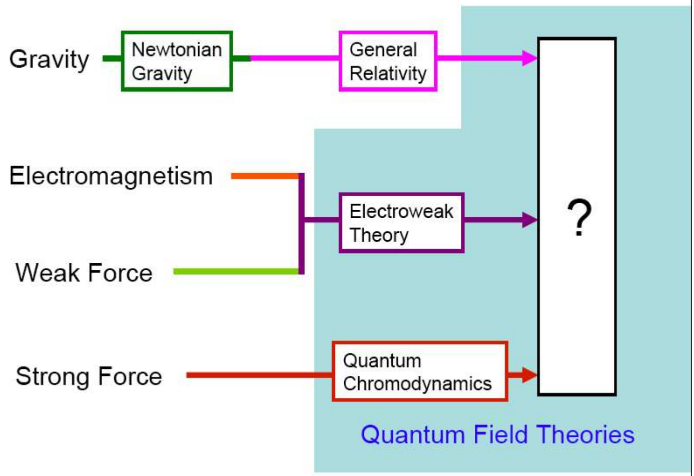
Types and properties of interactions (forces)

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60
mass (GeV)	0	80-90	0	0
range (m)	∞	10^{-18}	∞	$\leq 10^{-15}$
coupling constant	10^{-38}	10^{-5}	1/137	1
time (s)	–	$10^{-8} - 10^{-10}$	10^{-20}	10^{-23}

Unification of interactions at energy of 10^{15} GeV ???



– > ENERGY

Add supersymmetry: fermions $\leftrightarrows$ bosons

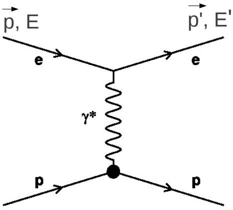
Standard Model of elementary interactions

- Family of elementary objects: at least 36 members of which at least 12 are interaction (or force) carriers.
- In our conditions we see at least 4 interactions; their relative strength changes with energy:
  - strong $\searrow$
  - electromagnetic $\nearrow$

  May be that immediately after the Big Bang all interactions had similar strength $\longrightarrow$ Grand Unification Theories (GUT), at E $\gtrsim$ 10^{15} GeV (proton mass: $\sim$ 1 GeV; largest proton energy in an accelerator (LHC) now: 4 TeV, soon: 7 TeV).
- Standard Model: perfectly agrees with experiment but DOES NOT predict several parameters, e.g. particle masses and features of forces (about 20 “free” parameters). Also: gravitation???

Interactions; probability amplitude; cross section

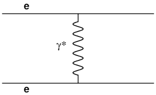
- (Electromagnetic) interaction = emission and absorption of a virtual photon, γ^*.
- Momentum transfer: $\vec{k} = (\vec{p} - \vec{p}\,')$
  Energy transfer: $\nu = (E - E')$.
- Define (negative) 4-momentum transfer squared (photon virtuality):
  $Q^2 = -q^2 = (\vec{p} - \vec{p}\,')^2 - (E - E')^2 = -M^2_{\gamma^*} \neq 0$!
- Define cross-section, σ: $\sigma \sim \mathrm{probability} = |f|^2$
- Observe that $f \sim \Delta t$ (time of the emission process)
  so that $f \sim \dfrac{1}{\sqrt{-M^2_{\gamma^*}}} = \dfrac{1}{Q}$
  or: $f = \dfrac{e}{Q} \Longrightarrow$ whole interaction: $f \sim \dfrac{e_1 e_2}{Q^2}$ and $\dfrac{\mathrm{d}\sigma}{\mathrm{d}Q^2} \sim \dfrac{e_1^2 e_2^2}{Q^4}$



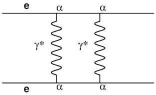
This probability amplitude is universal, i.e. describes several processes.

Feynman diagrams in Coulomb interactions

- Scattering amplitude: $f \sim \frac{ee}{Q^2} \Longrightarrow \frac{d\sigma}{dQ^2} \sim \frac{e^4}{Q^4} \sim \frac{\alpha^2}{Q^4}$



- For $2\gamma^*$ exchange $\sigma \sim \alpha^4$,
  i.e. σ is $\alpha^2 \approx \left(\frac{1}{137}\right)^2$ smaller than for $1\gamma^*$ exchange.

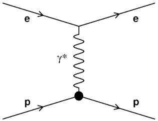


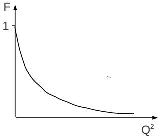
- Scattering from an effective charge eF:

$$\frac{d\sigma}{dQ^2} \sim \frac{\alpha^2 F^2(Q^2)}{Q^4}$$

with limiting conditions:

$$\lim_{Q^2 \to \infty} F(Q^2) = 0 \quad \text{and} \quad \lim_{Q^2 \to 0} F(Q^2) = 1$$

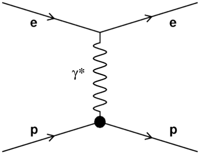




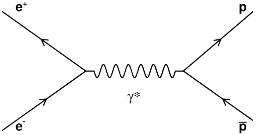
where $F(Q^2)$ – elastic nucleon (target) form factor.

Electrons in nucleon structure experiments

- Electron – nucleon (nucleus) scattering; electrons point-like, $r \lesssim 10^{-18}$m
- Background of ee scattering easy to separate (except from forward scattering).
- (Electromagnetic) processes which yield information on proton structure:



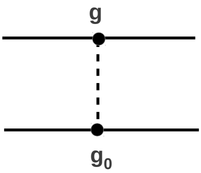
Rutherford scattering, $e^- p \to e^- p$
$M^2_{\gamma^*} < 0, \quad Q^2 > 0$



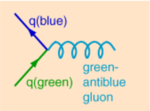
Annihilation: $e^+ e^- \to p\bar{p}$,
$M^2_{\gamma^*} > 0, \quad Q^2 < 0$

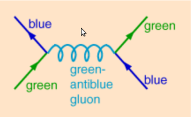
Strong interactions (between quarks)

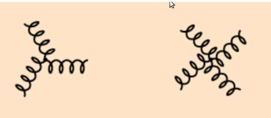
- Generally an interaction between 2 particles is an exchange of a boson of mass m.



Broken line = a boson
$g, \ g_0$ = “charges”
Scattering amplitude: $f(Q^2) = \frac{g g_0}{Q^2 + m^2}$

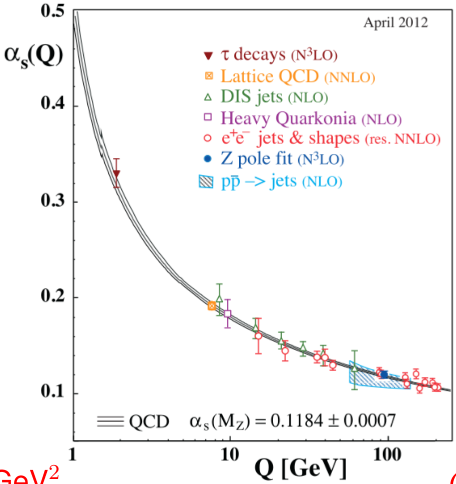






BUT $\alpha_s \sim 1$!!!!
multigluon exchanges!!!

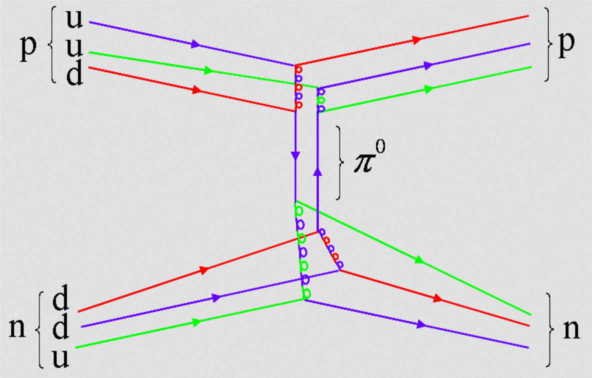
Strong coupling “constant”



$Q^2 \lesssim$ 1 GeV^2
Confinement

$Q^2 \to \infty$
“Asymptotic freedom”!!

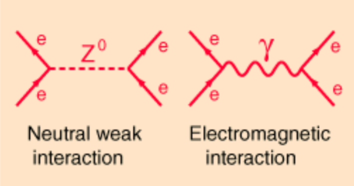
Residual strong interaction (in a nucleus)

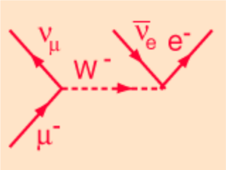


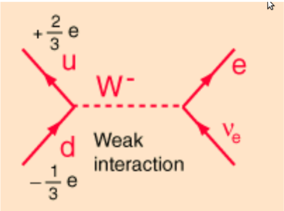
Final state quarks "dress up" into hadrons $\Longrightarrow$ fragmentation.

Factorization theorem: physics particles' cross section
= (calculable QCD parton cross-section) $\otimes$ (universal long-distance functions)

Weak interactions







Scattering amplitude: $f(Q^2) = \dfrac{g^2}{Q^2 + m^2_{Z(W)}}$

Outline

Why high energies?

Searching for elementary components demands using high–energy beams since:

- some elementary particles are heavy (e.g. $m_{\mathrm{Z}^0} \sim 90 m_{\mathrm{p}}$), and energy, $E = mc^2$, is needed to produce them;
- goal is to investigate small distances, $\Delta x \sim$ 1 fm, and since $\Delta x \Delta p \sim \hbar$ then Δp large and $\Longrightarrow p$ large too. Another argument: $\lambda \sim$ small $\Longrightarrow p$ large since $\lambda \sim h/p$.

Example 1: electrons of $\lambda \sim$ 1 fm have $E \sim$ 0.2 GeV.

Example 2: investigating protons, $\lesssim$ 1 fm, demands $Q^2 \gtrsim$ 1 GeV^2.

Reminder: centre-of-mass vs laboratory systems

- A beam particle A hits a target particle B:

$$p^2 = (\vec{p}_A + \vec{p}_B)^2 - (E_A + E_B)^2 = -m_A^2 - m_B^2 + 2(\vec{p}_A\vec{p}_B - E_A E_B) = -(E^{cms})^2$$

- Consider a fixed target experiment, i.e. $\vec{p}_B$ = 0 ($E_B = m_B$); here

$$p^2 = -(E^{cms})^2 = -m_A^2 - m_B^2 - 2\, E_A\, m_B$$

or, if particles masses are negligible with respect to their energies (momenta):

$$E_A = \frac{(E^{cms})^2}{2m_B}$$

- Consider a collider experiment, i.e. $\vec{p}_A \uparrow\downarrow \vec{p}_B$ (or: $\sphericalangle(\vec{p}_A, \vec{p}_B) = \pi$):

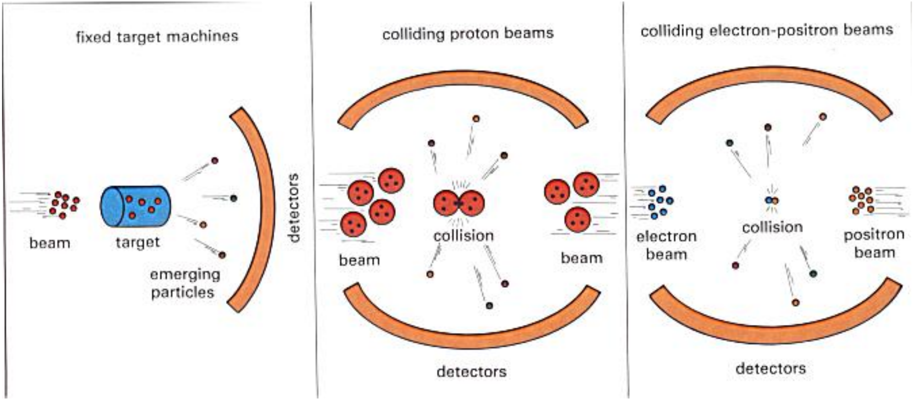
$$p^2 = -(E^{cms})^2 = -m_A^2 - m_B^2 + 2(-|\vec{p}_A|\, |\vec{p}_B| - E_A E_B)$$

or, if particle masses are negligible with respect to their energies (momenta):

$$p^2 = -(E^{cms})^2 \approx -4E_A E_B$$

- Important example: LHC operating at 7 TeV per proton beam: $E^{cms} = 2 \cdot 7$ TeV = 14 TeV
If such E^{cms} were to achieve in a fixed-target experiment then
a beam of $E_A \approx$ 100 000 TeV had to be prepared !!!! Not possible...
(Compare: highest observed energy of cosmic rays: $\sim 10^9$ TeV)

Types of high energy experiments



e.g. COMPASS/CERN e.g. LHC/CERN e.g. ILC (planned)

How many variables needed to describe a reaction?

Consider elastic ($ep \to ep$) and inelastic ($ep \to eX$) interactions where the initial state (i.e. masses and energies) is known.

	$ep \to ep$	$ep \to eX$
initial state	known	known
final state		
2 particles x 4 variables	8 variables	8 variables
-4 eqs (en.-mom. conservation)	4	4
-1 (azimuthal angle, φ)	3	3
known masses in the final state	1 variable	2 variables

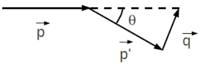
Thus for elastic scattering: 1 variable is enough, e.g. Q^2;
here also: $W = M$ (W - effective mass of the X system, M - proton mass).

Inelastic electron–proton scattering

For the inelastic scattering 2 variables needed, e.g. Q^2 and ν.
Try to find a relation $W \longleftrightarrow Q^2, \nu$. In the bottom vertex:

Energy conservation: $\nu + M = E_X$

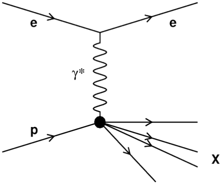
Momentum conservation: $Q^2 = \vec{k}^2 - \nu^2 = p_X^2 - \nu^2$

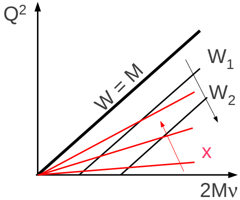


Result:

$$W^2 = 2M\nu + M^2 - Q^2 \qquad (1)$$

$$Q^2 = (\vec{p} - \vec{p}\,')^2 - (E - E')^2 = -2m^2 - 2pp' \cos\vartheta + 2EE' \approx 4EE' \sin^2 \frac{\vartheta}{2} \qquad (2)$$





Define:

$$x = \frac{Q^2}{2M\nu} \qquad (3)$$

so that for elastic: $x = 1$ or $W = M$ and for inelastic: $x < 1$ or $W > M$

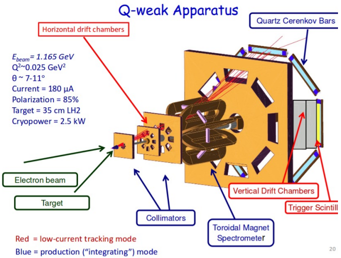
Nucleon structure main research centres

In red – running experiments, in green –future ones.

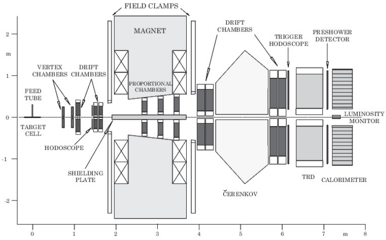
- SLAC (closed): several experiments, $E_e \lesssim$ 50 GeV, also polarised.
- CERN: μ, E_μ: 90 – 300 GeV, naturally polarised; proton and deuteron targets.
  - BCDMS (completed)
  - EMC (completed)
  - NMC (completed)
  - SMC (spin, completed)
  - COMPASS (spin)
- FNAL: exp. E665, μ, E_μ = 470 GeV.
- HERA (closed): e–p collider, 28 GeV + 300 GeV
  - H1 (being analysed)
  - ZEUS (being analysed)
  - HERMES, electrons, E_e = 27 GeV on fixed-target (spin, being analysed)
- RHIC: p-p, 250 GeV + 250 GeV, polarised
  - STAR (also spin)
  - PHENIX (also spin)
- JLAB: several experiments, $E_e \lesssim$ 6 GeV (also spin); soon $E_e \lesssim$ 12 GeV.
- LHC (CMS, ATLAS): p-p, 4 TeV + 4 TeV; soon: 7 TeV + 7 TeV.
- Large Hadron-electron Collider, LHeC and/or Electron Ion Collider, EIC: e–p and e–A

Examples of detectors

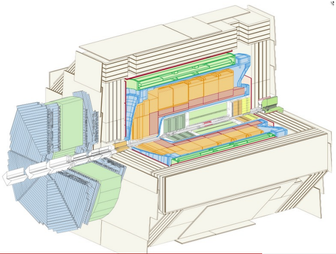
QWEAK/JLAB



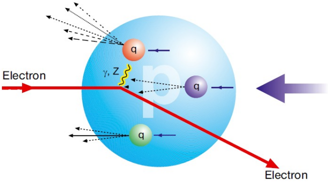
HERMES/DESY



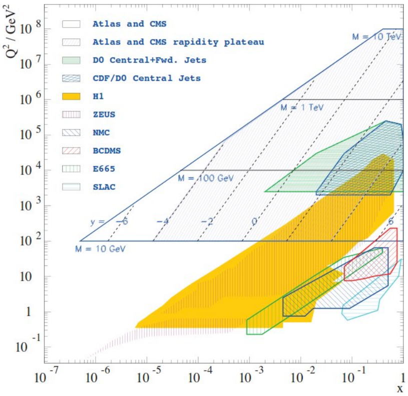
H1/DESY

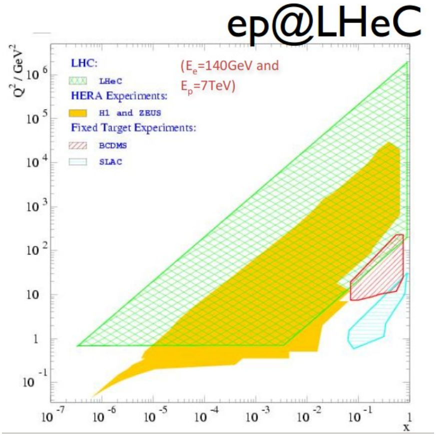


H1 kinematics



Acceptance of nucleon structure experiments





Electron beams: high statistics, high systematics (radiative processes), “cheap”

Muon beams: low statistics, low systematics, “expensive”

Proton beams: complicated analysis.