What is a proton?

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What is a proton?

Format inspired by the Wired Youtube channel. 5 levels of difficulty:

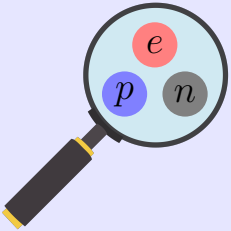
1. Child
2. Teen
3. Undergraduate
4. PhD student
5. Expert

1 Child

What is a proton?

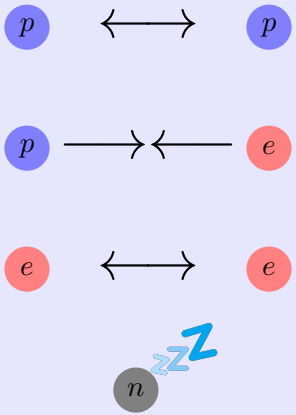
Lego

Real world



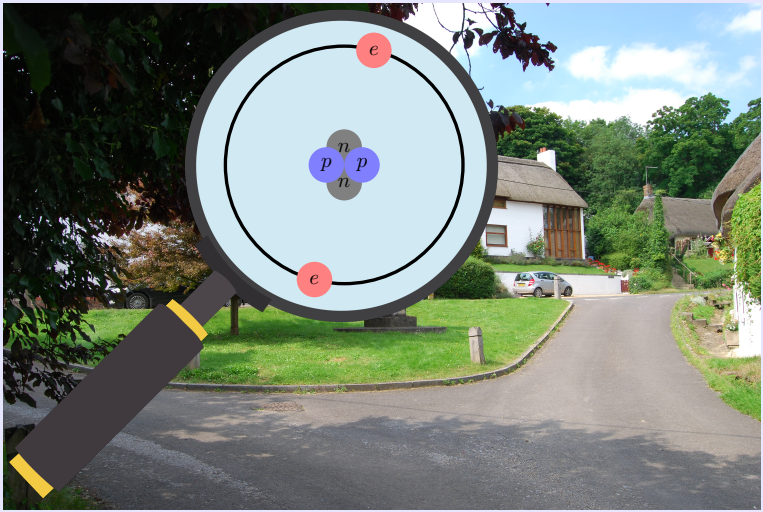
1 Child 2 Teen 3 Undergrad 4 PhD 5 Expert

What is a proton?

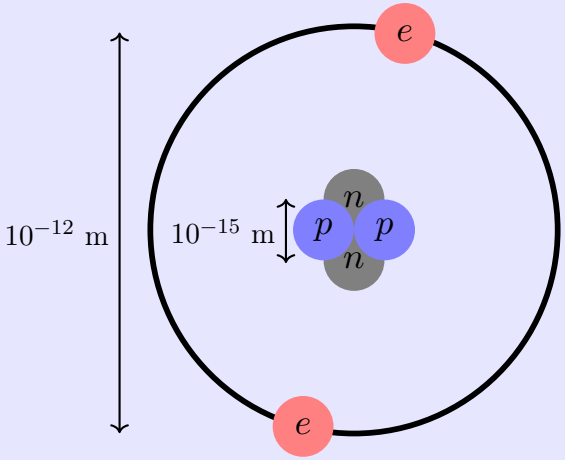


2 Teen

What is a proton?



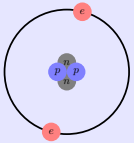
What is a proton?



What is a proton?

Dublin (10^4 m)

Human (10^0 m)

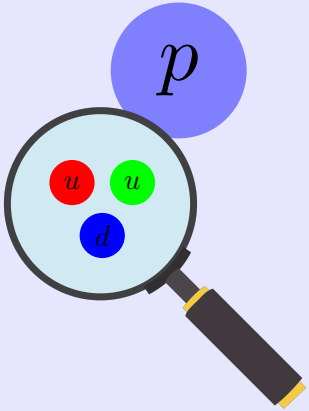


p

1 Child | 2 Teen | 3 Undergrad | 4 PhD | 5 Expert

❸ Undergraduate

What is a proton?



Properties:

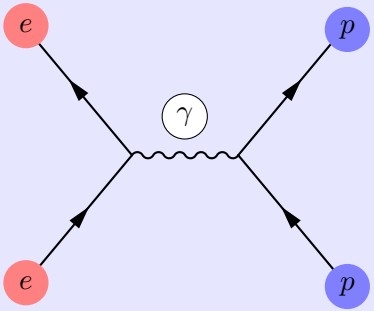
- Protons are **baryons** (bound state of 3 quarks)
- $Q = +1$ in units of e
- $s = \hbar/2$ so protons are **fermions**
- $m_p = 938.27\ \text{MeV}/c^2 \approx 1\ \text{GeV}/c^2$

Protons are **not elementary**!

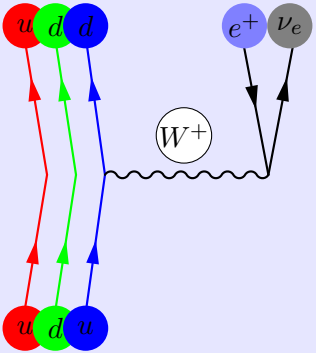
What is a proton?

The proton is ...

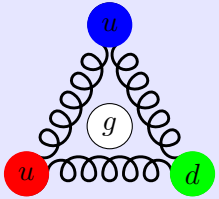
electromagnetic



weak



strong



1 Child 2 Teen 3 Undergrad 4 PhD 5 Expert

4 PhD student

What is a proton?

Quantum field theory says

$$|p\rangle \sim |uud\rangle \sim \Psi_u^\dagger \Psi_u^\dagger \Psi_d^\dagger |0\rangle,$$

$$\Psi_u(x) = \iiint \frac{d^3k}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{k}}}} \sum_{s=1,2} \left(u^s(k) a_u^s(\mathbf{k}) e^{-\mathrm{i}k\cdot x} + v^s(k) b_u^s(\mathbf{k}) e^{\mathrm{i}k\cdot x} \right).$$

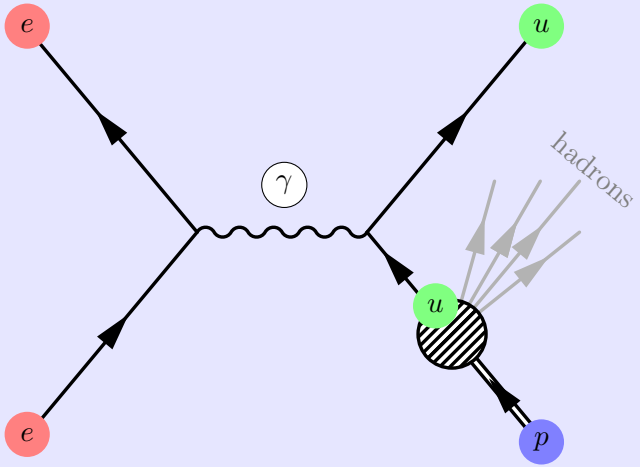
In terms of $\mathbf{d} = SU(d)$ fundamental reps, the proton can transform in various ways:

spin	$\mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2} = \mathbf{4} \oplus \mathbf{2} \oplus \mathbf{2}$	e/m (MRI),
isospin	$\mathbf{2} \otimes \mathbf{2} \otimes \mathbf{2} = \mathbf{4} \oplus \mathbf{2} \oplus \mathbf{2}$	weak (β-decay),
colour	$\mathbf{3} \otimes \mathbf{3} \otimes \mathbf{3} = \mathbf{10} \oplus \mathbf{8} \oplus \mathbf{8} \oplus \mathbf{1}$	strong (kind of).

Not the end of the story...

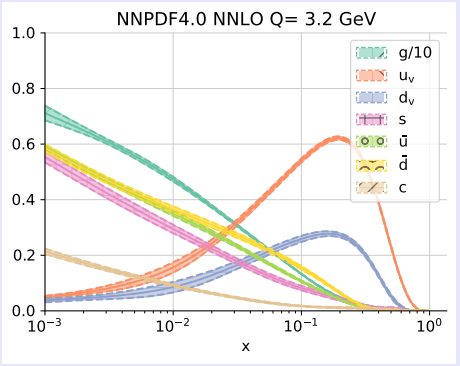
What is a proton?

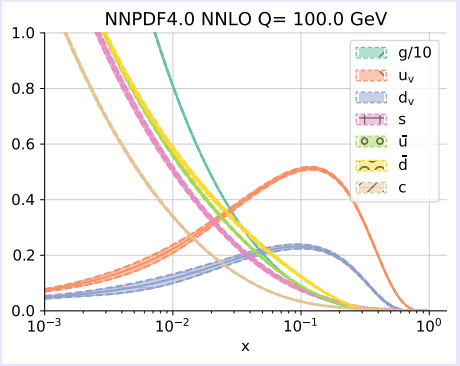
A proton is a collection of **partons** (Feynman 1969). Deep inelastic scattering:



What is a proton?

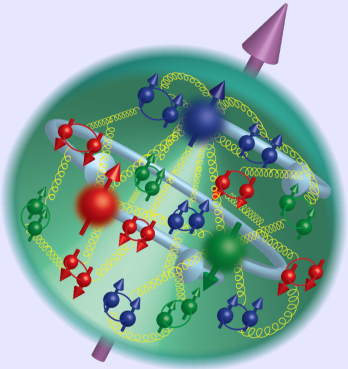
Parton distribution functions [arXiv:2109.02653]





5 Expert

What is a proton?



from Argonne

Properties (revisited):

- Collection of valence quarks (uud), gluons and sea quark vacuum condensate
- $Q = +1$ in units of e because of pdf sum rules and form factors
- $s = \hbar/2$
  - 30-40% from quark spins
  - 10-20% from quark orbital
  - the rest from gluon orbital
- $m_p \approx 1$ GeV$/c^2$
  - 10% from quark masses
  - 70% from quark and gluon kinetic energy
  - 20% from gluon anomalous contribution

What is a proton?

Unanswered questions:

- Why/is the proton stable?
- Why is colour confined?
- What is the 'radius' of a proton?
  (Charge radius root-mean-square is about 0.84×10^{-15} m.)

Research techniques:

- NNPDF: using machine learning to fit parton distribution functions
- NPLQCD: reproducing nuclear physics from lattice QCD *ab initio* calculations
- ...

Thank you

farrenal.github.io