Inside a proton:
“The most complex thing imaginable”!

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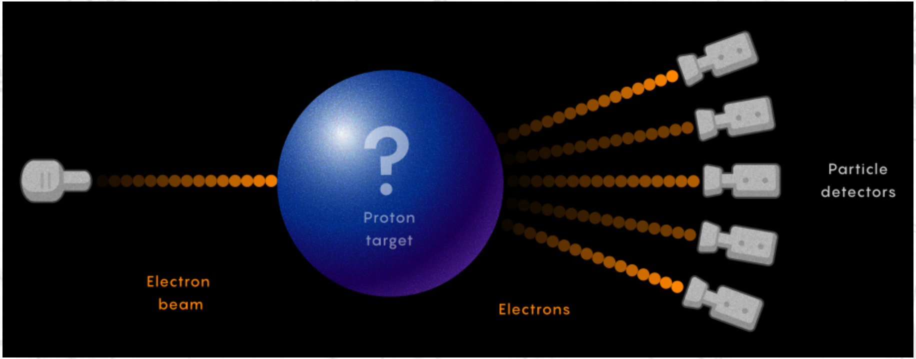
High Energy Physics - Phenomenology

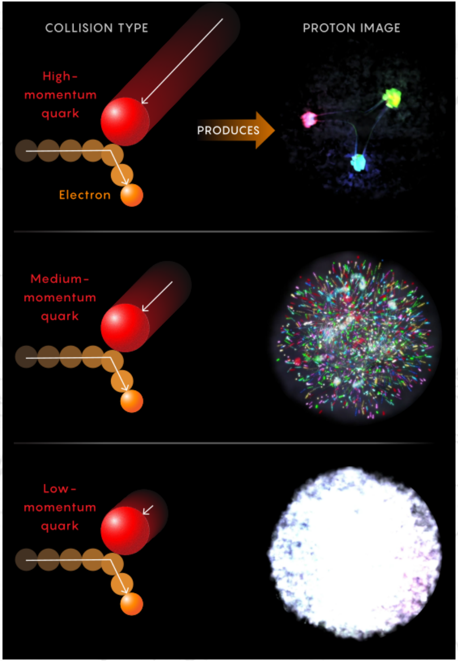
- Physicists are still having difficulty comprehending the proton, more than a century after Ernest Rutherford discovered the positively charged particle at the center of every atom.
- “You can’t imagine anything more complicated than this.”
  “You really have no idea how complicated it is.”
- The proton is a quantum mechanical entity that, up until an experiment compels it to assume a solid form, is only a haze of probability.
  Furthermore, the forms it takes on vary greatly based on the experimental setup used by the researchers.
- Generations of workers have tried to connect the particle’s several faces.
  “Our understanding of this system as a whole is still somewhat incomplete.”
- The proton is thought to include traces of charm quarks, which are particles heavier than the proton itself, according to a massive data study that was most recently released in August.

  Evidence for intrinsic charm quarks in the proton, The NNPDF Collaboration, Nature **608**, *483-487 (2022)*

- Experimentalists noticed that when electrons were hurled more violently at SLAC, they reacted differently.
  Deep inelastic scattering is the process by which the electrons struck the proton with such force that it broke, and there were bouncing off quarks, which are pointy fragments of the proton.
  “It was the first proof that quarks are real.” The discovery made by SLAC was awarded the 1990 Nobel Prize in Physics.



- Additionally, a greater variety of collision outcomes are produced by higher-energy colliders, allowing experimentalists to select distinct subsets of the released electrons for analysis.
  This adaptability has been essential to comprehending quarks, which vacillate within the proton with varying degrees of momentum.
- It can be determined whether a scattered electron has glanced off a quark carrying a significant portion of the proton's overall momentum or just a little amount by analyzing the energy and trajectory of each scattered electron.
  It is a sort of census by repeatedly colliding, ascertaining whether the majority of the proton's momentum is dispersed throughout numerous quarks or largely confined to a small number of them.


COLLISION TYPE
PROTON IMAGE
High-momentum quark
Electron
PRODUCES
Medium-momentum quark
Low-momentum quark

- The “quark model” proposed by Gell-Mann and Zweig is still a sophisticated concept for the proton.
  It has one “down” quark with a charge of $-1/3$, two “up” quarks with electric charges of $+2/3$ apiece, and a total proton charge of $+1$.
- However, the quark model has several flaws and is an oversimplification.
  For example, it breaks down when considering the spin of a proton, which is a quantum attribute similar to angular momentum. Both the proton and its up and down quarks have half a unit of spin.
- At first, physicists believed that the half-units of the two up quarks less the half-unit of the down quark had to equal half a unit for the proton as a whole, in a computation reminiscent of basic charge arithmetic.

- However, the European Muon Collaboration announced in 1988 that the sum of the quark spins is far smaller than half.

  A measurement of the spin asymmetry and determination of the structure function g_1 in deep inelastic muon-proton scattering,
  European Muon Collaboration,
  Physics Letters B **206**, *Issue 2, 19 May 1988, Pages 364-370*

- In a similar vein, the masses of one down quark and two up quarks make up only 1% of the mass of the proton.
  These deficiencies emphasized a fact that physicists were beginning to understand already:
  There are far more than three quarks in a proton.

- Operating in Hamburg, Germany, from 1992 to 2007, the Hadron-Electron Ring Accelerator (HERA) accelerated protons by around a thousand times the force of SLAC's electrons.
  Physicists might choose electrons from extremely low-momentum quarks—which could have as little as 0.005% of the proton's total momentum—to use in HERA studies.
  They were able to identify them because the electrons in HERA bounced back off a tangle of low-momentum quarks and antiquarks, which are their antimatter counterparts.

- The findings validated an elaborate and fantastical theory that, at that point, had superseded the quark model proposed by Gell-Mann and Zweig. It was a quantum theory of the “strong force” acting between quarks that was developed in the 1970s. According to the theory, force-carrying particles known as gluons tie quarks together. One of three “color” charges–red, green, or blue–is attached to each quark and each gluon.

  These charged particles gravitate toward one another and combine to form groups, like protons, whose colors add up to a neutral white. The vibrant hypothesis was later called quantum chromodynamics, or QCD.
- QCD suggests that gluons are able to absorb transient energy spikes. A gluon uses this energy to split into a quark and an antiquark, each of which has very little momentum, and then the pair annihilates and vanishes.

  This “sea” of transitory quarks, antiquarks, and gluons is what HERA directly observed thanks to its increased sensitivity to particles with lower momentum.

- Additionally, HERA detected proton-like features that might be detected by more potent colliders. These quarks, which originate from gluons, became more and more prevalent as physicists modified HERA to search for lower-momentum quarks. The findings implied that the proton might appear as a nearly pure gluon cloud in even higher-energy collisions.
- That is precisely what QCD predicts in the gluon dandelion.
  "Direct experimental evidence that QCD describes nature can be found in the HERA data."
- The victory of the youthful theory, however, was accompanied by a bitter truth: QCD, while able to describe the dance of short-lived quarks and gluons revealed by the intense collisions of HERA, is unable to explain the three long-lived quarks observed in the mild bombardment of SLAC.

- Only in situations where the strong force is relatively weak are QCD's predictions easily understood. Furthermore, quarks only get weaker in short-lived quark-antiquark pairs–that is, when they are incredibly close to one another.
  This key aspect of QCD was discovered in 1973 by Frank Wilczek, David Gross, and David Politzer; they were awarded the Nobel Prize for it thirty-one years later.
- However, in softer collisions such as SLACs, in which the proton behaves as three quarks preserving mutual distance, these quarks attract each other to such an extent that QCD calculations are no longer feasible.
  Therefore, experimenters have been tasked with further clarifying the three-quark picture of the proton.
  Key contributions have also come from researchers who do "digital experiments," which involve simulating QCD predictions on supercomputers.
  And experimentalists are constantly discovering surprises in this image with low resolution.

- Over 5,000 proton snapshots taken over the last 50 years were analysed by a team led by Juan Rojo of the National Institute for Subatomic Physics in the Netherlands and VU University Amsterdam.
  The team used machine learning to infer the motions of quarks and gluons inside the proton in a way that avoids theoretical guesswork.
- The photos' background blur, which had eluded earlier researchers, was detected by the latest examination. The majority of momentum in the typical trio of quarks—two ups and one down–was locked up in very gentle collisions that were only just beginning to split the proton.
  However, a tiny quantity of momentum seems to originate from a charm quark and charm antiquark, which are enormous fundamental particles that collectively weigh more than one-third of a proton.
- In the "quark sea" model of the proton, where gluons can divide into any of six quark kinds with sufficient energy, transient charms are common.
  However, Rojo and colleagues' findings imply that the charms are more persistent and noticeable in softer impacts.

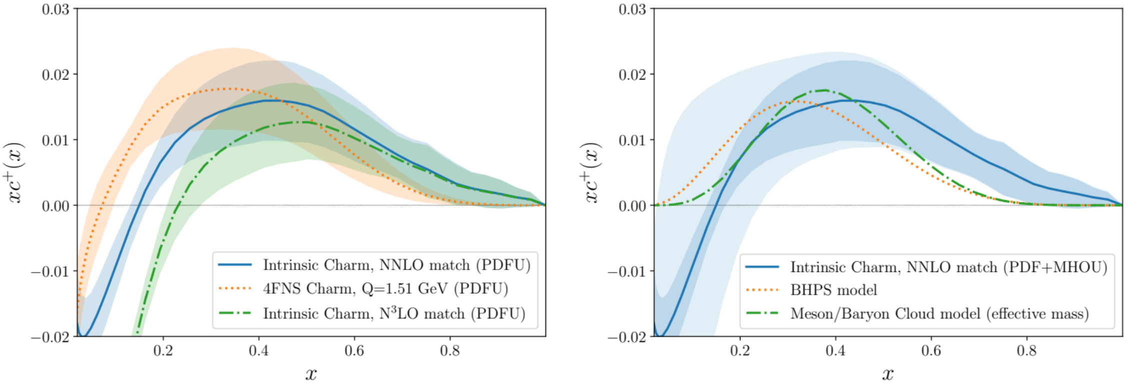


Figure 1. The intrinsic charm PDF and comparison with models. Left: the purely intrinsic (3FNS) result (blue) with PDF uncertainties only, compared to the 4FNS PDF, that includes both an intrinsic and radiative component, at $Q = m_c = 1.51$ GeV (orange). The purely intrinsic (3FNS) result obtained using N^{3}LO matching is also shown (green). Right: the purely intrinsic (3FNS) final result with total uncertainty (PDF+MHOU), with the PDF uncertainty indicated as a dark shaded band; the predictions from the original BHPS model [1] and from the more recent meson/baryon cloud model [5] are also shown for comparison (dotted and dot-dashed curves respectively).

- The proton appears as a quantum mixture, or superposition, of several states in these collisions: Typically, an electron comes into contact with the three light quarks.
  On the other hand, it will sporadically come into a rarer “molecule” consisting of five quarks, such as an up quark and charm antiquark on one side and an up, down, and charm quark clustered on the other.
- The sporadic appearance of large charm quarks at the Large Hadron Collider might upset the probability of producing more unusual particles.

Direct probe of the intrinsic charm content of the proton,
Tom Boettcher, Philip Ilten, and Mike Williams,
Phys. Rev. D **93***, 074008 – Published 7 April 2016*

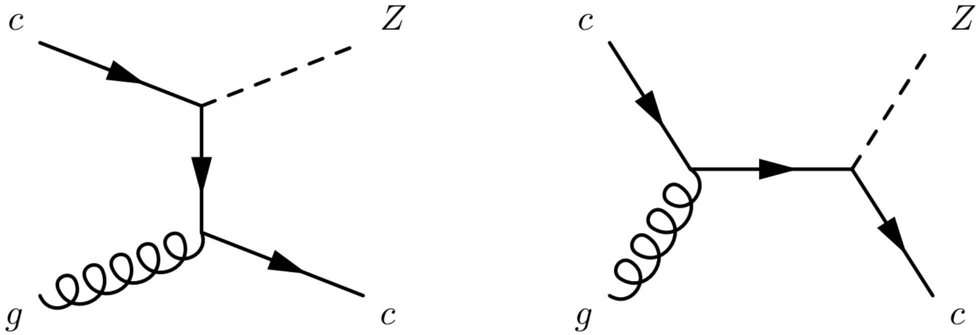


FIG. 1. Leading-order Feynman diagrams for $gc \rightarrow Zc$.

- Additionally, it was calculated in 2021 that charm quarks would appear at the appropriate times to shower Earth with extra-energetic neutrinos when protons known as cosmic rays hurtle here from space and collide into protons in Earth's atmosphere.

  Intrinsic charm in the nucleon and forward production of charm: a new constrain from IceCube Neutrino Observatory, Rafal Maciula, Victor P. Goncalves, and Antoni Szczurek, arXiv:2107.13852 [hep-ph]

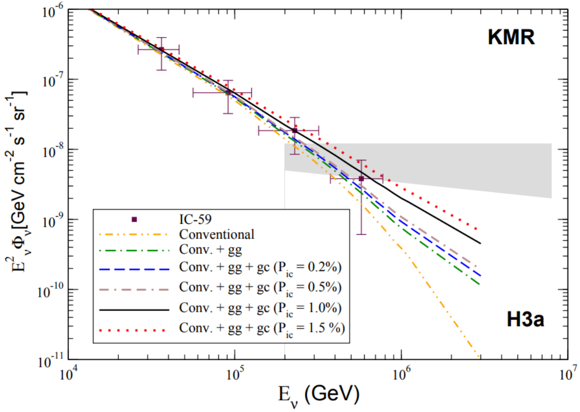


Figure 2: Comparison between our predictions and the experimental IceCube data [1] for the atmospheric ν_μ flux for the KMR uPDFs.