Shining Light on the Proton

A theorist's perspective

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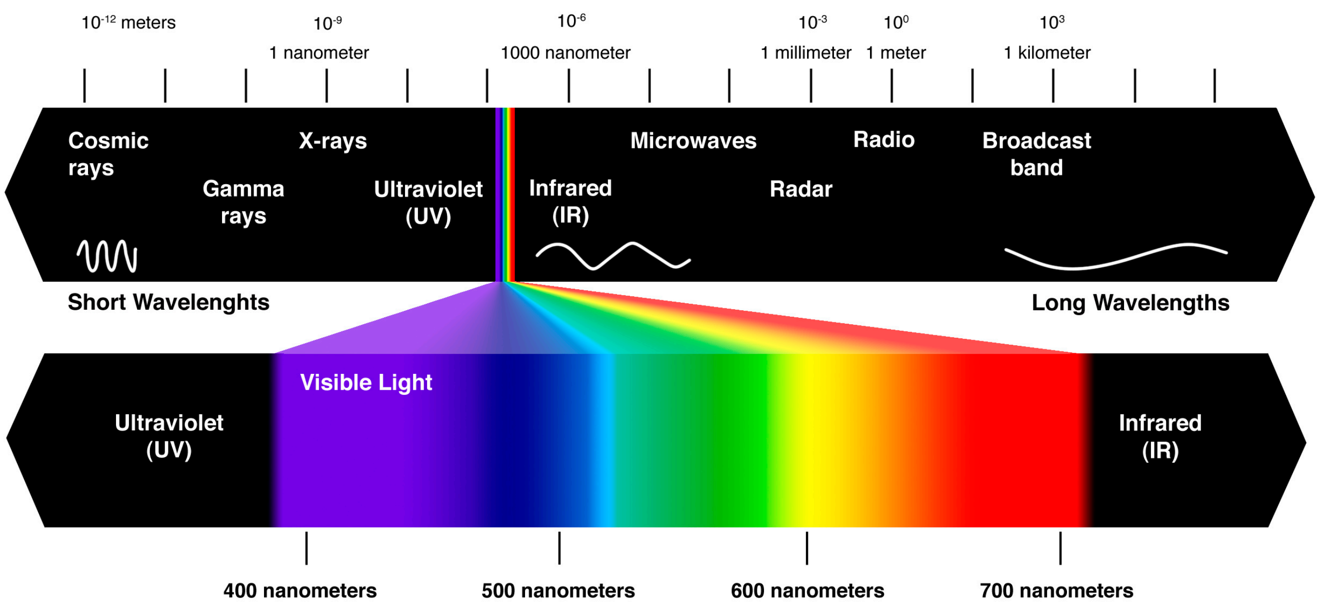
Overview

- Why theory, why protons?
- Locus-dependent effects at Seattle University
  - Proximity to UW, INT – collaborate – but identify projects to spin off for work with students
  - Theorists at PUI – the “explainers”
  - Recent keynote opportunity for bridge building
- Discussion of models

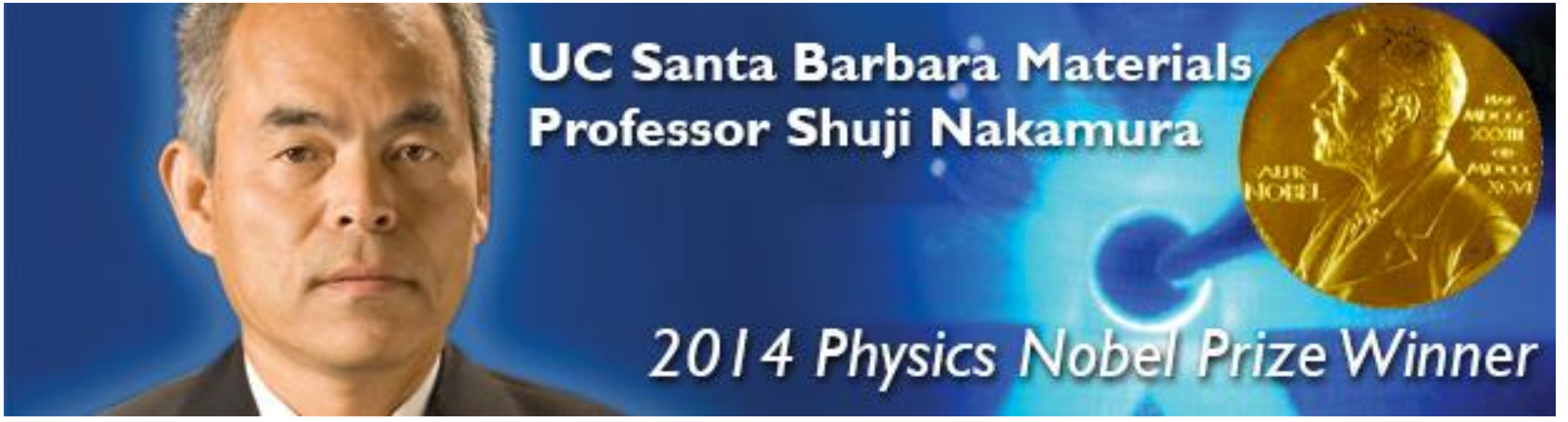
2015 – the International Year of Light

http://www.lumiere2015.fr/

- interdisciplinary – art, literature, science, technology
- "shining light" - illuminating, learning about, but also using light to discover structure



Latest UCSB Nobel



"For the invention of efficient blue light-emitting diodes, which has enabled bright and energy-saving white light sources"

light, a common thread in my research career

Undergraduate research at Wellesley

Mentor – Phyllis Fleming
experimental work

Photoconductivity of PbS films – shine light on a sample and measure the electric current

Long hours in the lab -> senior honors thesis -> first paper

Summer student research - experimental work at BNL

First job – US Atomic Energy Commission

- More experimental work – studied scattering of ^{137}Cs photons in sand – shielding for accelerators

Grad school – University of Washington

Theory – at last! Studied light emitted by exotic atoms

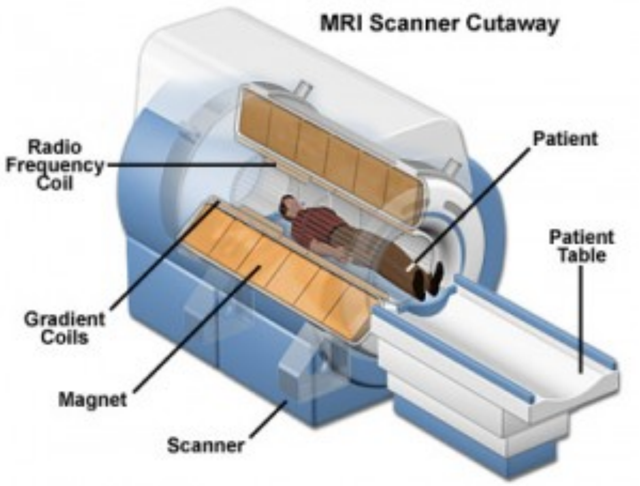
Oxford – another exotic atom – proton + antiparticle = protonium – different spectra

Systems getting simpler – decide to study proton itself

Why should we care about protons?

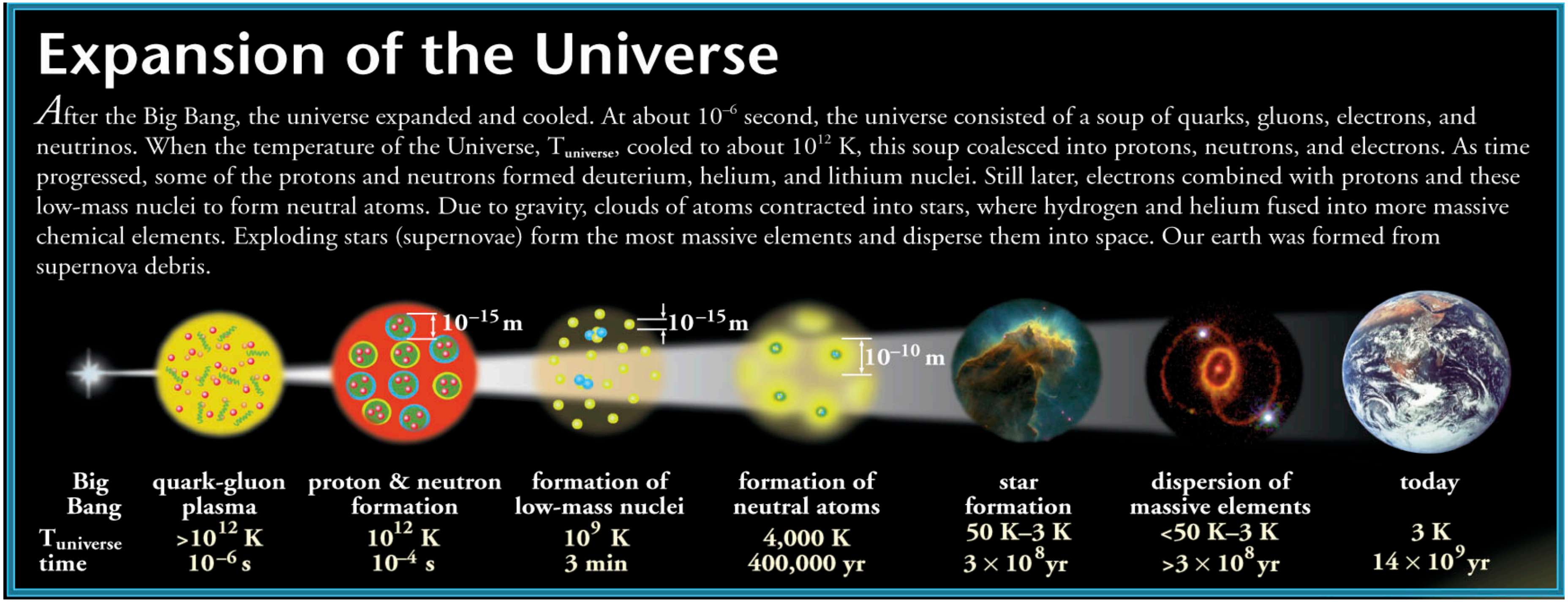
- the heart of every atom
- The fuel of stars

fusion reactions create energy in AE Aurigae: The Flaming Star

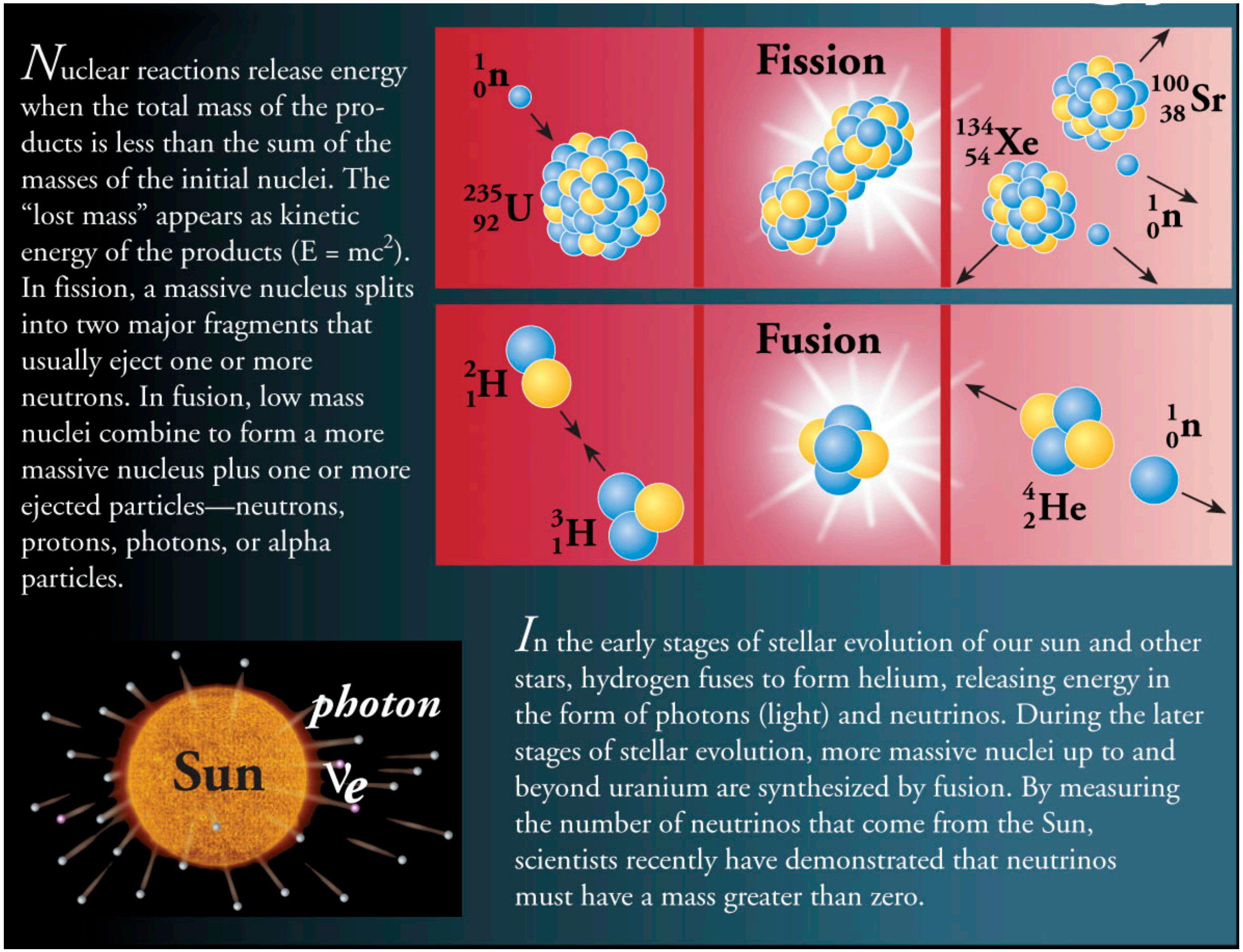


- applications – MRI
- proton therapy for cancer

Critical role in the expansion of the universe

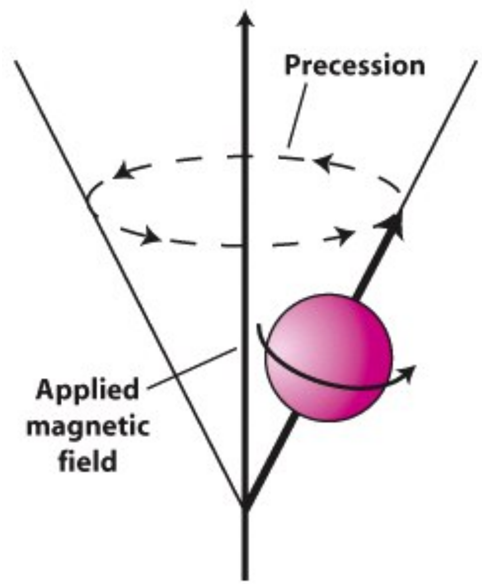


And stellar evolution



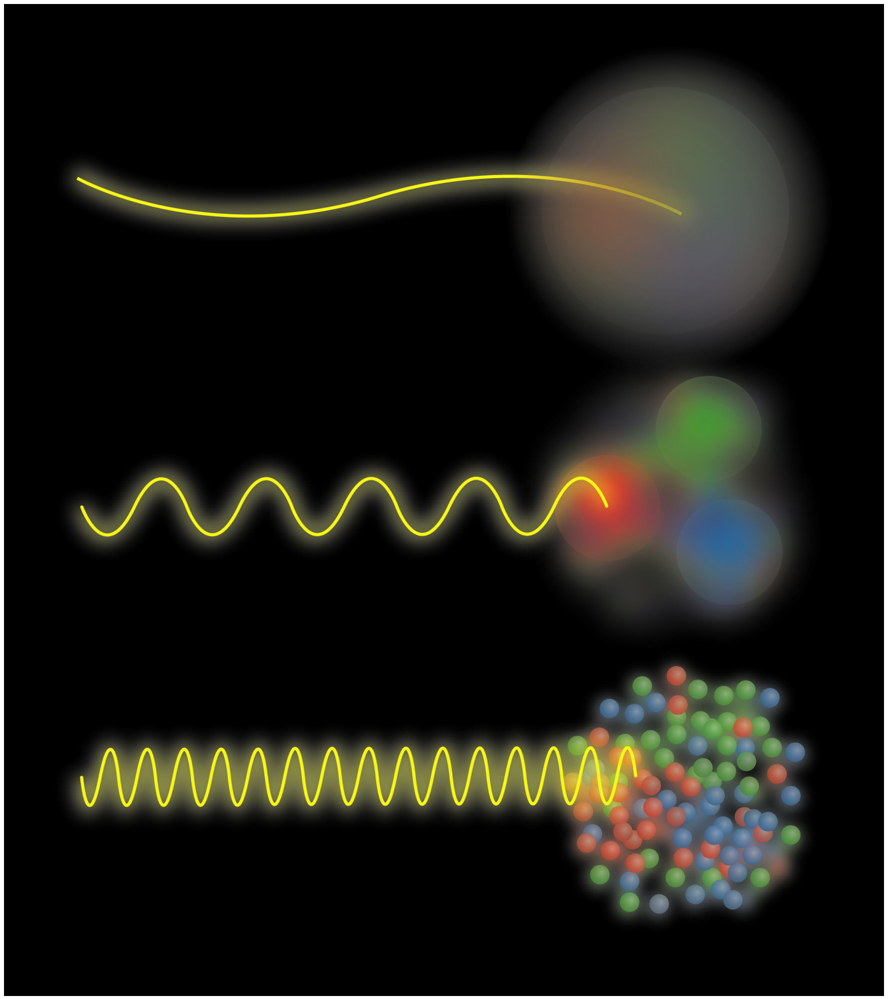
properties

- Charge: +1, which is extended in space
- Spin: looks like a little bar magnet
- Quantum rules: spin = ½, so it can point only up or down, and precess around a z-axis



But is it an elementary particle? Let's shine light on it, i.e. do scattering experiments

It all depends on the wavelength of light



Low resolution – a ball of positive charge

Medium resolution – 3 quarks are seen (1970's) at Stanford

High resolution – a sea of quarks, antiquarks and gluons

A revolution

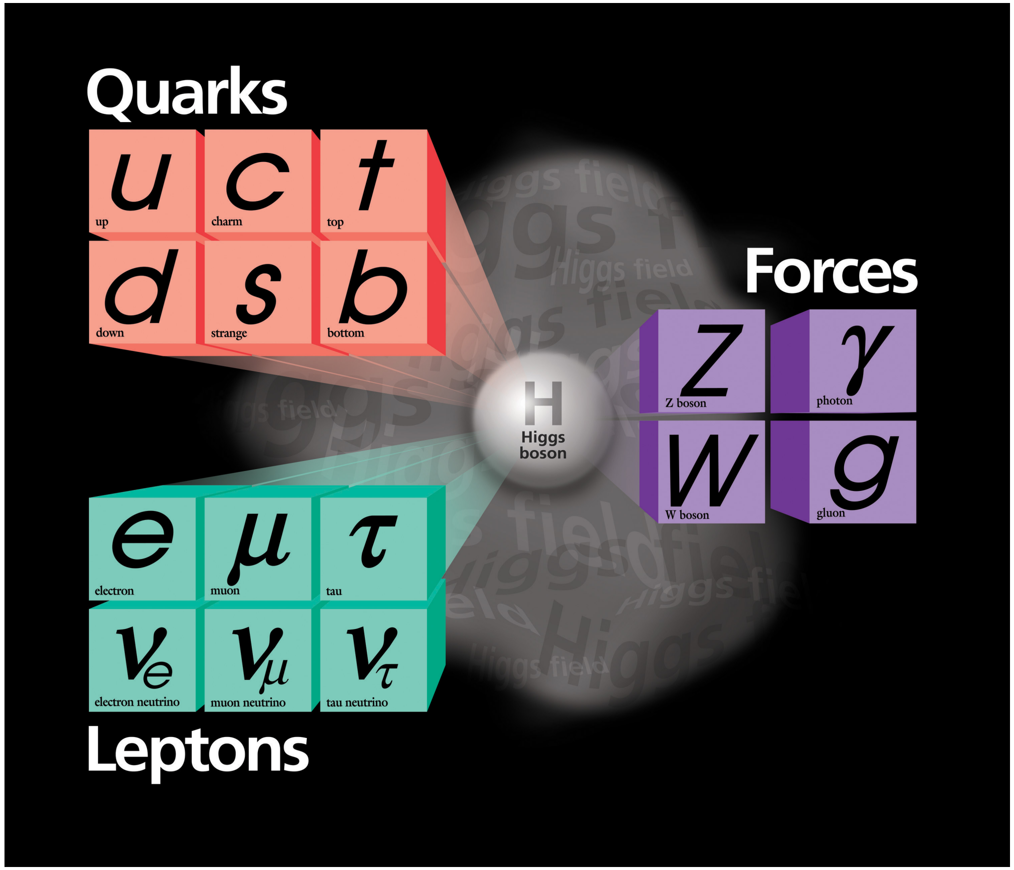
- The proton no longer considered a fundamental building block of matter, but a composite system, containing valence quarks, gluons, and a "sea" of quark-antiquark pairs.

- The theory of QCD, Quantum ChromoDynamics, tells us how to construct composite particles from the new building blocks, the quarks, and the gluons that carry the forces between them.

- The new "periodic table" given by the Standard Model is simpler, but the math much more challenging:

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$
$$= \bar{\psi}_i(i\gamma^\mu\partial_\mu - m)\psi_i - gG^a_\mu\bar{\psi}_i\gamma^\mu T^a_{ij}\psi_j - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a\,,$$

The “periodic table” of particle physics



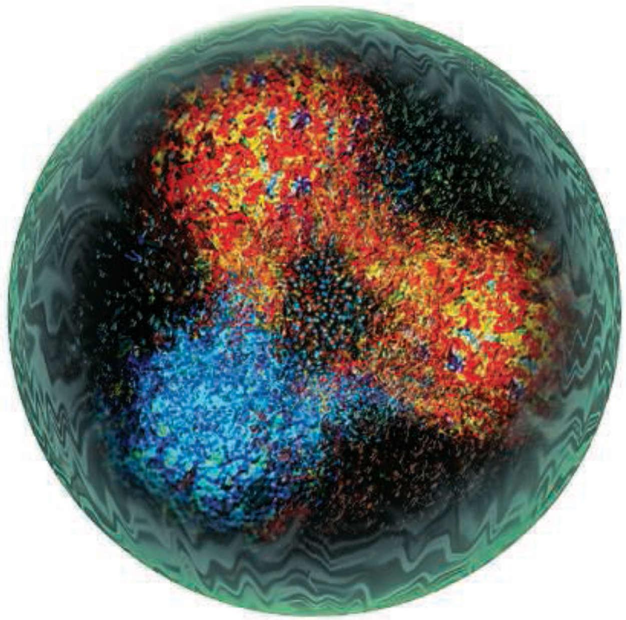
Courtesy Fermilab Visual Media Services

The science journalist's perspective

"Probing the Proton",
by Adrian Cho,

SCIENCE, 23 JANUARY 2015

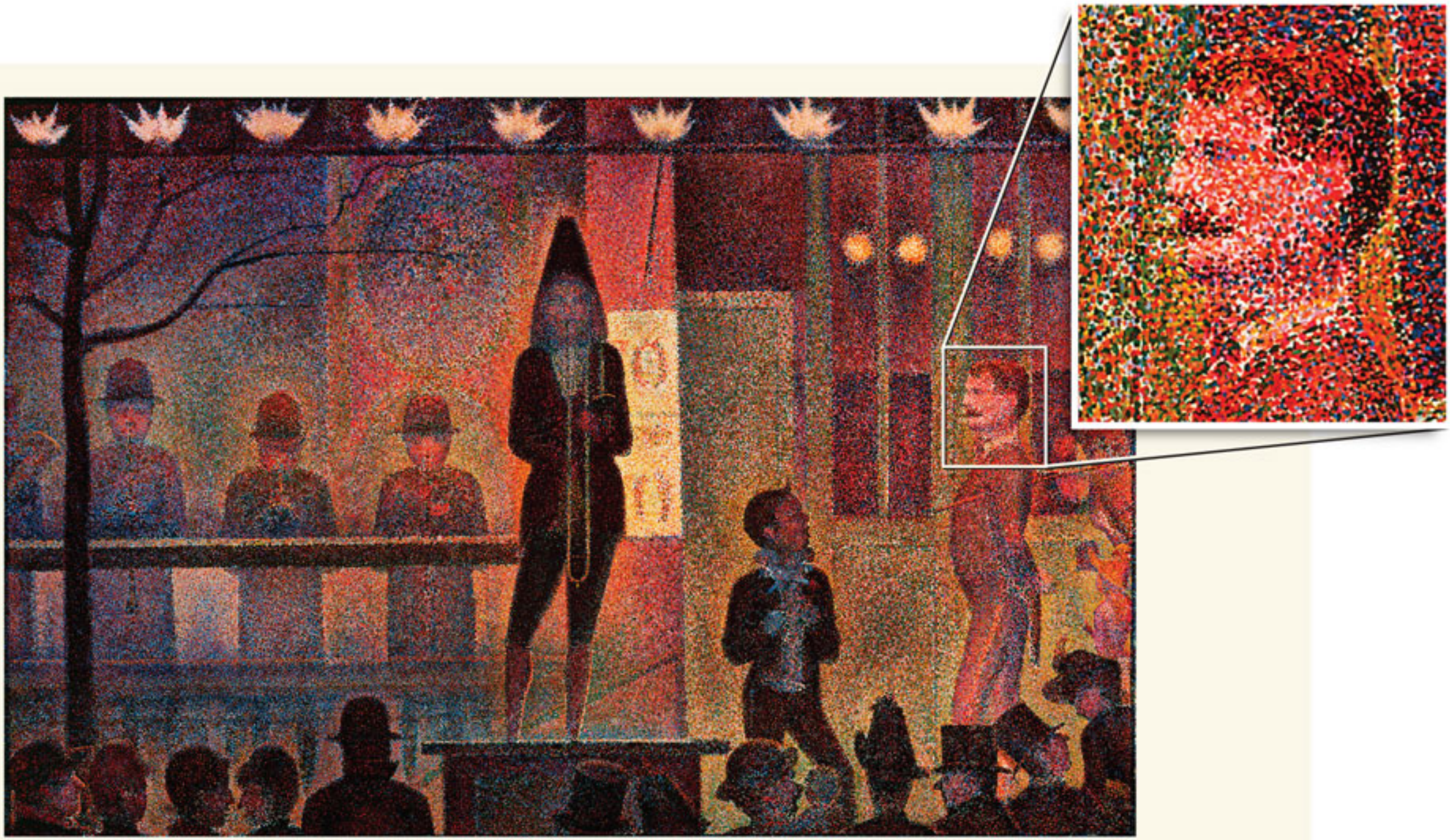
"the seething maelstrom at the heart of matter"



"The proton (artist's concept) is a bit like a troubled teenager:
a mess inside and nearly incomprehensible."

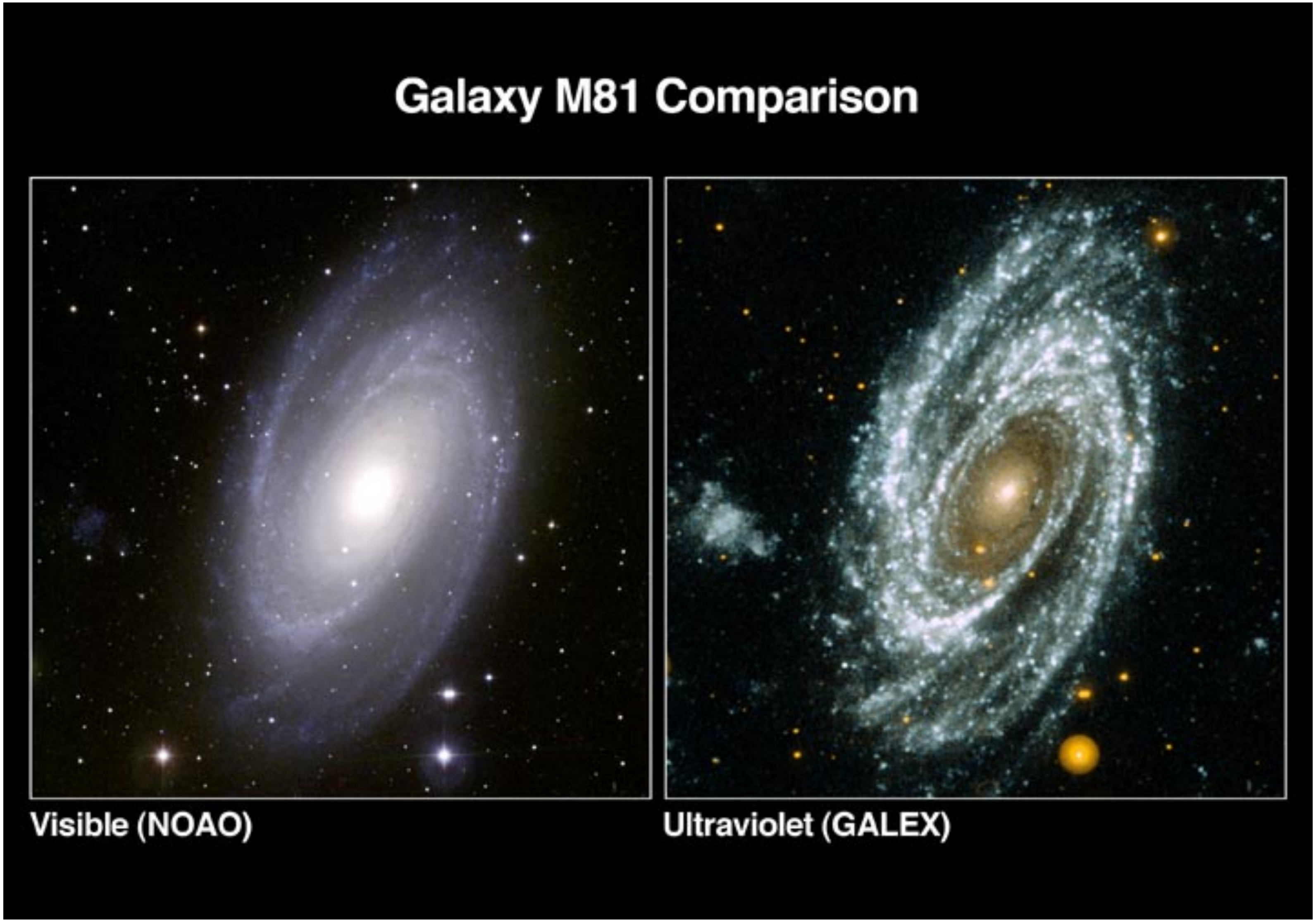
IMAGE: COURTESY OF JEFFERSON LAB

Similar resolution phenomena in art

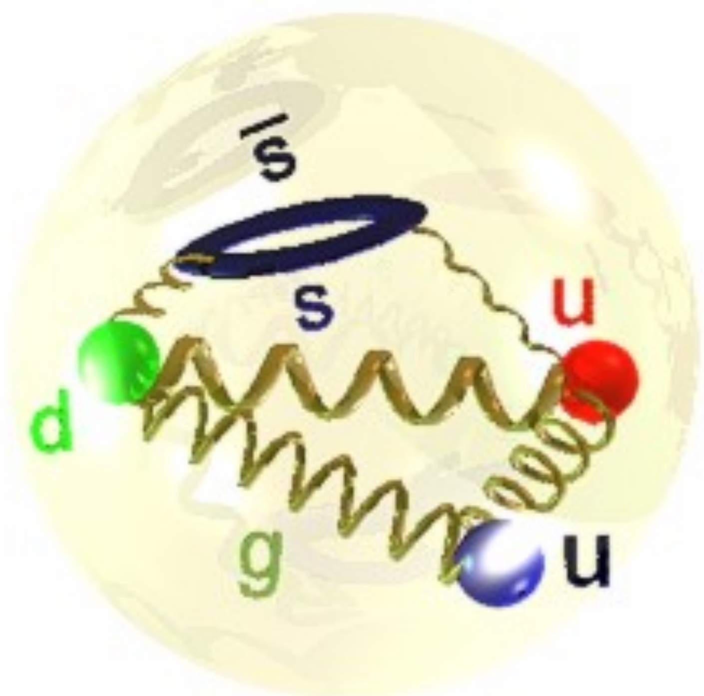


Seurat - La Parade de Cirque (1888)

and in astronomy



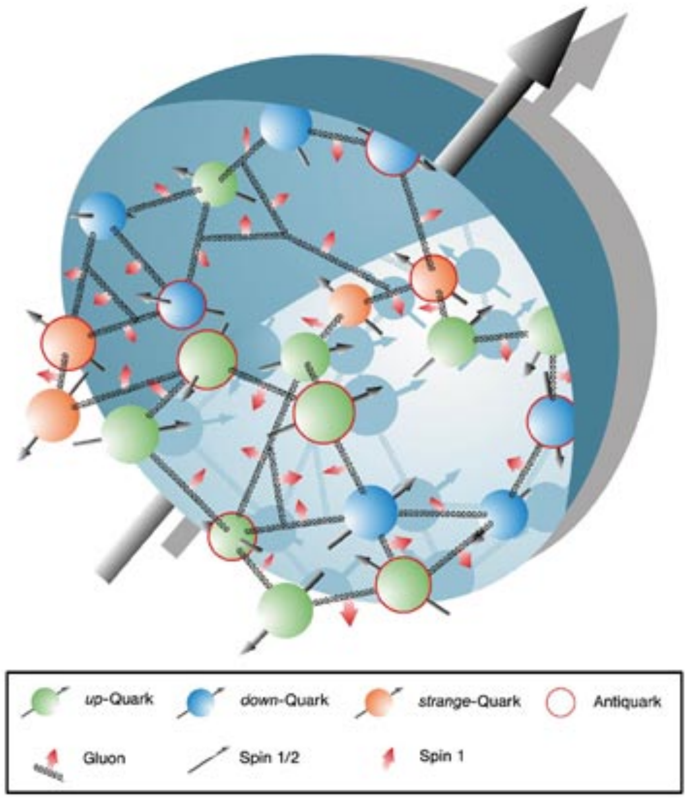
Proton Structure Project



Daphne

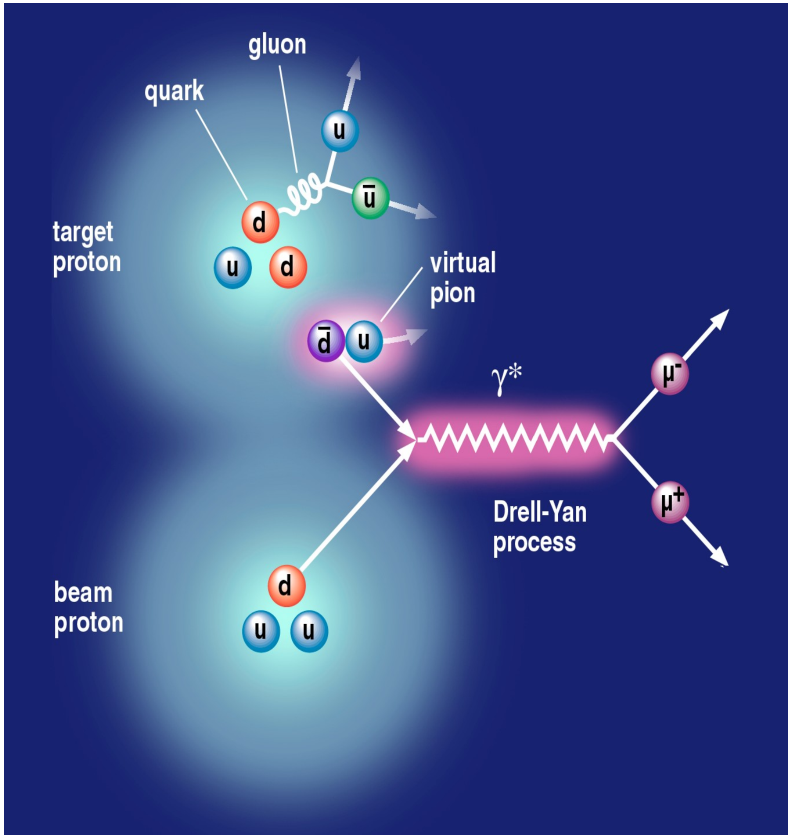
A fundamental goal of physics research is to understand the properties of composite particles, such as the proton, in terms of their constituents: quarks, antiquarks, and gluons.

The test of any model is to show that the known properties of the proton arise from the properties and interactions of the constituents. The proton has spin ½:



The quarks and antiquarks also have spin ½, and the gluons have spin 1. The quarks also may have orbital angular momentum relative to one another. Somehow, all these vector spins must always add up to ½. Solving this problem is a major challenge.

Experimental studies



E866 experiment at FermiLab

Drell-Yan scattering of a proton beam by a proton target (hydrogen gas).

A quark in the beam is annihilated by an antiquark in the target, creating a photon, which decays into 2 oppositely charged muons. The momentum of each muon is measured in a particle detector. The momenta of the quarks is determined from conservation of momentum.

Same techniques used at the LHC.

Some of the challenges:

- There are, overall, more d-dbar quark pairs than u-ubar pairs
  - Doesn’t make sense – they have about same mass
  - No difference in energy cost to make them
- But at large fractions of the proton’s momentum, there are more u-ubar quark pairs than d-dbar pairs
  - No one has been able to explain this
- There are strange quark pairs in this “sea” of quarks and antiquarks
  - Allowed by the Heisenberg uncertainty principle
  - Difficult to predict the probability that they are created

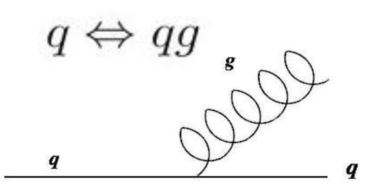
One of the models we have used is statistical – similar to theoretical work done in chemistry. Our first attempt to describe the asymmetry between the dbar and ubar sea.

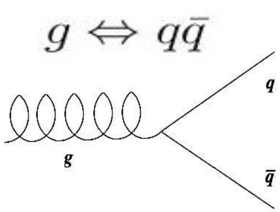
Fock state expansion:

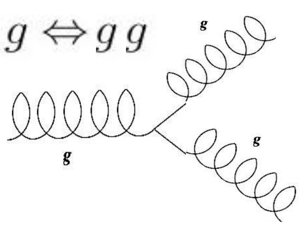
$$|\mathrm{p}\rangle = \sum c_{i,j,k} \left|\{uud\},\{i,j,k\}\right\rangle, \qquad \rho_{i,j,k} = \left|c_{i,j,k}\right|^2$$

in which $\{uud\}$ represents the valence quarks and $\{i,j,k\}$ represents the number of u-ubar pairs, d-dbar pairs, and gluons, respectively.

Processes included:







Detailed balance: $\rho_A R_{A\to B} = \rho_B R_{B\to A}$

in which the rates R are determined by the number of partons that can split or recombine:

$$|uudg\rangle \underset{1\times 3}{\overset{1}{\rightleftharpoons}} |uud\bar{u}u\rangle \qquad |uudg\rangle \underset{1\times 2}{\overset{1}{\rightleftharpoons}} |uud\bar{d}d\rangle \qquad |uud\rangle \underset{1\times 3}{\overset{3}{\rightleftharpoons}} |uudg\rangle$$

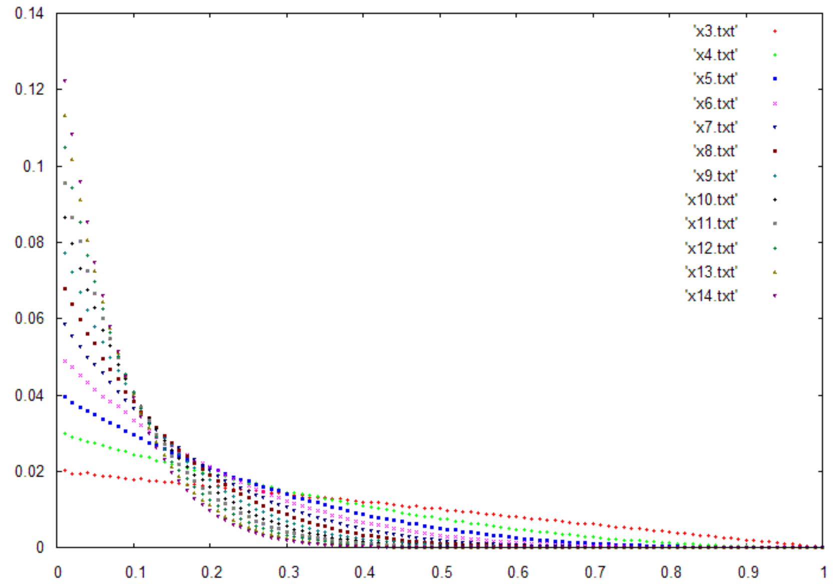
The relative probabilities of Fock state components are then determined:

$$\frac{\rho_{ijk}}{\rho_{000}} = \frac{1}{i!(i+2)!j!(j+1)!k!}$$

and an excess of dbar (j) over ubar (i) states in the proton sea results:

$\bar{d} - \bar{u} = 0.124$ experiment: $\bar{d} - \bar{u} = 0.118 \pm 0.012$

Momentum distributions:



Use Rambo to generate Monte Carlo distribution $f_n(x)$ of each n-parton state, with

$$n = 3 + 2\,(i + j) + k$$

The x-distributions of the sea quarks are:

$$\bar{u}(x) = \sum_{ijk} i\,\rho_{ijk} f_n(x) \quad \text{and} \quad \bar{d}(x) = \sum_{ijk} j\,\rho_{ijk} f_n(x)$$

Proton sea asymmetry – comparison with experiment

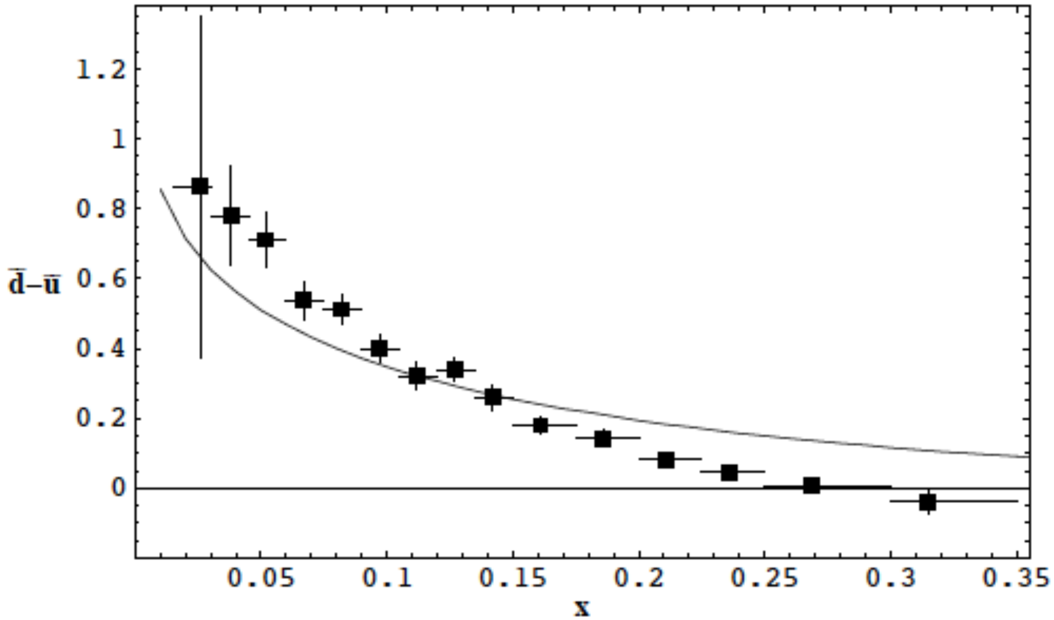


Fig. 8. Comparison of statistical model calculation with E866 experimental results[8] for $\bar{d} - \bar{u}$.

x represents the fraction of the proton's momentum carried by the antiquarks

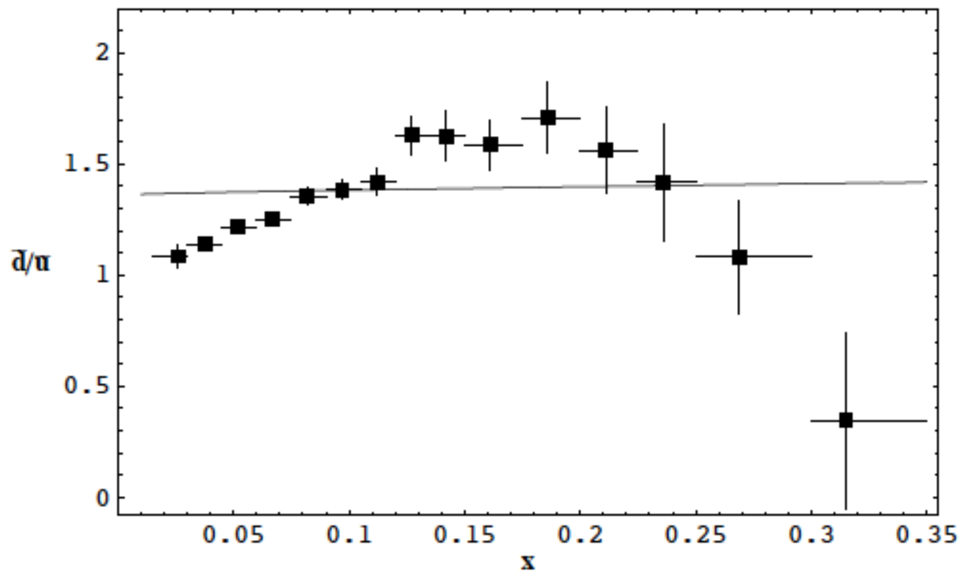


Fig. 9. Comparison of statistical model calculation with E866 experimental results[8] for $\bar{d}/\bar{u}$.

- calculated ratio is approximately constant
- need to include other processes (meson cloud)
- the proton can fluctuate into clusters of quarks – mesons and baryons

Meson Cloud Model

The wave function of the proton is written in terms of a Fock State expansion

$$| p\rangle = \sqrt{Z} \, | p\rangle_{\rm bare} + \sum_{MB} \int dy \, d^2\vec{k}_\perp \, \phi_{BM}(y, k_\perp^2) \, | B(y, \vec{k}_\perp) M(1-y, -\vec{k}_\perp)\rangle$$

Here Z is a wavefunction renormalization constant, $\phi_{BM}(y, k_\perp^2)$ is the probability amplitude for finding a physical nucleon in a state consisting of a baryon, B with longitudinal momentum fraction y and meson M of momentum fraction (1-y) and squared transverse relative momentum $k_\perp^2$.

For reviews, see Speth and Thomas (1997), Garvey and Peng (2001)

Distribution functions

Bare distribution + contribution from meson-baryon splitting

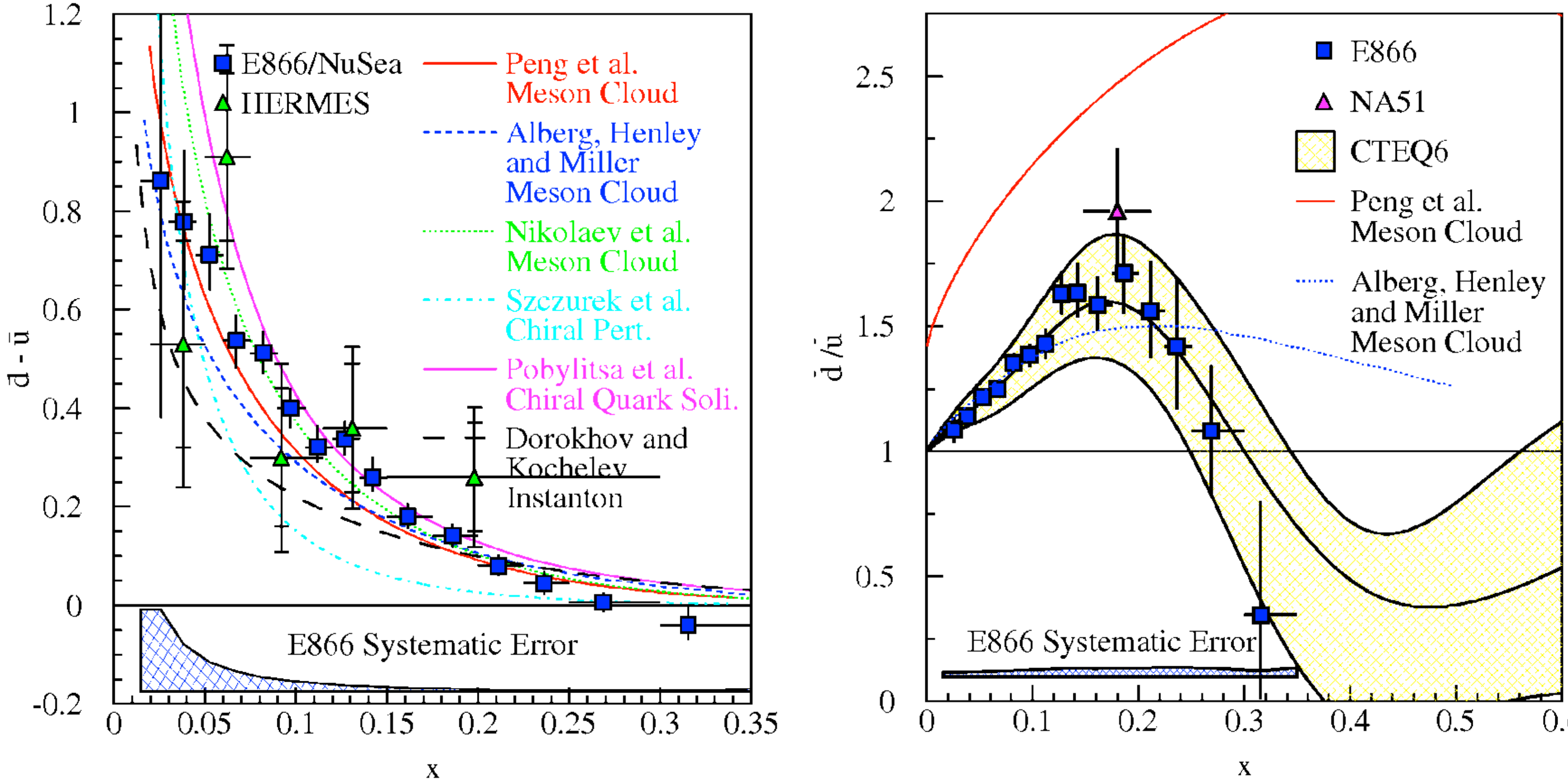
$$q(x) = q^{\text{bare}}(x) + \delta q(x) ,$$

$$\delta q(x) = \sum_{MB} \left(\int_x^1 f_{MB}(y) q_M(\frac{x}{y}) \frac{dy}{y} + \int_x^1 f_{BM}(y) q_B(\frac{x}{y}) \frac{dy}{y} \right) ,$$

$$f_{MB}(y) = f_{BM}(1-y) ,$$

$$f_{BM}(y) = \int_0^\infty | \phi_{BM}(y, k_\perp^2) |^2 \; d^2k_\perp .$$

- Splitting functions require cutoffs; exponential forms should be used
- Models differ in number of MB terms, q_M, q_B, coupling constants, cutoffs.



Adding a cloud of mesons – much better agreement with experiment
But challenge to explain high-x behavior remains

What about other flavors in the proton sea?

- Pairs of strange, charm, top, and bottom quarks can all be created
- Strangeness in the proton sea established by experiment: NuTev, ATLAS, Hermes
- Affects cross-sections for dark matter searches
- Strangeness asymmetry possible –momentum of proton may not be shared in the same way by s and sbar quarks

Strangeness in the proton

- Total Strangeness

$$S^{+}(x) \equiv s(x) + \overline{s}(x)$$

- Expect fewer s-sbar pairs than u-ubar and d-dbar; suppression due to strange quark mass

$$r_s = 0.5(s + \overline{s}) / \overline{d}$$

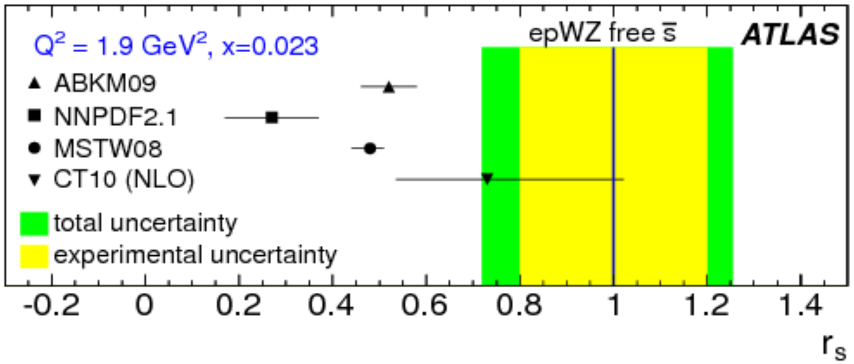
- Surprising evidence that for low *x*,

$$r_s \approx 1$$

- *x*-dependence of strange sea different than light quark sea

ATLAS

PRL **109**, 012001 (2012)

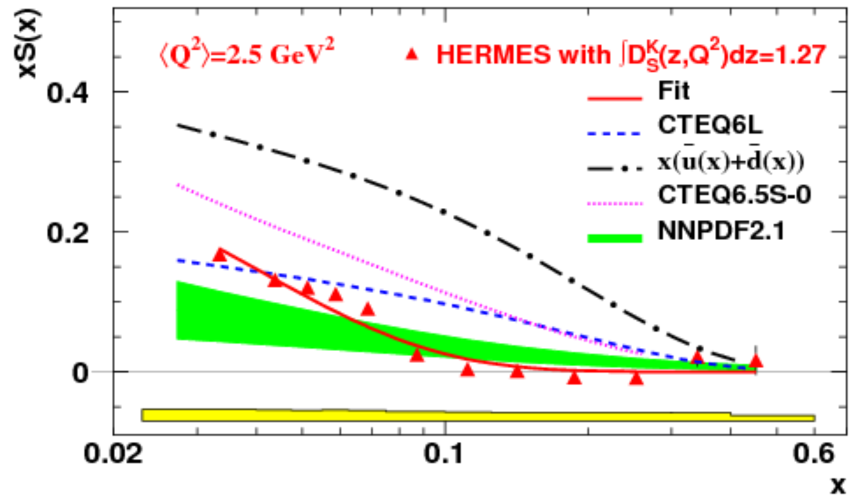


$$r_s = 0.5(s+\bar{s})/\bar{d}$$

- ATLAS measurements: inclusive W^+, W^-, and Z production at LHC
- Points – predictions from 4 global pdf analyses
- More strange sea than had been assumed

HERMES

Phys. Lett. **B666**, 446 (2008)
revised arXiv:1312.7028 (2013)



- HERMES – semi-inclusive DIS, flavor tagging of charged kaons, D^K is fragmentation function
- predictions of *xS(x)* from 3 global pdf determinations
- comparison to light sea pdf from CTEQ6L
- different shape and ratio for light vs. strange sea

Strangeness asymmetry

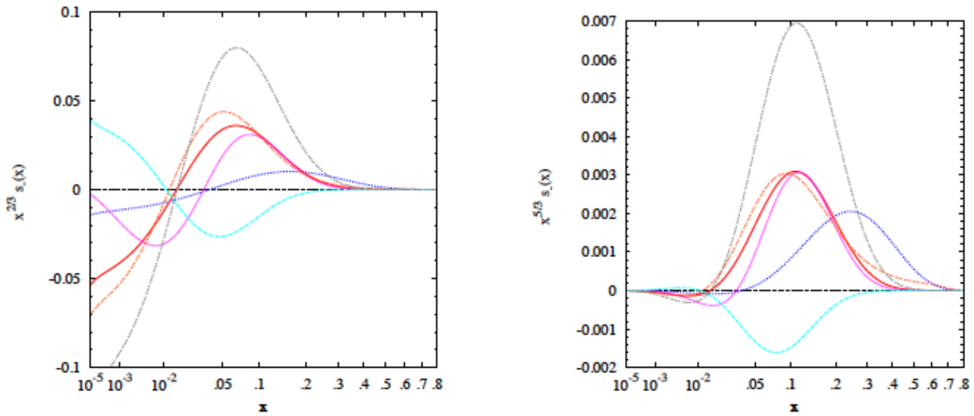


Figure 5: Examples of strangeness asymmetry function $s_{-}(x)$ that are consistent with existing experimental data (left panel); and the corresponding momentum distribution $x\,s_{-}(x)$ (right panel).

Constraints from CTEQ6.5S0: $-0.001 < S^{-} < 0.005$; best value 0.018

What determines shape and sign of asymmetry?

$$S^{-}(x) \equiv s(x) - \overline{s}(x)$$

Meson cloud model

Successful in explaining light sea asymmetry

$p(uud) \rightarrow n(udd) + \pi^+(u\bar{d})$ creates an excess of $\bar{d}$ over $\bar{u}$

Strange mesons and baryons in the cloud will contribute to the strange sea

$p(uud) \rightarrow \Lambda(uds) + K^+(u\bar{s})$ creates s and $\bar{s}$ in different environments - expect momentum asymmetry

ΛK^*, ΣK, , ΣK^* intermediate states should also be included

To test dependence of asymmetry on pdfs in the cloud, use our statistical model,

or light-cone wave functions:

$$s^B(x)=\int\frac{d\mathbf{k}_\perp^2}{16\pi^2}\left|A\exp\left[\frac{1}{8\alpha^2}\left(\frac{m_s+\mathbf{k}_\perp^2}{x}+\frac{m_D+\mathbf{k}_\perp^2}{1-x}\right)\right]\right|^2$$

$$\bar{s}^K(x)=\int\frac{d\mathbf{k}_\perp^2}{16\pi^2}\left|A\exp\left[\frac{1}{8\alpha^2}\left(\frac{m_s+\mathbf{k}_\perp^2}{x}+\frac{m_q+\mathbf{k}_\perp^2}{1-x}\right)\right]\right|^2$$

LCWF – use constituent quark masses in two-body wavefunctions, Gaussian form

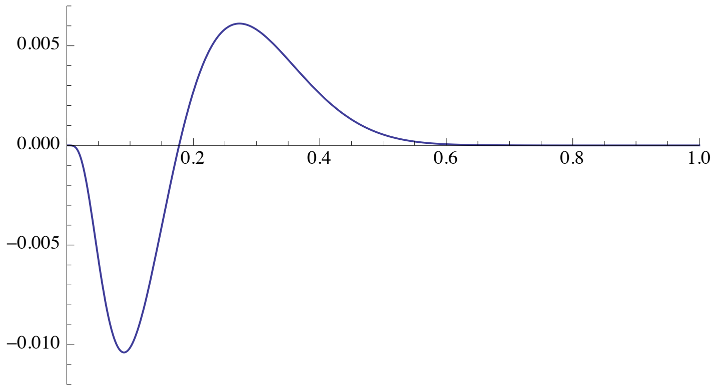
Hybrid Model

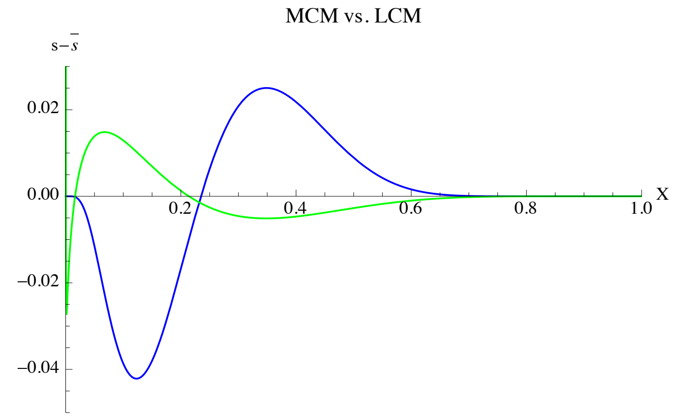
- Replace "bare" particle pdfs in meson cloud model with statistical model or LCWF pdfs:

$$\left| p \right\rangle = Z \left| p \right\rangle_{bare} + \sum_{MB} \int dy\, d^2 \bar{k}_\perp \phi_{MB}(y, k_\perp^2) \left| B(y, \vec{k}_\perp); M(1-y, -\vec{k}_\perp) \right\rangle$$

- Total strangeness determined by MCM splitting functions and cutoffs; independent of meson and baryon pdfs
- $S^+(x)$ and $S^-(x)$ affected by form of meson, baryon pdfs

student research project – Garrett Budnik - study of convolution: fluctuation ⊗ pdfs





MCM ⊗ LC: convolution of meson cloud model for fluctuations with light cone wavefunctions for meson and baryon pdfs

LC ⊗ LC – blue
MCM ⊗ global pdfs for meson and baryon parton distributions – green

(Cao and Signal, 1999)

Conclusion: sign and shape of asymmetry determined by pdfs of hadrons in the cloud

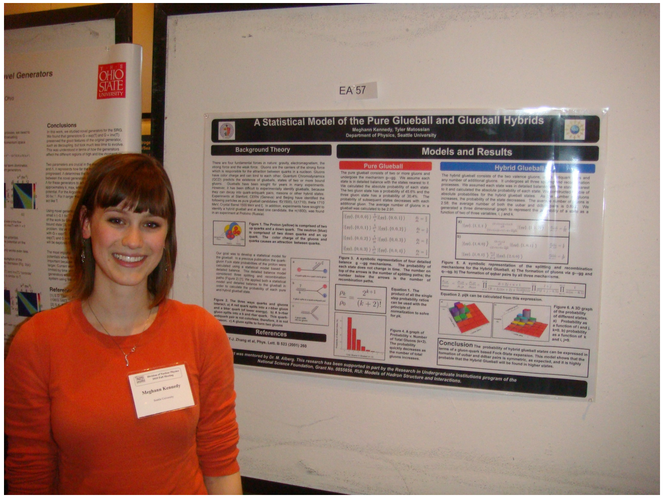
Paper with student co-authors in preparation

Summary

- A complete description of the proton is still elusive.
- At SU we have developed calculations that provide a qualitative picture of the way proton momentum is shared among its constituents. We are also investigating strangeness in the proton, and will study proton spin.
- Experiments are continuing and will present us with new data - and challenges - soon.

Thanks

- To my research students – at SU (22) and UPS, Harvey Mudd, Holy Cross
- SU colleagues
- Collaborators – UW, Adelaide, CERN, Colorado, Giessen, Liege,
  Los Alamos, Maryland, Munich, Uppsala
- Experimentalists – who make the measurements that challenge us



Megan Kennedy – Santa Fe, 2010

Sam Tuppan and Jordan Fox – Waikoloa, 2014

Students at poster sessions of the DNP Conference Experience for Undergraduates