Partonic Hadron Structure I

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Physics Division

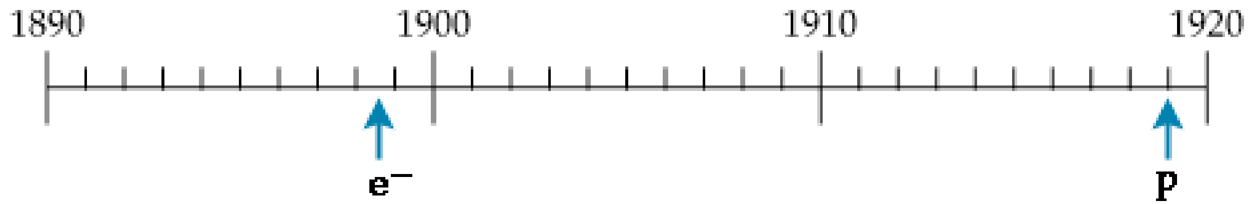
Argonne National Laboratory

July 2017

I. Why do you need hadrons to have internal structure?
   A. Quark Model
   B. Feynman's partons
   C. Electron scattering cross sections
II. Longitudinal parton distributions
   A. Extractions
   B. Assumptions

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

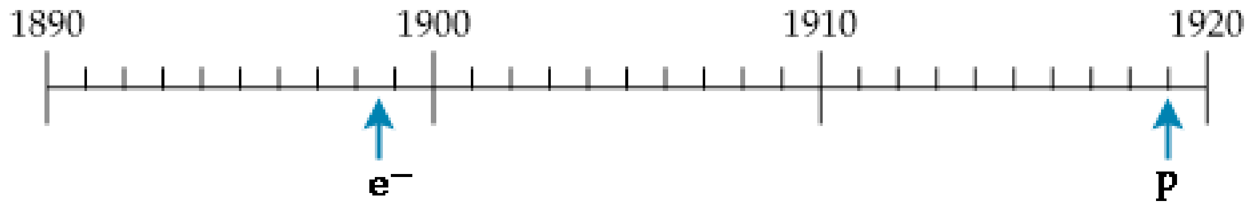
Classifications of Particles



- Chemists started classifying elements by their properties in the 19th century
  - Dmitri Mendeleev
    - Realized periodic nature of elements when arranged in order of increasing atomic mass
    - Allowed for gaps in the periodic structure
  - No good explanation for why the periodic structure existed

1																	18
1 **H** 1.008	2											13	14	15	16	17	2 **He** 4.0026
3 **Li** 6.94	4 **Be** 9.0122											5 **B** 10.81	6 **C** 12.011	7 **N** 14.007	8 **O** 15.999	9 **F** 18.998	10 **Ne** 20.180
11 **Na** 22.990	12 **Mg** 24.305	3	4	5	6	7	8	9	10	11	12	13 **Al** 26.982	14 **Si** 28.085	15 **P** 30.974	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.948
19 **K** 39.098	20 **Ca** 40.078	21 **Sc** 44.956	22 **Ti** 47.867	23 **V** 50.942	24 **Cr** 51.996	25 **Mn** 54.938	26 **Fe** 55.845	27 **Co** 58.933	28 **Ni** 58.693	29 **Cu** 63.546	30 **Zn** 65.38	31 **Ga** 69.723	32 **Ge** 72.630	33 **As** 74.922	34 **Se** 78.97	35 **Br** 79.904	36 **Kr** 83.798
37 **Rb** 85.468	38 **Sr** 87.62	39 **Y** 88.906	40 **Zr** 91.224	41 **Nb** 92.906	42 **Mo** 95.95	43 **Tc** (98)	44 **Ru** 101.07	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57-71 *	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.23	77 **Ir** 192.22	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89-103 #	104 **Rf** (265)	105 **Db** (268)	106 **Sg** (271)	107 **Bh** (270)	108 **Hs** (277)	109 **Mt** (276)	110 **Ds** (281)	111 **Rg** (280)	112 **Cn** (285)	113 **Nh** (286)	114 **Fl** (289)	115 **Mc** (289)	116 **Lv** (293)	117 **Ts** (294)	118 **Og** (294)
* Lanthanide series			57 **La** 138.91	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.36	63 **Eu** 151.96	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.05	71 **Lu** 174.97
# Actinide series			89 **Ac** (227)	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

Classifications of Particles



www.particleadventure.org

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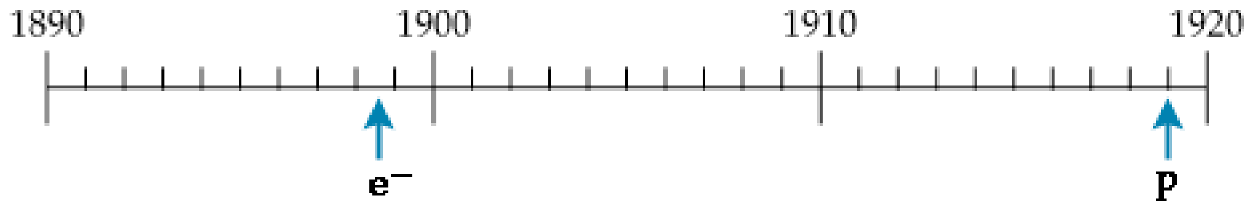
Physics—beginning to discover the modern picture

- 1874 **George Stoney** develops a theory of the electron and estimates its mass.
- 1895 **Wilhelm Röntgen** discovers x rays.
- 1898 **Marie and Pierre Curie** separate radioactive elements.
- 1898 **Joseph Thompson** measures the electron; puts forth his "plum-pudding" atomic model
- 1900 **Max Planck** suggests that radiation is quantized (it comes in discrete amounts.)

Classifications of Particles



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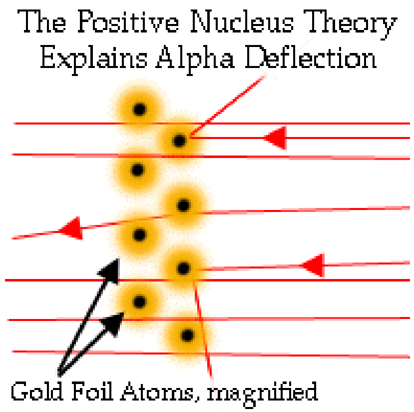

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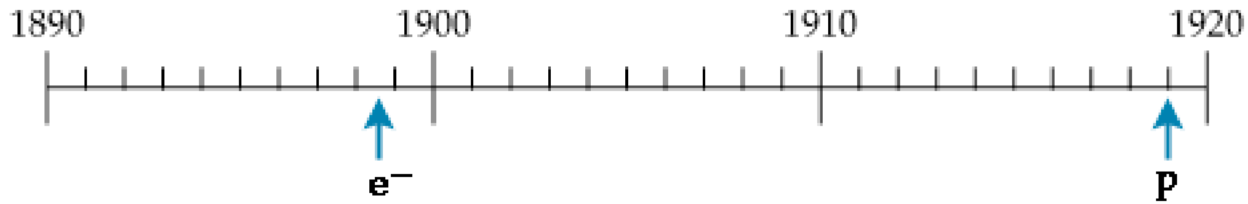
Rutherford

Classifications of Particles



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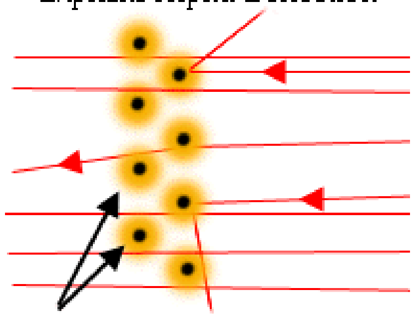

- 1913 **Henry Mosley** analyzed x-ray K lines and observed a periodic pattern in frequency

  $$\nu = \nu_0(n-a)^2$$

  Where n took on different integral values for each element

- 1913 **Niels Bohr** constructs a theory of atomic structure based on quantum ideas

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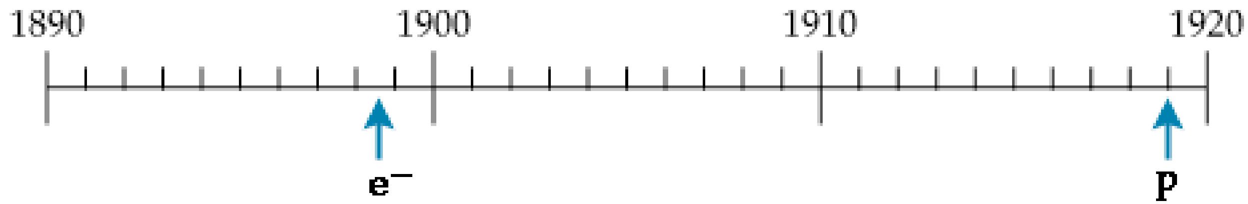

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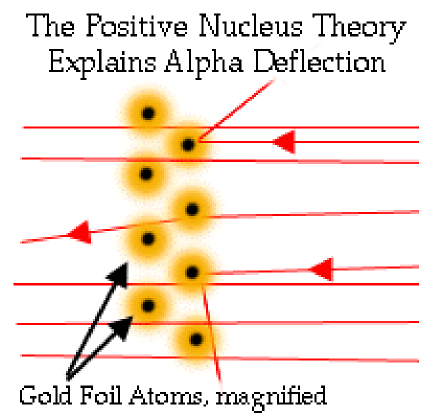

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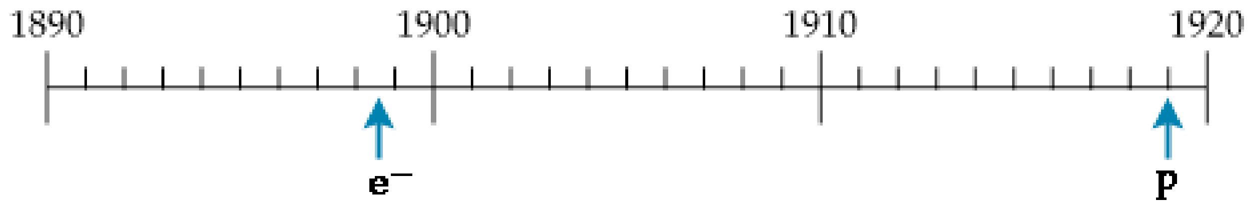
- 1913 **Niels Bohr** constructs a theory of atomic structure based on quantum ideas
- 1919 **Ernest Rutherford** finds the first evidence for a proton.

  $$^{14}N + \alpha \rightarrow {}^{17}O + p$$

Quark Model

- 1930 There are just three fundamental particles: protons, electrons, and photons.



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LIFE IS GOOD

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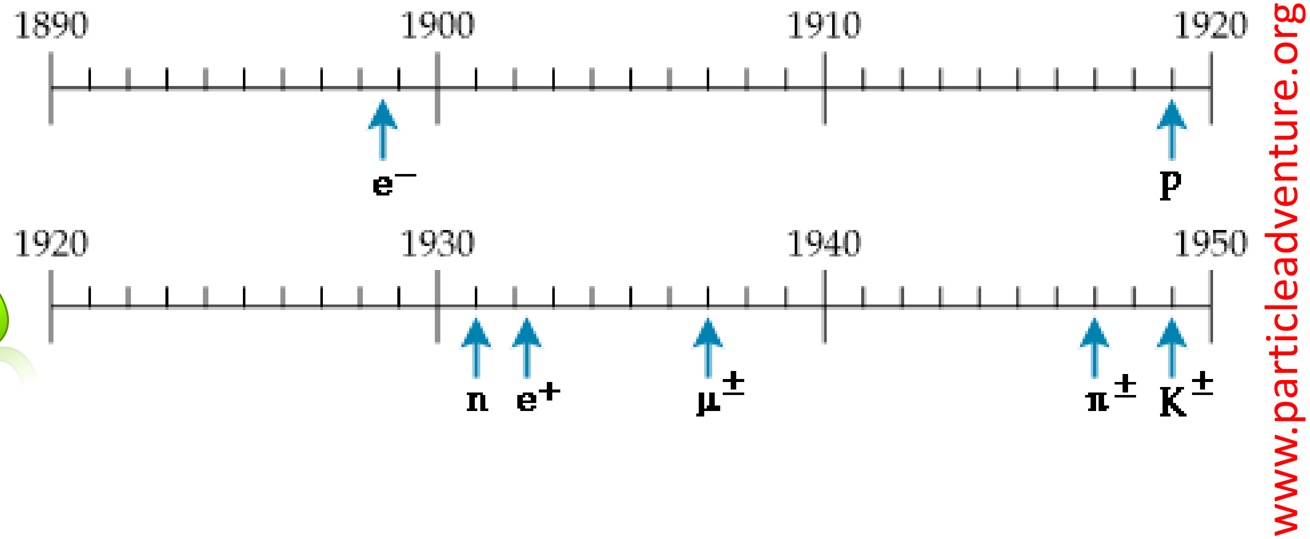

- 1930 **Wolfgang Pauli** suggests the **neutrino** to explain the continuous electron spectrum for beta decay.
- 1931 **Paul Dirac** realizes that the positively-charged particles required by his equation are new objects (he calls them "**positrons**").
- 1931 **James Chadwick** discovers the **neutron**. The mechanisms of nuclear binding and decay become primary problems.
- 1937 **muon** discovered, although first thought to be Yukawa's predicted pion (takes a decade to realize this).
- 1947 Strongly interacting **pion** discovered

Classifications of Particles

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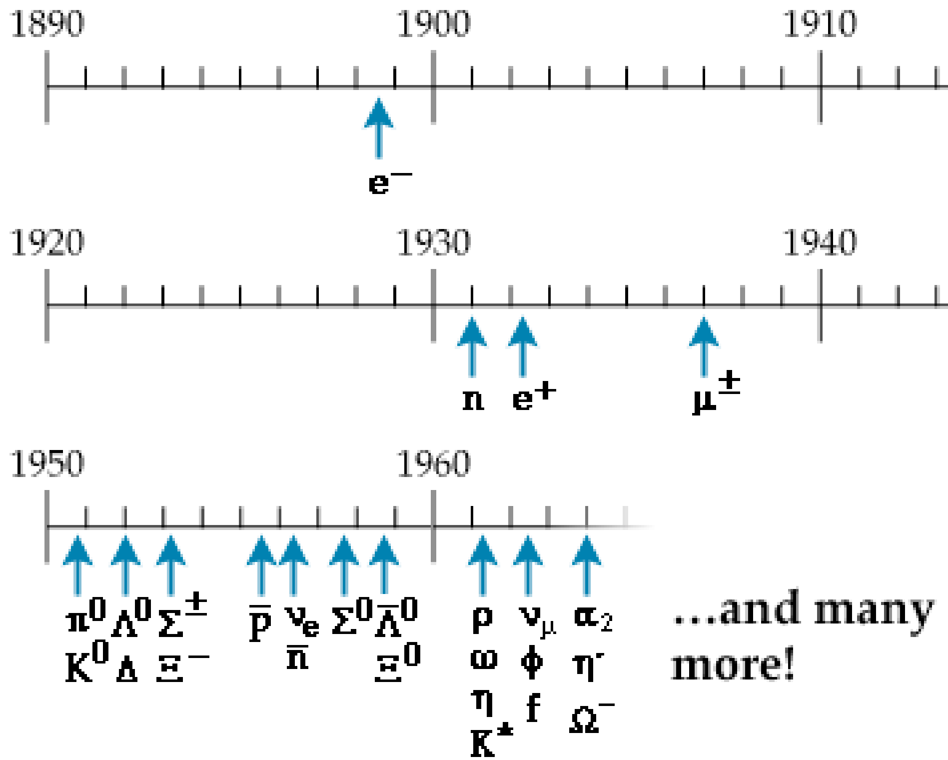
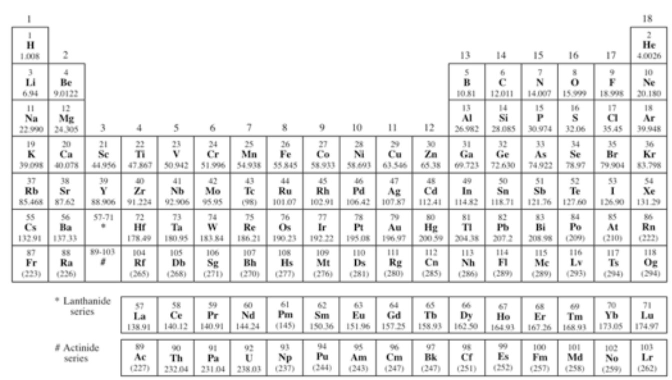
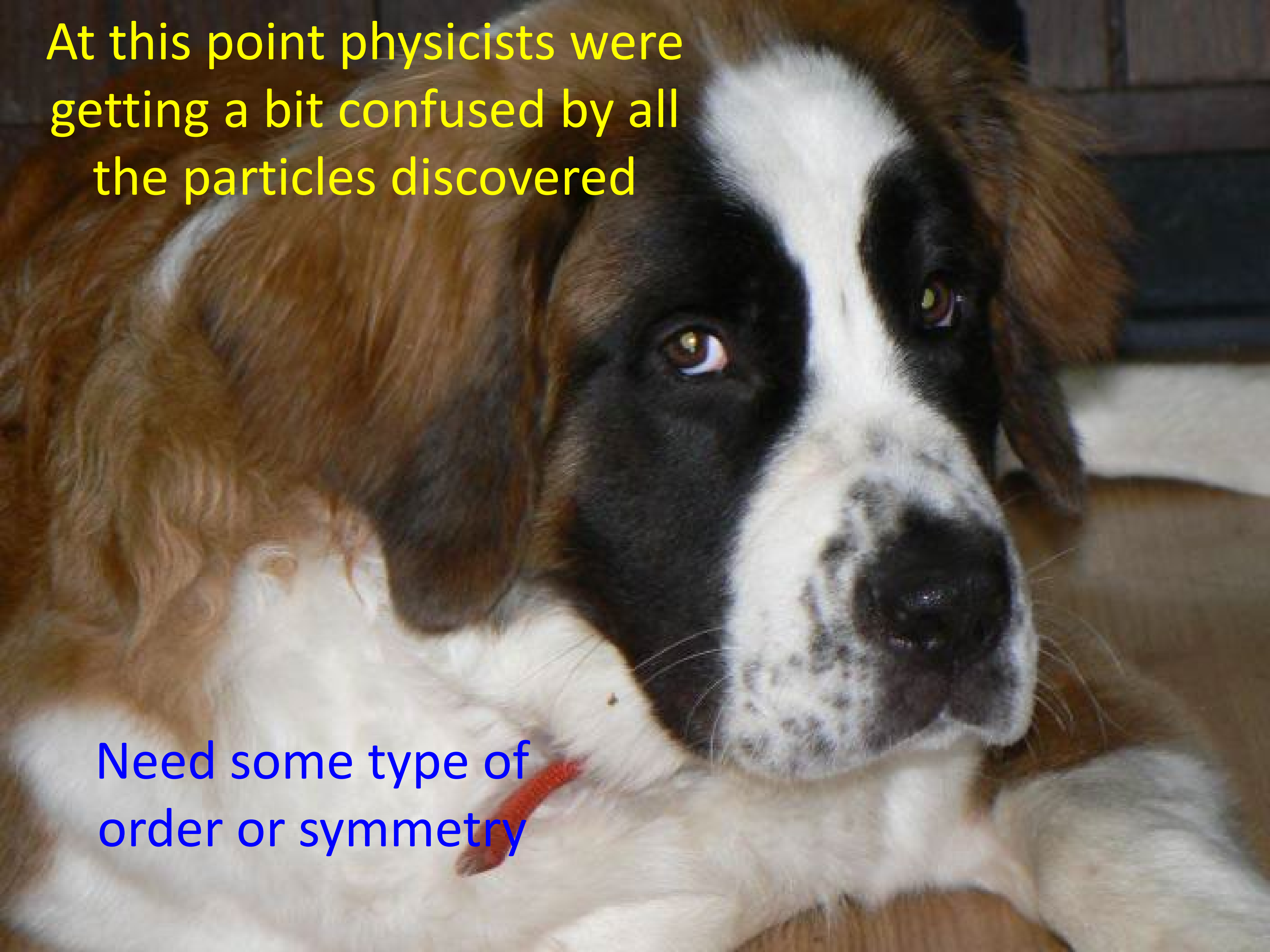


A title wave of new particles is discovered.

How to classify them—a periodic table of particles?




At this point physicists were getting a bit confused by all the particles discovered
Need some type of order or symmetry

Eight-fold way

Gel-Mann

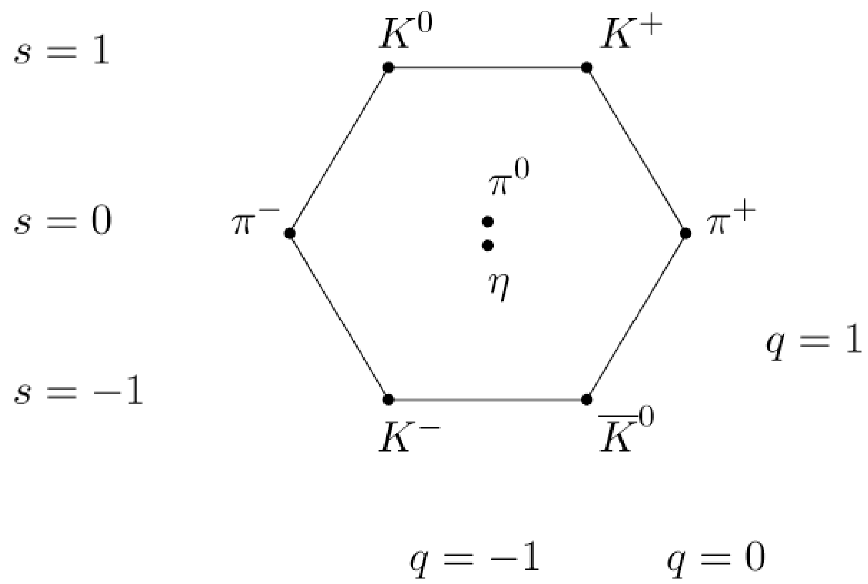
- Three new basic building blocks
  the quarks (u, d, s)
- Represented by the SU(3) group

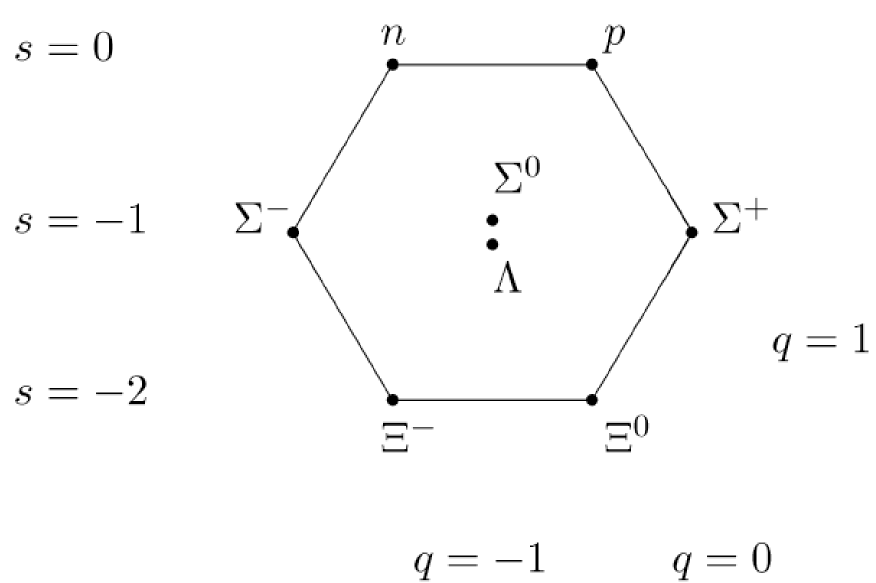
$$u = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} d = \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix} s = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

- Rotations in SU(3) space interchanged quarks. Rotations produced mesons and baryons with nearly the same mass because the strong force does not couple to flavor.

- Hypercharge and isospin (z projection)

	u	d	s
I_z	1/2	-1/2	0
Y	1/3	1/3	-2/3

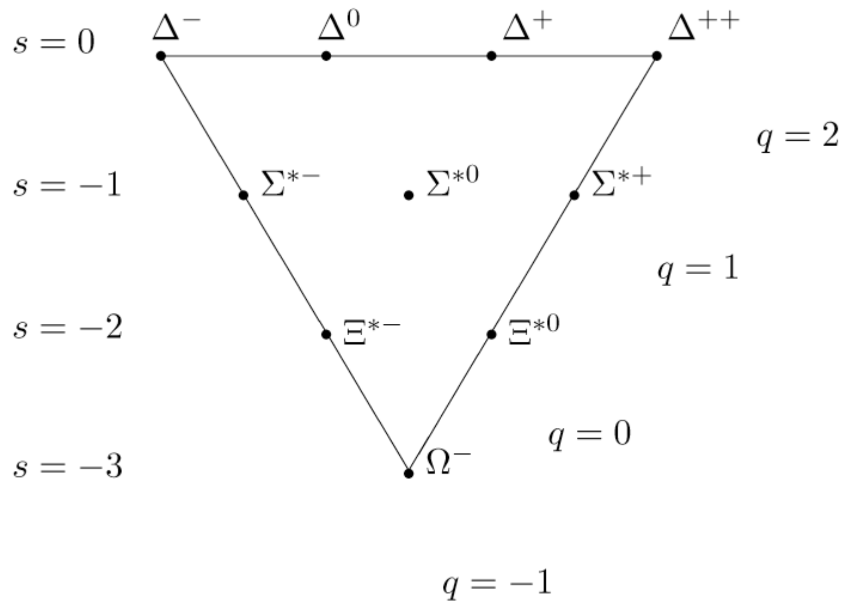


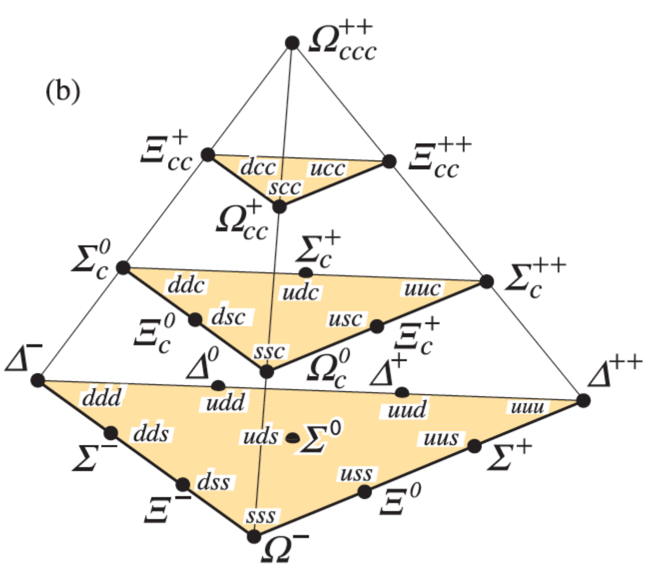


Eight-fold way

Ω^-

- Gell-Mann predicted a particle with
  - Strangeness −3, —Electric charge −1
  - Mass near 1680 MeV/c^2.
  - Discovered in 1964, at Brookhaven National laboratory
  - Gell-Mann received the 1969 Nobel Prize for the prediction of the Ω^-





SU(3) could be extended to SU(4) with the discovery of the charm quark

Thanks to PDG for illustrations—see Quark Model


Becky is now Happy!
Hadronic structure is understood! Or is it?

The need for partons—Elastic Scattering Cross Sections

- Rutherford cross section—scattering of a spinless point particle from a Coulomb field

$$\frac{d\sigma}{d\Omega}_{\mathrm{Ruth.}} = \frac{\alpha^2}{4E^2\sin^4\frac{1}{2}\theta}$$

- Mott cross section—add the electron's spin

$$\frac{d\sigma}{d\Omega}_{\mathrm{Mott}} = \frac{d\sigma}{d\Omega}_{\mathrm{Ruth}} \cos^2\frac{1}{2}\theta = \frac{\alpha^2\cos^2\frac{1}{2}\theta}{4E^2\sin^4\frac{1}{2}\theta}$$

- Include target mass and Dirac spin (½)

$$\frac{d\sigma}{d\Omega}_{\mathrm{Dirac}} = \frac{d\sigma}{d\Omega}_{\mathrm{Mott}} \frac{E'}{E}\left[1 - \frac{q^2}{2M^2}\tan^2\frac{1}{2}\theta\right] = \frac{\alpha^2\cos^2\frac{1}{2}\theta}{4E^2\sin^4\frac{1}{2}\theta}\frac{E'}{E}\left[1 - \frac{q^2}{2M^2}\tan^2\frac{1}{2}\theta\right]$$

Define

$$E' = \frac{E}{1 + \frac{2E}{M}\sin^2\frac{1}{2}\theta}$$

$$q^2 = -4EE'\sin^2\frac{1}{2}\theta$$

The need for partons—Elastic Scattering Cross Sections

Now, what if the target is not a point charge, but has a distribution of charge?

- Modify cross section by introduction of a "form factor"

$$F\left(q^2\right) = \int e^{i\mathbf{q}\cdot\mathbf{r}}\rho\left(r\right)d^3r$$

  Measurement of this form factor at $q^2 \to 0$ will give you the charge radius of the particle

- There are two distributions of charge to consider
  - Electric $F_1(q^2)$ Dirac form factor
  - Magnetic $F_2(q^2)$ Pauli form factor

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\mathrm{Mott}}\frac{E'}{E}\left[\left(F_1^2 + \mu\frac{q^2}{2M^2}F_2^2\right) + \frac{q^2}{2M^2}2\left(F_1 + \mu F_2\right)^2\tan^2\frac{1}{2}\theta\right]$$

  - Also know as the Rosenbluth cross section.
  - If the proton were a point-like Dirac particle then

$$\mu F_2^{\mathrm{elastic}}\left(q^2\right) = 0 \qquad F_1^{\mathrm{elastic}}\left(q^2\right) = 1$$

PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§‖¶

R. W. McAllister and R. Hofstadter
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California

(Received January 25, 1956)

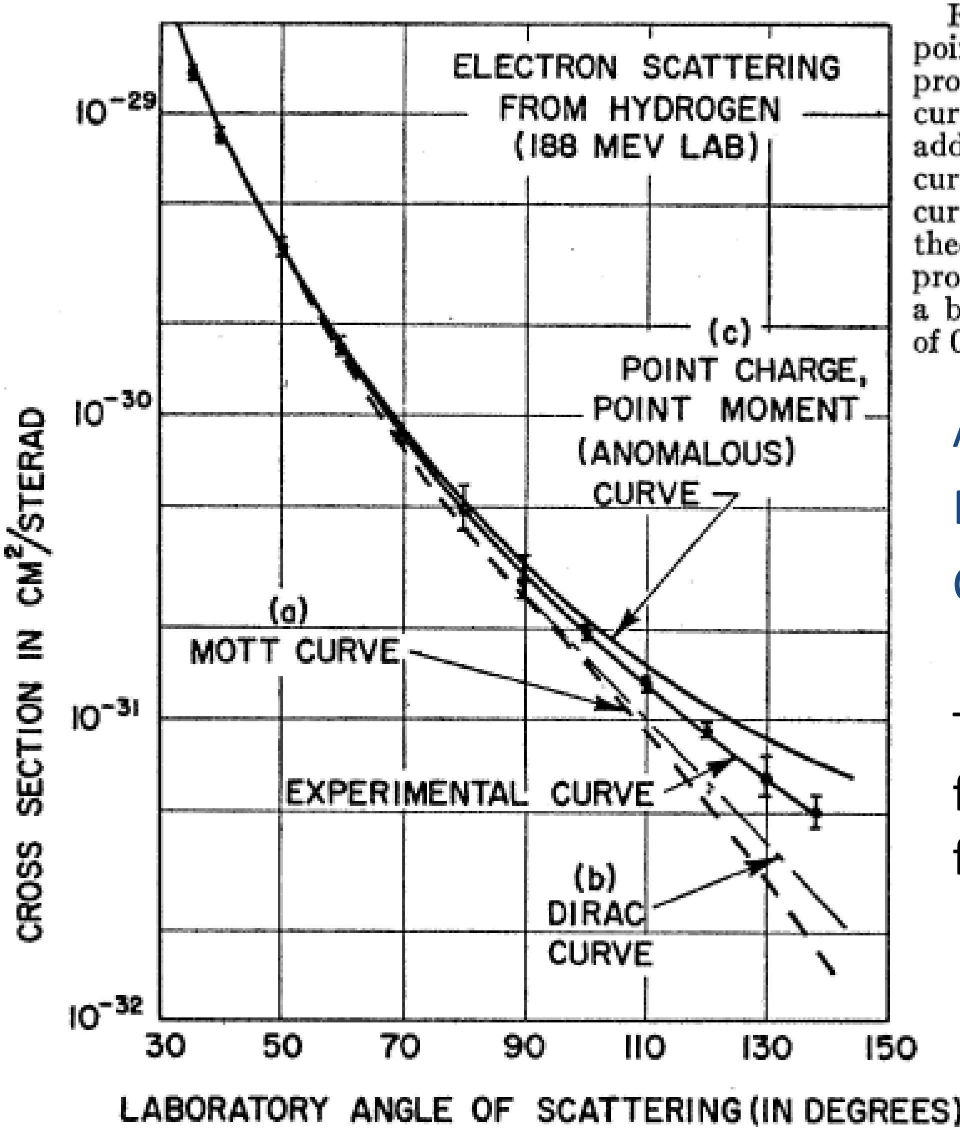


FIG. 5. Curve (a) shows the theoretical Mott curve for a spinless point proton. Curve (b) shows the theoretical curve for a point proton with the Dirac magnetic moment, curve (c) the theoretical curve for a point proton having the anomalous contribution in addition to the Dirac value of magnetic moment. The theoretical curves (b) and (c) are due to Rosenbluth.[8] The experimental curve falls between curves (b) and (c). This deviation from the theoretical curves represents the effect of a form factor for the proton and indicates structure within the proton, or alternatively, a breakdown of the Coulomb law. The best fit indicates a size of 0.70×10^{-13} cm.

A. Mott curve for spinless point proton
B. Mott for point proton w/μ_p= 2
C. Mott for point proton w/anomalous μ_p

The data agree with none of these, forcing a conclusion that the proton has a finite size to its charge distribution

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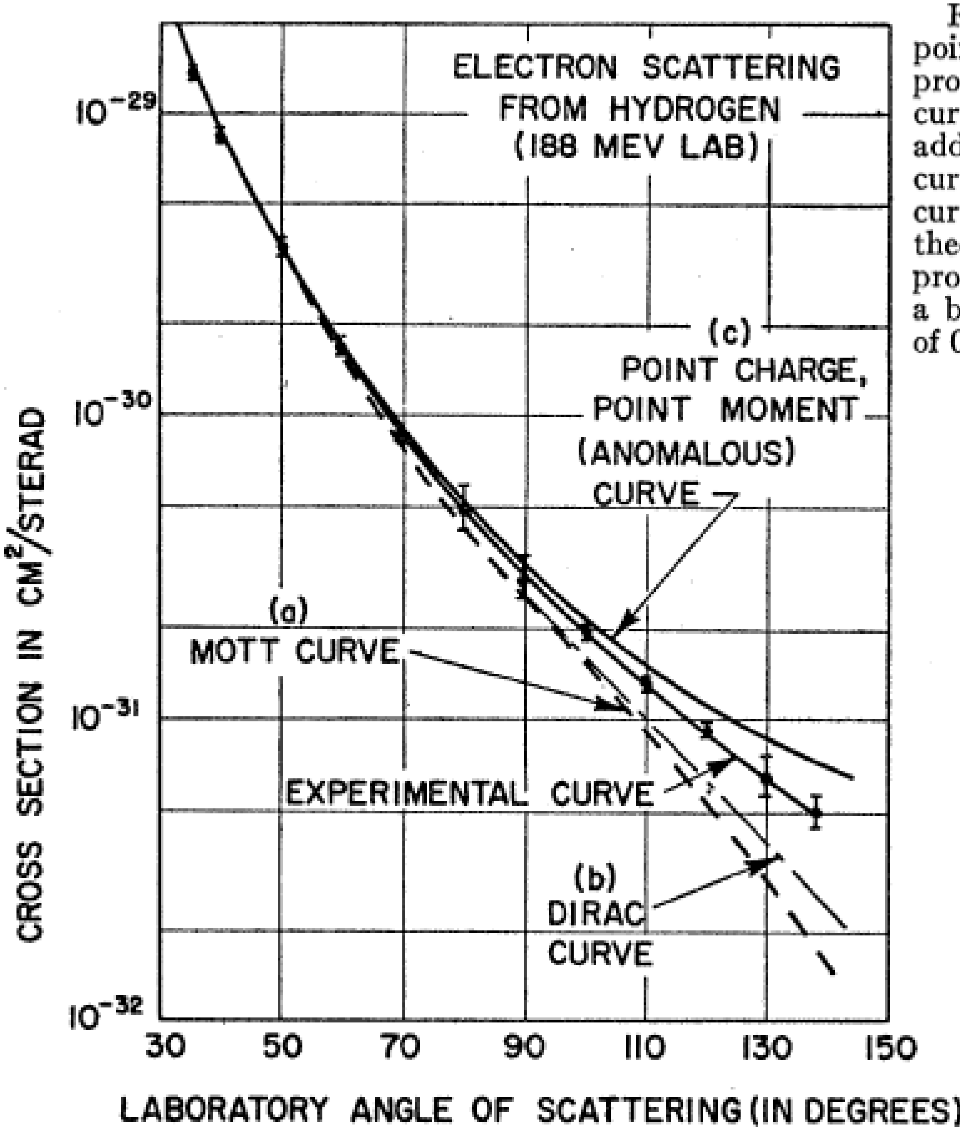

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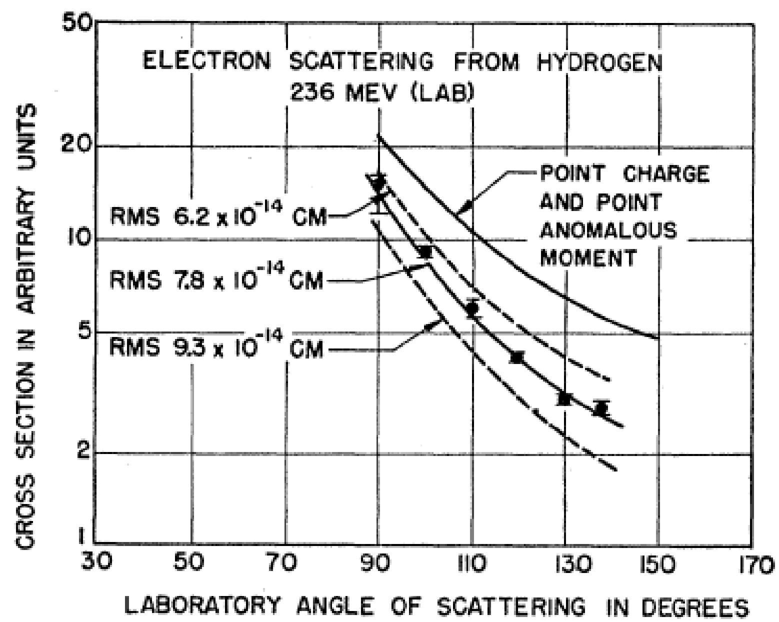


Fig. 6. This figure shows the experimental points at 236 Mev and the attempts to fit the shape of the experimental curve. The best fit lies near 0.78×10^{-13} cm.

Aside: Rosenbluth Formula

The Rosenbluth cross section for Elastic Scattering

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{E'}{E} \left[\left(F_1^2 + \mu \frac{q^2}{2M^2} F_2^2 \right) + \frac{q^2}{2M^2} 2 \left(F_1 + \mu F_2 \right)^2 \tan^2 \frac{1}{2}\theta \right]$$

Is more frequently written as

$$\tau = \frac{Q^2}{4M^2}$$

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{E'}{E} \left[F_1^{\text{Elas.}}\left(Q^2\right) + \tau \left[F_2^{\text{Elas.}}\left(Q^2\right) + 2\left[F_1^{\text{Elas.}}\left(Q^2\right) + F_2^{\text{Elas.}}\left(Q^2\right) \right]^2 \right] \tan^2 \frac{\theta}{2} \right] \\ &= \frac{d\sigma}{d\Omega}_{\text{Mott}} \frac{E'}{E} \left[\frac{{G_E}^2\left(Q^2\right) + \tau {G_M}^2\left(Q^2\right)}{1+\tau} + 2{G_M}^2\left(Q^2\right) \tan^2\left(\frac{\theta}{2}\right) \right] \end{aligned}$$

Defining the Sachs electric and magnetic form factors:

$$\begin{aligned} G_E\left(Q^2\right) &= F_1^{\text{Elas.}}\left(Q^2\right) - \tau F_2^{\text{Elas.}}\left(Q^2\right) \\ G_M\left(Q^2\right) &= F_1^{\text{Elas.}}\left(Q^2\right) + F_2^{\text{Elas.}}\left(Q^2\right) \end{aligned}$$

Aside: The size of the proton

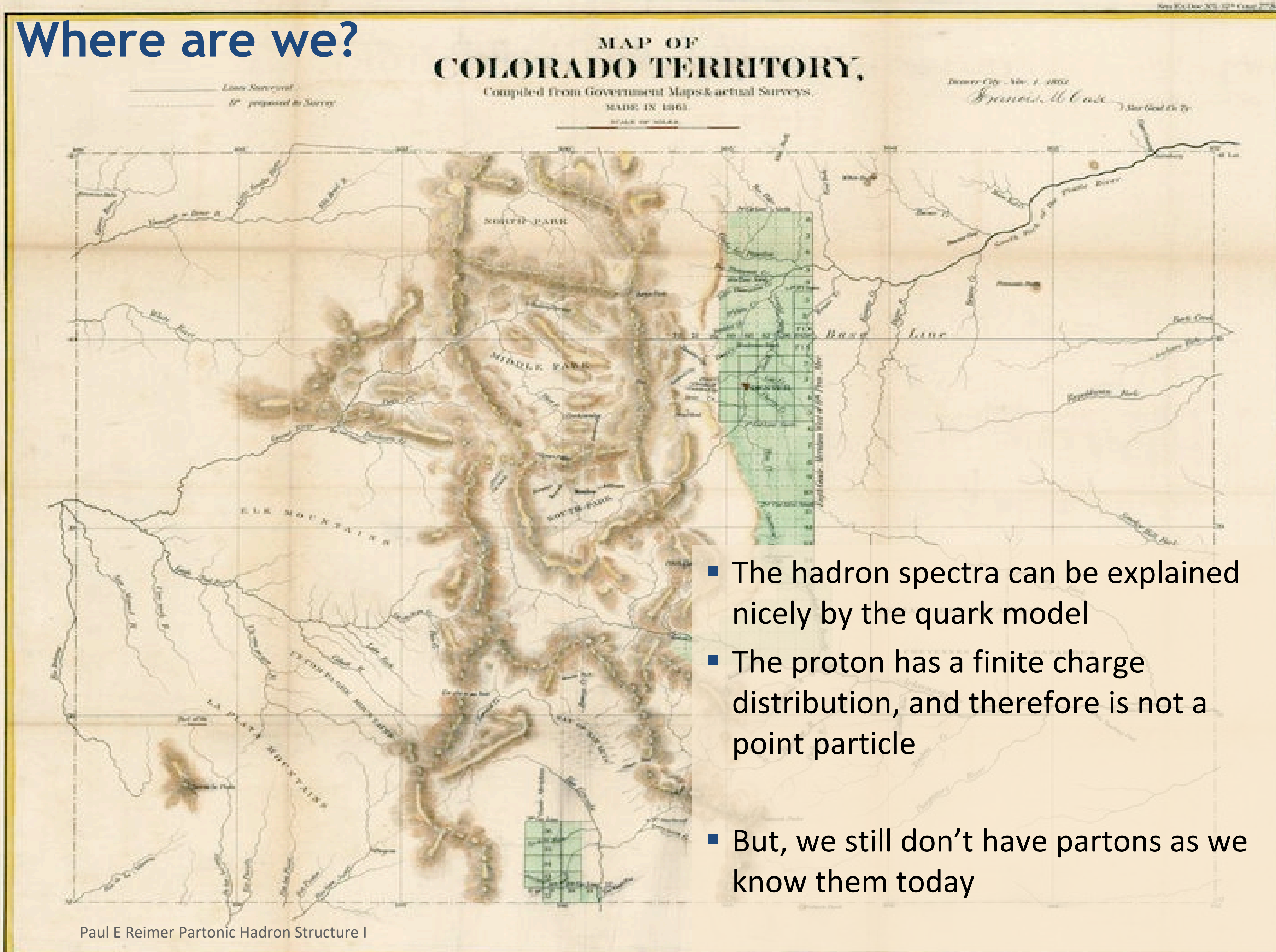
Now, what if the target is not a point charge, but has a distribution of charge?

- Modify cross section by introduction of a "form factor"

$$
\begin{aligned}
F\left(q^2\right) &= \int e^{i\mathbf{q}\cdot\mathbf{r}}\rho\left(r\right)d^3r \\
&\approx \int\left[1 + i\mathbf{q}\cdot\mathbf{r} - \frac{\mathbf{1}}{\mathbf{2}}\left(\mathbf{q}\cdot\mathbf{r}\right)^{\mathbf{2}} + \cdots\right]\rho\left(r\right)d^3r \\
&\approx 1 - \frac{q^2}{6}\left\langle r^2\right\rangle + \cdots
\end{aligned}
$$

The **charge radius** of the proton is apparently yet well known as **determinations** using electron elastic scattering and muonic hydrogen spectroscopy currently **disagree**!

Where are we?



- The hadron spectra can be explained nicely by the quark model
- The proton has a finite charge distribution, and therefore is not a point particle
- But, we still don't have partons as we know them today

Origins of the Parton Model—Richard Feynman

, NUMBER 24 PHYSICAL REVIEW LETTERS 15

VERY HIGH-ENERGY COLLISIONS OF HADRONS

Richard P. Feynman
California Institute of Technology, Pasadena, California
(Received 20 October 1969)

Proposals are made predicting the character of longitudinal-momentum distributions in hadron collisions of extreme energies.

By The Nobel Foundation

In the introduction Feynman writes:

"... I have difficulty in writing this note because it is not in the nature of a deductive paper, but is the result of an induction. I am more sure of the conclusions than of any single argument which suggested them to me for they have an internal consistency which surprises me and exceeds the consistency of my deductive arguments which hinted at their existence.

"Only the barest indications of the logical bases of these suggestions will be indicated here. Perhaps in a future publication I can be more detailed."

In the conclusion he says:

"Finally, for those special reactions which are partially exclusive. . . The cross section should vary as 1/s. Of this last conclusion I am less sure than of the others."

Only a very few people could publish in Phys. Rev. Lett. with such a disclaimer. Richard Feynman is one of them.

Origins of the Parton Model—Richard Feynman

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Feynman bases his argument on very general considerations

- Pondering about Hadronic collisions
- How the cross sections of inclusive and exclusive reactions scale with $W^2=s/2$.
- Considered multiplicities in terms of mom. and quantum numbers

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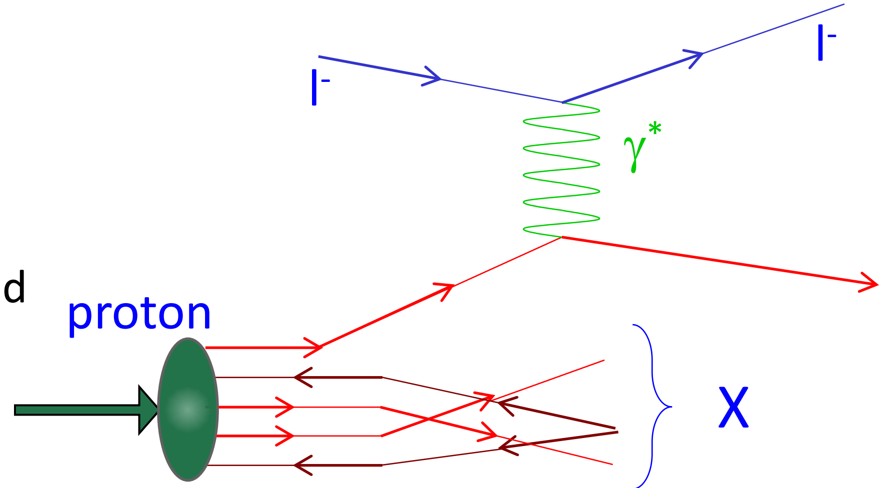
Feynman bases his argument on very general considerations

- Pondering about Hadronic collisions
- How the cross sections of inclusive and exclusive reactions scale with $W^2=s/2$.
- Considered multiplicities in terms of mom. and quantum numbers
- Concludes that
  - There are collisions of a vast number of point-like particles
  - The point-like particles (partons) each have some fraction, *x*, of the protons total momentum
  - Probability of finding a parton with momentum between *x* and *x+dx* as *f(x)dx*
  - *f(x)dx* is process independent

$$A + B \to C + \text{anything} \qquad f(x) \propto (1 - x_C)^{1-2\alpha(t)}$$

Deep Inelastic scattering

- Consider the situation in which not everything is detected—e.g. only the scattered electron
- Can still write a general cross section formula based on the form factor arguments of elastic scattering



$$\frac{d\sigma}{d\Omega dE'} = \frac{d\sigma}{d\Omega}_{\text{Mott}} \left[W_2 + 2W_1 \tan^2\frac{\theta}{2} \right]$$

$$\nu = E - E'$$

$$Q^2 = -q^2 = 4EE'\sin^2\frac{\theta}{2}$$

$$W^2 = M^2 + 2M\nu - Q^2$$

- Since ν and Q^2 are no longer independent, the structure functions are now a function of both

$$W_2\left(Q^2,\nu\right) \text{ and } W_1\left(Q^2,\nu\right)$$

For elastic scattering,
$W^2 = M^2$ so
$2M\nu = Q^2$

- Observation of scaling behavior:
  - The cross section did not fall with Q^2, but tended to depend on a single variable

$$\omega = \frac{2M\nu}{Q^2}$$

Deep Inelastic == Elastic scattering from points?

Bjorken

- What if deep inelastic scattering is just scattering off of point particles within the nucleus?
- Consider the Dirac point scattering formula, writing it in a Lorentz invariant form (following Perkins)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2 \frac{1}{2}\theta}{4E^2 \sin^4 \frac{1}{2}\theta} \frac{E'}{E} \left[1 - \frac{q^2}{2M^2} \tan^2 \frac{1}{2}\theta\right]$$

$$\frac{d\sigma}{dy} = \frac{4\pi\alpha^2 s}{Q^4} \left[\frac{1}{2}\left[1 + (1-y)^2\right] - \frac{M}{2E}y\right]$$

Lorentz invariants

$$Q^2 = 2xM\nu$$

$$s = 2ME$$

$$y = \frac{\nu}{E}$$

$$1 - y = \cos^2\frac{\theta}{2}$$

$$d\Omega = 2\pi d\cos\theta = 4\pi dy$$

- Now sum over the distributions of the partons:

$$\frac{d\sigma}{dy}_{\text{proton}} = \sum_{i\in\{parton\}} \frac{d\sigma}{dy}_{\text{parton}}$$

$$= \sum_{i\in\{parton\}} \frac{4\pi\alpha^2 x_i s}{Q^4} \left[\frac{1}{2}\left[1 + (1-y)^2\right] - \frac{M}{2E}x_i y\right] e_i^2 f_i(x) dx$$

Deep Inelastic == Elastic scattering from points?

$$\frac{d\sigma}{dy}_{\text{proton}} = \sum_{i\in\{parton\}} \frac{d\sigma}{dy}_{\text{parton}}$$

$$= \sum_{i\in\{parton\}} \frac{4\pi\alpha^2 x_i s}{Q^4}\left[\frac{1}{2}\left[1+(1-y)^2\right] - \frac{M}{2E}x_i y\right] e_i^2 f_i(x)dx$$

- Now identify form factors in terms of partons!

$$F_1\left(x,Q^2\right) = MW_1 = \frac{1}{2}\sum_{i\in\{\text{partons}\}} e_i^2 f_i(x)$$

$$= \frac{1}{2}\left[\frac{4}{9}u(x) + \frac{1}{9}d(x) + \frac{4}{9}\bar{u}(x) + \frac{1}{9}\bar{d}(x) + \cdots\right]$$

$$F_2\left(x,Q^2\right) = \nu W_2 = x\sum_{i\in\{\text{partons}\}} e_i^2 f_i(x)$$

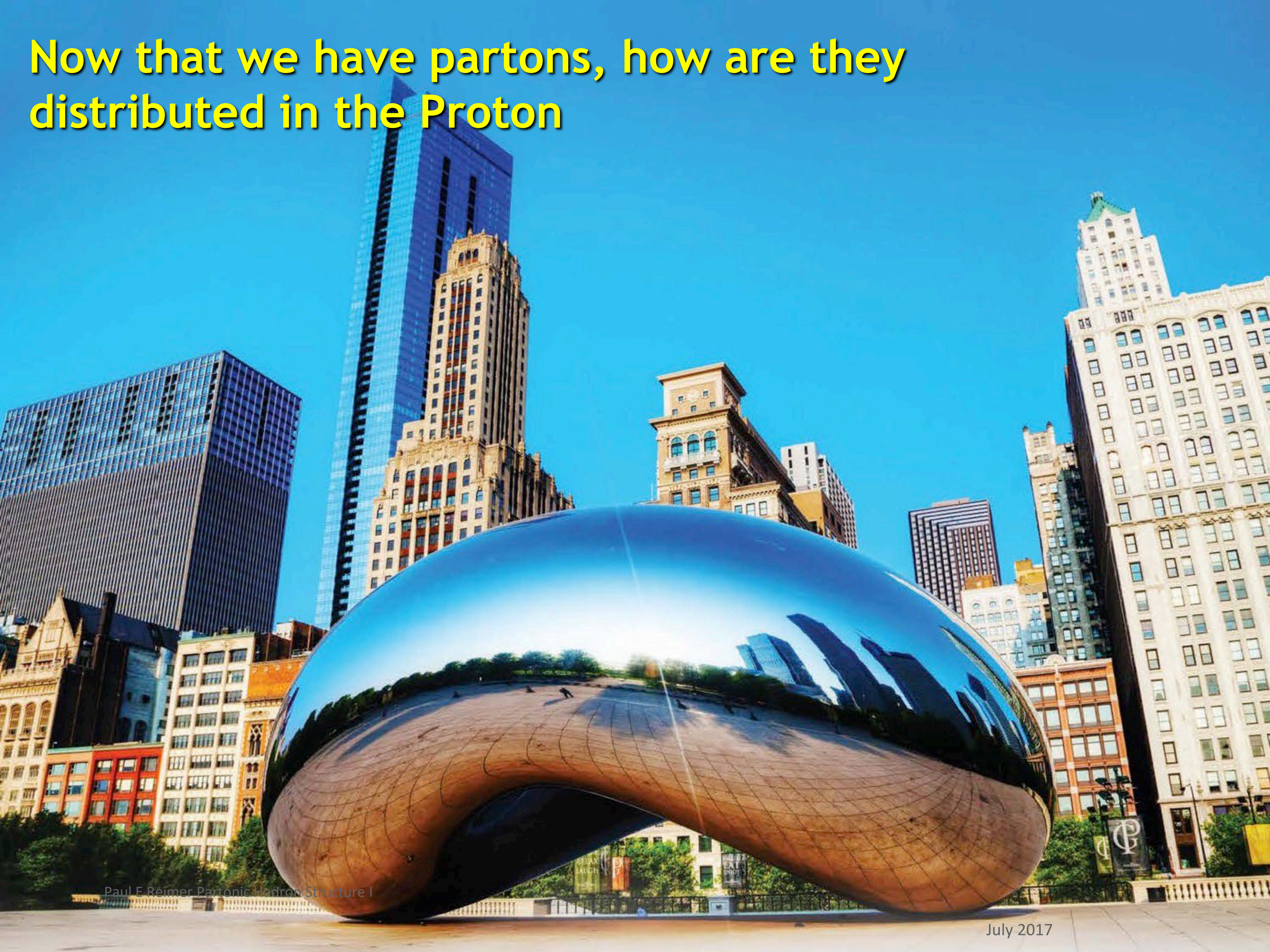
$$= x\left[\frac{4}{9}u(x) + \frac{1}{9}d(x) + \frac{4}{9}\bar{u}(x) + \frac{1}{9}\bar{d}(x) + \cdots\right]$$

- Note that ***$F_1(x,Q^2) = 2xF_2(x,Q^2)$*** in this identification.

  Often called the **Callan-Gross** relation

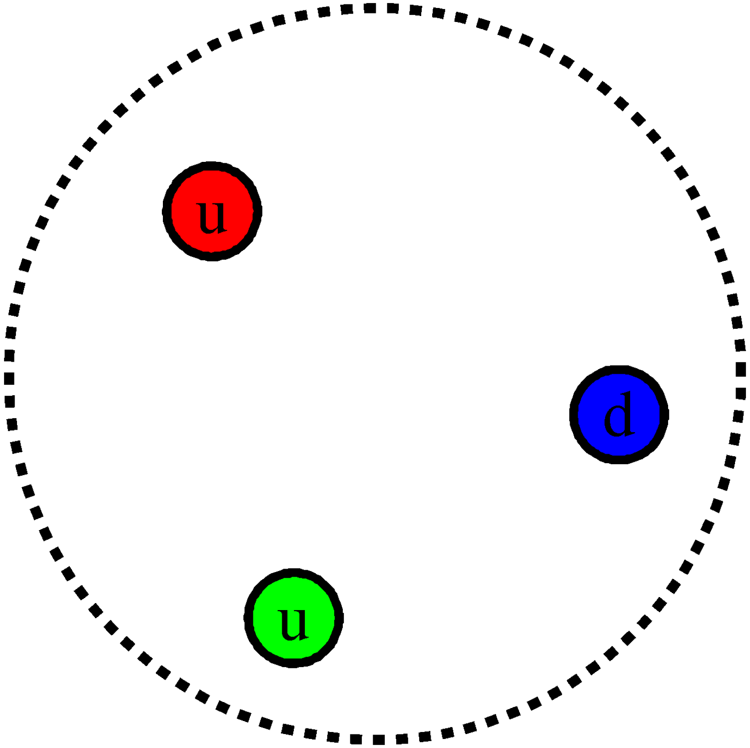
Becky is now Happy!

Now that we have partons, how are they distributed in the Proton



How do the parton distributions evolve?

- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV



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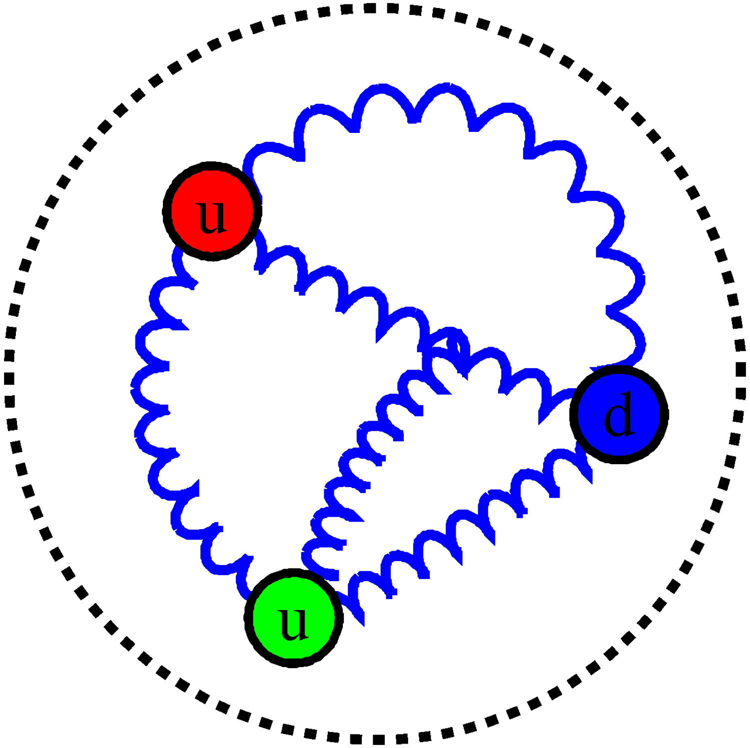
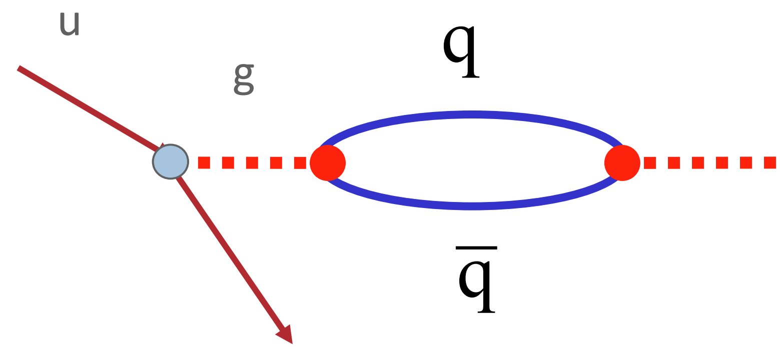
  - Add the binding strong force—glue



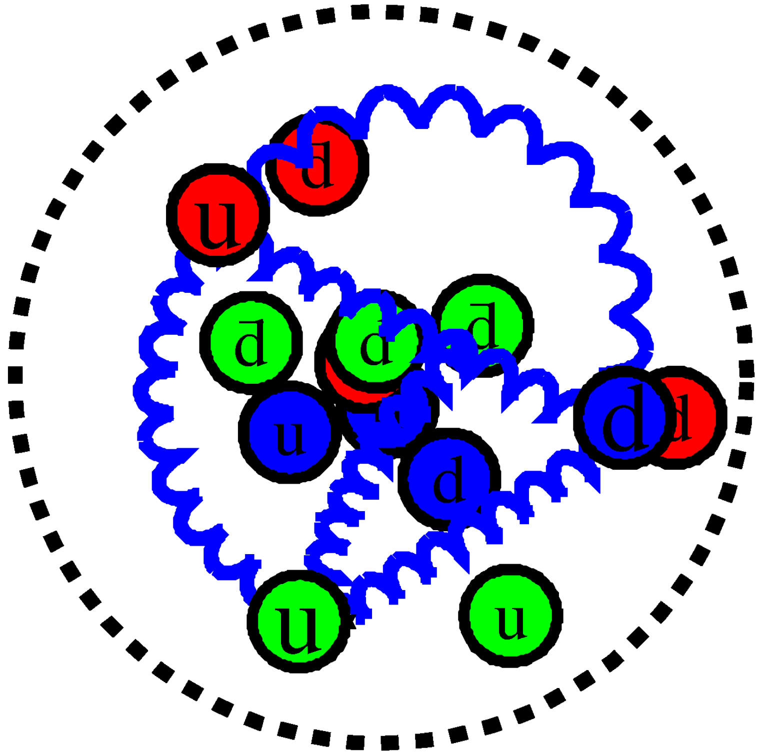
How do the parton distributions evolve?



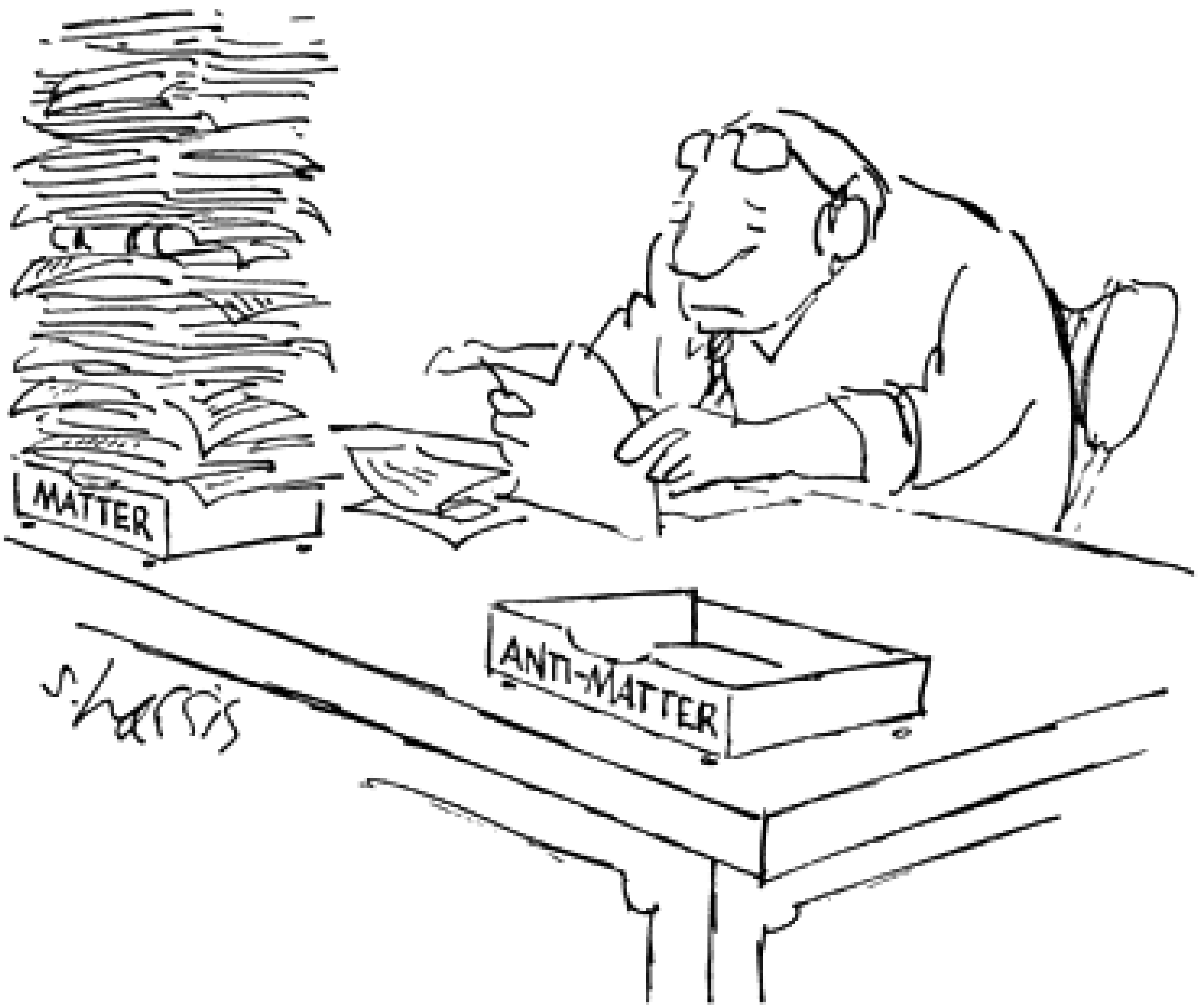
- Constituent Quark/Bag Model motivated valence approach
  - Use valence-like (primordial) quark distributions at some very low scale, Q^2, perhaps a few hundred MeV
  - Add the binding strong force—glue
  - Radiatively generate sea and glue

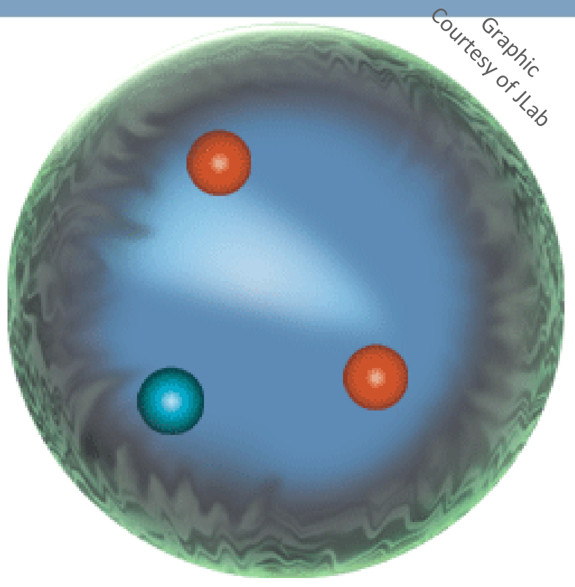
- Process known as QCD evolution
  - Solved and understood via DGLAP equations

  I'm not going in to these here. They are a black box computer package for solving differential/integral a very specific integral equation
  - Important: We can use parton distributions calculated at one energy for another energy.



What’s in the proton?

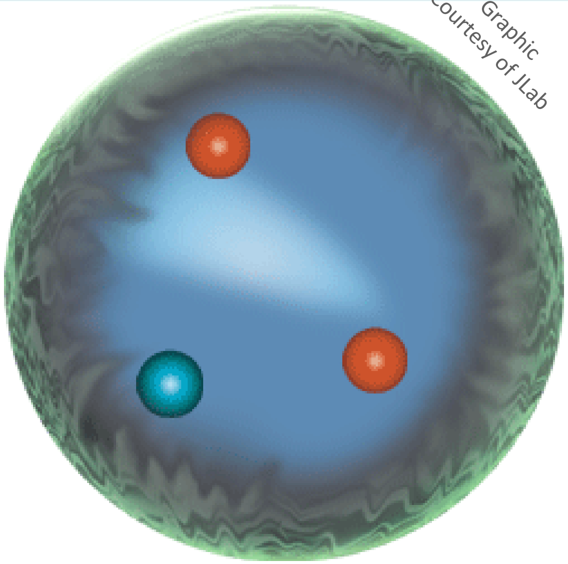




- Just three valence quarks?

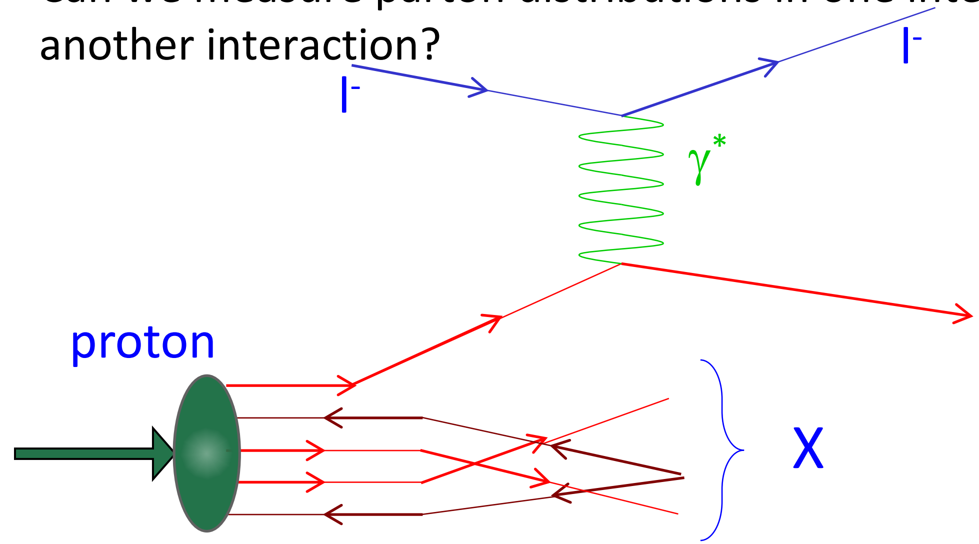
What's in the proton?

http://www.sciencecartoonsplus.com/index.htm

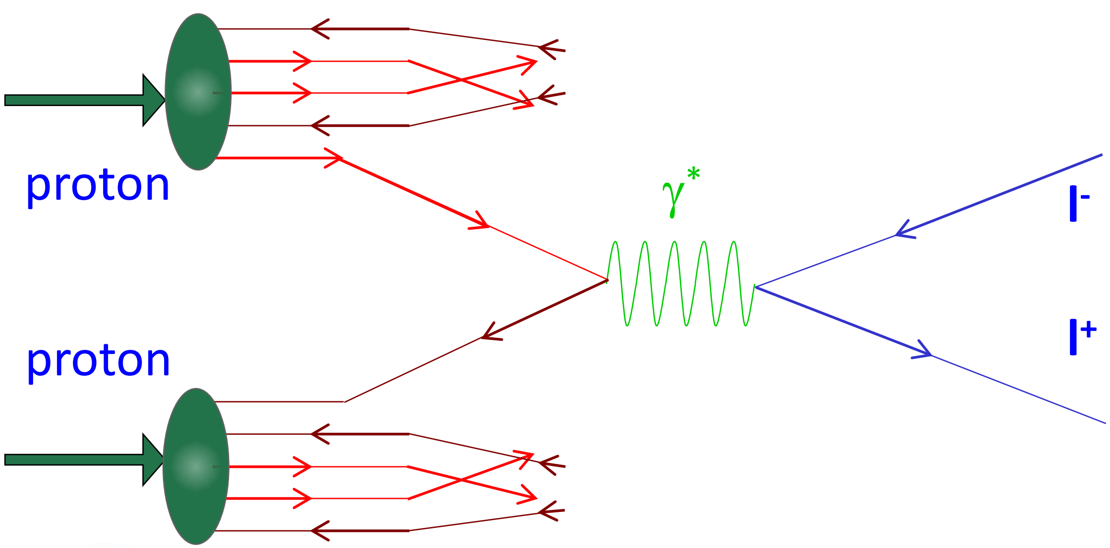


Are parton distributions process independent?

- Can we measure parton distributions in one interaction and expect them to be correct for another interaction?



- In particular, can one calculate a Drell-Yan cross section using DIS parton distributions?
- No! Well maybe Yes!



Early Muon Pair Data

VOLUME 25, NUMBER 21 PHYSICAL REVIEW LETTERS 23 NOVEMBER 1970

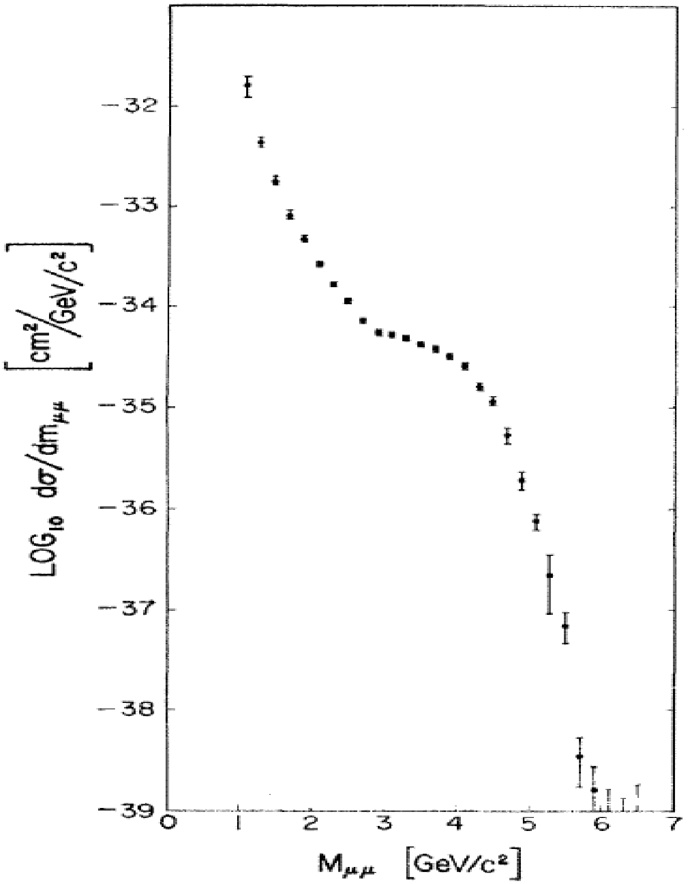
Observation of Massive Muon Pairs in Hadron Collisions*

J. H. Christenson, G. S. Hicks, L. M. Lederman, P. J. Limon, and B. G. Pope
Columbia University, New York, New York 10027, and Brookhaven National Laboratory, Upton, New York 11973

and

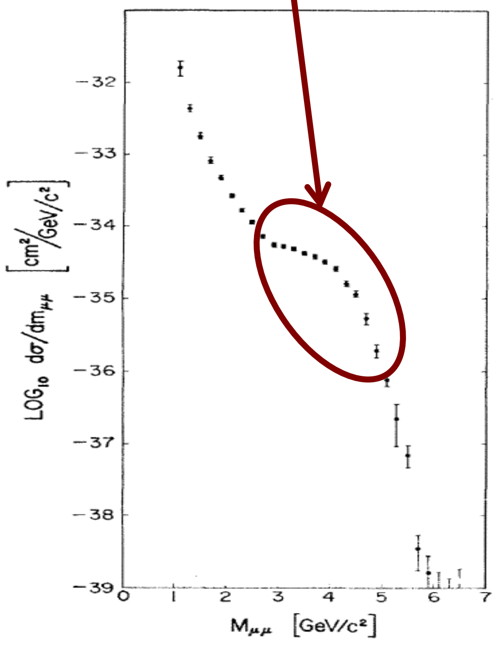
E. Zavattini
CERN Laboratory, Geneva, Switzerland
(Received 8 September 1970)

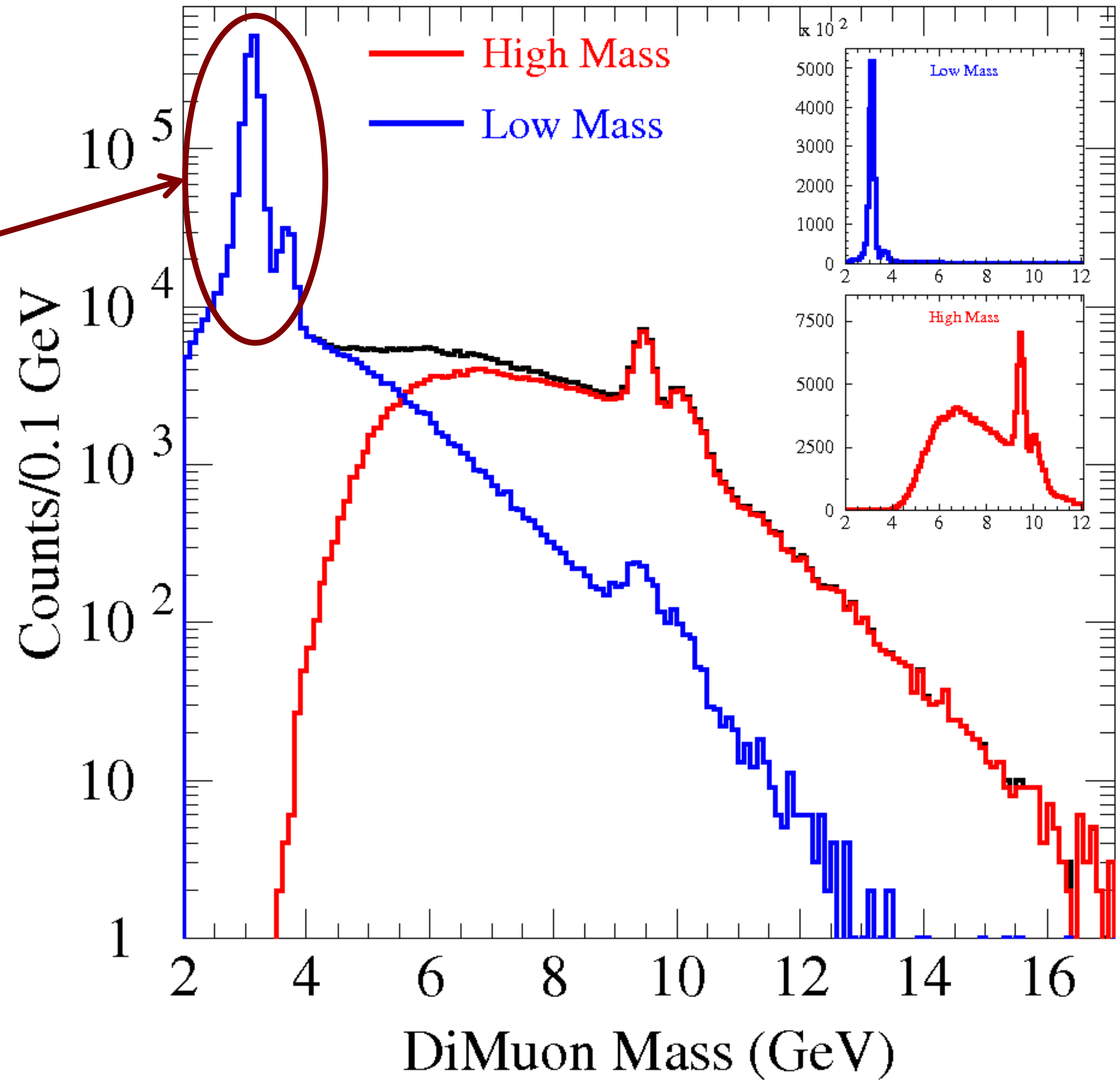
Muon Pairs in the mass range $1 < m_{\mu\mu} < 6.7$ GeV/c^2 have been observed in collisions of high-energy protons with uranium nuclei. At an incident energy of 29 GeV, **the cross section varies smoothly as $d\sigma/dm_{\mu\mu} \approx 10^{-32} / m_{\mu\mu}^5$ cm^2 (GeV/c)$^{-2}$ and exhibits no resonant structure.** The total cross section increases by a factor of 5 as the proton energy rises from 22 to 29.5 GeV.



Drell-Yan Mass Spectra

- What they could have seen if they had sufficient resolution
- Could have been a Nobel Prize!





Data from Fermilab E-866/NuSea

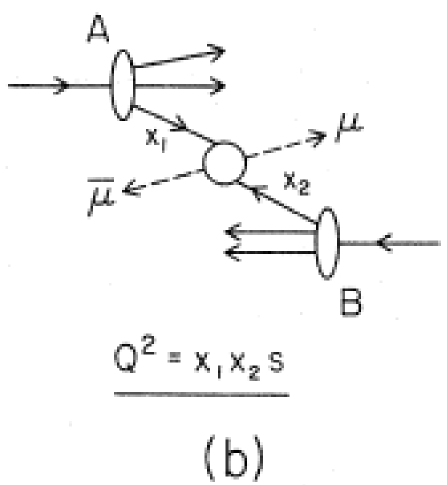
Drell and Yan's explanation

VOLUME 25, NUMBER 5 PHYSICAL REVIEW LETTERS 3 AUGUST 1970

MASSIVE LEPTON-PAIR PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES*

Sidney D. Drell and Tung-Mow Yan
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305
(Received 25 May 1970)

On the basis of a parton model studied earlier we consider the production process of large-mass lepton pairs from hadron-hadron inelastic collisions in the limiting region, $s \to \infty$, Q^2/s finite, Q^2 and s being the squared invariant masses of the lepton pair and the two initial hadrons, respectively. General scaling properties and connections with deep inelastic electron scattering are discussed. In particular, a rapidly decreasing cross section as $Q^2/s \to 1$ is predicted as a consequence of the observed rapid falloff of the inelastic scattering structure function νW_2 near threshold.



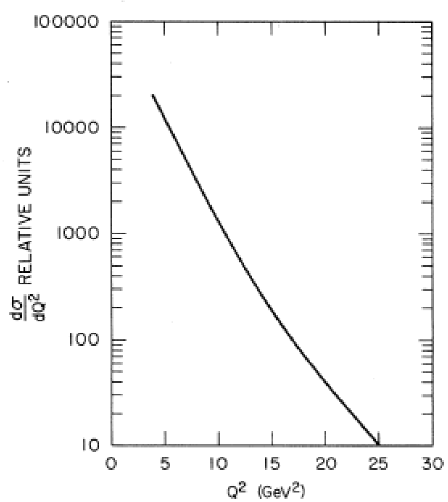
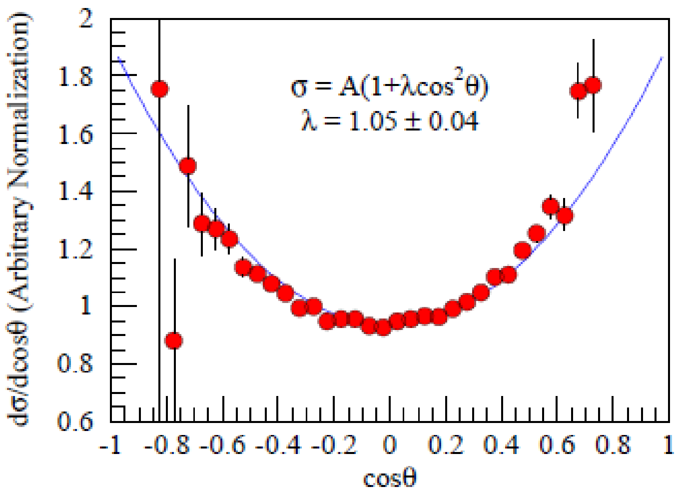
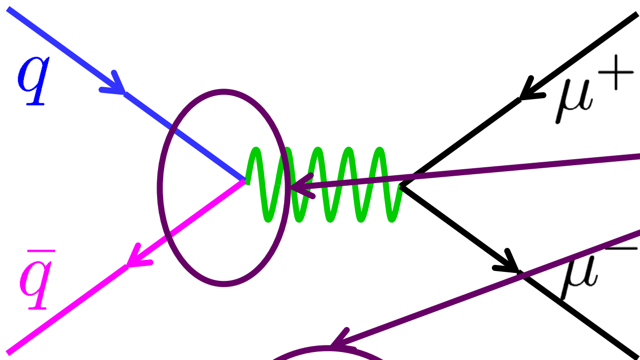


FIG. 2. $d\sigma/dQ^2$ computed from Eq. (10) assuming identical parton and antiparton momentum distributions and with relative normalization.

- Also predicted $\lambda(1+\cos^2\theta)$ angular distributions



The Drell-Yan reaction in leading order



Start with point cross section for two annihilating Fermions (See Halzen and Martin or Perkins)

$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s}\sum_{q\in\{u,d,s,\dots\}} e_q^2\left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})\right]$$

Calculate the probability of finding two quarks with momentum in the range $[x_t, x_t+dx_t]$ and $[x_b, x_b+dx_b]$

Drell-Yan partons

- Calculating the cross section with

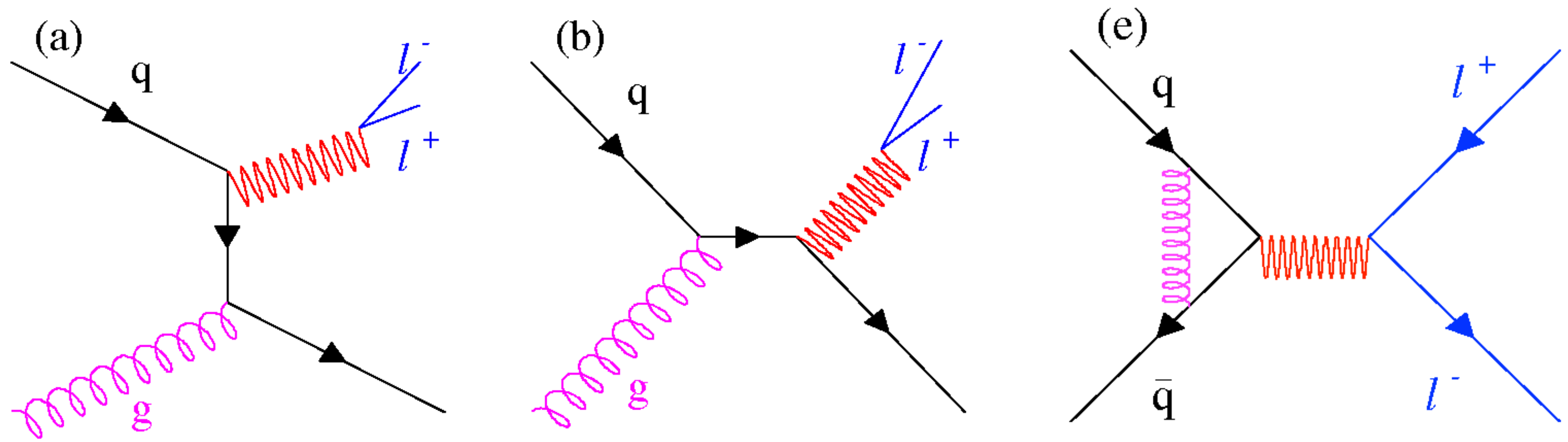
$$\frac{d^2\sigma}{dx_\mathrm{b}dx_\mathrm{t}} = \frac{4\pi\alpha^2}{x_\mathrm{b}x_\mathrm{t}s}\sum_{q\in\{u,d,s,\dots\}} e_q^2\left[\bar{q}_\mathrm{t}(x_\mathrm{t})q_\mathrm{b}(x_\mathrm{b}) + \bar{q}_\mathrm{b}(x_\mathrm{b})q_\mathrm{t}(x_\mathrm{t})\right]$$

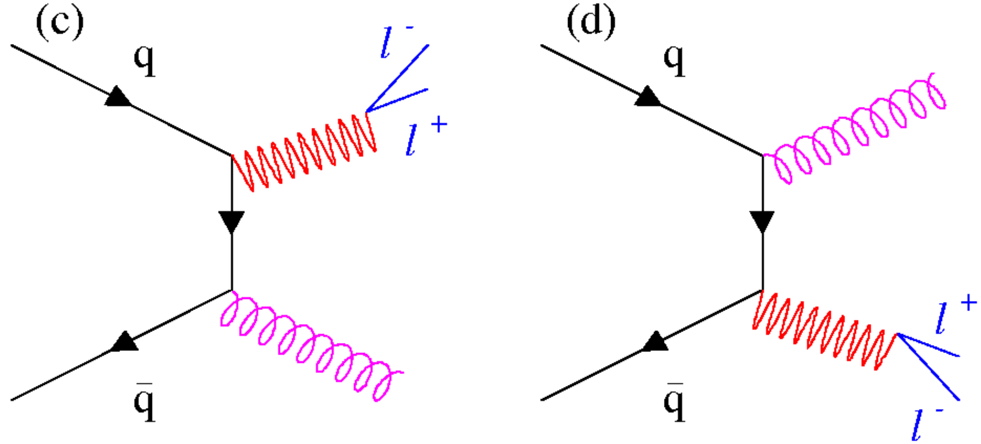
  – Predicts the correct mass and x dependence, but
  – Yields only half the measured cross section.

- First solution: Introduce a "fudge factor" called the K factor K = 2 and we are done but not satisfied.
- Real solution: Look at other contributions

Drell-Yan Cross Section—Next-to-leading order α_s

- These diagrams are responsible for approximately 50% of the measured cross section
- No artificial K-factor is needed in Next-to-leading order calculations (within expt. uncertainties).






Becky is now Happy!
Hadronic structure is understood! And parton distributions are universal—but how do we know what the are?

How can we measure the parton distributions?

- Measure hard scattering processes for which cross section calculations can be easily made.

- Deep Inelastic Scattering is the work horse here

$$F_2^{\mu p}(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2)-\bar{q}(x,Q^2)\right]$$

- Compile data from many experiments with different sensitivities and produce a global fit

How can we measure the parton distributions?

- Measure hard scattering processes for which cross section calculations can be easily made.

- Other processes

Semi-Inclusive deep inealstic scattering

$$N^{\pi^\pm} \propto \sum_{q\in\{u,d,\ldots\}} \left[q(x,Q^2)D^{\pi^\pm} + \bar{q}(x,Q^2)D^{\pi^\pm}\right]$$

W asymmetry

$$A_W(y) \propto \frac{u(x_1)\bar{d}(x_2) - d(x_1)\bar{u}(x_2)}{u(x_1)\bar{d}(x_2) + d(x_1)\bar{u}(x_2)}$$

Drell-Yan

$$\frac{d\sigma}{dx_1 dx_2} \propto \sum_{q\in\{u,d,\ldots\}} e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)\right]$$

- Compile data from many experiments with different sensitivities and produce a global fit

Global fit constraints

2 up valence quarks $$\int_0^1 [u(x) - \bar{u}(x)]\, dx = 2$$

1 down valence quarks $$\int_0^1 \left[d(x) - \bar{d}(x)\right] dx = 1$$

0 strange valence quarks $$\int_0^1 [s(x) - \bar{s}(x)]\, dx = 0$$

Momentum conservation $$\int_0^1 x \left[u(x) + \bar{u}(x) + d(x) + \bar{d}(x) + \cdots\right] dx = 1$$

- Adopt a convenient fitting form:

$$xq(x) = Ax^{\alpha}(1-x)^{\beta}(1 + \gamma\sqrt{x} + \epsilon x^2 + \cdots)$$

- Make other assumptions

Common initial assumption

Neutrons and protons are charge symmetric

- In most processes on the proton, there is a e^2 term giving u quarks twice the weight as d quarks
- Considering only protons, you initially have 2x more u quarks than d quarks
- This assumption
  - Allows the use of data with neutrons
  - gives us better access to the d quark distributions

- Some fits have dropped this assumption and found some room for charge symmetry violation, but not much and the χ^2 distributions were basically flat

$$u_p(x) = d_n(x)$$

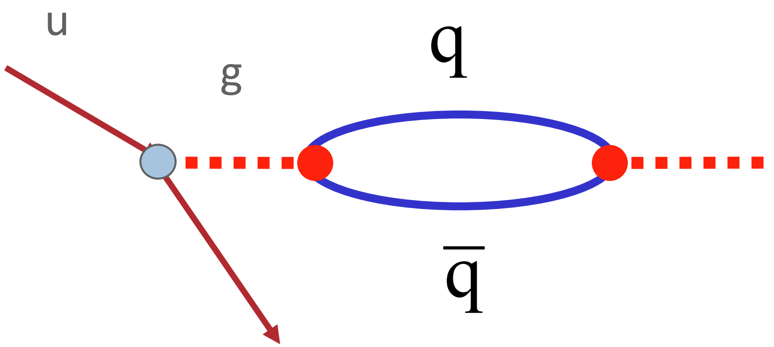
$$d_p(x) = u_n(x)$$

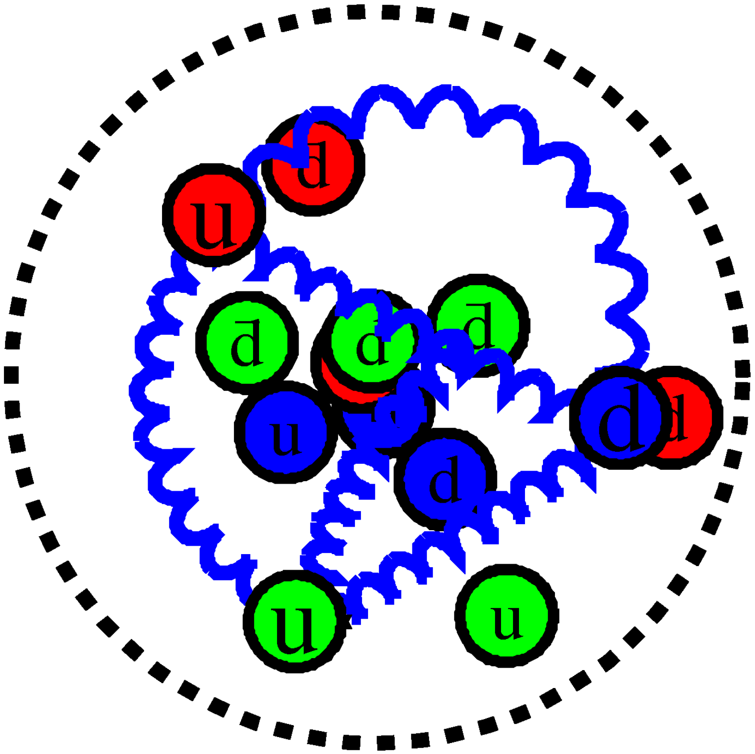
$$\bar{u}_p(x) = \bar{d}_n(x)$$

$$\bar{d}_p(x) = \bar{u}_n(x)$$

Common initial assumption

- QCD Evolution is the only process responsible for the generation of sea quarks





Sea is a fundamental part of the proton

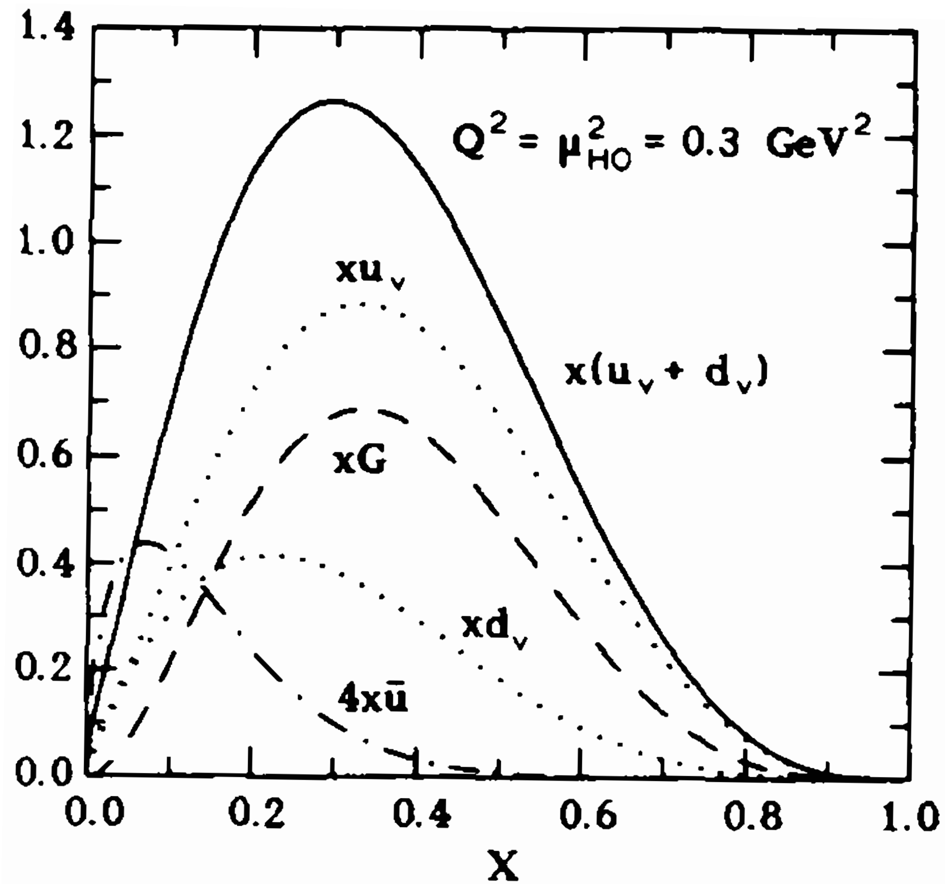
Parton distributions for high energy collisions

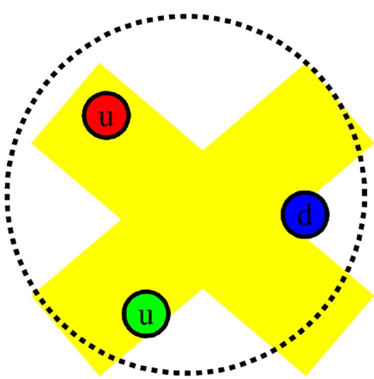
Gluck, Reya, Vogt, ZPC 53, 127 (1992)

M. Glück, E. Reya, A. Vogt
Institut für Physik, Universität Dortmund, Postfach 500500, W-4600 Dortmund 50, Federal Republic of Germany

Received 10 June 1991

Abstract. Recent data from deep inelastic scattering experiments at $x > 10^{-2}$ are used to fix the parton distributions down to $x = 10^{-4}$ and $Q^2 = 0.3\ GeV^2$. **The predicted extrapolations are uniquely determined by the requirement of a *valence*-like structure of *all* parton distributions at some low resolution scale** . . . .





Next common initial assumption

- The Sea is flavor symmetric

$$\bar{d}(x) = \bar{u}(x)$$

Gottfried sum rule

$$I_{GS} = \int_0^1 \left(F_2^{\mu p} - F_2^{\mu n}\right) \frac{dx}{x}$$

$$F_2^{\mu N}(x) = \sum_i e_i^2 x q_i(x)$$

$$I_{GS} = \int_0^1 \left[\sum_i e_i^2 \left(q_i^p - q_i^n\right)\right] dx$$

- Must assume charge symmetry

$$\begin{aligned} I_{GS} &= \frac{1}{3}\int_0^1 \left[\left(u^p + \bar{u}^p\right) - \left(d^p + \bar{d}^p\right)\right] dx \\ &= \frac{1}{3} + \frac{2}{3}\int_0^1 \left(\bar{u}^p - \bar{d}^p\right) dx \end{aligned}$$

$$\text{If } \bar{u}^p = \bar{d}^p \text{ then } I_{GS} = \frac{1}{3}$$

- Finally measured by the EMC at CERN

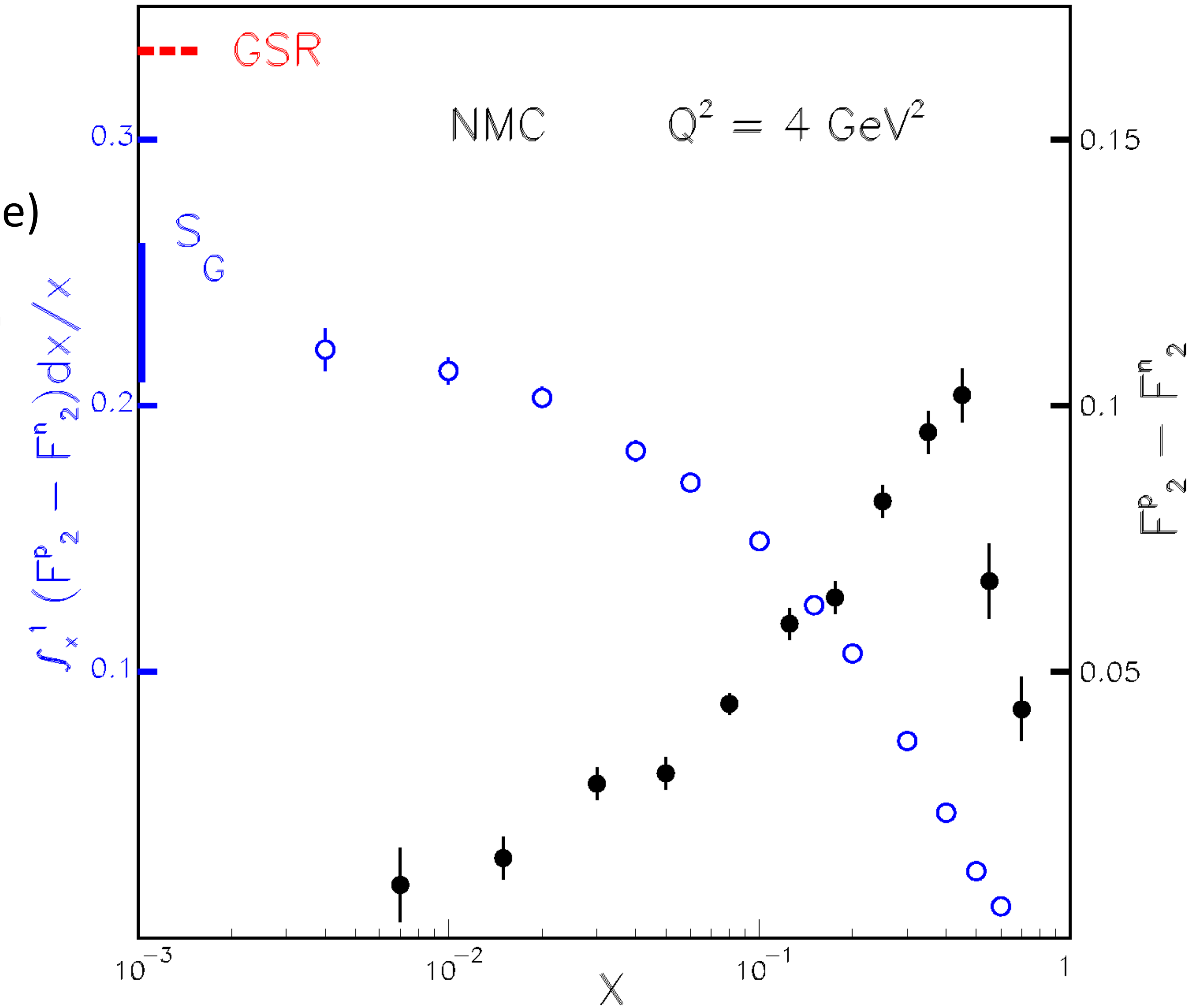
Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$



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- NMC (Gottfried Sum Rule)

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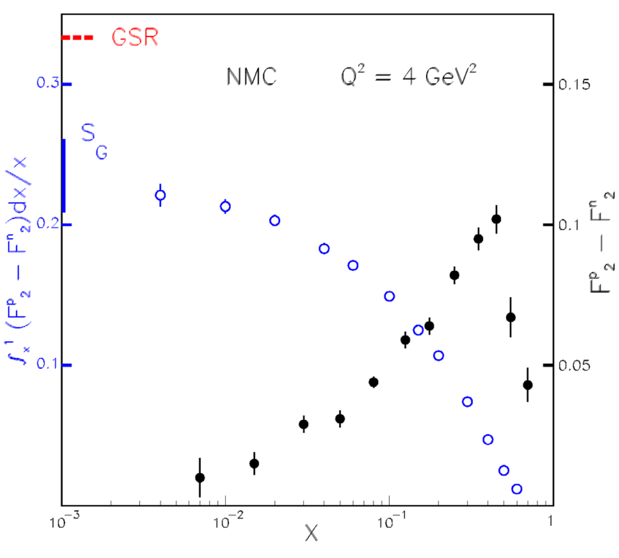
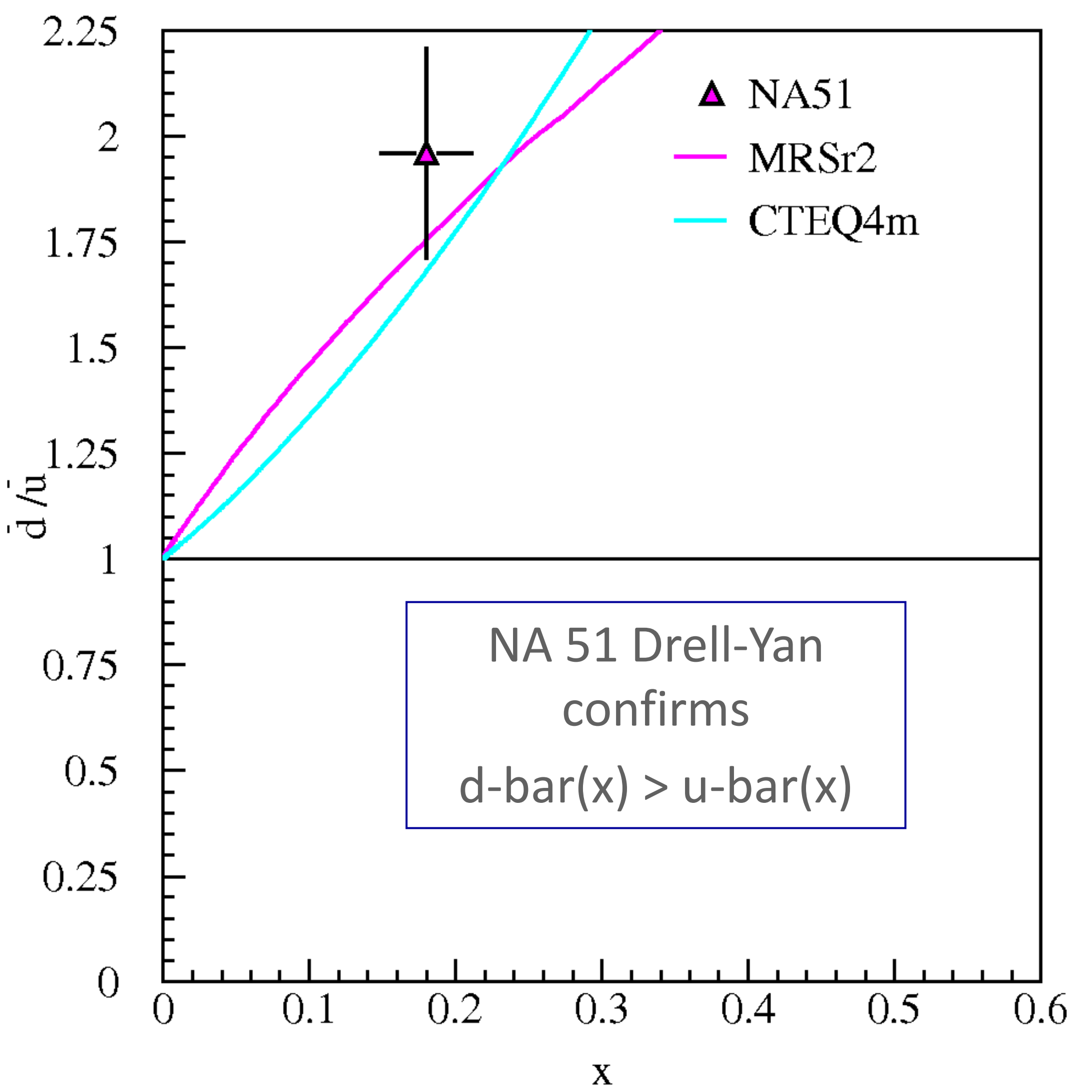
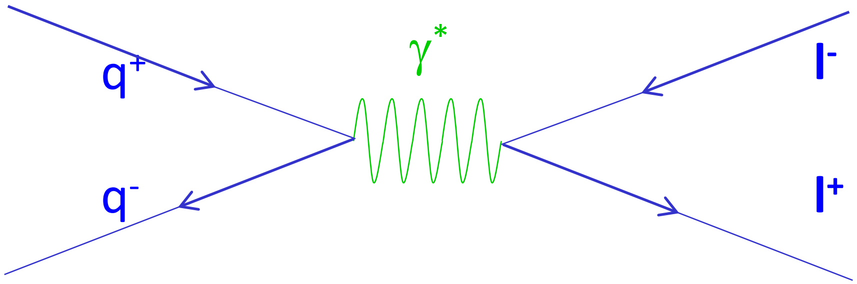
- NA51 (Drell-Yan)

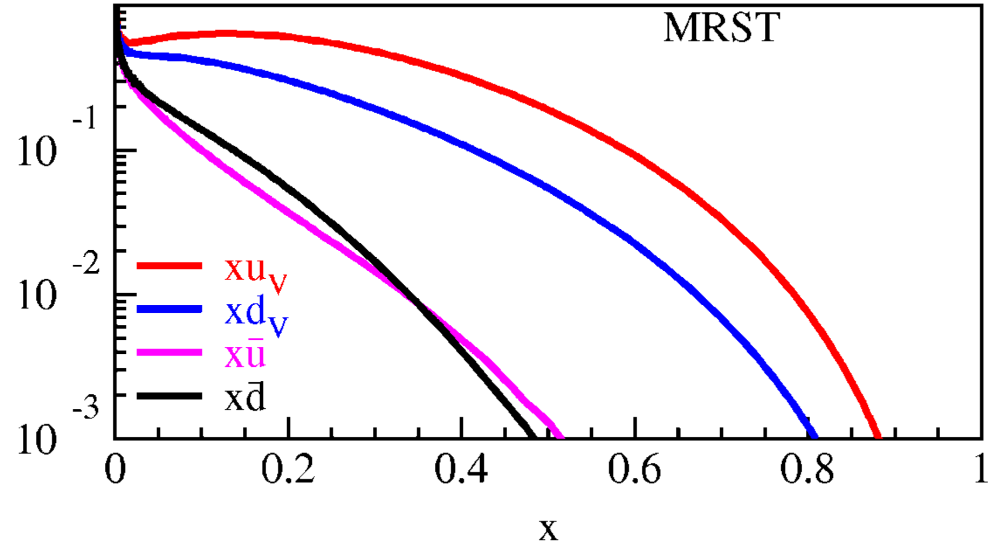
$$\bar{d} > \bar{u} \text{ at } x = 0.18$$





Drell-Yan Cross Section

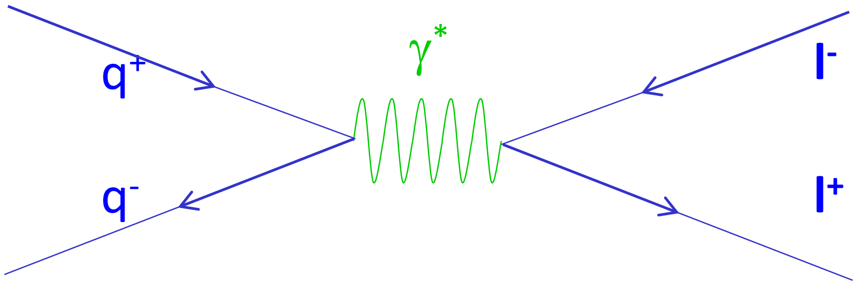


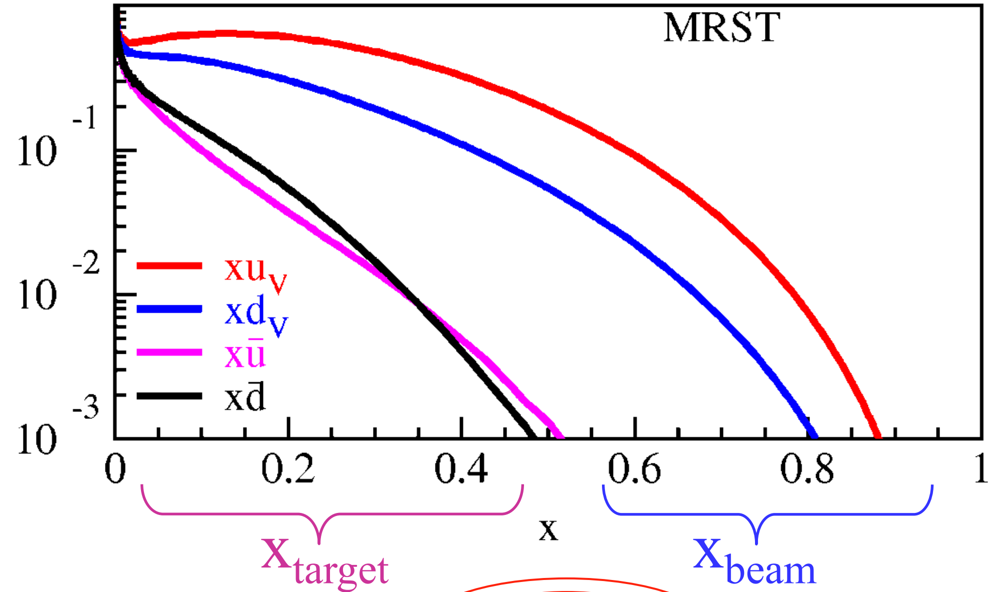


- Cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_{\rm b}dx_{\rm t}} = \frac{4\pi\alpha^2}{x_{\rm b}x_{\rm t}s} \sum_{q\in\{u,d,s,\dots\}} e_q^2 \left[\bar{q}_{\rm t}(x_{\rm t})q_{\rm b}(x_{\rm b}) + \bar{q}_{\rm b}(x_{\rm b})q_{\rm t}(x_{\rm t})\right]$$

Drell-Yan Cross Section





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$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s}\sum_{q\in\{u,d,s,\dots\}} e_q^2\left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \cancel{\bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})}\right]$$

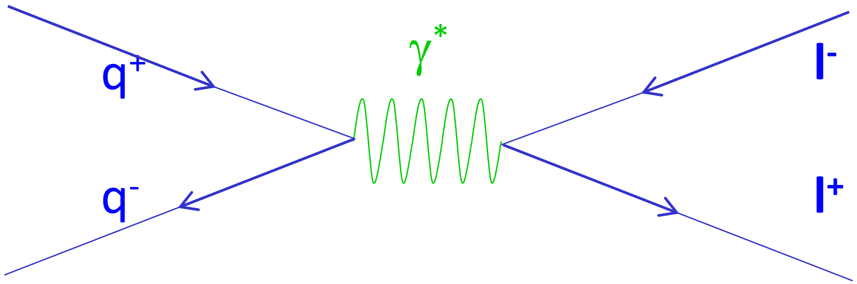
Acceptance limited

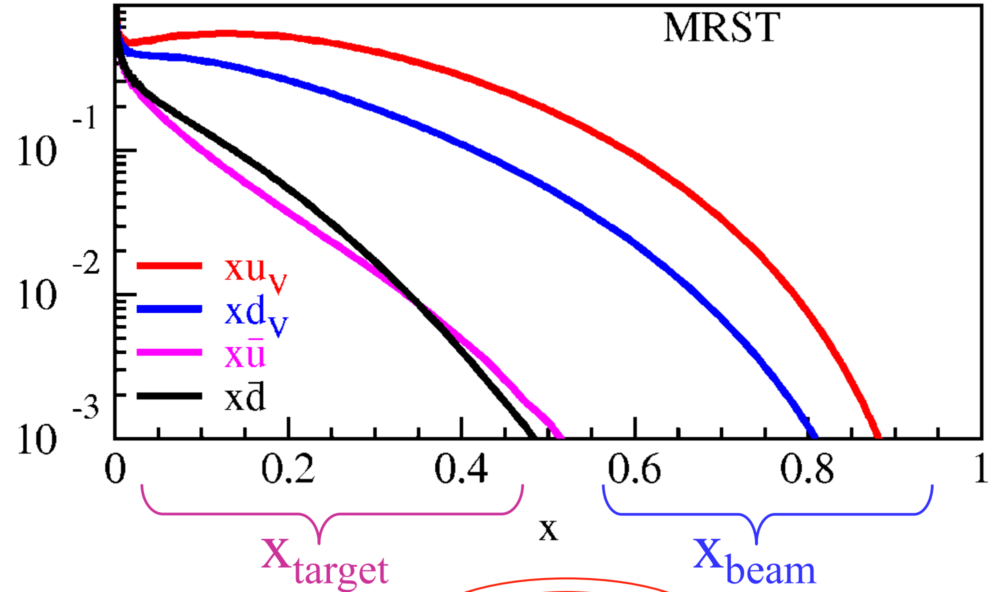
(Fixed Target, Hadron Beam)

- u-quark dominance
  $(2/3)^2$ vs. $(1/3)^2$

Beam	Sensitivity	Experiment
Hadron	Beam quarks target antiquarks	Fermilab, J-PARC RHIC (forward acpt.)
Anti-Hadron	Beam antiquarks Target quarks	J-PARC, GSI-FAIR Fermilab Collider
Meson	Beam antiquarks Target quarks	COMPASS, J-PARC

Drell-Yan Cross Section





- Cross section is a convolution of beam and target parton distributions

$$\frac{d^2\sigma}{dx_{\mathrm{b}}dx_{\mathrm{t}}} = \frac{4\pi\alpha^2}{x_{\mathrm{b}}x_{\mathrm{t}}s} \sum_{q\in\{u,d,s,\ldots\}} e_q^2 \left[\bar{q}_{\mathrm{t}}(x_{\mathrm{t}})q_{\mathrm{b}}(x_{\mathrm{b}}) + \cancel{\bar{q}_{\mathrm{b}}(x_{\mathrm{b}})q_{\mathrm{t}}(x_{\mathrm{t}})}\right]$$

Acceptance limited

(Fixed Target, Hadron Beam)

- u-quark dominance

  $(2/3)^2$ vs. $(1/3)^2$

$$\frac{\sigma^{\mathrm{pd}}}{2\sigma^{\mathrm{pp}}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right]$$

Light Antiquark Flavor Asymmetry: Brief History

- Naïve Assumption:

$$\bar{d}(x) = \bar{u}(x)$$

- NMC (Gottfried Sum Rule)

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx \neq 0$$

- NA51 (Drell-Yan)

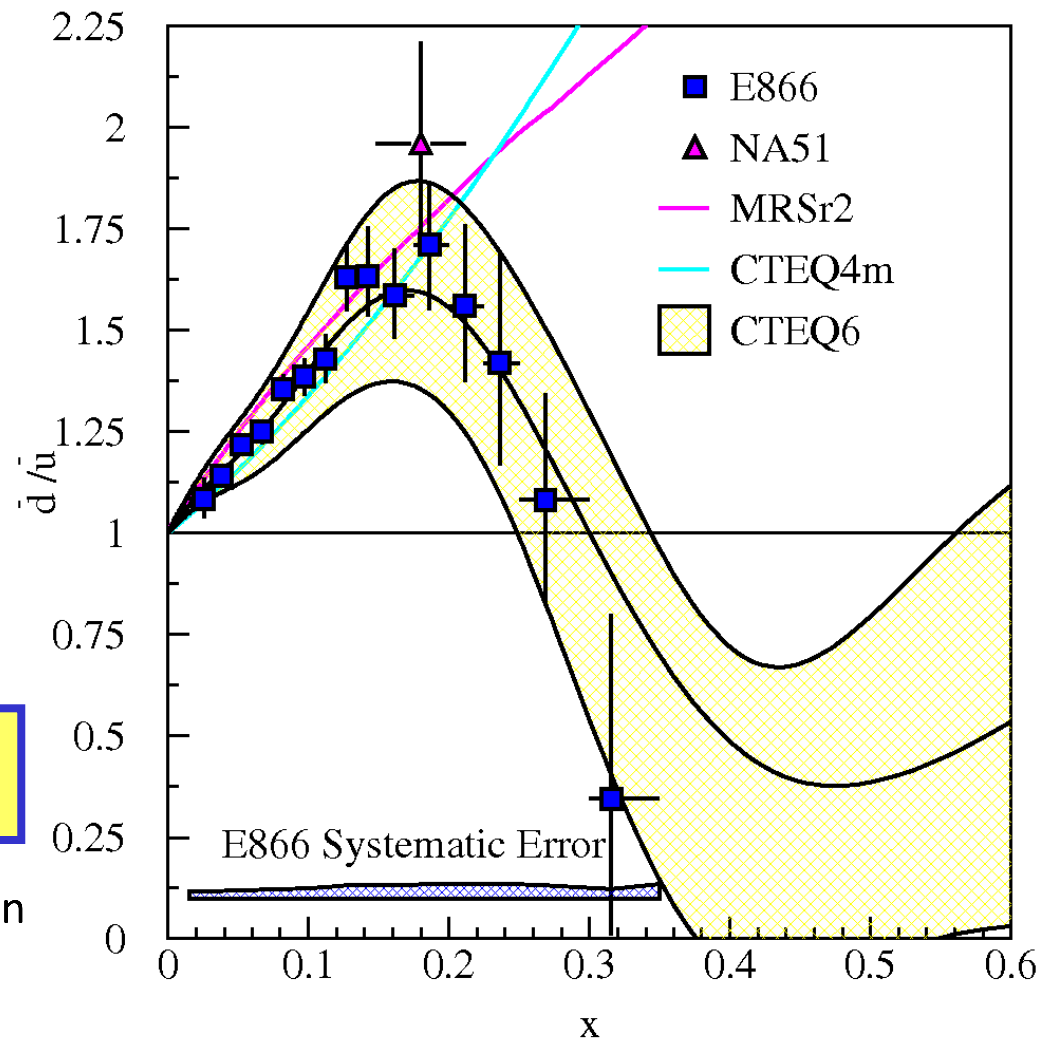
$$\bar{d} > \bar{u} \text{ at } x = 0.18$$

- E866/NuSea (Drell-Yan)

$$\bar{d}(x)/\bar{u}(x) \text{ for } 0.015 \leq x \leq 0.35$$

- Knowledge of sea dist. are data driven
  - Sea quark distributions are difficult for Lattice QCD

- Non perturbative QCD models can explain excess d-bar quarks, but not return to symmetry or deficit of d-bar quarks



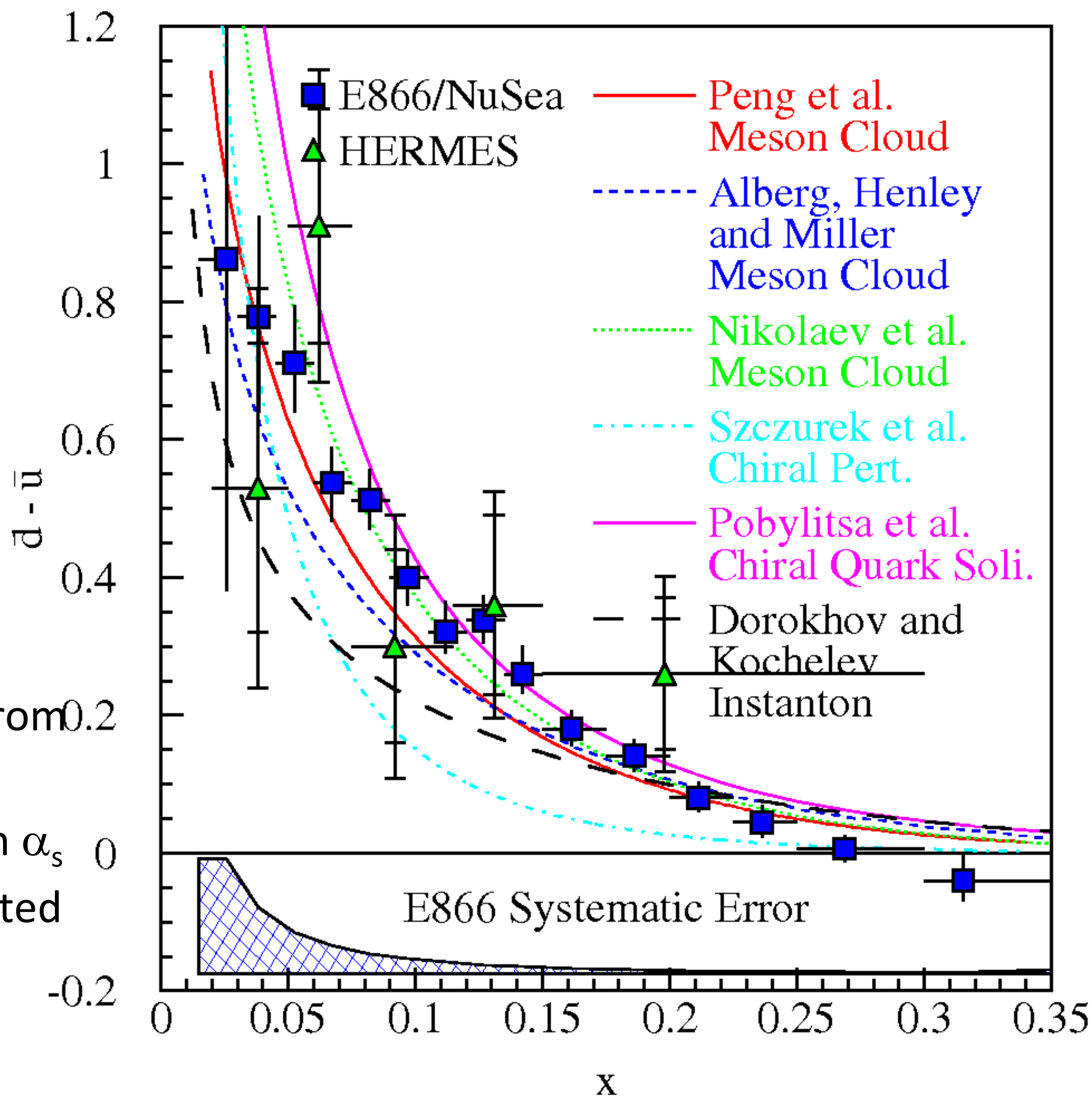
Proton Structure: By What Process Is the Sea Created?

- There is a gluon splitting component which is symmetric

$$\bar{d}(x) = \bar{d}_{\text{pQCD}}(x) + \bar{d}_{\pi}(x)$$
$$\bar{u}(x) = \bar{u}_{\text{pQCD}}(x) + \bar{u}_{\pi}(x)$$

$$\bar{q}_{\text{pQCD}}(x) = \bar{d}_{\text{pQCD}}(x) = \bar{u}_{\text{pQCD}}(x)$$

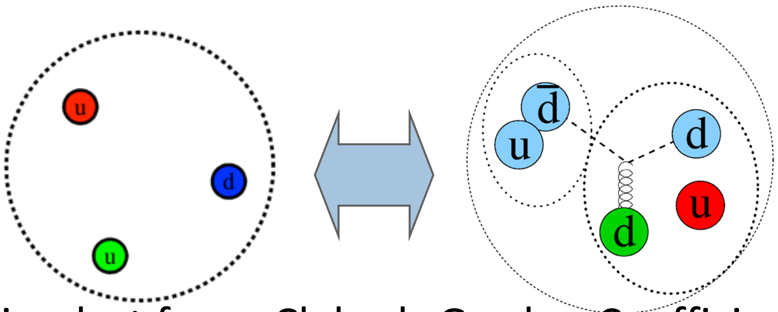
- $\bar{d}(x) - \bar{u}(x)$
  - Symmetric sea via pair production from gluons subtracts away
  - No Gluon contribution at 1st order in α_s
  - Nonperturbative models are motivated by the observed difference



Non-perturbative Models: Pion Cloud

- Meson Cloud in the nucleon Sullivan process in DIS

$$|p\rangle = |p_0\rangle + \alpha|N\pi\rangle + \beta|\Delta\pi\rangle + \gamma|\Lambda K\rangle + \ldots$$



- In its simplest form, Clebsch-Gordon Coefficients and πN, πΛ couplings

$$\bullet\ \alpha: \quad |N\pi\rangle = \begin{cases} |p,\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |n,\pi^+\rangle & u\bar{d} & \sqrt{\frac{2}{3}} \end{cases}$$

$$\bullet\ \beta: \quad |\Delta\pi\rangle = \begin{cases} |\Delta^{++},\pi^-\rangle & d\bar{u} & \sqrt{\frac{1}{2}} \\ |\Delta^{+},\pi^0\rangle & \frac{u\bar{u}+d\bar{d}}{2} & -\sqrt{\frac{1}{3}} \\ |\Delta^{0},\pi^+\rangle & u\bar{d} & \sqrt{\frac{1}{6}} \end{cases}$$

- Predicts

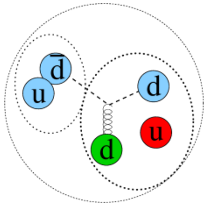
$$\bar{d} \geq \bar{u}$$

- Cannot have

$$\bar{d} \leq \bar{u}$$

Models Relate Antiquark Flavor Asymmetry and Spin

- Meson Cloud in the nucleon—Sullivan process in DIS



$$|p\rangle = (1 - a - b)\,|p_0\rangle + a|N\pi\rangle + b|\Delta\pi\rangle$$

Antiquarks in spin 0 object → No net spin

- Chiral Quark models—effective Lagrangians

$$\langle q|\bar{q}\rangle = \left[1 - \frac{3a}{2}\right]\langle q|\bar{q}\rangle + \frac{3a}{2}\langle q\pi|\bar{q}\pi\rangle$$

$$\int_0^1 \left[\bar{d}(x) - \bar{u}(x)\right] dx = \frac{2a}{3} \qquad g_A = \int_0^1 \left[\Delta u(x) - \Delta d(x)\right] dx = \frac{5}{3}3a$$

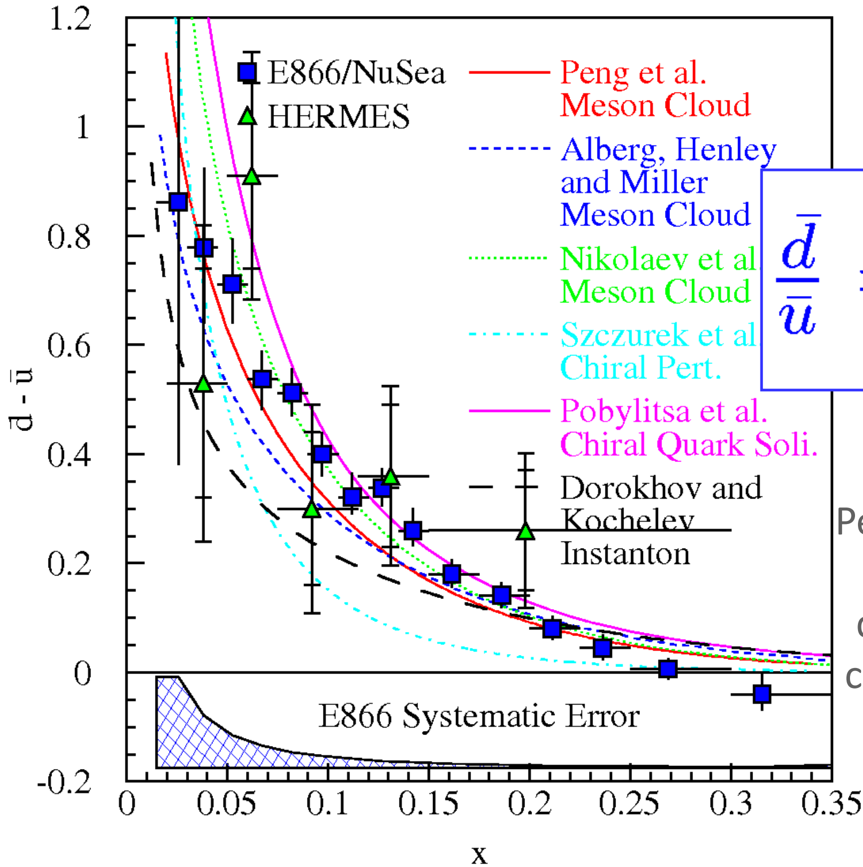
- Instantons

$$\mathcal{L} \propto \bar{u}_R u_L \bar{d}_R d_L + \bar{u}_L u_R \bar{d}_L d_R \qquad \bar{d}_I(x) - \bar{u}_I(x) = \frac{5}{3}\left[\Delta u_I(x) - \Delta d_I(x)\right]$$

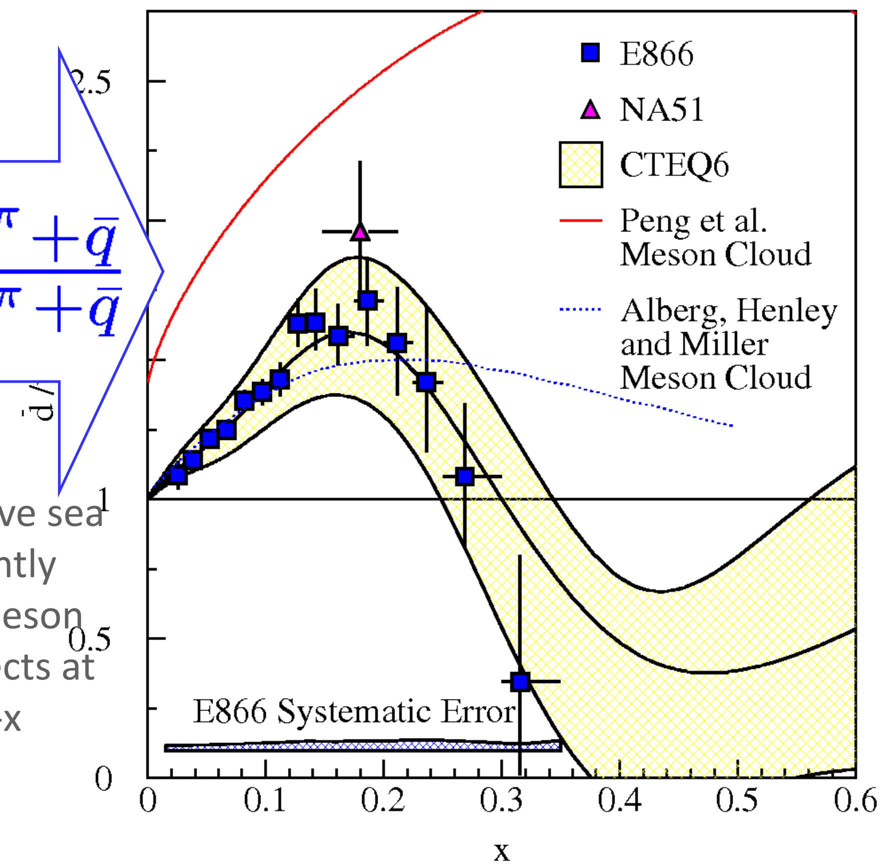
- Statistical Parton Distributions

$$\bar{d}(x) - \bar{u}(x) = \Delta\bar{u}(x) - \Delta\bar{d}(x)$$

Proton Structure: By What Process Is the Sea Created?



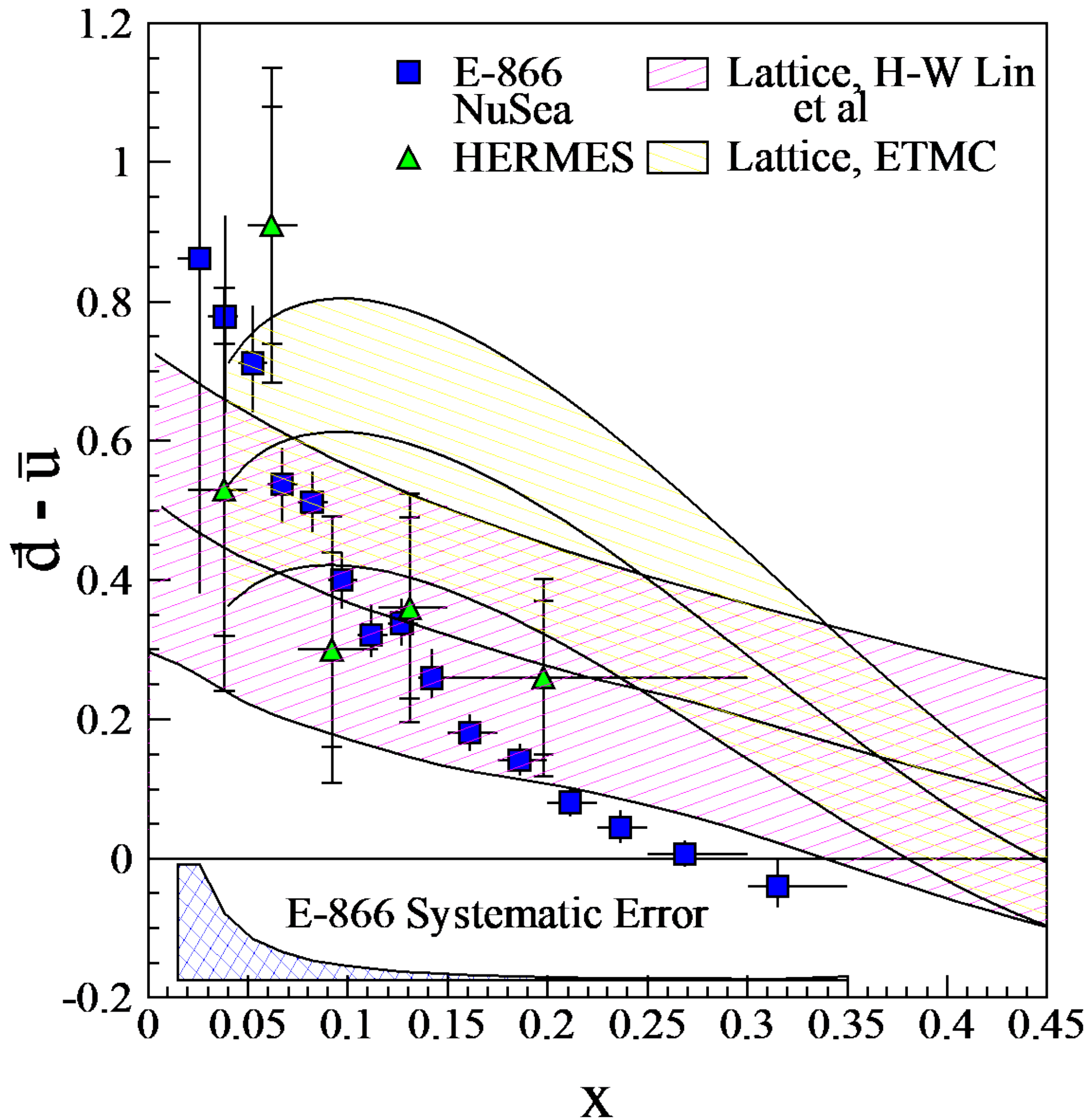
$$\frac{\bar{d}}{\bar{u}} = \frac{\bar{d}^{\pi} + \bar{q}}{\bar{u}^{\pi} + \bar{q}}$$



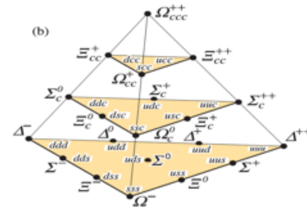
Perturbative sea apparently dilutes meson cloud effects at large-x

Proton Structure: By What Process Is the Sea Created?

- Lattice weighs in!!
- Only non perturbative parts



Conclusions



1. Physicists seek organization and order
2. The quark model can explain many of the properties of the observed hadronic spectra.
3. Elastic scattering shows that the proton is not a point particle

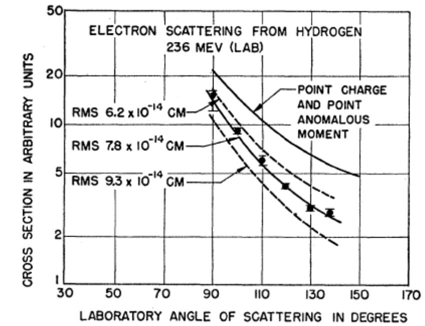


FIG. 6. This figure shows the experimental points at 236 Mev and the attempts to fit the shape of the experimental curve. The best fit lies near 0.78×10^{-13} cm.

4. **Richard Feynman was a genius.**
   - Hadron-hadron scattering is a collision of many point-like particles (partons)
   - Each parton carries a fraction of the hadron's momentum
   - Parton distributions can be described in terms of a probability distribution of a parton existing with momentum fraction in [x, x+dx]
5. Deep Inelastic Scattering cam be described in terms of a summation over point-like scattering from partons.
6. Parton distributions may be extracted from hard scattering data.
   - Generally requires data from multiple measurements
   - Care must be taken to avoid false assumptions

$$F_2^{\mu p}(x) \propto \sum_{q\in\{u,d,\dots\}} e_q^2 x\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$F_2^{\nu p}(x) + F_2^{\nu n} \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2)+\bar{q}(x,Q^2)\right]$$

$$xF_3^{\nu N}(x) \propto \sum_{q\in\{u,d,\dots\}} x\left[q(x,Q^2)-\bar{q}(x,Q^2)\right]$$

Becky is now Happy!