50th Anniversary of the the Discovery of Quarks at the Stanford Linear Accelerator Center

1969-1973

Nobel Prize Physics 1990

Arie Bodek, George E. Pake Professor of Physics

The University of Rochester, Rochester, New York, USA

Public lecture

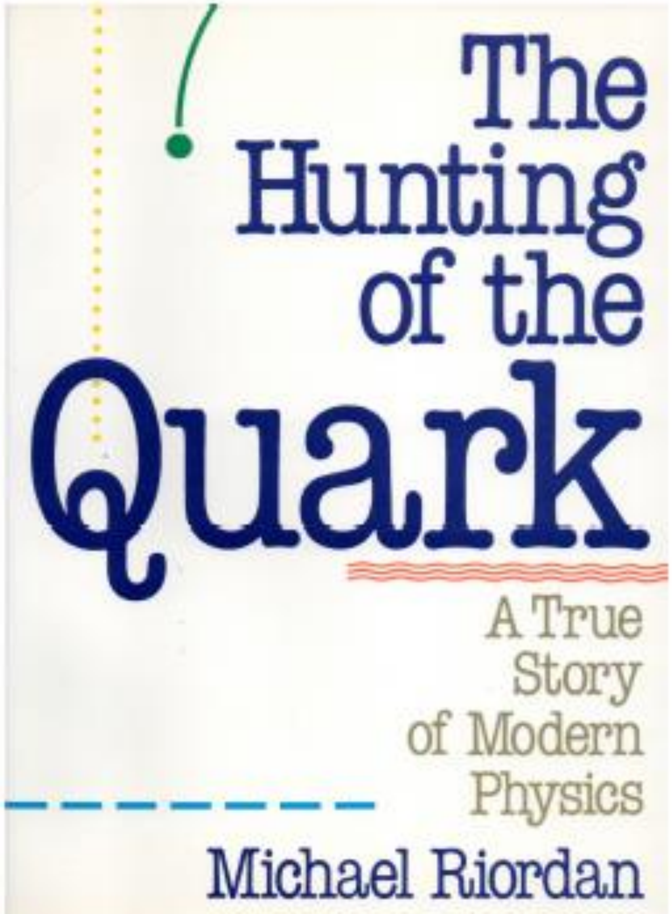
Orthodox Academy of Greece, Kolympari, Crete

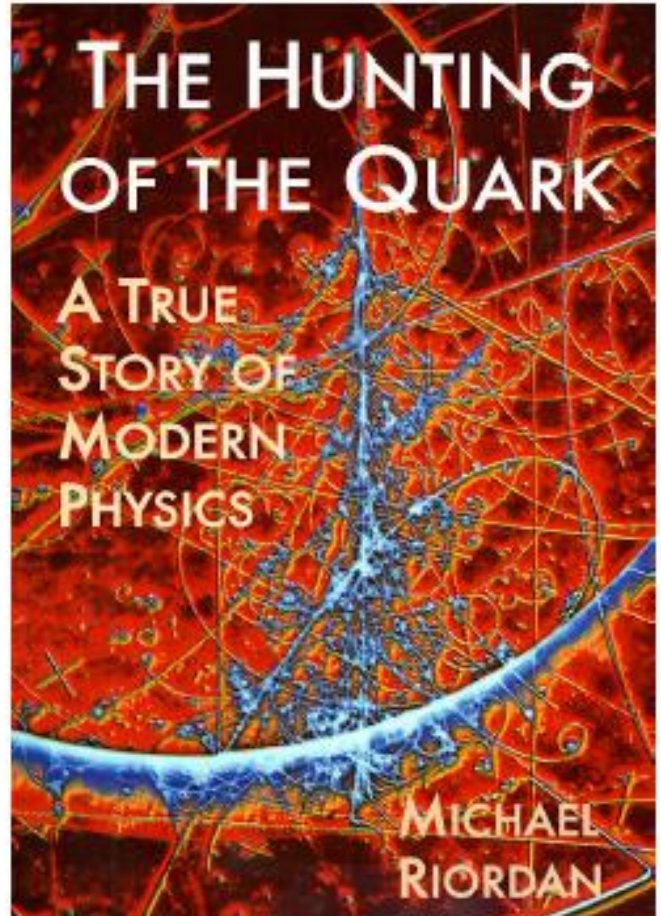
Hix 2019

Tuesday, August 20th

20:30 – 21:15

Simon & Schuster, 1987 **Plunkett Lake Press, 2018**





Arie Bodek George E. Pake Professor of Physics UNIVERSITY OF ROCHESTER

- *MIT 1968 BS Physics, MIT PhD 1972 --Discovery of the light quarks at the Stanford Linear Accelerator Center (SLAC), MIT-SLAC collaboration 1969-1972 - Nobel Prize 1990*

I am fortunate to have participated in the three most significant discoveries in particle physics in the past 50 years, starting with the discovery of the up and down quarks which are the constituents of the proton and the neutron.

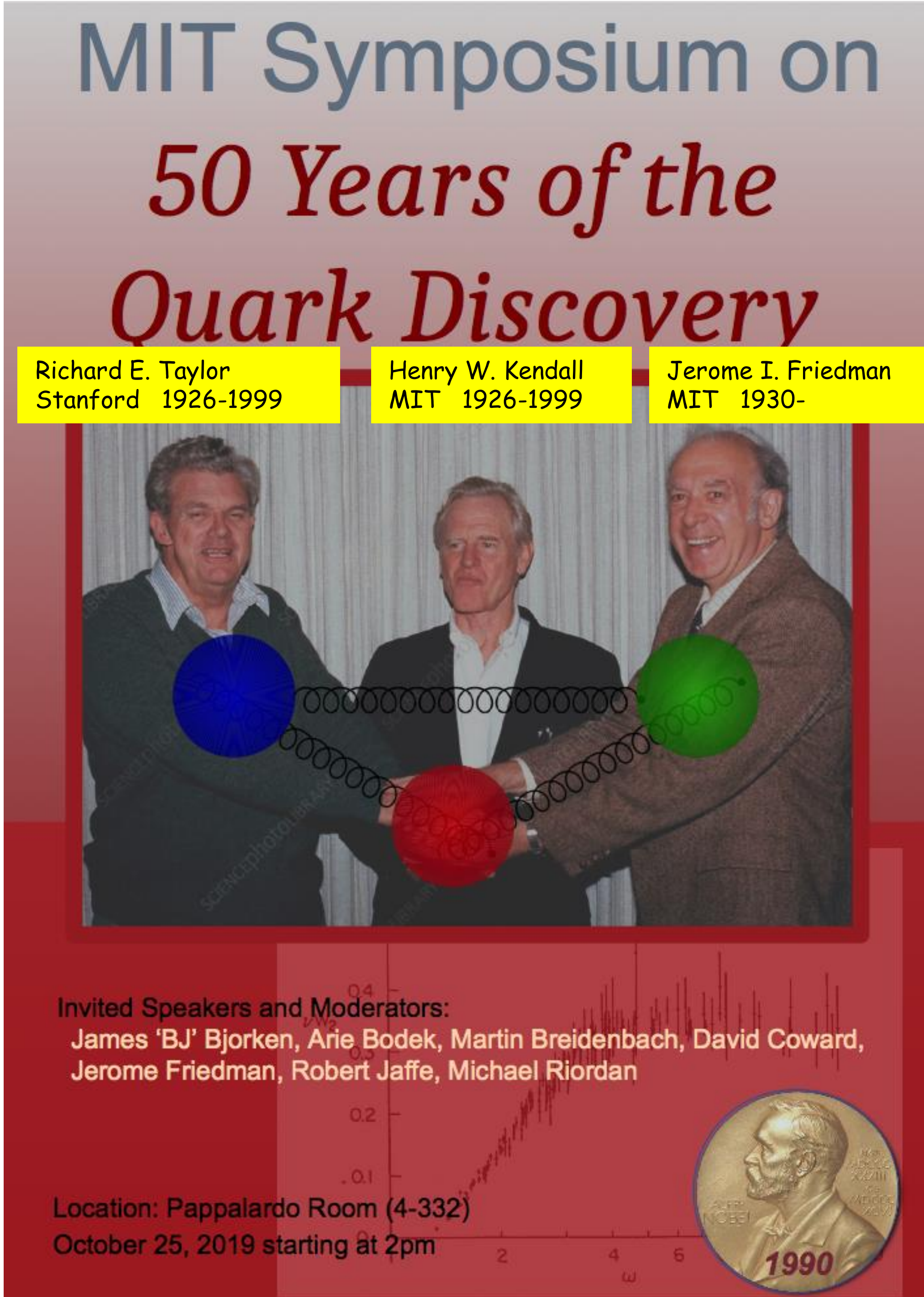
Arie Bodek George E. Pake Professor of Physics UNIVERSITY OF ROCHESTER

- *MIT 1968 BS Physics, MIT PhD 1972 --Discovery of the light quarks, MIT-SLAC collaboration 1969-1972 (25 people) - Nobel Prize 1990*

- *Participated in the Discovery of the Top quark (the heaviest quark), CDF collaboration (400 people) Fermilab- 1995 (2019 European Physical Society Prize to the members of the CDF collaboration)*

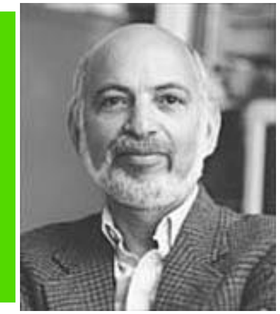
- *Participated in the discovery of the Higgs Boson – CMS Collaboration(2000 people) Large Hadron Collider at CERN (Geneva) - 2012 (2013 European Physical Society Prize to the members of the CMS collaboration)*

- *Continued working on structure of nucleon: Received the 2004 American Physical Society Panofsky Prize in Experimental Particle Physics for: "broad, sustained, and insightful contributions to elucidating the structure of the nucleon"*



Martin Briedenbach
(SLAC) Grad MIT
Partons

APS Panofsky prize
picture 2000
SLAC linear collider

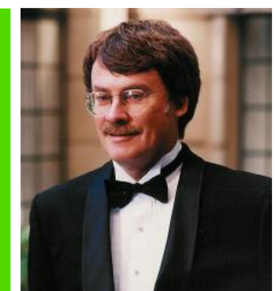


Arie Bodek (Rochester)
Grad MIT
Quark charge.

APS Panofsky Prize
picture 2004
Structure of nucleon

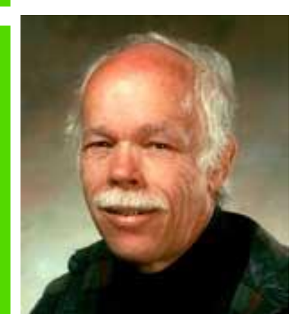
Michael Riordan
Grad MIT
Quark spin

Author :Hunting of the
Quark - 1987
AIP Gemant Science
writing award 2002.

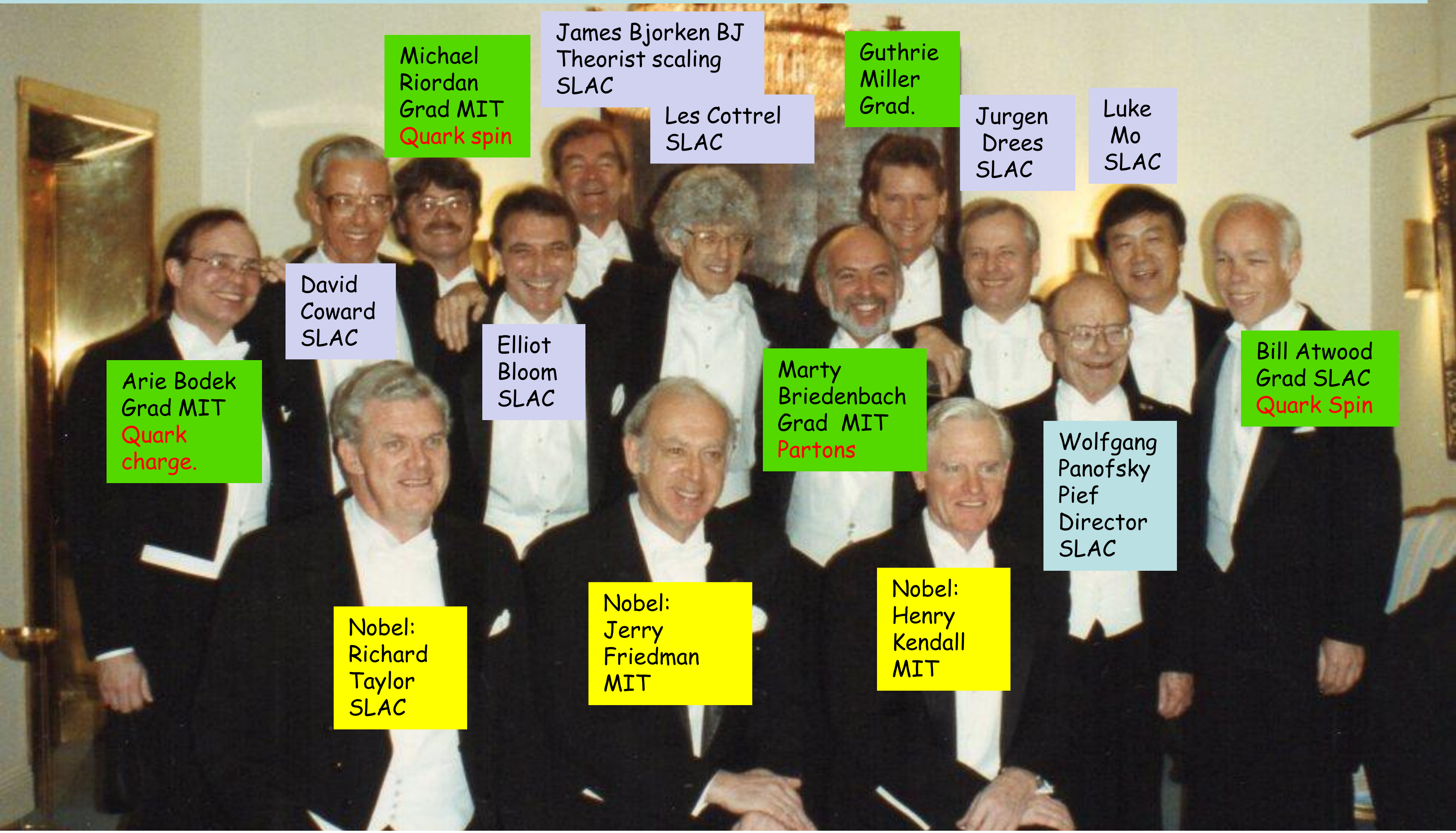


William Atwood
Santa Cruz) Grad
SLAC
Quark Spin

APS Panofsky Prize
picture 2012
Gamma Ray Astrnomy



Nobel 1990: "for pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics.



Left to Right: Front Row - Prize winners: Richard Taylor, Jerome Fiedman, Henry Kendal; Middle Row - Arie Bodek, Dave Coward, Elliot Bloom, Les Cottrell, Marty Breidenbach, Jurgen Drees, Luke Mo, Bill Atwood; Back Row - Ed Riordan, BJ Bjorken, Guthrie Miller. Missing Hobey DeStaebler

Dinner for 1500 guests

https://www.nobelprize.org/ceremonies/menus-at-the-nobel-banquet

Nobel Banquet Menu 1990

Timbale de perdix de neige
sur lit de salade à la Raineri
Sauce aux herbes, croissant Nobel

Omble-chevalier suédois
grillé à la genièvre avec asperge beurrée
Crème à l´aneth et riz

Parfait Glace Nobel
Petits fours
VINS

Moët & Chandon, Brut Impérial
1988 Château de Cruzeau
Grådask Very Old Superior
Vin sans alcool – St Regis
Eau minérale Ramlösa
Café

BUFFET
Absolut Vodka
Petite Liqueur par Moët & Chandon
Johnnie Walker Red & Black Label
Ron Bacardi
Gordon´s Gin
Hennessy V.S.
Boissons de Pripps

Stadshuskallaren, Stockholm - Kungsholmen - Menu, Prices ...
www.tripadvisor.com/Restaurant_Review-g189852-d...

If you're curious to know what's been served at the Nobel Prize banquets down the years, then you should head for Stadshusk llaren

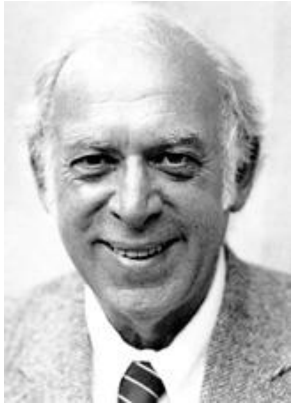
a restaurant in the basement of Stockholm town hall, which hosts the annual ceremony.

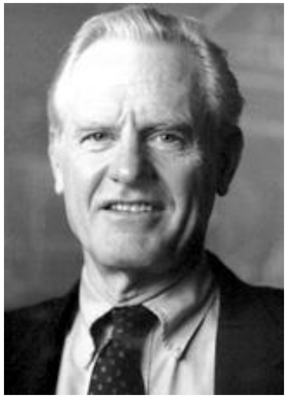
You can choose between any the Nobel menus since 1901.

https://www.nobelprize.org/ceremonies/menus-at-the-nobel-banquet

My trip to Stockholm 1991

My two PhD advisors





Jerome I. Friedman (MIT) 1930-

Henry W. Kendall (MIT) 1926-1999

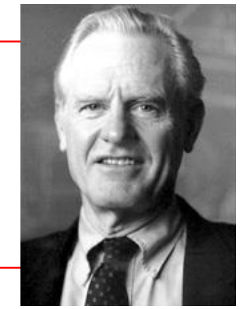
Richard E. Taylor (Stanford) 1929-2018

Lost Arrow rock,

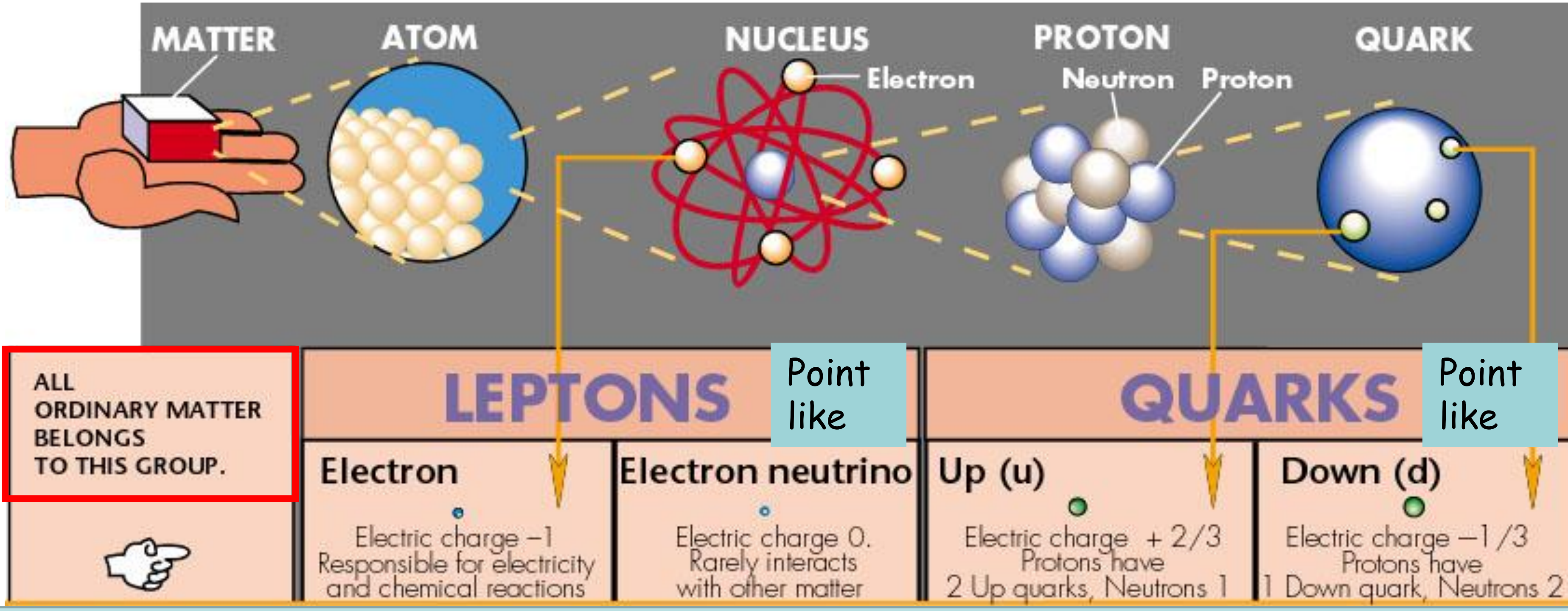
Yosemite Valley National Park,

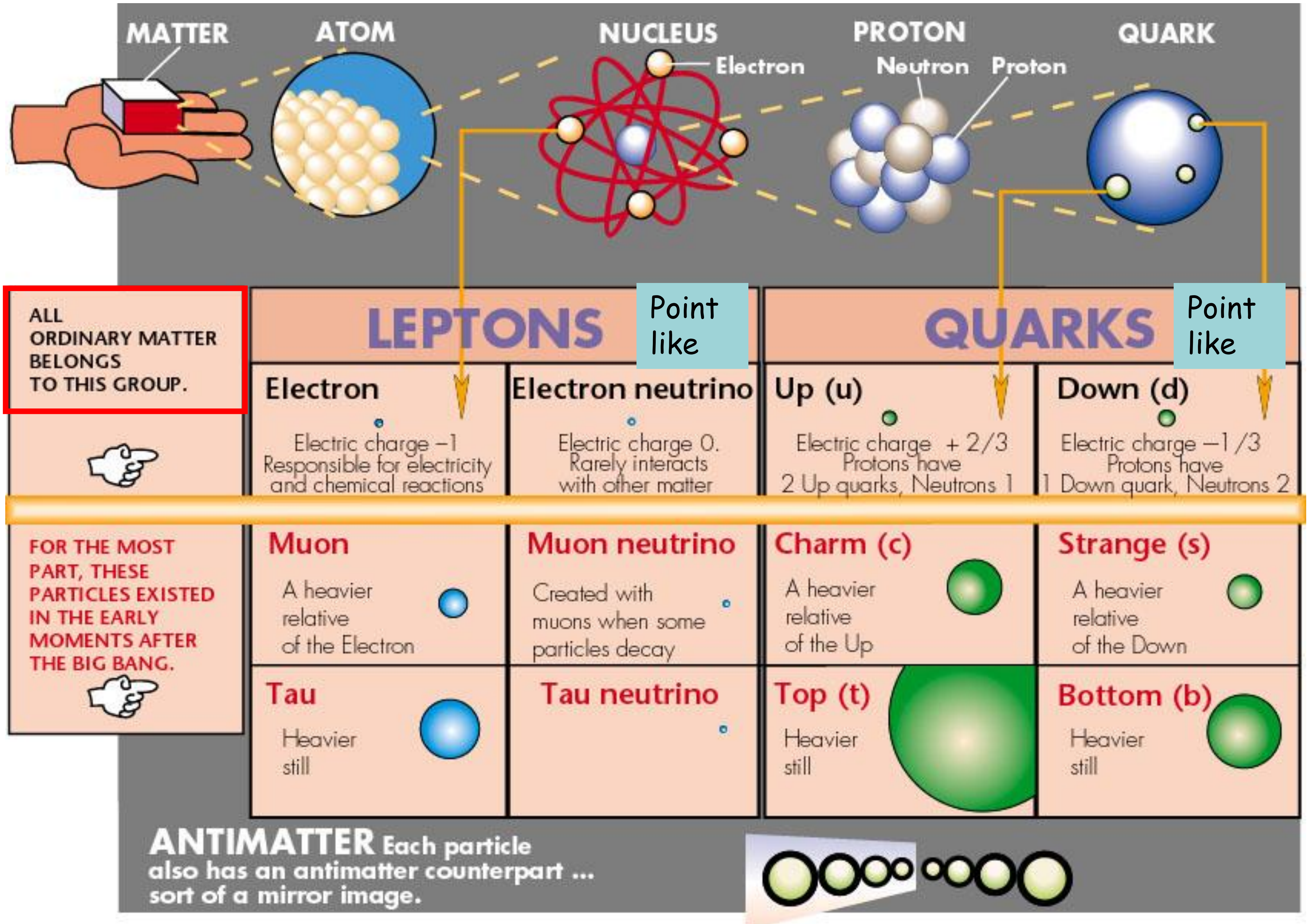
Sierra Nevada Mountains, California

Professor Henry Kendall was the first person to climb lost arrow.



Dr. Kendall accepting the Nobel Prize from the King of Sweden. December 1990


MATTER
ATOM
NUCLEUS
Electron
PROTON
Neutron
Proton
QUARK
ALL ORDINARY MATTER BELONGS TO THIS GROUP.
LEPTONS
Point like
QUARKS
Point like
Electron
Electric charge −1
Responsible for electricity and chemical reactions
Electron neutrino
Electric charge 0.
Rarely interacts with other matter
Up (u)
Electric charge +2/3
Protons have 2 Up quarks, Neutrons 1
Down (d)
Electric charge −1/3
Protons have 1 Down quark, Neutrons 2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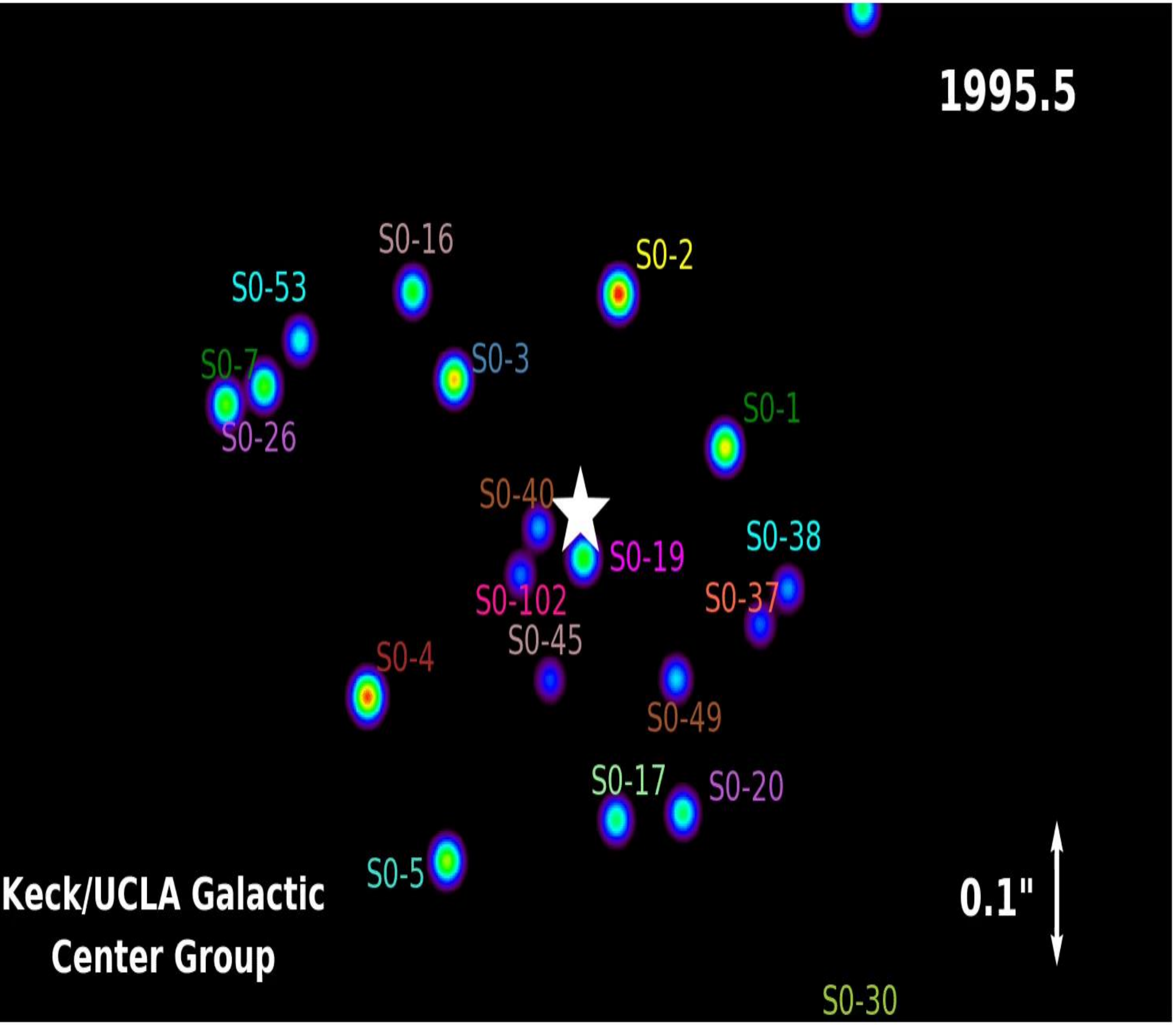
Down (d)
Electric charge −1/3
Protons have 1 Down quark, Neutrons 2
FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.
Muon
A heavier relative of the Electron
Muon neutrino
Created with muons when some particles decay
Charm (c)
A heavier relative of the Up
Strange (s)
A heavier relative of the Down
Tau
Heavier still
Tau neutrino
Top (t)
Heavier still
Bottom (b)
Heavier still
ANTIMATTER Each particle also has an antimatter counterpart ... sort of a mirror image.

How do we study an object that we cannot see?

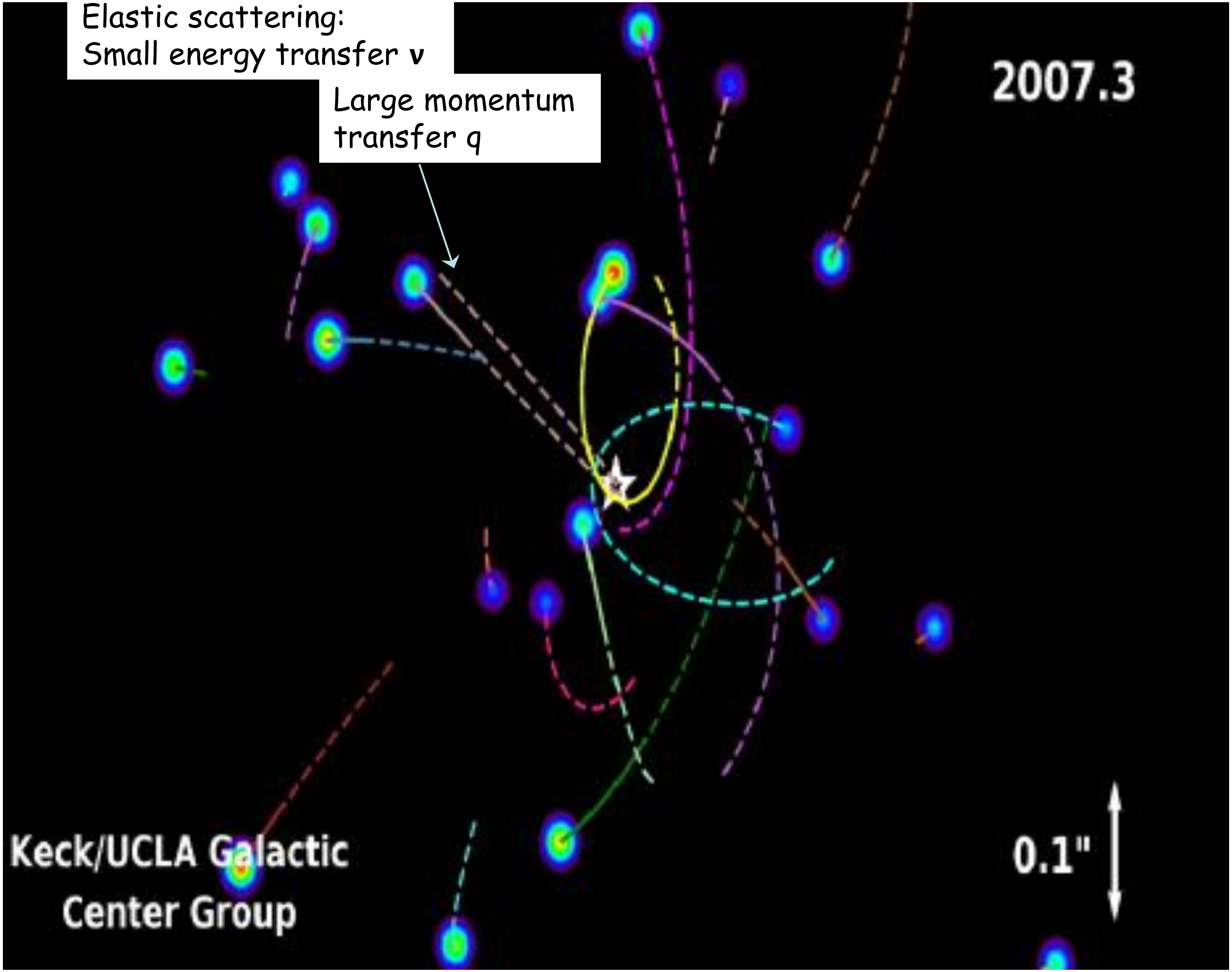
Science is fascination: Looking at a black hole



Follow the stars in the center of the galaxy over a period of 15 years 1995-2011.

A black hole with a mass of several million suns was discovered in the center of the galaxy

http://www.astro.ucla.edu/~ghezgroup/gc/animations.html

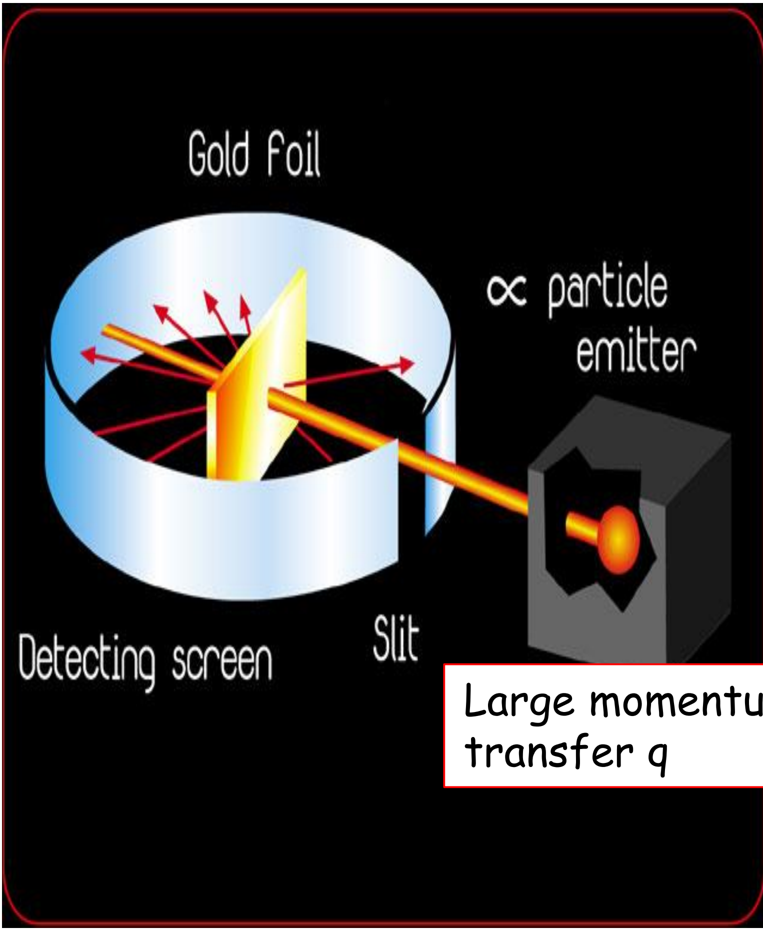

Elastic scattering:
Small energy transfer ν
Large momentum transfer q
2007.3
Keck/UCLA Galactic Center Group
0.1"

Rutherford Experiment – 1911 Discovery of the atomic nucleus-

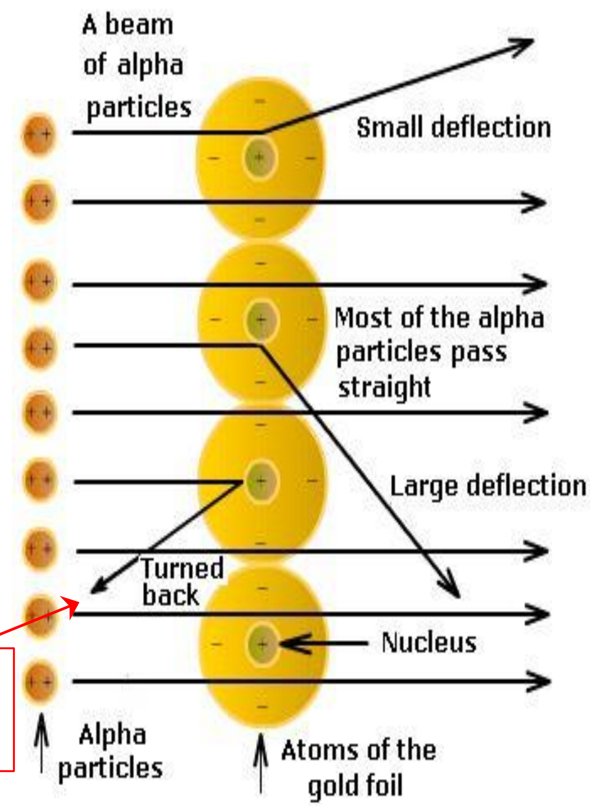
Lord Rutherford and two graduate students

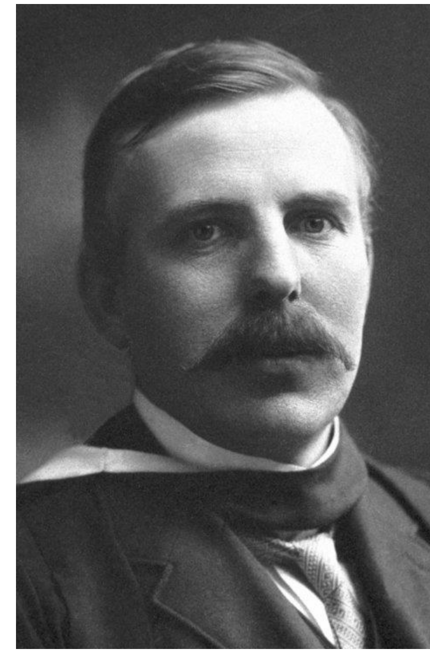
The nucleus is 100,000 times smaller than an atom. .

Elastic scattering:
small energy transfer ν



Large momentum transfer q





1871-1937

Atom is mostly empty space

The *Nobel Prize* in Chemistry 1908 was awarded to Ernest *Rutherford* "for his investigations into the disintegration of the elements, and the chemistry of radioactive substances."

Rutherford Experiment: Nuclear Atom

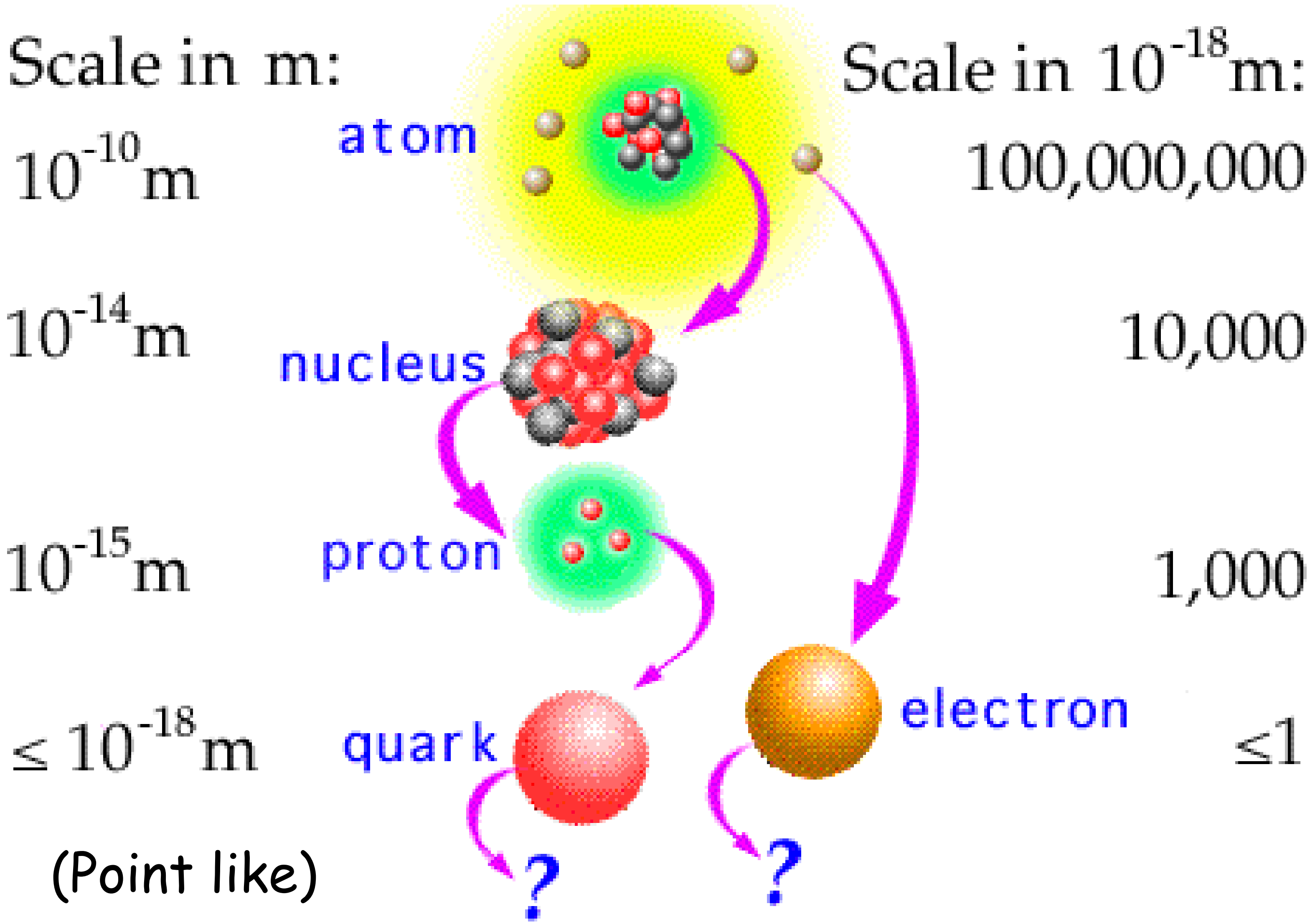
Robert Hofstadter

1915-1990

Nobel 1961: for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons"

Rutherford's alpha particles had energies of a few MeV. They scattered elastically. They made it inside the atom, but could not penetrate the inside the nucleus or proton.

Later electron elastic-scattering experiments in the 1950's had energies of several hundred MeV. They could get inside the proton, and it was determined that the proton had a radius of about 1 femtometer (1 Fermi).

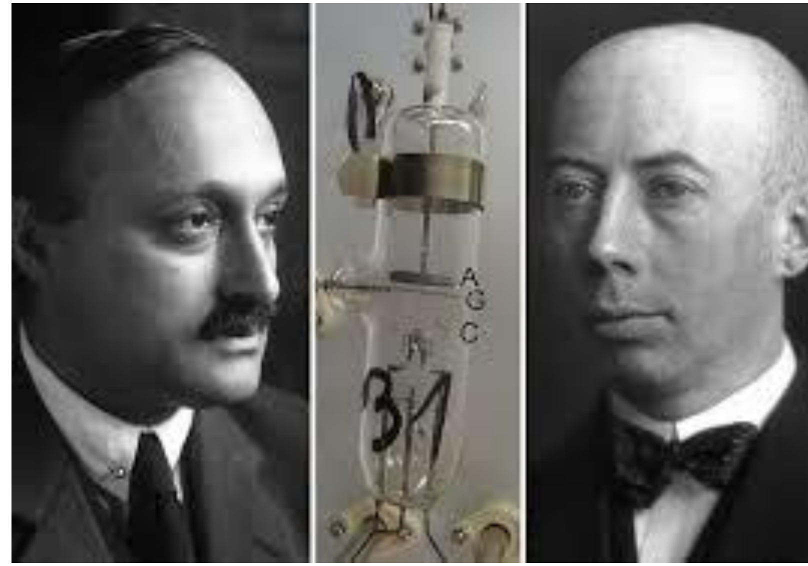


Scale in m:
Scale in 10^{-18}m:
atom
10^{-10}m
100,000,000
nucleus
10^{-14}m
10,000
proton
10^{-15}m
1,000
quark
$\leq 10^{-18}$m
electron
≤ 1
?
?
(Point like)

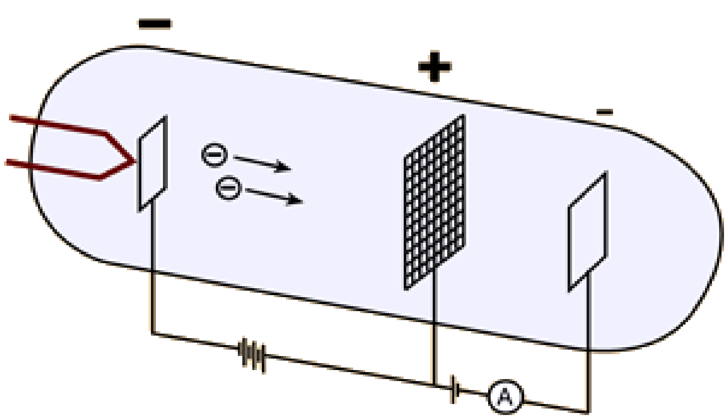
The Franck–Hertz experiment was **the first electrical measurement to clearly show the quantum nature of atoms,** and thus "transformed our understanding of the world". It was presented on April 24, 1914, to the German Physical Society in a paper by James Franck and Gustav Hertz.

The Nobel Prize in Physics 1925 was awarded jointly to James Franck and Gustav Ludwig Hertz "for their discovery of the laws governing the impact of an electron upon an atom."

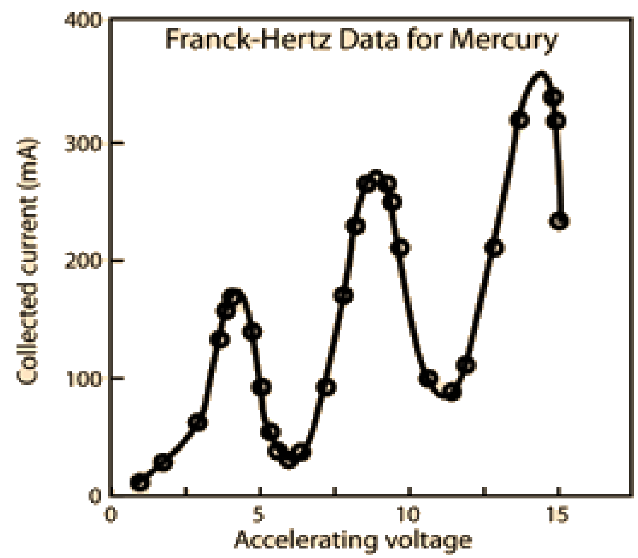
James Franck and Gustav Ludwig Hertz



1882-1964 1887-1975



Accelerating Apparatus



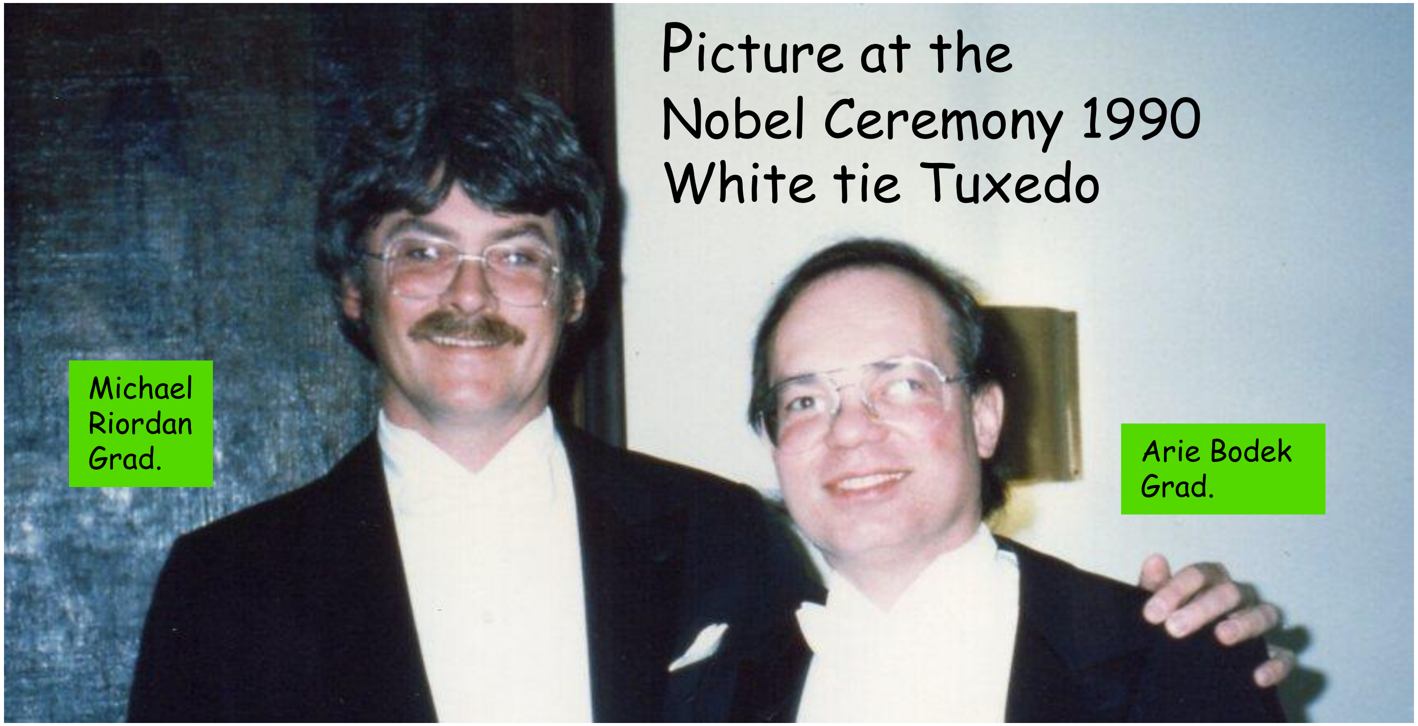
This is a case of inelastic scattering

inelastic scattering: large energy transfer ν

Stanford Linear Accelerator Center (SLAC)

The Early Days at SLAC – Experimental beginnings of the Standard Model

...As seen by an experimentalist graduate student beginning in ~1968



SLAC and the times

Traffic to San Francisco was almost negligible.

The Homebrew Computer Club met at SLAC in the old Panofsky Auditorium. Here Steve Jobs (left) and Steve Wosniak with the Apple 1

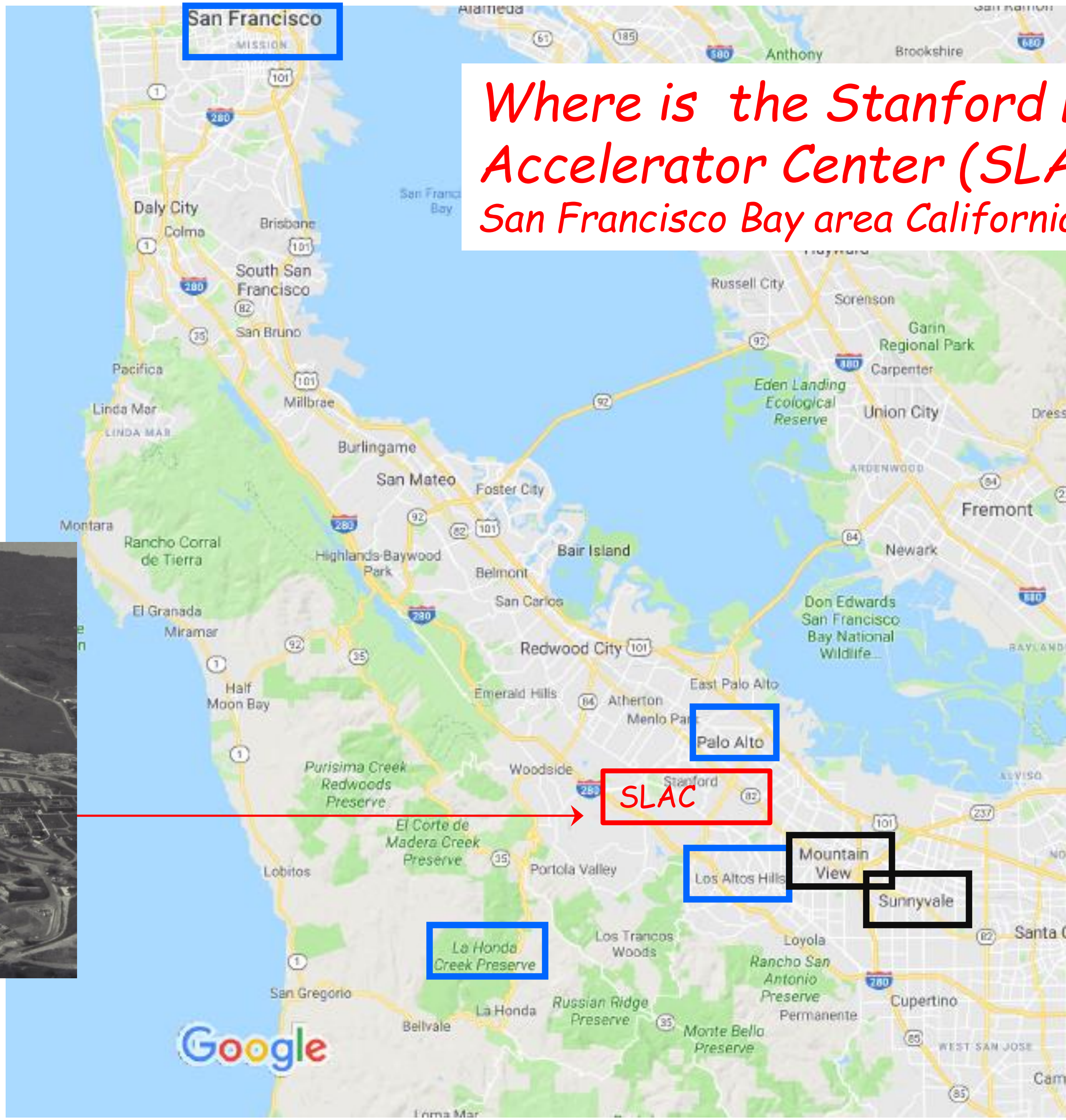
1967 Summer of Love in San Francisco

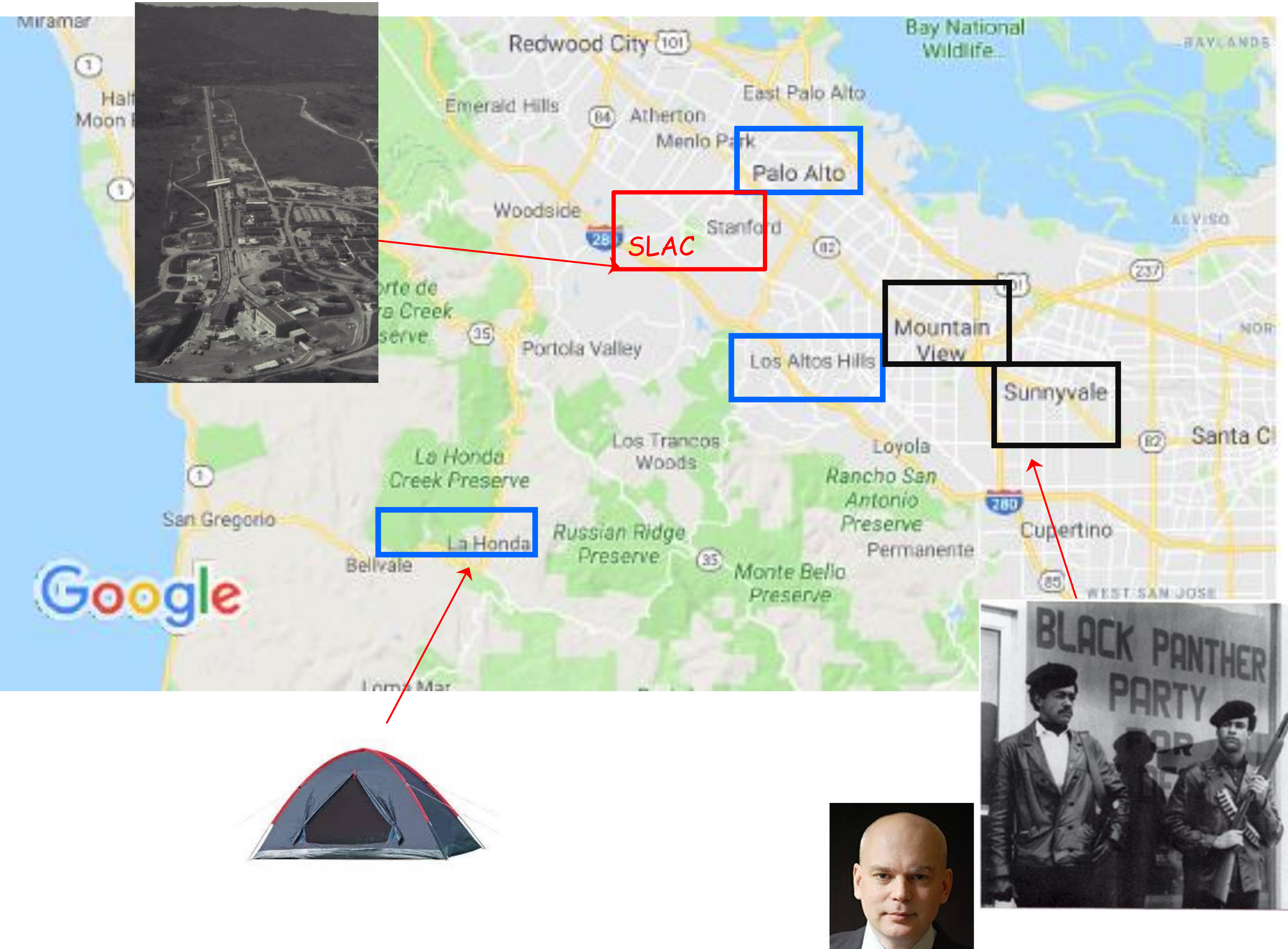
Vietnam War protests.

Black Panther Party founders Bobby Seale and Huey P. Newton

Where is the Stanford Linear Accelerator Center (SLAC)?

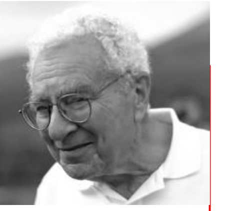
San Francisco Bay area California





Miramar
Half Moon Bay
Redwood City
Bay National Wildlife...
BAYLANDS
Emerald Hills
Atherton
East Palo Alto
Menlo Park
Palo Alto
Woodside
Stanford
SLAC
ALVISO
Purisima Creek Preserve
Portola Valley
Mountain View
Los Altos Hills
Sunnyvale
Santa Cl
Los Trancos Woods
Loyola
La Honda Creek Preserve
Rancho San Antonio Preserve
San Gregorio
Russian Ridge Preserve
Permanente
Cupertino
La Honda
Bellvale
Monte Bello Preserve
WEST SAN JOSE
Loma Mar
Google
BLACK PANTHER PARTY

Murray Gell-Mann
Nobel 1969
Quarks (Caltech)
1929-2019



- Quarks "began" in 1964:
  - Murray Gell-Mann, George Zweig
  - Means of generating "The eightfold Way" – SU(3) symmetry (building up hadrons)
  - Spin ½ and fractional charges worked on hadrons – 3 valence quarks for baryons, quark-anti-quark pair for mesons.
  - Many searches for free quarks – none successful!"
- But little belief in constituent quarks

George Zweigg Sakurai Prize 2015 Aces 1937-
Feyman's PhD student
Caltech

- "Additional data is necessary and welcome in order to destroy the picture of elementary constituents." bj Bjorken – Electron–Photon 67;
- "…we know that ..[mesons and baryons] are mostly, if not entirely, made up out of one another…The probability that a meson consists of a real quark pair rather than two mesons or a baryon and antibaryon must be quite small."

Murray Gell-Mann International Conference in High Energy Physics ICHEP 67

Murray Gell-Mann
Nobel 1969
Quarks (Caltech)
1929-2019

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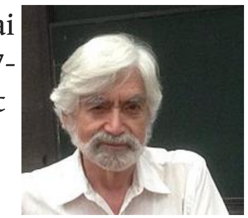

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Murray Gell-Mann International Conference in High Energy Physics ICHEP 67

BUT: NY times July 31, 2019-
………Nobel Prize-winning physicist Murray Gell-Mann, who discovered the quark……..

All known hadronic particles could be described as composed of 3-quraks, or quark-antiquark pairs.

The majority of physicists believed that quarks were not real.

They were assumed to be a convenient mathematical representation.

Why?

- No free quarks were ever seen
  (later solved by asymptotic freedom)

- Quarks has fractional charges - No charges smaller than that of an electron were ever seen.
  (later solved by asymptotic freedon)

- Quarks had spin 1/2. But they violated the Pauli exclusion principle (no two identical particles can occupy the same state at the same time).
  (later solved by a new quantum number –Color)

(Fred-Gillman SLAC theorist told me – Never say that quarks are real particles)

1967

PROPOSAL FOR SPECTROMETER FACILITIES

AT SLAC

presented by

SLAC "Group A"
W. K. H. Panofsky, D. H. Coward,
H. De Staebler, R. E. Taylor

in collaboration with
K. L. Brown, J. Wong,
SLAC

B. Richter, A. Boyarski, F. Bulos,
SLAC, "Group C"

C. Peck, J. Pine,
California Institute of Technology

and

J. I. Friedman, H. W. Kendall,
Massachusetts Institute of Technology.

"The main purpose of the inelastic program at SLAC was to study the electroproduction of resonances as a function of momentum transfer"!!!.

Henry Kendall called it the Frank Hertz experiment of the proton.

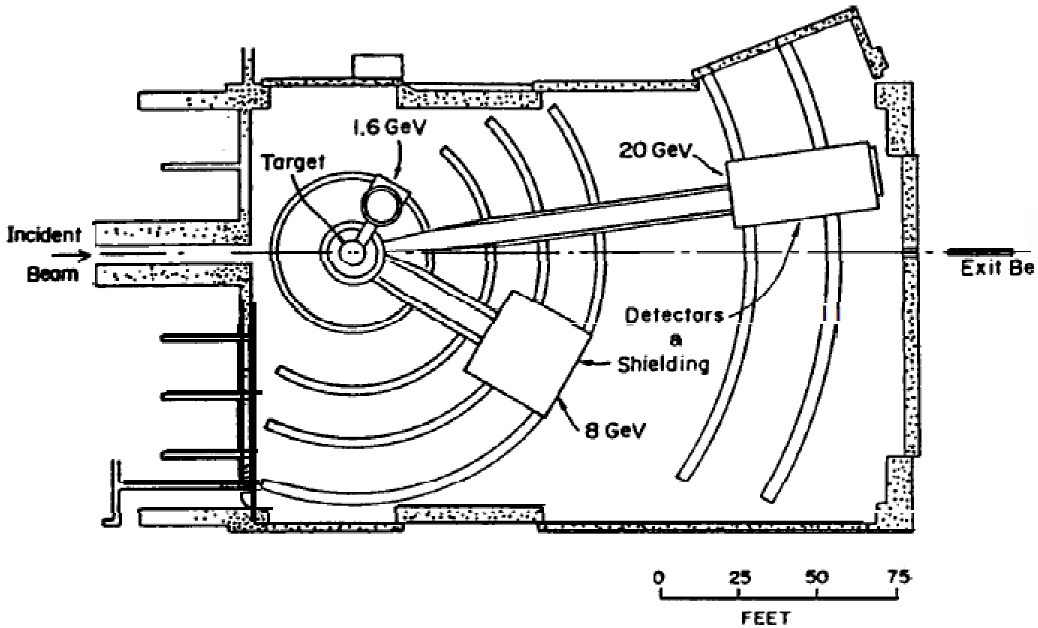
Measure the excited states of the proton. Here large excitation energy means a large increase in mass of the excited proton.

The SLAC beam was 20 GeV

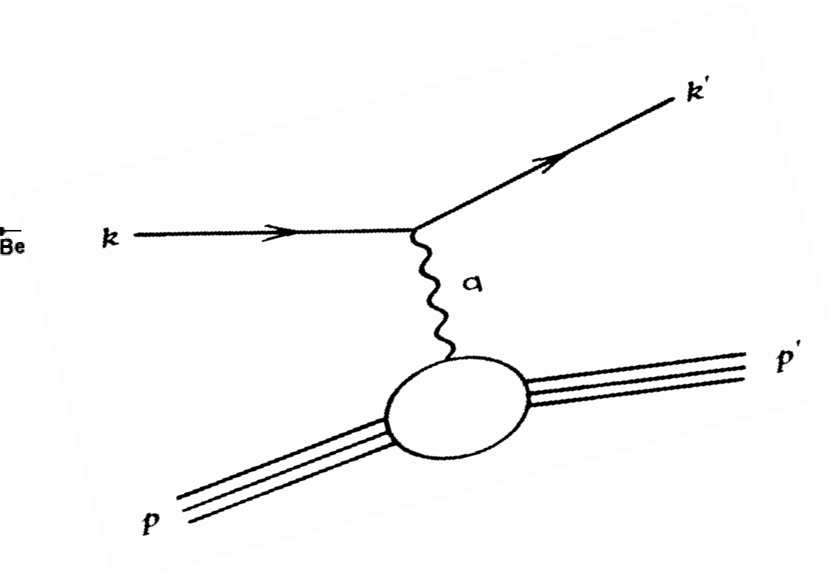
Mass of proton was 1 GeV.

1967

End Station A



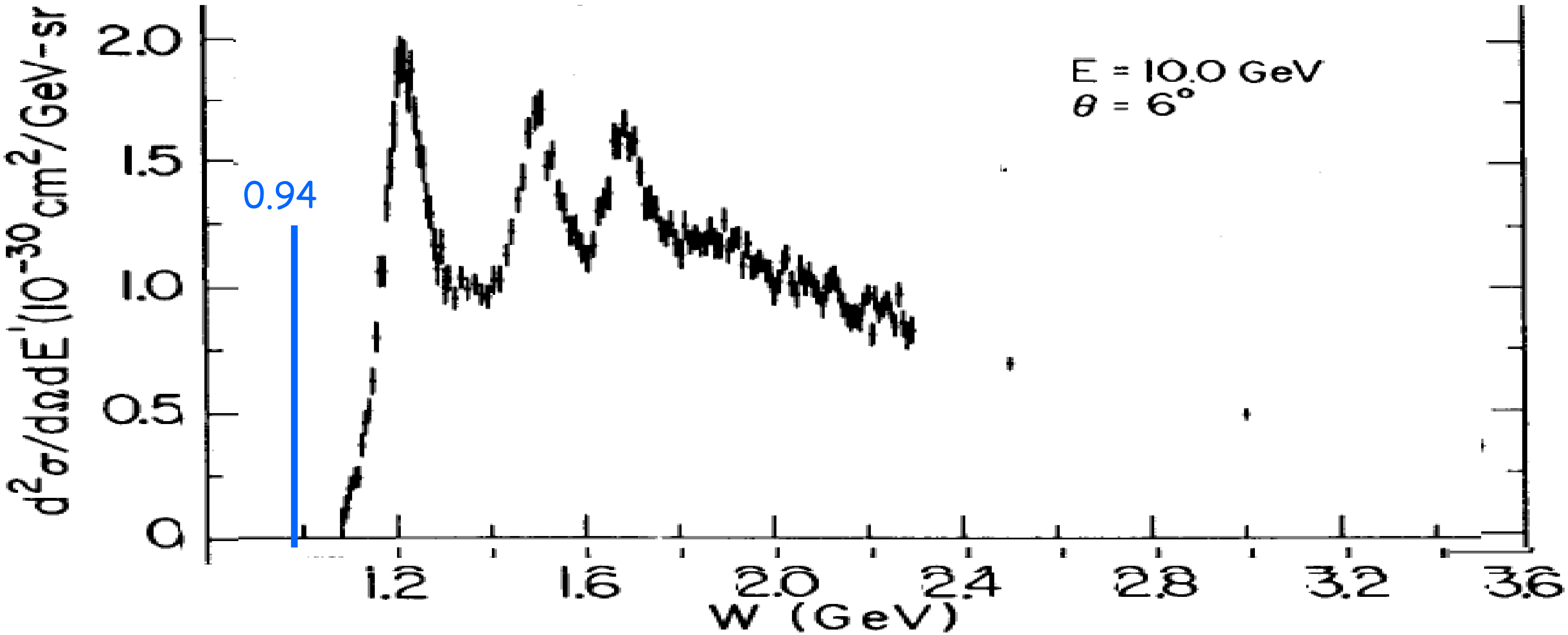
Feynman Diagram



Spectrometers measure scattered e^-, rejecting π's.
Small acceptance in ΔP/P, Δθ, Δϕ, all measured by hodoscopes – arrays of scintillators.

1968

Resonance Production, Frank Hertz experiment of the proton,.



M=mass of proton (0.94 GeV)

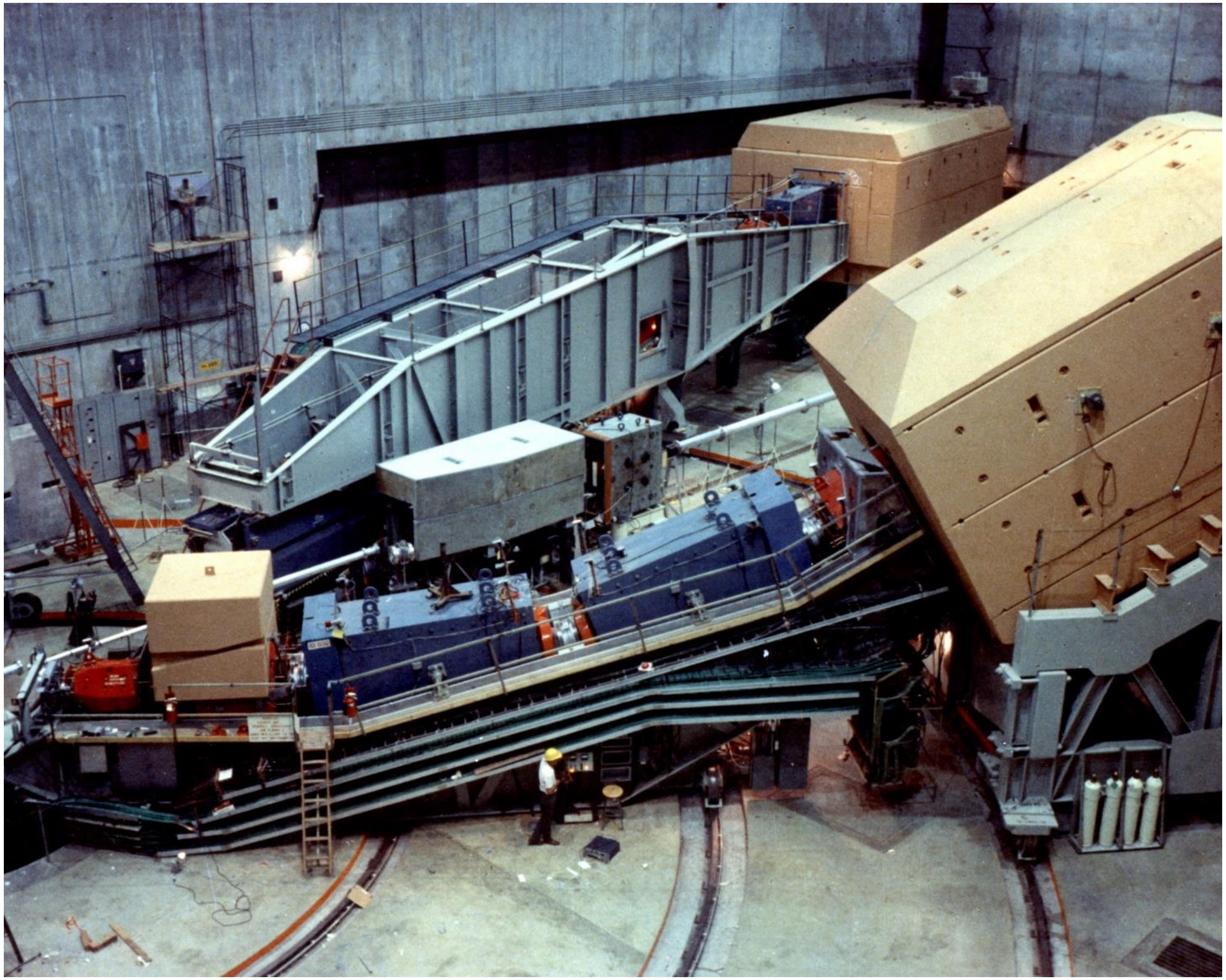
W= Mass of excited proton final state (from energy transfer ν)

q^2 = square of momentum transfer to proton

ν = energy transfer to proton (needed to add mass for the excited state)

1968

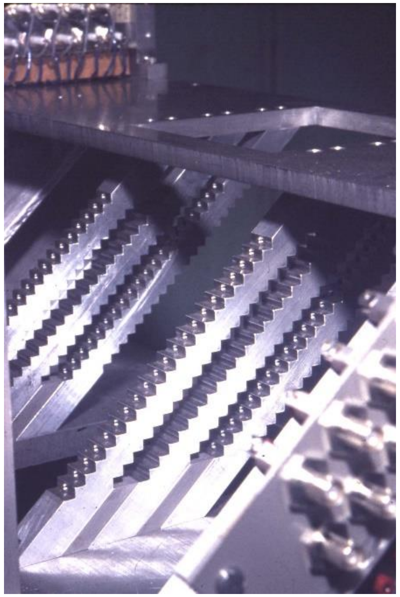
Looking into End Station A



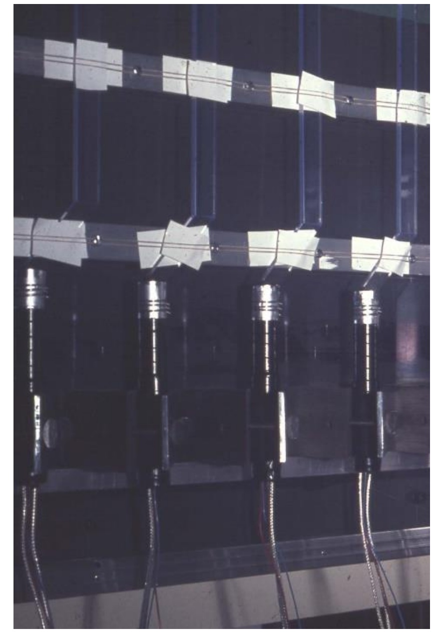
The End Station, the beamline, target and spectrometers were built by MIT and SLAC Experimental Group A and a team SLAC of engineers and techs.

1968

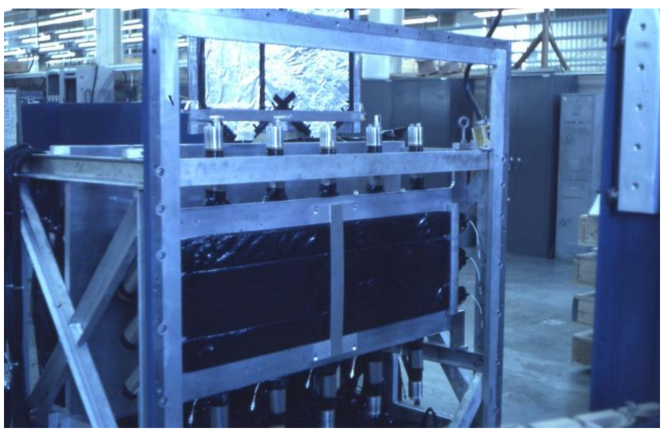
The spectrometer instrumentation and electronics for the 8 and 20 GeV spectrometers were designed and built by MIT.



Momentum Hodoscope – Precise supports for scintillator bars with PMT's



Trigger Counters

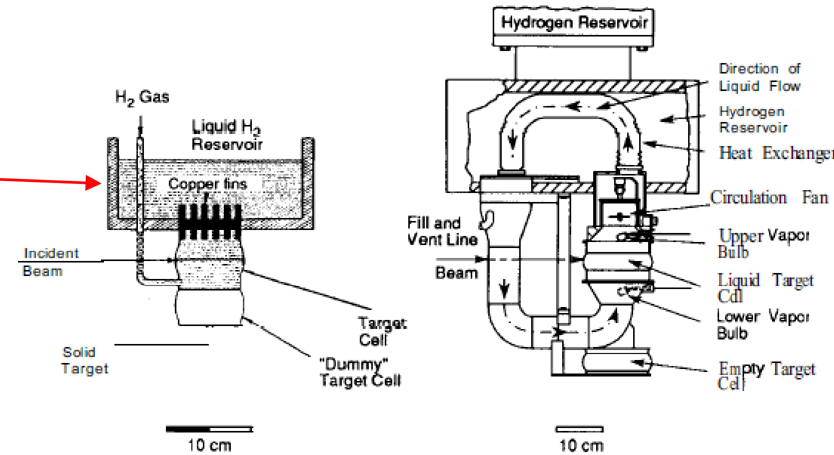


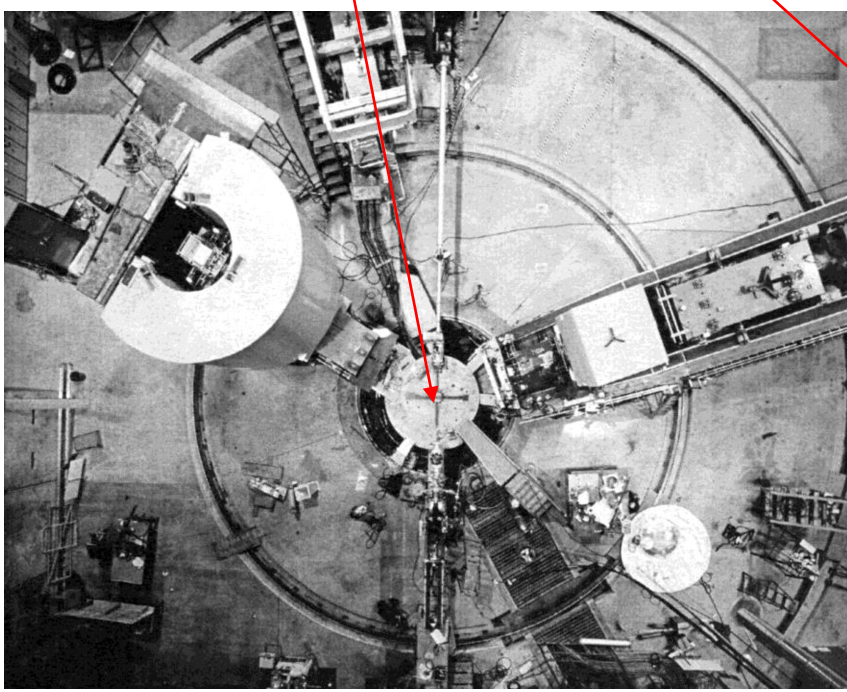
8 GeV Spectrometer – "π-e separator" i.e. EM Calorimeter
Designed long before EGS or GEANT shower Monte Carlos

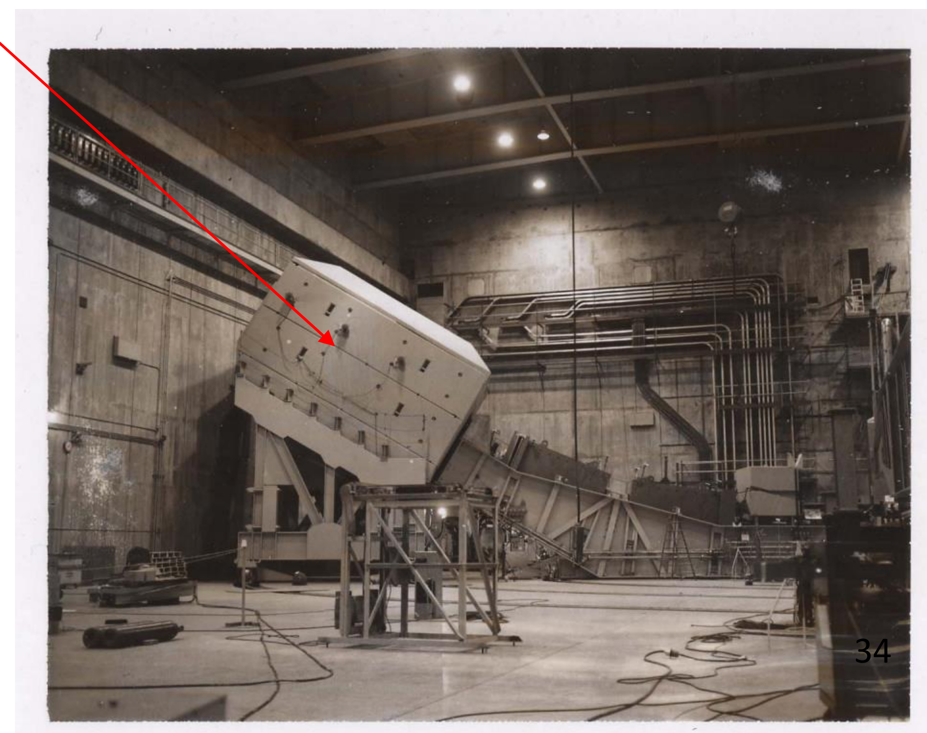
1968

20, 8, and 1.6 GeV/c Spectrometers

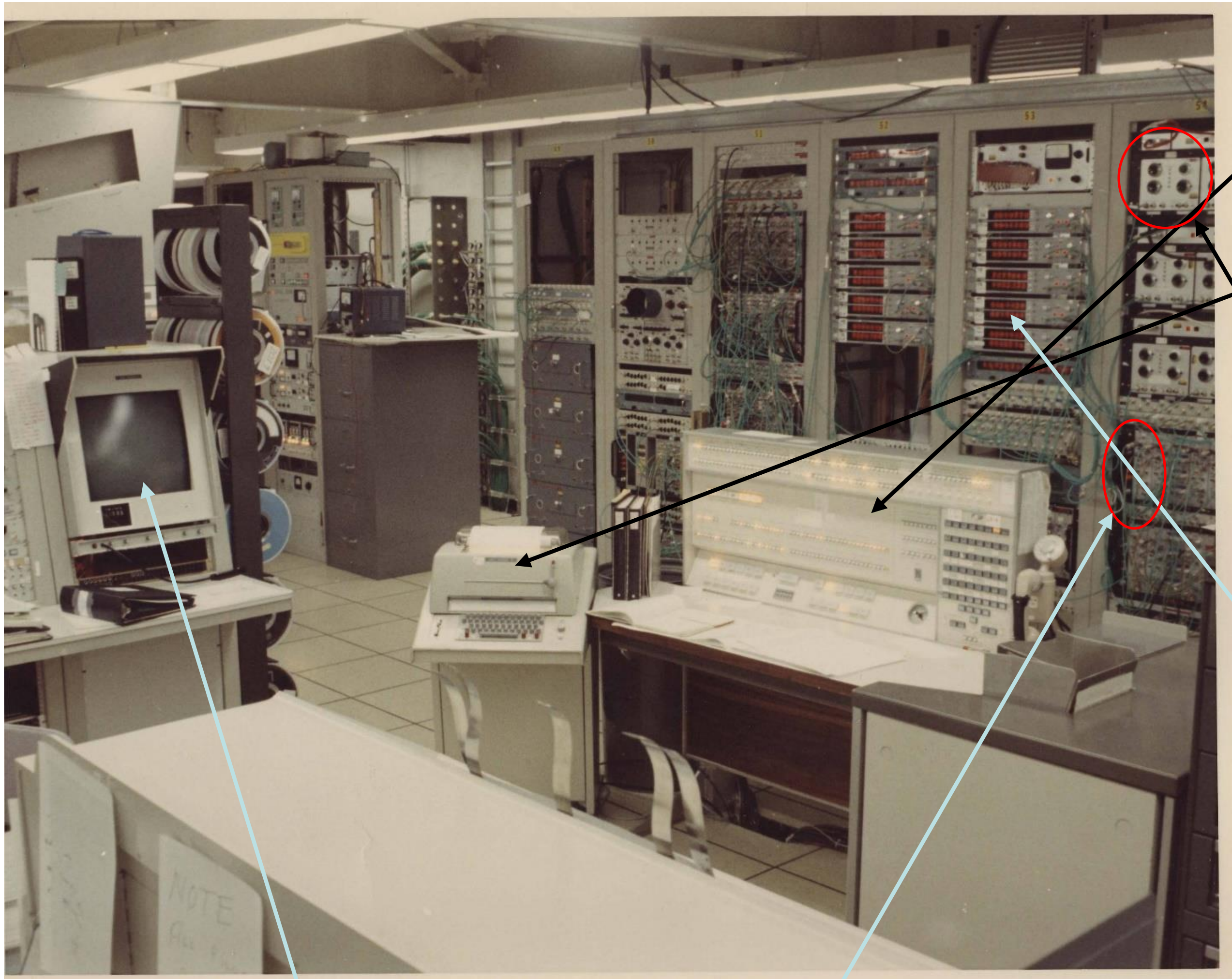
The SLAC primary e^- beam was momentum analyzed, collimated, and transported to a liquid hydrogen target, and the angle and momentum of the scattered e^- were measured…







1968 End Station A Counting House



SDS 9300 Computer
~ 1/4 Mflop (my old phone is ~500 Mflop)
96K bytes memory

Teletype Model 33
Human Interface Device

ADC (one channel!)

Scalers – Nixie Tube displays of counters

The only video display

Discriminator & Coincidence/Buffer for one electronics channel (PMT). Discrete transistors. ~ 2 liters/channel! [Modern is ~10^{-9} liters, totally dominated by connections.]

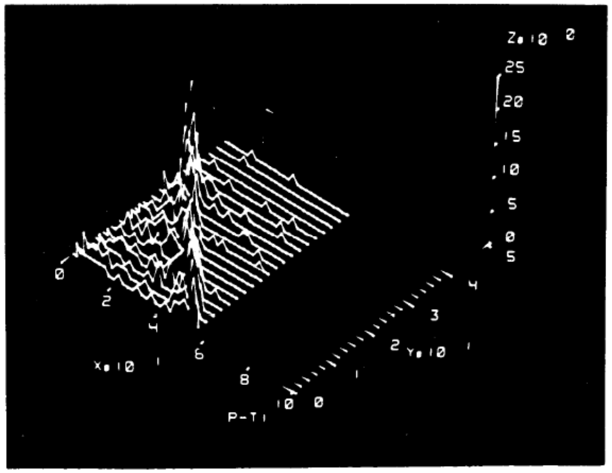
1968

The first experiments

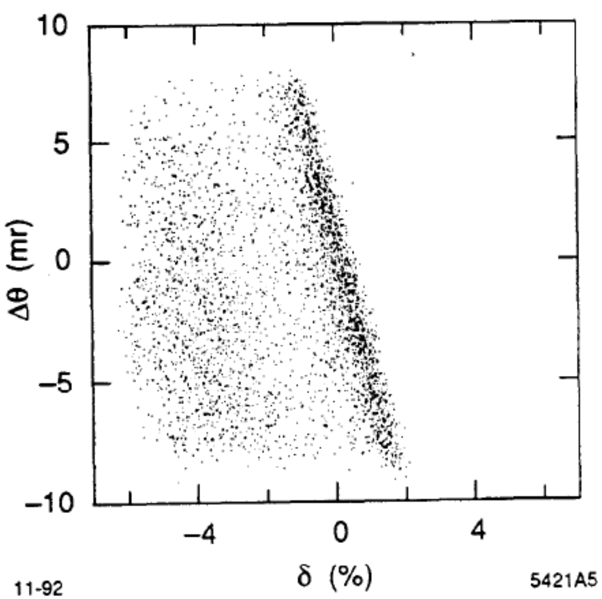
- The first physics experiments at SLAC were:
- e4a – Elastic scattering of e^- on protons
  - the high q^2 measurements were a wonderful lesson in the statistics of very low rate experiments.
- e4c – A comparison of e^- and e^+ scattering on protons
  - nothing really exciting expected, nothing really exciting found
- e4b – Deep inelastic scattering
  - first extensive data taken at 6^0 and 10^0
  - nothing really exciting expected, but that was (totally)wrong!

1968

Elastic Scattering ; Size of proton=1 Fermi

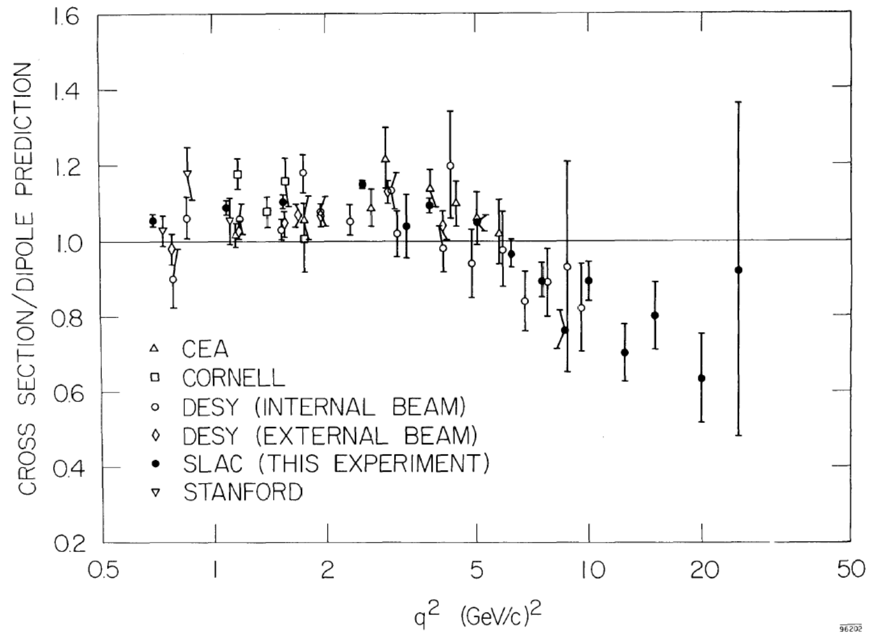


Realtime display from the 9300.
Elastic peak and radiative tail in the spectrometer acceptance.



As above, but offline.

Elastic σ/Dipole Model
Proton radius= 1 Fermi



q^2 = square of momentum transfer to proton

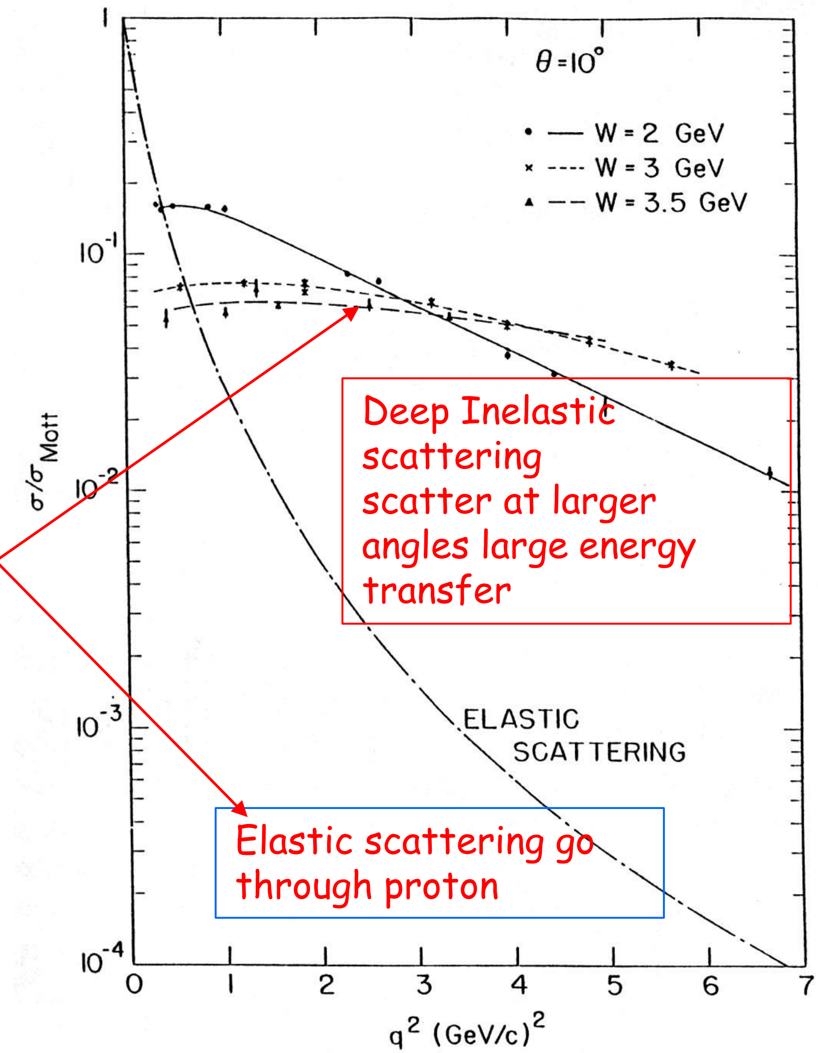
1968

- Spectrometer magnet calibrations checked with floating wire, elastic peak provided cross check.
- The analysis, by modern standards, was straightforward,
- The elastic scattering was interesting, but not dramatically different from expected.
- For the inelastic, there were some issues…

The deep inelastic – W > ~2 Gev: Weak q^2 dependence Larger cross section than expected.

M=mass of proton (0.94 GeV)
W= Mass of excited proton final state
q^2 = square of momentum transfer to proton
ν = energy transfer to proton

The data



Larger q^2=larger angle
Momentum transfer

From Richard Taylor

Supplement No. 2 to
SLAC Proposal No. 4-b

DATE: 26 July 1968

TO : Program Coordinator

FROM : R. E. Taylor

SUBJECT: Extension of Experiment 4b.

To date, we have used 196 hours of beam time in experiment 4b. A considerable amount of this time was spent in check out and testing. From this 196 hours, we have useful inelastic spectra at

$$\theta = 6^{\circ},\quad E_{o} = 7,\ 10,\ 13,\ \text{and } 16 \text{ GeV}$$
$$\theta = 4^{\circ},\quad E_{o} = 7 \text{ and } 16 \text{ GeV}$$
$$\theta = 8^{\circ},\quad E_{o} = 17 \text{ GeV}.$$

Several interesting results are evident even in this fragmentary data.

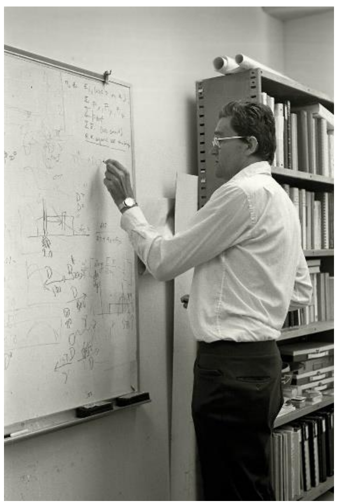
1. The dependence of the deep inelastic scattering (missing mass $W > 2$ GeV) on q^2 is much weaker than the elastic dependence. This scattering, therefore, becomes the dominant feature of the data even for moderate q^2 ($\sim 4\ (\text{GeV}/c)^2$).

Scaling - a universal function $\omega = 2M\nu/q^2$

Wolfs Prize 2015

1934-
Bjorken

- bj Bjorken in 1969, using current algebra, argued that in the limit of large q^2 and ν, and with $\omega=2M\nu/q^2$
  - $2MW_1(\nu,q^2) \rightarrow F1(\omega)$
  - $\nu W_2(\nu,q^2) \rightarrow F2(\omega$
  - $x = 1/\omega = q^2/2M\nu$



Bjorken

The dynamics of scaling took some time to sink in – although the word “quark” was used in the first inelastic papers.

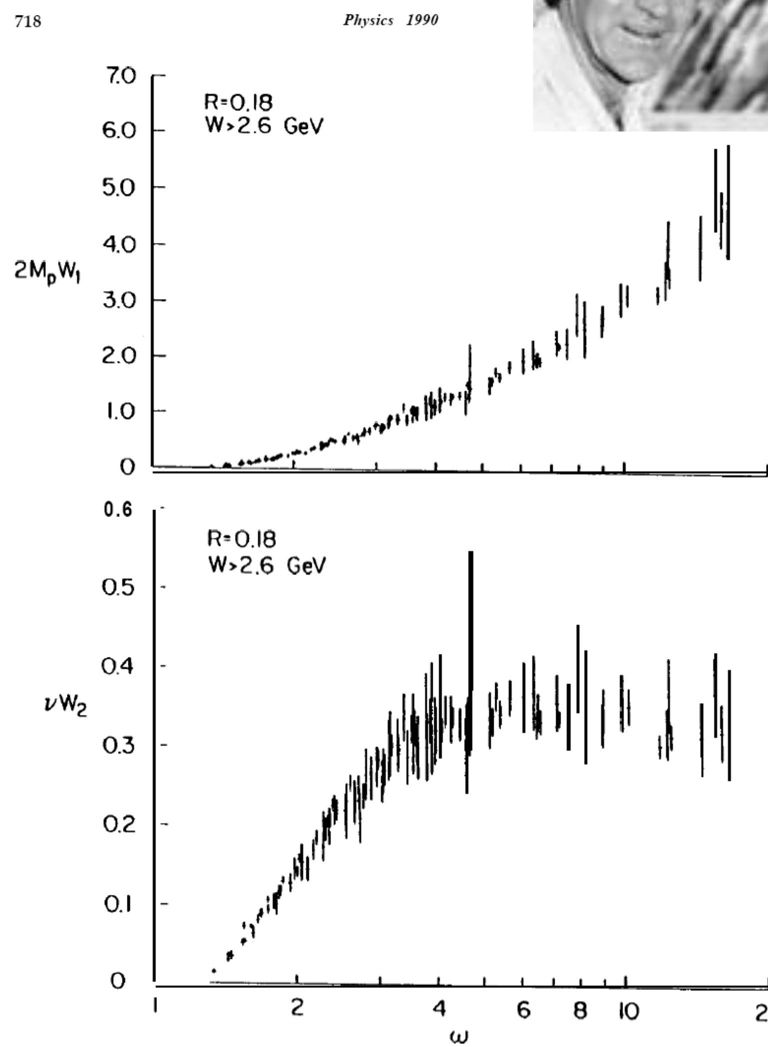
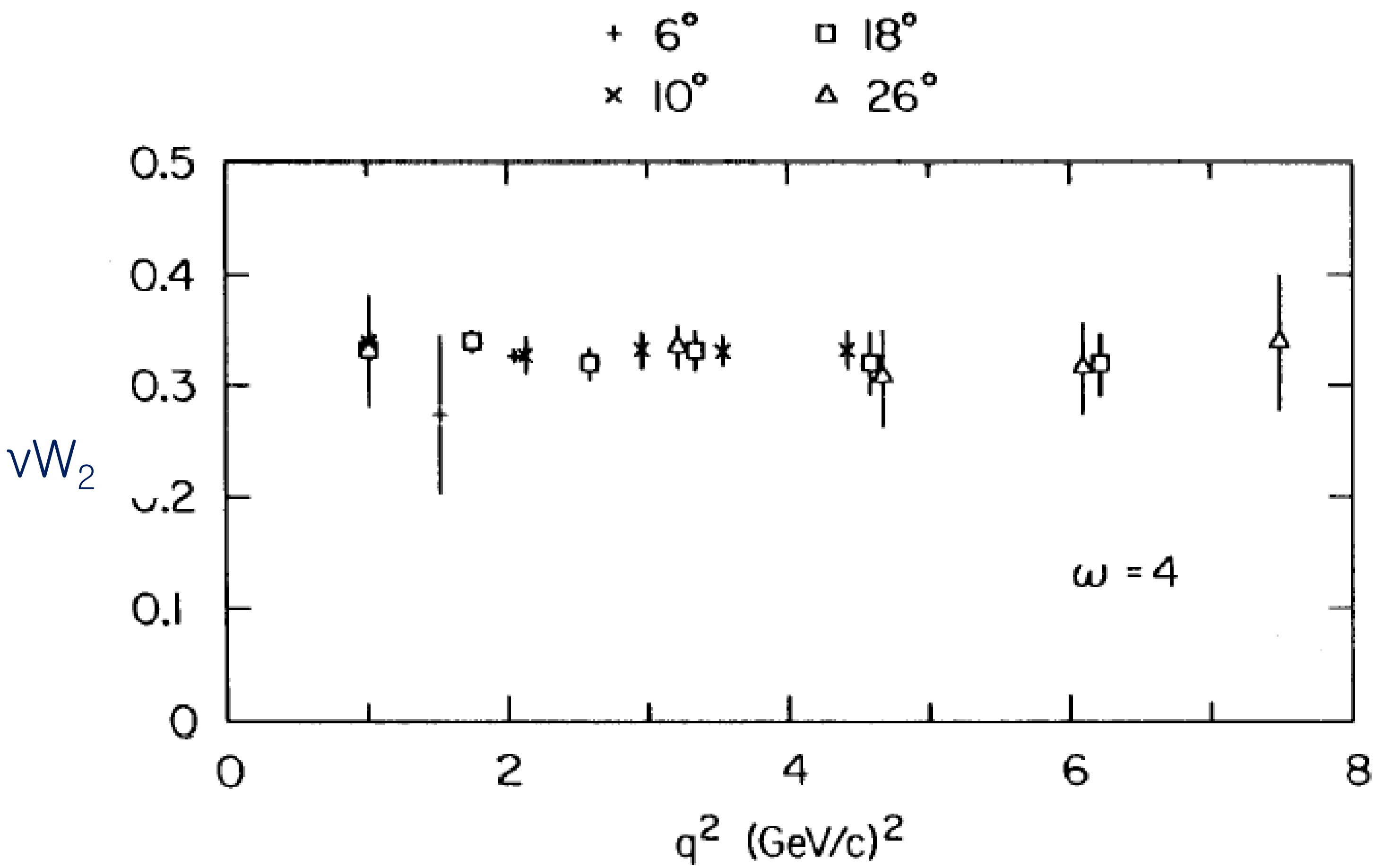


Fig. 2: $2MW_1$ and νW_2 for the proton as functions of ω for $W > 2.6$ GeV, $q^2 > 1(\mathrm{GeV}/c^2)$, and using R = 0.18. Data from Ref. [34]. The quantity *R* is discussed in the section of this paper entitled *Models*.

M=mass of proton (0.94 GeV)
W= Mass of excited proton final state
q^2 = square of momentum transfer to proton
ν = energy transfer to proton
$x = 1/\omega = q^2/2M\nu$

1969

Scaling: νW_2 for fixed $\omega = 2M\nu/q^2$ vs q^2



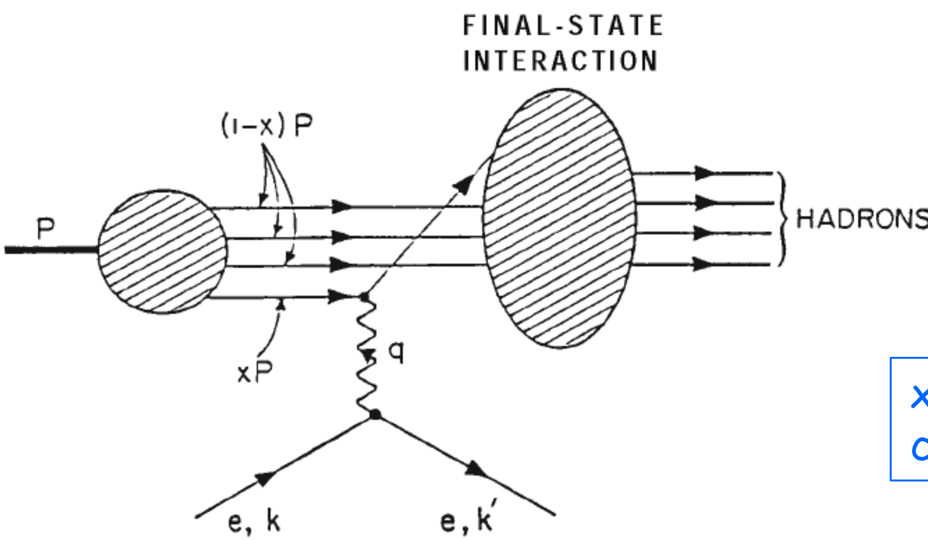
$x = 1/\omega = q^2/2M\nu$

Richard P. Feynman 1918 -1988 Nobel 1965 "for fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles

Richard Feyman's Partons 1969

- Many of us did not understand bj's current algebra motivation for scaling
- Feynman visited SLAC in August 1968. He had been working on hadron-hadron interactions with point like constituents called partons. We showed him the early data on the weak q^2 dependence and scaling – and he (instantly!) explained the data with his parton model.
- In an infinite momentum frame, the point like partons were slowed, and the virtual photon simply elastically scatters from one parton without interactions with the other partons – the impulse approximation.
- This was a wonderful, understandable model for us.

$$W_2^{(i)}(\nu,q^2)=Q^2_i\delta(\nu-q^2/2MX_i)$$
$$=Q^2_i x_i/\nu\ \delta(x_i-q^2/2M\nu)$$

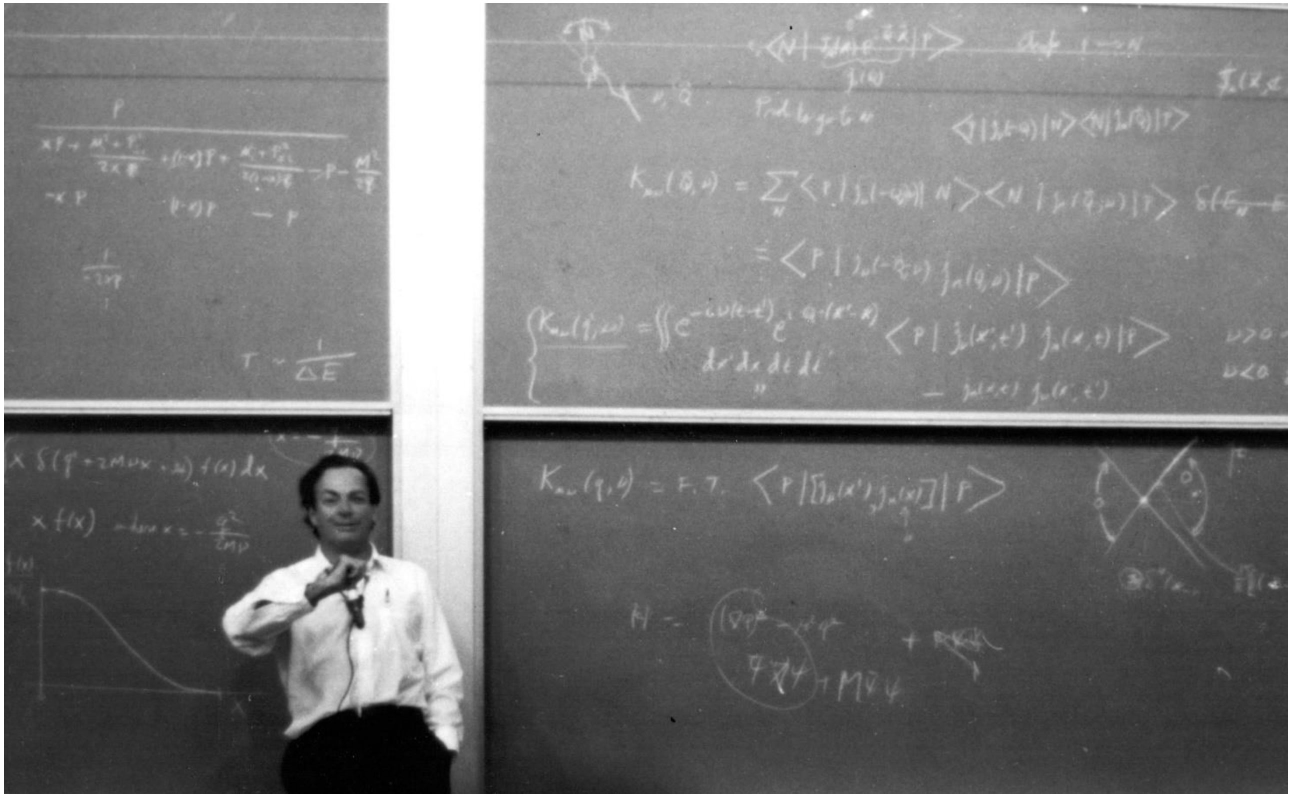


$$\nu W_2(\nu,q^2) =$$
$$\sum_N \mathcal{P}(N)\left\{\sum_{i=1}^{N} Q_i^{\,2}\right\} x f_N(x)=F_2(x)$$

$$x = \frac{q^2}{2M\nu} = \frac{1}{\omega}$$

x= fraction of momentum of the proton carried by the parton

Feynman explaining!



$$W_2^{(i)}(\nu,q^2)=Q^2_i\,\delta(\nu-q^2/2MX_i)$$
$$=Q^2_i x_i/\nu\;\delta(x_i-q^2/2M\nu)$$

x= fraction of momentum of the proton carried by the parton

$$\nu W_2(\nu,q^2) = \sum_N \mathcal{P}(N)\,\{\textstyle\sum_{i=1}^{N} Q_i^2\}\,x f_N(x)=F_2(x)$$

$$x = \frac{q^2}{2M\nu} = \frac{1}{\omega}$$

All the dark nights at SLAC

Yielded the first papers on the deep inelastic 1969

HIGH-ENERGY INELASTIC e-p SCATTERING AT 6° AND 10°*

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, G. Miller, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

M. Breidenbach, J. I. Friedman, G. C. Hartmann,† and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,‡
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 19 August 1969)

Cross sections for inelastic scattering of electrons from hydrogen were measured for incident energies from 7 to 17 GeV at scattering angles of 6° to 10° covering a range of squared four-momentum transfers up to 7.4 $(\mathrm{GeV}/c)^2$. For low center-of-mass energies of the final hadronic system the cross section shows prominent resonances at low momentum transfer and diminishes markedly at higher momentum transfer. For high excitations the cross section shows only a weak momentum-transfer dependence.

Inelastic electron-proton scattering at high four-momentum transfer and large electron-energy loss has been used to investigate the electromagnetic structure and interactions of the protered energies E', beginning at elastic scattering and ending at $E' \approx 3$ GeV. Only the scattered electron was detected. In this kind of measurement the two inelastic form factors[2] which describe

VOLUME 23, NUMBER 16 PHYSICAL REVIEW LETTERS 20 OCTOBER 1969

OBSERVED BEHAVIOR OF HIGHLY INELASTIC ELECTRON-PROTON SCATTERING

M. Breidenbach, J. I. Friedman, and H. W. Kendall
Department of Physics and Laboratory for Nuclear Science,*
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

E. D. Bloom, D. H. Coward, H. DeStaebler, J. Drees, L. W. Mo, and R. E. Taylor
Stanford Linear Accelerator Center,† Stanford, California 94305
(Received 22 August 1969)

Results of electron-proton inelastic scattering at 6° and 10° are discussed, and values of the structure function W_2 are estimated. If the interaction is dominated by transverse virtual photons, νW_2 can be expressed as a function of $\omega = 2M\nu/q^2$ within experimental errors for $q^2 > 1$ $(\mathrm{GeV}/c)^2$ and $\omega > 4$, where ν is the invariant energy transfer and q^2 is the invariant momentum transfer of the electron. Various theoretical models and sum rules are briefly discussed.

In a previous Letter,[1] we have reported experimental results from a Stanford Linear Accelerator Center–Massachusetts Institute of Technolbetween the behavior of the inelastic and elastic cross sections is also illustrated in Fig. 1, where the elastic cross section, divided by the Mott

What if you assume quarks were real.

(1) Measurement of Parton Charges
Comparison of electron scattering from neutrons and protons

- **Quark model - Isospin symmetry u, d in proton = d, u in neutron**

Proton: (u u d) = $(\frac{2}{3}\ \frac{2}{3}\ \frac{-1}{3})$; Neutron: (d d u) = $(\frac{-1}{3}\ \frac{-1}{3}\ \frac{2}{3})$

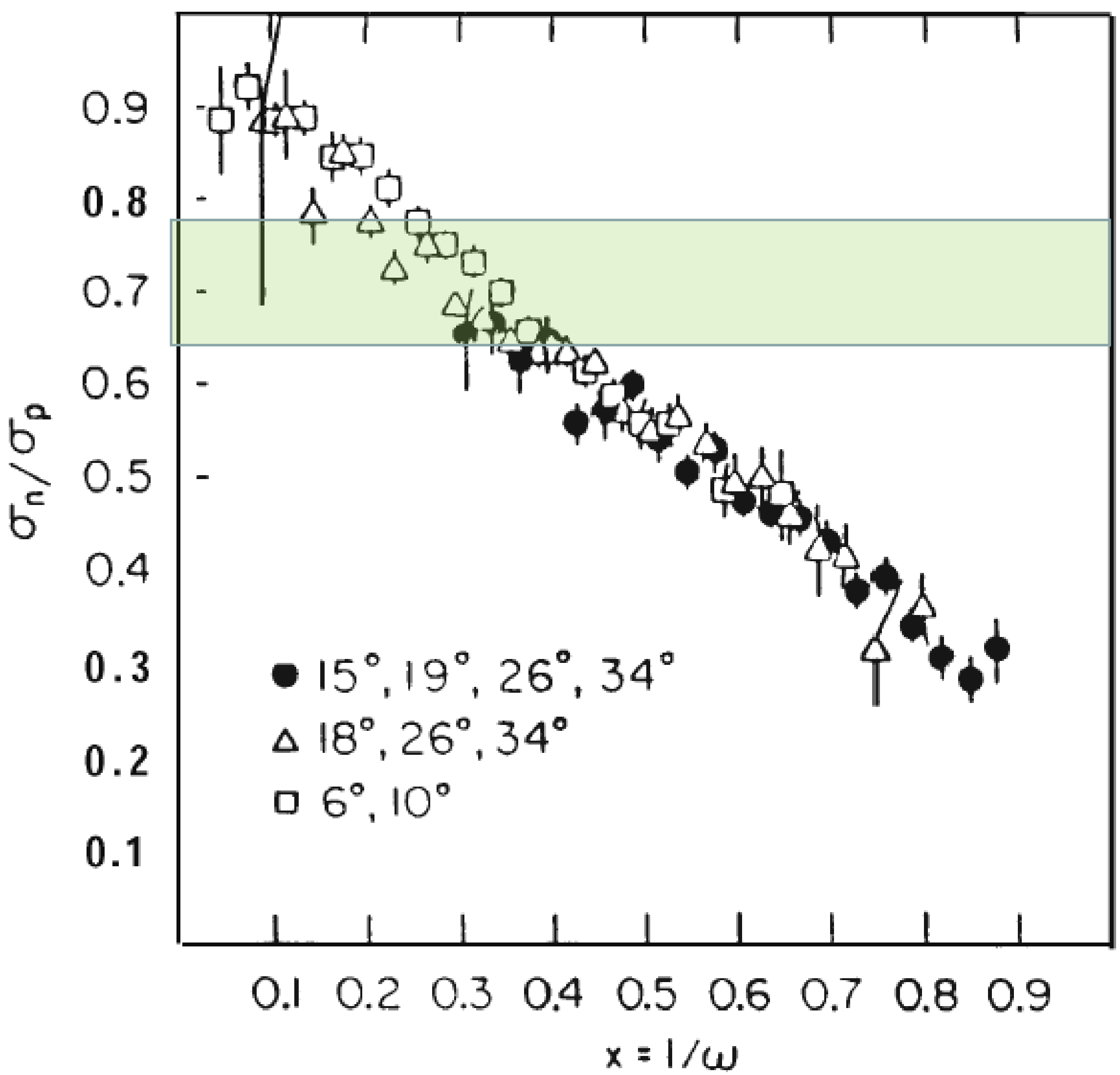
and at low x add : u-ubar, d-dbar, s-sbar sea

Prediction **F_{2N}/F_{2P} = 1** at small x (sea dominates)

Naïve quark model: average **F_{2N}/F_{2P} =** $\frac{\frac{1}{9}+\frac{1}{9}+\frac{4}{9}}{\frac{4}{9}+\frac{4}{9}+\frac{1}{9}} = \frac{6}{9} = \mathbf{\frac{2}{3}}$

If d quark dominates **F_{2N}/F_{2P}** > $\frac{\frac{1}{9}}{\frac{4}{9}} = \mathbf{\frac{1}{4}}$

My PhD Neutron to Proton Ratio measurements 1970-1971



- Data do not agree with predictions of non-partonic models such as resonance models which predict

F_{2N}/F_{2P} =0.66 to 0.78

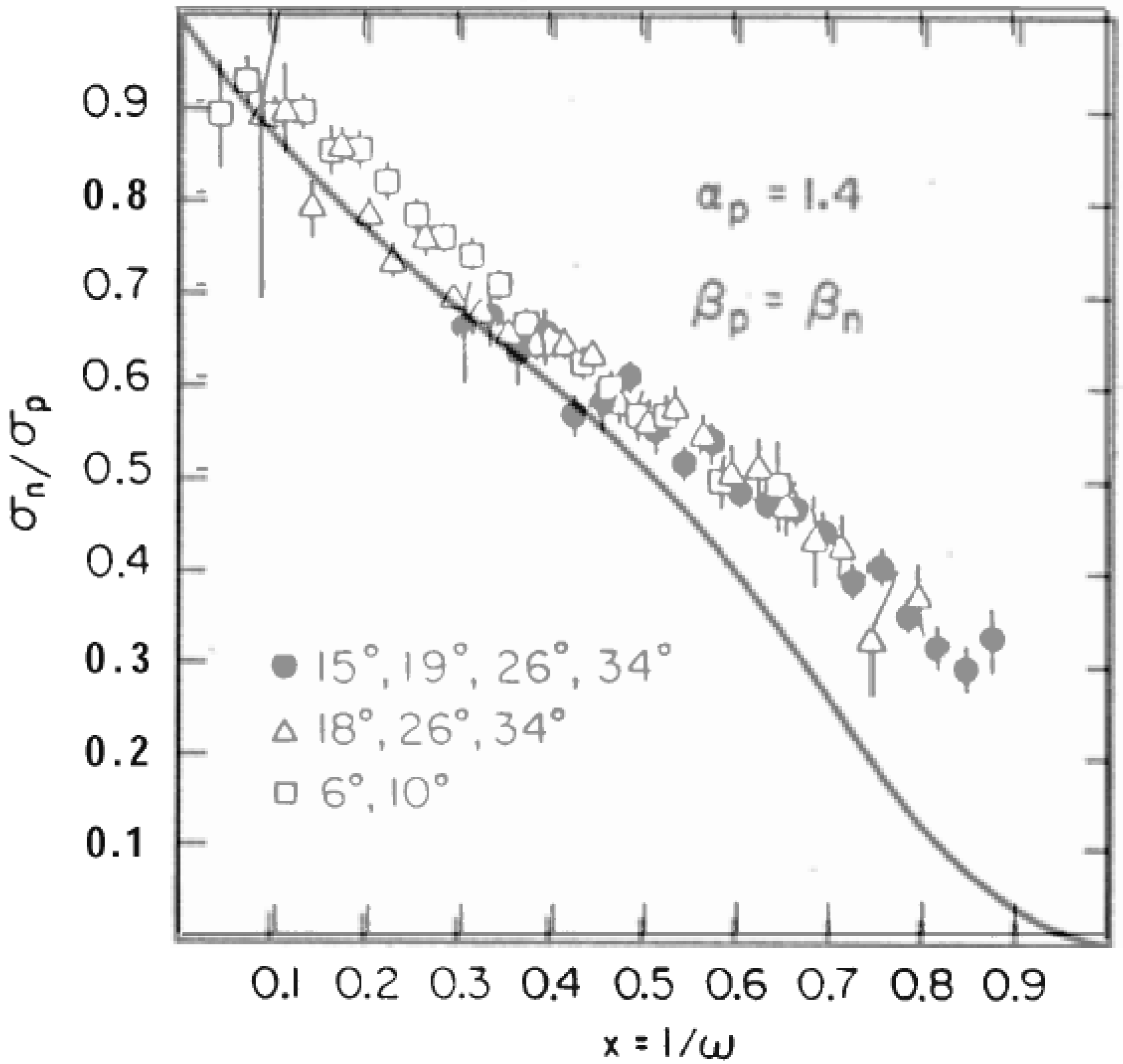
P. V. Landhsoff and J. C. Polkinghorne, Nucl. Phys. B19, 432 (1970)

$F_{2N}/F_{2P} = \frac{2}{3}$

G. Domokos, S. Kovesi-Domokos, E. Schonberg, Phys. Rev. D3, 1184, and 1191 (1971).

: F_{2N}/F_{2P} =0.70 to 0.78

Neutron to Proton Ratio

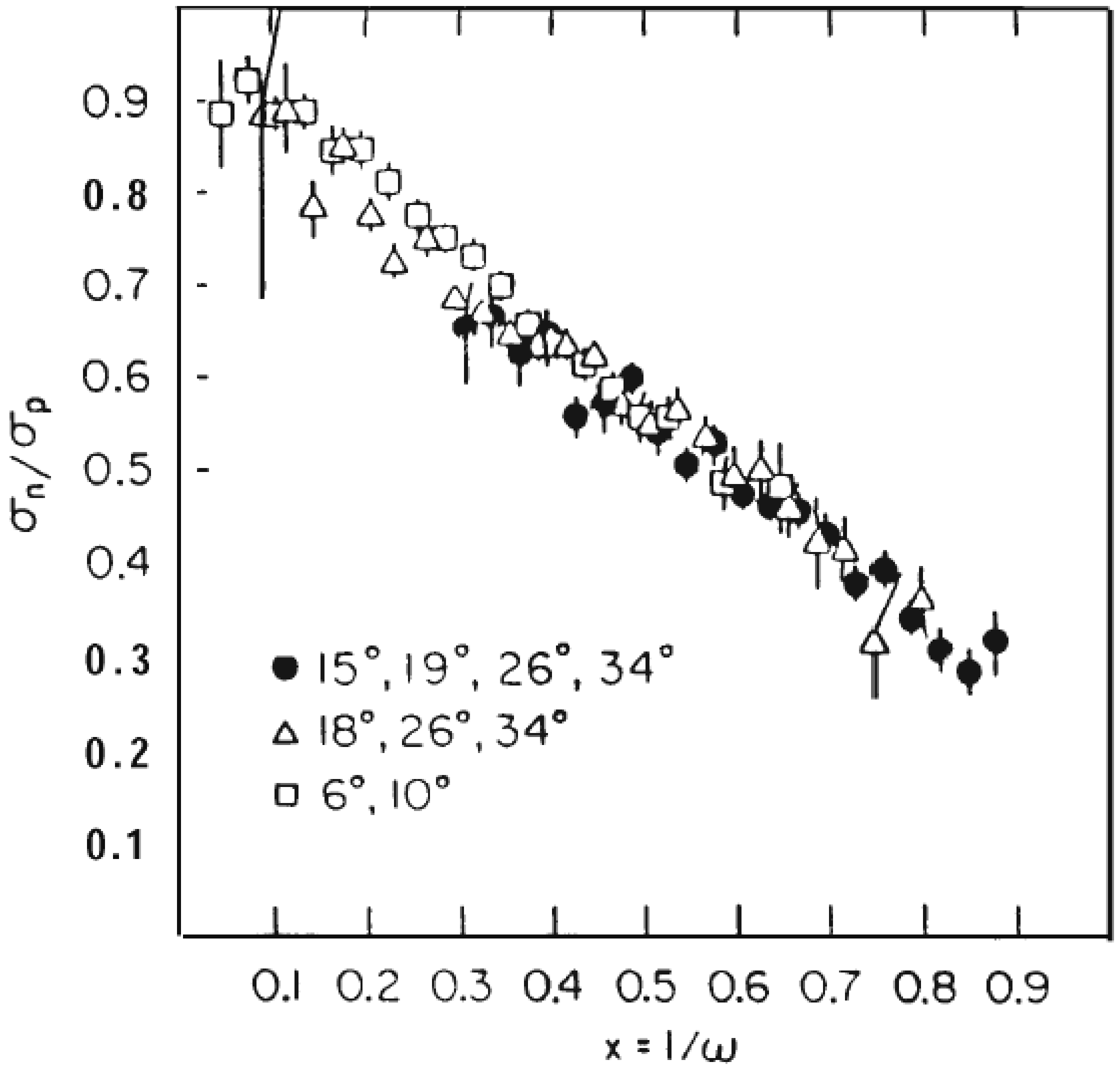


Data do not agree with Integrally charged partons (bare nucleons and bare pions): T. D. Lee and S. D. Drell, Phys Rev. D5, 1738 (1972)

which predict

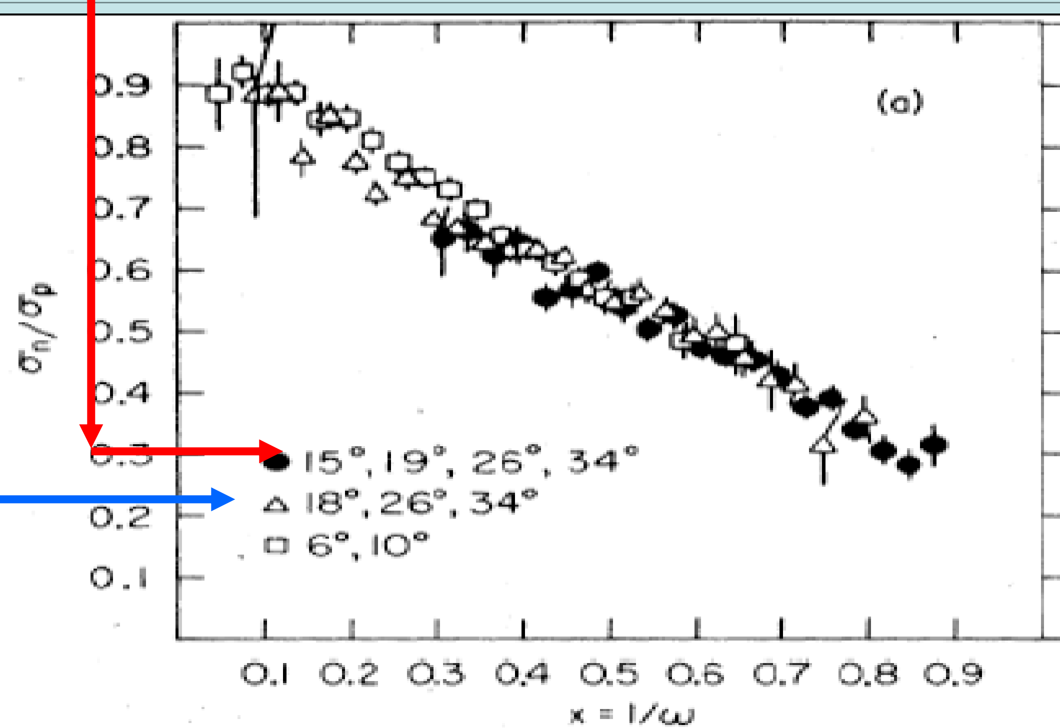
F_{2N}/F_{2P} =0 x → 1

Neutron to Proton Ratio vs quark model



- Quark model lower bound is 0.25
- Low value implies d quark from neutron and u quark from proton have the most important contributions (at large x).

- 1970-74 - **Neutron/Proton ratio - Partons are quarks** (Bodek PhD. MIT 1972)
  - **A. Bodek et al.**, *COMPARISONS OF DEEP INELASTIC ep AND en CROSS-SECTIONS.* **Phys.Rev.Lett.30:1087,1973**. (SLAC Exp. E49)
  - **A. Bodek** et al., *THE RATIO OF DEEP - INELASTIC en TO ep CROSS-SECTIONS IN THE THRESHOLD REGION* Phys.Lett.B51:417,1974 & (SLAC E87) **Rejected by Phys. Rev Letters.**
  - **A. Bodek**, *COMMENT ON THE EXTRACTION OF NUCLEON CROSS SECTIONS FROM DEUTERIUM DATA,* **Phys. Rev. D8, 2331 (1973).**



N =d d u + sea
1/3 1/3 2/3

P = u u d + sea
2/3 2/3 1/3

Large x N/P -> 0.25 Explained by valence d/u

$[(1/3) / (2/3)]^2 = 1/4$

Small x : N/P=1 explained by sea quarks

AND

PHYSICAL REVIEW LETTERS

(PUBLISHED FOR THE AMERICAN PHYSICAL SOCIETY)

BROOKHAVEN NATIONAL LABORATORY, UPTON, LONG ISLAND, NEW YORK 11973
Telephone (516) 924-6262, Ext. 2296

3 June 1974

Dear Dr. Coward,

The following manuscript has been reviewed by one of our referees: "Ratio of Deep-Inelastic e-n to e-p Cross Sections in the..." by A. Bodek, et al.

On the basis of his comments, our judgement is that while a report of this work may deserve publication, it is not of such novel and stimulating character as to warrant publication as a Letter. In addition, the report as submitted appears too abbreviated to be satisfactory as an Article.

For experts in the field, one recognizes the fact that more detailed measurements have been made since the original article of Bodek, et. al. {Physical Review Letters, 30, 1086 (1973)}. My major concern remains in that this paper offers no substantially new information or conclusion to the general readership of Physical Review Letters.

I regard this as an excellent piece of work to follow up the earlier experiment. However, it does not warrant a speedy publication in Physical Review Letters in view of the fact that dramatically new and potentially much more exciting results are forthcoming in data from NAL at high q^2 as well as from the e^+-e^- storage rings.

CALIFORNIA INSTITUTE OF TECHNOLOGY

CHARLES C. LAURITSEN LABORATORY OF HIGH ENERGY PHYSICS
PASADENA, CALIFORNIA 91109

December 6, 1972

Professor H. W. Kendall
Physics Department
Massachusetts Institute of Technology
Cambridge, Mass. 02139

Dear Kendall:

As you know I am very anxious to see the data on R, and your last letter saying I must wait a few weeks more was frustrating. However, I will be patient – take your time and get the figures right so we are not led astray.

You asked me on the telephone what I was thinking about the theory of R. I am only thinking the conventional thoughts, that the behavior of R versus ν and x can tell us whether the charged partons of which protons are made are purely spin 1/2 (in which case the scaling law is that νR is a function solely of x – or since $x = q^2/2M\nu$ say $R' = (\nu^2/q^2)R$ is a function solely of x), or there are some scalar partons (in which case R itself should scale, R itself should be a function only of x) at infinite ν the quantity R at each x gives a measure of the ratio of scalar to spin 1/2 partons having the fraction x of the protons momentum.

We are all betting (hoping for simplicity) that there are no other charged partons than quarks, and that it is $R' = (\nu^2/q^2)R$ which depends only on x, not on ν for large ν, (your letter had a misprint – you said you would plot for me $(\nu/q^2)R$, instead of $(\nu^2/q^2)R$ which I want). About how R will depend on x I do not have any clues. A vague suggestion that it goes as $1/x^2$ for the larger x is all I can come up with and even that is not based on truly sound physics. Murray Gell-Mann would like to test a sum rule he has involving R'.

Please analyze it any way which appears to you, in view of the errors, to be the best way to combine the data to resolve this question (e.g., plot R versus ν for a given x, or what not).

Sincerely,

Richard P. Feynman

Determination of parton spin

Eventually the notion that "…theoretical speculations are focused on the possibility that these data might give evidence on the behavior of point-like structures in the nucleon"* was accepted!

Finally, in 1990, the Nobel Prize!

*Panofsky – Vienna 1968

In the early 70's

- Nucleons have point like constituents consistent with quark charge assignment and spin = ½.
- Asymptotic Freedom, and QCD* (Quantum Chromodynamics) explained the absence of free quarks and Pauli principle (Color)
- Asymptotic freedom explains scaling, but needs deviations from scaling (which will show up!)
- Bootstrap, nuclear democracy, vector meson dominance, diffraction models all fading away.
- QCD color fixed the Pauli principle problems.
- QCD gluons carry half nucleon momentum, rest by quarks.

*Gross and Wilczek, Politzer

Photo from the Nobel Foundation archive.

David J. Gross

Prize share: 1/3

1941-

Photo from the Nobel Foundation archive.

H. David Politzer

Prize share: 1/3

1949-

Photo from the Nobel Foundation archive.

Frank Wilczek

Prize share: 1/3

1951-

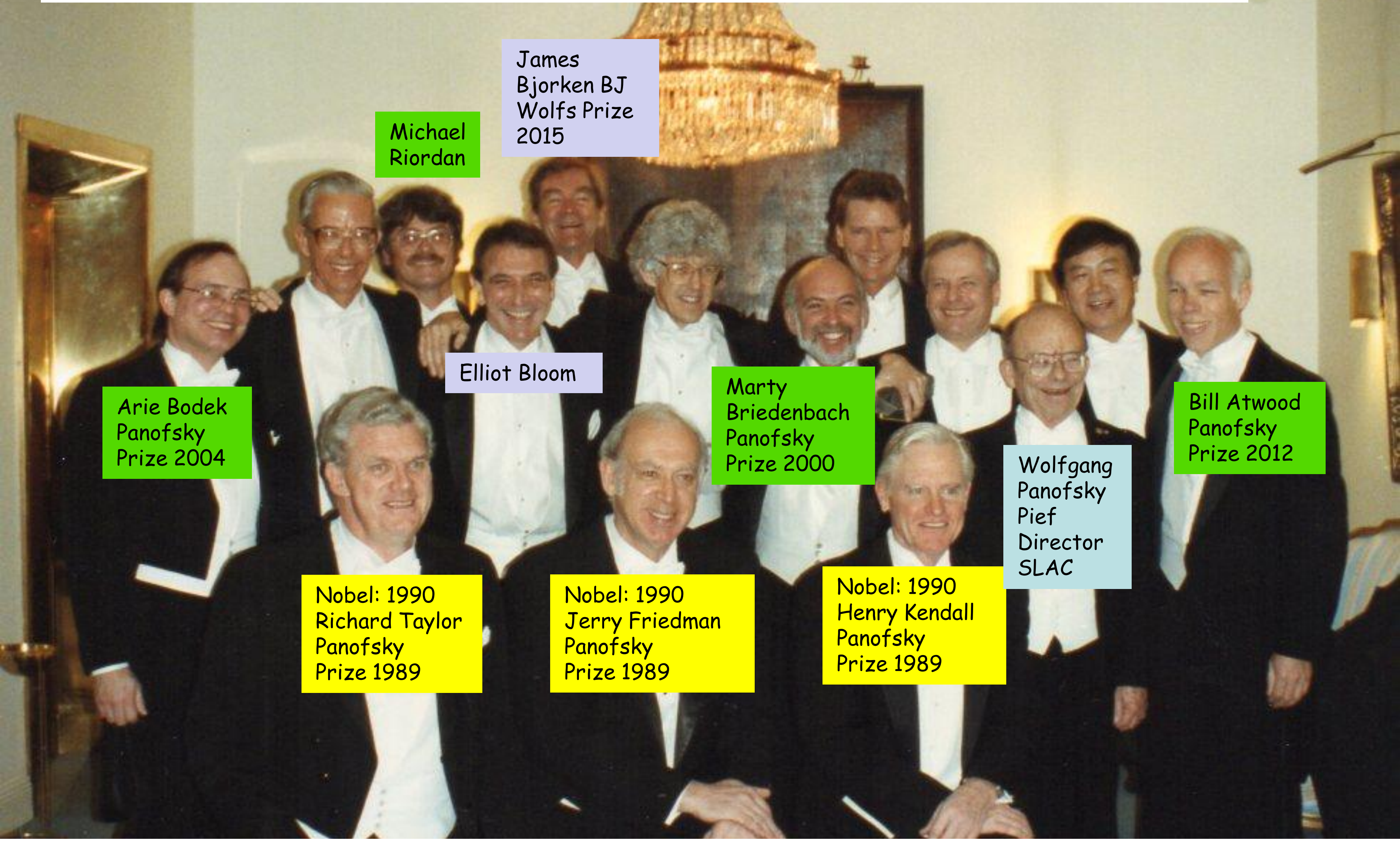
The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction."

Summary

In the late 60's to early 70's, the SLAC-MIT deep inelastic experiments provided the experimental evidence first for partons and then their identification as quarks.

These led to the formulation of Quantum Chromodynamics and the present Standard Model of Particle Physics.

The MIT-SLAC group was a small but exceptional



Left to Right: Front Row - Prize winners: Richard Taylor, Jerome Fiedman, Henry Kendal; Middle Row - Arie Bodek, Dave Coward, Elliot Bloom, Les Cottrell, Marty Breidenbach, Jurgen Drees, Luke Mo, Bill Atwood; Back Row - Ed Riordan, BJ Bjorken, Guthrie Miller. Missing Hobey DeStaebler

Extra Slides

Richard P. Feynman

1918 -1988

Nobel 1965 "for fundamental work in quantum electrodynamics, with deep-ploughing consequences for the physics of elementary particles."

From Richard Taylor full page

Supplement No. 2 to
SLAC Proposal No. 4-b

DATE: 26 July 1968

TO : Program Coordinator

FROM : R. E. Taylor

SUBJECT: Extension of Experiment 4b

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$\theta = 6^{o}$, E_{o} = 7, 10, 13, and 16 GeV
$\theta = 4^{o}$, E_{o} = 7 and 16 GeV
$\theta = 8^{o}$, E_{o} = 17 GeV.

Several interesting results are evident even in this fragmentary data.

1. The dependence of the deep inelastic scattering (missing mass $W > 2$ GeV) on q^2 is much weaker than the elastic dependence. This scattering, therefore, becomes the dominant feature of the data even for moderate q^2 (~ 4 $(\text{GeV}/c)^2$).
2. The resonant structure observed is dominated by resonances at 1236, 1510, and 1688. Some evidence can be obtained for excitation of the 1920 level. The first three resonances mentioned behave roughly in the manner predicted by Walecka and Zucker (Phys. Rev. 167, 1467 (1968)). The rapid fall off of the resonances with q^2 makes observation of the resonances difficult for $q^2 \sim 3\text{-}4 (\text{GeV}/c)^2$, and above. This experimental fact considerably narrows the range over which the resonances can be studied at SLAC.

We have also gained some experience in the experimental techniques necessary for reliable data taking.

1. Beam requirements seem to be more severe than other experiments. The large number of energy changes required are taking more time as the complexity of operations at SLAC increases. With many multiple beams, energy changes take much longer than anticipated, especially for low energies.

   The high resolution needed for these experiments makes it difficult to get a flat beam spill in multiple operation. Both these factors increase the calendar time necessary to get a given number of hours.

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