Discovery of the Quark Model
Physics 290E Spring 2020

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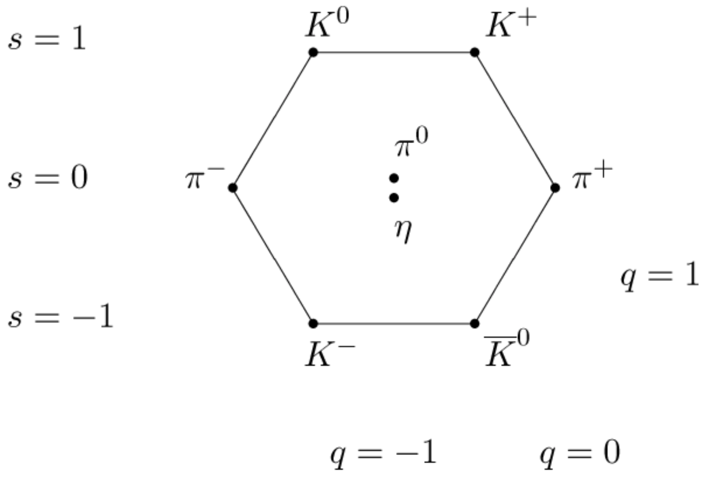
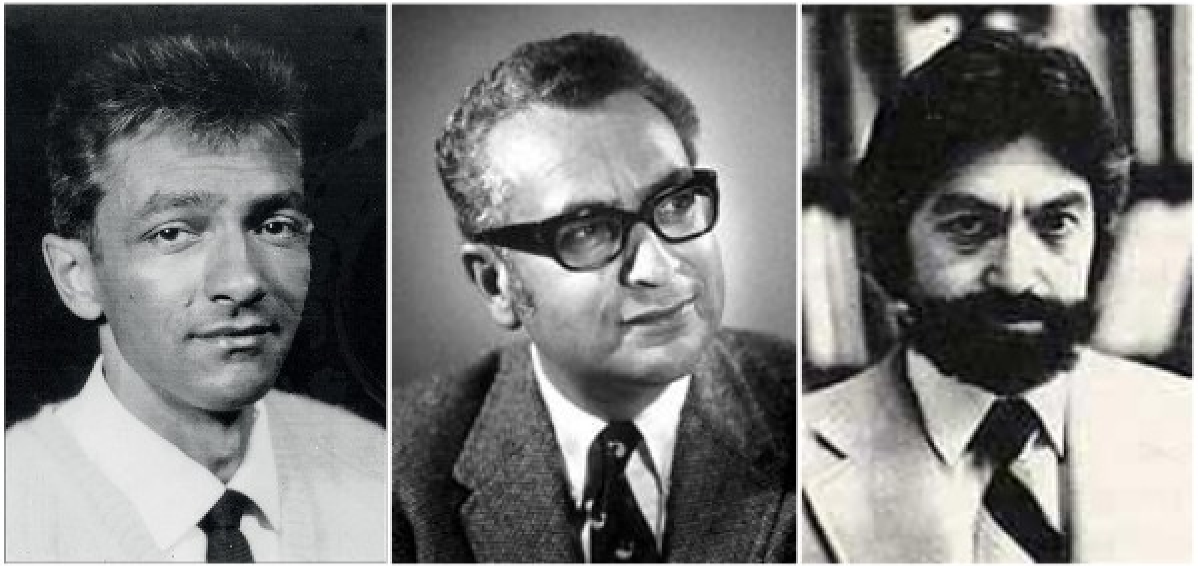
The Story So Far

- By 1960: Lots of Strongly interacting particles
  - Thought to be fundamental but not pointlike in “bootstrap model”
- 1961: Gell-Mann and Ne’eman use Lie algebras to organize the “Particle Zoo”
  - Largely successful by creating octets of mesons and baryons as well as the deciment spin 3/2 baryons
  - Theory here leading experiment



The People Involved



André Petermann — Elementary Spinors

Murray Gell-Mann — Quarks

George Zweig — Aces

The Beginnings of the Theory

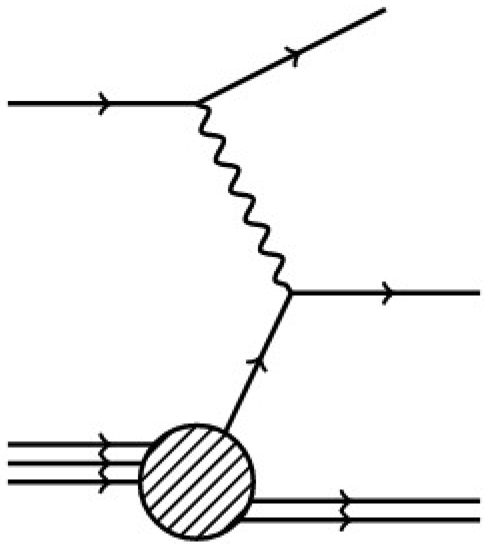
- By 1964 3(!) theorists had realized the SU(3) symmetry of hadrons was curiously well explained by more fundamental constituents
  - One negative consequence of this was the implication of fractional charges!
  - Fractional charges had not been observed in cosmic ray, collider, etc. experiments
  - Even Gell-Mann’s paper, A Schematic Model of Baryons and Mesons had a caveat: “It is fun to speculate about the way quarks would behave if they were physical particles of finite mass (instead of purely mathematical entities as they would be in the limit of infinite mass)”

Deep Inelastic Scattering

- Lepton (usually electrons) on protons (nuclei) leading to disassociation
- Dictated by lepton kinetmatics (initial and final state)
- Results usually formulated in terms of x-sec/ Mott x-sec (elastic)
- Variables:

$$W^2 = 2M(E - E') + M^2 - q^2$$

$$q^2 = 2EE'(1 - \cos\theta)$$



First SLAC-MIT e+p Scattering

- Accelerator and detector technology capable of deeply probing EM interacting content of proton
- Magnetic spectrometer, hodoscope, and showering detector for e/pi separation

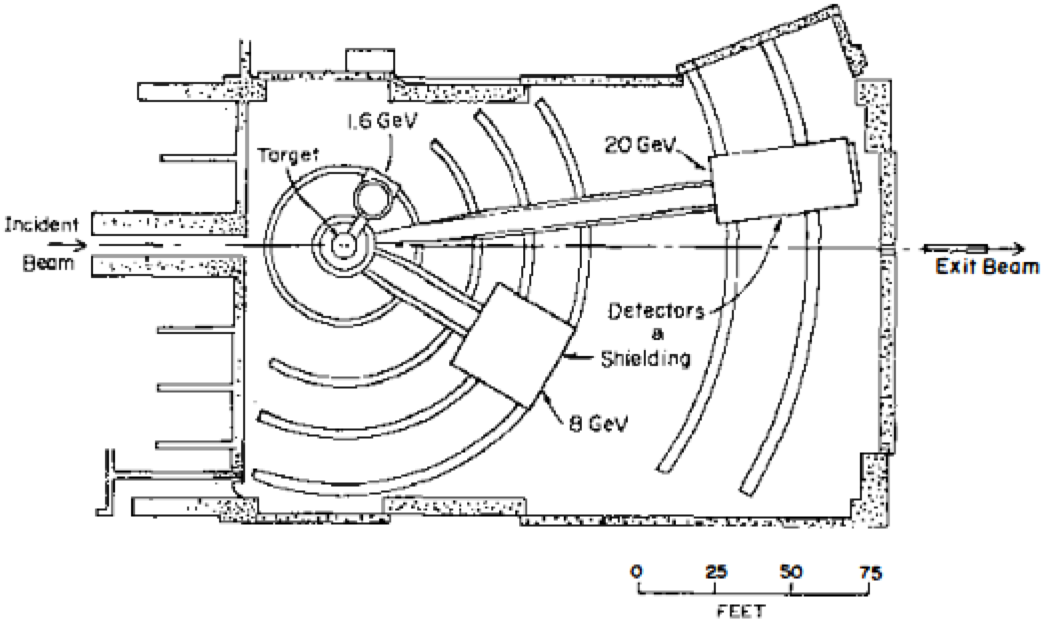


FIGURE 1. Plan view of the SLAC experimental area in which the MIT-SLAC deep inelastic electron scattering measurements were carried out.

Evidence for Pointlike Particles

- 1968: Large difference from elastic x-sec indicates internal structure
- Data was not precise enough to distinguish between three of the leading theories: vector meson dominance, Regge exchange, and parton (read quark) models

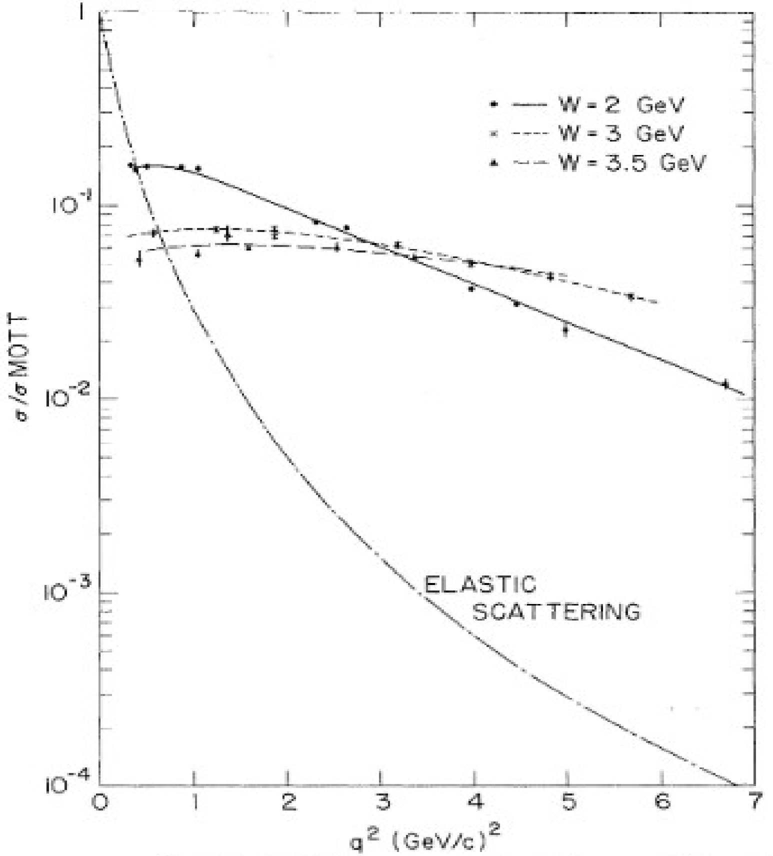


FIG. 1. $(d^2\sigma/d\Omega dE')/\sigma_{Mott}$, in GeV^{-1}, vs q^2 for $W = 2$, 3, and 3.5 GeV. The lines drawn through the data are meant to guide the eye. Also shown is the cross section for elastic $e-p$ scattering divided by σ_{Mott}, $(d\sigma/d\Omega)/\sigma_{Mott}$, calculated for $\theta = 10°$, using the dipole form factor. The relatively slow variation with q^2 of the inelastic cross section compared with the elastic cross section is clearly shown.

Feynman’s Copout

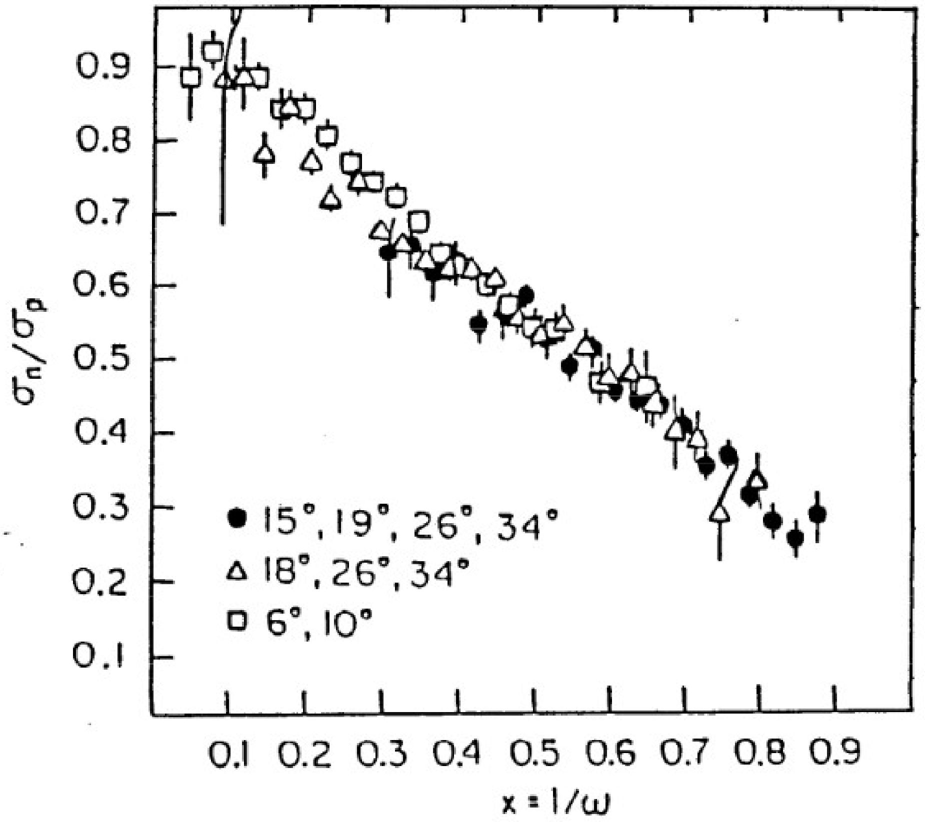
- Results from MIT-SLAC interpreted in terms of generic, pointlike particles whos Q#s should be determined from data (partons)
- Explains famous scaling behavior: Structure function of the proton W_2 is only a function of $(E-E')/Q^2$ and not each variable separately
- The proton structure function can then be related to the momentum distribution of the “partons”
- This could still be explained by some other competing theories

Further e+p Scattering results

- More data at different angles and energies came in 1969
- Clean measurements of both structure functions, the ratio of which is a direct test of proton structure models
- Scaling was again strongly observed, definitively ruling out vector meson dominance models
- Regge theories still could account for most features of the data
- Partons at this point are indicated to be spin 1/2

e+p and e+n: Separating u and d

- N and p x-sec ratio gives information about diffractive Regge models vs parton models
- For quark model, ratio als illuminates momentum distribution of partons inside proton



Sum Rules and Fractional Charges

- Theoretical calculations to explain experimental results informed the quantum numbers of partons
- Fractional charges were favored, as well as discrepencies that led to the positing of a neutral bosons that coupled to the partons
- One question remains: where are the bare quarks?

Brief Interleude: Other Evidence for Quarks

- Gargamelle: Neutrinos on protons showed structure functions consistent with pointlike proton constituents
- e+e- collisions: Hadron production too large to be explained by diffuse, extended objects
- Proton proton collisions at ISR: Rate of large angle production of particles exceeded Regge theory predictions

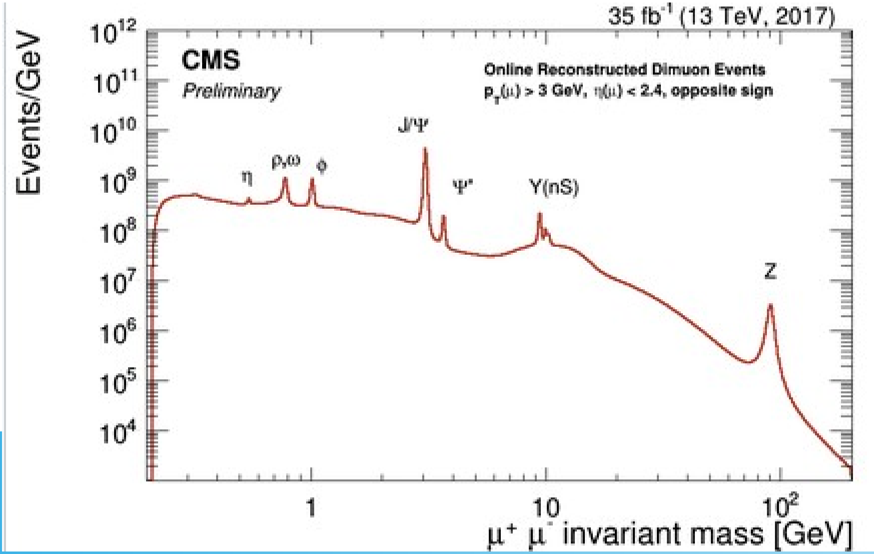
Quarks and QCD

- 1973: Asymptotic Freedom - theorized by Gross, Wilczek, and Politzer - gives correct behavior at short distances which explained the point like scattering from loosely bound constituents inside the proton
- Also predicted logrithmic scaling violations in DIS which were observed in subsequent experiments

$$\beta_1(\alpha) = \frac{\alpha^2}{\pi}\left(-\frac{11N}{6} + \frac{n_f}{3}\right)$$

Charm and Jets

- 1974: November Revolution and the discovery of the J/Psi was best explained in the context of a new quark in the quark model
- 1975: Observation of Jets solidified evidence of point like, strongly interacting proton constituents



And the Rest Is History

- Discovery of tau, and b shortly after 1975 started to flesh out the standard model
- Quarks were critical to explaining the experimental results related to the strong interaction
- Every talk about quarks should include one picture of James Joyce

James Joyce

Resource Links

- M. Riordan, *The Discovery of Quarks* Science 1992. Here
- V. A. Petrov, *Half a Century with Quarks* Here
- D. Bloom et al., Phys. Rev. Left. 23, 930 (1969); Here
- A. Bodek et al., Phys. Rev. Left. 30, 1087 (1973); Here