J/Ψ & QCD

DAVID GROSS

Kavli Institute for Theoretical Physics

IHEP October 20, 2024

1911-13 Nucleus

1925 Quantum Mechanics

1968-71 Electro-Weak

1973 QCD

1974 J/Ψ

1976— W,Z,tau, b,t,— 2012 Higgs

If SU(3) Why Not SU(4)?

Lepton-Quark Symmetry ?

J. D. Bjorken, S.L. Glashow Phys. Lett. 11:25, 1964
P. Tarjanne, V.L. Teplitz 1963; Y. Hara Phys Rev 134, B701
Z. Maki, Y. Ohnuki,1964

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Mills theory is discussed.

INTRODUCTION

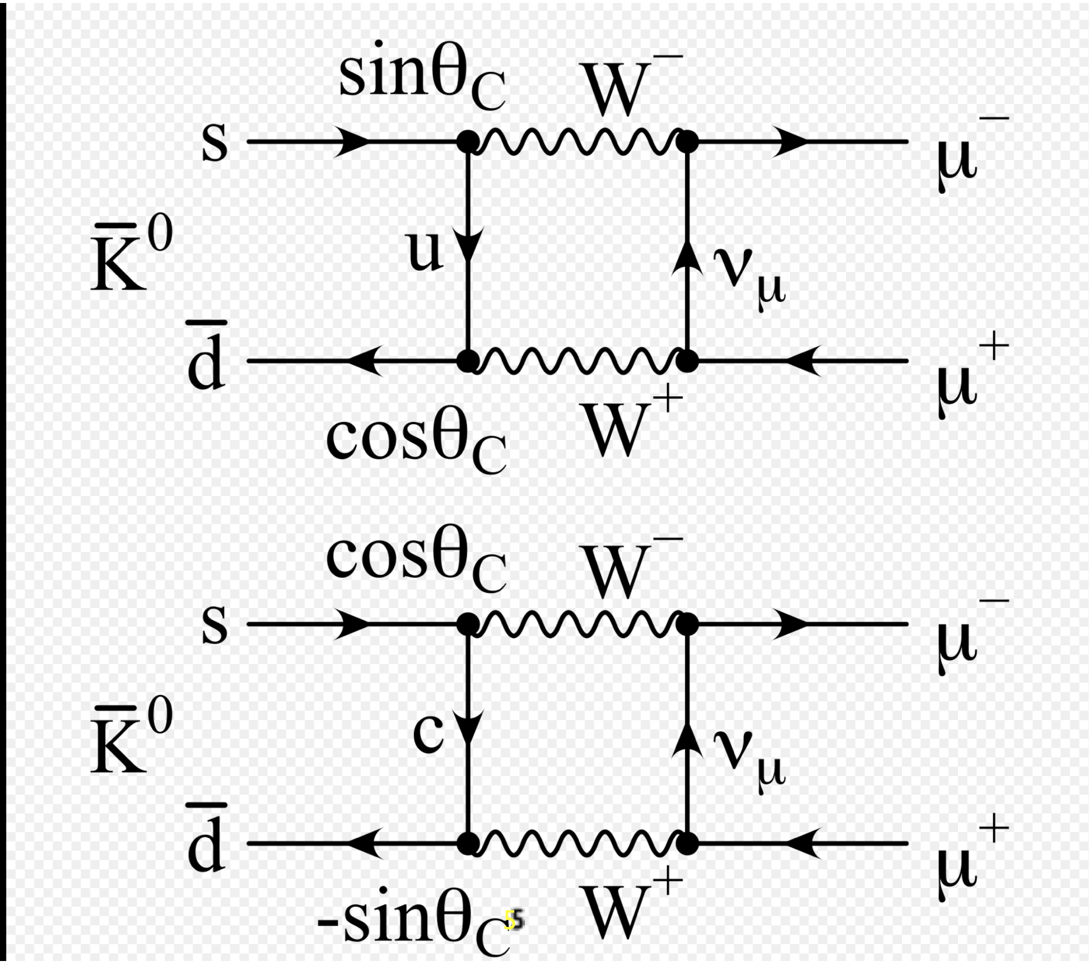
Weak-interaction phenomena are well described by a simple phenomenological model involving a single charged vector boson coupled to an appropriate current. Serious difficulties occur only when this model is considered as a quantum field theory, and is examined in other than lowest-order perturbation theory.[1] These troubles are of two kinds. First, the theory is too singular to be conventionally renormalized. Although our attention is not directed at this problem, the model of weak interactions we propose may readily be extended to a massive Yang-Mills model, which may be amenable to renormalization with modern techniques. The second problem concerns the selection rules and the relationships among coupling constants which are carefully and deliberately incorporated into the original phenomenological Lagrangian. Our principal concern is the fact that these properties are not necessarily maintained by higher-order weak interactions.

Weak-interaction processes, and their higher-order weak corrections, may be classified[2] according to their dependence upon a suitably introduced cutoff momentum Λ. Contributions to the S matrix of the form

* Work supported in part by the Office of Naval Research, under Contract No. N00014-67-A-0028, and the U. S. Air Force under Contract No. AF49(638)-1380.

Weak Interactions with Lepton-Hadron Symmetry*

S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)



AN ANOMALY-FREE VERSION OF WEINBERG'S MODEL

C. BOUCHIAT, J. ILIOPOULOS and Ph. MEYER
Laboratoire de Physique Théorique et Hautes Energies, Orsay, France ‡

Received 11 February 1972

We discuss the difficulties of carrying the renormalization program in a theory containing Adler anomalies. We present some models of weak and electromagnetic interactions, involving both lepton and quark fields, in which the troublesome anomalies cancel.

After the recent work of the Utrecht School [1], there has been a new interest in the attempts to construct a renormalizable theory of Weak Interactions. As it was suggested by Weinberg [2], the starting point is a Lagrangian obeying an exact gauge symmetry and containing a number of scalar fields. The symmetry is broken spontaneously by allowing some of the scalar fields to have a non-vanishing vacuum expectation value. It has been proven by Higgs [3] that, as a result of this symmetry breaking, the vector gauge fields acquire a mass and the massless scalar Goldstone bosons get decoupled. This program has been shown to be consistent in all orders of perturbation theory in a special renormalizable abelian model by Lee [4]. The question arises whether such a program can be carried through in a model including fermions coupled through both vector and axial currents. In this case one expects difficulties due to the well known anomalies of the axial current Ward identities [5]. In this letter we first exhibit given by the anomaly of the hadronic part of the axial current.

However, with the charge assignment given to the four quarks, it is impossible to construct a baryon octet with the observed electric charges. This is obvious for a three quark configuration and one can actually prove it ‡ for any configuration.

More realistic schemes ‡‡ are obtained if one considers more than one quark quartets. If the charge assignment for each quartet is Q_i, Q_i, $Q_i - 1$, $Q_i - 1$ for p', p, n and λ respectively, it is easy to verify that the cancellation of anomalies requires that the Q_i's satisfy the formula:

$$\sum_{i=1}^{n} Q_i = \tfrac{1}{2}(n+1)$$

where n is the number of quartets. Examples of such models are a three-quartet model with fractional charges $(\frac{2}{3}, \frac{2}{3}, -\frac{1}{3}, -\frac{1}{3})$ for all quartets, or the SU(4) generalization of the model proposed by Han and Nambu [9] with integral charges (+1, +1, 0, 0) (+1, +1, 0, 0) and (0, 0, -1, -1). The attractive feature of these models is that the baryon states can be constructed out of s-state $q_1 q_2 q_3$ combinations without introducing parastatistics.

‡ We thank Prof. S. L. Glashow for having brought this well-known fact to our attention.

‡‡ There exists always the obvious solution of constructing the hadronic weak current as $\bar{q}\gamma_\mu(1-\gamma_5)Cq$ and put the observed positive sign of g_A/g_V of neutron beta decay on the account of strong interaction renormalization effects. In this case the charge assignment must be (0, 0, -1, -1).

PHYSICAL REVIEW D VOLUME 6, NUMBER 2 15 JULY 1972

Effect of Anomalies on Quasi-Renormalizable Theories*

David J. Gross†
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

and

R. Jackiw
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 1 March 1972)

Apparently nonrenormalizable field theories, such as the new models for weak interactions, can become renormalizable when gauge invariance of the second kind is present. However, the anomaly associated with the axial-vector current may destroy this gauge invariance in perturbation theory, even though it is present in the Lagrangian. When this happens the theory remains nonrenormalizable. Nevertheless it is possible, by enlarging the theory, to remove the anomaly at the expense of introducing additional fermion fields, which correspond to as-yet-unobserved particles.

I. INTRODUCTION

In addition to the usual renormalizable and super-renormalizable field theories, there exist models which apparently yield, in conventional perturbation theory, a finite, well-defined, and

apparently nonrenormalizable theory into a quasi-renormalizable one, is gauge invariance of the second kind. In the massive-vector-meson example, the invariance, although "weakly" broken by the meson mass, is sufficiently operative to effect this desirable state of affairs. Similarly in anomalies. We can then couple the nucleons directly to the scalar mesons, or indirectly through a $(\sigma, \vec{\pi})$ multiplet of scalar mesons as suggested by Weinberg.[23]

The above model does not incorporate muons and strange hadrons; however, it is easy to construct models that do. In fact models involving leptons and quarks in a symmetric fashion have been introduced before.[24] These models are based on an SU(4) quartet of quark fields, and have the important advantage of eliminating first-order weak neutral strangeness-changing currents. The quark quartet is composed of the usual $\mathcal{P}$, $\mathcal{N}$, and λ SU(3) quarks with the addition of a $\mathcal{P}'$ quark, which differs from the triplet by one unit of a new quantum number (charm). In analogy with the above scheme for electrons and neutrons we assign to the antiquark the same charges as the four leptons. (One could always assign the quarks the same charges as the leptons; however, it would then be hard to understand why $G_A/G_V \approx +1$. The leptons and the quarks are then represented by the vector spinors[25]

$$l = \begin{pmatrix} \nu_e \\ \nu_\mu \\ e^- \\ \mu^- \end{pmatrix}, \quad q = \begin{pmatrix} \mathcal{N} \\ \lambda \\ \mathcal{P}' \\ \mathcal{P} \end{pmatrix}, \tag{5.7}$$

(5.12)

From the discussion above we know that there will be no anomalies associated with the SU(2) gauge fields alone (since $d_{abc} = 0$), and the anomalies in triangles with one or three B^μ fields clearly cancel. Furthermore, there are no neutral strangeness-changing weak currents, and the hadron weak current is still anomalous by itself, so π^0 can decay into two photons. The disadvantages of this scheme are (1) It forces us to a somewhat strange charge assignment for the quarks. In particular the charge operator has a singlet piece and the baryon octet cannot be built up from a single quartet of quarks.[26] As in the previous scheme, we must introduce a new quantum number (charm), for which there is no evidence. (2) The above theory places severe constraints on the strong interactions. Thus, for example, one cannot introduce neutral vector or axial-vector gluons, which mediate the strong interactions, since these would give rise to new anomalies. Scalar or pseudoscalar neutral gluons above are unacceptable, since the strong interactions would then be invariant under four charge-conjugation operations that act separately on each quark.[27] This would lead to an unacceptable degeneracy of charmed and

Heavy Quarks and e^+e^- Annihilation*

Thomas Appelquist† and H. David Politzer‡
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 19 November 1974)

The effects of new, heavy quarks are examined in a colored quark-gluon model. The e^+e^- total cross section scales for energies far above any quark mass. However, it is much greater than the scaling prediction in a domain about the nominal two–heavy-quark threshold, despite $\sigma_{e^+e^-}$ being a weak-coupling problem above 2 GeV. We expect spikes at the low end of this domain and a broad enhancement at the upper end.

We report some theoretical work on e^+e^- annihilation in asymptotically free, colored quark-gluon models of hadronic matter. Our fundamental assumption is that in addition to the light quarks that make up ordinary hadrons, there is a heavy quark, such as the charmed $\mathcal{P}'$. This has been suggested in several other contexts[1] and is consistent with the observed scaling and successful sum rules of inelastic lepton-hadron scattering. We argue that at energies well above the $\bar{\mathcal{P}}'\mathcal{P}'$ threshold ("threshold" and "mass" having technical definitions which in no way imply the existence of physical quarks), the total hadronic cross section scales as in the free-quark model because of the smallness of the asymptotic effective coupling. Scaling also holds in a region well above the $\bar{\lambda}\lambda$ threshold and well below the $\bar{\mathcal{P}}'\mathcal{P}'$ threshold, with the magnitude set by the light-quark charges. However, there are large enhancements in a finite region above and below the

the gauge-covariant derivative; and m is the quark mass matrix. We take the color gauge symmetry to be exact, giving rise to strong forces at large distances. Hence the gauge fields are massless, and each quark color multiplet has a given mass. We imagine $m_{\mathcal{P}}$, $m_{\mathfrak{N}}$, and m_λ to be small (< 1 GeV) while $m_{\mathcal{P}'} > 1$ GeV.

In renormalizing the theory, we define g in terms of the two- and three-point functions at some Euclidean momentum configuration of scale M. If asymptotic freedom is to explain Bjorken scaling, then for $M = 2$ GeV, $\alpha_s = g^2/4\pi$ must be small. m is related to the bare mass matrix m_0 by $m = Zm_0$, where Z is adjusted so that the $\mathcal{P}'$ propagator has a pole at $\not{p} = m_{\mathcal{P}'}$ to any finite order of perturbation theory.

The renormalization-group apparatus implies that in the one-photon approximation $\sigma(e^+e^- \to$ hadrons) is of the form $\sigma(s, g, m, M) = \sigma(s, \bar{g}(s), \hat{m}(s), s^{1/2})$, where s is the square of the center-of-mass

Search for charm

Mary K. Gaillard* and Benjamin W. Lee

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

Jonathan L. Rosner

University of Minnesota, Minneapolis, Minnesota 55455

A systematic discussion of the phenomenology of charmed particles is presented with an eye to experimental searches for these states. We begin with an attempt to clarify the theoretical framework for charm. We then discuss the $SU(4)$ spectroscopy of the lowest lying baryon and meson states, their masses, decay modes, lifetimes, and various production mechanisms. We also present a brief discussion of searches for short-lived tracks. Our discussion is largely based on intuition gained from the familiar —but not necessarily understood— phenomenology of known hadrons, and predictions must be interpreted only as guidelines for experimenters.

CONTENTS

et al., 1974; Barish *et al.*, 1974a, b; Lee *et al.*, 1974) of neutral currents point in the direction of a unified, renormalizable theory of weak interactions. However, other ingredients are necessary for the successful realization of such a theory; one possibility involves a fourth "charmed" quark, (Amati *et al.*, 1964a; Bjorken and Glashow, 1964; Maki and Ohnuki, 1964; Hara, 1964; Glashow *et al.*, 1970; Weinberg, 1971;

International Atomic Energy Agency

and

United Nations Educational Scientific and Cultural Organization

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

TOPICAL MEETING

ON THE PHYSICS OF COLLIDING BEAMS

20 - 22 June 1974

(SUMMARIES AND CONTRIBUTIONS)

	NAME	INSTITUTE	MEMBER STATE
3.	R. GATTO	Istituto di Fisica Università degli Studi Piazzale delle Scienze, 5 00185 Roma Italy	Italy
).	M.L. GOLDBERGER	Dept. of Physics Joseph Henry Laboratories Princeton University Jadwin Hall P.O. Box 708 Princeton, N.J. USA	U.S.A.
0	D. GROSS	Dept. of Physics Joseph Henry Laboratories Princeton University Jadwin Hall P.O. Box 708 Princeton, N.J. USA	U.S.A.
1.	J. HAÏSSINSKI	Laboratoire de l'Accélérateur Linéaire Centre d'Orsay Bâtiment 200 91405 Orsay France	France
2.	C.A. HEUSCH	Division of Natural Sciences II University of California Santa Cruz, Calif. 95064 USA	U.S.A./Fed. Rep. of Germany
3.	F.R. HUSON	Neutrino Department National Accelerator Lab. P.O. Box 500 Batavia, Ill. 60510 USA	U.S.A.
4.	M. JACOB	TH – CERN 1211 Genève 23 Switzerland	Switzerland/France
5.	K. JOHNSEN	ISR Department – CERN 1211 Genève 23 Switzerland	Switzerland/Norway
6.	P.T. MATTHEWS	Dept. of Theoretical Physics Imperial College of Science and Technology Prince Consort Road London SW7 England	U.K.

	NAME	INSTITUTE	MEMBER STATE
17.	C. MENCUCCINI	Laboratori Nazionali di Frascati Via Enrico Fermi 00044 Frascati (Roma) Italy	Italy
18.	B. RICHTER	Stanford Linear Accelerator Center P.O. Box 4349 Stanford, Calif. 94305 USA	U.S.A.
19.	ABDUS SALAM	Director International Centre for Theoretical Physics Trieste, Italy	Pakistan
20.	G. SALVINI	Istituto di Fisica Università degli Studi Piazzale delle Scienze, 5 00185 Roma Italy	Italy
21.	W. TONER	Rutherford Laboratory Chilton, Didcot Berks. OX11 0QX England	U.K.
22.	B.H. WIIK	DESY Notkestieg 1 2 Hamburg 52 Fed. Rep. Germany	Fed. Rep. of Germany/Norway
23.	A. ZICHICHI	NP Division CERN 1211 Genève 23 Switzerland	Switzerland/Italy

I. THE ROAD TO ASYMPTOTIC FREEDOM.

- In QUANTUM Field Theory B.J. Scaling requires

  ⟹ Asymptotic Freedom ≈ Strong Interactions "turn off" at short distances. (Callan + Gross)

- ASYMPTOTIC Freedom ⟹ Non-Abelian Gauge Theories of Strong Int. (Coleman Gross)

- Gauge Theories are Asym. Free (Gross w/ Wilczek, Politzer & 't Hooft)

  ⟹ BJ Scaling with $\ln Q^2$ corrections + Parton Model at short distances.

II. Structure of Asym. Free Gauge Theories

- Choice of Gauge Group, Color
- Low Energy Crisis. Containment.

III. Deep Inelastic Scattering.

- Where is Asymptopia?

Summary

Theoretical:

1. BJ Scaling ⇒ Asym. Free Gauge Theories ⇒ { BJ Scaling to within $\ln Q^2$. / Parton model at short distances }

2. By looking at short distances one can "see" { the Constituents of the Hadrons + Nature of the Strong Interactions. }

3. Asym. Freedom may provide mechanism for 1) Dyn. Sym. Breaking or 2) Containment of Quarks + Gluons.

4. Other Applications: 1. Use Weak Int. to probe short Distance Behavior of Strong Int
   $\Rightarrow \ln\left(\frac{M_W^2}{M_H^2}\right) \approx 10$. $\Delta I = \frac{1}{2}$ Rule (B. Lee + M. Gaillard, Altarelli + Maiani).
   2. Form Factors
   Large Angle Elastic
   Large $P_\perp$ Inclusive.
   ⋮

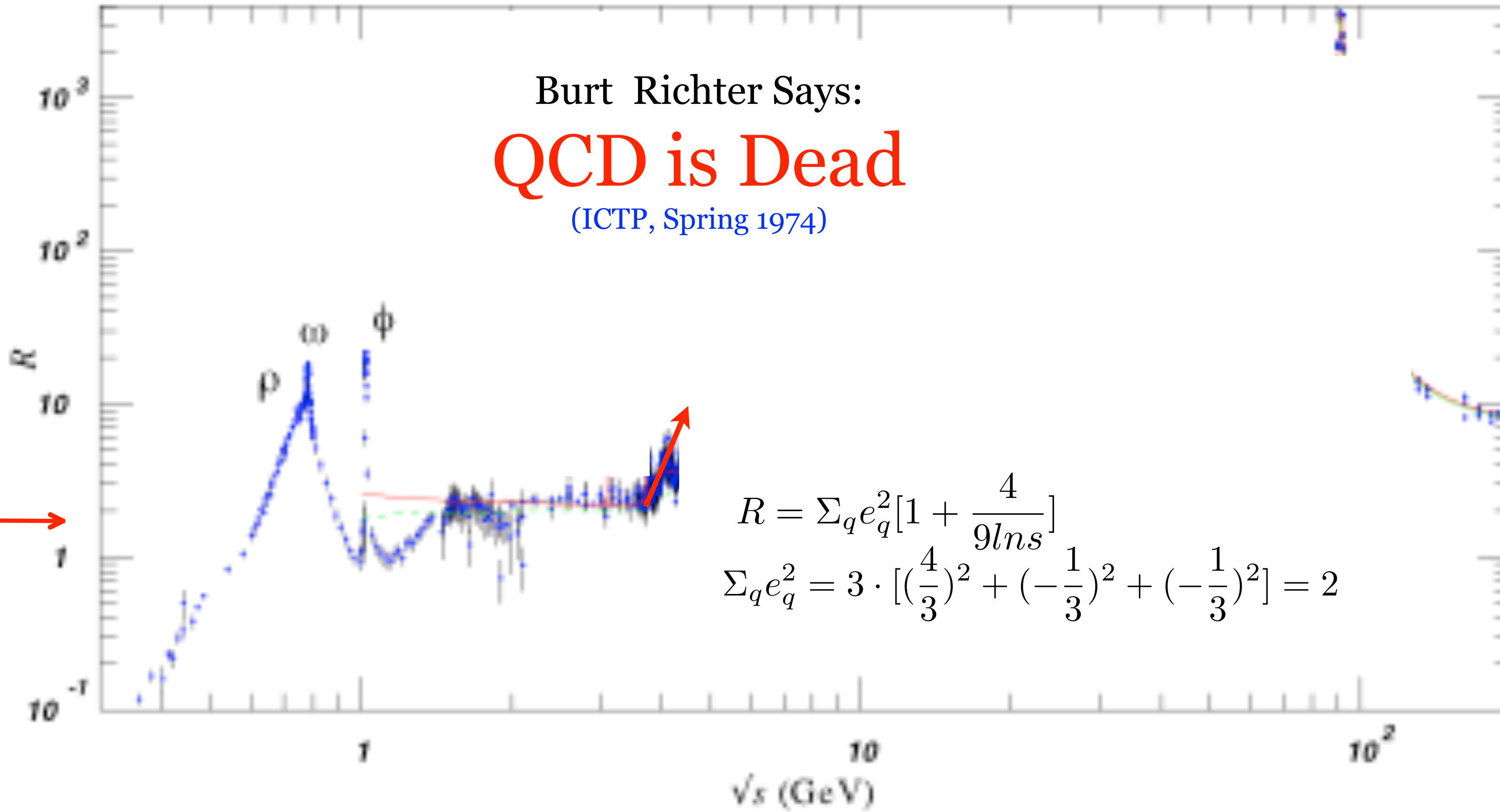
Exp. Tests

1. Expects substantial deviations from scaling, Q^2: 10–50 for small $\omega = \frac{2\nu}{Q^2}$.

2. Require: { High Precision 1~5% / Low ω }

   Ability to determine the ω-dependence of $\frac{F_L}{F_T}$, scaling violations, etc..

ELECTRON-POSITRON ANNIHILATION



Burt Richter Says:

QCD is Dead

(ICTP, Spring 1974)

3 colored quarks →

$$R = \Sigma_q e_q^2 [1 + \frac{4}{9 ln s}]$$

$$\Sigma_q e_q^2 = 3 \cdot [(\frac{4}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2] = 2$$

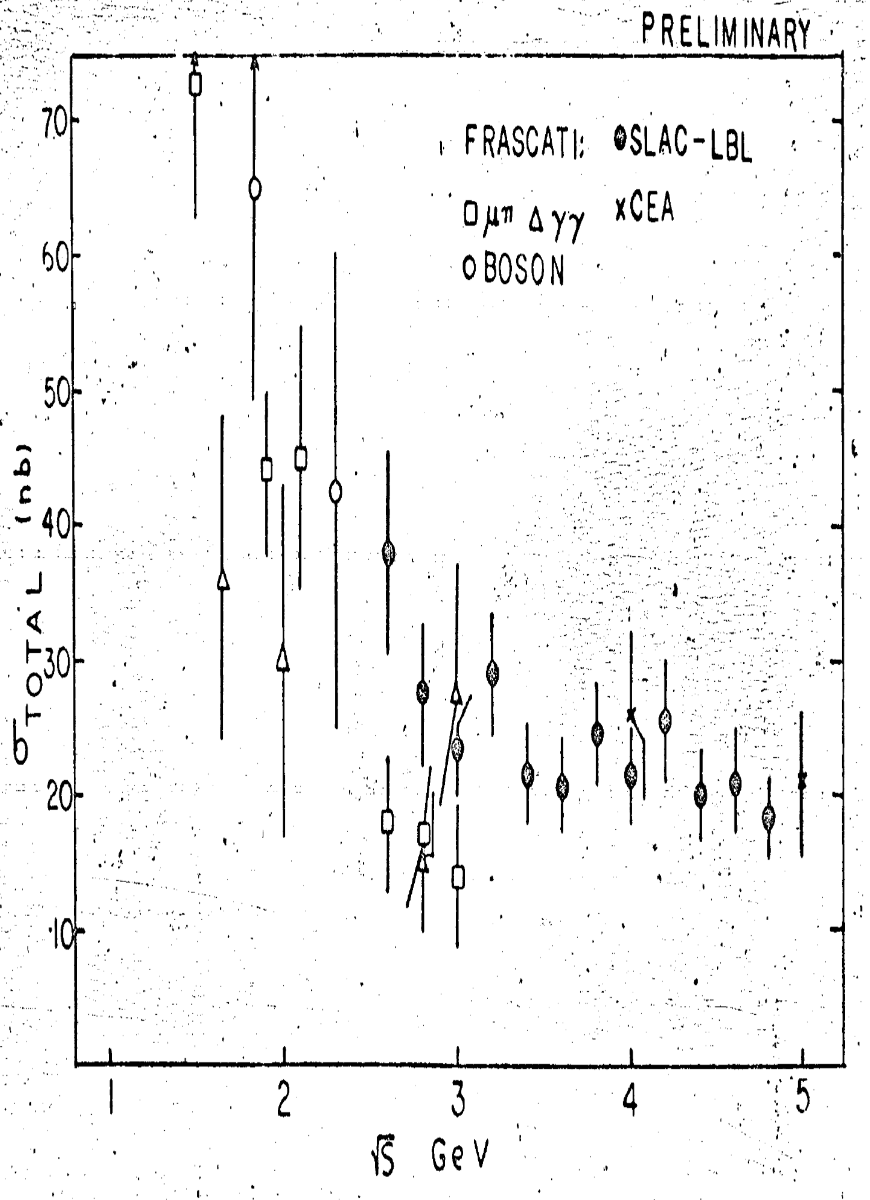


Fig. 5

-74-

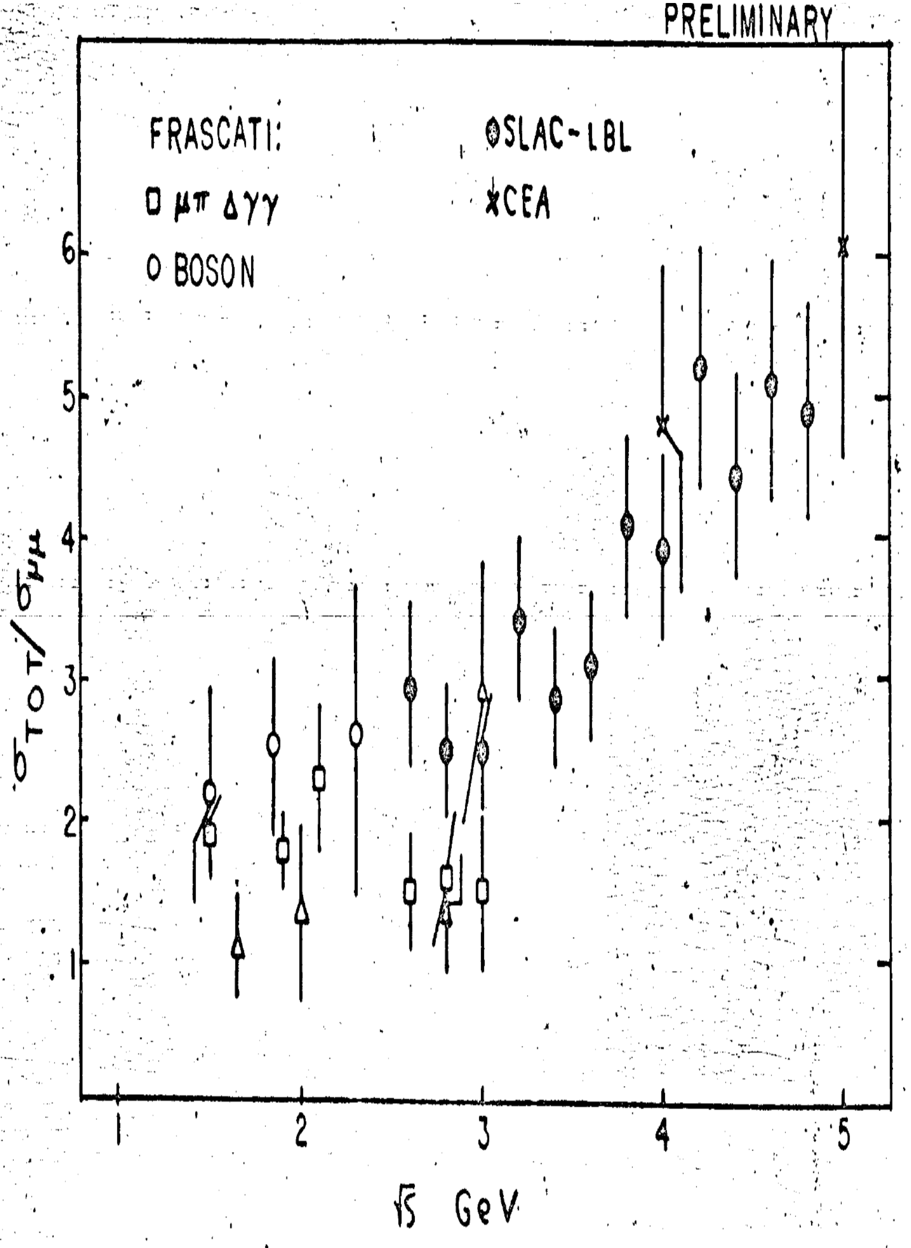


Fig. 6

-75-

Gaillard, Lee, Rosner
Search for Charm

C. $e\bar{e}$ annihilation

Once the energies of electron–positron colliding beams are high enough, pair production of charmed particles, and resonant production of ϕ_c are expected to proceed without inhibition.

The process $e+\bar{e}\rightarrow\phi_c$ should be very similar to $e+\bar{e}\rightarrow\phi$; in particular, $e+\bar{e}\rightarrow\phi_c\rightarrow\mu+\bar{\mu}$ presents a clean way of measuring the mass and width of the ϕ_c meson.

The processes $e+\bar{e}\rightarrow D+\bar{D}$ + pions, or $F+\bar{F}$ + pions, or $D+\bar{F}$ + pions and kaons, or its charge conjugate reaction should occur copiously above threshold. An interesting reaction is

$$e+\bar{e}\rightarrow D^0+\bar{D}^0$$
$$\bar{D}^0\rightarrow K^+ + \pi^-$$
$$D^0\rightarrow K^- + \pi^+$$

which will tell us about the mass of the D mesons unambiguously. [As pointed out by H. Lipkin (private communication), the process $e^+ + e^- \rightarrow D^0+\bar{D}^0$ is forbidden in the exact SU(4) limit.] Another signature of charm pair production is the observation of single μ's in coincidence with strange particles: these events can arise from one of the pair decaying leptonically and the other nonleptonically, i.e.,

$$e+\bar{e}\rightarrow D^+ + D^- + \cdots$$
$$D^-\rightarrow \mu^- + \cdots \text{ (leptonic)}$$
$$D^+\rightarrow \bar{K} + \cdots \text{ (hadronic)}$$

All these final states should occur in principle also in $p\bar{p}$ annihilation.

Finally, a remark is in order on the ratio R;

$$R=\frac{\sigma(e+\bar{e}\rightarrow \text{hadrons})}{\sigma(e+\bar{e}\rightarrow\mu+\bar{\mu})},$$

which is found to be in the neighborhood of 5 at the current SPEAR energies <5 GeV. In the three-color quark model which is asymptotically free, the asymptotic behavior of R is given by (Appelquist and Georgi, 1973; Zee, 1973)

$$R=2[1+\{C_3/\ln(s/\mu^2)\}],\qquad C_3=4/9 \tag{5.22}$$

for the quarks of charges 2/3, −1/3 and −1/3;

$$R=(10/3)[1+\{C_4/\ln(s/\mu^2)\}],\qquad C_4=12/25 \tag{5.23}$$

for four quarks of charges 2/3, 2/3, −1/3, and −1/3. We

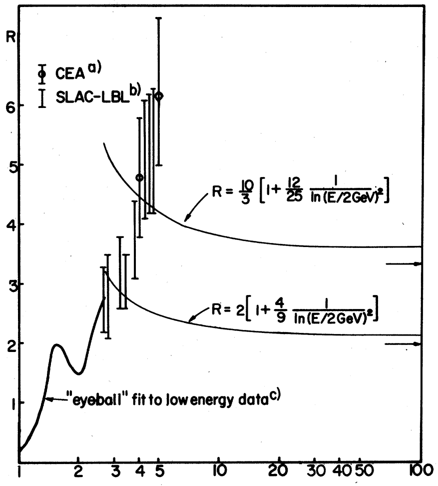


FIG. 8. Data on the ratio $R=\sigma(e\bar{e}\rightarrow\text{hadrons})/\sigma(e\bar{e}\rightarrow\mu\bar{\mu})$, and predictions of the asymptotically free quark model without charm (lower curve) and with charm (upper curve). (a) CEA data: Litke *et al.*, 1973. Tarnopolsky *et al.*, 1973. (b) SLAC–LBL data: Richter, 1974. (c) This is taken from Adler, 1974.

The following remarks were made to us by H. Lipkin, and we shall include them here with Professor Lipkin's kind permission.

1. The large charge of the charmed quark leads to a large predicted cross section for the production of charmed particle pairs once threshold effects are no longer relevant. Standard quark parton arguments would suggest that at sufficiently high energy 40% of all events should contain charmed particle pairs.

2. The dominant decay mode of charmed particles is nonleptonic with a strange particle in the final state. This implies that at sufficiently high energies roughly half of all events should contain strange particles in the final state. This is to be contrasted with prediction of the quark parton model for the case where there are no charmed particles which gives strange particles present in only one-sixth of the events.

3. The nonleptonic decay of a charmed particle into nonstrange particles is suppressed by a factor $\sin^2\theta$, where θ is the Cabibbo angle. However, if one of a pair of charmed particles decays in the nonstrange mode while the other decays into strange particles there will be an apparent violation of strangeness conservation in the final state which will contain only a single strange particle. If the probability

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen, J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \mathrm{Be} \to e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \to e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p/pulse. The beam is guided onto an extended target, normally nine pieces of 70-mil Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated daily with a thin Al foil. The beam spot size is 3×6 mm^2, and is monitored with closed-circuit television. Figure 1(a) shows the simplified side view of one arm of the spectrometer. The two arms are placed at 14.6° with respect to the incident beam; bending (by $M1$, $M2$) is done vertically to decouple the angle (θ) and the momentum (p) of the particle.

The Cherenkov counter C_0 is filled with one atmosphere and C_e with 0.8 atmosphere of H_2. The counters C_0 and C_e are decoupled by magnets $M1$ and $M2$. This enables us to reject knock-on electrons from C_0. Extensive and repeated calibra-

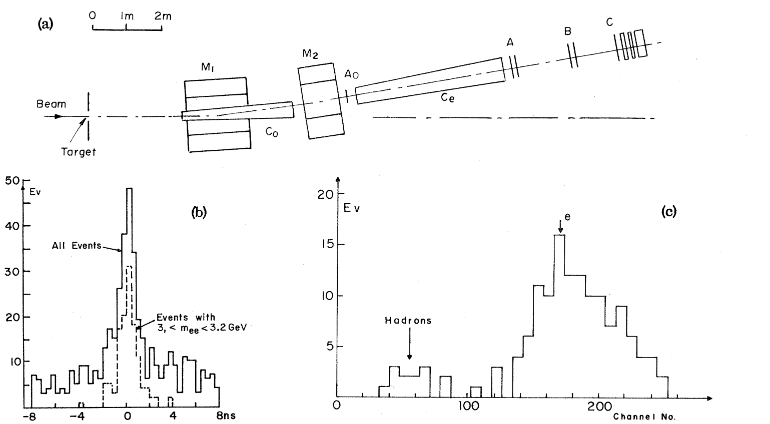
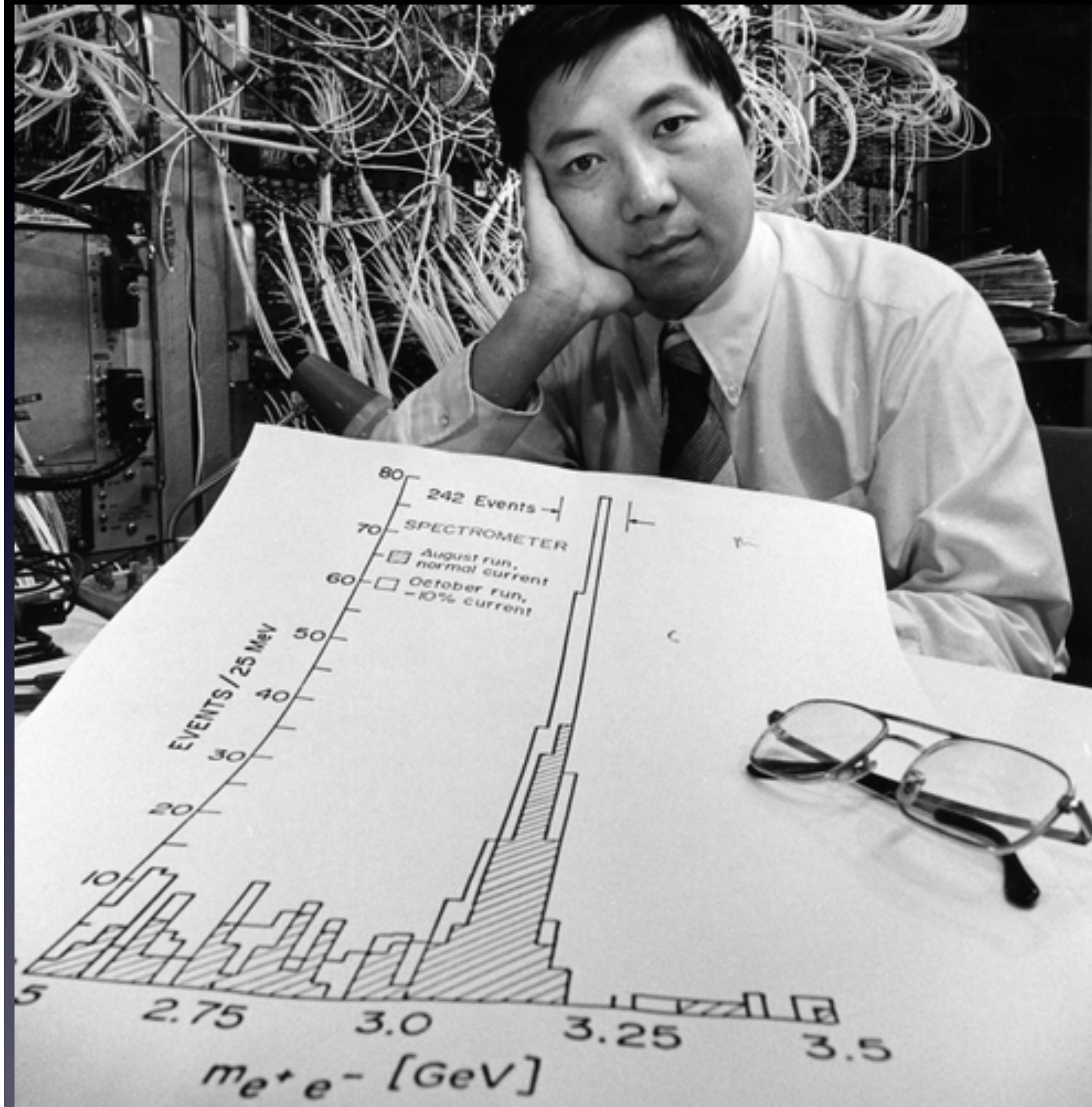


FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pairs and of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.



Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman, G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth, H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl, B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum, and F. Vannucci‡

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek, J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker, J. Wiss, and J. E. Zipse

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

We have observed a very sharp peak in the cross section for $e^+e^- \to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)–Lawrence Berkeley Laboratory magnetic detector[1] at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

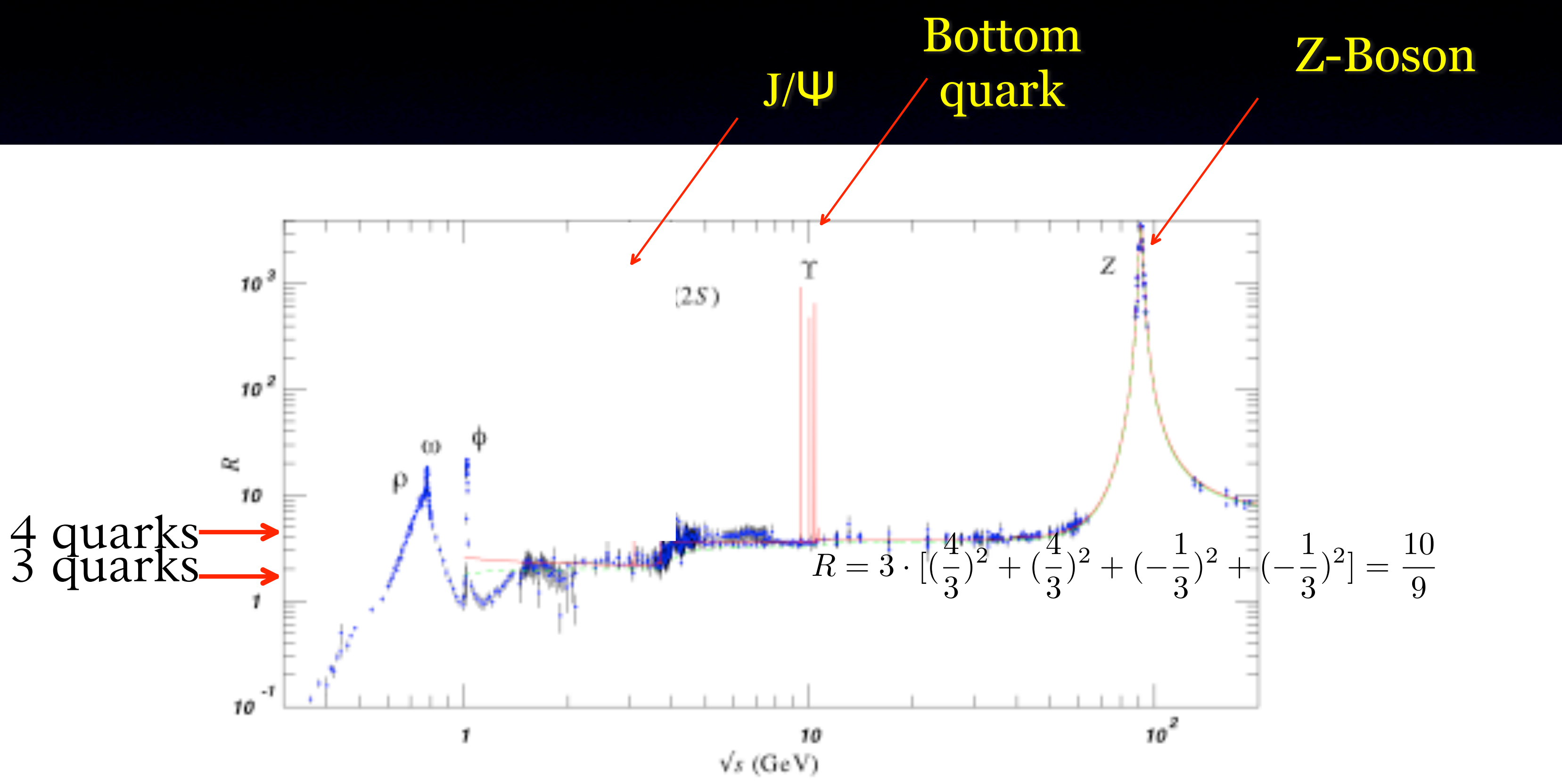
$$E = 3.105 \pm 0.003 \text{ GeV},$$

$$\Gamma \leqslant 1.3 \text{ MeV}$$

uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is $\geqslant 2300$ nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^- \to$ hadron cross section

ELECTRON-POSITRON ANNIHILATION



$$R = 3\cdot[(\frac{4}{3})^2 + (\frac{4}{3})^2 + (-\frac{1}{3})^2 + (-\frac{1}{3})^2] = \frac{10}{9}$$

Figure 39.6, Figure 39.7: World data on the total cross section of $e^+e^- \rightarrow hadrons$ and the ratio $R = \sigma(e^+e^- \rightarrow hadrons)/\sigma(e^+e^- \rightarrow \mu^+\mu^-$, QED simple pole). The curves are an educative guide. The solid curves are the 3-loop pQCD predictions for $\sigma(e^+e^- \rightarrow hadrons)$ and the R ratio, respectively [see our Review on Quantum chromodynamics, Eq. (9.12)] or, for more details, K.G. Chetyrkin *et al.*, Nucl. Phys. [illegible]

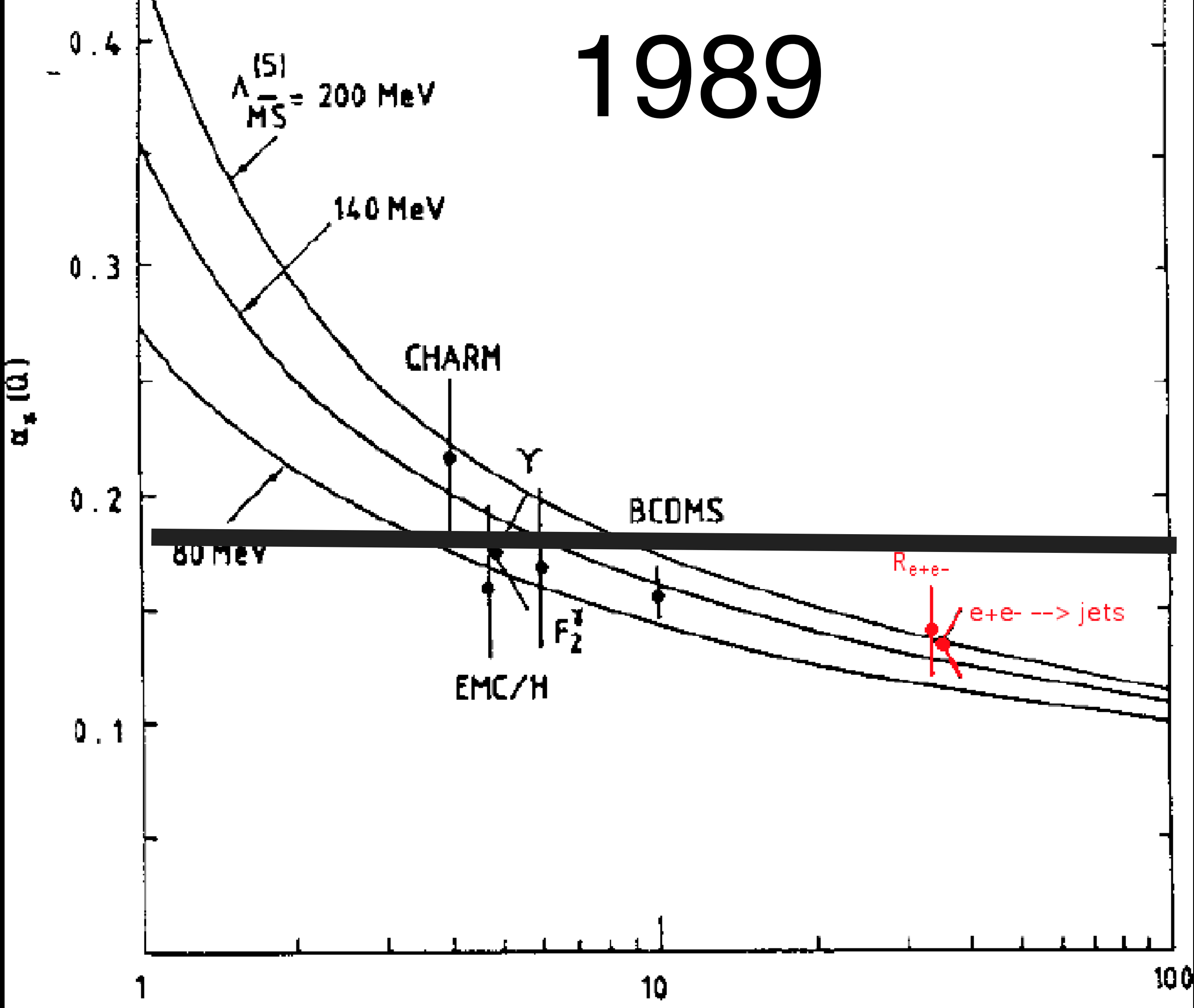
The discovery of the J/Ψ particle
was a pivotal moment for the Standard Model

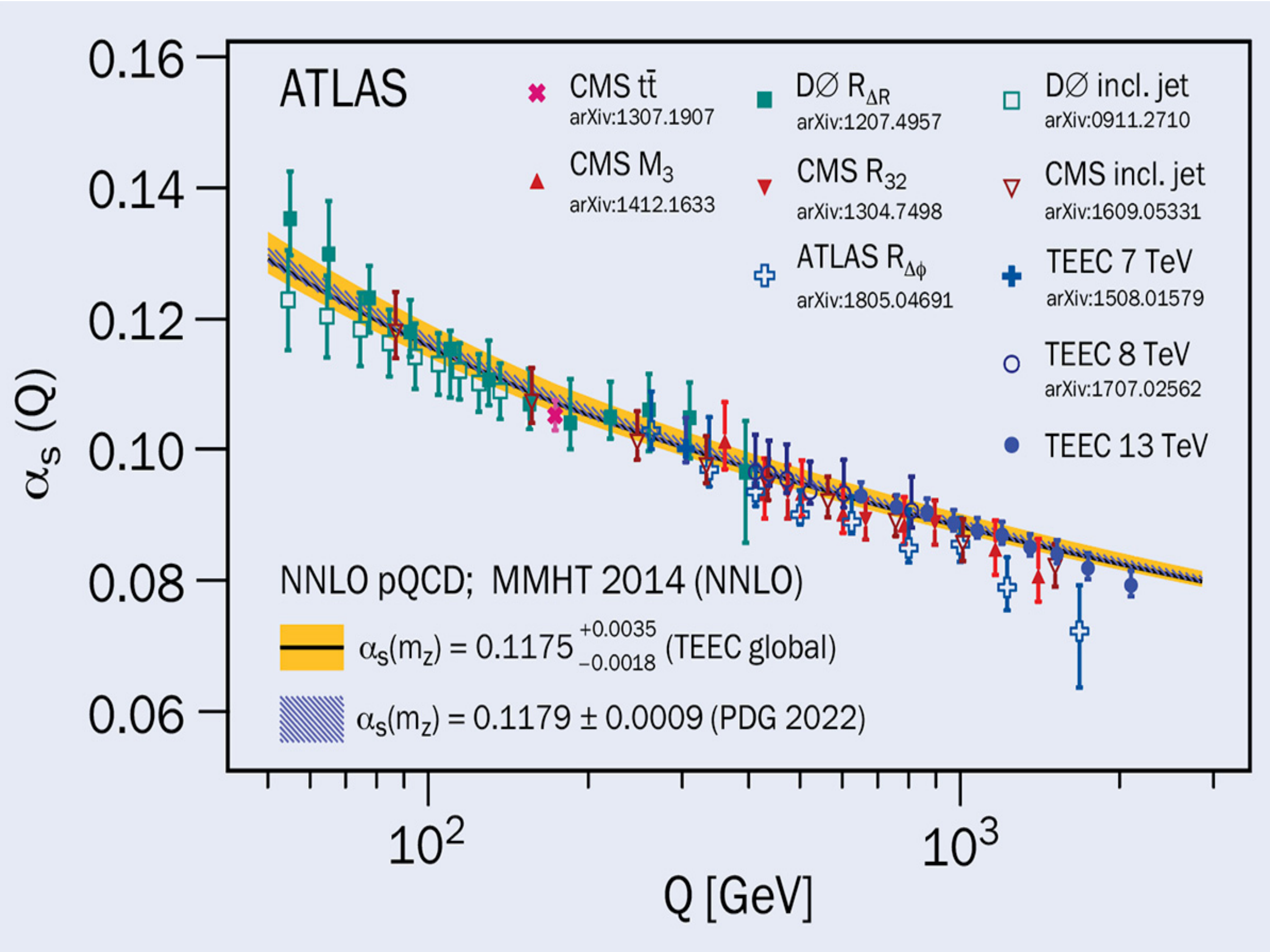
Electro-Weak: Essential for consistency of the SU(2)xU(1) Gauge theory of GWS.

Strong: Turning point for the acceptance of QCD. First evidence for heavy quark bound states that provide a rich laboratory for the study of perturbative and non-perturbative QCD.

ASYMPTOTIC FREEDOM

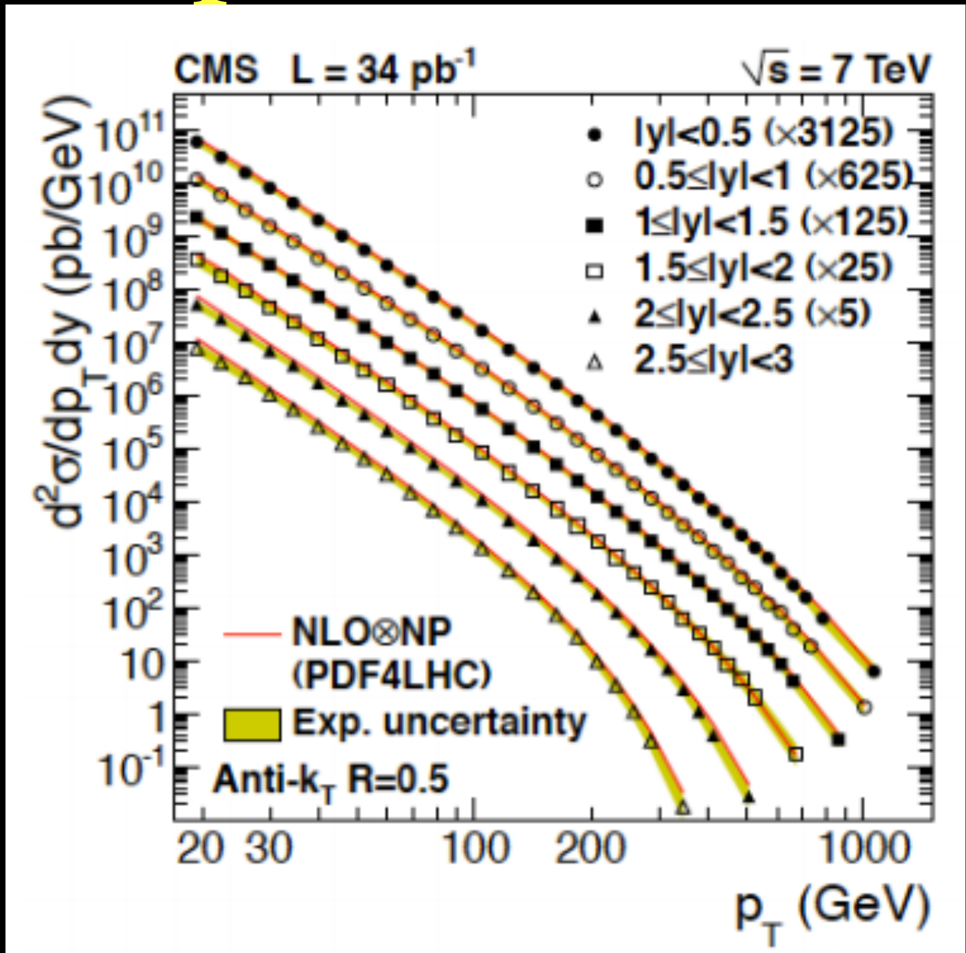
1989

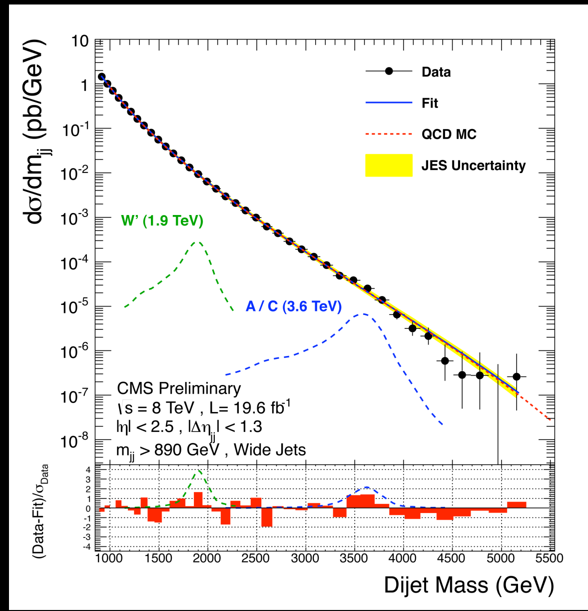


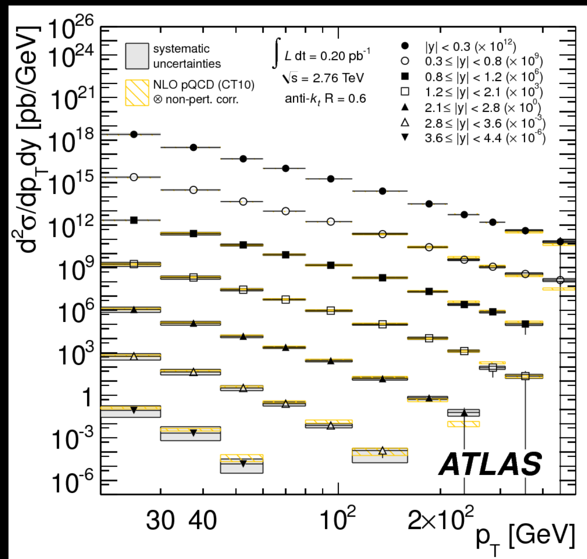


ATLAS
CMS tt̄
arXiv:1307.1907
DØ R_ΔR
arXiv:1207.4957
DØ incl. jet
arXiv:0911.2710
CMS M3
arXiv:1412.1633
CMS R32
arXiv:1304.7498
CMS incl. jet
arXiv:1609.05331
ATLAS R_Δϕ
arXiv:1805.04691
TEEC 7 TeV
arXiv:1508.01579
TEEC 8 TeV
arXiv:1707.02562
TEEC 13 TeV
NNLO pQCD; MMHT 2014 (NNLO)
αs(mz) = 0.1175 +0.0035 −0.0018 (TEEC global)
αs(mz) = 0.1179 ± 0.0009 (PDG 2022)
αs (Q)
Q [GeV]
0.16
0.14
0.12
0.10
0.08
0.06
10^2
10^3

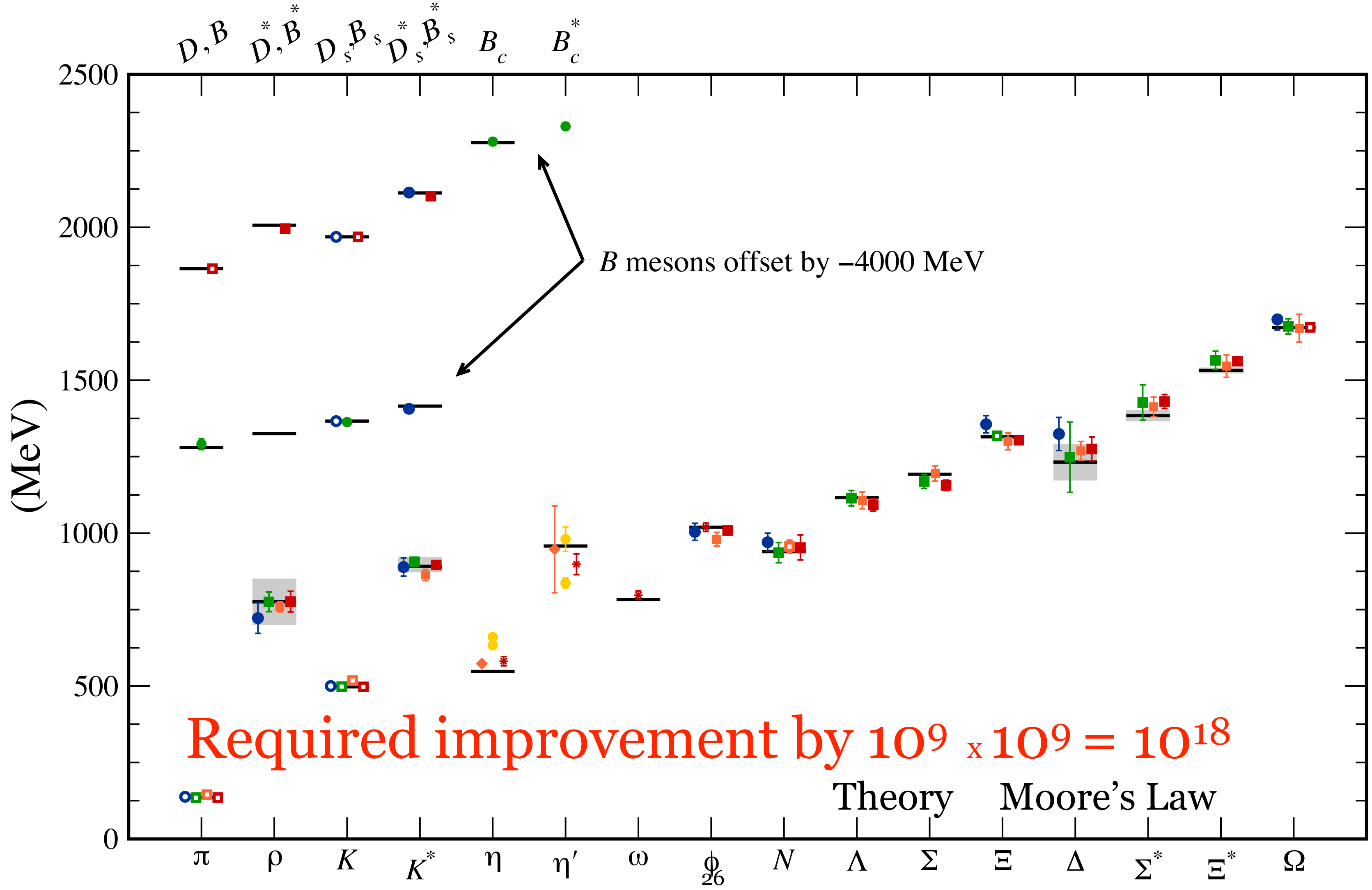
Thousands Of Impressive Tests







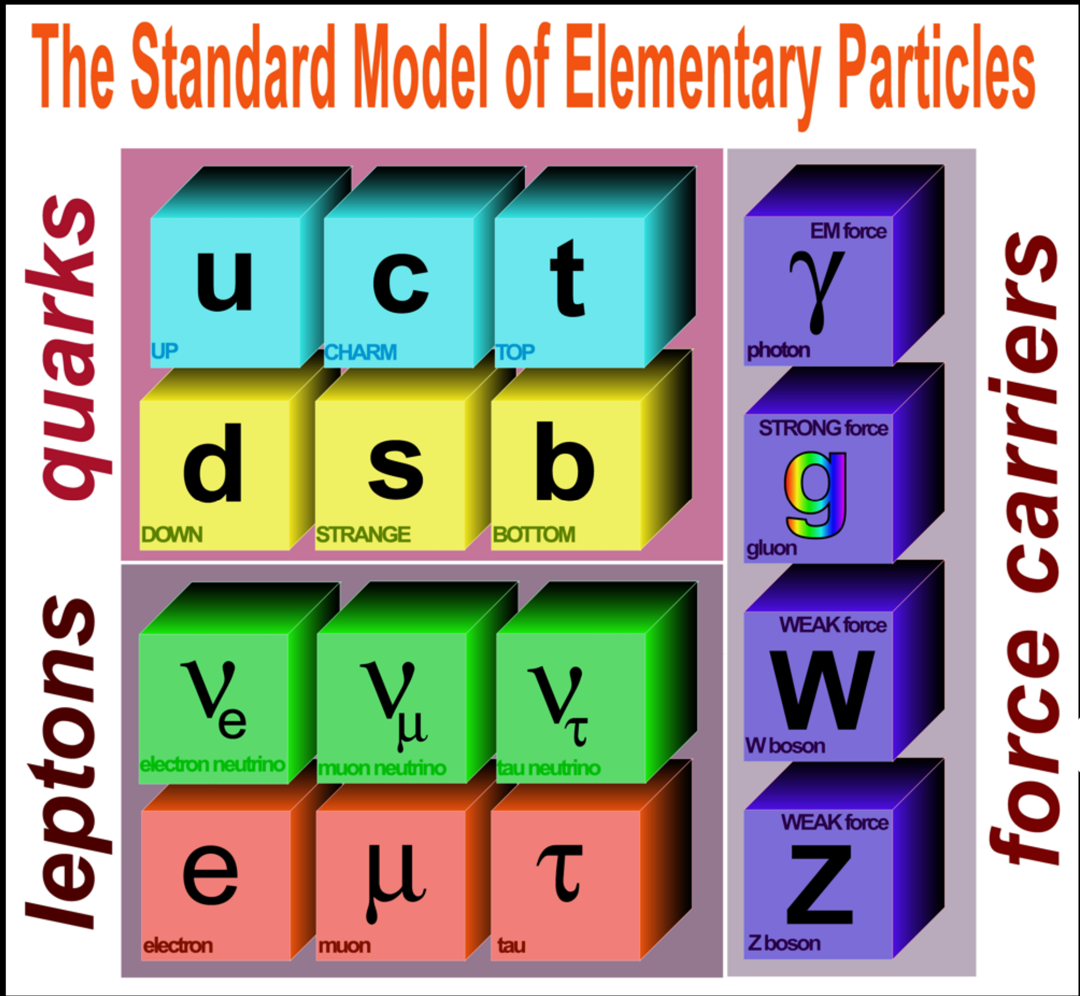
The Light Hadron Spectrum Of Qcd



Required improvement by $10^9 \times 10^9 = 10^{18}$

Theory Moore's Law

THE STANDARD MODEL



1 E & M

2 WEAK

3 STRONG

HIGGS

May the next 50 years be as exciting as the last 50 years!

THE END