A Brief History of Quarks and Gluons

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Today's Outline

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2. Quarks 101
3. From Atoms to Top
4. Nuclear Attraction
5. A Strange Encounter
6. "Three quarks for Muster Mark!"
7. Deep-Inelastic Scattering
8. Electron-Positron Collisions
9. Epilogue
10. Quarks in Action

A Quick Survey…

Word Cloud: *What physics analysis are you working on?*

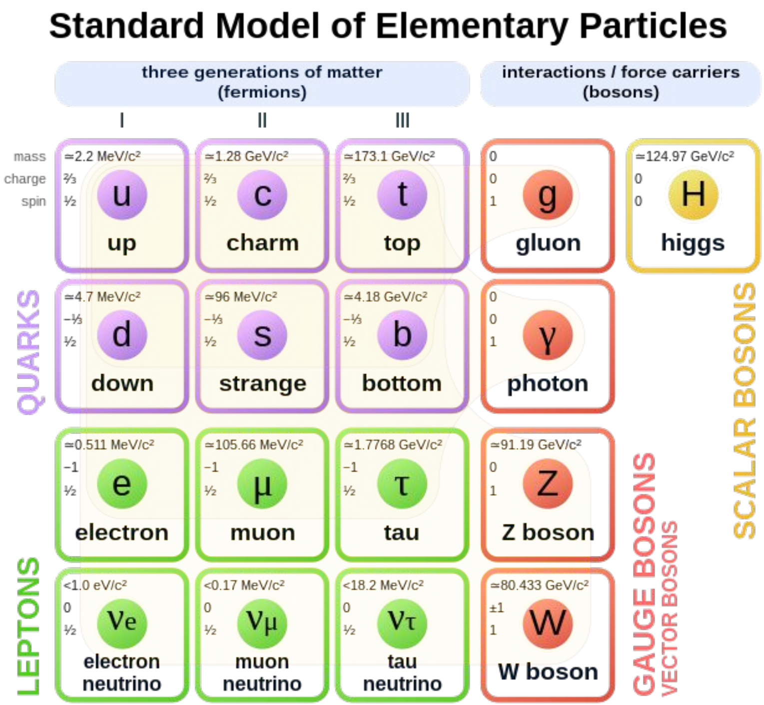
- *Go to slido.com and enter code #7941083*

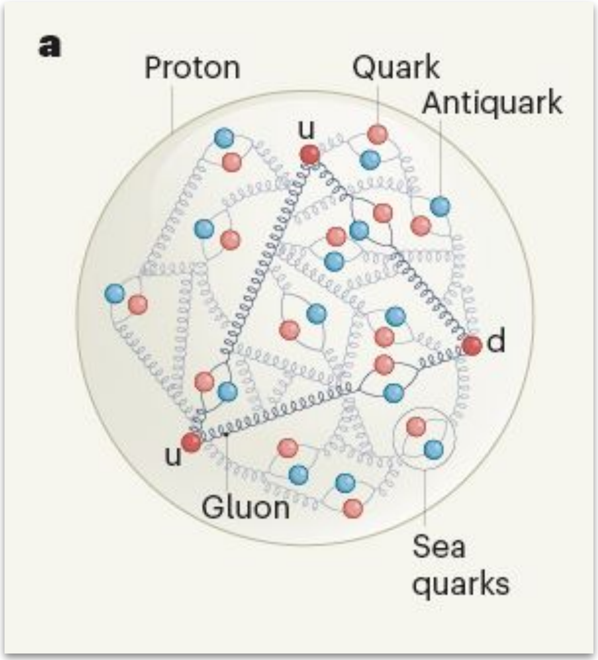
Quarks 101

Let's do a quick review of the basics of the Standard Model quark...

Join Kahoot

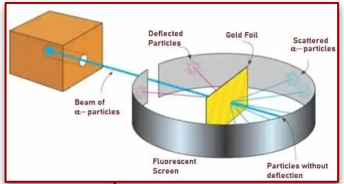
Quarks 101 – Standard Model



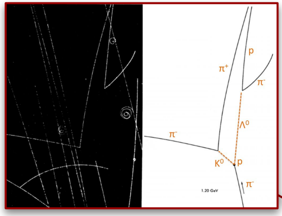


From Atoms to Top

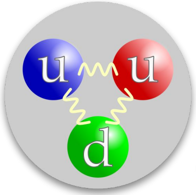
Rutherford discovers protons and nucleus using gold foil (1911)



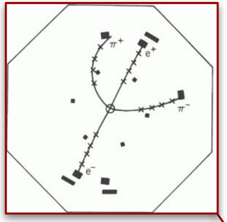
Kaon (K-meson) tracks observed from cosmic rays (1947)



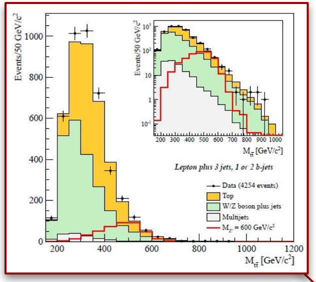
Gell-Mann proposes quark (*uds*) theory (1964)



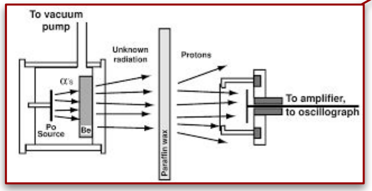
November Revolution: Charm quark discovered via J/Psi production by SLAC and BNL (1974)



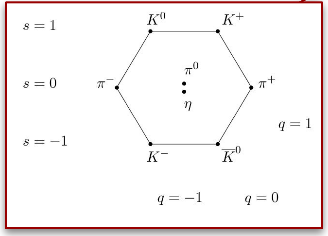
Top quark discovered via tt decay at FNAL Tevatron by CDF and D0 (1995)

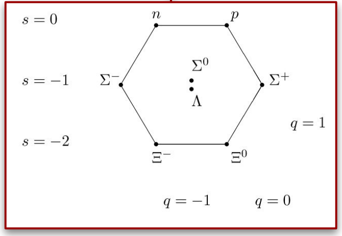


1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970 1975 1980 1985 1990 1995

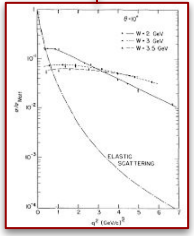


Chadwick discovers the neutron ejected from paraffin wax (1932)

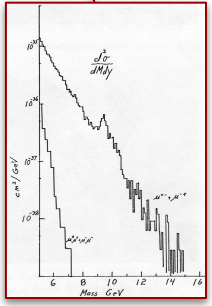




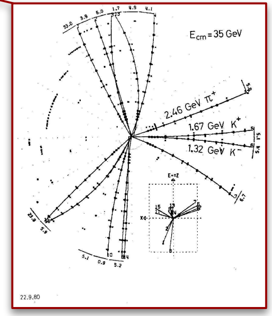
Oppenheimer describes the plethora of new hadrons being discovered throughout the 50s as the "Particle Zoo"



Quarks observed via deep-inelastic scattering by SLAC-MIT (1968)



Bottom Quark discovered via Upsilon at FNAL (1977)



Gluon discovered at DESY PETRA (1979)

Nuclear Attraction

After establishing the nuclear atomic model, two questions remained:

- How does the proton-neutron nucleus stay together?
- Why is an alpha particle emitted?

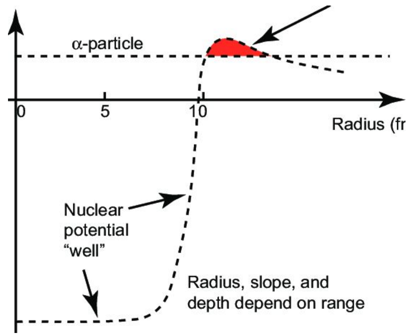
Strong force more attractive than protons are repulsive

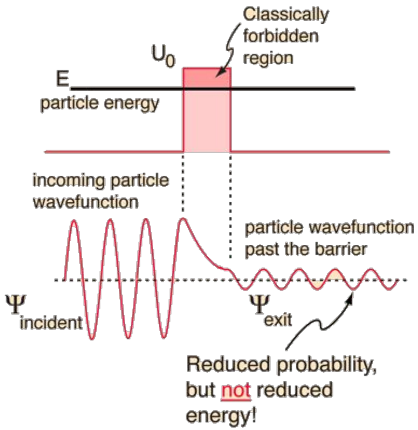
- H. Yukawa proposes a "mesotron" to mediate strong nuclear force in 1935
- Mesotron mass predicted via uncertainty principle to be ~100 MeV

Nuclear binding energy minimizes potential energy of alpha particle

Quantum tunneling allows "escaping" the classical Coulomb potential

In 1911, beta decay hints at weak interaction → "flavor" transformation





A *Strange* Encounter

First (indirect) evidence of quarks was with observation of cosmic ray kaon in 1947

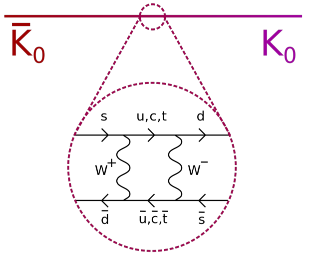
- *Cloud chamber tracks from G.D. Rochester and C.C. Butler*
- $K^{\pm}$ *found to have multiple decay modes*
- K^{0} *found to have two distinct lifetimes*

*The solution: **strangeness** (A. Pais) and **parity** (Lee, Yang, Wu)*

- *Strangeness and parity conserved in strong interactions*
- *Strangeness and parity not conserved in weak interactions*
- *Implication → two neutral kaons made up from "mixing"* K^{0} *and anti-*K^{0}

"Particle Zoo" leads to Gell-Mann's "Eightfold Way" for hadrons

Kaon Oscillations



$K_S^0 \quad \frac{\Psi(d\bar{s})+\Psi(\bar{d}s)}{\sqrt{2}}$ *Lifetime* $9x10^{-11}$ sec

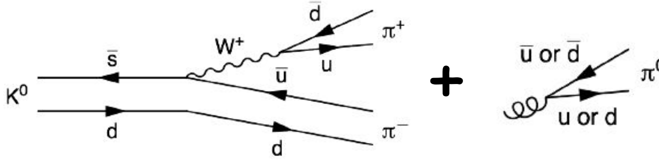
$K_L^0 \quad \frac{\Psi(d\bar{s})-\Psi(\bar{d}s)}{\sqrt{2}}$ *Lifetime* $5x10^{-8}$ sec

Parity Conserved

$$K_S^0 \rightarrow \pi^+ + \pi^-$$
$$K_S^0 \rightarrow \pi^0 + \pi^0$$

Parity Not Conserved

$$K_L^0 \rightarrow \pi^+ + \pi^- + \pi^0$$
$$K_L^0 \rightarrow \pi^0 + \pi^0 + \pi^0$$



“Three Quarks for Muster Mark!”

By 1964, there is a **need** for an attractive nuclear force as well as **evidence** of “strange” particles fitting Yukawa’s strong force mediator

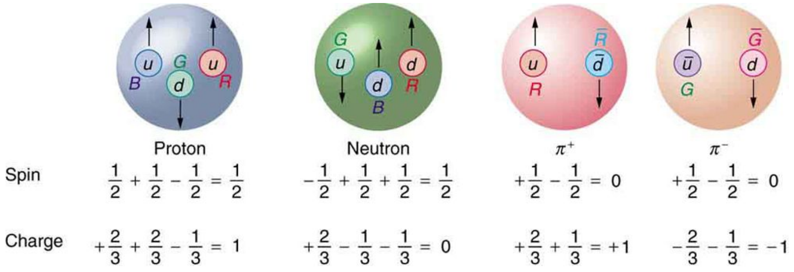
Gell-Mann and Zweig introduce quark model in 1964

- *Motivated by explaining the strange kaons*
- *Initially only considered up, down and strange*

Quark model was difficult to accept due to fractional charge ⟶ <u>“A search for stable quarks of charge -⅓ or +⅔ … would help to reassure us of the non-existence of real quarks”</u>

Features of Gell-Mann’s quark model:

- *SU(3) ⟶ these would eventually be color charge*
- *Fermionic with charges of ±1/3 and ±2/3*
- *Mesons are quark, anti-quark pairs*
- *Baryons are quark triplets*
- *Quarks can “transform” via beta decay down to most stable “up” quark*



Deep-Inelastic Scattering (1)

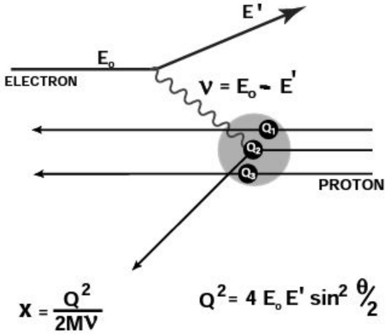
In 1963, SLAC-MIT collaboration begins with plans to collide electrons into protons (liquid hydrogen)

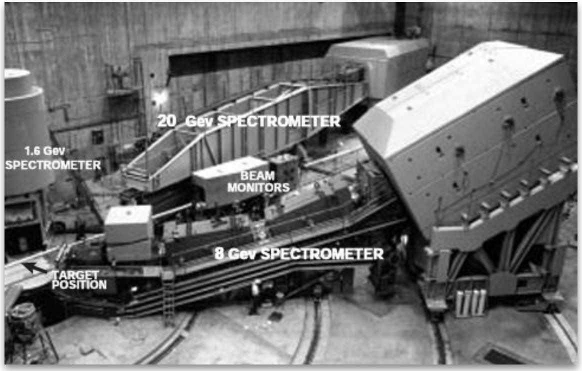
- Measure deflected electron energy at various angles of θ
- Analogous to Rutherford's gold-foil alpha-scattering experiment in 1911

Established three spectrometers to measure electrons with momentum of 20,8 and 1.6 GeV

In 1968, accelerating electrons up to 17.7 GeV achieving momentum transfers up to 7.4 GeV at 6° and 10°

- Either excite or "shatter" the proton ⟶ observe resultant hadron
- MIT and SLAC separately apply radiative corrections to data





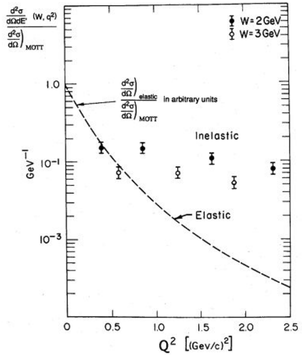
Deep-Inelastic Scattering (2)

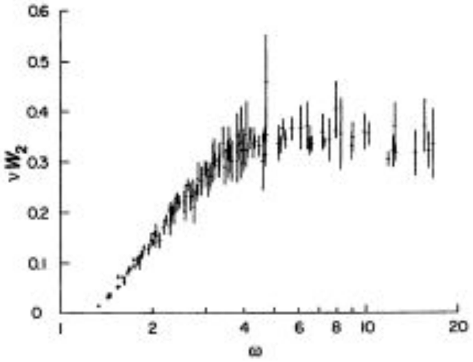
1968 cross-section measurements in the deep inelastic scattering region show slower dependence on momentum transfer (Q^2) *than if only elastic scattering*

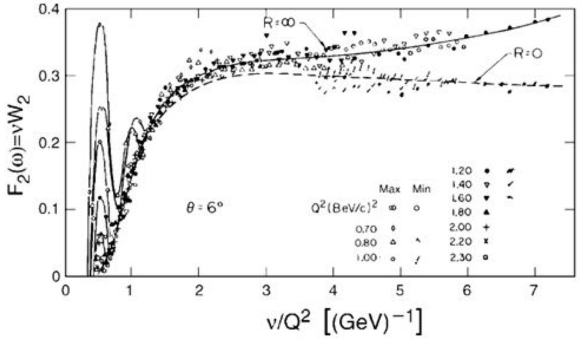
- *Evidence of "partonic" structure* $\rightarrow$ *theory described by Feynman*
- *Needs more proof for quark spin and fractional charge*

Parton model predicted that νW_2 *dependent on ratio of* ν/Q^2 *and not* ν *and* Q^2 *independently* $\rightarrow$ *"scaling"*

- ν *is the energy lost by electron*
- W_2 *is proton structure function*
- *Can also define via* $1/x = \omega = 2M_p\nu/Q^2$
- x *is the fraction of proton momentum carried by the quark*







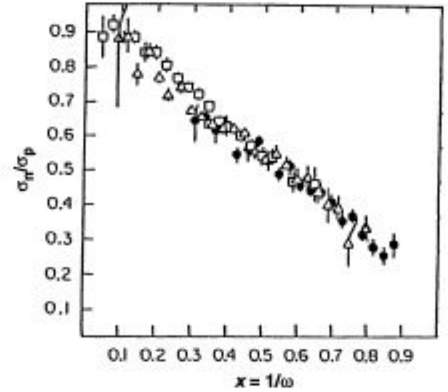
Deep-Inelastic Scattering (3)

Spin determined from the ratio of the proton's photon absorption longitudinally versus transversely

From 1970 to 1973, fractional charge determined from the ratio of the neutron to proton cross section

- σ_n / σ_p = ⅔ ⟶ *sum of the squared quark charge*
- *Found ratio scaling between 0.3 (high x) and 1 (low x)*

However, calculations of the parton "sum rules" over the structure functions indicated missing half the parton momentum ⟶ hinting at gluons



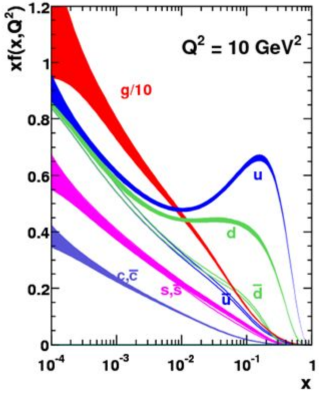


TABLE 3. Sum Rule Results—Theory and Measurement[b]

	Expected Value[a]		Measurement	ω_m	q^2(GeV/c)^2
	3 Quark	3 Quark+'Sea'			
I_1^P	1/3	$2/9+\frac{1}{3\langle N\rangle}$	0.159±.005	20	1.0
			0.165±.005	20	1.5
			0.172±.009[c]	20[c]	1.5[c]
			0.154±.005	12	2.0
I_1^N	2/9	2/9	0.120±.008	20	1.0
			0.115±.008	20	1.5
			0.107±.009	12	2.0

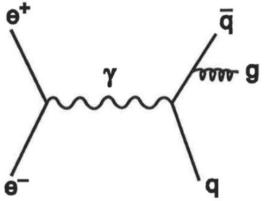
Electron-Positron Collisions (1)

Gluons arise theoretically when the gauge theory successfully applied for the weak force (1964) is then applied to the quark model

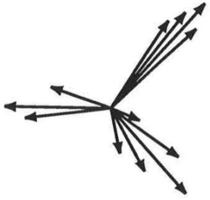
- Gauge theory proposed **massive** weak force mediators $W^{\pm}$ and Z^0
- Gauge bosons are spin-1 (i.e. photons, $W^{\pm}$, Z0, gluon)

DESY constructs the Positron-Electra Tandem Ring Accelerator (PETRA) in 1978 and the TASSO collaboration builds a detector to discover the gluon in a three-jet event (qqg) in 1979

- Began at $\sqrt{s}$ = 13 GeV in 1978, reaching 27 GeV by 1979
- Jets are the hadronization of quarks emerging from a particle collision in a defined cone



$e^+e^- \longrightarrow q\bar{q}g$



Three-Jet Events

Electron-Positron Collisions (2)

Why three jets from $e^+e^- \longrightarrow qqg$?

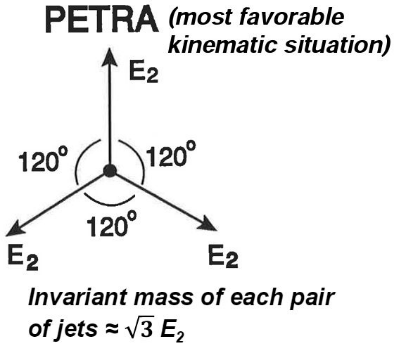
- *Spin conservation demands the third jet to be integer spin*
- *Hadronization $\longrightarrow$ cannot be color singlet*

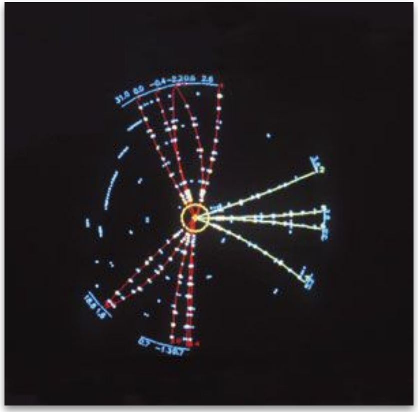
Higher energies in the collision necessary to resolve the three jets

- *Ideally, each jet would have ~4.3 GeV to be oriented at 120° to one another*
- *To resolve further $\longrightarrow$ total event energy of ≥20 GeV*

Analysis strategy: minimize the total sphericity of the three jets

In 1980, Gluon spin confirmed to be 1 $\longrightarrow$ confirmation of gauge theory





Epilogue

QCD and "color charge" established in 1973

- Non-observation of isolated quark explained by color confinement and asymptotic freedom

1974 November Revolution when the **charm** is discovered via the **J/Psi meson** by SLAC and BNL

- Predicted in 1970 via GIM mechanism which suppressed FCNC by introducing charm quark

"Accidental" tau lepton discovery in 1975 when observing $e^+e^- \rightarrow e^+\mu^-$ suggests third generation (if symmetry is desired)

Bottom quark discovered in 1977 via the **Upsilon meson** by Fermilab's E288 experiment

Top quark discovered in 1995 via **ttbar** production at Fermilab's Tevatron by CDF and D0

Quarks in Action

In modern particle physics, we have certain norms in which we view quarks/jets:

- *"Heavy flavor" = charm, bottom, top*
- *"Light flavor" or "QCD jets" = up, down, strange and gluon*
- *We tend to focus a lot on **bottom**-flavor jet tagging (i.e. identifying if the hadron contains a b quark)*
    - *Displaced vertices in our detectors due to extended lifetime*
    - *Heavier mass*
    - *Strong association to the top decay*
- *Jets are important in nearly every analysis for distinguishing between signal and background*
    - *Since the W decays hadronically $2/3$ the time, any "heavy" event will have multiple jets*
    - *We are using a proton-proton collision → many "soft" jet backgrounds*
- *Many jet-related variables are derived via "jet substructure" perspective → radiation pattern inside jets*
    - *Derive new variables that are IRC (infrared and collinear safe) → insensitive to infinitesimally soft or exactly collinear emissions*

Further Readings...

Recommendations:

- GIM Mechanism and the prediction of the Charm → "50 years of the GIM mechanism" in the CERN Courier
- Yang-Mills theory → "Yang-Mills theory" on nLab
- Renormalization → "How Mathematical 'Hocus-Pocus' Saved Particle Physics" in Quanta Magazine
- Asymptotic Freedom, Color Confinement → Nobel Lecture by Frank Wilczek
- Kaon short and long lifetimes → Appendix II of "The CKM Matrix and CP Violation"
- Jet Substructure → Jet Substructure at the LHC: A Review of Recent Advances in Theory and Machine Learning
- Discovery of the Neutron: Quantum Spin and Nitrogen → Nobel Lecture by James Chadwick
- Sum Rules → Section X of "Deep Inelastic Electron Scattering" in 1972 Annual Review of Nuclear Science
- Modern Proton Understanding → "The proton laid bare" by Amanda Cooper-Sarker in the CERN Courier