Discovery of the Gluon

Physics 290E Seminar, Spring 2020

Outline

- Knowledge known at the time
- Theory behind the discovery of the gluon
  - Key predicted interactions
    - Jet properties
- Relevant experiments
- Analysis techniques
- Experimental results
- Current research pertaining to gluons
- Conclusion

Knowledge known at the time

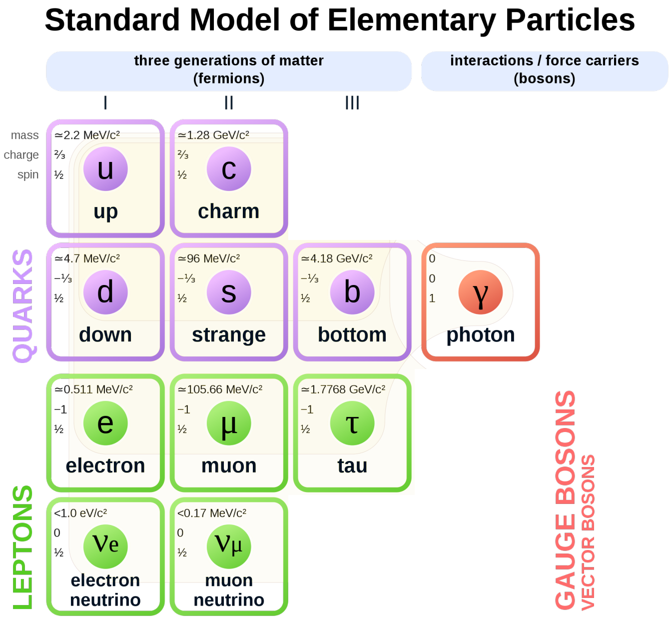
The year is 1978,

During this time, particle physics was arguable a mature subject. 5 of the 6 quarks were discovered by this point (the bottom quark being the most recent), and the only gauge boson that was known was the photon.

There was also a theory of the strong interaction, quantum chromodynamics, that had been developed up to this point by Yang, Mills, Gell-Mann, Fritzsch, Leutwyler, and others.

Trying to understand the structure of hadrons.

Gluons can self-interact!


Standard Model of Elementary Particles

Theory behind the discovery

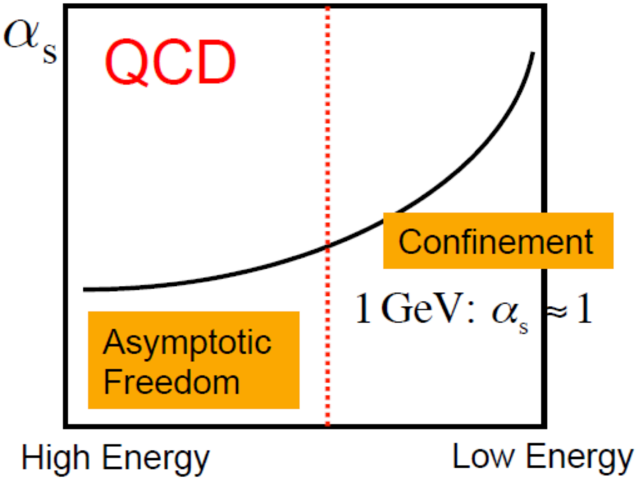
Analogous to QED, the strong interaction between quarks and gluons with a gauge group of SU(3) symmetry is known as quantum chromodynamics (QCD). Where the force mediating particle is the gluon.

In QCD, we have some quite particular features such as asymptotic freedom and confinement.

Short range: $V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r}$

Long range: $V_{QCD}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr$

(Between a quark and antiquark)

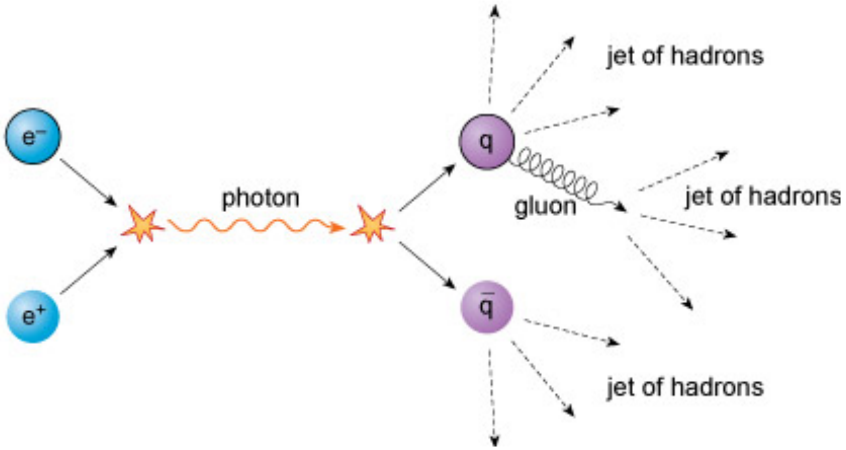


Quantum fluctuations cause the bare color charge to be screened causes coupling strength to vary. Features are important for an understanding of jet formation.

Theory behind the discovery

John Ellis postulated the search for the gluon through bremsstrahlung radiation in electron–proton annihilation processes in 1976.

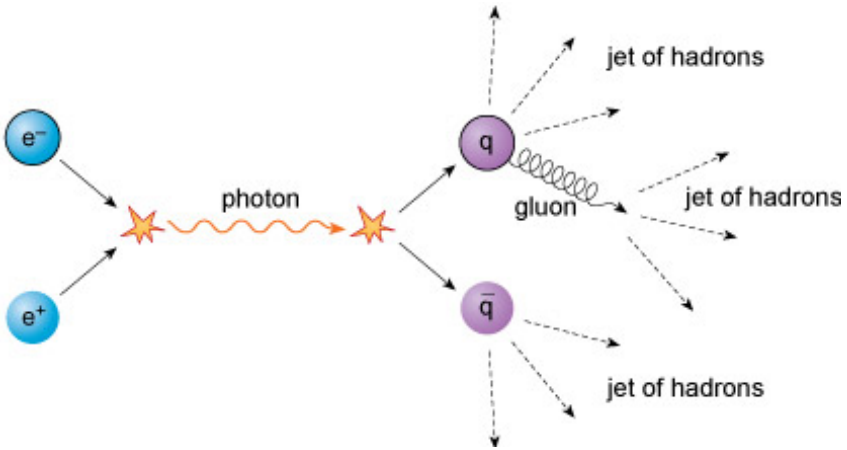
Such a process will produce jets of hadrons: $e^- e^+ \longrightarrow q\bar{q}g$



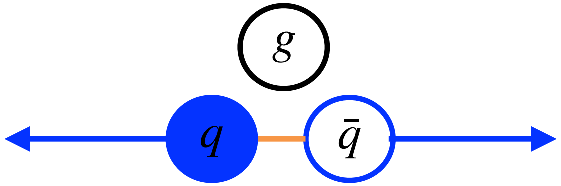
Furthermore, Mary Gaillard, Graham Ross, and John Ellis wrote a paper ("Search for Gluons in e+e− Annihilation.") that described that the PETRA collider at DESY and the PEP collider at SLAC should be able to observe this process. Energy range needed to increase.

Theory behind the discovery

Allow us to talk a bit more about the jets. (From confinement we know that we cannot expect the direct detection of gluons and quarks, instead we see a shower of hadrons). More specifically, a three-jet collision event, which is relevant to the discovery of the gluon.



Lund string model



Gluon produce quark anti-quack pair with a strong potential gluon string between them

The breaking of the gluon string produces quark anti-quark pairs and this process will produce jets (hadronization)

Then an attempt can be made on measuring such jets with proper detector technology.

Relevant experiments

The two experiments discussed by John Ellis and company were the PETRA collider at DESY and the PEP collider at SLAC.

PEP collider at SLAC

MARK I at SPEAR in 1975 showed evidence for two-jet events in low energy electron-positron collisions.

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

A higher energy PEP was in preparation and it was estimated that the three-jet signal should be observed.

PETRA collider at DESY

New collider designed in 1974 that wanted to exceed the collider energies of SPEAR as much as possible.

It took less than 3 years for the project to reach completion (almost two years ahead of the PEP collider at SLAC).

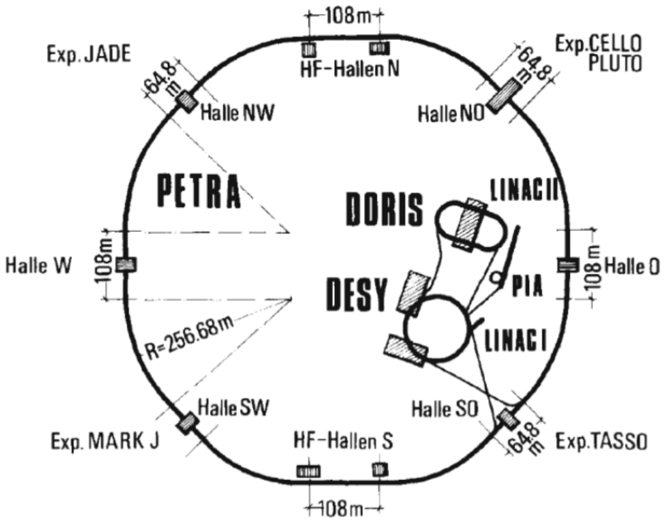
Relevant experiments

The Positron Electron Tandem Ring Accelerator (PETRA) had a 2.3 km circumference.

4 interaction regions in which electrons and positrons were to collide, and where detectors were installed. The 4 detectors are:

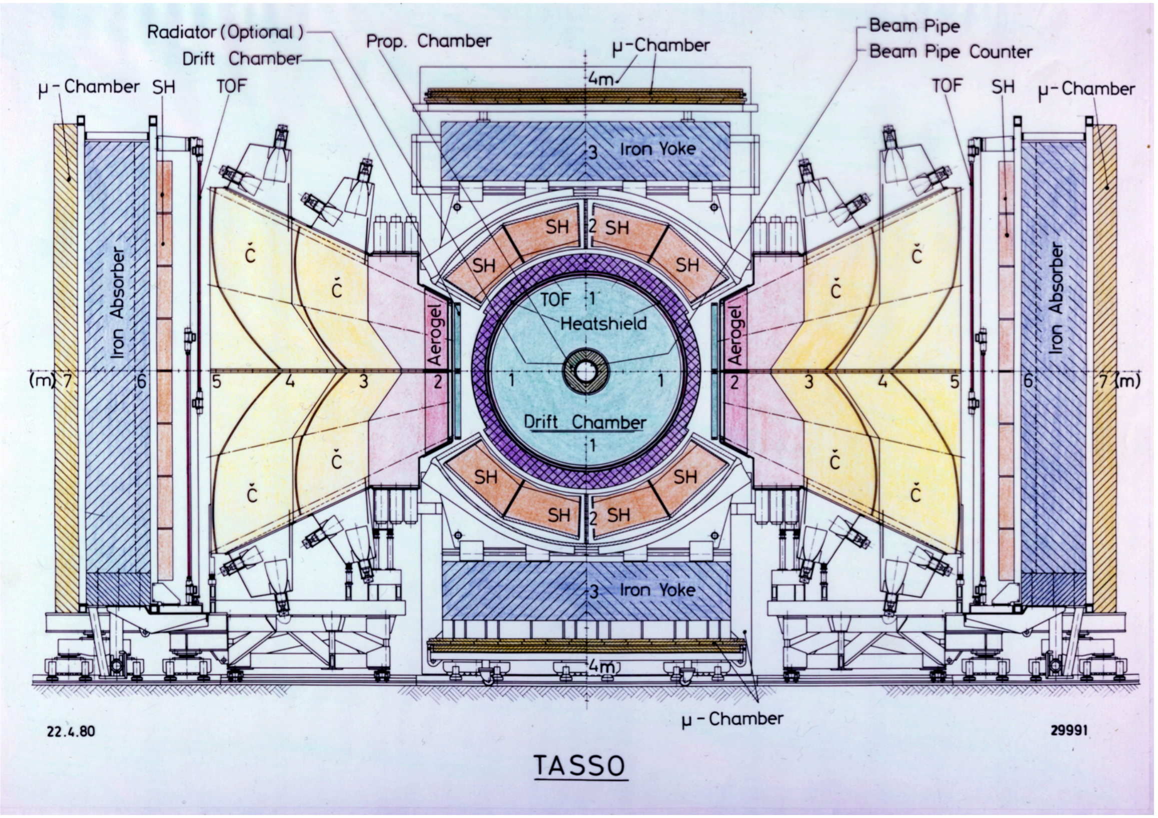
- JADE
- MARK J
- CELLO
- TASSO

Was operational in November 1978 with an initial center of mass energy of 13 GeV. The center of mass energy would be increased 27 GeV on a few months later.



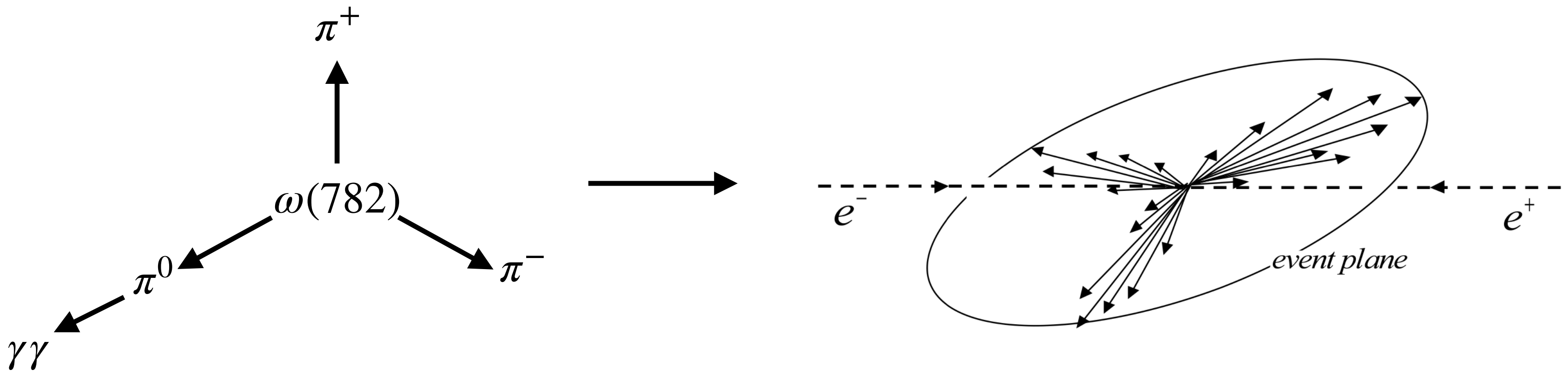
Relevant experiments

We will focus on the Two-Arm Spectrometer Solenoid (TASSO) detector at PETRA.



Analysis techniques

Now getting these three-jet events utilized energy and momentum conservation. For two-jets this translates to having them produced back to back. For three-jets they must be coplanar.



As a result, is you could find a two-dimensional plane, called the event plane, to find the three-jet events. Such a method was developed by Wu and Zobernig.

Analysis techniques

This program was implemented into an algorithm, which was ready to use by the end of 1978. The procedure was as follows:

1. Determine the event plane in which the quark, anti-quark, and gluon lie as the one with the least average transverse momentum.

2. All the measured momentum are projected on the event plane (p_j, θ_j) and arranged in a cyclic order

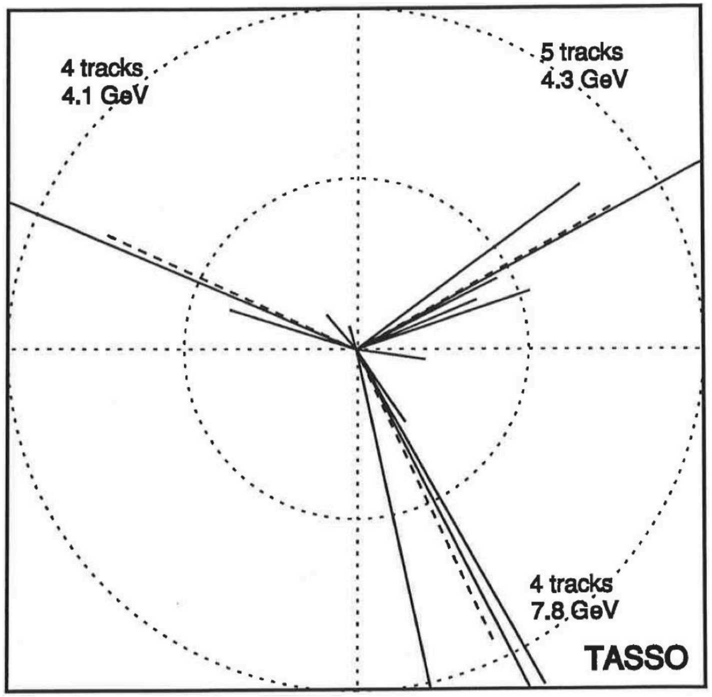
$$0 \leq \theta_1 \leq \theta_2 \leq \theta_3 \leq \ldots \leq 2\pi$$

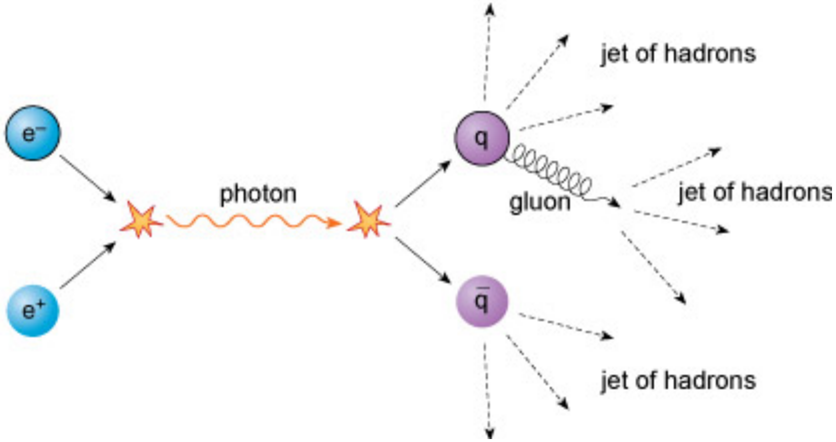
3. Group the particles into three different sets. Choose the set that minimizes the traverse momentum with respect to the jet axes, these are chosen as our three jets

Computing power was quite slow during this time with respect to todays standards.

Experimental result

First results of PETRA in June 1979 at the Bergen International conference.

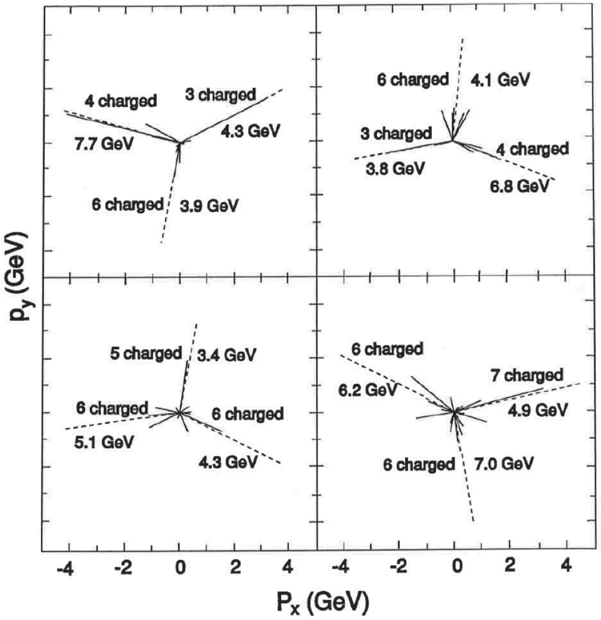




A candidate for a three-jet event observed by the TASSO group at 27 GeV! (Can’t identify the gluon jet exactly at the time we could guess)

Experimental result

More three-jet events were found later on by Wu and Zobernig. These lower any uncertainties that accompanies seeing just a single event (statistical fluctuations). Two weeks later:



Four more three-jet events were seen at TASSO (seen in the event plane above).

Experimental results

How do know that this third jet is from a gluon? Given that our three-jet signal was motivated by a gluon bremsstrahlung process.

Well we utilize the information provided earlier. We start with two fermions and get three jets. We cannot get three quarks out of this so this implies we need at most two quarks were produced along with a new particle (new boson).

This new particle also hadronizes; Therefore, it isn’t a color singlet.

The gluon analysis is the most likely explanation!

Relevant experiments

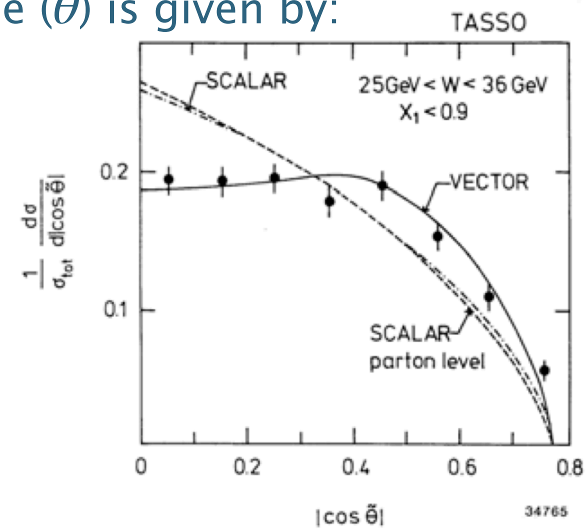
As time progressed, more data was collected by the detectors at PETRA. It was shown at the new particle did indeed have a spin of 1 in 1980.

It was found that by comparing the angular distribution of the three jets. Define:

$$x_j = \frac{E_j}{E_{beam}} \qquad\qquad x_3 < x_2 < x_1$$

Where E_j is the energy of the jet. The Ellis-Karliner angle ($\bar{\theta}$) is given by:

$$|cos(\bar{\theta})| = \frac{x_2 - x_3}{x_1}$$



Current research pertaining to gluons

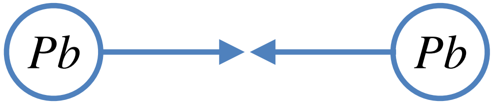
Studying the phase of matter known as quark-gluon plasma at ALICE.

By looking a photon-jet correlations can see the properties of this state of matter.

- The photon doesn't interact with the plasma.
- But quarks and gluons interact with the medium, gluons interact more since they have a larger color charge
  - Such interactions could be collisional or via stimulated gluon emission

Since the we know that the jet should have the same momentum as the photon measured in the EMCal we can infer the momentum lost to the medium.

Can learn more about the QGP and, as a result, the early state of the universe.

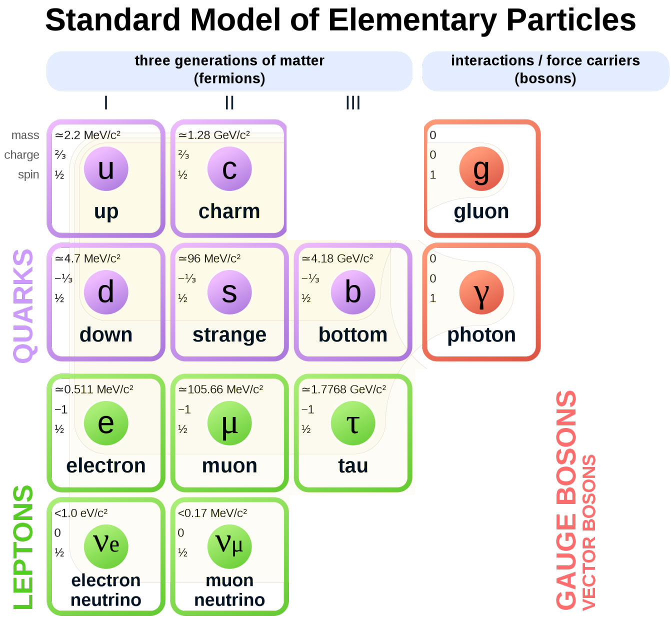


Conclusion

- The three-jet events seen at PETRA were a result of gluon bremsstrahlung radiation in electron-position annihilations seen through the algorithm of Wu and Zobernig.

- It was the second gauge boson, first non-Abelian gauge boson, to be discovered.

- It is still highly relevant in physics questions.



Sources

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