Discovery of the Gluon

This talk is dedicated to the memory of Bjørn Wiik

Sau Lan Wu

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Symposium on the Standard Model at 50
Department of Physics & Institute for the Science of Origins
Case Western Reserve University, 1-4 June 2018

Discovery of the Gluon

The gluon was discovered at the electron-positron collider PETRA of DESY, Germany, in late spring of 1979.

It is the second gauge boson to have been discovered experimentally, the first one being the photon more than 50 years earlier.

The gluon is the non-Abelian gauge particle for strong interactions. The strong interactions between quarks are mediated by the gluon.

Analogous to QED, the theory of strong interactions between quarks and gluons with the gauge group SU(3) is referred to as QCD – quantum chromodynamics.

Discovery of the Gluon

The exchanged particles responsible for the interactions are called gauge particles. Up until 1979, the only gauge particle that has been observed experimentally is the photon.

Yang and Mills predicted that there is a fundamental difference between the gluon and the photon: while a photon cannot emit or absorb another photon, the gluon can emit and absorb another gluon.

This means: the gluon has self-interactions, while the photon does not. The experimental discovery of the gluon is the discovery of the first Yang-Mills non-Abelian gauge particle.

Discovery of the Gluon

The gluon discovery was followed, four years later in 1983, by that of the second and the third non-Abelian gauge particles, the Z and the W, by Carlo Rubbia and Simon van der Meer, CERN.

This talk gives the history of the discovery of the gluon. This is accomplished through the observation of three-jet events from the process

$$e^+e^- \rightarrow q\,\bar{q}\,g$$

Indirect indication of gluons was given by:

- *deep inelastic electron scattering – SLAC-MIT;*
- *neutrino scattering – Gargamelle, BEBC, CDHS;*
- *etc.*

PETRA Storage Ring at DESY
(Positron Electron Tandem Ring Accelerator)

As already stated, the gluon was discovered at PETRA in the late spring of 1979.

PETRA (Positron–Electron Tandem Ring Accelerator) was a 2.3 kilometer electron and positron storage ring located in the German National Laboratory called Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Germany.

This laboratory was established in 1959 under the direction of Willibald Jentschke, and has played a crucial role in the re-emergence of Germany as one of the leading countries in physics.

PETRA Storage Ring at DESY
(Positron Electron Tandem Ring Accelerator)

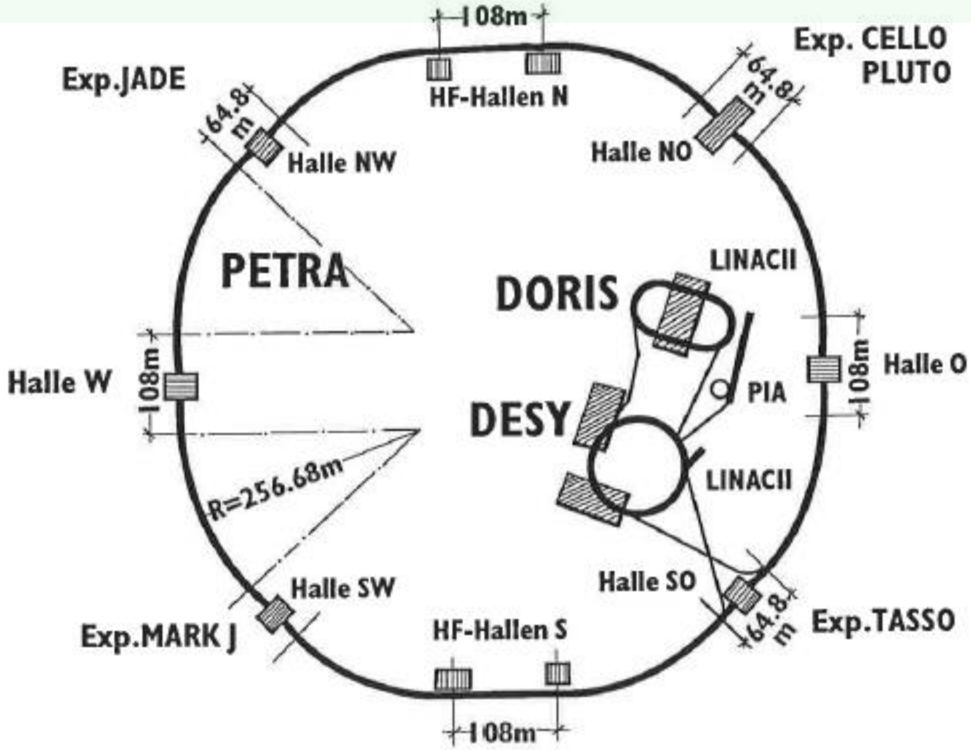
The proposal for the project for the construction of PETRA was submitted to the German government in November 1974, and was approved one year later.

The hero of the construction of PETRA was Gustav Voss; under his leadership, the electron beam was first stored on July 15, 1978, more than nine months ahead of schedule — a feat that was unheard of.

PETRA started its operation in November 1978 at 13 GeV C. M. energy and increased to 27 GeV in the spring of 1979. The maximum energy of 46 GeV was reached in 1984.

PETRA Storage Ring at DESY
(Positron Electron Tandem Ring Accelerator)

Four experiments occupied the four interaction regions: JADE, PLUTO (later replaced by CELLO), MARK J, and TASSO.



The TASSO Detector
(Two – Arm Spectrometer SOlenoid)

TORQUATO TASSO
1544- 1595
Italian Poet

The TASSO detector was constructed and operated by a collaborating effort of 90 physicists from nine institutions in Germany, England, Israel, and the United States.

The TASSO Detector
(Two – Arm Spectrometer SOlenoid)

R. Brandelik, W. Braunschweig, K. Gather, V. Kadansky, K. Lübelsmeyer, P. Mättig, H.-U. Martyn, G. Peise, J. Rimkus, H. G. Sander, D. Schmitz, A. Schultz von Dratzig, D. Trines and W. Wallraff.

I. Physikalisches Institut der RWTH Aachen, Germany

H. Boerner, H.M. Fischer, H. Hartmann, E. Hilger, W. Hillen, G. Knop, W. Korbach, P. Leu, B. Löhr, F. Roth, W.Rühmer, R. Wedermeyer, N. Wermes and M.Wollstadt.

Physikalisches Institut der Universität Bonn, Germany

R. Bühring, R. Fohrmann, D. Heyland, H. Hultschig, P. Joos, W. Koch, U. Kötz, H. Kowalski, A. Ladage, D.Lüke, H.L. Lynch, G. Mikenberg, D. Notz, J. Pyrlik, R. Riethmüller, M. Schliwa, P. Söding, B. H. Wiik and G. Wolf.

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

M. Holder, G. Poelz, J. Ringel, O. Römer, R. Rüsch and P. Schmüser.

II. Institut für Experimentalphysik der Universität Hamburg, Germany

The TASSO Detector
(Two – Arm Spectrometer SOlenoid)

D. M. Binnie, P. J. Dornan, N. A. Downie, D.A. Garbutt, W. G. Jones, S. L. Lloyd, D. Pandoulas, A. Pevsner, J. Sedgebeer, S. Yarker and C. Youngman .

Department of Physics, Imperial College, London, England

R. J. Barlow, R. J. Cashmore, J. Illingworth, M. Ogg and G. L. Salmon.

Department of Nuclear Physics, Oxford University, England

K. W. Bell, W. Chinowsky, B. Foster, J. C. Hart, J. Proudfoot, D.R. Quarrie, D. H. Saxon and P. L. Woodworth .

Rutherford Laboratory, Chilton, England

Y. Eisenberg, U. Karshon, E. Kogan, D. Revel, E. Ronat and A. Shapira.

Weizmann Institute, Rehovot, Israel

J. Freeman, P. Lecomte, T. Meyer, Sau Lan Wu and G. Zobernig.

Department of Physics, University of Wisconsin, WI, USA

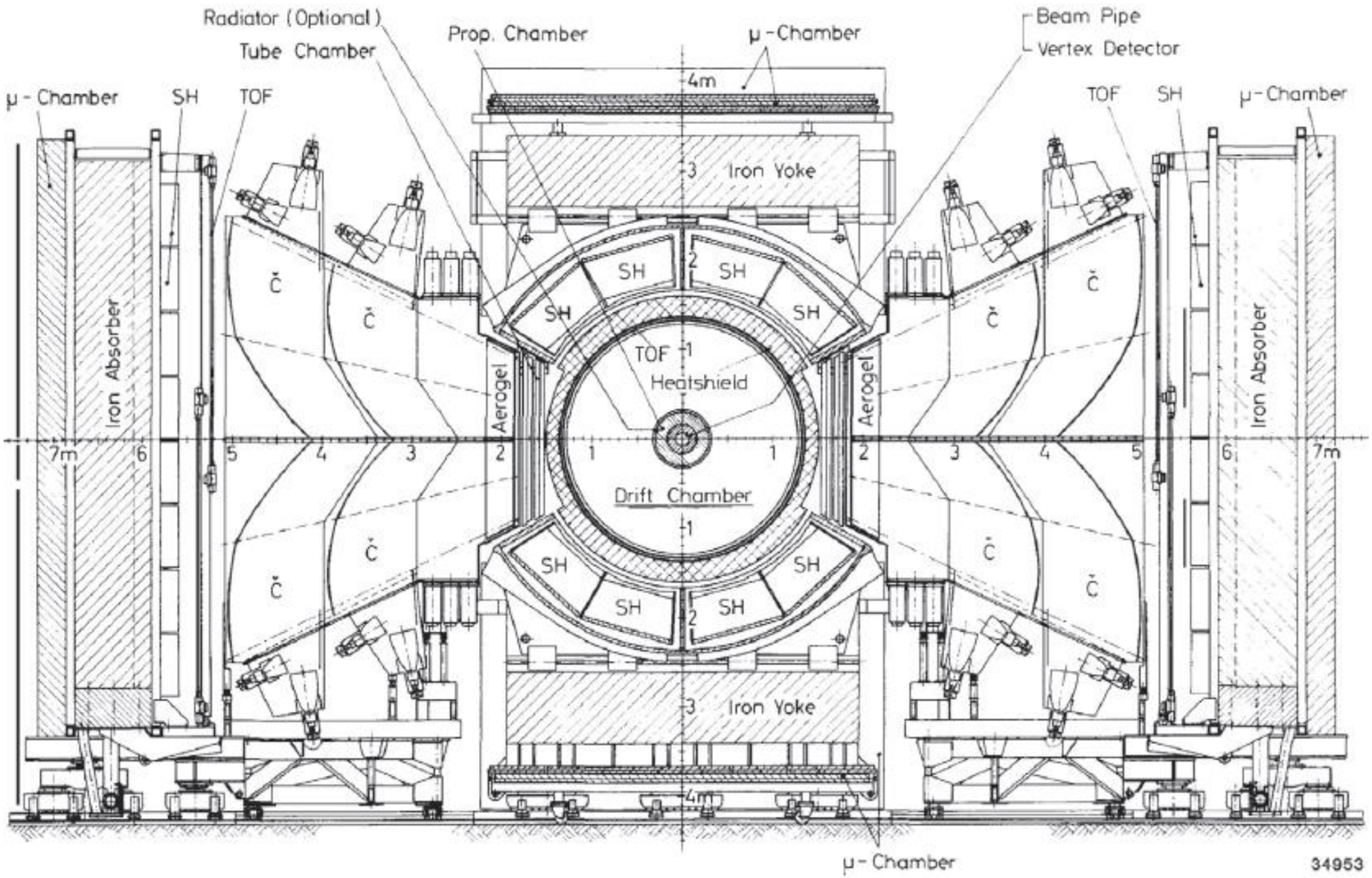
TASSO Detector

The main elements of the TASSO detector were:

- ***a set of proportional chambers and drift chambers inside a 5kG solenoid magnet to measure the momenta of charged particles***
- ***a system of liquid argon shower counters to measure the energies of photons and electrons***
- ***a system of muon chambers***
- ***a time-of-flight system***
- ***luminosity monitor***
- ***two spectrometer arms to identify particles (γ, $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, p and $\bar{p}$)***

The excellent performance of the central tracking was crucial for this discovery of the first non-Abelian gauge particle – the gluon.

TASSO Detector



End view of the TASSO detector.

TASSO Detector

Bjørn Wiik and the author relaxing after tedious work on drift-chamber cabling. The cables carried the timing information from the preamplifier boxes of the large central drift chamber. They were to be connected to the read-out electronics. ***Dr. Ulrich Kötz of DESY/TASSO took this photograph in 1978.***

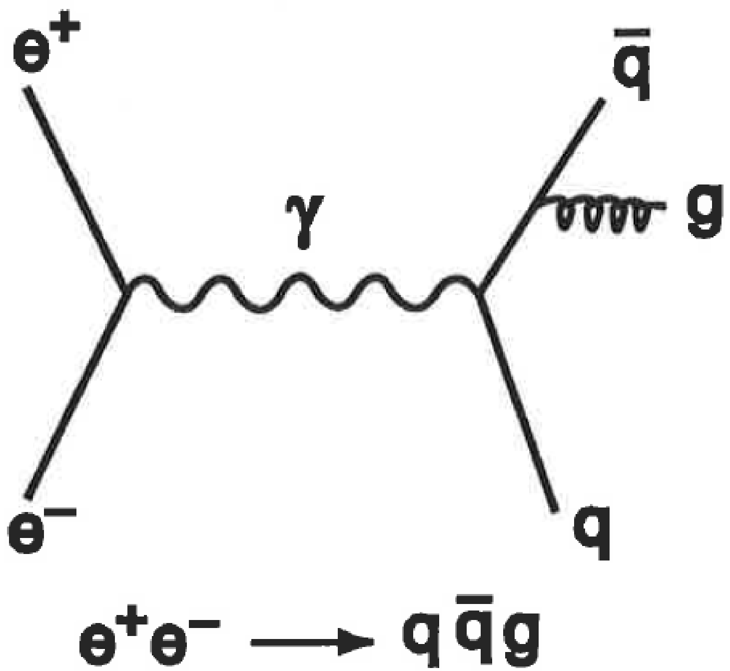
The discovery of the gluon requires direct observation.

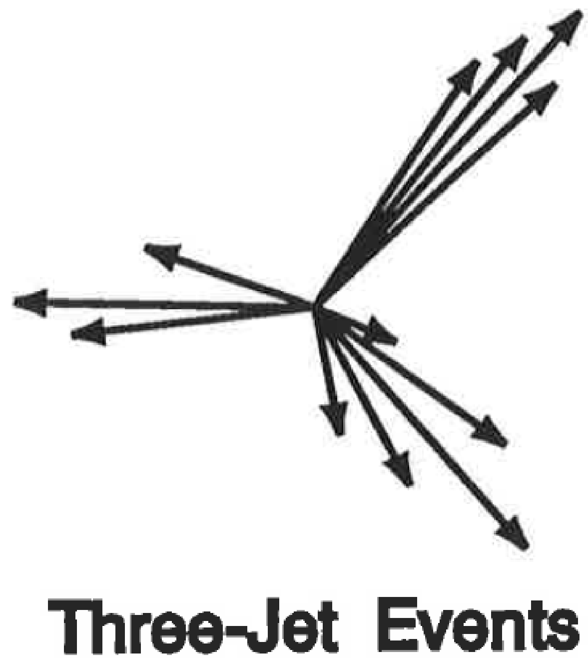
Since the gluon is the gauge particle for strong interactions, the simplest way to produce a gluon is by the gluon bremsstrahlung process:

$$e^+e^- \to q\,\bar{q}\,g$$

Discovery of the Gluon

In 1975, SPEAR at SLAC was first to observe a two-jet structure in $e^+e^- \to q\,\bar{q}$. Since the gluon, similar to the quark, is expected to hadronize into a jet, this process leads to three-jet events.





Discovery of the Gluon

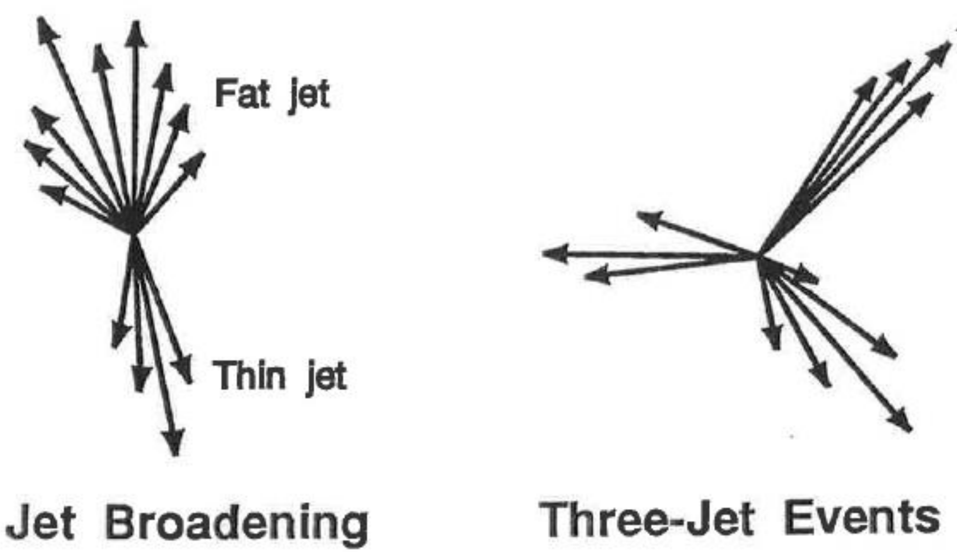
You had heard yesterday Mary K. Gaillard giving her excellent presentation on

Charm, beauty, $R\,\frac{(e^+e^-\to 3\,Jets)}{(e^+e^-\to 2\,Jets)}$

Discovery of the Gluon

At the PETRA turn-on in 1978, I was concentrating on looking for three-jet events. At that time, a number of groups were interested in jet broadening.

Jet broadening means that one of the two jets becomes broader at high energies.



Discovery of the Gluon

The main question that I asked myself was:

Is the center-of-mass energy of PETRA going to be high enough to see three-jet events clearly in 1978-1979?

I carried out a rough estimate and reached the conclusion:

Three times the energy of the e^+e^- collider SPEAR is likely to be sufficient to see three-jet events clearly.

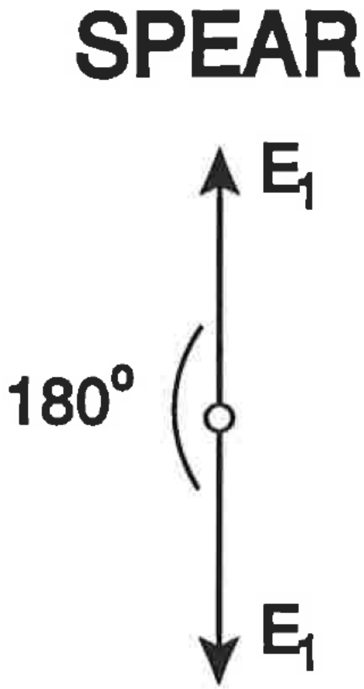
[The SPEAR center-of-mass energy was 7.4 GeV.]

This estimate of mine was very encouraging because PETRA was scheduled to reach this energy of

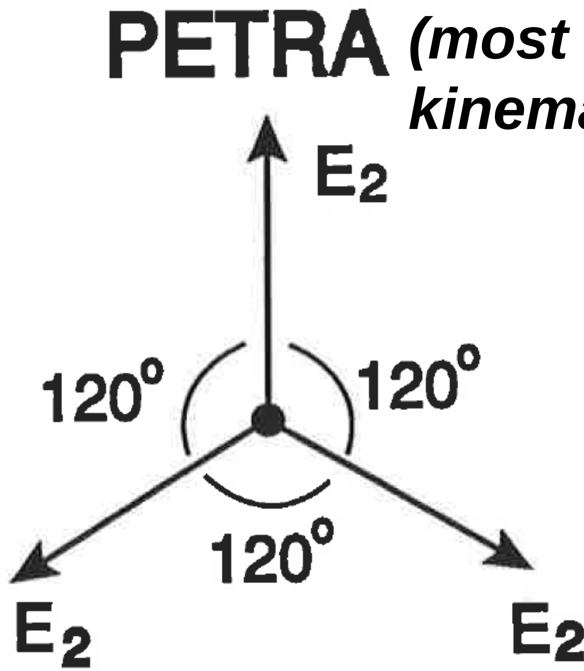
3 x 7.4 ~ 22 GeV shortly after turn-on.

Discovery of the Gluon

The arguments were as follows:



Invariant mass of the pair of jets = 7.4 GeV



(most favorable kinematic situation)

Invariant mass of each pair of jets ≈ $\sqrt{3}\,E_2$

$\Rightarrow$ $\sqrt{3}\,E_2 \approx 7.4$ GeV $\quad E_2 = 4.3$ GeV

Discovery of the Gluon

The total energy of the three jets is thus 13 GeV.

It must be further increased because each jet has to be narrower than the SPEAR jets. This additional factor is estimated to be 180°/ 120°= 1.5, leading to about 20 GeV.

Phase space considerations further increase this energy to about 22 GeV.

Discovery of the Gluon

Next Question:

How can I find three-jet events?

Simple but important observation:

By energy and momentum conservation two jets in $e^+e^- \to q\,\bar{q}$ must be back-to-back; three jets in $e^+e^- \to q\,\bar{q}\,g$ must be coplanar.

The search for the three-jet events can be carried out in the two-dimensional "EVENT PLANE" – the plane formed by the momenta of q, $\bar{q}$ and g.

Why is the event plane so important?

The point is this: the event plane is two-dimensional, and, in two dimensions, the momenta of the detected particles can be put in cyclic order using the polar angle. This is not possible in three dimensions.

This cyclic ordering reduces greatly the necessary computer time. At that time in 1978-79, the speed of the available computers were of course very much slower compared with what is available now.

Discovery of the Gluon

In 1979 Wu and Zobernig published

"A Method of Three-Jet

Analysis in e^+e^- Annihilation"

(Z. Phys. C, Particles and Fields 2 (1979) 107-110)

and later using this method to find the first three-jet events at a center-of-mass energy of 27.4 GeV at PETRA in June 1979.

My personal gratitude to Haimo G. Zobernig for his dedicated work on the three-jet analysis. He was my first postdoc(1977), when I began my assistant professorship at the University of Wisconsin.

Discovery of the Gluon

This publication gives algorithms to:

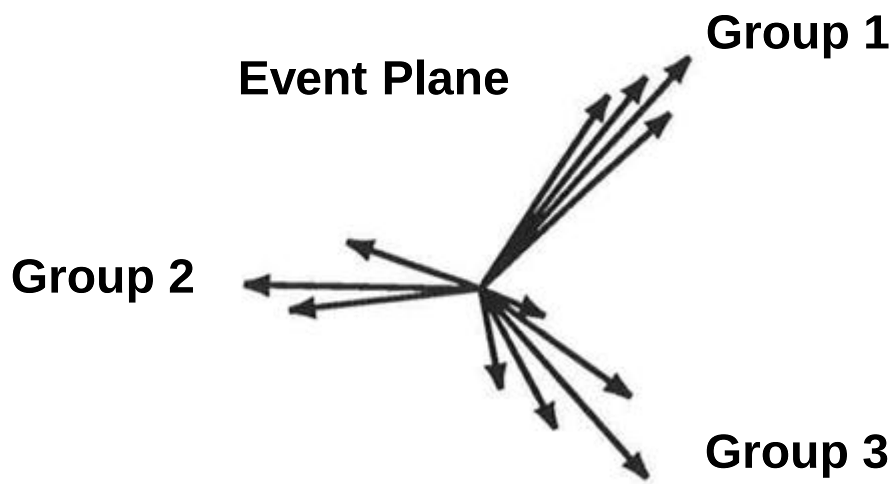
- ***Determine the event plane in which the quark, antiquark, and gluon lie.***

  (Finding a plane where the sum of the square of the transverse momenta of all the observed particles is minimized)

- ***Project all the measured momenta into the event plane and rearrange them into a cyclic order.***

Discovery of the Gluon

- ***Group the particles into three contiguous sets. Choose the group by minimizing the sum of the three sphericities of the three sets of contiguous momentum vectors.***



- ***These three sets are identified as the three jets . Once the three jets are identified, one can study the characteristics of a jet by measuring the average P_T of the jet, for example.***

Discovery of the Gluon

S.L. Wu
June 1978

June 1978

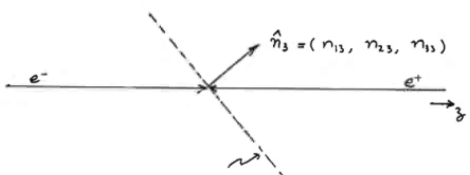
Analysis of Jets

1. Two opposite jets
2. Two non-opposite jets
3. Planar case
4. Three jets

P9
4-9

the analysis of 3 jets events

A With suitable χ^2 cuts, pick out the events from the region marked "Planar Distribution". For these events, T_3 is relatively small. Let $\hat{n}_3$ be ~~eigenvalue~~ eigenvector corresponding to T_3, and we project out this $\hat{n}_3$ component.



We choose n_{33} to be positive
Let the X-axis be determined by projecting the x-axis to the $\hat{n}_1 - \hat{n}_2$ plane

$$\hat{X} = \frac{\hat{x} - \hat{n}_3(\hat{x}\cdot\hat{n}_3)}{|\hat{x} - \hat{n}_3(\hat{x}\cdot\hat{n}_3)|}$$

and the Y-axis by orthogonality

$$\hat{Y} = \hat{n}_3 \times \hat{X} = \frac{\hat{n}_3 \times \hat{x}}{|\hat{x} - \hat{n}_3(\hat{x}\cdot\hat{n}_3)|}$$

P10
4-10

Instead of $\vec{P}_i$, we now have a list

$$\{P_{iX}, P_{iY}\} \qquad i = 1, 2, \cdots N$$

Rearrange the i's such that θ_i is in asending (wrt X-axis) order:

$$0 \le \theta_1 \le \theta_2 \le \theta_3 \le \cdots \le \theta_N \le 2\pi$$

where $P_{iX} + iP_{iY} = \sqrt{P_{iX}^2 + P_{iY}^2}\, e^{i\theta_i}$

B. A possible procedure for numerically treat these projected momenta is a follows

Choose three integers N_1 N_2 N_3 such that

a) $1 \le N_1 < N_2 < N_3 \le N$
N = no of measured tracks

b) $\underset{\substack{\uparrow \\ \text{last track of group 1}}}{\theta_{N_2-1}} - \underset{\substack{\uparrow \\ \text{first track of group 1}}}{\theta_{N_1}} \le \pi$

c) $\underset{\substack{\uparrow \\ \text{last track of group 2}}}{\theta_{N_3-1}} - \underset{\substack{\uparrow \\ \text{first track of group 2}}}{\theta_{N_2}} \le \pi$

d) $\underset{\substack{\uparrow \\ \text{last track of group 3}}}{2\pi + \theta_{N_1-1}} - \underset{\substack{\uparrow \\ \text{first track of group 3}}}{\theta_{N_3}} \le \pi$

These conditions are imposed so that each jet goes more or less in a definite direction not in both direction

---

P11
4-11

In this way, the N momenta have been split into three sets

$$\mathcal{S}_1 = \{N_1, N_1+1, \cdots, N_2-1\}$$
$$\mathcal{S}_2 = \{N_2, N_2+1, \cdots, N_3-1\}$$
$$\mathcal{S}_3 = \{N_3, N_3+1, \cdots, N_1-1\}$$

For each set we essentially go through the procedure of Hanson. More precisely, define

$$M_{jk}^{(t)} = \sum_{i \in \mathcal{S}_t} P_{ij} P_{ik} \qquad j, k = X, Y \qquad t = 1, 2, 3 \text{ groups}$$

Find the larger eigenvalue of the 2x2 matrix

$$M^{(t)} = \begin{bmatrix} M_{XX}^{(t)} & M_{YX}^{(t)} \\ M_{XY}^{(t)} & M_{YY}^{(t)} \end{bmatrix}$$

Call it $\lambda^{(t)}$ more precisely

$$\lambda^{(t)2} - (M_{XX}^{(t)} + M_{YY}^{(t)})\lambda^{(t)} - (M_{XX}^{(t)} M_{YY}^{(t)} - M_{XY}^{(t)2}) = 0$$

choose the larger value

$$\lambda^{(t)} = \frac{1}{2}\left\{ M_{XX}^{(t)} + M_{YY}^{(t)} \pm \sqrt{(M_{XX}^{(t)} + M_{YY}^{(t)})^2 - 4(M_{XX}^{(t)} M_{YY}^{(t)} - M_{XY}^{(t)2})} \right\}$$

$$= \frac{1}{2}\left\{ M_{XX}^{(t)} + M_{YY}^{(t)} \pm \sqrt{(M_{XX}^{(t)} - M_{YY}^{(t)})^2 + 4 M_{XY}^{(t)2}} \right\}$$

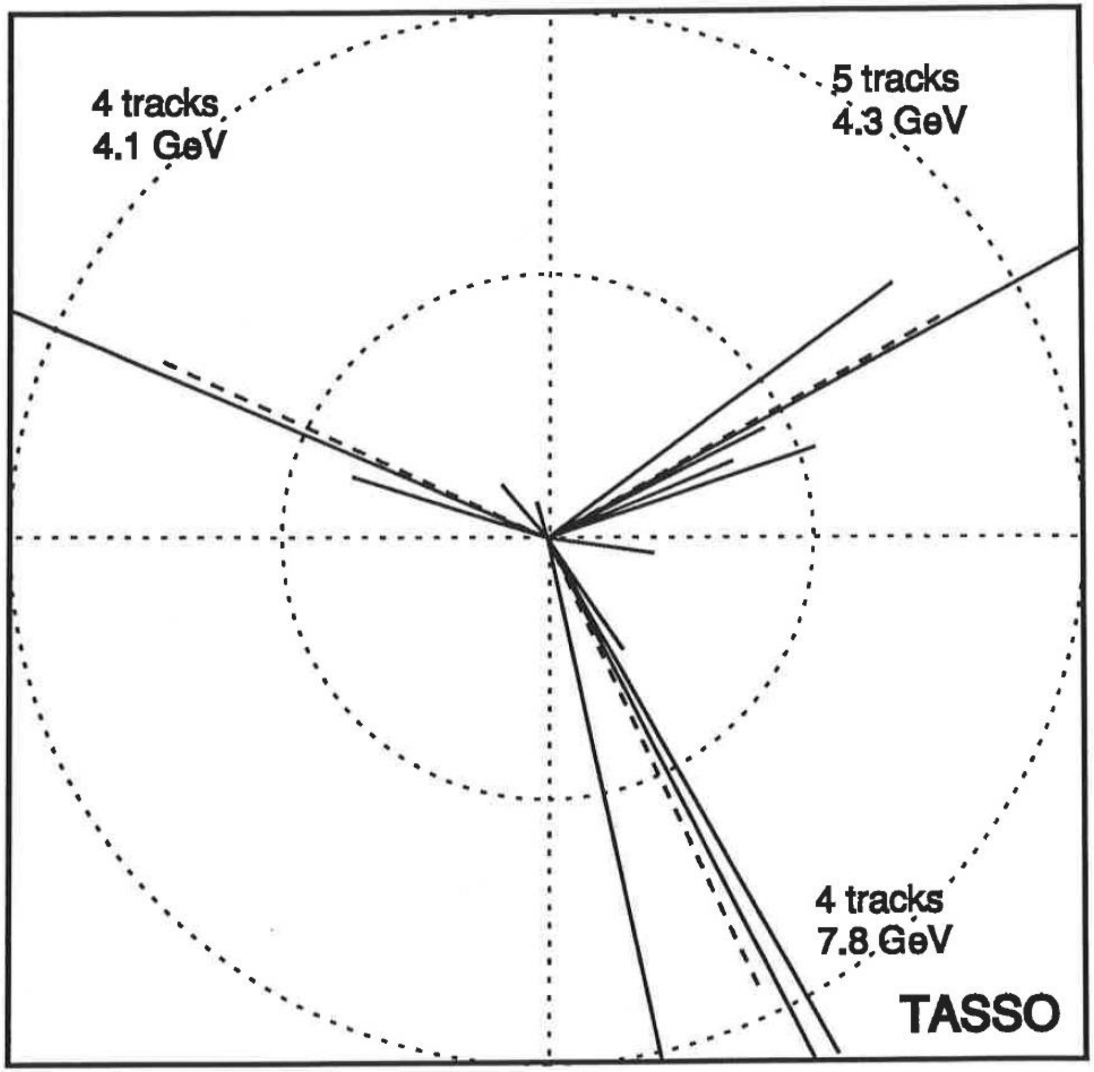
Four of the pages from my notes of June 1978 on jet analysis.

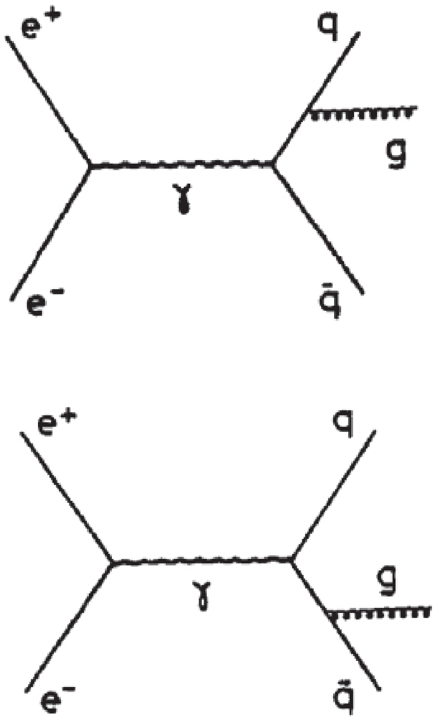
Discovery of the Gluon

- ***The computer program for this algorithm was ready in the fall of 1978.***
- ***In 1978-79 PETRA started at a centre-of-mass energies at 13 GeV and 17 GeV and we found no three-jet events.***
- ***In June 1979, a few days before the Neutrino 79 International Conference in Bergen, Zobernig and I found one gold-plated three-jet event out of a total of 40 hadronic events collected at a center-of-mass energy of 27.4 GeV.***
- ***This event was shown by Bjørn Wiik in his talk at the Bergen conference: Neutrino 79, International Conference on Neutrinos, Weak Interactions and Cosmology, June 18-22 1979.***

"First Results from PETRA"

Discovery of the Gluon





First three-jet event from PETRA shown by B. Wiik of TASSO at Bergen Conference 1979

Discovery of the Gluon

The following is quoted from Wiik's Bergen Conference talk: *(First Results from PETRA, in Proceedings of Neutrino 79, International Conference on Neutrinos, Weak Interactions and Cosmology, Volume 1, Bergen, June 18–22 1979, pp. 113–154)*

"If hard gluon bremsstrahlung is causing the large $p_\perp$ values in the plane then a small fraction of the events should display a three jet structure. The events were analyzed for a three jet structure using a method proposed by Wu and Zobernig[27)] . . . A candidate for a 3 jet event, observed by the TASSO group at 27.4 GeV, is shown in Fig. 21 viewed along the $\hat{n}_3$ direction. Note that the event has a three clear well separated jet and is just not a widening of a jet."

As soon as I returned from Bergen, I wrote a TASSO note with Zobernig on the observation of this three-jet event.

Discovery of the Gluon

TASSO Note No. 84
26.6.1979

From Sau Lan Wu and Haimo Zobernig

On: A three-jet candidate (run 447 event 13177)

We have made a three jet analysis to all the hadronic candidates (43 events for $\sum_i |P_i| \geq 9$ GeV) of the May 1979 data at $E_{cm} = 27.4$ GeV using our method described in DESY 79/23 (A method of three jet analysis in e^+e^- annihilation).

Fig. 1 gives the triangular plot of the normalized eigenvalues Q_1, Q_2 and Q_3 ($Q_1 \leq Q_2 \leq Q_3$) of the momentum matrix

$$M_{\alpha\beta} = \sum_j (P_{j\alpha} \; P_{j\beta})$$

(See equation (1) and Fig. 1 of DESY 79/23). We find two three jet candidates

run 447 event 13177

run 439 event 12845

We then display each event on the 3 planes

plane 1: normal to $\hat{n}_1$, the normalized eigenvector corresponding to Q_1. $\sum_i |P_{i\perp}|^2$

with respect to this plane is minimized.

plane 2: normal to $\hat{n}_2$, the normalized eigenvector ~~to~~ $\hat{n}_2$ corresponding to Q_2

plane 3: normal to $\hat{n}_3$, the normalized eigenvector corresponding to Q_3.

Fig. 2 displays the three jet candidate (run 447 event 13177) on planes 1, 2, 3.

Fig. 3 displays plane 1 of this event in a blow up scale.

The axis for each of the three jets are found. Given the axes and $\sum_i |P_i|$ of each jet, the total energy of each jet is determined assuming the mass of each quark (or gluon) is zero.

Fig. 4 displays the event run 439 event 12845. This event looks like two charged jets and one neutral jet.

A three-jet candidate (run 447 event 13177)

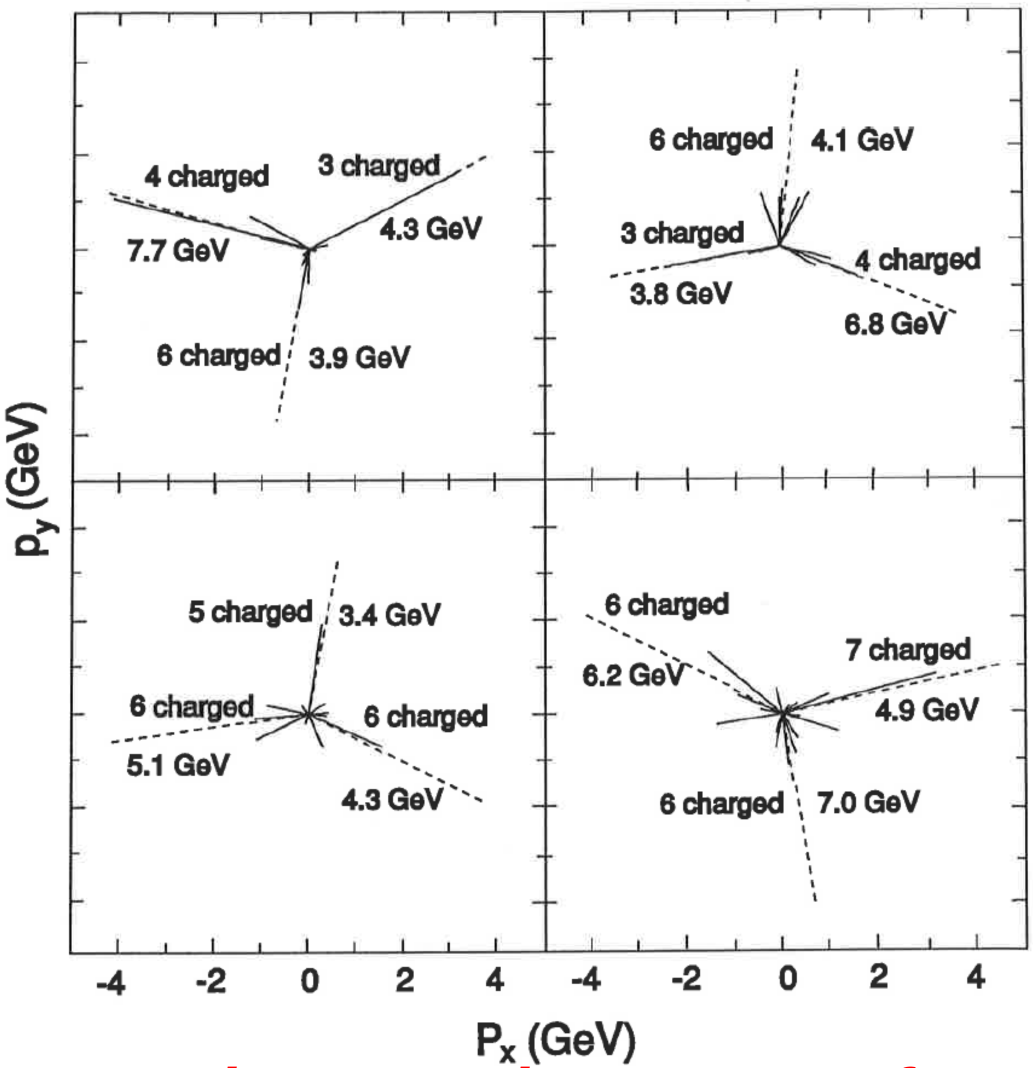
The first page of TASSO Note No. 84, June 26, 1979, by Wu and Zobernig.

Discovery of the Gluon

Before the question of statistical fluctuation of one event could seriously be raised, more events of $e^+e^- \rightarrow$hadrons from E_{cm} = 27.4 GeV rolled in and we found more three-jet events.

Less than two weeks after the Bergen Conference, four TASSO three-jet events were shown by Paul Sőding at the European Physical Society Conference in Geneva, 27 June – 4 July, 1979. ***(Conference on High Energy Physics, Geneva, Switzerland, 27 June-4 July, 1979.)***

Discovery of the Gluon



TASSO

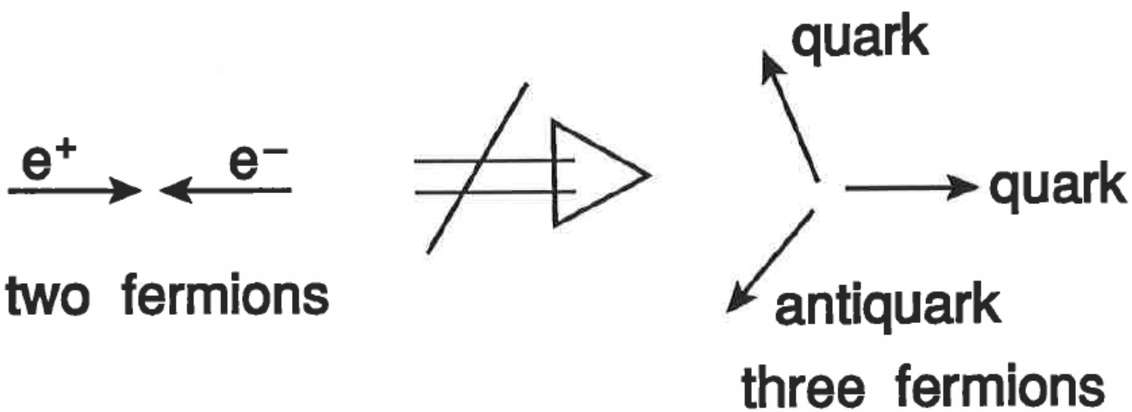
Three-jet events shown at the EPS Conference in Geneva, June 27-July 4, 1979, by Paul Söding of TASSO.

Discovery of the Gluon

The search for the three-jet events at PETRA was motivated by the gluon bremsstrahlung process $e^+e^- \to q\,\bar{q}\,g$. After such events have been found, the next question is:

What can the three jets be?

Since quarks and antiquarks are fermions and two fermions (e^+, e^-) cannot turn into three fermions, these three jets cannot all be quarks and antiquarks.



The experimental observation of three-jet events in e^+e^-annihilation, implies the discovery of a NEW PARTICLE (a new boson).

Discovery of the Gluon

Similar to the quarks, this new particle hadronizes into a jet, and therefore cannot be a color singlet.

(color singlets, such as π, K, and p do not metamorphose into jets)

These three-jet events are therefore most naturally explained by hard non-collinear bremsstrahlung

$$e^+e^- \rightarrow q\,\bar{q}\,g$$

Discovery of the Gluon

In late spring of 1979, these two talks at the Bergen conference by Wiik and the EPS Geneva conference by Söding:

generated considerable interest and stimulated an enormous analytical effort because the only viable interpretation was based on the creation of gluons by quark bremsstrahlung.

Discovery of the Gluon

Two months later, at the Lepton-Photon Conference at FNAL in late August of 1979, all four experiments at PETRA:

JADE, MARK J, PLUTO, and TASSO

gave more extensive data, confirming the earlier discovery of TASSO.

Discovery of the Gluon

As soon as there were enough data, the TASSO Collaboration determined* the spin of the gluon to be indeed 1 in September 1980.

One month later, the PLUTO Collaboration reached the same conclusion. This result was confirmed subsequently by the other PETRA Collaborations.

****The Ellis – Karliner angle was used with the above three – jet analysis.***

European Physical Society High Energy and Particle Physics Prize, July 1995.

EUROPEAN PHYSICAL SOCIETY

1995

HIGH ENERGY AND PARTICLE PHYSICS PRIZE

of the

EUROPEAN PHYSICAL SOCIETY

The 1995 High Energy and Particle Physics Prize of the European Physical Society is awarded to

Paul Söding
Björn Wiik
Günther Wolf
Sau Lan Wu

for the first evidence for three-jet events in e^+e^- collisions at PETRA.

Brussels, 27 July 1995

H. Schopper
President
European Physical Society

G. Jarlskog
Chairman
High Energy and Particle Physics Division

European Physical Society High Energy and Particle Physics Prize, 1995.

The four Prize Recipients at the ceremony of the 1995 European Physical Society High Energy and Particle Physics Prize in Brussels, Belgium. Front row: Günter Wolf and Sau Lan Wu; second row: Bjørn Wiik and Paul Söding.

Discovery of the Gluon

The early papers related to the PETRA three-jet events are the following.

(1) Sau Lan Wu and Georg Zobernig, Z. Phys. C — Particles and Fields 2, 107 (1979).

(2) B. H. Wiik, Proceedings of International Conference on Neutrinos, Weak Interactions and Cosmology, Bergen, Norway, June 18–22, 1979, p. 113.

(3) Sau Lan Wu and Haimo Zobernig, TASSO Note 84, June 26, 1979.

(4) P. Söding, Proceedings of European Physical Society International Conference on High Energy Physics, Geneva, Switzerland, 27 June–4 July, 1979, p. 271.

(5) TASSO Collaboration (R. Brandelik et al.), Phys. Lett. B 86, 243 (1979) [received on August 29, 1979].

Discovery of the Gluon

(6) MARK J Collaboration (D. P. Barber et al.), Phys. Rev. Lett. 43, 830 (1979) [received on August 31, 1979].

(7) PLUTO Collaboration (Ch. Bergen et al.), Phys. Lett. B 86, 418 (1979) [received on September 13, 1979].

(8) JADE Collaboration (W. Bartel et al.), Phys. Lett. B 91, 142 (1980) [received on December 7, 1979].

(9) JADE Collaboration, MARK J Collaboration, PLUTO Collaboration and TASSO Collaboration, Proceedings of 1979 International Symposium on Lepton and Photon Interactions at High Energies, Fermi National Accelerator Laboratory (FNAL), Batavia, Illinois, August 23–29, 1979.

Recent Developments

Important role of Gluon in the Higgs discovery

The gluon – the non-Abelian gauge particle for strong interactions – was discovered thirty nine years ago. During these thirty nine years, it has become more and more important, one prominent example being its role in the recent discovery of the Higgs particle* by the ATLAS Collaboration and the CMS Collaboration using the Large Hadron Collider (LHC) at CERN.

****F. Englert and R. Brout, 1964; P. W. Higgs, 1964***

G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, 1964.

This observation of the Higgs particle in 2012 has led to the award of the 2013 Nobel Prize in physics to Englert and Higgs. Brout had unfortunately died a year and half earlier.

Recent Developments

Important role of Gluon in the Higgs discovery

Since the gluon is the gauge particle for strong interactions, to a good approximation a proton consists of a number of gluons in addition to two u quarks and one d quark.

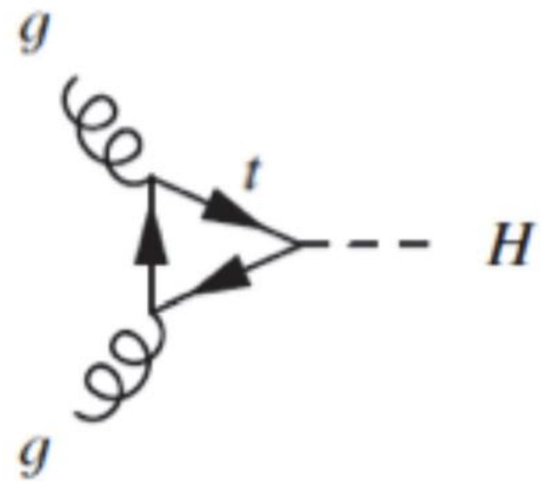
Since the coupling of the Higgs particle to any elementary particle is proportional to its mass, there is little coupling between the Higgs particle and these constituents of the proton.

Therefore, some heavy particle needs to be present in a proton–proton collision at LHC, and is then used to couple to the Higgs particle. Among all the known elementary particles, the top quark t, with a mass of 173 GeV/c^2, is the heaviest.

Important role of Gluon in the Higgs discovery

Higgs Production

Gluon-Gluon fusion



Feynman diagram for the Higgs (H) production by gluon–gluon fusion (also called gluon fusion).

Because of color conservation—the gluon has color but not the Higgs particle—the top and anti-top pair produced by a gluon cannot annihilate into a Higgs particle.

In order for this annihilation into a Higgs particle to occur, it is necessary for the top or the anti-top quark to interact with a second gluon to change its color content. It is therefore necessary to involve two gluons, one each from the protons of the two opposing beams of LHC.

Recent Developments
Important role of Gluon in the Higgs discovery

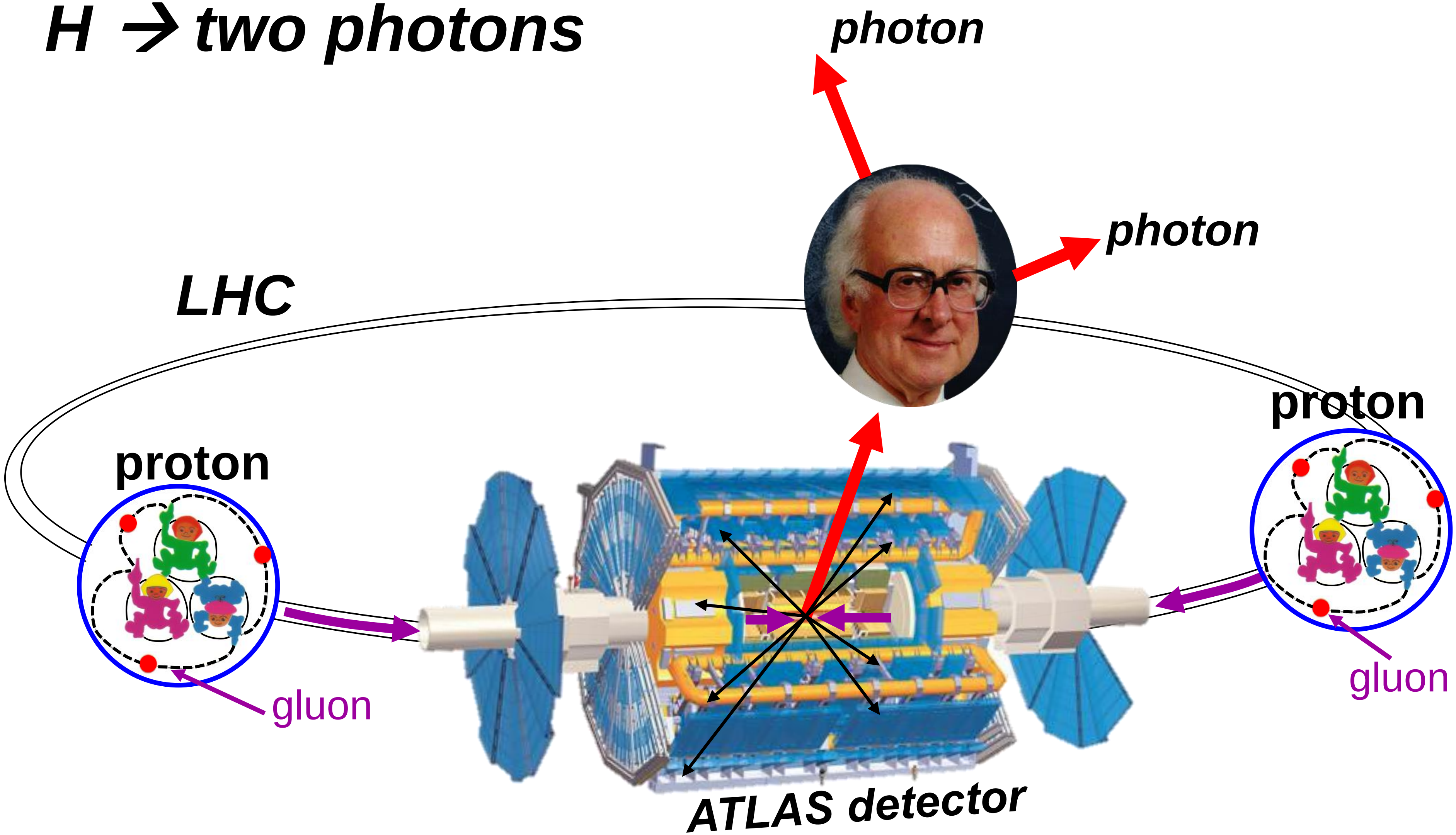
This production process is called "gluon–gluon fusion" (also called "gluon fusion"). As expected from the large mass of the top quark, this gluon–gluon fusion is by far the most important Higgs production process.

The mass of the Higgs particle has been found to be 125 GeV/c^2 by the ATLAS Collaboration and the CMS Collaboration. At this mass, the gluon contributes about 90% of Higgs production cross section through gluon–gluon fusion. In this way the gluon played the central role in the discovery of the Higgs particle in 2012.

A more dramatic way of saying the same thing is that, if there were no gluon, the Higgs particle could not have been discovered so soon in 2012!

Higgs discovery channel

H → two photons



Summary (1)

(1) Discovery of the Gluon

- ***The experimental observation of three-jet events in e^+e^- annihilation was first accomplished by the TASSO Collaboration in the late spring of 1979 and confirmed by the other Collaborations at PETRA two months later in the summer.***

- ***Since two fermions e^+e^- cannot turn into three fermions, 3-jet events imply the discovery of a new particle.***

Summary (2)

- ***Similar to the quarks, this new particle hadronizes into a jet, and therefore cannot be a color singlet.***

- ***These three-jet events are most naturally explained by hard noncollinear bremsstrahlung***

$$e^+e^- \rightarrow q\,\bar{q}\,g.$$

- ***One year later, the spin of the gluon was determined experimentally to be indeed 1, as it should be for gauge particles.***

Summary (3)

(2) Gluon – the first Yang-Mills non-Abelian gauge particle.

- ***Thus the 1979 discovery of the second gauge particle, the gluon, occurred more than half a century after that by Compton of the first, the photon.***
- ***This second gauge particle is also the first non-Abelian gauge particle, i.e., a gauge particle with self-interactions.***
- ***Four years later, in 1983, the second and the third non-Abelian gauge particles, the W and the Z, were discovered at the CERN proton–antiproton collider.***
- ***These two discoveries complete the observation of all the gauge particles except the graviton.***

Summary (4)

(3) The important role of gluon in the Higgs discovery

- ***Since its first observation thirty nine years ago, the importance of the gluon in particle physics has grown significantly.***

- ***An especially noticeable example is its essential role in the discovery of the Higgs particle produced through gluon-gluon fusion in 2012 by the ATLAS Collaboration and the CMS Collaboration at the Large Hadron Collider at CERN.***

- ***If there were no gluon, the Higgs particle could not have been discovered so soon in 2012!***