Aula Magna dell’Università di Milano, Via Festa del Perdono 7, Milano

SIMPOSIO INTERNAZIONALE “*HIGHLIGHTS IN PHYSICS TODAY: ONE HUNDRED YEARS AFTER THE BIRTH OF BEPPO OCCHIALINI*”

THE BEPPO PARTICLE

Antonino Zichichi

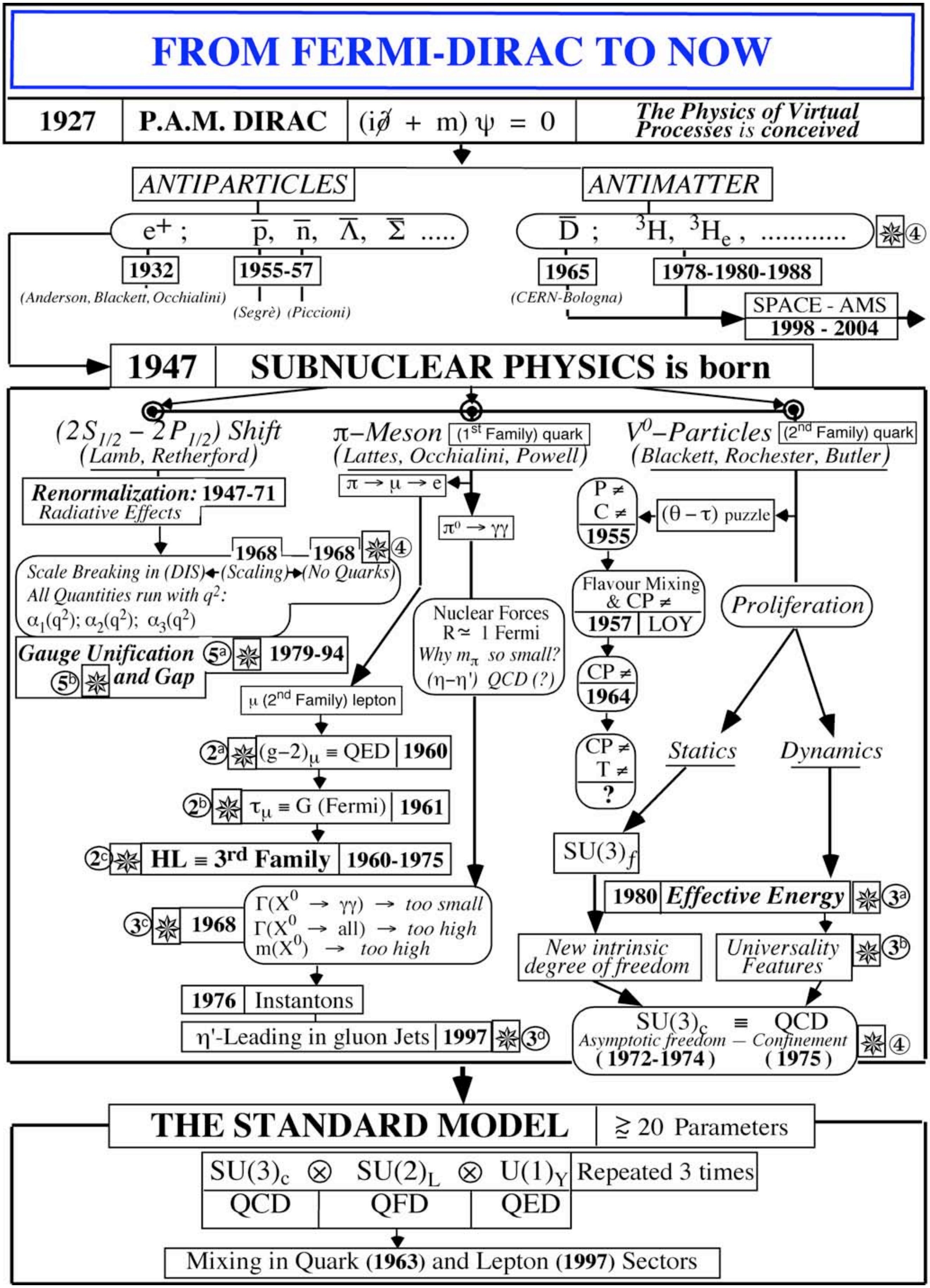
INFN and University of Bologna, Italy
CERN, Geneva, Switzerland
World Federation of Scientists, Beijing, Geneva, Moscow, New York

Venerdì 16 febbraio 2007, ore 15.10

ONE HUNDRED YEARS AFTER THE BIRTH OF BEPPO OCCHIALINI

60 Years After the Discovery of the π Meson

The pseudoscalar mesons and the Beppo particle (1947-2007).



FROM FERMI-DIRAC TO NOW
1927
P.A.M. DIRAC
$(i\not\partial + m)\psi = 0$
The Physics of Virtual Processes is conceived
ANTIPARTICLES
ANTIMATTER
e^+ ; $\bar{p}$, $\bar{n}$, $\bar{\Lambda}$, $\bar{\Sigma}$ .....
$\bar{D}$; $^3\bar{H}$, $^3\bar{H}_e$, ...
4
1932
(Anderson, Blackett, Occhialini)
1955-57
(Segrè) (Piccioni)
1965
(CERN-Bologna)
1978-1980-1988
SPACE - AMS
1998 - 2004
1947
SUBNUCLEAR PHYSICS is born
$(2S_{1/2} - 2P_{1/2})$ Shift
(Lamb, Retherford)
π–Meson
(1st Family) quark
(Lattes, Occhialini, Powell)
V^0–Particles
(2nd Family) quark
(Blackett, Rochester, Butler)
Renormalization: 1947-71
Radiative Effects
$\pi \to \mu \to e$
$\pi^0 \to \gamma\gamma$
P ≠
C ≠
1955
$(\theta - \tau)$ puzzle
1968
1968
4
Scale Breaking in (DIS)←(Scaling)→(No Quarks)
All Quantities run with q^2:
$\alpha_1(q^2)$; $\alpha_2(q^2)$; $\alpha_3(q^2)$
Flavour Mixing & CP ≠
1957
LOY
Proliferation
Nuclear Forces
R ≃ 1 Fermi
Why m_π so small?
$(\eta-\eta')$ QCD (?)
Gauge Unification
5a
1979-94
5b
and Gap
CP ≠
1964
μ (2nd Family) lepton
Statics
Dynamics
2a
$(g-2)_\mu \equiv$ QED
1960
CP ≠
T ≠
?
2b
$\tau_\mu \equiv G$ (Fermi)
1961
2c
HL ≡ 3rd Family
1960-1975
$SU(3)_f$
1980
Effective Energy
3a
3c
1968
$\Gamma(X^0 \to \gamma\gamma) \to$ too small
$\Gamma(X^0 \to$ all$) \to$ too high
$m(X^0) \to$ too high
New intrinsic degree of freedom
Universality Features
3b
1976
Instantons
η'-Leading in gluon Jets
1997
3d
$SU(3)_c \equiv$ QCD
Asymptotic freedom — Confinement
(1972-1974)
(1975)
4
THE STANDARD MODEL
≳ 20 Parameters
$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$
Repeated 3 times
QCD
QFD
QED
Mixing in Quark (1963) and Lepton (1997) Sectors

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE BEPPO PARTICLE: η' THE π−MESON 50 YEARS LATER

Antonino Zichichi
Academy of Sciences - Bologna, Italy
CERN - Geneva, Switzerland
INFN - Bologna, Italy
University of Bologna, Italy

ABSTRACT

In order to explain the range of the Nuclear Forces, Yukawa postulated the existence of a massive quantum of these forces, whose mass had to be intermediate (here is the origin of the name "meson") between the lightest and the heaviest particles known at that time: the electron and the nucleon. The discovery of the π−meson gave a great impetus to Nuclear Physics and opened new horizons in the field of Subnuclear Physics. The π−meson is now understood as the first example of a quark−antiquark pair bound by gluons: the quanta of the Fundamental non-Abelian Force (QCD) acting between the constituents of the π−mesons, quarks and gluons. Yes, gluons interact with gluons.

The π−meson's new horizons are: the Spontaneous Symmetry breaking of a Global Symmetry, the Gauge Principle, the existence of non-Abelian Forces and the Instantons. A critical test of these ideas was the search for the ninth elusive member (called η') of the nonet of pseudoscalar mesons of which the π is the first member. In this nonet the η and η' played a fundamental role in questioning the validity of QCD: in particular neither the masses nor the mass difference between η' and η (the eight member of the nonet) could be understood without instantons.

Fifty years were needed to go from the lightest to the heaviest pseudoscalar meson. On the occasion of the 50th anniversary of the π discovery, we would like to pay tribute to Beppo Occhialini by proposing to those who have contributed to understanding the basic steps of the heaviest pseudoscalar meson, the η', to call it the Beppo particle.

Nuclear physics owes its origin to the Yukawa ‘meson’ [3],

(*) Hideki Yukawa, *Interaction of Elementary Particles*, Part I, Proc. Physico-Math. Soc. Japan 17, 48 (1935); e *Models and Methods in the Meson Theory*, Reviews of Modern Physics 21, 474 (1949).

Experimentally discovered in 1947 by Lattes, Occhialini and Powell [4].

(**) C.M.G. Lattes, H. Muirhead, G.P.S. Occhialini e C.F. Powell, *Processes Involving Charged Mesons*, Nature 159, 694 (1947); C.M.G. Lattes, G.P.S. Occhialini e C.F. Powell, *Observations on the Tracks of Slow Mesons in Photographic Emulsions*, Nature 160, 454 (1947).

Sixty years later we know that the nuclear forces do not exist as fundamental forces.

They are secondary effects of the fundamental force which is QCD.

On the occasion of the 60th anniversary of the discovery of the π−meson, we would like to draw attention to the impressive series of conceptual developments linked with this discovery:

i) The existence of a global symmetry property: chirality;
ii) The spontaneous symmetry breaking of this global symmetry;
iii) The ABJ anomaly;

iv) The existence of a non-Abelian fundamental force (QCD) acting between the constituents of the π–meson (quarks and gluons) and being generated by the gauge-principle which does not destroy chirality–invariance;

v) The existence of another property of the non-Abelian force (QCD): the instantons;

vi) The fact that chirality–invariance can be broken in a non-spontaneous way, thanks to the instantons.

Global chirality–invariance, spontaneous symmetry breaking, anomalies, gauge principle for non-Abelian forces, instantons: all originated from the π–meson and reached the final step with the η'–meson.

It should be noticed that nearly all the credit for the π discovery went to Cecil Powell, a great leader and a very distinguished physicist.

But the contribution of Beppo Occhialini deserves a recognition from the physics community.

Thus, 60 years later, we propose the following.

We started with the nuclear forces where the π–meson has played a central role; sixty years later we have the fundamental force QCD acting between the π–constituents: quarks and gluons.

In QCD the $(\eta - \eta')$ problem has been a challenge for experimental and theoretical physicists.

The role played by the X^0–meson is crucial. First, very few believed it could be a pseudoscalar meson. Its mass and its width were too big and there was no sign of its 2γ decay mode.

Once the X^0 was established to be a pseudoscalar meson, its gluonic affinity was needed and this was finally understood thanks to an important QCD development: the instantons.

This theoretical picture has been experimentally proved to be correct with the discovery of the leading η' production in gluon–induced jets.

To sum up, the η' represents the conclusion of the π–meson challenge, and the basic steps are:

1 - The X^0–meson is discovered.
2 - The 2γ decay mode of the X^0–meson is discovered. The X^0–meson becomes the ninth member of the pseudoscalar multiplet and is called η'.
3 - The η'–meson is theoretically understood as being a mixture of $(q\bar{q})$ with a strong gluonic component, thanks to the QCD instantons.
4 - The strong gluon content in the η'–meson is experimentally proved to be present.

Both the experimental and theoretical front contributed to the physics of the η'–meson.

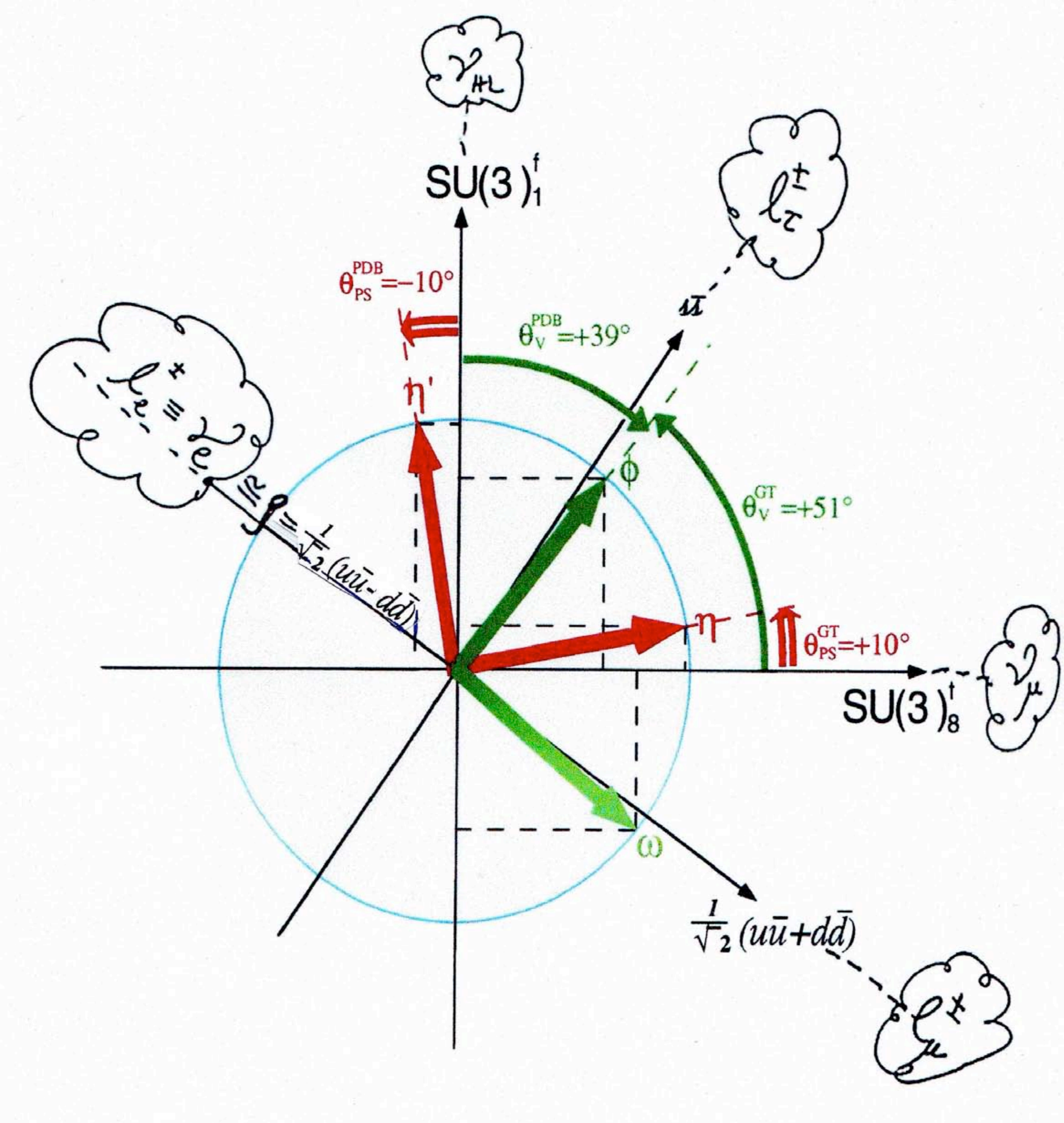
We would like to propose
to the physicists
who have contributed
to the four basic steps
quoted above,

that the η'–meson

be called

the Beppo Particle,
to celebrate the outstanding
contributions

of **BEPPO OCCHIALINI**
to **PHYSICS**,
his **HUMANITY**,
MODESTY
and **DEVOTION** to **SCIENCE**.



PDB ≡ Particle Data Book
GT ≡ Gerardus 't Hooft

What Yukawa was thinking is right, in terms of an 'effective' theory, the fundamental one being drastically different.

We now know that Yukawa's theory worked so well because the pion is much lighter than the nucleon.

The question thus arises: Why is the π–meson so light?

The answer is threefold:

i) It could be thought that the π–meson should be light since it consists of a quark–antiquark ($q\bar{q}$) pair of the first family, which is made of very light quarks.

$\pi \equiv q_I \bar{q}_I$ { $q_I \equiv$ quark of the first family},

the q_I–mass being $\lesssim$ 10 MeV. However there is a problem. In fact the confinement energy needed to keep ($q_I \bar{q}_I$) together amounts to $\cong$ 1000 MeV, as proved by the mass of the nucleon

$$(q_I \, q_I \, q_I)$$

made of 3 quarks of the first family, all being nearly massless. So, the π–meson should be as heavy as the nucleon since the energy needed to keep quarks together is $\cong$ 1000 MeV.

ii) The quarks of the first family start as being nearly massless. They can therefore exist only as left or right states. This means that matter is chiral at the origin. What happens when we switch on QCD? This symmetry property (chirality) is not spoiled by the interaction between quarks and gluons. Why? Because the quanta of the non-Abelian force (QCD) are vectors. In fact, QCD is generated by a local invariance (the so-called gauge principle).

iii) Chirality is spontaneously broken and since chirality–invariance is a global symmetry, its breaking must produce a physical effect, which is a massless particle, the Nambu-Goldstone-boson [5]. The π–meson is a (quasi perfect) Nambu-Goldstone-boson.

IL NUOVO CIMENTO VOL. XIX, N. 1 1° Gennaio 1961

Field Theories with «Superconductor» Solutions.

J. GOLDSTONE

CERN - Geneva

(ricevuto l'8 Settembre 1960)

Summary. — The conditions for the existence of non-perturbative type «superconductor» solutions of field theories are examined. A non-covariant canonical transformation method is used to find such solutions for a theory of a fermion interacting with a pseudoscalar boson. A covariant renormalisable method using Feynman integrals is then given. A «superconductor» solution is found whenever in the normal perturbative-type solution the boson mass squared is negative and the coupling constants satisfy certain inequalities. The symmetry properties of such solutions are examined with the aid of a simple model of self-interacting boson fields. The solutions have lower symmetry than the Lagrangian, and contain mass zero bosons.

1. – Introduction.

This paper reports some work on the possible existence of field theories with solutions analogous to the Bardeen model of a superconductor. This possibility has been discussed by NAMBU (1) in a report which presents the general ideas of the theory which will not be repeated here. The present work merely considers models and has no direct physical applications but the nature of these theories seems worthwhile exploring.

The models considered here all have a boson field in them from the beginning. It would be more desirable to construct bosons out of fermions and this type of theory does contain that possibility (1). The theories of this paper have the dubious advantage of being renormalisable, which at least allows one to find simple conditions in finite terms for the existence of «supercon-

(1) Y. NAMBU: Enrico Fermi Institute for Nuclear Studies, Chicago, Report 60-21.

To sum up, the reason why the π–meson exists and is light, has to do with the existence of quarks which are matter fields, nearly massless, and therefore obeying chirality–invariance, a global symmetry property of nature.

And it so happens that the strong force respects chirality–invariance because it is originated by a local invariance (for symmetry operations controlled by SU(3) in a fictitious space in three complex dimensions).

The π–meson is there to tell us that the original global symmetry of the matter fields (quarks) is spontaneously broken.

If it were not for the spontaneous breaking of chirality-invariance, the π–meson could not have 140 MeV mass and nuclear physics would not have started as the physics of a 'fundamental' force of nature, having as typical range

$$R \cong (140 \text{ MeV})^{-1} \cong \text{one Fermi.}$$

The π–meson is not the quantum of the fundamental force (QCD). The quantum of this force is the gluon.

Does a meson which is made with quanta of a fundamental force exist?

Is this meson a pseudoscalar state?

Is this meson the lightest state produced by the fundamental force?

The answer is three times ‘yes’, and this meson is the η'–particle.

Its mass is nearly one GeV, like the mass of another particle, the nucleon (made of three light quarks)

$$\eta' \, (g\bar{g}) \;\equiv>\; \text{mass} \;\cong\; 1000 \text{ MeV}$$
$$N \, (qqq) \;\equiv>\; \text{mass} \;\cong\; 1000 \text{ MeV} \;.$$

The reason being that a large fraction of the mass is due to confinement.

In fact,

the mass of a gluon:

$m(g) = \text{zero}$

the mass of a quark:

$q_I \lesssim 10$ MeV

and

$3q \Rightarrow \lesssim 30$ MeV $\Rightarrow$

$\Rightarrow 938$ MeV (proton).

$2g \Rightarrow \lesssim \text{zero}$ MeV $\Rightarrow$

$\Rightarrow 958$ MeV (η').

Thus the mass of the lightest pseudoscalar particle made with two quanta of the fundamental force of nature (whose secondary effects produce nuclear physics) is as heavy as the 'nucleon'.

Sixty years after the particle imagined by Yukawa, we have now identified the lowest pseudoscalar state of what should be a particle made with quanta of the fundamental force acting between the constituents of a π–meson: gluons and quarks.

This pseudoscalar state is the η' and this particle is as heavy as the heaviest known in 1947.

The η' typical range is therefore much smaller:

$$R \cong [(1000)\ \ \mathrm{MeV}]^{-1}$$

than that of

the nuclear forces.

For some time, after its discovery in 1964 [6], this pseudoscalar meson, the η',was called X^0, since its pseudoscalar nature was not established and there were mesonic states needed in the tensor multiplet of $SU(3)_f$.

A meson with spin 2 cannot easily decay into 2γ and in fact the 2γ decay mode of the X^0 had not been observed, even when searched for, down to a branching ratio level several times below that of the 2γ decay mode of the η^0, the well-known pseudoscalar neutral meson made of a quark–antiquark pair.

This missing 2γ decay mode of the X^0–meson prevented the X^0–meson being considered as the singlet 9th member of the pseudoscalar $(q\bar{q})$ SU(3)–flavour multiplet structure of Gell-Mann and Ne'eman.

The discovery of the 2γ decay mode of the X^0–meson [7] gave a strong support to its pseudoscalar nature.

(***) A. Zichichi, *A New Decay Mode of the X^0 Meson: $X^0 \rightarrow 2\gamma$*, in Annals of Physics <u>66</u>, 405 (1971).

However its composition in terms of a quark-antiquark pair remained unclear. In fact, if a meson is made of a ($\bar{q}q$) pair, since quarks carry electric charges, the 2γ decay must be easily allowed.

As mentioned above, the branching ratios of the 2γ decay mode of the two heavy pseudoscalar mesons were quite different and the absolute widths of the three pseudoscalar mesons,

$$\Gamma\,(\pi^0 \rightarrow \gamma\,\gamma),$$

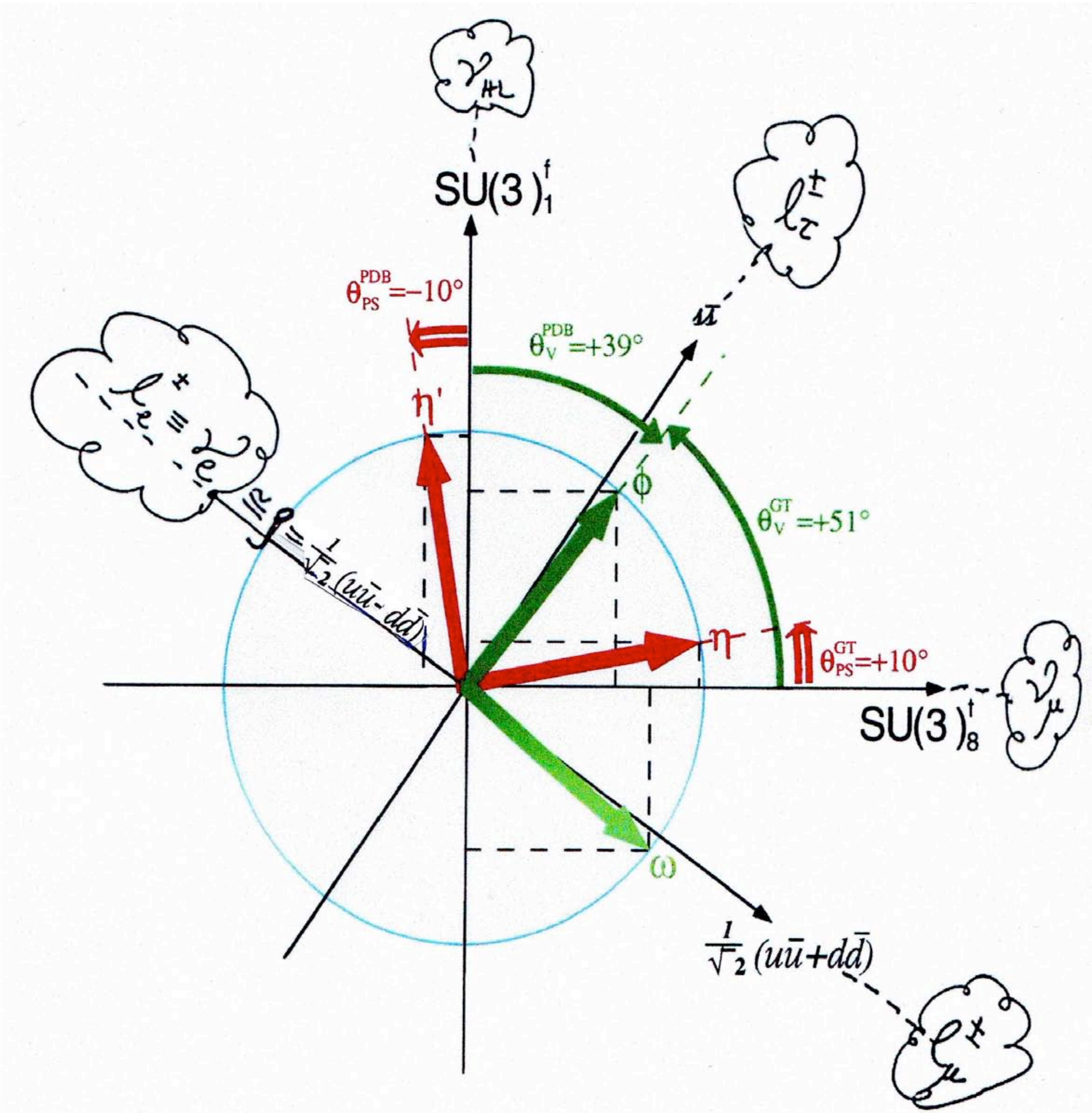
$$\Gamma\,(\eta^0 \rightarrow \gamma\,\gamma\,)$$

and $$\Gamma\,(X^0 \rightarrow \gamma\,\gamma\,)$$

did not follow the theoretical expectations.

Another difficulty was the X^0–mass. If the X^0–meson had to follow the Gell-Mann-Okubo (quadratic) mass formula, the mixing angle needed for these two pseudoscalar mesons was very small because the X^0–mass is nearly one GeV, compared with the ≅ 0.5 GeV η^0–mass.

This mixing, when compared with the (ω–ϕ) mixing, also measured [8] to be large (as expected), was the smallest known in all meson physics [9].



PDB ≡ Particle Data Book
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By now, the pseudoscalar nature of the X^0–meson is accepted and this meson is designated with the symbol η'.

The notation now used is:

i) η^8, to indicate the 8^{th} component of the $(\bar{q}q)$ content of the pseudoscalar meson $SU(3)_f$ multiplet.

ii) η^0, to indicate the $SU(3)_f$ singlet component of the pseudoscalar $(\bar{q}q)$ system.

These two components, η^8 and η^0, are not enough to describe the η' composition.

In fact, we think we know the reason why the $(\eta-\eta')$ mixing angle is so anomalously small, namely the large gluonic content of the η'.

In QCD, the η and η' have played a decisive role. In the early days there was the so-called η–problem [10].

The theory appeared to demand a pseudoscalar η as an isosinglet made of non-strange quarks, and an η' as an ($\bar{s}s$) state. As it is the case for the vector mesons.

Consequently the η–meson had to be close to the pion mass and the η' mass had to be near the K mass.

The fact that experiments gave a quite different picture was attributed to the ABJ anomaly [11, 12] by Gell-Mann, Fritzsch and Leutwyler [10] and finally explained as an instanton effect by G. 't Hooft [13, 14].

Instantons induce a strong coupling between the η' and the two gluon state, and give this state a high mass, both of which may explain why the total width of the η' is so much bigger than that of the η.

And consequently why the γγ branching ratio of the η' is so small [15].

Concerning experiments, for a number of years many attempts have been made to find out the gluonic content of the η', for example via a comparative study of the radiative decays of the (J/ψ) into η and η'.

However all the methods adopted were based on indirect evidence.

It took many years for the first direct evidence of a strong gluonic composition of the η'–meson to be discovered [2].

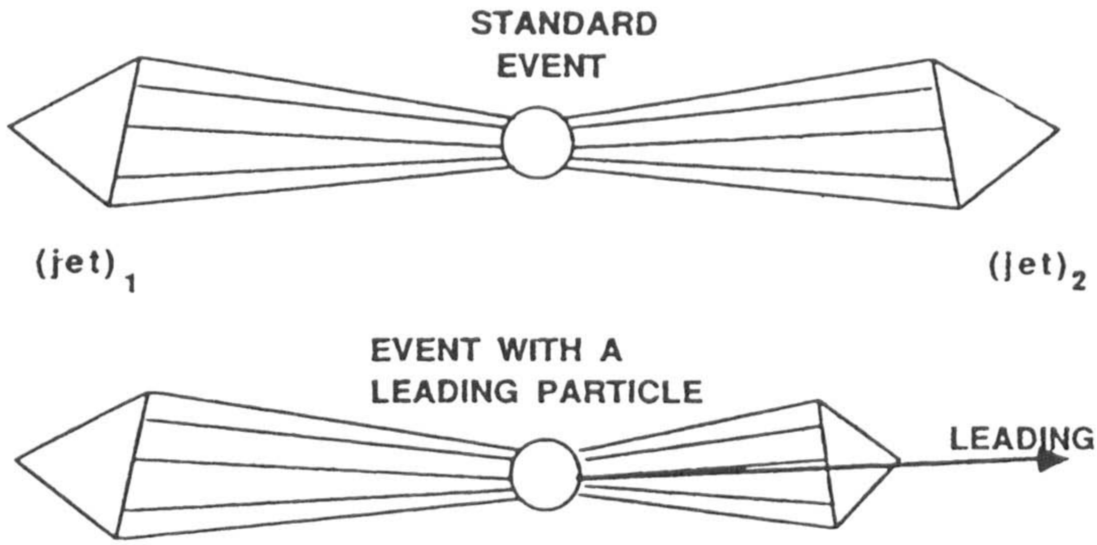
If the η' has a strong gluon pair component, we should expect to see a typical QCD non-perturbative effect: the leading production in gluon-induced jets.

In fact the leading effect had been observed in all hadronic processes where some conserved ***quantum numbers flow*** from the initial to the final state did occur.

If the gluon quantum numbers flow from an initial state made of two gluons into a final state made of η', this meson should be produced in a leading mode when the initial state is made of gluons.

Question: is it possible to have a leading effect also in (e^+e^-) annihilation?

The answer came from PETRA, where the production of D* from charm-quark in (e^+e^-) annihilation gave a clear leading effect:



The data are shown in Figure 1 (not corrected for the leading effect) and in Figure 2 (corrected for the leading effect).

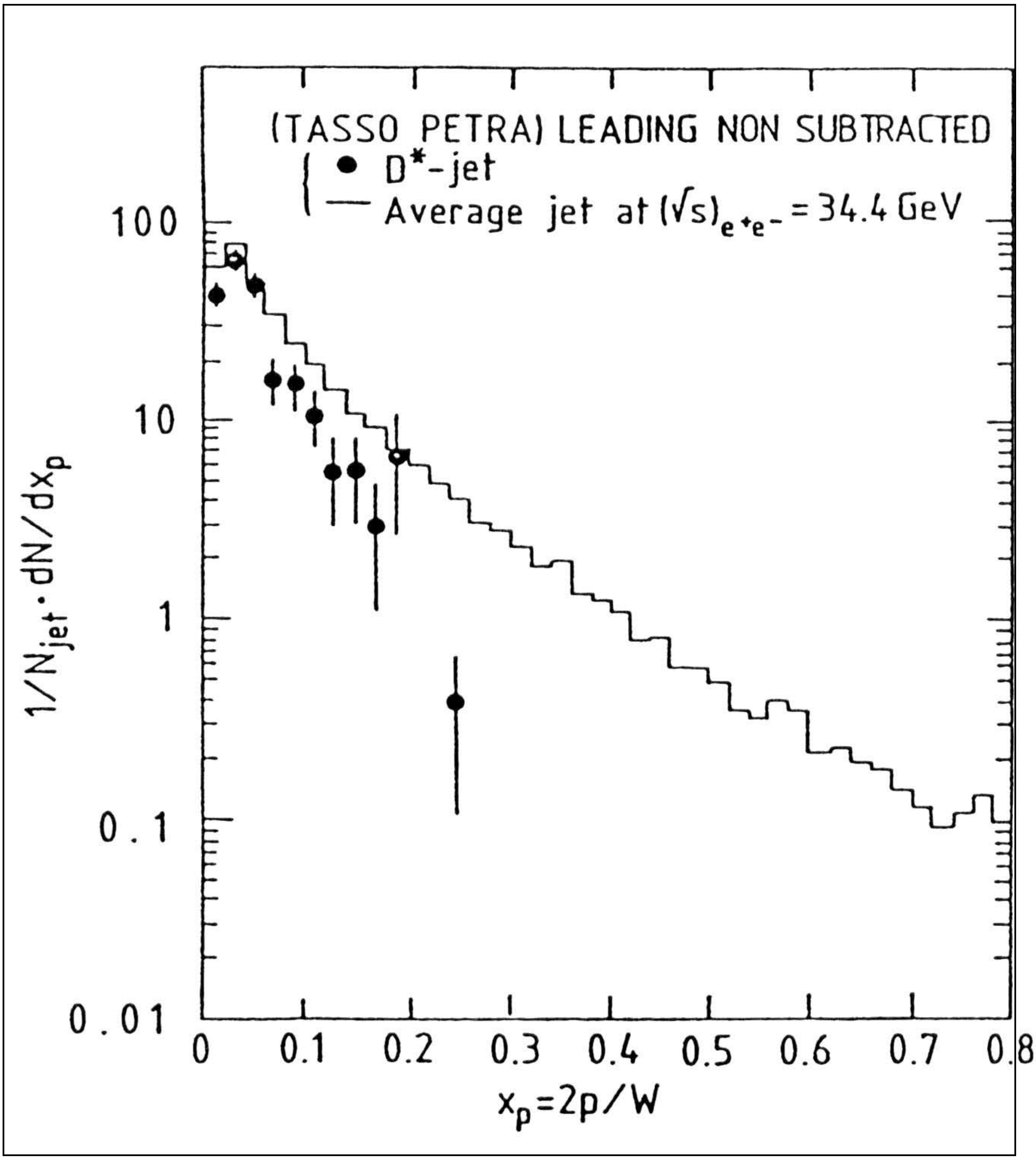


Figure 1: PETRA-TASSO collaboration. The distribution

$$\frac{1}{N_{jet}} \cdot \frac{dN}{dx_p}$$

measured in standard jets and in jets containing a D^* at $(\sqrt{s}\,)_{e^+e^-} = 34.4$ GeV (Figure from Reference 1).

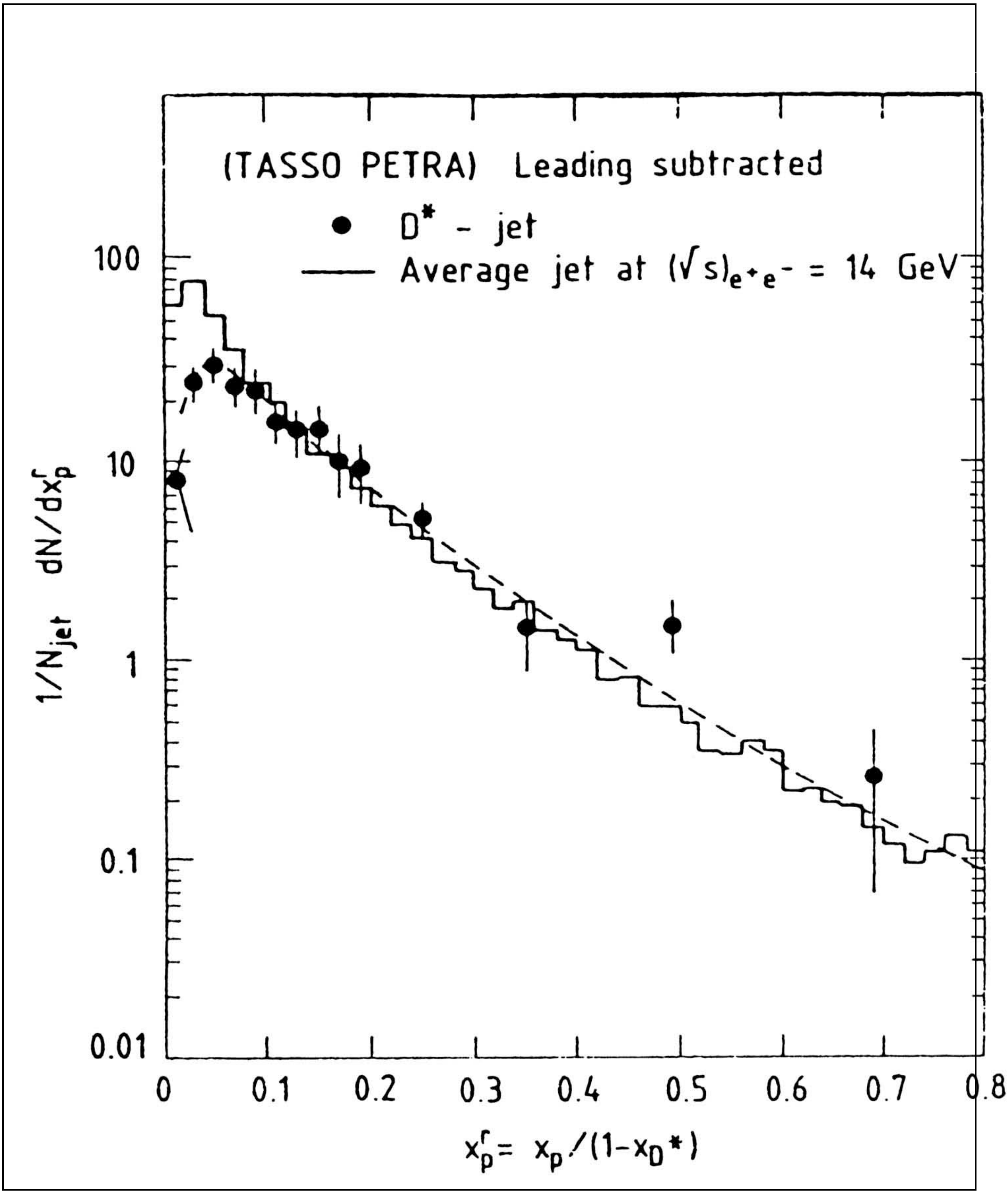


Figure 2: (Figure from Reference 1). As Figure 1 but at $(\sqrt{s}\,)_{e+e-} = 14$ GeV.

The only place where a leading effect had never been detected is in gluon-induced-jets.

It is not easy to be sure that a jet is of gluonic origin.

Detailed studies using the L3 detector at LEP allowed one to select a set of gluonic jets.

Here the evidence for η' leading production has been reported.

It was the last missing point in all this matter, where the use of the "**Effective Energy**" has allowed one to put an enormous variety of different initial states into the same box, where the only distinction left was in terms of quarks and gluons as primary elements to produce jets.

I will limit myself to report only one graph where η and η' production in gluon-induced-jets are compared (Figure 3).

For a detailed report see Reference [2].

The interest of this finding is that the η'–meson, in order to be leading in a gluon-induced-jet, must have a strong coupling which can only be provided by its gluonic composition.

It thus appears that the η' is the lowest pseudoscalar state generated by the fundamental force (QCD) which, as a by-product, produces the nuclear forces and therefore the π. In a sense, the π should have been the η'.

This is exactly the effect which has been discovered in the production of the η'–mesons in gluon-induced jets.

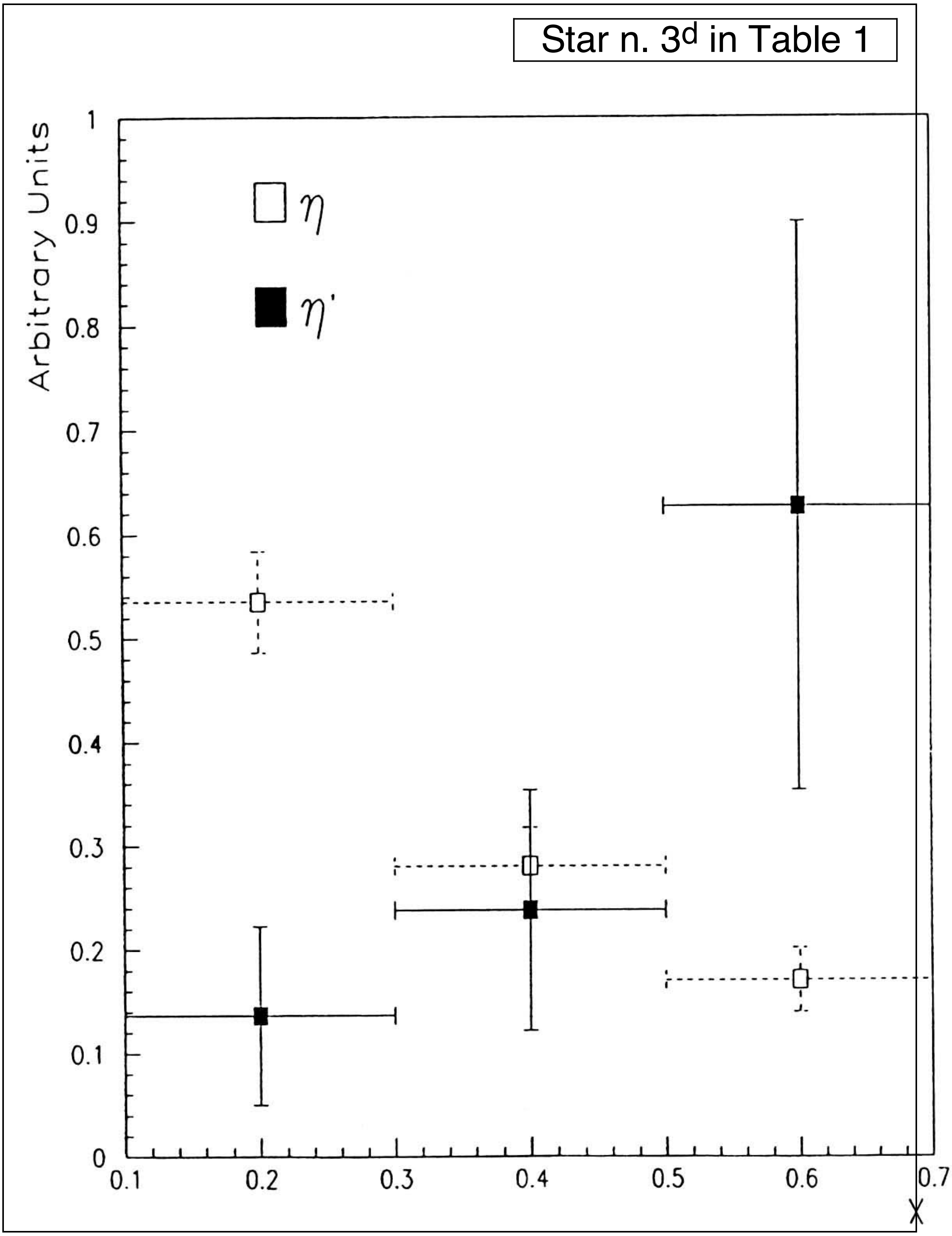


Figure 3: x−distributions for η and η' production, showing the leading effect (Figure from Reference 2).

Sixty years after the original idea of Yukawa that the quantum of the nuclear forces has to exist, we have found that this meson, called π, has given rise to a fantastic development in our thinking, the last step being the η'–meson. But the pseudoscalar nonet of mesons has been for many years a big problem for QCD.

To solve it, many theorists had to think and work hard. Let me name them: Callan, Dashen, Gell-Mann, Gribov, Gross, Fritzsch, Jackiw, Leutwyler, Polyakov, Vainshtein, Veneziano, Witten, Zakharov and, most importantly, Gerardus 't Hooft who was able to finally explain the mass, the width and thus the $\gamma\gamma$ branching ratio of the η', introducing the instantons in QCD.

CONCLUSION

The η'–meson

should be called

the Beppo Particle,
to celebrate the outstanding contributions

of **BEPPO OCCHIALINI**
to **PHYSICS**,
his **HUMANITY**,
MODESTY
and **DEVOTION** to **SCIENCE**

«Erice, Città della Scienza per la Pace»

Città di Erice

Il Sindaco

Chiarissimo Professore Antonino Zichichi
Presidente della Fondazione Ettore Majorana
E Centro di Cultura Scientifica
Via Guarnotta, 26 – 91016 Erice

Chiarissimo Professore,

La ringrazio per le note relative agli scienziati cui sono dedicate alcune strade di Erice. Nella mia qualità di Sindaco e d'intesa con il Presidente della Regione On. Salvatore Cuffaro, ho il piacere di comunicarLe l'approvazione da parte nostra delle sue proposte relative alla dedica di Aule, Istituti, Chiostri, Sale di discussione, Strade e Piazze a figure eminenti della cultura scientifica che hanno contribuito a creare nel mondo lo "Spirito di Erice" per una scienza senza segreti e senza frontiere.

È con grande piacere che, a tal proposito, desidero informarLa che l'attuale via Salerno sarà intitolata alla memoria del grande scienziato Giuseppe Paolo Stanislao Occhialini con la motivazione da Lei proposta e che il Comune ha fatto sua.

Nel comunicare con viva soddisfazione culturale queste nostre definitive approvazioni colgo l'occasione per porgere i più cordiali saluti.

Erice, 13 febbraio 2007

Ignazio Sanges

MOTIVAZIONE
per dare il nome di Beppo Occhialini all'attuale Via Salerno di Erice

GIUSEPPE PAOLO STANISLAO OCCHIALINI
(Fossombrone 1907 - Parigi 1993)

Nel 1933 scopre con Patrick Blackett, nel Cavendish Laboratory a Cambridge in Inghilterra, la produzione simultanea di elettroni ed antielettroni nei raggi cosmici usando la tecnica delle cosiddette "Camere di Wilson" immerse in campo elettromagnetico. Nel 1947 scopre, insieme a Lattes e Powell, il primo esempio di "colla nucleare" noto anche come "mesone-pi-greco" usando la tecnica delle "lastre fotografiche" delle quali era un esperto a livello mondiale. Tornato a Milano fonda la Scuola di Fisica tra le più prestigiose al mondo. Pioniere negli studi spaziali, il primo satellite italiano per lo studio dei raggi gamma porta il suo nome "Beppo-SAX".

INTERNATIONAL SCHOOL OF COSMIC PHYSICS «GIUSEPPE P.S. OCCHIALINI»

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PAUL A.M. DIRAC	*ORESTE PICCIONI*	*BJORN H. WIIK*
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DIRECTOR OF THE SCHOOL

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CERN, 1211 Geneva 23

Geneva, 14 February 2007

HUNDREDTH ANNIVERSARY OF GIUSEPPE P.S. OCCHIALINI
THE BEPPO OCCHIALINI SCHOLARSHIPS

Dear Professor Zichichi,

In the scope of the naming of National Scholarships after eminent scientists, I have the pleasure of confirming that 10 Beppo Occhialini Scholarships were awarded, in 2006, in the following countries:

- Azerbaijan — Mustafa Baghirov
- Belarus — Vladimir Burakevich
- Bulgaria — Pavel Kerchev
- Estonia — Moonika Teppo
- Kazakhstan — Ainur Daribay
- Kyrgyzstan — Uulu Nurbek
- Malaysia — Stella Ho
- Pakistan — Adnan Sarwan
- Senegal — Fama Gning Dia
- The Ukraine — Oleksandr Dikaryev

Yours sincerely,

g.c. Manoli

Claude G. Manoli
Secretary General

Main centres:
OPERATIONAL CENTRE – CERN, Bldg.#29, CH-1211 Geneva 23, Switzerland - Tel: +41/227679957 - Fax: +41/227679965 - E-mail: info@worldlab.ch
CENTRAL EUROPE - ICTP, I 34100 TRIESTE - PO BOX 586 - Tel: +39/40/2240318 or 2240319 or 2240329 - Fax: +30/40/224163 - Telex: 460392
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UKRAINE - 252054 KIEV - 32-A Str. Turguenevskaya - Tel: +380/44/2167012 - Fax: +380/44/2167012 - Telex: 131376 IDEA SU
USA - Colombia University in the City of New York, NY 10027 NEW YORK - 538 West 120th Street - Tel: +1/212/8543339 - Fax: +1/212/9323169
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