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SYMPOSIUM FOR THE CENTENNIAL CELEBRATION OF HIDEKI YUKAWA

HIDEKI YUKAWA
AND
NUCLEAR PHYSICS

FROM THE YUKAWA PARTICLE TO THE QGCW

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ABSTRACT

The remarkable consequences of the Yukawa particle, theoretically proposed in 1935, are reviewed. The production, the decay and the intrinsic structure of the Yukawa particle opened new frontiers with laws and regularities which brought us to the discovery of subnuclear physics and now to the quark-gluon-coloured world (QGCW).

Tokyo, June 3, 2007

ONE HUNDRED YEARS AFTER THE BIRTH OF HIDEKI YUKAWA

CONTENT

1

INTRODUCTION

The Yukawa 'particle' theoretically proposed by Hideki Yukawa in 1935 [1], represents a gold mine which has its roots in

the **production**,

the **decay** and

the **intrinsic structure**

of the Yukawa particle.

The gold mine is still
being explored nowadays,
and
its present frontier is the
quark-gluon-coloured-world
(QGCW)
whose properties could open
unprecedented horizons
in understanding the
Logic of Nature.

2

PRODUCTION

Thanks to Yukawa,
to search for particles
with masses
in-between the electron
and the nucleon
masses became
a very hot topic,
during first third
of the XXth Century.

In fact, Yukawa proposed to study the production of a particle with a mass in-between (this is the origin of ‘mesotron’, now meson) the light electron, m_e, and the heavy nucleon, m_N, (proton or neutron).

This mass value
was deduced by
Yukawa
from the range
of the
nuclear forces.

The first
experimental evidence
for the existence of
a cosmic ray particle
having a mass of
about 130 times
the electron mass
was obtained
by J.C. Street
and E.C. Stevenson
in 1937 [2].

One year later,
S.H. Neddermeyer
and C.D. Anderson
(the same fellow who
had discovered the
anti-electron in 1933 [3])
confirmed the existence
of a cosmic ray particle
in the mass range
predicted by Yukawa
and were able to give a
much better determination
of its mass:
240 electron masses [4].

The meson theory of
the strong nuclear forces
proposed by
Hideki Yukawa
appeared to have excellent
experimental confirmation
but the Yukawa idea
sparked an enormous
interest in the search
for cosmic rays
having masses in this
‘intermediate’ range,
and here a **gold mine**
was to be found.

In the search for the **gold mine opened by Yukawa,** a group of young Italian physicists, Marcello Conversi, Ettore Pancini and Oreste Piccioni, decided to study how the negative 'mesotrons' were captured by nuclear matter. Using a strong magnetic field in order to clearly separate the negative from the positive rays, they discovered that the 'negative' mesotrons were not strongly coupled to the nuclear matter [5].

Fermi, Teller and Weisskopf
pointed out that
‘The decay of negative
mesotrons in matter’
(this is the title
of their paper) [6]
was twelve powers of ten
longer
that the time needed
for the so much wanted
Yukawa particle
to be captured by a nucleus
via the mechanism
of the nuclear forces.

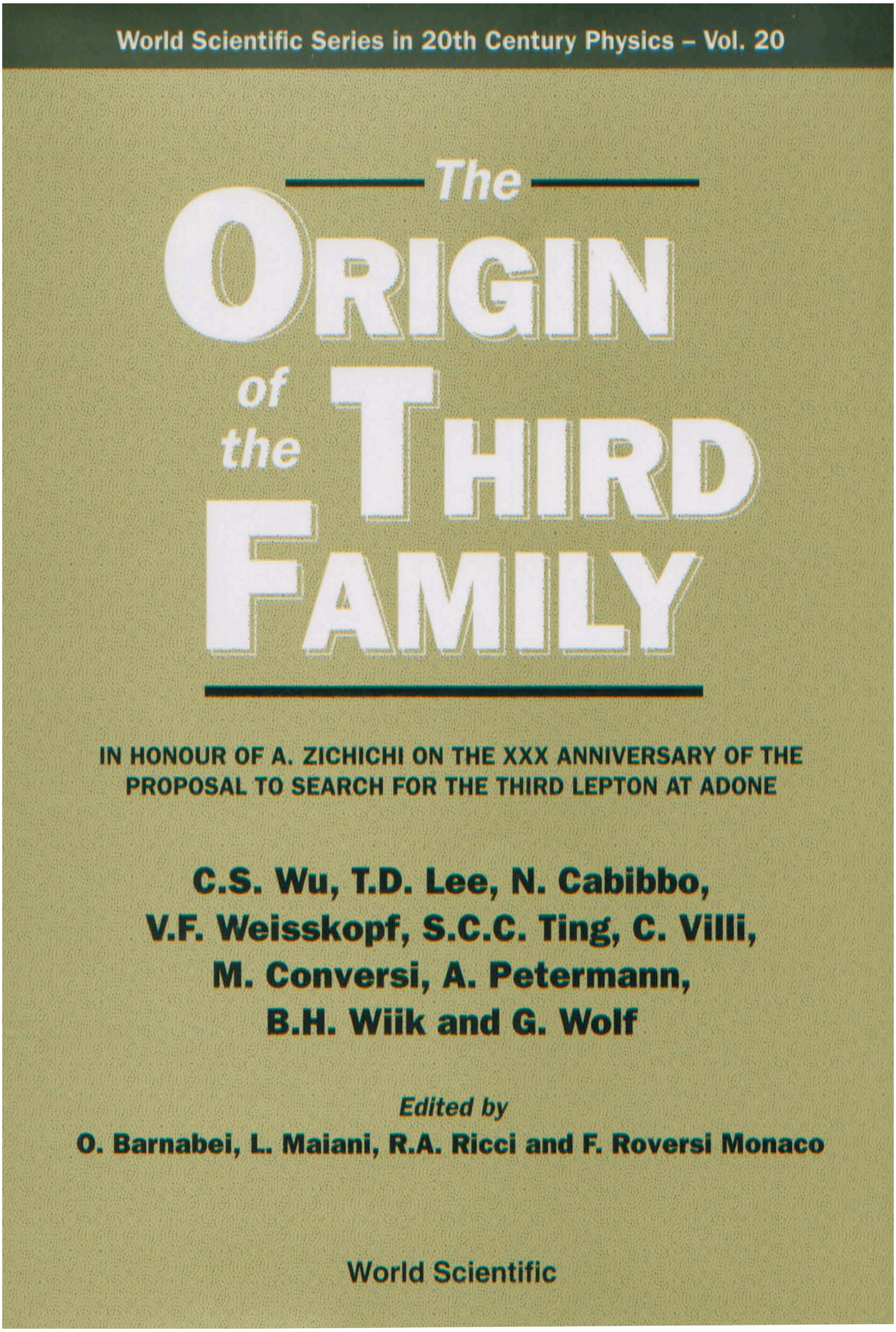
In this paper,
Fermi, Teller
and Weisskopf
introduced
the symbol μ
(for mesotron)
to specify the nature
of the negative
cosmic ray particle
being
experimentally
investigated.

In this field
of frontier physics
there is a special link
between Japan and Italy.
In fact, in addition to
Conversi, Pancini, Piccioni
and Fermi, another Italian,
G.P.S. Occhialini,
was needed to complete
the understanding of
the **gold mine**
opened by Yukawa.

For this further step
to be accomplished,
the technology needed was
the photographic emulsion
and Occhialini was
the world expert in this technique.
With Lattes and Powell,
Occhialini discovered [7]
that the negative muons were the
decay products of another meson,
the 'primary' one
(this is the origin of the symbol π).
It is this particle which is
produced by the nuclear forces,
as wanted by Yukawa.

The π discovery
provided the
'glue'
for the
nuclear forces
and this was great.
But
this was not
the end
of the
gold mine.

In the sixties,
it was realized that
if it were not for the π meson
it would not have been
easy to have so many muons.
Their existence
could only go via
photo-production processes.
If another ‘meson’
like the Yukawa one
existed in the
‘heavy’ mass region,
a third lepton [8],
heavier than the muon,
could have easily been produced
as decay-product of this
heavy meson strongly produced
by the nuclear forces.



World Scientific Series in 20th Century Physics – Vol. 20

The ORIGIN of the THIRD FAMILY

IN HONOUR OF A. ZICHICHI ON THE XXX ANNIVERSARY OF THE PROPOSAL TO SEARCH FOR THE THIRD LEPTON AT ADONE

C.S. Wu, T.D. Lee, N. Cabibbo,
V.F. Weisskopf, S.C.C. Ting, C. Villi,
M. Conversi, A. Petermann,
B.H. Wiik and G. Wolf

Edited by
O. Barnabei, L. Maiani, R.A. Ricci and F. Roversi Monaco

World Scientific

The absence of this
third lepton
was not to be considered
a fundamental absence,
but a consequence of
the fact that
a meson heavier
than the third lepton
was not there,
since the
remarkable coincidence
of the (π–μ) case
was unique.

3

DECAY

The discovery by Lattes, Occhialini and Powell [7] allowed the observation of the complete decay-chain-reaction

$$\pi \rightarrow \mu \rightarrow e \ , \qquad (1)$$

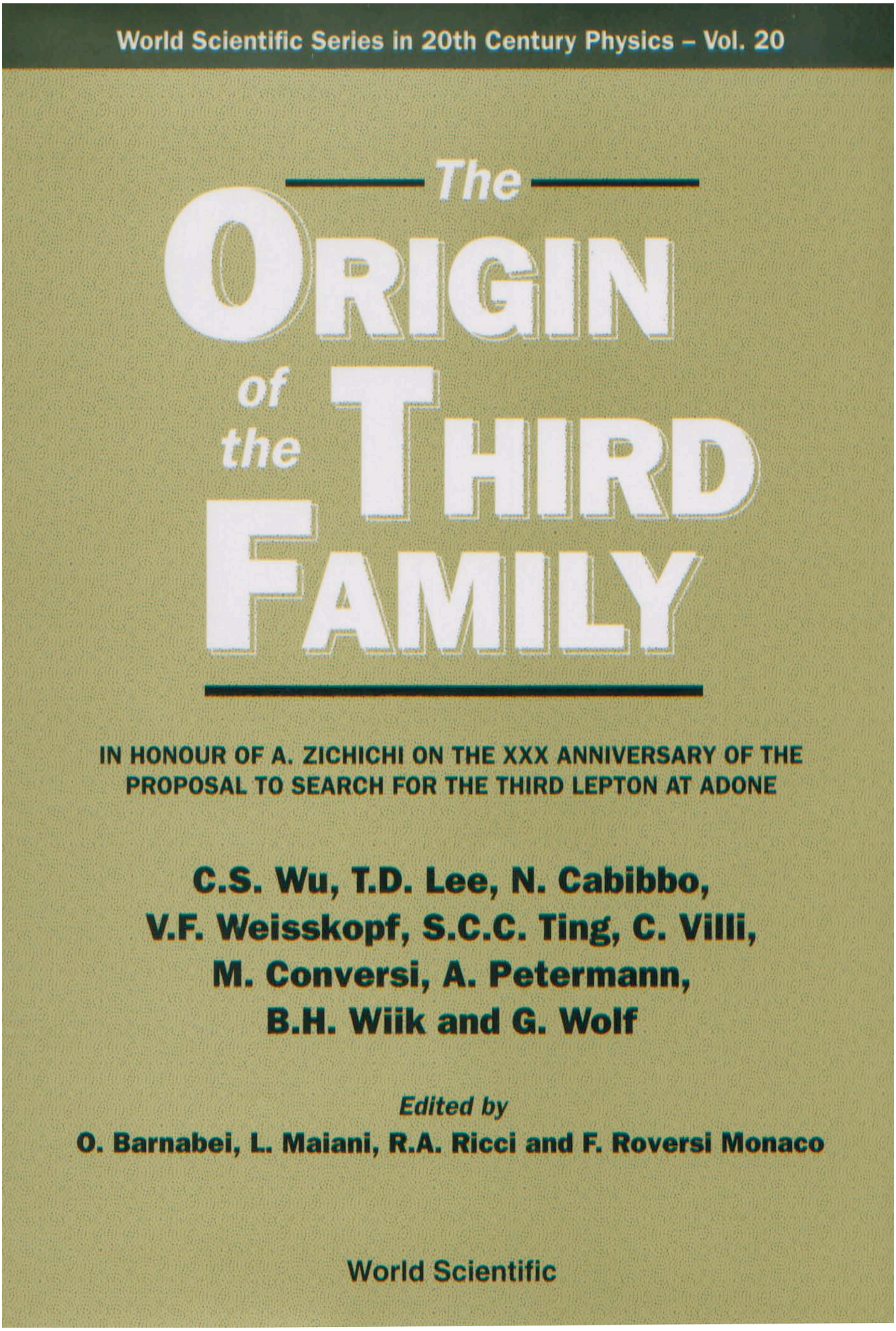
which was the basis to understand the real nature of the cosmic ray particle observed in 1938 by Anderson and Neddermeyer [4], and proved by Conversi, Pancini and Piccioni to have no nuclear coupling with matter [5].

In the Yukawa mass range,
the gold mine had not only
the π–*meson* but also the μ–*meson*.
This last one opened a
completely unexpected new field,
now called the *leptonic world*.
The first member of this new world
is the last particle in the
decay-chain-reaction (1),
the electron.
The second member is the muon (μ)
which is not any more called ‘meson’;
its correct name being ‘lepton’.
The lepton μ has the same
electromagnetic properties of
the ‘electron’ but with a 200 times
heavier mass and no nuclear charge.

This
incredible
property
prompted
Rabi
to make
the famous statement

'Who ordered that?'

reported by
T.D. Lee [8].



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Once again,
this is
not the end
of the
gold mine.
As a consequence of
the decay properties
of the Yukawa particle,
the gold mine
was found
to contain the field
of the Weak Forces.

In fact, the discovery of
the leptonic world
opened the field of the
universal Fermi interaction
and in 1949 Lee,
Rosenbluth and Yang [9]
proposed the existence
of the intermediate boson,
called W
because it was the quantum
of the Weak Forces.
It was later discovered
that the W weak boson
was the source of the
breaking of symmetry laws:
parity P and charge
conjugation invariance C [10].

[10] *Question of Parity Conservation in Weak Interactions*
T.D. Lee and C.N. Yang, *Phys. Rev.* 104, 254 (1956).

In the same year
(1947)
of the π meson discovery,
another meson,
later called 'strange',
was discovered
in the Blackett Lab [11]
studying cosmic rays.
This strange meson,
called θ,
was decaying
into
two Yukawa mesons.

It took nearly ten years
to find out that this
θ meson and another one,
with equal mass
and lifetime,
called τ
and decaying into
three Yukawa mesons,
were not
two different mesons but
two different decay modes
of the same particle,
the K-meson,
which solved the famous
(θ–τ) puzzle [12-14].

This was achieved by
T.D. Lee and C.N. Yang [10],
who proved that
no experimental evidence
existed to establish
the validity of Parity and
Charge Conjugation invariance
in weak interactions.
The experimental evidence
came immediately after [15].

The gold mine
opened by Yukawa in 1935
gave rise, two decades later,
to the discovery that
the invariance laws,
P and C,
are broken in
decay processes,
involving two and three
Yukawa mesons.
The violation of P and C
generated the problem of
PC conservation,
and therefore of
time reversal, invariance, T,
(because of the PCT theorem).

This invariance law
was proposed by Landau [16],
while Lee, Oehme and Yang
(LOY) [17]
remarked the lack of
experimental evidence for
T-invariance.
The experimental proof that
LOY were on the right track
came in 1964 when
Christenson, Cronin, Fitch and
Turlay [18]
discovered that
the meson called K_2^0
was also decaying into
two Yukawa mesons.

The famous Rabi’s statement became

‘Who ordered all that?’

All

being the content of
the **Yukawa gold mine**.

To close with
the gold mine in
the **decay** of
the Yukawa particle,
I would like to recall
the 2γ decay of
the neutral [19-25] Yukawa meson:

$$\pi^0 \longrightarrow \gamma\gamma.$$

This generated
the celebrated chiral anomaly
also known as
ABJ (Adler, Bell, Jackiw) anomaly [26],
with its remarkable consequences [27]
also in the non abelian forces [28].

One consequence is the
important ingredient in
theoretical model building, called
‘**anomaly-free condition**’,
which explains why
the number of fundamental
quark-fermions must be equal to
the number of
fundamental lepton-fermions.
This allowed the
theoretical prediction
to be made for the existence of
the **heaviest quark**,
in addition to the b-quark
in the 3rd family
of elementary fermions,
the top-quark.

4

INTRINSIC STRUCTURE

We now turn to the
analysis of the intrinsic structure
of the Yukawa particle,
which is made of
a pair of the lightest,
nearly-massless,
elementary fermions:
the ‘up’ and ‘down’ quarks.
This allows to understand
why chirality invariance
– a global symmetry property –
should exist in
the field of strong interactions.
It is the spontaneous breaking
of this global symmetry
which generates the
Nambu-Goldstone boson [29, 30].

[29] *A ‘Superconductor’ Model of Elementary Particles and Its Consequences*
Y. Nambu: Proceedings of the Midwest Conference on Theoretical Physics, eds. F. J. Belinfante, S. G. Gartenhaus and R. W. King, Purdue University, Lafayette, Indiana (April 1-2, 1960).

[30] *Field Theories with ‘Superconductor’ Solutions*
J. Goldstone, *Nuovo Cimento* 19, 154 (1961).

The intrinsic structure
of the Yukawa particle
needs the existence of a
non-Abelian fundamental
force (QCD)
acting between the
constituents of the π–meson
(quarks and gluons) and
being originated by
a gauge-principle.
Thanks to this principle,
the QCD quantum is
a vector and does not destroy
chirality–invariance.

To understand the
non-zero-mass of
the Yukawa meson,
another property of the
non-Abelian force (QCD)
had to exist:
the instantons.
Thanks to the instantons,
chirality–invariance
can be broken also
in a non-spontaneous way.
If this was not to be the case,
the π could not be so ‘heavy’;
it would have to be
nearly mass-less.

Thus the problem arises:
can a pseudoscalar meson
exist with a mass
as large as the nucleon?
The answer is Yes:
its name is η'
and represents the final step
in the gold mine started
with the π–meson.
Its mass is not intermediate,
between the very light electron
and the very heavy nucleon;
the η' mass is nearly the same
as the nucleon mass.

This η'–meson
is a pseudoscalar meson,
like the Yukawa π,
and was originally called
X^0.
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.

The missing
2γ decay mode
of the X^0–meson
prevented it
from being considered
the singlet 9th member
of the pseudoscalar
$SU(3)_{uds}$–flavour
multiplet of
Gell-Mann and Ne'eman.

The discovery of
the 2γ decay mode
of the X^0–meson [31]
gave
a strong support
to its
pseudoscalar nature.

Once the
X^0
was established to be
a pseudoscalar meson,
its gluonic content
was
theoretically expected
by the
QCD instantons.

If the η' has a strong
gluon 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 [32]
where some conserved
quantum numbers flow,
from the initial
to the final state,
did occur.

The gluon
quantum numbers flow
would go from
an initial state
made of two gluons
into a final state
made of η',
if this meson had
a strong gluon component.
In this case
the η'
should be produced
in a leading mode.

This is exactly the effect
which has been discovered
in the production of
the η'–mesons
in gluon-induced jets,
as reported in Figure 1,
where η and η' production
in gluon-induced-jets
are compared.
The leading effect is not
present in the η production,
while the η' has
a strong leading effect [33].

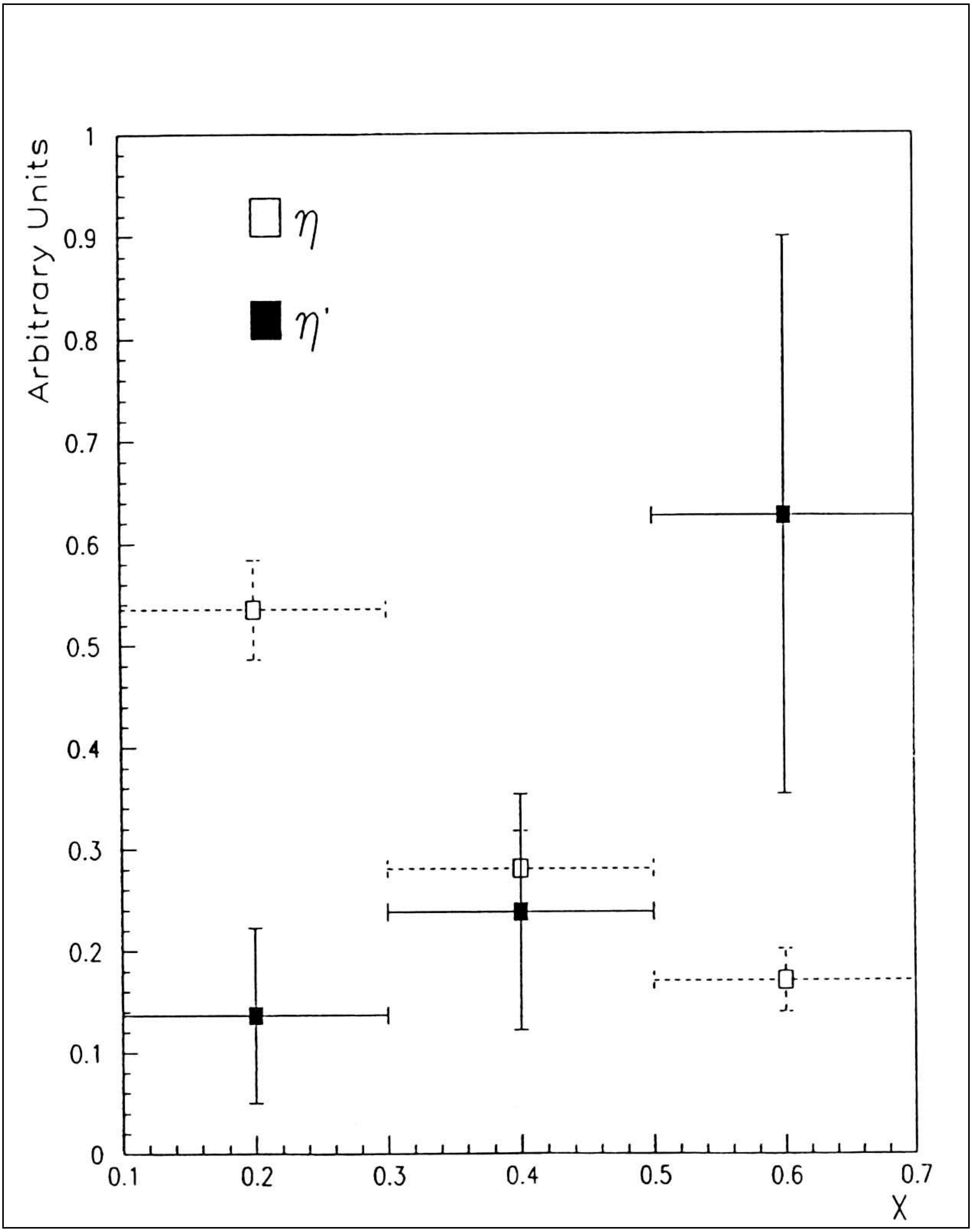


Figure 1: The Feynman x–distributions for η and η' production, showing the η' leading effect (Figure from Reference 33).

The interest of this finding
is that the η'–meson,
in order to be leading
in a gluon-induced-jet, must
– as mentioned before –
have a strong gluonic content.
It thus appears that
the η'
is the lowest pseudoscalar state
having the strongest contribution
from the quanta of the QCD force.
The η' is the particle
which is most directly linked
with the original idea
of Yukawa, who was advocating
the existence of a quantum
of the nuclear force field.

The η',
thanks to
its strong
gluonic component,
is
the Yukawa particle
in the
QCD Era.

Seventy-two 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.

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

1 - 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'.

2 - The η'–meson is theoretically understood as being a mixture of $(q\overline{q})$ with a strong gluonic component.

3 - The strong gluon content in the η'–meson is experimentally proved to be present with the leading effect in the gluon-induced jets.

5

THE YUKAWA LESSON FOR THE QGCW

There is
a further lesson
which is coming
from the
gold mine
opened
by Hideki Yukawa:
the impressive series of
totally unexpected
discoveries.

Let me quote just three of them:

1 The first experimental evidence for a cosmic ray particle believed to be the Yukawa meson was a lepton: the muon.

2 The decay-chain: $\pi \rightarrow \mu \rightarrow e$ was found to break the symmetry laws of Parity and Charge Conjugation.

3 The intrinsic structure of the Yukawa particle was found to be governed by a new Fundamental Force of Nature,

Quantum ChromoDynamics:
QCD.

This is perfectly consistent
with the great steps
in physics:
all totally unexpected.
The totally unexpected
events (UEEC) called by
historians, Sarajevo-type-
effects, characterize
'COMPLEXITY'.

A detailed analysis [34]
shows that
the experimentally
observable quantities,
which characterize the
existence of ‘complexity’
in a given field,
do exist in physics;
the Yukawa gold mine is
a proof of it.

This means that
‘complexity’ exists at the
fundamental level,
therefore,
totally unexpected effects
should show up
in physics:

- **Effects**, which are impossible to be predicted on the basis of **present knowledge**.

- Where these effects are most likely to be no one knows.
  All we are sure of is that
  new experimental facilities are needed;
  and this is what is going on
  in Japan,
  in Europe and
  in other regions of the planet.

- In Europe, with the advent of the LHC, it will be possible to study the properties of the Quark-Gluon-Coloured-World (**QGCW**) [35, 36], which is a world totally different from our world made of QCD vacuum with colourless baryons and mesons.
  Yukawa would tell us to search for specific effects due to the fact that the colourless condition is avoided.

[35] The first experiments to study the QGCW have been proposed and implemented under the guidance of T.D. Lee with the relativistic heavy ion collider (RHIC) at BNL.

From Reductionism to Holism

T.D. Lee, in Proceedings of the 2000–Erice Subnuclear Physics School. ‘*Theory and Experiment Heading for New Physics*’, The Subnuclear Series Vol. 38, page 1, (A. Zichichi ed), World Scientific (2001).

1st problem –

In the QGCW there are all states allowed by the $SU(3)_c$ colour group. The number of possible states is by far more numerous than the number of colourless baryons and mesons which have so far been built in all Labs, since the colourless condition is not needed. **Question**: What are the consequences on the properties of the QGCW?

2nd problem –

Light quarks versus heavy quarks. Are the coloured quark masses **the same** as the values we derive from the fact that baryons and mesons need to be in a colourless state?

It could be that all six quark flavours are associated with nearly ‘massless’ states, similar to those of the 1st family (u, d).

In other words,
the reason why the ‘top’ quark
appears to be so heavy
($\simeq 10^2$ GeV)
could be the result of some,
so far unknown,
condition related
to the fact that
the final state must be
QCD-‘colourless’.

We know that
confinement produces masses
of the order of a GeV.
Therefore, according to
our present understanding,
the QCD ‘colourless’ condition
could not explain
the heavy quark mass.
However, since the origin of
the quark masses
is still not known,
it cannot be excluded that
in a QCD coloured world,
the six quarks are all
nearly massless and that
the colourless condition is
‘flavour’ dependent.

If this was the case,
the masses we measure
are heavier than the effective
coloured quark masses.
In this case,
all possible states
generated by ‘heavy’ quarks
would be produced
in the **QGCW**
at a much lower temperature
than the one needed
in our world made
with baryons and mesons,
i.e. QCD colourless states.

Here again,
we should try to see
if with masses totally
different
from those expected,
on the basis of what
we know about colourless
baryons and mesons,
new **effects**
could be detected due to
the existence of all flavours
(even those which could
exist in addition to
the six so far detected)
at relatively low temperature
in the QGCW world.

3rd problem –

To search for effects on the thermodynamic properties of the QGCW.

Are these properties going to be along the ‘extensivity’ and / or ‘non-extensivity’ conditions?

In the QGCW,
an enormous number of
QCD-open-colour-states
allowed by $SU(3)_c$ will exist;
this number is
by far higher that the number
of baryons and mesons
detected so far.
In principle,
many different phase transitions
could take place and a
vast variety of complex systems
should show up.
The properties of
this ‘new world’ should open
unprecedented horizons
in understanding
the Logic of Nature [37].

4th problem –

Derive the equivalent Stefan-Boltzmann Radiation Law for the QGCW.

In classical Thermodynamics the relation between **energy density** at emission **U**, and **Temperature** of the source **T**, is

$$U = cT^4.$$

In the QGCW, the correspondence should be

$U \equiv p_\perp$ (transverse momentum)

$T \equiv$ average energy in the CM system.

In the QGCW, the production of ‘heavy’ flavours should be studied

$$\text{versus } \langle p_\perp \rangle \text{ and}$$
$$\text{versus } \langle E \rangle.$$

The expectation is

$$\langle p_\perp \rangle \equiv C \cdot \langle E \rangle^4$$

and any deviation would be extremely important.

The study of the properties
of the QGCW should produce
the correct mathematical structure
able to correctly describe
the QGCW.
The same mathematical
formalism should allow to go
from QGCW to the Physics
of Baryons and Mesons (PBM)
and from here to a restricted
component of PBM,
namely Nuclear Physics,
where all properties of the
nuclei should find
a correct description.

How to study the new world: QGCW

With the advent of the LHC supercollider, we propose the development and the realisation of a new technology able to implement the collision between different particle states

(p, n, π, K, μ, e, γ, ν)

and the QGCW

in order to study the properties of the **Quark-Gluon-Coloured-World (QGCW)** [35, 36].

An example
of how to study
the QGCW
is illustrated in Figure 2,
where beams
of known particles
(p, n, π, K, μ, e, γ, ν)
bombard the QGCW.
A special set
of detectors will measure
the properties
of the outcoming particles.

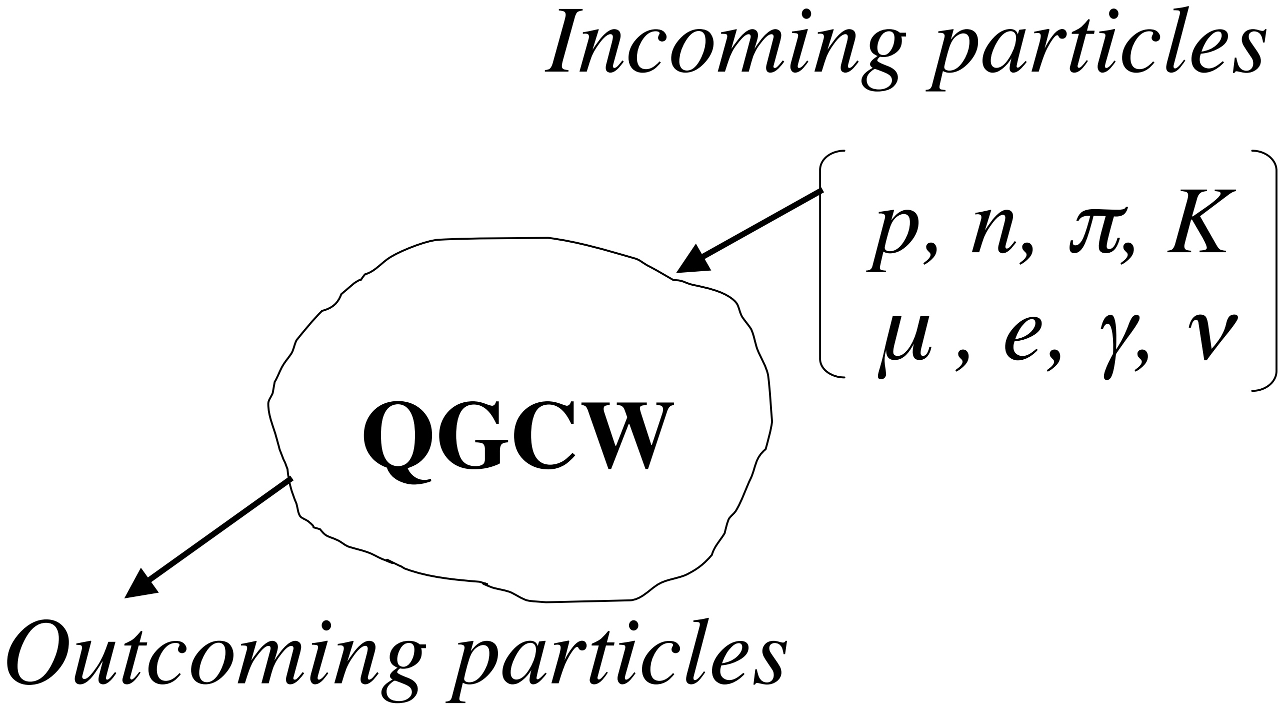


Figure 2: A simplified diagram to illustrate how to study the QGCW; the special set of detectors is not shown.

The QGCW
is produced in a collision
between heavy ions
($_{208}$Pb^{82+})
at the maximum energy
so far available,
i.e. 1150 TeV and
a design luminosity of
10^{27} cm^{-2}s^{-1}.
For this to be achieved,
CERN needs to upgrade
the ion injector chain comprising
Linac3, LEIR, PS
and SPS machine [36].

Once the lead-lead collision
is available,
the problem is to synchronize
the 'proton' beam
with the QGCW produced.
This problem is being studied
at the present time.
The detector technology
is also under intense R&D
since the synchronization
needed is at a
very high level of precision.

Totally unexpected effects
should show up if
Nature follows
the Logic of Complexity at
the Fundamental level [34],
following the example of the
Yukawa gold mine.

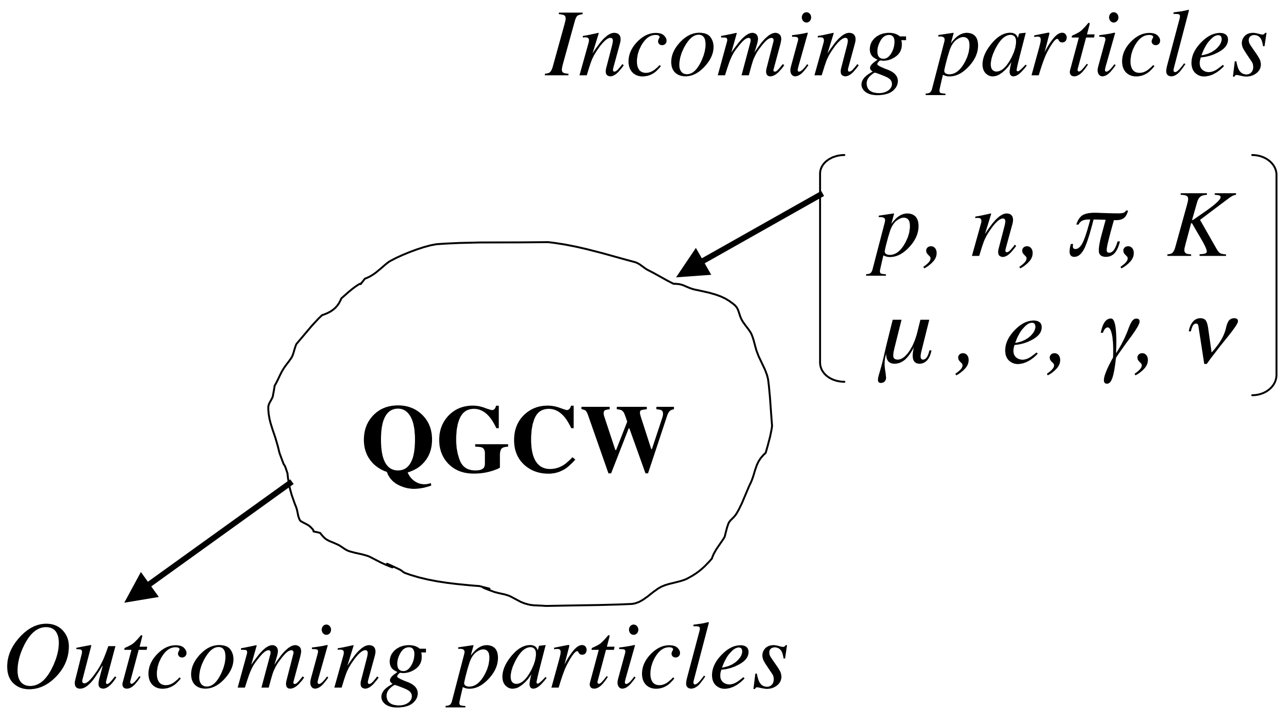


Figure 2: A simplified diagram to illustrate how to study the QGCW; the special set of detectors is not shown.

6

CONCLUSIONS ON THE GOLD MINE OPENED BY HIDEKI YUKAWA

On the occasion of the Yukawa
Centenary Celebrations,
we would like to draw attention
to the impressive series
of conceptual developments
linked with his meson:
Chirality–invariance,
Spontaneous Symmetry Breaking,
Anomalies,
and
Anomaly-Free Condition,
Gauge Principle
(for Non-Abelian Forces),
Instantons
and
Symmetry Breaking of
Fundamental Invariance Laws.

All the pieces of the
Yukawa gold mine
could not have been discovered
if the experimental technology
was not at the frontier
of our knowledge. Example:
the **Cloud-Chambers**
(Anderson, Neddermeyer),
the **Photographic Emulsions**
(Lattes, Occhialini, Powell),
the **High Power Magnetic Fields**
(Conversi, Pancini, Piccioni) and
the **Powerful Particle Accelerators**
and **Associated Detectors**
for the discovery
– **the world over** –
of the intrinsic structure of
the **Yukawa particle**
(quarks and gluons).

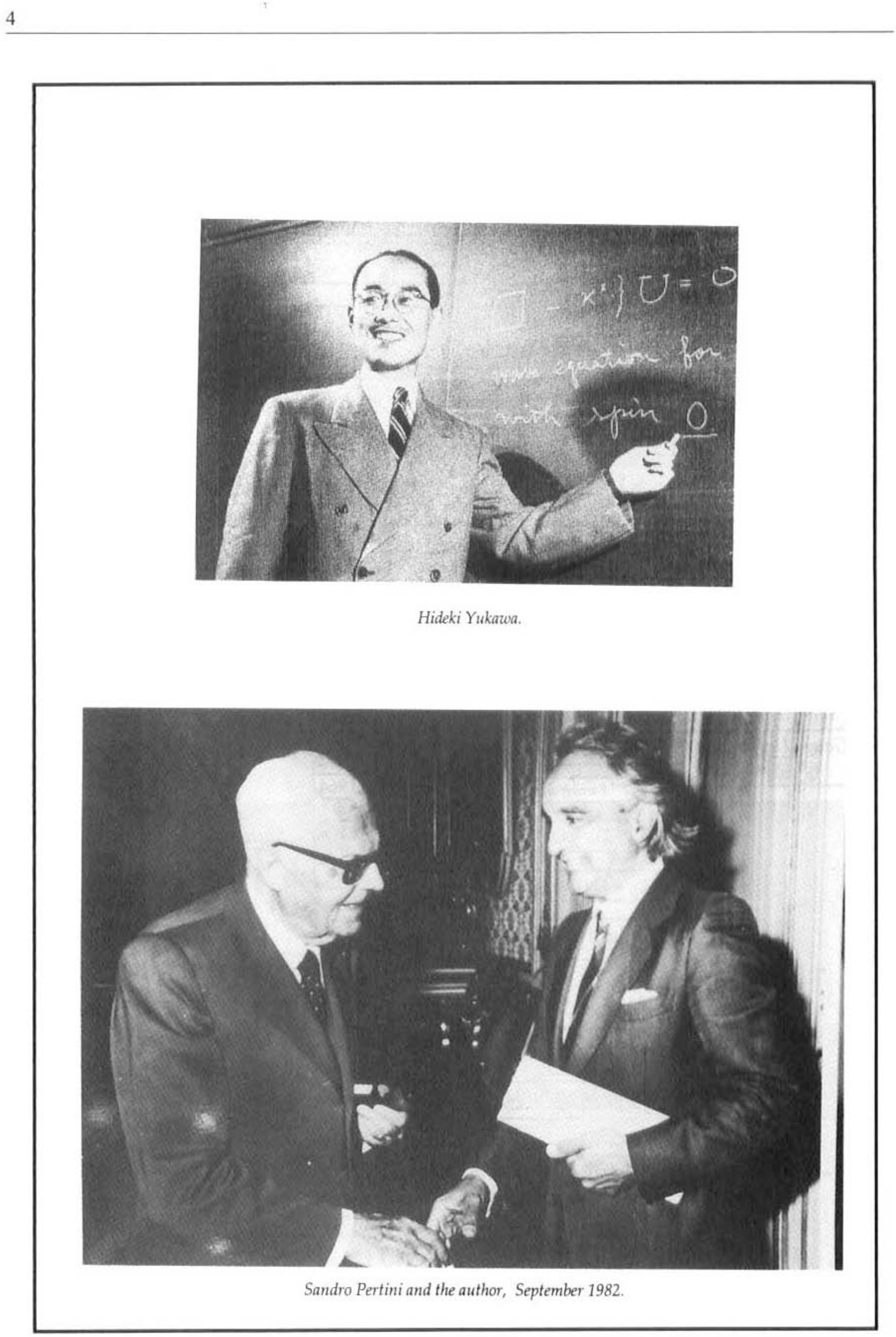
This means that we must be prepared with the most advanced technology for the discovery of totally unexpected events like the ones found in the Yukawa gold mine.

This is the last lesson from Hideki Yukawa

Let me close this lecture by showing Figure 3 which reproduces page n. 4 of my book ‘Subnuclear Physics’ [37], where the picture of Hideki Yukawa is presented together with a photo of the President of the Italian Republic, Sandro Pertini, a strong supporter of the field of physics, which owes so much to Yukawa.

On September 1982 I presented the Erice Statement (signed by 10.000 scientists from 115 countries)
to President Pertini
and this is how the Special Law for the Erice Prize started to be.

The Erice Prize could not have existed without the gold mine opened
by Hideki Yukawa.

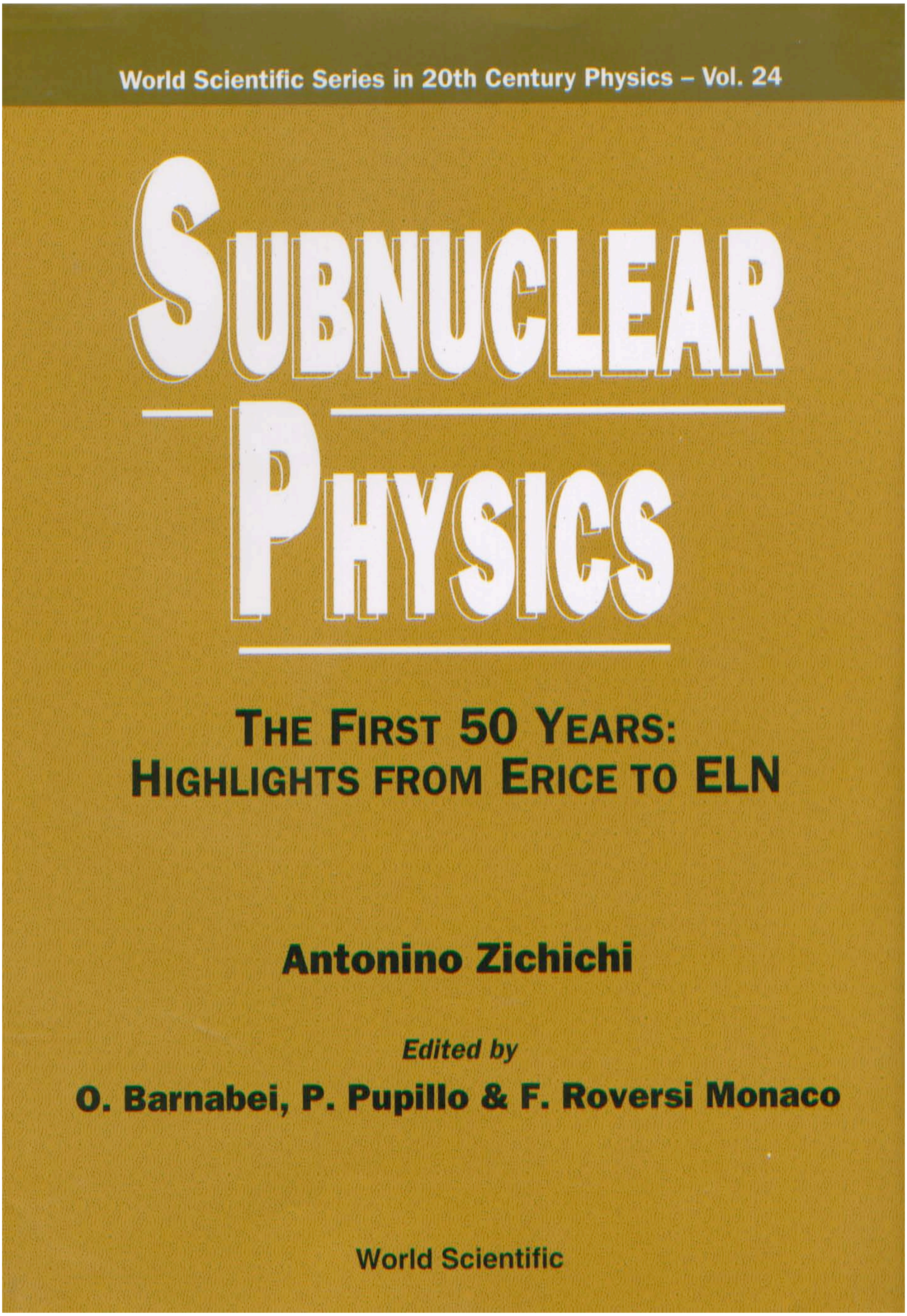


4

Hideki Yukawa.

Sandro Pertini and the author, September 1982.

Figure 3: The close link between Hideki Yukawa and Italy.



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SUBNUCLEAR PHYSICS

THE FIRST 50 YEARS:
HIGHLIGHTS FROM ERICE TO ELN

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Figure 4

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